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Affordable Solid Panel "Perfect Wall" System

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Affordable Solid Panel "Perfect Wall" System

Prepared for:
U.S. Department of Energy Building America Program
Office of Energy Efficiency and Renewable Energy

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This material is based upon work supported by the Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Building Technologies Office under Award Number EE0007568.

The work presented in this EERE Building America report does not represent performance of any product relative to regulated minimum efficiency requirements.

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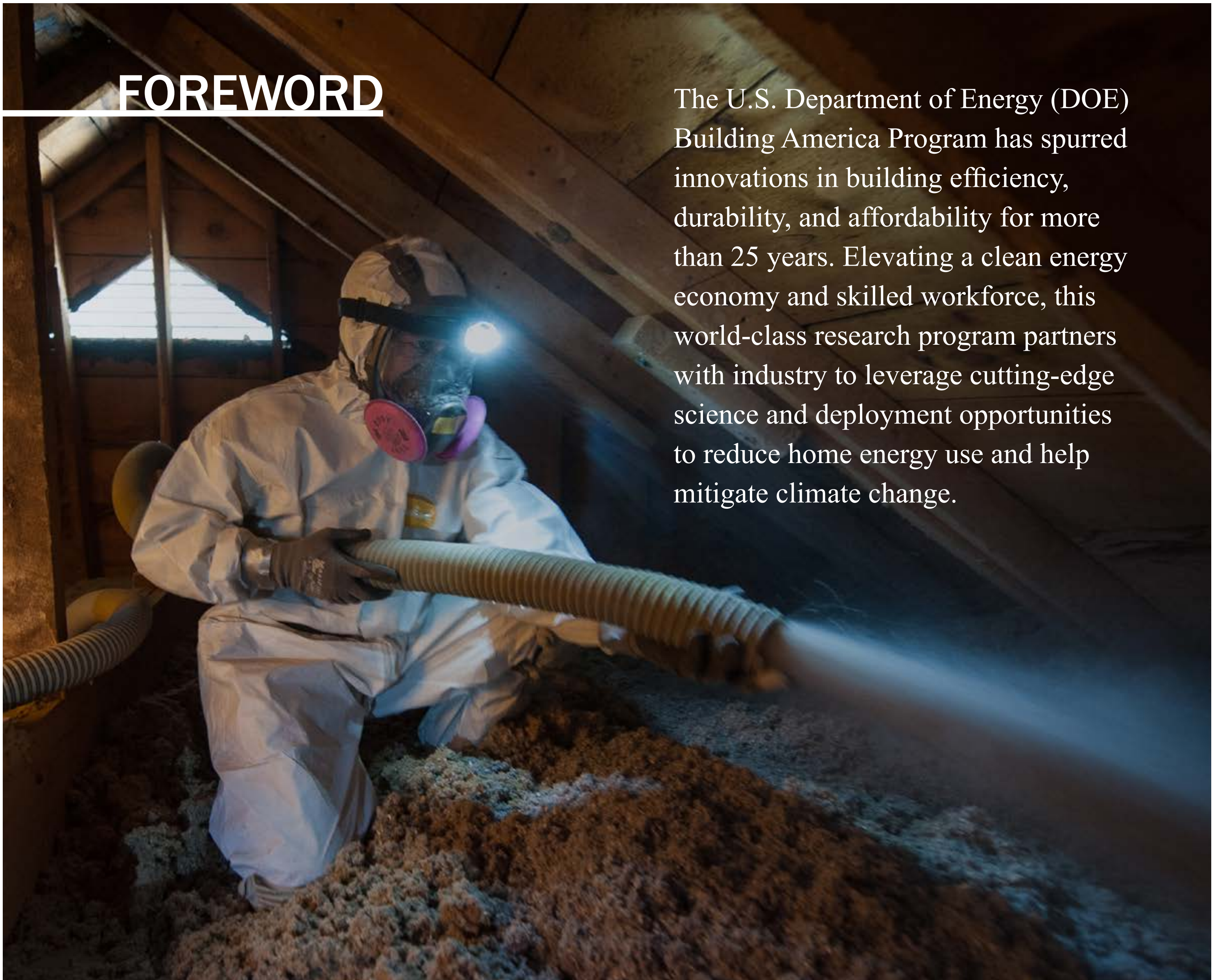
Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

FOREWORD



The U.S. Department of Energy (DOE) Building America Program has spurred innovations in building efficiency, durability, and affordability for more than 25 years. Elevating a clean energy economy and skilled workforce, this world-class research program partners with industry to leverage cutting-edge science and deployment opportunities to reduce home energy use and help mitigate climate change.

In cooperation with the Building America Program, University of Minnesota 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, *Affordable Solid Panel "Perfect Wall" System*, reviews and analyzes a novel building assembly—which features an innovative large-format Solid Panel Structure and utilizes the "perfect wall" concept of having high-performance moisture and thermal control layers on the exterior of the structural components.

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.

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The authors also wish to acknowledge the support that we have received from the project and technical managers at DOE's Building Technologies Office and the National Renewable Energy Laboratory as well as all of the Building America partners. The frequent open and candid conversations about this project with Building America colleagues provided additional insights into potential directions that could enhance this innovative building technology and its market adoption.

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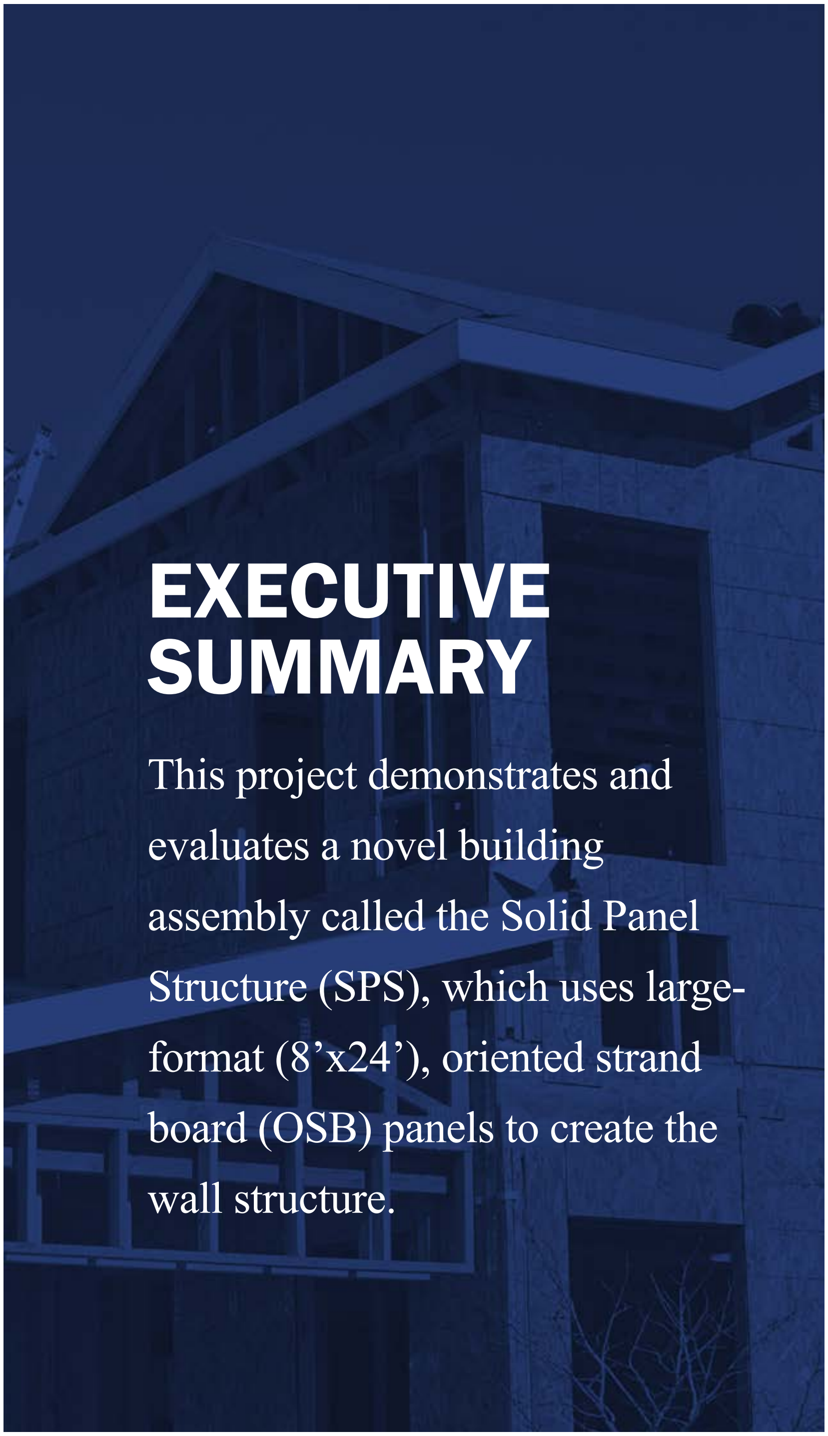
LIST OF ACRONYMS

DOE	U.S. Department of Energy
HERS	Home Energy Rating System
HVAC	heating, ventilating, and air conditioning
MEP	mechanical, electrical, and plumbing
OSB	oriented strand board
RH	relative humidity
SPS	Solid Panel Structure
UMN	University of Minnesota
XPS	extruded polystyrene
ZERH	DOE's Zero Energy Ready Home Program



EXECUTIVE SUMMARY

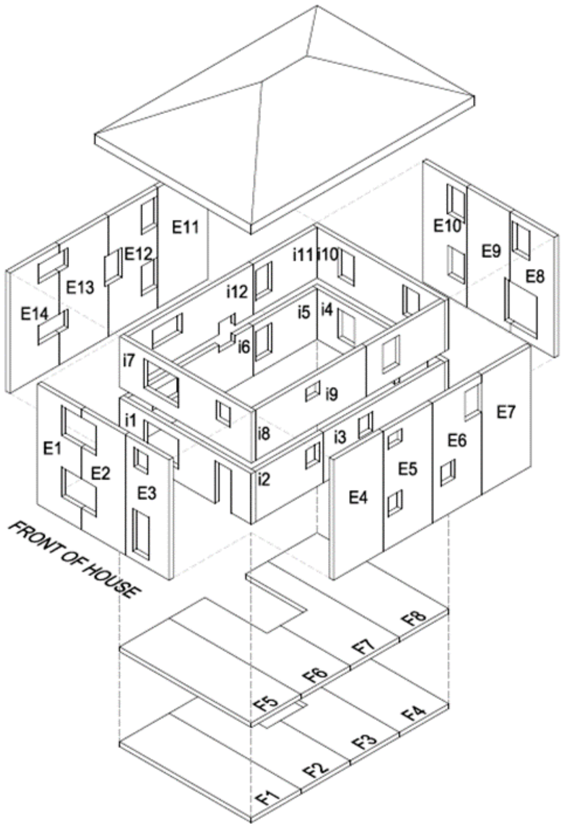
This project demonstrates and evaluates a novel building assembly called the Solid Panel Structure (SPS), which uses large-format (8’x24’), oriented strand board (OSB) panels to create the wall structure.

The SPS is an innovative interpretation of the “perfect wall” concept, in which environmental control layers are located on the exterior side of the structural components, as opposed to traditional cavity-insulated, stud-framed walls. The primary objective of this study is to validate the SPS technology in terms of its constructability, cost, and performance. Specifically for this project, we partnered with two affordable housing nonprofits in Minnesota—Twin Cities Habitat for Humanity and Urban Homeworks—to build five new houses using SPS walls, as well as two high-performance stud-framed comparison homes. We also reviewed cost and performance data from 13 SPS homes built prior to this project by MonoPath and Spero Environmental Builders. Reviewing the outcomes of these 20 homes total, we find promising results in terms of constructability, cost, and performance, although more structural performance data are needed before this new technology can see widespread adoption.

Objectives of the Research Project

This project is a comparative analysis between conventional stud framing and the SPS “perfect wall” system with external thermal, air, and moisture management. Our project partners built new homes with identical floor plans to provide a comparative analysis of the following:

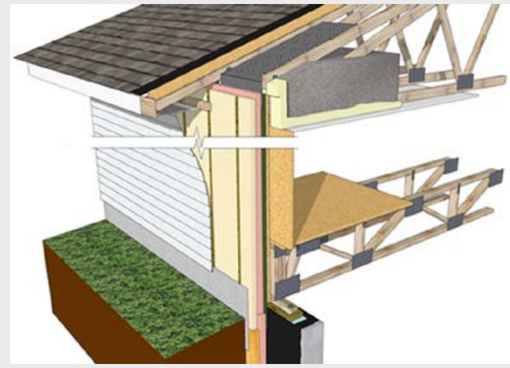
Goal 1—Constructability: This analysis is focused on validating the ease, speed, and quality of the SPS system compared with stud-frame wall systems using different energy and moisture performance packages. We quantified labor through various time studies and time lapse video. We also conducted follow-up interviews with builders to document strengths and weaknesses of the construction technologies.



Goal 2—Cost: The second analysis demonstrates and verifies the affordability of SPS construction through cost reduction strategies and the use of a single enclosure contractor for each of the houses. Cost comparisons of the three enclosure systems are based on actual construction cost data provided by Twin Cities Habitat for Humanity along with supporting cost data from online cost calculators and external bids.

Goal 3—Performance: The test houses provided both modeled and measured data to analyze and validate performance, including energy efficiency, moisture control, and durability. Specifically for energy efficiency, we used BEopt™ and REM/Rate for modeling, and compared that with a wireless data acquisition system and blower door testing for energy and airtightness. For moisture management, we used WUFI modeling and field measurements using a wireless data acquisition system for comparison. In addition, we investigated SPS structural performance with a small-scale OSB panel testing project conducted by Home Innovation Research Labs.

Brief Description of Houses



Twin Cities Habitat for Humanity (Habitat): 5 houses

Habitat built five houses in Minneapolis in 2017 and 2018 with identical plans using three different building approaches:

- 1 "base case" ENERGY STAR® version 3 (v3) certified house, using 2x6 framing with R-21 batt and R-3 exterior extruded polystyrene (XPS) foam insulation.

- 1 2x4 hybrid house built to Zero Energy Ready Home (ZERH) standards, using 2x4 walls with R-13 batts and exterior control layers including R-15 XPS foam insulation.

- 3 SPS "perfect wall" houses built to ZERH standards, with exterior control layers including R-20 XPS foam insulation.

Urban Homeworks: 2 houses

Urban Homeworks built two SPS houses with the same overall plans as the Habitat houses. The first house in St. Paul was finished in 2018, and the second house in Minneapolis was completed in 2019.

- 2 SPS "perfect wall" houses built to ZERH standards, with exterior control layers including R-20 XPS foam insulation.

MonoPath and Spero Environmental Builders: 13 houses

Just prior to this Building America project, Spero Environmental Builders and MonoPath constructed 13 houses in St. Paul between 2014 and 2016. This house design was used as the template for the homes that would be built by Habitat and Urban Homeworks. However, there were some differences in the floor plan and mechanical systems used in these houses.

- 7 original SPS houses built in 2014 and 2015.

- 6 slightly redesigned SPS houses built in 2015 and 2016.

Summary of Most Important Results

Constructability: We compared constructability based on cycle time, efficiency of framing assembly, required skill level, and contractor training. The Habitat and Urban Homeworks houses were constructed using volunteer labor, and panel installation crews observed significant improvements in speed and efficiency when working on their second house, particularly reductions in crane time and membrane installation. However, it is unlikely that all reductions in time were fully captured in this project, and we expect to see further time savings and improvements as this technology is used in future construction.

Cost: In the comparison house study, the cost of the SPS wall system with the high-performance control layers showed a comparative cost increase of 6.8% compared to the base case house using conventional stud framing. This resulted in overall hard construction cost increase of less than 2%, for a significantly higher-performing assembly. Additional likely cost reductions could bring the overall SPS system costs on par with more traditional high-performing enclosure systems.

Performance: According to REM/Rate estimates, the heating and cooling design loads for the SPS two-story house design are quite small—less than 24 kBTU/hr for heating and less than 15 kBTU/hr for cooling. That represents a 40% and 25% reduction, respectively, compared to the baseline energy code version of this plan. This suggests that variable capacity equipment will be an important component of the heating, ventilating, and air-conditioning (HVAC) systems to address partial-load issues such as short-cycling and dehumidification, while realizing the largest energy reductions.

Modeled heating and cooling energy consumption and costs for the SPS version achieved roughly 50% heating and cooling savings compared to the 2015 Minnesota energy code. Whole-house energy savings were approximately 30%, because the performance and cost of domestic hot water and electric loads were very similar to the baseline code home. The SPS house, as well as the 2x4 hybrid wall, easily surpassed the DOE ZERH requirements.

The SPS wall system follows the principles of the "perfect wall" approach and employs multiple strategies to keep the critical structural panel moisture safe. The SPS wall provides a more robust method of air and water leakage control than ENERGY STAR v3. Furthermore, the continuous exterior insulation places the sheathing in a warmer, more protected position. Both modeling and monitoring of the sheathing moisture content clearly demonstrated that the SPS wall remained more stable and consistent.

Summary and next steps: The SPS performance in our research was very encouraging, and the constructability and cost data show clear potential for gains in new home construction. However, before these panels can see widespread adoption at a broader national scale, we need additional data on the design and constructability, specifically related to structural behavior of the SPS. In this project, we completed a preliminary engineering study with the help of Home Innovation Research Labs in Maryland. These results help support a separate Building America project to conduct more robust and comprehensive structural testing and evaluation of the SPS technology.

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1 Introduction

1.1 Overview and Problem Statement

This project demonstrates and validates a novel building system that features an innovative Solid Panel Structure (SPS) and employs the "perfect wall" concept of having the high-performance moisture, air, and thermal control layers on the exterior of the structural components. The SPS system utilizes two cross-laminated layers of large-format (1-1/8"x8'x24') industrial oriented strand board (OSB) panels to create the wall structure.

The University of Minnesota Northern*STAR* Team specifically designed this project to address "Roadmap A: High-Performance, Moisture-Managed Envelope Solutions" in DOE's *Building America Research-to-Market Plan* (Werling 2015). The Roadmap states, "the tighter the building enclosure, the less it can dry when needed. Building America will provide high-performance construction and retrofit solutions that manage moisture risks, reduce mold potential, and improve building durability." The SPS system directly addresses these requirements with a unique structural approach and exterior control layers to ensure a high-performance building assembly.

1.2 Background

As consumers and building codes demand improved building envelopes, the homebuilding industry has responded by adding more insulation to the building enclosure. However, this insulation is often added without simultaneous concern for proper management of moisture and airflows. Ultimately, the increased insulation reduces heat flow through the enclosure. Without deliberate measures to limit potential wetting mechanisms, this can lead to prolonged moisture accumulation in traditional stud-framed, cavity-insulated wall systems. In addition, most highly insulated cavity walls have limited drying potential. Over the past several decades this has contributed to a host of building durability failures and greater perceived risk of highly efficient wall assemblies.

The home building industry needs wall systems that provide effective protection against internal and external environmental forces. Moisture (water and vapor) movement, heat transfer, and air leakage through the wall assembly can cause durability and comfort issues as well as increased energy loss. Designers and builders have attempted to achieve higher-R value wall systems by simply increasing cavity insulation within the traditional stud-frame construction. This approach requires careful management of air and moisture flows from both sides due to the large temperature drop across the insulation during periods of significant heating and cooling.

1.2.1 The "Perfect Wall"

As a dramatically different wall-building approach from traditional cavity-insulated stud framing, a "perfect wall" places the control layers for heat, air, and moisture *externally* to the building's structural components. Studies have shown that this can provide optimal protection and maintain integrity of the structure while maximizing the energy efficiency and moisture durability. This concept goes back many decades and has been referenced in several different ways. The term "perfect wall," however, was coined and popularized by Joseph Lstiburek of Building Science Corporation (Lstiburek 2010). Lstiburek introduced the "perfect wall" as an environmental separator comprising three major parts: the building structure; external control layers to manage rain, air, vapor, and heat; and cladding that is drained and dried.

Lstiburek calls this approach the "perfect wall" because it (1) keeps critical structural components within the conditioned space, (2) presents an ideal sequence of assembly layers, and (3) allows for secure and reliable wall-to-roof and wall-to-slab connections. Straube (2017) describes the control layers with more detail and how they can use a variety of materials and be applied to various structure types. The control layers are covered with a cladding system that can drain and dry. This approach is applicable to all climate zones and for all structural systems. It is also remarkably flexible and can be executed with a diverse set of material choices.

However, this "perfect wall" approach has yet to see widespread implementation in the building industry. The principles of the "perfect wall" need to be adapted to the building type and climate zone and be installed correctly (Werling 2016). There is also builder resistance to applying more durable water-resistive barriers along with continuous insulation on the exterior of the building structure. There is concern that exterior insulation presents a challenge for construction workers and will ultimately result in higher costs. The residential construction market has thus far tried to address these internal and exterior environmental forces with a myriad of ideas and options to improve external, cavity, and indoor moisture control. Some have been marginally successful; others have not. So, the issue of moisture intrusion and lack of drying potential continues and serve as an impediment to meeting Building America goals and homeowners' expectations of high performance, durability, and resilience over time.

1.2.2 Inspiration for This Project and Evolution of the SPS System

This project to test and validate a new structural building system that applies the "perfect wall" concept emerged from several complementary research investigations in Minnesota.

In the 1990s, Australian inventor Robert Leslie built 25 houses in the Minneapolis-St. Paul area using a new panelized assembly using three thin cross-laminated layers of off-the shelf ½"x4'x8' oriented strand board (OSB) sheathing. A few years later the Huber Engineered Woods group of the J.M. Huber Corporation developed and began producing "jumbo panels" that were 1-1/8"x8'x24' for industrial use. These Huber panels became a substitute for the thin multi-layer Leslie wall. All exterior and some interior walls and floors in our SPS houses use the Huber Engineered Woods large-format OSB panels, too.

In 2001, the idea of the SPS system was developed for affordable housing via a partnership between The Wilder Foundation of St. Paul and the University of Minnesota. A grant from the U.S. Department of Housing and Urban Development was awarded to build "workforce" houses that are architecturally appropriate using innovative, cost-reducing approaches for urban infill lots. In 2002, the Wilder/University of Minnesota team began building homes with these jumbo panels. Four prototypes built between 2002 and 2006, are shown in Figure 1.

Figure 1. Wilder/University of Minnesota prototype SPS houses 1–4, built between 2002 and 2006

Shortly after the fourth house was built, the economic slow-down made new construction projects difficult and the project was discontinued. The houses were sold (some multiple times). Unfortunately, access to these homes for follow-up testing has been unsuccessful. However, the blower door tests for these houses at the time of completion showed significant reduction in air leakage when compared with traditional stud-frame houses, presumably due to the panel system and the fully adhered "peel and stick" membrane. The airtightness results for the four prototype houses are shown in Table 1. The overall design and panel approach for House #3 were selected for future production as the best all-around performing and most suitable for infill construction in urban neighborhoods.

Table 1. Airtightness of Original Prototype Houses

Blower Door Test	cfm@50	ACH@50	cfm@50/sf
House #1	207	0.90	0.12
House #2	369	1.25	0.23
House #3	145	0.45	0.08
House #4	259	0.70	0.21

In 2014, MonoPath and Spero Environmental Builders (Spero) began construction of seven SPS houses under a subsidized affordable housing program in St. Paul. These were two-story homes (redesigned, but similar to the Wilder/University of Minnesota House #3 prototype). The houses were built quickly and efficiently while managing cost and quality. The same framing contractor was used for speed and accuracy. The houses were erected and weathertight in approximately five days. The following link is a time lapse video of one of the houses, showing completion of the building enclosure in five days: https://www.youtube.com/watch?v=lKpTf9u71dc.

The redesigned House 3 prototype was named the "Cedar" and is shown in Figure 2. Spero went on to build six more SPS houses in 2015 and 2016 under the same St. Paul program. Although they were not an official partner of the University of Minnesota Northern*STAR* Building America team they agreed to share their data with us including performance measurements and construction costs on all 13 of their houses.

Figure 2. "Cedar" model used by MonoPath and Spero in 2014 houses

For our current SPS study we also use this Cedar house design, although with minor modifications. Plans for the Cedar house can be found in Appendix A. It is a two-story model with three or four bedrooms and 1,536 square feet of finished floor area. It has 2,304 square feet of conditioned floor area and is designed to accommodate one or two more bedrooms with a bathroom in the basement level. This two-story model has been built 18 times in the Minneapolis/St. Paul area.

1.3 Scope and Objectives of This Study

The goal of this study is to measure constructability of the SPS building technology, compare its cost and performance with traditional stud-frame houses, and demonstrate market delivery within the current affordable housing market.

1.3.1 Overall Project Scope

Five houses with identical floor plans were built on scattered sites by Twin Cities Habitat for Humanity: (1) "base case" house with conventional 2x6 stud framing and ENERGY STAR v3 specifications, (2) "2x4 hybrid" stud-frame house using 2x4 stud framing with exterior control layers and adhering to ZERH requirements, and (3) three SPS houses also built to ZERH requirements. Two additional SPS houses were built by the nonprofit Urban Homeworks for this project. The outcomes of all of these homes, including the 13 houses built prior to the project by Spero and MonoPath, were analyzed.

Comparative analysis provided data in three main categories: constructability, cost, and performance. Monitoring protocols were developed and followed over the course of the study. Procedures for field monitoring of the construction processes for each wall system were developed to determine the specific critical aspects of the sequencing and methods and how to capture them equally in each comparison house. The plan led to the development of "whole house as a system" optimization comparison within the context of meeting ZERH requirements and effective delivery to the affordable housing target market.

Building these houses validates the cost-effectiveness and performance demonstrated by optimizing speed, quality control, economies of scale, and training an enclosure contractor. The comparative analyses demonstrate to other nonprofits and builders how upgrading to ZERH performance can be cost-effective using the whole-house SPS system.

1.3.2 Project Objectives

Our goal is to answer three key research questions:

1. How can constructability of SPS be demonstrated in comparison to stud-framed houses?

The original intent was to find a single enclosure contractor for all of the SPS houses. However, due to difference in production and contracting, each group used a different set of contractors to deliver the SPS system. In the end, the SPS houses were built using three different enclosure contractors (one for Habitat, one for Urban Homeworks, and one for Spero/MonoPath). Although there is a learning curve involved with any new technology, speed naturally increases with more repetitions. In addition, construction managers and crews tend to develop enhanced construction methods as opportunities arise, further increasing speed and quality. A major improvement with SPS is the speed of enclosing the building often known as "dried-in." Each builder managed that time from their own means and methods. Training and on-site experience helped each builder adapt to panel installation.

2. How does cost of the SPS system compare to conventional stud-framed construction?

Opportunities exist for material substitutions to save cost and/or increase speed and performance. These improvements are measured using time studies of the construction process facilitated in part by the use of time lapse photography and site visits. Cost reductions were documented by examining detailed cost breakdowns and budgets of each project.

3. How does the SPS system compare to other high-performance enclosure strategies with respect to energy performance and moisture management?

This research question was addressed using data generated from the houses. First, blower door results were used to describe the consistency and level of airtightness reached for each SPS house. Second, in-situ monitoring of whole-house energy consumption and heating energy use of the comparison houses helped characterize overall energy performance. Monitoring of indoor temperature and relative humidity was implemented in these houses to understand operational differences that may affect energy and moisture performance.

1.4 Detailed Description of SPS Building Technology

The SPS building system is based on an innovative structural approach. Traditional stud-frame platform construction uses a simple column (studs) and beam (headers and plates) design for the wall systems. Sheathing is added to stiffen the wall members, transfer loads across members, and provide resistance to buckling and shear. The floor and roof systems sit on top of these walls and are connected to act as horizontal diaphragms to provide overall building stiffness and the transfer of shear loads. In contrast, the structural panels for SPS system uses large panels to form these wall elements.

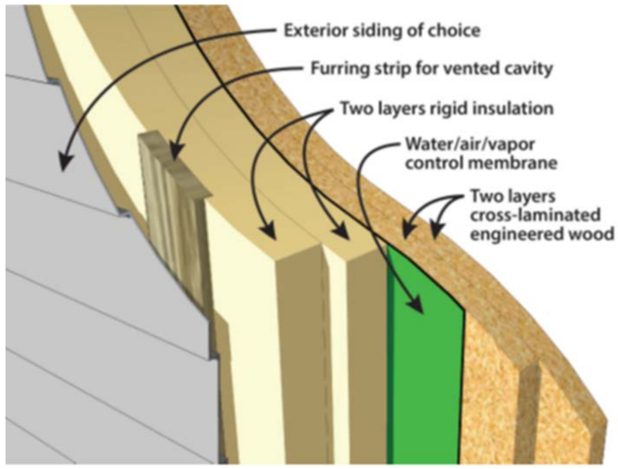


Figure 3. Illustration of SPS system with exterior control layers

The SPS system brings a novel construction approach to home building that is potentially stronger, more cost-effective, and ultimately better than stud-framed buildings. Because the wall panel is solid, the only way to make the structure high performing is by adding the control layers to the exterior of the structure. This structural system creates a built-in incentive for builders to upgrade the whole house with "perfect wall" components. We believe that the SPS wall system can be:

- **Stronger:** Panels are assembled to provide a monolithic structure for the entire four walls. The panels are high quality and engineered for strength. The monolithic structure is engineered to withstand loads including wind, shear, and vertical loads at higher rates than stud-framed structures.

- **Less Expensive:** Depending on the lumber market the OSB composite panel cost can be more stable and about the same cost as dimensional lumber. The framing assembly can be less expensive because skilled framers are not required, and it takes fewer workers (but requires a crane) to build. The wall and floor system can be installed faster than stud framing.

- **Better:** The solid wall makes it easier to manage heat, air, and moisture with virtually no errors or leaks. Also, the solid panels create the opportunity for the builder to eliminate drywall on perimeter walls and also eliminate expensive floor coverings. The panels used in this project are industrial OSB panels that are 1-1/8" thick and come in 8'x24' sheets. A vertical and horizontal panel are cross-laminated on-site to simultaneously serve as the columns, beams, and sheathing. The exterior panel runs vertically from the foundation sill plate all the way past the vertical leg of the raised-heel roof truss. A second interior panel runs horizontally between the floor and roof elements. Once fastened together, these two panels act like a singular plate or diaphragm from foundation to roof and from corner to corner. Wall plates are securely fastened to each other and interlocked with the horizontal floor and roof diaphragms. At this point the system is analogous to a monocoque-like structural shell.

1.4.1 SPS Design Considerations

There are several key design features of the SPS system. Although this panel (or plate) system can be quite flexible, early designs have focused on optimizing the dimensions to fully utilize the 8’x24’ panels. The most predominant house design thus far has been 24’x32’. This cross-laminated panel approach can easily accommodate normal window and door openings. However, it is preferable to avoid vertical seams to maintain panel plate integrity.

The system uses three vertical panels for the front and rear elevations and four vertical panels for the side elevations, as shown in Figure 4. Advanced planning for the two-story design (assuming 8’ walls, two 18” floor systems, and 12” roof truss leg) will leave a 4’x8’ panel that can be used for interior applications. The horizontal panels go corner to corner on the front and back elevations. Two horizontal panels are needed for the longer sides with a seam that is hidden at an interior partition wall.

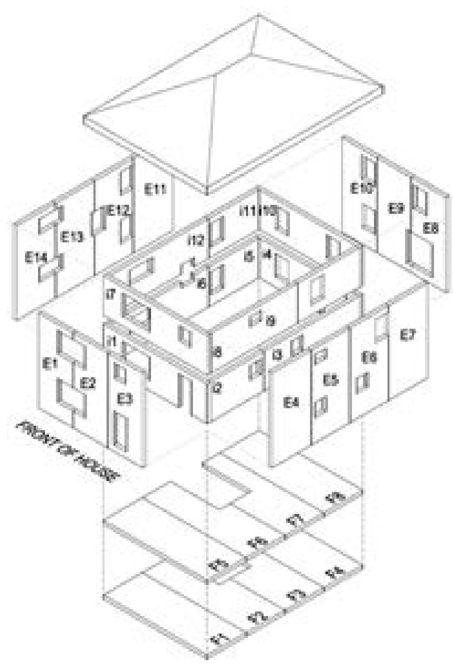


Figure 4. Panel layout for SPS

1.4.2 SPS Delivery Sequence

A site-fabricated building system is shown below in Figure 5. The exterior frame walls are replaced by the large-format OSB panels. The current two-story design requires 24 panels for the cross-laminated wall system and an additional eight panels to use as floor sheathing on the first and second floor. These replace the exterior studs, headers, plates, and sheathing. Once the foundation has been poured, exterior control layers installed, and rough backfill is completed, the full sheet OSB structural panels arrive on-site and are set near the building site. A cut-sheet is provided for each house design. While some panels are used without cutting, many will require a single cut in preparation for erection. These cuts are easily completed while the crane is setting a previous panel. A special set of grabbers (commonly used for sheet steel) are used to lift panels in both the vertical position for walls and the flat condition for the floors. A more detailed photo sequence of the construction process is included in Appendix B.

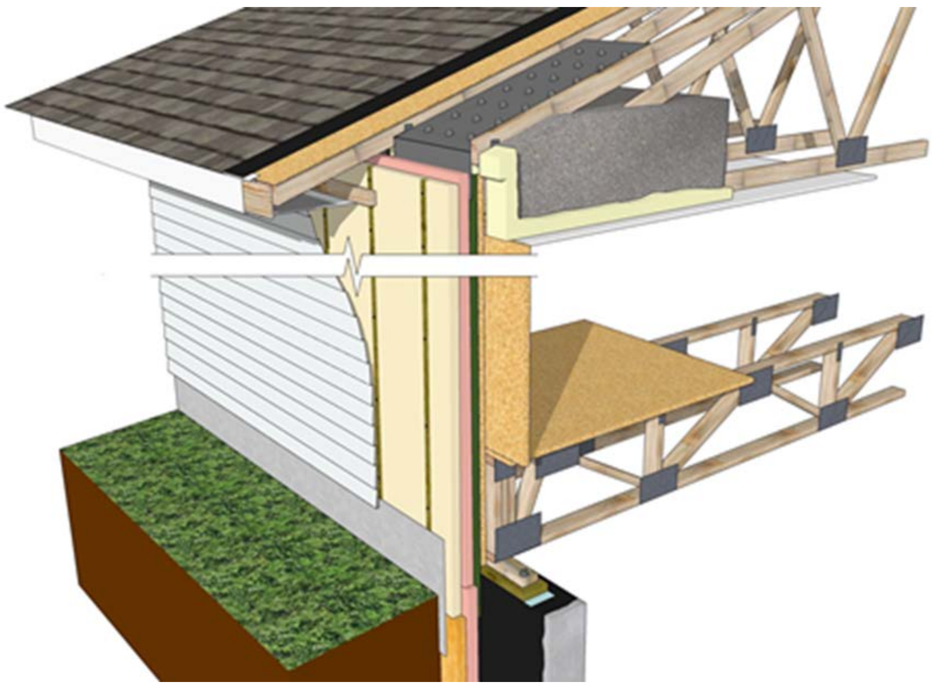


Figure 5. SPS system layers

- **Site Preparation and Excavation:** All site preparation and excavation are the same as typical construction.
- **Footings, Foundation Wall, and Basement Slab:** All the project homes used cast-in-place concrete footings and foundation walls similar to typical construction. All basements include one or more egress windows to accommodate code requirements and a future bedroom. These must be integrated into the exterior water and thermal control layers.
- **First-Floor Platform:** The first-floor platform is installed on the foundation. This process is similar to traditional floor construction with a couple of significant differences. The traditional sill plate is replaced by a sill plate receiver for the vertical panel. It is composed of a regular sill plate over a sill plate sealer with a second

receiver plate (usually one dimension smaller than the sill plate) and spaced in 1-1/8" from the outer edge of the sill plate. Both plates are carefully squared and measured to match the panel dimensions and then fastened to the foundation to meet code requirements. The vertical panel sits on the sill plate and is fastened to the receiver plate. Once the sill plate receiver is in place, the floor trusses are set and the OSB panels are delivered.

- **Exterior Wall Vertical Panel Erection:** At this point the crane arrives on-site. The first-floor sheathing panels are installed. The first vertical wall panel is cut to size at the pile. The crane lifts this panel to one of the rear corners where it is temporarily braced. The next panel is cut and set to the same corner. These panels are securely fastened in the corner and braced to be square and plumb. This is repeated for the remaining three corners. The remaining vertical panels are then installed. To provide better sightlines for the crane operator, the middle panel nearest the crane is not installed until the completion of the shell.

- **Exterior Wall First-Floor Horizontal Panel:** The horizontal interior panels are placed on all four walls. The front and rear panels are full sheets, but the longer side elevations require a full sheet plus a partial panel. This partial panel is strategically placed so the vertical seam can be concealed by an interior partition wall. If the interior partition walls are panels or pre-framed, they can be loaded onto the first-floor platform.

- **Installation of Second Floor:** The second-floor joists are installed inside the exterior panels and on top of the interior panel. The interior panel provides dimensional registration but is not a ledger for bearing. Instead, the floor trusses are fastened in place with designated screws from the outside through the exterior panel and into the vertical blocking at the end of the trusses. The second-floor sheathing is then installed.

- **Exterior Wall Second-Floor Horizontal Panel:** Same as exterior wall first-floor horizontal panel, above.

- **Roof Trusses and Sheathing:** Roof truss are set in a manner similar to typical construction with one notable exception. The trusses are designed to have a vertical leg that will sit inside the exterior panel and on top of the interior panel. The rafters are fastened in place with designated screws from the outside through the exterior panel and into the vertical truss leg. This type of attachment of each truss as it is erected simplifies truss bracing requirements. The top chord of the truss extends outward to provide the roof overhang. The remainder of the roof construction is the same as typical construction. At this point the crane work is complete.

- **Window Openings:** For the SPS houses in this study, the window selection was simplified to three window sizes. This allows a simple jig used to properly layout and cut each window opening. The openings can be cut-out with a worm drive circular saw, heavy-duty reciprocating saw, or small chainsaw. The larger window size provides a 3' cut-out that can be used for the stair treads. Window units with a narrow profile fit cleanly in the OSB structural panels and can be conventionally trimmed on the interior.

- **Exterior Control Layers and Window Installation:** This phase is quite different than typical construction with several key steps. The first step is priming the OSB and begin installing the fully adhered "peel and stick" membrane from foundation up to the head of the first-floor windows and doors. This includes the preparation and proper integration of all penetrations within the first-floor system. Next the first-floor windows can be installed with a panned sill, compatible jamb tape, and proper integration, sealing and flashing at the head. The primer and membrane are then installed on the upper level along with the second-floor windows. The exterior rigid board insulation is then installed with two layers staggered at both vertical and horizontal seams. The first insulation layer is set into place starting at the foundation and can be tacked minimally to the wall as needed. The second insulation layer is then placed over the first and the furring strips are installed and secured to the OSB panel.

- **Exterior Finishes**: The exterior cladding and trim is installed over 3/4" furring strips fastened through the foam and into the exterior OSB panel. For vinyl or metal siding, the furring strips are embedded in the rigid board foam or 3/4" foam board is added between the strips to support the cladding. For wood or fiber cement siding a 1"x 4" furring strip is used.

- **Interior Framing:** Interior faming can be the same as typical stud-frame construction. However, it is possible to use the 1-1/8" OSB panels for interior walls. If these panels are used as partitions, a furring strip is added around the perimeter of the door openings to accommodate normal door jamb thickness and trim.

- **Mechanical/Electrical/Plumbing (MEP) Rough-in:** MEP is very similar to typical construction. However, a key scheduling benefit and opportunity to further shorten the construction cycle is that the MEP rough-ins can occur immediately after the enclosure has been completed. One significant difference is that all MEP penetrations to the exterior have been preplanned and placed once the SPS walls have been completed. There are special sleeves and devices for each opening to ensure they can be integrated with the peel and stick water and air control membrane. The MEP contractors are not allowed to drill any holes to the outside and must use the opening that was provided for them. Additional plugged openings are provided to meet future needs.

- Mechanical (HVAC) design, equipment, and installation are very similar to typical high-performance stud-frame construction.
- Electrical installation is similar with one notable exception. The electrical outlets on the perimeter structural panels are contained in tall and slightly deeper baseboards. Two horizontal furring strips are placed on the wall where the wiring and outlet boxes are installed. A cover board, such as a stair skirt, with a trim molding at the top is installed.
- Plumbing design and installation are very similar to typical high-performance stud-frame construction. However, if the OSB panels are used for interior partitions the plumbing wall simply adds a spacer and a second OSB panel. With careful planning this panel can be removable to access, inspect, or repair the plumbing.

- **Interior Finishes:** Interior finishes can be the same as typical residential construction including surface finishes, cabinetry, and trim. However, there are a couple of optional exceptions with the exterior wall finish and the floor finish. The OSB panels can be covered with drywall and finished in the typical manner, or the walls can be primed and painted. This can provide an acceptable and durable finish at a much lower cost. This can be further enhanced with a fogged or knock-down primer coat prior to painting to provide a very attractive and highly durable finish. If the OSB flooring sheathing panel is protected during construction, it is easy to sand and finish with several coats of polyurethane. When sanded these panels have a marbled (not flaky) appearance and make a very attractive and durable floor surface.
- **Mechanical/Electrical/Plumbing Final:** All of the MEP final fixtures, hook-ups, and finishes are the same as typical construction.

1.4.3 Achieving ZERH with the SPS System

A key premise of this project was to demonstrate how the SPS “perfect wall” building system can affordably meet the DOE ZERH requirements. Following are details on how that was achieved:

- **Site Preparation and Excavation:** All site preparation and excavation follow sound water management principles.
- **Footings, Foundation Wall, and Basement Slab:** A protected exterior drain tile system is used around the footing and connected to an interior sealed sump. The foundation walls include all exterior control layers: waterproofing to control air, water, and vapor and 4” of extruded polystyrene (XPS) rigid foam insulation. The basement slabs in all project homes have 2” of XPS rigid foam insulation and a polyethylene vapor barrier installed over 4” of large washed aggregate for drainage, a capillary break, and radon reduction system.

- **Wall and Rim Joist:** The structural OSB panels are primed and covered with a fully adhered “peel and stick” membrane properly integrated with all penetrations and fenestration. The project houses all used two layers of 2” XPS staggered at both vertical and horizontal seams. This provides a continuous R-20 including the floor joist. The furring strips are installed and secured to the OSB panel to provide drainage and drying behind the exterior cladding. The cladding is installed to the furring strips to minimize fasteners that penetrate the insulation and water control layers. This wall system provides maximum integrity of the exterior control layers and is instrumental in achieving airtightness levels that are repeatedly one-half of the 2 ACH@50Pa ZERH requirements.

- **Windows and Doors:** All windows are double-pane with low-e coating and gas-fill that meet ZERH requirements.

- **Ceiling/Roof:** All ceilings received a single pass of closed-cell spray polyurethane foam. This is installed after ceiling drywall has been installed and goes across the drywall, up the OSB panel at the vertical truss leg, and onto the vent baffles in each truss bay. Blow-in insulation is placed on top of the foam layer to achieve an R-value of R-50 or more.

- **Mechanical/Electrical/Plumbing (MEP):** All mechanical equipment and installation meet ZERH requirements. A sealed combustion, 94% efficient furnace is coupled with a SEER 15 split system air conditioner and MERV 11 filtration. All ductwork is in conditioned space. A high-efficiency, two-pipe sealed combustion water heater with carefully designed hot water distribution system is used to meet ZERH requirements. A ducted energy recovery ventilator with 60% sensible heat recovery provides fresh air to the forced air system for whole-house distribution. This design eliminates exhaust-only bath fans. However, due to the extremely tight building enclosure, make-up air provisions are necessary for the range hood and clothes dryer. A make-up air unit with a preheater for use when exterior temperature are below freezing is installed and deployed when the clothes dryer or range hood are activated.

- **Lights and Appliances:** All applicable appliances are ENERGY STAR rated and more than 90% of the installed lighting is LED.

- **Indoor Air:** The houses are all built to EPA Indoor airPLUS, including comprehensive moisture control, low-volatile-organic-compound (VOC) materials and finishes, whole-house ventilation, filtration, and radon reduction. All garages are detached.

- **Renewable Ready:** Both the house and mechanical room are designed for a future renewable energy photovoltaic system.

2 Constructability

Significant panel efficiency and erection speed comes from the architectural design in which the house walls are developed to utilize the factory panel dimensions. Building the solid panel houses required both training and field experience for new framing contractors to learn construction of the SPS building system. The research team assembled an approach that focused strictly on the solid panel assembly and "perfect wall" enclosure system. Training was provided in three ways: a 6-hour contractor training class, a series of live videos that document wall and panel installation, and live construction experience guided by the project team (see Appendix C). A clear increase in speed and confidence was observed between the first and second houses.

2.1 Research Design

As noted in Section 1, Twin Cities Habitat for Humanity built three identical house plans using different building approaches: (1) a base case ENERGY STAR v3 house (2x6 with R-21 batt and R-3 exterior foam), (2) a ZERH 2x4 hybrid wall house (2x4 walls with R-13 batts and exterior control layers including R-15 foam), and (3) three SPS "perfect wall" houses (with exterior control layers including R-20 foam). These houses were carefully analyzed to develop comparative cost, constructability, and performance.

We measured overall building constructability using several methods. We conducted a time study of the construction process, noting times to reach critical milestones (e.g., dry-in, enclosure completion) using timelapse videos. This was not as useful as planned and needed to be supplemented with daily on-site logs. Site visits were used to document construction defects at critical points in the construction process. Follow-up interviews with builders were conducted to document strengths and weaknesses of the three construction technologies. In general, the contractors acknowledged that significant time reductions would be expected with additional homes, especially in the required crane time and the days to dry-in if they used their own employees.

2.2 Data Collection

Data were collected in various ways to match the research question and the team's ability to gather meaningful results in a cost-effective manner. The proposed market context for this study was specifically the affordable housing market. Nationwide, the affordable house market utilizes volunteers to help defray labor cost. Because of the large volume of affordable single-family homes, the use of volunteer labor often determines whether houses can be built in some areas. Therefore, having a high-performing affordable house that is "volunteer friendly" is critical.

We recorded elapsed construction time to reach specific milestones such as dry-in time and enclosure completion. If an affordable SPS house is built with volunteer labor and can be framed faster than a framing contractor on a consistent basis, then it is notably an incentive for nonprofits to use the SPS system. We also recorded quality control of each control layer and specific details such as penetration flashing, airtightness, etc. Anecdotal information from contractors regarding the strength and weaknesses of each system was documented. In terms of constructability, a primary research goal was a general comparison of construction cycle time and quality.

2.2.1 Cycle Time Comparison

Preliminary data were collected for the three comparison houses. The three measurement benchmarks are:

- Completion of structural enclosure components (including interior floors, excluding interior nonstructural walls)
- Dry-in (establishment of an interior that is free of risk from precipitation-caused wetting, thereby enabling interior mechanical and finish work to begin)
- Enclosure completion (including insulation, cladding, and interior finish on exterior walls).

We placed time-lapse cameras at the site under the control of the general contractor or site supervisor. These cameras took an image from a fixed location every 10 minutes. The video was processed to remove times of inactivity. These videos were analyzed to determine how many workers were involved with these steps and the amount of time taken to complete the steps. However, it became clear the videos were not providing a complete documentation of the process. At that point the data needed to be corroborated with Habitat for Humanity staff to verify crew sizes on individual days. Job sites were visited routinely, and photographs and observations were used to verify any assumptions.

Habitat for Humanity employed a contractor to complete the enclosure on the SPS houses. However, the other two comparison houses (2x4 hybrid wall and ENERGY STAR v3) were built by volunteers with highly variable levels of expertise. In addition, the SPS house contractor had no previous experience with the solid panel technology. Therefore, the initial cycle times are not representative of industry standards or potential speed of construction. RSMeans was used in time estimating data along with staff experience with the SPS system based on previous work to derive optimized cycle times for the three systems.

The three primary builders of the SPS houses shared two significant improvements:

- There was consistent improvement house-to-house in the time it took to dry-in the structures. The reporting ranged from 10% to 50% faster. Dry-in includes structure, water-resistive barriers, windows and doors, and roofing.
- Based on the number of hours of crane rental used to install the OSB panels, there was a learning curve time improvement from the first house to the second house—20% to 33%. Two of the builders each reported 24 hours of crane rental for their first house, and 16 hours on the second house.

2.3 Partners and Market Entry

For the purposes of this research project, entry into the market was through the nonprofit affordable housing sector. Affordable housing is a very large market and includes cost subsidies, guaranteed sales, and continuous demand. Access to the affordable housing market is typically through nonprofit networks and local and national sources. Delivery of affordable housing is heavily guided by federal agencies and municipalities. The research was designed to demonstrate that optimization at all levels, especially design, materials, and construction methods, along with a single enclosure contractor, could facilitate faster erection and lower cost while ensuring high quality and performance.

As mentioned previously, Twin Cities Habitat for Humanity and Urban Homeworks, the two nonprofit affordable housing partners in the Twin Cities area, both used a previously developed two-story solid panel house design originally developed by MonoPath.

2.3.1 Twin Cities Habitat for Humanity

The Twin Cities Habitat for Humanity affiliate works to bring affordable housing to the Twin Cities area communities and families. They build, repair, and sell homes to families with an affordable mortgage while connecting them to the community through their neighborhood revitalization projects. The high demand for affordable housing in the Twin Cities area has prompted them to look for ways to deliver more houses with their existing staff and volunteer workforce. Twin Cities Habitat for Humanity wanted to study the SPS technology and delivery system to determine if it could meet that need. To meet their target owner demographic, Twin Cities Habitat for Humanity modified the house design to add a fourth bedroom on the upper floor.

Each Habitat house in this project was processed through multiple funding sources from city, state, and federal programs managed by the City of Minneapolis and thus are considered affordable housing. Each house received a subsidy of $50,000 to $100,000 that was required to fill the gap between the actual total development cost and the real estate market value as determined by mortgage lenders.

2.3.2 Urban Homeworks

Urban Homeworks focuses the combined resources of the public, private, and faith sectors to transform vacant, condemned, or underutilized properties and vacant lots into quality, attainable places to live for low- to moderate-income households. They have a strong desire and commitment to increase their capacity to deliver new infill houses in the Twin Cities area. Urban Homeworks saw the SPS building system as a potential means to increase their capacity for delivery of new homes in the Minneapolis and St. Paul urban center.

2.3.3 Spero Environmental Builders (Spero)

In partnership with MonoPath, Spero developed and delivered seven affordable solid panel houses in 2014 and 2015. That experience and lessons learned served as the catalyst for this project. In 2016, Spero redesigned and built six more solid panel houses. Certain cost and commissioning data from these 13 houses have been incorporated into this report.

2.3.4 Future Market Opportunities

Thrive Home Builders (Thrive) participated in preliminary discussions as part of this project but has not yet built any SPS homes. Thrive is based in Denver, Colorado, and is a for-profit production builder. Thrive is nationally recognized for their early adoption and delivery of high-performance homes. They considered using SPS technology for both rowhouse or detached single-family homes. However, Thrive determined that not enough structural and engineering data were available to move forward. University of Minnesota, with the help of Home Innovation Research Labs, is currently working on a Building America project looking to remedy this including a myriad of structural performance and material testing.

2.4 Significant Results

This section details the results of our constructability comparison. Note that this portion of the project relied heavily on our partner network, and that this qualitative component does not include a specific protocol and measurement regime. We plan to pursue continued use by our affordable housing partners and uptake by other nonprofit and for-profit builders. The market delivery success of this building approach is highly dependent on the levels achieved by other measures such as cost and cycle times. Other influences that could play a large role in the market attractiveness of this building system include the current shortage in the availability of skilled labor, the increase in lumber and framing costs (Haynes 2003), and the push to reduce time to secure/dried-in.

2.4.1 Habitat for Humanity

Twin Cities Habitat for Humanity completed three SPS houses and the two comparison houses. They entered this project to evaluate the SPS system to meet a growing demand for new affordable housing units. Unfortunately, the system did not fit their current delivery system. They have invested heavily in a panelizing system within their material warehouse so the future owners and volunteers can fabricate exterior and interior wall panels in controlled conditions. Furthermore, the panel erection was not volunteer friendly. At this time, they are unlikely to use the SPS system on houses built using volunteers. However, Habitat indicated that recruiting volunteers is becoming more difficult while funding for building is growing. They may consider using SPS again if external general contractors are used to meet their growing unit projections.

2.4.2 Urban Homeworks

Urban Homeworks completed two SPS houses in 2018 and 2019 using the Cedar design. Urban Homeworks was very eager to uncover deeper cost reduction to meet the affordable housing needs for their target demographic. Much of this effort was focused on a garden-level, split-entry house design. Unfortunately, that design was rejected when it was determined that the foundation stem-wall and panel connection would require significant engineering and elevated cost. Still, Urban Homeworks invested heavily in training a crew to install the SPS system and had two additional houses planned for 2020. However, city funding issues forced them to delay building those houses.

2.4.3 Spero

Although Spero is not an official partner in this project, they have successfully deployed the solid panel technology on their 13 two-story homes built between 2014 to 2016. Spero agreed to provide the project team with information on costs and performance for these houses to complement and compare to the SPS houses built by the other partners.

2.5 Market Delivery Summary

The overall experience with market exploration while building 20 affordable homes provided confidence that the SPS system would be of value for many builders. We learned that successful market delivery would require the following:

- A larger production builder or component builder that could realize the benefits of speed and economies of scale. The large panel size and dimensional stability would help with manufacturing components from off-site building for walls, stairways, floor systems, and set-in-place rooms, etc.
- A model similar to MonoPath that would manage design, engineering, training, and building science for medium to large production developers.
- Completion of structural strength engineering testing. This testing would provide data for local and national codes and give builders the confidence to build custom (one-off) homes.
- Further SPS testing will also provide opportunities for commercial and multifamily construction.

3 Cost

3.1 Research Design and Data Collection

Twin Cities Habitat for Humanity's houses were carefully analyzed to develop comparative cost, constructability, and performance between the SPS and comparison houses. Cost comparisons are based on actual construction cost and supplemented with primary data provided by Twin Cities Habitat for Humanity along with supporting cost data from online cost calculators and external bids.

3.2 Analysis

The SPS system house is compared to standard stud-frame houses using the exact same footprint and floor plan. This allows us to focus on the differences between the two wall types—solid panels vs. stud framing. Also included in our analysis are aspects of the building enclosure that impact, enhance, or change other components. This includes moving interior walls, eliminating drywall on the exterior perimeter walls, and sanding and coating the OSB floors for a final finish. Room partitions can be built with the OSB panels in a manner similar to stud-framed walls. The primary components of the SPS are large OSB panels that provide both enclosure and structure from the sill plate to the rafter tails. The floor joists can be the same in both wall types. Although similar roof trusses are used with the SPS, they are modified slightly to accommodate a more robust fastening system that ties them to the solid panels. This provides greater rigor than the typical stud-wall connection where the rafters simply sit on top of the walls with nails or straps that fasten them to the top plate. This roof/wall connection is critical for two reasons. First, it provides the use of heavy load lag screws through the OSB into the rafters, giving greater resistance to roof wind uplift. Second, it provides greater stiffness to the 2-ply OSB wall to enhance shear strength. This attachment method has additional cost with both labor and materials compared to convention wall and rafter construction.

In addition to the panel and attachment differences, the SPS system has further budget impacts with the implementation of the "perfect wall" control layers. These include a fully adhered "peel and stick" membrane and two layers of rigid foam insulation. Both are applied to the outside of the panels or sheathing. A stud-framed house can use either the "perfect wall" control layer approach or use batt insulation in the wall cavity with an interior air barrier and vapor retarder and an exterior house wrap. Table 2 provides a comparison of the components of each wall type, and Table 3 provides the exact prices. The cost comparison evaluates these wall system differences for both materials and labor.

Table 2. Components of Wall Systems* for Cost Comparison

2x6 Stud-Frame ENERGY STAR v3	2x4 Stud-Frame Hybrid Wall	SPS Perfect Wall
Traditional customized 2x6 stud framing with headers and assembled with 7/16" sheathing	Traditional customized 2x4 stud framing with headers and assembled with 7/16" sheathing	2-ply solid cross-laminated OSB (1-1/8"x8'x24') panels for walls with a total thickness of 2-1/4"
Manually assembled and placed using platform framing techniques	Manually assembled and placed using platform framing techniques	Site-fabricated with minimal alteration and installed with crane
4'X8' floor sheathing installed manually (48–50 panels)	4'X8' floor sheathing installed manually (48–50 panels)	Floor panels (1-1/8"x8'x24') installed with crane (8 panels)
6-mil poly vapor retarder inside and house wrap outside	40-mil fully adhered "peel and stick" rubberized membrane outside	40-mil fully adhered "peel and stick" rubberized membrane outside
R-15 fiberglass batts in stud cavity with R-5 foam over the sheathing	3" of continuous exterior foam insulation with R-13 batts in cavity	4" of continuous foam insulation installed on the exterior
Windows and doors are generally installed sometime after the house wrap is installed	Windows and doors are installed at the same time as membrane to make house weathertight by enclosure contractor	Windows and doors are installed at the same time as membrane to make house weathertight by enclosure contractor
Normal drywall finishes	Normal drywall finishes	Drywall is not required for exterior walls, but is used for the ceiling and interior walls
Normal floor finishes	Normal floor finishes	OSB floor panels can be sanded and finished with polyurethane

* All homes had similar construction methods and materials for the foundation and attic insulation.

Table 3 shows a breakdown of costs for the three house types built by the Twin Cities Habitat for Humanity. The houses have identical two-story design and floor plans, and the costs are derived primarily from actual project invoices. In a few cases costs were obtained from outside bids or online bid calculators. The construction costs relative to the enclosure and associated components are categorized in this table—the table does not show final full-house prices. The houses were built with different site supervisors and different volunteer crews, making it difficult to get consistent labor hours and costs. The three houses were also built consecutively over a one-year period where material prices fluctuated. Actual invoice prices were used for most items, and bids were obtained to establish costs for framing labor. Some items, such as fasteners, differed because they were purchased through different vendors. Using actual invoice prices provided a real-world comparison that was close enough to draw some conclusions about how the SPS system compared to the two stud-frame wall systems.

Table 3. Cost Comparison (Two-Story Houses)

Cost Study Comparison	2x6 Stud-Frame ENERGY STAR v3	2x4 Stud-Frame Hybrid Wall	SPS Perfect Wall
Foundation			
Control layers (material and labor)	$3,780	$3,780	$3,780
Framing Systems			
Wall framing material			
Exterior walls	$6,453	$5,633	$7,770
Interior walls	w/ exterior walls	w/ exterior walls	$3,944
Wall sheathing	$1,511	$1,241	NA
Miscellaneous lumber	$791	$1,212	$1,185
Floor framing material			
Floors trusses	$3,304	$3,412	$2,938
Floor sheathing	$1,100	$1,098	$2,568
Roof framing material			
Roof trusses	$2,226	$1,464	$2,634
Roof sheathing	$558	$581	$581
Framing labor			
Exterior walls, floors, roof	$17,462	$16,937	$7,516
Interior walls	w/ exterior	w/ exterior	$4,200
Crane	NA	NA	$3,700
Fasteners	$1,262	$1,506	$1,750
Control layers (material and labor)			
Wall membranes	$539	$2,322	$2,322
Wall batt insulation	$700	$500	NA
Wall foam insulation	$1,764	$3,150	$5,237
Furring strips	NA	$589	w/ insulation
Rim joist insulation	$546	NA	NA
Sealant (gun foam)	$324	NA	NA
Membrane labor	$750	$900	$900
Insulation labor	$1,080	$2,200	$1,920
Subtotal	**$40,370**	**$42,745**	**$49,165**
Roof (not in framing above)			
Control layers (material and labor)			
Air barrier spray foam	NA	$1,125	$1,125
Blown-in insulation	$1,245	$1,035	$1,035
Attic labor	$250	$225	$225
Subtotal	**$1,495**	**$2,385**	**$2,385**
Other			
Floor finishes/coverings	$4,000	$4,000	$1,000
Drywall (walls and ceiling)	$5,000	$5,000	$2,500
Front porch	$7,000	$7,000	$7,000
Subtotal	**$16,000**	**$16,000**	**$10,500**
Total	**$61,645**	**$64,910**	**$65,830**

The totals in Table 3 show an additional cost for the SPS house at $4,185 ($65,830 versus $61,645). For the enclosure items listed, this is 6.8% higher than the Twin Cities Habitat for Humanity ENERGY STAR v3 house. With full construction costs of $270,430 for the Twin Cities Habitat for Humanity ENERGY STAR v3 house and an average of $274,617 for the SPS houses, there is a 1.6% cost increase for an SPS house.

Additional cost analysis using documents from the 13 Spero construction budgets shows average total building enclosure cost for the first seven houses built in 2014 at $94,000. The next six houses constructed in 2016 averaged $78,000. Even though Spero did not participate directly in this demonstration project, they provided sworn construction statements for those houses. These detailed bids are required before funding and permits can be secured. Final or actual costs are typically within 2% to 5%. One of the major differences in cost was due to using an outside enclosure contractor (MonoPath) for the first seven houses. For the second set of six houses the enclosure was completed by Spero's own internal builder and crew. Spero also found additional cost reductions with direct purchase of the OSB panels and the use of a liquid-applied water control membrane.

3.3 Significant Results

Several affordable housing cost reduction strategies were built into the overall building and system design since the prototype houses that were constructed in the early 2000s. The interior of the perimeter walls can be painted directly instead of a traditional drywall finish. The floors can be sanded and coated for an attractive and durable floor finish. These options were successfully included and accepted in most of the early houses. Porches were also considered a cost reduction strategy as well as a concern for structural and enclosure performance in traditional construction.[1]

The SPS system proved to be slightly more costly to build than conventional stud-framed wall systems. However, better utilization of the previous cost reduction strategies along with an enhanced learning curve for panel installation should continue to bring down the overall cost. Also, the performance metrics of the SPS system (see Section 4) have demonstrated a substantial energy savings and greater durability with the robust thermal and moisture management strategy.

[1] The porch is designed to be free-standing with piers in the front and against the foundation in the back. This design removes a significant load off the wall and eliminates the need for a watertight deck ledger and roof connection. The design also minimizes thermal bridging and air leakage by eliminating holes with bolts or screws penetrating the insulation and membrane, though some fasteners are needed to prevent lateral movement. The 8-foot-wide pergola porch was small and less intrusive to the enclosure. The cost was about $1,800 compared to a full width front porch and roof of about $7,000. The first 13 houses built by Spero used the less expensive pergola design and were quite successful. Those houses were the design and cost basis for the original proposal. However, against the team's cost reduction recommendations, the nonprofit builder partners insisted on the more expensive porches.

4 Performance

Energy and hygrothermal performance for the various assembly types were estimated using modeling software, while in-situ monitoring of energy consumption and moisture behavior provided actual performance data. For comparison purposes, initial modeling work was conducted to evaluate the energy and moisture performance of five proposed construction types: A 2x6 code base assembly, a 2x6 ENERGY STAR assembly, a 2x6 ZERH assembly, the 2x4 hybrid assembly, and the SPS system. In-situ performance was tracked across four completed buildings constructed by Twin Cities Habitat for Humanity: One ENERGY STAR house, one 2x4 hybrid house, and two SPS houses. Certification data and field commissioning results were collected as well.

4.1 Energy Performance

4.1.1 Research Design

We compared energy performance using both modeled (BEopt™ and REM/rate) and actual energy consumption from the occupied homes. The energy monitoring included both electricity and gas consumption for equipment and appliances impacting heating and cooling energy consumption. The monitoring was conducted using a commercial remote data acquisition system. Sensors were placed on each floor and outside to track interior and exterior ambient temperatures and humidity for each house. Blower door testing was completed on each house to enable comparison of actual airtightness achieved. Houses were tested as they were completed, commissioned, and certified to meet ENERGY STAR and DOE ZERH requirements. These data were collected to compare both the SPS vs. non-SPS wall comparison and as the way to look for variation among the SPS houses.

4.1.2 Data Collection

4.1.2.1 Energy Modeling

Energy modeling work was conducted using REM/Rate v14.5. For consistency, the energy models used to investigate each wall system were all based on the same floor plan—the two-story "Cedar" plan. Modeled energy performance was also compared to actual monitored energy consumption but the sample size was small and occupancy impacts varied greatly across the four monitored houses.

4.1.2.2 Energy Monitoring

Electricity use was tracked using Omnisense S-60 current transformer (CT) clamps that monitored circuits dedicated to six primary appliances: furnace fan, A/C condenser unit, energy recovery ventilator, range hood, clothes dryer, and make-up air unit. Each monitor, as seen in Figure 6, sent data to a wireless gateway that forwarded the usage information to an Omnisense online tracking portal.

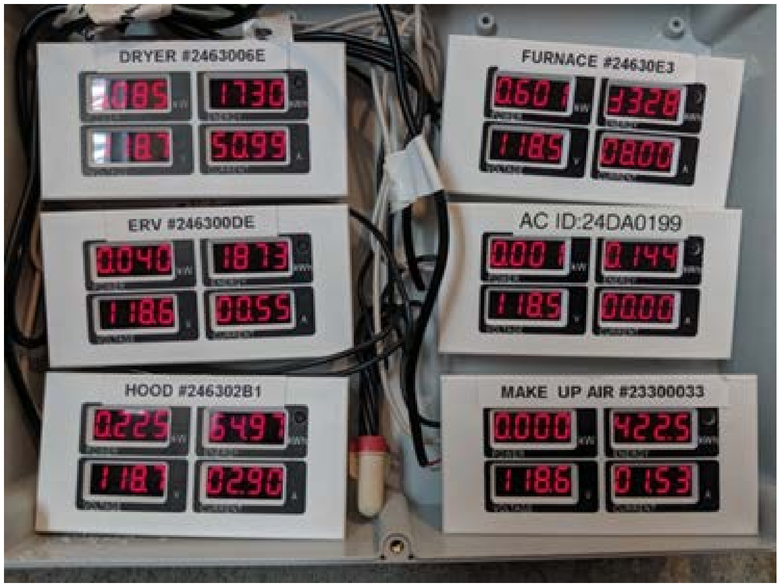


Figure 6. Electric current monitors

Natural gas consumption was measured by EKM PGM-075 pulse counting submeters installed on the gas lines to the furnace and water heater, as shown in Figure 7.

Figure 7. Typical natural gas submeter installation

Ambient temperatures and relative humidity were tracked using Omnisense S-10 sensors placed in representative locations in the basement, first floor, second floor, and front porch of each house.

4.1.2.3 Commissioning and Certification

Commissioning and certification data on project houses were collected by industry partner Building Knowledge, Inc. and included the final HERS ratings and airtightness measurements.

Houses were tested when they were completed, commissioned, and certified to meet ENERGY STAR and DOE ZERH requirements. Data were used to evaluate the three-house wall comparison and as the way to look for variation between the SPS houses.

4.1.3 Energy Performance Analysis

4.1.3.1 Energy Modeling

Five separate REM/Rate models using the same Cedar single-family house plan were used to estimate the energy loads, energy consumption, and energy cost of the various enclosure systems in the Minneapolis/St. Paul climate. The models have the same building geometry and window arrangement, but assume different mechanical systems reflective of Habitat for Humanity policy, and different insulation levels and airtightness reflective of enclosure type.

Two energy models provided baselines for comparison, one using a basic 2x6 stud-framed enclosure meeting the Minnesota 2015 residential energy code and another meeting the minimum requirements of the ZERH program.

The other three REM/Rate models followed specifications from the project homes of each type built by Twin Cities Habitat for Humanity. The ENERGY STAR v3 version followed the minimum prescriptive requirements of ENERGY STAR v3, while the SPS and 2x4 hybrid versions surpassed the minimum requirements because Habitat design specifications for the lighting, energy recovery ventilator, and air conditioner for these versions required higher efficiency than the DOE ZERH program.

Energy cost assumptions were based on local Minneapolis/St. Paul 2016 Xcel Energy electricity and natural gas rates. Gas and electricity rates were broken into separate heating and cooling season averages that included surcharges, delivery/distribution charges, taxes, and other rate adjustments to represent the full cost of energy. Monthly base charges/service fees were added separately. Cost assumptions are summarized in Appendix D.

Modeled energy consumption and cost results along with the HERS rating are summarized in Table 4. HERS scores followed the expected pattern, with 2015 MN Energy Code at 70, ENERGY STAR v3 at 60, and DOE ZERH at approximately 50. The SPS and 2x4 hybrid versions achieved slightly better HERS scores and lower energy use because their wall performance (whole-wall R-value and airtightness) exceeded DOE ZERH program requirements.

Table 4. Modeled Energy Consumption, Energy Cost, and HERS Index Results

House Type	HERS	Total Energy		Heating & Cooling	
		Energy (MMBtu)/yr	Costs/yr	Energy (MMBtu)/yr	Costs/yr
2015 MN Energy Code	70	135.6	$2,140	80.0	$729
ENERGY STAR v3 (minimum)	60	114.0	$1,935	60.6	$579
DOE ZERH (minimum)	49	92.8	$1,689	47.2	$476
2x4 Hybrid (Habitat)	43	79.3	$1,521	35.5	$385
SPS (Habitat)	44	81.5	$1,536	37.7	$400

4.1.3.2 Energy Monitoring

Equipment to measure electrical and natural gas consumption was deployed in four completed comparison houses (one ENERGY STAR v3, one 2x4 hybrid, and two SPS) to monitor space and water heating energy use. The monitoring package included separate submeters for natural gas consumption by the furnace and the water heater. Electrical monitoring included six appliances: furnace fan, A/C condenser unit, energy recovery ventilator, range hood, clothes dryer, and make-up air unit. As with any household energy monitoring effort, it is important to note that occupancy and operation of these houses could be quite different. The monitoring protocol did not explicitly attempt to account for variations in occupant numbers or usage habits.

Energy consumption was tracked for four houses: one with the ENERGY STAR v3 wall, one with the hybrid wall, and two with the SPS system. Unfortunately, we experienced difficulty accessing houses with occupants for timely installation as well as some equipment failure. The numbers presented in this section are accurate but incomplete as noted. Annual usage was derived using either 365-day totals where available or using an average of successive 365-day periods to provide a “typical” usage year for each house.

The raw data are presented in Table 5. No adjustments were made for degree days or to accommodate for differences in number of occupants or account for occupant-determined variations such as thermostat or water heater settings. As could be anticipated in Minnesota, the highest single energy end use was for space heating, followed by water heating. Of particular note is that space heating is strikingly similar across all houses with a less than 9% difference between the highest and lowest space heating energy usage. Water heating is nearly identical between the ENERGY STAR and 2x4 hybrid houses while water heating in the SPS houses varied significantly with over 100% difference in water heating energy usage between the two SPS system houses. The significant variation is most likely due to differences in number of occupants and the associated bathing and laundry hot water demands.

Table 5. Comparison of Total Annual Energy Consumption (kBtu)

House Type	ENERGY STAR v3	2x4 Hybrid	SPS #1	SPS #2
Gas—Furnace	51,301	52,031	56,275	58,132
Gas—DHW	17,428	17,342	25,142	11,858
Electricity—Furnace fan	2,426	1,814	1,665	3,616
Electricity—ERV	62	860	1,361	3,072
Electricity—Dryer	322	1,427	373	1,490
Electricity—Range hood	241	96	12	43
Electricity—A/C	NA	Insufficient data	1,884	884
Electricity—Makeup air unit	NA	282	273	76
Total (kBtu)	**71,780**	**73,570**	**84,828**	**79,169**

As shown in Table 6, the furnace heating energy was highest for the two SPS houses. Interior temperatures during the heating season do not appear to correlate to heating energy usage. Interior temperatures are provided as a proxy for thermostat settings (which were not tracked). Open windows or other uncontrolled ventilation is unknown and could vary from house to house and affect heating energy usage despite recorded interior temperatures.

Table 6. Heating Use and Indoor Temperatures

House Type	ENERGY STAR v3	2x4 Hybrid	SPS #1	SPS #2
Furnace gas (therms/yr)	51,301	52,031	56,275	58,132
Average interior temp (heating season)	75ºF	72ºF	72ºF	74ºF

4.1.3.3 Energy Comparison

Because only certain energy end-use components were measured it is difficult to effectively compare the modeled and monitored energy consumption. There is no clear indication why the monitored consumption deviates so significantly from the modeled estimates. However, the occupancy and internal gains, along with ventilation and make-up air usage, varied widely across the four houses. With the small sample size and potential variations in occupant behavior and operation, the energy use differences are not surprising.

4.1.3.4 Commissioning and Certification

Building Knowledge, Inc. completed plan reviews and calculated a preliminary HERS index for the three wall type comparison houses built by Twin Cities Habitat for Humanity and for the additional SPS houses built by Urban Homeworks. This included energy modeling, on-site verification, and blower door and duct leakage testing. Spero Environmental Builders provided commissioning records for the 13 houses completed in St. Paul; the energy ratings and ENERGY STAR certifications for those houses were completed by Neighborhood Energy Consortium (now Center for Energy and Environment).

Table 7 shows the results including the HERS Index and blower door results. As could be expected the stud-frame assembly was the least airtight. The SPS assemblies were generally very airtight but there were significant differences in airtightness between different builders. It is not clear what may have contributed to the differences although they did use different windows and had some variation in HVAC equipment. However, the lower HERS Index seems to coincide with the lower blower door test numbers.

Table 7. Commissioning Test Results

Builder and House #	Enclosure Type	Blower Door Test Results			HERS	Conditioned Shell Area (sf)
		ACH@50	cfm@50	cfm@50Pa per sf shell		
Twin Cities Habitat for Humanity #1	2x6 ENERGY STAR v3	1.38	489	0.106	48	4,563
Twin Cities Habitat for Humanity #2	2x4 Hybrid	0.85	290	0.064	43	4,563
Twin Cities Habitat for Humanity #3	SPS	0.26	88	0.019	41	4,563
Twin Cities Habitat for Humanity #4	SPS	0.41	140	0.031	39	4,563
Twin Cities Habitat for Humanity #5	SPS	0.44	146	0.032	39	4,563
Urban Homeworks #1	SPS	1.01	404	0.089	43	4,563
Urban Homeworks #2	SPS	1.11	379	0.083	38	4,563
Spero Builders #1	SPS	1.16	368	0.081	42	4,547
Spero Builders #2	SPS	1.25	428	0.094	42	4,547
Spero Builders #3	SPS	1.30	445	0.098	47	4,547
Spero Builders #4	SPS	0.64	203	0.045	41	4,547
Spero Builders #5	SPS	1.03	318	0.070	47	4,547
Spero Builders #6	SPS	1.60	250	0.056	47	4,547
Spero Builders #7	SPS	1.16	231	0.051	47	4,547
Spero Builders #8	SPS	0.65	207	0.050	41	4,547
Spero Builders #9	SPS	1.16	292	0.050	46	4,457
Spero Builders #10	SPS	1.00	317	0.070	42	4,547
Spero Builders #11*	SPS	1.03	318	0.070	47	4,457

*The commissioning results for Spero houses #12 and #13 are not available at this time.

4.2 Moisture Performance

4.2.1 Research Design

Moisture safety for this research is defined as the susceptibility of wood-based construction materials to moisture damage during typical operational conditions. Both moisture modeling and moisture monitoring were used to determine moisture safety. Moisture modeling was conducted using a two-pronged approach: an extended thermal and vapor profile method (Glaser), and a WUFI simulation. Moisture monitoring was conducted using a commercial remote and wireless data acquisition system.

4.2.2 Data Collection

4.2.2.1 Moisture Modeling

A. Steady-State Glaser Analysis:

Glaser analysis was conducted to quantitatively compare the moisture performance of the three wall assemblies at steady-state winter conditions (ASHRAE 2017; Straube 2005). Additional variants of the SPS wall were also tested to determine the flexibility and adaptability of the SPS wall for different insulation types. (These results are shown and discussed in Appendix E.) Exterior boundary conditions were set to the average winter temperature and relative humidity (RH) for the three coldest months in Minneapolis/St. Paul—18.7°F and 75% RH. Interior boundary conditions were assumed to be 68°F and 40% RH (Lstiburek 2017).

Outputs (both vapor pressure and temperature profile graphs) from the Glaser analysis for each wall type are shown in Appendix E. A summary of the results is shown in Figures 8 and 9.

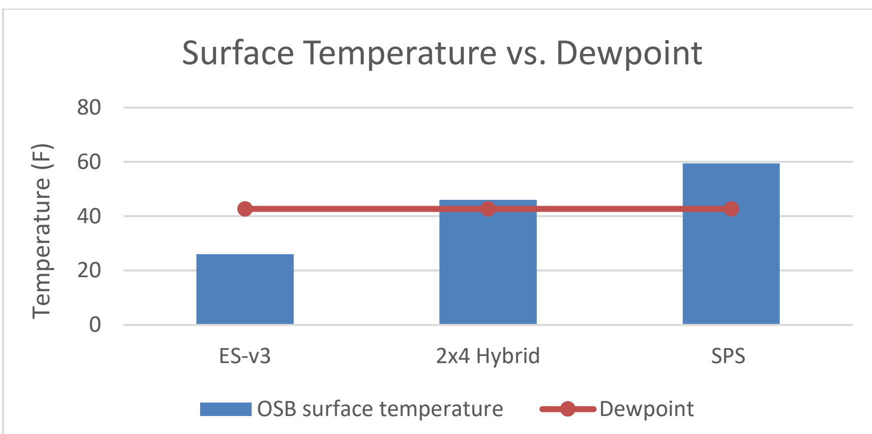


Figure 8. OSB surface temperature compared to dewpoint temperature at average winter conditions

Condensation risk increases when the surface temperature of the sheathing is close to or below the dewpoint temperature. As expected, the wall systems with a greater proportion of exterior insulation (outboard of the sheathing) perform the best in terms of dewpoint analysis (Lstiburek 2017) because the exterior insulation keeps the sheathing warmer. At average winter conditions, the sheathing on the ENERGY STAR wall (with 1/2” of exterior XPS) is well below the dewpoint temperature, increasing the potential for condensation. This wall has 12% of its R-value outside of the sheathing. The sheathing on the Hybrid wall (with 3" of exterior XPS) is slightly above the dewpoint. This wall has 55% of its R-value outside of the sheathing. With 100% of its insulation outside of the OSB, the SPS wall maintains its structural sheathing temperature well above the dewpoint.

Note that a simple dew-point analysis is not recommended as the sole means of determining the moisture risk of a wall assembly since it does not include the effects of phase change, moisture storage, air flow, bulk water intrusion, and other important moisture mechanisms (ASHRAE 2021). These additional mechanisms can often be the determining factor when evaluating moisture risk and potential for material degradation.

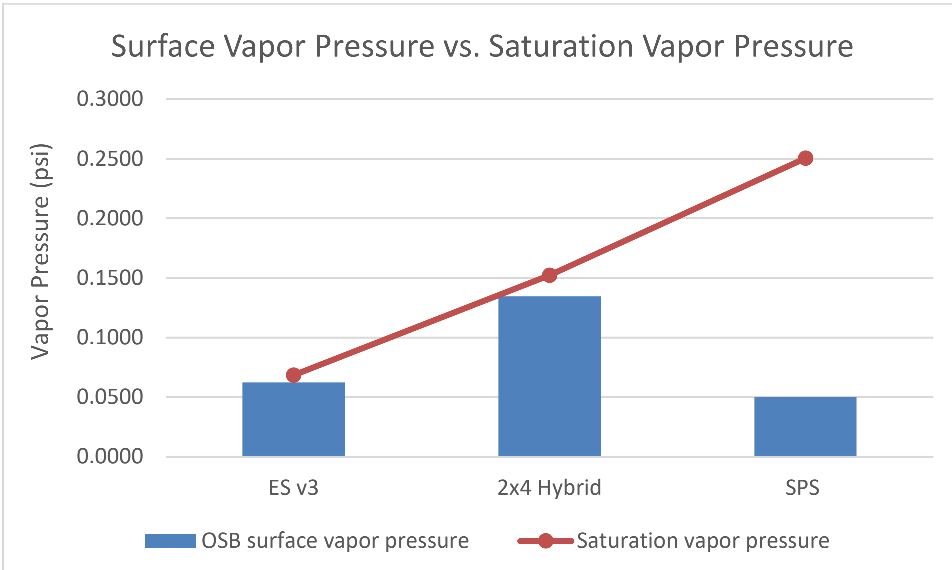


Figure 9. OSB surface vapor pressure compared to saturation vapor pressure at average winter conditions

Diffusion risk increases when the vapor pressure at the surface of the sheathing is consistently above or close to the saturation vapor pressure. The figure above shows that all three wall types keep the sensitive sheathing layer below the saturation vapor pressure at average winter conditions. However, there are important differences between them. Note that the saturation vapor pressure increases as the temperature of the surface increases, affording greater moisture safety.

- The 2x6 ENERGY STAR v3 wall protects the sheathing from outward vapor drive in the winter with the use of fragile 4-mil polyethylene membrane. Common construction practices do not prioritize keeping this important layer intact. Even with the poly throttling down the outward vapor pressure, the sheathing is still very close to the saturation vapor pressure because the temperature is so low. As the wall warms up in the spring, rapid drying will be essential to avoid moisture issues. However, it will be effectively shut off from inward drying by the poly and hindered from outward drying by the class II vapor retarder created by the foam sheathing.

- The 2x4 hybrid wall protects the sheathing from outward vapor drive in the winter primarily by keeping the sheathing warm with the use of 3” of exterior XPS. Compared to the ENERGY STAR wall this is a more robust approach and does not rely on fragile sheet goods on the interior side of the wall. Also, the sheathing layer can dry readily to the interior in spring.

- The SPS wall system employs multiple robust strategies to keep the critical OSB structural panel moisture safe. These include 100% continuous exterior insulation and placement of the panel adjacent to the indoor air, which facilitates drying. The panel is warm and well below the saturation vapor pressure. This wall system follows the principles of the “perfect wall” approach that has been shown to manage moisture effectively in all climate zones (Lstiburek 2010). Critical structural layers are protected from damage functions by exterior air, vapor, water, and thermal control layers.

B. Dynamic WUFI Analysis:

Typically in a dynamic WUFI simulation, the interior boundary conditions are set according to an ASHRAE 160 methodology that combines the exterior climate file with some information about the moisture generation and removal rates inside the house. With WUFI Plus, the interior boundary conditions are determined by a whole-building energy simulation that accounts for the heating and cooling requirements, geometry, mechanical system, and other characteristics of the modeled building (DOE-EERE 2016). In this case the Cedar house plan was used as the basis for all WUFI Plus wall simulations.

The resulting interior climate was examined closely to determine its suitability for the hygrothermal wall simulations. Interior setpoints were 68°F during the heating season and 76°F during the cooling season. A maximum of 70% RH was set to simulate the use of an air conditioner and/or dehumidifier to control humidity during the peak times of year. The resulting interior relative humidity graph is shown in Figure 10. Comparing the interior RH graph from WUFI Plus to that derived from the ASHRAE 160 methodology (shown in Appendix E, with discussion) shows close agreement.

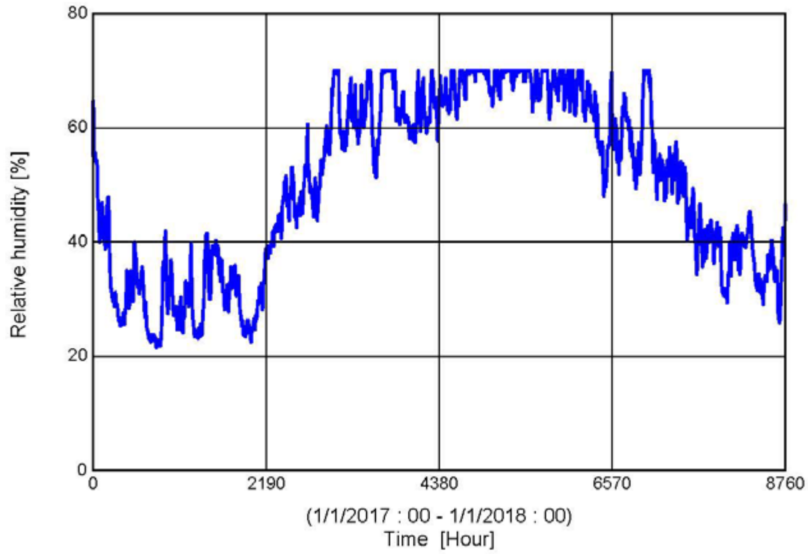


Figure 10. Interior RH conditions used as input for the WUFI Plus hygrothermal models

The exterior boundary condition selected for WUFI Plus simulations was the Minneapolis ASHRAE climate, cold year. In an effort to homogenize the material inputs for both the Glaser analysis and WUFI Plus analysis, a consistent set of thermal conductivity and moisture permeability data were used for all the wall materials. This material data set is summarized in Appendix E. To create this data set actual building material specifications and product data sheets provided by Twin Cities Habitat for Humanity for the Cedar were first compared to the available material database in WUFI. An acceptable match was found for almost all the materials. The selected materials from the database were then used for inputs for the material conductivity and permeability values in the Glaser analysis. In Appendix E, the chart values shown in red indicate significant discrepancies between the WUFI data set and the specified material/product from the actual, monitored wall assembly. For example, both the XPS and OSB as modeled with the Glaser analysis and WUFI were significantly more vapor closed than the actual products specified according to manufacturer data sheets. This would likely reduce the drying potential of walls with these materials in the simulations.

Once the interior and exterior boundary conditions were identified and the appropriate materials were selected from the WUFI database, the wall assembly models were created. These inputs followed the methodology suggested by BTO’s *Modeling Enclosure Design in Above-Grade Walls* (Lstiburek 2016). Most notably, 70% of the incident rainfall was modeled to stay on the cladding with 1% of that penetrating through the cladding to the weather barrier. In turn, 1% of this moisture was added as a moisture source to the sheathing to represent leakage through the weather barrier. In addition, “flanking flows” (airflow from both the interior and exterior entering the stud cavity) were modeled for the ENERGY STAR wall. Only the interior flanking flow was modeled for the 2x4 hybrid wall with the expectation that the fully adhered “peel and stick” membrane on the outside of the sheathing would effectively prevent outside air leakage from reaching the stud cavity. The SPS system was modeled without flanking flows because it has no cavities. The most important WUFI inputs for each wall assembly are shown in Appendix E.

WUFI modeling results for the three wall assemblies are shown in Figure 11. The gold line tracks moisture results from the exterior face of the OSB sheathing. The brown line tracks results from the interior face of the OSB sheathing. The results depict the highest moisture content, typically from the eastern exposure, that receives the greatest share of wind driven rain according to the climate file.

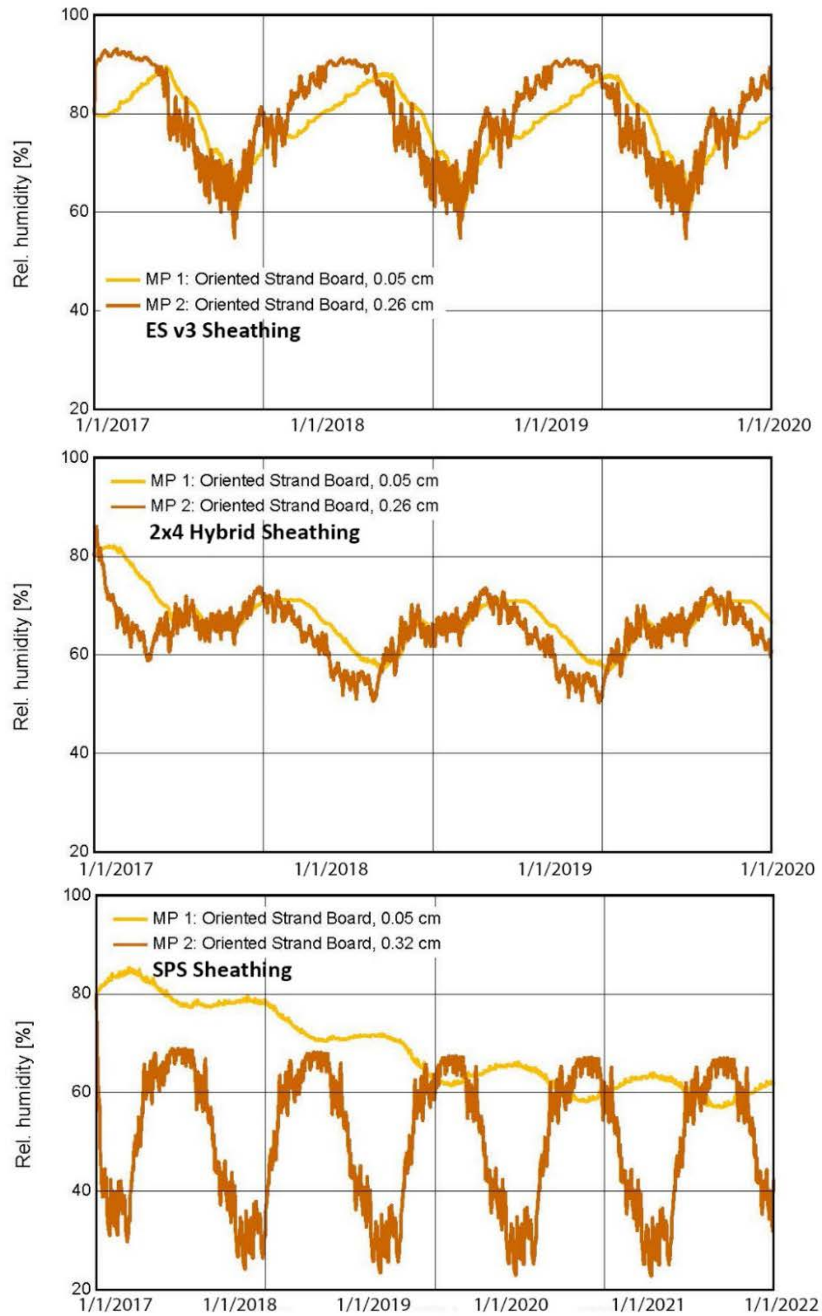


Figure 11. WUFI Plus-modeled relative humidity levels for sheathing in ENERGY STAR v3, 2x4 hybrid, and SPS wall types. Gold shows outer sheathing surface; brown shows inner sheathing surface.

- **ENERGY STAR v3 Wall:** The 2x6 ENERGY STAR v3 wall exhibits typical moisture behavior for a standard-framed wall in a cold climate. The exterior sheathing gets very wet in the winter with an RH above 80% for the entire heating season. This is due to the combined effects of bulk water leakage (1% leakage past the cladding), flanking airflows (leakage of moisture-laden indoor air into the wall cavity), moisture diffusion, and limited drying potential due to lack of heat. Fortunately, mold growth cannot occur during most of this time because temperatures are mostly below freezing. However, it is imperative that the sheathing dries quickly in the spring as average temperatures climb back above freezing. In this case, the exterior insulation (1/2" of exterior XPS) is too thin to significantly warm the sheathing but it does create a class II vapor retarder on the cold side of the wall. More simulations are necessary to determine the impacts of this thin layer of XPS. In the third year of the simulation, the peak moisture content (not shown in the above graph) of the sheathing in this wall assembly was approximately 23.4%. This occurred midwinter on the inside face of the sheathing.

- **2x4 Hybrid Wall:** The 2x4 hybrid wall sheathing behaves quite differently in terms of moisture content, RH, and temperature. Peak RH occurs in the fall after a summer of moisture loading from high RH conditions inside the house. Indoor humidity is highest in the summer because the house cannot ventilate with drier outdoor air as it does in the winter. Note that the sheathing in the 2x4 hybrid wall is not protected from high indoor RH levels by a vapor retarder as in the ENERGY STAR v3 wall. During the winter, interior RH levels fall and the sheathing, warmed by 3" of exterior XPS, dries out. Overall, the sheathing appears to have good drying potential though it dries to the inside in the winter rather than the outside in the summer as the ENERGY STAR v3 wall does. Sheathing RH levels are elevated but never approach 80% RH. In the third year of the simulation, the peak moisture content of the sheathing in this wall assembly was approximately 10.5%. This occurred on the inside face of the sheathing in the early fall.

- **SPS Wall:** The moisture behavior of the OSB panel in the SPS exhibits low drying potential. Following standard WUFI modeling conventions, the initial RH across all materials and layers was set at 80%. It took an extended WUFI simulation of five years for the exterior face of the panel to dry and stabilize into a consistent repeating pattern. This may be in part due to the small amount of rain leakage (0.01%) that is added to that face every year. The high interior RH in the summer may also lengthen drying time. Likely the largest factor is the impermeability and thickness of the SPS panel itself. Huber provided permeability data for the OSB used in its Advantech panels at 0.618 perm inches. At the construction thickness of 2.25 inches, this is equal to a moisture permeance of 0.27 perms. This qualifies as a class II vapor retarder, similar to several inches of closed cell spray foam. The average permeance of the panel as modeled in WUFI Plus was even less, probably around 0.15 perms, although the exact value is not possible to determine because the material's permeability varies dynamically with fluctuating RH levels.

Because the interior face of the OSB structural panel is directly exposed to the inside, it tracks the RH of the interior air very closely. In the summer, RH is just below 70%. In the winter the RH hovers around 30%. At this thickness, the exterior face of the panel cannot dry quickly to the inside and the exterior face of the OSB panel eventually settles around 60% RH. The lack of drying potential results in a significant lag in the peak RH for the outside face of the panel. While the inside face of the panel experiences peak moisture content in the early fall, similar to the 2x4 hybrid wall, the outside face of the panel experiences its peak in winter. In the fifth year of the simulation the peak moisture content of the OSB in this wall assembly was approximately 8.9%. This occurred in the early fall on the inside face of the panel. Due to its location in the enclosure and the high degree of protection from bulk water afforded by the fully adhered "peel and stick" membrane, the OSB structural panel takes on less water overall than both the 2x4 hybrid wall and the 2x6 ENERGY STAR wall.

4.3.2.2 Moisture Monitoring

Moisture monitoring protocols were followed for each house as it was constructed. Measurements were taken at one ENERGY STAR v3 house, one 2x4 hybrid house, and two SPS panel houses. Temperature, humidity, and moisture content sensors (OmniSense S-10) were installed in each. The sensor package included ambient temperature and RH sensors on all three levels (basement, first, and second floor) and outdoors at each house. Temperature and moisture content sensors were installed to monitor conditions in the critical layer (OSB sheathing) of the enclosure, at a variety of locations. These included the north and east, or north and west, walls on both first and second floors. Sensors installed in the walls of the SPS houses measured moisture content at both the inside and outside faces of the composite panels and temperature at the inside face. Sensors placed in the top and bottom of the stud cavity walls of the ENERGY STAR v3 and 2x4 hybrid houses measured temperature and moisture content at the inside face of the sheathing. Eight sheathing locations were monitored in total for each house. The Omnisense S-10 wood moisture content meters had a lower limit of detection of 6%. In other words, levels below 6% were too low to measure accurately. All sensors recorded data hourly.

In the houses with cavity walls, moisture meters were installed as shown in Figure 12. A small hole was made in the drywall, the vapor retarder carefully cut, the meter installed with screw pins into the sheathing, fiberglass insulation replaced around the units, and the vapor barrier resealed with 3M 8067 tape. Each pin meter was battery powered and sent data to a wireless gateway, then to an online tracking portal hosted by Omnisense. Ambient temperature and relative humidity were tracked using Omnisense S-10 sensors placed in representative locations in the basement, first floor, second floor, and front porch of each house.

Figure 12. Typical moisture sensor installation in a frame wall showing top and bottom stud cavity locations

In the houses with panelized walls, moisture meters were installed with pins of two different lengths to measure moisture on the interior and exterior faces of the panel as shown in Figure 13. A hole was cut in the drywall, and the pins were screwed directly into the OSB panel.

Figure 13. Typical moisture sensor placement in SPS wall showing interior surface and exterior surface panel depths

4.2.3 Analysis

Moisture monitoring results are shown in the grouping of three charts in Figure 14. These charts show the exterior (ambient) relative humidity, the average indoor relative humidity, and the highest daily relative humidity recorded in the OSB sheathing across all the wall sensors. The three graphs in this figure illustrate three important points:

- The sheathing in each wall tended to track the relative humidity of its most closely connected environment. For the ENERGY STAR v3 wall, the sheathing is located adjacent to the cladding and experienced nearly the full range of temperature and humidity conditions of the exterior environment. The orange (sheathing) and gray (exterior ambient) relative humidity lines tracked each other closely. The sheathing for the SPS house is located adjacent to the interior drywall without a poly vapor retarder separating them. The orange (sheathing) and blue (interior ambient) relative humidity lines tracked each other very closely. In the 2x4 hybrid wall, the sheathing is positioned midwall between an exterior and an interior layer of insulation. Although it is protected from exterior moisture by a robust peel and stick membrane and 3” of foam, it still experienced an average of the exterior and interior temperatures. The 2x4 hybrid wall sheathing’s relative humidity (orange line) tracked in the middle between exterior and interior RH.

- All wall types demonstrated an acceptable level of moisture safety. Mold can grow on surfaces at relative humidity levels as low as 80% as long as nutrients are available and temperatures are above 32°F. For all the locations where moisture sensors were installed, relative humidity levels remained below 80% in the sheathing year-round. Each wall type experienced a high of approximately 70% RH.

- Higher levels of exterior insulation led to drier overall conditions for the sheathing. Although each wall demonstrated an acceptable level of moisture safety, walls with a higher proportion of exterior insulation kept the sheathing drier than walls with little exterior insulation. The ENERGY STAR v3 wall with 1/2” of exterior XPS outboard of the sheathing exhibited the highest relative humidity in the sheathing year-round. RH in the sheathing never dropped below 60% and was frequently above 70%. The 2x4 hybrid wall with 3” of exterior XPS outboard of the sheathing kept RH levels at or below 50% for much of the year. The SPS wall with 4” of exterior XPS and no interior insulation kept RH levels at or below 40% for much of the winter and performed similarly to the 2x4 hybrid wall for the remainder of the year.

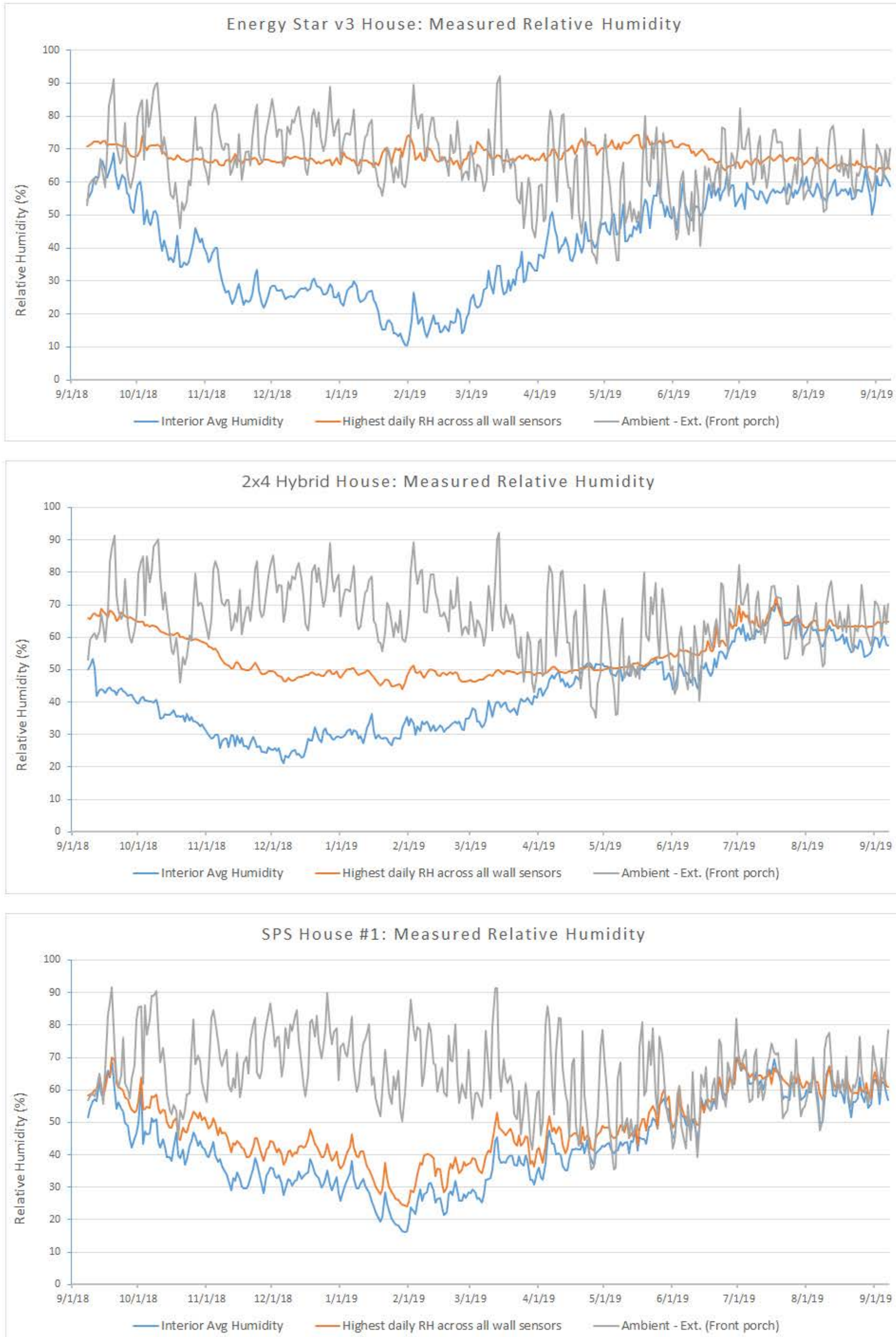


Figure 14. ENERGY STAR v3, 2x4 hybrid, and SPS house #1—measured ambient, interior, and OSB sheathing relative humidity

4.3 Structural Performance

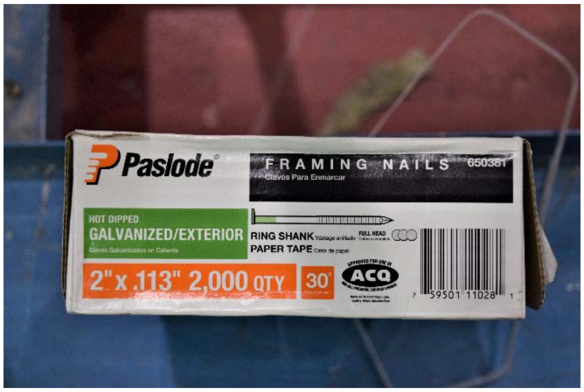
This research project included a concurrent effort to bring the SPS system to the single-family production market. We discussed possibilities with our partner, Thrive Home Builders, a prominent homebuilder in Denver, Colorado—a market that excels in high-performance and ZERH homes. However, early in the project, Thrive's structural engineers expressed concerns with the 2-ply SPS approach for use in their Model 740 (see Appendix A) that had a 10' first floor ceiling height and a 9' second floor ceiling height. Their continued request was for more structural data to properly assess the SPS application to this house design. At that point the research team suggested that Thrive contract with Home Innovation Research Labs to conduct preliminary tests on a series of 1-ply and 2-ply structural OSB panel specimens of various heights to determine axial compressive performance. As of the publishing of this report, no Thrive homes have been completed with SPS walls, but we are optimistic that they may be able to use SPS panels in future builds.

4.3.1 Research Design

The primary objective of this preliminary research between Thrive and Home Innovation Research Labs was to determine the compressive/buckling performance (maximum load) of nominal 4' wide OSB panels of 1-1/8" thickness for both 1- and 2-ply specimens as used in the SPS wall configuration. The tests were conducted on panels that were 48" wide and a variety of heights under compressive loads. The load was applied onto the edges of the specimens in a manner where the loading and supporting elements were not able to rotate. This test configuration mimics a "fixed/semi-fixed" joint condition

4.3.2 Data Collection

Test Set-Up: The layers for 2-ply specimens were nailed together using a pneumatic nail gun and screwed together using an electric driver, as shown in Figure 15. Glue was not used. The fastening schedule was provided by the University of Minnesota to match the on-site practice of builders who have used this method for one- and two-story residential construction in various field demonstrations. The typical field pattern and fastening schedule is shown in Appendix F.



Counterclockwise, from left:

- Screws used in testing
- Nails used in testing
- Nailing a 2-ply specimen; nails and screws were alternated per the construction guidance from University of Minnesota

Figure 15. 2-ply specimen construction

The panel dimensions shown in Table 8 are nominal test sizes. All of the panels were identical in width (nominally 48"). All panel heights are nominal as the final test height was allowed to be slightly shorter to ensure that all specimens in each test height set were uniform for both 1-ply and 2-ply specimens. Ultimately, no specimens deviated from the nominal dimensions by more than 1/8". The letters in Table 8 are used to show the layout on the panel cut sheets.

Table 8. Layout of Test Panels

1-Ply Tests								
Panel Height	**Vertical Orientation**			**Horizontal Orientation**			**Nominal Size**	**# Reps**
4'	A	B	C				4' x 4'	3
6'	A	B	C				4' x 6'	3
8'	A	B	C				4' x 8'	3
9'	A	B	C				4' x 9'	3
10'	A	B	C				4' x 10'	3
8'				D	E	F	4' x 8'	3
2-Ply Tests (Fasteners Only)								
Panel Height	**Vertical Ply**			**Horizontal Ply**			**Nominal Size**	**# Reps**
4'	A	B	C	D	E	F	4' x 4'	3
6'	A	B	C	D	E	F	4' x 6'	3
8'	A	B	C	D	E	F	4' x 8'	3
9'	A	B	C	D	E	F	4' x 9'	3
10'	A	B	C	D	E	F	4' x 10'	3

Test Apparatus: In the field, all fasteners for 2-ply SPS wall panels are installed from the outside of the building. The loads are transferred from floors and the roof at joist connections, and the tendency is for the SPS panels to bow outward toward the vertically oriented panel. A Universal Test Machine with a capacity of 200,000 lbs. was used to apply vertical, in-plane compressive force to the specimens similar to the setup and loading regime described in ASTM E72 (Figure 16). One-inch 90-degree flanges were bolted to the loading beams at top and bottom to hold the sample in place during setup but to avoid constraining the sample during load application.

Figure 16. Universal Test Machine test setup per ASTM E72

Panels were brought to failure as evidenced by the load increasing to a peak and then falling off. At this point any further compression resulted in additional buckling rather than greater load resistance. Tests were stopped once the load dropped 20% from the peak.

4.3.3 Analysis

The following data and observations are the result of testing conducted by Home Innovation Research Labs from December 2019 through March 2020. Figure 120 illustrates a typical load test with bowing. The maximum loads for all specimens are shown in Appendix F. The compressive load data have been averaged and displayed by height in Figure 17 for a 1-ply panel and in Figure 18 for a 2-ply panel.

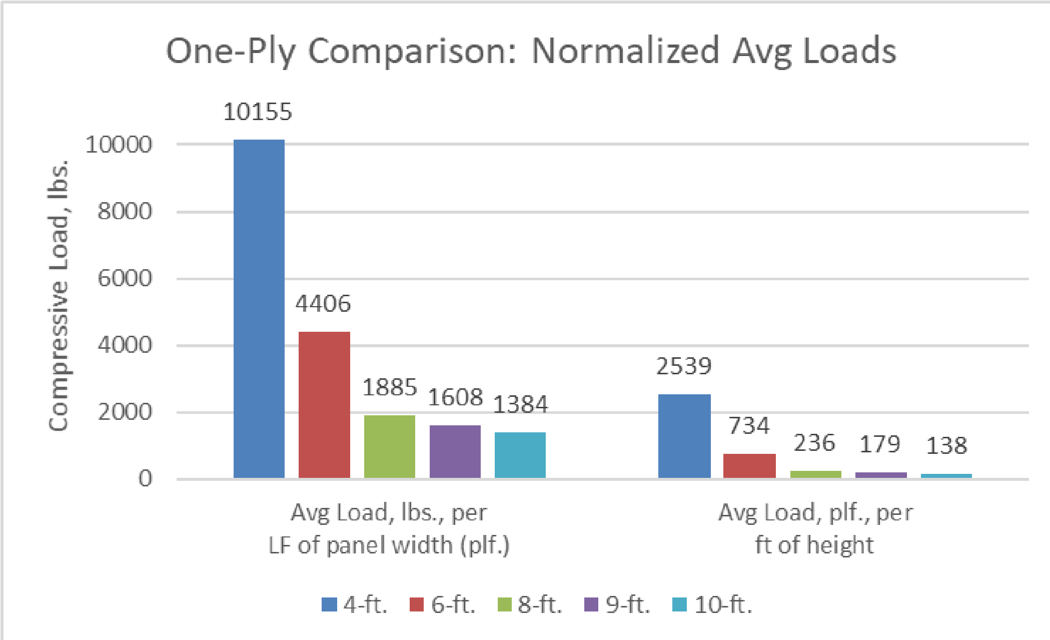


Figure 17. Normalized average loads for 1-ply—all specimen heights

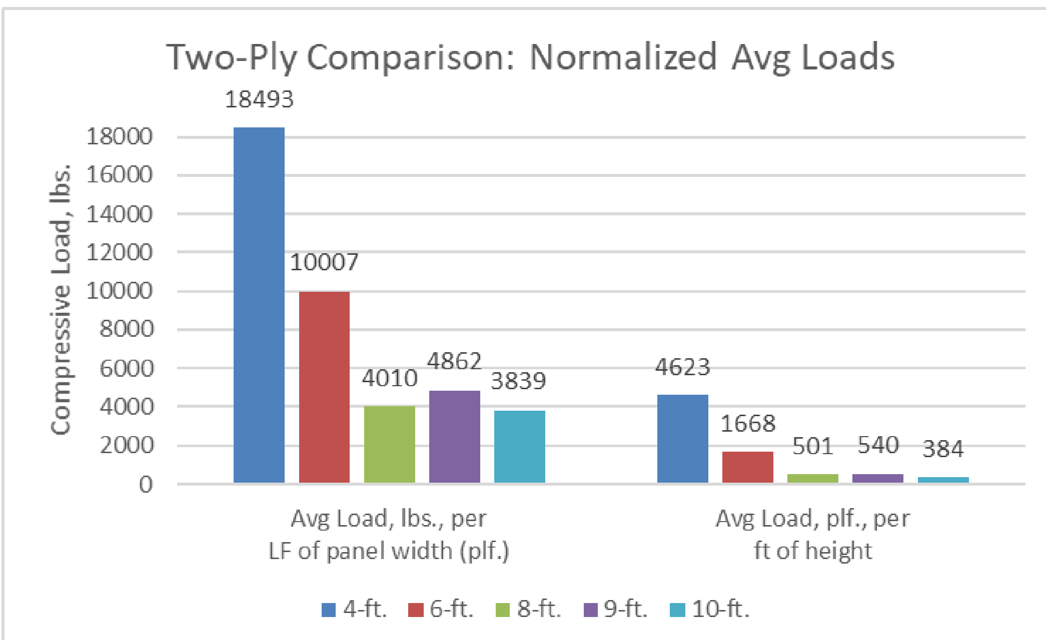


Figure 18. Normalized average loads for 2-ply—all specimen heights

4.4.4 Significant Results

In total, 30 specimens were tested, ranging from 4 ft. high to 10 ft. high. Specific observations on each specimen can be found in the table in Appendix F. General observations from these tests include:

- For both 1-ply and 2-ply specimens, shorter height panels exhibited higher load capacity than taller height panels, ranging from:
  - For 1-ply, over 10,000 plf. for 4-ft. panels to just under 1,400 plf. for 10-ft. panels.
  - For 2-ply, over 18,000 plf. for 4-ft. panels to just under 4,000 plf. for 10-ft. panels.
- At any given height, 2-ply panels had greater capacity than 1-ply panels; the increased capacity of 2-ply panels ranged from 80% higher than 1-ply (4-ft. and 8-ft. panels) to 200% higher than 1-ply (9-ft. panels).
- A set of three specimens 8 ft. high were tested in the horizontal direction in addition to the vertical direction and exhibited a 64% reduction in capacity.
- 2-ply panels were typically not twice as strong as 1-ply panels. This is likely due to the lower strength of the second panel in the horizontal orientation.
- For most panel heights, all three replicates performed within a narrow band of under 5%.
- For both 1-ply and 2-ply panels, the normalized load (plf. per ft. of panel height) decreased less (on a per foot of height basis) with increasingly tall panel heights.
- Both 1-ply and 2-ply panels exhibited elastic behavior by accommodating significant deflection in buckling (up to several inches for the tallest specimens) and quickly returning to a fairly straight uniform profile though they never returned back to pre-stressed state.
  - Panels were brought to failure as evidenced by the load increasing to a peak and then falling off; further compression resulted in additional buckling rather than greater load resistance.
  - With one notable exception panel failure appeared to be general and diffuse. No significant material cracking or shedding was observed. Crushing at top and bottom edges of specimens was minimal and uniform. A single 4-ft. panel exhibited catastrophic failure after loading by cracking near the midline of the specimen.

5 Discussion and Conclusions

5.1 Interpretation and Significance of Results

The Twin Cities Habitat for Humanity houses resulted in an informative comparison study. The three wall systems (2x6 ENERGY STAR v3 wall, 2x4 hybrid wall, and SPS system) showed distinct results when comparing speed, constructability, performance, and market acceptance. Overall, we believe the results show strong potential for future use and continued study of the SPS system.

5.1.1 Constructability

Constructability, as a qualitative component, did not include a specific protocol and measurement regime. Overall, volunteer construction crews made progress in building subsequent houses quicker than the first, and ultimately the houses were built successfully, and the houses sold well. Continued use is planned by Urban Homeworks, and although Twin Cities Habitat is unlikely to use SPS panels in imminent construction, we are encouraged by likely future uptake by other nonprofit and for-profit builders once additional structural testing is completed. As mentioned, large production builders such as Thrive Home Builders in Denver, Colorado, have expressed interest in the value of quickly erecting enclosures with high performance as an essential aspect of selling homes.

Overall, the market delivery success of this building approach is highly dependent on the levels achieved by other measures such as cost and cycle times. Other influences are the current decrease in the availability of skilled labor, the increase in lumber and framing costs, and the push to reduce time to secure dried-in. These could all play a large role in the market attractiveness of this building system.

Labor Challenges:

NAHB reported a record shortage of rough framing carpenters in fall of 2018 (NAHB 2018). Locally, large national contractors were left with land and without framing carpenters. This led to a shortage of framing contractors with opportunities of higher pay from these large national companies. This situation drove up the price of framing from 2017 to 2019 and affected the construction budget for the SPS houses in this project.

Lumber prices also rose significantly during the same period. However, the structural OSB panel prices remained steady during that period and labor was about the same due to Habitat and Urban Homeworks using their own internal staff to perform the framing. If these partners had relied on outside framing contractors, the SPS framing cost would have risen. Spero outsourced its first seven houses to MonoPath as a single enclosure contractor. For the second six houses, Spero used internal construction staff and showed consistent and substantial reduction in framing cost.

When construction labor prices go up and contractors find new means and methods to reduce their cost or increase speed (like using SPS walls), savings are not typically passed on to the owner or developer. Therefore, larger contractors will hire experienced framers to capitalize on the efficiencies of larger production volumes thereby increasing their margins.

Design Changes:

Design changes are often a barrier to cost reduction in any type of construction. For the Spero/MonoPath houses, they focused on optimizing the design, materials, and labor efficiency relative to the building enclosure. Much of that work and optimization was developed while building the first seven houses in 2014 and 2015.

As Habitat for Humanity planned their construction, however, they requested more than 60 individual design changes from MonoPath's optimized plans. Many of these were simple preference, finish, or specification changes, but some changes required additional structural analysis (e.g., changing bathroom configuration). This caused time delays, increased design costs, and pushed up the cost of the SPS houses.

Framing vs. Panels:

Comparative constructability based on cycle time, efficiency of framing assembly, skill level required for site build and contractor training was observed. To observe cycle time for the enclosure assembly lapse videography along with tracking times for construction supervisors and project staff was used. It was hoped to capture incremental time improvements similar to the 2014 time-lapse video referenced earlier. The houses constructed by Habitat and Urban Homeworks used volunteer labor. This process made it difficult to determine an industry comparative data approach. However, improvements by panel installation crews working on their second house were observed. Crane time was reduced from 2.5 days (22 hours) to 1.75 days (14 hours). Labor time for installing the fully adhered membrane was cut nearly in half by changing the method of application.

Trades and Training:

Building SPS houses requires training and field experience for new framing contractors. Building a SPS without any structural stud framing is very different for experienced carpenters. The research team assembled an approach that focused strictly on the solid panel framing and "perfect wall" enclosure system. Training for framing contractors was provided in three ways. First, MonoPath provided a six-hour Contractor Training class that was recorded and produced 20 topical videos that are accessible on the University of Minnesota's Northern*STAR* website,[2] Second, the website also includes three live videos showing wall and panel installation. The third approach was live construction experience guided by the project team. Experienced staff trained workers on-site as they built each SPS enclosure. A noticeable increase in speed and confidence was observed between the first and second houses. Much of that quick reaction is likely due to the elimination of the "fear factor." Once experienced contractors realized the simplicity of the process, they embraced the method and were able to work faster.

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[2] Videos can be viewed at: https://bbe.umn.edu/research/building-systems/northernstar/affordable-solid-panel-perfect-wall-building-and-delivery.

On-Site Fabrication:

A common question is how the SPS system might intersect off-site fabrication. Most noteworthy is that once the larger format structural OSB panels are cross laminated, they are too large for transport. For one of the early pilot solid panel houses MonoPath requested the 8'x24' panels be delivered to a fabricating plant where they were cut to size and window rough openings pre-cut with a computer numeric control (CNC) router. The panels were then loaded on a truck and delivered to the building site for erection. The time and additional plant cost that it took to cut the panels indicated that it was not a cost-effective approach.

For site fabrication, the panels are unloaded near the house location. A crane off-loads panels from the truck and places them in a single stack. The current 24'x32' two-story design uses 32 panels, a stack about 3 ft. high. There is only one cut per panel; some panels are installed without any cutting. One carpenter can make a panel cut in less than 5 minutes. It takes approximately 5 minutes for the crane to hook up and position the panel in place and be secured by the carpenters. The crane also sets the second floor and roof trusses. This very efficient process can be implemented with one lead carpenter and three less-skilled workers.

Optimizing Panel Configuration:

The key to panel efficiency and erection speed comes from the architectural design and dimensions in which the house walls are developed to utilize the panel dimensions and can be seen in Figure 19. This is done for proper sequencing and to minimize cutting and waste. For instance, the two floors are composed of four panels per floor. The walls are exactly 24' wide with the 8' width seams falling on the truss grid. The floor can be installed in 20 minutes. Glue application to each truss can slow the process. However, if the glue is kept warm, electric glue guns can be used to speed the process.

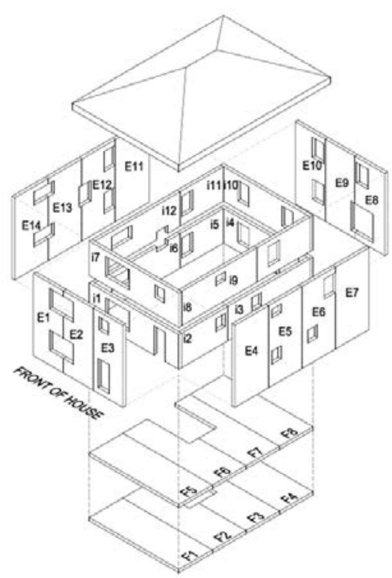

Figure 19. SPS panel layout

5.1.1.1 Twin Cities Habitat for Humanity

Twin Cities Habitat for Humanity is committed to their extensive volunteer program to produce a large number of houses each year in the Twin Cities area. They believe they can utilize stud construction with volunteers in their own panel plant at a lower cost than using the SPS walls. However, their growth in housing need is superseding the number of volunteers available to build more houses. To maintain momentum, they will need to hire general contractors to complete many houses without the use of the normal volunteer base. They clearly recognize the value of improved performance using the exterior control layers.

Overall, Twin Cities Habitat for Humanity engaged in this project to gain experience with the SPS system and evaluate it as a viable approach to ramp up house numbers in their future business plans. While their interest in SPS continues, they are currently waiting for the engineering study to be completed before constructing additional SPS houses.

5.1.1.2 Urban Homeworks

At this time Urban Homeworks' primary construction target is moving toward urban rehabilitation. However, they plan to continue to build two or more SPS houses per year. Once the engineering is confirmed they will evaluate its use for small multifamily house projects.

5.1.1.3 Spero Environmental Builders (Spero)

Spero has been dissolved, but a new version of the company will consider the SPS system for mid-priced homes within a pocket neighborhood design. They are waiting for sufficient engineering on the panel system that would enable them to be the first to custom build SPS houses.

5.1.1.4 Thrive Home Builders (Thrive)

According to the Thrive team, the SPS system has several benefits and constraints for widespread adoption by for-profit production builders. Key benefits include reduction of waste, cycle time, and warranty cost. Designs that fully utilize the structural panel dimensions will have much less loose lumber and waste. It is clear the SPS system can facilitate faster construction to a fully dried-in and secure building. The "perfect wall" should reduce warranty callbacks and costs for air leakage, cold walls, condensation, and water intrusion.

Current constraints include the lack of code compliant engineering, higher incremental costs, unknown panel supply chain, and lack of experienced trade base. The lack of adequate engineering data for simple SPS design and code acceptance forced Thrive to use a more costly hybrid 1-ply with 2x4 frame system. In addition, the extra costs for the exterior control layers are significant. The traditional supply chain used by most builders does not carry the large format OSB panels. Finally, the lack of experience with the SPS system within the current trade base will cause an increase in labor cost until comfort levels improves and competition increases.

Production builders are always looking for ways to obtain the benefits that the SPS system can provide. However, first cost continues to be an inhibitor to adopting new systems able to deliver those benefits. For Thrive, solving the engineering issue will be a key first step in pushing this system closer to cost parity with traditional framing. As exterior insulation and rainscreen siding applications become more widely used, this wall system should prove to be an attractive option for production builders. Smooth adoption will depend on the supply of materials through traditional lumber sources and proper training for field teams that can support the transition.

5.1.2 Costs

When the proposal was written for this project, MonoPath and Spero had successfully produced a business model that served as the basis for this study. In 2014 an experienced framing crew that worked as a team for several years was identified; they constructed seven solid panel houses. This company quickly worked through the learning curve associated with large format OSB panels and the SPS wall system. They performed their work on a time-lapse video documenting the house weather tight in five days.[3]

By 2017 when this project was ramping up for house construction, the original framing crew had moved on to other projects and was no longer available. At that point the two nonprofit partners with internal carpentry staff were trained to become certified "single enclosure contractors." These nonprofit crews were able to quickly learn the SPS shell structure and delivery process, confirming the building potential of the SPS system. A small for-profit builder completed enclosure framing for one of the Urban Homeworks SPS houses but declined to take on other houses due to unrelated business concerns. Two other framing companies were contacted and expressed genuine interest in the SPS system. However, they later declined the work due to the favorable framing opportunities in market-based housing.

Lumber prices nearly doubled in the latter part of 2018 but softened somewhat in early 2019. This price fluctuation directly affected the stud wall framing industry. Some material changes and construction methods were attempted with hopes of reducing cost. Spero, for example, changed from the fully adhered peel and stick membrane to liquid-applied membrane on the outside of the OSB panel. After completing several houses, a new method for applying the peel and stick membrane resulted in a reduction of 20 to 25 hours of labor. Originally, the membrane was installed from the top of the wall down to the foundation. The new method was simply to break the membrane application into two parts. In the first part the membrane is applied from the foundation to the top of the main floor window opening. Two workers were able to work from a step ladder and install the windows as they completed one side of the house. The second part is completed when provisions are in place to install the second-floor windows. This change was deemed to be safer and reduced the number of membrane rolls by one. However, the unintended outcome of these optimizations is that the labor savings were not reflected in the final price of the house. Through field experience, other changes were discovered. Some were related to the "learning curve" on panel installation and several were able to reduce the crane rental time.

[3] To view the video, see: https://www.tchabitat.org/blog/innovative-building-solutions-partnership-with-u-of-m.

System Cost Trade-Offs:

The construction of the SPS "perfect wall" system based on the numbers on Table 4 show that costs are very close. The higher price for OSB panels plus the fully adhered membrane and rigid foam insulation are key. However, there are trade-offs that helped offset some cost. The trade-offs include:

- The exterior perimeter walls require no drywall as the OSB panel can be primed and painted.
- The OSB floor can be sanded and coated with polyurethane for an attractive and durable finish.
- The large format panels can be installed more quickly reducing potential for weather damage and holding costs.
- The SPS system with the large cross-laminated panels and fully adhered membrane achieves extreme airtightness and provides remarkable moisture resistance.
- The monolithic panel whole-house system is likely to show greater moisture resilience to catastrophic events and potentially improved resistance to wind loads. (Note: The structural aspects of the SPS system with laboratory testing for various types of loads is being conducted under a separate DOE project.)
- The study could not conclusively show a time and construction efficiency savings with the SPS system but there is strong indication that building multiple houses will increase speed and improve other efficiencies.

The nonprofit partners for this project chose to take advantage of some of these trade-offs. Painting the exterior perimeter OSB walls reduces approximately 1,800 square feet of drywall and taping plus any furring strips required to fasten the drywall. Sanding the floors and applying a polyurethane finish can be done by volunteers for less than $1,000. Various floor coverings would cost $4,000 to $6,000 if installed by contractors (see Table 4).

The previously mentioned time lapse video shows a house being constructed to a point of being weathertight (also referred to as dried-in) and secured in five days. Experience from this project has shown that two weeks might be a more likely target for new contractors. In general, market-rate builders report experience of three to six months of battling weather and holding costs before reaching the weathertight level for typical stud-frame construction. Spero consistently reported increasingly shorter erection times with the 13 houses built between 2014 through 2106.

5.1.3 Performance

5.1.3.1 Energy Summary

According to REM/Rate estimates shown in Table 9, the heating and cooling design loads for the Cedar Habitat projects (both SPS and 2x4 hybrid) are quite small—less than 24 kBTU/hr of heating and less than 15 kBTU/hr of cooling. That represents a 40% and 25% reduction, respectively, compared to the baseline energy code version. This suggests that variable capacity/speed equipment must be an important component of the HVAC system for these homes to help address partial-load issues such as dehumidification and short-cycling.

Table 9. Modeled Design Loads

	Design Load (kBtu/hr)	
Model Name	**Heating**	**Cooling**
Cedar MN Energy Code	40.2	19.0
Cedar Energy Star v3	34.0	17.7
Cedar DOE ZERH	27.9	15.2
Cedar 2x4 Hybrid (Habitat)	23.0	14.5
Cedar SPS (Habitat)	23.9	14.6

Modeled heating and cooling energy consumption and costs for the SPS version of the Cedar achieved roughly 50% savings compared to the 2015 MN energy code version. Total energy consumption and energy cost were reduced by 30%. As shown in Figure 20 and Figure 21, the electric loads (appliance, plug, lighting) make up a disproportionately large share of total energy costs but are not reduced substantially through enclosure or mechanical system improvements.

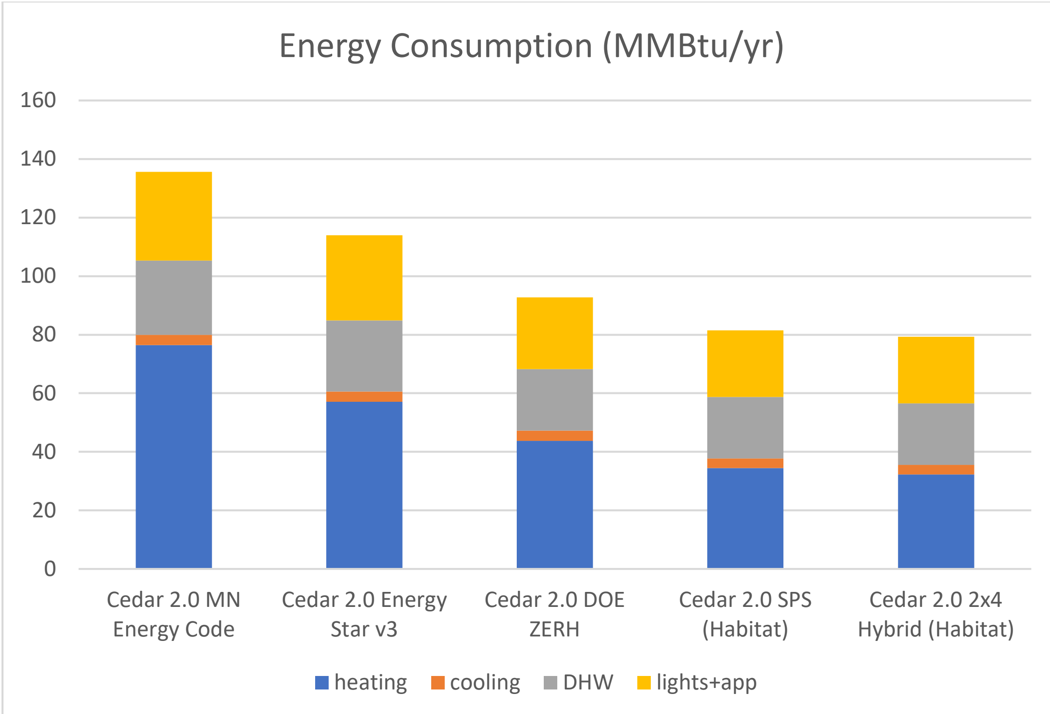

Figure 20. Annual energy consumption breakdown by type/use

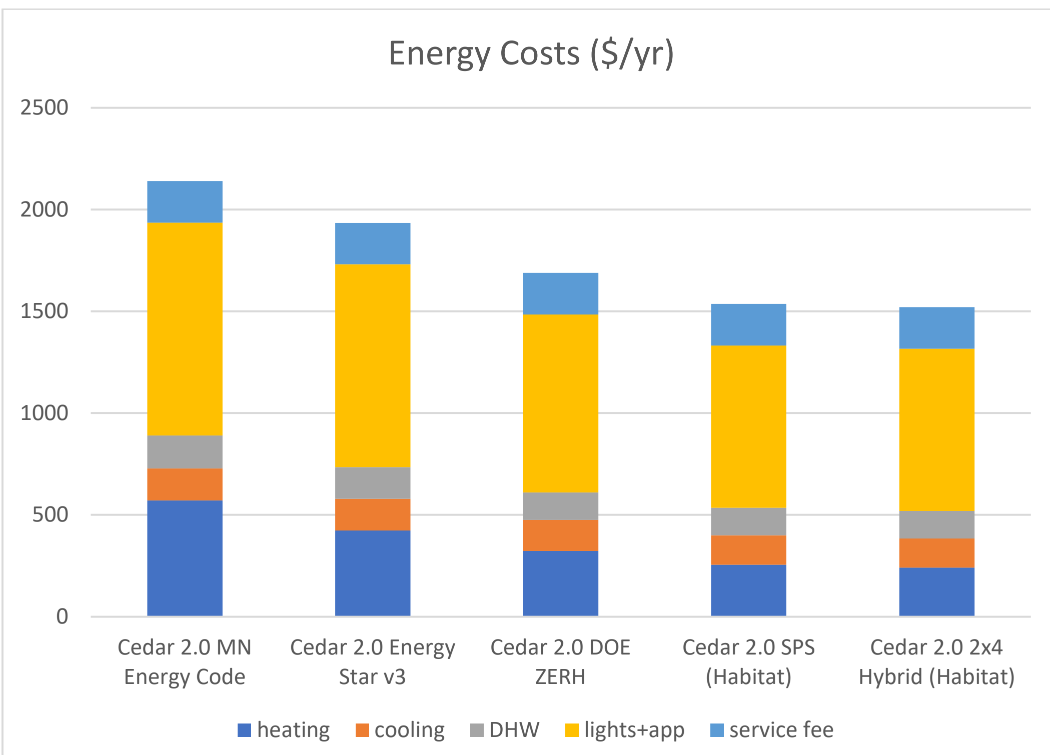

Figure 21. Annual energy cost breakdown by type/use

Energy modeling results show that both the SPS and 2x4 hybrid versions of the Cedar as built by Habitat Twin Cities will surpass the DOE ZERH level of performance and afford significant utility cost savings for homeowners.

While house geometry is one possible option to explore for further energy savings, the SPS system itself is well suited to achieving deeper energy reductions. Inherently high levels of airtightness and reduced thermal bridging provide energy benefits as well as durability benefits. The system is flexible, easily accommodating changes to insulation type and thickness thanks to the benefits of perfect wall principles and solid panel construction. As moisture modeling and monitoring results suggest, a variety of different insulation types could be used, including products that are quite vapor closed such as closed-cell spray foam or foil-faced polyisocyanurate. Since the wood portions of the wall dry to the inside, these high performance, high R-value types of insulation products could be used without risk of creating a cold side vapor retarder. In addition, the continuous exterior insulation minimizes thermal bridging and the total R-value of these high R-value insulation types is preserved rather than bypassed. The structural OSB panels provide a solid base for application of thicker exterior insulation as well since screws used for cladding attachment or furring strips do not have to be driven into narrow studs.

Typically, high R-value walls have a greater moisture risk since there is less heat flow and therefore a lower drying potential. The SPS approach minimizes this risk by dramatically reducing air leakage, eliminating stud cavities and condensing surfaces within the wall, and allowing the wood portions of the enclosure to dry directly to the inside. These benefits make the SPS wall particularly well-suited to high R-value enclosures and deeper energy savings.

5.1.3.2 Moisture Summary

Each wall system uses a different set of strategies to maintain moisture safety. These strategies vary not only in their effectiveness but also in terms of their robust ability to withstand defects, damage, and incidental water penetration.

Dynamic moisture modeling supports the assertion that using more exterior insulation leads to warmer sheathing and drier conditions. Figure 22 combines the modeled moisture content from all three wall types on a single graph for comparison. It is readily apparent that the coldest sheathing (ENERGY STAR v3 wall) is also the wettest. The warmest sheathing (SPS wall) remains the driest. The sheathing in the 2x4 hybrid wall is warmer than that in the ENERGY STAR v3 wall, but not as warm as the SPS sheathing. Its moisture content falls in the middle. Although these results show that the critical sheathing layer remains below 18%–20% moisture content for all walls, the ENERGY STAR v3 wall sheathing is clearly wetter and accordingly leaves less room for failure of its moisture management layers.

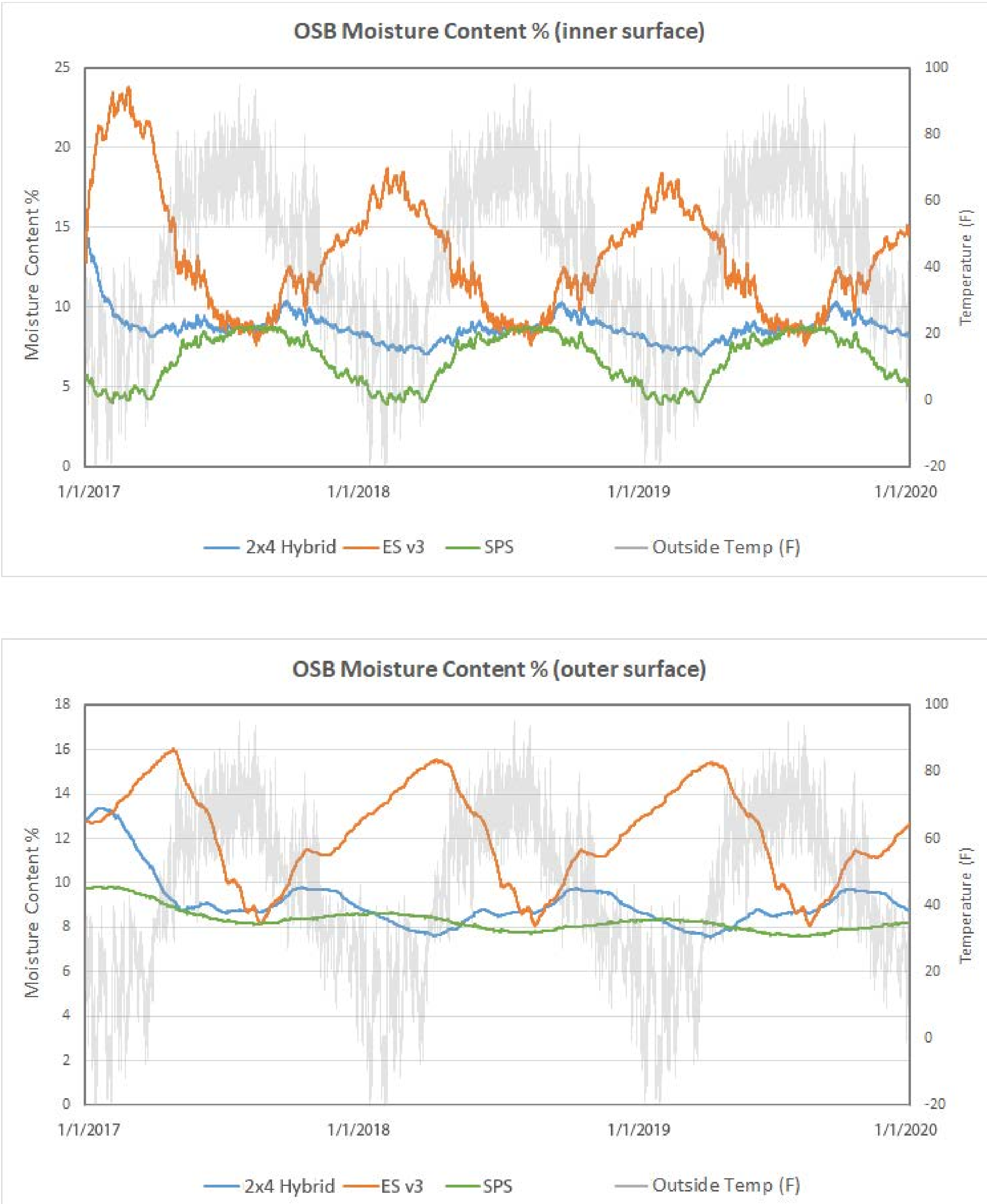

Figure 22. WUFI Plus simulation, OSB inner and outer surface moisture contents over 3 years

The bottom graph in Figure 22 tracks the moisture content of the *outer* surface of the OSB. While this graph agrees in general with the upper graph tracking the moisture content of the *inner* surface of the OSB, there is an important difference to note. The moisture content of the outer surface of the SPS panel is delayed by several months compared to the plot of its inner surface. The other two wall systems do not display this type of behavior. Their inner and outer surface layer moisture levels remain much more closely aligned and in sync with each other. It is probable that the relative thickness and impermeability of the SPS panel leads to this time lag. Higher moisture levels at the inner surface take time to work their way to the outer surface and vice versa. This theory is bolstered by earlier graphs showing that the SPS panel takes 5 years to reach a consistent, stable moisture content pattern. Clearly, there is room to improve the drying capacity of the SPS wall.

To investigate options for improving the drying capacity of the SPS wall, several different materials for the control layers were tried in versions constructed by Spero and tested with additional WUFI modeling. These variations showed that different insulation and weather barrier product types could be used safely with the SPS wall, but more vapor permeable exterior insulation combined with a vapor permeable weather barrier works the best to improve drying capacity. These results are shown and discussed in Appendix E.

A comparison of modeled to monitored sheathing moisture content shows fairly consistent agreement between data sets. Figure 23 depicts the range of moisture content (minimum to maximum) observed from the third year of the WUFI Plus simulation alongside the corresponding moisture content range from the first year of monitoring data. A clear progression from the wettest enclosure type to the driest is visible in both data sets. The ENERGY STAR v3 wall is generally the wettest and has the widest moisture content range, while the SPS wall is generally the driest with the smallest variability. Both the monitoring and modeling data sets show that the 2x4 hybrid wall falls in the middle. This pattern in moisture content from wettest and most variable to driest and least variable is expected and corresponds to the location of the sheathing in the wall assembly. The more protected the sheathing is from the exterior extremes of moisture and temperature the drier and more stable it is. A more detailed comparison of moisture modeling and monitoring data is shown and discussed in Appendix E.

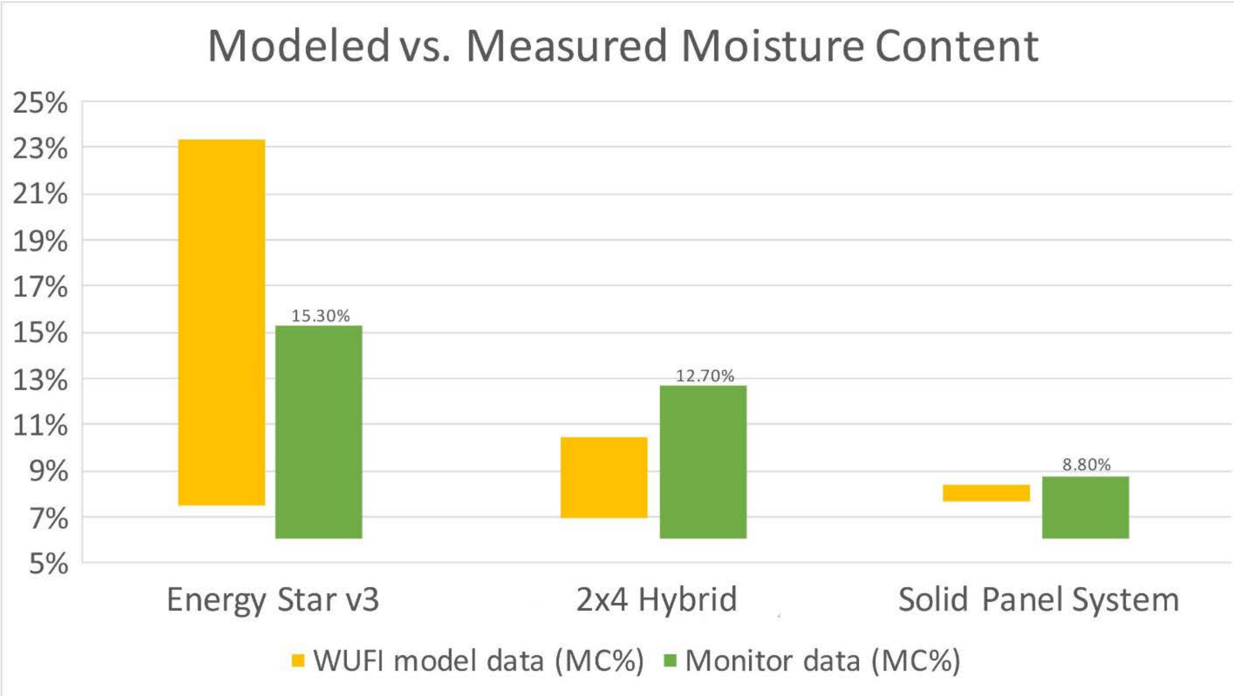

Figure 23. Modeled vs. measured moisture performance

5.1.3.3 Commissioning Summary

During construction all houses received inspections by an energy rater. Once completed, they were tested, commissioned, and certified to meet ENERGY STAR. The 2x4 hybrid and all SPS houses met DOE ZERH requirements and were certified. These data were collected to compare the three-house wall comparison as well as a way to look for performance variation between the SPS houses.

Commissioning results for the SPS houses, as illustrated in Table 7, were very good. The SPS houses had remarkable HERS Index scores and were very airtight. However, there was some significant differences between builders, perhaps due to different windows and variation in HVAC equipment. The lower HERS Index seems to coincide with the lower blower door test numbers.

5.1.3.4 Structural Summary

A preliminary panel test conducted by Home Innovation Research Labs provided significant insight and confidence in the behavior of the structural OSB panels in both 1-ply and 2-ply configurations (Figure 24 and Figure 25). The study shows that 1-ply panels may be adequate to carry typical residential vertical buckling loads for 8-ft. walls. The 2-ply panel system should be able to meet the buckling loads requirements for walls up to 10 ft. Additional full-scale tests have been funded under a separate DOE project. The primary goal of that project is to develop sufficient engineering data so it will be easy for designers and builders to get code approval for the design and construction of the SPS system.

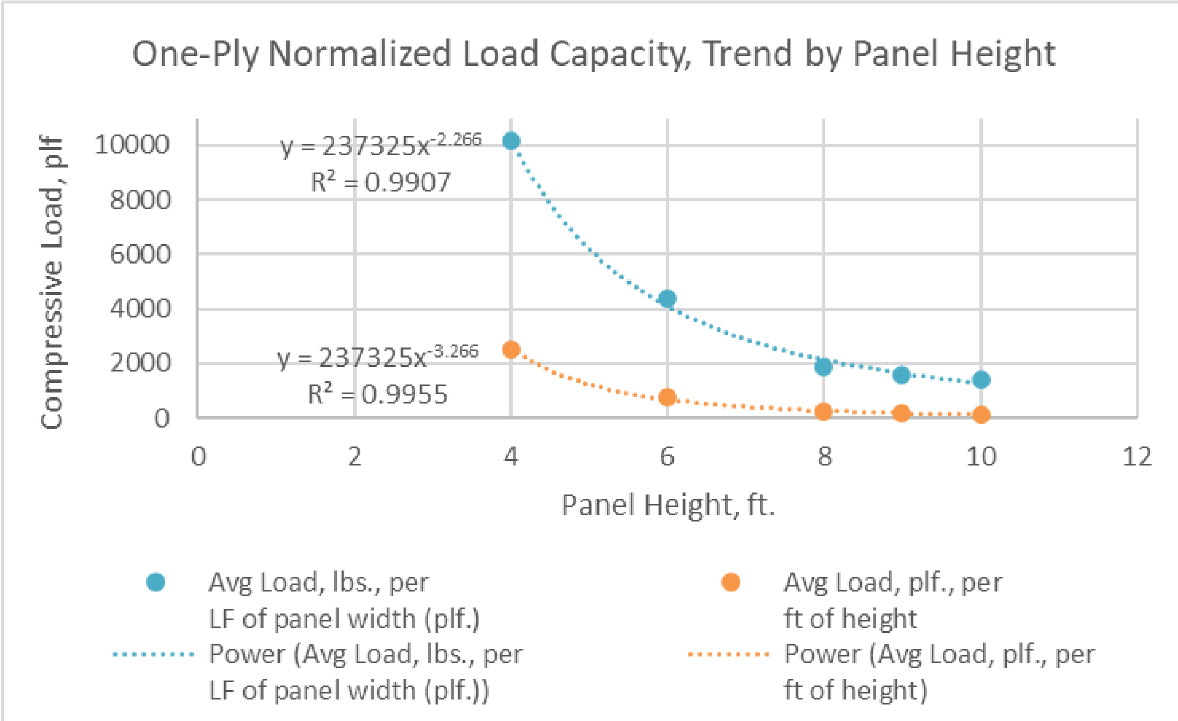

Figure 24. 1-ply load capacity trend by panel height

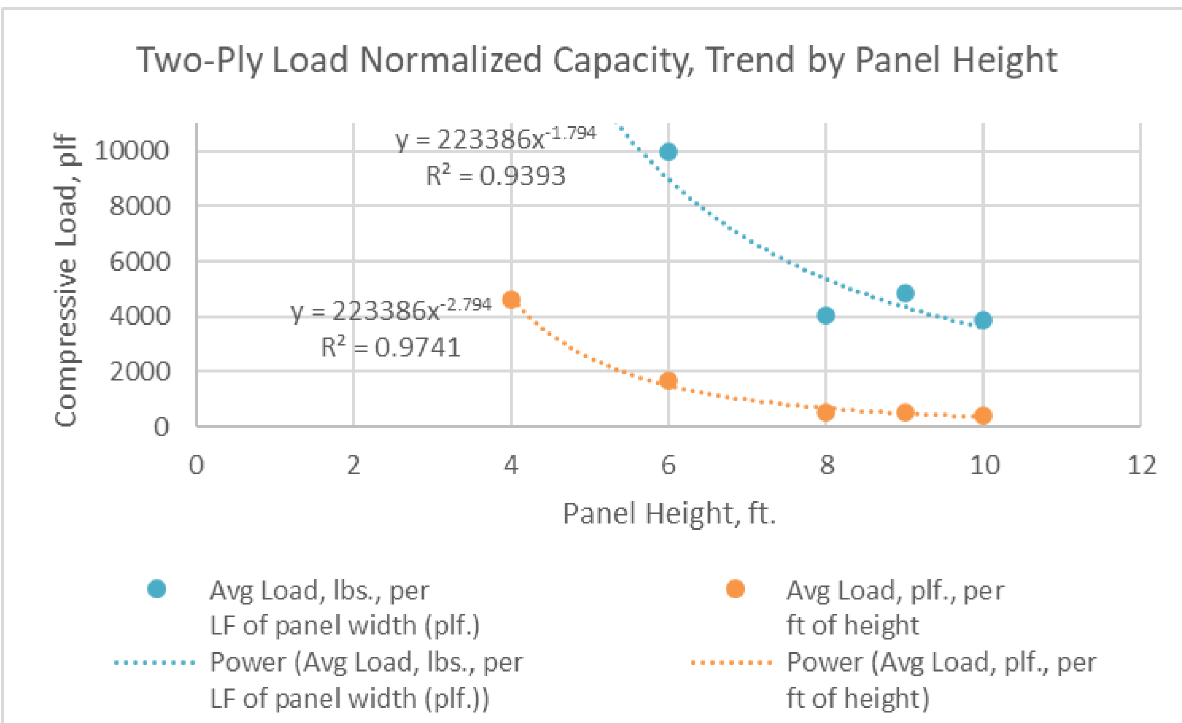

Figure 25. 2-ply load capacity trend by panel height

5.2 Potential Limitation of Experimental Design

Other barriers to market acceptance are related to residential construction market conditions:

- A shortage of skilled labor, especially structural framing, made it difficult to recruit and retain enclosure contractors.
- The grant partner, MonoPath, that developed much of the solid panel system design, along with means and methods, declined to continue as a partner after the first year.

Two for-profit builders initially agreed to participate but backed out at the last minute because they were committed to other for-profit projects.

Both Twin Cities Habitat for Humanity and Urban Homeworks continue to look to the SPS system to address the demand for housing units and their growing labor issues. In fact, Urban Homeworks has a framing team that is certified to build SPS houses.

5.3 Applicability of Findings and Actionable Guidance

Houses from previous studies—the 1990s houses and the University of Minnesota/Wilder houses—remain in use today. We do not have performance data but they were built to be more energy efficient than code requirements, and at a lower cost. The 13 Spero homes showed that higher energy savings than the current codes and lower cost could be achieved using the SPS system.

The outcomes of the five SPS houses indicate that SPS houses are a viable and high-performance building system. However, adoption of the SPS technology has not been realized. Reasons for that include:

- There is and always has been a general resistance to a sweeping change in construction methods and materials they are inherently risk adverse.
- Builders are hesitant to spend time training to achieve the efficiencies and other economies of scale.
- An unprecedented reduction and shortage of carpenter/framers dramatically increased the labor price.
- The “single enclosure contractor” approach was a component of this research to demonstrate cost reduction, speed increase, and quality control for a new construction process. This approach was successfully implemented prior to the proposal. However, engaging, training, and retaining a single enclosure contractor proved to be challenging due to extraordinary delays by the developers and the economics of the building industry during the time of the research.

- Twin Cities Habitat for Humanity, Urban Homeworks, and many similar nonprofits rely heavily on donated materials and volunteers to complete homes. Ultimately, through this project, Habitat and Urban Homeworks determined that the use of the large format panels to construct the building enclosure was not conducive to their volunteer workforce.

- The SPS system has not been codified by building codes. At the time of this research, each house required engineering certification, adding cost and just as importantly, extra time to complete the building permit process.

Current constraints on for-profit production builders include the lack of code-compliant engineering, panel supply chain, higher incremental costs, and lack of experienced trade base. The SPS houses currently have higher engineering costs to satisfy code officials. The traditional supply chain used by most builders does not carry the large format OSB panels. In addition, the extra costs for the exterior control layers are significant. Finally, the lack of experience with the SPS system within the current trade base will cause an increase in labor cost until comfort levels improves and competition increases.

The preliminary panel testing conducted by the Home Innovation Research Labs provided significant insight and confidence in the behavior of the structural OSB panel in both 1-ply and 2-ply configurations. The study shows that 1-ply panels may be adequate to carry typical residential vertical buckling loads for 8-ft. walls. The 2-ply panel system should be able to meet the buckling loads requirements for walls up to 10 ft. With DOE support, a new large-scale structural testing project is underway at Home Innovation Research Labs with some promising early results. These test results, both previous, current, and future, have the potential to support acceptance of the SPS system in leading categories for structural storm resistance and high-performance durability and energy efficiency.

A number of companies have expressed interest in pursuing the SPS system once the structural testing is complete. There is significant interest in using the wall system to build other products such as garages, commercial buildings, warehouses, and motels. Multifamily rental home development is growing quickly along with interest in townhomes and two- to four-unit apartment buildings. Large production builders have expressed interest in the value of quickly erecting enclosures with high performance.

Key successes from the project include the cost-effectiveness for the SPS, and that the "perfect wall" systems showed that increased performance over almost all other building models had a cost increase of 2.5%, a relatively small increment for the demonstrated performance savings. Further, the preliminary structural testing shows clear potential for meeting and exceeding code compliance metrics.

5.4 Future Work

From this project, it is clear the largest hurdle to broader market adoption is a simplified approach to meet engineering requirements and code compliance. The engineering issue is mostly related to the thin wall construction as determined by the structural OSB panels. The 2-ply wall is 2.25” thick. There are no common tables or calculations to determine the vertical load capacity and buckling potential of the wall with an 8-ft. height. The solution to this “thinness” problem is found in the whole-house-as-a-box or monocoque structure. While there were a couple of local engineers who understood this type of building structure and would certify the plans for a building permit, many engineers did not want to be involved without further testing to verify loading behavior. Two local firms are willing to stamp SPS structures. However, without high level testing it will be difficult to move the SPS “perfect wall” system into the market at a significant scale. As mentioned, a new DOE-funded project is underway to conduct comprehensive testing of the SPS system at the Home Innovation Research Labs over the next two years.

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Appendix A. House Plans and Elevations

A.1 Twin Cities Habitat for Humanity—Cedar

CEDAR 2.0

2313 JAMES AVENUE NORTH
MINNEAPOLIS, MN 55411

PROJECT DIRECTORY

OWNER / PROJECT MANAGER:
Twin Cities Habitat for Humanity
Chad Dipman - 612-305-7172, 612-209-3754
Chad.Dipman@tchabitat.org
1954 University Avenue West
St. Paul, MN 55104

ENVELOPE CONTRACTOR:

ARCHITECT:
Campbell-Schirber Industries
2704 Pillsbury Ave S, #1, Minneapolis, MN 55408
Andy Campbell, AIA - (612) 432-1891

ENGINEER:
Mattson Macdonald Young
901 North 3rd St, Suite 100, Minneapolis, MN 55401
Kirk Davis, PE - (612) 827-7825

GENERAL NOTES

1.All dimensions shall be field verified prior to construction. Do not scale drawings.
2.Perimeter dimensions are to face of concrete or ext. face of wall sheathing.
3. Interior dimensions are to finished face of wall.
3. Verify all existing site conditions and provide necessary adjustments for construction.
5. All structural members to be sized accordingly by structural engineer. Do not substitute structural members without engineer signoff.

PROJECT RENDERING

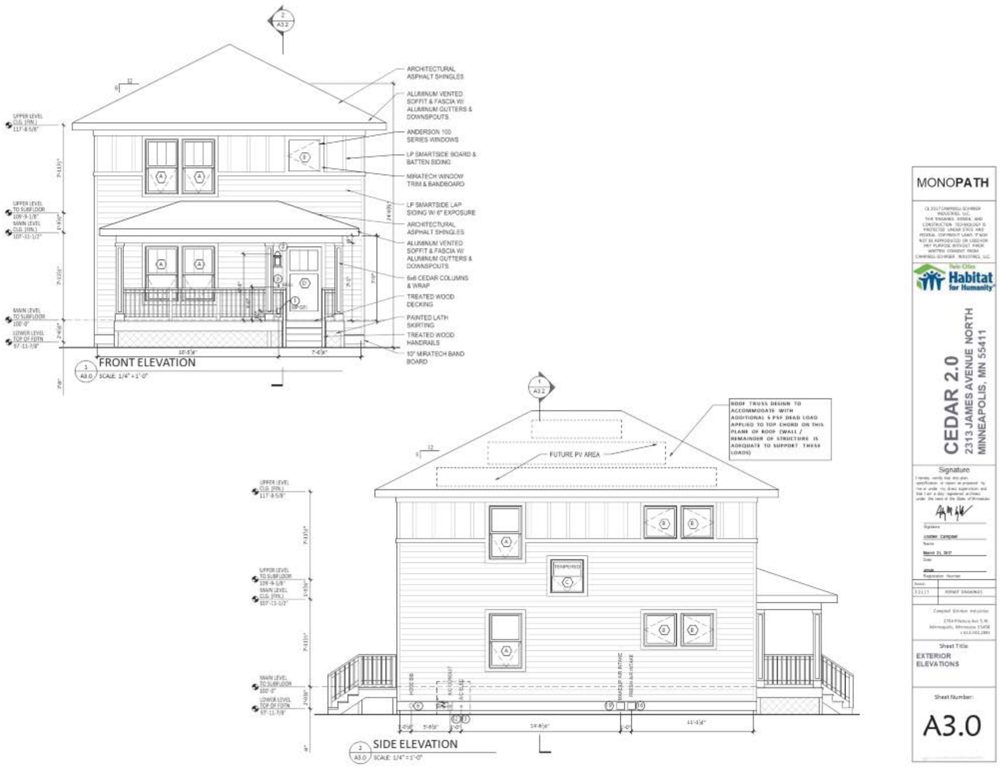
MONOPATH

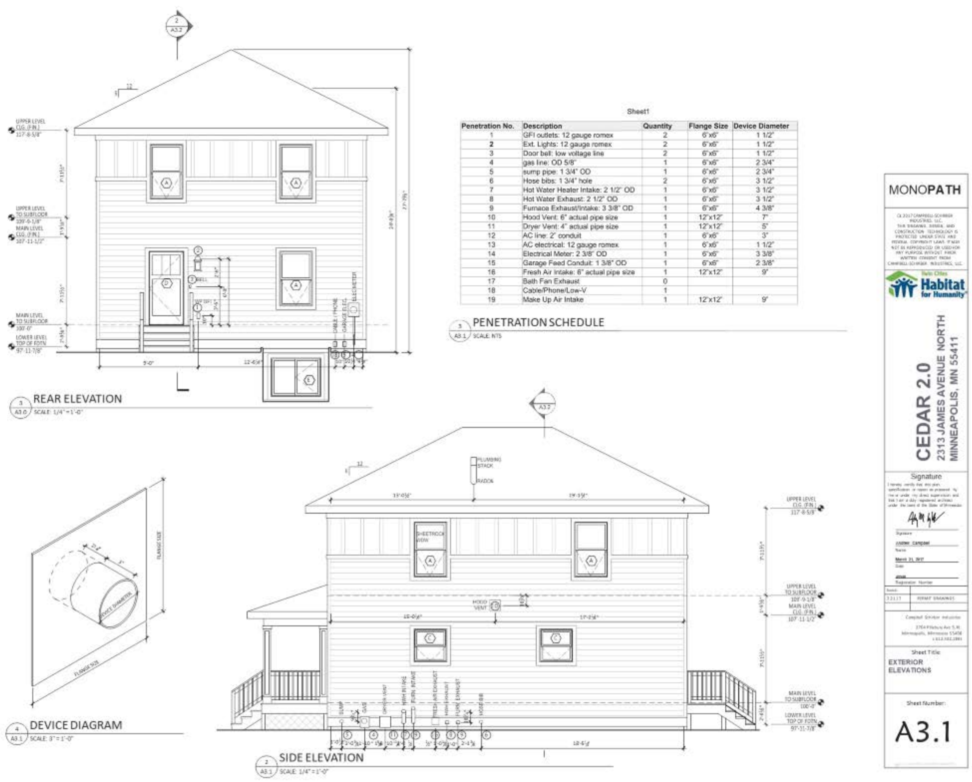
CEDAR 2.0
2313 JAMES AVENUE NORTH
MINNEAPOLIS, MN 55411

Signature

Sheet Title:
COVER SHEET

Sheet Number:
CVR

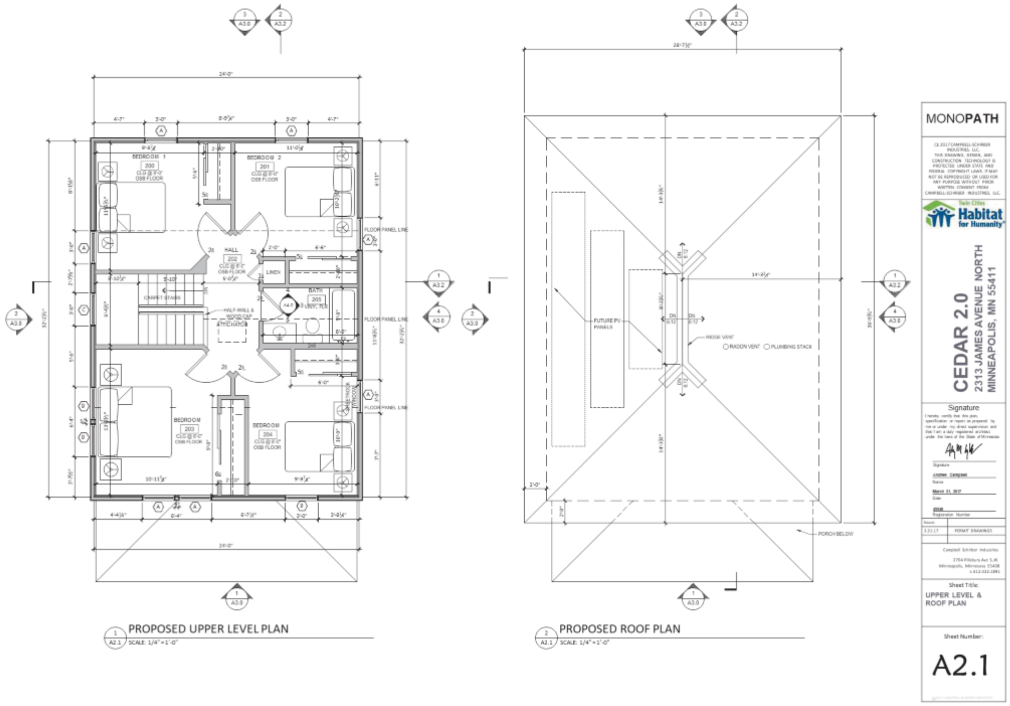


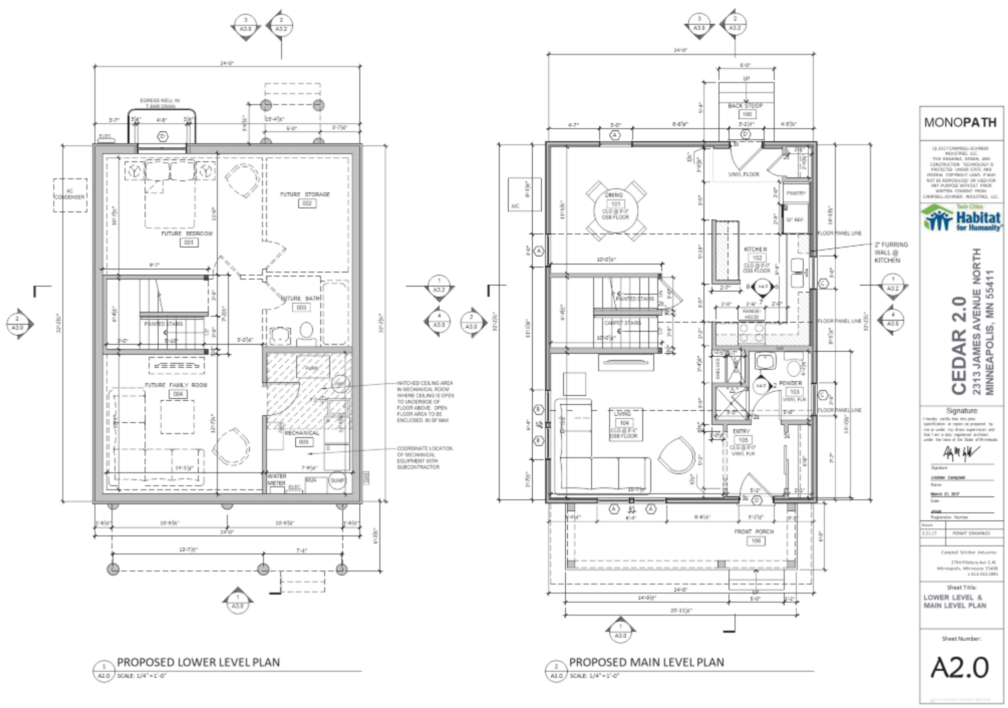


Sheet1

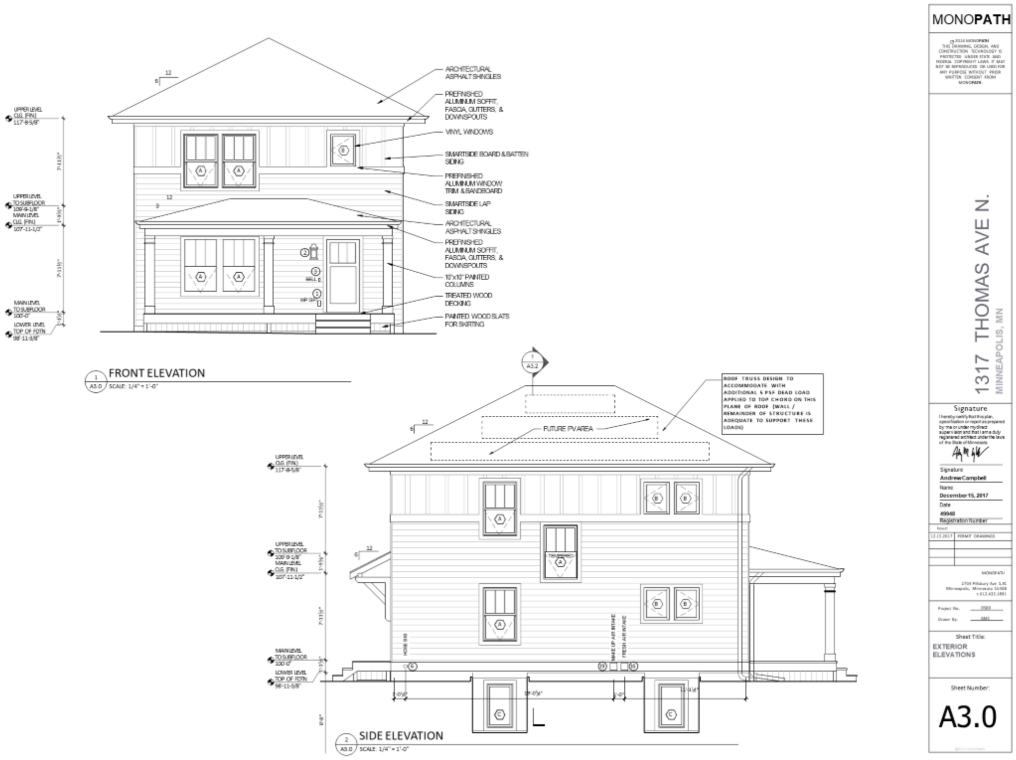
Penetration No.	Description	Quantity	Flange Size	Device Diameter
1	GFI outlets: 12 gauge romex	2	6"x6"	1 1/2"
2	Ext. Lights: 12 gauge romex	2	6"x6"	1 1/2"
3	Door bell: low voltage line	2	6"x6"	1 1/2"
4	gas line: OD 5/8"	1	6"x6"	2 3/4"
5	sump pipe: 1 3/4" OD	1	6"x6"	2 3/4"
6	Hose bibs: 1 3/4" hole	2	6"x6"	3 1/2"
7	Hot Water Heater Intake: 2 1/2" OD	1	6"x6"	3 1/2"
8	Hot Water Exhaust: 2 1/2" OD	1	6"x6"	3 1/2"
9	Furnace Exhaust/Intake: 3 3/8" OD	1	6"x6"	4 3/8"
10	Hood Vent: 6" actual pipe size	1	12"x12"	7"
11	Dryer Vent: 4" actual pipe size	1	12"x12"	5"
12	AC line: 2" conduit	1	6"x6"	3"
13	AC electrical: 12 gauge romex	1	6"x6"	1 1/2"
14	Electrical Meter: 2 3/8" OD	1	6"x6"	3 3/8"
15	Garage Feed Conduit: 1 3/8" OD	1	6"x6"	2 3/8"
16	Fresh Air Intake: 8" actual pipe size	1	12"x12"	9"
17	Bath Fan Exhaust	0		
18	Cable/Phone/Low-V	1		
19	Make Up Air Intake	1	12"x12"	9"

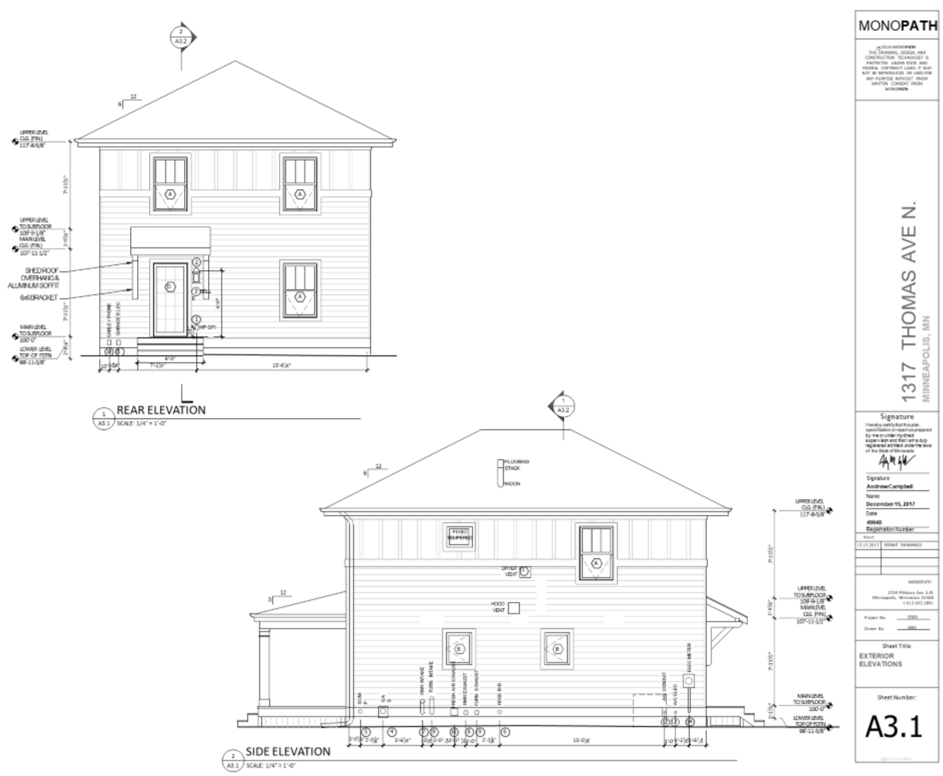
PENETRATION SCHEDULE
SCALE: NTS

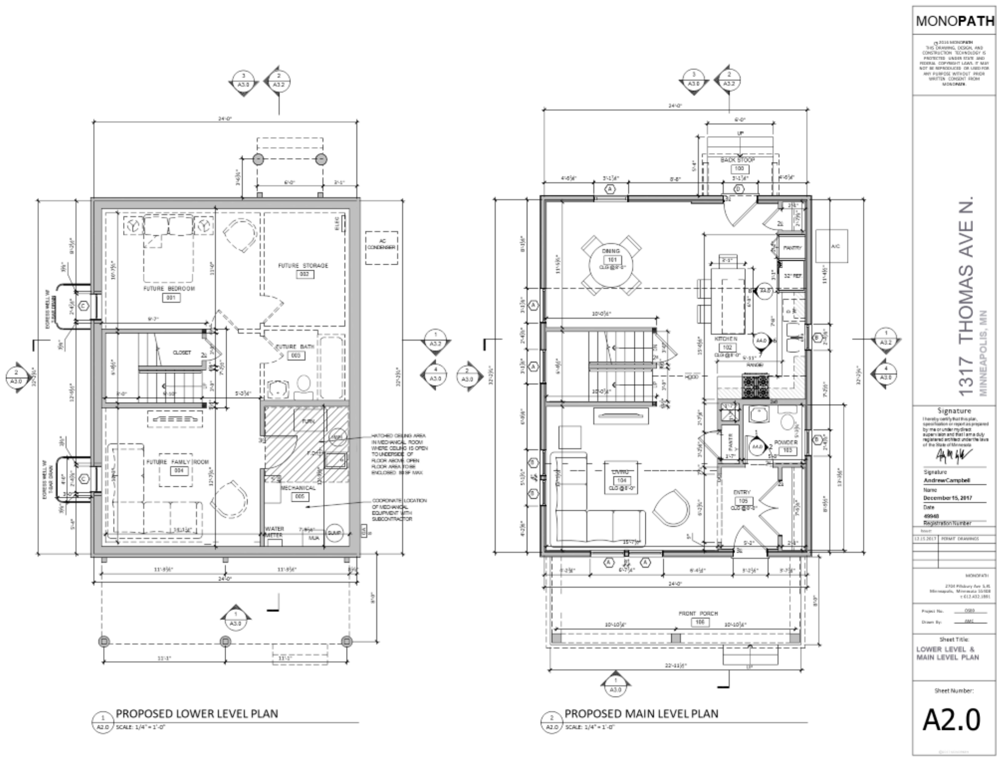

PROPOSED UPPER LEVEL PLAN
PROPOSED ROOF PLAN
MONOPATH
Habitat for Humanity
CEDAR 2.0
2313 JAMES AVENUE NORTH
MINNEAPOLIS, MN 55411
UPPER LEVEL & ROOF PLAN
A2.1

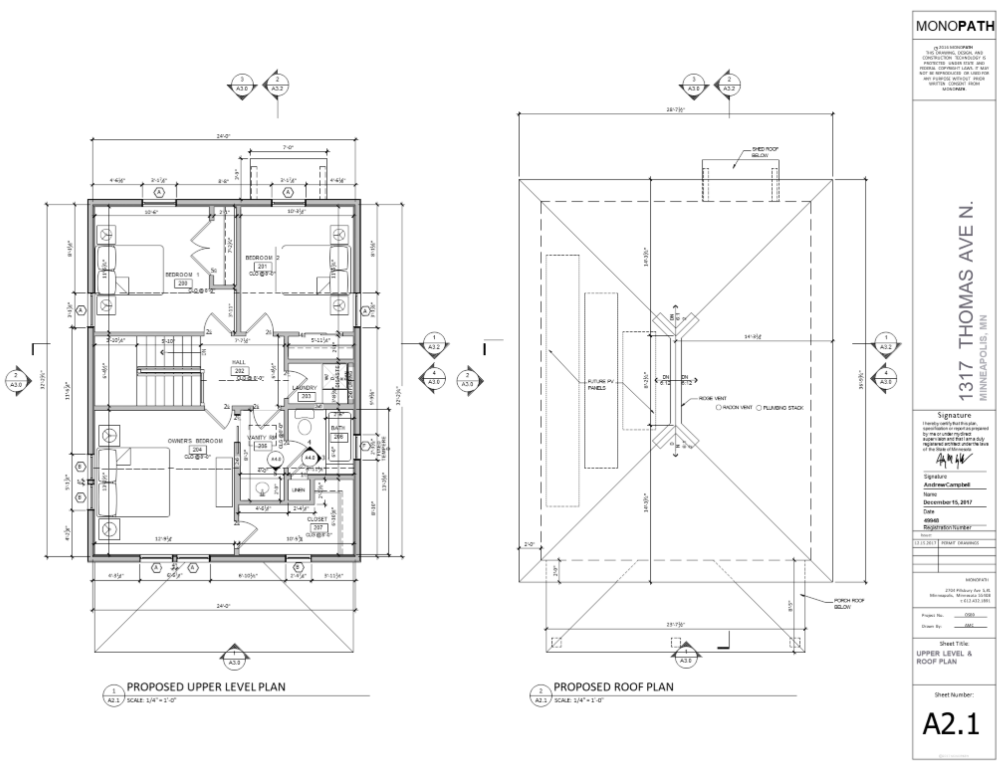

PROPOSED LOWER LEVEL PLAN
PROPOSED MAIN LEVEL PLAN
MONOPATH
Habitat for Humanity
CEDAR 2.0
2313 JAMES AVENUE NORTH
MINNEAPOLIS, MN 55411
LOWER LEVEL & MAIN LEVEL PLAN
A2.0

A.2 Urban Homeworks—Cedar

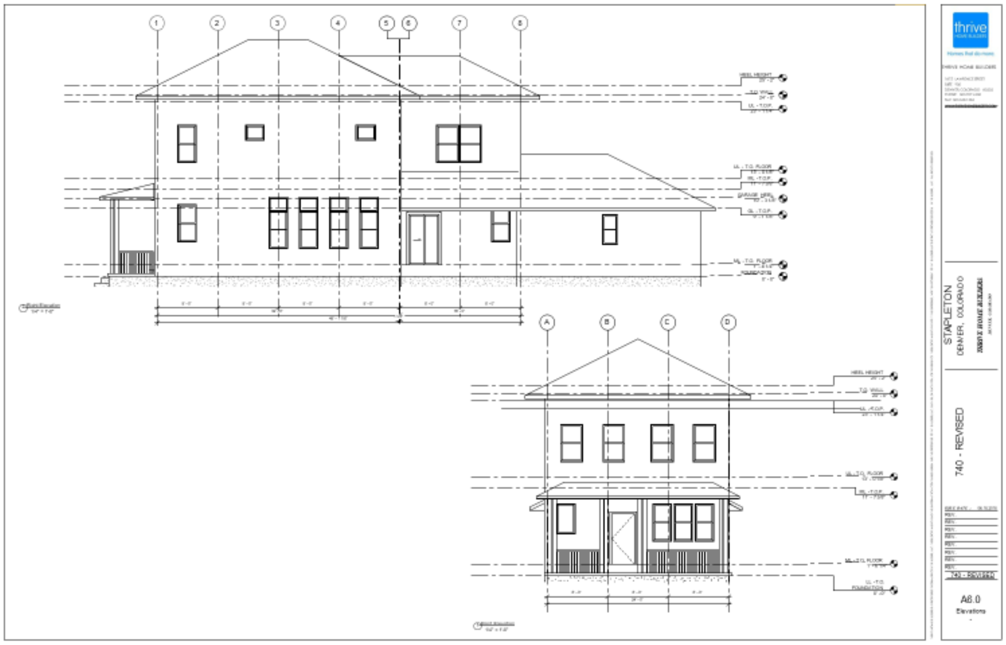


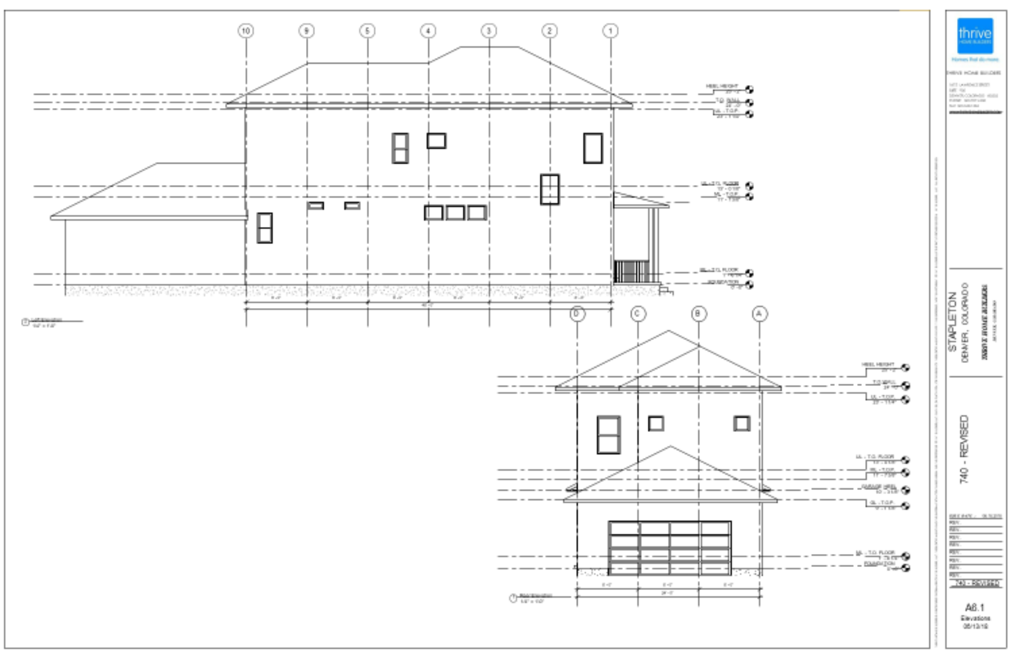


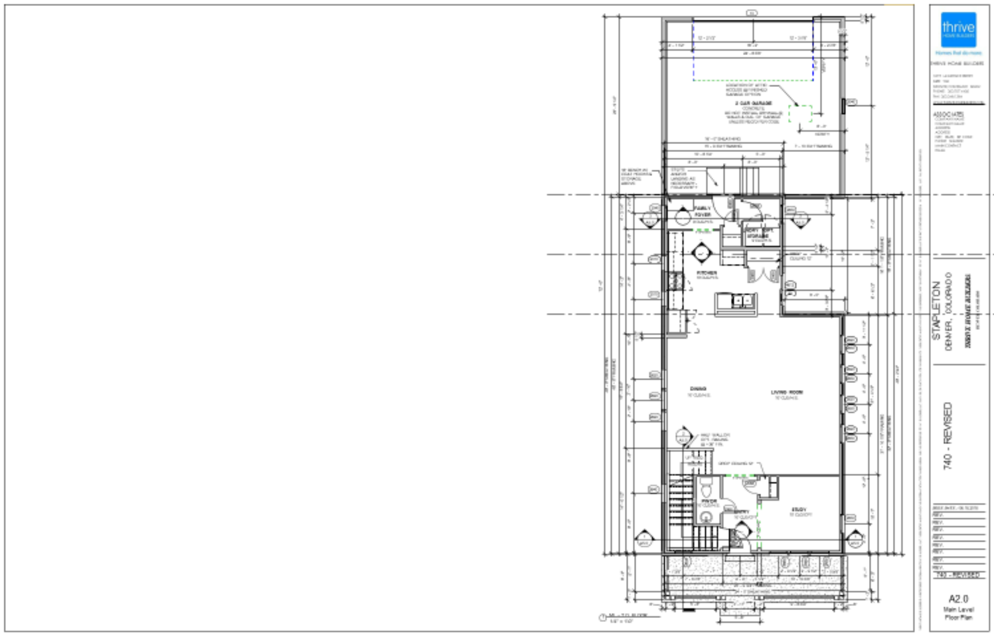

MONOPATH
1317 THOMAS AVE N.
MINNEAPOLIS, MN
FUTURE BEDROOM
FUTURE STORAGE
FUTURE BATH
FUTURE FAMILY ROOM
MECHANICAL
DINING
KITCHEN
LIVING
POWDER
ENTRY
PANTRY
BACK STOOP
FRONT PORCH
PROPOSED LOWER LEVEL PLAN
PROPOSED MAIN LEVEL PLAN
Signature
LOWER LEVEL & MAIN LEVEL PLAN
A2.0

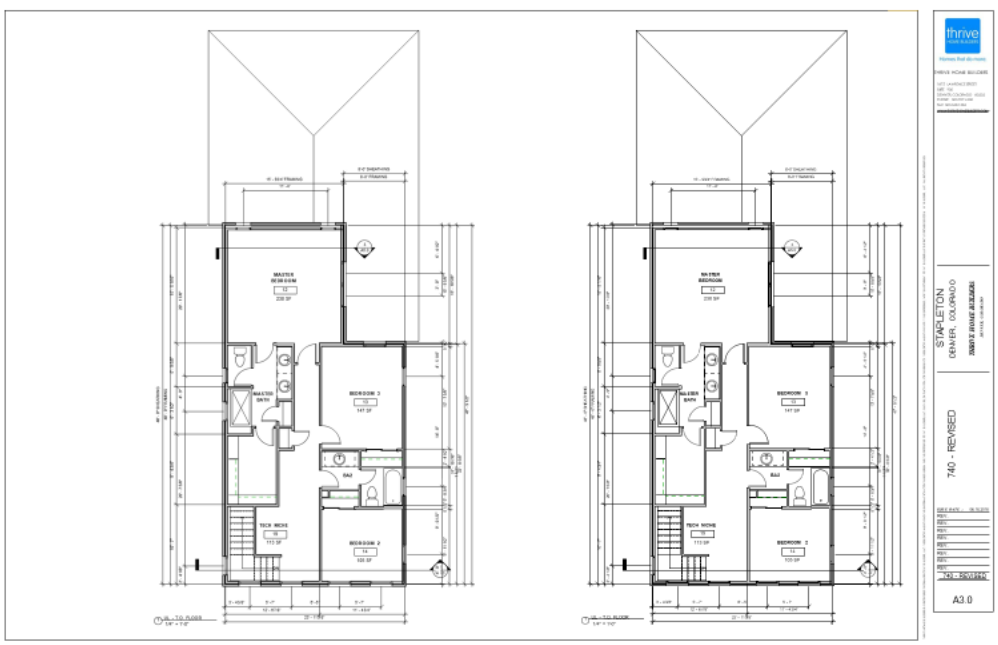

MONOPATH
1317 THOMAS AVE N.
MINNEAPOLIS, MN
BEDROOM 1
BEDROOM 2
HALL
LAUNDRY
OWNERS BEDROOM
BATH
CLOSET
PROPOSED UPPER LEVEL PLAN
PROPOSED ROOF PLAN
Signature
UPPER LEVEL & ROOF PLAN
A2.1

A.3 Thrive Home Builders—Model 740






thrive
STAPLETON
DENVER, COLORADO
740 - REVISED
A2.0
Main Level
Floor Plan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STAPLETON
DENVER, COLORADO
740 - REVISED
A3.0

Appendix B. Photos of Construction Sequence

B.1 Pre-Crane Phase

Figure B-1. Basement foundation with control layers

Figure B-2. Window well for basement egress integrated with control layers

Figure B-3. Receiver plate and first floor joists installed

B.2 Crane Phase

Figure B-4. First floor sheathing installation

Figure B-5. Exterior vertical panels are set (plumb, square, and level) at corners

Figure B-6. Installing first floor interior horizontal panels

Figure B-7. Installation of second floor joists and sheathing

Figure B-8. Installation of second floor interior horizontal panels

Figure B-9. Completed exterior vertical wall panels (with cut rear entry)

Figure B-10. Roof trusses are set inside the vertical panels and on the horizontal panels

B.3 Post-Crane Phase

Figure B-11. Installation of roof sheathing, building paper, and shingles (dried-in)

Figure B-12. Cutting window openings

Figure B-13. All penetrations (with a couple of spares) are pre-located and cut

Figure B-14. All penetrations are integrated with the air, water, and vapor control membrane

Figure B-15. Lower-level window installation integrated with air, water, and vapor control membrane

Figure B-16. Installing exterior control layers with embedded furring strip for vinyl cladding

Figure B-17. Furring strips over foam for fiber-cement cladding installation (note porch connection)

Appendix C. Training Videos

To assist potential solid panel structure (SPS) users, a series of videos were produced to provide both classroom and field training. These can be accessed on the Northern*STAR* website at https://bbe.umn.edu/research/perfect-wall-building-and-delivery-system. The length of each video in minutes is listed in parentheses in the lists below.

C.1 Classroom Training Videos

- Intro to Single Enclosure Contractor (7:46)
- Foundation Control Layers (6:15)
- Transition from Foundation to Envelope System (13:20)
- Structure in the Solid Panel Structure System (14:43)
- Large Oriented Strand Board (18:22)
- Fasteners and Adhesive (14:07)
- Install First Floor Deck and Attaching Vertical Panels (13:25)
- Details of Panel Connection (22:50)
- Penetrations, Membrane, and Window Installation (19:47)
- Critical Membrane Details (11:18)
- Rigid Foam Insulation and Furring Strips (8:24)
- Attic Insulation (17:14)
- Siding, Airtightness, and Electrical (5:25).

C.2 Field Videos

- Foundation and Waterproofing (15:19)
- First Floor Installation (10:08)
- Panel Installation – Part 1 (13:00)
- Panel Installation – Part 2 (13:27)
- Applying Membrane Details (17:12)
- Penetrations, Membrane, Insulation, Siding, and Finishes (18:15).

C.3 Whole House Time Lapse

- Complete Building Enclosure (2:51).

Appendix D. Additional Background, Assumptions, and Results for Energy Performance

Modeled energy consumption by appliance is shown in Table D-1.

Table D-1. Annual Gas and Electricity Consumption by Appliance

House Types	ENERGY STAR v3		2x4 Hybrid		SPS #1		SPS #2	
Gas – Furnace	51,301	therms/yr	52,031	therms/yr	56,275	therms/yr	58,132	therms/yr
Gas – Domestic hot water	17,428	therms/yr	17,342	therms/yr	25,142	therms/yr	11,858	therms/yr
Electricity – Furnace fan	711	kWh/yr	532	kWh/yr	488	kWh/yr	1,060	kWh/yr
Electricity – Energy recovery ventilator	18	kWh/yr	252	kWh/yr	399	kWh/yr	900	kWh/yr
Electricity – Dryer	94	kWh/yr	83	kWh/yr	109	kWh/yr	437	kWh/yr
Electricity – Range hood	70	kWh/yr	418	kWh/yr	4	kWh/yr	13	kWh/yr
Electricity – Air conditioning	NA	NA	*	kWh/yr	552	kWh/yr	259	kWh/yr
Electricity – Make-up air unit	NA	NA	83	kWh/yr	80	kWh/yr	22	kWh/yr
*Insufficient data								

Table D-2 provides the energy cost assumptions used for this study.

Table D-2. Utility Cost Assumptions

Month	Natural Gas		Electricity	
	Total Rate $/therm	Base Charge $/month	Total Rate $/kWh	Base Charge $/month
April–September	$0.6010	$9.00	$0.1540	$8.00
October–March	$0.6808	$9.00	$0.1400	$8.00

A more detailed breakdown of annual energy consumption and costs are shown in Tables D-3 and D-4, respectively.

Table D-3. Breakdown of Modeled Annual Energy Consumption

Model Name	Annual Energy Consumption (MMBtu/yr)								
	Heating	Heating kBTU/sf	Cooling	Cooling kBTU/sf	Water Heating	Lights + Appl.	Total	Total kBTU/sf	Savings to Code
Cedar MN Energy Code	76.4	31.6	3.6	1.5	25.3	30.3	135.6	56.1	NA
Cedar ENERGY STAR v3	57.1	23.6	3.5	1.4	24.3	29.1	114	47.2	16%
Cedar DOE ZERH	43.8	18.1	3.4	1.4	21.0	24.6	92.8	38.4	32%
Cedar 2x4 Hybrid (Habitat)	32.3	13.4	3.2	1.3	21.0	22.8	79.3	32.8	41%
Cedar SPS (Habitat)	34.5	14.3	3.2	1.3	21.0	22.8	81.5	33.7	40%

Table D-4. Breakdown of Modeled Annual Energy Cost

Model Name	Annual Energy Cost ($/yr)						
	Heating	Cooling	Water Heating	Lights + Appl.	Service Charges	Total	Savings to Code
Cedar MN Energy Code	571	158	162	1045	204	2140	NA
Cedar ENERGY STAR v3	424	155	156	996	204	1935	205
Cedar DOE ZERH	323	153	135	874	204	1689	451
Cedar 2x4 Hybrid (Habitat)	241	144	135	797	204	1521	619
Cedar SPS (Habitat)	256	144	135	797	204	1536	604

Table D-5. Energy Modeling Assumptions

	2015 MN Energy Code		Energy Star v 3		DOE ZERH		As Designed - SPS		As Designed - 2x4 Hybrid	
Component	**Values**	**Notes**	**Values**	**Notes**	**Values**	**Notes**	**Values**	**Notes**	**Values**	**Notes**
		Climate Zone 6		**Climate Zone 6**		**Climate Zone 6**		**Climate Zone 6**		**Climate Zone 6**
Ceiling R-value	49.0	2015 MN Energy Code	49.0	ES v3 (2012 IECC)	49.0	DOE ZERH (ES v3 (2012/2015 IECC)	60.0	design	49.0	design
Wall R-value	20[1]	2015 MN Energy Code	20+5[2]	ES v3 (2012 IECC)	20+5[2]	DOE ZERH (ES v3 (2012/2015 IECC)	20[3]	design	13+15[4]	design
Rim joist R-value	20.0	same as wall	20+5	same as wall	20+5	same as wall	20.0	design	13+15	design
Basement Wall R-value	15.0	2015 MN Energy Code	15.0	ES v3 (2012 IECC)	15.0	DOE ZERH (ES v3 (2012/2015 IECC)	15.0	design	15.0	design
Slab R-value	0.0	2015 MN Energy Code	0.0	ES v3 (2012 IECC)	0.0	DOE ZERH (ES v3 (2012/2015 IECC)	10.0	design	10.0	design
Fenestration U-factor (avg.)	0.32	2015 MN Energy Code	0.27	ES v3	0.27	DOE ZERH (ES v3)	0.26	Anderson 100 Series	0.26	Anderson 100 Series
Fenestration SHGC (avg.)	0.26	approx. industry average	0.26	approx. industry average	0.26	approx. industry average	0.31	Anderson 100 Series	0.31	Anderson 100 Series
Door U-factor (opaque)	0.25	?	0.17	ES v3	0.17	DOE ZERH (ES v3)	0.17	DOE ZERH (ES v3)	0.17	DOE ZERH (ES v3)
Airtightness (ACH@50Pa)	3.0	2015 MN Energy Code	3.0	ES v3	2.0	DOE ZERH	1.0	design	1.0	design
Window-to-Floor Area Ratio	0.104	as designed, Cedar2.0	0.104	as designed, Cedar2.0	0.104	as designed, Cedar2.0	0.104	as designed, Cedar2.0	0.104	as designed, Cedar2.0
Overall UA										
Furnace AFUE	90	Federal minimum, 2015	95	ES v3	95	DOE ZERH	95	design	94	design
Air Conditioner SEER	13.0	Federal minimum, 2015	13.0	ES v3	13.0	DOE ZERH	15.0	design	15.0	design
DHW ER (50g assumed)	0.60	Federal minimum, 2015	0.60	Federal minimum (ES v3 0.59)	0.67	DOE ZERH	0.67	design	0.67	design
Ventilation Rate (cfm cont.)	70.0	2015 MN Energy Code*	70.0	2015 MN Energy Code*	70.0	2015 MN Energy Code*	70.0	2015 MN Energy Code*	70.0	2015 MN Energy Code*
Sensible Recovery Eff. (%)	0.0	no heat recovery required	0.0	no heat recovery required	60.0	DOE ZERH	67.0	Venmar AVS E15 (57% total recove	67.0	Venmar AVS E15 (57% total recover
Ventilation Fan Eff. (cfm/watt)	1.0	industry standard, basic model	1.0	industry standard, basic model	1.2	DOE ZERH	2.2	Venmar AVS E15	2.2	Venmar AVS E15
Duct location	x	conditioned space	x	conditioned space	x	conditioned space	x	conditioned space	x	conditioned space
Programmable thermostat	no		yes		yes		yes		yes	
Lighting CFL percentage	40%	Resnet Defaults	45%	"90% of RESNET-defined Qualifying	80%	DOE ZERH	100%	design	100%	design
dryer EF	2.67	Resnet Defaults	2.67	Resnet Defaults	3.93	Energy Star, moisture sensing	3.93	Energy Star, moisture sensing	3.93	Energy Star, moisture sensing
clotheswasher (kWh/yr)	487	Medium Efficiency Resnet Default	487	Medium Efficiency Resnet Default	96	Energy Star	96	Energy Star	96	Energy Star
dishwasher (kWh/yr)	467	Resnet Defaults (eq. to EF 0.46)	220	Energy Star	220	Energy Star	220	Energy Star	220	Energy Star
refrigerator (kWh/yr)	727	Resnet Defaults	530	Energy Star	530	Energy Star	530	Energy Star	530	Energy Star

* Continuous rate = 0.5 x (0.02 x 2417 + (15 x (5+1))) = 69.2 cfm, for Cedar plan

1 Calculated whole wall R-14.1 (grade 3 installation, 23% FF)
2 Calculated whole wall R-22.7 (grade 1 installation, 23%FF)
3 Calculated whole wall R-23.8 (continuous)
4 Calculated whole wall R-27.8 (grade 1 installation, 23%FF)

Appendix E. Additional Background, Assumptions, and Results for Moisture Performance

E.1 Background, Assumptions, and Results for Moisture Modeling

Table E-1. Wall Section Descriptions and Material Data for WUFI Plus and Glaser Models

Energy Star	Specified Material/Product	Thickness	R-value/inch	Vapor flow	Density (lbs/ft3)	Selected WUFI Material	R-value/inch	Vapor flow	Density (lbs/ft3)
paint	2-coats latex	-	-	10 perms (BSC guideline)	-	surface transfer coefficient	-	10 perms	-
drywall	gypsum board	0.5"	0.9	36.5 perms @ 1/2 inch	?	Gypsum Board (USA)	0.89	43.62	53.1
vapor retarder	4 mil polyethylene	4 mil	-	0.08 perms	-	vapor retarder	-	0.1 perms	-
cavity insulation	fiberglass batt	3.5"	3.7	106 perms @ 1 inch	0.7 (approx.)	Low Density Glass Fibre Batt Insulation	3.33	106.45 perm in	0.55
sheathing	OSB	7/16"	1.5	1 perm at 1/2 inch	?	Oriented strand board	1.57	0.158 perm in	40.6
weather barrier	Tyvek	-	-	48 perms	-	Spun Bonded Polyolefin Membrane (SB	-	49 perms	-
exterior insulation	Dow XPS 'Square Edge'	1/2"	5	1.5 perms @ 1 inch	?	Extruded Polystyrene Insulation	5.95	0.755 perm in	1.8
cladding	LP Smartside (no back ventilation)	5/16"	1.5	0.6 - 1.4 perms @ 1 inch	40.0	Composite Wood Siding	1.54	2.43 perm in	46.2
paint	3-coats latex	-	-	5 perms		surface transfer coefficient	-	5 perms	-
2x4 Hybrid									
paint	2-coats latex	-	-	10 perms (BSC guideline)	-	surface transfer coefficient	-	10 perms	-
drywall	gypsum board	0.5"	0.9	36.5 perms @ 1/2 inch	?	Gypsum Board (USA)	0.89	21.46 perm in	53.1
cavity insulation	fiberglass batt	3.5"	3.7	106 perms @ 1 inch	0.7 (approx.)	Low Density Glass Fibre Batt Insulation	3.33	106.45 perm in	0.55
sheathing	OSB	7/16"	1.5	1 perm at 1/2 inch	?	Oriented strand board	1.57	0.158 perm in	40.6
weather barrier	Grace Perm-a-Barrier	3/64"	-	0.05 perms	-	PE-Membrane 0,15mm (sd = 70m)	-	0.047 perms	-
exterior insulation	Dow XPS 'Square Edge'	3"	5	1.5 perms @ 1 inch	?	Extruded Polystyrene Insulation	5.95	0.755 perm in	1.8
cladding	LP Smartside (backventilated on 1x4s)	5/16"	1.5		40.0	Composite Wood Siding	1.54	2.43 perm in	46.2
paint	3-coats latex	-	-	5 perms		surface transfer coefficient	-	5 perms	-
SPS									
paint	2-coats latex	-	-	10 perms (BSC guideline)	-	surface transfer coefficient	-	10 perms	-
SEP panel	Huber Advantech Flooring	1 1/8"	1.4 - 1.5	0.86 perms @ 23/32" (equiv to 0.618 perm in)	40.1	Oriented strand board	1.57	0.158 perm in	40.6
weather barrier	Grace Perm-a-Barrier	3/64"	-	0.05 perms	-	PE-Membrane 0,15mm (sd = 70m)	-	0.047 perms	-
exterior insulation	Dow XPS 'Square Edge'	4"	5	1.5 perms @ 1 inch	?	Extruded Polystyrene Insulation	5.95	0.755 perm in	1.8
cladding	LP Smartside	5/16"	back ventilated at 10 ACH		40.0	Composite Wood Siding	1.54	2.43 perm in	46.2
paint	3-coats latex	-	-	5 perms		surface transfer coefficient	-	5 perms	-
SPS - Spero									
paint	2-coats latex	-	-	10 perms (BSC guideline)	-	surface transfer coefficient	-	10 perms	-
SEP panel	Huber Advantech Flooring	1 1/8"	1.4 - 1.5	0.86 perms @ 23/32" (equiv to 0.618 perm in)	40.1	Oriented strand board	1.57	0.158 perm in	40.6
weather barrier	Sto Gold Coat	8 mils DFT	-	19 perms	-	weather resistive barrier (sd=0.2m)	-	16.5 perms	-
exterior insulation	CertiStud from Diversifoam	4"	5	1.1 perms @ 1 inch	1.55	Extruded Polystyrene Insulation	5.95	0.755 perm in	1.8
cladding	Vinyl siding	3/16" air gap	back ventilated at 200 ACH			PE-Membrane 0,15mm (sd = 70m)	-	0.047 perms	-
SPS - Mineral wool									
paint	2-coats latex	-	-	10 perms (BSC guideline)	-	surface transfer coefficient	-	10 perms	-
SEP panel	Huber Advantech Flooring	1 1/8"	1.4 - 1.5	0.86 perms @ 23/32" (equiv to 0.618 perm in)	40.1	Oriented strand board	1.57	0.158 perm in	40.6
weather barrier	Sto Gold Coat	8 mils DFT	-	19 perms	-	weather resistive barrier (sd=0.2m)	-	16.5 perms	-
exterior insulation	Roxul Comfortboard 110	5"	4	116 perm in	11	Roxul TopRock DD	4.01	107 perm in	11
cladding	LP Smartside	5/16"	back ventilated at 10 ACH		40.0	Composite Wood Siding	1.54	2.43 perm in	46.2
paint	3-coats latex	-	-	5 perms		surface transfer coefficient	-	5 perms	-
Hybrid - Thrive									
paint	2-coats latex	-	-	10 perms (BSC guideline)	-	surface transfer coefficient	-	10 perms	-
drywall	gypsum board	0.5"	0.9	36.5 perms @ 1/2 inch	?	Gypsum Board (USA)	0.89	21.46 perm in	53.1
cavity insulation	fiberglass batt	3.5"	3.7	106 perms @ 1 inch	0.7 (approx.)	Low Density Glass Fibre Batt Insulation	3.33	106.45 perm in	0.55
sheathing	Huber Advantech Flooring	1 1/8"	1.4 - 1.5	0.86 perms @ 23/32"	40.1	Oriented strand board	1.57	0.158 perm in	40.6
weather barrier	Grace Perm-a-Barrier	3/64"	-	0.05 perms	-	PE-Membrane 0,15mm (sd = 70m)	-	0.047 perms	-
exterior insulation	Dow XPS 'Square Edge'	3"	5	1.5 perms @ 1 inch	?	Extruded Polystyrene Insulation	5.95	0.755 perm in	1.8
cladding	LP Smartside (backventilated on 1x4s)	5/16"	1.5		40.0	Composite Wood Siding	1.54	2.43 perm in	46.2
paint	3-coats latex	-	-	5 perms		surface transfer coefficient	-	5 perms	-

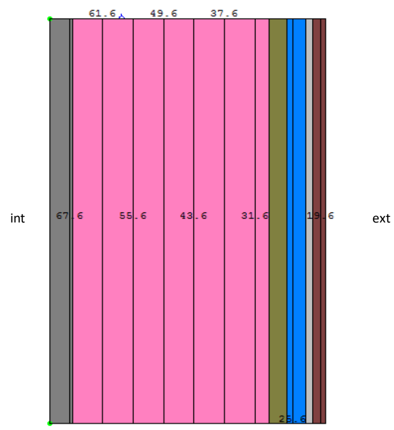
E.1.1 Glaser Model Results

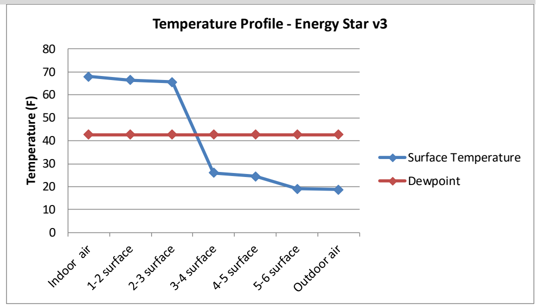
Energy Star v3

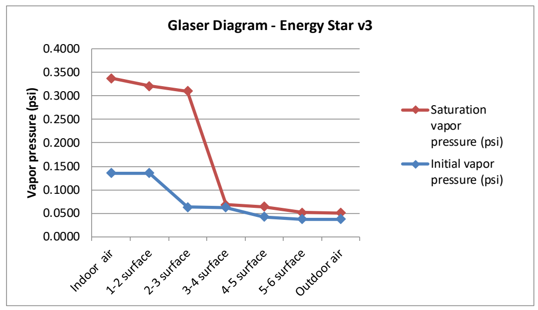
Layers

1	inside air film	-
2	gypsum + latex paint + 4 mil poly	dark gray
3	fiberglass insulation	pink
4	OSB sheathing + Tyvek	olive
5	XPS	blue
6	outside air film	light gray

THERM Model - winter conditions







Conditions

Exterior	Temp	RH	**Interior**	Temp	RH
Winter	18.7	75%	Winter	68	50%
Summer	86	55%	Summer	75	60%

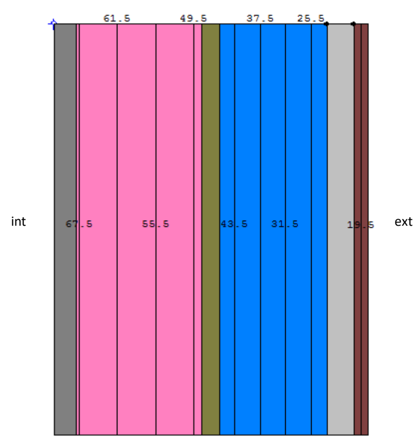
Figure E-1. ENERGY STAR v3 wall results

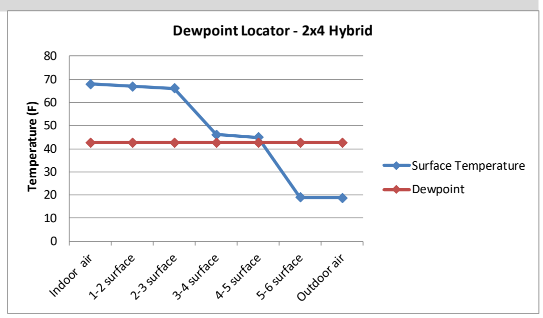
2x4 Hybrid

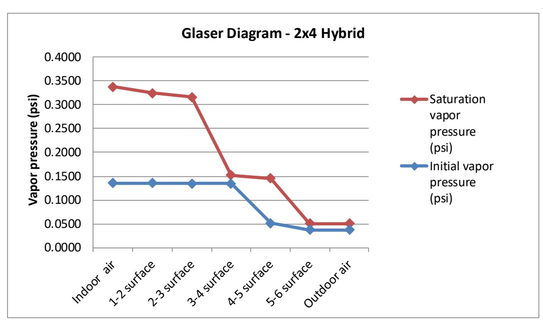
Layers

1	inside air film	-
2	gypsum+latex paint	dark gray
3	fiberglass insulation	pink
4	OSB sheathing + Perm-a-Barrier	olive
5	XPS	blue
6	outside air film	light gray

THERM Model - winter conditions







Conditions

Exterior	Temp	RH	**Interior**	Temp	RH
Winter	18.7	75%	Winter	68	50%
Summer	86	55%	Summer	75	60%

Figure E-2. 2x4 hybrid wall results

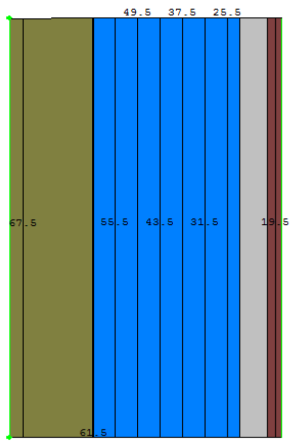
SPS

Layers

1	inside air film	-
2	SEP Panel + paint + Perm-a-Barrier	olive
3	XPS	blue
4	outside air film	light gray

THERM Model - winter conditions

int



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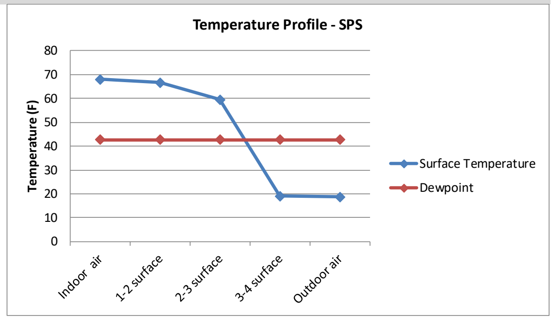
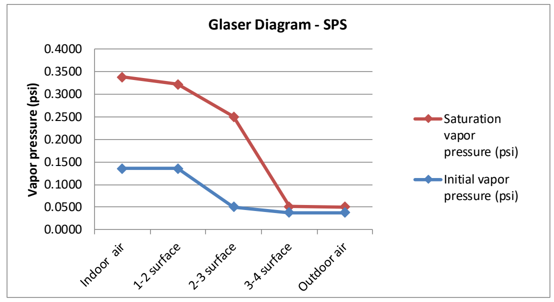




Conditions

Exterior	Temp	RH	**Interior**	Temp	RH
Winter	18.7	75%	Winter	68	40%
Summer	86	55%	Summer	76	60%

Figure E-3. SPS wall results

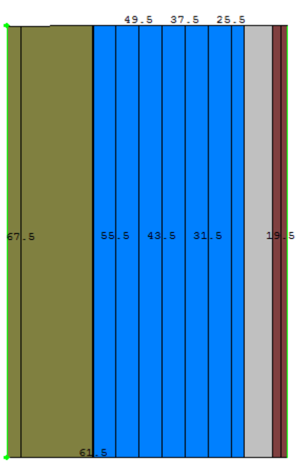
SPS - Spero

Layers

1	inside air film	-
2	SEP Panel + paint + Sto Gold Coat	olive
3	XPS	blue
4	outside air film	light gray

THERM Model - winter conditions

int



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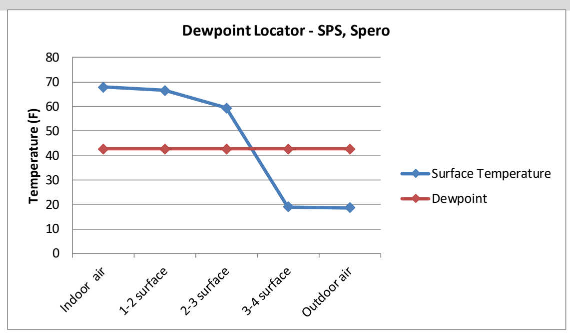
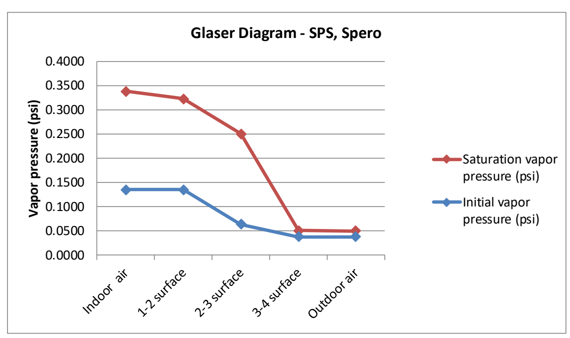




Conditions

Exterior	Temp	RH	**Interior**	Temp	RH
Winter	18.7	75%	Winter	68	50%
Summer	86	55%	Summer	75	60%

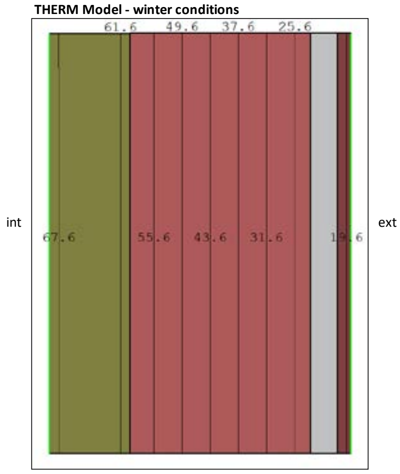
Figure E-4. SPS—Spero wall results

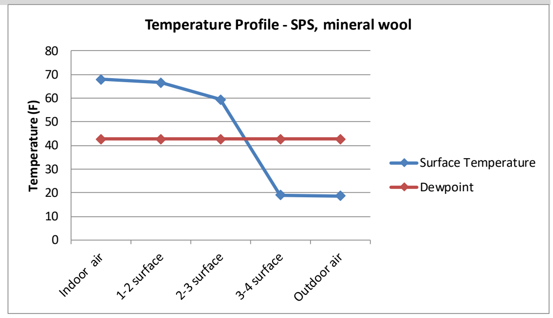
SPS - Mineral Wool

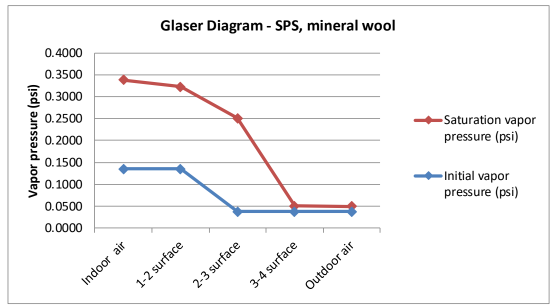
Layers

1	inside air film	-
2	SEP Panel + paint + Sto Gold Coat	olive
3	mineral wool	maroon
4	outside air film	light gray

THERM Model - winter conditions







Conditions

Exterior	Temp	RH	**Interior**	Temp	RH
Winter	18.7	75%	Winter	68	50%
Summer	86	55%	Summer	75	60%

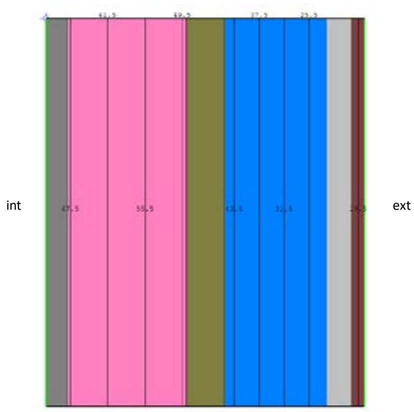
Figure E-5. SPS—Spero with mineral wool wall results

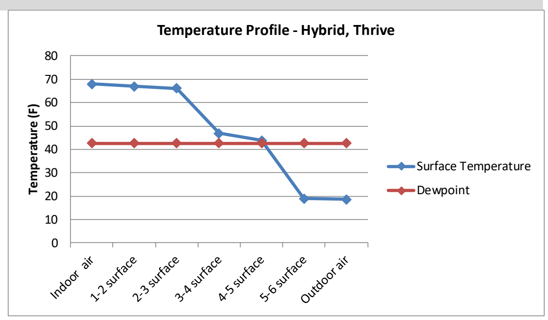
Hybrid - Thrive

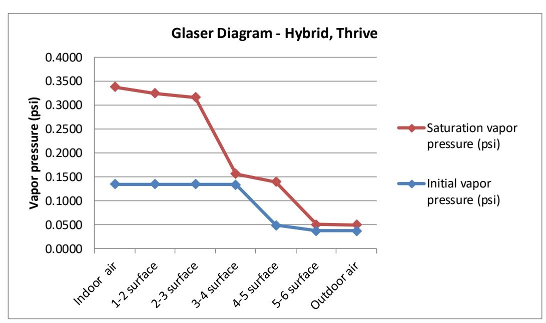
Layers

1	inside air film	-
2	gypsum+latex paint	dark gray
3	fiberglass insulation	pink
4	SEP Panel + Perm-a-Barrier	olive
5	XPS	blue
6	outside air film	light gray

THERM Model - winter conditions







Conditions

Exterior	Temp	RH	**Interior**	Temp	RH
Winter	18.7	75%	Winter	68	50%
Summer	86	55%	Summer	75	60%

Figure E-6. Thrive 1-ply hybrid wall results

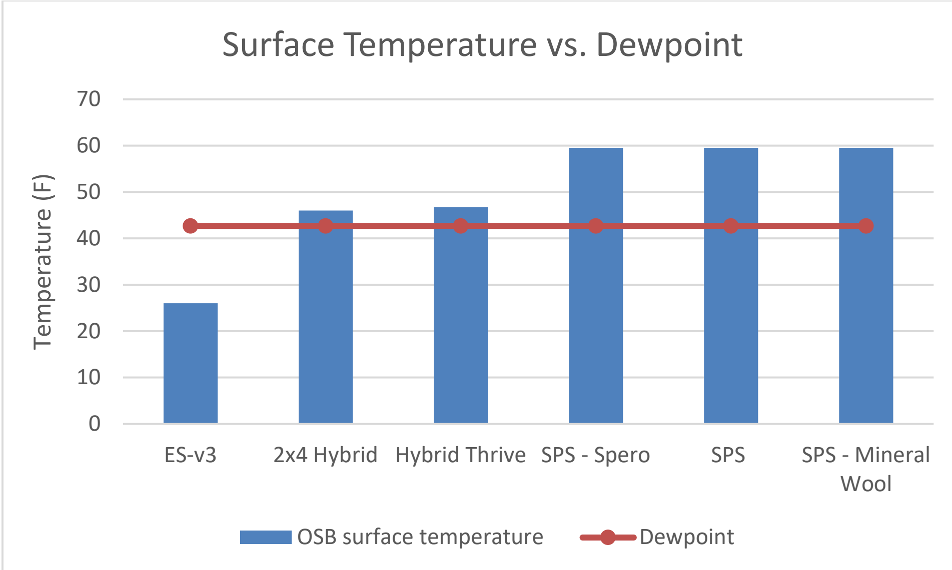


Figure E-7. Wall type summary showing temperature profile results

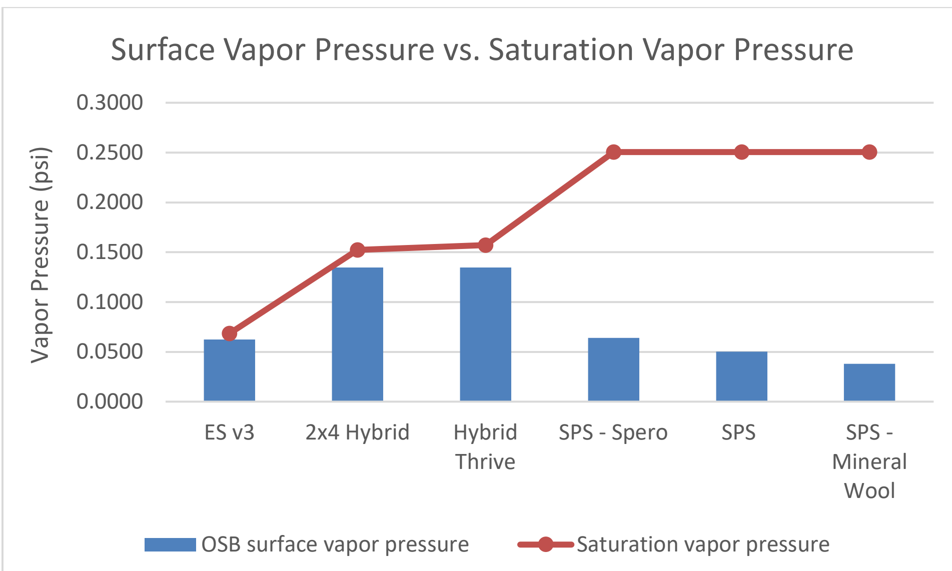


Figure E-8. Wall type summary showing vapor pressure profile results

Temperature profile and diffusion risk results for the SPS variants with a liquid applied water-resistive barrier (WRB; SPS—Spero) and with exterior mineral wool (SPS—Mineral Wool) appear very similar to the basic SPS wall. No significant change in the temperature profile results was expected given that they all achieve a similar R-value and the insulation is placed in the same location. The liquid applied WRB used by Spero replaces the low permeability "peel and stick" membrane used by the traditional SPS wall.

In terms of vapor diffusion moisture risk, this has very little impact because the SPS panel itself is already very low permeability. The mineral wool option also uses the liquid applied WRB but replaces the exterior XPS with vapor open mineral wool. The mineral wool is of greater thickness but has an equivalent overall R-value. In this case, the vapor pressure at the exterior surface of the structural panel is actually reduced, even without the impermeable peel and stick membrane, because the exterior insulation outboard of the oriented strand board (OSB) surface is no longer creating a cold-side vapor retarder. Based on steady-state analysis, it appears that this assembly exhibits the best diffusion performance during winter conditions. If subject to wetting, it will also have much greater capacity to dry than either the traditional version of SPS used by Twin Cities Habitat for Humanity or the modified version used by Spero Environmental Builders.

The hybrid wall used by Thrive was very similar to the 2x4 hybrid wall, except that the half-inch OSB sheathing in the 2x4 hybrid wall was replaced by the thicker OSB panel used in the SPS wall. Glaser results for the Thrive hybrid wall were, therefore, very similar to the 2x4 hybrid wall.

E.1.2 ASHRAE 160 Interior/Exterior Climate

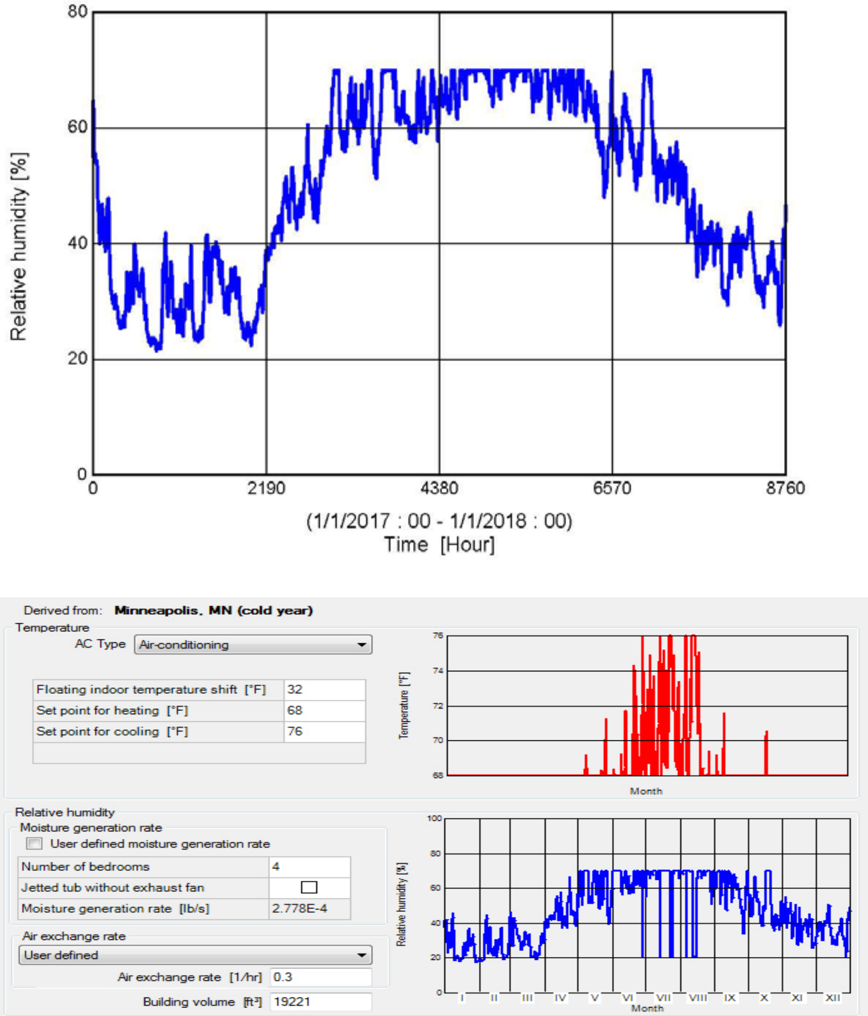


Figure E-9. Interior conditions from standard ASHRAE 160 input screen (bottom) for comparison to WUFI Plus-derived interior climate (top). The interior relative humidity (RH) shows close agreement.

It is apparent that the house is quite humid during the summer, with relative humidity (RH) frequently rising to the 70% maximum. This is most likely due to the high occupant density (five people and four bedrooms in the 2,400 ft^2 house), small volume, and a tight enclosure. Although challenging, this may represent the RH in Twin Cities Habitat for Humanity homes quite well. The house was modeled with a combined air exchange rate (mechanical + air leakage) of 0.3 ACH including an energy recovery ventilator. The energy recovery ventilator does help reduce the interior RH during the summer, with a minor increase in the winter. Because RH above 60% supports dust mites, it would be desirable if the RH were controlled to a lower setpoint. However, these conditions set up a challenging moisture regime against which the performance of the wall assemblies could be tested. The winter boundary condition is not as challenging, with interior RH cycling between 20% and 40%. This is in fair agreement with the Glaser method that used a slightly more challenging interior RH of 40%.

E.1.3 WUFI Plus Modeling

A. WUFI Plus Wall Section Inputs—2 x 6 ENERGY STAR v3 Wall

ENERGY STAR Wall Input Data

Component 3: General data

Name	Exterior wall
Type	Opaque
Inner side	Zone 1: Zone 1
Outer side	Outer air
Assembly	ENERGY STAR w flanking flows
U [Btu/hr ft² °F]	0.0387
Geometry	
Area [ft²]	1732.8
Inclination [°]	90°
Orientation []	South (29%), East (19%), West (21%), North (31%)
Surface	
Rse / Rsi (According to component type) [-]	0.23 / 0.74
Absorption / Emission (Wood (spruce):weathered (silver-gray)) [-]	0.7 / 0.9
Permeance - outer (User defined) [perm]	5
Permeance - outer (User defined) [perm]	10
Rain load R1 / R2 (According to component type) [-]	0 / 0.07
Rain absorption (According to inclination) [-]	0.7
Reduction factor constant shading [-]	1
Solar radiation on inner surface [-]	0.354
Height above ground (From visualized geometry)	0

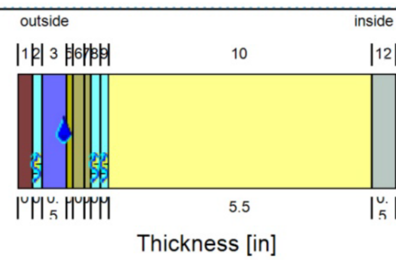
Assembly (Id.9): ENGERY STAR® with flanking flows

Homogenous layers

Thermal resistance: 24.852 hr ft² °F/Btu (without Rsi, Rse)

Heat transfer coefficient(U-value): 0.04 Btu/hr ft² °F

Thickness: 7.919 in



Nr.	Material/Layer (from outside to inside)	ρ [lb/ft³]	c [Btu/lb °F]	λ [Btu/hr ft °F]	Thickness [in]	Color
1	Composite Wood Siding	46.2	0.45	0.0543	0.313	
2	Air Layer 5 mm	0.08	0.24	0.0272	0.197	
3	Extruded Polystyrene Insulation	1.79	0.35	0.0144	0.5	
4	Spun Bonded Polyolefin Membrane (SBP)	27.97	0.36	1.3867	0.008	
5	Oriented Strand Board	40.58	0.45	0.0532	0.125	
6	Oriented Strand Board	40.58	0.45	0.0532	0.25	
7	Oriented Strand Board	40.58	0.45	0.0532	0.125	
8	Air Layer 5 mm	0.08	0.24	0.0272	0.197	
9	Air Layer 5 mm	0.08	0.24	0.0272	0.197	
10	Low-Density Glass Fiberglass Batt Insulation	0.55	0.2	0.0248	5.5	
11	Vapor Retarder (0.1perm)	8.12	0.55	1.3081	0.039	
12	Gypsum Board (USA)	53.06	0.21	0.0942	0.5	

Layer 2, Air Layer 5 mm, Air change source	
Air change source type	Constant value
Air exchange rate [1/hr]	20
Mix with air from	Outside

Layer 4, Spun Bonded Polyolefin Membrane (SBP), Moisture source	
Spread area	One element
Moisture source type	Fraction of driving rain
Depth in layer [in]	0.004
Fraction [-]	0.01
Source term clipping	Clipping to free water saturation

Layer 5, Oriented Strand Board, Moisture source	
Spread area	One element
Moisture source type	Fraction of driving rain
Depth in layer [in]	0.01
Fraction [-]	0.0001
Source term clipping	Clipping to free water saturation

Layer 8, Air Layer 5 mm, Air change source	
Air change source type	Constant value
Air exchange rate [1/hr]	10
Mix with air from	Outside

Layer 9, Air Layer 5 mm, Air change source	
Air change source type	Constant value
Air exchange rate [1/hr]	10
Mix with air from	Inside

B. WUFI Plus Wall Section Inputs—2 x 4 Hybrid Wall

2x4 Hybrid Wall Input Data

Component 3: General data

Name	Exterior wall
Type	Opaque
Inner side	Zone 1: Zone 1
Outer side	Outer air
Assembly	2x4 Hybrid interior flanking flow only
U [Btu/hr ft² °F]	0.0301
Geometry	
Area [ft²]	1732.8
Inclination [°]	90°
Orientation	South (29%), East (19%), West (21%), North (31%)
Surface	
Rse / Rsi (According to component type) [-]	0.23 / 0.74
Absorption / Emission (Wood (spruce):weathered (silver-gray)) [-]	0.7 / 0.9
Permeance - outer (User defined) [perm]	5
Permeance - outer (User defined) [perm]	10
Rain load R1 / R2 (According to component type) [-]	0 / 0.07
Rain absorption (According to inclination) [-]	0.7
Reduction factor constant shading [-]	1
Solar radiation on inner surface [-]	0.354
Height above ground (From visualized geometry)	0

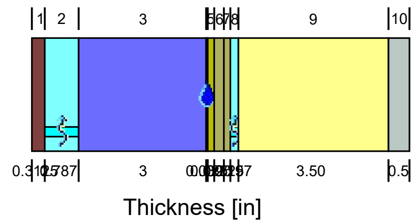
Assembly (Id.8): 2x4 Hybrid interior flanking flow only

Homogenous layers

Thermal resistance: 32.233 hr ft² °F/Btu (without Rsi, Rse)

Heat transfer coefficient(U-value): 0.03 Btu/hr ft² °F

Thickness: 8.836 in



Nr.	Material/Layer (from outside to inside)	ρ [lb/ft³]	c [Btu/lb °F]	λ [Btu/hr ft °F]	Thickness [in]	Color
1	Composite Wood Siding	46.2	0.45	0.0543	0.313	
2	Air Layer 20 mm	0.08	0.24	0.0751	0.787	
3	Extruded Polystyrene Insulation	1.79	0.35	0.0144	3	
4	PE-Membrane 0.15 mm (sd = 70 m)	8.12	0.53	1.2711	0.039	
5	Oriented Strand Board	40.58	0.45	0.0532	0.125	
6	Oriented Strand Board	40.58	0.45	0.0532	0.25	
7	Oriented Strand Board	40.58	0.45	0.0532	0.125	
8	Air Layer 5 mm	0.08	0.24	0.0272	0.197	
9	Low-Density Glass Fiberglass Batt Insulation	0.55	0.2	0.0248	3.5	
10	Gypsum Board (USA)	53.06	0.21	0.0942	0.5	

Layer 2, Air Layer 20 mm, Air change source	
Air change source type	Constant value
Air exchange rate [1/hr]	10
Mix with air from	Outside

Layer 4, PE-Membrane 0.15 mm (sd = 70 m), Moisture source	
Spread area	One element
Moisture source type	Fraction of driving rain
Depth in layer [in]	0.01
Fraction [-]	0.01
Source term clipping	Clipping to free water saturation

Layer 5, Oriented Strand Board, Moisture source	
Spread area	One element
Moisture source type	Fraction of driving rain
Depth in layer [in]	0.01
Fraction [-]	0.0001
Source term clipping	Clipping to free water saturation

Layer 8, Air Layer 5 mm, Air change source	
Air change source type	Constant value
Air exchange rate [1/hr]	10
Mix with air from	Inside

C. WUFI Plus Wall Section Inputs—SPS Wall

SPS Wall Input Data

Component 3: General data

Name	Exterior wall
Type	Opaque
Inner side	Zone 1: Zone 1
Outer side	Outer air
Assembly	SEP ETTMS
U [Btu/hr ft² °F]	0.0346
Geometry	
Area [ft²]	1732.8
Inclination [°]	90°
Orientation	South (29%), East (19%), West (21%), North (31%)
Surface	
Rse / Rsi (According to component type) [-]	0.23 / 0.74
Absorption / Emission (Wood (spruce):weathered (silver-gray)) [-]	0.7 / 0.9
Permeance - outer (User defined) [perm]	5
Permeance - outer (User defined) [perm]	10
Rain load R1 / R2 (According to component type) [-]	0 / 0.07
Rain absorption (According to inclination) [-]	0.7
Reduction factor constant shading [-]	1
Solar radiation on inner surface [-]	0.354
Height above ground (From visualized geometry)	0

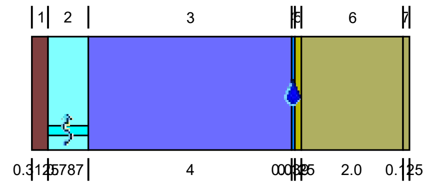
Assembly (Id.3): SPS

Homogenous layers

Thermal resistance: 27.959 hr ft² °F/Btu (without Rsi, Rse)

Heat transfer coefficient(U-value): 0.03 Btu/hr ft² °F

Thickness: 7.389 in



Nr.	Material/Layer (from outside to inside)	ρ [lb/ft³]	c [Btu/lb °F]	λ [Btu/hr ft °F]	Thickness [in]	Color
1	Composite Wood Siding	46.2	0.45	0.0543	0.313	
2	Air Layer 20 mm	0.08	0.24	0.0751	0.787	
3	Extruded Polystyrene Insulation	1.79	0.35	0.0144	4	
4	PE-Membrane 0,15 mm (sd = 70 m)	8.12	0.53	1.2711	0.039	
5	Oriented Strand Board	40.58	0.45	0.0532	0.125	
6	Oriented Strand Board	40.58	0.45	0.0532	2	
7	Oriented Strand Board	40.58	0.45	0.0532	0.125	

Layer 2, Air Layer 20 mm, Air change source	
Air change source type	Constant value
Air exchange rate [1/hr]	10
Mix with air from	Outside

Layer 4, PE-Membrane 0,15 mm (sd = 70 m), Moisture source	
Spread area	One element
Moisture source type	Fraction of driving rain
Depth in layer [in]	0.01
Fraction [-]	0.01
Source term clipping	Clipping to free water saturation

Layer 5, Oriented Strand Board, Moisture source	
Spread area	One element
Moisture source type	Fraction of driving rain
Depth in layer [in]	0.01
Fraction [-]	0.0001
Source term clipping	Clipping to free water saturation

D. WUFI Plus Wall Section Inputs—SPS Wall, Spero Variant

SPS Wall – Spero Input data

Component 3: General data

Name	Exterior wall
Type	Opaque
Inner side	Zone 1: Zone 1
Outer side	Outer air
Assembly	Assembly (Id.6): SEP ETTMS Spero
U [Btu/hr ft² °F]	0.0355
Geometry	
Area [ft²]	1732.8
Inclination [°]	90°
Orientation	South (29%), East (19%), West (21%), North (31%)
Surface	
Heat transfer coefficient convective, extern [Btu/hr ft² °F]	3.25804
Heat transfer coefficient radiant, extern [Btu/hr ft² °F]	1.14472
Heat transfer coefficient convective, intern [Btu/hr ft² °F]	0.5622
Heat transfer coefficient radiant, intern [Btu/hr ft² °F]	0.7925
Rse / Rsi (According to component type) [-]	0.2271 / 0.7382
Absorption / Emission (Wood (spruce):weathered (silver-gray)) [-]	0.7 / 0.9
Permeance - outer (No coating) [perm]	----
Permeance - outer (User defined) [perm]	10
Rain load R1 / R2 (According to component type) [-]	0 / 0.07
Rain absorption (According to inclination) [-]	0.7
Shading factor constant [-]	1
Solar radiation on inner surface [-]	0.354
Height above ground (From visualized geometry) [ft]	0

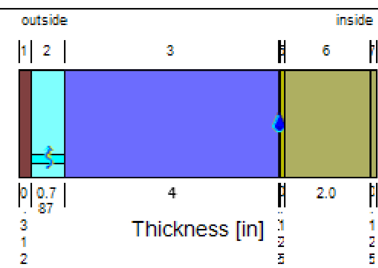
Assembly (Id.6): SPS Spero

Homogenous layers

Thermal resistance: 27.213 hr ft² °F/Btu (without Rsi, Rse)

Heat transfer coefficient (U-value): 0.035 Btu/hr ft² °F

Thickness: 7.389 in



Nr.	Material/Layer (from outside to inside)	ρ [lb/ft³]	c [Btu/lb °F]	λ [Btu/hr ft °F]	Thickness [in]	Color
1	Composite Wood Siding	46.2	0.45	0.0543	0.313	
2	Air Layer 5 mm; without additional moisture capacity	0.08	0.24	0.0272	0.197	
3	Extruded Polystyrene Insulation	1.79	0.35	0.0144	4	
4	Weather-resistive barrier (sd=0.2m)	8.12	0.55	1.3289	0.039	
5	Oriented Strand Board	40.58	0.45	0.0532	0.125	
6	Oriented Strand Board	40.58	0.45	0.0532	2	
7	Oriented Strand Board	40.58	0.45	0.0532	0.125	

Layer 2, Air Layer 5 mm; without additional moisture capacity, Air change source	
Air change source type	Constant value
Air exchange rate [1/hr]	120
Mix with air from	Outside

Layer 4, weather resistive barrier (sd = 0.2 m), Moisture source	
Spread area	One element
Moisture source type	Fraction of driving rain
Depth in layer [in]	0.01
Fraction [-]	0.01
Source term clipping	Clipping to free water saturation

Layer 5, Oriented Strand Board, Moisture source	
Spread area	One element
Moisture source type	Fraction of driving rain
Depth in layer [in]	0.01
Fraction [-]	0.0001
Source term clipping	Clipping to free water saturation

E. WUFI Plus Wall Section Inputs—SPS Spero Mineral Wool Variant

SPS Wall – Mineral Wool Input data

Component 3: General data

Name	Exterior wall
Type	Opaque
Inner side	Zone 1: Zone 1
Outer side	Outer air
Assembly	Assembly (Id.8): SEP ETTMS Mineral wool
U [Btu/hr ft² °F]	0.0386
Geometry	
Area [ft²]	1732.8
Inclination [°]	90°
Orientation	South (29%), East (19%), West (21%), North (31%)
Surface	
Heat transfer coefficient convective, extern [Btu/hr ft² °F]	3.25804
Heat transfer coefficient radiant, extern [Btu/hr ft² °F]	1.14472
Heat transfer coefficient convective, intern [Btu/hr ft² °F]	0.5622
Heat transfer coefficient radiant, intern [Btu/hr ft² °F]	0.7925
Rse / Rsi (According to component type) [-]	0.2271 / 0.7382
Absorption / Emission (Wood (spruce):weathered (silver-gray)) [-]	0.7 / 0.9
Permeance - outer (User defined) [perm]	5
Permeance - outer (User defined) [perm]	10
Rain load R1 / R2 (According to component type) [-]	0 / 0.07
Rain absorption (According to inclination) [-]	0.7
Shading factor constant [-]	1
Solar radiation on inner surface [-]	0.354
Height above ground (From visualized geometry) [ft]	0

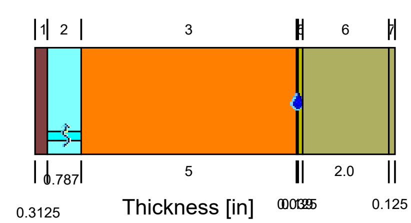
Assembly (Id.8): SPS Mineral wool

Homogenous layers

Thermal resistance: 24.914 hr ft² °F/Btu (without Rsi, Rse)

Heat transfer coefficient (U-value): 0.039 Btu/hr ft² °F

Thickness: 8.389 in



Nr.	Material/Layer (from outside to inside)	ρ [lb/ft³]	c [Btu/lb °F]	λ [Btu/hr ft °F]	Thickness [in]	Color
1	Composite Wood Siding	46.2	0.45	0.0543	0.313	
2	Air Layer 20 mm	0.08	0.24	0.0751	0.787	
3	Roxul TopRock DD	10.99	0.2	0.0208	5	
4	Weather-resistive barrier (sd=0.2m)	8.12	0.55	1.3289	0.039	
5	Oriented Strand Board	40.58	0.45	0.0532	0.125	
6	Oriented Strand Board	40.58	0.45	0.0532	2	
7	Oriented Strand Board	40.58	0.45	0.0532	0.125	

Layer 2, Air Layer 20 mm, Air change source	
Air change source type	Constant value
Air exchange rate [1/hr]	10
Mix with air from	Outside

Layer 4, weather resistive barrier (sd=0.2m), Moisture source	
Spread area	One element
Moisture source type	Fraction of driving rain
Depth in layer [in]	0.01
Fraction [-]	0.01
Source term clipping	Clipping to free water saturation

Layer 5, Oriented Strand Board, Moisture source	
Spread area	One element
Moisture source type	Fraction of driving rain
Depth in layer [in]	0.01
Fraction [-]	0.0001
Source term clipping	Clipping to free water saturation

F. WUFI Plus Wall Section Inputs—Thrive 1-Ply Hybrid Wall

Hybrid Wall – Thrive Input data

Component 3: General data

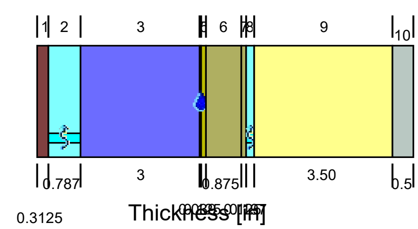
Name	Exterior wall
Type	Opaque
Inner side	Zone 1: Zone 1
Outer side	Outer air
Assembly	Assembly (Id.9): Thrive Hybrid interior flanking flow only
U [Btu/hr ft² °F]	0.0293
Geometry	
Area [ft²]	1732.8
Inclination [°]	90°
Orientation	South (29%), East (19%), West (21%), North (31%)
Surface	
Heat transfer coefficient convective, extern [Btu/hr ft² °F]	3.25804
Heat transfer coefficient radiant, extern [Btu/hr ft² °F]	1.14472
Heat transfer coefficient convective, intern [Btu/hr ft² °F]	0.5622
Heat transfer coefficient radiant, intern [Btu/hr ft² °F]	0.7925
Rse / Rsi (According to component type) [-]	0.2271 / 0.7382
Absorption / Emission (Wood (spruce):weathered (silver-gray)) [-]	0.7 / 0.9
Permeance - outer (User defined) [perm]	5
Permeance - outer (User defined) [perm]	10
Rain load R1 / R2 (According to component type) [-]	0 / 0.07
Rain absorption (According to inclination) [-]	0.7
Shading factor constant [-]	1
Solar radiation on inner surface [-]	0.354
Height above ground (From visualized geometry) [ft]	0

Assembly (Id.9): Thrive Hybrid interior flanking flow only

Homogenous layers

Thermal resistance: 33.213 hr ft² °F/Btu (without Rsi, Rse)

Heat transfer coefficient (U-value): 0.029 Btu/hr ft² °F



Thickness: 9.461 in

Nr.	Material/Layer (from outside to inside)	ρ [lb/ft³]	c [Btu/lb °F]	λ [Btu/hr ft °F]	Thickness [in]	Color
1	Composite Wood Siding	46.2	0.45	0.0543	0.313	
2	Air Layer 20 mm	0.08	0.24	0.0751	0.787	
3	Extruded Polystyrene Insulation	1.79	0.35	0.0144	3	
4	PE-Membrane 0.15 mm (sd = 70 m)	8.12	0.53	1.2711	0.039	
5	Oriented Strand Board	40.58	0.45	0.0532	0.125	
6	Oriented Strand Board	40.58	0.45	0.0532	0.875	
7	Oriented Strand Board	40.58	0.45	0.0532	0.125	
8	Air Layer 5 mm	0.08	0.24	0.0272	0.197	
9	Low-Density Glass Fiberglass Batt Insulation	0.55	0.2	0.0248	3.5	
10	Gypsum Board (USA)	53.06	0.21	0.0942	0.5	

Layer 2, Air Layer 20 mm, Air change source	
Air change source type	Constant value
Air exchange rate [1/hr]	10
Mix with air from	Outside

Layer 4, PE-Membrane 0,15 mm (sd = 70 m), Moisture source	
Spread area	One element
Moisture source type	Fraction of driving rain
Depth in layer [in]	0.01
Fraction [-]	0.01
Source term clipping	Clipping to free water saturation

Layer 5, Oriented Strand Board, Moisture source	
Spread area	One element
Moisture source type	Fraction of driving rain
Depth in layer [in]	0.01
Fraction [-]	0.0001
Source term clipping	Clipping to free water saturation

Layer 8, Air Layer 5 mm, Air change source	
Air change source type	Constant value
Air exchange rate [1/hr]	10
Mix with air from	Inside

E.1.4 WUFI Plus Moisture Modeling Outputs

A. 2 x 6 ENERGY STAR v3 Wall

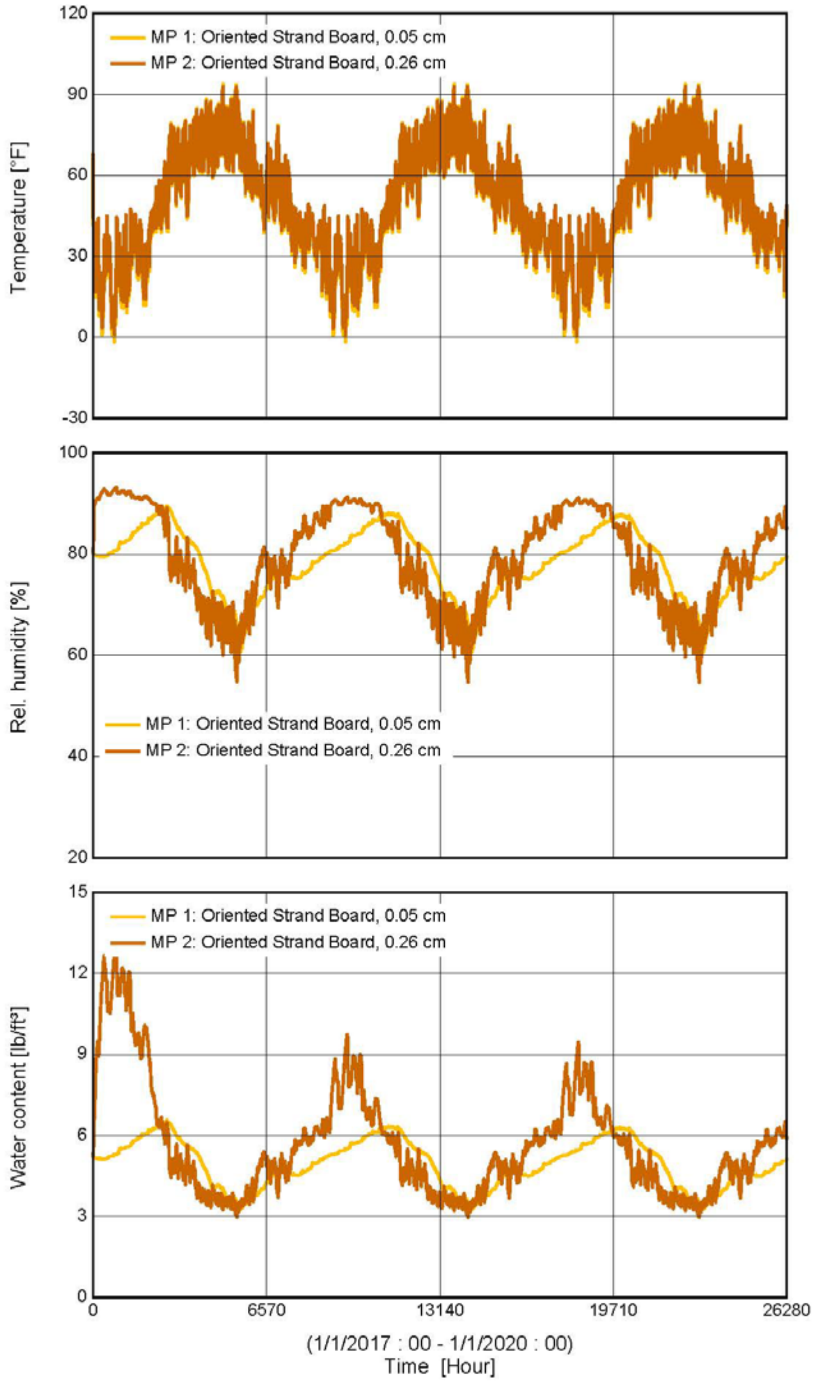


Figure E-10. 2x6 ENERGY STAR v3 wall sheathing temperature, RH, and moisture content (yellow = outer, brown = inner surface)

B. 2 x 4 Hybrid Wall

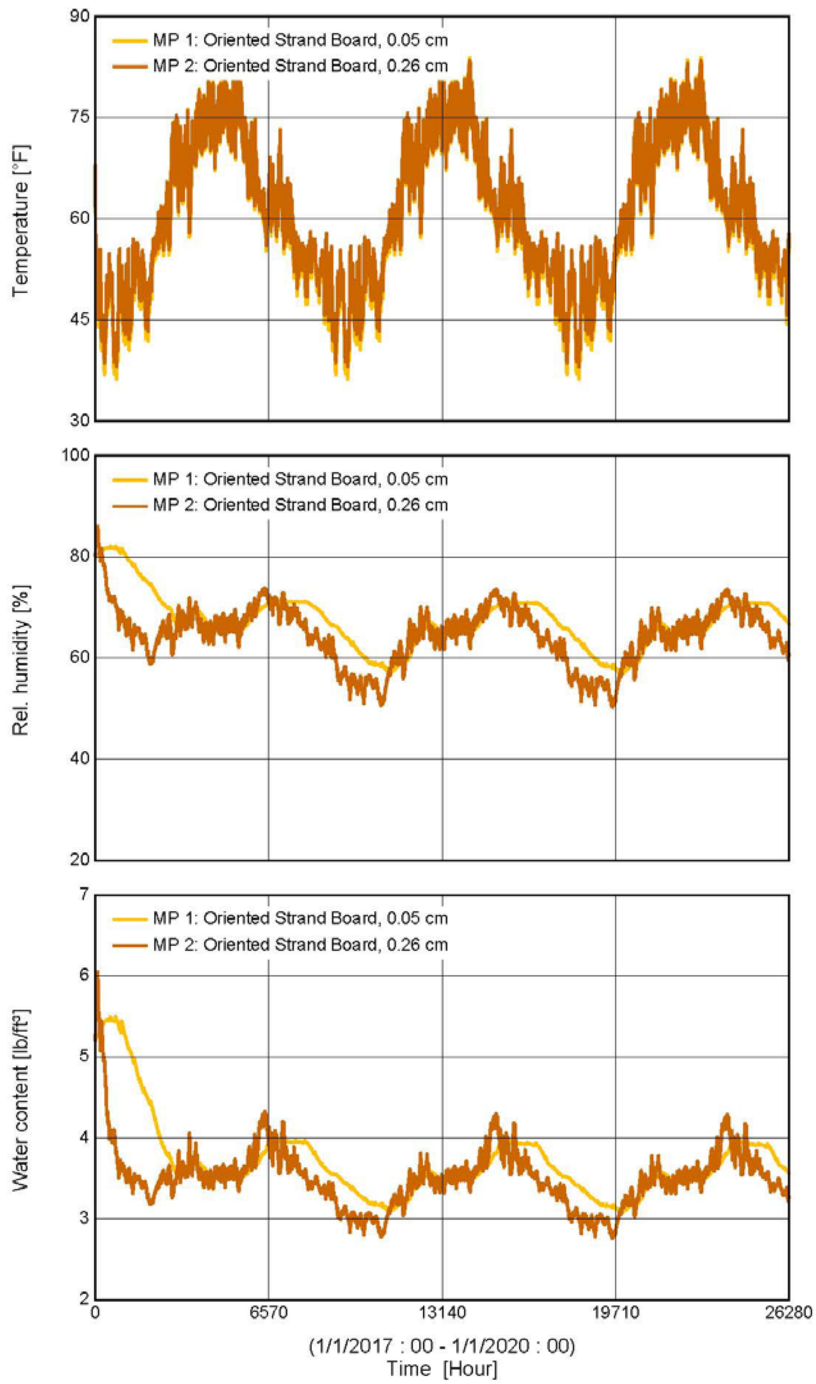


Figure E-11. 2x4 hybrid wall sheathing temperature, RH, and moisture content (yellow = outer, brown = inner surface)

C. SPS Wall

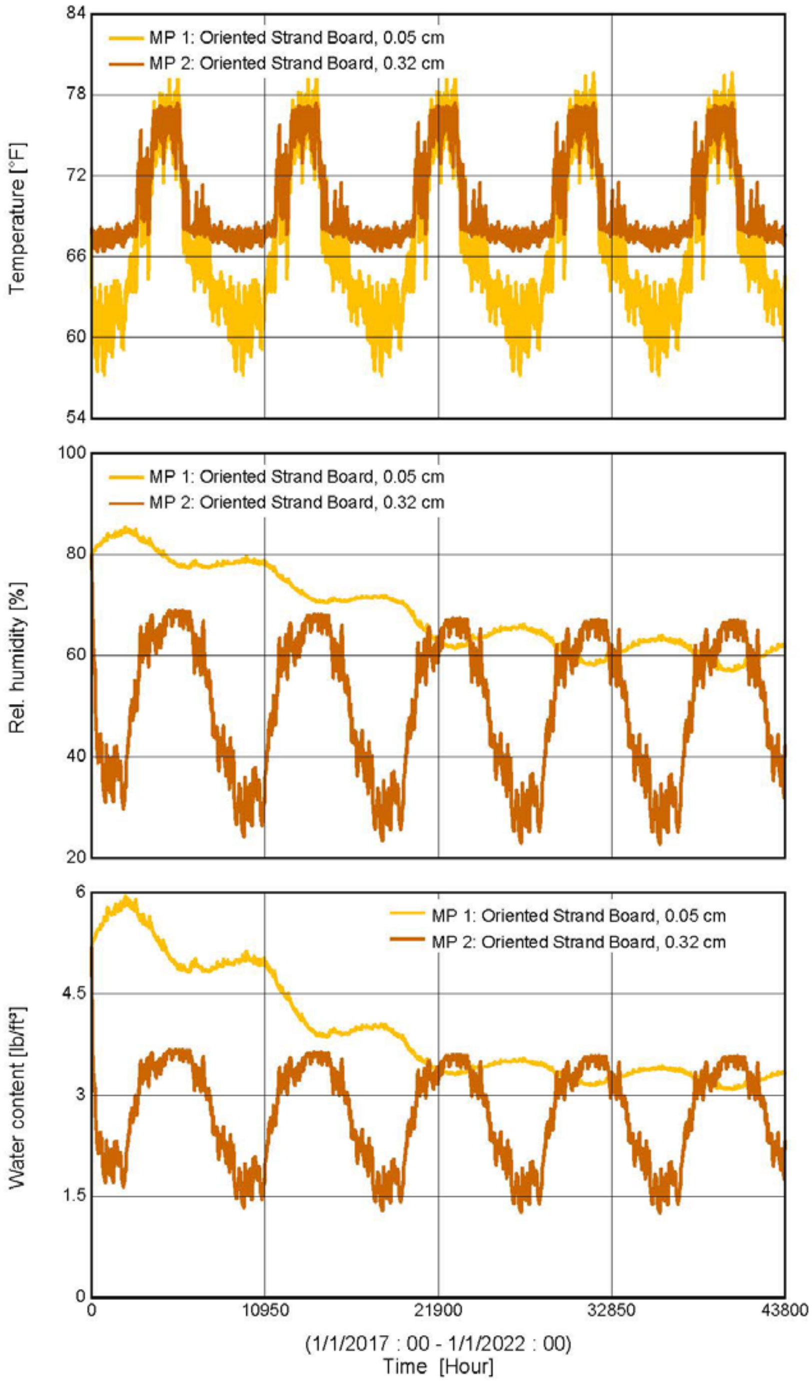


Figure E-12. SPS wall structural panel temperature, RH, and moisture content (yellow = outer, brown = inner surface)

E.1.5 WUFI Plus Moisture Modeling Comparisons—SPS Wall Variants

Moisture content levels were also modeled for the SPS wall variants: SPS Spero, SPS with mineral wool, and Hybrid Thrive. Spero Environmental Builders (Spero) replaced the impermeable peel and stick membrane (0.05 perms) on the outside of the structural OSB panel with a vapor open liquid applied WRB (19 perms, modeled in WUFI Plus at 16.5 perms). The mineral wool version used the vapor open WRB as well, but also replaced the vapor closed exterior XPS (0.37 perms at 4") with vapor open mineral wool (23.2 perms at 5"). The mineral wool thickness was increased from 4" to 5" to provide the same R-value as the XPS. The moisture content plots of the inner and outer surface of the structural OSB panel for these two variants are overlaid on top of the basic wall versions (ESv3, 2x4 Hybrid, and SPS) in Figures E-13 and E-14.

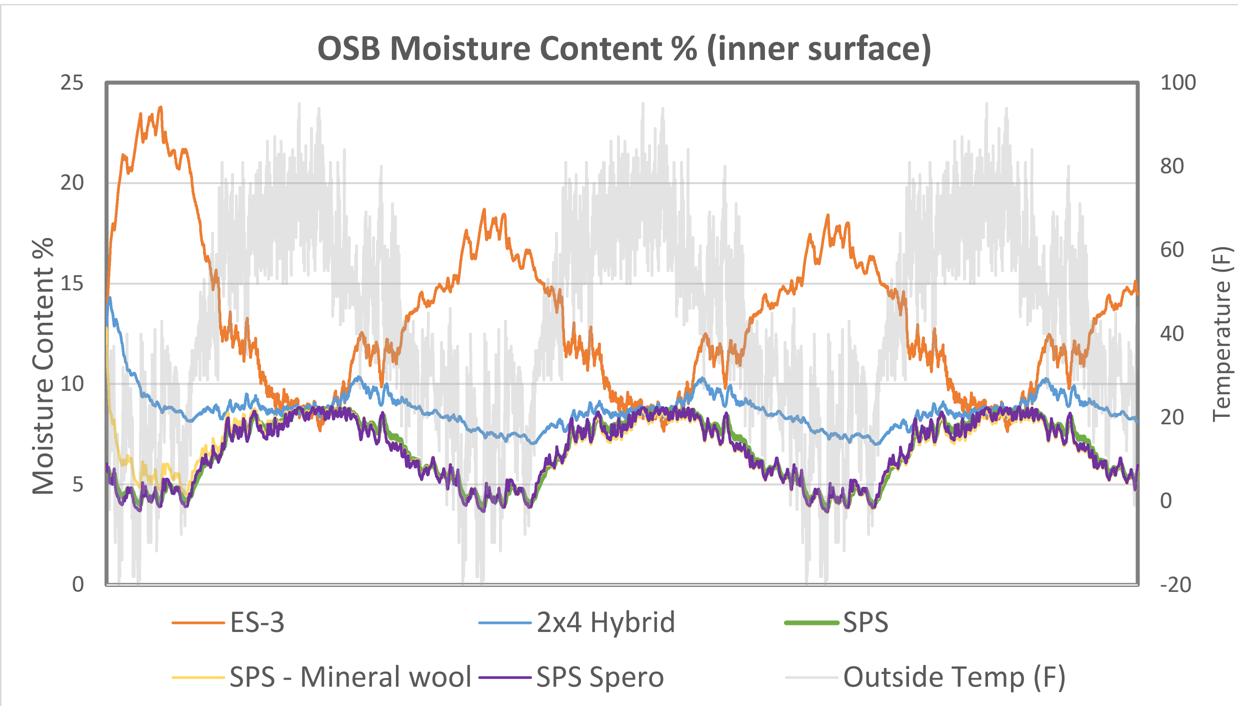


Figure E-13. WUFI Plus simulation, OSB inner surface moisture contents over three years including SPS variants

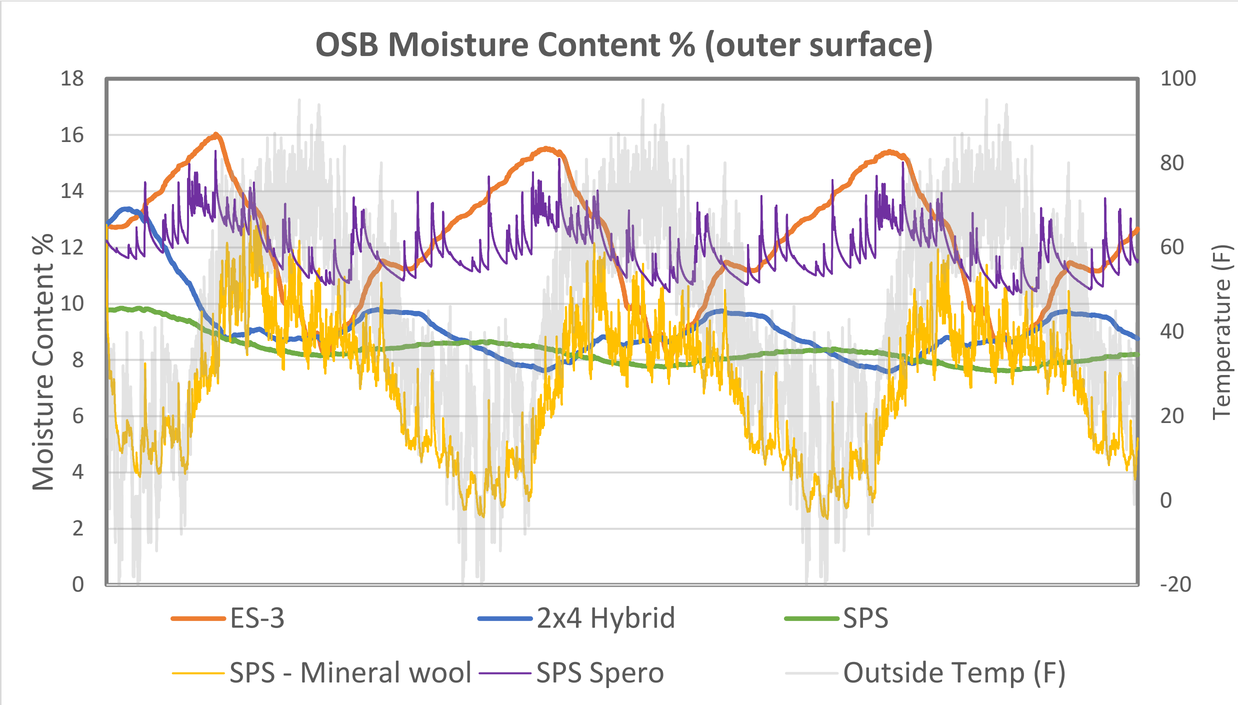


Figure E-14. WUFI Plus simulation, OSB outer surface moisture contents over three years including SPS variants

Analysis of the moisture content at the inner OSB surface of the SPS wall variants shows that there is almost no change compared to the basic version of the SPS wall system. The plots fall almost exactly on top of one another. This behavior is expected because in all of the SPS systems, the inner surface of the structural OSB panel is exposed almost directly to indoor conditions. However, the graph showing the moisture content at the outer surface of the OSB reveals some remarkable differences in moisture behavior.

In the version of the SPS wall built by Spero, the moisture content of the structural panel at the outer surface is much greater than the other SPS walls. Spikes in moisture content rise to levels very similar to the ESv3 wall, frequently surpassing 14%. The spiky behavior of the moisture content in the outer surface of the structural panel suggests that water vapor from wind-driven rain events (1% deposited on the outer surface of the WRB) is being driven through the vapor permeable WRB into the OSB. This moisture may remain trapped between the impermeable thickness of the structural OSB panel and the semi-impermeable exterior XPS insulation, keeping the moisture content at the outer surface of the OSB relatively high. The moisture design goal of this SPS variant was to increase the drying potential of the SPS panel to the outside. However, it is apparent that the XPS is acting as a strong vapor retarder preventing outward drying and, instead, the WRB has become too permeable to inward-driven moisture.

The mineral wool version of the SPS wall succeeds in opening up a drying pathway to the outside by replacing the XPS with mineral wool. In this case, the moisture content plot at the outer surface of the structural panel shows that the OSB is extremely dry in the winter. This is expected given that it is kept very warm yet remains connected to the dry exterior environment through an open diffusion pathway. Moisture levels do rise in the summer but remain lower than both the Spero SPS version and the ESv3 wall. Spiky behavior at the outer surface can again likely be attributed to inward-driven moisture during precipitation events, but the outward drying capacity of this wall allows this moisture to easily diffuse to the exterior again. The version of the SPS wall with mineral wool is the only SPS version that achieves a stable, consistent moisture content pattern within the first year of the simulation. This indicates a significantly improved drying capacity compared to the other SPS options that were investigated. This wall design can be considered the most robust option when it comes to handling incidental water leakage.

A WUFI Plus simulation was also completed for the 1-ply hybrid wall proposed by Thrive Home Builders. Thrive’s hybrid wall uses a single 1-1/8” vertical structural OSB panel with 2 x 4 stud stiffeners on the interior side and control layers that are similar to the 2x4 Hybrid wall section. A plot of the moisture content of the inner and outer surface of the structural OSB panel is overlaid in the following two figures. These graphs show that the structural panel is significantly wetter than the half-inch OSB in the basic 2x4 Hybrid wall design, but remains at safe moisture levels throughout the year. It also largely follows the wetting and drying cycles of the 2x4 Hybrid wall, but with a several month delay, so that its drying period is aligned with late winter and spring followed by a wetting period in late summer and fall. It may be that the increased moisture storage capacity and impermeability of the thick OSB panel creates this lag, similar to the effects of the structural panel in the SPS wall system. The graphs also show that the presence of the structural OSB panel slows drying considerably so that it takes three years for the OSB to read a consistent, repeating pattern versus one year for the thinner OSB in the basic 2x4 Hybrid wall.

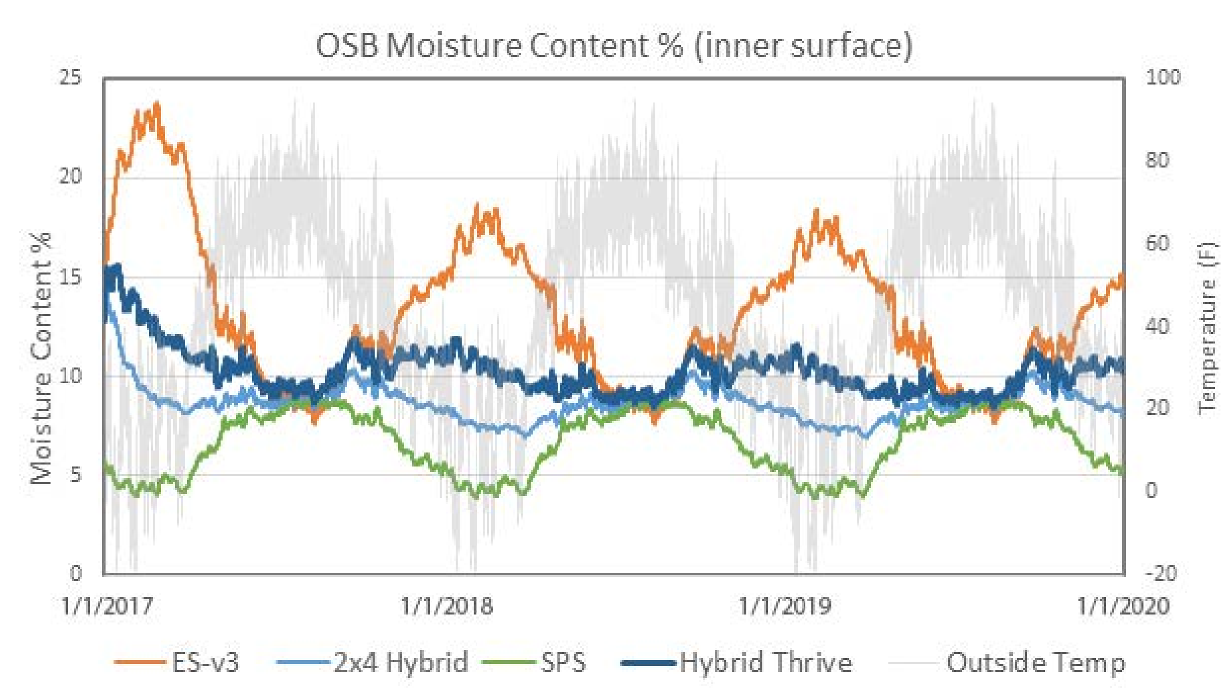


Figure E-15. WUFI Plus simulation, OSB inner surface moisture contents over three years including Thrive’s hybrid wall design

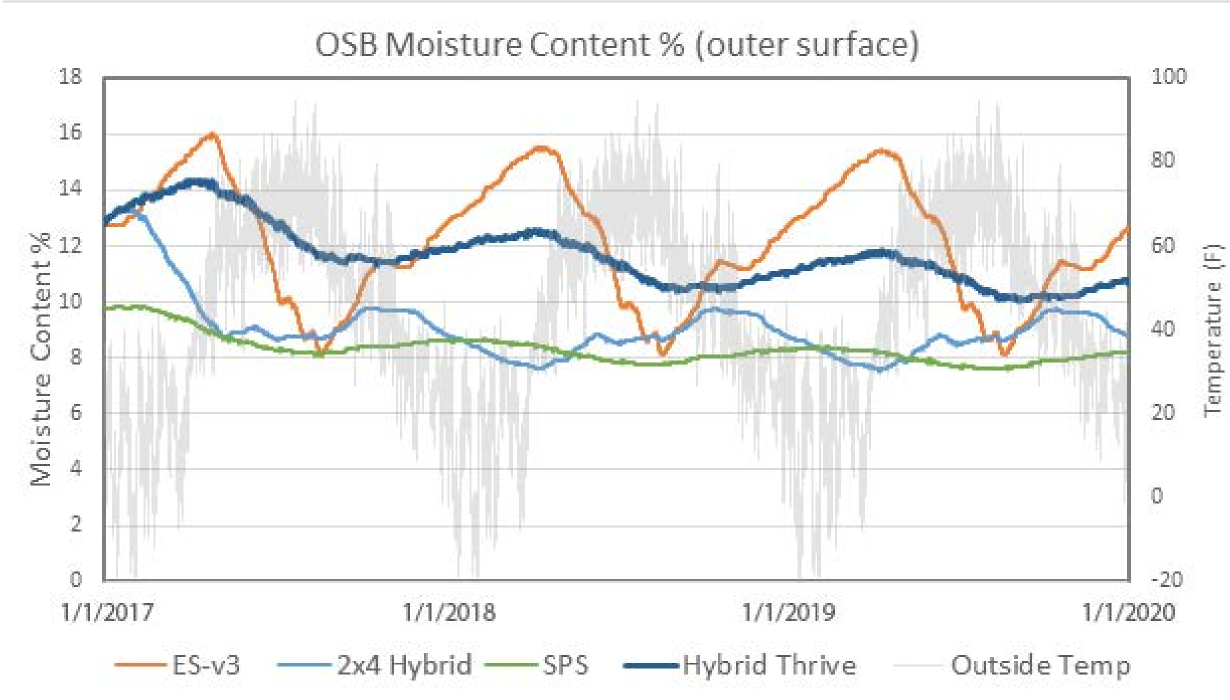
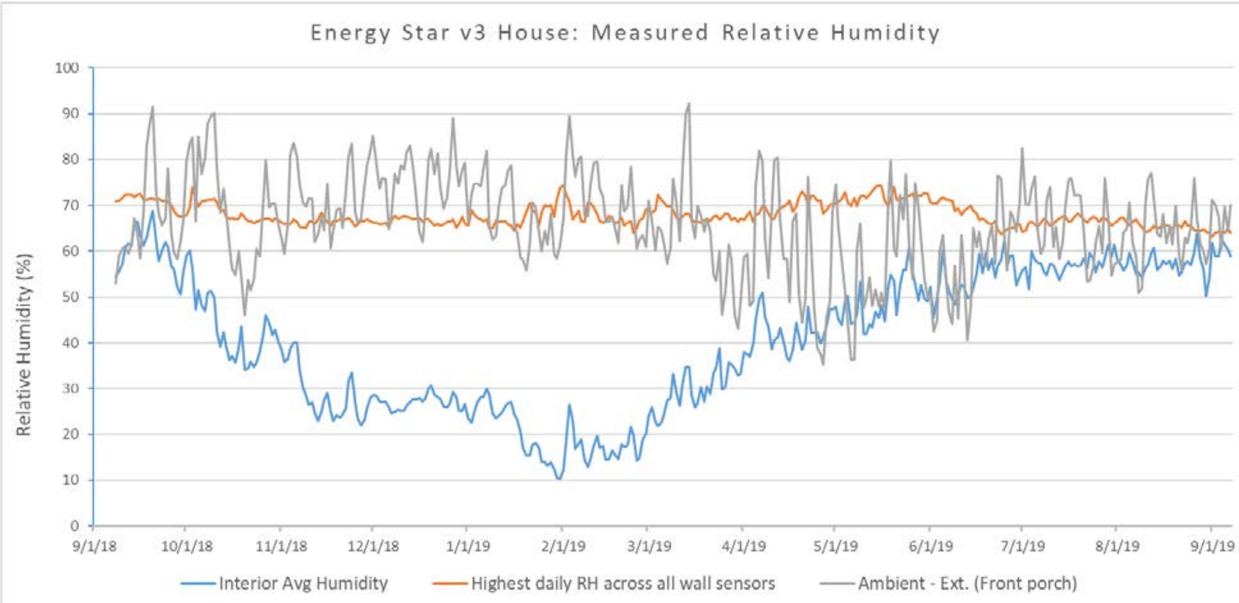


Figure E-16. WUFI Plus simulation, OSB outer surface moisture contents over three years including Thrive's hybrid wall design

E.2 Background, Assumptions, and Results for Moisture Monitoring

A. ENERGY STAR v3 Wall



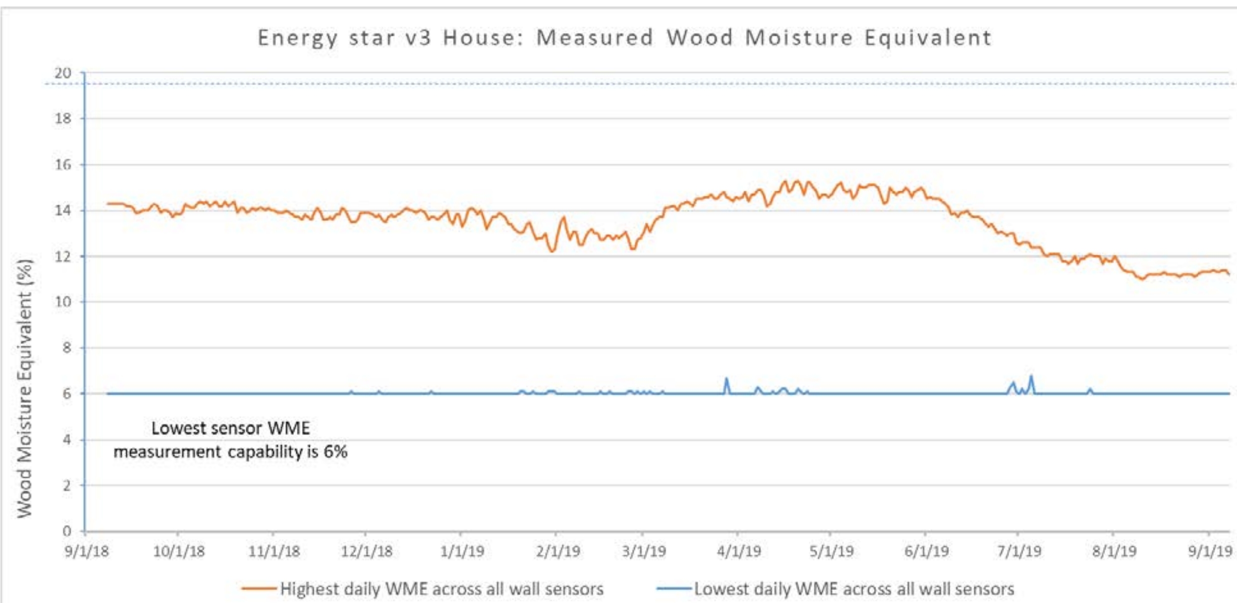
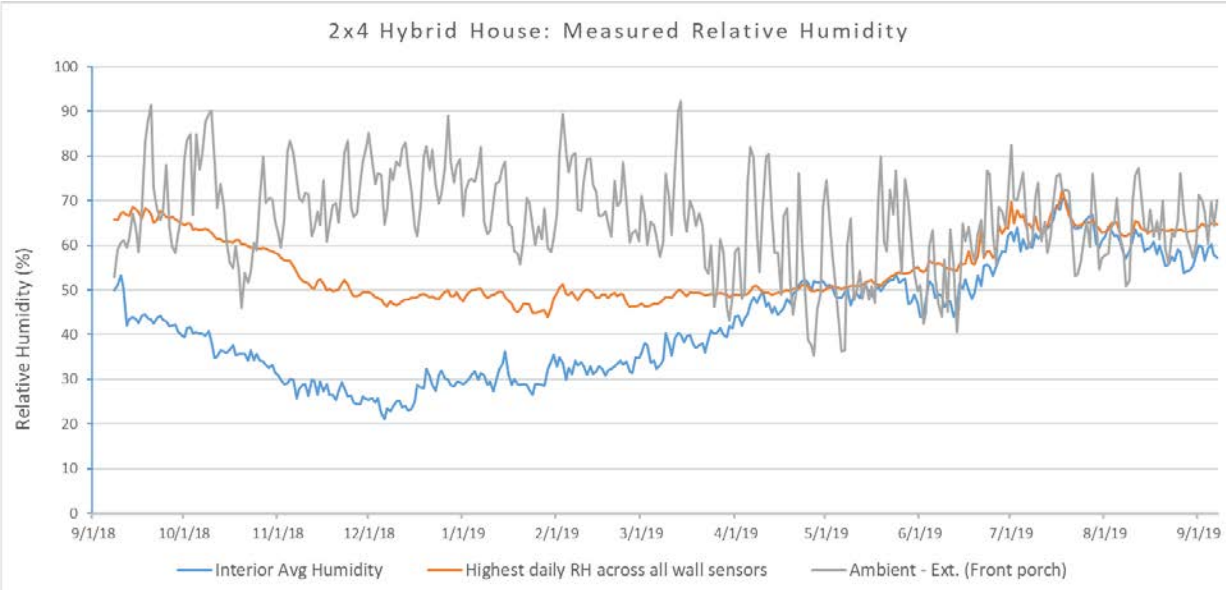


Figure E-17. ENERGY STAR v3 wall sheathing—measured moisture content and RH

B. 2x4 Hybrid Wall



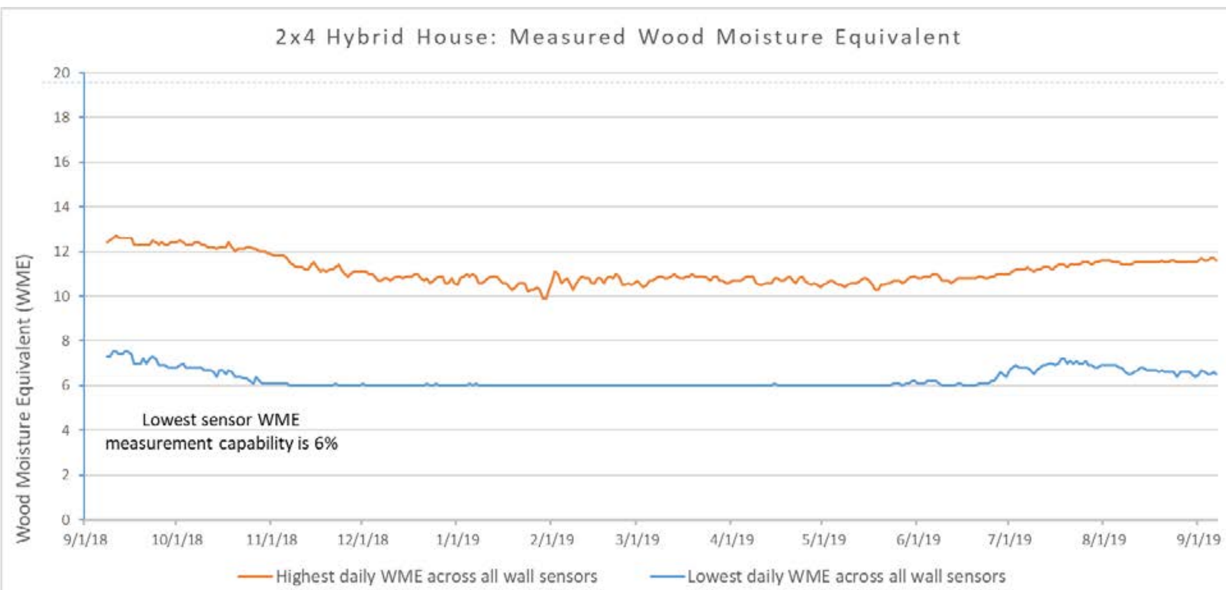
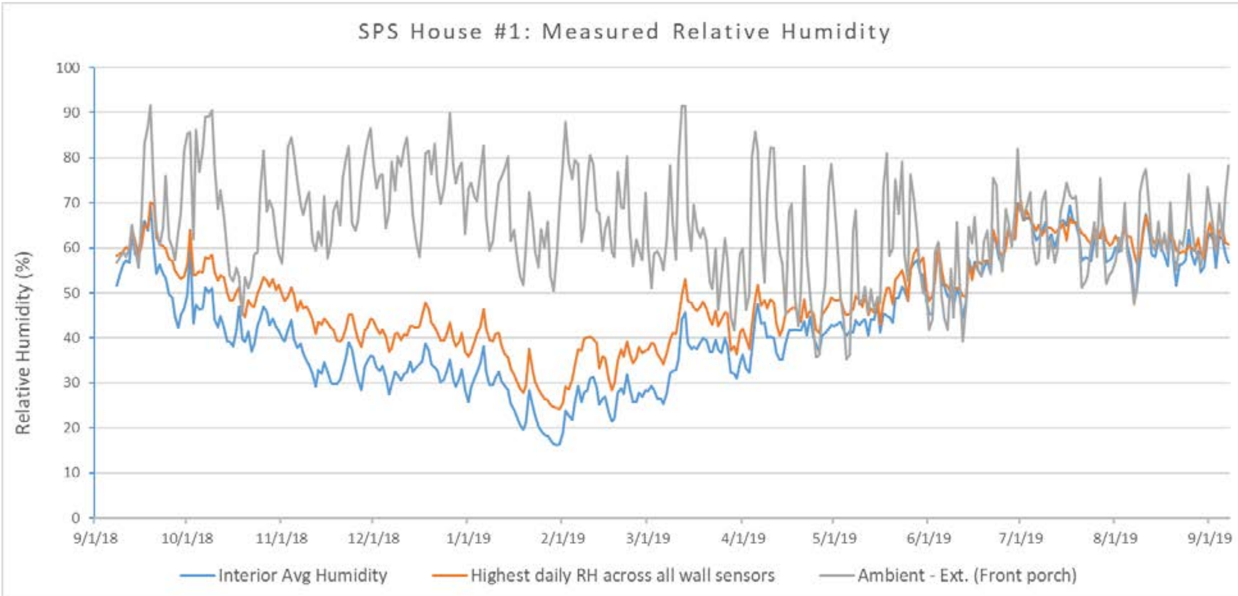


Figure E-18. 2x4 hybrid wall sheathing—measured moisture content and RH

C. SPS Wall, House 1



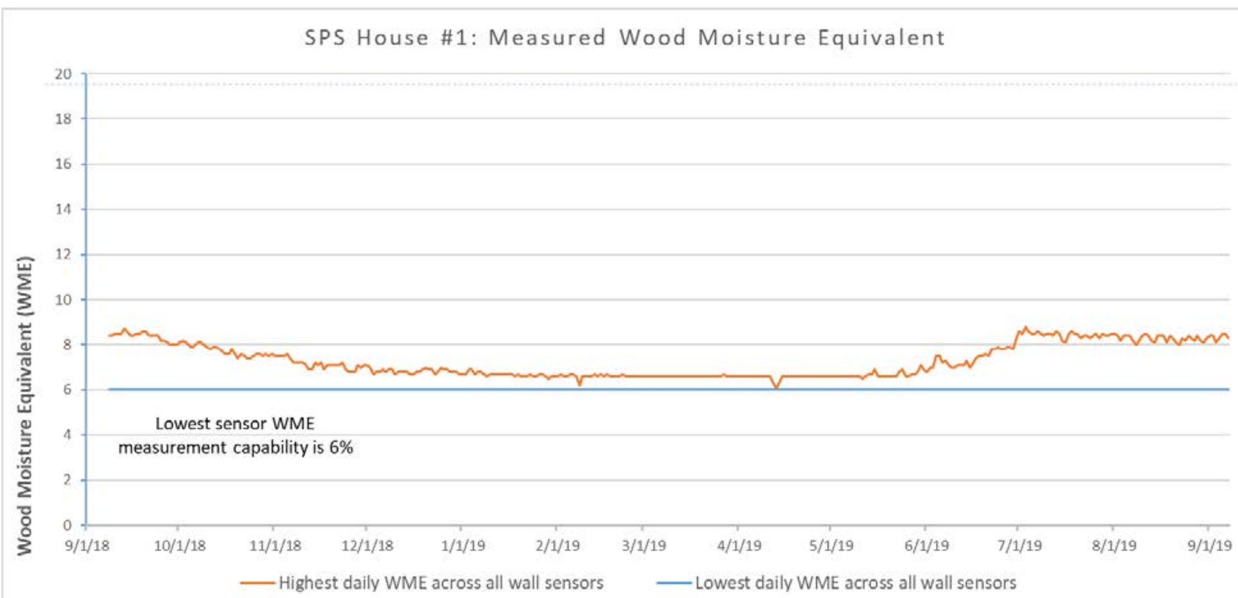


Figure E-19. SPS house 1 wall sheathing—measured moisture content and RH

D. SPS Wall, House 2

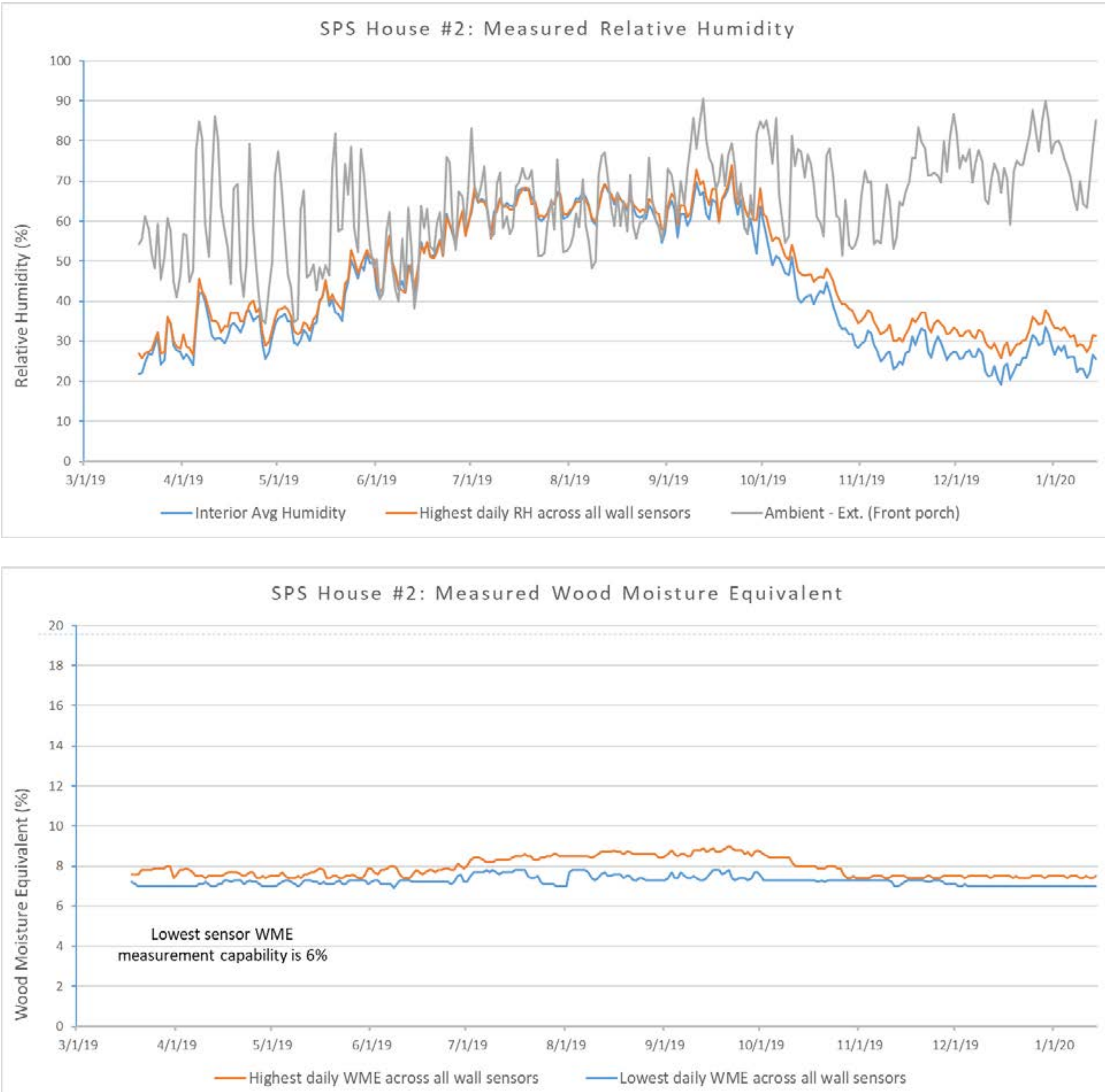


Figure E-20. SPS house 2 wall sheathing—measured moisture content and RH

E.3 Detailed Comparison of Moisture Modeling and Monitoring Data

This section compares the monitored moisture content of the sheathing in the completed houses with modeled data from the WUFI simulations. The modeled data from WUFI depicts the highest moisture content, typically from the eastern exposure that receives the greatest share of wind driven rain according to the climate file. To afford the best comparison, the monitoring data also show the highest measured moisture content taken in hourly increments from any sheathing sensor location. For reference, an average moisture content plot across all the sheathing sensors for a given wall type is shown as well.

Given the precision of WUFI modeling, moisture levels very close to the inner and outer surface of the sheathing could be tracked separately. However, with the relatively thin sheathing that was used for both the ENERGY STAR v3 and 2x4 hybrid houses (approximately 1/2”) compared to the size and installation method used for the moisture content sensors, it was not possible to provide separate inner and outer surface readings for the monitored data. The sheathing used for the SPS houses was an exception since the OSB panels were considerably thicker at 2-1/4”. The increased thickness afforded the opportunity to track inner and outer surface moisture content separately, which could be compared more directly with the modeled data.

The monitored moisture content in the ENERGY STAR v3 wall sheathing, shown in Figure E-21, began tracking generally in the same pattern and range as the modeled moisture content after an initial drying period (July to January). This pattern consisted of a wetting period in late winter and spring followed by a drying period during the summer. Starting the following fall, moisture content levels began rising again, similar to the modeled data. However, the monitoring data reached a higher peak, above 20% moisture content, and arrived there sooner than modeling data suggested. The modeled moisture content peaked at 17%–18% moisture content in late February while the monitoring data appeared to reach a peak of 22%–23% moisture content two months earlier. The monitored moisture content level could be risky if it stays elevated during warmer temperatures when mold growth is possible. It is possible that the data for this portion of the graph are coming from a sensor location that is exposed to unusually high levels of interior air leakage or possibly some bulk water intrusion. When graphing the average monitored moisture content across all ENERGY STAR v3 sheathing sensors moisture levels appear substantially lower and fall mostly below the range suggested by the modeling data. This is expected because the modeling data represent only the wettest orientation.

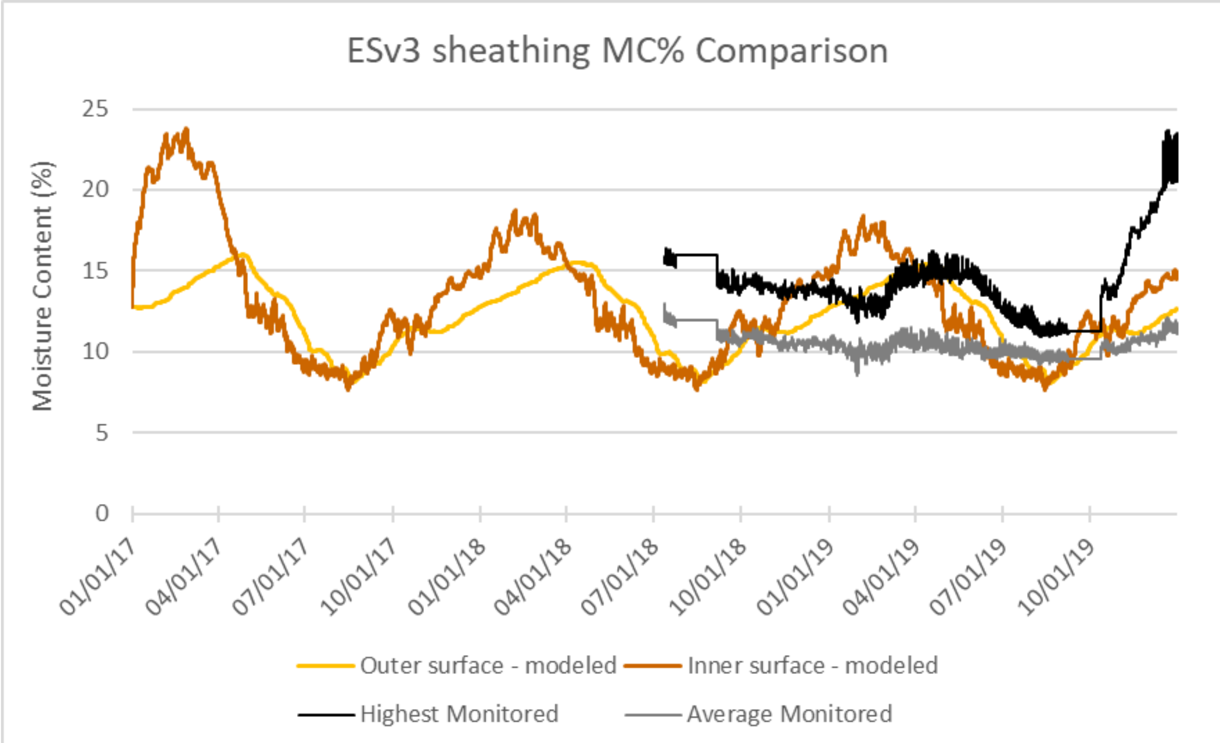


Figure E-21. Comparison between modeled and monitored sheathing moisture content for ENERGY STAR v3 wall

Monitoring data show that the sheathing of the 2x4 Hybrid house experiences an initial drying out period similar to the ENERGY STAR v3 house, as shown in Figure E-22. After this, monitored moisture content tracks in the same general pattern suggested by the modeling data, with drying periods in the winter and wetting periods in the summer. This is reflective of the sheathing being more connected to moisture levels inside the house than the exterior. The highest monitored moisture content across all sensors stays roughly 3% higher than the highest modeled moisture content. Looking at the average moisture content across all sheathing sensors, moisture levels are substantially lower and show close agreement with the range and pattern of wetting and drying suggested by the modeling data. However, because the modeled data represent only the wettest orientation, this implies that the actual moisture levels in the 2x4 Hybrid sheathing may be slightly higher than predicted by the WUFI models.

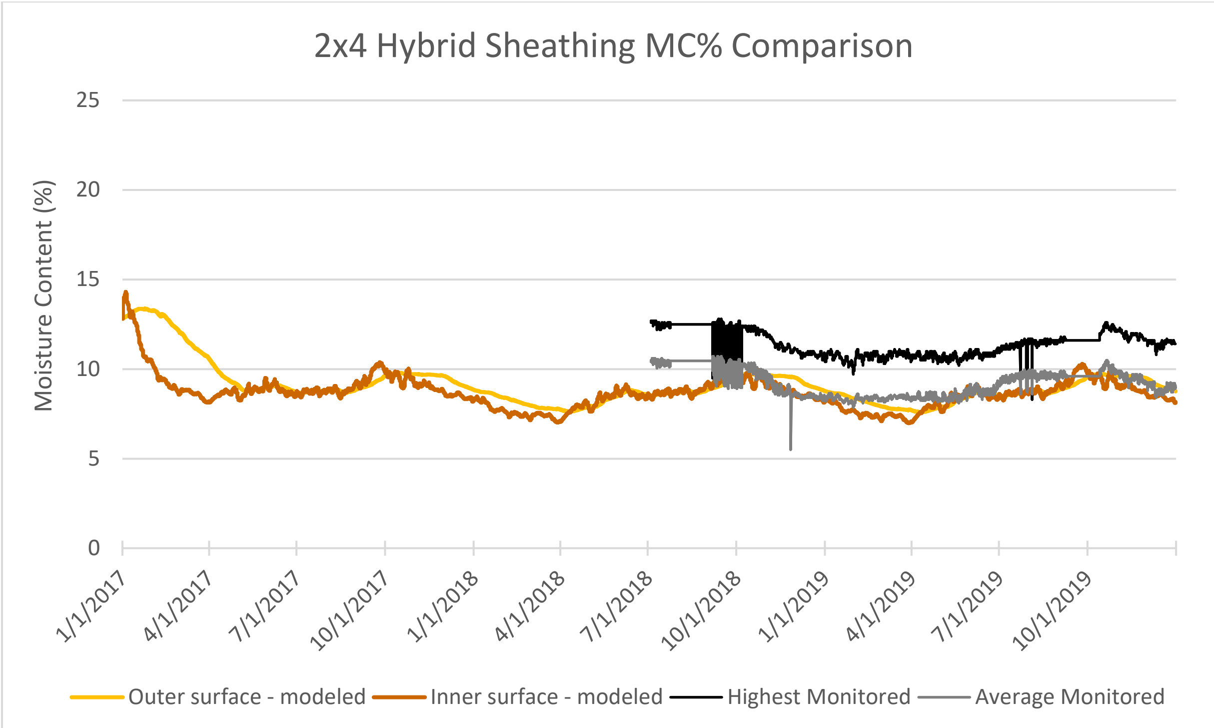


Figure E-22. Comparison between modeled and monitored sheathing moisture content for the 2x4 Hybrid wall

Sheathing moisture content for the SPS houses were measured at two locations: close to the inner surface and close to the outer surface of the thick OSB panels. Modeled moisture contents at these two locations were also tracked in WUFI. Figure E-23 shows that the highest monitored moisture content of the panel at the inner surface followed very closely to the modeled moisture content in the summer but was slightly higher in the winter. The winter discrepancy may have been due to differences between the modeled and actual indoor relative humidity with actual indoor relative humidity in the houses higher than expected. This would tend to increase the moisture content of the panel at the inner surface, which is almost directly exposed to interior conditions.

The highest monitored moisture content of the structural OSB panel at the outer surface is very close to the range suggested by the modeling, with a maximum discrepancy of about 2% moisture content. However, the outer surface moisture content does not follow the same pattern of winter wetting and summer drying suggested by the modeling data. Instead, the monitoring data track much more closely with the inner surface in terms of both the moisture content range and the timing of wetting and drying periods. This discrepancy could be the result of differences between the modeled and actual material properties of the OSB panel itself. The OSB material used in the WUFI modeling was "Oriented Strand Board" with a permeability of 0.158 perm in. Data from Huber on the permeability of the Advantech panels suggested a permeability closer to 0.618 perm in. This difference is made more important by the increased thickness of the panel at 2-1/4 inches compared to most OSB sheathing. Compared to the WUFI OSB material, greater permeability would allow the Advantech OSB to equilibrate more quickly, keeping the inner and outer surface moisture contents more similar and in sync, as shown by the monitoring data.

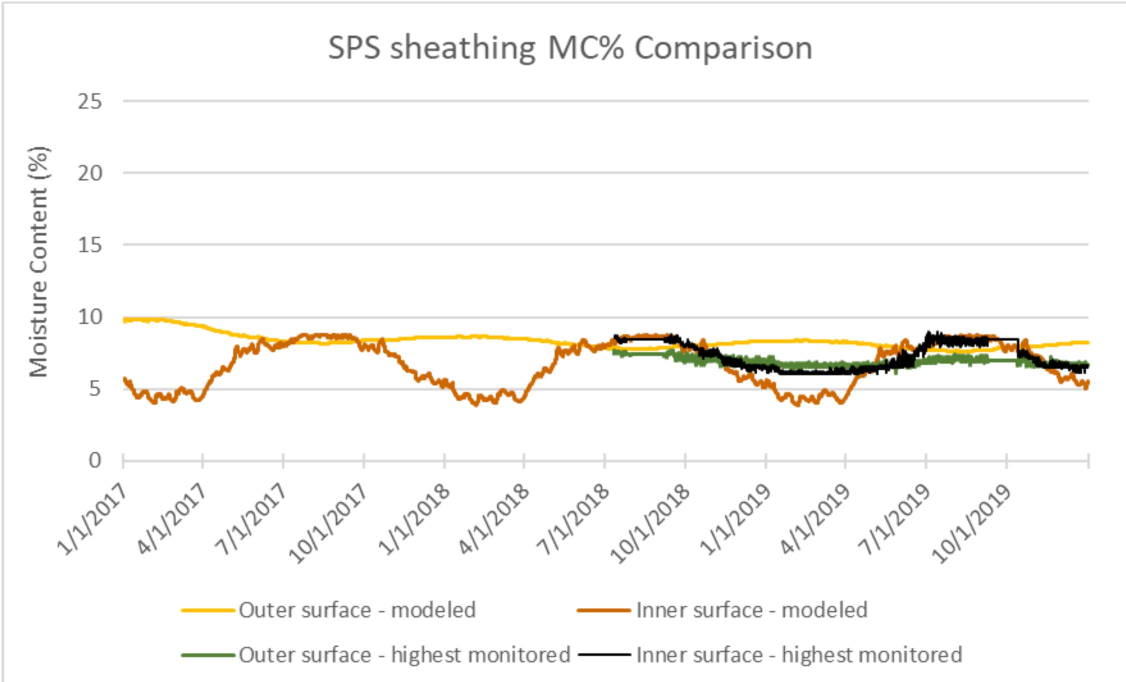


Figure E-23. Comparison between modeled and monitored sheathing moisture content for the SPS walls

Overall, moisture monitoring and modeling results agree closely. The largest observed discrepancy (greater than 8% moisture content) is for the ENERGY STAR v3 wall type. This could be expected because that wall type places the sheathing in the most risky position where it is relatively exposed to exterior conditions. Because of the method of air barrier and weather barrier installation this wall type is also the most likely to exhibit air and water leakage. Monitoring data for both the 2x4 hybrid and SPS wall types are a closer fit to the modeling data with a maximum discrepancy in the range of 3% moisture content. These wall types provide a more robust method of air and water leakage control and place the sheathing in a warmer, more protected position. The sheathing moisture content is expected to remain more stable and consistent, with monitoring results supporting this claim.

Appendix F. Additional Background, Assumptions, and Results for Structural Testing

F.1 Test Setup

For each nominal height, the 2-ply specimens were fabricated first. The specimens were cut using a track saw, capable of cutting through the full thickness of a 2-ply specimen, clamped to the face of the specimen. This cutting method was used to ensure a straight and uniform cut on each specimen in order to enable a uniform load transfer at the edges for testing purposes. The compression load and the loading table movement were measured. Three replicates for both 1-ply and 2-ply panels were tested in a range of heights from 4' to 10'.

1. GRK R4 #9 x 2" screws at 1'-0" o.c. horizontally and 2'-0" o.c. vertically. The screw head should be firmly engaged with the panel surface.

2. 0.113" x 2" PASLODE ringshank gun-nail at 0'-8" o.c vertically between the GRK Screws. The nail heads should be flush (or nearly so) with the panel surface.

3. Use this pattern through the field of the panel.

4. At the edge simply bring the fastener in one inch (reduces the spacing at the perimeter by 1").

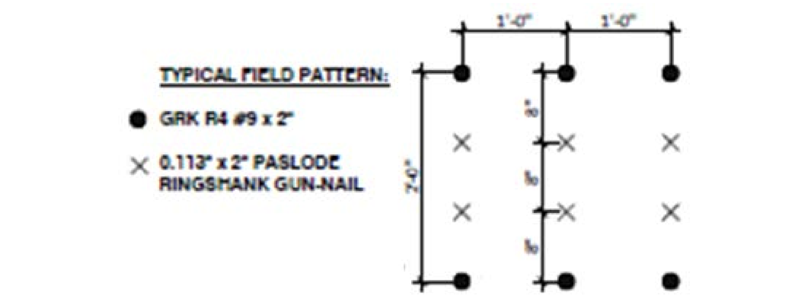


Figure F-1. Typical field pattern for construction of 2-ply SPS panels

Flanges were bolted to the top and bottom I-Beams to achieve the 1/3 centerline offset prescribed by E72, and the panels were installed in the universal test machine (UTM) in such a way as to force the direction of buckling in the direction of the fastener heads to mimic in-use conditions (Figure F-1). The first three specimens tested—8 A-D, 8 B-E, and 8 C-F—were inadvertently installed in the UTM backwards, forcing the direction of buckling to be away from the fastener heads. Subsequent specimens were installed correctly unless otherwise stated.

Figure F-2. Flanges bolted to the I-beams allow the specimen to be loaded into the UTM at the 1/3 distance prescribed by E72 to force the direction of buckling

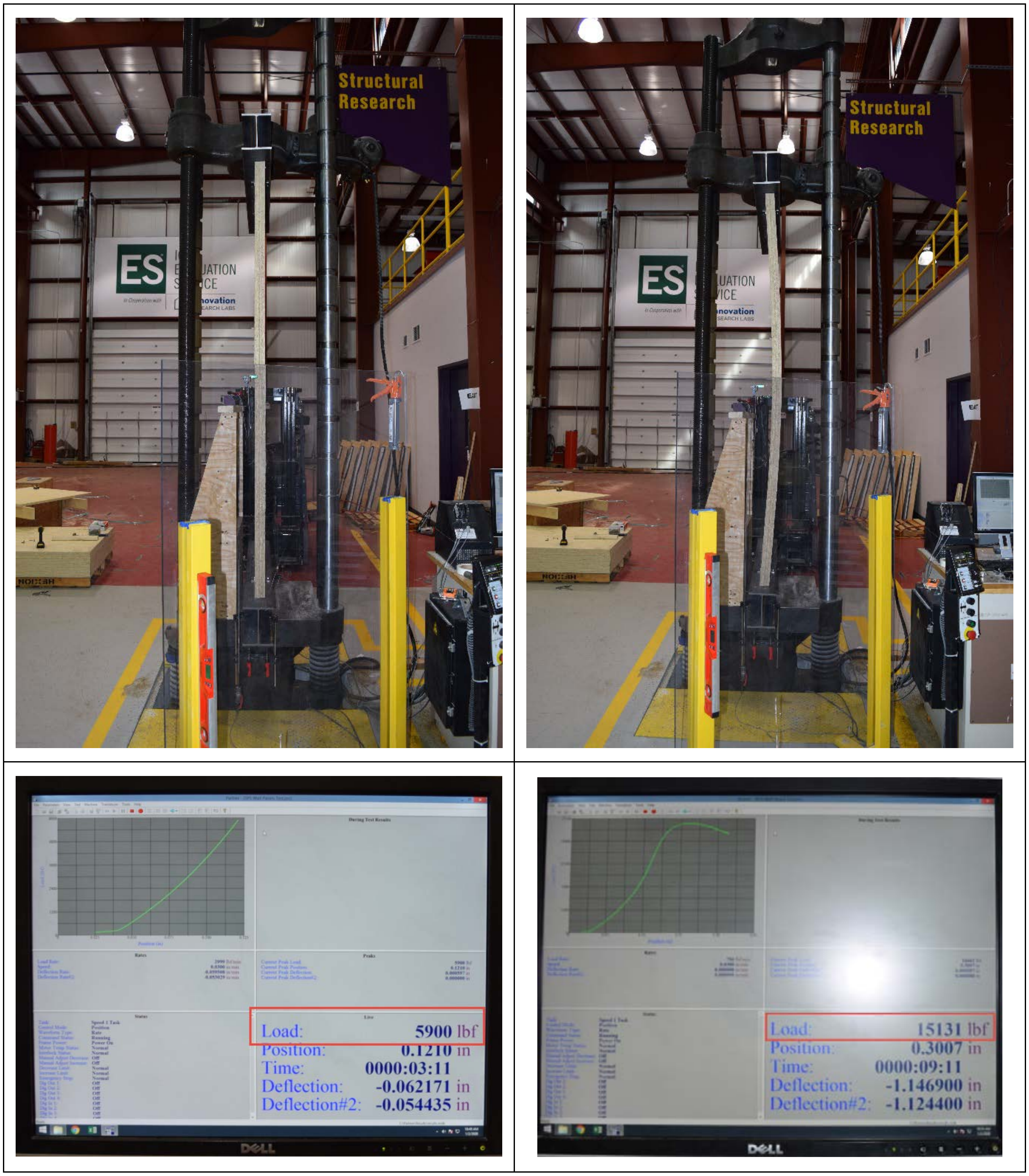


Figure F-3. At 15,000 lbs of force, bowing was observed at the midline of the 2-ply SPS specimens

F.2 Data Collection and Analysis

Table F-1 and F-2 show the maximum loads for the 1-ply and 2-ply panels, respectively. Table F-3 is a comparison of the panels based on the orientation of the OSB panel strength axis.

Table F-1. 1-ply Maximum Loads in Compression (Buckling)

1-1/8" OSB [All specimens 4-ft width]									
1-Ply Panels	Specimen ID Panel height, ft.	A	B	C	Avg. load in lbs. per panel	Avg. load in lbs. per lf of panel (plf)	Avg. load in plf, per ft. of height	Load reduction per ft. of ht., % wrt prev. load	Variation % among replicates against average
Maximum Load in Buckling (lbs.)	4'	38913	41406	41544	40621	10155	2539	NA	4.2%
	6'	18264#	17354#	17256	17625	4406	734	36%	3.6%
	8'	7255	7402	7964	7540	1885	236	34%	5.6%
	9'	6447#	6412#	6433#	6431	1608	179	24%	0.3%
	10'*	4802√	4991√	6809√	5534	1384	138	23%	23.0%

During testing the panel bowed opposite to the intended direction
√ Specimen contained a noticeable bow; an 8-ft. level showed a slight longitudinal bow
* Constructed using panels from the second shipment of panels, vertical orientation

Table F-2. 2-ply Maximum Loads in Compression (Buckling)

1-1/8-in. OSB [All specimens 4-ft width]										
2-Ply Panels	Specimen ID Panel height, ft.	A-D	B-E	C-F	Avg. load in lbs. per panel	Avg load in lbs. per lf. of panel (plf)	Avg load in plf. per ft. of height	Load reduction per ft. of ht., % wrt prev. load	Variation % among replicates against average	Load ratio, 2-ply /1-ply
Maximum Load in Buckling (lbs.)	4'	71756	70255	79902	73971	18493	4623	NA	8.0%	1.82
	6'	40710	40108	39261	40026	10007	1668	32%	1.9%	2.27
	8'^	15589#	16662#	15866#	16039	4010	501	35%	3.9%	2.13
	9'*	19037	21083	18220	19447	4862	540	-8%	8.4%	3.02
	10'*	15316#√	15836#√	14916#√	15356	3839	384	29%	3.1%	2.77

^ All three 2-ply 8-ft. specimens were installed in the Universal Test Machine "backwards," with fastener heads on the concave side of the bow
# During testing the panel bowed opposite to the intended direction
√ Specimen contained a noticeable bow; an 8-ft. level showed a slight longitudinal bow
* Constructed using panels from the second shipment of panels, vertical orientation

Table F-3. Comparison of Compressive Strength—Horizontal vs. Vertical Axes (8-ft. Specimens)

1-1/8-in. OSB [All specimens 4-ft width]										
Compare Maximum Load in Buckling, (lbs.)	Specimen ID Panel height, ft.	A	B	C	Avg. load in lbs. per panel	Avg. load in lbs. per lf. of panel width (plf)	Avg. load, plf, per ft. of height	Load reduction per ft. of ht., % (horiz vs. vert)	Variation % among replicates against average	1-ply load ratio, (horiz /vert)
Vertical	8	15589	16662	15866	16039	4010	501	---	3.9%	---
Horizontal	8	6118	5454	5518	5697	1424	178	64%	7.4%	0.36

The charts and graphs from Figures F-4 to F-8 show the results of SPS panel buckling tests for both 1-ply and 2-ply configurations under vertical compressive load.

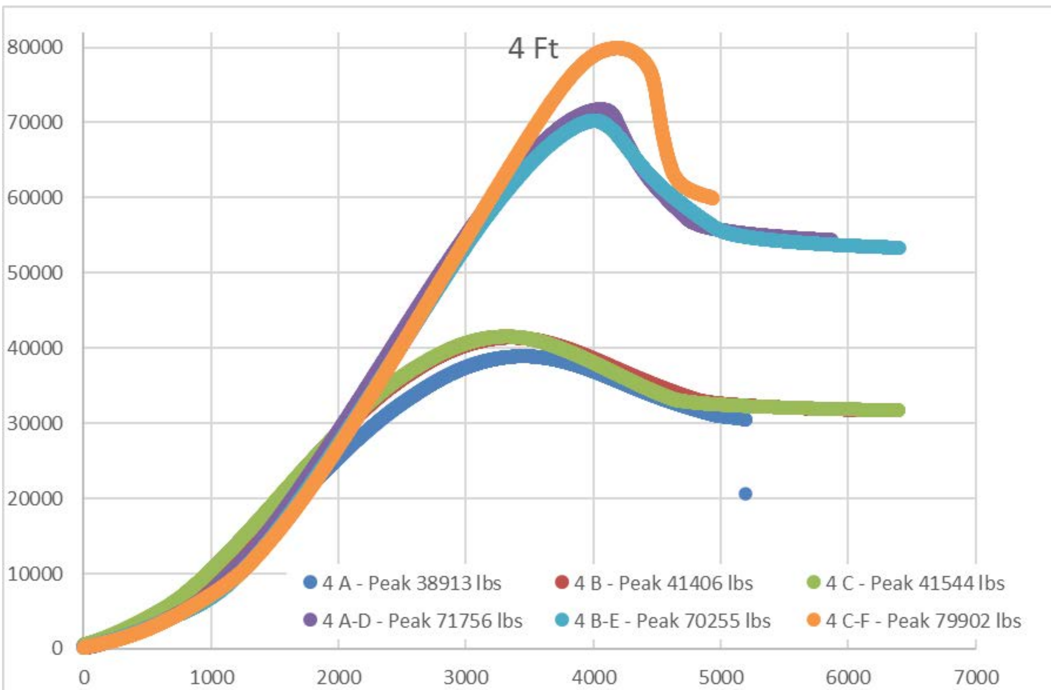


Figure F-4. Load curves—comparison of 4-ft panels (lbs per panel)

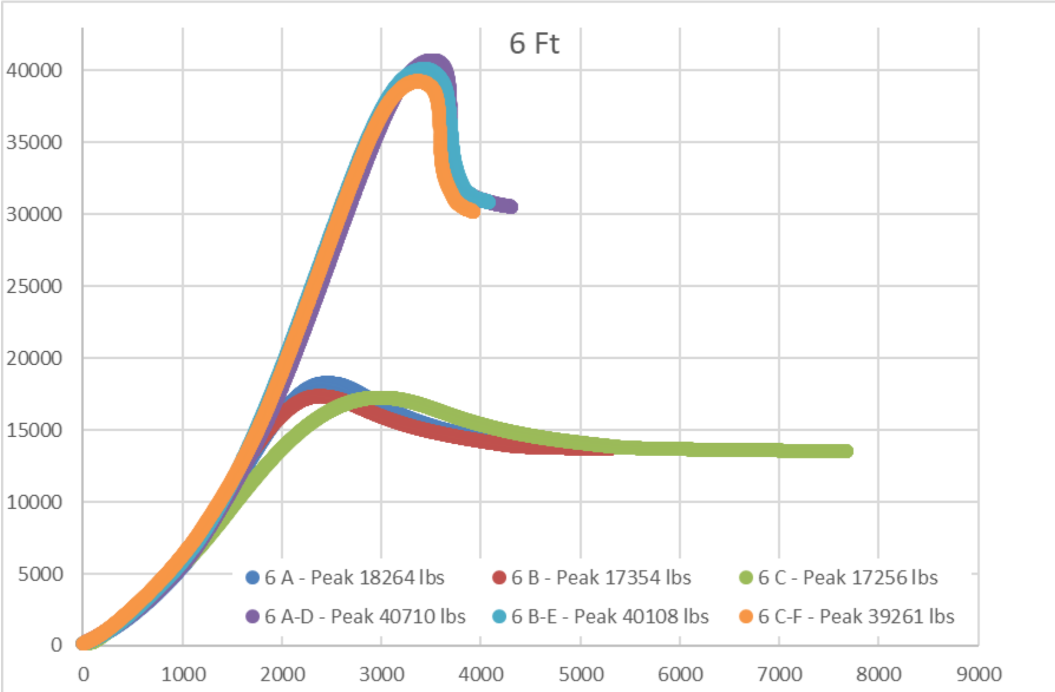


Figure F-5. Load curves—comparison of 6-ft panels (lbs per panel)

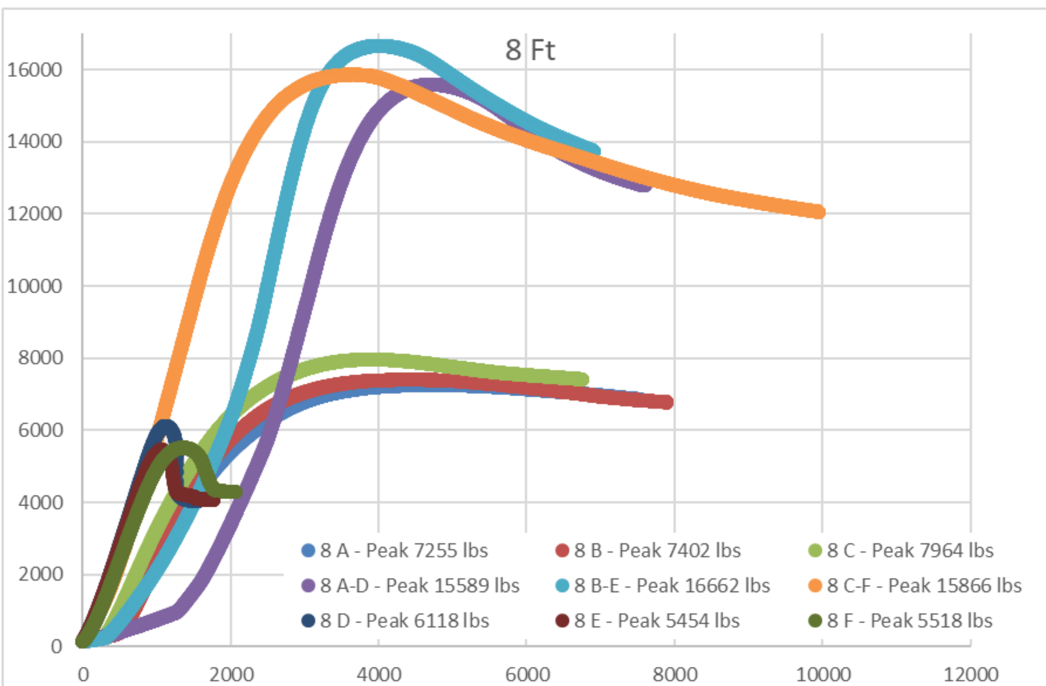


Figure F-6. Load curves—comparison of 8-ft panels (lbs per panel)

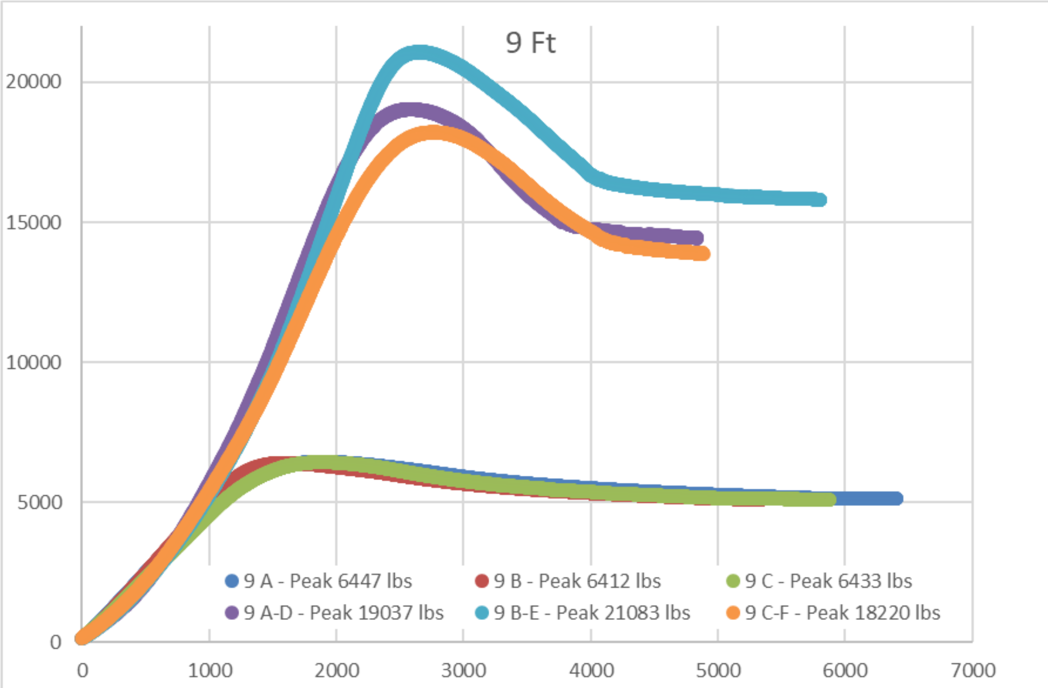


Figure F-7. Load curves—comparison of 9-ft panels (lbs per panel)

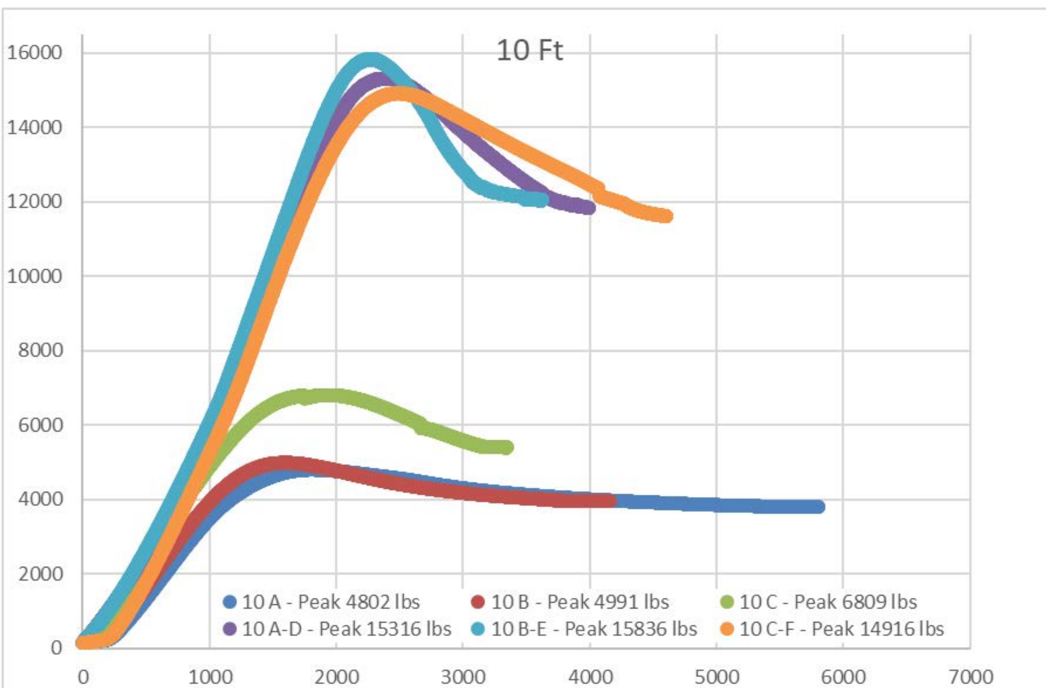


Figure F-8. Load curves—comparison of 10-ft panels (lbs per panel)

F.3 Results

Figure F-9 shows the load plots for the 1-ply test specimens.

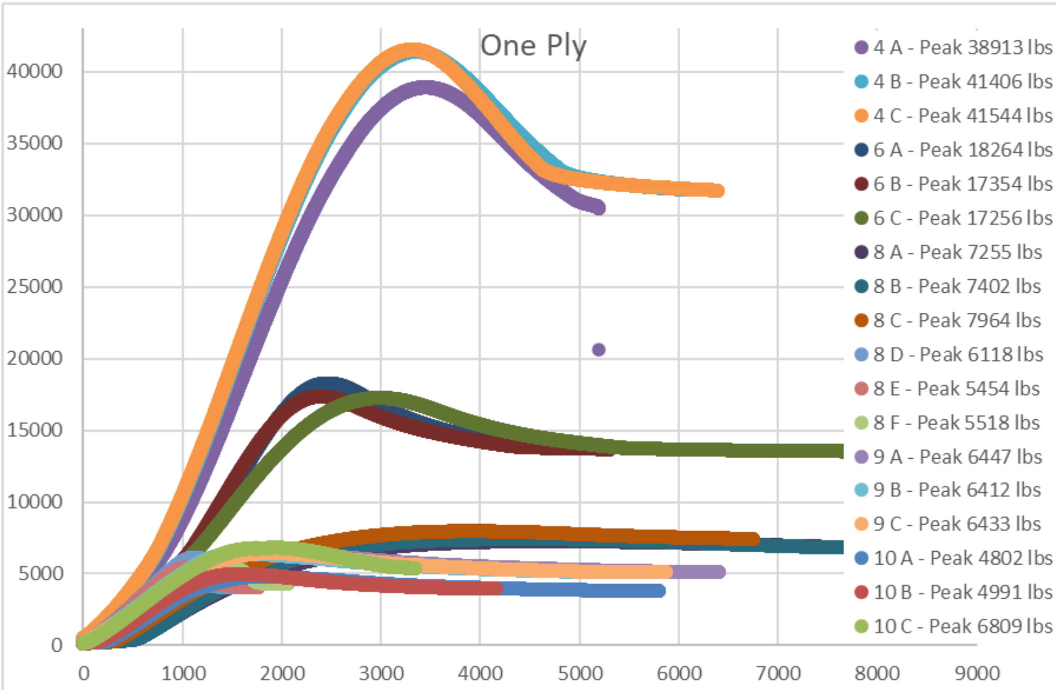


Figure F-9. 1-ply load curves (lbs per panel)

Shorter height panels exhibited higher load capacity than taller height panels: the capacity of 4-ft panels was more than twice that of 6-ft panels and more than seven times that of 10-ft panels.

Ten-ft tall 1-ply panels exhibited a large variation in capacity, evidently due to a pre-existing bow in the raw panels as delivered from the manufacturer, which was discovered following some unexpected results. Measurement using an 8-ft level revealed that the center of the panel had an approximate 0.125-in gap. Panels 4-A and 4-B appear to have been loaded into the UTM with directed bowing with the direction of the existing bow. Panel 4-C was deliberately loaded with directed bowing against the direction of the existing bow. Panel 4-C had nearly 50% greater capacity in this direction. The panel was observed to resist the load, gradually straightening, and then began to bow in the “correct” direction. Pre-existing bowing of panels shorter than 10 ft was not apparent by visual inspection.

Figure F-10 shows the load plots for the 2-ply test specimens.

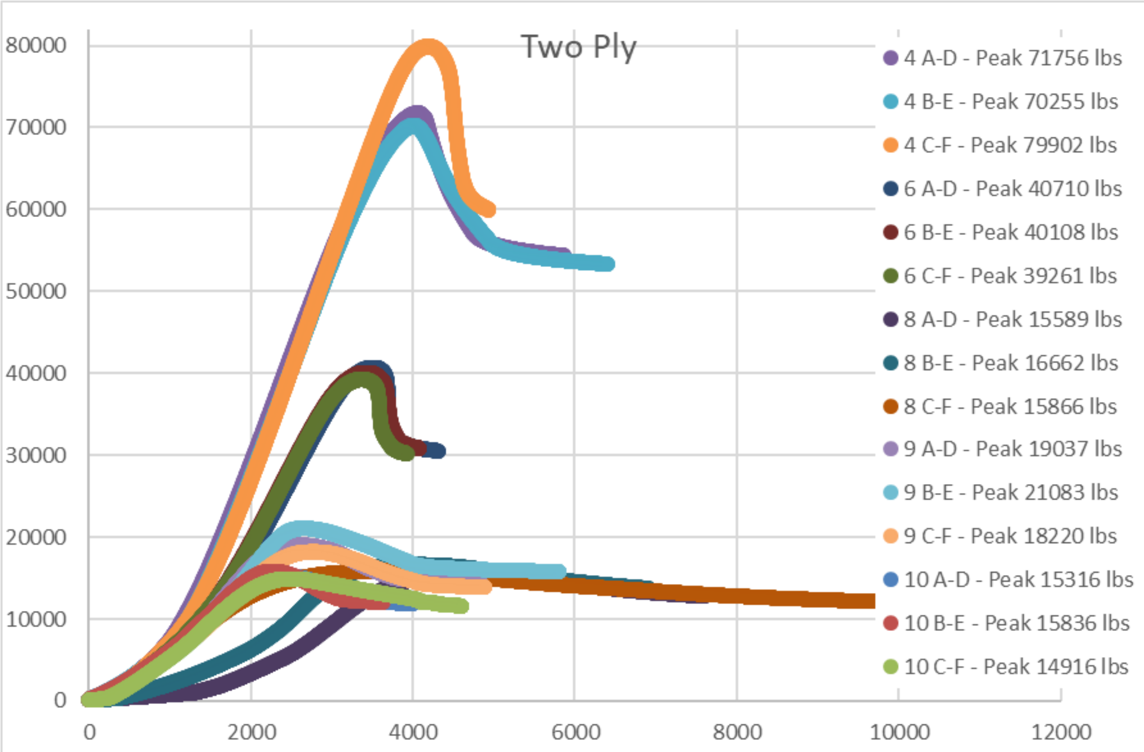


Figure F-10. 2-ply load curves (lbs per panel)

Shorter height panels exhibited higher load capacity than taller height panels: the capacity of 4-ft panels was more than twice that of 6-ft panels and 4.5 times that of 10-ft panels. SPS 6-ft panels showed a slight "S" curve at ~35,000 lbs.

The cluster of results between 10,000 and 20,000 lbs appears to be due to 8-ft and 10-ft specimens bowing in the "wrong" direction (towards the horizontal-oriented panel).

Table F-4. Test Observations by Specimen

Test	Notable Observations	Peak Load (lbs)
4 A	Catastrophic failure during hold for picture. Only specimen that experienced catastrophic failure.	38,913
4 B	None	41,406
4 C	None	41,544
4 A-D	None	71,756
4 B-E	Very slight gap between panels observed post-test	70,255
4 C-F	None	79,902
6 A	Bowed wrong way	18,264
6 B	Bowed wrong way	17,354
6 C	None	17,256

Test	Notable Observations	Peak Load (lbs)
6 A-D	Slight "S" curve observed at 35,000 lbs	40,710
6 B-E	Slight "S" curve observed at 35,000 lbs	40,108
6 C-F	Slight "S" curve observed at 35,000 lbs	39,261
8 A	None	7,255
8 B	None	7,402
8 C	None	7,964
8 A-D	Installed in UTM backwards. Bowing towards horizontal panel instead of vertical. This was changed after this set.	15,589
8 B-E	Installed in UTM backwards. Bowing towards horizontal panel instead of vertical. This was changed after this set.	16,662
8 C-F	Installed in UTM backwards. Bowing towards horizontal panel instead of vertical. This was changed after this set.	15,866
8 D	None	6,118
8 E	None	5,454
8 F	None	5,518
9 A	Bowed wrong way	6,447
9 B	Bowed wrong way	6,412
9 C	Bowed wrong way. Installed in reverse of 9A and 9B in an attempt to force it to bow the correct way.	6,433
9 A-D	None	19,037
9 B-E	None	21,083
9 C-F	None	18,220
10 A	Installed with pre-existing bow	4,802
10 B	Installed with pre-existing bow	4,991
10 C	Installed against pre-existing bow	6,809
10 A-D	Installed against pre-existing bow. Bowed wrong way, causing gap to appear in horizontal panels.	15,316
10 B-E	Installed against pre-existing bow. Bowed wrong way, causing gap to appear in horizontal panels.	15,836
10 C-F	Installed backwards, with pre-existing bow, in an attempt to force it to bow the correct way. Bowed wrong way, causing gap to appear in horizontal panels.	14,916

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