Wood Structural Panel & Foam Insulation Systems:

Hygrothermal Behavior & Lateral Load Resistance—Experimental Studies

JOINT RESEARCH REPORT

September 30, 2014

USDA Joint Venture Agreement
11-JV-11111136-070

APA

WOOD STRUCTURAL PANEL AND FOAM INSULATION SYSTEMS: HYGROTHERMAL BEHAVIOR AND LATERAL LOAD RESISTANCE – EXPERIMENTAL STUDIES

Final Report
USDA Joint Venture Agreement 11-JV-11111136-070

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EXECUTIVE SUMMARY

During the construction of a new structure, there are two basic ways to install rigid foam plastic insulation on the exterior of a wall assembly: the foam can either be attached directly to the studs, or the walls can be conventionally sheathed with wood structural panels (WSP) before the foam is installed. Structurally speaking, the WSP is better installed directly to studs (i.e., foam over WSP). However, this method may create a problem for the drying potential of the wall system in some climate zones.

In 2011, a joint research project by *APA – The Engineered Wood Association* and the USDA Forest Service, Forest Products Laboratory was initiated. The objective of this project was to evaluate the possibility of combining wood structural panel sheathing and rigid foam plastic insulation in wall applications to satisfy both the structural and energy conservation requirements in the U.S. building codes.

In order to investigate the moisture movement through the wall assemblies, and the wall performance in response to natural and artificial environmental changes when foam insulation is installed over WSP sheathing, the construction and evaluation of full-scale walls at the Natural Exposure Testing (NET) facilities located on the Washington State University (WSU) Agriculture Research campus in Puyallup, Washington (Climate Zone Marine 4) was conducted for a period of 24 months. Based on data collected from the moisture sensors located within the wall cavities, the moisture content of the walls was within a range that is considered safe from mold or decay. In addition, the drying of the walls to a pre-injection level, following an artificial wetting, appeared to occur within 4 to 6 weeks, depending on the wall and location.

From the structural performance perspective, the wall performs better with WSP installed directly to studs (i.e., foam over WSP), as compared to WSP over foam. However, the installation of wall cladding over foam insulation is a structural concern due to the lack of fastener holding capacity of foam insulation. Testing was conducted to investigate viable methods to attach WSP sheathing over foam insulation of various thicknesses. Only one of the tested wall configurations, 10d box (0.128 inch x 3 inches) nails spaced 4 inches on center in the panel boundary and 12 inches on center in the field, performs equivalently to conventional WSP wall bracing in the IRC. As a result, the use of 1x wood strips over foam insulation, as currently applied by builders, is a better practice than installing the wall cladding directly through the foam over WSP into the stud. Another solution is to use WSP as nailable sheathing in accordance with APA Technical Topics TT-109 [2] and Section R703.3.2 of the 2015 International Residential Code (IRC) [9].

This research was supported in part by funding granted by the USDA Forest Products Laboratory, which is acknowledged and greatly appreciated by the project team.

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1. INTRODUCTION

All buildings, regardless of size or location, must be designed to safely resist the structural loads anticipated during their service life, including vertical (gravity), transverse, and lateral (in-plane shear) loads. In conventional construction, the lateral load resistance, as typically provided by the wall bracing, is essential to the structural performance of the building.

The historical performance of light-frame construction in North America has been very good due, in part, to model building codes that are designed to safeguard life safety. These model building codes have spawned continual improvement and refinement of engineering solutions needed to meet changing public preferences of building design and functionalities, as well as the consideration for sustainability and energy conservation. For example, the continuing increase in the energy conservation requirements in the International Energy Conservation Code (IECC) [10] has encouraged the use of rigid foam plastic insulation products in most climate zones in the U.S.

In an effort to meet the energy conservation requirements, some builders may sometimes inadvertently over-emphasize the energy efficiency without a full understanding of its impact to the structural safety of the building. In some instances, the use of low permeance rigid foam plastic insulation may inadvertently hinder the moisture movement in and out of the wall, which may lead to condensation or reduced drying potential of the wall assemblies.

During the construction of a new structure, the rigid foam plastic insulation may be installed on the exterior of a wall assembly by attaching the rigid foam plastic insulation over wood structural panel (WSP) sheathing that has been attached directly to wall studs (i.e., "foam-over-sheathing") or the WSP sheathing may be attached to wall studs through rigid foam plastic insulation ("sheathing-over-foam") that is sandwiched between WSP and wall studs. Structurally speaking, the foam-over-sheathing configuration is expected to perform better than the sheathing-over-foam configuration. However, the foam-over-sheathing configuration may result in a moisture issue on the wall assembly in some climate zones. In addition, the foam-over-sheathing configuration will require the use of vertical 1x lumber furring strips to facilitate the exterior cladding attachment when the foam thickness exceeds a threshold specified by the cladding manufacturer. On the other hand, the sheathing-over-foam configuration will weaken the in-plane shear resistance of the wall assembly.

In 2011, a joint research project by *APA – The Engineered Wood Association* and the USDA Forest Products Laboratory (FPL) was initiated to study the foam-over-sheathing and sheathing-over-foam configurations for structural and hygrothermal performance. The main objectives of this project were to evaluate the possibility of combining WSP sheathing and rigid foam plastic insulation in wall applications to satisfy both the structural and energy conservation requirements in the U.S. building codes.

This study included 2 phases of hygrothermal monitoring in the field of Marine 4 climate zone (Puyallup, Pierce County, Washington) using the foam-over-sheathing configuration. The Phase 1 study was conducted from February 2012 through February 2013 and Phase 2 from March 2013 through July 2014. An artificial water injection into the wall cavity was introduced in Phase 2 to simulate water leakage to the walls and to evaluate the rate of drying under the natural environments. In addition, shearwall tests were conducted at the APA Research Center in Tacoma, Washington, using the sheathing-over-foam configuration to determine the likelihood of this configuration in meeting the minimum requirements of wall bracing in accordance with the International Residential Code (IRC). This report provides detailed results of the hygrothermal studies and the in-plane shearwall evaluation.

2. HYGROTHERMAL STUDY—PHASE 1

The moisture movement through the wall assemblies, and the wall performance in response to natural environmental changes, when foam plastic insulation is installed over WSP was studied by APA and FPL in collaboration with the Washington State University (WSU). The evaluation of full-scale walls was conducted at the Natural Exposure Testing (NET) facilities located on the WSU Agriculture Research campus in Puyallup, Pierce County, Washington, which is classified as the Marine 4 climate zone in accordance with IECC.

The NET was located on the property to provide maximum exposure of the test walls facing south or north. For south-facing test walls, this optimizes exposure to wind-driven rainfall, which occurs primarily in the fall and winter. The walls facing the north are exposed to limited wind-driven rain but lack direct exposure to sun in the winter, setting up an alternative critical condition. The NET is in an open field with no obstructions within 1,300 feet of the south-facing wall. To the north, there are a few one-story low-rise buildings located 200 feet or more away.

The NET is a 14-foot-by-70-foot one-story hut designed using open beam construction to maximize openings for test walls in segments. A 2-foot-high insulated knee wall was poured with a slab on grade. The building's structural frame was constructed with structural insulated panels (SIPs). Two 35-foot-long structural composite lumber (SCL) beams were used to support the roof panels. SIP construction was used to facilitate airtightness and provide required insulation performance. Roof overhangs were limited to approximately 10 inches to allow maximum exposure of the test walls to the weather. The choice of roofing and siding materials was based on a request by the University to be compatible with campus architecture. Gutters were provided to collect run-off rainwater.

The NET is segmented into two 14-foot x 35-foot rooms with HVAC systems for each. This was done to allow creation of different interior environments in each of the two rooms when necessary. Each room is equipped with an independent electric heating unit, wall mount air conditioner, and humidifier/dehumidifier.

A plan view of the NET is shown in Figure 1. Figure 2 shows the south-facing walls of the NET. Note the walls are segmented and can be independently configured to fit specific test purposes.

FIGURE 1

NET FLOOR PLAN

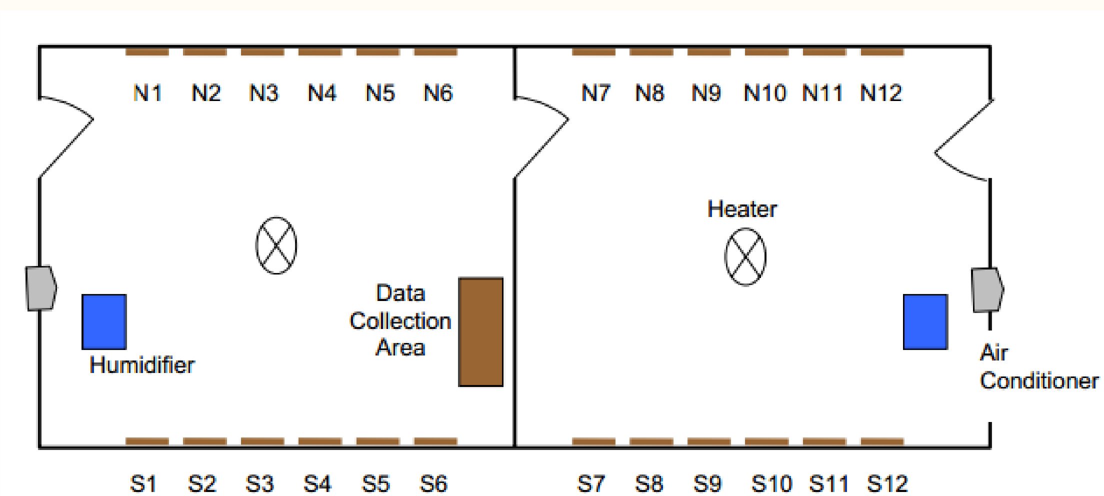


FIGURE 2

SOUTH-FACING SIDE OF THE WSU NET FACILITY IN PUYALLUP, WASHINGTON

2.1 Test Wall Design

Four test walls were constructed based on a 4-foot by 9-foot design. All of the test walls used standard 2x4 wood studs as wall frame that included a double top plate and a single bottom plate placed on a floor plate and rim board. This frame design provides two 14.5-inch x 91.5-inch primary wall cavities for testing. The wall cavities are protected from edge effects by smaller buffer cavities. The floor plate is insulated to the interior to separate the bottom plate of the test wall from unusual interior environmental loads. The top plate is insulated to expose the wall frame to both interior and exterior temperature differences that typically occur at the intersection with wood-frame roof truss. Figure 3 provides an illustration of the wall frame used in this study. A schematic of the wall configuration is shown in Figure 4. The differences between the four test walls used in this study are summarized in Table 1.

TABLE 1

TEST WALL CONFIGURATION

<table>
<tr><th>Wall ID</th><th>Stud</th><th>Stud Spacing</th><th>Wall Sheathing</th><th>Insulation</th><th>Cavity Insulation</th><th>Water Resistive Barrier</th><th>Vapor Barrier</th><th>Interior</th><th>Wall Orientation</th></tr>
<tr><td>N7</td><td rowspan="4">2x4 DF lumber</td><td rowspan="4">16 inches oc</td><td rowspan="4">7/16-inch OSB Rated 24/16 (strength axis vertical)</td><td>1-inch XPS[a]</td><td rowspan="4">R-13 fiberglass batt</td><td>None</td><td rowspan="4">Class III (latex primer/ paint)</td><td rowspan="4">1/2-inch gypsum</td><td>North</td></tr>
<tr><td>N8</td><td>1-1/4-inch MWI[b]</td><td>Tyvek housewrap</td><td>North</td></tr>
<tr><td>S11</td><td>1-inch XPS[a]</td><td>None</td><td>South</td></tr>
<tr><td>S12</td><td>1-1/4-inch MWI[b]</td><td>Tyvek housewrap</td><td>South</td></tr>
</table>

(a) 1-inch extruded polystyrene (R-5) Foamular,® Owens Corning Insulating Systems, LLC

(b) 1-1/4-inch mineral wool insulation (R-5) ComfortBoard™ IS, Roxul Inc.

FIGURE 3

WALL FRAME FOR EACH TEST WALL

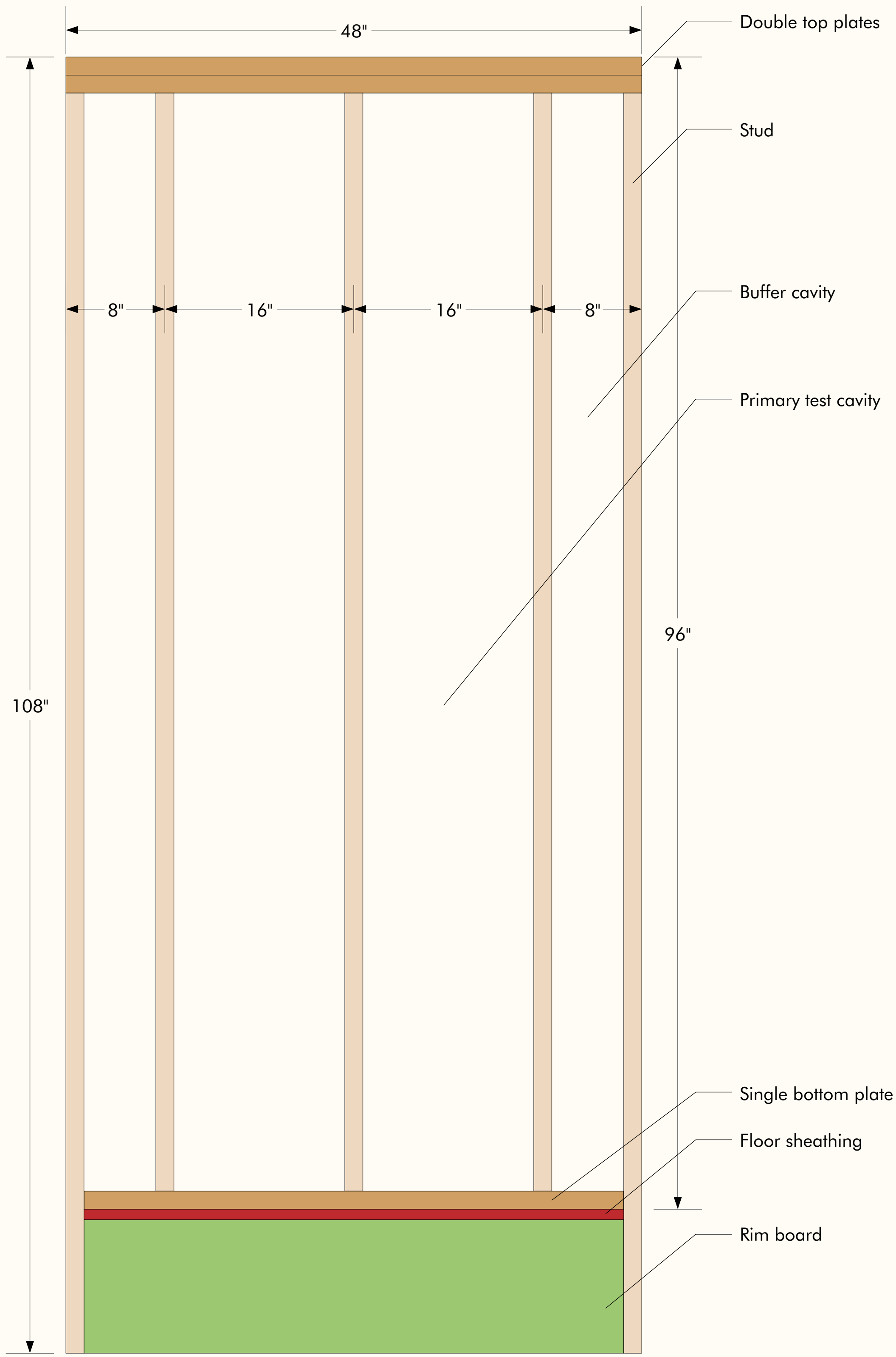
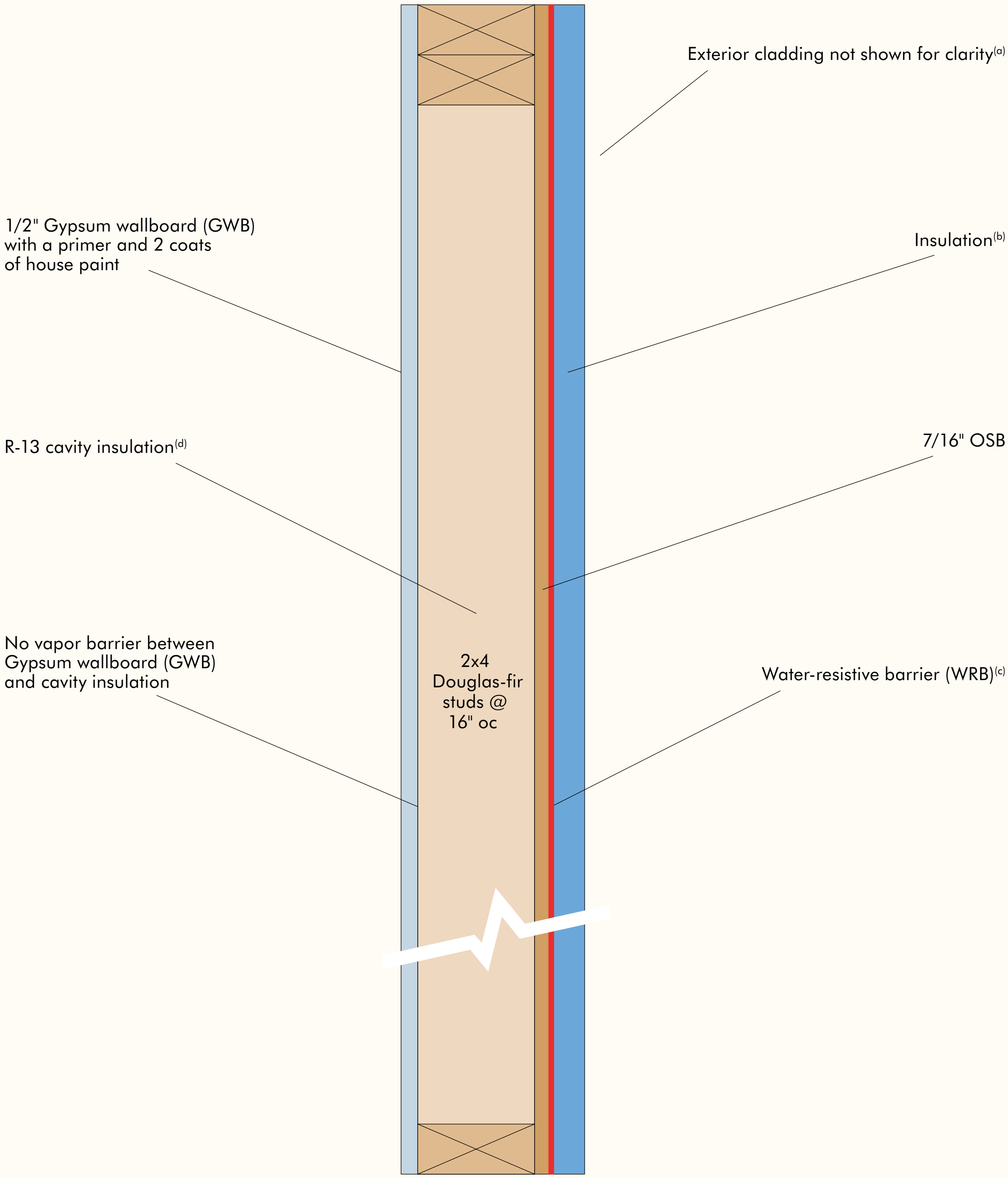


FIGURE 4

SCHEMATIC CONFIGURATION OF TEST WALLS



(a) Vinyl siding (white color) without furring strips installed based on the manufacturer's recommendations.

(b) Insulation used: 1" XPS (R-5) square edge (with joint taping) or 1-1/4" mineral wool insulation (MWI) (R-5) (Roxul ComfortBoard IS-8 pcf).

(c) Water-resistive barrier (WRB) required for mineral wool insulation (MWI) (Roxul). WRB not required for extruded polystyrene (XPS).

(d) Unfaced fiberglass batt.

2.2 Test Wall Systems

Framing

All test walls were constructed with wood framing systems. The 2x4 framing lumber used in all test walls was kiln-dried Douglas-fir obtained from a local building material supplier.

Structural Sheathing

The structural sheathing for the test walls was 7/16 Performance Category oriented strand board (OSB) made primarily of aspen, also obtained from a local building material supplier.

Insulation

The insulation consisted of R-13 fiberglass batts within the wall cavities and R-5 rigid insulation on the exterior side of the OSB sheathing. The exterior rigid insulation was either 1-inch extruded polystyrene (XPS) (Foamular®, Owens Corning Insulating Systems, LLC) or 1-1/4-inch mineral wool insulation (MWI) (ComfortBoard™ IS, Roxul Inc.). Figure 5 provides photographs of walls with both insulation types on the exterior.

FIGURE 5

TEST WALLS WITH 1-1/4-INCH MWI (Left) AND 1-INCH XPS (Right)

Drywall, Interior Paint and Vapor Retarder

All of the test walls included 1/2-inch drywall painted with one coat of latex primer and two coats of latex paint, as permitted by the code in the Marine 4 climate zone.

For a single coat of paint used on interior drywall, the ASHRAE Handbook of Fundamentals [3] lists permeance ranges from 6.28 to 8.62 perms. The paint selected for the test walls included a latex primer and two coats of acrylic latex paint. This is typical of new construction in the Pacific Northwest. APA testing confirmed the expected permeance for this coating. As reported in detail later in this report, the standard wet cup rating for the drywall, one coat of primer and two coats paint was approximately 7.2 perms and the standard dry cup rating was approximately 2.2 perms (see Table 3).

Water-Resistive Barrier (WRB)

For the walls constructed with MWI, Tyvek® HomeWrap® was applied to the OSB sheathing prior to installation of the MWI. As reported by the manufacturer, the permeance of the WRB is 56 perms and 54 perms when tested to ASTM E96 [4], *Standard Test Methods for Water Vapor Transmission of Materials,* Methods A and B, respectively.

Cladding

Vinyl siding, white in color, was attached without furring strips on the exterior side of the rigid insulation per the manufacturer's recommendations.

2.3 Instrumentation

A data acquisition system was installed to continuously monitor the hygrothermal performance of the test walls. Outdoor environmental conditions were monitored by a high quality weather station located on site. The interior environment was monitored using instruments meeting the same standards. The instrumentation plan for the test facility was developed to provide direct feedback on the performance of the test walls exposed to the Pacific Northwest environment and to provide data for comparison to hygrothermal computer models used by the FPL.

2.3.1 Data Loggers

Measurements were made using Campbell Scientific CR10 Measurement and Control Modules, two Campbell Scientific CR10X Measurement and Control Modules, and 9 Campbell Scientific AM 16/32 Relay Multiplexers. Sampling occurred every five minutes and was averaged hourly. Logger clocks were set nightly to a computer that was set daily to an atomic clock. The computer and loggers followed daylight savings time. These loggers also controlled the humidifier and heater/air conditioner inside the building.

Data Logger 1

5 Campbell Scientific AM 16/32 Relay Multiplexers
Recording Temperature
Condensation Sensors
Gypsum Sensors

Data Logger 2

4 Campbell Scientific AM 16/32 Relay Multiplexers
Relative Humidity sensors
Moisture Content sensors

Data Logger 3

Weather Instrumentation
5S500 Temperature and Relative Humidity Probe
TE525 Tipping Bucket Rain Gauge
05103 RM Young Wind Monitor
SPLite1 Solar Radiation

2.3.2 Weather Instruments

The primary weather instruments were located on top of the building at the southwest corner of the NET (see Figure 2). Additional pyranometer locations are noted below. Weather instruments were measured every five minutes and averaged every hour.

Outdoor Temperature and Relative Humidity—Outdoor temperature and relative humidity were measured using a Campbell Scientific CS500 Temperature and Relative Humidity Probe mounted in a radiation shield.

Solar Radiation—Solar radiation (sun plus sky radiation) was measured using a Campbell Scientific SP-Light Silicon Pyranometer. It measures the energy received from the entire hemisphere (i.e., an 180-degree field of view). One pyranometer was included in the roof-mounted weather station and provides vertical measurements. Two additional pyranometers were utilized: one was mounted facing north, the other facing south. Both were mounted halfway up the wall in the center of the building.

Wind Speed and Direction—An RM Young Wind Monitor was used to measure wind speed and direction. This logger records hourly average, minimum and maximum wind speed in several standard formats.

Precipitation—Vertically falling rainfall was measured using the Campbell Scientific 525 Tipping Bucket Rain Gauge located on the roof. Not long after the experiment began, the rain gauge on top of the building stopped measuring rain for an unknown reason. Rain data was supplemented with rain gathered at another weather station on the campus approximately 0.6 km (0.4 mi) from the NET facility.

Two additional rain gauges were mounted horizontally on the north and south sides of the building. These were used for measuring wind-driven rain.

2.3.3 Test Wall Instrumentation

Temperature (T)

The temperature channels were measured using a simple voltage divider circuit consisting of a Fenwal/Elmwood thermistor (Honeywell# 192-103LET-A01) wired in series with a 10K precision resistor. The resistor and thermistor form a three-wire half bridge. Three wires come from the sensor: ground, excitation, and output (Figure 6). The output of the half bridge is:

$$\frac{v}{vo} = \frac{R_o}{R_T} + R_o \tag{1}$$

where $\frac{v}{vo}$ is the ratio of output voltage to applied voltage for the half bridge, R_o is the pickoff resistor value (10K, which is also the thermistor resistance at 77°F), and R_T is the thermistor resistance. Solving for R_T:

$$R_T = R_o * (vo/v) - 1 \tag{2}$$

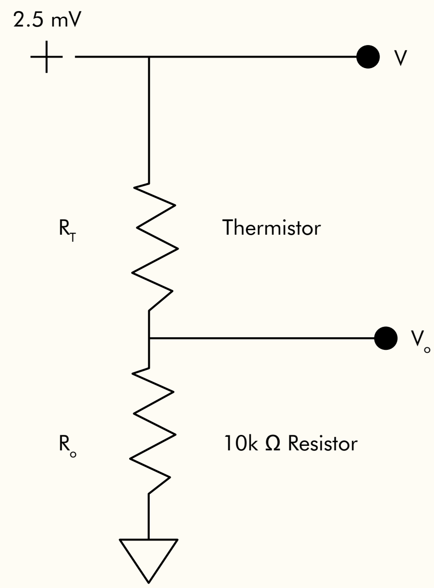
The relationship between the logarithm of the ratio of thermistor resistance to resistance at 77°F and temperature is well fit by a third order polynomial. Departures of the fit from actual values are less than the thermistor accuracy (0.36°F) from –40 to +140°F. Assuming x = In(R_T), then:

$$T = 32 + \frac{9}{5}(-0.101x^3 + 4.346x^2 - 77.18x + 446.05)\ (°F) \tag{3}$$

The Campbell Scientific CR10X Data Logger implements Equation 3, giving a temperature output in degrees F.

FIGURE 6

THREE-WIRE HALF BRIDGE FOR TEMPERATURE MEASUREMENT



Relative Humidity (RH_c)

Relative Humidity was measured using a Hycal IH-3610-1 (Honeywell HIH) using a similar circuit to the temperature sensing circuit (Figure 7). It uses a precision 121k Ω resistor.

$$RH = (V_{out} - 0.958)/0.03068 \qquad (4)$$

The Campbell Scientific CR10X Data Logger implements Equation 4. Then in the log, a range filter is applied: 0 < RH < 150%.

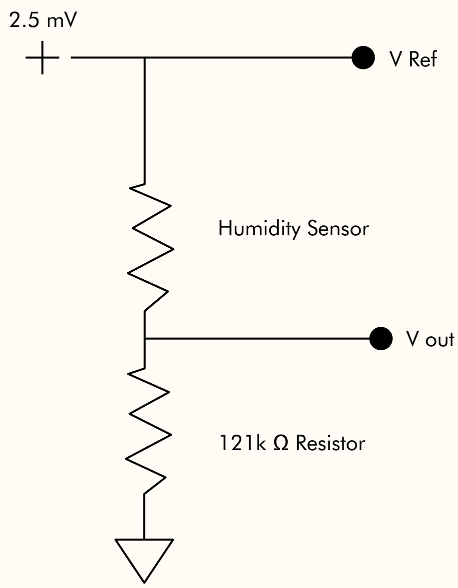
Relative Humidity (temperature correction)

$$RH_c = RH/[1.0546 - 0.00216\,(T - 32)\frac{5}{9}] \qquad (5)$$

where T is in °F. In the logs, a correction based on Equation 5 is implemented in the Honeywell HIH product sheet. This correction is based on the thermistor, which is coupled with each humidity sensor.

FIGURE 7

THREE-WIRE HALF BRIDGE FOR RH MEASUREMENT



Wood Moisture Content (MC_c)

Wood moisture content was measured in the framing at the following locations: top plate near the exterior sheathing (MC1), bottom plate near the exterior sheathing (MC7), and the center stud at mid-height (MC3). Moisture content was measured in the OSB sheathing at the following locations: near the top plate (MC2); below the water injection tube (MC4 and MC5); and near the bottom plate (MC6).

The moisture content sensor consists of two brass nails wired to the data logger. The nails were coated to assure that the measurement only occurs at the tip of the sensor. The two nails were inserted into the wood 1 inch apart. Sensors were typically at a depth of approximately 1/8 inch. The one exception is MC4, which was inserted to measure the exterior moisture content of the sheathing board. The MC4 sensor was inserted to a depth to reach within 1/8 inch of the exterior surface of the sheathing.

To make a measurement, voltage was measured across a fixed resistor, which was placed in series with the moisture pins. This provided a reading in millivolts. Every five minutes, three measurements were taken in quick sucession and values that were not negative were averaged and placed in temporary memory of the loggers. Every hour, these measurements were averaged and stored as permanent data. A range filter was applied to the final values $0 \leq MC < 6998$. Each moisture content sensor is partnered with a temperature sensor described below.

The millivolt readings were then converted to percent wood moisture content as part of data analysis. The following formula was applied to convert the moisture content sensor readings with the temperature sensor readings to provide a temperature-corrected moisture content in percent. The post-processing values were noted in this report as Moisture Content corrected (MC_c).

For each wood product a set of wood species correction factors was applied. The frame lumber and OSB correction factors were provided by Straube, *et. al.* [11].

Frame lumber	a = 0.853	b = 0.398
Oriented Strand Board	a = 1.114	b = 0.36

$$MC_c = \frac{1}{a}\left\{\frac{\left[(10^{2.99-2.113\times Log_{10}(Log_{10}(1000000\times MC))}+0.567)-0.026T\right]+0.000051T^2}{0.881\times 1.0056^T}-b\right\} \quad (6)$$

where,

T = temperature in °C (converted from °F)
b = wood species function as defined above
a = wood species function as defined above

The moisture content values are accurate in the range of 10 to 25 percent. In particular, as the moisture content increases above 25 percent, the readings are less accurate. It is also important to note that the moisture content readings are only spot readings, and do not reflect the total moisture content of the entire specimen. For example, the sensors embedded 1/8 inch into framing lumber only reflect the moisture present near the surface of the specimen in the specific location of the sensor. This reading does not indicate that the entire frame is in equilibrium with the sensor reading.

Sensor Location in the Test Walls

The sensor locations are illustrated in Figures 8 and 9.

FIGURE 8

PLACEMENT OF MOISTURE CONTENT/TEMPERATURE SENSORS IN TEST WALLS

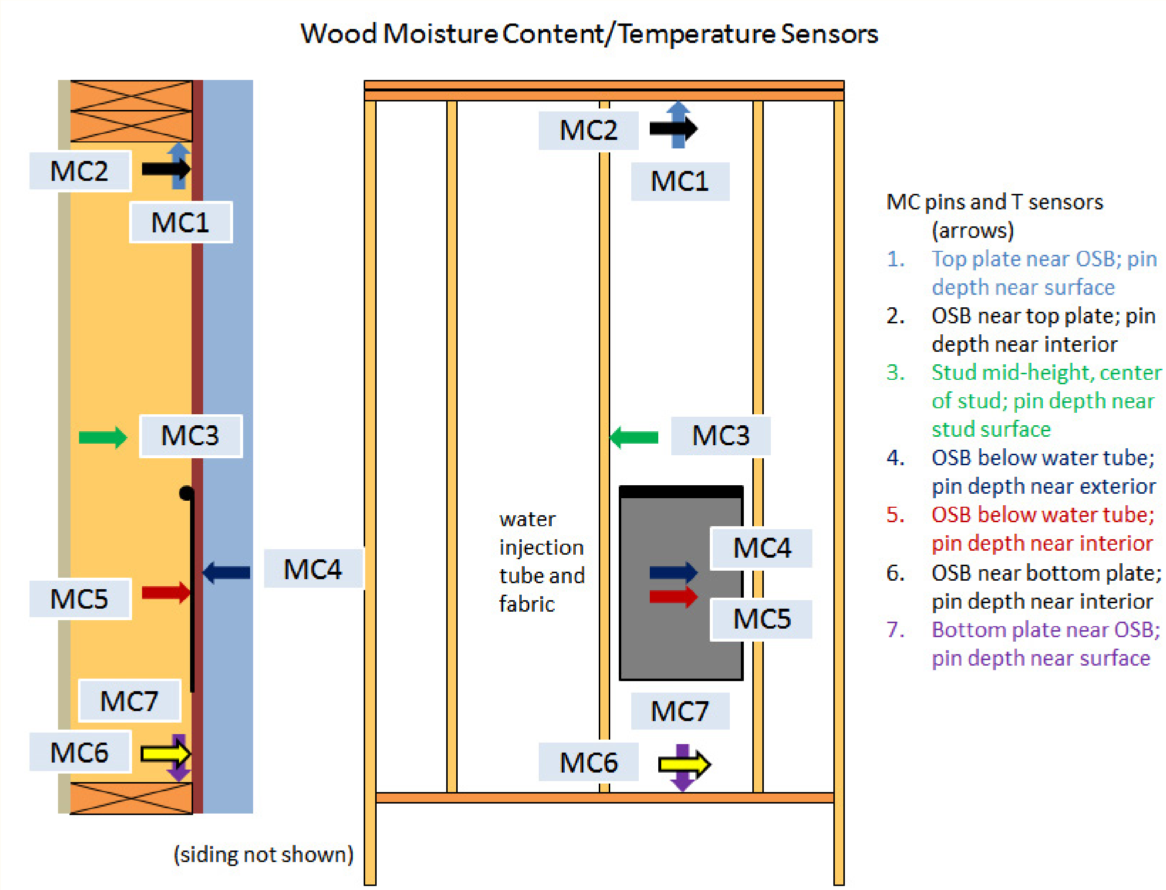
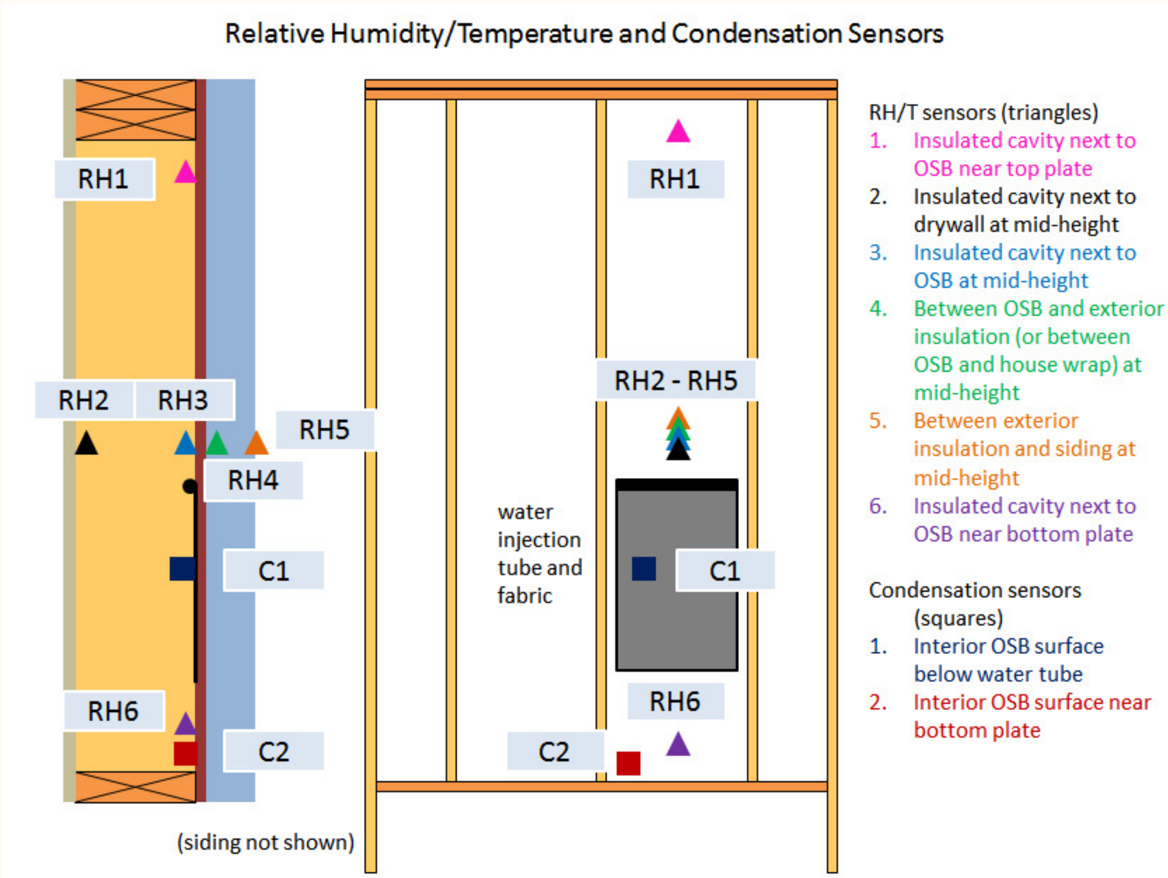


FIGURE 9

PLACEMENT OF RELATIVE HUMIDITY/TEMPERATURE AND CONDENSATION SENSORS IN TEST WALLS



2.4 Test Wall Moisture Content, Relative Humidity, And Temperature

The test walls were subjected only to exterior and interior environmental loads during Phase 1 of the study, i.e., no additional, artificial loads were introduced to the wall cavities. For homes in the Pacific Northwest, moisture loading from the exterior and interior environments is most likely to take place in the months of October through January. This is when there is greatest rainfall, highest outdoor humidity, and highest vapor drive from the interior. In the spring, there is a transition period where the driving forces, which influence wall moisture volumes and distribution, are in flux. There are periods of moisture elevation followed by drying. By early summer, the wall will typically be dry. They remain dry until October when the new cycle begins.

WSU monitored the performance of the test walls for over one year (February 2012 through February 2013), capturing the effects of one full wetting and drying cycle for the test walls. Weekly averaged data are presented in **Appendix A**. Detailed test data are available upon request.

The collected data indicate the following:

1) Recorded moisture content levels are below 14 percent for the investigated time period.
2) The seasonal fluctuation in moisture content is minor (the moisture content in summer and winter differs typically by less than 2 percent.
3) Differences between north- and south-facing walls appear to be insignificant.
4) Differences between wall assemblies constructed with MWI and XPS exterior rigid insulation appear to be insignificant.

2.5 Indoor And Outdoor Environmental Conditions

To provide context for the performance of the test walls, a discussion of the environmental loads is important. The performance of the test walls is influenced by the indoor and outdoor environmental conditions. For outdoor conditions, this is the local weather during the testing period. For indoor conditions, the temperature and interior humidity were controlled to provide an appropriate test condition for the walls. This section will provide a brief summary of both indoor and outdoor environmental conditions that occurred during the test cycle.

Indoor Conditions

Indoor temperature and humidity settings were selected to provide a robust, but realistic interior load. Target settings for the experiment were a temperature of 68 to 70°F and relative humidity of 50 to 55 percent. These settings were maintained throughout the experiment using heating, cooling, and humidification and dehumidification equipment. The indoor relative humidity variation was low during the study period. Monthly averages ranged from 48 percent in October 2012 to 51 percent in July 2012. It should be noted that indoor temperature and humidity measurements were not available for three time periods (August 29, 2012–October 6, 2012, December 26, 2012–January 31, 2013, and February 5, 2013–February 8, 2013) due to equipment issues at WSU.

Outdoor Conditions

For any given year, the outdoor environmental conditions vary from one season to another. Weekly averaged weather data are presented in **Appendix B**. It should be noted that the cumulative precipitation during this study period was virtually the same as the historical norm.

2.6 Water Vapor Transmission Testing

Testing was conducted at the APA Research Center in Tacoma, Washington in accordance with ASTM E96, *Standard Test Methods for Water Vapor Transmission of Materials*. Water vapor permeance was determined at environmental conditions of 73°F and 50 percent relative humidity for both painted (one coat latex primer, two coats of latex paint) and unpainted gypsum wallboard, and the 7/16 Performance Category OSB used in the wall assemblies at the NET facility. Permeance values were determined based on both desiccant (dry- cup) and water (wet-cup) methods.

Specimens were cut to a size of either 5-5/16 inches x 5-5/16 inches or 5-5/16 inches x 5-7/16 inches in dimension. The slight variation was due to a difference in the cup size. Two specimens of each material type were prepared for a "control" group. Four specimens were prepared for each material type and test condition, as shown in Table 2.

TABLE 2

TEST MATRIX

Test Material	Pan Condition	Direction of Material in Pan	Specimen ID	Specimen Size (inches)
Unpainted gypsum	Empty (control)	Up Down	u.e.1up u.e.2dn	5-5/16 x 5-7/16
Painted gypsum	Empty (control)	Up Down	p.e.1up p.e.2dn	5-5/16 x 5-7/16
7/16-inch OSB	Empty (control)	Up Down	o.e.1up o.e.2dn	5-5/16 x 5-7/16
Unpainted gypsum	Wet	Up Down Up Down	u.w.1up u.w.2dn u.w.3up u.w.4dn	5-5/16 x 5-5/16
Unpainted gypsum	Dry	Up Down Up Down	u.d.1up u.d.2dn u.d.3up u.d.4dn	5-5/16 x 5-7/16
Painted gypsum	Wet	Up Down Up Down	p.w.1up p.w.2dn p.w.3up p.w.4dn	5-5/16 x 5-5/16
Painted gypsum	Dry	Up Down Up Down	p.d.1up p.d.2dn p.d.3up p.d.4dn	5-5/16 x 5-7/16
7/16-inch OSB	Wet	Up Down Up Down	o.w.1up o.w.2dn o.w.3up o.w.4dn	5-5/16 x 5-5/16
7/16-inch OSB	Dry	Up Down Up Down	o.d.1up o.d.2dn o.d.3up o.d.4dn	5-5/16 x 5-7/16

All specimens were tested after equilibrating to environmental conditions of 73 ± 2°F and 50 ± 2% relative humidity in accordance with ASTM E96. The edges of the specimens were masked with a foil tape prior to testing, as shown in Figure 10.

FIGURE 10

TEST SPECIMEN EDGE SEALED WITH FOIL TAPE FOR TESTING

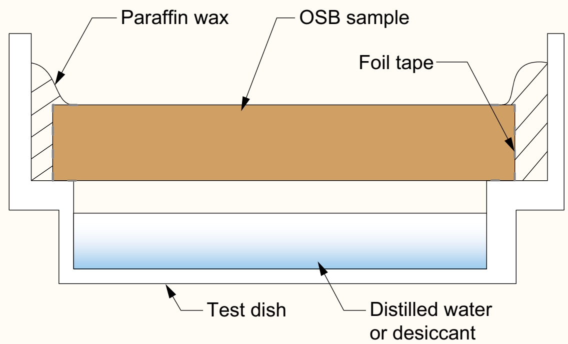
For the water (wet-cup) method, 100 grams of distilled water was put in the bottom of each aluminum dish. A plastic grid was placed in the bottom of each dish to reduce water surges, as shown in Figure 11. On the other hand, the desiccant (dry-cup) specimens were prepared with 150 grams of desiccant leveled out in the bottom of each aluminum dish. Paraffin wax was used to seal the gaps between the dish edge and the sides of the specimens, as shown in Figure 12 (the wet-cup method shown).

FIGURE 11

ALUMINUM DISH WITH PLASTIC GRID

FIGURE 12

SPECIMEN PREPARATION FOR MEASURING WATER VAPOR PERMEANCE (WET CUP SHOWN)



The dish assemblies were weighed before and after specimen fabrication. Dish assemblies were stored in a conditioning chamber under the same conditions as specified above. The ASTM E96 standard requires the specimens to be weighed until at least 6 data points follow a linear trend. However, due to prior experience, additional data points were collected to ensure the steady-state was reached. The specimens were weighed six times per week for a total of 44 days. The duration of time for determining permeance was the same for all specimens at the same cup conditions.

The permeance of the specimens was determined in accordance with Section 13 of ASTM E96 by selecting ranges with more than 6 equally spaced data points that maintain a linear trend in weight change. To ensure steady-state conditions, a total of 10 data points were used to calculate the permeance of each specimen. The recorded specimen weights were corrected based on the average weight change of the control specimens in accordance with Section 13.1.1 of ASTM E96. It should be noted that the calculated slope of weight change over time for the wet cup specimens was adjusted to the absolute value. The water vapor transmission values were calculated utilizing Equation (7):

$$\mathrm{WVT} = [(G/t)/A] \tag{7}$$

where:

WVT = water vapor transmission rate (grains/h•ft^2),
G = weight change in test dishes (grains),
t = time during which G occurred (hours),
A = test area of the specimen in test dishes (ft^2).

Since the specimens had been edge masked, the following equation had to be applied based on Section 13.4.2.1 of ASTM E96, to correct for the excess WVT.

$$\text{Percent excess WVT} = \frac{400t}{\pi S_1} \times \log_e \left(\frac{2}{1 + e^{-(2\pi b/t)}} \right) \tag{8}$$

where:

t = specimen thickness (in.),
b = width of masked edge (in.),
S_1 = four times the test area divided by the perimeter (in.).

After the water vapor transmission values from Equation (7) were corrected, the permeance values were calculated based on Equation 9.

$$\text{Permeance} = WVT_c / \Delta_p = WVT_c / [S\,(R_1 - R_2)] \qquad (9)$$

where:

Permeance (perm)	=	rate of moisture movement through a material as a function of the water vapor pressure gradient between two specific surfaces (grains/h•ft^2•in. Hg),
WVT_c	=	corrected water vapor transmission rate (grains/h-ft^2),
Δ_p	=	vapor pressure difference (in. Hg),
S	=	saturation vapor pressure at test temperature (in. Hg),
R_1	=	relative humidity at vapor source (expressed as a fraction), and
R_2	=	relative humidity at vapor sink (expressed as a fraction).

The saturation vapor pressure at test temperature, S, was determined from Table D-196 of the *CRC Handbook of Chemistry and Physics* [8]. The relative humidity at vapor source, R_1, using the wet-cup method is assumed to be 100 percent inside the dish between the water and the specimen. The relative humidity at vapor sink, R_2, is based on the relative humidity of the environmental chamber, which as previously stated was 50 percent. For the dry-cup method, the relative humidity at the vapor source, R_1, is based on the relative humidity of the environmental chamber which was 50 percent. The relative humidity at vapor sink, R_2, is assumed to be 0 percent inside the dish between the desiccant and the specimen.

Permeance values of each specimen and test group are summarized in Table 3. The mean measured weight for each wet-cup test group as a function of time is presented in Figure 13 and the mean measured weight for each dry-cup test group as a function of time is presented in Figure 14. With only two or four replications for each group tested in this study based on ASTM E96, coefficients of variation (COV) were not presented.

It is important to note the relatively high permeance of unpainted gypsum, as indicated by a steep decrease in wet-cup weight over time (see Figure 13). As a result, the water required for wet-cup testing was depleted before the end of the testing period. The sample weight, however, decreases linearly for more than 6 equally spaced data points, which is assumed to be under steady-state according to ASTM E96. The data points following the depletion of water were not used in the permeance calculations.

TABLE 3

PERMEANCE TEST RESULTS

Test Material	Test Method	Specimen ID	Average Specimen Thickness (in.)	Permeance (perms)[a] Specimen	Permeance (perms)[a] Mean
Unpainted gypsum	Water (wet cup)	u.w.1up	0.493	46.20	45.09
		u.w.2dn	0.493	44.77	
		u.w.3up	0.493	43.23	
		u.w.4dn	0.494	46.17	
Painted gypsum	Water (wet cup)	p.w.1up	0.500	6.08	8.16
		p.w.2dn	0.500	10.54	
		p.w.3up	0.499	6.37	
		p.w.4dn	0.500	9.67	
7/16 OSB	Water (wet cup)	o.w.1up	0.503	7.08	7.30
		o.w.2dn	0.513	6.54	
		o.w.3up	0.430	7.45	
		o.w.4dn	0.415	8.16	
Unpainted gypsum	Desiccant (dry cup)	u.d.1up	0.494	29.55	28.95
		u.d.2dn	0.492	29.04	
		u.d.3up	0.497	29.54	
		u.d.4dn	0.495	27.69	
Painted gypsum	Desiccant (dry cup)	p.d.1up	0.499	2.57	2.58
		p.d.2dn	0.500	2.15	
		p.d.3up	0.498	2.29	
		p.d.4dn	0.499	3.32	
7/16 OSB	Desiccant (dry cup)	o.d.1up	0.512	1.43	1.80
		o.d.2dn	0.513	1.97	
		o.d.3up	0.414	1.84	
		o.d.4dn	0.409	1.95	

(a) Assumed relative humidity of 100% inside **wet-cup** and 50% RH in environmental cabinet, therefore assumed average RH across specimen is 75%. Assumed relative humidity of 0% inside **dry-cup** and 50% RH in environmental cabinet, therefore assumed average RH across specimen is 25%.

FIGURE 13

MEAN SPECIMEN WEIGHT FROM 2 DAYS TO 44 DAYS FOR WET CUP TEST GROUPS

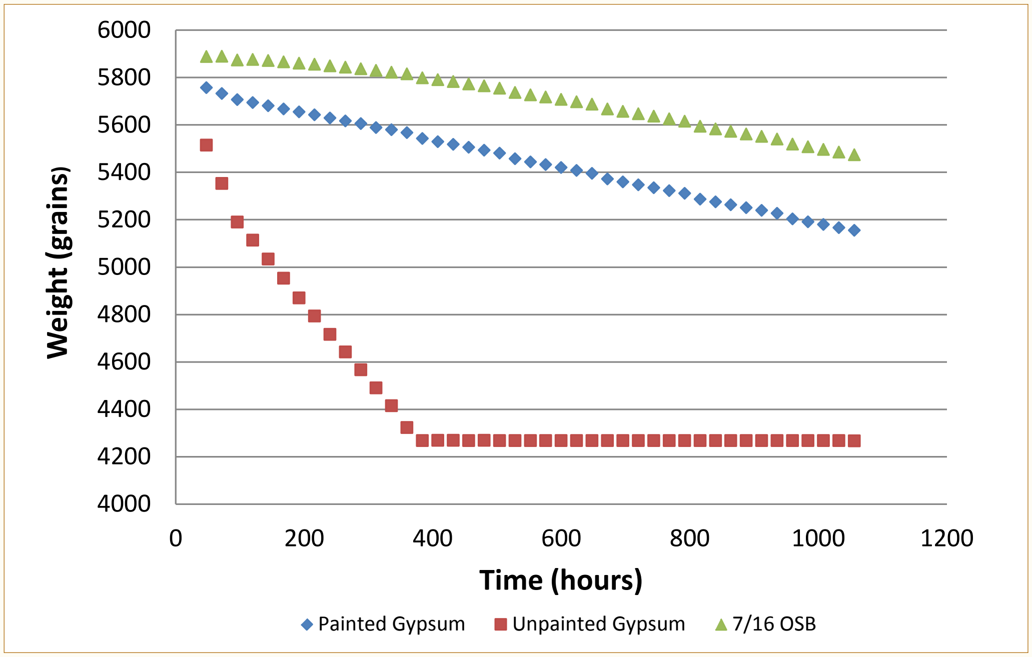
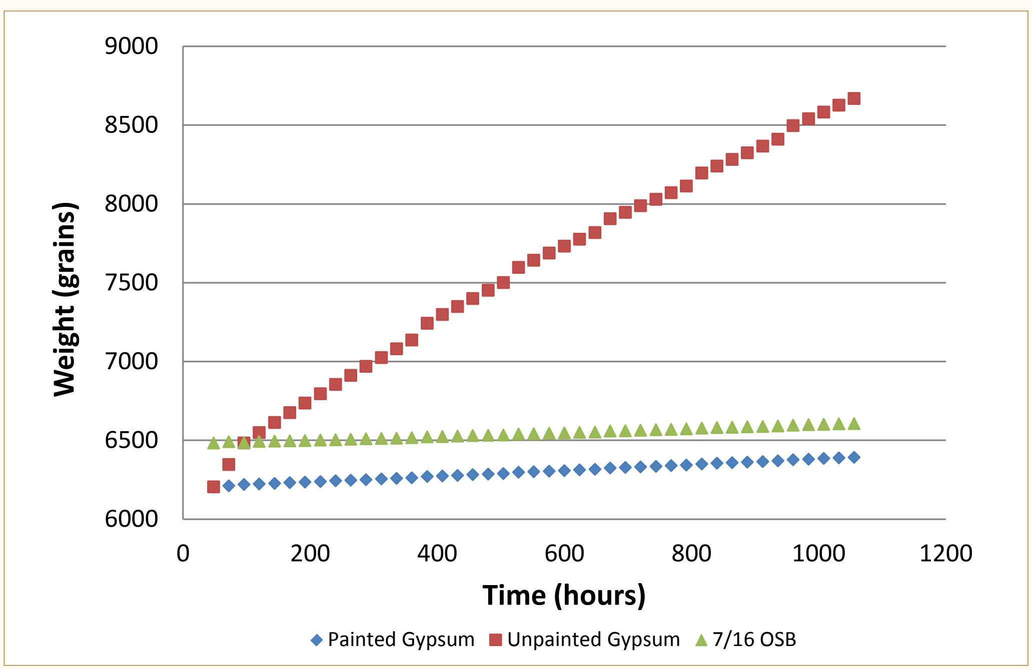


FIGURE 14

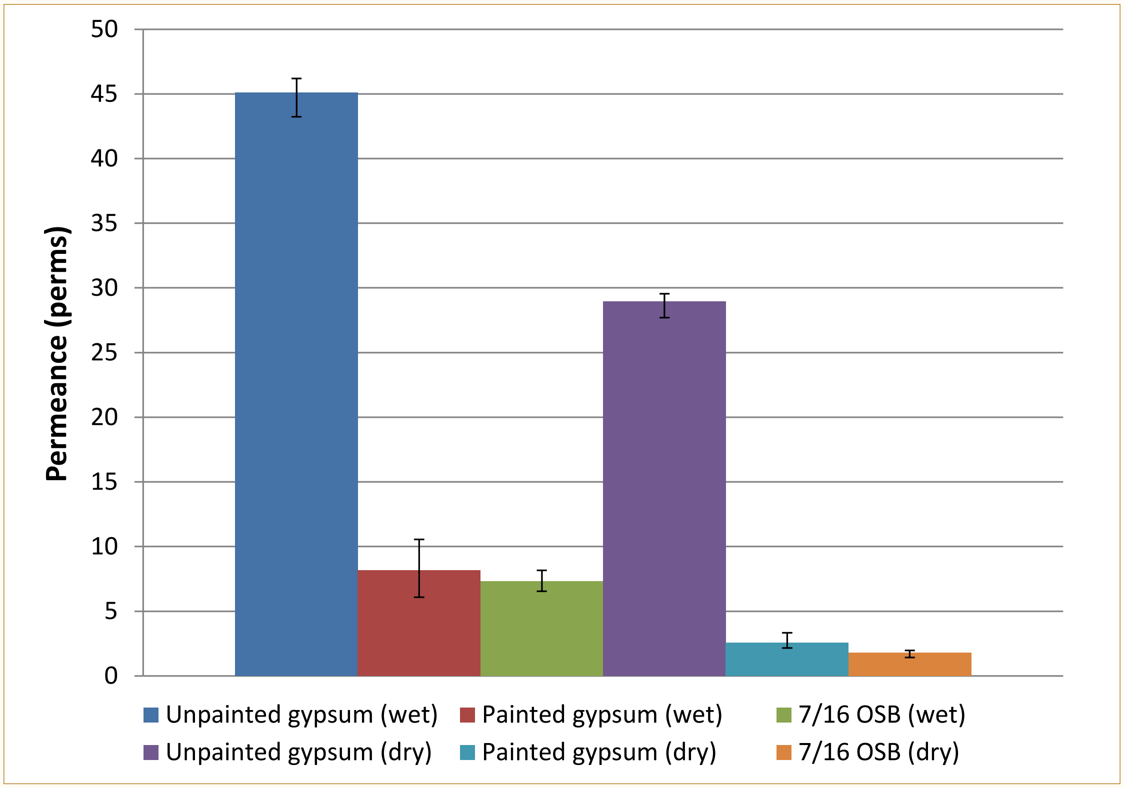
MEAN SPECIMEN WEIGHT FROM 2 DAYS TO 44 DAYS FOR DRY CUP TEST GROUPS



The permeance values of the OSB specimens determined in this study, as shown in Figure 15, were similar to the typical OSB permeance, as presented in *APA Technical Note, Water Vapor Permeance of Wood Structural Panels and Wood Wall Construction,* Form J450 [1]. It should be noted that the top of the vertical bar in Figure 15 represents the mean value for each test group and the vertical line represents the range of permeance values.

FIGURE 15

MEAN PERMEANCE BETWEEN TEST GROUPS



2.7 Phase 1 Results And Discussion

Due to the intent to continue this study for a longer time period, the test walls were not "opened" for inspection at the end of Phase 1. Therefore, the discussion provided in this section is based on the test data only, i.e., no visual inspection. For all test walls, there was no indication that there were water leakages from the exterior cladding. There were no indications that bulk moisture reached the structural sheathing during rain events. The test walls showed increased humidity in the insulated stud cavity and some increase in wood moisture content during the fall and winter months. Late in spring and summer all of the walls became very dry.

In summary, the test walls appeared to demonstrate acceptable performance over the tested interior and exterior environmental conditions.

3 HYGROTHERMAL BEHAVIOR—PHASE 2

3.1 Test Procedures

The Phase 1 study focused on test walls subjected only to exterior and interior environmental loads, i.e., no additional, artificial loads were introduced to the wall cavities. To provide additional field data on the performance of the test walls, Phase 2 of this study (March 2013 through July 2014) was designed to simulate water leakage into the wall cavity in existing walls from Phase 1, as could be expected to occur during the normal service life of a structure.

To introduce water leakage into the wall cavity, a controlled method based on the experience of WSU from prior research was used. The test method employed irrigation tubing and a medium that would hold the water in each primary test wall cavity. The medium was located in the interior side of the sheathing in the wall cavity, as shown in Figures 8 and 9. In theory, the water enters the medium and distributes the moisture in the wall cavity through evaporation.

The process of injecting water into the water cavity was somewhat tricky. In addition, there were cases where the medium did not hold all of the water injected into the wall cavity through the irrigation tubing. There were times when the water left the medium in a liquid state rather than vapor and it was distributed in a large concentration to the bottom plate.

Over the test periods, two targeted amounts of water were injected into the wetting medium based on the following schedule:

- A series of injections were performed from March 25, 2013 to March 29, 2013 (total five days). Injections of 60 ml of water were made every day, resulting in a load of 300 ml on each wall over the course of five days.
- A series of injections were performed from January 20, 2014 to January 24, 2014 (total five days). Beginning on January 20, 50 ml was injected into each of the four walls at 11 am and 1 pm (total 100 ml, each day). This was repeated on January 21, 22, and 23, 2014. On January 24, 2014, 50 ml was injected at 11 am, resulting in a total of 450 ml for each wall over the course of five days.

After the water injection, the walls were monitored to evaluate the drying rate from March 2013 through July 2014. Weekly averaged data are presented in **Appendix C**.

3.2 Indoor And Outdoor Environmental Conditions

Indoor

Indoor temperature and humidity target settings were the same as Phase 1. The relative humidity variation was also low during the Phase 2 study with the monthly averages of 38 percent in February 2014 and 51 percent in August and September 2013. The temperature stayed relatively constant with the monthly averages of about 70°F throughout the period of Phase 2 study.

Outdoor

The weekly averaged outdoor environmental data are presented in **Appendix D**. It should be noted that the cumulative precipitation was about 2 percent lower than the historical norm during this study period.

3.3 Phase 2 Results And Discussion

The results of this study should be viewed with caution as the water injection was not as consistent as originally envisioned. It was determined that the artificial wetting was inconsistent in that the flow rates of the water injections were not identical between test walls due to the variation in the performance of irrigation tubing. In addition, the WSU condensation sensors placed in the wall cavities (Figure 9) were found to be dysfunctional. Fortunately, the bottom plate moisture sensors did identify the existence of water when liquid water reached the bottom plate. In addition, subsequent to the wetting, it was discovered that the medium in Wall N8 had not fully deployed. This allowed water to reach the bottom plate more easily than the other walls.

As similar to Phase 1, for all test walls, there was no indication that there was a water leakage from the exterior cladding. There were no indications that bulk moisture reached the structural sheathing during rain events. Based on data collected from the moisture sensors located within the wall cavities, the wall drying following the artificial wetting appeared to be at a reasonable rate. Moisture content measurements of the wood returned to pre-injection levels within 4 to 6 weeks, depending on the wall and/or sensor location. The relative humidity within the wall cavities was quite variable. However, as previously mentioned, the inconsistencies in water injections and other difficulties have made comparisons among the test walls difficult.

In summary, results obtained from Phase 2 seem to indicate that the drying rate after water leakage of the wall configurations studied in this project is reasonable (in 4 to 6 weeks), assuming that the source of water intrusion is quickly recognized and remedied.

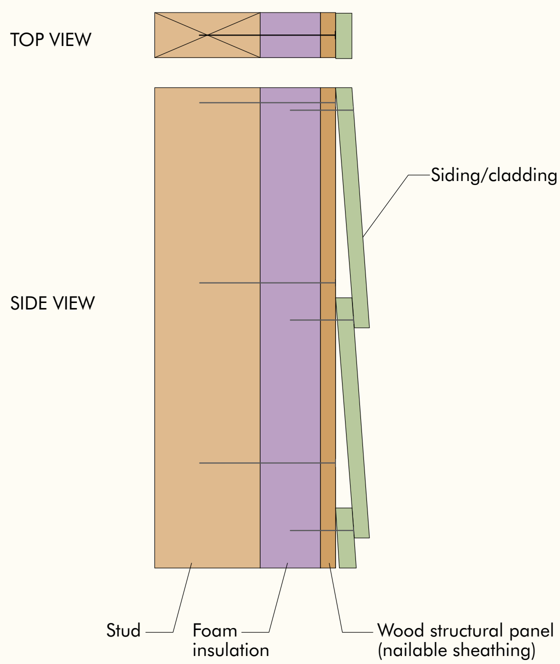
4. WALL RACKING TESTS

4.1 Introduction

As previously discussed, the foam-over-sheathing configuration is a better choice for structural performance. However, there are very limited wall racking data for the sheathing-over-foam configuration. Therefore, this portion of the project was intended to investigate a structurally viable method for sheathing-over-foam applications, as shown in Figure 16.

FIGURE 16

SHEATHING-OVER-FOAM CONFIGURATION



Initial full-scale shearwall tests were conducted in January 2012 using the monotonic test method of ASTM E72 [6], *Standard Test Methods of Conducting Strength Tests of Panels for Building Construction,* at APA using an 8-foot x 8-foot wall section constructed with 2x4 studs spaced 24 inches on center. A 1-1/2-inch-thick expanded polystyrene (EPS) foam sheathing (1.0 lbf/ft^3 density) was nailed to the framing with 6d box (0.099 inch x 2 inches) smooth-shank nails spaced 8 inches on center along supported panel edges and 12 inches on center on interior supports. WSP sheathing of 15/32 Performance Category Structural I OSB was installed vertically over the foam sheathing with 0.131 inch x 4 inches smooth-shank nails spaced 6 inches on center along supported panel edges and 12 inches on center on interior supports. The result of this wall test was compared to the "control" walls, i.e., without foam sheathing, with the WSP attached using 8d common (0.131 inch x 2-1/2 inches) nails to maintain a constant nail diameter and penetration. Both the foam-over-sheathing wall and the control walls were tested without gypsum board installed on the interior side of the wall or wall cladding installed on the exterior of the wall.

The data showed that the sheathing-over-foam wall had a significantly lower load capacity (approximately 63 percent of the control walls) and was significantly more flexible. In this type of wall construction, since the nails are cantilevering through the foam plastic insulation, it is more flexible than traditional wall construction. Figure 17 shows the typical failure mode of sheathing-over-foam walls. Based on these initial data, the objective of the test series program was to investigate the feasibility of attaching WSP sheathing over 1-inch expanded polystyrene as an acceptable configuration to meet the minium performance of wall bracing in accordance with the IRC.

FIGURE 17

NAIL YIELDING FOR A SHEATHING-OVER-FOAM WALL

4.2 Wall Configuration

All tested walls were 8 feet x 8 feet, consisting of two 4-foot x 8-foot OSB and 1-inch-thick expanded polystyrene panels. Stud framing was assembled in accordance with ASTM E72. The OSB and foam panels were attached vertically to the framing, while the 1/2-inch gypsum wallboards were attached horizontally with unblocked horizontal wall joints on the opposite face of the wall. Testing was conducted on the APA wall racking test frame, as shown in Figure 18.

FIGURE 18

TEST FRAME WITH TEST WALL IN PLACE

4.2.1 Wood Structural Panels

The wall assembly was sheathed with 3/8 Performance Category OSB, APA Rated Sheathing, 24/0, Exposure 1.

4.2.2 Rigid Foam Insulation

The wall assembly was sheathed with 1-inch-thick expanded polystyrene foam sheathing (1.0 lbf/ft^3 density), 4 feet x 8 feet (R-Tech® Insulation, Insulfoam). The foam sheathing was nailed to the framing with 4d common (0.099 inch x 1-1/2 inches) smooth-shank nails spaced 8 inches on center along supported panel edges and 12 inches on center on interior supports.

4.2.3 Interior Sheathing

The interior sheathing consisted of 1/2-inch gypsum board attached with 1-1/4-inch Type W or S drywall screws spaced 7 inches on center along all supports. Unblocked horizontal panel joints were left unfinished, without taping or texturing.

4.2.4 Wall Framing

Lumber used for the wall assembly was 2x4 Douglas-fir No. 2. The Douglas-fir lumber framing was visually screened such that it contained few natural defects and was weighed to ensure that no low specific gravity pieces were used. The framing was assembled in accordance with ASTM E72.

4.2.5 Fasteners

Fasteners used to attach the OSB panels (through the foam insulation) to framing were 6d common (0.113 inch x 2 inches), 8d cooler (0.113 inch x 2-3/8 inches), 8d common (0.131 inch x 2-1/2 inches), 10d box (0.128 inch x 3 inches) or 10d common (0.148 inch x 3 inches) nails, conforming to ASTM F1667 [7], *Standard Specification for Driven Fasteners: Nails, Spikes, and Staples.* The framing was nailed together with 16d common (0.162 inch x 3-1/2 inches) nails, conforming to ASTM F1667. The fasteners used to attach the 1/2-inch gypsum wallboard to framing were Type W or Type S screws, conforming to ASTM C1002 [5], *Standard Specification for Steel Self-Piercing Tapping Screws for the Application of Gypsum Panel Products or Metal Plaster Bases to Wood Studs or Steel Studs,* and Section R702.3.6 of the 2012 IRC.

4.2.6 Test Assembly Preparation

Shearwalls with dimensions of 8 feet x 8 feet were constructed in accordance with current industry practice. All walls had an intermediate stud spacing of 24 inches on center. The distance from the fastener to panel edge was 3/8 inch. A description of each wall, including fastener schedule, is provided in Table 4. Each wall had double 2x4 framing as the end posts (tension and compression chords) and a single 2x4 for the center stud.

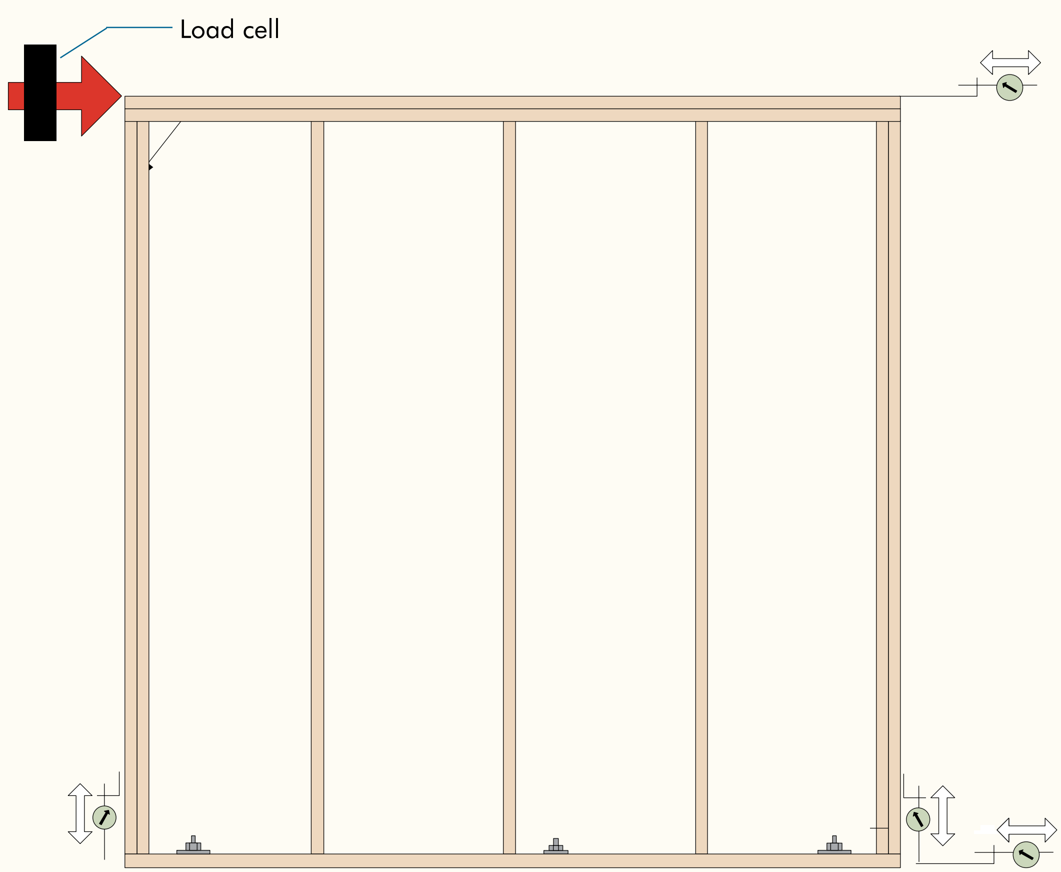
All nuts used to tighten the bottom plate were finger-tightened plus a 1/4 turn. To reduce sliding caused by 5/8-inch-diameter anchor bolts bearing on 7/8-inch-diameter steel holes in the steel test frame, combined with finger-tight nuts, a stop no larger than the 2x4 bottom plate was placed on each end to prevent excessive wall sliding on the steel test frame during testing.

4.3 Instrumentation

Instrumentation was provided, as shown in Figure 19. Linear potentiometer devices were attached to the wall assembly and test frame. The applied load was measured with a load cell located between the hydraulic actuator and the load head.

FIGURE 19

TEST WALL INSTRUMENTATION



4.4 Test Procedures

All testing was conducted with materials as-received, i.e., without preconditioning. Each wall was tested in accordance with ASTM E72, Section 14. The loading rate was in accordance with PS 2 [12], *Performance Standard for Wood-based Structural-use Panels*, Section 7.3.3, based on a design load of 150 plf, i.e., 1,200 lbf, 5,200 lbf, and ultimate. Complete load displacement response for each wall was recorded. Loading was continued until ultimate failure occurred.

4.5 Test Requirements

This test program was designed to demonstrate that the sheathing-over-foam wall assemblies could meet the minimum racking load performance criteria for wall bracing. The performance criteria were a maximum deflection of 0.2 inch at 150 plf, 0.6 inch at 300 plf, and a minimum ultimate load of 650 plf, in accordance with PS 2.

4.6 Wall Racking Results and Discussion

The typical failure mode was the failure of the nailed connections at the perimeter of the panels. A summary of the racking shear test results is provided in Table 5. The net deformation is defined as the top of wall deformation minus the uplift, crushing, and translation deformation. The ASTM E72 plots for each test are shown in **Appendix E**.

Walls C1 and C2 were tested as the control walls, i.e., without the expanded polystyrene installed between the WSP and studs, without and with gypsum wall boards, respectively, in order to evaluate the suitability of the wall components, e.g., WSP, nails, studs, for the test program, as well as to verify the assumed 100 plf allowable load contribution of the 1/2-inch gypsum wall boards recognized by the IRC. The construction of Walls C1 and C2 are to be considered as the code minimum for wall bracing. Walls 3 and 4 were matched with Walls C1 and C2, respectively, with the primary differences being the former walls contained 1-inch expanded polystyrene and, consequently, less nail penetration into the studs.

Walls tested with 8d cooler or common nails failed to meet the required ultimate load of 650 plf for wall bracing regardless of the tested fastener spacing in the panel perimeter. Wall 6 (10d box nails with fastener spacing of 6 inches in the panel perimeter) also failed to meet the ultimate load requirements. As a result, the fastener spacing in the panel perimeter was decreased to 4 inches for Walls 7, 8, and 9. The resulting average ultimate load of the 3 replicates was approximately 755 plf. In order to provide an alternate nailing schedule, Walls 10, 13, and 14 were constructed with 10d common nails and 6-inch spacing in the panel perimeter. The results, unfortunately, also failed to meet the ultimate load requirements of 650 plf with an average ultimate load of 570 plf.

Test results in Table 5 show that walls having nails spaced at 4 inches on center in the panel perimeter and 12 inches on center in the field have a higher ultimate load capacity (about 33–39 percent) than walls having nails spaced at 6 inches on center in the panel perimeter and 12 inches on center in the field. The higher loads may be attributed to tighter nail spacing of 4 inches on center in the panel perimeter, which results in 50 percent more nails in the panel perimeter, when compared to the 6 inches on center spacing.

Because only one of the tested wall configurations (10d box nails spaced 4 inches on center in the panel perimeter and 12 inches on center in the field) met the requirements of wall bracing, further testing may be considered to provide alternative wall configurations. For example, the use of deformed shank nails or thicker (7/16 Performance Category) panels may achieve the required structural performance for wall bracing.

TABLE 4

DESCRIPTION OF WALL CONFIGURATIONS[a]

Wall	C1[c,d]	C2[d]	3[c]	4	5[e]	6	7	8	9	10	11	12	13	14	15
Fastener type:[b]	6d com	6d com	8d cooler	8d cooler	8d cooler	10d box	10d box	Replicate of Wall-7	Replicate of Wall-7	10d com	8d com	8d com	Replicate of Wall-10	Replicate of Wall-10	Replicate of Wall-12
Approximate nail penetration in stud (in.)	1-5/8	1-5/8	1	1	1	1-5/8	1-5/8			1-5/8	1-1/8	1-1/8			
Fastener edge spacing (in.)	6	6	6	6	4	6	4			6	6	4			
Fastener interior spacing:								12							
Test load (plf)	150	250							150						

(a) Wall test numbers were assigned in the order as tested.

(b) Nails used were 6d common (0.113 inch x 2 inches), 8d cooler (0.113 inch x 2-3/8 inches), 8d common (0.131 inch x 2-1/2 inches), 10d box (0.128 inch x 3 inches) or 10d common nails (0.148 inch x 3 inches).

(c) Tested without gypsum interior sheathing.

(d) Tested without 1-inch expanded polystyrene installed between WSP and studs.

(e) Wall 5 was incorrectly assembled and tested with a stud spacing of 16 inches o.c.

TABLE 5

RESULTS OF WALL RACKING TESTS[a]

Wall	Criteria[a]	C1[c,d]	C2[d]	3[c]	4	5[e]	6	7	8	9	10	11	12	13	14	15
Net deformation at 150 plf (in.)	0.2 max	0.084	0.071	1.016	0.165	0.018	0.030	0.044	0.020	0.031	0.021	0.017	0.037	0.055	0.041	0.027
Net deformation at 300 plf (in.)	0.6 max	0.300	0.277	NA	0.912	0.110	0.224	0.156	0.121	0.133	0.140	0.205	0.190	0.256	0.217	0.165
Ultimate load (plf)	650 min	756	856	260	365	596	543	773	623	871	610	422	561	548	552	550
Load factor	—	5.04	3.43	1.73	2.43	3.97	3.62	5.15	4.15	5.81	4.06	2.81	3.74	3.66	3.68	3.67
Result	—	PASS	PASS	FAIL	FAIL	FAIL	FAIL	PASS	FAIL	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL

See Footnotes to Table 4.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. APA – The Engineered Wood Association. 2009. *Water Vapor Permeance of Wood Structural Panels and Wood Wall Construction*. Form No. J450. Tacoma, WA.

2. APA – The Engineered Wood Association. 2010. *Wood Structural Panels Used as Nailable Sheathing*. Technical Topics TT-109. Tacoma, WA.

3. ASHRAE. 2009. *ASHRAE Handbook—Fundamentals*. Atlanta, GA.

4. ASTM International. 2009. *Standard Test Methods for Water Vapor Transmission of Materials*. ASTM E96. West Conshohocken, PA.

5. ASTM International. 2012. *Standard Specification for Steel Self-Piercing Tapping Screws for the Application of Gypsum Panel Products or Metal Plaster Bases to Wood Studs or Steel Studs*. ASTM C1002. West Conshohocken, PA.

6. ASTM International. 2012. *Standard Test Methods of Conducting Strength Tests of Panels for Building Construction*. ASTM E72. West Conshohocken, PA.

7. ASTM International. 2012. *Standard Specification for Driven Fasteners: Nails, Spikes, and Staples*. ASTM F1667. West Conshohocken, PA.

8. CRC Press Inc. 1980. *CRC Handbook of Chemistry and Physics*. 61st Edition. Boca Raton, Florida.

9. ICC. 2012. *International Residential Code*. International Code Council. Country Club Hills, Illinois.

10. ICC. 2012. *International Energy Conservation Code*. International Code Council. Country Club Hills, Illinois.

11. Straube, J., D. Onysko, and C. Schumacher. 2002. *Methodology and Design of Field Experiments for Monitoring the Hygrothermal Performance of Wood Frame Enclosures*. Journal of Thermal Env. & Bldg. Sci. 26:2. October 2002.

12. US Department of Commerce. 2010. *Performance Standard for Wood-based Structural-use Panels*. PS 2-10. National Institute of Standards and Technology. Gaithersburg, MD.

APPENDIX A.
PHASE 1
WALL MC, RH, AND TEMPERATURE

(Weekly Averages from February 2012 through February 2013)

FIGURE A1

WALL N7—WOOD MOISTURE CONTENT

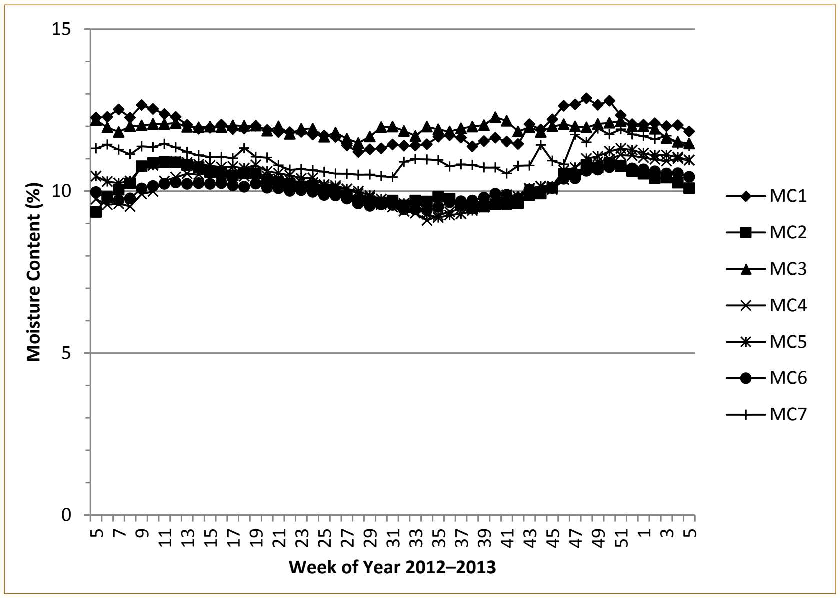


FIGURE A2

WALL N7—CAVITY RELATIVE HUMIDITY

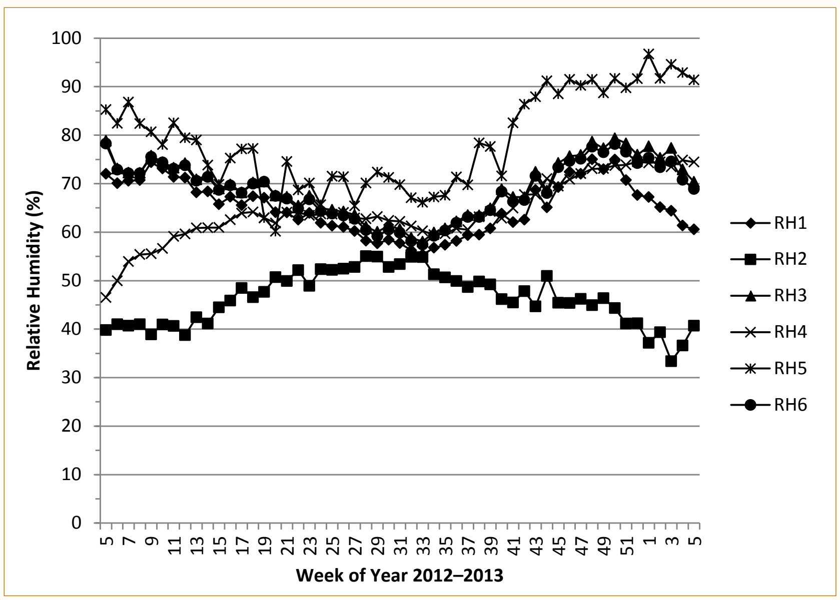


FIGURE A3

WALL N7—TEMPERATURE

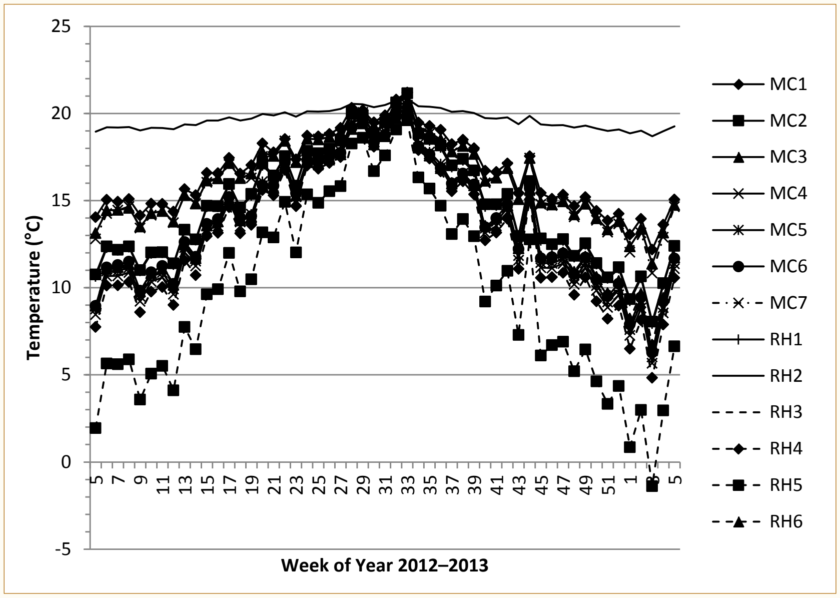


FIGURE A4

WALL N8—WOOD MOISTURE CONTENT

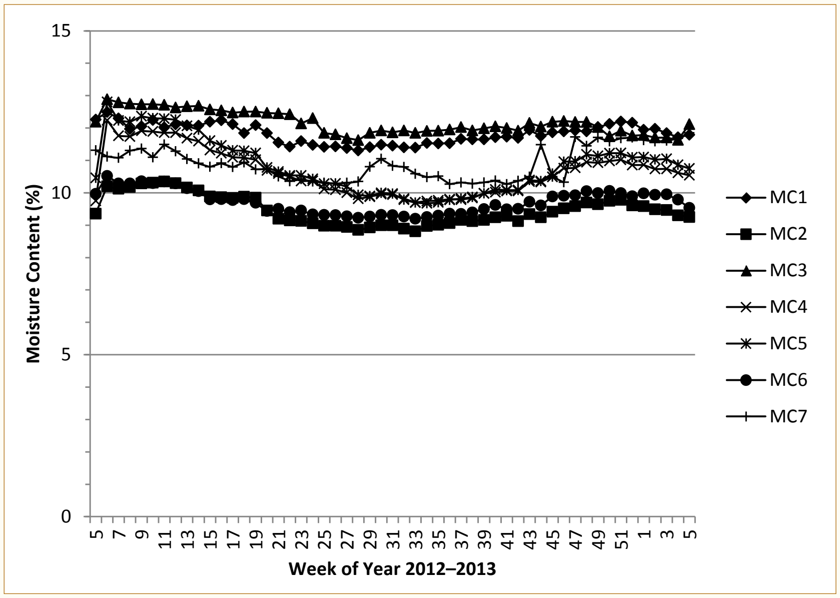


FIGURE A5

WALL N8—CAVITY RELATIVE HUMIDITY

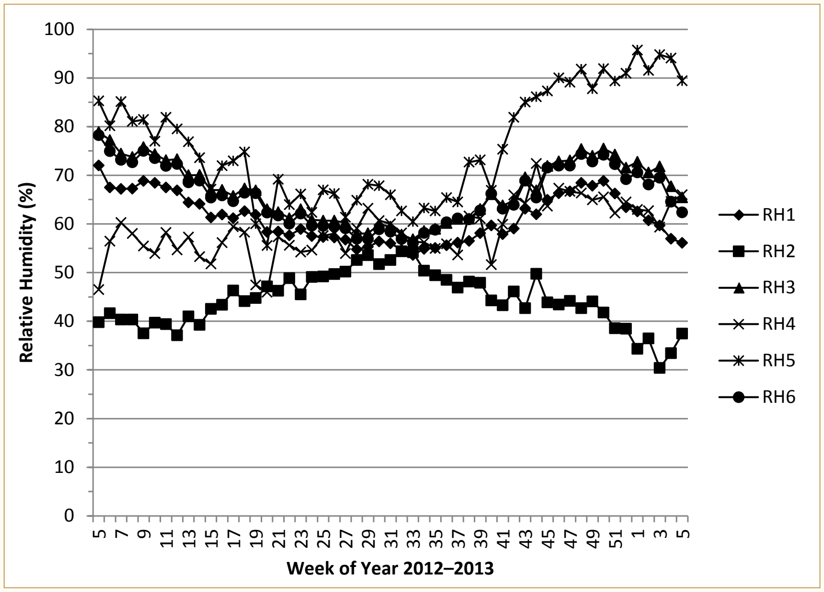


FIGURE A6

WALL N8—TEMPERATURE

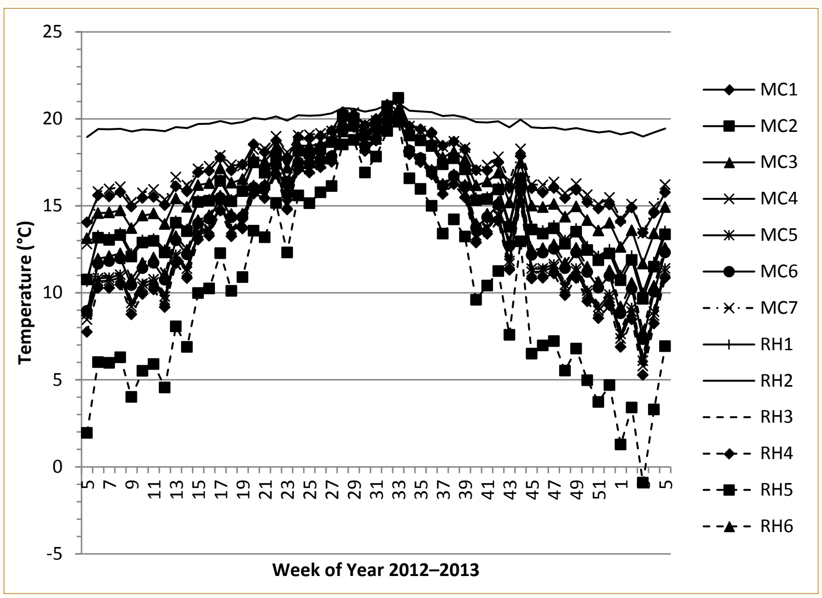


FIGURE A7

WALL S11—WOOD MOISTURE CONTENT

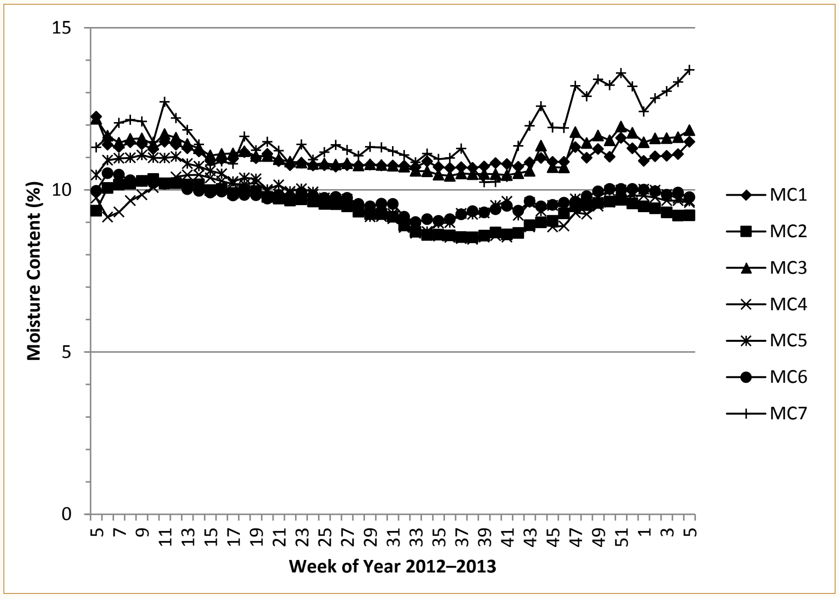


FIGURE A8

WALL S11—CAVITY RELATIVE HUMIDITY

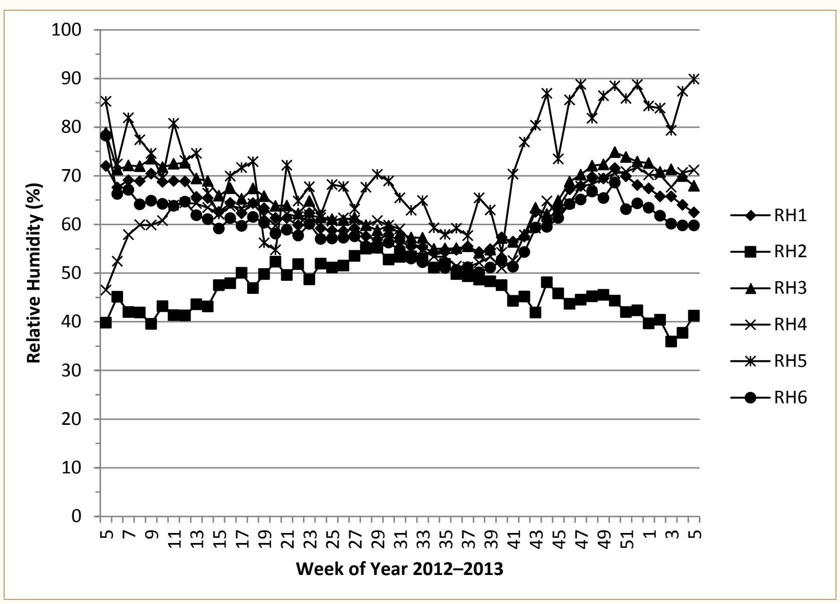


FIGURE A9

WALL S11—TEMPERATURE

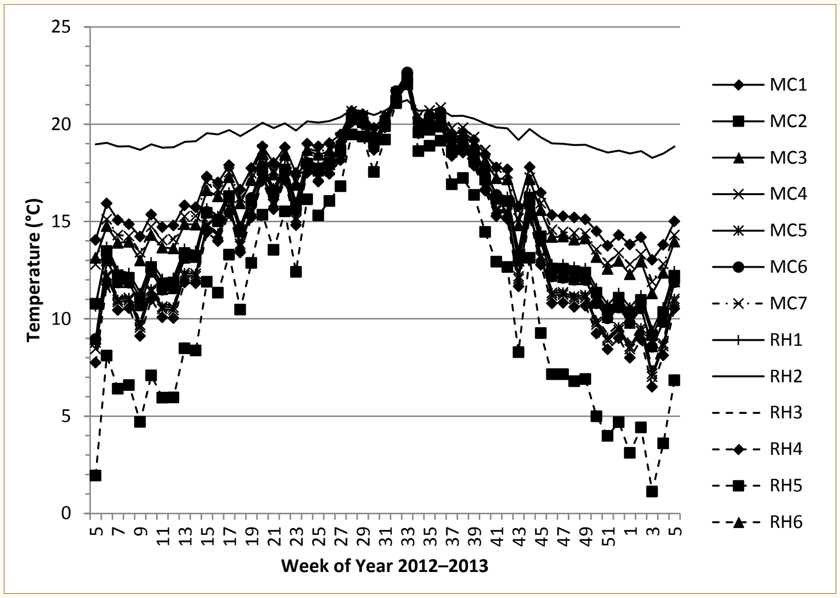


FIGURE A10

WALL S12—WOOD MOISTURE CONTENT

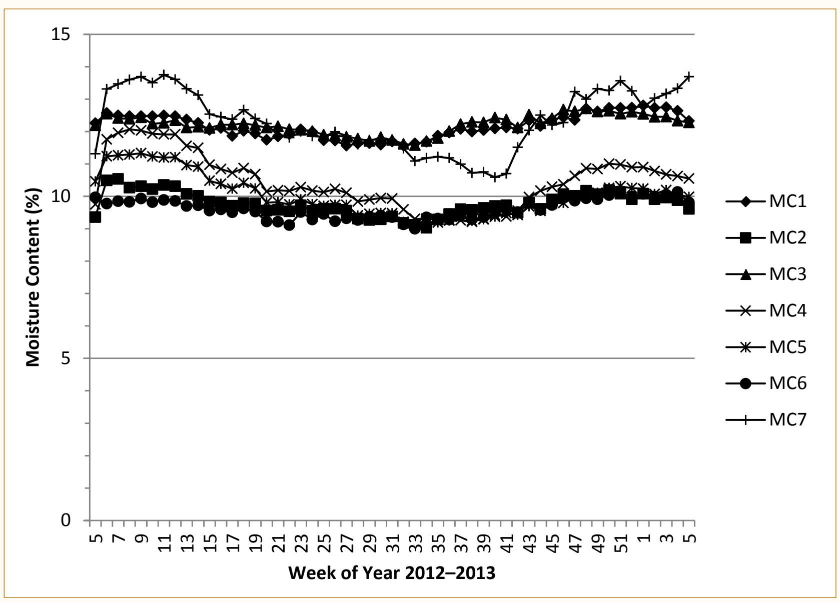


FIGURE A11

WALL S12—CAVITY RELATIVE HUMIDITY

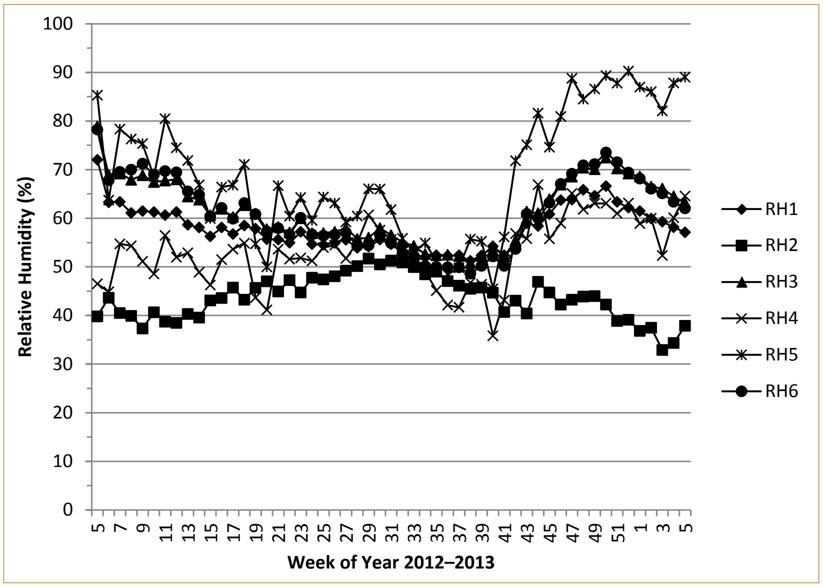
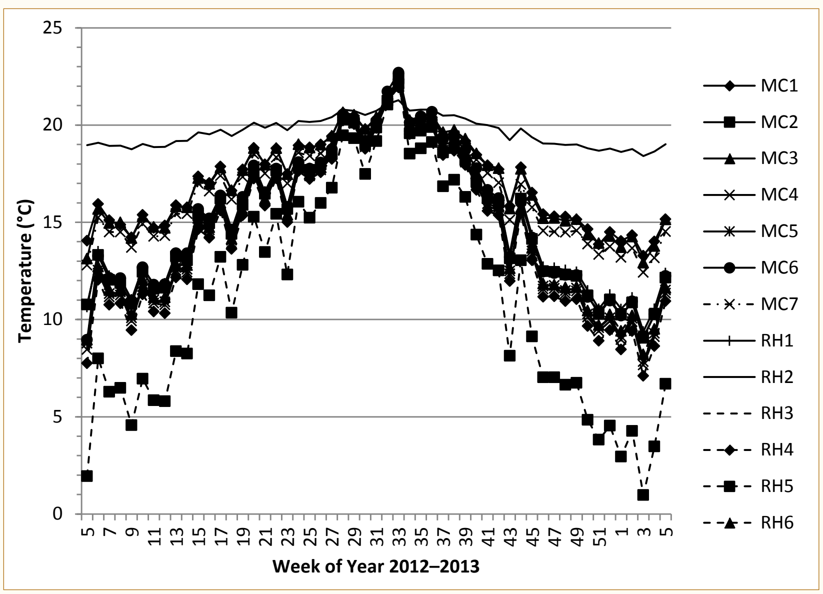


FIGURE A12

WALL S12—TEMPERATURE



APPENDIX B.
PHASE 1
INDOOR AND OUTDOOR ENVIRONMENTAL CONDITIONS

(Weekly Averages from February 2012 through January 2013)

FIGURE B1

OUTDOOR AND INDOOR TEMPERATURE

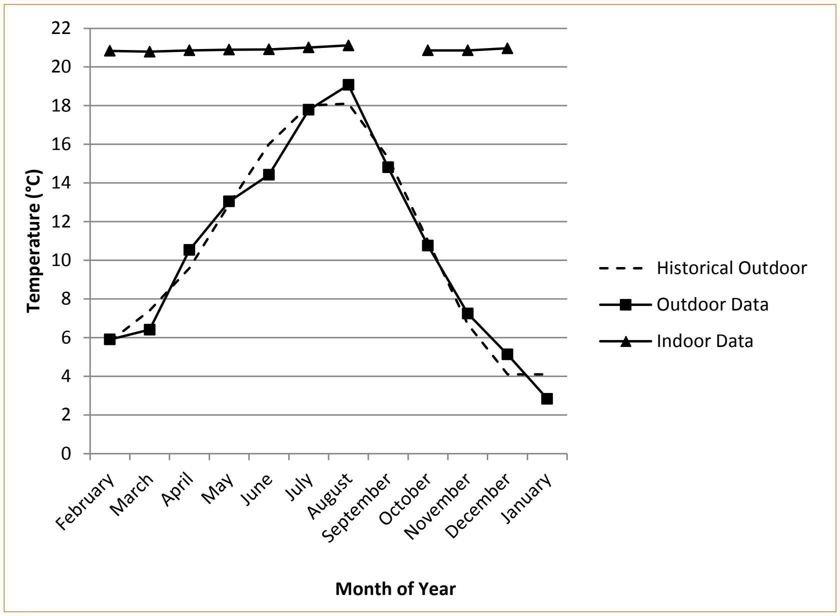


FIGURE B2

OUTDOOR AND INDOOR RELATIVE HUMIDITY

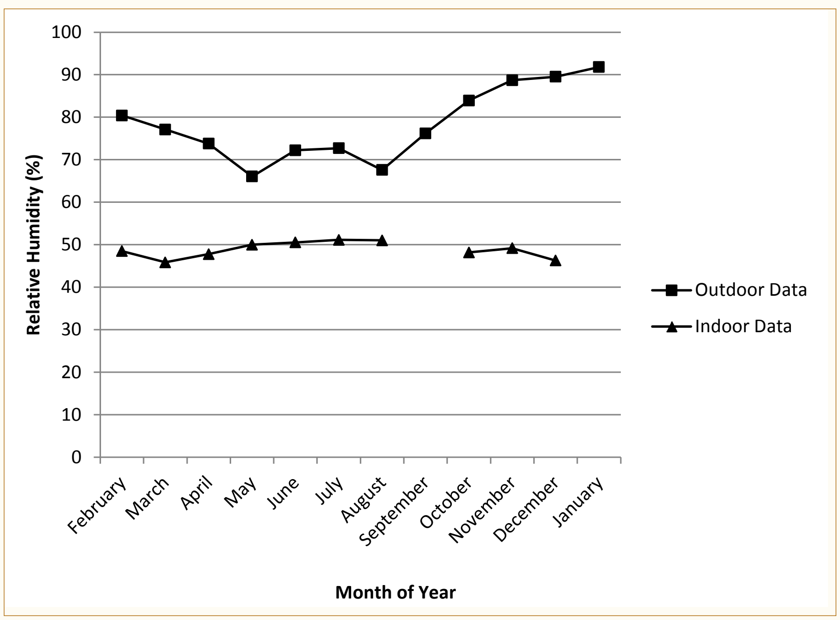


FIGURE B3

SUM OF PRECIPITATION

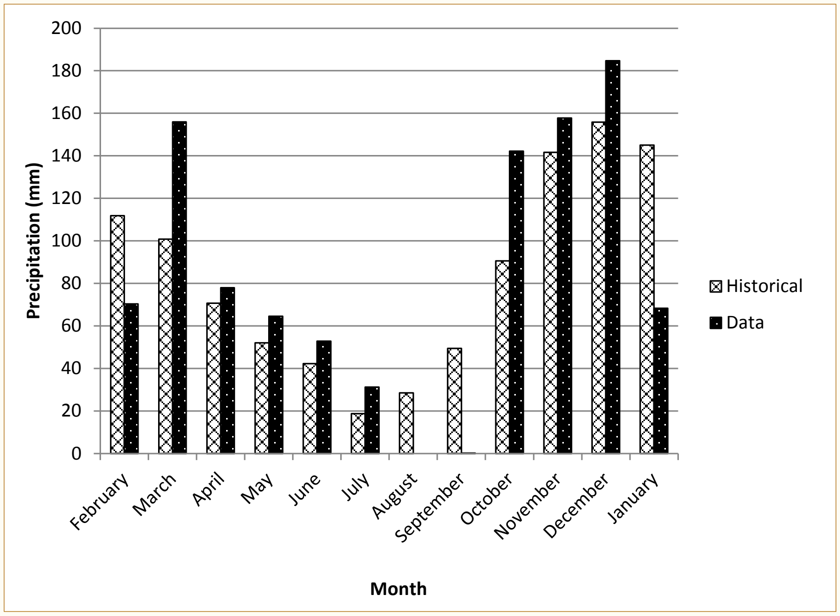


FIGURE B4

CUMULATIVE PRECIPITATION

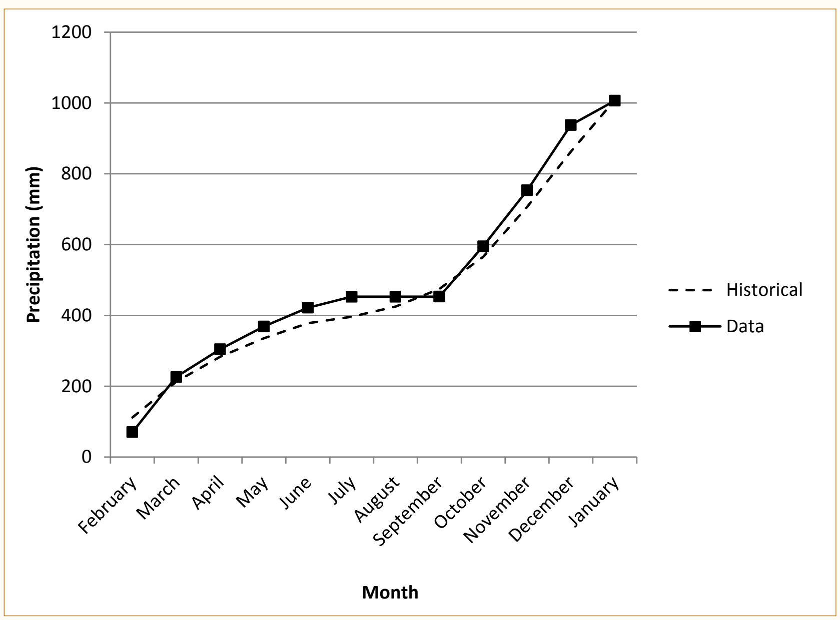


FIGURE B5

SUM OF VERTICAL AND HORIZONTAL SOLAR RADIATION

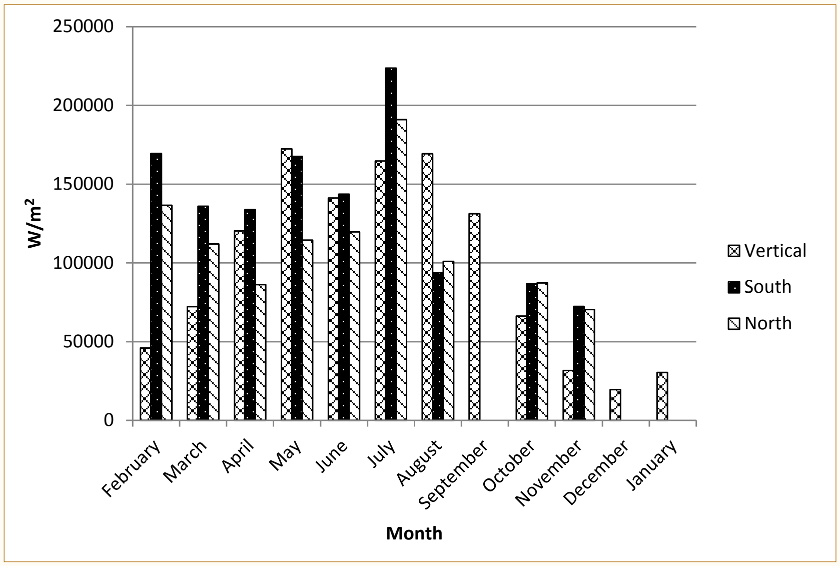
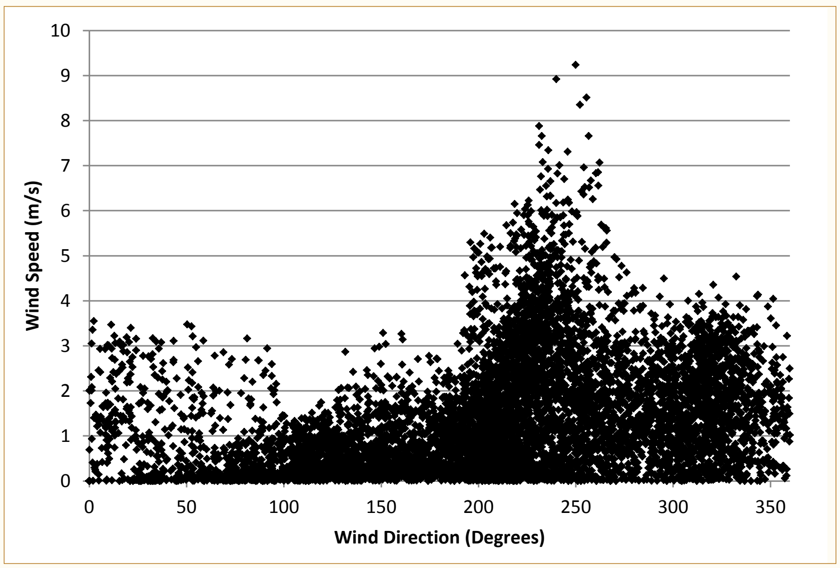


FIGURE B6

WIND SPEED BY WIND DIRECTION



APPENDIX C.
PHASE 2
WALL MC, RH, AND TEMPERATURE

(Weekly Averages from March 2013 through July 2014)

FIGURE C1

WALL N7—WOOD MOISTURE CONTENT

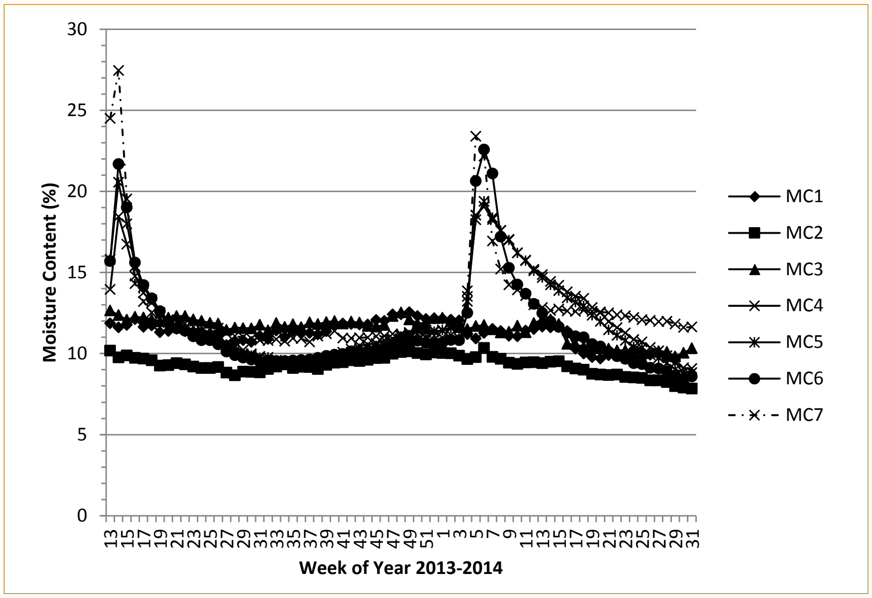


FIGURE C2

WALL N7—CAVITY RELATIVE HUMIDITY

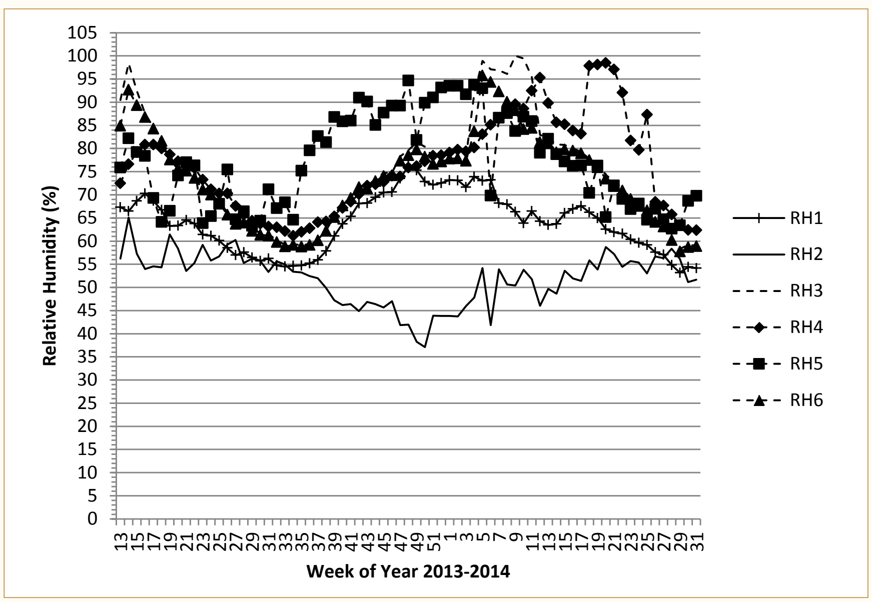


FIGURE C3

WALL N7—TEMPERATURE

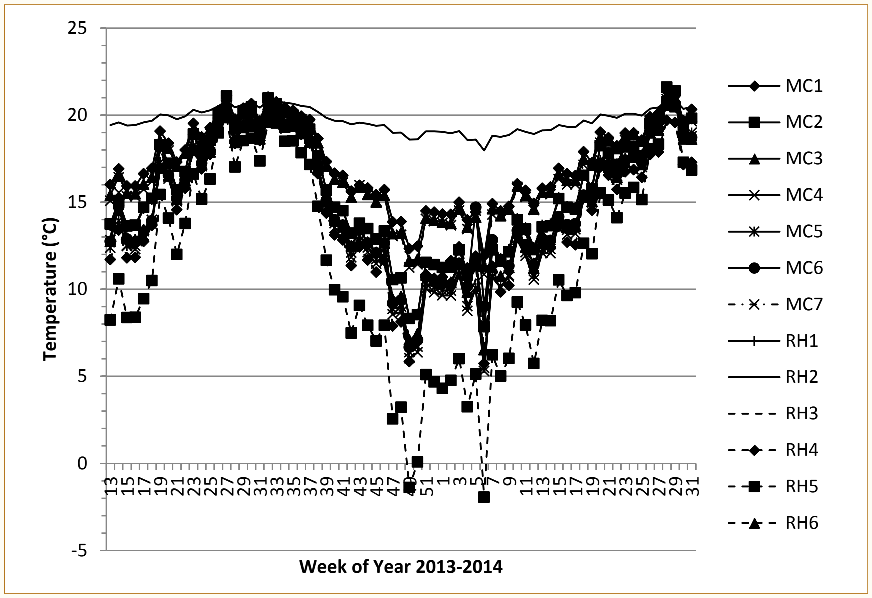


FIGURE C4

WALL N8—WOOD MOISTURE CONTENT

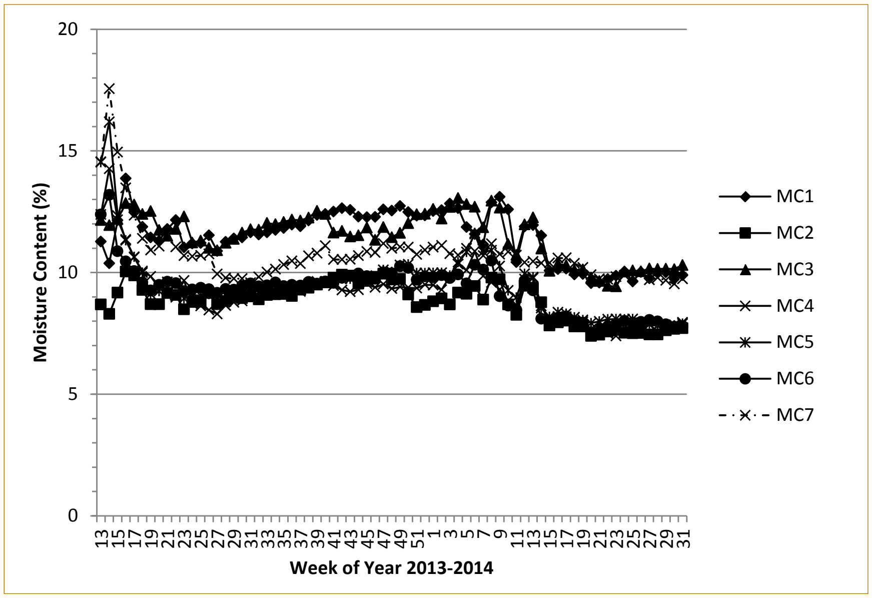


FIGURE C5

WALL N8—CAVITY RELATIVE HUMIDITY

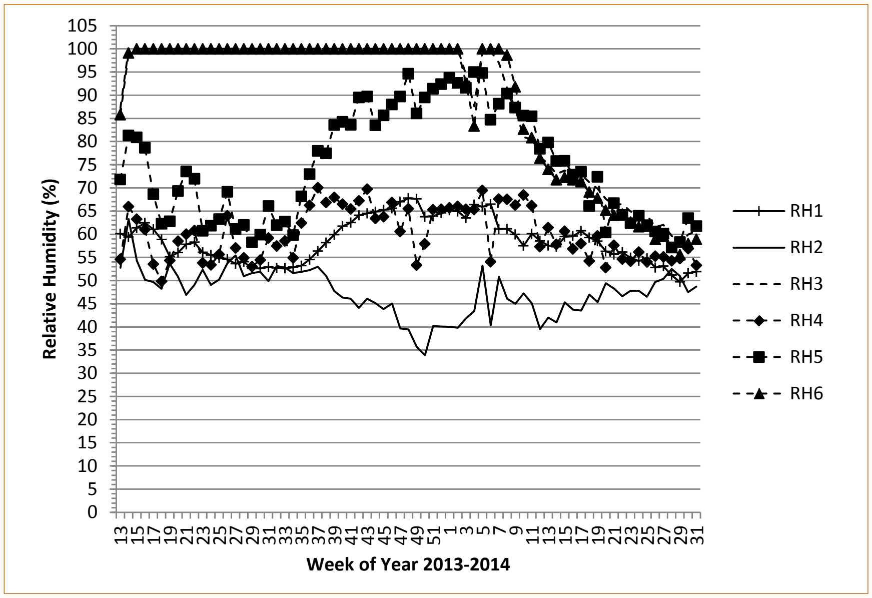


FIGURE C6

WALL N8—TEMPERATURE

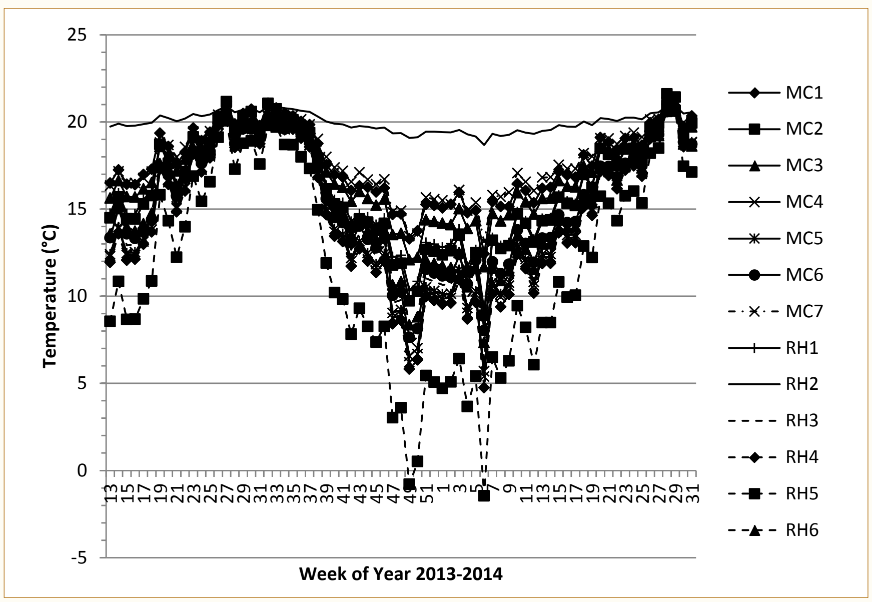


FIGURE C7

WALL S11—WOOD MOISTURE CONTENT

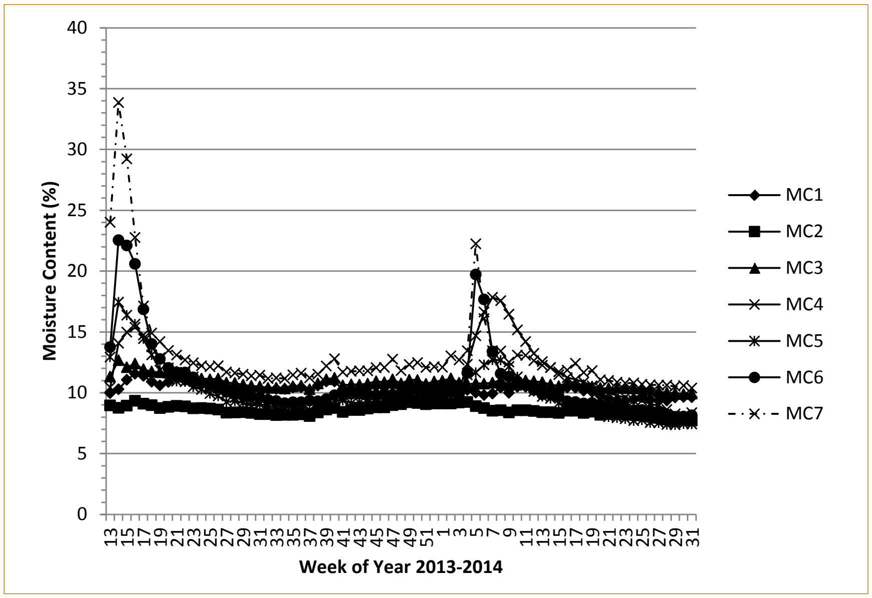


FIGURE C8

WALL S11—CAVITY RELATIVE HUMIDITY

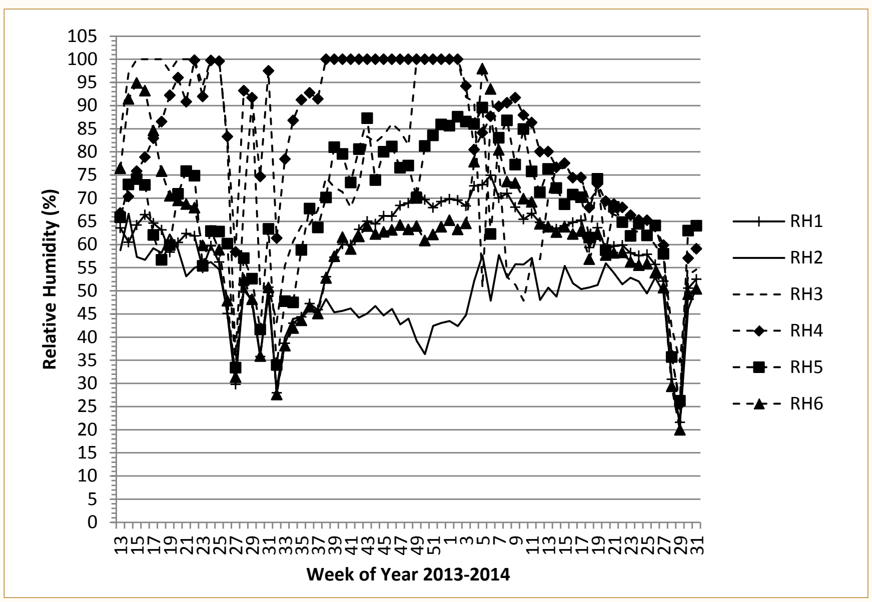


FIGURE C9

WALL S11—TEMPERATURE

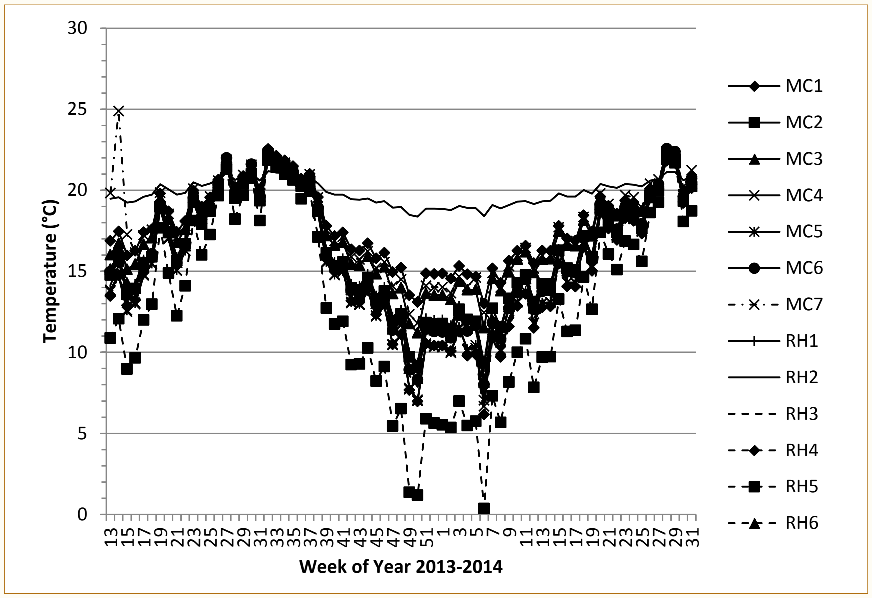


FIGURE C10

WALL S12—WOOD MOISTURE CONTENT

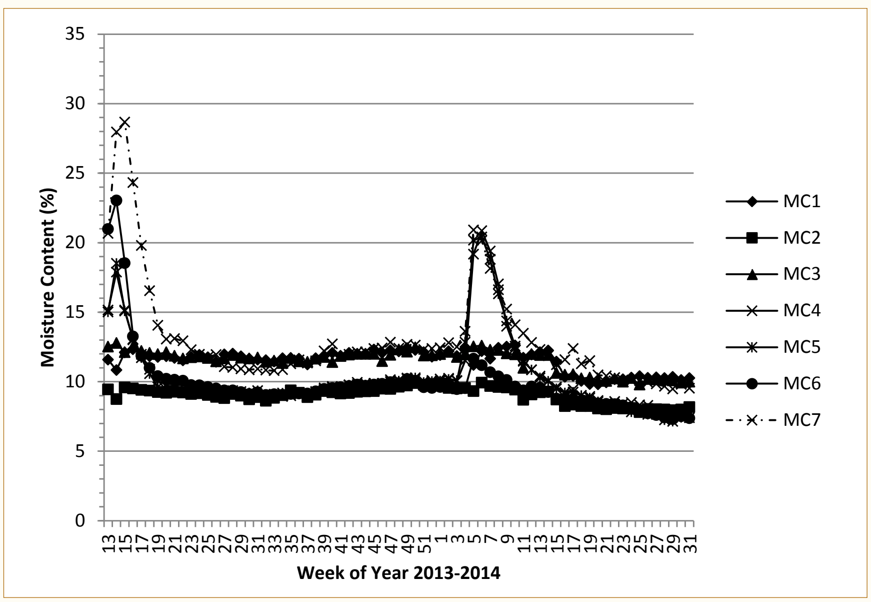


FIGURE C11

WALL S12—CAVITY RELATIVE HUMIDITY

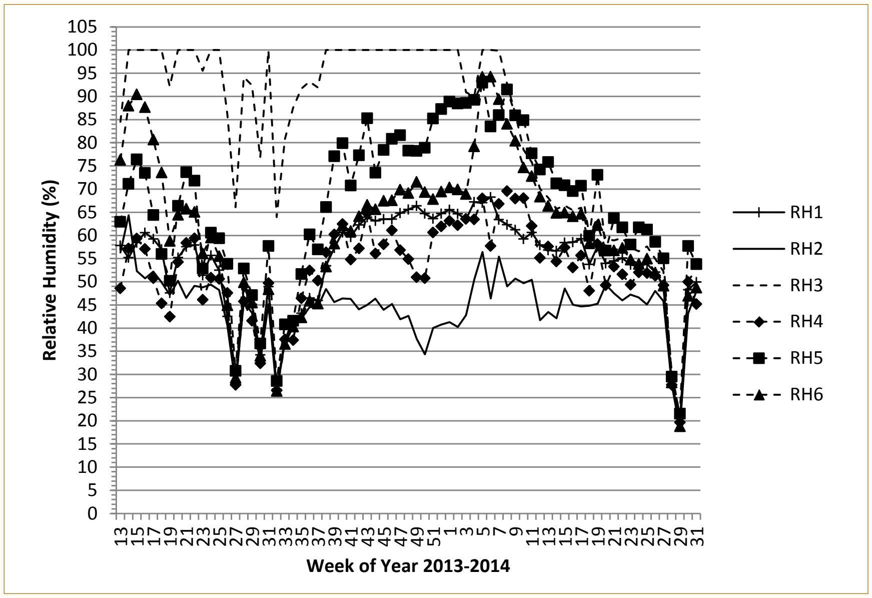
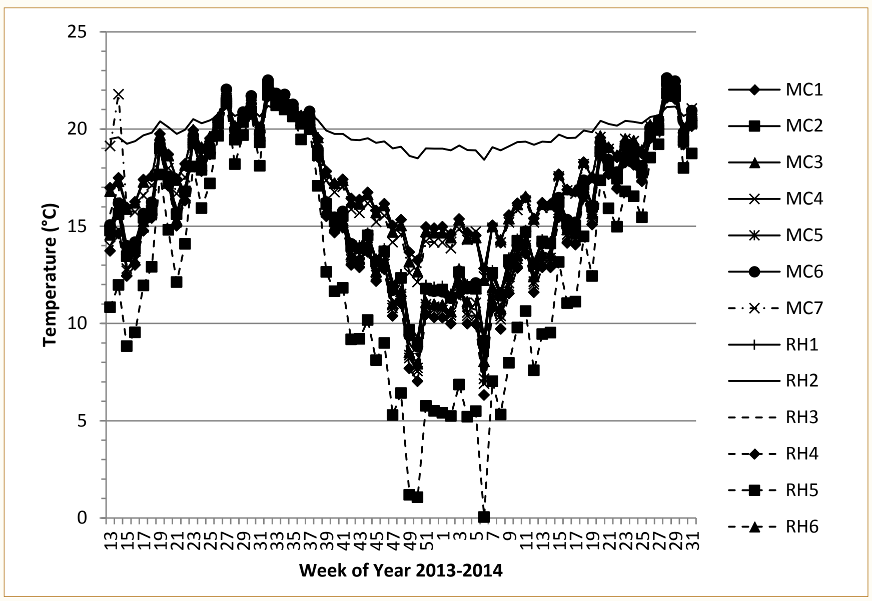


FIGURE C12

WALL S12—TEMPERATURE



APPENDIX D.
PHASE 2
INDOOR AND OUTDOOR ENVIRONMENTAL CONDITIONS

(Weekly Averages from March 2013 through July 2014)

FIGURE D1

OUTDOOR AND INDOOR TEMPERATURE

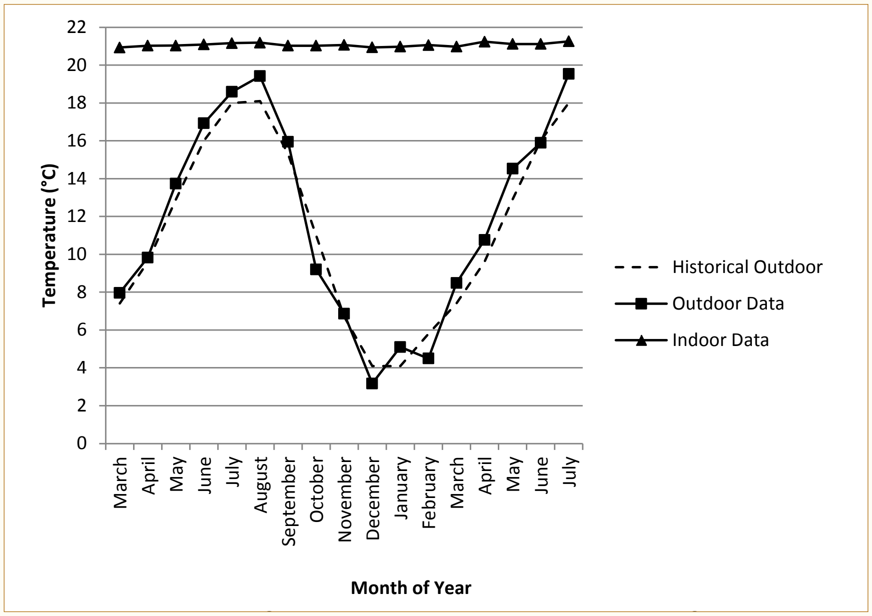


FIGURE D2

OUTDOOR AND INDOOR RELATIVE HUMIDITY

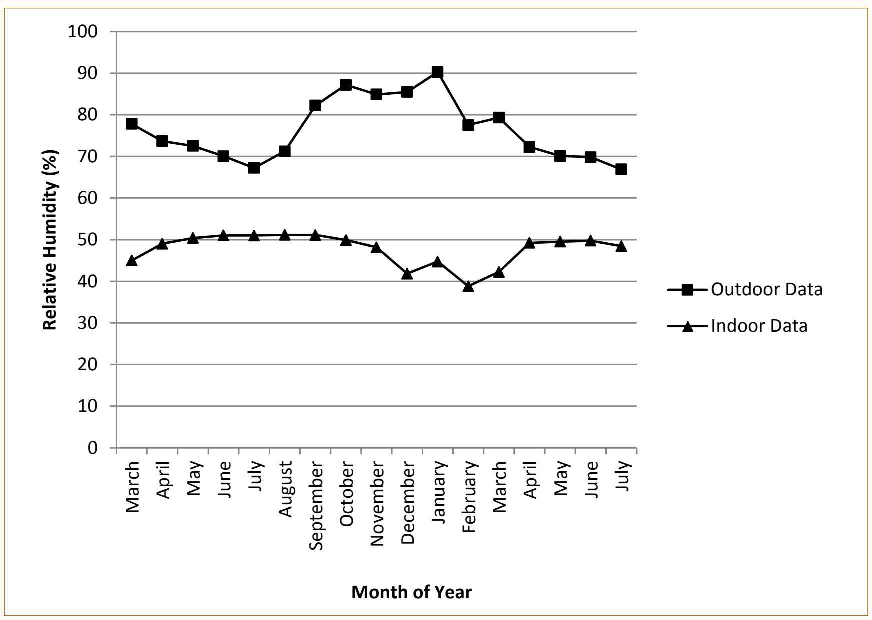


FIGURE D3

SUM OF PRECIPITATION

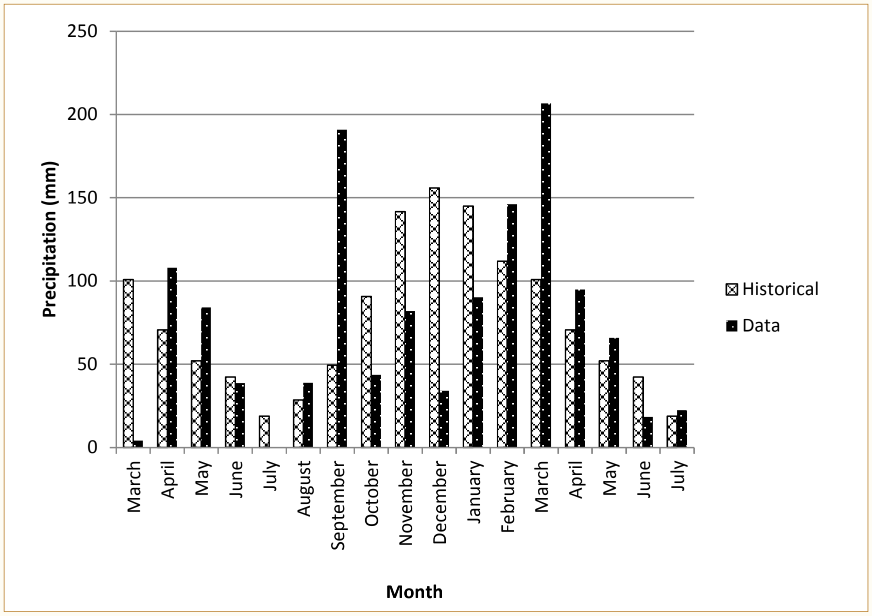


FIGURE D4

CUMULATIVE PRECIPITATION

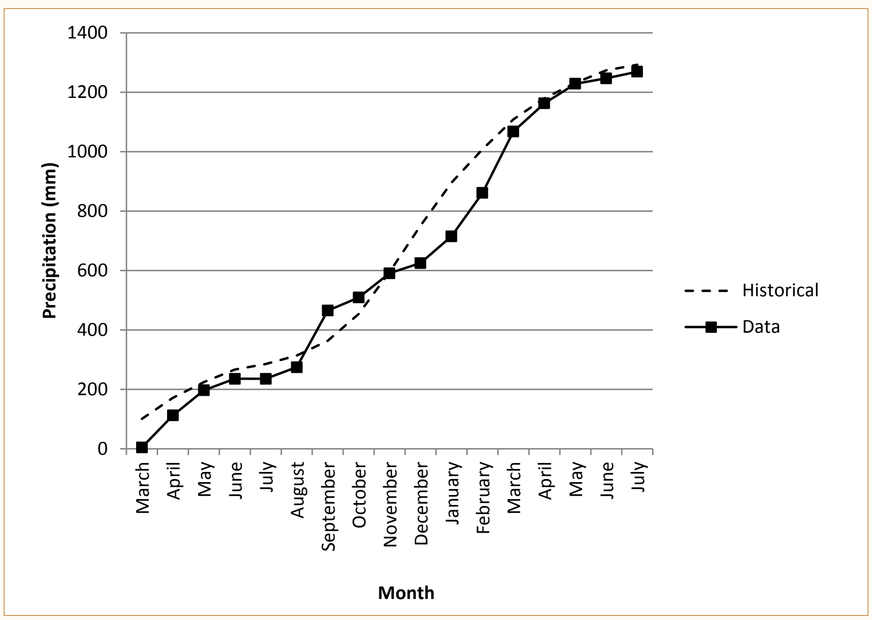


FIGURE D5

SUM OF VERTICAL AND HORIZONTAL SOLAR RADIATION (W/m²).

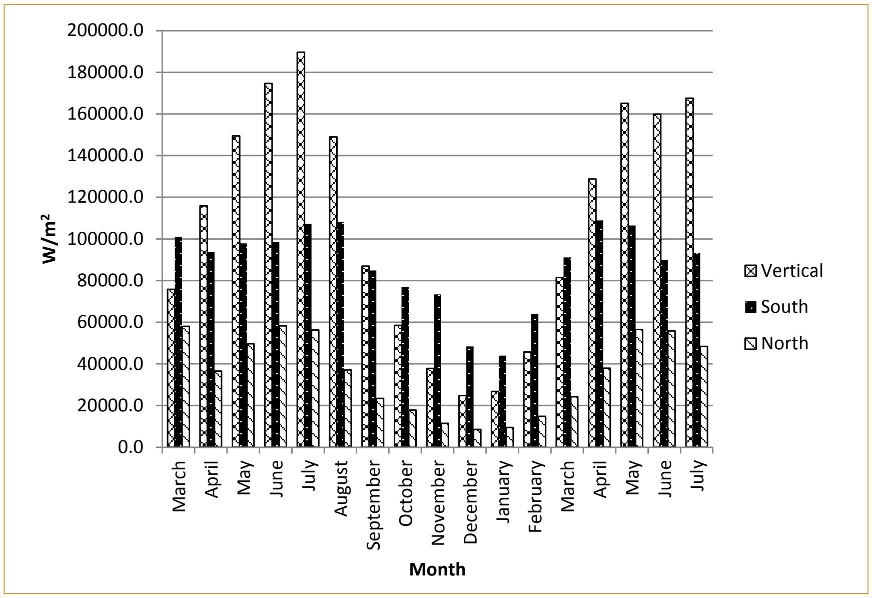
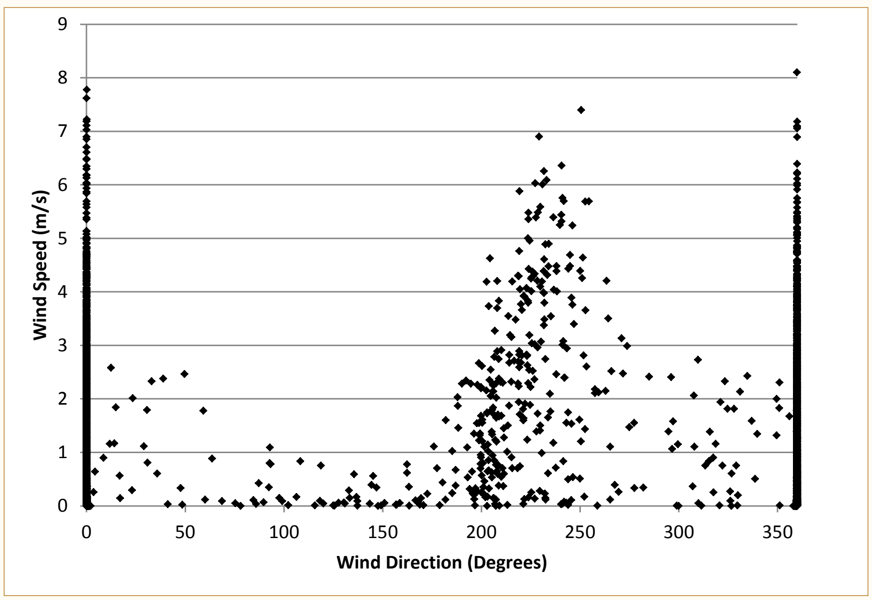


FIGURE D6

WIND SPEED BY WIND DIRECTION



APPENDIX E.
ASTM E72 WALL RACKING TEST PLOTS

FIGURE E1

WALL C1 DATA (ASTM E72 Loading Cycle)

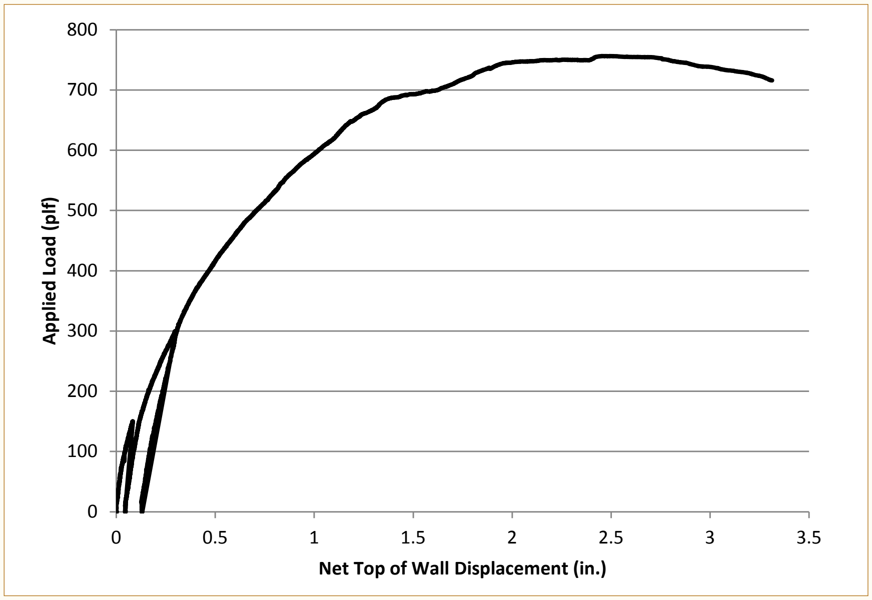


FIGURE E2

WALL C2 DATA (ASTM E72 Loading Cycle)

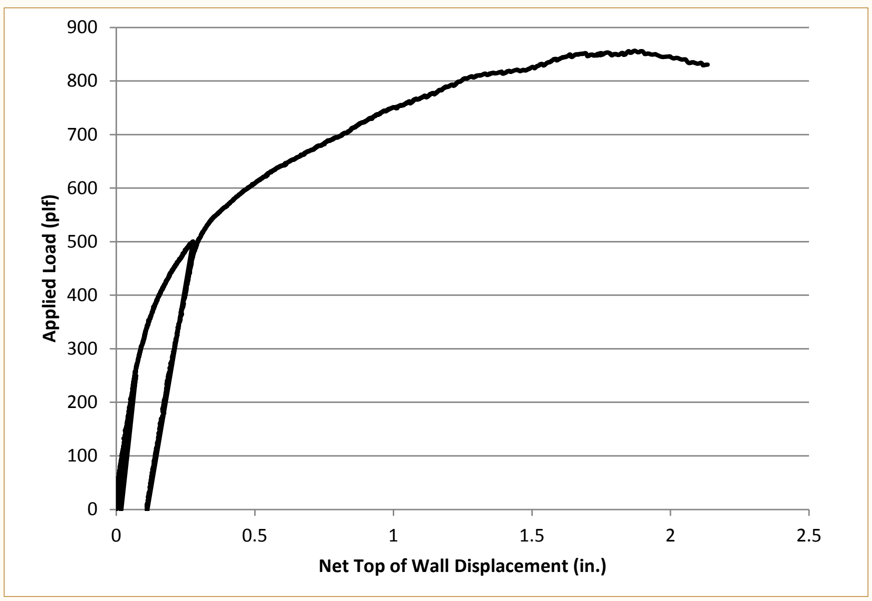


FIGURE E3

WALL 3 DATA (ASTM E72 Loading Cycle)

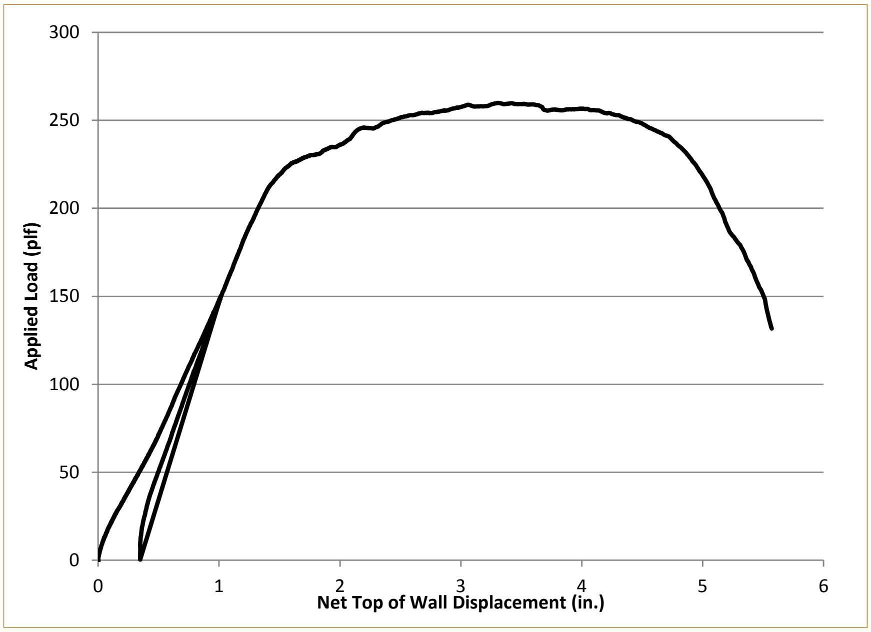


FIGURE E4

WALL 4 DATA (ASTM E72 Loading Cycle)

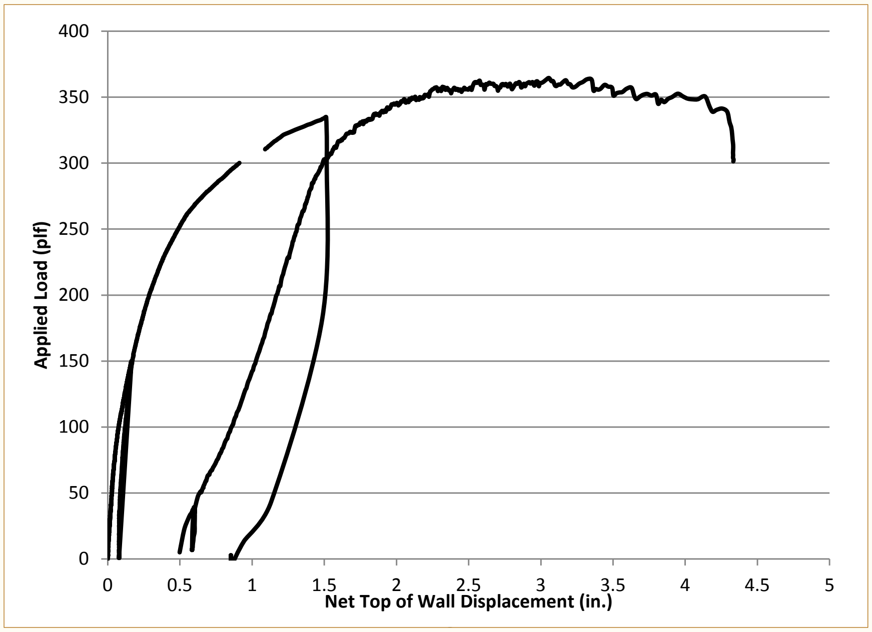


FIGURE E5

WALL 5 DATA (ASTM E72 Loading Cycle)

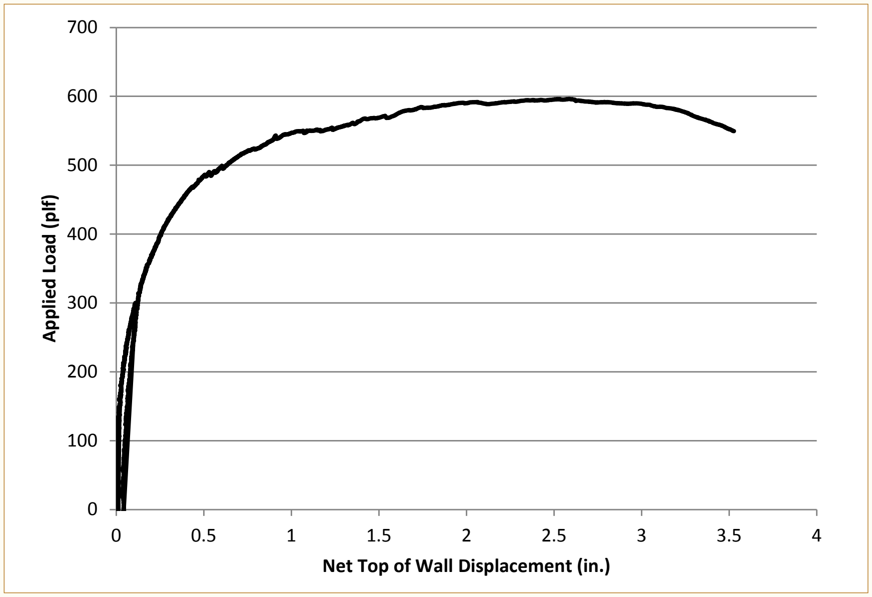


FIGURE E6

WALL 6 DATA (ASTM E72 Loading Cycle)

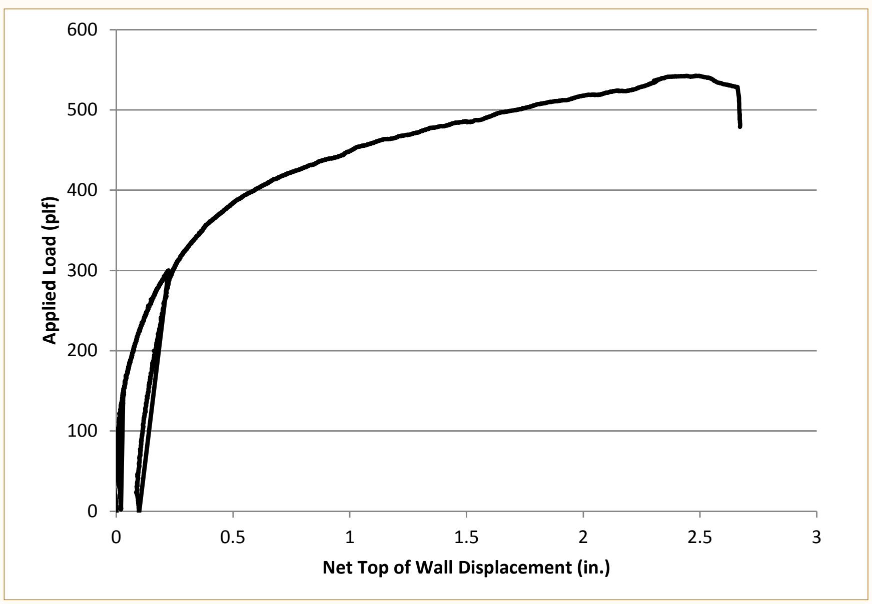


FIGURE E7

WALL 7 DATA (ASTM E72 Loading Cycle)

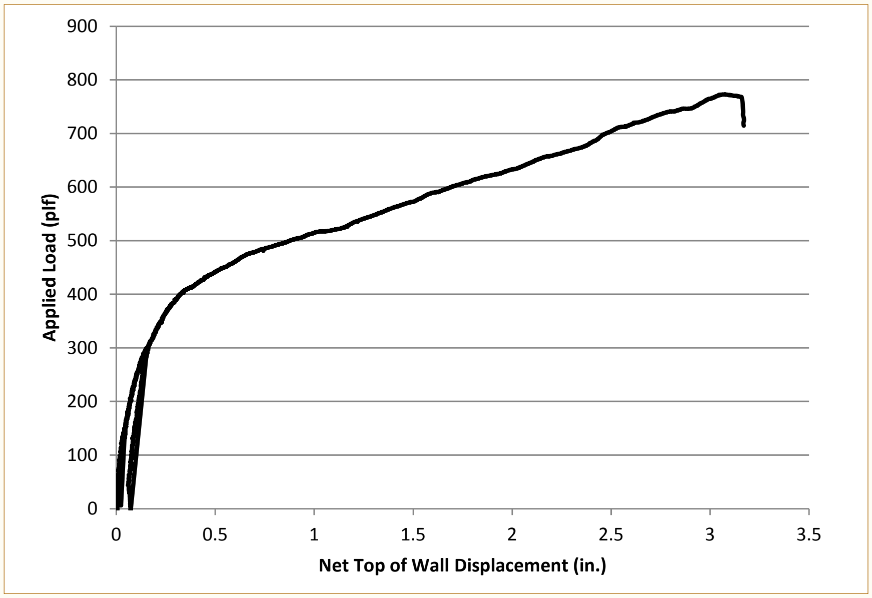


FIGURE E8

WALL 8 DATA (ASTM E72 Loading Cycle)

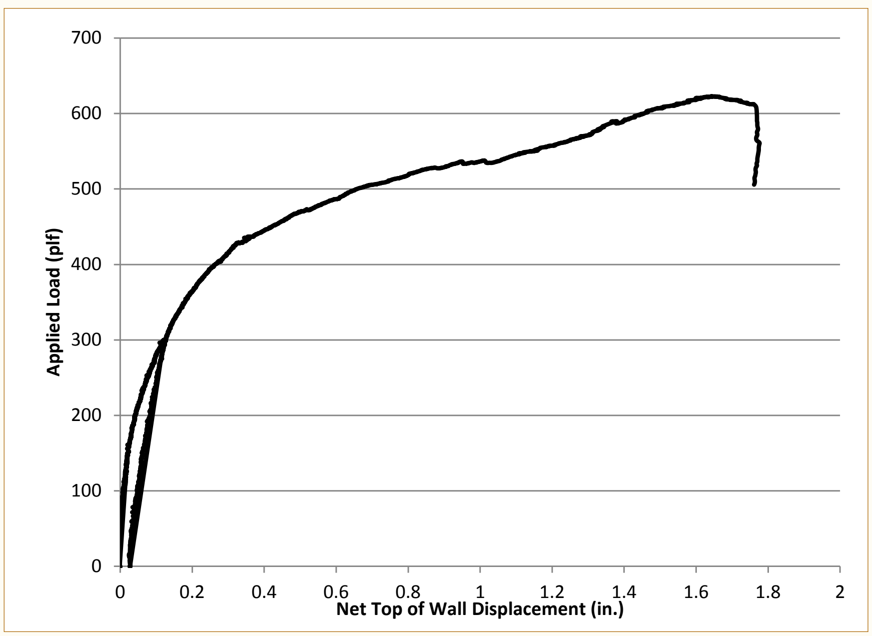


FIGURE E9

WALL 9 DATA (ASTM E72 Loading Cycle)

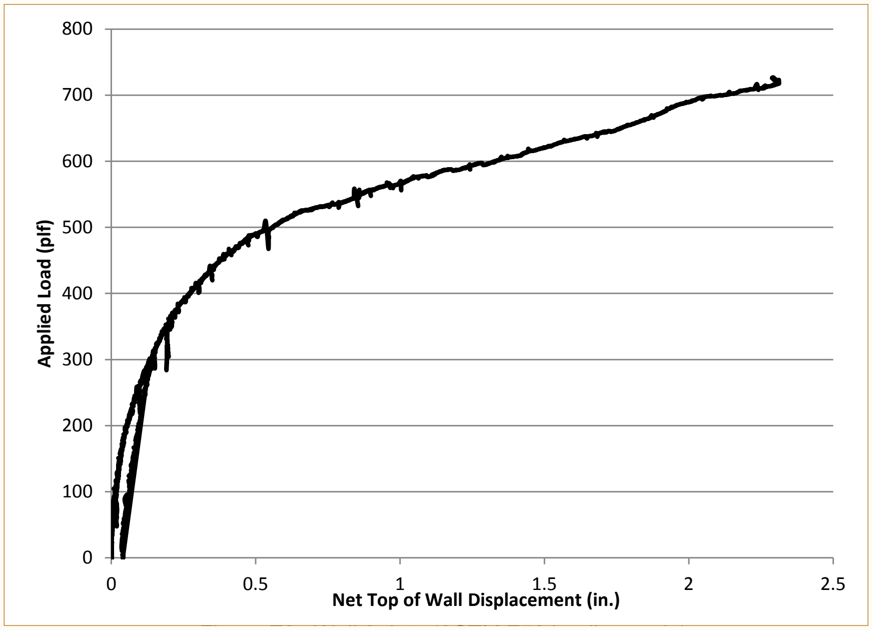


FIGURE E10

WALL 10 DATA (ASTM E72 Loading Cycle)

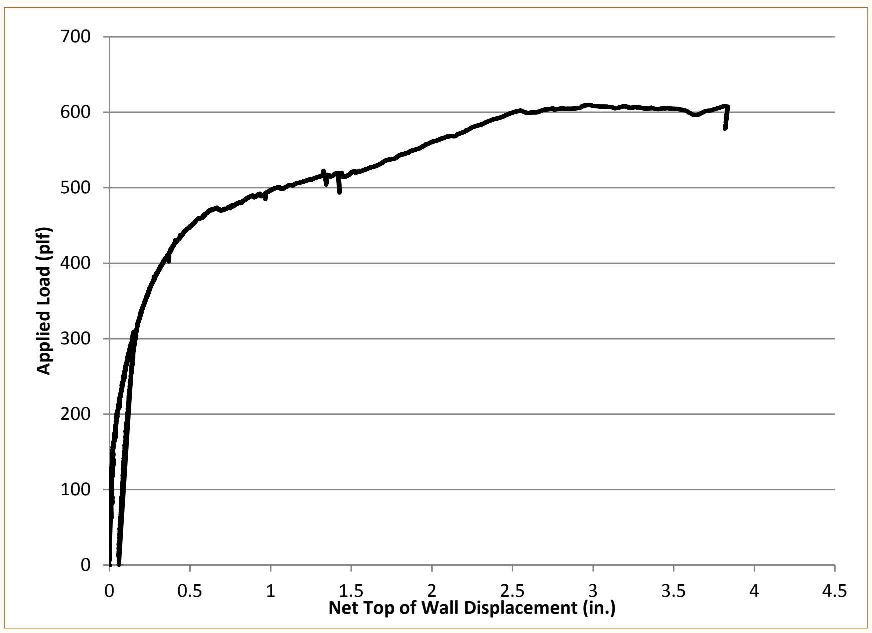


FIGURE E11

WALL 11 DATA (ASTM E72 Loading Cycle)

FIGURE E12

WALL 12 DATA (ASTM E72 Loading Cycle)

FIGURE E13

WALL 13 DATA (ASTM E72 Loading Cycle)

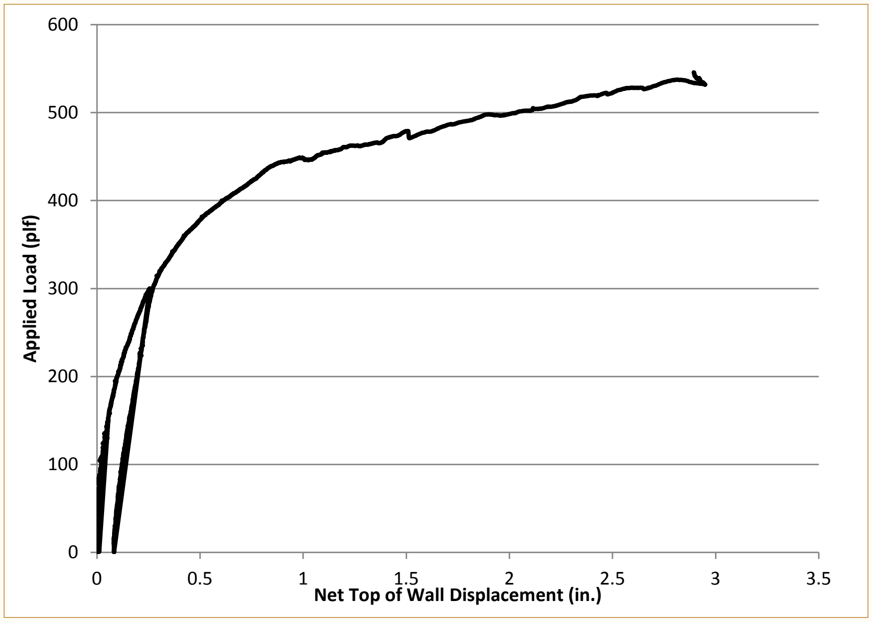


FIGURE E14

WALL 14 DATA (ASTM E72 Loading Cycle)

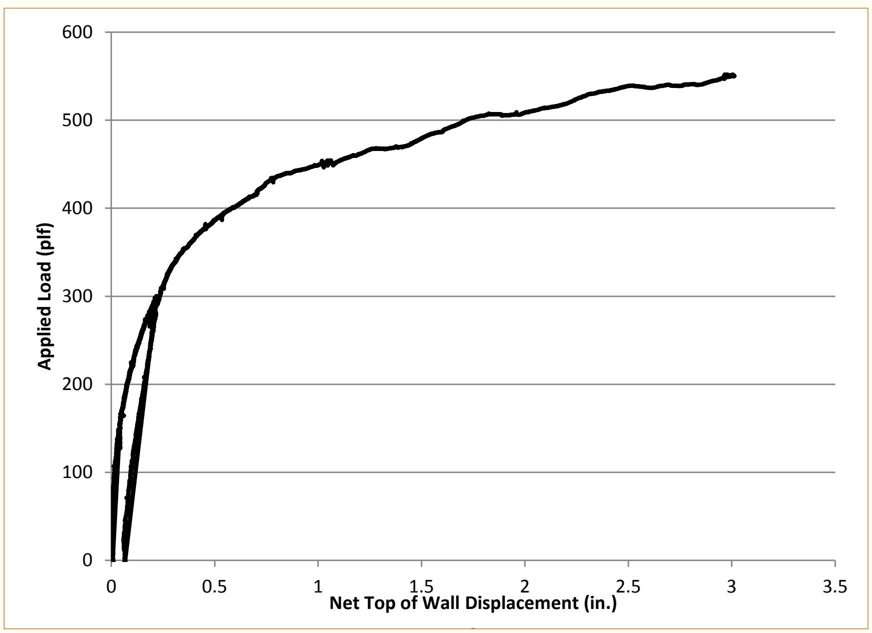
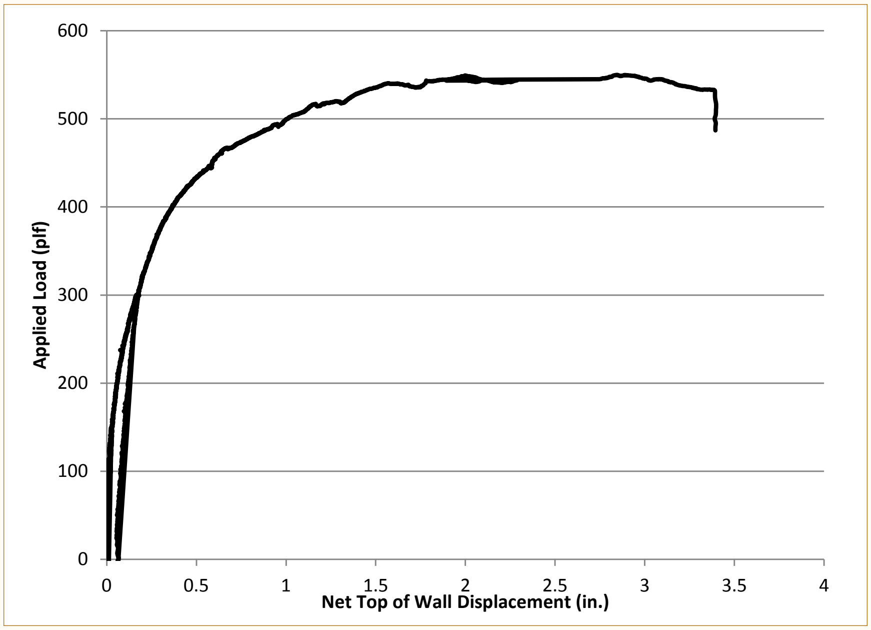


FIGURE E15

WALL 15 DATA (ASTM E72 Loading Cycle)



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