Home Innovation
RESEARCH LABS™

MOISTURE PERFORMANCE OF WALLS IN ENERGY EFFICIENT HOMES

Prepared For

NAHB Construction Technology Research Subcommittee (CTRSC)

September 2015

Report No. 3368.001.20150925

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Disclaimer

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DEFINITIONS

ACH50	Building air changes per hour at a 50 Pascal interior pressure differential with respect to the exterior
batt	Insulation configured as a blanket or sheet element that is typically designed to fit within the framing wall cavity
ccSPF	Closed cell spray polyurethane foam
CZ	Climate zone (applicable to building energy efficiency analysis) defined based on heating degree days, average temperatures, and precipitation, and developed along county lines for the United States.
DOE	United States Department of Energy
EPA	United States Environmental Protection Agency
ERV	Energy Recovery Ventilator
Flash coat	A layer of closed-cell spray foam installed on the exterior sheathing that does not typically fill the building cavity to allow for installation of another type of cavity insulation.
HRV	Heat Recovery Ventilator
HSPF	Heating Seasonal Performance Factor, defined as the ratio between the thermal energy supplied and the electrical energy absorbed by the heat pump over the heating season
IECC	International Energy Conservation Code, an energy conservation building code for residential and commercial structures, most recently published as the 2015 IECC by the International Code Council
IRC	International Residential Code, a building code for residential one- and two-family structures, most recently published as the 2015 IRC by the International Code Council
Kraft facing	Face layer on batt insulation that is generally vapor semi-impermeable (Class II)
NAHB	National Association of Home Builders
ocSPF	Open cell spray polyurethane foam
OSB	Oriented strand board
RA	Return air, air removed from conditioned space and circulated or exhausted

R-value	Magnitude of the insulation resistance to heat flow with the dimension of hr·°F·ft^2/Btu
SEER	Seasonal Energy Efficiency Ratio, is the total cooling output (in British thermal units or Btu) provided by the air conditioning unit (or heat pump) during its normal annual usage period divided by its total energy input (in watt-hours) during the same period
Vinyl	Vinyl siding used as the outermost exterior finish
WME	Wood moisture equivalent, a percent value describing the relative moisture content of a material and used in this study applied to wood species and compensated for the temperature of the measured element
WRB	Water Resistive Barrier (sometimes referred to as a weather resistive barrier)
XPS	Extruded polystyrene rigid foam board insulation

REPORT UPDATE

This report is an update of an earlier report issued under the same title in August of 2014 that summarized the results for the first two years of monitoring[1].

PURPOSE

Recent changes in the minimum energy code (2012/2015 IECC) significantly increased wall insulation levels and reduced wall air leakage targets for light-frame wood walls, relative to the 2006 and 2009 IECC. The long-term moisture performance of these new wall systems is not well understood with regard to vapor drive, condensation risk, and drying capability. With moisture performance increasingly becoming a design consideration in the selection of wall systems, home builders and designers need practical guidance for construction of walls that ensure durability of residential buildings.

As part of a broad multi-year research program on the moisture performance of residential wall systems, this project focuses on characterization of energy efficient walls in a sample of new, occupied homes recently constructed around the country in moist or marine climate zones. The data also provides the range of indoor relative humidity levels measured during the monitoring period. The wall system designs and target house air infiltration rates were selected to meet or exceed minimum performance levels outlined in the 2012/2015 IECC, EPA ENERGY STAR Version 3 program, and DOE Zero Energy Ready Home program (formerly Challenge Home program).

The objectives of this ongoing research are to document seasonal wall cavity moisture characteristics, wood structural panel sheathing moisture characteristics, and indoor relative humidity levels in occupied homes. The study scope extends across various climate zones where the wall construction is designed to substantially increase thermal performance and whole-house air sealing achieves much lower infiltration rates.

Empirical field moisture data is necessary to evaluate the impact of added wall material layers installed under realistic construction conditions and subject to occupant driven loads. This testing will help provide sufficient details to isolate the variables or combination of variables that may result in unsatisfactory moisture performance of common wall system designs used in high performance homes. Likewise, the field data provides a unique perspective on the cyclic behavior of wall systems as it pertains to variable moisture characteristics both inside and outside the thermal enclosure.

The purpose of this ongoing effort is to evaluate wall systems designed and installed by builders in the field as part of their commercial enterprise. In some cases, deviations from the builder's standard practice in terms of material selection and wall layers were requested to provide a comparative measurement of wall system designs in the same house environment. The wall system designs vary across climate zones and are based on current best practices from construction experience and building science knowledge from manufacturers and industry professionals.

[1] Home Innovation Research Labs, August 2014, Moisture Performance of Walls in Energy Efficient Homes, Upper Marlboro, Maryland. (The report is available for download at www.homeinnovation.com.)

BACKGROUND

With the new code requirements for highly insulated wall systems, concerns were raised by builders through the NAHB committees of potential moisture problems in walls when new materials are layered in and outside of the wall cavity in these new wall designs. To better understand the moisture response of the wall system, an effort to develop a base of wall cavity moisture characteristic field data was embarked upon in 2010. Initial wall moisture measurement results were obtained for a select set of homes with reported OSB buckling in the Midwestern states and Pennsylvania. The homes were located in cold climates (Climate Zones 5 and 6) or at the boundary between the cold and mixed-humid climates (Climate Zone 4).

This original monitoring effort provided details on OSB expansion characteristics, the air-tightness of the test homes, wall cavity moisture characteristics including the OSB moisture content, the temperature and humidity in the cavity near the OSB panel, and the indoor temperature and humidity (NAHB Research Center, 2012). All of the homes in that study were framed 2x4, except for one 2x6 framed home, and used standard batt insulation with Kraft facing. The infiltration rate for all of the homes was less than 4 ACH50 (ranging from 2.4-3.7 ACH50). The field test results indicated that some OSB panels had expansion characteristics that could potentially exceed the standard recommended gap between panels. For some monitored wall cavities, the OSB moisture content exceeded 20%, with one wall cavity exceeding 25%. The wall systems monitored exhibited a cyclic response such that, as expected, winter moisture content levels were higher than summer levels. Summer levels were typically below 12% moisture content and winter levels ranged between 12% and 20% moisture content with some notable excursions to over 25%.

Analytical tools such as WUFI simulation software[2] or simplified "dew point" calculations are used to analyze the moisture characteristics of a framed wall system given assumed exterior and interior environmental conditions. Simulation estimates have a range of capabilities depending on the software and may include specific material characteristics, dimensional heat flows, effects of layered vs. parallel-path material installation, effects of air leakage and solar effects on the exterior surfaces, and other variables that can impact moisture and heat transfer. Calculations to estimate the potential for condensation in the cavity near the sheathing provide a general framework for wall design that limits moisture-related risk but do not generally predict the resulting moisture content of materials such as the sheathing. Also, these calculations are dependent on the variable mix of indoor and outdoor temperature and humidity conditions.

However, these analysis tools are the least cost approach to evaluating wall designs that are resistant to problematic moisture conditions such as mold growth and material degradation. While software tools and design methodologies are continually improved, there is a need for field data to complement and validate the software analysis. The field data can provide the tangible material response to actual environmental conditions. This relationship is important since it accounts for the variations of diurnal occupant and environmental drivers, whereas many analysis tools rely on long term averages. Interior relative humidity is one such driver that is difficult to predict since it is very specific to occupant behavior.

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[2] WUFI is software for calculating the coupled heat and moisture transfer in building components.

The ongoing field monitoring effort described herein provides both the measured conditions in the home and in the wall cavity near the exterior sheathing. The moisture characteristics are reported on a daily average basis; however, higher resolution data is available should a specific measured result require more detail. Field monitoring provides a snapshot of actual conditions encountered and thus can help provide confidence in assumptions used in analytical tools. The obvious limitation to field measurements is the relatively narrow band of information provided unless a large sample size is available. This report provides a set of field data for high performance framed wall assemblies to identify the range of wall cavity moisture conditions and provides an introduction to the cyclic nature of the moisture characteristics in walls. The data can also be used to catalog wall systems that, under the documented conditions, appear to function in a manner that would not be expected to lead to moisture problems.

RESEARCH METHODOLOGY

In this project, the research methodology used for the field tests was developed in conjunction with NAHB members including builders, manufacturers, building scientists, and others related to the building industry. The methodology incorporates the following general outline:

- Identify test homes in select climate zones based on a minimum set of design criteria (IECC 2012);
- Collect relevant design, construction, and material data for each selected test home;
- Locate and install wall cavity moisture sensors in select wall sections;
- Compile relevant "as-built" construction documentation and infiltration test results for each selected home;
- Compile and chart moisture-related data; and
- Compile a matrix of climate-based wall assemblies and documented moisture characteristics.

This report summarizes all the field test data acquired since 2011 for the test homes in the study. This three-year set of monitoring data enabled Home Innovation to assess repeatability of the results and identify any changes to the environmental conditions or the response of the wall cavity moisture characteristics to changing environmental conditions.

Research Home Criteria and Selected Locations

Using a network of builder relationships throughout the U.S., a matrix of homes was developed that included climate zone and wall system variables. Efforts were made to select multiple homes in one climate zone with similar wall systems to provide more data for any given design. The focus of the study was on homes located in Moist climate zones.

The builder or the builder's representative provided all documentation of the house construction details, installation of sensors, and infiltration measurements.

Builders and homes were solicited based on following minimum requirements:

- Insulation levels that meet or exceed prescriptive requirements of the 2012 IECC;
- Infiltration target rate of 3 ACH50 (5 ACH50 in Climate Zone 2) per the 2012 IECC; and
- Whole-house ventilation using exhaust fans or a dedicated ventilation system.

A total of 22 homes were identified by the Home Innovation Research Labs for acceptance into the study. Figure 1 diagrams the locations of the 22 test homes.

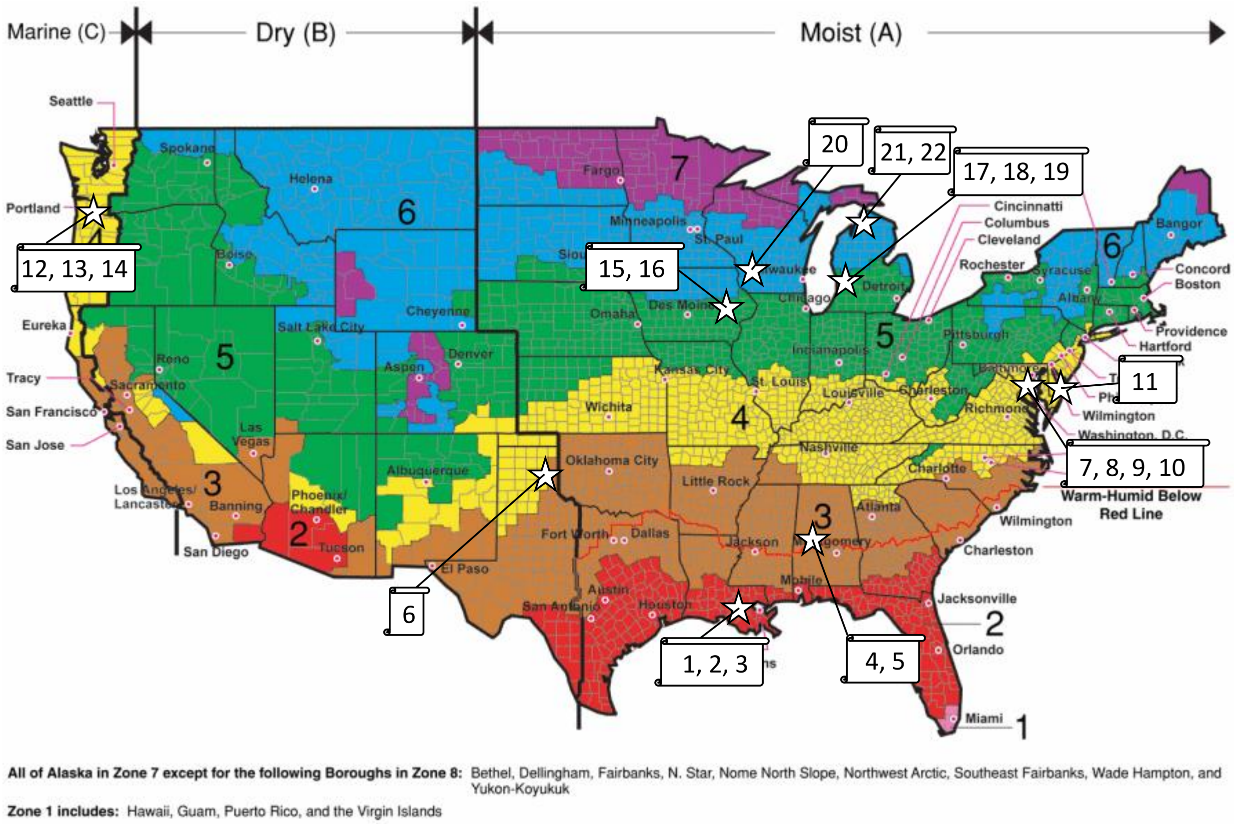

Figure 1. Map Showing Locations of Test Home Sites

A summary of the test house locations and other key relevant parameters is provided in Table 1. Blower door tests were used to determine infiltration rates and were performed after completion of construction.

Table 1. Summary of Test Sites

Test Site	State + ID	Climate Zone	Conditioned Floor Area, ft^2	Foundation	Infiltrat. ACH50	Ventilation	Monitoring Start Date
1	LA1	2A	1,896	crawlspace	4.4	Exhaust fans	3/30/2012
2	LA2	2A	1,896	crawlspace	4.3	Exhaust fans	3/30/2012
3	LA3	2A	1,896	crawlspace	2.0	Exhaust fans	3/30/2012
4	AL1	3A	1,094	slab on grade	1.3	Exhaust fans	2/17/2012
5	AL2	3A	1,094	slab on grade	2.2	Exhaust fans	2/17/2012
6	TX1	3A	2,115	slab on grade	1.8	HRV	6/30/2012
7	MD1	4A	4,407	basement	1.9	RA supply	5/24/2011
8	MD2	4A	4,648	basement	2.3	RA supply	12/8/2011
9	MD3	4A	4,371	basement	2.4	RA supply	11/10/2011
10	MD4	4A	4,486	basement	2.3	RA supply	11/9/2011
11	DE1	4A	4,893	basement	1.0	RA supply	1/26/2012
12	WA1	4C	3,199	slab on grade	3.1	Exhaust fans	11/1/2012
13	WA2	4C	2,735	slab on grade	3.4	Exhaust fans	10/3/2012
14	WA3	4C	2,815	slab on grade	2.2	HRV	4/25/2013
15	IA1	5A	5,293	basement	<2.0	HRV	11/8/2012
16	IA2	5A	3,256	basement	<2.0	HRV	12/1/2012
17	MI1	5A	1,352	basement	3.4	ERV	12/14/2012
18	MI2	5A	1,352	basement	3.3	ERV	12/14/2012
19	MI3	5A	1344	basement	1.5	ERV	1/4/2013
20	WI1	6A	1,368	slab on grade	<4.0	HRV	1/20/2012
21	MI1	6A	4,318	basement	0.8	ERV	12/17/2011
22	MI2	6A	1,261	basement	0.9	ERV	12/14/2012

Wall System Configurations and Sensor Locations

The purpose of this testing is to document the moisture characteristics of wall systems that have insulation levels that meet or exceed the prescriptive minimums established in the 2012/2015 IECC, EPA ENERGY STAR Certified Homes program[3], and the DOE Challenge Home program[4]. In some cases with the agreement of the builder, multiple wall configurations were employed in the same house. The purpose is to provide more cases of comparative wall systems that experience the same environmental conditions. Table 2 outlines the wall configurations for each Test House by climate zone. Appendix C shows a detailed diagram of each wall. The majority of walls did not have a dedicated interior vapor retarder (only gypsum and standard primer/paint). There were a total of four test homes with a dedicated interior vapor retarder (Test Home 4 – Kraft paper [Class II]; Test Homes 15&16 – polyethylene [Class I]; Test Home 20 – paint [Class III]).

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[3] Find more at www.energystar.gov.

[4] Information about the DOE Challenge Home program can be found at www.energy.gov.

Table 2. Wall Configurations in Test Houses

Test Site	Wall Ref.	State + ID	CZ	Framing	OSB	WRB[c]	Ext. Insulating Sheathing and Nominal R-value[a]	Cavity Insulation and Nominal R-value[b]	Interior Vapor Retarder/Barrier	Exterior Cladding
1	A	LA1	2A	2x4	Y	Y	N/A	Fiberglass Batt (R13)	Kraft paper	Fiber Cement (FC)
2	B	LA2		2x4	Y	N	1/2" Foam (R3)	Spray Cellulose (R15)	Kraft paper	Vinyl Siding (VS)
3	I	LA3		2x6	Y	Y	N/A	Spray Rockwool (R24)	Gypsum/paint	L.P. Smart Siding
				2x6	Y	Y	Reflective WRB (E/W)	Spray Rockwool (R24)	Gypsum/paint	L.P. Smart Siding
4	C	AL1	3A	2x4	Y	N	1" XPS Foam (R5)	Fiberglass Batt (R13)	Kraft paper	Vinyl Siding
5	G	AL2		2x4	Y	Y	N/A	Closed Cell Foam (R18)	Gypsum/paint	Vinyl Siding
6	P	TX1		2x6	Y	Y	N/A	Open Cell Foam (R16)	Gypsum/paint	Brick Veneer
7	H	MD1	4A	2x6	Y	Y	N/A	Blown Fiberglass (R23)	Gypsum/paint	Fiber Cement
	U			(2) 2x6	Y	Y	N/A	Blown Fiberglass (R46)	Gypsum/paint	Fiber Cement
8	H	MD2		2x6	Y	Y	N/A	Blown Fiberglass (R23)	Gypsum/paint	Fiber Cement
9	H	MD3		2x6	Y	Y	N/A	Blown Fiberglass (R23)	Gypsum/paint	Fiber Cement
10	H	MD4		2x6	Y	Y	N/A	Blown Fiberglass (R23)	Gypsum/paint	Stone Front, FC
11	H	DE1		2x6	Y	Y	N/A	Blown Fiberglass (R23)	Gypsum/paint	Vinyl Siding
12	Q	WA1	4C	Offset 2x4	Y	Y	N/A	Blown Fiberglass (R24)	Gypsum/paint	FC, Shake Siding
13	Q	WA2		Offset 2x4	Y	Y	N/A	Blown Fiberglass (R24)	Gypsum/paint	FC, Shake Siding
14	Q	WA3		Offset 2x4	Y	Y	N/A	Blown Fiberglass (R24)	Gypsum/paint	Fiber Cement
	D			2x4	Y	N	1" XPS Foam (R5)	Blown Fiberglass (R15)	Gypsum/paint	Fiber Cement
15	X	IA1	5A	2x6	Y	Y	N/A	Blown Fiberglass (R23)	4 mil Polyethylene	Stone Front, VS
16	X	IA2		2x6	Y	Y	N/A	Blown Fiberglass (R23)	4 mil Polyethylene	Stone Front, VS
17	R	MI1		2x6	Y	Y	1" XPS Foam (R5)	ccSPF Flash, Blown Cellulose (R21)	Gypsum/paint	Fiber Cement
	W			2x6	Y	Y	1" XPS Foam (R5)	Blown Cellulose (R21)	Gypsum/paint	Fiber Cement
18	R	MI2		2x6	Y	Y	1" XPS Foam (R5)	ccSPF Flash, Blown Cellulose (R21)	Gypsum/paint	Fiber Cement
	W			2x6	Y	Y	1" XPS Foam (R5)	Blown Cellulose (R21)	Gypsum/paint	Fiber Cement
19	T	MI3		Offset 2x4	Y	Y	1.5" XPS Foam (R7.5)	Blown Cellulose (R21)	Gypsum/paint	Vinyl Siding
	V			Offset 2x4	Y	Y	1.5" XPS Foam (R7.5)	ccSPF Flash, Blown Cellulose (R21)	Gypsum/paint	Vinyl Siding
20	J	WI1	6A	2x6	Y	N	1/2" Foil Faced Foam (R2.5)	Blown Cellulose (R19)	Vapor barrier paint	Cedar Siding
	K			2x6	N	N	1" Foil Faced Foam (R5)	Blown Cellulose (R19)	Vapor barrier paint	Cedar Siding
21	N	MI1		2x6	Y	N	1" XPS Foam (R5)	ccSPF Flash, Blown Fiberglass (R23)	Gypsum/paint	Vinyl Siding
	O			2x6	N	N	1" XPS Foam (R5)	ccSPF Flash, Blown Fiberglass (R23)	Gypsum/paint	Vinyl Siding
	L			2x6	Y	N	1" XPS Foam (R5)	Blown Fiberglass (R20)	Gypsum/paint	Vinyl Siding
	M			2x6	N	N	1" XPS Foam (R5)	Blown Fiberglass (R20)	Gypsum/paint	Vinyl Siding
	E			2x4	Y	N	2" XPS Foam (R10)	Blown Fiberglass (R13)	Gypsum/paint	Vinyl Siding
	F			2x4	N	N	2" XPS Foam (R10)	Blown Fiberglass (R13)	Gypsum/paint	Vinyl Siding
22	S	MI2	6A	2x6	Y	N	2" XPS Foam (R10)	Blown Fiberglass (R20)	Gypsum/paint	Vinyl Siding

ST – State; CZ – Climate Zone; N/A –not applicable/not installed

[a] The nominal R-value of the insulating sheathing.

[b] The nominal R-value of the cavity portion of the wall (excluding the insulating sheathing).

[c] The WRB represents spun-bonded polyolefin house wrap.

Table 3 organizes the different wall sections monitored in this study by construction type.

Table 3. Summary of Test Wall Configurations by Construction Type

Wall I.D.	Test Site	Wall Configuration	Climate Zones Where Installed
A	1	2x4, OSB, R13 batt cavity	2A
B	2	2x4, 1/2" XPS, OSB, R15 spray cellulose	2A
C	4	2x4, 1" XPS, OSB, R13 fiberglass batt	3A
D	14	2x4, 1" XPS, OSB, R15 blown fiberglass	4C
E	21	2x4, 2" XPS, OSB, blown fiberglass	6A
F	21	2x4, 2" XPS, blown fiberglass	6A
G	5	2x4, OSB, CC foam cavity	3A
H	7, 8, 9, 10, 11	2x6, OSB, blown fiberglass	4A
I	3	2x6, Foil WRB, OSB, R24 blown rock wool	2A
J	20	2x6, 1/2" Foil Faced Foam, OSB, R19 blown cellulose	6A
K	20	2x6, 1" Foil Faced Foam, R19 blown cellulose	6A
L	21	2x6, 1" XPS, OSB, blown fiberglass	6A
M	21	2x6, 1" XPS, blown fiberglass	6A
N	21	2x6, 1" XPS, OSB, flash/blown fiberglass	6A
O	21	2x6, 1" XPS, flash/blown fiberglass	6A
P	6	2x6, OSB, OC foam 4"-5" of cavity	3A/B
Q	12, 13, 14	2x6 plates, 2x4 offset studs, OSB, R24 blown fiberglass	4C
R	17, 18	2x6, 1" XPS, OSB, flash/blown cellulose	5A
S	22	2x6, 2" XPS, OSB, blown fiberglass	6A
T	19	2x6 plates, 1-1/2" XPS, OSB, 2x4 offset studs, blown cellulose	5A
U	7	(2) 2x6, OSB, blown fiberglass	4A
V	19	2x6 plates, 1-1/2" XPS, OSB, 2x4 offset studs, flash/blown cellulose	5A
W	17, 18	2x6, 1" XPS, OSB, blown cellulose	5A
X	15, 16	2x6, OSB, blown fiberglass, 4 mil polyethylene	5A

Each Test House has specific wall sections in which sensors are located. Generally, multiple sensors are placed in the north and east orientations with fewer sensors located in the west and south orientations since previous experience has demonstrated that the north and east orientations generally show the highest moisture content of sheathing (reduced or no direct solar radiation). Where the same homes have different wall configurations, additional sensors have been employed. Figure 2 shows an example layout of sensor locations identified for the builder. Once the sensors are installed, the builder returns this layout with ID labels from the individual sensor installed at that location. Figure 3 through Figure 5 show pictures of installed sensors.

In some wall cavities in the same test house, an effort was made to compare the moisture characteristics of the sheathing with and without a layer of foam (ccSPF) flash in the cavity. In another comparison, the wall cavity moisture characteristics are compared in homes with OSB sheathing and without sheathing. Sensors installed in cavities without OSB sheathing are installed in the wood framing near the foam sheathing (see Figure 6).

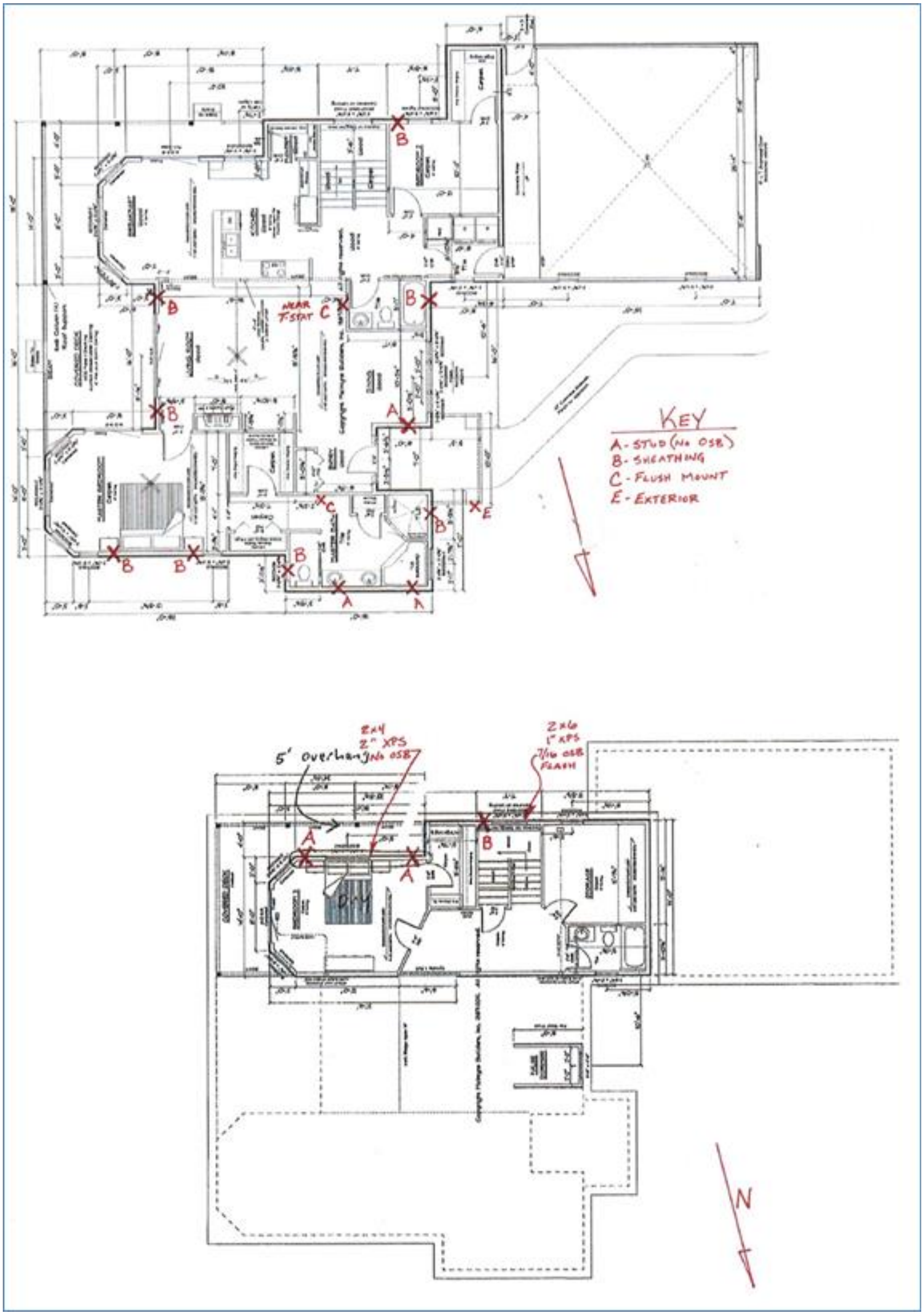

Figure 2. Example Sensor Layout for a Test House

Figure 3. Sensor Installed in OSB Sheathing That Will be Foamed Over in This Test House

Figure 4. Sensor Installed in OSB Sheathing That Will Not be Foamed Over in This Cavity

Figure 5. Sensor After Foam Flash and Before Insulation

Figure 6. Sensor Installed in Lumber in Cavity With Only Foam Sheathing

Builders of the test homes were asked to install the sensors in the identified locations prior to cavity insulation and identify a sensor ID with each location. Sensors were also installed in the interior of the home near the thermostat, in the main bathroom where wall cavity sensors were installed, in the basement (if applicable), and on the exterior of the home and preferably on the north side of the house. Where data from exterior sensors was not available, exterior conditions from a local weather station were used in the report.

Monitoring System and Data Collection

Once the house was completed, the builder installed a receiver box containing the sensor receiver and a transmitter. When activated, the receiver recorded data from each sensor on a minimum 15-minute basis and transmitted the data to a website. As long as the receiver had power, data was recorded by the receiver regardless of the internet connection. During a power outage, the sensor data was not recorded.

The data collected from the sensors included the temperature and relative humidity at the sensor body and, via screw pin terminals, the moisture content (from the conductance of the wood). The moisture content of the wood was temperature compensated based on the sensor temperature reading. The data set available based on sensor measurements included temperature, relative humidity, wood moisture content, dew point temperature, grains of moisture per pound of dry air, and the battery voltage of the sensor. The system is described in greater detail in the following section.

Sensors were installed in test homes in wall sections identified by orientation. For multi-story above grade homes, sensors were placed in both the first and second story wall sections. Interior sensors provide temperature and relative humidity data in the main living space and were located as near the thermostat as practical. A second interior sensor was located in the main bathroom and where wall cavity sensors are located. For basement foundations, a third interior sensor was located in the basement area to provide temperature and humidity data in the below grade portion of the home. An exterior sensor was used to record the ambient temperature and relative humidity and was shielded using a white PVC cap.

Sensor data was transmitted at a minimum on a 15-minute basis. All data was uploaded continuously to a website for data storage. The raw data was processed to calculate the dew point and grains of moisture based on the temperature and relative humidity. The moisture content data was calibrated to a standard wood moisture content based on the measured temperature at the wood surface.

The data set stored on the website was downloaded periodically and averaged on a daily basis for further analysis and charting. Each wall sensor was associated with the location in the room, orientation, and the wall and house configuration.

Monitoring of In-Service Environmental Conditions

Wall cavity moisture characterization of higher energy-efficient wall systems is used as a means to support system design methodologies by providing real life data under actual field conditions in various climates. The field data differs from modeling and laboratory testing as neither the interior nor ambient conditions that drive the moisture cycles in the wall system are controlled. In addition, the wall systems are constructed using typical methodologies and materials found in the field and as specified by the builders. It is the intent of the project to monitor field walls consistent with the builder’s standard practice without Home Innovation Research Labs engagement in the builder’s design and construction processes. This was generally achieved in most of the locations except for one location where the ventilation system was designed, specified, and inspected through support of a trade association, and in instances where the builder used specific types of wall materials in order to expand the variety of wall systems for the field study.

Monitoring System

Small Omnisense S-900-1 wireless sensors, shown in Figure 7 and Figure 8, were installed in walls in all field homes to measure the following parameters:

- Cavity Temperature (-40 to 185°F);
- Cavity Relative Humidity (0 to 100%);
- Cavity Dew Point Temperature; and
- OSB Sheathing Moisture Content (7 to 40%).

The temperature and relative humidity are measured by an internal sensing element located inside the sensor's plastic housing. The wood moisture content is determined using two screw pins driven into the sheathing and is based on the measured resistivity of the OSB material between the two pins. The sensors were prepared at Home Innovation with a protective covering that inhibits moisture or other materials from entering the sensor body through the battery compartment and the stand-off legs were removed so that the temperature and relative humidity sensor directly abutted the interior surface of the OSB. In this manner, the sensors were successfully instrumented in place where expanding foam covers the sensor body.

Figure 7. Omnisense S-900-1 Sensor

Figure 8. Screws used to Install Moisture Sensors

Sensor Calibration

The manufacturer-stated accuracy for the sensor models used is ± 2.0% relative humidity and ±0 .3°C. The Home Innovation Research Labs has performed numerous calibrations to verify both sensor accuracy and its correlation with moisture content. Moisture content correlation has been performed comparing to readings on handheld electrical conductance type moisture meters as well as comparing moisture content readings with gravimetric measurement calculations. The wood moisture content value reported through the sensor technology is the ratio of the water content of wood relative to the dry weight as a percentage. The sensor manufacturer calibrates their devices based on wood species and temperature compensation relationships outlined by the U.S. Department of Agriculture. For calibration purposes, a set of sensors were installed in OSB samples and placed inside an environmental chamber capable of controlling relative humidity and temperature. Figure 9 shows the set of sensors in the environmental chamber where temperature and humidity were tightly controlled at various levels for calibration purposes. At various levels of humidity and when equilibrium was achieved (equilibrium moisture content, EMC) based on specimen weight consistency, the specimens were removed, weighed, oven dried, and weighed again. The resultant ratio of the measurements provides the gravimetric moisture content of the specimen.

Figure 9. Sensors in the Environmental Chamber for Calibration

Figure 10 plots the sensor moisture content readings, the oven dry moisture contents and various reference curves from literature and shows the calibration relationship between the sensor reading and the measured OSB specimen moisture content. A curve for solid wood is also included as a reference. In all cases, the reported sensor reading is higher than the gravimetric calculation by 1-3% moisture content. The NIST (National Institute of Standard and Technology) reference curves align well with the gravimetric measurements. The OSB moisture content sensor readings presented in this report have been adjusted based on calibration using the gravimetric measurements as shown in Figure 10. Stud measurements are based on the sensor manufacturers' calibration to solid lumber species and reported without adjustment.

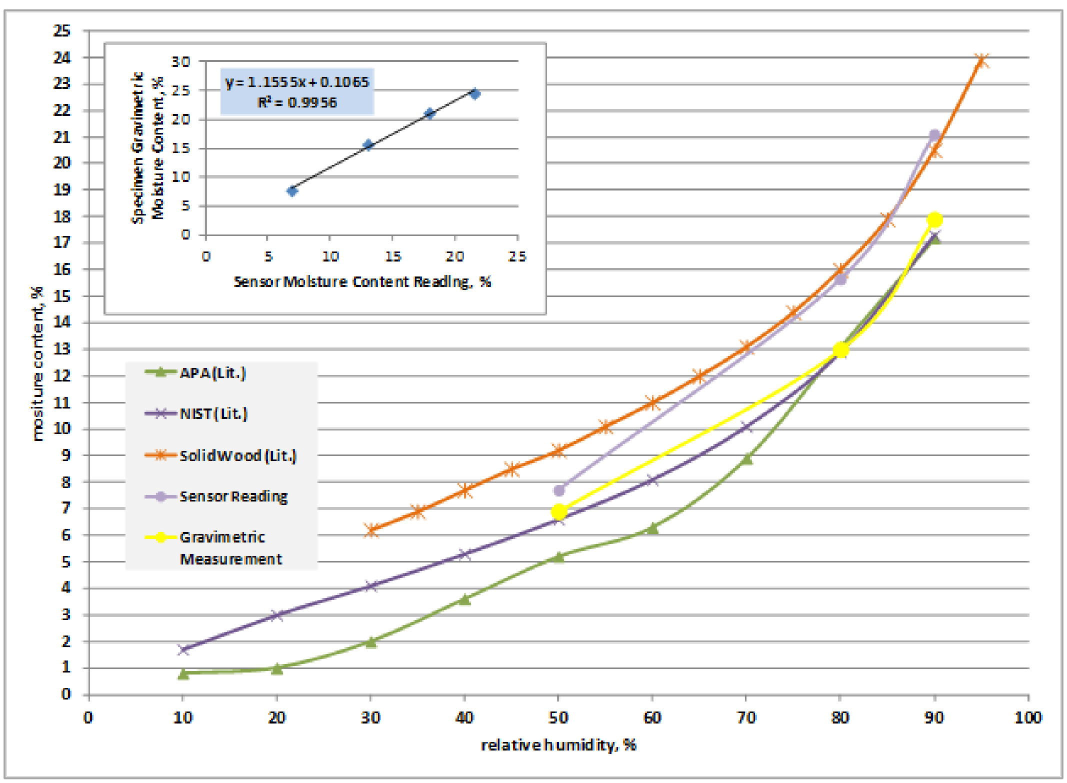

Figure 10. OSB Moisture Content Sensor Calibration Curves

FIELD MEASUREMENT RESULTS

The available recorded measurements for each home are presented individually to demonstrate the differences in wall orientation and, where available, to compare various wall configurations. Indoor and ambient environmental conditions are also presented to provide a context for the wall cavity moisture characteristics.

The primary characteristic shown in the charts below is the moisture content of the OSB. For measurements in the same wall cavity, the OSB moisture content is consistently higher than the framing OSB content (in addition the fiber saturation point for solid wood is higher than for OSB). Therefore, the OSB sheathing moisture content is always the more critical performance variable compared to framing moisture content. Framing moisture content is reported for locations where OSB was not used, e.g., foam sheathing was used as the primary sheathing material.

Wall orientation for each sensor is indicated on the graphs and tables by the first letter of the closest cardinal point as follows: S – south, W – west, N – north, and E – east.

Reference Moisture Content

The fiber saturation point refers to the moisture content where the wood fibers cannot absorb more water within the cellular structure. Though equilibrium moisture content varies for different wood species, generally 30% moisture content is considered the maximum fiber saturation point moisture content for solid wood (Wood Handbook, FPL). For OSB the equilibrium moisture content is three to five percentage points below that of solid wood products (Carll and Wiedenhoeft). An OSB fiber saturation point of 26% is used in this report.

OSB Sheathing Moisture Content Results by Test Site

A primary performance factor of interest in evaluating the moisture characteristics of wall systems is the peak level and seasonal cyclic behavior of the moisture content in the wood sheathing material. This is of particular interest because the wood sheathing provides structural support for the framing (and often the siding) and sustained high levels of moisture in the sheathing may compromise the long-term structural performance. Similarly, high levels of moisture at the sheathing, under certain conditions of temperature, can lead to mold growth on organic surfaces. Using the available data for each site, charts of the average sheathing (or where no sheathing is used, wood stud) moisture content are shown. The OSB moisture content sensor readings have been calibrated based on the sensor calibration discussion above. All figures in this section are daily average moisture content readings over the entire monitoring period for walls in an individual test house in the specific location. For reference, wood fiber saturation level estimates for OSB panels (estimated at 26% moisture content) are shown on all charts. Where multiple homes are located in the same climate zone, a numeric designation is used to identify the home. Summary analyses for each climate zone are provided following either a specific test home or a set of test homes.

Climate Zone 6A (Test Homes 20, 21 & 22)

Summary results for the daily OSB moisture content are shown in Figure 11 for Test Home 21 in Michigan, Climate Zone 6A. The following observations can be made:

- For the majority of the monitoring period, the OSB moisture content was well below the 26% OSB fiber saturation level in all walls. In two walls (East and North orientation), the OSB moisture content approached fiber saturation point in February of 2014 (one of the colder winters), but both walls were able to dry out quickly after the onset of spring. In both walls, 1-inch exterior XPS foam sheathing was used and the sensor was not covered with a flash coat of ccSPF.

- Where a wall section with ccSPF flash coat showed an increase in moisture content during the first winter following construction (e.g., yellow line for west bathroom below), a slower rate of drying was observed in the spring compared to walls without ccSPF flash coat. That wall section dried out to 15% moisture content towards the end of summer and remained at that general level for the duration of the monitoring period.

- Interior relative humidity was consistently low in the 29-32% range throughout the four winters (winter average relative humidity). An ERV was used and was effective at controlling the relative humidity levels in this very air-tight house (ACH50 at about 1.0).

- The initial peak moisture content of the north master bedroom wall OSB was 25% in the winter of 2011 – 2012. That wall was able to dry out to be around 15% during the 2012 summer and peaked at about 23% with the same pattern as the first year. The wall moisture content sensor stopped working after Nov. 2013. (The premature failure of the sensor is likely the result of extended exposure to high relative humidity and moisture content levels.) The rate of the moisture content rise for that sensor in the fall of 2013 suggests that this wall section was likely to again reach a moisture content level higher than the rest of the monitored walls. This observation (as also supported by the first bulleted observation) suggests that the use of 1 inch of XPS exterior insulation in Climate Zone 6 without closed-cell spray foam in the cavity (or another type of interior vapor retarder) does not provide adequate moisture performance in all situations.

- Use of a closed cell spray polyurethane foam (ccSPF) flash coat over the interior OSB lowers the moisture content of the OSB in the first winter after construction and helps maintain lower moisture content in subsequent years. Where ccSPF is not used, an interior vapor retarder with a variable vapor permeance may be recommended to reduce the vapor drive without creating a double vapor barrier condition.

- The uninsulated exposed cavity in an unheated garage follows a similar pattern as other sensors located in wall cavities adjacent to conditioned space.

- Use of exterior foam greater than 1 inch in thickness, generally results in lower OSB moisture content readings than wall systems with less or no exterior foam.

- Walls with 2 inches of exterior foam sheathing showed some of the lowest moisture content levels.

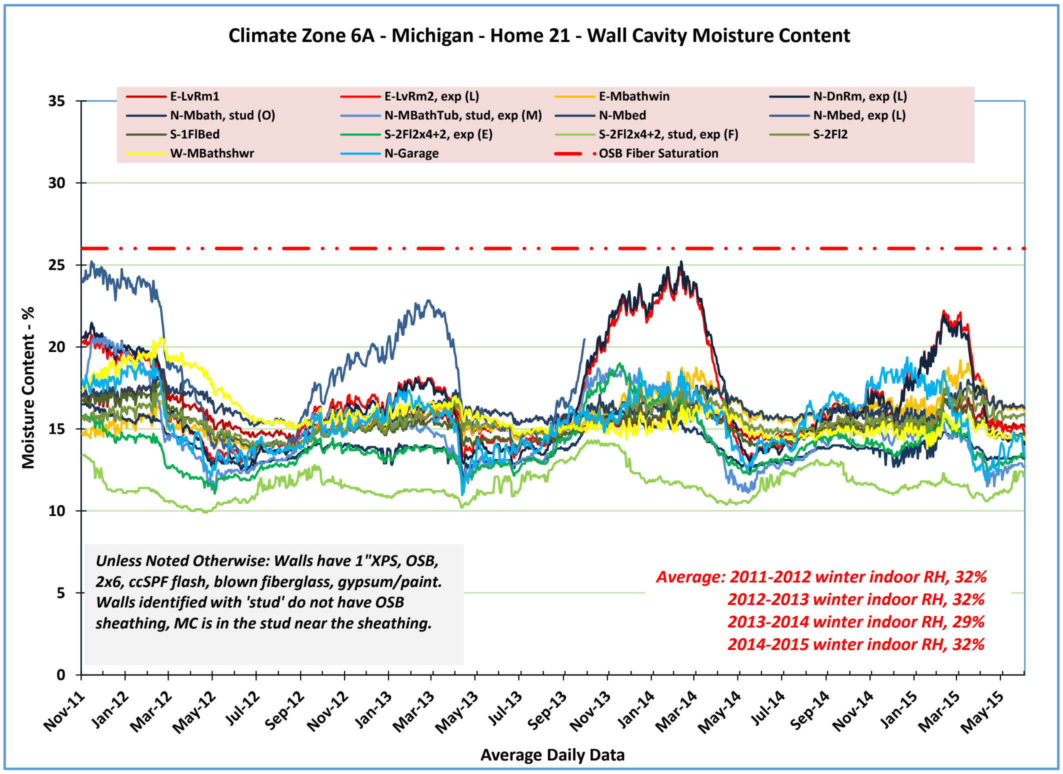

Figure 11. Daily OSB Moisture Content for Climate Zone 6A, MI (1), Test Home 21

Summary results for Test Home 22 in Michigan, Climate Zone 6A, are shown in Figure 12. (Note that the straight portions of the curves in Figure 12 indicate that the data acquisition system was interrupted and the field data were not recorded.) The following observations can be made:

- In the first winter season following construction, the OSB moisture content was high due to the high indoor relative humidity in the winter (46%), likely the result of construction moisture caused by drying of building materials. The peaks for the north wall of the 2nd floor bedroom and the east wall of the living room were at 26% OSB fiber saturation level for more than two months.

- All OSB panels dried out quickly after the first winter and stayed at a low moisture content of 10-12% during the summer of 2013. The winter moisture content peak values in the subsequent years were lower (by 5% or more) indicating reduced moisture loads after the construction moisture had a chance to dissipate. This observation is also supported by a 10-11% reduction in the average indoor relative humidity levels for the 2014 and 2015 winters. An ERV was used and was effective at controlling the relative humidity levels in this very air-tight house (ACH50 at about 1.0).

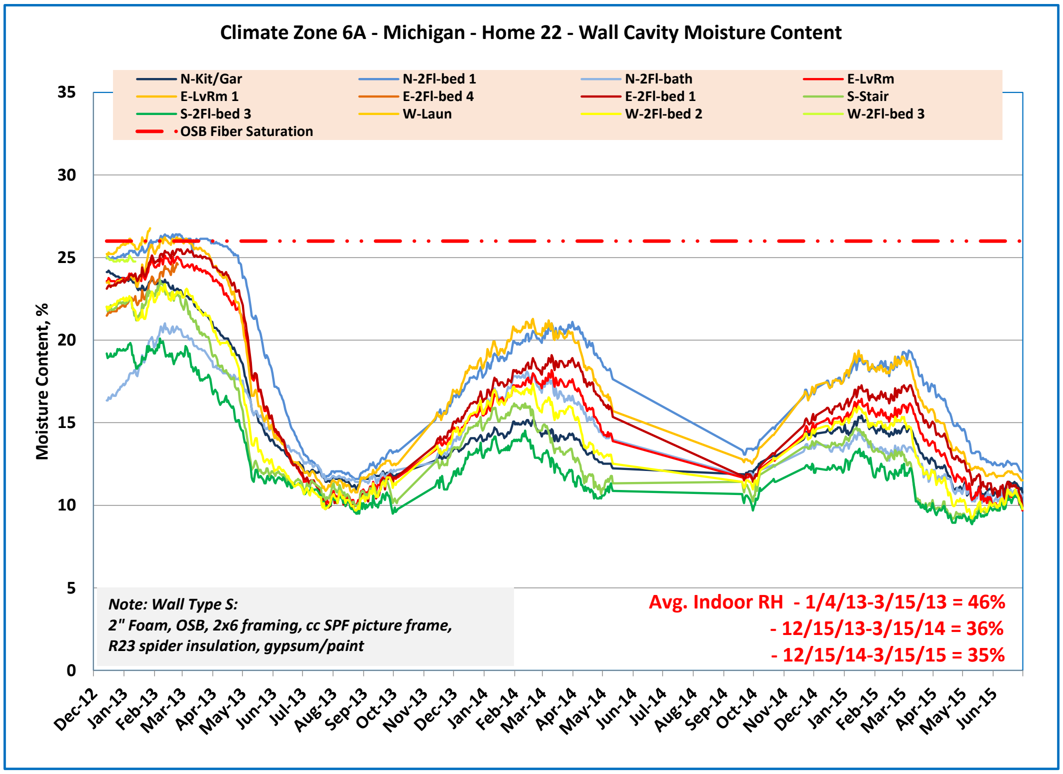

Figure 12. Daily OSB Moisture Content for Climate Zone 6A, MI (2), Test Home 22

Summary results are shown in Figure 13 for Test Home 20, in Wisconsin, Climate Zone 6A. At this test home, most of the sensors appeared to have suffered damage as they ceased reading following the installation of the insulation, likely due to the use of wet blown cellulose insulation. Based on the limited data set from several sensors that worked, the following observations can be made:

- In the first winter season following construction, the OSB and lumber moisture content was high as a result of absorbing moisture from the wet-blown cellulose insulation.
- At two of the three locations (kitchen and laundry room) where sensors continued reading, the wood dried out during the first summer and stayed consistently below 13% over the next 3 years with 2-3% seasonal fluctuations. It is noted that the OSB (red line) dried out faster than the lumber (light blue line), but the OSB had slightly higher seasonal fluctuations.
- At the master bedroom (dark blue line), the drying was slower and required about 16 months for the lumber moisture content to drop below 15%. The moisture levels stayed at those levels for the next two years with small (1-2%) seasonal fluctuations.
- All sensors showed high initial moisture content, even in solid wood members, and it required over a year for wall materials to dry out. After the construction moisture was removed, the system continued to respond in a stable manner with only minor seasonal fluctuations.
- Although the exterior insulation didn't achieve the prescriptive R-value level for 2x6 walls without an interior vapor retarder in Climate Zone 6A (R11.25 minimum), based on this very

limited data set the performance appears stable. This performance is attributed to the use of rated vapor retarder paint and cellulose cavity insulation which has moisture storage capacity reducing seasonal cyclic fluctuation.

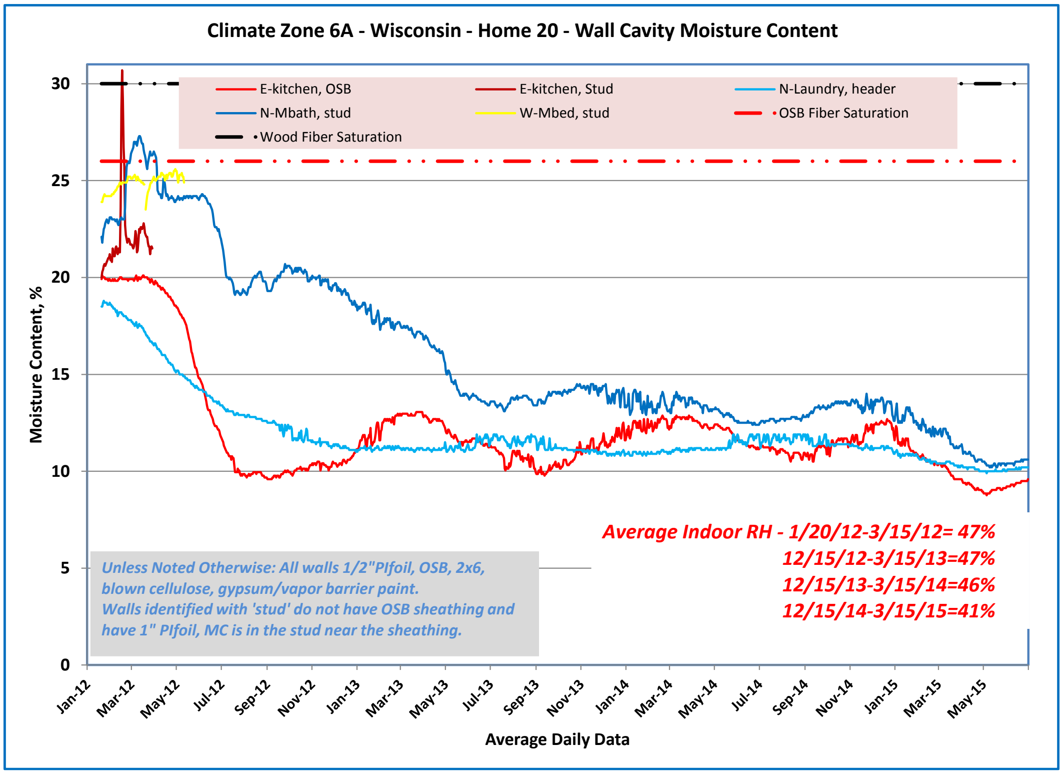

Figure 13. Daily OSB Moisture Content for Climate Zone 6A, WI, Test Home 20

Figure 14 summarizes outdoor temperature and cumulative precipitation for the MI site in Climate Zone 6A for the monitoring period. The 2014-2015 winter had the lowest outdoor temperature with the daily average reaching -9°F.

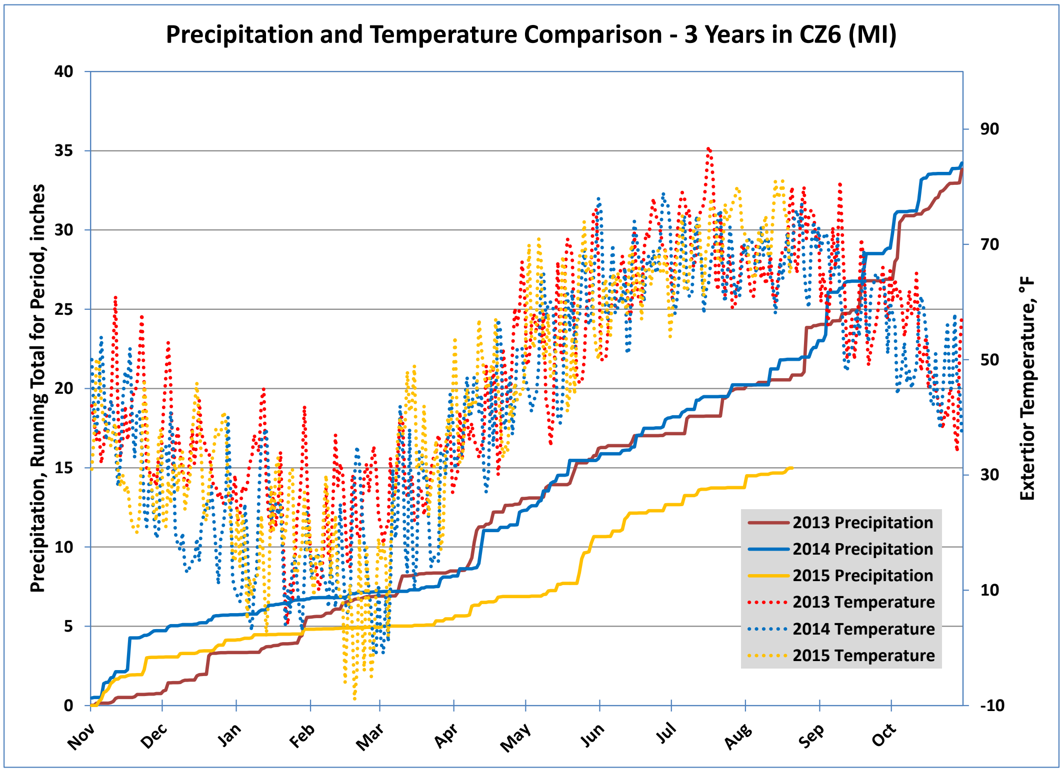

Figure 14. Climate Zone 6A Precipitation and Temperature Comparison

Figure 15 is provided as a summary for all walls in Climate Zone 6A. It shows the daily average moisture content measurements for each wall section for the entire monitoring period from 2011 to 2015. This condensed format allows for a quick overview of the performance of the wall systems as discussed previously in this section. Only data from the north-facing walls are used because this orientation generally shows the highest, sustained moisture levels in the home and all other wall orientations would be equal or less in seasonal average levels. The seasonal interior relative humidity levels are reported in Table 4.

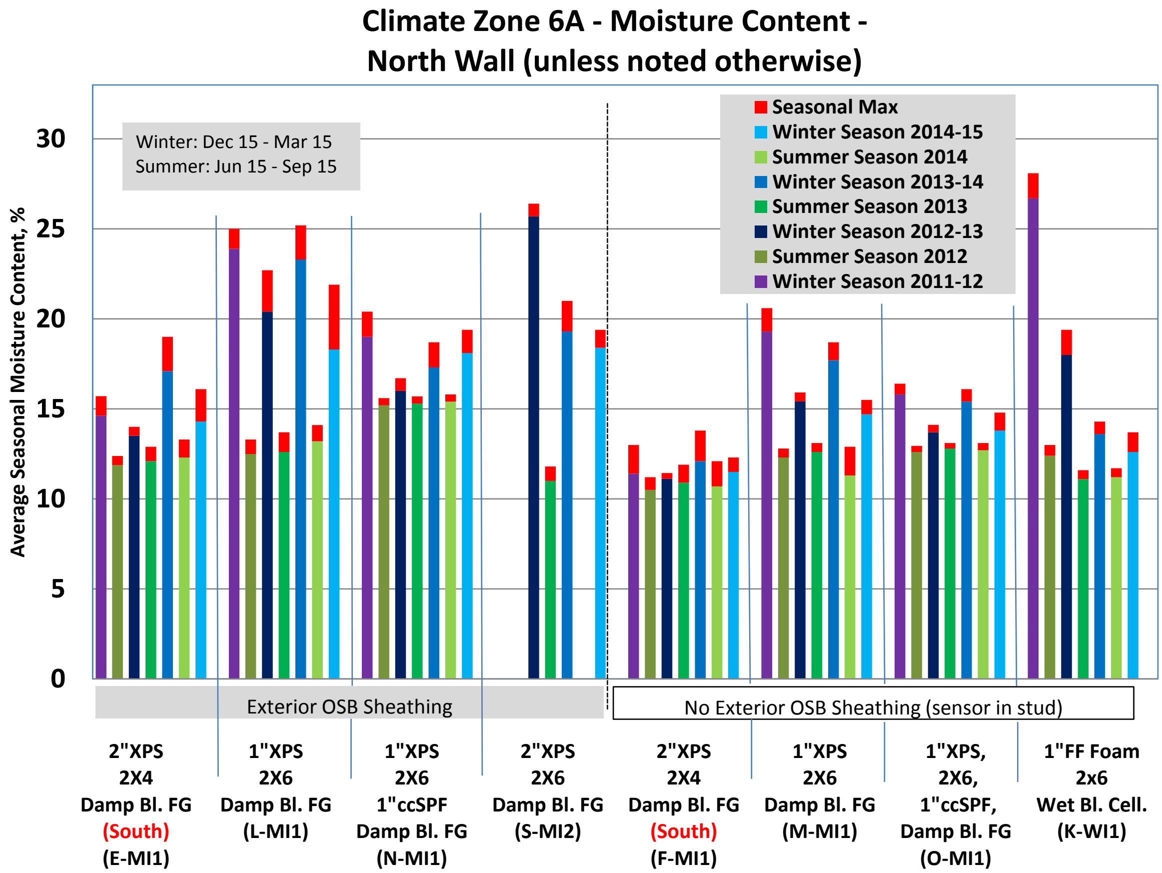

Figure 15. Climate Zone 6A Summary Moisture Content Data

Table 4. Winter Average Seasonal Indoor Relative Humidity for Climate Zone 6A Test Walls

Wall Type I.D.	Interior Relative Humidity			
	2011-2012	2012-2013	2013-2014	2014-2015
E, L, N, F, M, O	32%	32%	29%	32%
S (MI2)	N/A	46%	36%	35%
K (WI)	47%	47%	46%	41%

Climate Zone 5A (Test Homes 15, 16, 17, 18 & 19)

Summary results are shown in Figure 16 and Figure 17 for Test Homes 18 and 17, in Michigan, Climate Zone 5A. The following observations can be made:

1. <u>Test Home No. 18:</u>

- The OSB moisture content showed an upward trend reaching saturation levels in the 2x6 walls without ccSPF flash coat in the first winter following construction. These high moisture content levels sustained for up to six months. Starting mid to late spring, the moisture content dropped at a relatively high rate down to about 15%. The peak moisture content values for the subsequent winters were below 23% indicating that the initial high levels were associated with construction moisture from the damp-sprayed cellulose insulation.

- Walls with ccSPF performed better in the first year (moisture content below 23%) and each subsequent year (stable moisture content at below 15% throughout the year). The ccSPF coat was effective at protecting the OSB from the construction moisture and the interior vapor drive.

- Walls with only blown cellulose insulation in the cavity (without ccSPF) and 1 inch of XPS exterior sheathing (R5) are susceptible to elevated OSB moisture content levels following construction and exhibit higher amplitude seasonal cycles. This observation is consistent with the conclusions drawn from other homes in Climate Zones 6A and 5A. If a smart vapor retarder is used to mitigate the winter upward cycles, the characteristics of the smart vapor retarder should be such that it does not significantly impede the drying of the construction moisture and any other incidental moisture that may be deposited in the cavity.

- An ERV was used in this house and was generally effective at controlling the relative humidity levels, with the highest winter interior relative humidity level of 38% in the 2014-2015 winter.

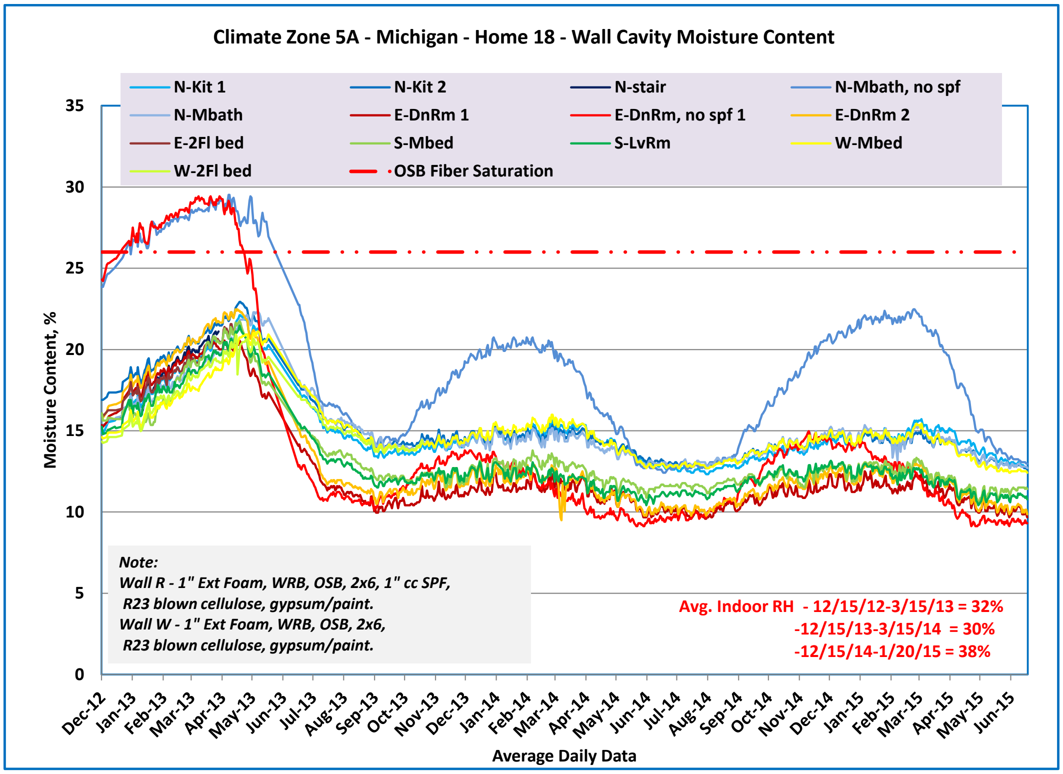

Figure 16. Daily OSB Moisture Content for Climate Zone 5A, MI (2), Test Home 18

2. Test Home No. 17:

- Due to the malfunction of sensors in this home, only portions of data were obtained for the winter of December 2012 to March 2015. As with Test Home 20, the high rate of sensor failure is likely caused by the sustained elevated moisture levels in the wall from the damp-sprayed cellulose insulation.

- Similar to Test Home 18, during the first winter season, the OSB moisture content showed an upward trend to a maximum 32% in the 2x6 walls without ccSPF flash coat, suggesting complete saturation of the sheathing. The OSB moisture content in the north master bathroom wall without ccSPF remained at the saturation level for six months. For both east-facing dining room walls without ccSPF, the OSB moisture content remained at 26% or higher for about four months.

- All walls with ccSPF showed reduced moisture content levels during the first winter ranging between 18% and 23%, below the 26% OSB fiber saturation mark.

- The walls with only damp-applied cellulose insulation in the cavity and 1 inch of XPS exterior sheathing do not provide adequate moisture control and exhibit elevated levels of OSB moisture content immediately after construction. Where an additional 1-inch flash coat of ccSPF was installed separating the cellulose and the OSB, the performance noticeably improved because of the water resistant and vapor retarding characteristics of the ccSPF.

- Data beyond the first year is limited for this house. While the drying capacity of the walls is clearly evident, the amplitude of the seasonal moisture cycles is not known. Because House 17 is effectively a replica of House 18, similar seasonal trends should be expected.

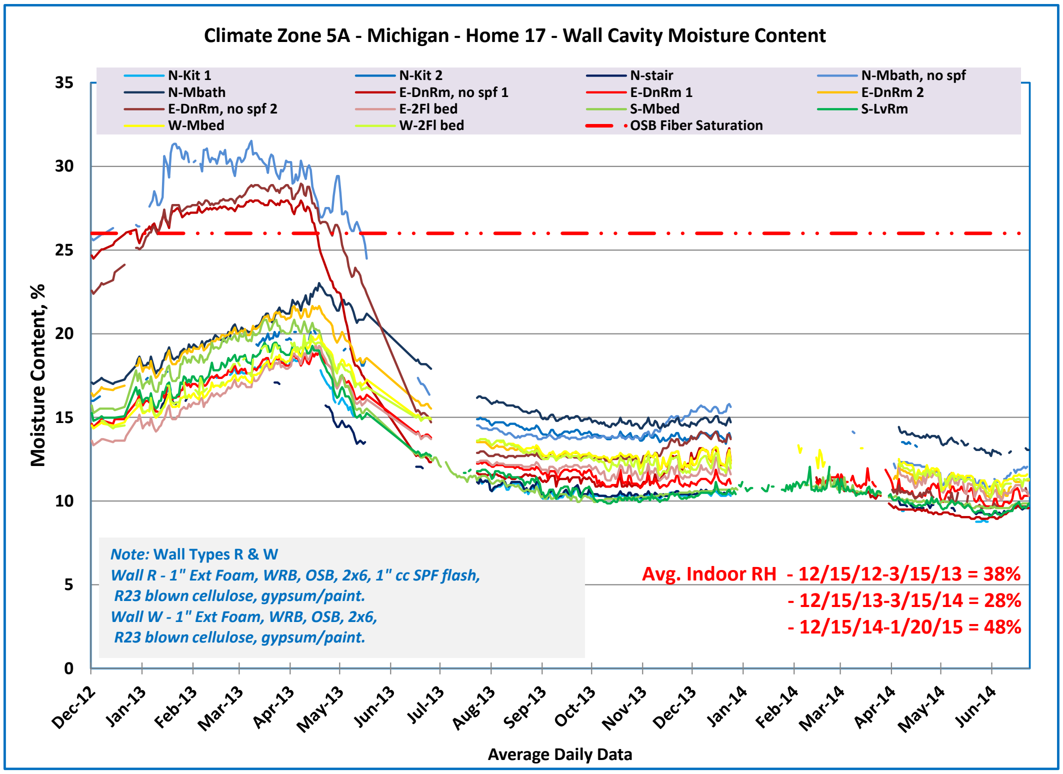

Figure 17. Daily OSB Moisture Content for Climate Zone 5A, MI (1), Test Home 17

Summary results are shown in Figure 18 for Test Home 19, in Michigan, Climate Zone 5A. The following observations can be made:

- As observed in other homes, the OSB moisture content showed an upward trend reaching saturation levels in the 2x6 walls without ccSPF flash coat in the first winter following construction. These high moisture content levels sustained for up to four months. Starting mid to late spring, the moisture content dropped at a relatively high rate down to below 15%. The peak moisture content values for the subsequent winters were below 20% indicating that the initial high levels were associated with construction moisture from the damp-sprayed cellulose insulation.

- Similar to Test Home 18, walls with ccSPF performed better in the first year (moisture content below 23%) and each subsequent year (stable moisture content at below 15% throughout the year). The ccSPF coat was effective at protecting the OSB from the construction moisture and the interior vapor drive.

- Comparing walls without ccSPF in Test Homes 18 and 19 during the 2014-2015 winter, it can be observed that walls with R7.5 on the exterior (1.5 inch XPS) were more effective at controlling OSB moisture content than walls with R5 (1 inch XPS).

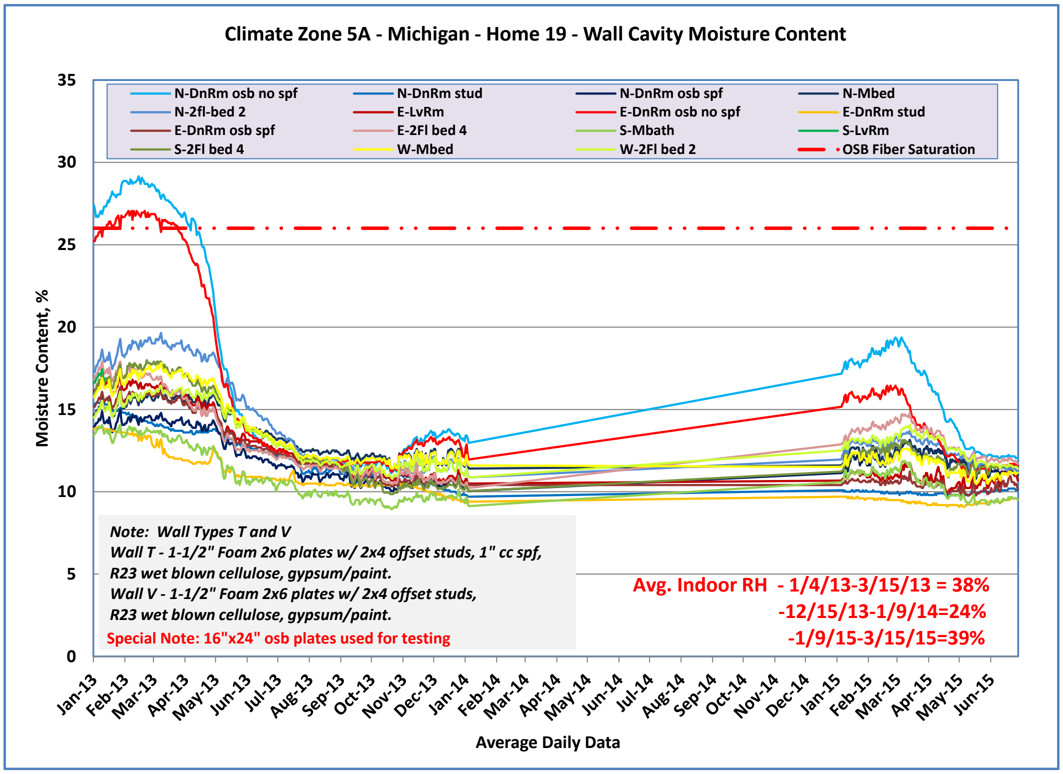

Figure 18. Daily OSB Moisture Content for Climate Zone 5A, MI (3), Test Home 19

Summary results are shown in Figure 19 and Figure 20 for Test Homes 15 and 16, in Iowa, Climate Zone 5A. (Note that the data acquisition system for Test Home 16 stopped functioning after the spring of 2013.) The following observations can be made:

- Sheets of 4-mil polyethylene used as an interior vapor barrier are effective at controlling vapor drive in conventional 2x6 walls. The OSB moisture content ranged between 8% and 14% during the monitoring period in both homes.
- There is an observed difference in the OSB moisture content levels between the two homes during the first winter season. The OSB moisture content for Test Home 15 is generally below 10%, whereas for Test Home 16 OSB moisture content levels as high as 14% are recorded at several locations. The difference was likely caused by the difference in indoor relative humidity: 40% in Test Home 16 versus 26% in Test Home 15. This effect is likely attributed to air leakage around the polyethylene.
- The moisture contents in the first winter after construction are generally flat for all sensors – another indicator of the effectiveness of polyethylene as a vapor retarder.

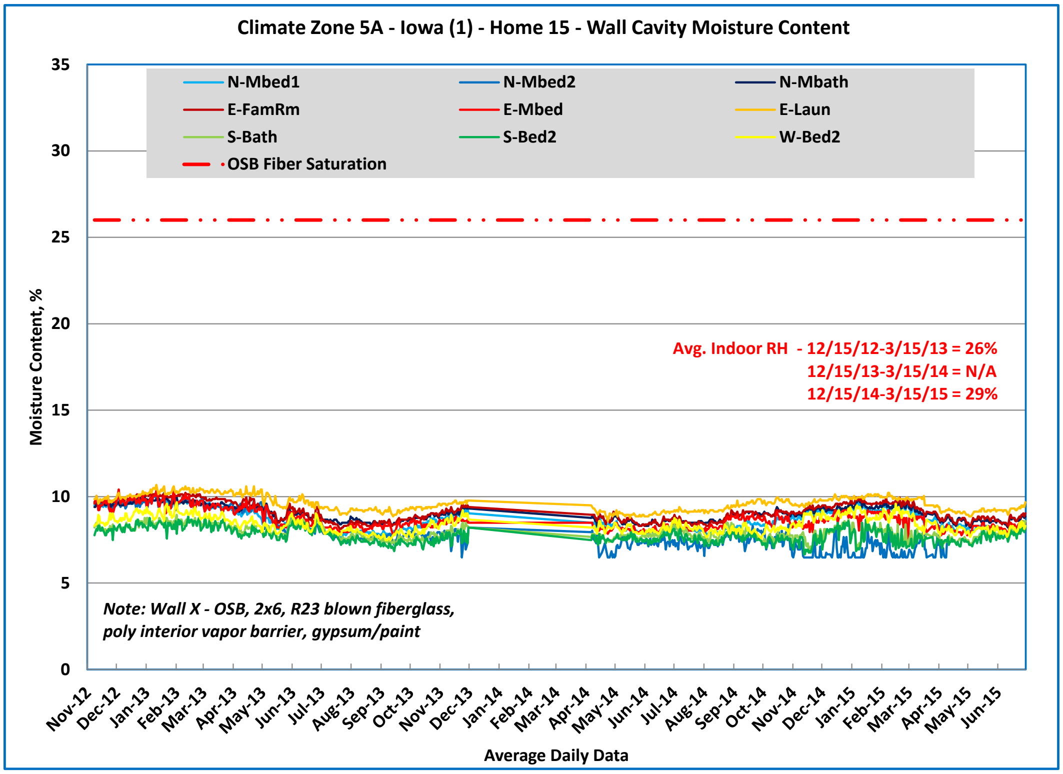

Figure 19. Daily OSB Moisture Content for Climate Zone 5A, IA (1), Test Home 15

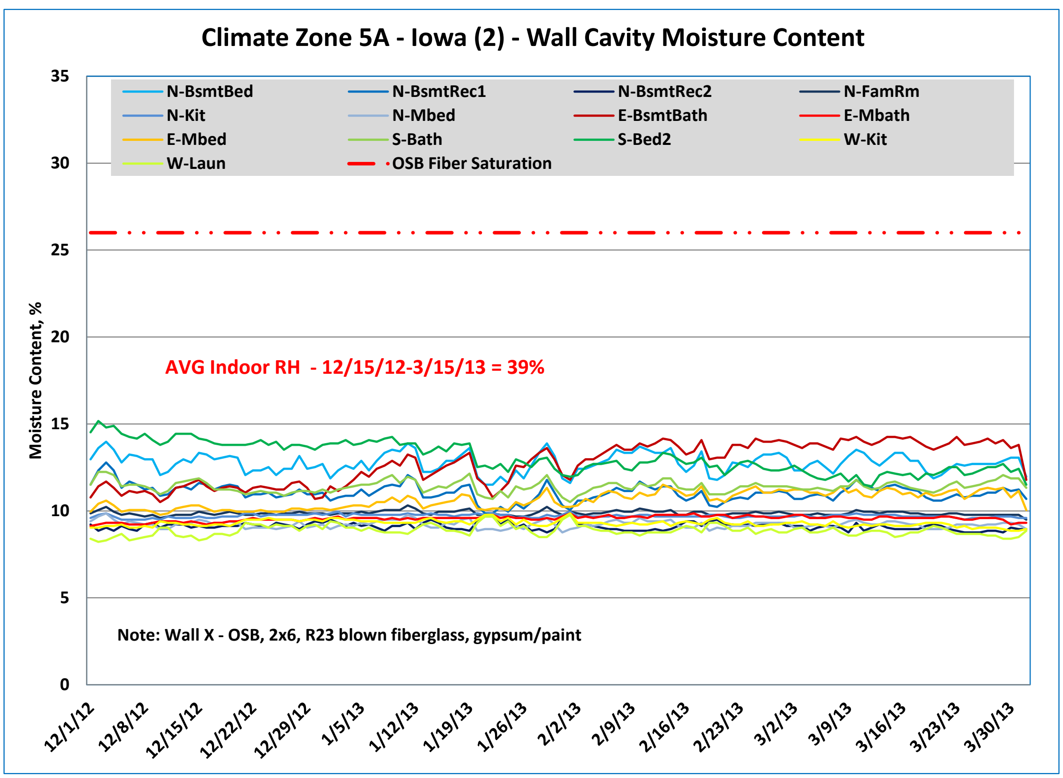

Figure 20. Daily OSB Moisture Content for Climate Zone 5A, IA (2), Test Home 16 for a 4-Month Period

Figure 21 summarizes outdoor temperature and cumulative precipitation for the MI site in Climate Zone 5A for the monitoring period. The winter temperatures reached 0°F. Figure 22 summarizes outdoor temperature and cumulative precipitation for the IA site in Climate Zone 5A for the monitoring period. The winter temperatures reached -10°F.

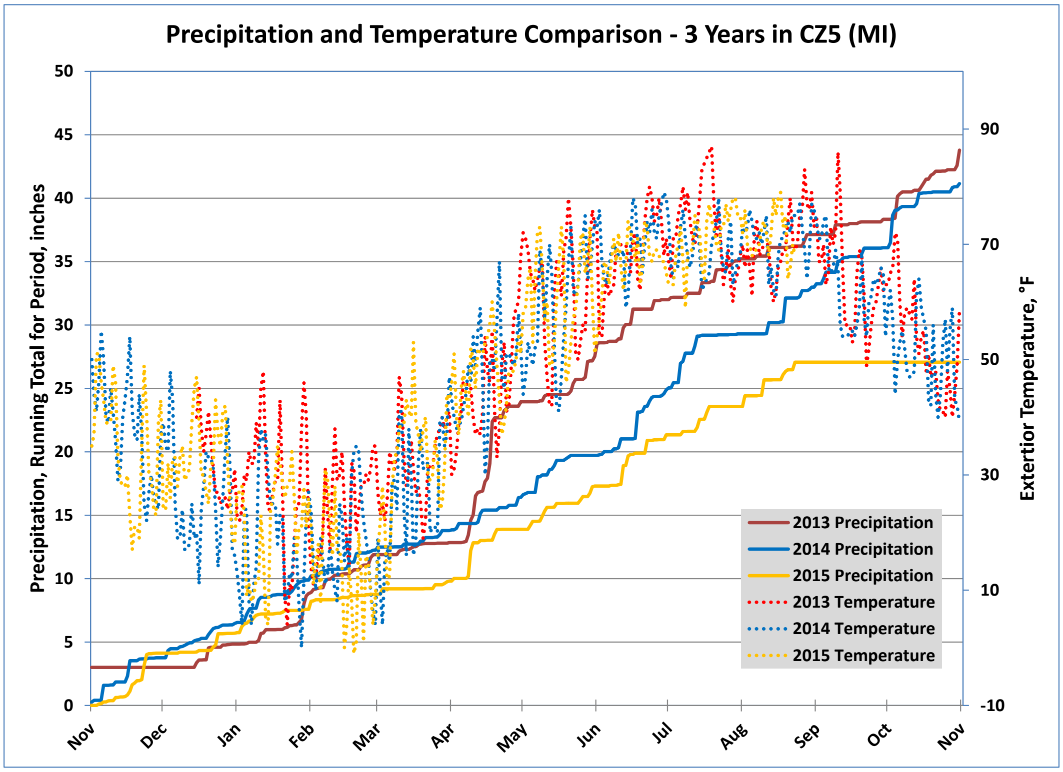

Figure 21. MI Climate Zone 5A Precipitation and Temperature Comparison

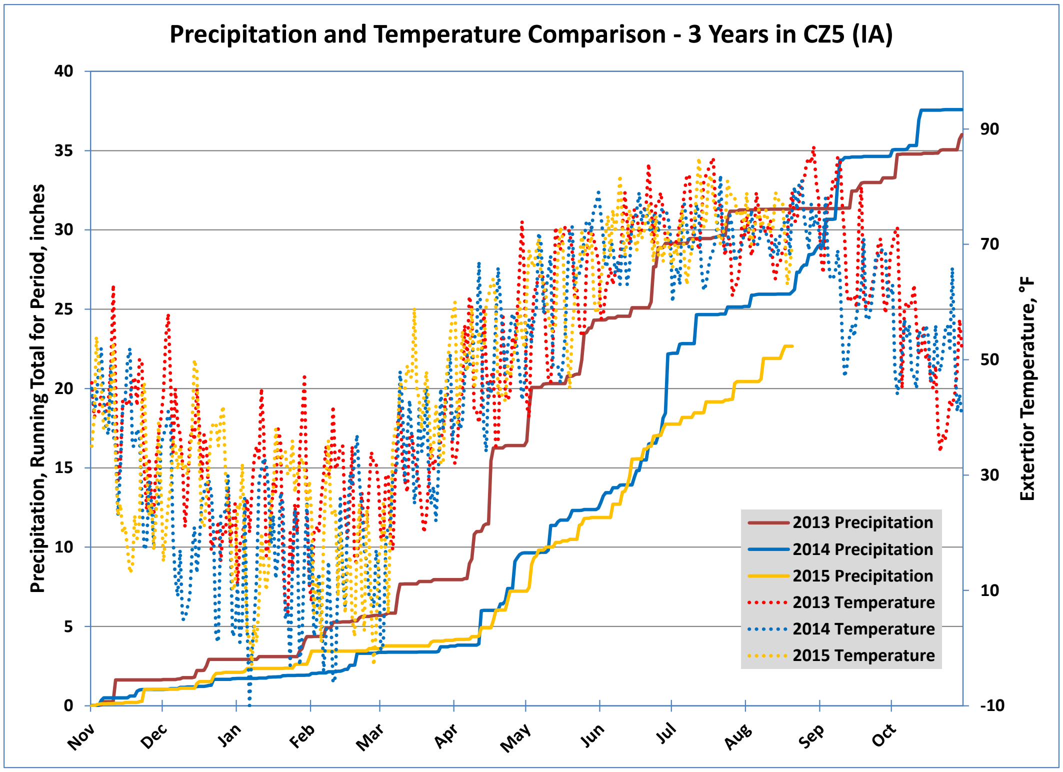

Figure 22. IA Climate Zone 5A Test House Precipitation and Temperature Comparison

Figure 23 is provided as a summary for all walls in Climate Zone 5A. It shows the daily average moisture content measurements for each wall section for the entire monitoring period from 2011 to 2015. This condensed format allows for a quick overview of the performance of the wall systems as discussed previously in this section. Only data from the north-facing walls are used because this orientation generally shows the highest, sustained moisture levels in the home and all other wall orientations would typically be equal or less in seasonal average levels. The seasonal interior relative humidity levels are reported in Table 5.

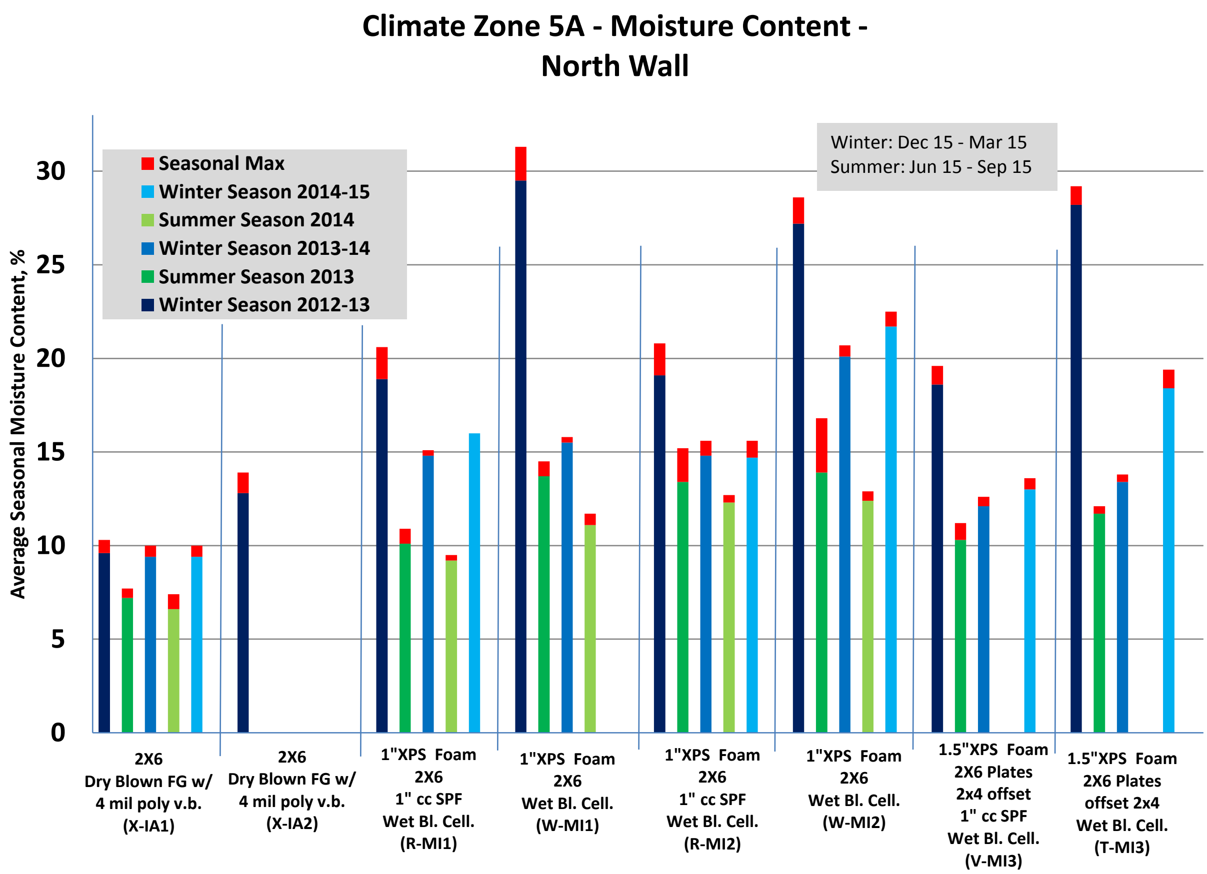

Figure 23. Climate Zone 5A Summary Moisture Content Data

Table 5. Winter Average Seasonal Interior House Relative Humidity for Climate Zone 5A Test Walls

Wall Type I.D.	Interior Relative Humidity		
	2012-2013	2013-2014	2014-2015
X (IA1)	26%	N/A	29%
X (IA2)	39%	N/A	N/A
R, W (MI1)	38%	28%	48%
R, W (MI2)	32%	30%	38%
V, T (MI3)	38%	24%	39%

Climate Zone 4C (Test Homes 12, 13, 14)

Figure 24 through Figure 27 show results for three Test Homes 12, 13, and 14 in Washington State, Climate Zone 4C. Because the builder didn't submit the sensor maps for these houses, the orientation of the walls is not known and not labeled on the graph. For Test Homes 13 and 14, interior sensors were not installed, thus interior relative humidity and temperature are not available. The following observations can be made:

1. Test Home 12:

    - Interior relative humidity was high in all three winters, with the first winter following construction having the highest interior relative humidity at 66%. The higher level of interior relative humidity in the first winter is likely caused by the remaining construction moisture within the house. It is noted that ventilation was provided using bathroom exhaust fans and didn't provide an effective mechanism for controlling interior relative humidity levels in this particular house.

    - While OSB sheathing at one location reached the saturation level and at several other locations approached saturation levels in the first winter, all walls dried out to 10% or less during the spring.

    - OSB moisture content elevated in the second winter but never exceeded 20%. The interior relative humidity levels were also lower in the second winter (58% vs. 66%).

    - Although interior relative humidity levels were high in this Climate Zone (4C), the impact on the OSB moisture content was not as pronounced as in Climate Zone 4A as discussed later in this report. This difference in response is likely the result of smaller temperature difference (and shorter duration of colder temperatures) between the indoor and outdoor environment (i.e., delta T) and the correspondingly smaller winter vapor drive.

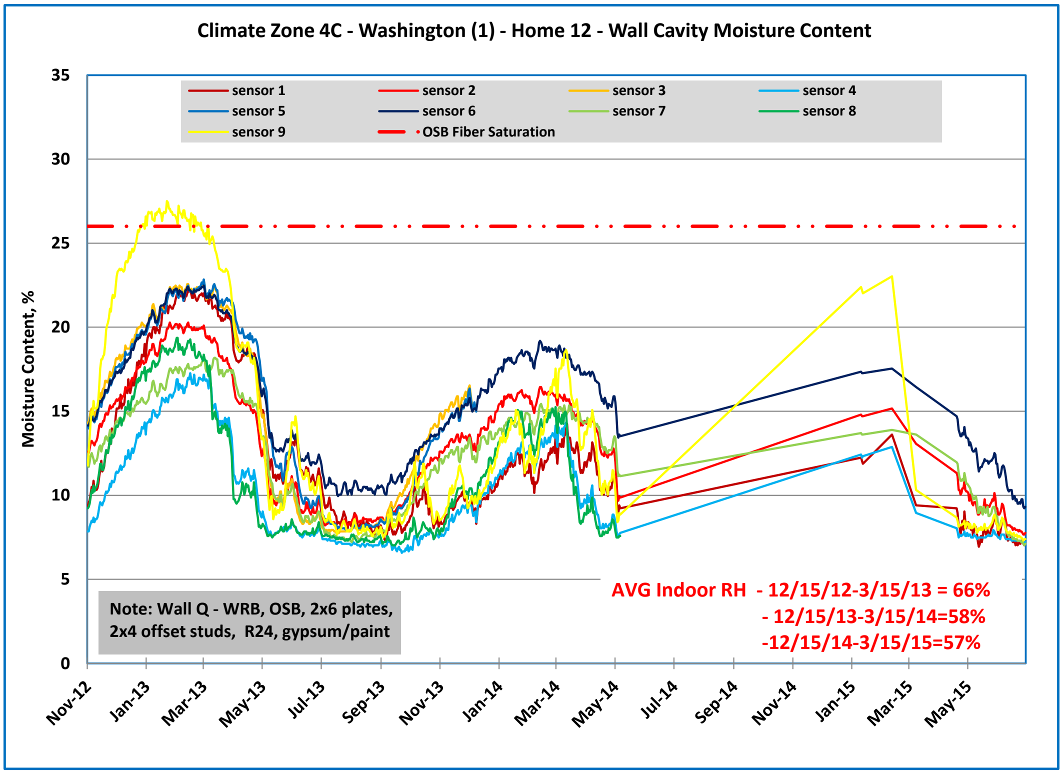

Figure 24. Daily OSB Moisture Content for Climate Zone 4C, WA (1), Test Home 12

2. Test Home 13:

- The seasonal cyclic response was consistent with Test Home 12, but with reduced amplitudes. The OSB peak moisture content remained below 19% in the first winter and at or below 15% in the next two winters, indicating an overall stable response.

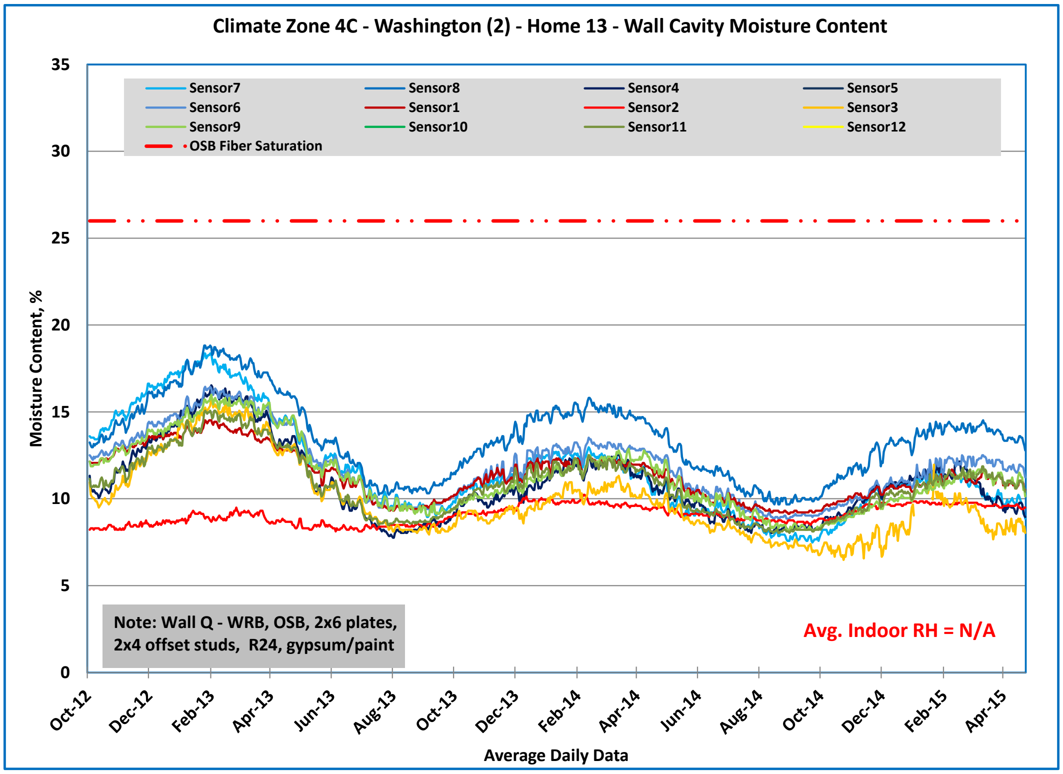

Figure 25. Daily OSB Moisture Content for Climate Zone 4C, WA (2), Test Home 13

3. Test Home 14:

- The trends observed in this house are not consistent with trends in the other two homes in Climate Zone 4C or other homes in Climate Zone 4A, with the exception of one sensor that showed an increase in OSB moisture content during the coldest 2013-2014 winter.
- Because of unsuccessful attempts for follow-up communications with the builder, it was not possible to further inquire about this house, its interior humidity levels, or any deviations in construction of this house to better understand the reasons for the observed performance. There are several possible explanations for the apparent reduction in OSB moisture content fluctuations relative to Test Homes 12 and 13, including:
    - The HRV ventilation system used in House 14 was more effective at controlling interior relative humidity levels compared to the exhaust-only ventilation used in Houses 12 and 13 resulting in reduced vapor drive.
    - An interior vapor retarder was used such as a rated paint or Kraft-paper-faced fiberglass batts.

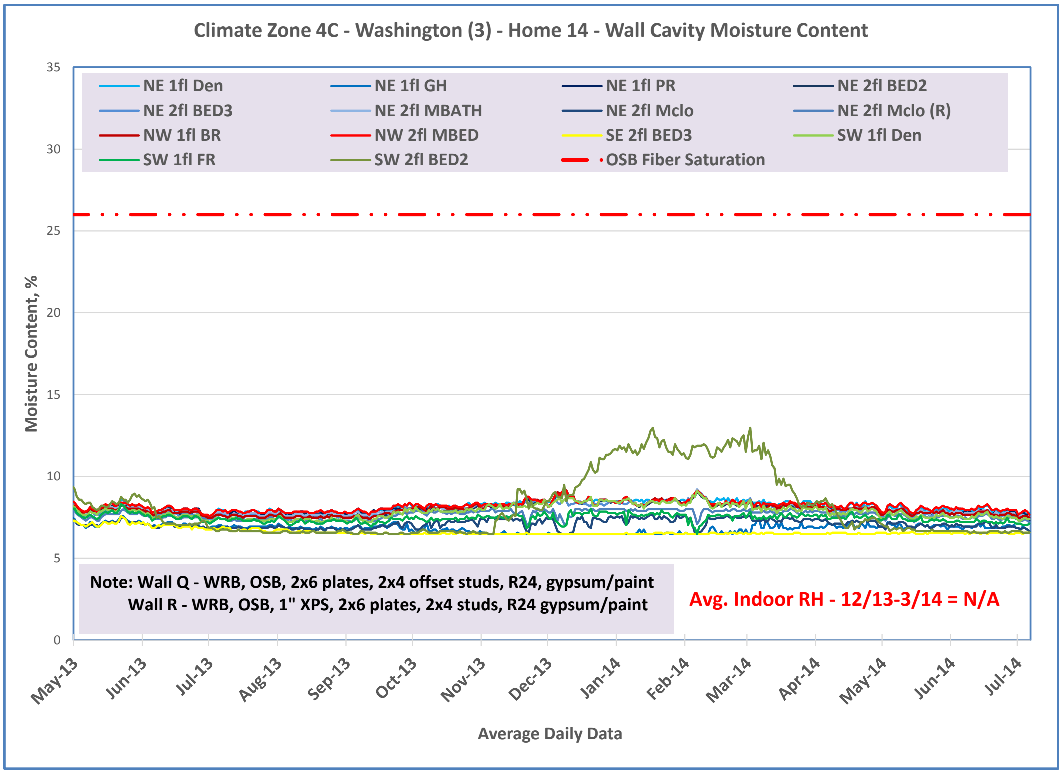

Figure 26. Daily OSB Moisture Content for Climate Zone 4C, WA (3), Test Home 14

The vapor-open wall design in this Climate Zone (4C) showed seasonal cyclic fluctuations with the moisture content level in general within acceptable performance range.

Figure 27 summarizes outdoor temperature and cumulative precipitation for the WA site in Climate Zone 4C for the monitoring period. The winter temperatures for the majority of the monitoring period stayed above 30°F with two short periods in the 2013-2014 winter when the temperature dropped to about 21°F.

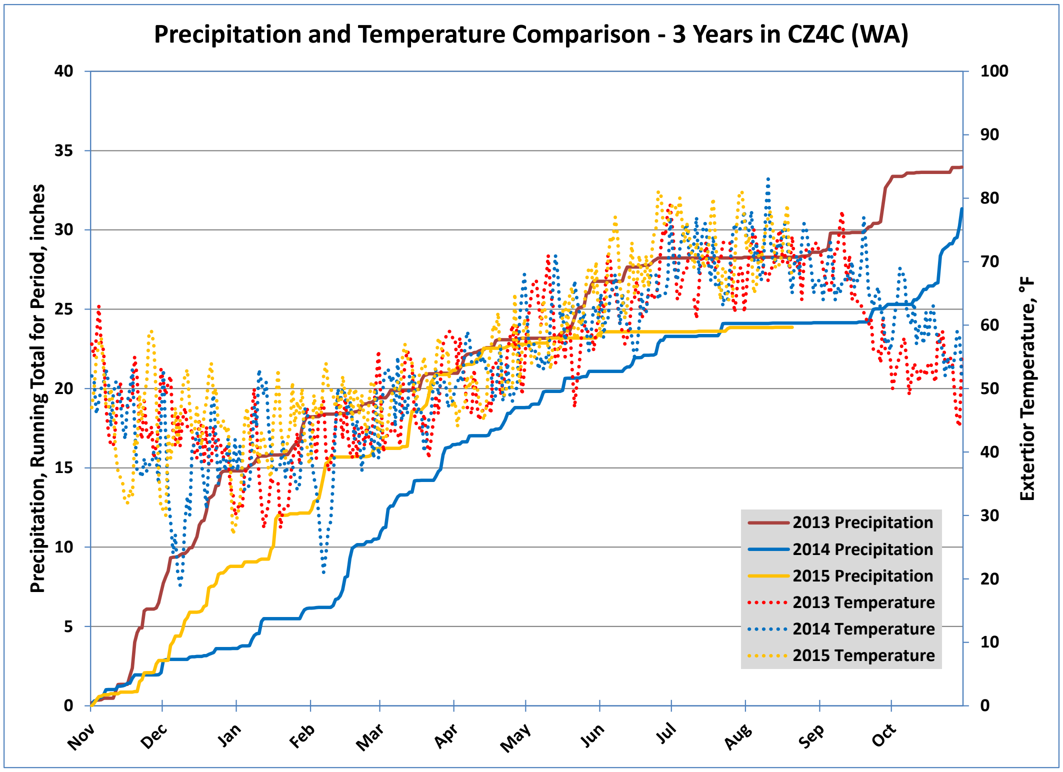

Figure 27. Climate Zone 4C Test Site Precipitation and Temperature Comparison

Figure 28 is provided as a summary for all walls in Climate Zone 4C. It shows the daily average moisture content measurements for each wall section for the entire monitoring period from 2011 to 2015. This condensed format allows for a quick overview of the performance of the wall systems as discussed previously in this section. Only data from the north-facing walls are used because this orientation generally shows the highest, sustained moisture levels in the home and all other wall orientations would be equal or less in seasonal average levels. The seasonal interior relative humidity levels are reported in Table 6.

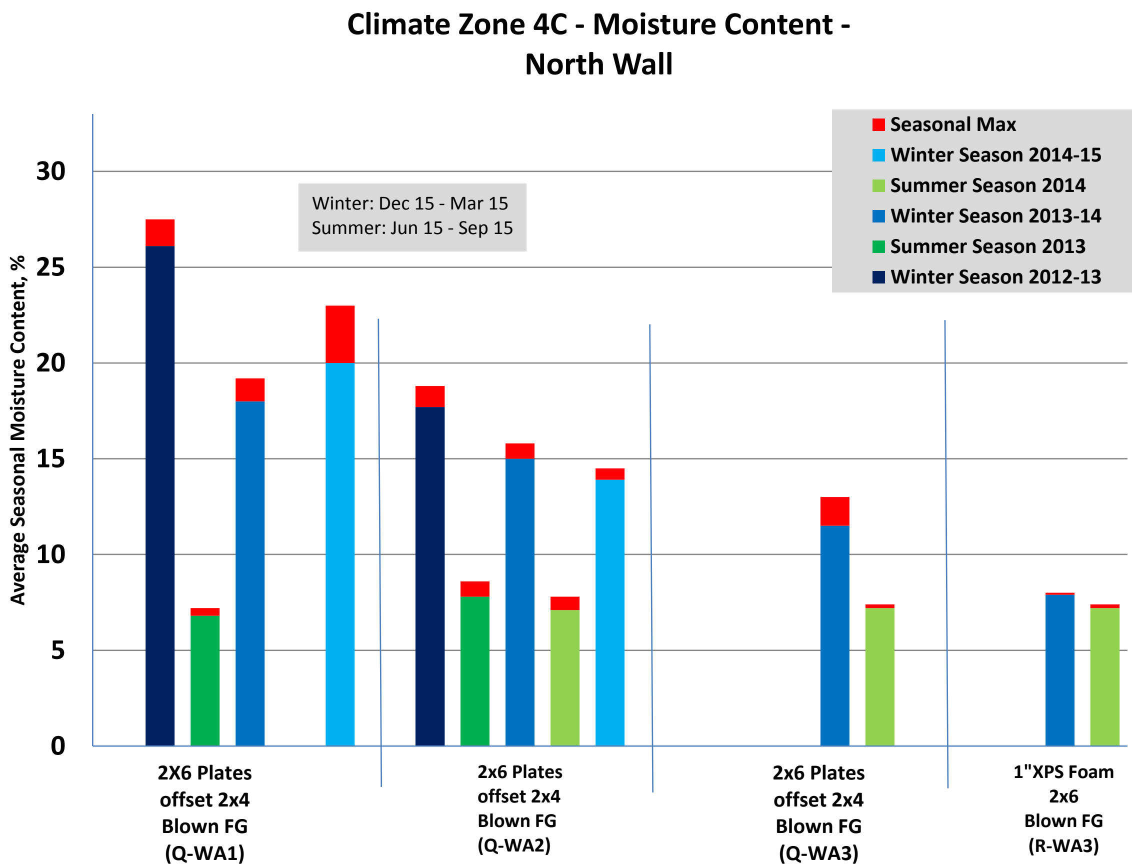

Figure 28. Climate Zone 4C Summary Moisture Content Data

Table 6. Winter Average Seasonal Interior House Relative Humidity for Climate Zone 4C Test Walls

Wall Type I.D.	Interior Relative Humidity		
	2012-2013	2013-2014	2014-2015
Q (WA1)	66%	58%	57%
Q (WA2)	N/A	N/A	N/A
Q, R (WA3)	N/A	N/A	N/A

Climate Zone 4A (Test Homes 7, 8, 9, 10 & 11)

Figure 29 through Figure 32 show summary results for four test homes with the same type of wall system (located in Delaware and Maryland). Test Home 7 was unoccupied during the first heating period but is used as an active model by the builder with a humidifier operating; the home was occupied during most of the second winter period and thereafter. Over four full heating seasons, the following observations can be made:

- For conventional 2x6 walls without a dedicated vapor retarder, the OSB moisture content is highly dependent on the combination of two factors: (1) the interior relative humidity; and (2) outdoor temperature. As evidenced by the first two winter seasons, the OSB moisture content fluctuated in the 10-20% range as the interior relative humidity ranged between 32% and 47%. The following two winters recorded sustained lower temperatures (reaching below 20°F daily average, see Figure 33) which had a significant impact on the OSB moisture content in homes with the higher ranges of relative humidity (46% or higher). Homes where the relative humidity was below 40% were not noticeably impacted by the colder winters. Test Home 7 provides an example of this trend – with the relative humidity reduced from 47% to 33% from year 3 to year 4, the OSB moisture content dropped from saturation levels to 18% levels even though the winter temperatures remained low.
- For Test Homes 7 and 9, where the high relative humidity conditions overlapped with the cold outdoor temperatures, the OSB moisture content reached fiber saturation at several locations and remained at those levels for extended periods of time.
- All walls demonstrated capacity for rapid drying in the spring with OSB moisture content levels reaching 10% or below.
- The moisture response is represented by distinct seasonal cycles. This cyclic behavior is typical for many wall types and does not represent an issue in itself. However, controlling the amplitude of the cycles is important for ensuring acceptable long-term moisture performance. One of the unknown factors is the impact of high-amplitude moisture fluctuations on the long-term structural performance of wood structural panels (OSB or plywood).
- OSB sheathing on the north and northwest walls has generally higher moisture content that other orientations, consistent with other test homes.

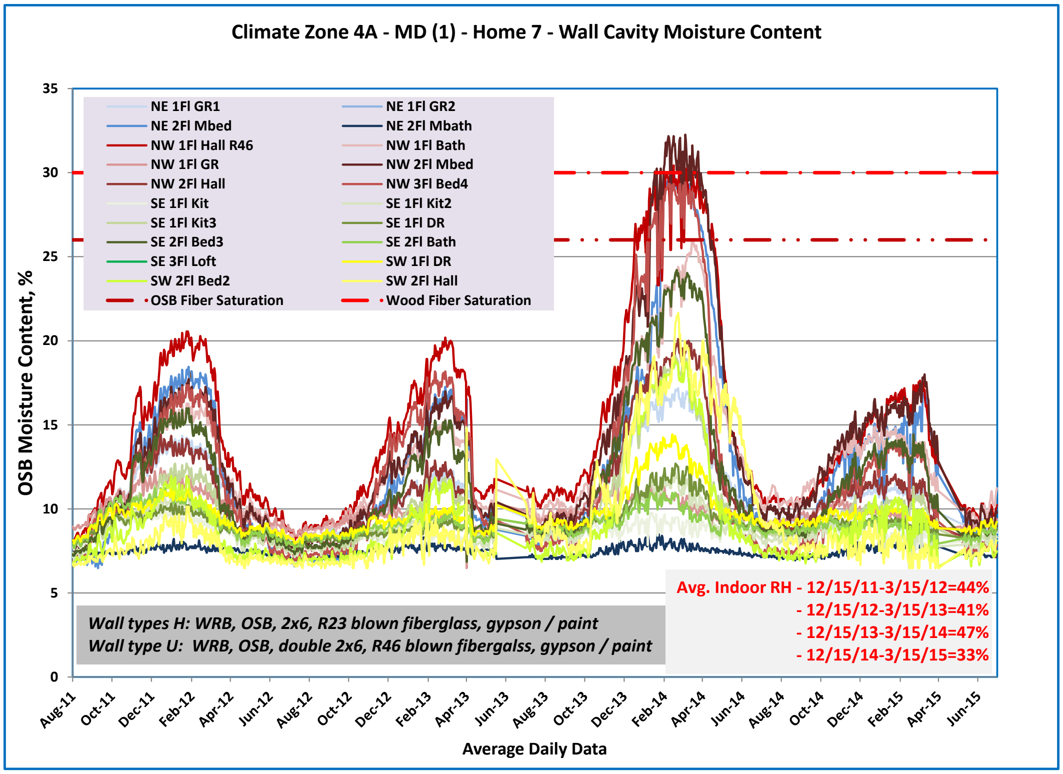

Figure 29. Daily OSB Moisture Content for Climate Zone 4A, MD (1), Test Home 7

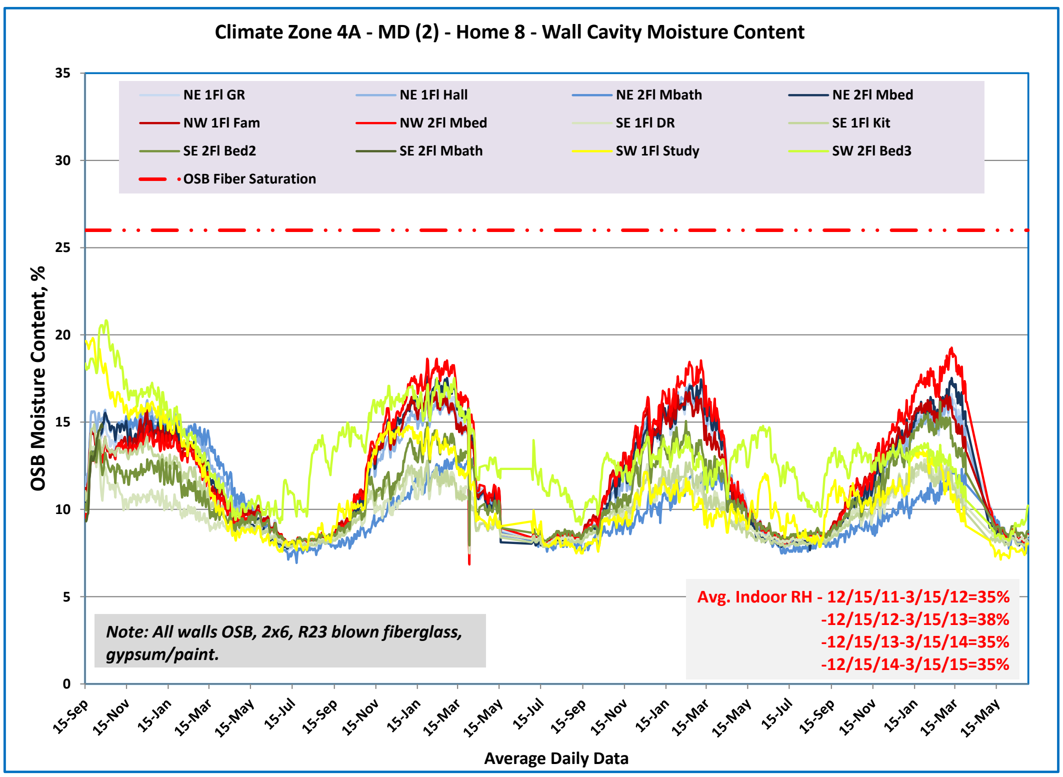

Figure 30. Daily OSB Moisture Content for Climate Zone 4A, MD (2), Test Home 8

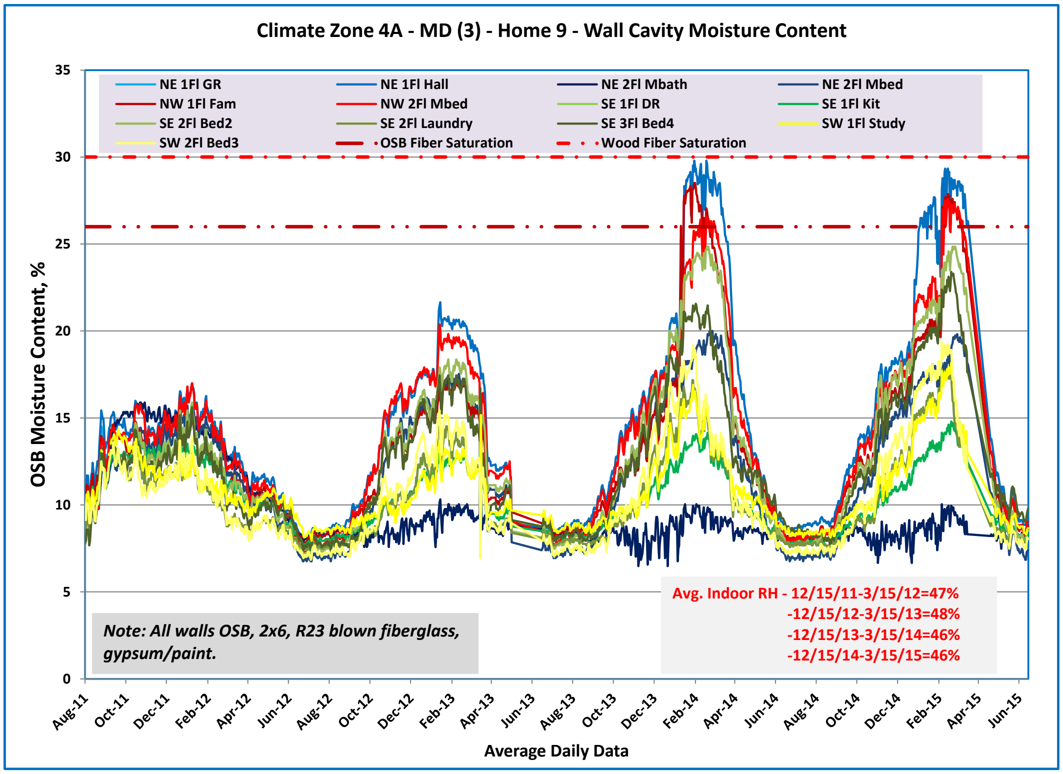

Figure 31. Daily OSB Moisture Content for Climate Zone 4A, MD (3), Test Home 9

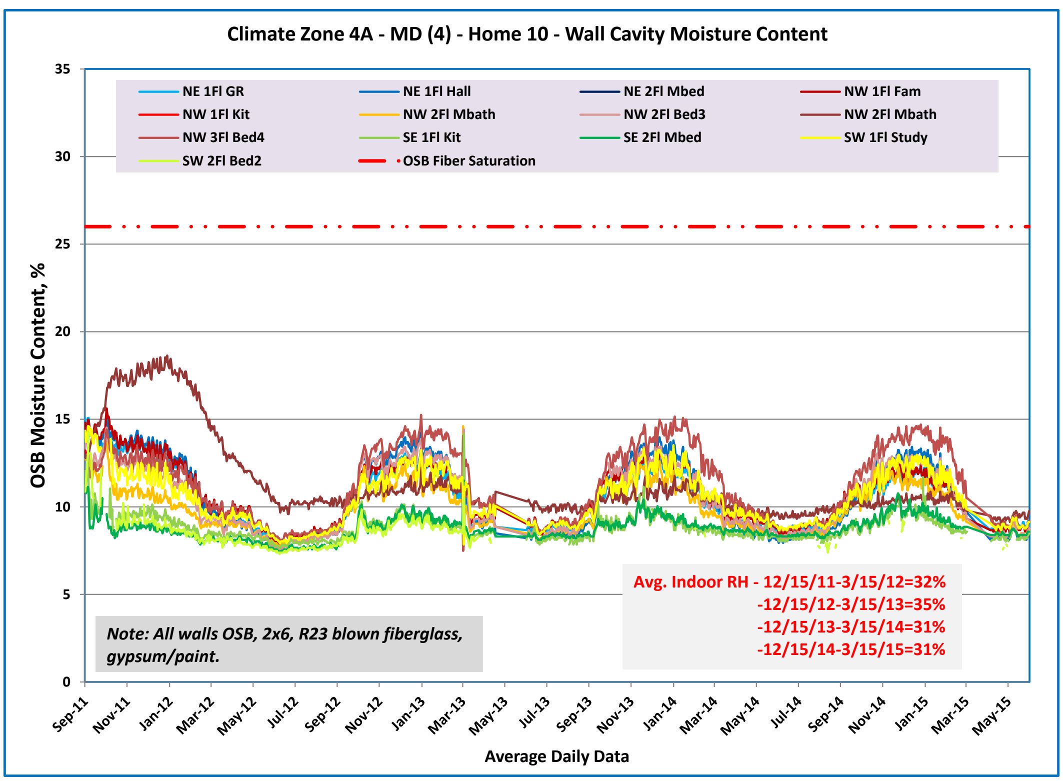

Figure 32. Daily OSB Moisture Content for Climate Zone 4A, MD (4), Test Home 10

Figure 33 summarizes outdoor temperature and cumulative precipitation for the MD sites in Climate Zone 4A for the monitoring period. The winter temperatures stayed below freezing for extended periods in the last two winters (2013-2014 and 2014-2015) reaching as low as 14°F (daily average).

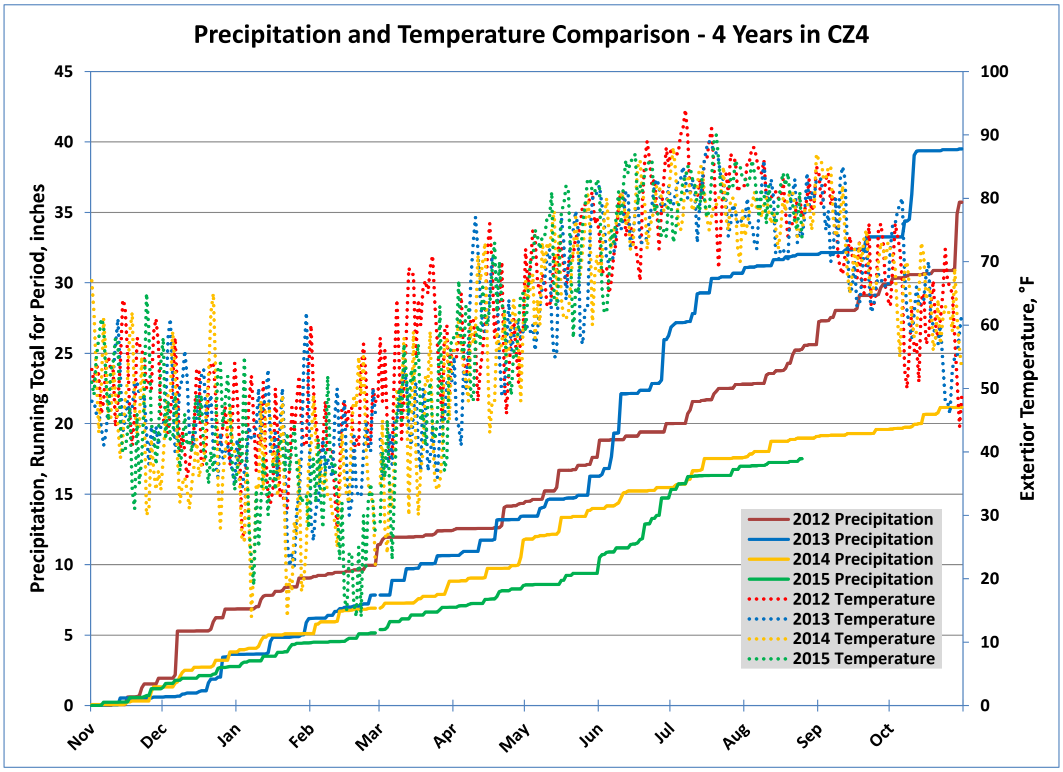

Figure 33. MD Climate Zone 4A Precipitation and Temperature Comparison

Summary results for Test Home 11 in Delaware, Climate Zone 4A, are shown in Figure 34. (Data acquisition was concluded by the occupant in 2014.) The following observations can be made:

- Maximum OSB moisture content level of 18% was observed in the 2013-2014 winter in the master bathroom; OSB moisture content in all other walls remained below 15%.
- The cyclic behavior is consistent with the trends observed in the four Maryland homes. A comparison of interior relative humidity at the house thermostat with the interior relative humidity for the master bathroom shows an average winter increase of 2.5% in the master bathroom. The measured corresponding increase in the OSB moisture content further supports the observation that these types of walls are highly sensitive to the interior relative humidity levels. It is noted that relative humidity levels depend on occupant behavior and cannot be accurately predicted or reliably controlled by systems installed by the builder in most cases.
- As consistent with other homes in the study, the north-facing and east-facing walls show the higher OSB moisture content levels in the winter. The south-facing walls have the advantage of solar gain helping drive the moisture out of the OSB panels.
- All OSB moisture contents had summertime minimums of less than 10%.

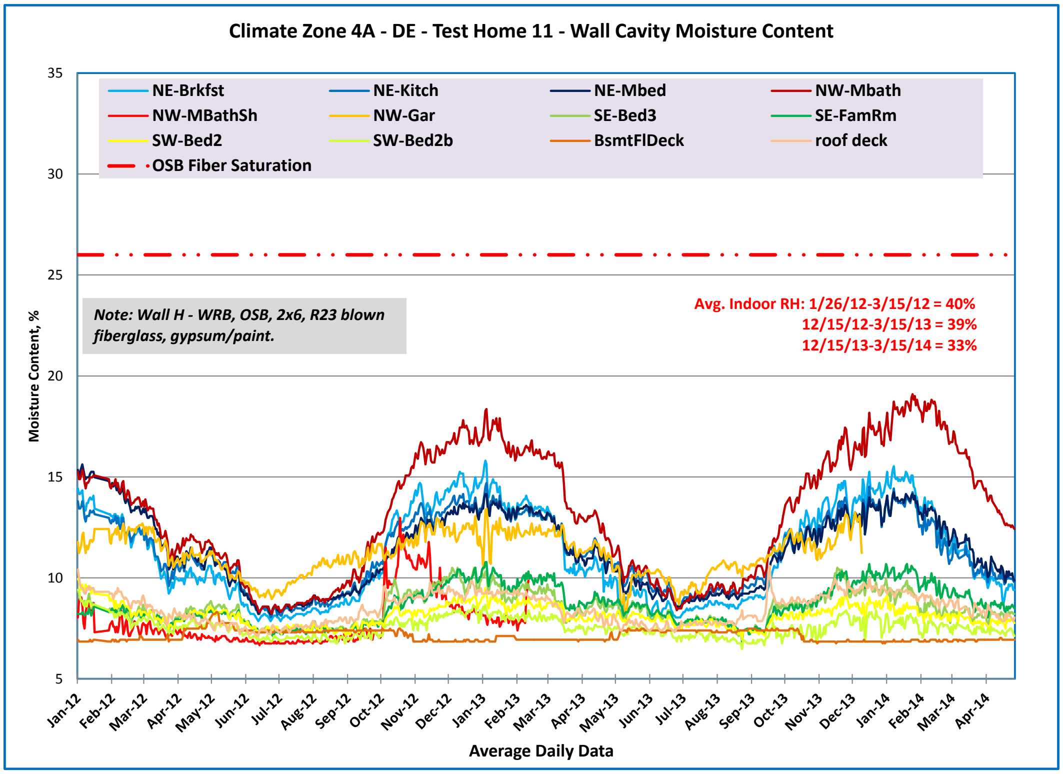

Figure 34. Daily OSB Moisture Content for Climate Zone 4A, DE, Test Home 11

Figure 35 is provided as a summary for all walls in Climate Zone 4A. It shows the daily average moisture content measurements for each wall section for the entire monitoring period from 2011 to 2015. This condensed format allows for a quick overview of the performance of the wall systems as discussed previously in this section. Only data from the north-facing walls are used because this orientation generally shows the highest, sustained moisture levels in the home and all other wall orientations would be equal or less in seasonal average levels. The seasonal interior relative humidity levels are reported in Table 7.

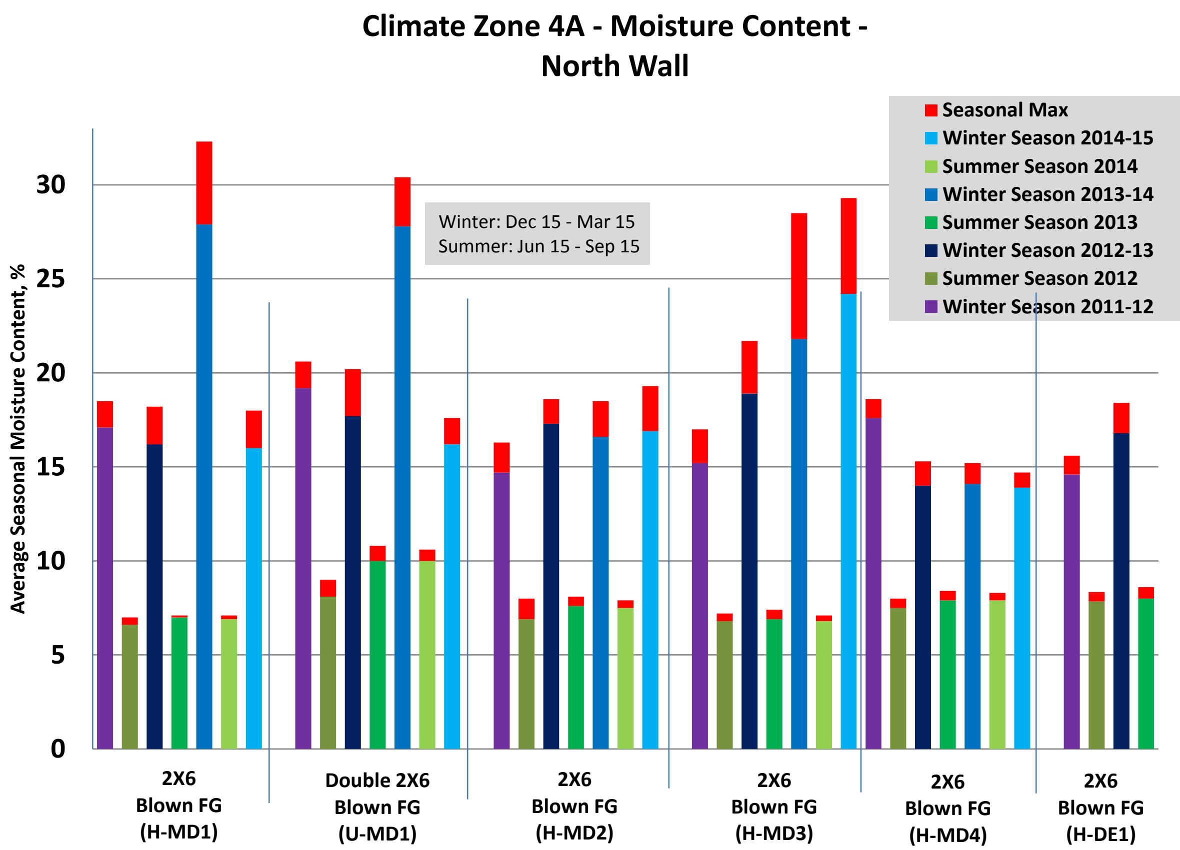

Figure 35. Climate Zone 4A Summary Moisture Content Data

Table 7. Winter Average Seasonal Interior House Relative Humidity for Climate Zone 4A Test Walls

Wall Type I.D.	Interior Relative Humidity			
	2011-2012	2012-2013	2013-2014	2014-2015
H (MD1), U	44%	41%	47%	33%
H (MD2)	35%	38%	35%	35%
H (MD3)	47%	48%	46%	46%
H (MD4)	32%	35%	31%	31%
H (DE1)	40%	39%	33%	N/A

Climate Zone 3A (Test Homes 4, 5 & 6)

Summary results for Alabama, Climate Zone 3A, are shown in Figure 36 and Figure 37. The following observations can be made:

- High relative humidity levels were observed in both homes ranging from 46% to 57%. The relative humidity levels were a few percentage points higher in Test Home 5, reaching 57% in the third year of monitoring. In the winter, Test Home 5 was often heated to temperatures at or above 75°F – a range higher than usual, further contributing to high vapor drive in that house.

- In Test Home 4, there were only slight seasonal moisture content fluctuations over the entire monitoring period even as winter relative humidity levels measured at 46% to 51% and outdoor temperatures dropped as low as 19°F (daily average). This behavior demonstrates the effectiveness of Kraft paper facing as an interior vapor retarder when used in combination with R5 exterior insulation (note that R5 on the exterior keeps the wall cavity warmer and at lower relative humidity). This energy efficient wall system provides a unique combination of features including minimal impact on construction practices (exterior foam sheathing is limited to 1 inch in thickness) and excellent moisture performance (Kraft paper is a smart vapor retarder in case any leakage occurs into the wall cavity). Further study is needed to evaluate any limitations of this wall system for use in colder climate zones.

- In Test Home 5, the OSB moisture content remained below 20% for all sensors and below 17% for the majority of the sensors throughout the entire monitoring period.

- Greater seasonal cyclic fluctuations were observed in walls with ccSPF insulation in the cavity in Test Home 5. The increase in the amplitude of these seasonal fluctuation corresponded with the colder winters when the outdoor temperature dropped as low as 19°F in 2014 and 21°F in 2015 (vs 35°F in 2013). The indoor relative humidity levels were high ranging from 49% to 57%. The combination of these factors was sufficient to lead to increases in OSB moisture content during the winter, with the highest moisture content in the master bathroom. This observation reinforces the importance of winter indoor relative humidity levels on the moisture performance of walls even for walls that include an interior vapor retarder (ccSPF in this case). It should be noted that the ccSPF sensor is installed between the OSB and the ccSPF such that the thickness of the spray foam coat at that location is reduced to approximately 1.5 inches (ccSPF was applied at about 2.5 inches throughout the cavity). An ocSPF with higher vapor permeance characteristics would lead to substantially higher moisture content levels under these specific conditions.

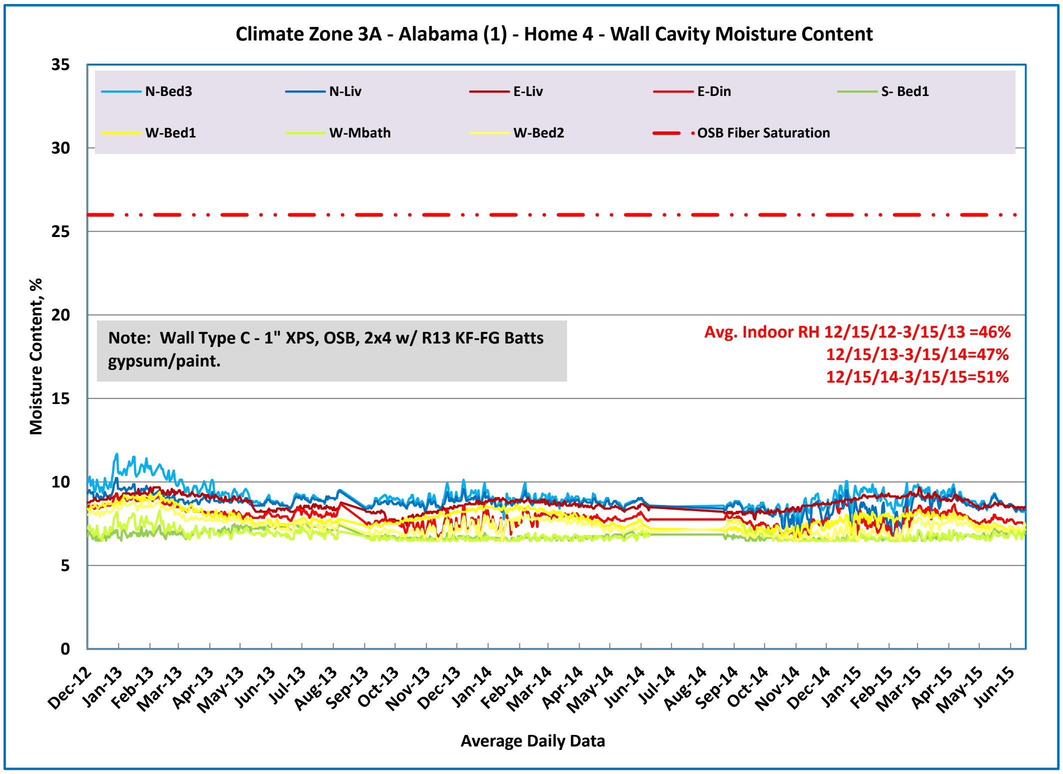

Figure 36. Daily OSB Moisture Content for Climate Zone 3A, AL (1), Test Home 4

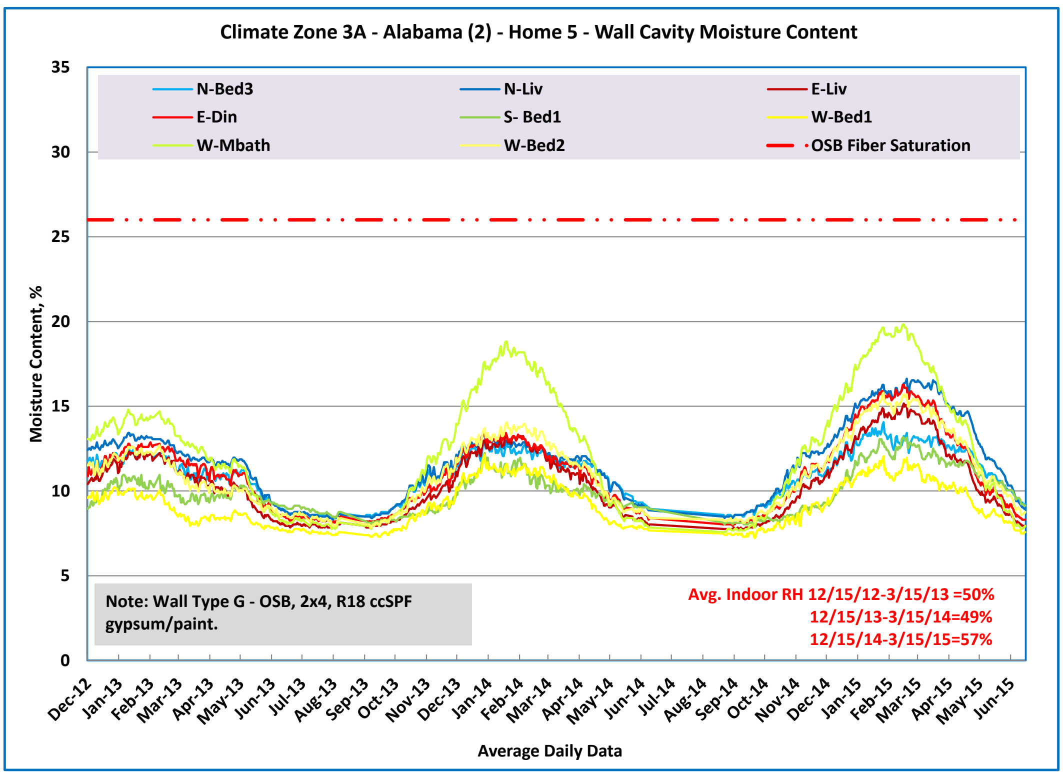

Figure 37. Daily OSB Moisture Content for Climate Zone 3A, AL (2), Test Home 5

Summary results for Test Home 6 in Texas, Climate Zone 3A, are shown in Figure 38. This test house is located at the cusp of the area designated as "Dry (B)" in accordance with the IECC Climate Zone map. The following observations can be made:

- Moisture contents for all wall and roof sheathing remain below 15% for all sensors and below 10% for the majority of sensors throughout the monitoring period.
- Interior relative humidity remained low during the entire monitoring period ranging from 25% to 32%. An HRV was installed in this house.
- A single spike in OSB moisture content recorded in mid to late spring of 2015 is likely associated with an exterior moisture source.
- A comparison with the Alabama site that used ccSPF cavity insulation (Test Home 5) again reinforces the importance the interior relative humidity conditions on the moisture performance of walls in a heating climate. The winter temperature at the Texas site dropped to as low as 10°F in the 2014 winter, yet it didn't have an effect on the OSB moisture content even though the cavity insulation is an order of magnitude more permeable in Test Home 6 (Texas) compared to Test Home 5 (Alabama).

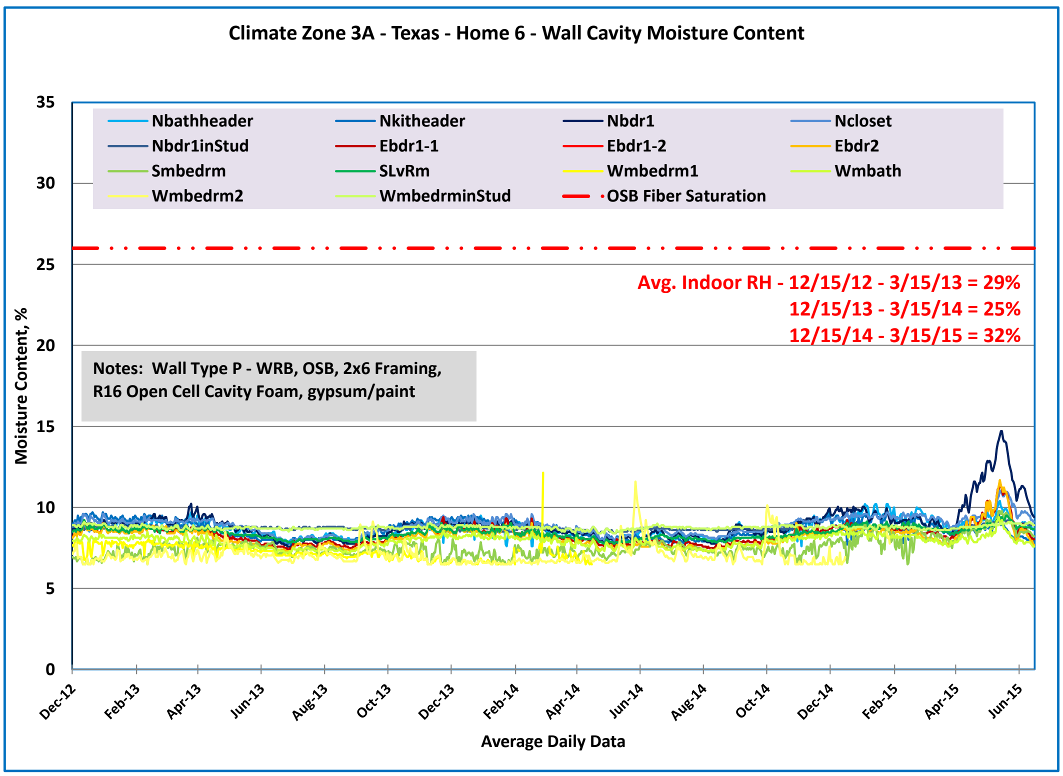

Figure 38. Daily OSB Moisture Content for Climate Zone 3A, TX, Test Home 6

Figure 39 summarizes outdoor temperature and cumulative precipitation for the AL site in Climate Zone 3A for the monitoring period. Figure 40 summarizes outdoor temperature and cumulative precipitation for the TX site in Climate Zone 3A for the monitoring period.

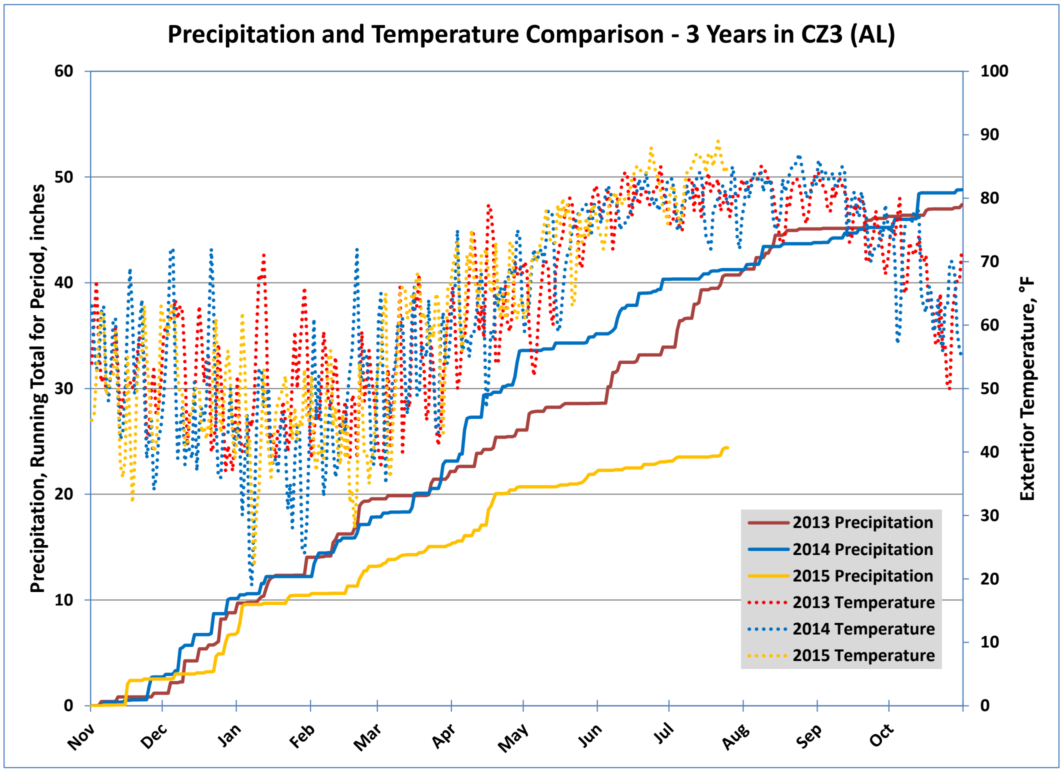

Figure 39. AL Climate Zone 3A Precipitation and Temperature Comparison

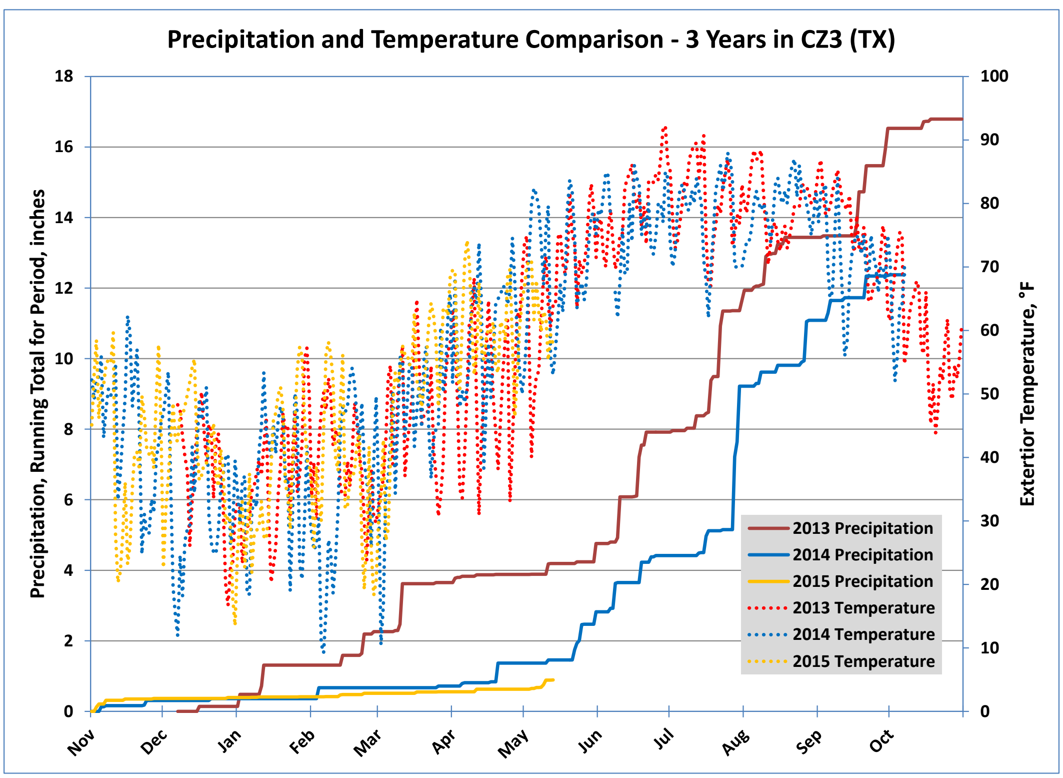

Figure 40. TX Climate Zone 3A Precipitation and Temperature Comparison

Figure 41 is provided as a summary for all walls in Climate Zone 3A. It shows the daily average moisture content measurements for each wall section for the entire monitoring period from 2011 to 2015. This condensed format allows for a quick overview of the performance of the wall systems as discussed previously in this section. Only data from the north-facing walls are used because this orientation generally shows the highest, sustained moisture levels in the home and all other wall orientations would typically be equal or less in seasonal average levels. The seasonal interior relative humidity levels are reported in Table 8.

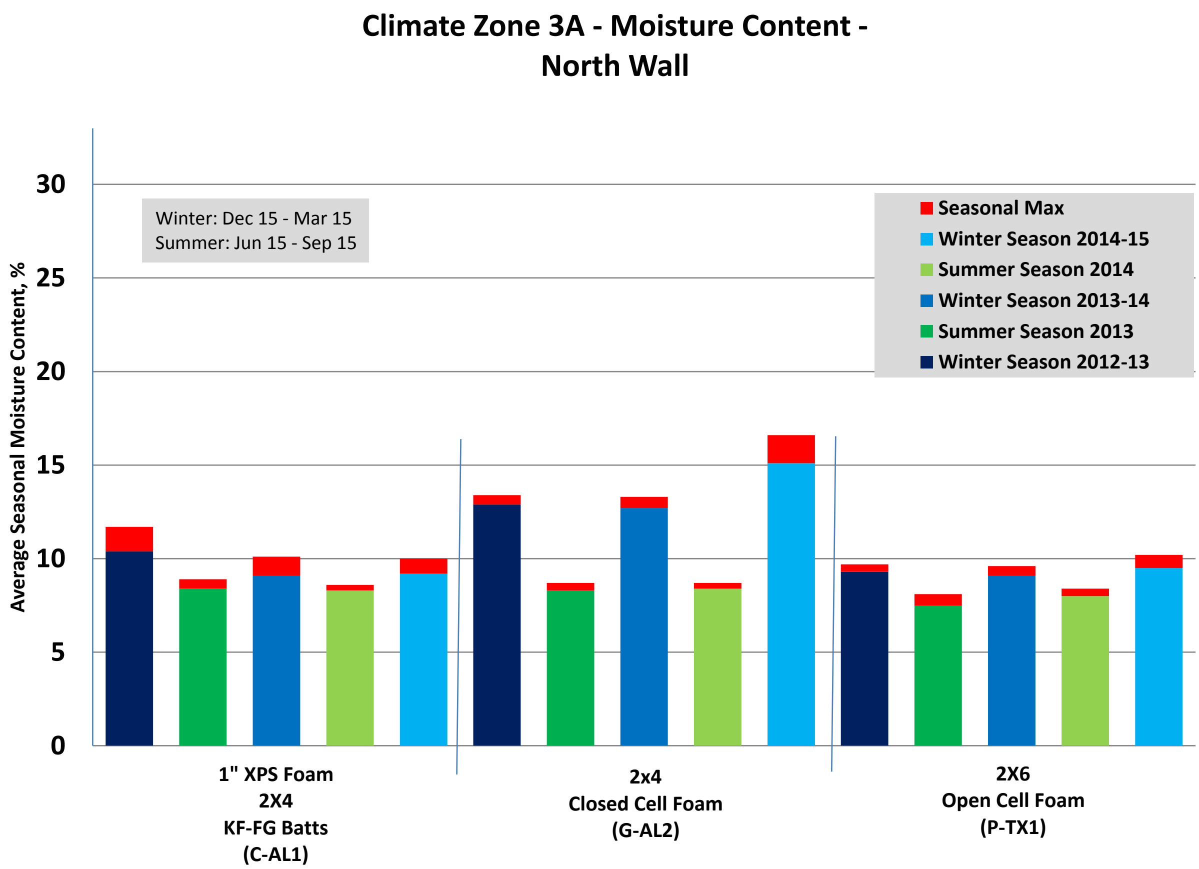

Figure 41. Climate Zone 3A Summary Moisture Content Data

Table 8. Winter Average Seasonal Interior Humidity for Climate Zone 3A Test Walls

Wall Type I.D.	Interior Relative Humidity		
	2012-2013	2013-2014	2014-2015
C	46%	47%	51%
G	50%	49%	57%
P	29%	25%	32%

Climate Zone 2A (Test Homes 1, 2 & 3)

Summary results for Louisiana, Climate Zone 2A, are shown in Figure 42, Figure 43, and Figure 44. Each of the three homes featured a different wall system. The following observations can be made:

- Moisture contents for wall sections in all three homes are similar despite the differences in wall systems and remained low throughout the entire monitoring period.
- Based on the available data, all LA test homes show relatively small moisture content change over the heating season (data acquisition system was not functioning for extending periods of times).
- The relative humidity levels ranged between 49% and 60% and the exterior temperatures reached below 30°F in 2015 for a short period of time. Otherwise, the temperatures stayed at or above 40°F for the majority of the monitoring period. It is stipulated that because the winter temperatures were not sufficiently low and the lower temperatures were sustained for only a short time period, even with the high interior relative humidity each of the 3 wall types showed good performance in Climate Zone 2A.

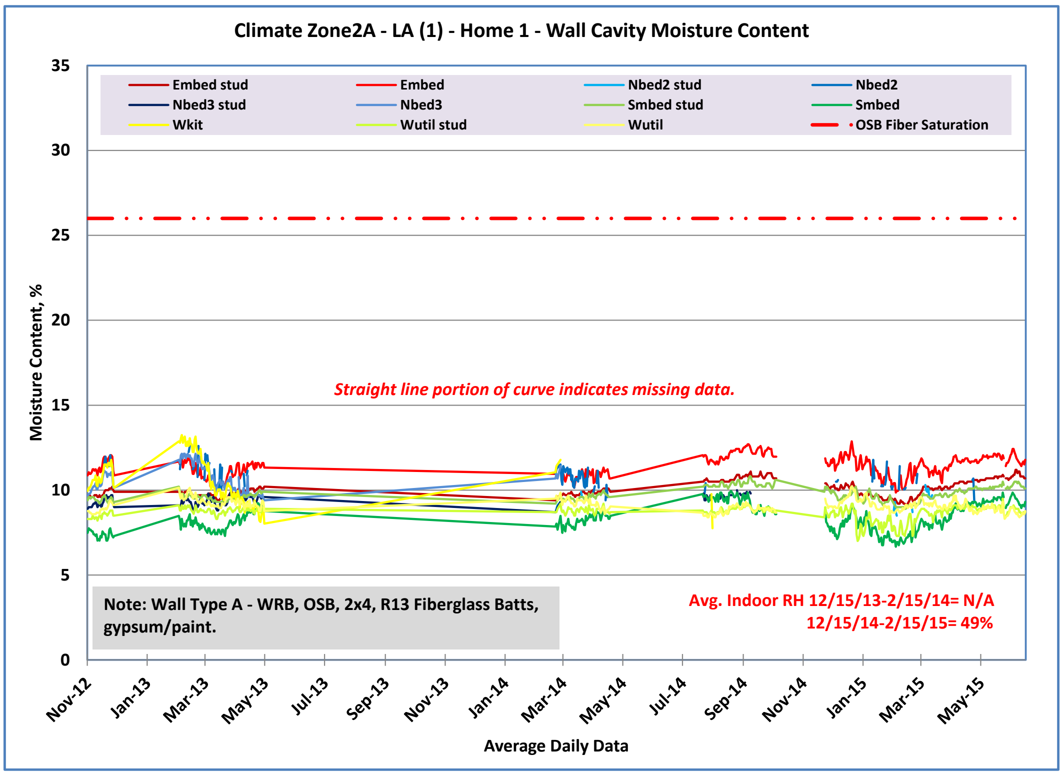

Figure 42. Daily OSB Moisture Content for Climate Zone 2A, LA (1), Test Home 1

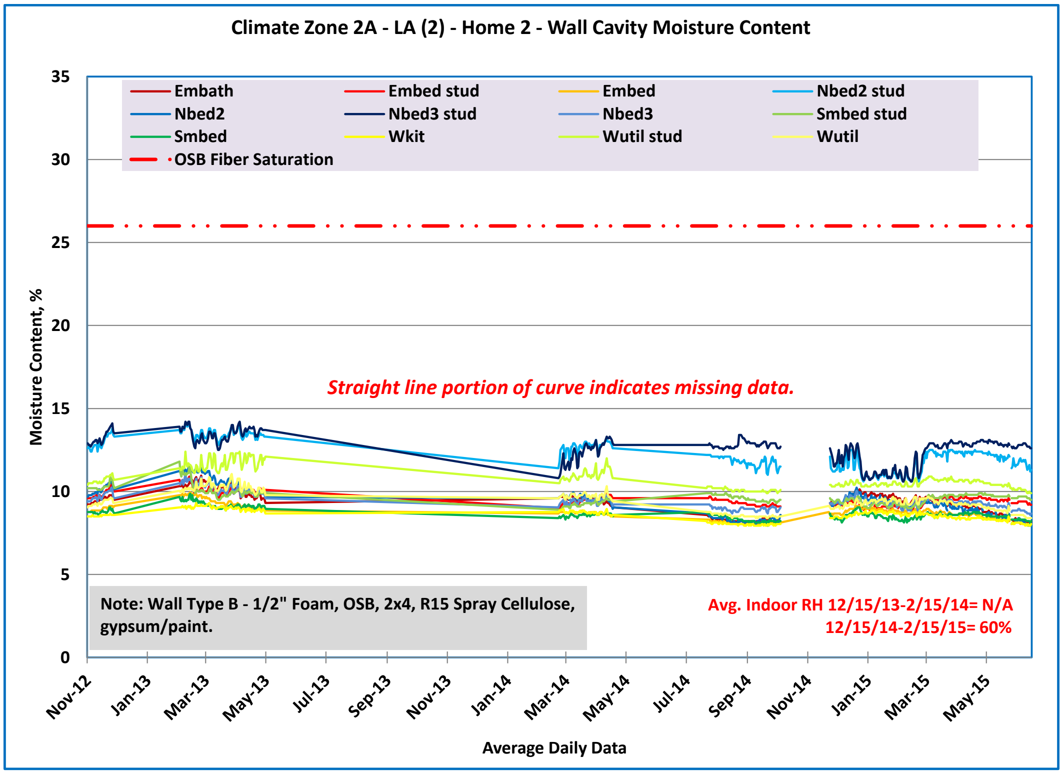

Figure 43. Daily OSB Moisture Content for Climate Zone 2A, LA (2), Test Home 2

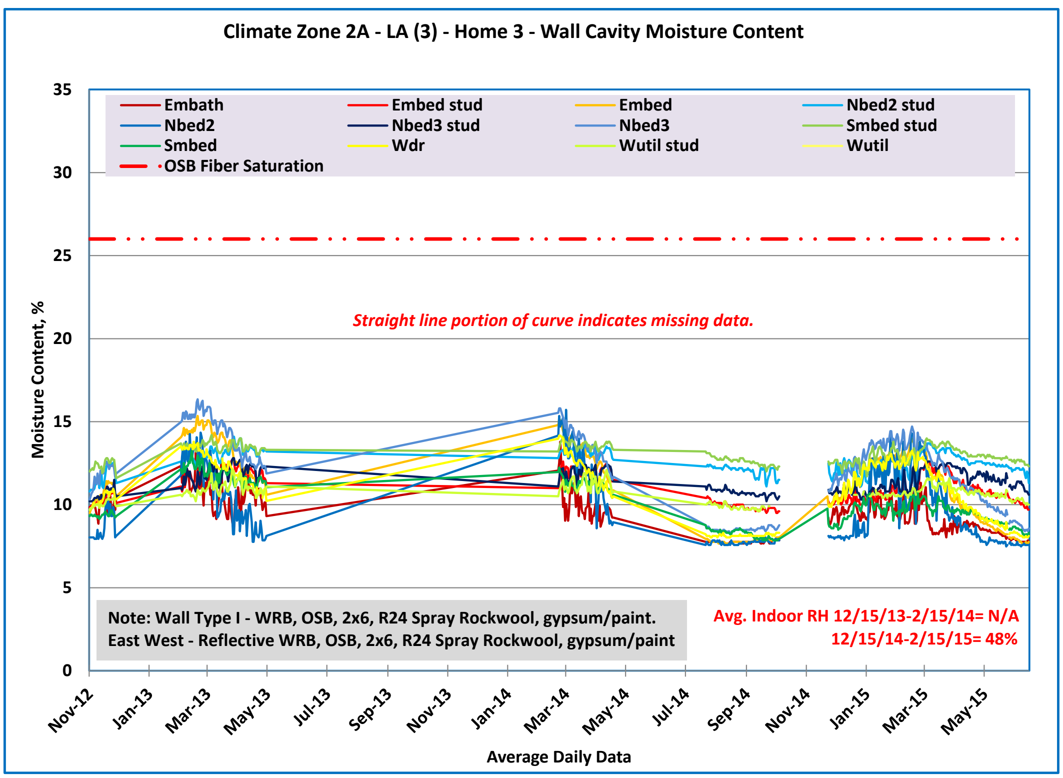

Figure 44. Daily OSB Moisture Content for Climate Zone 2A, LA (3), Test Home 3

Figure 45 summarizes outdoor temperature and cumulative precipitation for the LA site in Climate Zone 2A for the monitoring period.

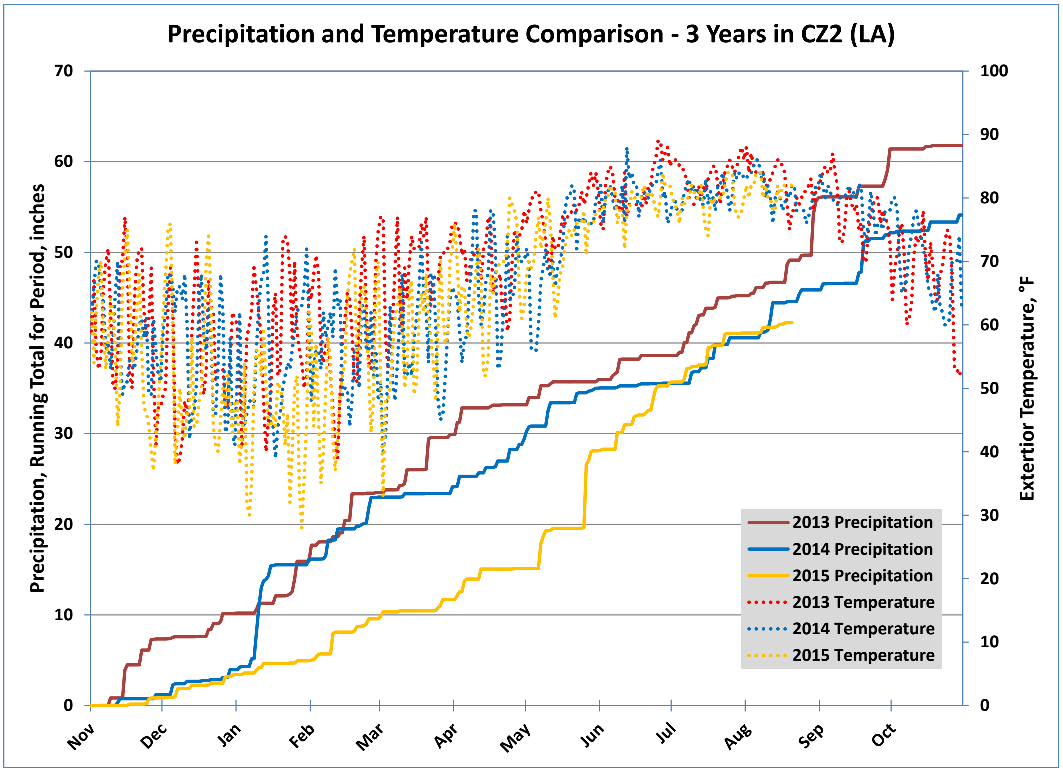

Figure 45. LA Climate Zone 2A Precipitation and Temperature Comparison

Figure 46 is provided as a summary for all walls in Climate Zone 2A. It shows the daily average moisture content measurements for each wall section for the entire monitoring period from 2011 to 2015. This condensed format allows for a quick overview of the performance of the wall systems as discussed previously in this section. Only data from the north-facing walls are used because this orientation generally shows the highest, sustained moisture levels in the home and all other wall orientations would typically be equal or less in seasonal average levels. The seasonal interior relative humidity levels are reported in Table 10.

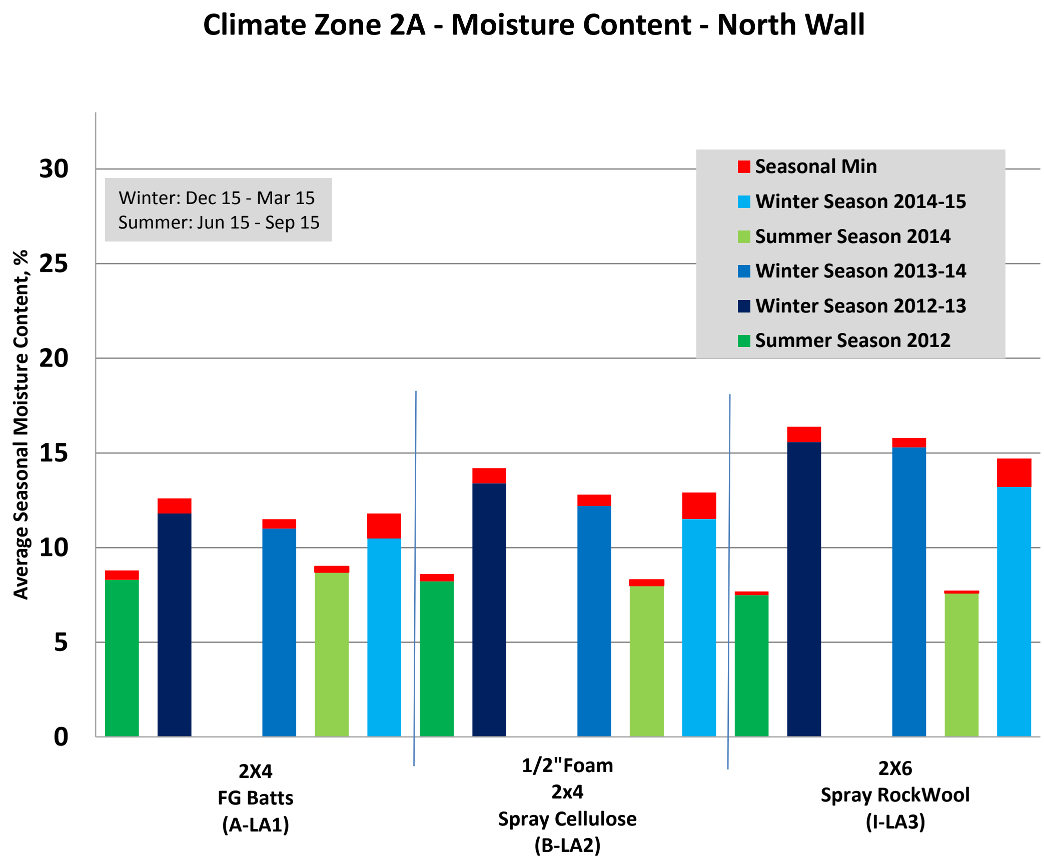

Figure 46. Climate Zone 2 Summary Moisture Content Data

Table 9. Winter Average Seasonal House Interior Relative Humidity for Climate Zone 2A Test Walls

Wall Type I.D.	Interior Relative Humidity		
	2012-2013	2013-2014	2014-2015
A	56%	N/A	49%
B	54%	N/A	60%
I	64%	N/A	48%

Condensation Resistance Analysis

One moisture performance parameter analyzed for wall cavities is the potential for condensation, particularly at the wood sheathing surface. Condensation at cold surfaces can occur when warmer moist air leaks or diffuses through interior wall materials into the cavities. Condensation at the sheathing surface is of most interest since that is where the moisture can be absorbed into the wood material, grow mold at right temperatures, and lead to performance and durability problems. Condensation is possible when the dew point temperature of the air is higher than the surface temperature of the sheathing. In the heating season, the amount of moisture contained in interior air directly affects the wall cavity moisture characteristics and determines the potential for increased moisture content of the OSB sheathing. The configuration of the wall cavity including interior vapor retarders on the interior, cavity insulation materials, and sheathing material will affect the drying potential of the moisture that enters the wall cavity by either air leakage or vapor diffusion.

A methodology to determine the potential for the sheathing interior cavity surface to cause condensation uses the calculation of the surface temperature given exterior and interior ambient temperatures. The sheathing interior cavity surface temperature is dependent on the relative insulation levels to the interior and exterior of the sheathing surface at the interior of the cavity (see Figure 47). For the cavity path, the temperature at any surface in the path is derived from the formula:

$$T_{surface\ a} = \left[\left(\frac{sum\ R_{values\ a-o}}{sum\ R_{values\ i-o}}\right) \times DT_{i-o}\right] + T_o$$

where: $T_{surface\ a} \equiv$ temperature of the surface of interest

$R_{values\ a-o} \equiv$ sum of the path R_{value} from surface of interest to the exterior

$R_{values\ i-o} \equiv$ sum of the path R_{value} from the inside surface to the outside surface

$DT_{i-o} \equiv$ air temperature difference from the inside to the outside

$T_o \equiv$ outside air temperature

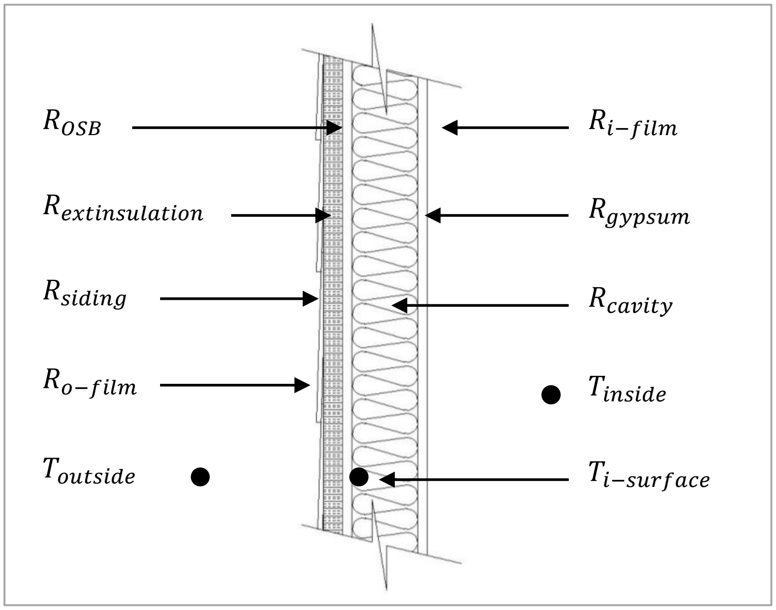

Figure 47. Condensing Surface Calculation Parameters

For several test homes, the traditional simplified dew point calculation approach is compared to field measurements. The monthly average outdoor temperature is used as the outdoor temperature reference and the daily average measured indoor temperature and relative humidity is used for the indoor temperature estimate for the calculation of the dew point temperature. The wall system configuration is based on the typical wall system(s) for the test home. These theoretical calculations are shown graphically followed by charts of measured data of condensation potential (calculated when the dew point temperature is higher than the surface temperature of the sheathing, shown as negative values on the charts).

For two test homes (Test Home 21 in MI and Test Home 7 in Maryland), Figure 48 through Figure 51 compare the theoretical condensation potential (based on the wall construction, average historic monthly exterior temperatures, and standard indoor environmental conditions) with the dew point calculated based on the measured temperature and humidity data at the OSB surface.

Comparison of the analytical results with field-based dew point estimates shows a correlation in terms of the identified risk of condensation. The primary difference is that the dew point estimated based on measured data occurs for shorter duration intervals, which is particularly evident for the Maryland site.

A comparison of both methodologies with the field moisture content measurements indicate a weaker correlation between dew point estimates and the OSB sheathing moisture content levels (refer to Figure 11 and Figure 29). Therefore, although dew point calculation can be useful as a design tool, if used as the sole method for evaluating wall assemblies it can overestimate the risk of moisture issues. One of the plausible reasons for the observed acceptable performance is that the wood material in the cavity has the capacity to absorb and buffer some levels of moisture without reaching fiber saturation levels.

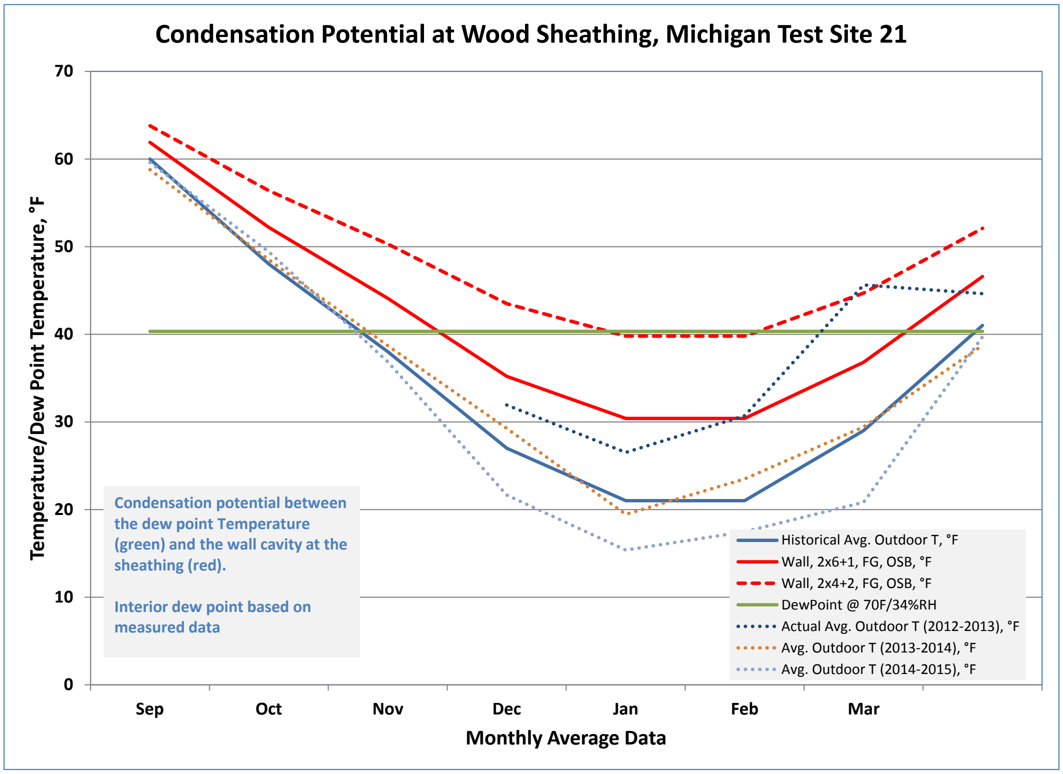

Figure 48. MI Test Site 21, Theoretical Condensation Potential

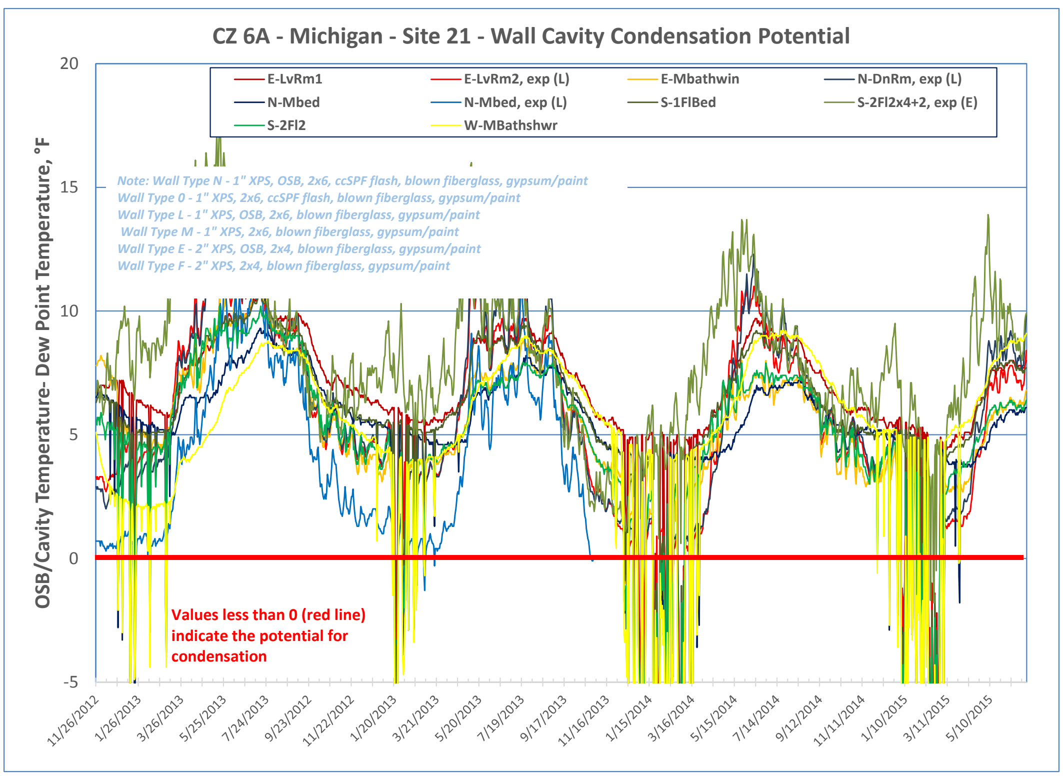

Figure 49. MI Test Site 21, Measured Condensation Potential

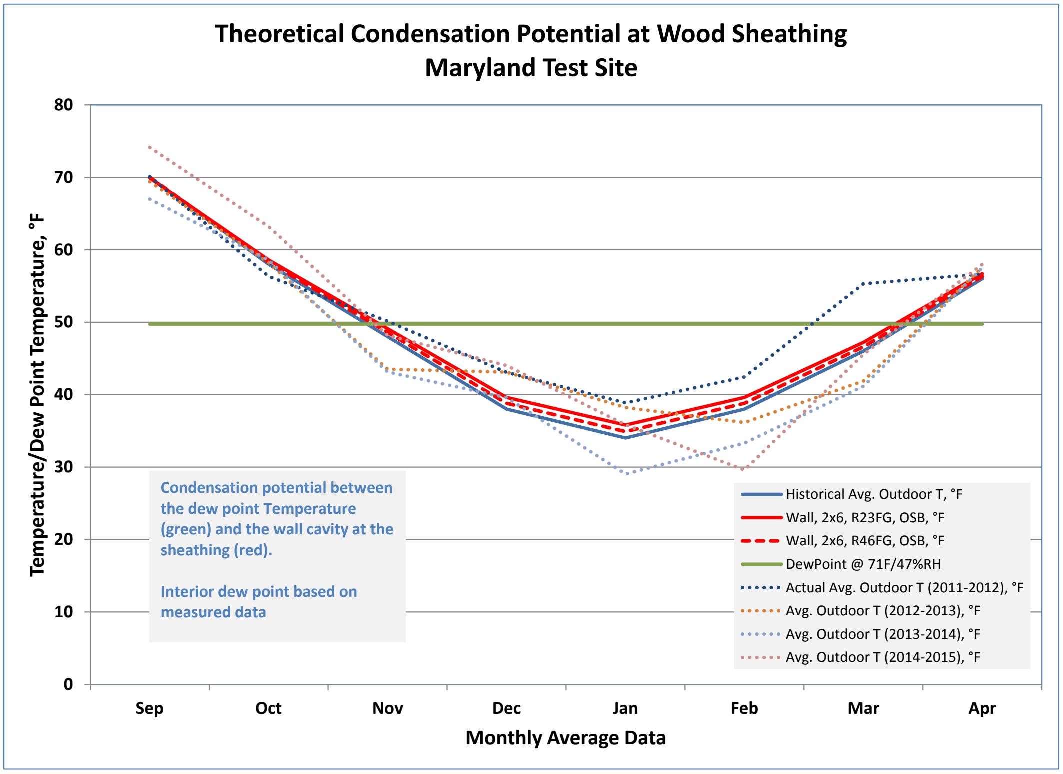

Figure 50. MD Test Site, Theoretical Condensation Potential

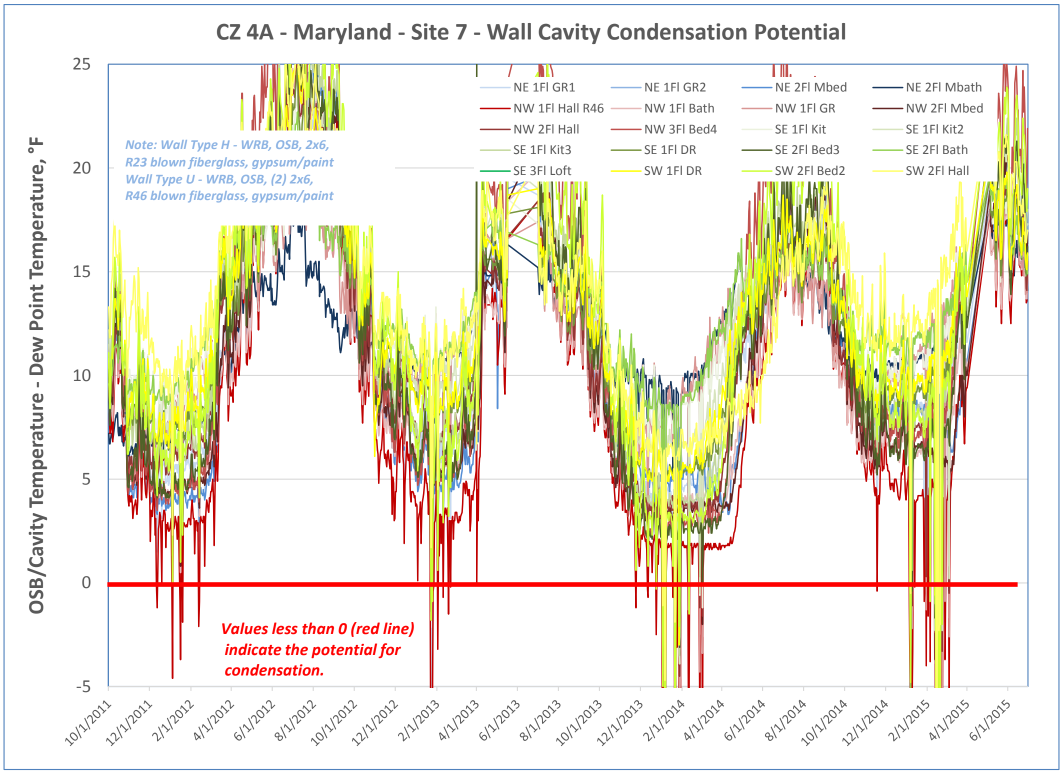

Figure 51. MD Test Site 7, Measured Condensation Potential

For comparison, interior temperature and relative humidity conditions can be seen for each site in Appendices A and B; however, generally the measured interior conditions are lower in temperature and relative humidity than the 71°F/44% relative humidity conditions used in the condensation potential calculations.

Analysis Based on ASHRAE 160-2009

Prior to this study, one of the home builders in Ohio reported that while repairing walls with buckled OSB following the winter of 2009, a “mold like substance” was often present on the interior face of the OSB panels. To investigate the potential for mold growth in the test homes monitored in this study, the observed environmental conditions of the wall cavity are evaluated using the threshold established by ASHRAE Standard 160-2009 “Criteria for Moisture-Control Design Analysis in Buildings” (ASHRAE, 2009). Standard 160 provides temperatures and associated relative humidity ranges necessary to minimize mold growth on building envelope components (Table 10).

Table 10. Standard 160 Condition Criteria Necessary to Minimize Mold Growth

Duration	Relative Humidity When	Temperature is in Range
30 days	< 80% Relative Humidity	41°F < T < 104°F

The wall cavity temperatures and relative humidity levels are evaluated for the test sites with available data according to these criteria with an example result shown in Figure 52. For each test site, the ASHRAE 160 Section 6.1 criteria was calculated based on the 30-day running averages at the wall cavity sheathing surface. The charts plot the instances (non-zero values) when the criteria were exceeded.

Each wall cavity, and including some indoor and outdoor air conditions, was plotted using a unique ID for the wall cavity. For example, wall cavity ID [18] (vertical axis) exceeded the ASHRAE 160 Section 6.1 criteria for a continuous 12 week period from mid-February to early May (horizontal axis) during the 2011-2012 winter (Figure 52).

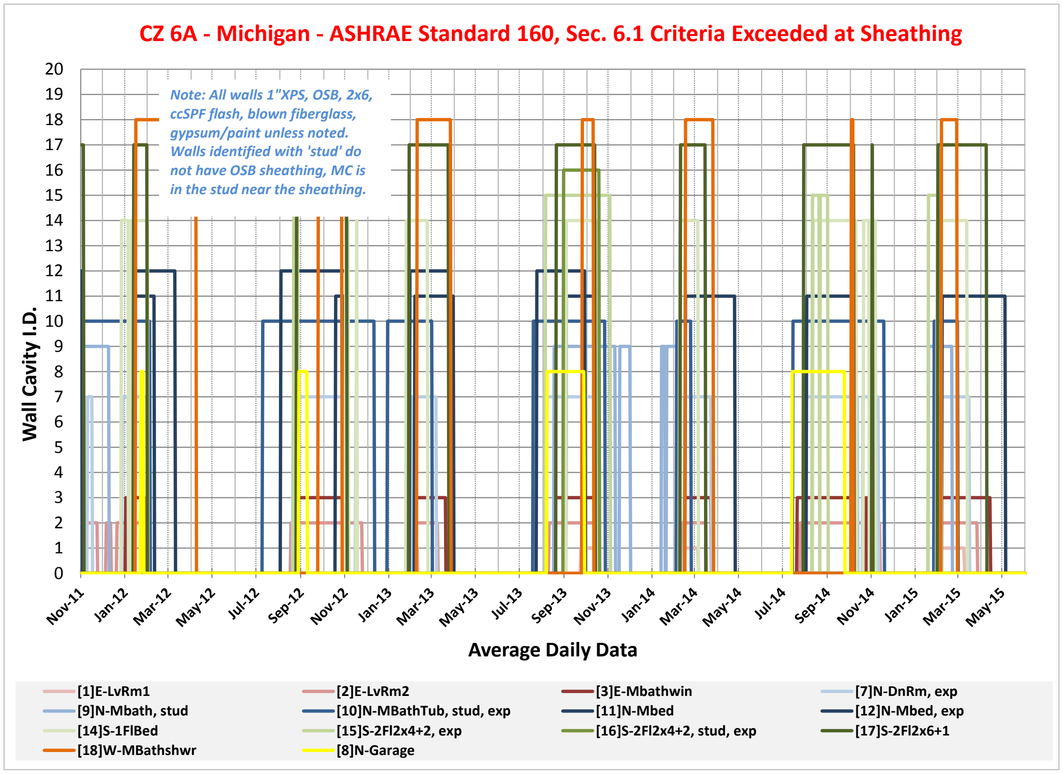

Figure 52. MI Test Site, Duration When ASHRAE Section 6.1 Criteria Exceeded in Cavity

An analysis for the Alabama test site shows no periods when the cavity conditions exceed the ASHRAE 160 criteria for Section 6.1, Conditions Necessary to Minimize Mold Growth.

In summary, many walls cycle through a period when the ASHRAE 160 criteria are exceeded. There is, however, little consistency among wall sections within a home, including orientation, and the length of time that the criteria is exceeded. Furthermore, there is little evidence at this time to correlate the moisture criteria with actual wall system performance risk and hence the relevance of such criteria for wall design purposes is of unknown value at this time. It is also noted that the ASHRAE committee charged with overseeing ASHRAE 160 is currently reviewing mold growth criteria and evaluating alternative metrics to achieve a better correlation with the field performance.

Wall Cavity Inspection

In April 2013, following the winter season reported herein, the builder of the Maryland test houses undertook an investigation to visually evaluate the wall sections where the highest moisture contents were recorded in a winter period. One such wall section was a double 2x6 wall with full-fill blown fiberglass cavity insulation (Figure 53 and Figure 54). This wall section was otherwise constructed identical to the 2x6 walls in the house.

Figure 53. Insulation Removed from R-46 Wall for Observation

Figure 54. Moisture Sensor Located

The builder cut open wall sections near the sensors, insulation was moved, the sheathing visually inspected for moisture effects, and the moisture content of the wood sheathing was recorded (see Figure 55).

Figure 55. Moisture Meter Reading Correlated with Sensor

The visual inspection revealed pristine conditions of the OSB sheathing after two years of service with interior humidity over 40% during the winter heating periods. The double 2x6 wall section inspected had recorded sheathing moisture contents of 20% in the winter months with summer drying to about 10% moisture content. Other wall sections with over 16% moisture content were evaluated in a similar manner, all with identical positive results.

There was no opportunity for re-inspection following the more recent winters which showed a greater moisture demand on these wall assemblies. Access to test walls post-monitoring is one of the limitations of field testing. Using dedicated test structures (e.g., test huts) to evaluate wall moisture performance enables inspection of walls after the test exposure. A further study on the impact of cyclic moisture fluctuation of various amplitudes and duration on the structural characteristics of structural sheathing materials is needed to be able to evaluate the long-term performance of these products in walls based on the results of moisture monitoring.

GENERAL OBSERVATIONS BASED ON SEASONAL MEASURED DATA

The major moisture characteristics and performance factors are summarized as follows.

Indoor Humidity

The indoor relative humidity varied widely between test homes and by climate zone. Figure 56 provides a summary of indoor relative humidity levels by climate zone including average value and peak values (minimum and maximum). The relative humidity levels for individual houses are reported with the data for those houses in the section on Field Measurement Results.

The average winter indoor relative humidity for Climate Zones 4A through 6A ranged from the mid to upper 30% range with the highest average in several cases in the upper 40% range.

The average winter indoor relative humidity for Climate Zone 3 (A/B boundary) was consistently low for all three years ranging from 25% to 32%. It is noted that only one house was monitored at the dry/moist boundary (A/B boundary), but the results are consistent with the expected performance for this location and the house ventilation system (HRV).

The average winter indoor relative humidity levels were elevated in Climate Zones 2A, 3A, and 4C consistently registering in the upper 40% range, often in the 50% range, and in some cases exceeding 60%.

Appendix D contains charts of the daily temperature and relative humidity for each test home where data is available.

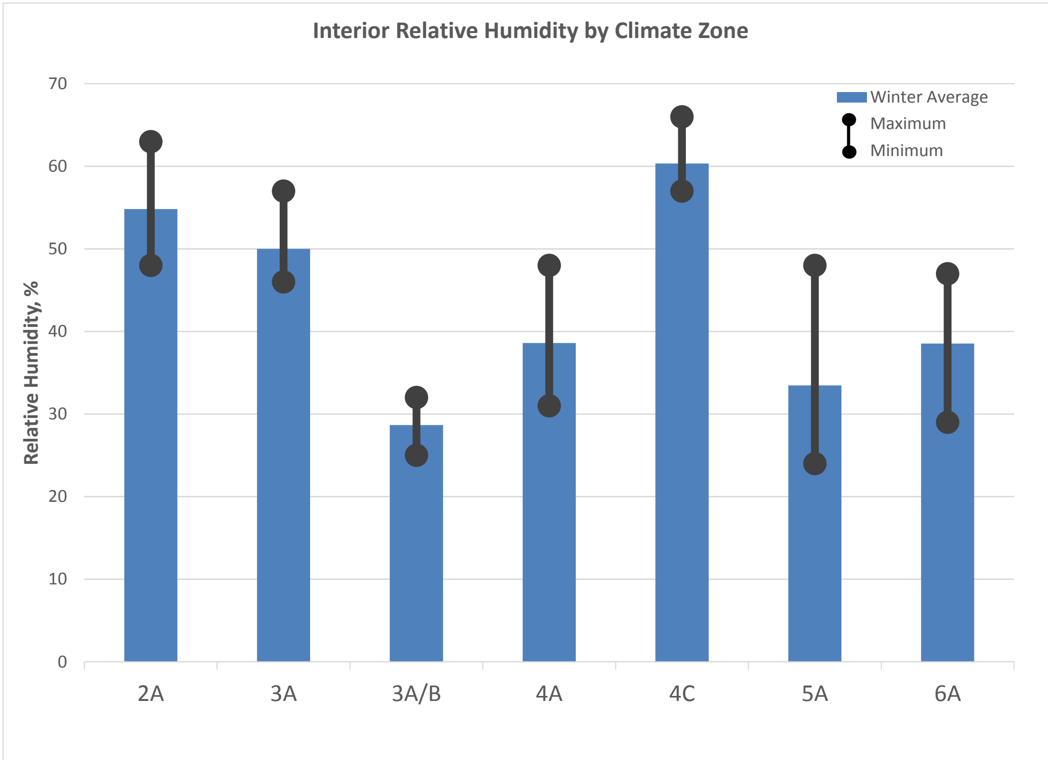

Figure 56. Indoor Relative Humidity Averages for 20 Test Sites by Climate Zone

OSB Moisture Content

Figure 57 provides the highest moisture content level reached by each test wall at least once during the monitoring period. Out of the 23 total test walls, 10 walls either approached or reached the fiber saturation point (estimated at 26%) at least for a short period of time.

Seasonal average levels for the OSB moisture content were less than the fiber saturation point for the majority of walls. All walls that reached a higher level of moisture content were able to dry out over the following spring-summer period.

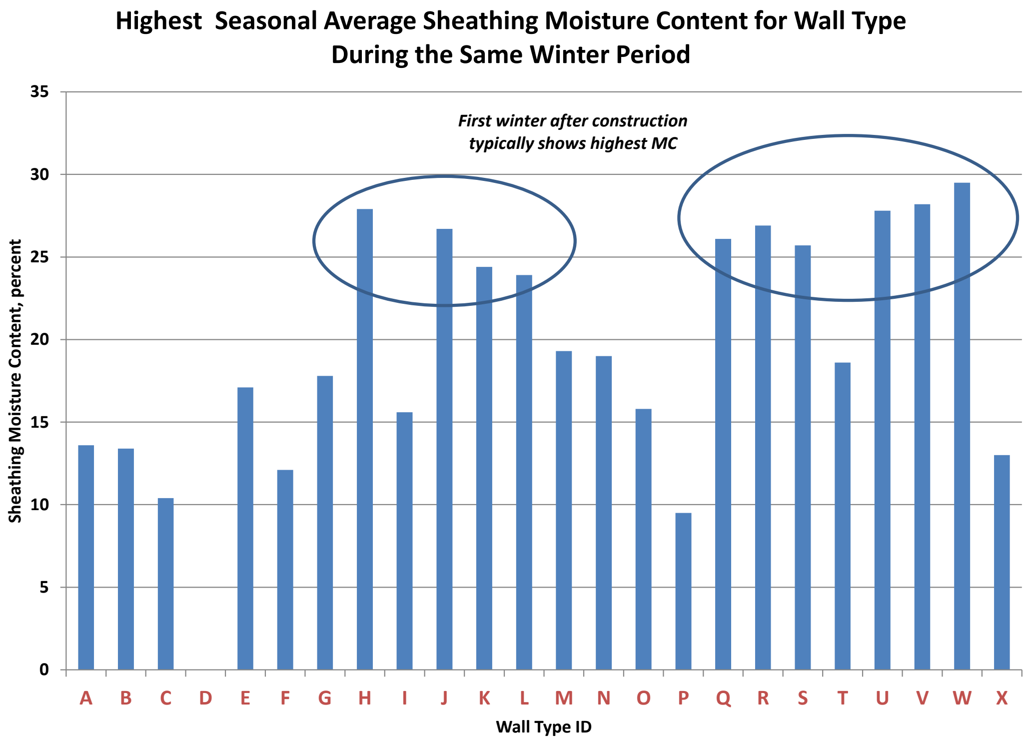

Figure 57. Wall Cavity Seasonal Average Moisture Content

The following observations can be made from the summary moisture content data (refer to Table 2 for description of wall configurations):

- All wall systems tested in Climate Zone 2A are at or below 15% moisture content in the worst case wall orientation during heating periods.
- All wall systems tested in Climate Zone 3A are at or below 20% moisture content in the worst case wall orientation during heating periods, with the majority of walls at or below 15%.
- Although the majority of wall systems tested in Climate Zone 4A are at or below 20% moisture content in the worst case wall orientation during heating periods, several walls approached or exceeded the fiber saturation point for an extended period of time.
- A wide range of peak moisture content levels during the heating periods was observed in Climate Zone 3C ranging from below 10% to saturation levels. The higher levels of moisture content were driven by the relative humidity levels and initial construction moisture.
- In Climate Zone 5A and 6A the moisture content in the heating season was highly dependent on the vapor retarder, source of construction moisture, and levels of exterior insulation. In several cases, the moisture content levels reached the fiber saturation point.

Dew Point Calculations

Comparisons of simplified dew point calculations with measured moisture characteristics indicate that this approach can be used to identify potential for condensation and higher levels of moisture content, however, in many cases it overestimated the extent of the dew point condition and has a weak correlation with the measured moisture content levels.

ASHRAE 160 Criteria

Most wall cavities in the northern climates exceeded the ASHRAE 160 Moisture Performance Evaluation Criteria for at least some period of time. There is no evident correlation between the criteria and identified risk, and in particular for wall systems that historically have been used successfully in a given climate zone.

Wall orientation

Higher sheathing moisture content levels were typically observed in walls facing north and east (refer to Figure 11 as an example). This result is attributed to the difference in direct solar radiation.

SUMMARY CONCLUSIONS AND RECOMMENDATIONS

Light frame wall cavities in 22 homes were instrumented with sensors to record temperature, relative humidity at the interior cavity side of the wood structural sheathing, and the moisture content in the wood framing. Test homes are located in Climate Zones 2A through 6A, and 4C, all moist climates (except for the Texas site that is borderline dry) based on the DOE climate zone map as shown in Figure 1. The homes were all occupied during the study period. Temperature and humidity sensors were also located within the living space and on the exterior of the home. House features such as wall configuration, ventilation system and control, and infiltration test results were catalogued for each home.

The wall system moisture performance results presented here represent actual field measurements in occupied homes. This data demonstrates both the cyclic nature of the wall cavity moisture characteristics and the maximum sheathing moisture content that might be expected when the interior humidity conditions are generally near the averages for these homes (i.e., high interior moisture loads could skew these results).

Based on the monitoring data, the following conclusions can be made:

General

- For the types of walls monitored in this study, the primary moisture considerations were associated with the heating season in Climate Zones 3 and higher.
- The following factors are critical to the moisture performance of walls during the heating season:
    - Interior relative humidity
    - Outdoor temperature

    - Interior vapor retarder
    - R-value of exterior insulation
    - Construction moisture (e.g., concrete curing, framing drying, drywall drying)
- In several circumstances, a combination of critical factors led to conditions where the OSB sheathing moisture content approached or reached the fiber saturation point for an extended period of time. Where occurred, these trends became more evident in the last two monitored seasons when the exterior winter temperatures were 8-10°F lower than the previous monitoring periods.
- For many of the homes, the first year following construction showed the highest moisture load levels as a result of construction moisture sources.
- A range of energy-efficient wall designs tested in warmer climates (Climate Zones 2 and 3) indicates acceptable stable performance for all monitored wall types.

Interior Relative Humidity and Ventilation

- In several homes, the highest moisture content levels were observed in the bathroom. This observation reinforces the importance of point source ventilation at locations with higher than average moisture load in the house.
- A wide range of interior home winter relative humidity levels was observed during the winter season, commonly reaching 40% levels and in some cases exceeding 50% levels. A climate zone dependency is observed for the interior winter relative humidity levels. The winter relative humidity was somewhat higher in Climate Zones 2A, 3A, and 4C compared to other climate zones.
- Based on the available dataset, no definitive trend has been identified between the observed relative humidity level and ventilation method used in the house. Similarly, no definitive trend was observed between air-tightness (ACH50) and winter indoor relative humidity. It is not a conclusion of this study that these trends don't exist. However, the relationships between multiple variables (including occupant behavior and use of humidifiers) impacting the interior relative humidity levels are complex, non-linear, and interdependent. The limited scope of this study does not allow for these trends to sufficiently crystalize. The primary conclusion is that high levels of humidity can be present in homes and have a direct impact on the design and performance of walls.

Interior Vapor Retarders

- 2x6 walls without a vapor retarder in Climate Zones 4A showed a wide range of performance that was highly dependent on the interior relative humidity and outdoor temperate. When these walls were subjected to colder winter temperatures and high interior relative humidity, the OSB sheathing reached fiber saturation point for an extended period of time. It is noted that these walls were air sealed and the majority of the moisture load can be attributed to vapor diffusion. Therefore, the results of this study warrant an evaluation of making a recommendation to specify an interior Class II vapor retarder such as Kraft paper for standard 2x6 walls in Climate Zone 4A.

- Where Class I or Class II interior vapor retarders were used, they were effective at controlling the moisture content levels in the walls regardless of the levels of interior relative humidity.
- Polyethylene (Class I) served as an effective vapor retarder for standard 2x6 walls in Climate Zone 5A.

Wall with exterior foam sheathing

- In walls with exterior foam, spring/summer drying is observed. It is suggested that the primary direction for this drying is to the inside. It is noted that none of the walls had a double vapor barrier condition.
- Damp-sprayed cellulose used in combination with exterior foam sheathing results in high initial OSB moisture content. These walls were able to dry out in the spring and summer season following construction and showed stable performance thereafter. All of the monitored walls had a Class III or no interior vapor retarder and allowed drying to the inside.
- 2x6 walls with 1 inch of exterior foam sheathing (R5) and without an interior vapor retarder may not be appropriate for colder climate zones (5 and higher). It is recommended to investigate the effect of a variable ("smart") vapor retarder (e.g., Kraft paper) to control vapor drive from the interior in the winter.
- 2x6 walls with 2 inch of exterior foam sheathing (R5) in Climate Zone 6 and 1.5 inch of exterior foam (R7.5) in Climate Zone 5 showed reduced winter moisture content level. However, these walls did experience seasonal fluctuations.
- A wall system featuring 1 inch of XPS foam sheathing on the exterior and Kraft paper interior vapor retarder in Climate Zone 3 showed very stable low moisture level throughout the entire monitoring period even at high levels of interior relative humidity. It is recommended to evaluate this type of wall assembly in colder climate zones to determine the upper limit on its use. The benefit of this wall system is in minimizing the impact of transitioning to a more energy efficiency wall on the wall's constructability (use of 1-inch foam has minimal impact of construction details for installation of windows and claddings).
- A combination of 1 inch of exterior foam and an interior flash coat of closed spray foam is effective at controlling OSB moisture uptake from the interior vapor drive. However, this system would be susceptible to retaining moisture that penetrated the drainage plane as a result of the reduced drying rates.
- South-facing 2x4 walls with 2 inches of exterior foam without an interior vapor retarder consistently show low moisture content levels in OSB and framing suggesting that the solar vapor drive was effective at drying any construction moisture to the inside. Further study is needed to expand testing to include north-facing exposure.

Recommendations and Analytical Considerations

- Many of the monitored walls showed significant seasonal fluctuations. The long-term effect of repetitive high-amplitude moisture content fluctuations on the structural characteristics of OSB are unknown and evaluation of such effects are not part of the qualification procedures for wood structural panels. As a future study, it is recommended to evaluate the impact of seasonal moisture fluctuations on the long-term characteristics of structural sheathing materials.
- Based on comparison of monitored results with analytical calculations, there is a weak correlation between the dew point estimates (obtained via simplified calculations or based on monitored data) and observed moisture content levels.
- Analysis of select wall assemblies indicates that moisture performance criteria established in ASHRAE 160-09 (including 2012 Addendum C) is often exceeded. It is recommended that in the future the data set be re-evaluated using the next generation of the criteria that is currently under development under the ASHRAE 160 (expected for 2016 publication).

RECOMMENDATIONS FOR POTENTIAL CODE REVISIONS

Based on the results of the study, several recommendations for potential revisions to the IRC provisions related to the moisture performance of walls are provided:

- In Climate Zone 4, a Class II vapor retarder, a variable (“smart”) vapor retarder, or a layer of exterior insulation should be required. (The appropriate R value for the exterior insulation for the code change should be established through hygrothermal analysis.)
- For Climate Zones 6 and higher, requirements of IRC Section R702.7 Vapor Retarders should be coordinated with IECC Section R402.1.2 Insulation and Fenestration Criteria. The current energy code specifies R20+5 as a method of compliance with the wall insulation requirements. However, vapor retarder provisions require a Class I or II interior vapor retarder in this application. If a low-perm exterior insulation is used, a double vapor barrier condition is created. Proposed options for the revised vapor retarder requirements include a Class II or a variable (“smart”) vapor retarder.
- The IRC at this time does not have provisions for guarding against a double vapor barrier. It is recommended to add a provision that would limit application of walls with a Class I interior vapor retarder and low-perm exterior cladding/insulation systems.
- Standard latex and enamel paint does not provide sufficient vapor retarder characteristics. It is recommended to revise the classification of vapor retarders by removing standard paint options from the Class III category.
- IRC provisions are correct in not requiring an interior vapor retarder in Climate Zones 1, 2, and 3. It is recommended that a new provision be added to not allow Class I vapor retarders in Climate Zones 1 and 2 and potentially in Climate Zone 3.
- It is recommended to revise the vapor retarder classification to add vapor retarders with variable permeability. Such vapor retarders can be provided as an option for walls with low-perm exterior cladding/insulation systems.

It is noted that these recommendations are preliminary and have not been vetted by industry stakeholders.

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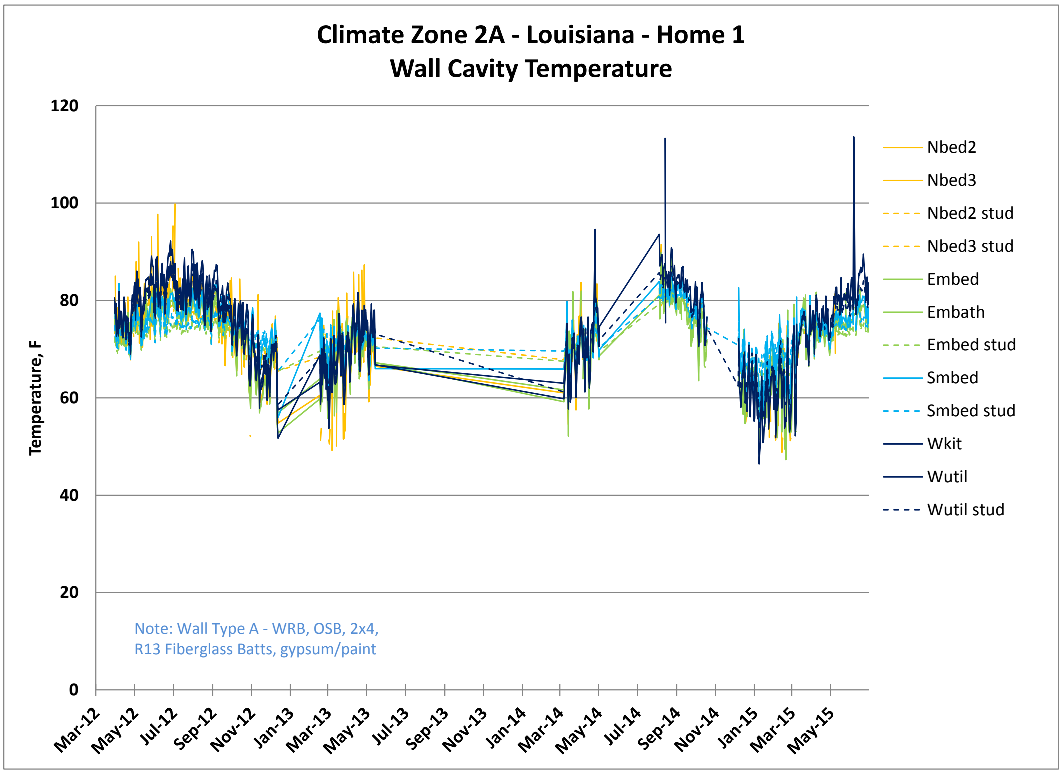
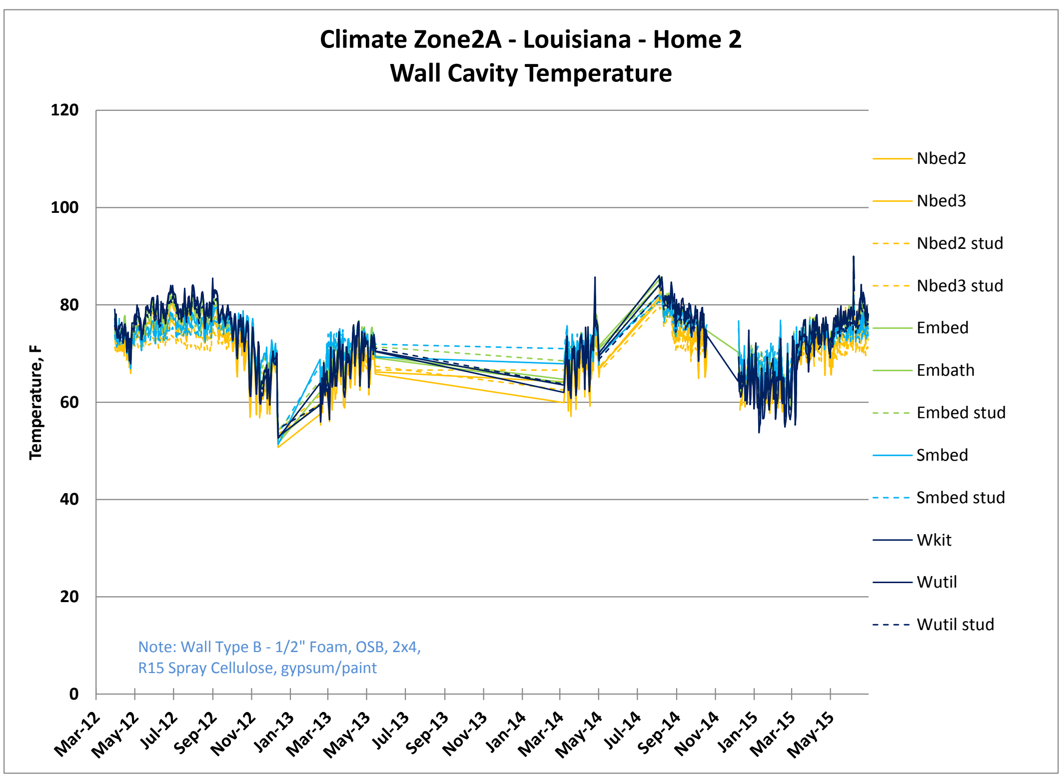
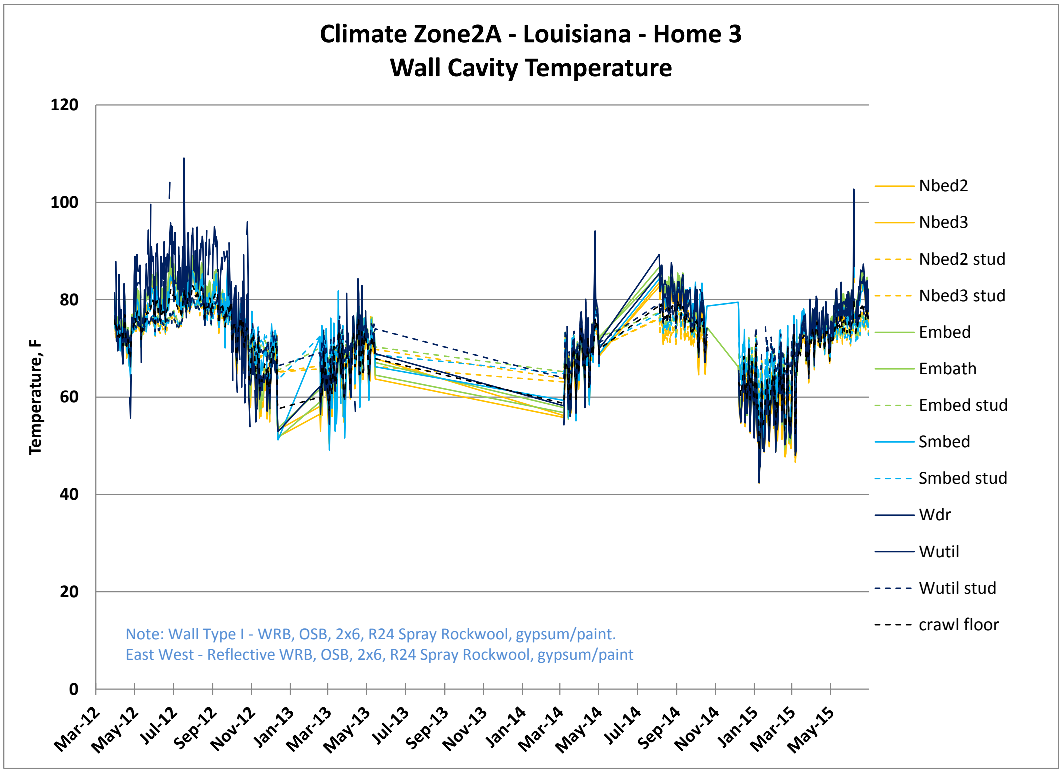
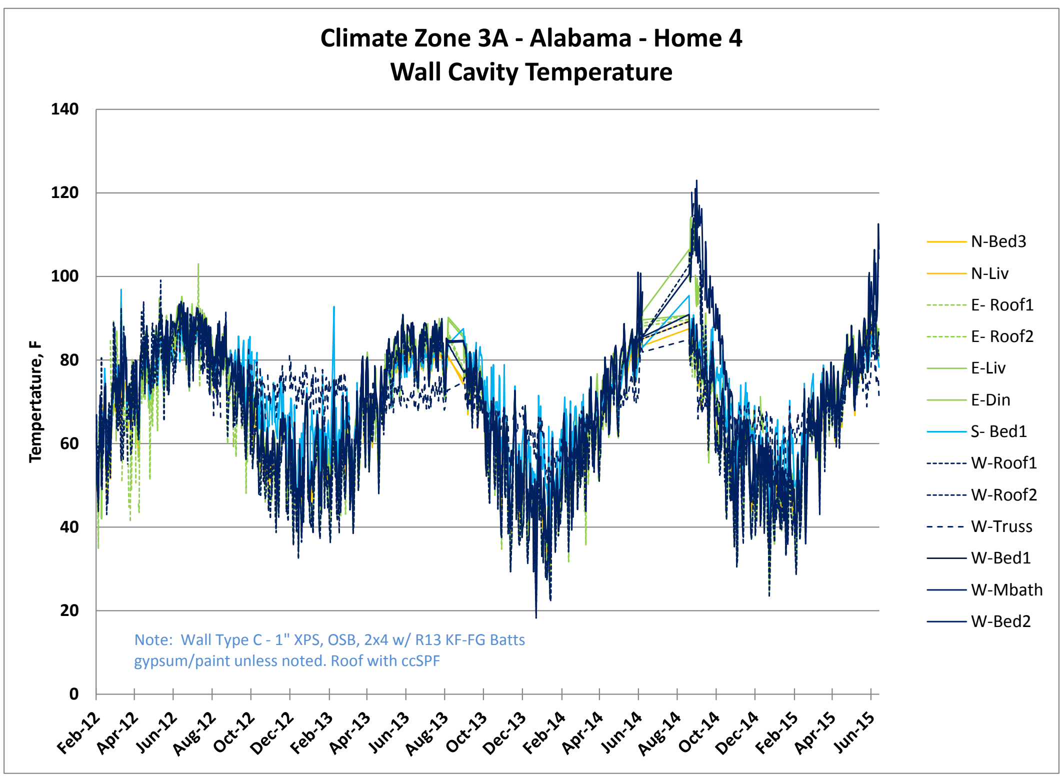
APPENDIX A:
WALL CAVITY TEMPERATURE CHARTS






Climate Zone2A - Louisiana - Home 3
Wall Cavity Temperature
Temperature, F
120
100
80
60
40
20
0
Nbed2
Nbed3
Nbed2 stud
Nbed3 stud
Embed
Embath
Embed stud
Smbed
Smbed stud
Wdr
Wutil
Wutil stud
crawl floor
Note: Wall Type I - WRB, OSB, 2x6, R24 Spray Rockwool, gypsum/paint.
East West - Reflective WRB, OSB, 2x6, R24 Spray Rockwool, gypsum/paint
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15


Climate Zone 3A - Alabama - Home 4
Wall Cavity Temperature
Tempertature, F
140
120
100
80
60
40
20
0
N-Bed3
N-Liv
E- Roof1
E- Roof2
E-Liv
E-Din
S- Bed1
W-Roof1
W-Roof2
W-Truss
W-Bed1
W-Mbath
W-Bed2
Note: Wall Type C - 1" XPS, OSB, 2x4 w/ R13 KF-FG Batts
gypsum/paint unless noted. Roof with ccSPF
Feb-12
Apr-12
Jun-12
Aug-12
Oct-12
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
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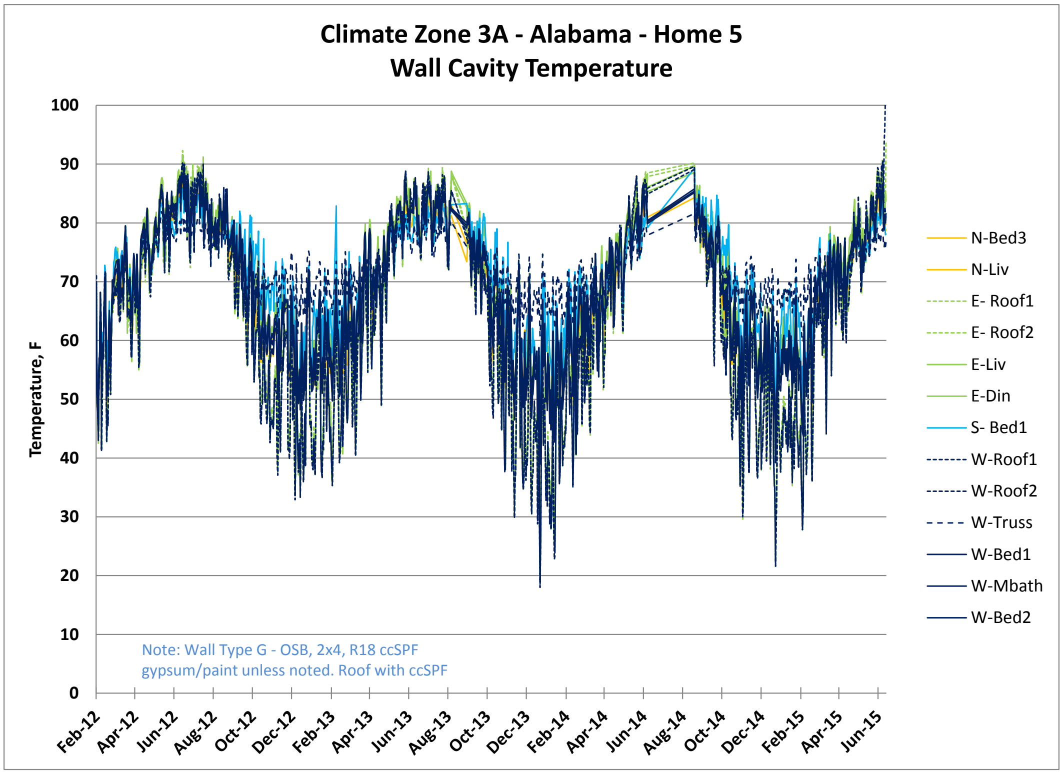
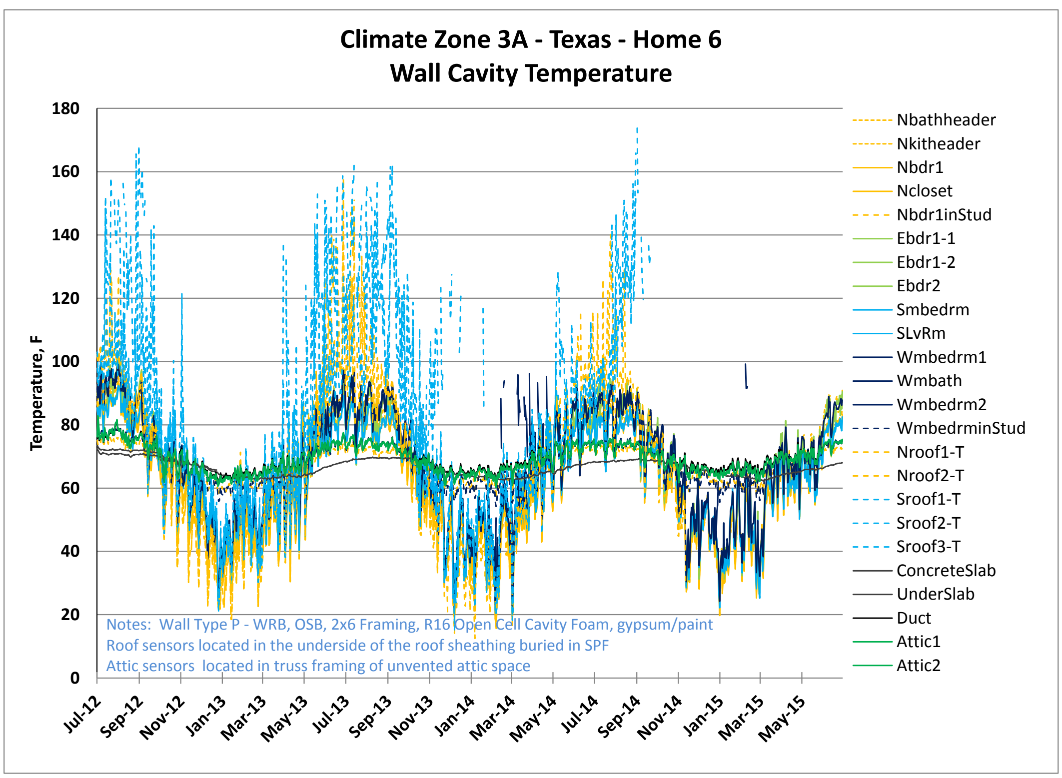
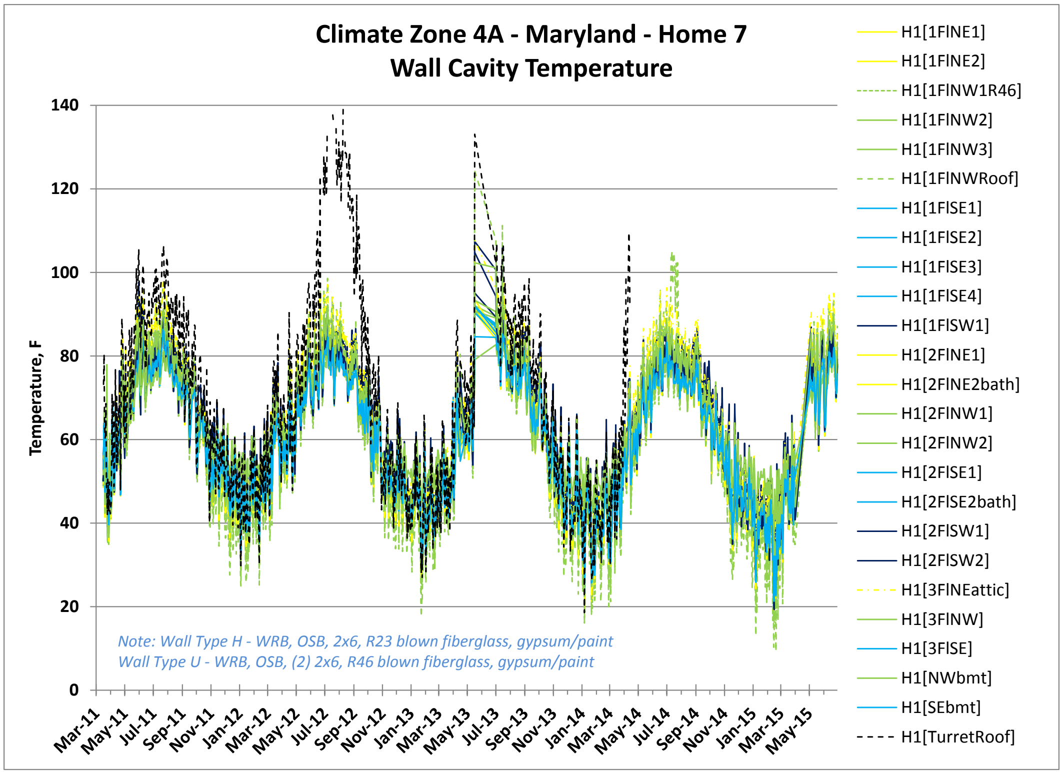
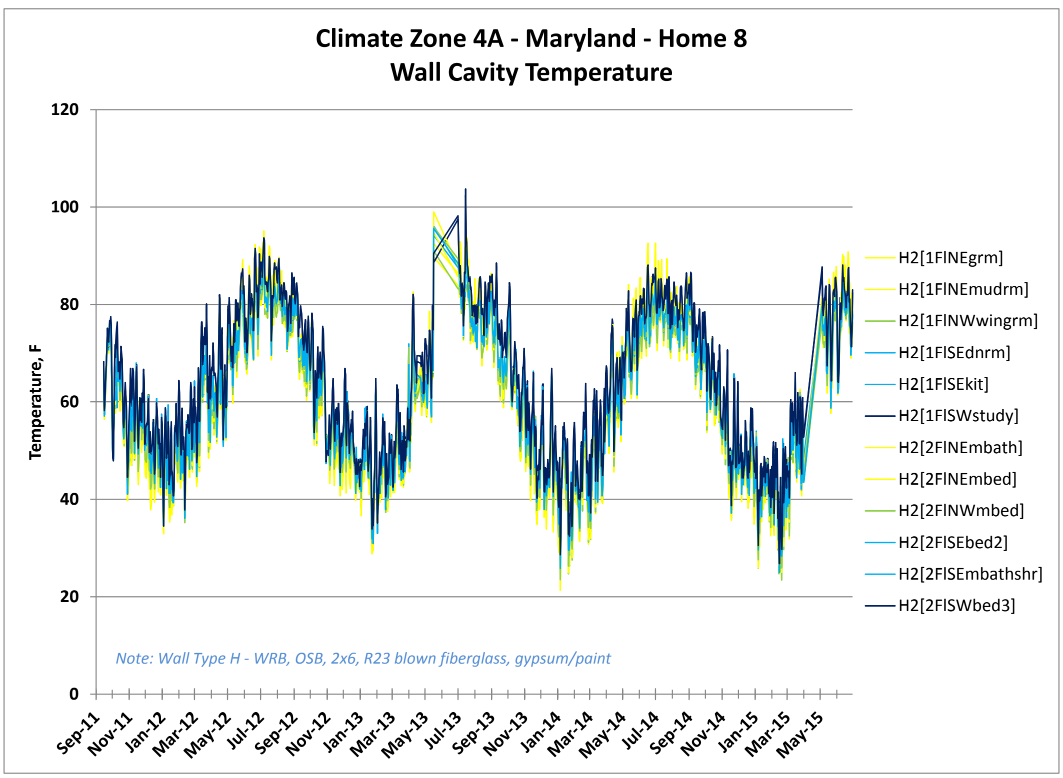
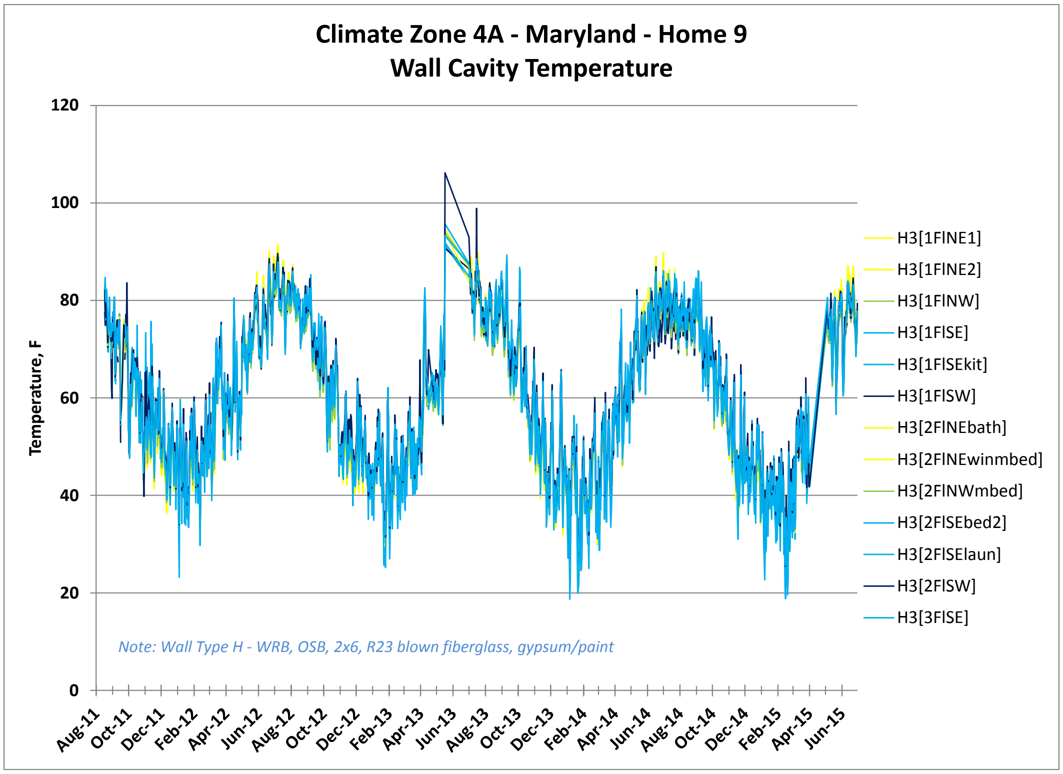
Dec-14
Feb-15
Apr-15
Jun-15


Climate Zone 3A - Alabama - Home 5
Wall Cavity Temperature
Temperature, F
Note: Wall Type G - OSB, 2x4, R18 ccSPF
gypsum/paint unless noted. Roof with ccSPF
N-Bed3
N-Liv
E- Roof1
E- Roof2
E-Liv
E-Din
S- Bed1
W-Roof1
W-Roof2
W-Truss
W-Bed1
W-Mbath
W-Bed2

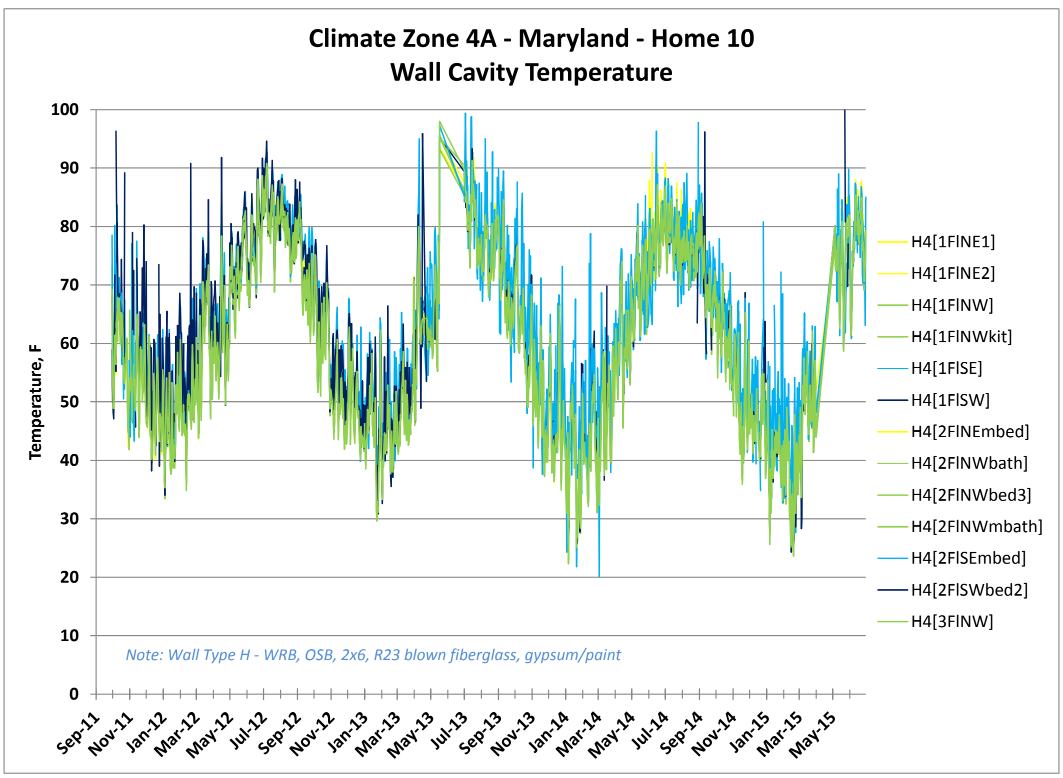

Climate Zone 3A - Texas - Home 6
Wall Cavity Temperature
Temperature, F
Notes: Wall Type P - WRB, OSB, 2x6 Framing, R16 Open Cell Cavity Foam, gypsum/paint
Roof sensors located in the underside of the roof sheathing buried in SPF
Attic sensors located in truss framing of unvented attic space
Nbathheader
Nkitheader
Nbdr1
Ncloset
Nbdr1inStud
Ebdr1-1
Ebdr1-2
Ebdr2
Smbedrm
SLvRm
Wmbedrm1
Wmbath
Wmbedrm2
WmbedrminStud
Nroof1-T
Nroof2-T
Sroof1-T
Sroof2-T
Sroof3-T
ConcreteSlab
UnderSlab
Duct
Attic1
Attic2


Climate Zone 4A - Maryland - Home 7
Wall Cavity Temperature
Temperature, F
Note: Wall Type H - WRB, OSB, 2x6, R23 blown fiberglass, gypsum/paint
Wall Type U - WRB, OSB, (2) 2x6, R46 blown fiberglass, gypsum/paint
H1[1FlNE1]
H1[1FlNE2]
H1[1FlNW1R46]
H1[1FlNW2]
H1[1FlNW3]
H1[1FlNWRoof]
H1[1FlSE1]
H1[1FlSE2]
H1[1FlSE3]
H1[1FlSE4]
H1[1FlSW1]
H1[2FlNE1]
H1[2FlNE2bath]
H1[2FlNW1]
H1[2FlNW2]
H1[2FlSE1]
H1[2FlSE2bath]
H1[2FlSW1]
H1[2FlSW2]
H1[3FlNEattic]
H1[3FlNW]
H1[3FlSE]
H1[NWbmt]
H1[SEbmt]
H1[TurretRoof]


Climate Zone 4A - Maryland - Home 8
Wall Cavity Temperature
Temperature, F
Note: Wall Type H - WRB, OSB, 2x6, R23 blown fiberglass, gypsum/paint
H2[1FlNEgrm]
H2[1FlNEmudrm]
H2[1FlNWwingrm]
H2[1FlSEdnrm]
H2[1FlSEkit]
H2[1FlSWstudy]
H2[2FlNEmbath]
H2[2FlNEmbed]
H2[2FlNWmbed]
H2[2FlSEbed2]
H2[2FlSEmbathshr]
H2[2FlSWbed3]



Climate Zone 4A - Maryland - Home 9
Wall Cavity Temperature
Temperature, F
120
100
80
60
40
20
0
H3[1FlNE1]
H3[1FlNE2]
H3[1FlNW]
H3[1FlSE]
H3[1FlSEkit]
H3[1FlSW]
H3[2FlNEbath]
H3[2FlNEwinmbed]
H3[2FlNWmbed]
H3[2FlSEbed2]
H3[2FlSElaun]
H3[2FlSW]
H3[3FlSE]
Note: Wall Type H - WRB, OSB, 2x6, R23 blown fiberglass, gypsum/paint
Aug-11
Oct-11
Dec-11
Feb-12
Apr-12
Jun-12
Aug-12
Oct-12
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Apr-14
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Jun-15



Climate Zone 4A - Maryland - Home 10
Wall Cavity Temperature
Temperature, F
100
90
80
70
60
50
40
30
20
10
0
H4[1FlNE1]
H4[1FlNE2]
H4[1FlNW]
H4[1FlNWkit]
H4[1FlSE]
H4[1FlSW]
H4[2FlNEmbed]
H4[2FlNWbath]
H4[2FlNWbed3]
H4[2FlNWmbath]
H4[2FlSEmbed]
H4[2FlSWbed2]
H4[3FlNW]
Note: Wall Type H - WRB, OSB, 2x6, R23 blown fiberglass, gypsum/paint
Sep-11
Nov-11
Jan-12
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
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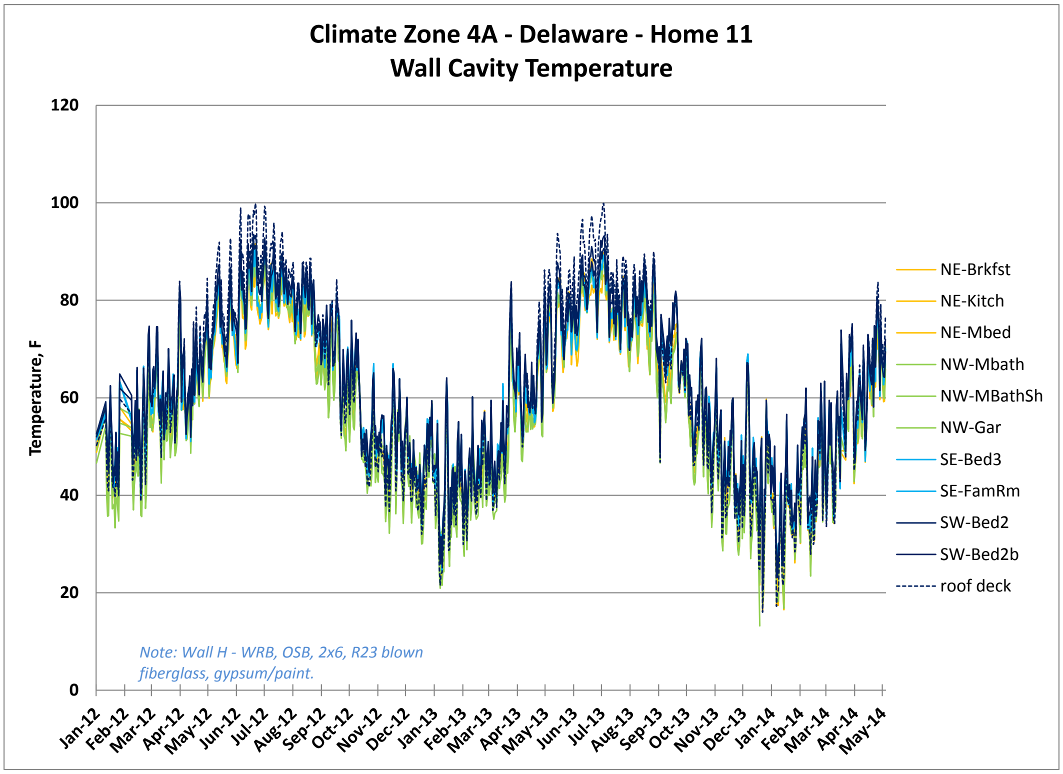
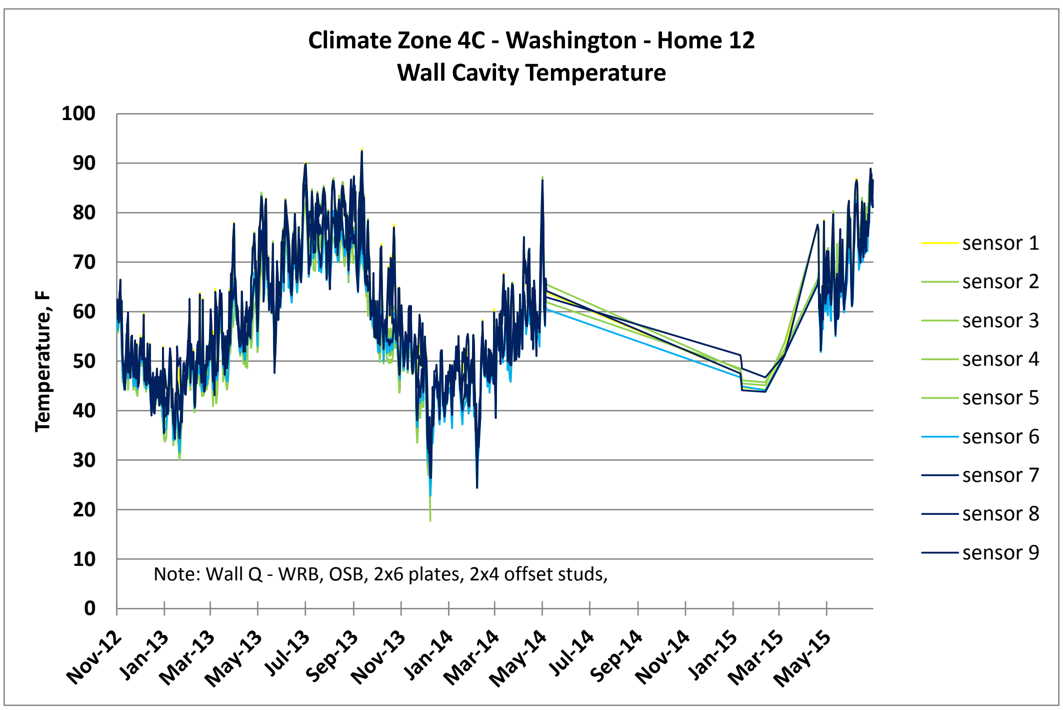
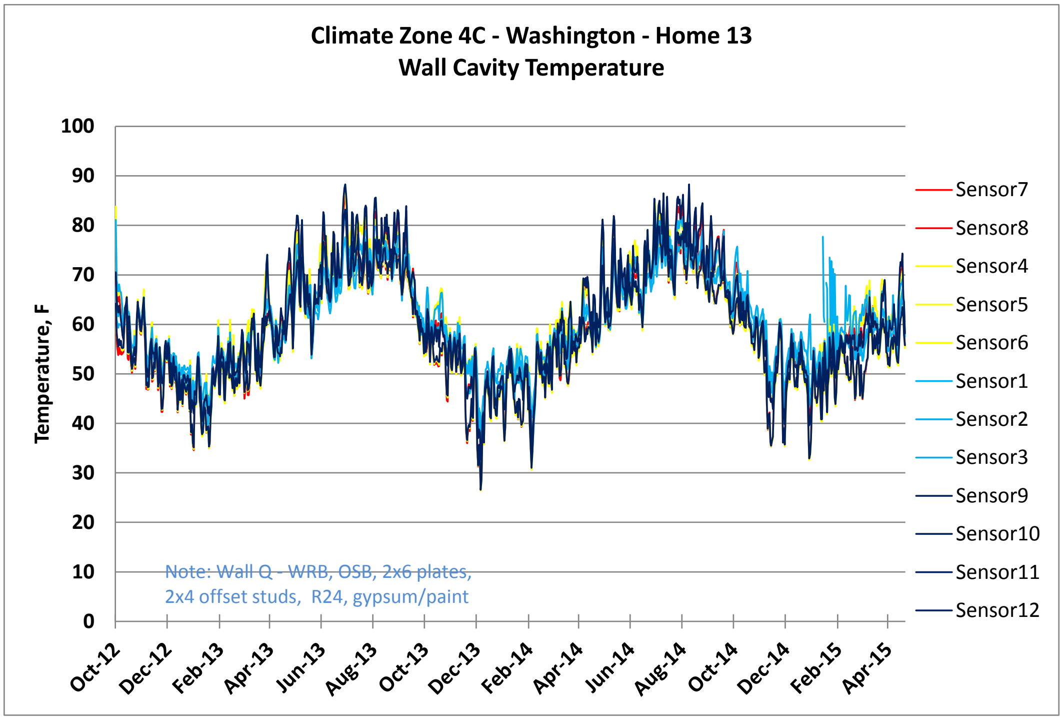
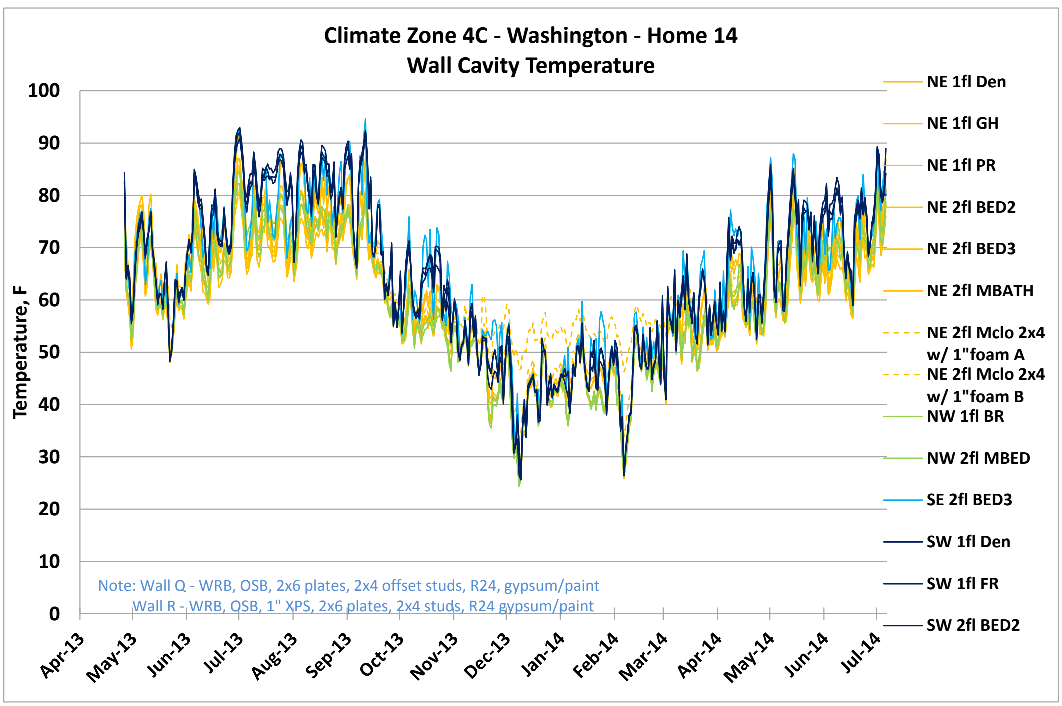
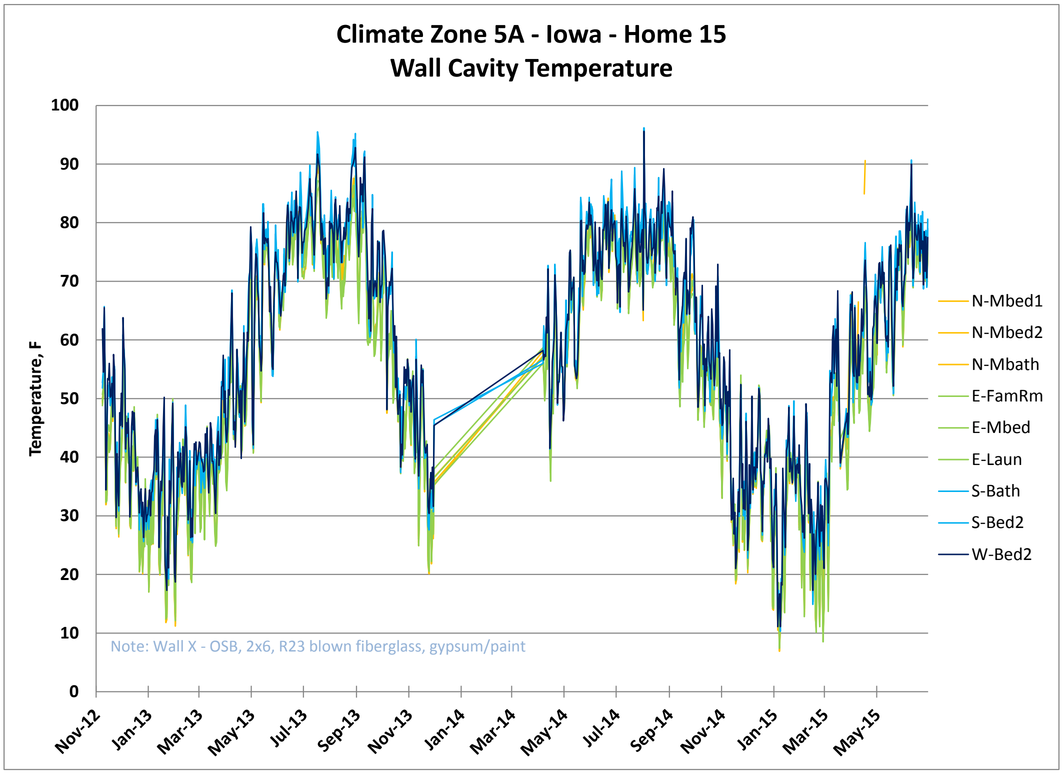
Sep-14
Nov-14
Jan-15
Mar-15
May-15


Climate Zone 4A - Delaware - Home 11
Wall Cavity Temperature
Temperature, F
NE-Brkfst
NE-Kitch
NE-Mbed
NW-Mbath
NW-MBathSh
NW-Gar
SE-Bed3
SE-FamRm
SW-Bed2
SW-Bed2b
roof deck
Note: Wall H - WRB, OSB, 2x6, R23 blown fiberglass, gypsum/paint.

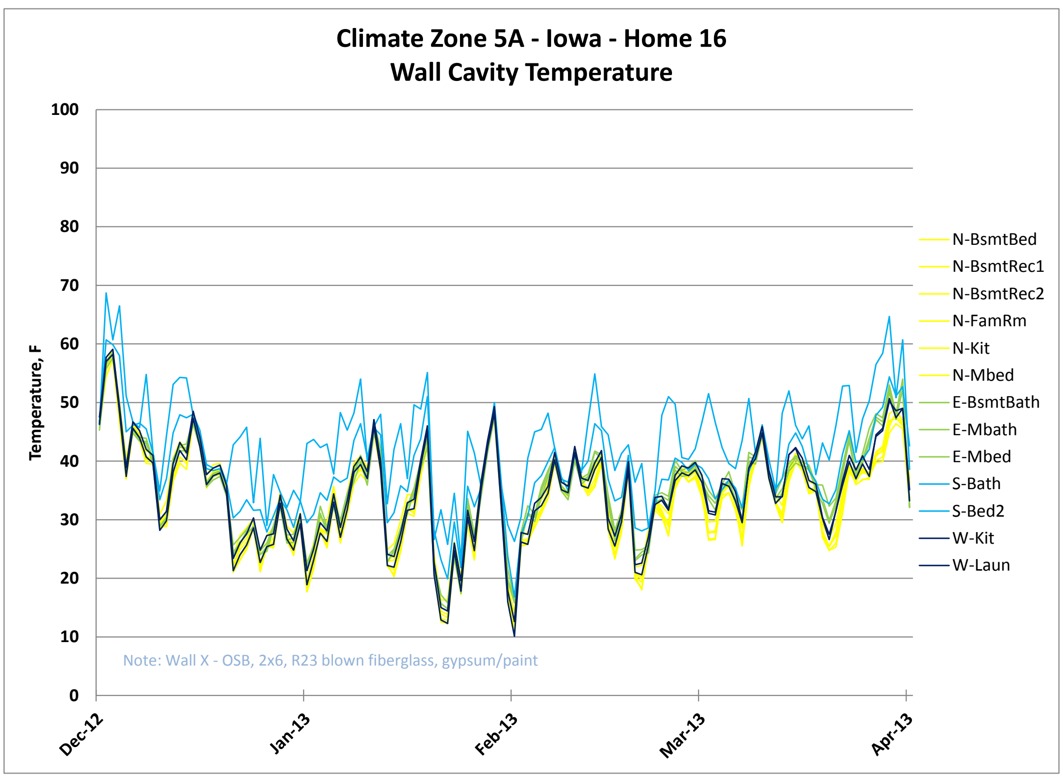

Climate Zone 4C - Washington - Home 12
Wall Cavity Temperature
Temperature, F
sensor 1
sensor 2
sensor 3
sensor 4
sensor 5
sensor 6
sensor 7
sensor 8
sensor 9
Note: Wall Q - WRB, OSB, 2x6 plates, 2x4 offset studs,


Climate Zone 4C - Washington - Home 13
Wall Cavity Temperature
Temperature, F
100
90
80
70
60
50
40
30
20
10
0
Oct-12
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Apr-14
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Sensor7
Sensor8
Sensor4
Sensor5
Sensor6
Sensor1
Sensor2
Sensor3
Sensor9
Sensor10
Sensor11
Sensor12
Note: Wall Q - WRB, OSB, 2x6 plates,
2x4 offset studs, R24, gypsum/paint

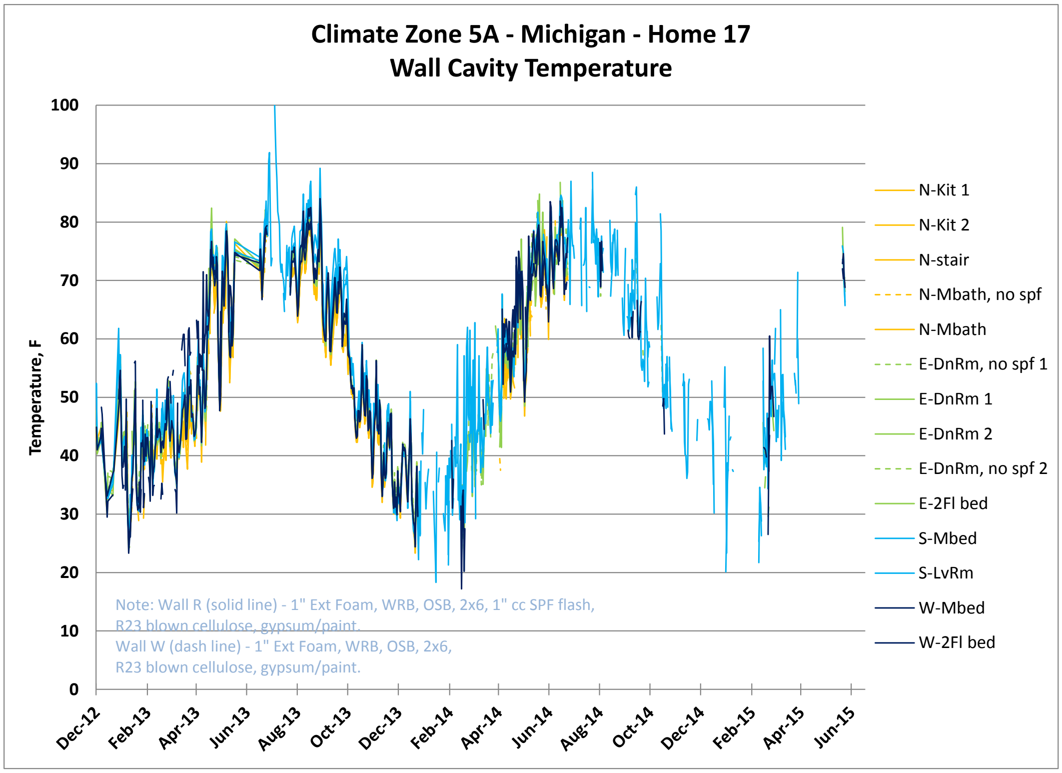

Climate Zone 4C - Washington - Home 14
Wall Cavity Temperature
Temperature, F
100
90
80
70
60
50
40
30
20
10
0
Apr-13
May-13
Jun-13
Jul-13
Aug-13
Sep-13
Oct-13
Nov-13
Dec-13
Jan-14
Feb-14
Mar-14
Apr-14
May-14
Jun-14
Jul-14
NE 1fl Den
NE 1fl GH
NE 1fl PR
NE 2fl BED2
NE 2fl BED3
NE 2fl MBATH
NE 2fl Mclo 2x4 w/ 1"foam A
NE 2fl Mclo 2x4 w/ 1"foam B
NW 1fl BR
NW 2fl MBED
SE 2fl BED3
SW 1fl Den
SW 1fl FR
SW 2fl BED2
Note: Wall Q - WRB, OSB, 2x6 plates, 2x4 offset studs, R24, gypsum/paint
Wall R - WRB, OSB, 1" XPS, 2x6 plates, 2x4 studs, R24 gypsum/paint



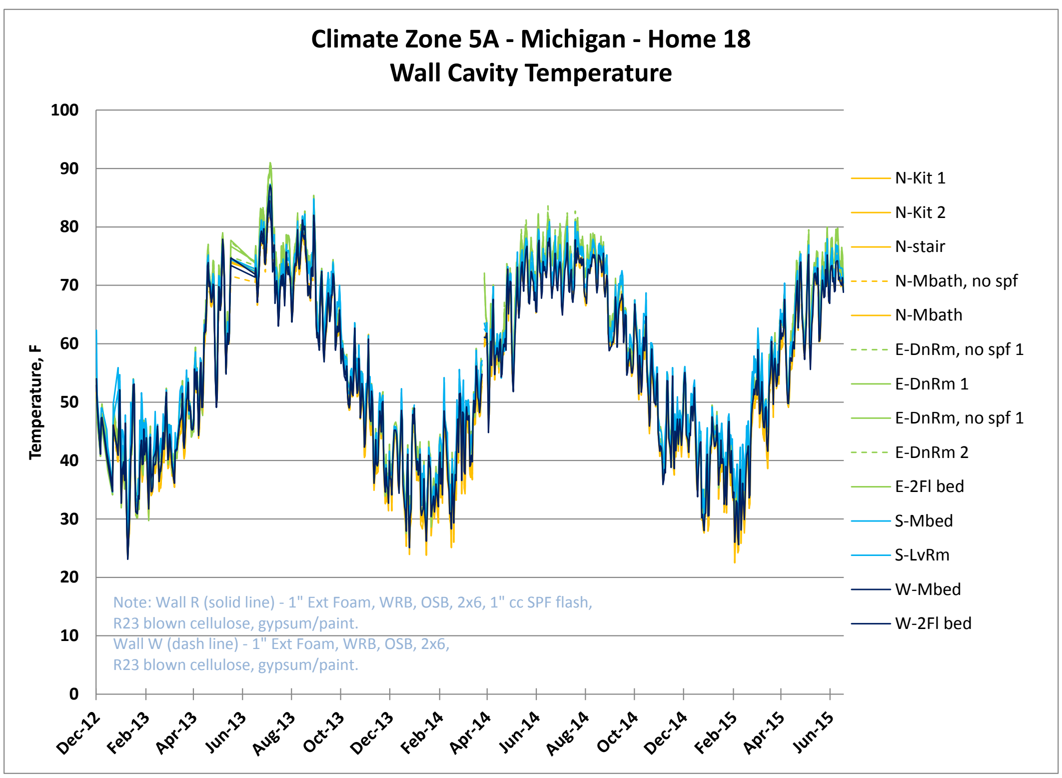
Climate Zone 5A - Iowa - Home 15
Wall Cavity Temperature
Temperature, F
100
90
80
70
60
50
40
30
20
10
0
Note: Wall X - OSB, 2x6, R23 blown fiberglass, gypsum/paint
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
N-Mbed1
N-Mbed2
N-Mbath
E-FamRm
E-Mbed
E-Laun
S-Bath
S-Bed2
W-Bed2



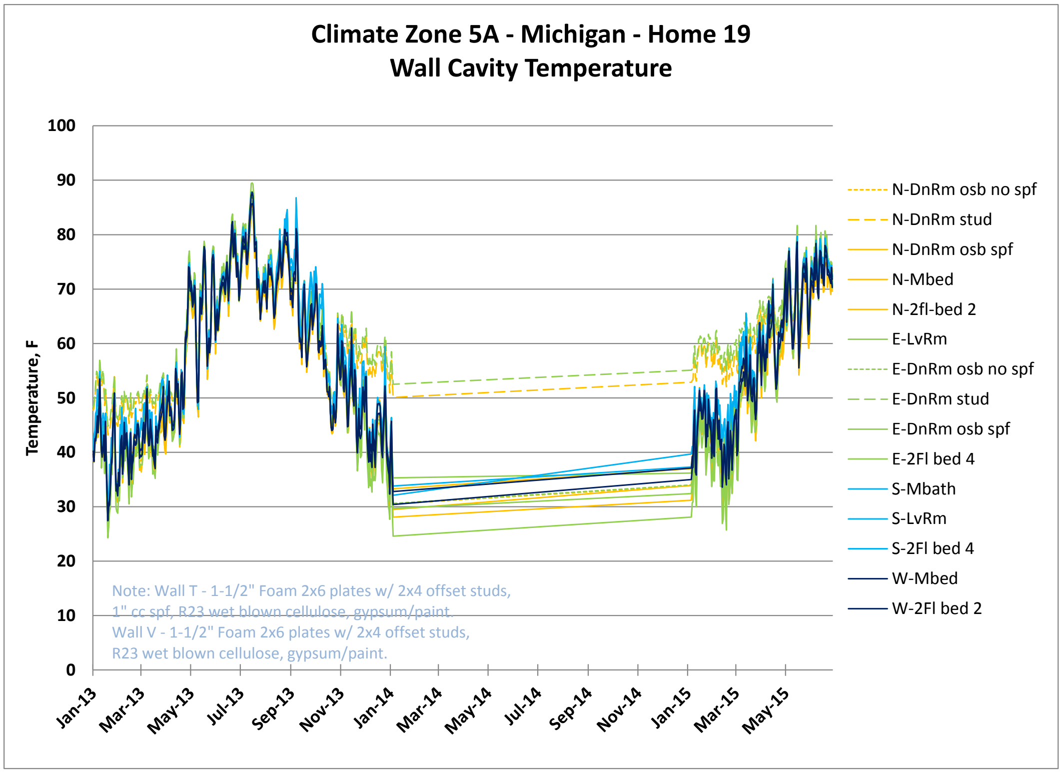
Climate Zone 5A - Iowa - Home 16
Wall Cavity Temperature
Temperature, F
100
90
80
70
60
50
40
30
20
10
0
Note: Wall X - OSB, 2x6, R23 blown fiberglass, gypsum/paint
Dec-12
Jan-13
Feb-13
Mar-13
Apr-13
N-BsmtBed
N-BsmtRec1
N-BsmtRec2
N-FamRm
N-Kit
N-Mbed
E-BsmtBath
E-Mbath
E-Mbed
S-Bath
S-Bed2
W-Kit
W-Laun

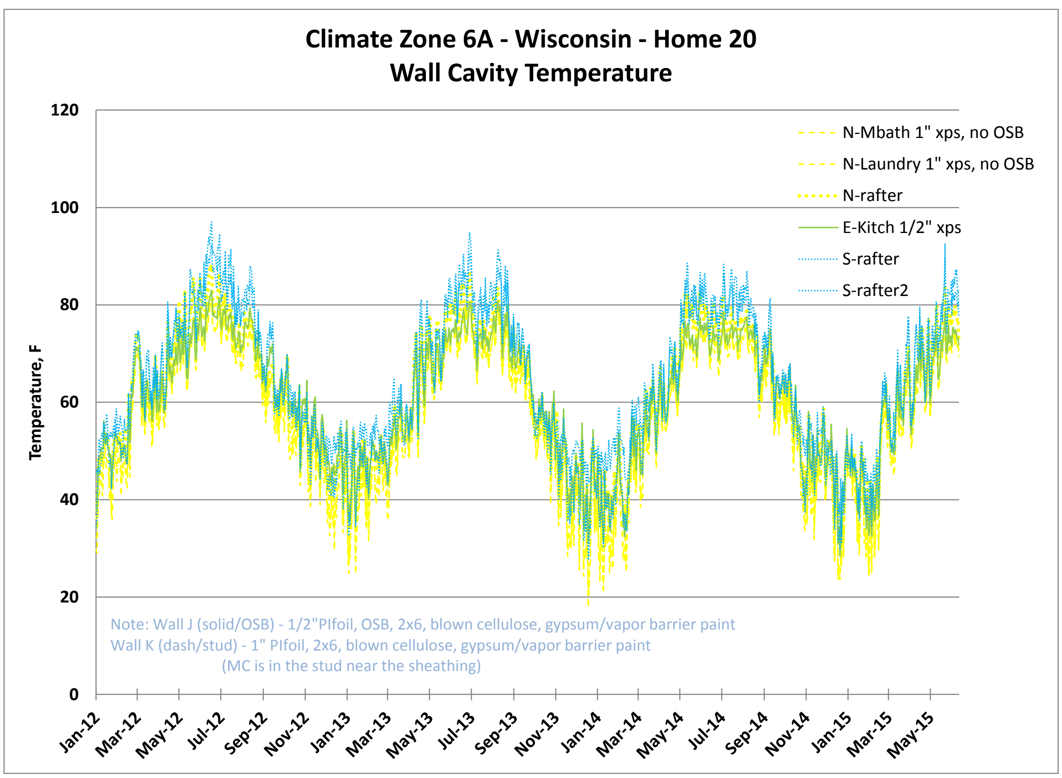


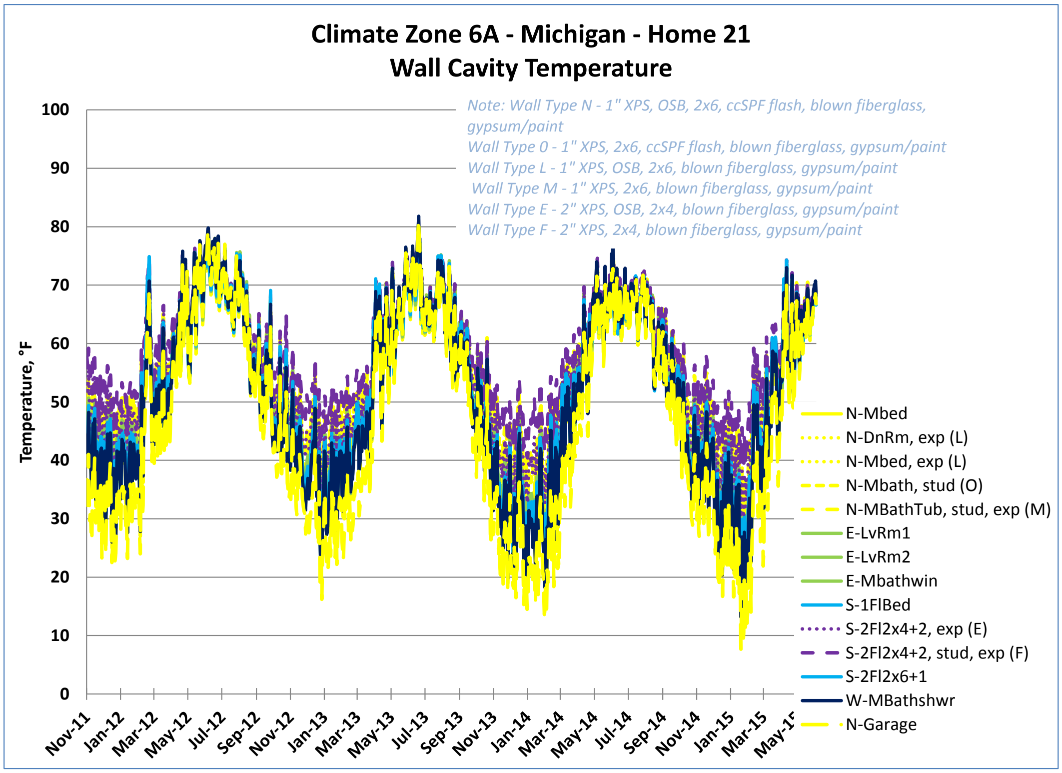
Climate Zone 5A - Michigan - Home 17
Wall Cavity Temperature
Temperature, F
0
10
20
30
40
50
60
70
80
90
100
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Apr-14
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Jun-15
Note: Wall R (solid line) - 1" Ext Foam, WRB, OSB, 2x6, 1" cc SPF flash,
R23 blown cellulose, gypsum/paint.
Wall W (dash line) - 1" Ext Foam, WRB, OSB, 2x6,
R23 blown cellulose, gypsum/paint.
N-Kit 1
N-Kit 2
N-stair
N-Mbath, no spf
N-Mbath
E-DnRm, no spf 1
E-DnRm 1
E-DnRm 2
E-DnRm, no spf 2
E-2Fl bed
S-Mbed
S-LvRm
W-Mbed
W-2Fl bed

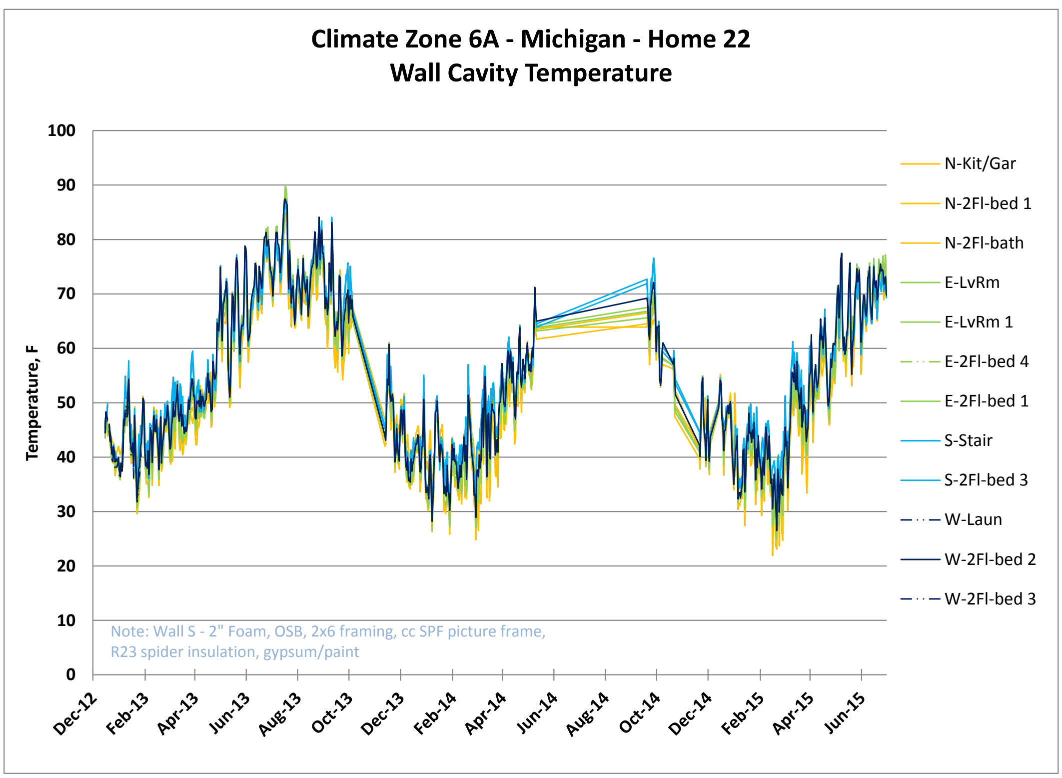


Climate Zone 5A - Michigan - Home 18
Wall Cavity Temperature
Temperature, F
0
10
20
30
40
50
60
70
80
90
100
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Apr-14
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Jun-15
Note: Wall R (solid line) - 1" Ext Foam, WRB, OSB, 2x6, 1" cc SPF flash,
R23 blown cellulose, gypsum/paint.
Wall W (dash line) - 1" Ext Foam, WRB, OSB, 2x6,
R23 blown cellulose, gypsum/paint.
N-Kit 1
N-Kit 2
N-stair
N-Mbath, no spf
N-Mbath
E-DnRm, no spf 1
E-DnRm 1
E-DnRm, no spf 1
E-DnRm 2
E-2Fl bed
S-Mbed
S-LvRm
W-Mbed
W-2Fl bed

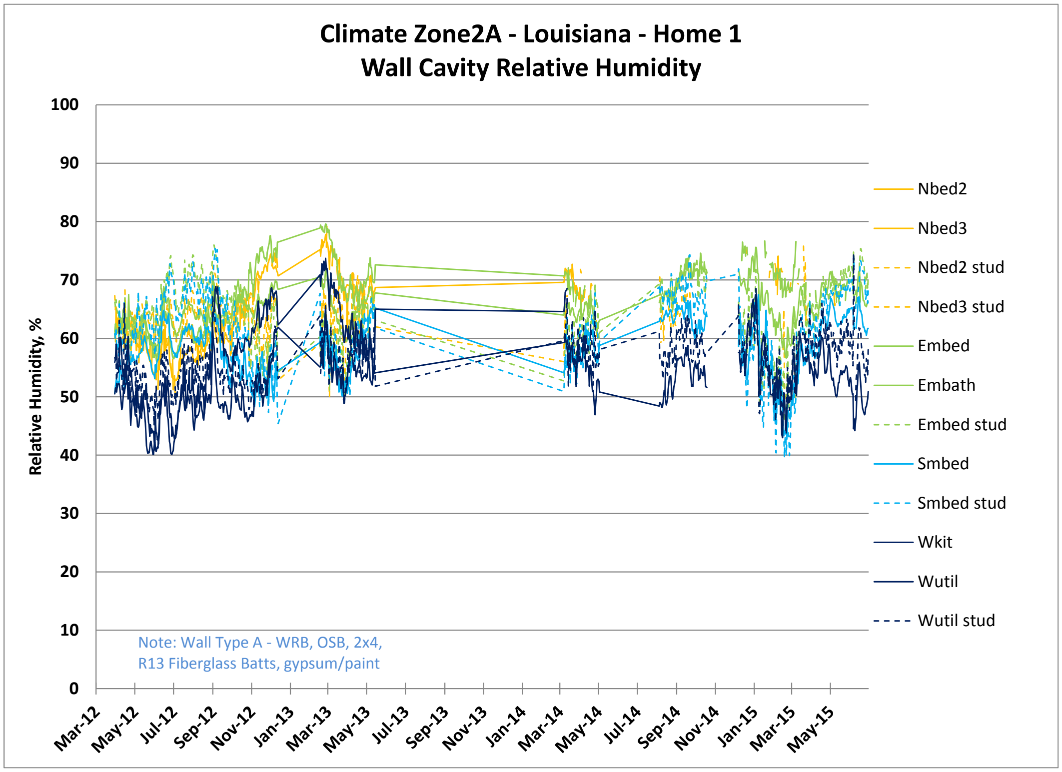

Climate Zone 5A - Michigan - Home 19
Wall Cavity Temperature
Temperature, F
100
90
80
70
60
50
40
30
20
10
0
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
N-DnRm osb no spf
N-DnRm stud
N-DnRm osb spf
N-Mbed
N-2fl-bed 2
E-LvRm
E-DnRm osb no spf
E-DnRm stud
E-DnRm osb spf
E-2Fl bed 4
S-Mbath
S-LvRm
S-2Fl bed 4
W-Mbed
W-2Fl bed 2
Note: Wall T - 1-1/2" Foam 2x6 plates w/ 2x4 offset studs,
1" cc spf, R23 wet blown cellulose, gypsum/paint.
Wall V - 1-1/2" Foam 2x6 plates w/ 2x4 offset studs,
R23 wet blown cellulose, gypsum/paint.

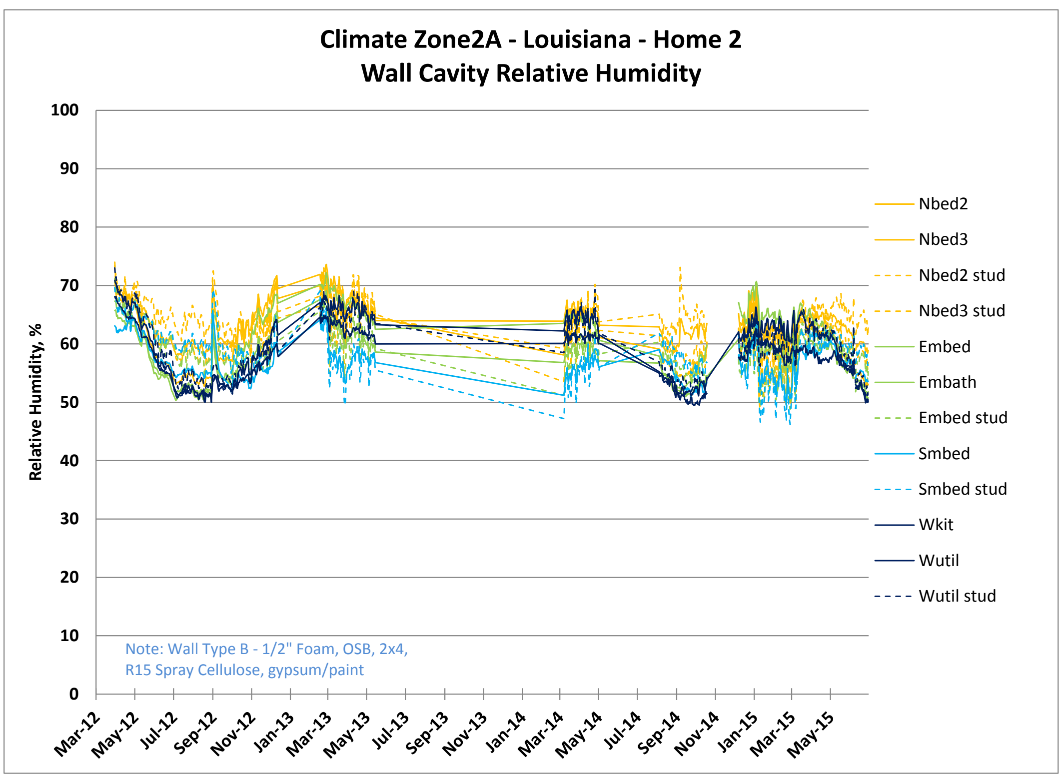

Climate Zone 6A - Wisconsin - Home 20
Wall Cavity Temperature
Temperature, F
120
100
80
60
40
20
0
Jan-12
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
N-Mbath 1" xps, no OSB
N-Laundry 1" xps, no OSB
N-rafter
E-Kitch 1/2" xps
S-rafter
S-rafter2
Note: Wall J (solid/OSB) - 1/2"PIfoil, OSB, 2x6, blown cellulose, gypsum/vapor barrier paint
Wall K (dash/stud) - 1" PIfoil, 2x6, blown cellulose, gypsum/vapor barrier paint
(MC is in the stud near the sheathing)

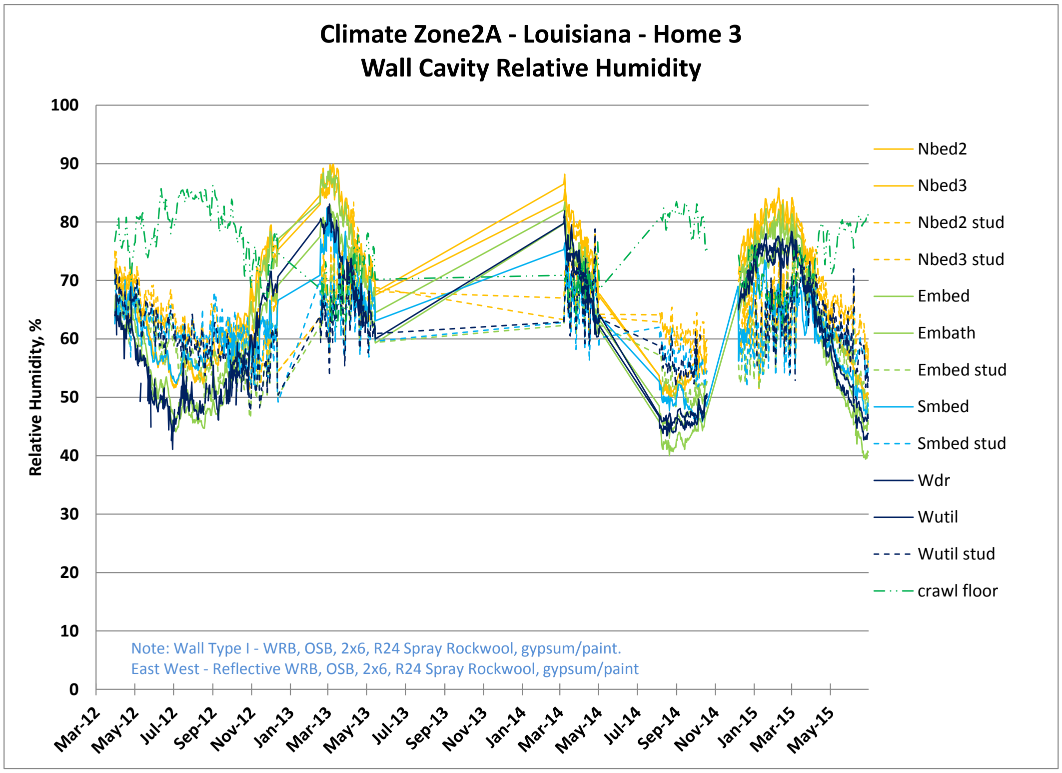

Climate Zone 6A - Michigan - Home 21
Wall Cavity Temperature
Note: Wall Type N - 1" XPS, OSB, 2x6, ccSPF flash, blown fiberglass, gypsum/paint
Wall Type 0 - 1" XPS, 2x6, ccSPF flash, blown fiberglass, gypsum/paint
Wall Type L - 1" XPS, OSB, 2x6, blown fiberglass, gypsum/paint
Wall Type M - 1" XPS, 2x6, blown fiberglass, gypsum/paint
Wall Type E - 2" XPS, OSB, 2x4, blown fiberglass, gypsum/paint
Wall Type F - 2" XPS, 2x4, blown fiberglass, gypsum/paint
Temperature, °F
N-Mbed
N-DnRm, exp (L)
N-Mbed, exp (L)
N-Mbath, stud (O)
N-MBathTub, stud, exp (M)
E-LvRm1
E-LvRm2
E-Mbathwin
S-1FlBed
S-2Fl2x4+2, exp (E)
S-2Fl2x4+2, stud, exp (F)
S-2Fl2x6+1
W-MBathshwr
N-Garage

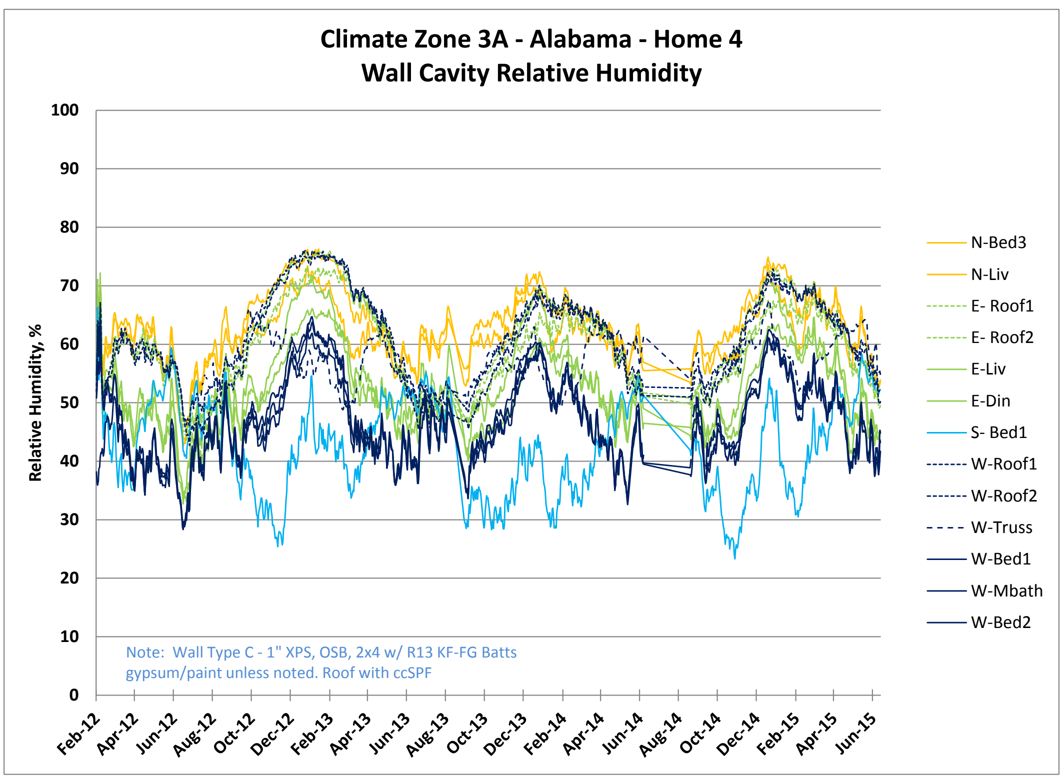

Climate Zone 6A - Michigan - Home 22
Wall Cavity Temperature
Temperature, F
Note: Wall S - 2" Foam, OSB, 2x6 framing, cc SPF picture frame, R23 spider insulation, gypsum/paint
N-Kit/Gar
N-2Fl-bed 1
N-2Fl-bath
E-LvRm
E-LvRm 1
E-2Fl-bed 4
E-2Fl-bed 1
S-Stair
S-2Fl-bed 3
W-Laun
W-2Fl-bed 2
W-2Fl-bed 3

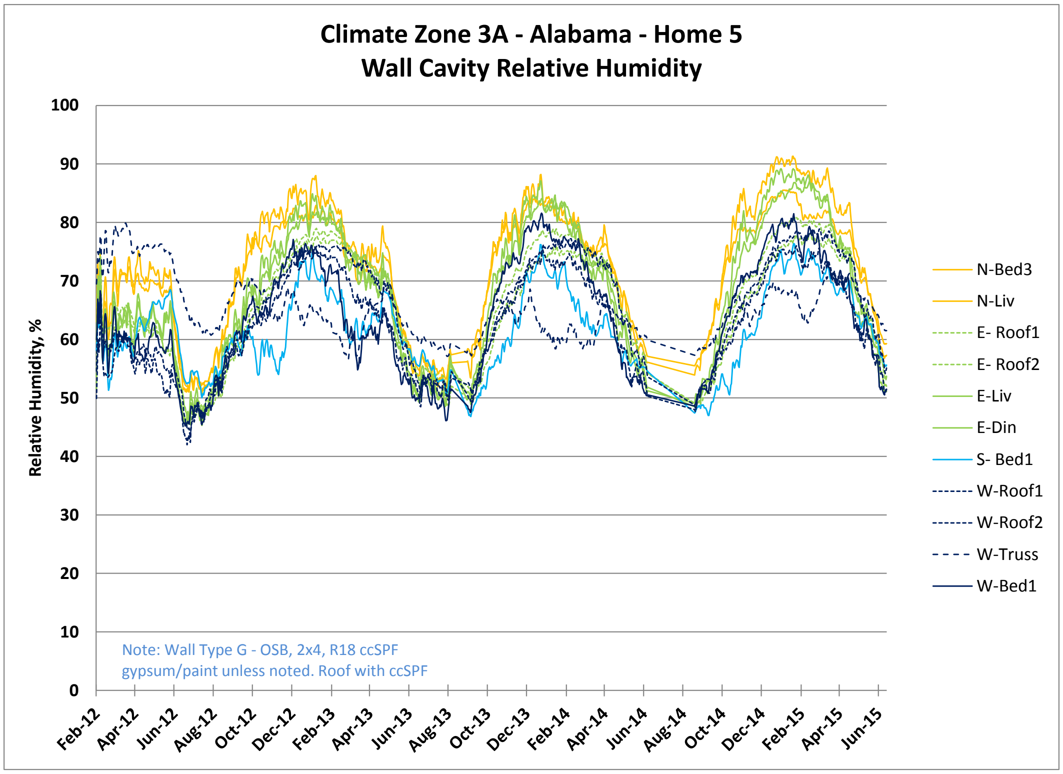
APPENDIX B:
WALL CAVITY RELATIVE HUMIDITY CHARTS



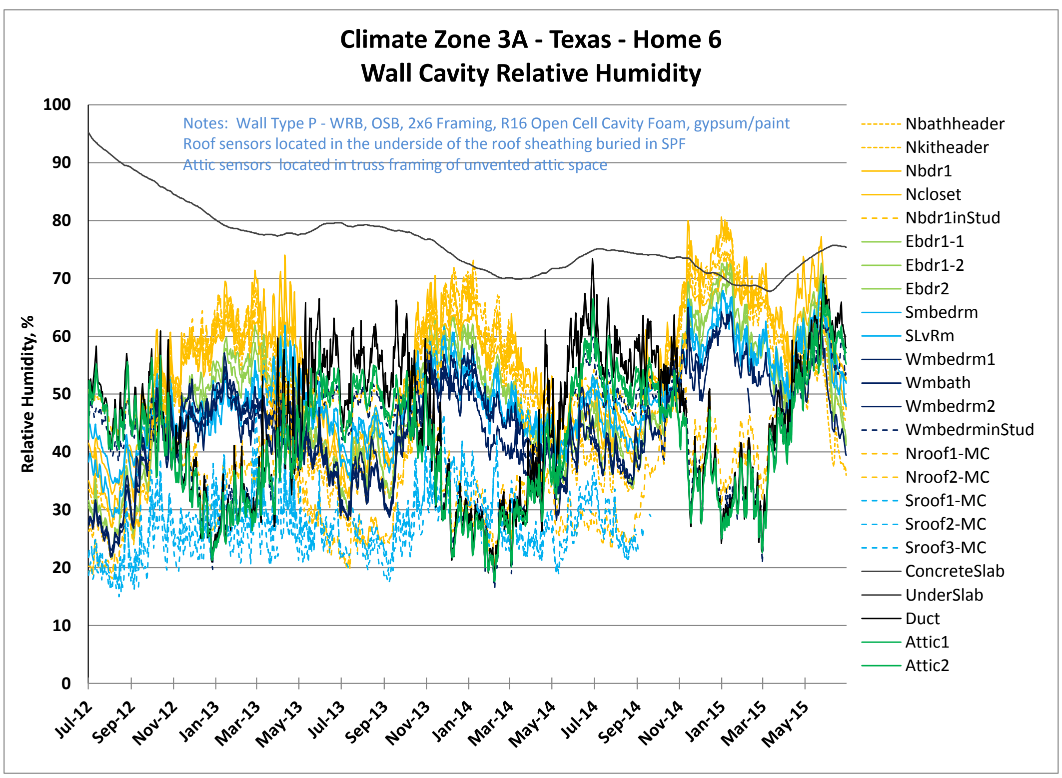



Climate Zone2A - Louisiana - Home 3
Wall Cavity Relative Humidity
Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
Nbed2
Nbed3
Nbed2 stud
Nbed3 stud
Embed
Embath
Embed stud
Smbed
Smbed stud
Wdr
Wutil
Wutil stud
crawl floor
Note: Wall Type I - WRB, OSB, 2x6, R24 Spray Rockwool, gypsum/paint.
East West - Reflective WRB, OSB, 2x6, R24 Spray Rockwool, gypsum/paint

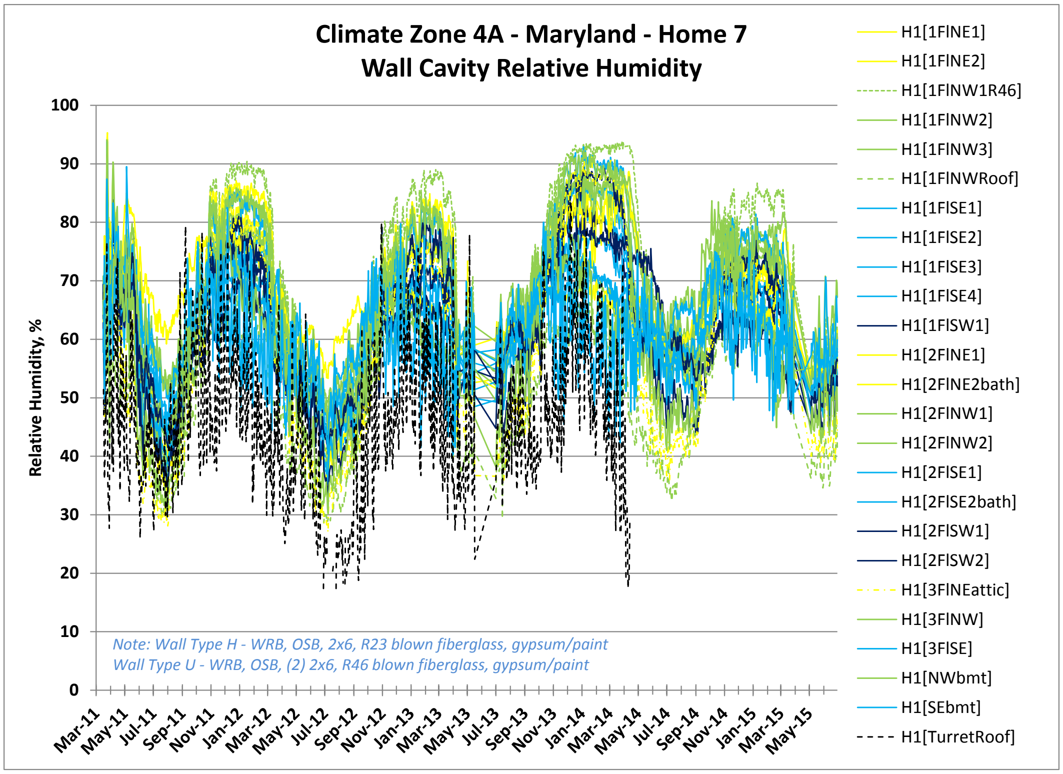

Climate Zone 3A - Alabama - Home 4
Wall Cavity Relative Humidity
Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Feb-12
Apr-12
Jun-12
Aug-12
Oct-12
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Apr-14
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Jun-15
N-Bed3
N-Liv
E- Roof1
E- Roof2
E-Liv
E-Din
S- Bed1
W-Roof1
W-Roof2
W-Truss
W-Bed1
W-Mbath
W-Bed2
Note: Wall Type C - 1" XPS, OSB, 2x4 w/ R13 KF-FG Batts
gypsum/paint unless noted. Roof with ccSPF



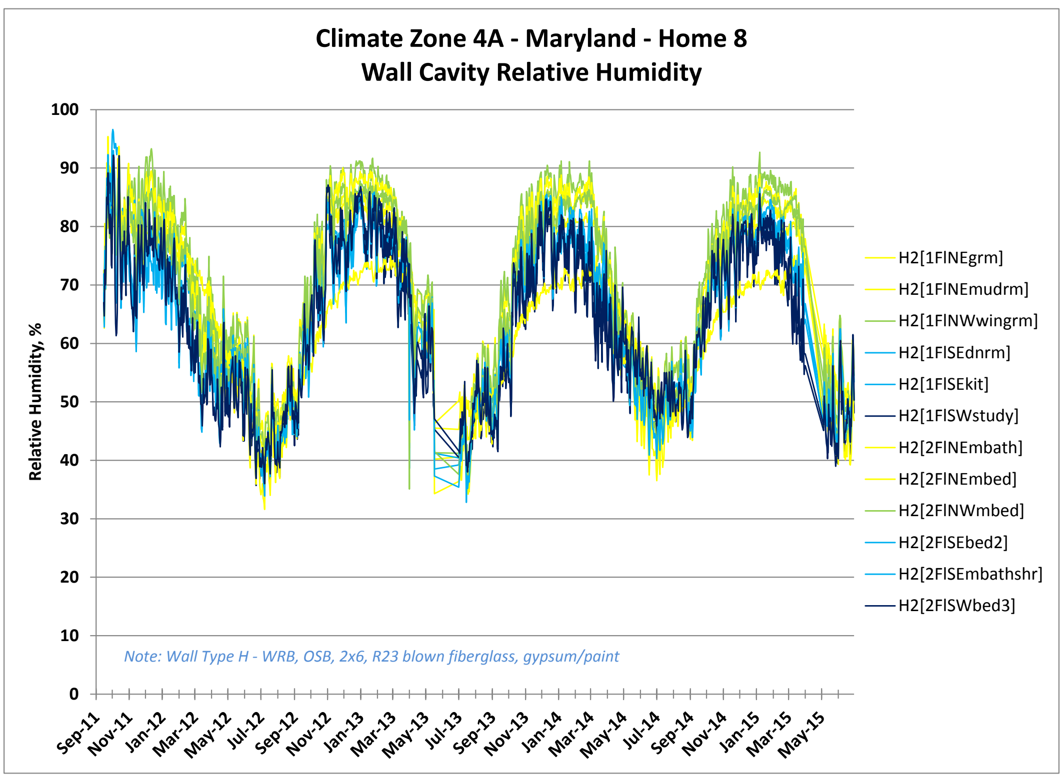
Climate Zone 3A - Alabama - Home 5
Wall Cavity Relative Humidity
Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Note: Wall Type G - OSB, 2x4, R18 ccSPF
gypsum/paint unless noted. Roof with ccSPF
Feb-12
Apr-12
Jun-12
Aug-12
Oct-12
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Apr-14
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Jun-15
N-Bed3
N-Liv
E- Roof1
E- Roof2
E-Liv
E-Din
S- Bed1
W-Roof1
W-Roof2
W-Truss
W-Bed1



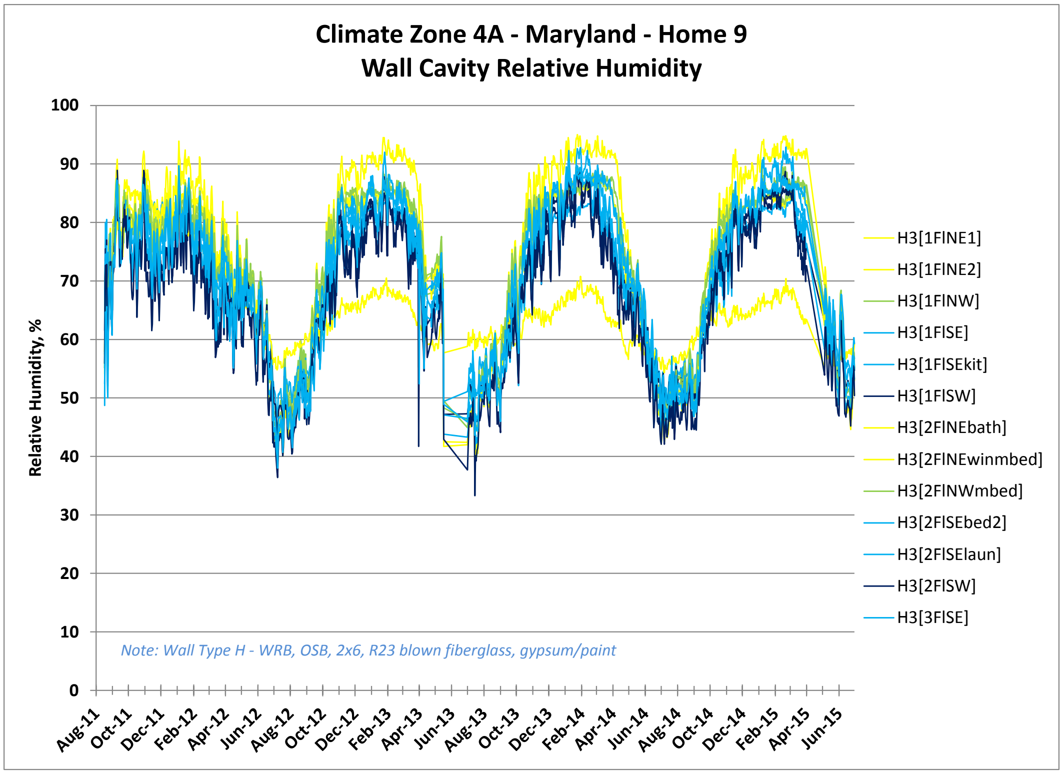
Climate Zone 3A - Texas - Home 6
Wall Cavity Relative Humidity
Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Notes: Wall Type P - WRB, OSB, 2x6 Framing, R16 Open Cell Cavity Foam, gypsum/paint
Roof sensors located in the underside of the roof sheathing buried in SPF
Attic sensors located in truss framing of unvented attic space
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
Nbathheader
Nkitheader
Nbdr1
Ncloset
Nbdr1inStud
Ebdr1-1
Ebdr1-2
Ebdr2
Smbedrm
SLvRm
Wmbedrm1
Wmbath
Wmbedrm2
WmbedrminStud
Nroof1-MC
Nroof2-MC
Sroof1-MC
Sroof2-MC
Sroof3-MC
ConcreteSlab
UnderSlab
Duct
Attic1
Attic2

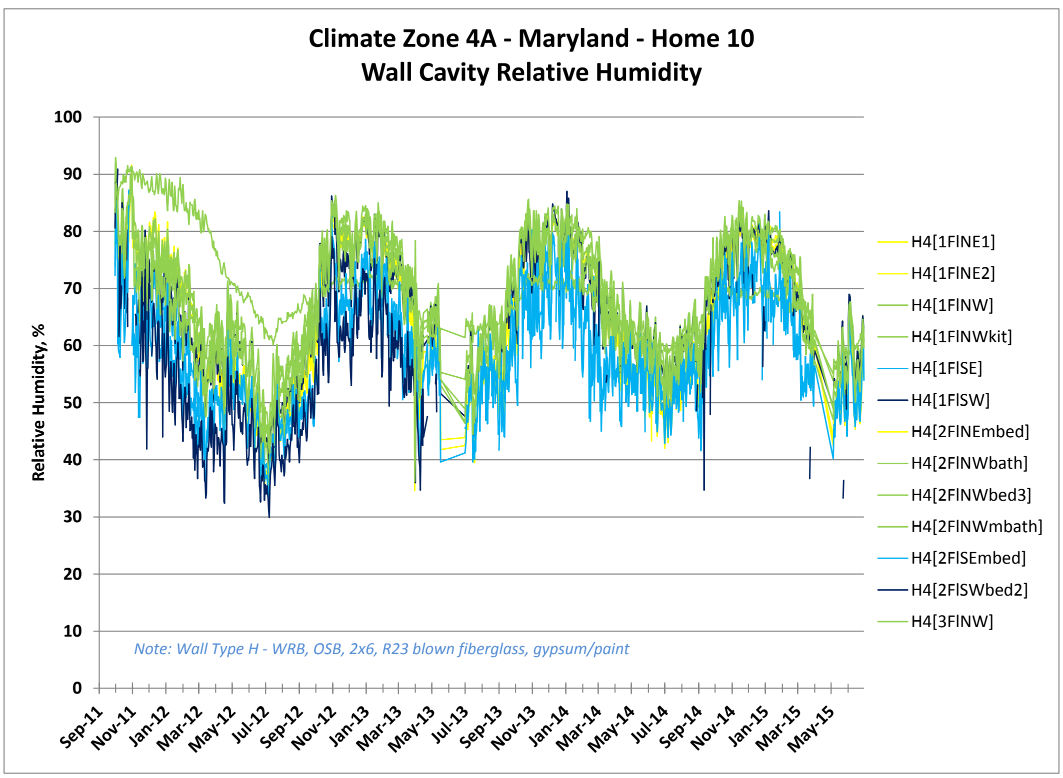


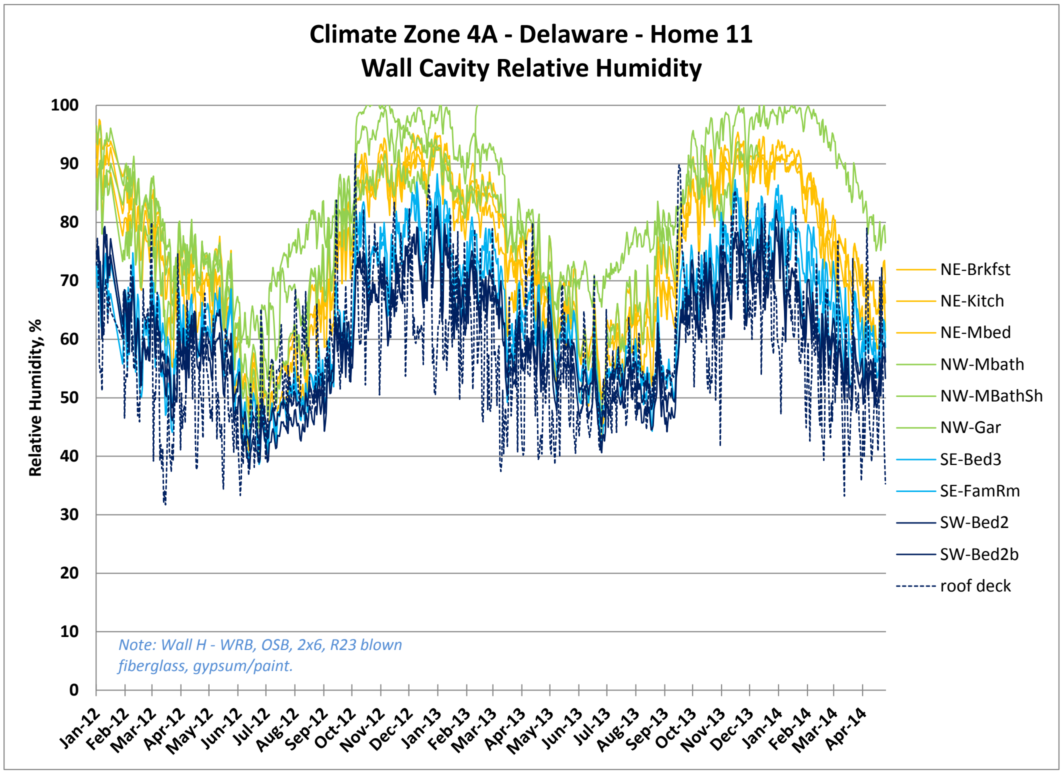
Climate Zone 4A - Maryland - Home 7
Wall Cavity Relative Humidity
Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Note: Wall Type H - WRB, OSB, 2x6, R23 blown fiberglass, gypsum/paint
Wall Type U - WRB, OSB, (2) 2x6, R46 blown fiberglass, gypsum/paint
Mar-11
May-11
Jul-11
Sep-11
Nov-11
Jan-12
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
H1[1FlNE1]
H1[1FlNE2]
H1[1FlNW1R46]
H1[1FlNW2]
H1[1FlNW3]
H1[1FlNWRoof]
H1[1FlSE1]
H1[1FlSE2]
H1[1FlSE3]
H1[1FlSE4]
H1[1FlSW1]
H1[2FlNE1]
H1[2FlNE2bath]
H1[2FlNW1]
H1[2FlNW2]
H1[2FlSE1]
H1[2FlSE2bath]
H1[2FlSW1]
H1[2FlSW2]
H1[3FlNEattic]
H1[3FlNW]
H1[3FlSE]
H1[NWbmt]
H1[SEbmt]
H1[TurretRoof]

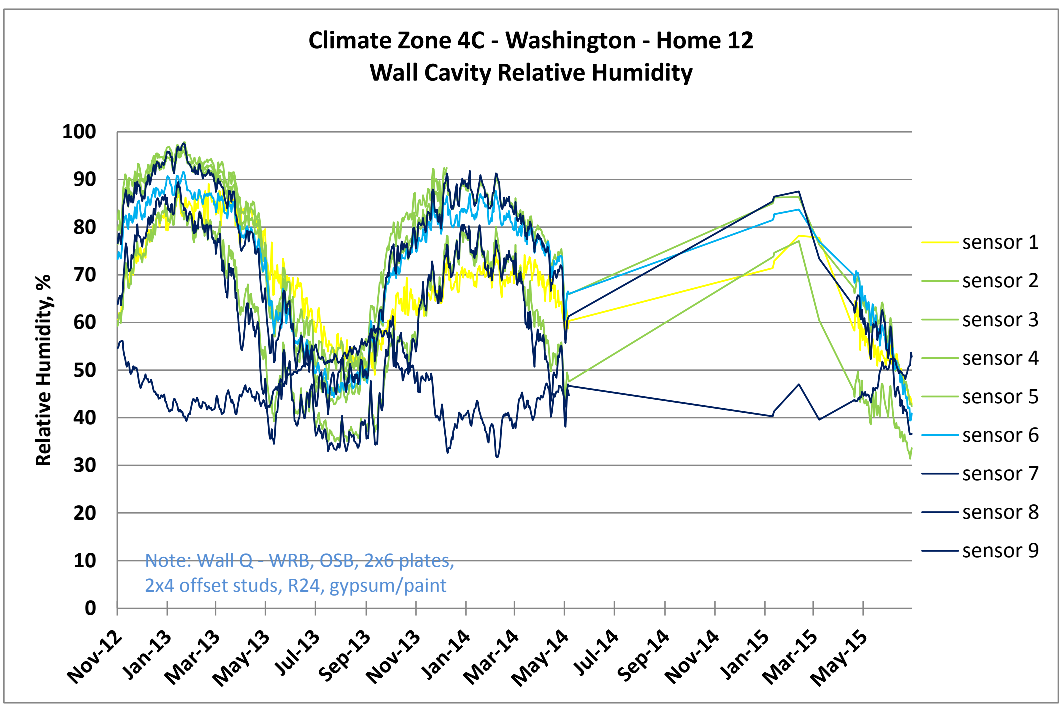


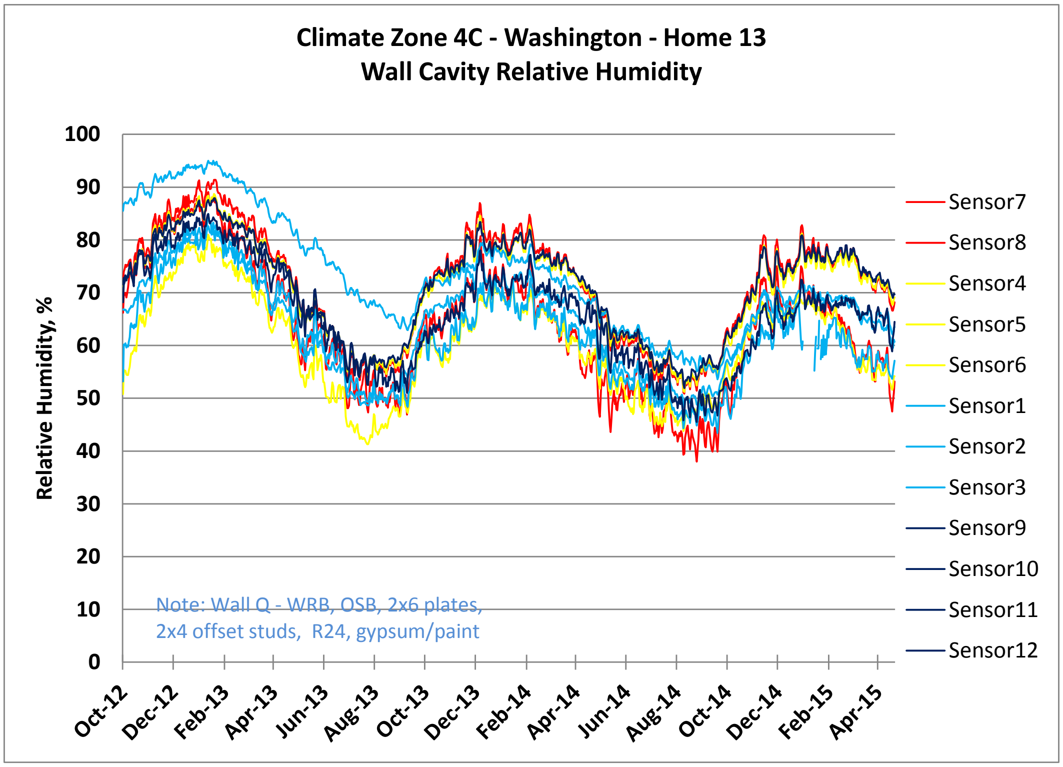
Climate Zone 4A - Maryland - Home 8
Wall Cavity Relative Humidity
Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Note: Wall Type H - WRB, OSB, 2x6, R23 blown fiberglass, gypsum/paint
Sep-11
Nov-11
Jan-12
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
H2[1FlNEgrm]
H2[1FlNEmudrm]
H2[1FlNWwingrm]
H2[1FlSEdnrm]
H2[1FlSEkit]
H2[1FlSWstudy]
H2[2FlNEmbath]
H2[2FlNEmbed]
H2[2FlNWmbed]
H2[2FlSEbed2]
H2[2FlSEmbathshr]
H2[2FlSWbed3]

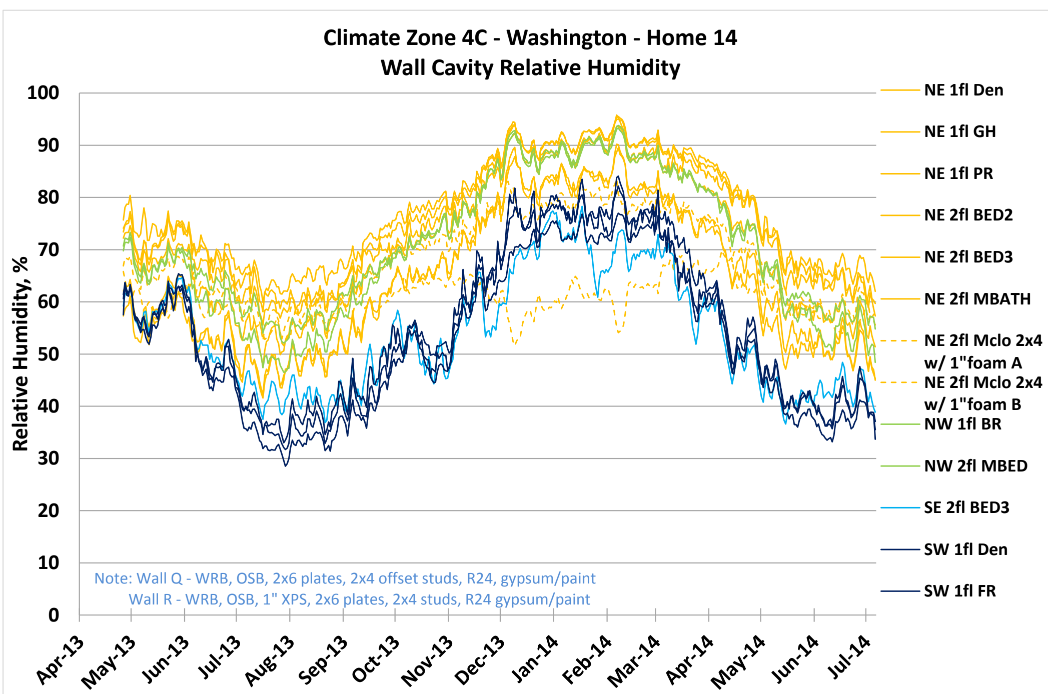

Climate Zone 4A - Maryland - Home 9
Wall Cavity Relative Humidity
Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Note: Wall Type H - WRB, OSB, 2x6, R23 blown fiberglass, gypsum/paint
Aug-11
Oct-11
Dec-11
Feb-12
Apr-12
Jun-12
Aug-12
Oct-12
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Apr-14
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Jun-15
H3[1FlNE1]
H3[1FlNE2]
H3[1FlNW]
H3[1FlSE]
H3[1FlSEkit]
H3[1FlSW]
H3[2FlNEbath]
H3[2FlNEwinmbed]
H3[2FlNWmbed]
H3[2FlSEbed2]
H3[2FlSElaun]
H3[2FlSW]
H3[3FlSE]

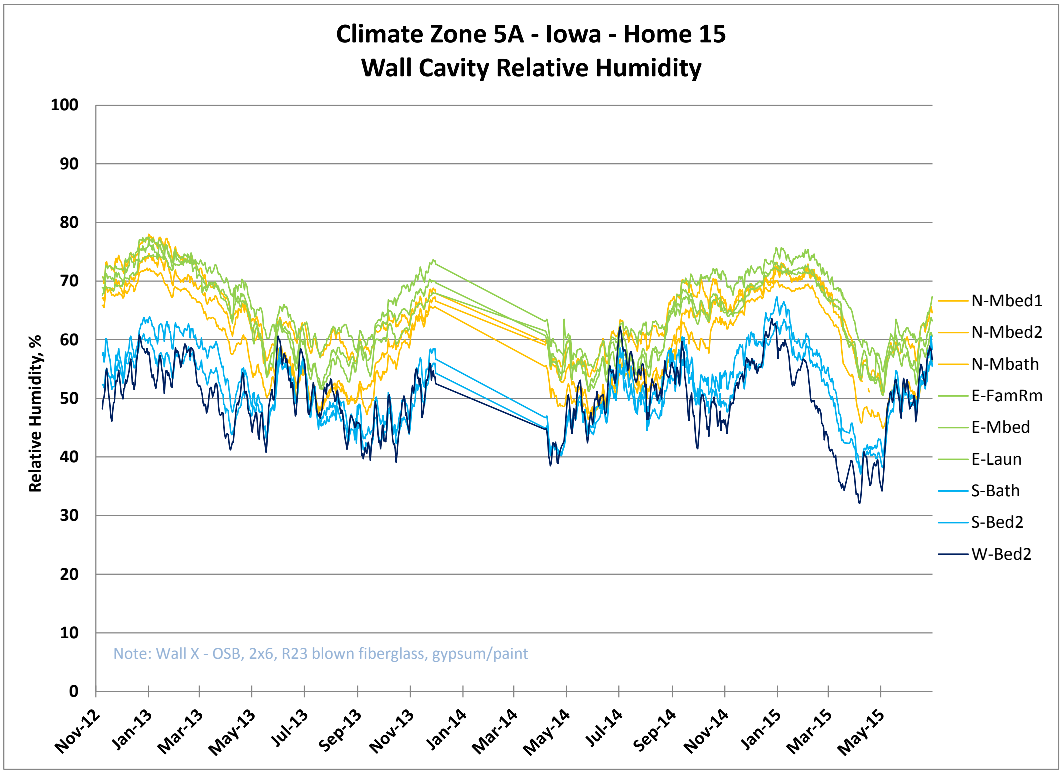

Climate Zone 4A - Maryland - Home 10
Wall Cavity Relative Humidity
Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Note: Wall Type H - WRB, OSB, 2x6, R23 blown fiberglass, gypsum/paint
Sep-11
Nov-11
Jan-12
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
H4[1FlNE1]
H4[1FlNE2]
H4[1FlNW]
H4[1FlNWkit]
H4[1FlSE]
H4[1FlSW]
H4[2FlNEmbed]
H4[2FlNWbath]
H4[2FlNWbed3]
H4[2FlNWmbath]
H4[2FlSEmbed]
H4[2FlSWbed2]
H4[3FlNW]


Climate Zone 4A - Delaware - Home 11
Wall Cavity Relative Humidity
Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Jan-12
Feb-12
Mar-12
Apr-12
May-12
Jun-12
Jul-12
Aug-12
Sep-12
Oct-12
Nov-12
Dec-12
Jan-13
Feb-13
Mar-13
Apr-13
May-13
Jun-13
Jul-13
Aug-13
Sep-13
Oct-13
Nov-13
Dec-13
Jan-14
Feb-14
Mar-14
Apr-14
NE-Brkfst
NE-Kitch
NE-Mbed
NW-Mbath
NW-MBathSh
NW-Gar
SE-Bed3
SE-FamRm
SW-Bed2
SW-Bed2b
roof deck
Note: Wall H - WRB, OSB, 2x6, R23 blown fiberglass, gypsum/paint.

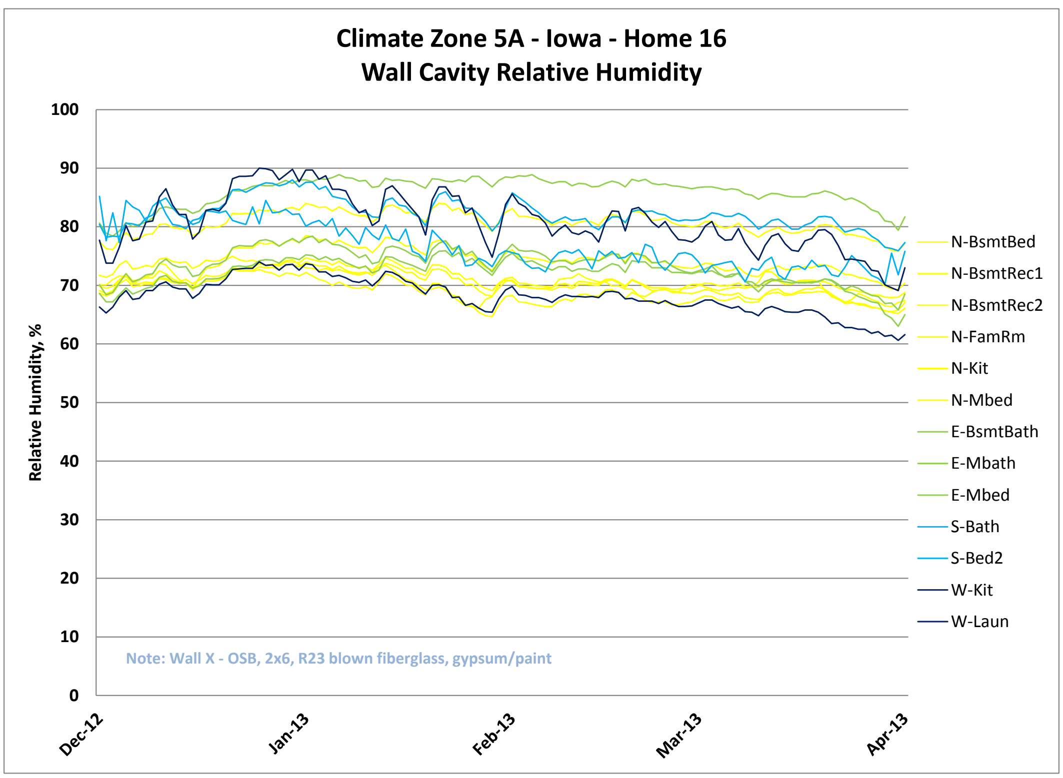

Climate Zone 4C - Washington - Home 12
Wall Cavity Relative Humidity
Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
sensor 1
sensor 2
sensor 3
sensor 4
sensor 5
sensor 6
sensor 7
sensor 8
sensor 9
Note: Wall Q - WRB, OSB, 2x6 plates, 2x4 offset studs, R24, gypsum/paint


Climate Zone 4C - Washington - Home 13
Wall Cavity Relative Humidity
Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Note: Wall Q - WRB, OSB, 2x6 plates,
2x4 offset studs, R24, gypsum/paint
Oct-12
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Apr-14
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Sensor7
Sensor8
Sensor4
Sensor5
Sensor6
Sensor1
Sensor2
Sensor3
Sensor9
Sensor10
Sensor11
Sensor12

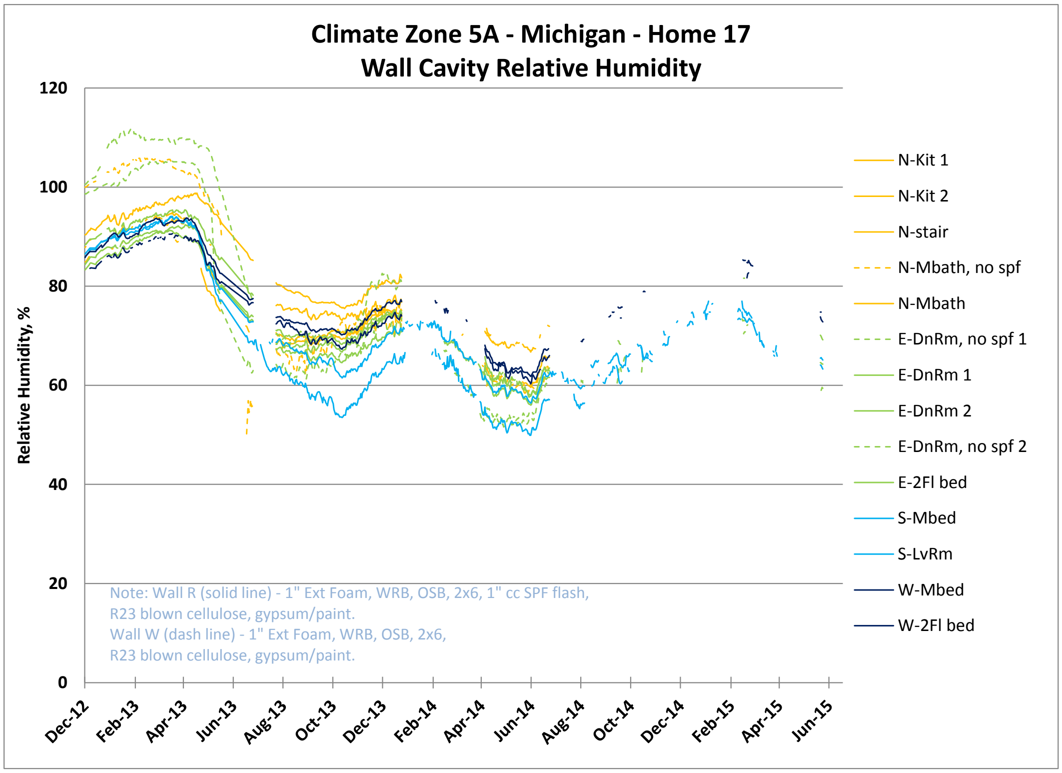

Climate Zone 4C - Washington - Home 14
Wall Cavity Relative Humidity
Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Note: Wall Q - WRB, OSB, 2x6 plates, 2x4 offset studs, R24, gypsum/paint
Wall R - WRB, OSB, 1" XPS, 2x6 plates, 2x4 studs, R24 gypsum/paint
Apr-13
May-13
Jun-13
Jul-13
Aug-13
Sep-13
Oct-13
Nov-13
Dec-13
Jan-14
Feb-14
Mar-14
Apr-14
May-14
Jun-14
Jul-14
NE 1fl Den
NE 1fl GH
NE 1fl PR
NE 2fl BED2
NE 2fl BED3
NE 2fl MBATH
NE 2fl Mclo 2x4 w/ 1"foam A
NE 2fl Mclo 2x4 w/ 1"foam B
NW 1fl BR
NW 2fl MBED
SE 2fl BED3
SW 1fl Den
SW 1fl FR

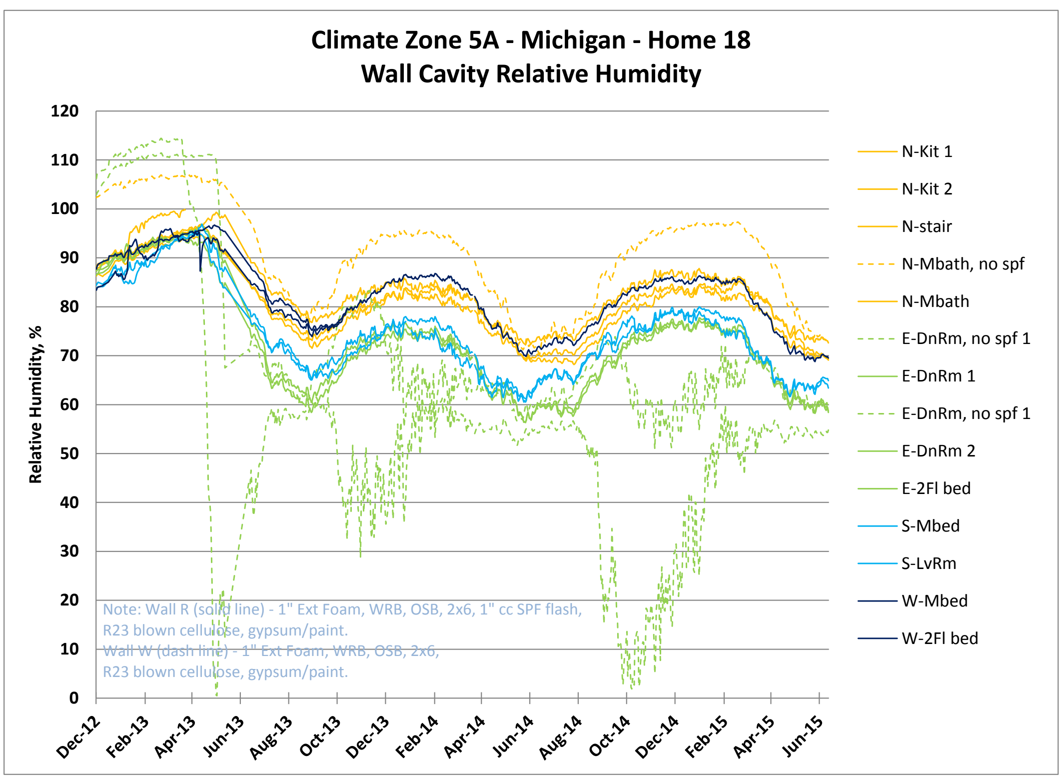


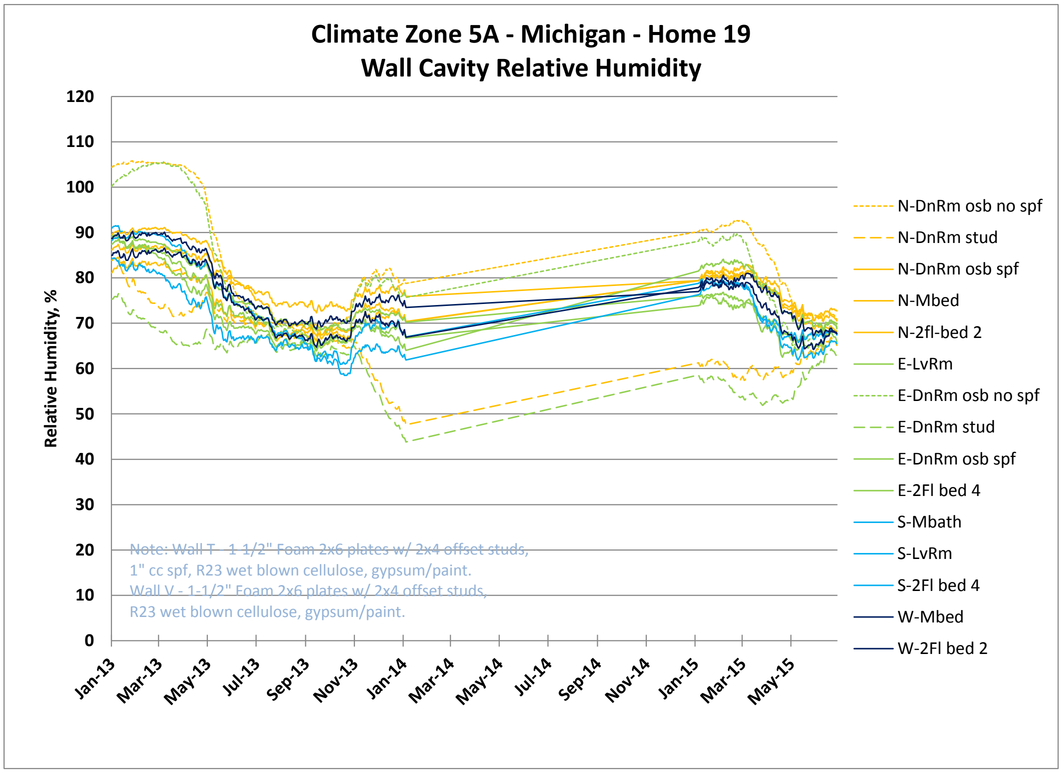
Climate Zone 5A - Iowa - Home 15
Wall Cavity Relative Humidity
Relative Humidity, %
Note: Wall X - OSB, 2x6, R23 blown fiberglass, gypsum/paint
N-Mbed1
N-Mbed2
N-Mbath
E-FamRm
E-Mbed
E-Laun
S-Bath
S-Bed2
W-Bed2

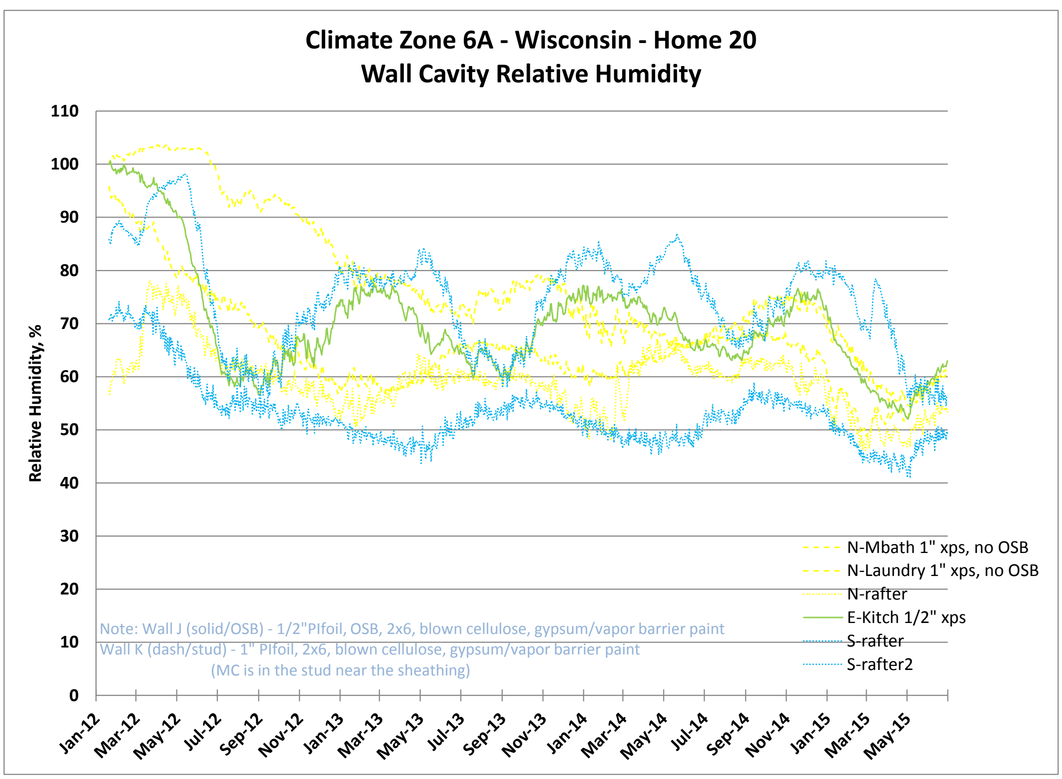


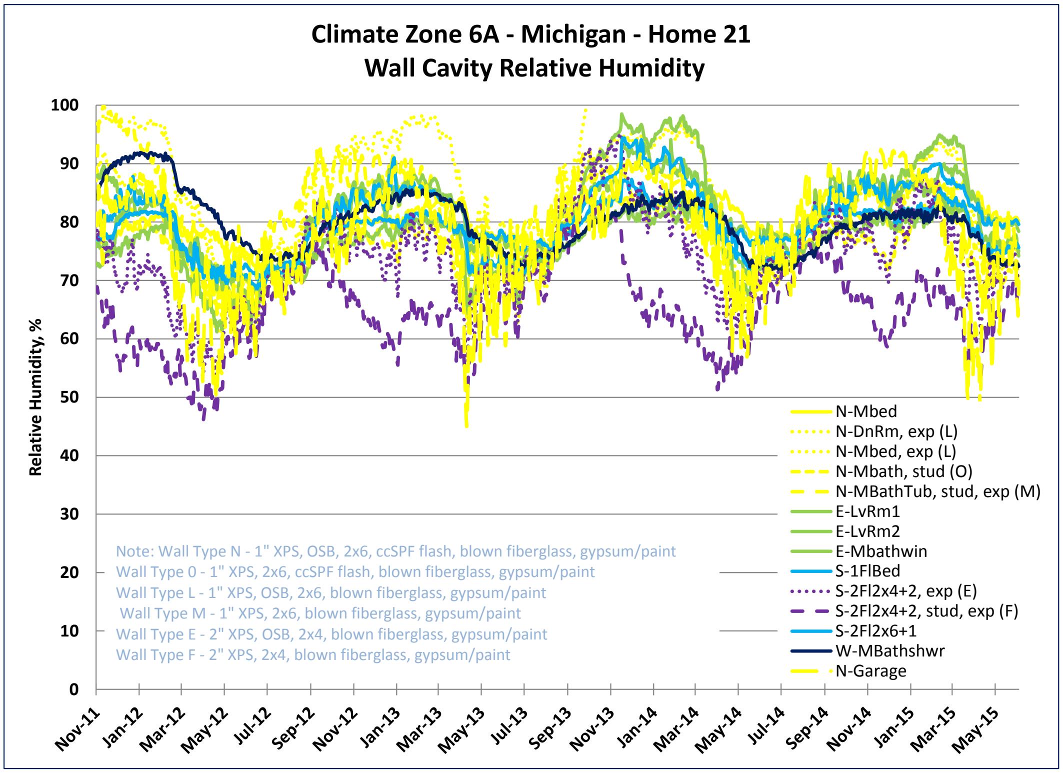
Climate Zone 5A - Iowa - Home 16
Wall Cavity Relative Humidity
Relative Humidity, %
Note: Wall X - OSB, 2x6, R23 blown fiberglass, gypsum/paint
N-BsmtBed
N-BsmtRec1
N-BsmtRec2
N-FamRm
N-Kit
N-Mbed
E-BsmtBath
E-Mbath
E-Mbed
S-Bath
S-Bed2
W-Kit
W-Laun

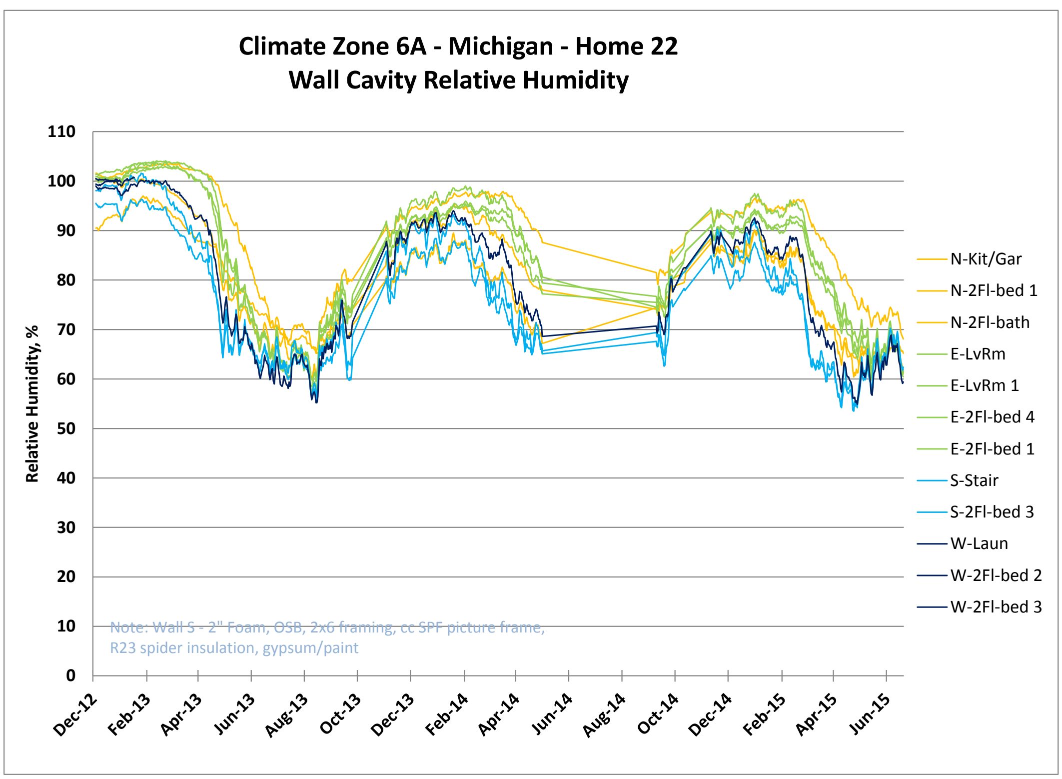

Climate Zone 5A - Michigan - Home 17
Wall Cavity Relative Humidity
Relative Humidity, %
120
100
80
60
40
20
0
Note: Wall R (solid line) - 1" Ext Foam, WRB, OSB, 2x6, 1" cc SPF flash,
R23 blown cellulose, gypsum/paint.
Wall W (dash line) - 1" Ext Foam, WRB, OSB, 2x6,
R23 blown cellulose, gypsum/paint.
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Apr-14
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Jun-15
N-Kit 1
N-Kit 2
N-stair
N-Mbath, no spf
N-Mbath
E-DnRm, no spf 1
E-DnRm 1
E-DnRm 2
E-DnRm, no spf 2
E-2Fl bed
S-Mbed
S-LvRm
W-Mbed
W-2Fl bed


Climate Zone 5A - Michigan - Home 18
Wall Cavity Relative Humidity
Relative Humidity, %
120
110
100
90
80
70
60
50
40
30
20
10
0
Note: Wall R (solid line) - 1" Ext Foam, WRB, OSB, 2x6, 1" cc SPF flash,
R23 blown cellulose, gypsum/paint.
Wall W (dash line) - 1" Ext Foam, WRB, OSB, 2x6,
R23 blown cellulose, gypsum/paint.
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Apr-14
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Jun-15
N-Kit 1
N-Kit 2
N-stair
N-Mbath, no spf
N-Mbath
E-DnRm, no spf 1
E-DnRm 1
E-DnRm, no spf 1
E-DnRm 2
E-2Fl bed
S-Mbed
S-LvRm
W-Mbed
W-2Fl bed


Climate Zone 5A - Michigan - Home 19
Wall Cavity Relative Humidity
Relative Humidity, %
0
10
20
30
40
50
60
70
80
90
100
110
120
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
N-DnRm osb no spf
N-DnRm stud
N-DnRm osb spf
N-Mbed
N-2fl-bed 2
E-LvRm
E-DnRm osb no spf
E-DnRm stud
E-DnRm osb spf
E-2Fl bed 4
S-Mbath
S-LvRm
S-2Fl bed 4
W-Mbed
W-2Fl bed 2
Note: Wall T - 1 1/2" Foam 2x6 plates w/ 2x4 offset studs,
1" cc spf, R23 wet blown cellulose, gypsum/paint.
Wall V - 1-1/2" Foam 2x6 plates w/ 2x4 offset studs,
R23 wet blown cellulose, gypsum/paint.


Climate Zone 6A - Wisconsin - Home 20
Wall Cavity Relative Humidity
Relative Humidity, %
0
10
20
30
40
50
60
70
80
90
100
110
Jan-12
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
N-Mbath 1" xps, no OSB
N-Laundry 1" xps, no OSB
N-rafter
E-Kitch 1/2" xps
S-rafter
S-rafter2
Note: Wall J (solid/OSB) - 1/2"PIfoil, OSB, 2x6, blown cellulose, gypsum/vapor barrier paint
Wall K (dash/stud) - 1" PIfoil, 2x6, blown cellulose, gypsum/vapor barrier paint
(MC is in the stud near the sheathing)

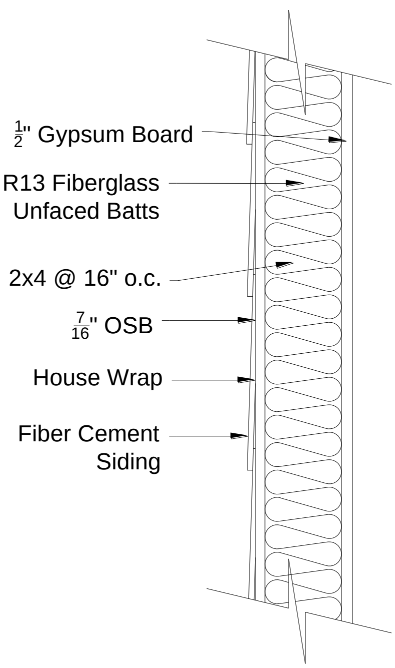

Climate Zone 6A - Michigan - Home 21
Wall Cavity Relative Humidity
Relative Humidity, %
N-Mbed
N-DnRm, exp (L)
N-Mbed, exp (L)
N-Mbath, stud (O)
N-MBathTub, stud, exp (M)
E-LvRm1
E-LvRm2
E-Mbathwin
S-1FlBed
S-2Fl2x4+2, exp (E)
S-2Fl2x4+2, stud, exp (F)
S-2Fl2x6+1
W-MBathshwr
N-Garage
Note: Wall Type N - 1" XPS, OSB, 2x6, ccSPF flash, blown fiberglass, gypsum/paint
Wall Type 0 - 1" XPS, 2x6, ccSPF flash, blown fiberglass, gypsum/paint
Wall Type L - 1" XPS, OSB, 2x6, blown fiberglass, gypsum/paint
Wall Type M - 1" XPS, 2x6, blown fiberglass, gypsum/paint
Wall Type E - 2" XPS, OSB, 2x4, blown fiberglass, gypsum/paint
Wall Type F - 2" XPS, 2x4, blown fiberglass, gypsum/paint


Climate Zone 6A - Michigan - Home 22
Wall Cavity Relative Humidity
Relative Humidity, %
N-Kit/Gar
N-2Fl-bed 1
N-2Fl-bath
E-LvRm
E-LvRm 1
E-2Fl-bed 4
E-2Fl-bed 1
S-Stair
S-2Fl-bed 3
W-Laun
W-2Fl-bed 2
W-2Fl-bed 3
Note: Wall S - 2" Foam, OSB, 2x6 framing, cc SPF picture frame,
R23 spider insulation, gypsum/paint

APPENDIX C:
TEST WALL CONFIGURATIONS

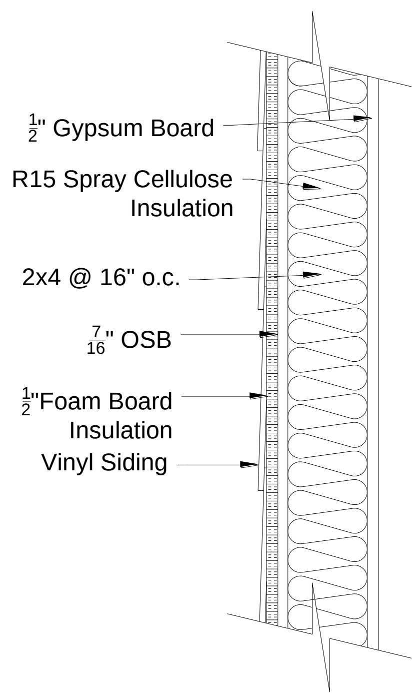
Wall Type A

Description:
OSB, WRB, 2x4 Framing w/ R13 fiberglass batts, and gypsum w/ paint



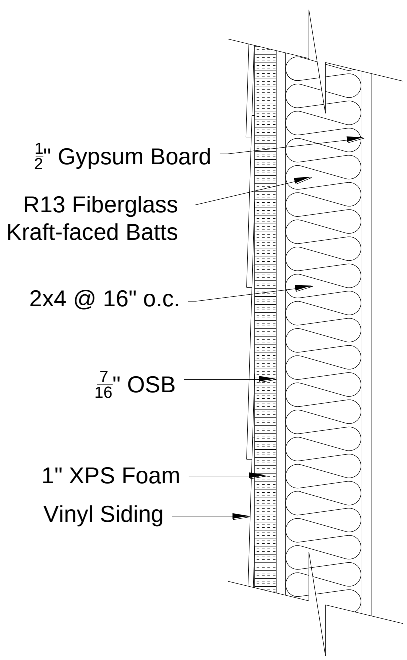
Wall Type B

Description:
OSB, 1/2" Foam R3, 2x4 Framing w/ R15 spray cellulose, and gypsum w/ paint



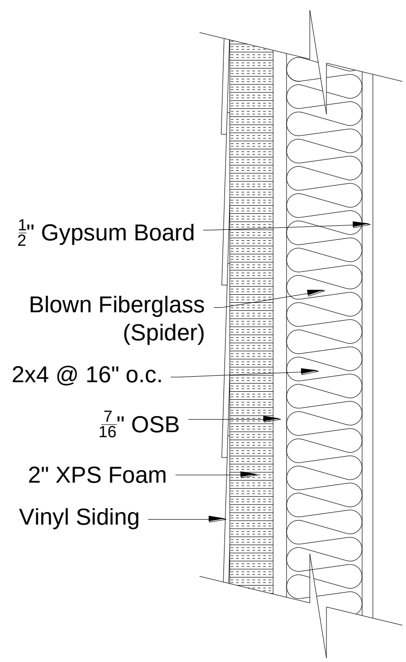
Wall Type C

Description:
OSB, 1" xps foam R5, 2x4 Framing w/ R13 fiberglass batts, and gypsum w/ paint



Wall Type E

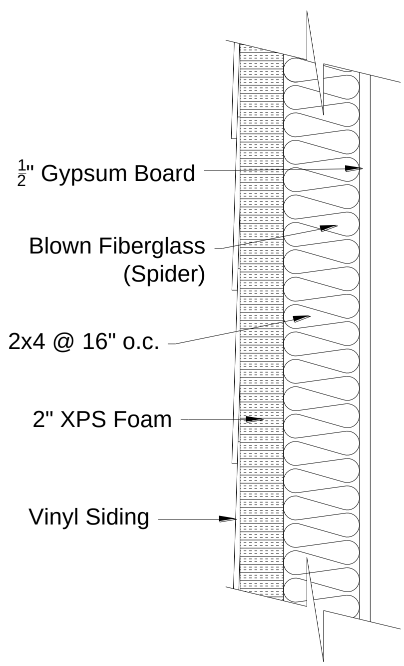
Description:
OSB, 2" xps foam R10, 2x4 Framing w/ R13 blown fiberglass, and gypsum w/ paint



Wall Type F

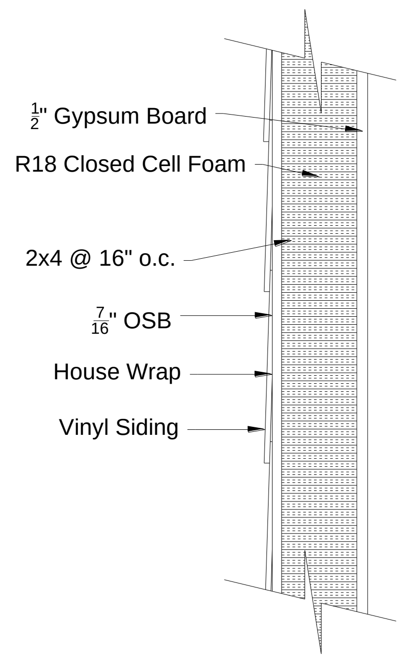
Description:
No OSB, 2" xps foam R10, 2x4 Framing w/ R13 blown fiberglass, and gypsum w/ paint

Sensor in Stud, Not OSB



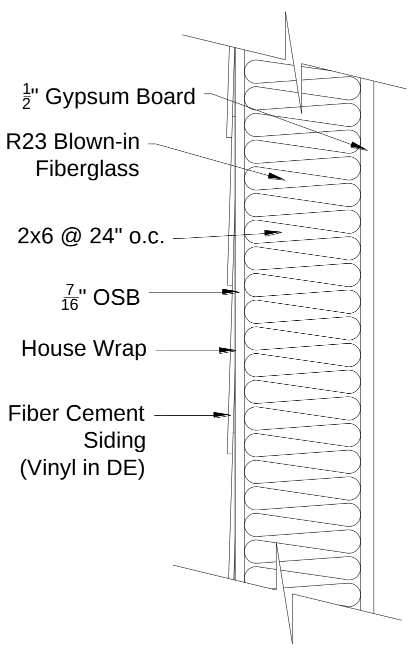
Wall Type G

Description:
OSB, WRB, 2x4 Framing w/ R18 closed cell foam, and gypsum w/ paint



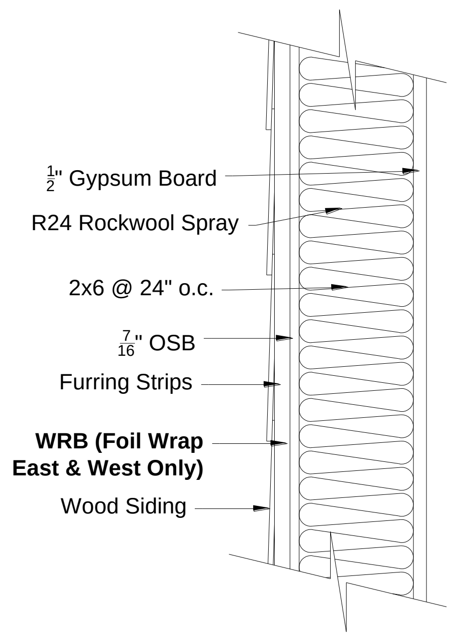
Wall Type H

Description:
OSB, WRB, 2x6 Framing w/ R23 blown fiberglass, and gypsum w/ paint



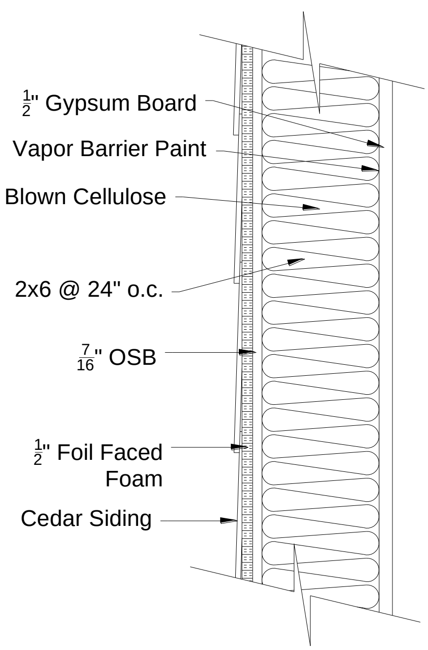
Wall Type I

Description:
OSB, WRB, 2x6 Framing w/ R24 spray rockwool, and gypsum w/ paint. WRB on east and west is reflective



Wall Type J

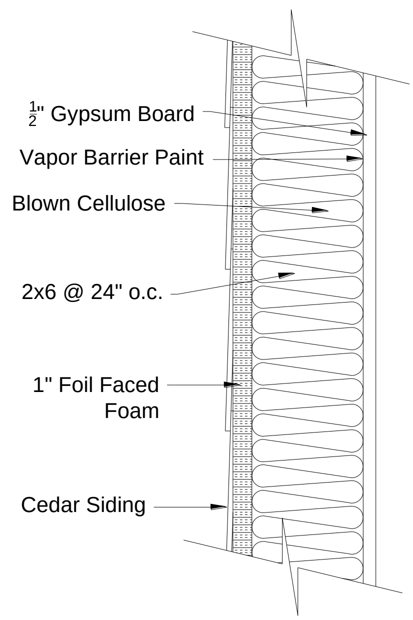
Description:
OSB, 0.5" foil faced foam R2.5, 2x6 Framing w/ R19 blown cellulose, and gypsum w/ paint



Wall Type K

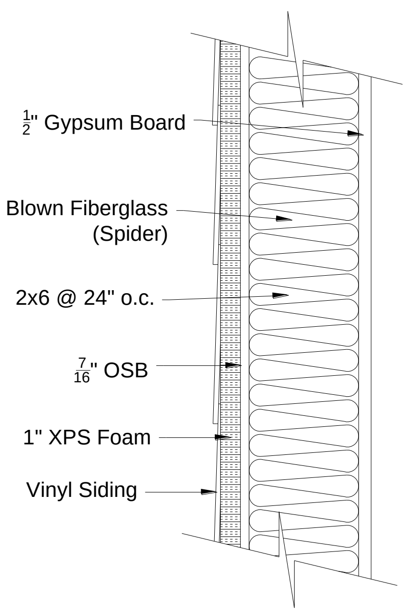
Description:
No OSB, 1" foil faced foam R5, 2x6 Framing w/ R19 blown cellulose, and gypsum w/ paint

Sensor in Stud, Not OSB



Wall Type L

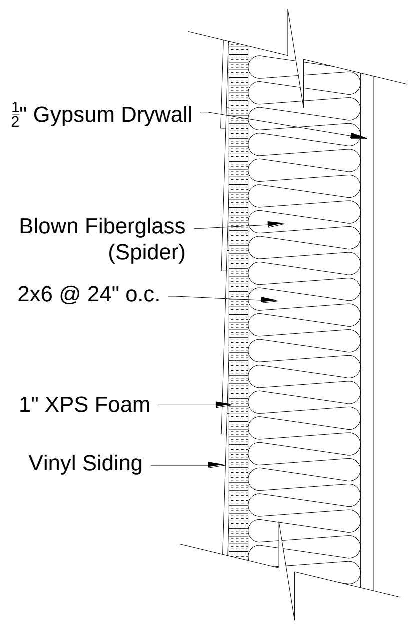
Description:
OSB, 1" xps foam R5, 2x6 Framing w/ R20 blown fiberglass, and gypsum w/ paint



Wall Type M

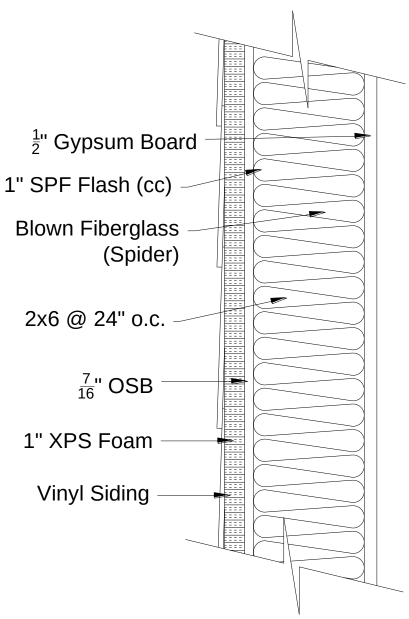
Description:
No OSB, 1" xps foam R5, 2x6 Framing w/ R20 blown fiberglass, and gypsum w/ paint

Sensor in Stud, Not OSB



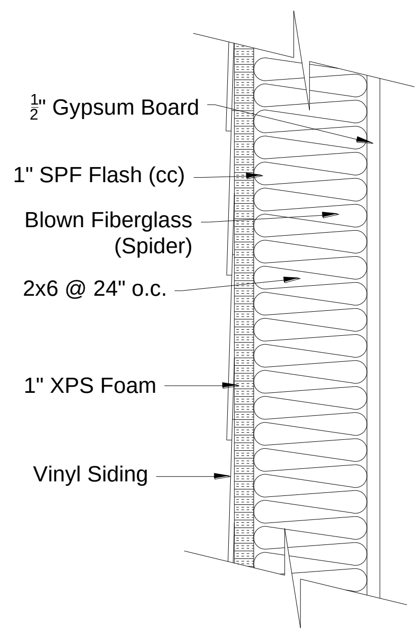
Wall Type N

Description:
OSB, 1" xps foam R5, 2x6 Framing w/ ccSPF flash & R23 blown fiberglass, and gypsum w/ paint



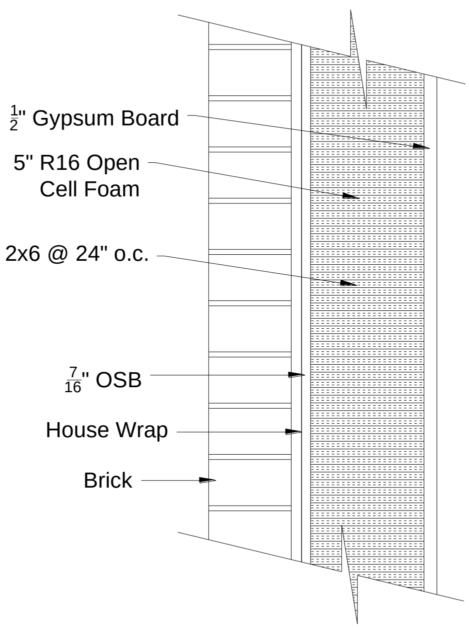
Wall Type O

Description:
No OSB, 1" xps foam R5, 2x6 Framing w/ ccSPF flash & R23 blown fiberglass, and gypsum w/ paint
Sensor in Stud, Not OSB



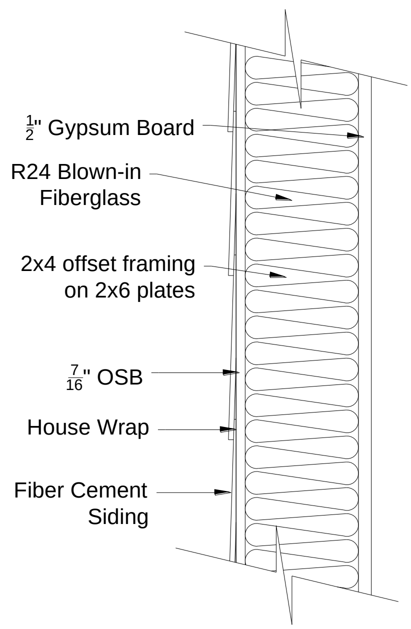
Wall Type P

Description:
OSB, WRB, 2x4 Framing w/ R13 fiberglass batts, and gypsum w/ paint



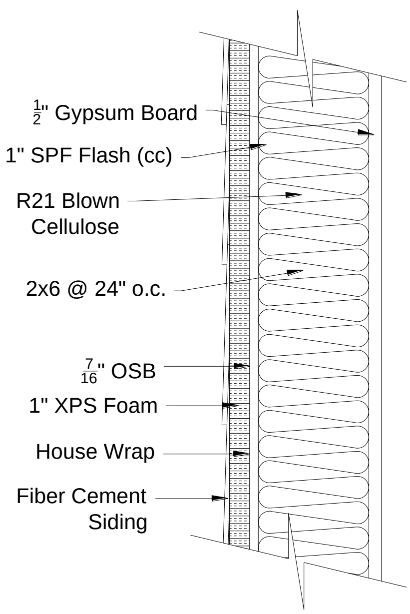
Wall Type Q

Description:
OSB, WRB, 2x6 plates w/ 2x4 offset framing & R24 blown fiberglass, and gypsum w/ paint



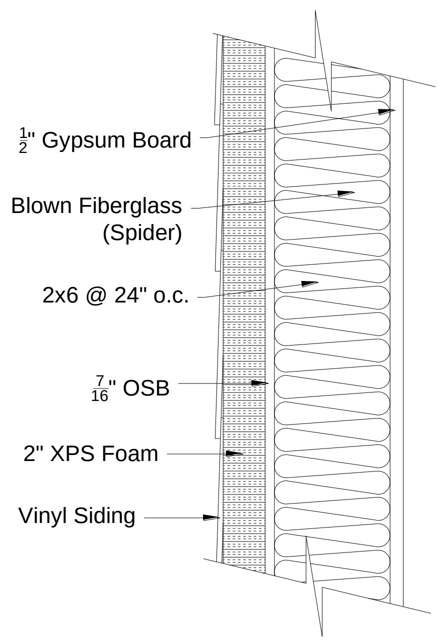
Wall Type R

Description:
OSB, 1" XPS Foam R5, WRB, 2x6 Framing w/ 1" ccSPF Flash and R21 blown cellulose, and gypsum w/ paint



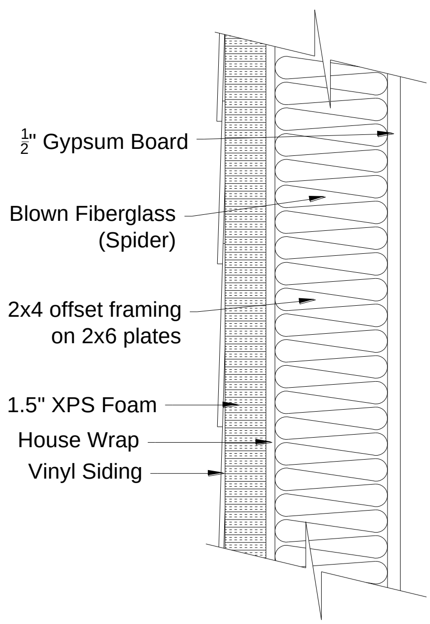
Wall Type S

Description:
OSB, 2" xps foam R10, 2x6 Framing w/ R20 blown fiberglass, and gypsum w/ paint



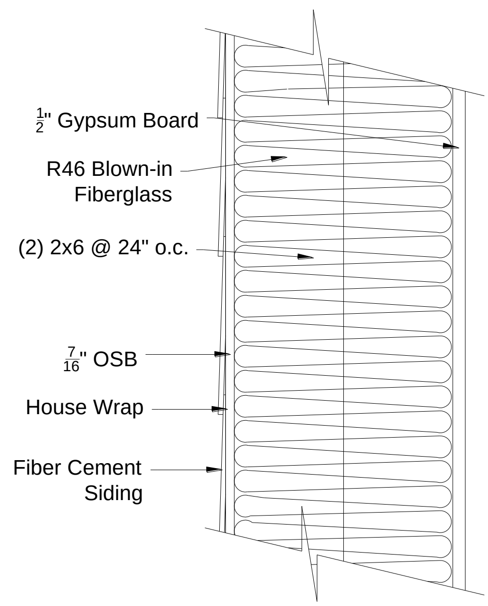
Wall Type T

Description:
OSB, 1.5" xps foam, WRB, 2x6 plates w/ 2x4 Framing w/ R21 blown cellulose, and gypsum w/ paint



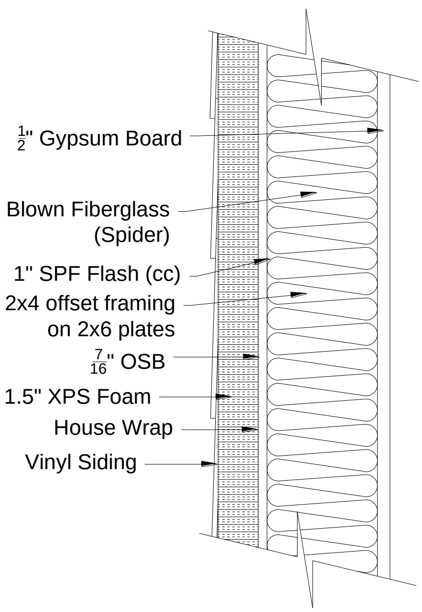
Wall Type U

Description:
OSB, WRB, (2) 2x6 Framing w/ R46 blown fiberglass, and gypsum w/ paint



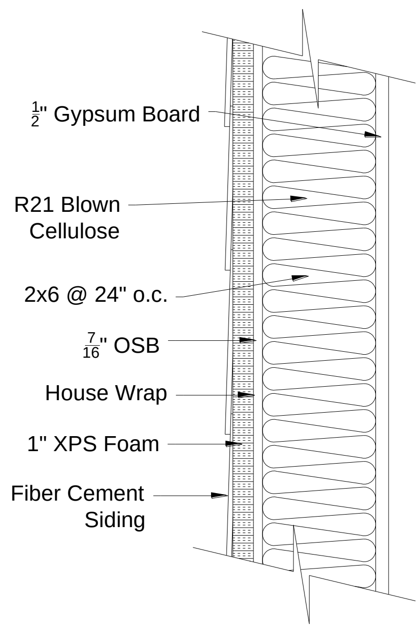
Wall Type V

Description:
OSB, 1.5" xps foam, WRB, 2x6 plates w/ 2x4 Framing & ccSPF Flash w/ R21 blown cellulose, and gypsum w/ paint



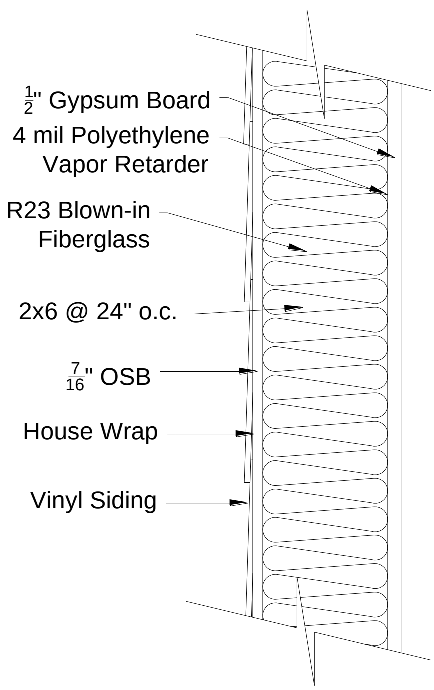
Wall Type W

Description:
OSB, 1" XPS Foam R5, WRB, 2x6 Framing w/ R21 blown cellulose, and gypsum w/ paint

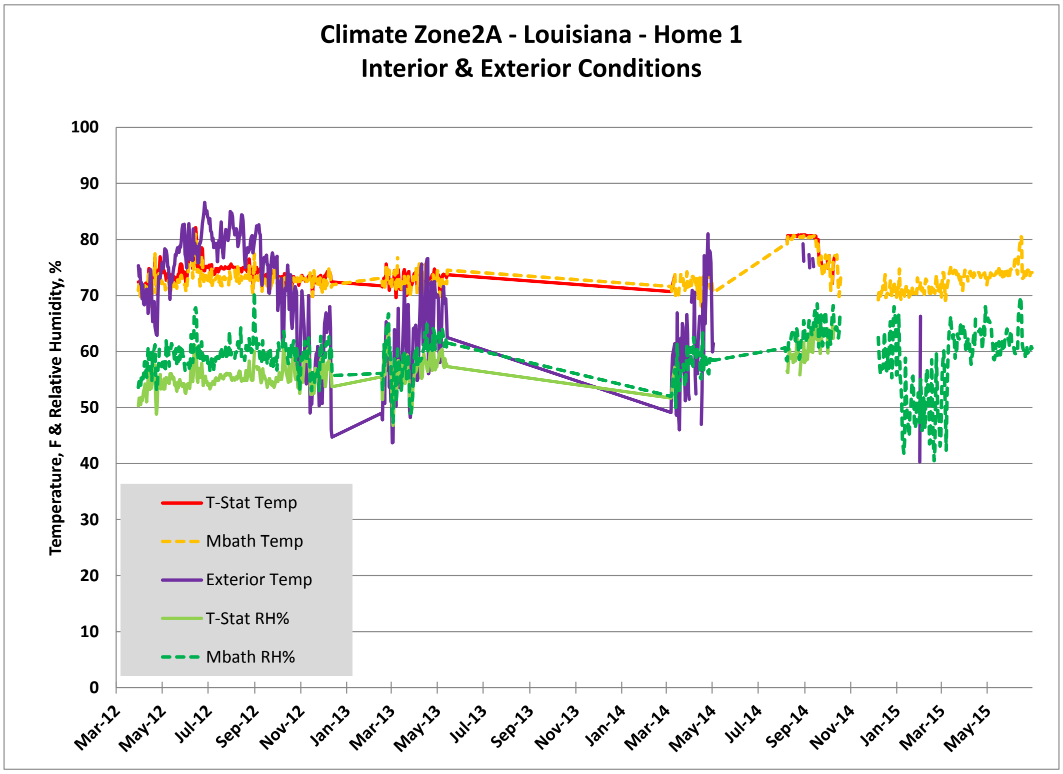


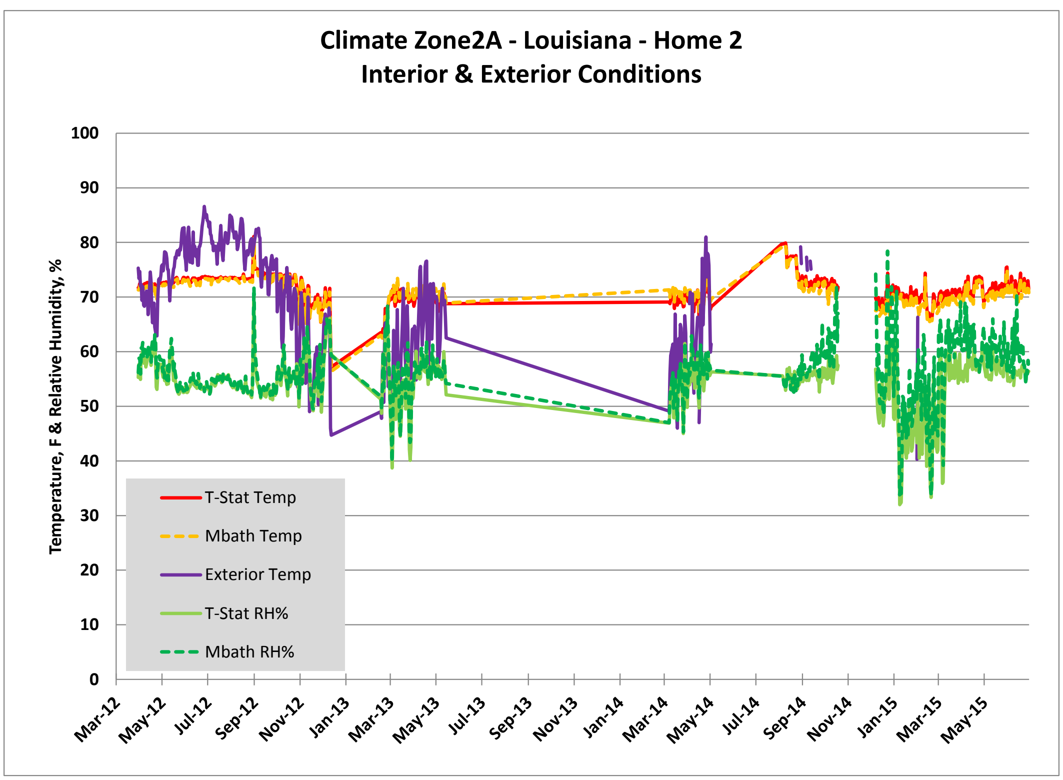
Wall Type X

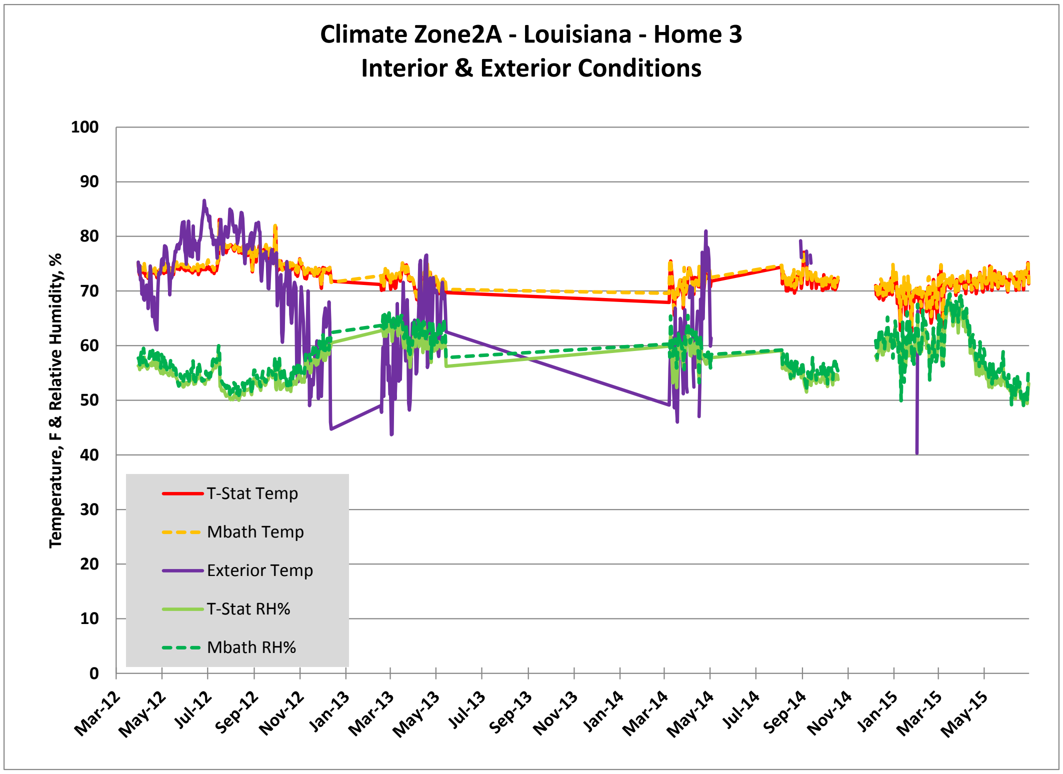
Description:
OSB, WRB, 2x6 Framing w/ R23 blown fiberglass, and gypsum w/ paint



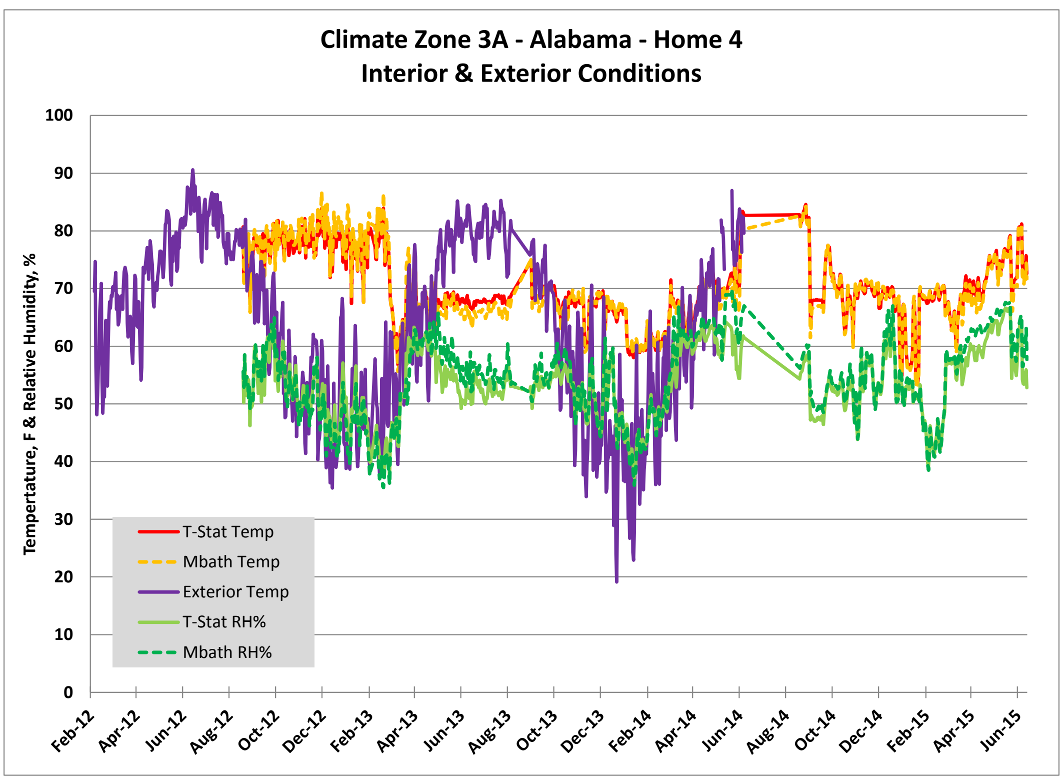
APPENDIX D:
DAILY INDOOR TEMPERATURE AND RELATIVE HUMIDITY FOR EACH TEST SITE



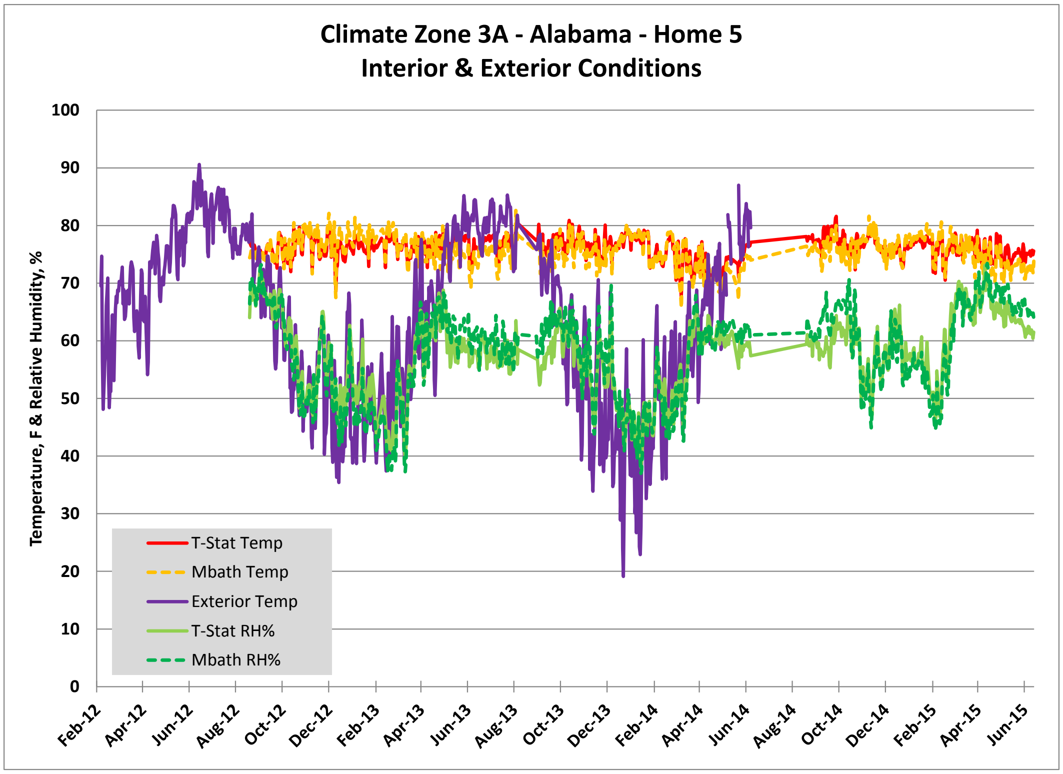




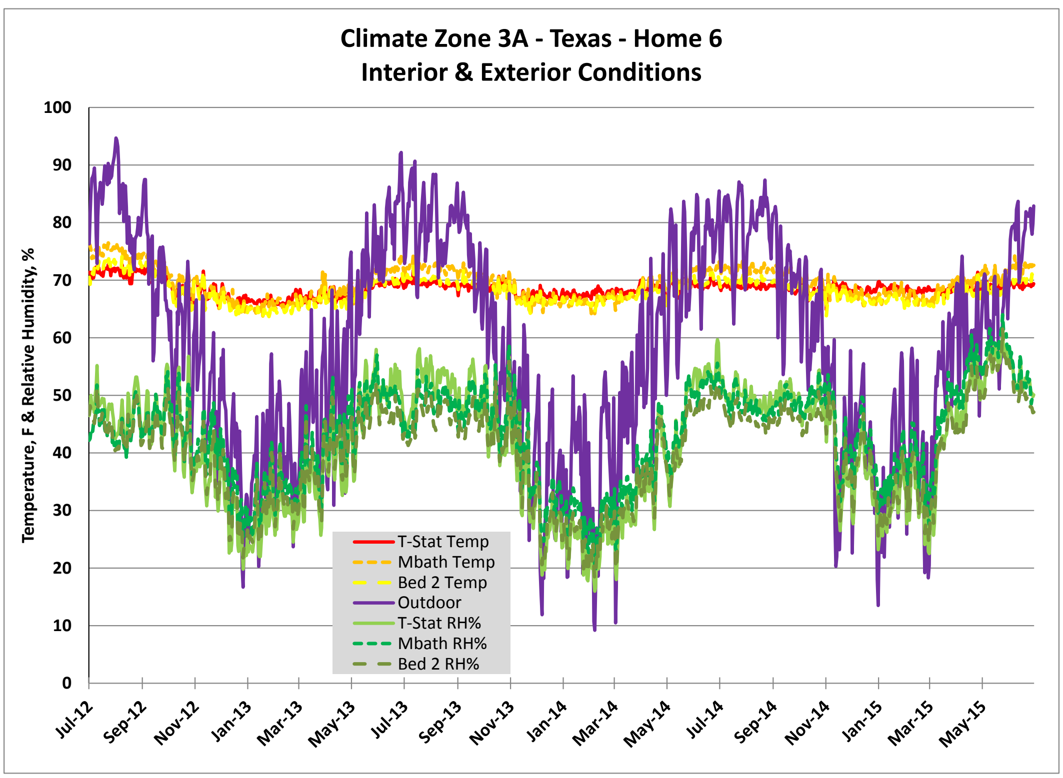
Climate Zone2A - Louisiana - Home 3
Interior & Exterior Conditions
Temperature, F & Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15
T-Stat Temp
Mbath Temp
Exterior Temp
T-Stat RH%
Mbath RH%



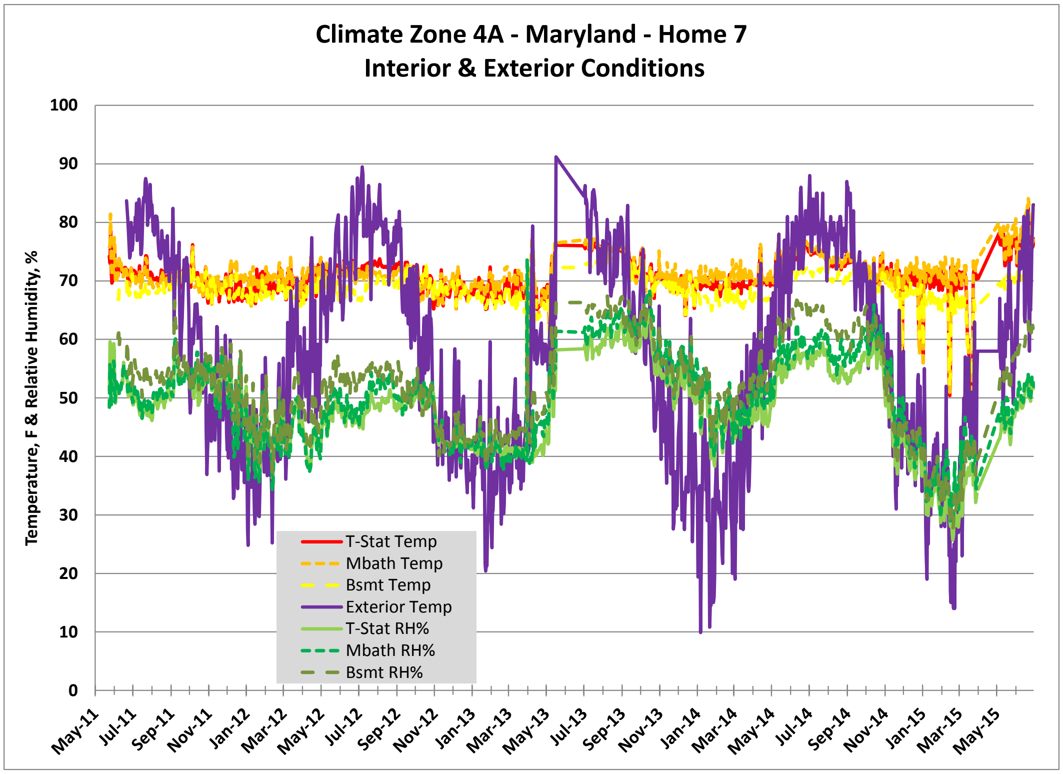
Climate Zone 3A - Alabama - Home 4
Interior & Exterior Conditions
Tempertature, F & Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Feb-12
Apr-12
Jun-12
Aug-12
Oct-12
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Apr-14
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Jun-15
T-Stat Temp
Mbath Temp
Exterior Temp
T-Stat RH%
Mbath RH%



Climate Zone 3A - Alabama - Home 5
Interior & Exterior Conditions
Temperature, F & Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
T-Stat Temp
Mbath Temp
Exterior Temp
T-Stat RH%
Mbath RH%
Feb-12
Apr-12
Jun-12
Aug-12
Oct-12
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Apr-14
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Jun-15



Climate Zone 3A - Texas - Home 6
Interior & Exterior Conditions
Temperature, F & Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
T-Stat Temp
Mbath Temp
Bed 2 Temp
Outdoor
T-Stat RH%
Mbath RH%
Bed 2 RH%
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15


Climate Zone 4A - Maryland - Home 7
Interior & Exterior Conditions
Temperature, F & Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
T-Stat Temp
Mbath Temp
Bsmt Temp
Exterior Temp
T-Stat RH%
Mbath RH%
Bsmt RH%
May-11
Jul-11
Sep-11
Nov-11
Jan-12
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
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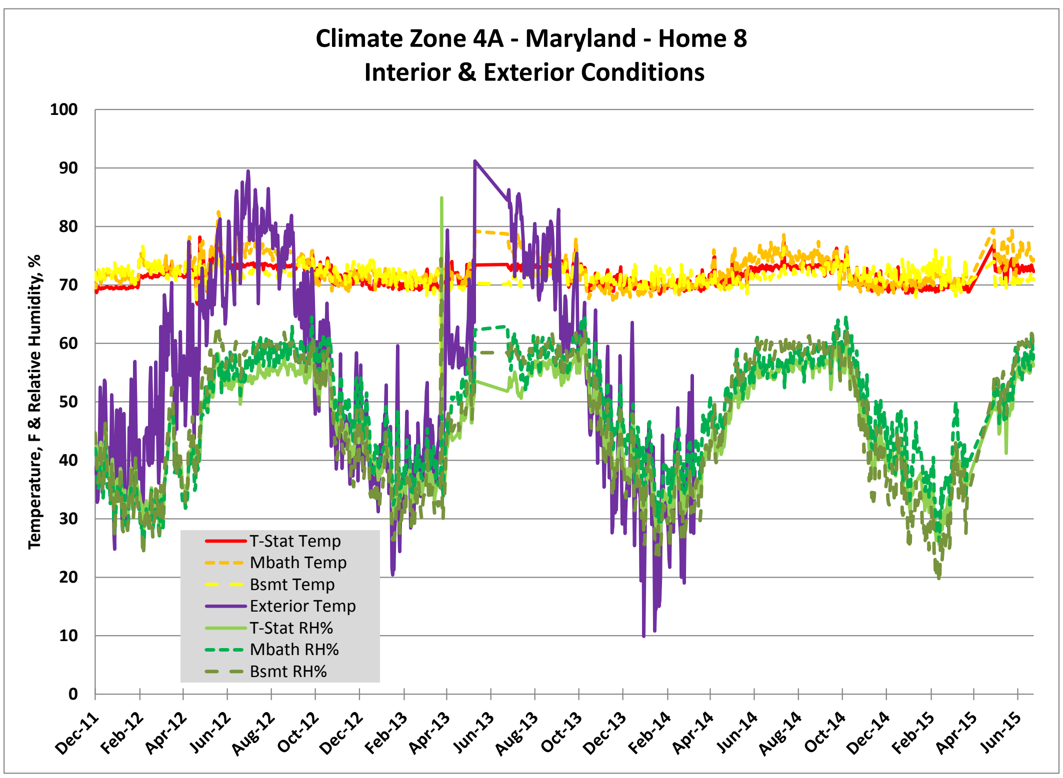
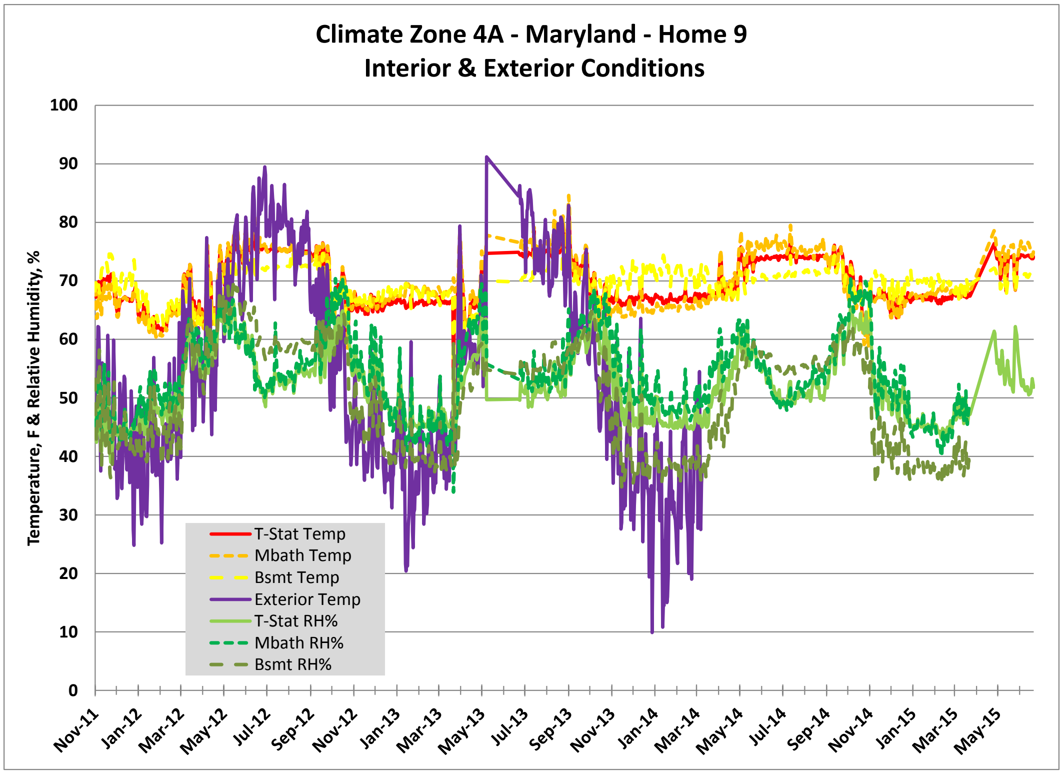
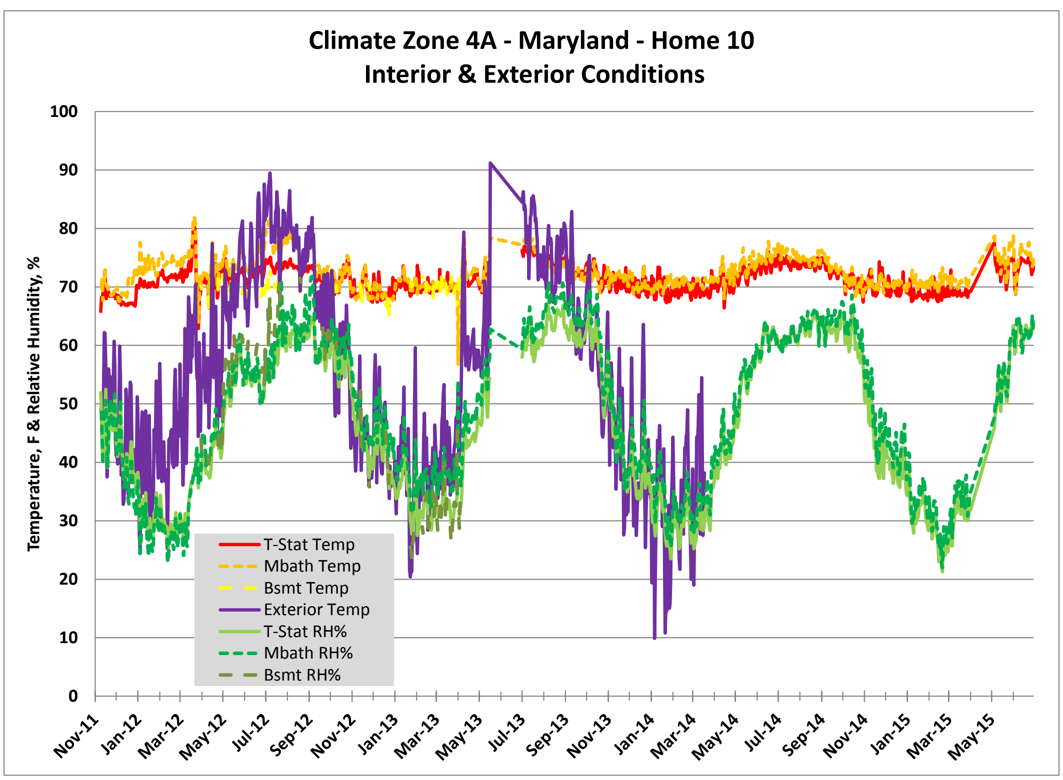
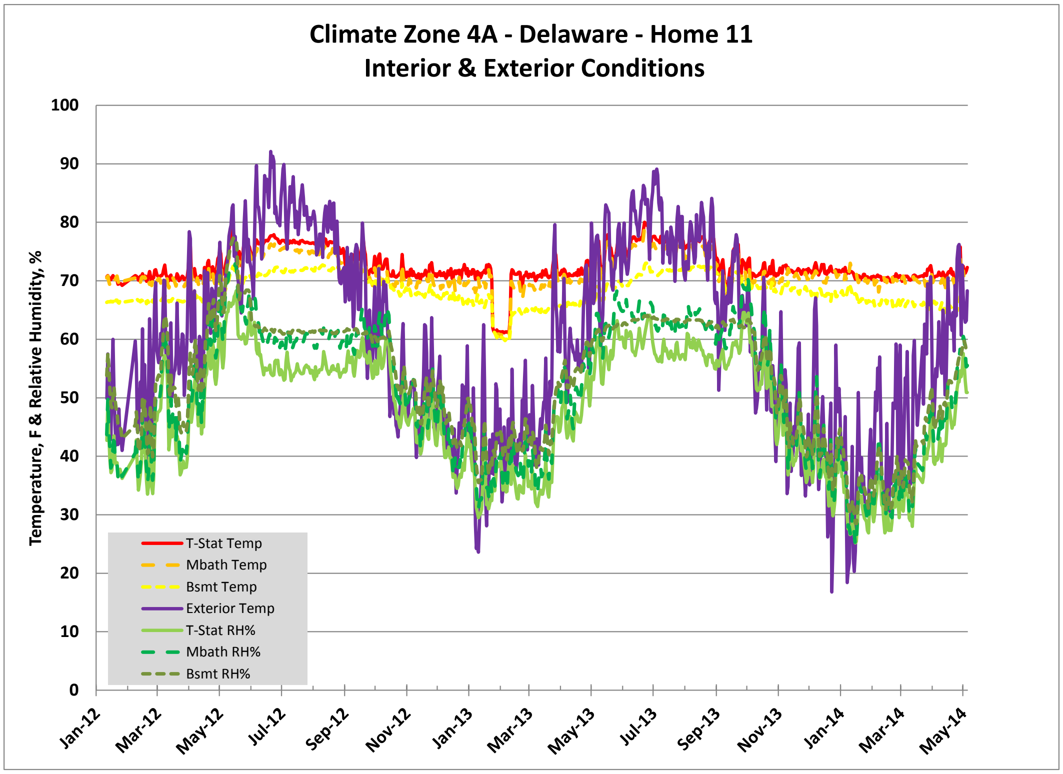
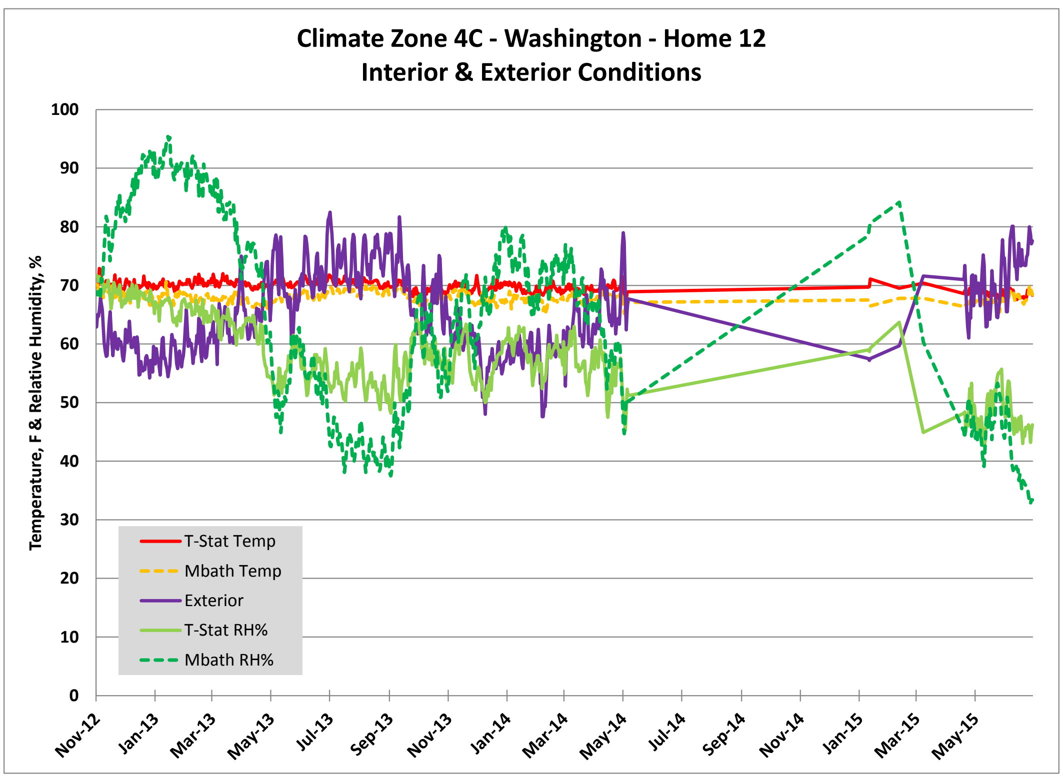
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15

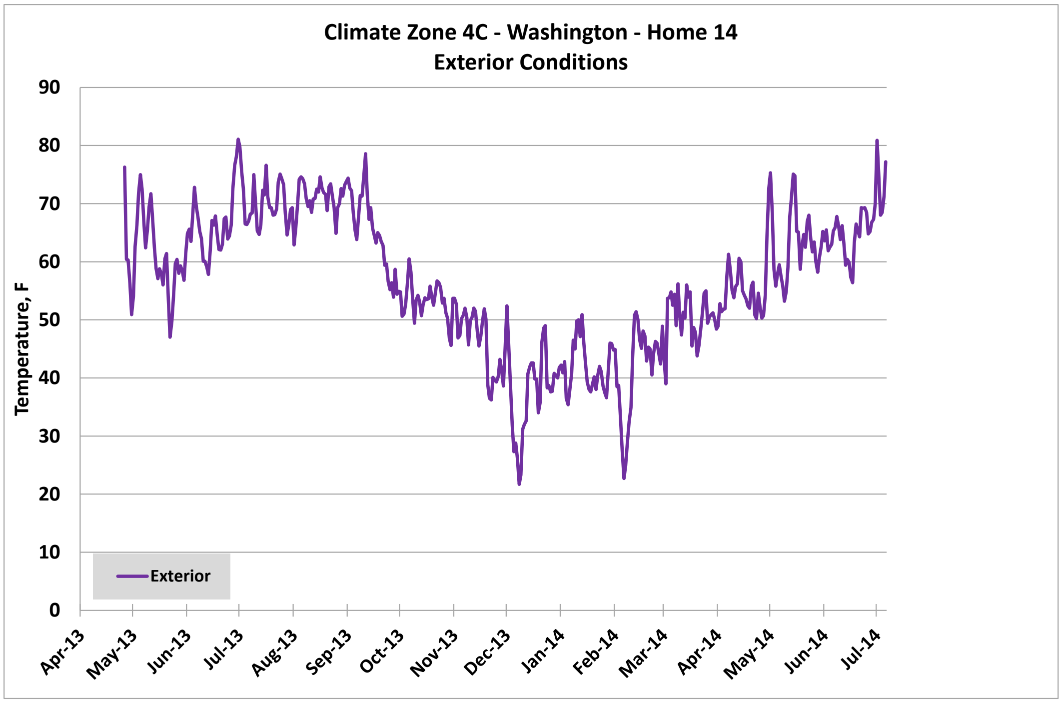

Climate Zone 4A - Maryland - Home 8
Interior & Exterior Conditions
Temperature, F & Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
T-Stat Temp
Mbath Temp
Bsmt Temp
Exterior Temp
T-Stat RH%
Mbath RH%
Bsmt RH%
Dec-11
Feb-12
Apr-12
Jun-12
Aug-12
Oct-12
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Apr-14
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Jun-15

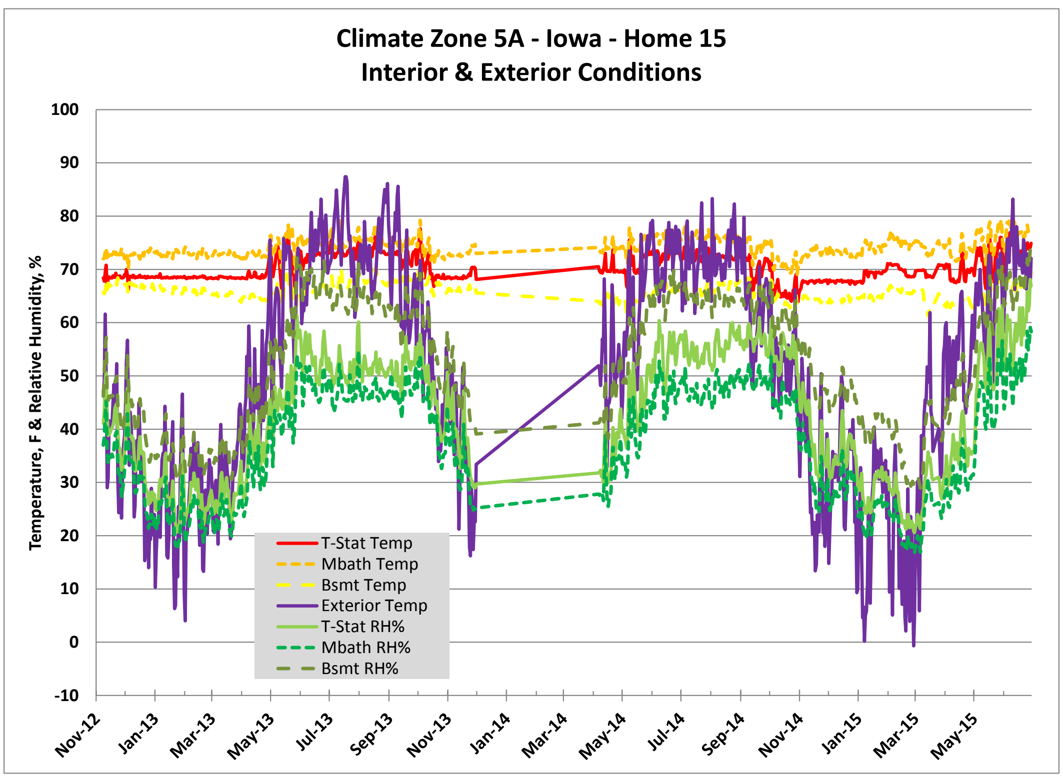

Climate Zone 4A - Maryland - Home 9
Interior & Exterior Conditions
Temperature, F & Relative Humidity, %
T-Stat Temp
Mbath Temp
Bsmt Temp
Exterior Temp
T-Stat RH%
Mbath RH%
Bsmt RH%
Nov-11
Jan-12
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15

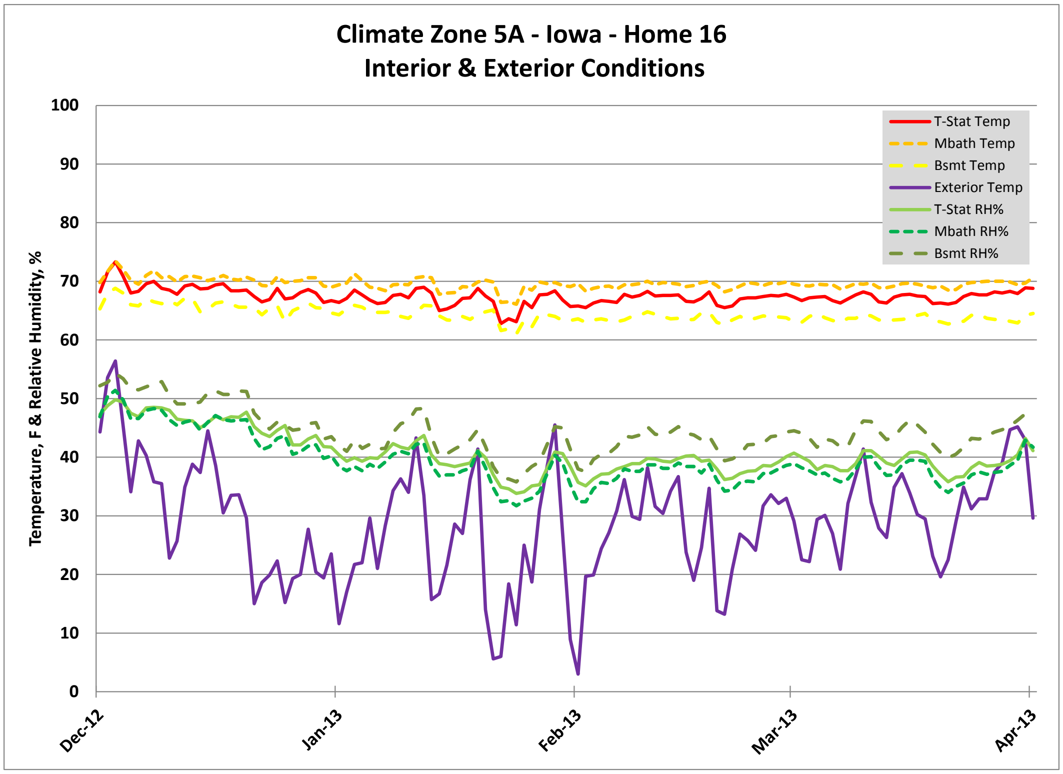

Climate Zone 4A - Maryland - Home 10
Interior & Exterior Conditions
Temperature, F & Relative Humidity, %
T-Stat Temp
Mbath Temp
Bsmt Temp
Exterior Temp
T-Stat RH%
Mbath RH%
Bsmt RH%
Nov-11
Jan-12
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15

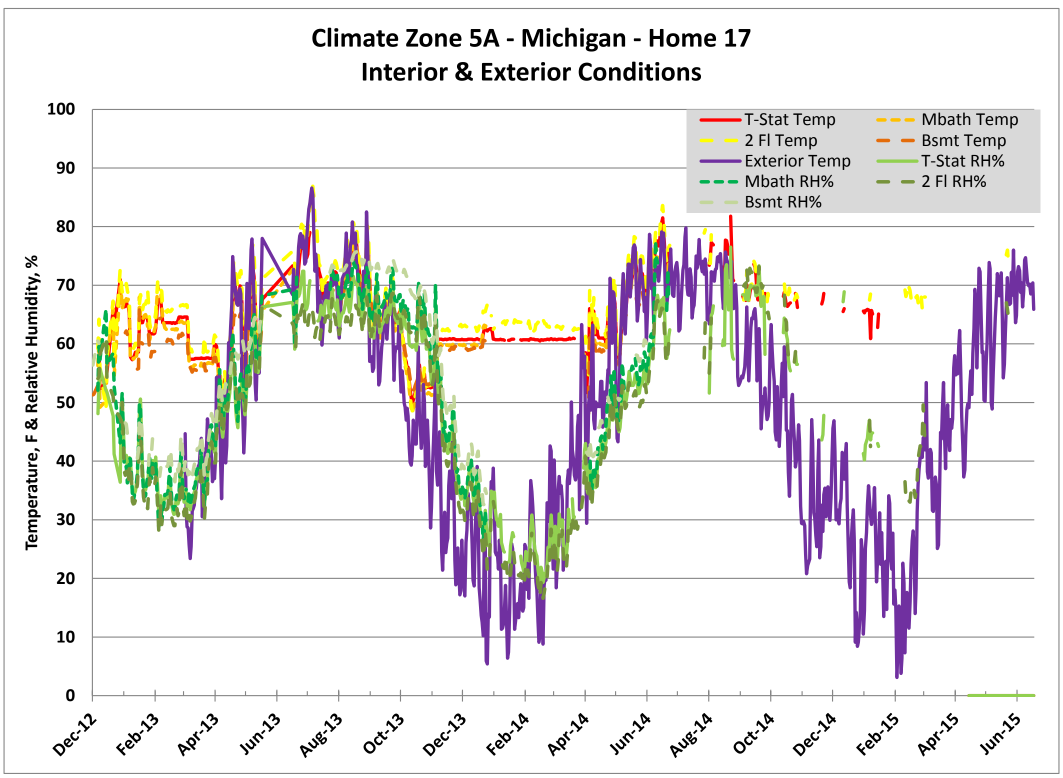

Climate Zone 4A - Delaware - Home 11
Interior & Exterior Conditions
Temperature, F & Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
T-Stat Temp
Mbath Temp
Bsmt Temp
Exterior Temp
T-Stat RH%
Mbath RH%
Bsmt RH%
Jan-12
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14

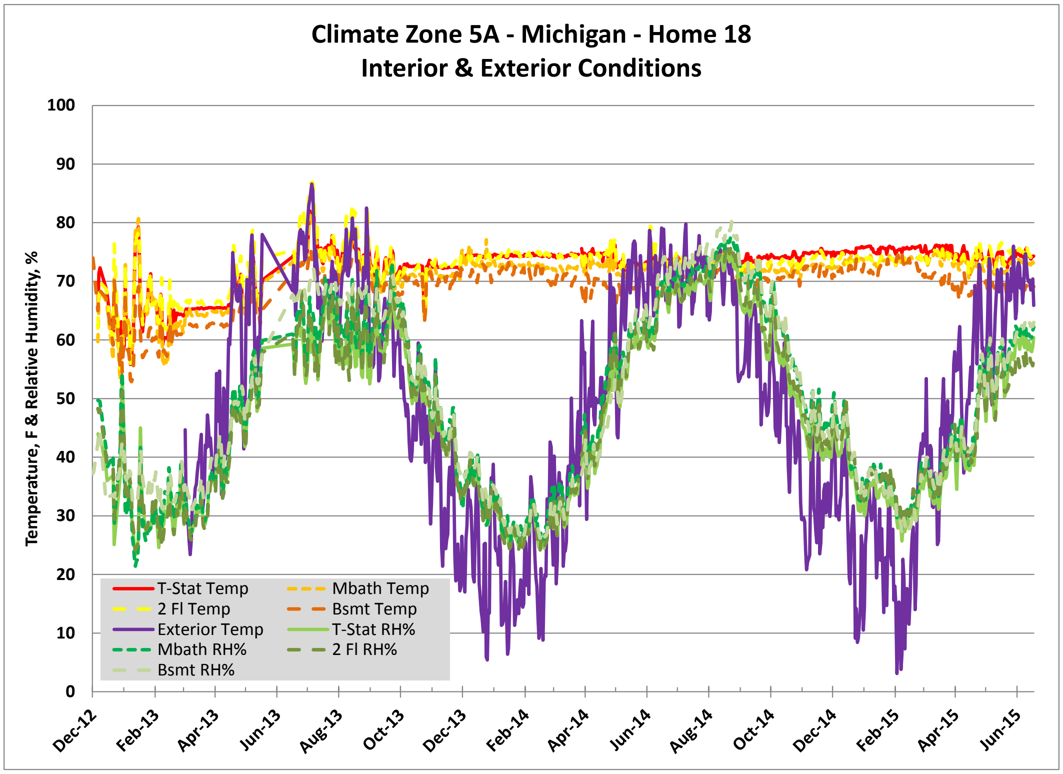

Climate Zone 4C - Washington - Home 12
Interior & Exterior Conditions
Temperature, F & Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
T-Stat Temp
Mbath Temp
Exterior
T-Stat RH%
Mbath RH%
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15

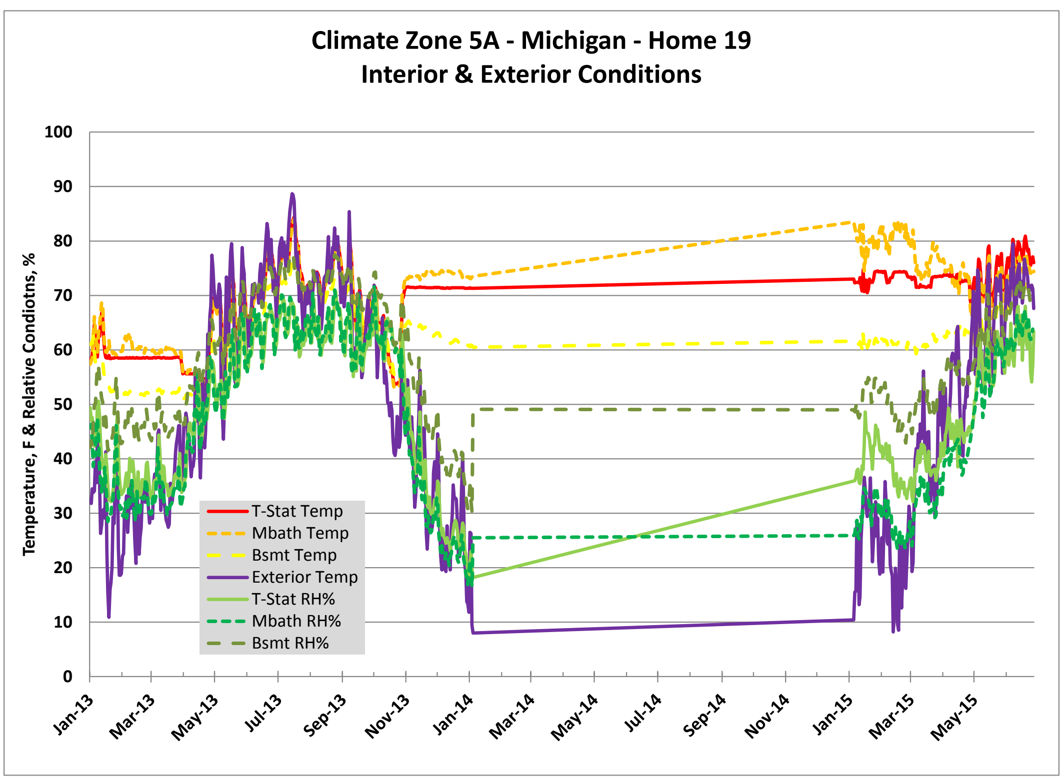

Climate Zone 4C - Washington - Home 14
Exterior Conditions
Temperature, F
Exterior
Apr-13
May-13
Jun-13
Jul-13
Aug-13
Sep-13
Oct-13
Nov-13
Dec-13
Jan-14
Feb-14
Mar-14
Apr-14
May-14
Jun-14
Jul-14

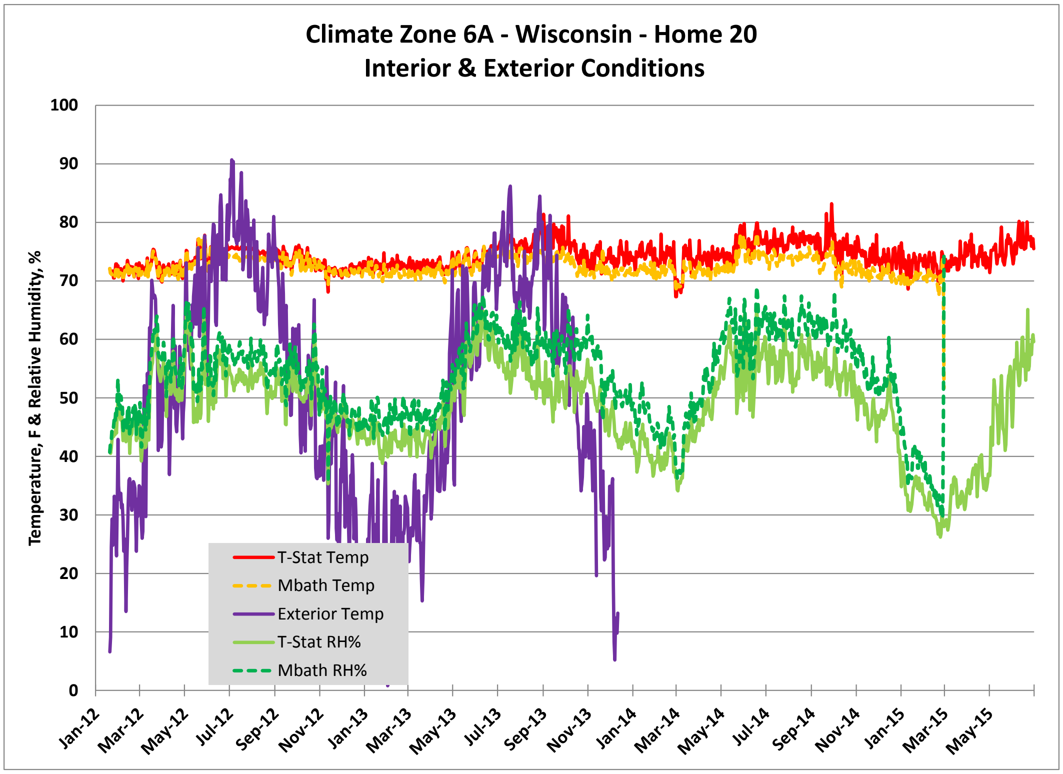

Climate Zone 5A - Iowa - Home 15
Interior & Exterior Conditions
Temperature, F & Relative Humidity, %
T-Stat Temp
Mbath Temp
Bsmt Temp
Exterior Temp
T-Stat RH%
Mbath RH%
Bsmt RH%
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15

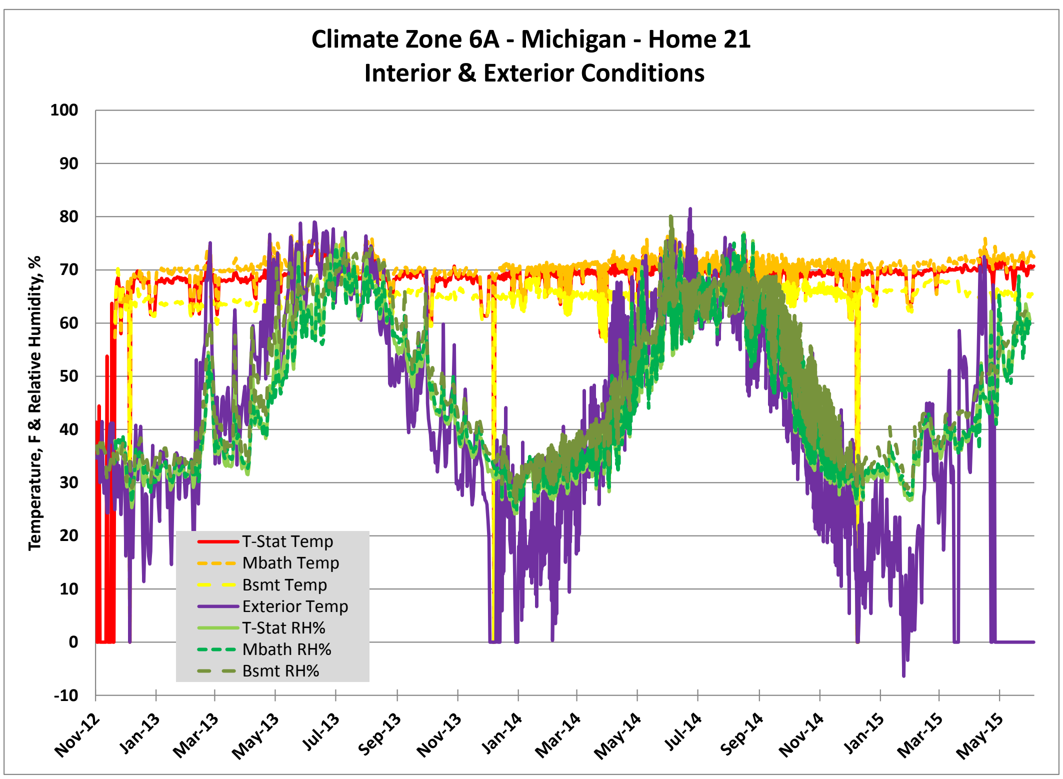

Climate Zone 5A - Iowa - Home 16
Interior & Exterior Conditions
T-Stat Temp
Mbath Temp
Bsmt Temp
Exterior Temp
T-Stat RH%
Mbath RH%
Bsmt RH%
Temperature, F & Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Dec-12
Jan-13
Feb-13
Mar-13
Apr-13

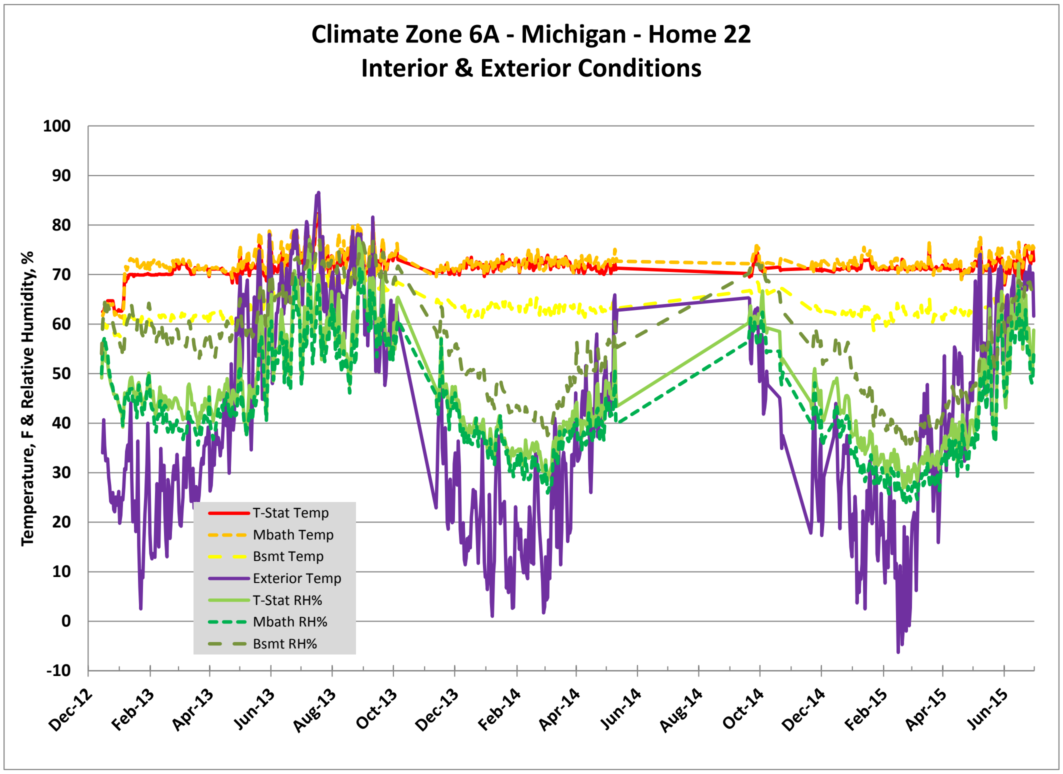

Climate Zone 5A - Michigan - Home 17
Interior & Exterior Conditions
T-Stat Temp
Mbath Temp
2 Fl Temp
Bsmt Temp
Exterior Temp
T-Stat RH%
Mbath RH%
2 Fl RH%
Bsmt RH%
Temperature, F & Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Apr-14
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Jun-15


Climate Zone 5A - Michigan - Home 18
Interior & Exterior Conditions
Temperature, F & Relative Humidity, %
T-Stat Temp
2 Fl Temp
Exterior Temp
Mbath RH%
Bsmt RH%
Mbath Temp
Bsmt Temp
T-Stat RH%
2 Fl RH%
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Apr-14
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Jun-15


Climate Zone 5A - Michigan - Home 19
Interior & Exterior Conditions
Temperature, F & Relative Condiotns, %
T-Stat Temp
Mbath Temp
Bsmt Temp
Exterior Temp
T-Stat RH%
Mbath RH%
Bsmt RH%
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15


Climate Zone 6A - Wisconsin - Home 20
Interior & Exterior Conditions
Temperature, F & Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
T-Stat Temp
Mbath Temp
Exterior Temp
T-Stat RH%
Mbath RH%
Jan-12
Mar-12
May-12
Jul-12
Sep-12
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15


Climate Zone 6A - Michigan - Home 21
Interior & Exterior Conditions
Temperature, F & Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
-10
T-Stat Temp
Mbath Temp
Bsmt Temp
Exterior Temp
T-Stat RH%
Mbath RH%
Bsmt RH%
Nov-12
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Jan-15
Mar-15
May-15



Climate Zone 6A - Michigan - Home 22
Interior & Exterior Conditions
Temperature, F & Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
-10
T-Stat Temp
Mbath Temp
Bsmt Temp
Exterior Temp
T-Stat RH%
Mbath RH%
Bsmt RH%
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Apr-14
Jun-14
Aug-14
Oct-14
Dec-14
Feb-15
Apr-15
Jun-15

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