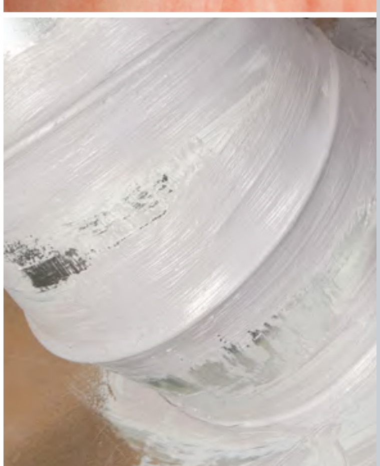
U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY



Moisture Performance of High-R Wall Systems

May 2018

Building America
U.S. Department of Energy

Available electronically at SciTech Connect www.osti.gov/scitech

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062

OSTI www.osti.gov
Phone: 865.576.8401
Fax: 865.576.5728
Email: reports@osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

NTIS www.ntis.gov
Phone: 800.553.6847 or 703.605.6000
Fax: 703.605.6900
Email: orders@ntis.gov

Moisture Performance of High-R Wall Systems

Prepared for:
U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Buildings Technologies Office

and

National Association of Home Builders

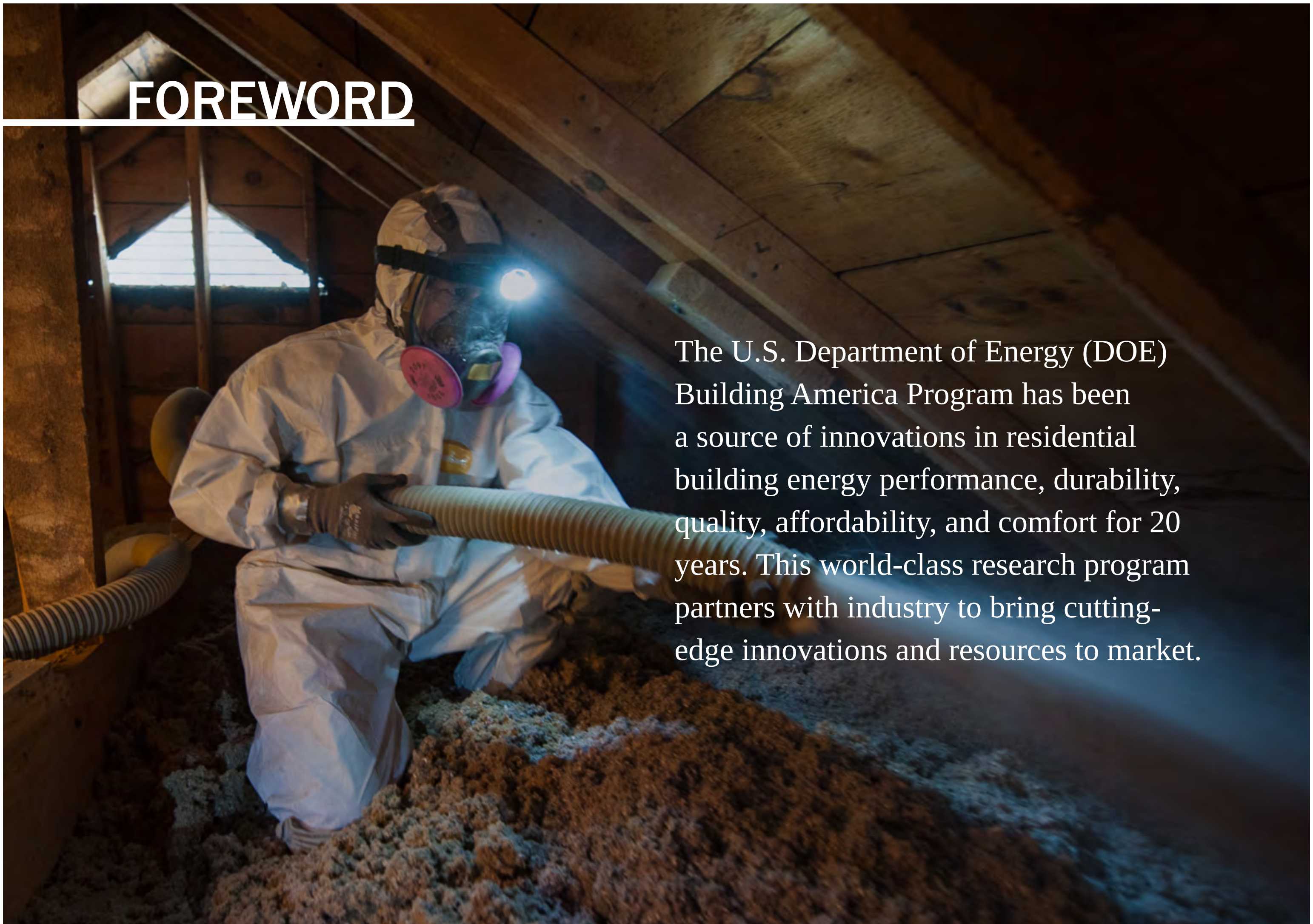
Prepared by:
N. Shah and V. Kochkin
Home Innovation Research Labs
400 Prince George's Blvd.
Upper Marlboro, MD 20774

May 2018

Suggested Citation
Shah, N., and V. Kochkin. 2018. *Moisture Performance of High-R Wall Systems*. Upper Marlboro, MD: Home Innovation Research Labs. DOE/EE-1784.
https://www.osti.gov/biblio/1439443-moisture-performance-high-wall-systems

This material is based upon work supported by the Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Building Technologies Office under Award Number(s) EE0007054.

FOREWORD



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

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

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

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

This report, "Moisture Performance of High-R Wall Systems," examines the moisture characteristics of high-R wall systems as part of a broader effort to offer solutions that increase builders' confidence with the adoption of energy-efficient technologies.

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

PREFACE

High-performance homes offer improved comfort, lower utility bills, and assured durability. The next generation of building enclosures is a key step toward achieving high-performance goals through decreasing energy load demand and enabling advanced space-conditioning systems. Yet the adoption of high-R enclosures and particularly high-R walls has been a slow-growing trend because mainstream builders are hesitant to make the transition. In a survey of builders on this topic, one of the challenges identified is an industry-wide concern about the long-term moisture performance of energy-efficient walls. This study takes a step toward addressing this concern through direct monitoring of the moisture performance of high-R walls in occupied homes in several climate zones. In addition, the robustness of the design and modeling tools for selecting high-R wall solutions is evaluated using the monitored data from the field. The information and knowledge gained through this research will provide an objective basis for decision-making so that builders can implement advanced designs with confidence.

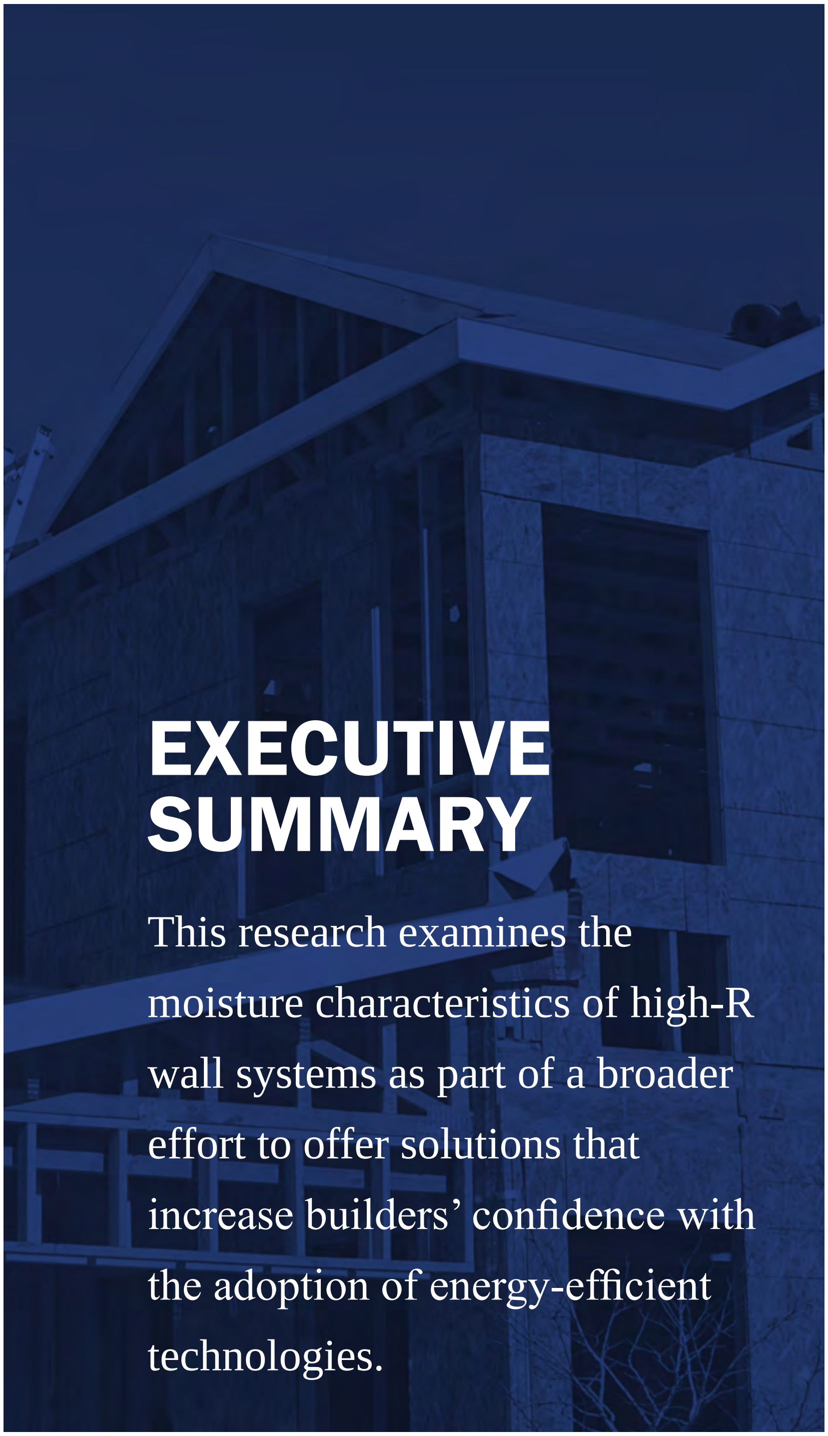
ACKNOWLEDGMENTS

Home Innovation Research Labs acknowledges the U.S. Department of Energy Building America Program, American Chemistry Council, National Association of Home Builders, and Vinyl Siding Institute for sponsoring this research. We also extend our sincere appreciation to all participating builders who were willing to turn their homes into small research laboratories for the benefit of the industry and to those who volunteered their time for this study. Their commitment to advancing our knowledge of buildings and their dedication to providing the best product to their customers made this project possible.

Photos from iStock 178447161, 184944590, 467972591, 183245764, 496703961, 148484827; Dennis Schroeder, NREL 28764; courtesy of Home Innovations Research Labs

NOMENCLATURE

2x4	Nominal 2×4 dimension lumber (1½ in. × 3½ in. actual)
2x6	Nominal 2×6 dimension lumber (1½ in. × 5½ in. actual)
ACH50	Air changes per hour at 50 pascals, a measure for the rate of airflow in the building, either for deliberate ventilation or with respect to envelope infiltration
ERV	Energy recovery ventilator
High-R	Reference to wall systems with thermal resistance exceeding historical practice and/or energy code minimum requirements
HRV	Heat recovery ventilator
IRC	International Residential Code for One- and Two-Family Dwellings
OSB	Oriented strand board
RH	Relative humidity
R-value	Quantitative measure of resistance to conductive heat flow (h·°F·ft2/Btu)
WRB	Water-resistive barrier
WSP	Wood structural panel
XPS	Extruded polystyrene foam
ZIP	OSB wood structural panel faced with a water-resistive membrane (made by Huber) *Note: ZIP performance measured in this study may not be applicable to other WSP products with a laminated facer.*
ZIP-R	Insulated sheathing made by combining 7⁄16-in.-thick ZIP wall sheathing with a layer of rigid foam plastic insulation laminated to its interior face (made by Huber)



EXECUTIVE SUMMARY

This research examines the moisture characteristics of high-R wall systems as part of a broader effort to offer solutions that increase builders' confidence with the adoption of energy-efficient technologies.

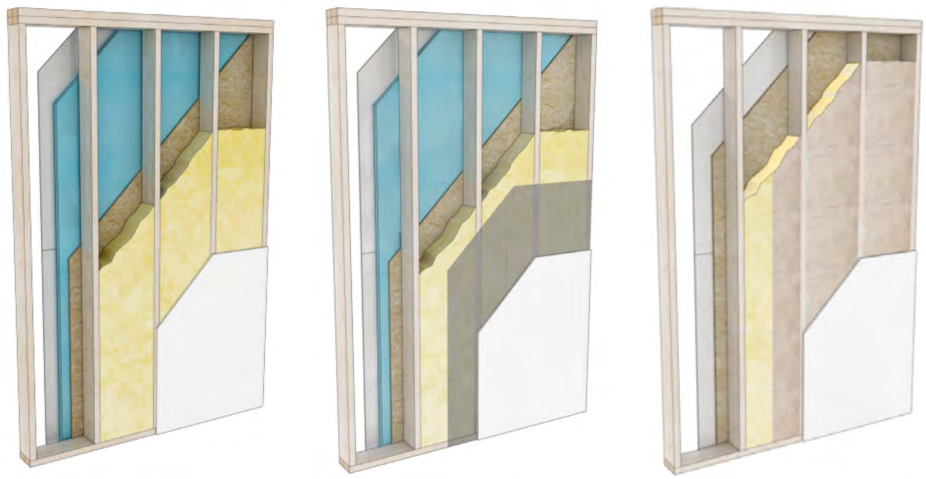
The high-R walls feature increased wall insulation levels, reduced wall air leakage, and often reduced permeance of material layers. Wall assemblies are subjected to various moisture loads, such as bulk water, built-in moisture (construction moisture), water vapor, and capillary transport through materials in contact with water or in contact with the ground.

The objectives of the research include: (1) demonstrating the moisture performance of various high-R walls, (2) identifying wall systems with marginal moisture performance and recommending a set of improvements, and (3) developing a set of design criteria that ensures the durability of high-performance walls. The research extends across cold climate zones where the wall construction is designed to meet substantially increased thermal performance and whole-house air sealing levels.

A total of 22 houses were identified by Home Innovation Research Labs for acceptance into the study. The range of energy-efficient walls of interest was divided into three key research areas:

- Key Research Area 1: Continuous Insulation and Cavity Insulation (no dedicated interior vapor retarder, temperature-controlled cavity)
- Key Research Area 2: Continuous Insulation, Cavity Insulation, and an Interior Vapor Retarder (Hybrid wall)
- Key Research Area 3: Cavity-Only Insulation (vapor-open walls or walls with an interior vapor retarder).

This project supports the U.S. Department of Field observations for each house were compared to WUFI simulations conducted in two formats: (1) blind predictions using a general set of material properties and boundary conditions and (2) modified predictions that used more accurate inputs (if available) for material properties (e.g., interior paint) and interior relative humidity (RH) levels.



The study was designed to monitor the moisture performance of energy-efficient homes in climate zones 4–7 where a substantial vapor drive to the exterior is present during the winter. Key research findings include:

- The majority of walls showed moisture content levels less than the fiber saturation point during the monitoring period or following the initial drying.
- Exterior insulation can be an effective method for controlling the effects of the interior vapor drive.
- Walls that showed an upward moisture content trend in the winter showed a drying trend in the spring. This performance pattern included walls with exterior foam sheathing, confirming that these types of walls have a capacity for drying.
- The 2x6 framed walls with extruded polystyrene foam (XPS) R-5 exterior foam sheathing and Kraft paper vapor retarder showed very stable moisture content levels and show promise as a practical option for achieving insulation levels as high as R-24 using standard materials with only small changes to conventional construction practices.

- Walls with a polyethylene sheet interior vapor retarder (Class I) show stable low moisture content levels. This observation is consistent with previous studies and applies to walls with various sheathing and cladding combinations. (Note that this study included homes in climate zones 4A and higher.)

- Walls without exterior insulation and without an interior vapor retarder in climate zones 4A or 4C can be subject to substantial seasonal moisture fluctuations.

- In Climate Zone 5A, walls with damp-sprayed cellulose without an interior vapor retarder and without exterior insulation are subject to large seasonal moisture fluctuations.

- In Climate Zone 5A, walls with batt insulation and Kraft facing can be subject to seasonal fluctuations as a result of air leakage inside the wall cavity from the house interior.

- For spray foam cavity insulation, it is critical that the product with permeability characteristics specified in the design is installed in the field. Based on the field observations, the moisture content levels can reach the fiber saturation point where the spray foam appears not to meet the design specifications.

- For rim joists in all walls with exterior insulation, the moisture content was less than 15% and did not exhibit significant seasonal fluctuations.

- For rim joists in walls without exterior insulation, rim joists with open-cell spray foam showed larger seasonal fluctuations; however, the levels of the fluctuations did not necessarily approach the fiber saturation point.

- Average interior RH levels in all newly constructed homes remained less than 45% during the winter season.
- Overall, WUFI simulations can provide a valuable design and decision-making tool for the selection of wall assemblies. WUFI's ability to accurately predict in-field performance depends on the accuracy of the input parameters for material properties and boundary conditions. A broad range of predictive power was observed; many predictions reasonably followed the measured data, and a few substantially diverged from the data. Further research and analysis is recommended to better understand the fundamental reasons for the observed spread in the few cases where the predictions did not track the field data.
- Vapor-open wall designs (e.g., no interior vapor retarder) were typically more sensitive to the modeling inputs. In contrast, vapor barrier designs (e.g., polyethylene sheet at the interior face) were stable and predictable.

Table of Contents

List of Figures

List of Tables

1 Background

1.1 Introduction

High-R walls continue to remain a laggard technology, even among more advanced builders. Yet the path to achieving system solutions for energy-efficient homes must include significant improvements to walls. One of the challenges to the wider adoption of high-R wall systems is an industry-wide concern about the long-term moisture performance of these systems in airtight, high-performance homes.

The high-R walls feature increased wall insulation levels, reduced wall air leakage, and reduced permeance of material layers. The long-term moisture performance of these wall systems with regard to vapor drive, condensation risk, and drying capability continues to raise questions. With moisture performance increasingly becoming a design consideration in the selection of wall systems, home builders and designers need practical criteria and guidance for construction that ensures the durability of high-performance residential buildings. This type of design guidance is particularly needed because various industry groups are advocating for and against specific wall design solutions based on incomplete information.

The objectives of the research include (1) demonstrating the moisture performance of various high-R walls, (2) identifying wall systems with marginal moisture performance and recommending a set of improvements, and (3) developing a set of design criteria that ensures the durability of high-performance walls. In addition, the observed data will provide an initial library of interior relative humidity (RH) in high-performance homes and its relationship with the performance of the monitored walls. The research extends across climate zones 4–7 where the wall construction is designed to meet substantially increased thermal performance and whole-house air sealing levels.

This research examines the moisture characteristics of high-R wall systems as part of a broader effort to offer solutions that increase builders' confidence in the adoption of energy-efficient technologies. Moisture characteristics are evaluated based on the peak level and seasonal cyclical behavior of the moisture content in the wood structural panel (WSP) sheathing material (oriented strand board [OSB], plywood, or ZIP) and the framing. The moisture characteristics of the WSP are of particular interest regarding high-R wall systems because WSP is a critical structural member and sustaining high levels of moisture may impact the system's long-term structural performance. WSP is the primary condensation plane in many types of light-frame wall assemblies.

The research focuses on in situ data of moisture characteristics to identify wall configurations with problematic performance, confirm the performance of well-designed walls, expand the empirical database, identify trends, and validate simulation results. The range of wall construction variables in the study include various types of exterior insulation with a range of permeability, claddings, air sealing strategies, drainage plane types, wall orientation, cavity insulation types and R-value, interior vapor retarders, ranges of interior RH, and climate zones. The research will also document external factors, such as occupancy; local weather; house/wall orientation; type of heating, ventilating, and air-conditioning system; and other relevant house details.

1.2 Moisture in Walls

Wall assemblies are subjected to various moisture loads, such as bulk water, built-in moisture (construction moisture), water vapor, and capillary transport through materials in contact with water or in contact with the ground. Therefore, moisture-management techniques in the walls include an appropriate balance and combination of materials and air sealing methods. The material properties that substantially influence a wall's moisture performance include the (1) water vapor permeance of interior and exterior layers and (2) R-value and vapor permeance of the cavity insulation and exterior insulation.

The correct combination of the materials in addition to air sealing strategies can effectively control moisture in wall assemblies. The design principles for moisture control can be summarized as follows:

1. Implement an effective water-resistive barrier (WRB) system to keep exterior moisture from getting inside the wall.

2. Control the diffusion of water vapor from indoors and outdoors into the wall cavity.

3. Maintain the wall assembly's ability to adequately dry in at least one direction (avoid a double-vapor-barrier condition).

Based on these concepts, this research addresses the relationship between the permeability of the exterior cladding/WRB system and the interior finishes/membrane layers. Practical examples where this interaction is becoming an issue include 2x6 or 2x4 walls with 1 or 1.5 in. of exterior foam sheathing. This level of insulation is often preferred by builders because of the simplified attachment of the cladding; however, in Climate Zone 5 and above, the International Residential Code for One- and Two-Family Dwellings (IRC) requires higher exterior insulation levels to control the cavity RH (e.g., R-7.5 or higher for 2x6 walls in Climate Zone 5).

1.3 Background Studies by Home Innovation Research Labs

Home Innovation Research Labs conducted several studies on the moisture performance of walls in buildings that included the monitoring and analysis of walls in occupied homes and controlled test structures. This section provides summaries of the most relevant studies.

In 2010, Home Innovation conducted a study on the *Moisture Performance of OSB-Sheathed Walls in Homes in Climate Zone 4 and 5* in response to builder reports of buckling OSB wall sheathing in the winter of 2008–2009. The study showed a trend for all test homes indicating an increase in moisture content with an increase in RH. One of the home builders from that study, based in Ohio, reported that a "mold-like substance" was present when repairing buckled OSB. This observation prompted an evaluation on the potential of mold growth in wall cavities in climate zones 4 and 5 using the threshold established by ASHRAE Standard 160: Criteria for Moisture-Control Design Analysis in Buildings (ASHRAE 2009).

A 2015 study on the *Moisture Performance of Energy-Efficient and Conventional Wood-Frame Wall Assemblies in a Mixed-Humid Climate* by Glass et al. (2015) examined the performance of several energy-efficient wall systems and established a relationship between the WUFI simulations and the measured performance of walls. The monitoring portion of the study was performed on unoccupied test buildings (test huts) with controlled interior temperature and RH simulating a range of conditions expected in a building. The monitored interior and exterior conditions bounded the inputs for the WUFI simulations. This study allowed WUFI modelers to calibrate simulations by changing the boundary conditions, material properties, or design conditions for hygrothermal component simulations to match those used in the experiment.

Home Innovation conducted a research study on the *Field Moisture Results of Walls in Energy Efficient Homes* (2014) that used in situ data to determine the moisture performance of walls. The research highlighted these following factors that are critical to the moisture performance of walls: outdoor temperature, R-value of continuous insulation, interior vapor retarder, and construction moisture. Walls with continuous insulation showed some of the lowest moisture content levels, and these walls dried toward the inside when a Class III or no interior vapor retarder was installed. A key recommendation is to evaluate the impact of seasonal moisture fluctuations on the long-term characteristics of structural sheathing materials.

In addition to the wall assembly materials and exterior factors, indoor RH control (e.g., ventilation in the winter or dehumidification in the spring/summer) is important for all wall assembly types and is a crucial factor of performance, as found in a number of case studies and experiences (Tsongas 2009; Home Innovation 2014; ASTM 2009). Therefore, the interior RH will be monitored as part of the study to better understand the relationships among the RH, construction moisture, selected air sealing strategy, and whole-house ventilation systems.

1.4 Cost-Effectiveness

The research evaluates a range of existing wall construction technologies. The key consideration is avoiding unintended consequences of potential industry-wide or individual failures that can become a long-term barrier to the adoption of high-R wall enclosures. The study is not attempting to evaluate the cost of added energy-saving measures.

2 Research Methodology

2.1 General

This research project was performed in accordance with the following general outline:

- Identify houses in select climate zones based on a minimum set of design criteria for the overall building and the wall assemblies (IRC 2015; International Energy Conservation Code 2015).
- Collect relevant design, construction, and material data for each selected test home.
- Install moisture sensors in select wall sections at specific locations and inside the house.
- Compile relevant "as-built" construction documentation and blower door test results for each selected home.
- Conduct blind WUFI simulations on selected wall assemblies.
- Compile and chart field moisture performance data.
- Evaluate the predictive ability of the WUFI simulations and perform model calibrations.
- Compile a matrix of climate-based wall assemblies and documented moisture characteristics.

This report summarizes all field data acquired since Summer 2016 for the houses enrolled in the study.

2.2 Key Research Areas and House Locations

The range of energy-efficient walls of interest was divided into three key research areas:

- Key Research Area 1: Continuous Insulation and Cavity Insulation (no dedicated interior vapor retarder, temperature-controlled cavity)
- Key Research Area 2: Continuous Insulation, Cavity Insulation, and an Interior Vapor Retarder (Hybrid wall)
- Key Research Area 3: Cavity-Only Insulation (vapor-open walls or walls with an interior vapor retarder).

This type of grouping is used because (1) each of these wall types relies on a distinct strategy for moisture management, and (2) it enables practical and transparent communications of findings with builders and other industry stakeholders based on construction preferences for high-R walls.

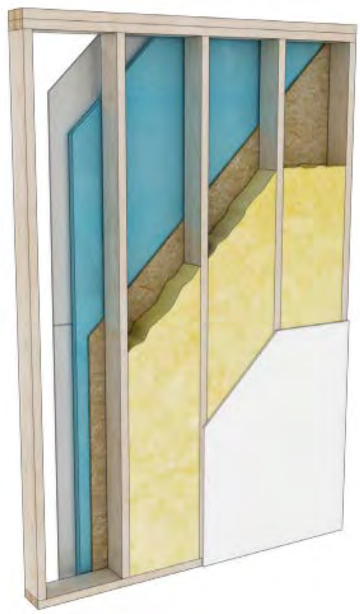


Figure 1. Wall type: Key Research Area 1 example

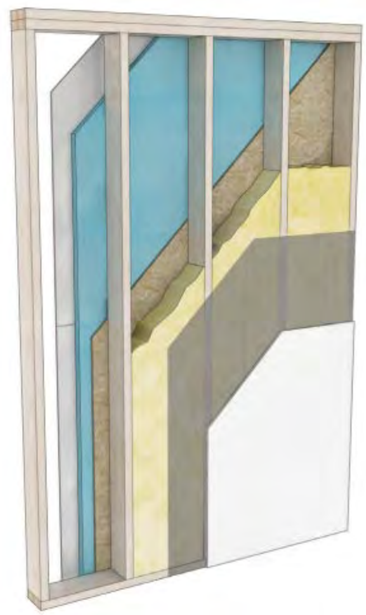


Figure 2. Wall type: Key Research Area 2 example

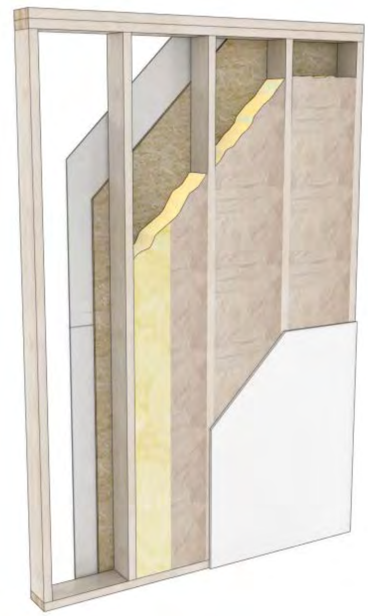


Figure 3. Wall type: Key Research Area 3 example

Key Research Area 1 walls tend to require thicker foam layers for a given climate zone, whereas Key Research Area 2 walls may enable a reduction in foam thickness, potentially simplifying the installation of cladding and fenestration. Key Research Area 3 walls offer solutions for increasing thermal performance using cavity insulation and rely on vapor control via coordination of diffusion characteristics of interior and exterior wall layers. By evaluating all three wall types, the study helps develop solutions for each type and provides builders with options for compliance based on their design and construction preferences.

An active builder recruitment campaign was launched through multiple communications channels. 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 houses located in Climate Zone 4 and above in moist climates.

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

A total of 22 houses were identified by Home Innovation Research Labs for acceptance into the study. Figure 4 shows the location of the 22 houses.

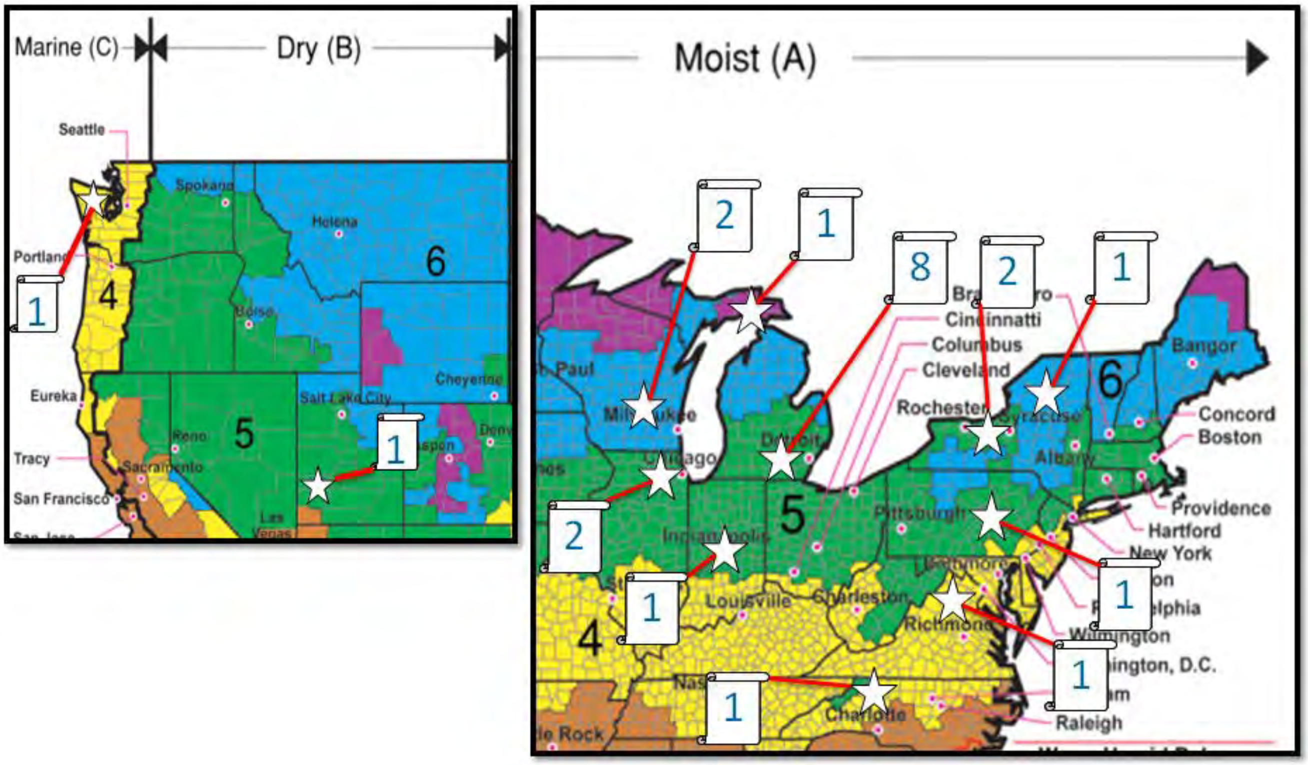


Figure 4. Map showing the location and number of houses by state and climate zone

Table 1 provides a summary of the house locations and other key relevant parameters. Blower door tests were used to determine the infiltration rates, and they were performed after the completion of construction.

Table 1. Summary of Test Sites

Test Site	State + ID	Climate Zone	Conditioned Floor Area, ft^2	Foundation	Infiltration ACH50[a]	Ventilation[a]	Monitoring Start Date
1	VA	4A	2,875	Basement	0.34	HRV[b]	5/1/2016
2	NC	4A	1,667	Slab on grade	1.5	HRV	10/1/2016
3	MI1	5A	2,384	Basement	0.81	ERV[c]	9/22/2016
4	MI2	5A	1,294	Slab on grade	3.35	Exhaust fans	1/25/2017
5	UT	5B	1,886	Slab on grade	4.2	Exhaust fans	10/1/2016
6	NY1	6A	3,450	Basement	0.52	ERV and HRV	1/1/2017
7	PA	5A	2,404	Basement	4.6	Balanced: return-air supply and exhaust fans	1/9/2017
8	MI3	5A	1,250	Basement	X	ERV	2/15/2017
9	MI4	5A	1,250	Basement	X	ERV	2/15/2017
10	MI5	5A	1,680	Basement	3.04	Exhaust fans	12/1/2016
11	MI6	7A	1,092	Slab on grade	X	X	12/10/2016
12	IN	4A	1,358	Slab on grade	4.3	Exhaust fans	9/10/2016
13	WA	4C	3,085	Slab on grade	X	X	9/12/2016
14	MI7	5A	1,294	Slab on grade	3.30	Exhaust fans	1/26/2017
15	IL1	5A	1,400	Basement	0.84	ERV	7/22/2016
16	IL2	5A	3,000	Basement	0.99	Balanced: return-air supply and exhaust fans	4/1/2016
17	MI8	5A	1,627	Basement	3.0	Balanced: return-air supply and exhaust fans	8/25/2016
18	MI9	5A	1,627	Basement	X	Balanced: return-air supply and exhaust fans	9/12/2016
19	NY2	5A	1,858	Basement	1.81	Balanced: return-air supply and exhaust fans	7/1/2016
20	NY 3	5A	3,800	Basement	4.24	ERV	9/15/2016
21	WI1	6A	2,600	Slab on grade	2.3	HRV	8/1/2016
2.8	WI2	6A	3,600	Basement	2.8	Exhaust fans	12/16/2016

[a] Where information is not noted, builders did not provide the requested information.
[b] Heat recovery ventilator
[c] Energy recovery ventilator

2.3 Wall System Configurations and Sensor Locations

Table 2 outlines the wall configurations for each home. The walls are grouped by key research area and climate zone. Framing, sheathing, insulation, cladding, and vapor retarder materials are identified for each wall.

As part of the instrumentation protocol for each home, wall sections were identified for the installation of sensors. The sensors were installed in the wall cavity to measure the moisture content of the sheathing material (OSB, plywood, or ZIP sheathing), studs, and rim joist. The sensors also measured temperature and RH at those locations. Generally, multiple sensors were placed in the walls with north or east orientations because multiple previous studies have demonstrated highest moisture levels in these orientations because of reduced or no direct solar radiation. Additional sensors were placed in the west and south orientations with the primary goal to measure reference conditions for the overall building. When different wall configurations were used in the same building, each configuration was instrumented individually. Two interior sensors and one exterior sensor were also installed to collect boundary temperature and RH data inside and outside the house, respectively.

Table 2. Wall Configuration in Houses

Wall Ref.	Test Site	State + ID	Key Research Area	CZ	Framing	Sheathing Type	Exterior Insulating and Nominal R-value[a]	Cavity Insulation and Nominal R-value[b]	Interior Vapor Retarder/Barrier	Exterior Cladding
A	1	VA	1	4A	2x6	Plywood	2" Mineral Wool (R-8)	Damp Cellulose (R-21)	Gypsum/Paint	Wood siding with furring strips
B	2	NC		4A	2x6	Plywood	1" XPS (R-5)	Fiberglass Batt (R-20)	Gypsum/Paint	Fiber Cement
C	3	MI1		5A	2x6	OSB	2" EPS (R-8)	Fiberglass BIBS (R-21)	Gypsum/Paint	Hardie Board Siding with furring strips
D				5A	2x6	OSB	2" EPS (R-8)	Fiberglass BIBS (R-21)	Gypsum/Paint	Brick veneer with air gap
E	4	MI2		5A	2x4	OSB	1" XPS (R-5)	Blown Cellulose (R-13)	Gypsum/Paint	Vinyl Siding
F	5	UT		5B	2x6	OSB	1" T&G EPS foam (R-5)	Blown Fiberglass (R-22)	Gypsum/Paint	Stucco with acrylic topcoat
G	6	NY1		6A	2x6	Zip System	2" poly-iso (R-12)	ocSPF (R-21)	Gypsum/Paint	Vinyl Siding
H				6A	2x6	Zip System	2" poly-iso (R-12)	Fiberglass Batt (R-19)	Gypsum/Paint	Vinyl Siding
I	11	MI6		7A	2x6	OSB	2" XPS (R-10)	Damp Cellulose (R-21)	Gypsum/Paint	Vinyl Siding
J	6	NY1	2	6A	2x6	Zip System	2" poly-iso (R-12)	Fiberglass Batt (R-19)	Kraft paper	Vinyl Siding
K	7	PA		5A	2x6	Zip System	1.5" PIC (R-9)	Fiberglass Batt (R-19)	Kraft paper	Cement board siding
L	8	MI3		5A	2x6	OSB	1" XPS (R-5)	Fiberglass Batt (R-19)	Kraft paper	Vinyl Siding
	9	MI4		5A	2x6	OSB	1" XPS (R-5)	Fiberglass Batt (R-19)	Kraft paper	Vinyl Siding
M	10	MI5		5A	2x4	OSB	1" Foil Faced poly-iso (R-6.5)	Fiberglass Batt (R-13)	4 mil Polyethylene	Vinyl Siding
N	11	MI6		7A	2x6	OSB	2" XPS (R-10)	Damp Cellulose (R-21)	Smart Vapor Retarder	Vinyl Siding
O	12	IN	3	4A	2x4	OSB	N/A	Flash & Batt (R-15)	Polyethylene	Vinyl Siding
P	13	WA		4C	2x6	OSB	N/A	Fiberglass Batt (R-19)	Gypsum/Paint	Fiber Cement
Q	14	MI7		5A	2x6	OSB	N/A	Damp Cellulose (R-19)	Gypsum/Paint	Vinyl Siding
R	15	IL1		5A	2x8 with 2x4 offset studs	Plywood	N/A	Damp Cellulose (R-26)	Gypsum/Paint	Hardie Panel
S	16	IL2		5A	2x4 studs on 2x6 plates	Zip System	N/A	Damp Cellulose (R-21)	Gypsum/Paint	Hardie Lap siding with furring strips
T	17	MI8		5A	2x6	OSB	N/A	Fiberglass Batt (R-19)	Kraft paper	Vinyl Siding
	18	MI9		5A	2x6	OSB	N/A	Fiberglass Batt (R-19)	Kraft paper	Vinyl Siding
U	19	NY2		5A	2x6	OSB	N/A	Fiberglass Batt (R-19)	Polyethylene	Vinyl Siding
V	20	NY3		5A	2x6	OSB	N/A	2" ccSFP + R-13 FG Batts	Gypsum/Paint	Hardie Board Siding
W	21	WI1		6A	2x6 vertical + 2x4 horizontal	OSB	N/A	Fiberglass Batts (R-19 + R-11)	Smart VR between 2x6 & 2x4	Vinyl Siding
X	22	WI2		6A	2x6	Zip System	N/A	Blown Fiberglass (R-21)	Polyethylene	Fiber Cement

CZ -- Climate Zone; KRA -- Key Research Area; 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).

2.4 Data Collection

After the house was completed, the builder installed a receiver box containing a cellular gateway. When activated, the gateway recorded data from each sensor on a minimum 15-minute basis and transmitted the data to a website. When the receiver had power, data were recorded by the receiver regardless of the Internet connection. During a power outage, the sensor data were not recorded.

The data collected from the sensors included temperature and RH at the sensor body and, via screw pin terminals, the moisture content of the substrate. The moisture content of the wood was temperature compensated based on the sensor temperature reading. In addition, the data set from each sensor included the battery voltage of the sensor. The system is described in greater detail in the following section.

For multistory homes, sensors were placed in both the first- and second-story wall sections. For walls with ZIP panels, longer screws were used to penetrate through the insulation to reach the OSB sheathing.

Figure 5. Sensors installed in the oriented strand board and stud

Figure 6. Sensor installed in the rim joist

Figure 7. Exterior sensor attached to the cladding

Figure 8. Interior sensors placed near the thermostat

The raw data were processed to calculate the dew point and grains of moisture based on the temperature and RH.

The data were 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.

2.5 Monitoring System

OmniSense S-900-1 wireless sensors were used in all monitored homes. These sensors offer the following range of measurements:

- Temperature (-40°F–185°F)
- Relative humidity (0%–100%)
- Wood moisture content (7%– 40%).

OmniSense uses a capacitive sensor element for measuring RH. Temperature is measured by a bandgap sensor. Moisture content is determined by measuring the electric resistance between the two screws of the OmniSense sensor assembly. The measuring elements and battery are housed in a plastic box roughly 2.5-in. wide, 1.5-in. high, and 1-in. deep, as shown in Figure 9. For installation, the sensor is positioned with an 1/8-in. air gap between the body of the sensor housing and the substrate to allow for air circulation, and it is secured using screws supplied with the device (Figure 10).

Figure 9. OmniSense S-900-1 sensor

Figure 10. Sensor attached with screws

2.5.1 Sensor Calibration

The manufacturer-stated accuracy for the sensor models used in this study is ±3.5% RH and ±0.4°C. Home Innovation Research Labs has performed numerous calibrations to verify both sensor accuracy and its correlation with other methods of moisture content measurement using handheld electrical conductance-type moisture meters and gravimetric calculations. Specific calibration equations were developed for 7/16-in. OSB sheathing, ½-in. plywood sheathing, ZIP sheathing, wood-composite lumber rim joist, and spruce-pine-fur lumber using the gravimetric method as the baseline. The gravimetric calibration study was conducted using a controlled environmental chamber where temperature and humidity were set at various levels to enable the capture of a broad range of moisture content levels that can be experienced in an exterior wall. Figure 11 shows specimens in a conditioning chamber during the calibration study. The specimen weight was measured when equilibrium was achieved, and the calculated moisture content was used to calibrate the sensors.

Figure 11. Sensors in the environmental chamber for calibration

Figure 12 plots the OSB gravimetric (oven-dry) moisture contents, including two reference curves from the literature, and it shows the relationship between RH and moisture content.

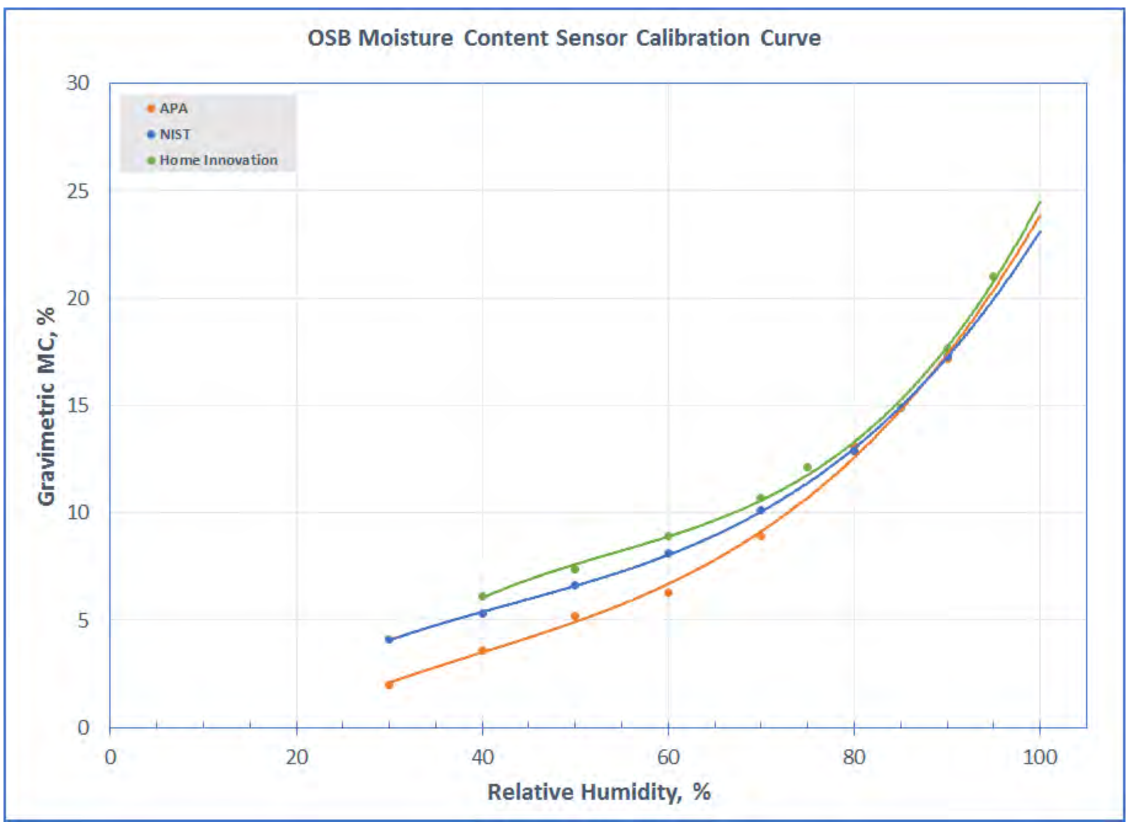


Figure 12. OSB moisture content sensor calibration curves

The wood moisture content sensor readings presented in this report were adjusted based on product-specific, gravimetric calibration equations shown in Table 3.

Table 3. Summation of Calibration Equations

Wood Product	Calibration Equation
OSB	$MC_{gravimetric} = 0.83^{*} MC_{sensor} + 1.16$[a]
Plywood	$MC_{gravimetric} = 0.81^{*} MC_{sensor} + 0.01$
ZIP panel	$MC_{gravimetric} = 0.97^{*} MC_{sensor} + 0.11$
Composite rim joist	$MC_{gravimetric} = 0.77^{*} MC_{sensor} + 2.20$
SPF lumber	$MC_{gravimetric} = 1.22^{*} MC_{sensor} + 0.23$
[a] **Moisture content**	

2.6 Material Properties

The vapor permeability of individual materials influences the moisture performance of the entire wall assembly. Therefore, the meaningful evaluation of a wall system requires understanding the permeability characteristics of its layers. Home Innovation collected information from builders on the brand of WRB, type of interior vapor retarder, and brand and specific type of paint and primer used in each house.

Because the vapor permeability characteristics for paints or primers are not readily available from manufacturers, Home Innovation conducted an ASTM E-96 (Standard Test Methods for Water Vapor Transmission of Materials) study to determine the permeability of layering different paints and primers on the drywall. The specific paint products used in the construction of several test homes were used in the laboratory measurement study to allow for direct evaluation in the analysis of the monitored wall systems.

Table 4 shows the permeance of paint and primer, WRB, and interior vapor retarder categorized by each wall type. The permeability for WRB and interior vapor retarder were sourced from manufacturers' literature.

Table 4. Perm Rating of Different Layers in a Wall Assembly

Wall Ref.	Test Site	Layer of Paint and Primer	Paint: Dry Cup (perm)	Paint: Wet Cup (perm)	Interior Vapor Retarder (perm)	WRB (perm)
A	1	1 layer paint + 1 layer primer	N/A	N/A	-	58
B	2	1 layer paint + 1 layer primer	7.0	28.8	-	12
C D	3	2 layers paint + 1 layer primer	4.6	29.0	-	54
E	4	2 layers paint	5.9	31.1	-	14
F	5	1 layer paint	16.1	37.6	-	50
G H	6	2 layers paint + 1 layer primer	2.0	10.6	-	12
I	11	N/A			-	16
J	6	2 layers paint + 1 layer primer	2.0	10.6	0.3/1.8[a]	12
K	7	1 layer paint + 1 layer primer	7.0	28.8	0.3/1.8[a]	12
L	8	1 layer paint	16.1	37.6	0.3/1.8[a]	54
	9	1 layer paint	16.1	37.6	0.3/1.8[a]	54
M	10	N/A			~0.4	N/A
N	11	N/A			1 – 10	N/A
O	12	N/A			<0.1	54
P	13	N/A			-	54
Q	14	2 layers paint	5.9	31.1	-	14
R	15	1 layer paint + 1 layer primer	7.0	28.8	-	33
S	16	2 layers paint + 1 layer primer	4.6	29.0	-	12
T	17	1 layer paint	16.1	37.6	0.3/1.8[a]	54
	18	1 layer paint	16.1	37.6	0.3/1.8[a]	54
U	19	2 layers paint + 1 layer primer	2.8	10.1	-	8
V	20	1 layer paint	16.1	37.6	-	54
W	21	N/A			<0.7	50
X	22	1 layer paint	6.7	28.7	<1	N/A
		Drywall only (baseline)	40.9	55.7	-	-

[a] Dry cup/wet cup perm

2.7 WUFI Simulation

Tested wall assemblies have been modeled using WUFI Pro 6.0 Software (Fraunhofer Institute for Building Physics, Holzkirchen, Germany) for one-dimensional transient heat and moisture transfer. The moisture content of the wood sheathing was simulated. The simulations were performed in two phases: (1) blind prediction simulations using a generic set of inputs and (2) modified simulation using updated inputs based on more detailed information obtained for the specific house.

The blind prediction simulations used scenarios with standard material properties, house characteristics, climate conditions, and interior relative conditions. Material properties from the literature or WUFI databases were used. The blind prediction simulations were also used to evaluate the walls' drying capabilities during the course of 2 years. The blind simulations also allowed for the evaluation of incremental changes in wall assembly to help prioritize properties based on the degree of their effect on the walls' performance.

For the modified simulations, the models were updated based on the specific information obtained during the study, including parameters such as indoor RH and temperature, initial moisture content levels, permeability of paint and WRB, infiltration rate, etc. When detailed information was not available, modified simulations used generic values for those specific properties or modified simulations were not performed.

The results of the modified simulations are shown alongside the field measurement data as applicable. The objective of the modified simulations was to evaluate the potential for achieving improved predictive ability of simulated models when compared to in-field performance if select material properties and boundary conditions are known.

3 Field Measurement Results

The measured wall cavity moisture characteristics are presented individually for each home and wall assembly. Indoor and ambient environmental conditions are also presented, where available, to provide a context for the observed wall performance.

The primary characteristic shown in the following tables is the moisture content of the WSP sheathing (OSB, plywood, or ZIP sheathing) or rim joists. The WSP sheathing moisture content is always the more critical performance variable in the wall cavity compared to framing member moisture content.

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.

The outdoor temperature is a key characteristic for the evaluation of wall performance during a heating season in a cold climate. To help in the analysis of observed results, Table 5 summarizes the lowest outdoor temperatures that were either measured at the site with a sensor or obtained from a local weather station when site-specific measurements were not available. A wide range is observed within each climate zone. For example, in Climate Zone 5A the negative peaks range from 19.5°F–1.0°F.

Table 5. Negative Peak Outdoor Temperatures at Site

Test Site	State + House ID	Climate Zone	Min. Winter Temp (°F)
1	VA	4A	16.6
2	NC	4A	14
3	MI1	5A	10.1
4	MI2	5A	19.5
5	UT	5B	2.0
6	NY1	6A	20.9
7	PA	5A	15.5
8	MI3	5A	8.0
9	MI4	5A	8.0
10	MI5	5A	18.8
11	MI6	7A	1.6
12	IN	4A	1.8
13	WA	4C	25.9
14	MI7	5A	19.5
15	Il1	5A	1.0
16	Il2	5A	12.3
17	MI9	5A	10.5
18	MI10	5A	11.1
19	NY2	5A	13.7
20	NY 3	5A	12.5
21	WI1	6A	-0.5
22	WI2	6A	-4.0

3.1 Wood Sheathing Moisture Content Results by Key Research Area and 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 and wood composite rim joists. This is of interest because the wood sheathing provides structural support for the framing (and often the siding), and sustained elevated levels of moisture in the sheathing may compromise the long-term structural performance of the wall. (Note that additional studies are needed to better understand the impact of elevated moisture levels on the walls' structural performance.) Similarly, elevated 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 wood stud, where no sheathing is used) moisture content are shown. The wood 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 during the entire monitoring period for walls in an individual 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. When multiple homes are located in the same climate zone, a numeric designation is used to identify the home. The analysis is divided by wall type for each key research area (refer to Section 2.2).

3.2 Key Research Area 1: Continuous Insulation and Cavity Insulation

Figure 13 shows the summary results for the wood sheathing moisture content for House 1, located in Virginia, Climate Zone 4A. The following observations can be made:

- For most of the monitoring period, the plywood moisture content was significantly less than the 26% threshold for all sensors. The initial spike in moisture content is attributed to the placement of damp cellulose in the wall cavity. The insulation installation was completed around mid-May, which is consistent with the spike in the graph. Note that the builder was operating a construction dehumidifier starting in the middle of July after the building was enclosed.

- The initial higher moisture content dissipated during the course of 45–60 days after the installation of damp cellulose, and the moisture content remained stable, ranging from 10%–15%, throughout the following three seasons.

- It is notable that this wall configuration did not have a winter trend of increasing moisture content as is typical for many walls in climates with heating seasons. Therefore, the wall was effective at controlling vapor drive from the interior during the winter with temperatures as low as 16°F. The following wall characteristics help with vapor drive control: (1) R-8 exterior insulation keeps the wall cavity warmer, (2) 2x6 cavity insulation with moisture storage capacity modulates moisture load, and (3) interior paint reduces vapor movement across drywall (specific vapor-retarder properties of paint for this site are unknown).

- Note that the builder was operating a construction dehumidifier starting in the middle of July after the house was enclosed to help remove moisture from the building materials.

- The average interior RH was in the range of mid-40% throughout the winter and early spring (heating season). This level of RH for Climate Zone 4A was consistent with the results of the previous study. A heat recovery ventilator (HRV) was used to provide whole-house ventilation. It was effective at controlling the RH levels in this extremely airtight house (0.34 ACH50).

- Wall A can be described as a vapor-open configuration. It uses vented cladding (wood siding with furring strips), no dedicated interior vapor retarder (except interior paint), a high-perm WRB (58 perms), plywood sheathing (more permeable than OSB), vapor-permeable cavity insulation (cellulose), and a porous exterior insulation (mineral wool).

- The modified WUFI simulation of the plywood sheathing moisture content showed overall trends that are similar to the field measurements. The followings differences are observed between the field data and the WUFI predictions:
  - The WUFI prediction overstated the rate of drying afforded by the wall system. The drying time measured in the field was substantially longer than the model prediction.
  - It is possible that the initial moisture content level of the cellulose at the time of enclosure with the drywall was higher than the default level of 25% used by the WUFI model.
  - The measured stabilized moisture content levels were consistently 2%–5% more than the WUFI predictions. This difference is, again, likely the result of the model overestimating the wall's capacity for dissipating the absorbed moisture.

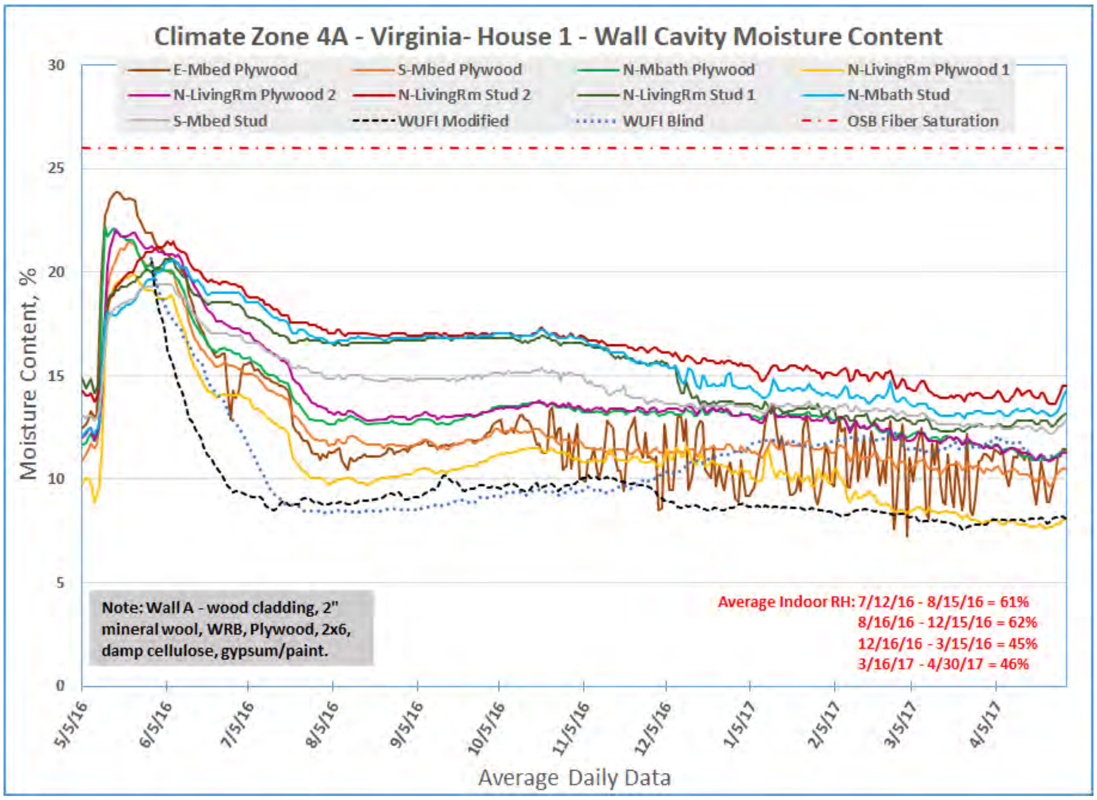


Figure 13. Plywood moisture content for Climate Zone 4A, Virginia, House 1

Figure 14 shows the summary results for the plywood sheathing moisture content for House 2, located in North Carolina, Climate Zone 4A. The following observations can be made:

- For the whole monitoring period, the plywood moisture content was less than 14% for all sensors. The wall did not exhibit elevated initial moisture content, suggesting that the wall construction was complete and that the building was enclosed without subjecting materials to significant rain events.
- Throughout the entire 7-month monitoring season, from September 2016 through April of 2017, the moisture content remained stable and low. This observation is consistent with solid wood members (studs), as shown in Appendix 6.2. Therefore, this wall assembly was effective at controlling the interior vapor drive during the winter with temperatures as low as 14°F in January.

- Interior RH averaged 45% during the winter season. This level of interior RH during heating season is in the upper range of levels observed in previous studies for this climate zone. An HRV was used, and it was effective at controlling the RH levels in this airtight house (1.5 ACH50).
- As typically observed in wall monitoring studies, the north-facing walls had a slightly higher moisture content (up to 13%) compared to walls facing south (as low as 7%). The following difference can be attributed to the lack of solar vapor drive in north-facing walls.
- The primary drying direction for Wall B is expected to be toward the interior. The exterior layers of the wall include unvented cladding (fiber cement), low-perm WRB (12 perm), and low-perm XPS exterior insulation (1 perm). The interior path for vapor is more open with the paint perm rating at 7 perms (dry cup) and 29 perms (wet cup). Because there were no elevated moisture levels at any point during the monitoring period, the effectiveness of the drying mechanisms in this wall assembly was not quantified; however, results of other monitoring have indicated that the interior drying path can provide an effective escape method for moisture during non-heating seasons (i.e., when the primary vapor drive is to the interior or neutral).
- The modified WUFI simulation of the plywood sheathing moisture content showed trends that are overall consistent with field measurements throughout the entire monitoring period: the moisture levels are low and stable. Comparing the field data from the north orientation to the WUFI results that are also based on a north orientation indicates a consistent delta of 2%–3% starting in December. This pattern may again suggest that the WUFI predictions overestimate the rate at which walls release moisture (i.e., rate of drying).

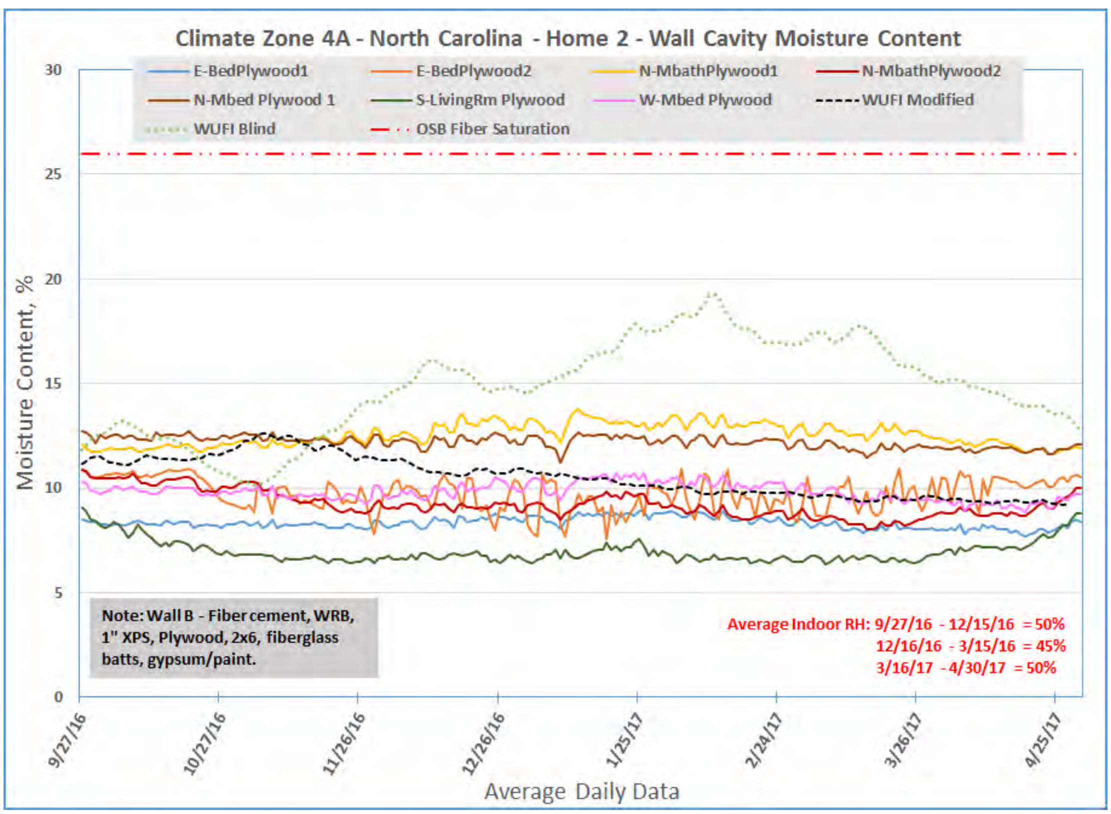


Figure 14. Plywood moisture content for Climate Zone 4A, North Carolina, House 2

Figure 15 and Figure 16 shows the summary results for the OSB sheathing moisture content for Wall C and Wall D, respectively, in House 3, located in Michigan, Climate Zone 5A. Wall C and D use different claddings—fiber cement over furring strips and brick veneer, respectively; the two walls are identical in all other aspects. Data during the fall period (September–November) is limited for this house because the gateway was disconnected during construction until occupants moved into the house. Although limited to only a few days, the initial data points from early readings are included to provide information on the starting moisture content levels following construction of the wall. Consistent data acquisition began in November. The following observations can be made:

- Moisture content remained low for both walls C and D throughout the monitoring period, with the highest recoded levels of 16% during the winter season (outdoor temperatures as low as 10°F).
- Both walls experienced a mild upward trend in moisture content during the heating season. This trend was somewhat more pronounced in walls with fiber cement siding, but the difference was not sufficient to suggest a specific pattern caused by the cladding type. Because both claddings were installed with a vented gap, the walls were expected to perform similarly. Note that Wall C was predominantly east-facing and Wall D was west-facing—the difference in orientation is the more likely explanation for any observed difference in moisture levels.
- The interior RH averaged 40% in the winter period, which is consistent overall with the ranges observed in previous studies for Climate Zone 5 (perhaps slightly above average). The very airtight (0.81 ACH50) house is ventilated with an energy recovery ventilator (ERV).
- The primary drying direction for walls C and D is expected to be toward the interior. With 2 in. of unfaced expanded polystyrene foam on the wall's exterior (~1.5 perm), the interior path for vapor is more open, with the paint perm rating at 4.6 perms (dry cup) and 29 perms (wet cup). Some level of drying to the outdoor may also take place. The data indicate a drying trend beginning at the end of the heating season, with the moisture content decreasing to the prewinter levels relatively quickly by the middle of March. This observation indicates that walls with exterior foam have the capacity for drying.
- The modified WUFI predictions for both walls did not capture the observed winter upward trend in the OSB. Two sensitivity studies were conducted to evaluate the model by (1) simulating a higher interior RH and (2) simulating a lower drying rate to the outdoors. Under each of those scenarios, the model indicated some level of elevated moisture content of OSB during the winter season—a trend observed in the field data. Therefore, the WUFI predictions appeared to somewhat overstate the wall's ability to manage moisture (not to a degree that should cause any questions for this specific wall assembly in this climate zone). In a more general sense regarding WUFI's predictive capabilities, it is suggested that sensitivity studies be conducted for each model used in the design, particularly when the modeling results suggest performance on the cusp of the established pass-fail criteria.

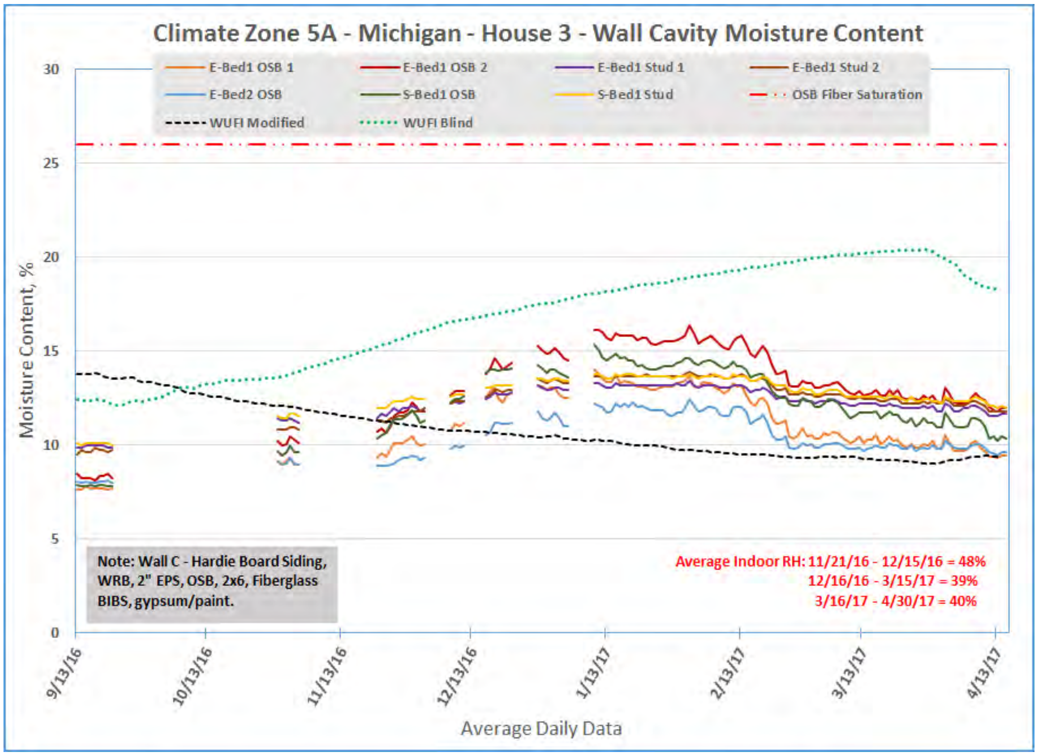


Figure 15. Daily oriented strand board moisture content for Climate Zone 5A, Michigan (1), House 3 (Wall C)

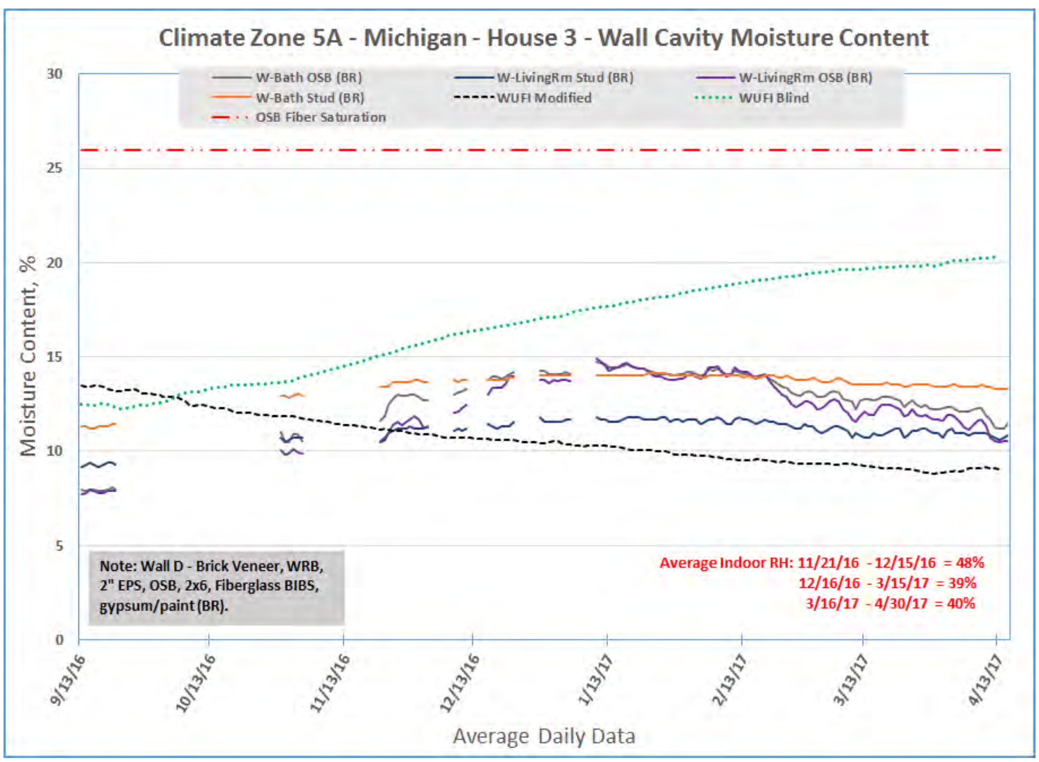


Figure 16. Daily oriented strand board moisture content for Climate Zone 5A, Michigan (1), House 3 (Wall D)

Figure 17 shows the summary results for the OSB sheathing moisture content for House 4, located in Michigan, Climate Zone 5A. Because of the construction schedule, the data period for House 4 starts in the middle of winter. The house has a limited number of sensors because of the limited amount of wall area available—the house is a narrow townhouse with a large area of openings. Wall E meets the minimum IRC prescriptive code provisions for Climate Zone 5A for the R-value of exterior foam sheathing for walls with a Class III interior vapor retarder (R-5 over 2x4 wall). The following observations can be made:

- As expected with the placement of damp-sprayed cellulose insulation in the wall cavity, the initial moisture content of the OSB and framing ranged from 20%–25%. These high moisture content levels were sustained throughout the winter, with a drying trend starting in April.
- The house was not occupied during the winter, and the interior RH was low, averaging 25%. A longer monitoring period is needed to better understand the long-term moisture-management characteristics of the wall, particularly during a winter season when the house is occupied.
- Initial data suggest that Wall E has good drying capacity. As with other walls with exterior foam sheathing, Wall E—which has 1 in. of XPS (~1.0 perm)—is expected to dry primarily to the interior. Some level of drying to the outdoors may also take place.
- Both blind and modified WUFI predictions show an excellent agreement with the measured data during the short initial monitoring period.

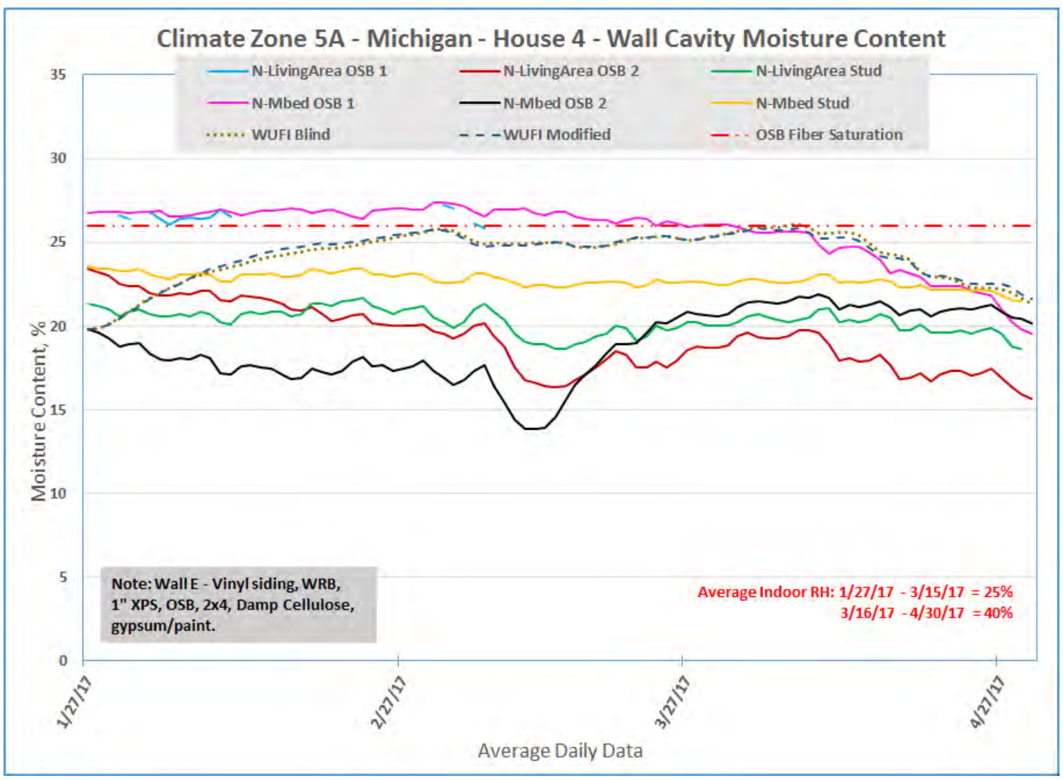


Figure 17. Daily oriented strand board moisture content for Climate Zone 5A, Michigan (2), House 4

Figure 18 shows the summary results for the OSB sheathing moisture content for House 5, located in Utah, Climate Zone 5B. This is the only house included in the study from an area designated as dry on the climate zone map. The cladding is one-coat stucco over 1-in. expanded polystyrene foam and an acrylic topcoat. Data for the winter period were not collected because the data acquisition system was turned off by the occupant except during 2 days at the end of December. The interior sensors were removed by the occupant. The following observations can be made:

- The initial moisture content of the OSB sheathing was low (7%) and remained low (less than 13%) based on available data during the monitoring period. The low moisture levels in the walls can be attributed to the dry climate region, summer construction, benefits of adding exterior insulation to stucco, and dry installation method for the cavity insulation (blown fiberglass). The exterior winter temperature was as low as 2°F.
- Evidence shows some winter increase in the OSB moisture content for the north orientation. The level of the increase is unknown because of the data acquisition interruption, but it appears to be small, with an onset sometime after December. Moisture content trends remained flat in all other orientations, suggesting that solar drive is an important factor for drying. It is also expected that the foam sheathing limits the entrance of solar-driven moisture from the stucco.
- The drying mechanism for Wall F is expected to be toward the interior. The interior paint tested at 16 perm (dry cup), which is above the upper boundary (10 perm) for the level of a Class III vapor retarder. The specific permeability of the acrylic topcoat is not known; stucco manufacturers typically offer permeable acrylic finishes with reported perm ratings of 10 or more.
- The modified WUFI simulations for the north orientation showed a flat trend of low moisture content. The modeled performance is consistent with data for all orientations except the north. The model does not indicate a seasonal impact as suggested by the tail of the winter data.

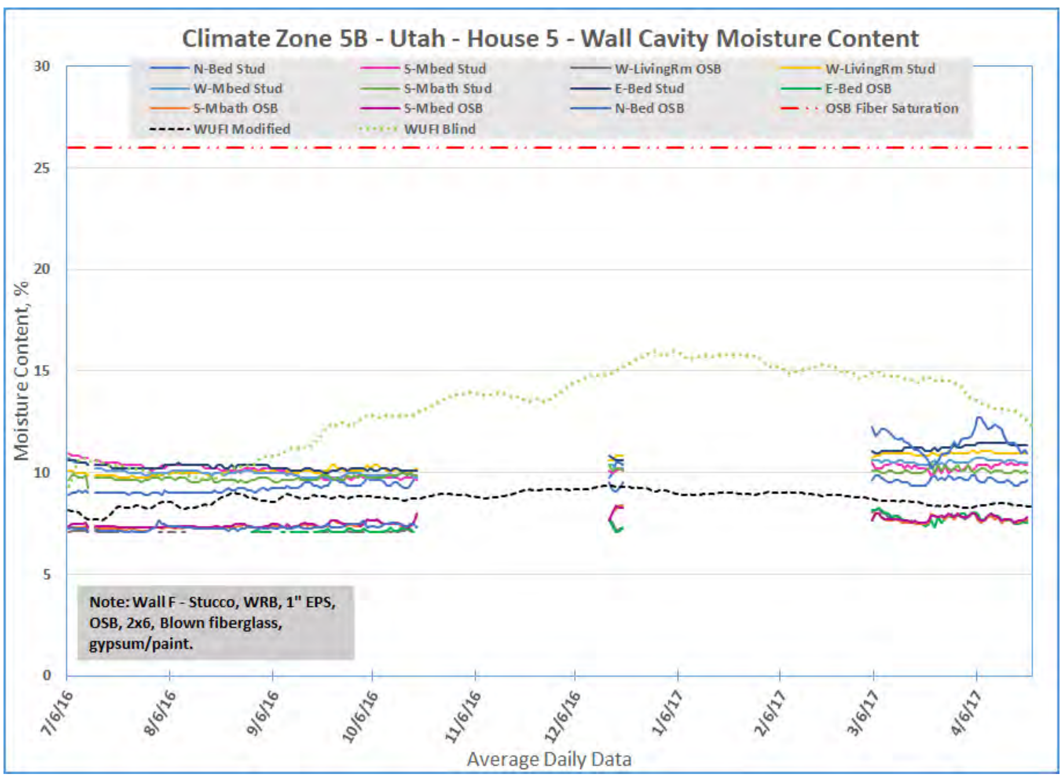


Figure 18. Daily oriented strand board moisture content for Climate Zone 5B, Utah, House 5

Figure 19 shows the summary results for the ZIP sheathing moisture content for both Wall G and H for House 6, located in New York, Climate Zone 6A. The following observations can be made:

- The OSB moisture content was trending flat at less than 14% for all sensors in all orientations. The coldest outside temperature was 21°F, suggesting a relatively mild winter for the climate zone.
- With the majority of the walls using open-cell spray foam rated at 5 perm for the full depth of the wall cavity, one wall bay in the north orientation was insulated with fiberglass batts to provide a baseline for comparison (Wall H, shown by the dotted line in Figure 19). The cavity insulated with vapor-open and air-open fiberglass was trending slightly higher than all other wall sections. The combination of the exterior insulation at R-12, keeping the wall cavity warm, and interior paint at 2 perm (dry-cup), helping control interior moisture drive, was effective at moisture control.
- With the OSB sheathing exterior to the foam insulation (ZIP system), the observed stable OSB moisture content throughout the winter suggests that exposing OSB to cold temperatures does not lead to elevated moisture levels provided an adequate vapor retarder and an air barrier are separating the OSB from the wall interior.
- The average RH during the winter season was within the typical range at 38%. An ERV was used to provide outdoor ventilation and was effective at controlling the RH levels in this extremely airtight house (0.52 ACH50).
- Evidence showed no apparent dependency of moisture content on wall orientation relative to cardinal directions. This could be the result of the effectiveness of the exterior insulation and/or shading at the site.
- With vented vinyl siding, the expected primary drying mechanism for the OSB in the ZIP panels is to the outside.
- The WUFI predictions for both walls trended to be slightly more than most of the sensors. Overall, WUFI simulations were effective at predicting the stable behavior of the walls.

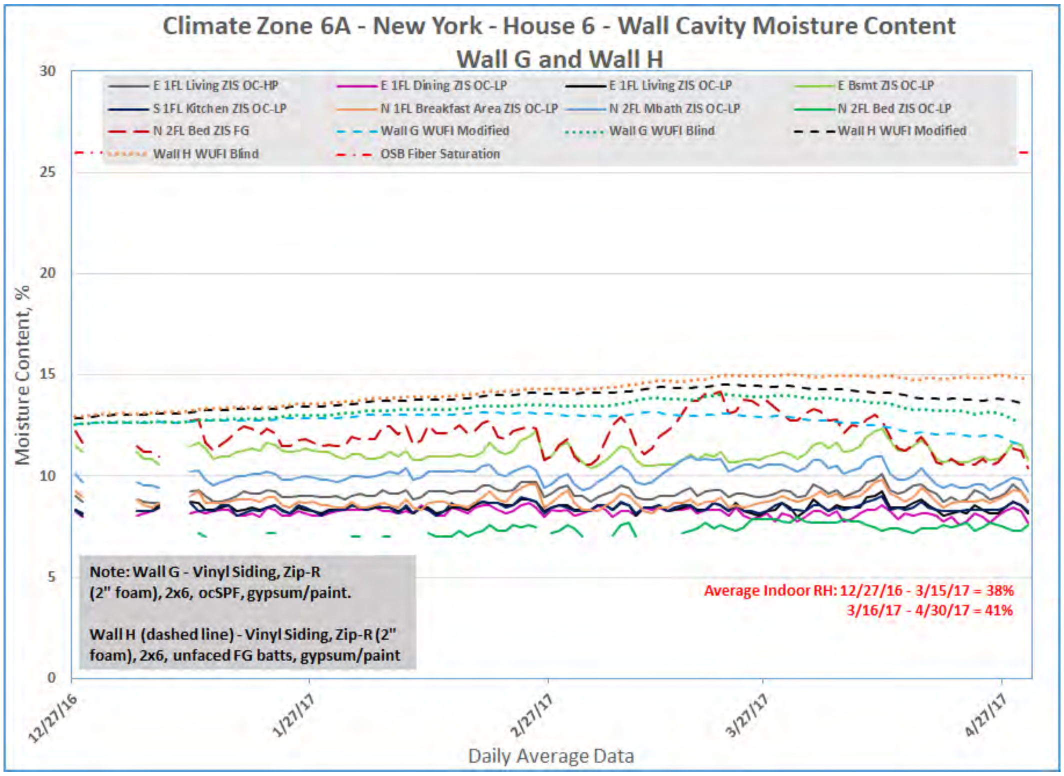


Figure 19. ZIP sheathing moisture content for Climate Zone 6A, New York (1), House 6

Figure 20 shows the summary results for the OSB and stud moisture content for House 11, located in Michigan, Climate Zone 7A. The following observations can be made:

- As a result of the construction moisture from the installation of damp cellulose, the OSB and stud moisture content remained high throughout the entire heating season. A definitive drying trend for all sensors began in March, with the OSB drying at a faster rate than the lumber. Several sensors remained at levels more than 20% at the end of April.
- The direction of drying is expected to be primarily toward the indoors. The permeability of paint is not known for this house.
- The interior RH remained low (29% on average) throughout the winter season. The ventilation system has not been reported for this house.
- WUFI simulations captured the overall trend well, and the modified predictions accurately envelope the entire range of performance throughout the monitoring period.

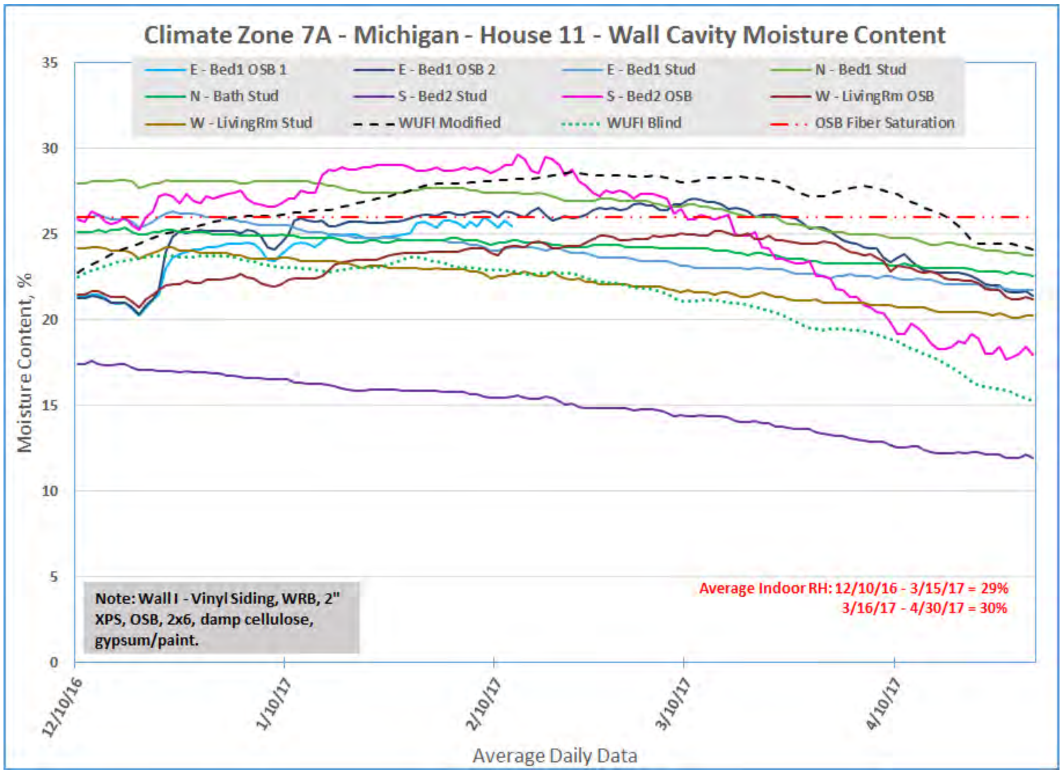


Figure 20. Oriented strand board sheathing moisture content for Climate Zone 7A, Michigan (6), House 11

Seasonal Summary of Moisture Content Data for Key Research Area 1

Figure 21 provides a summary of seasonal averages and seasonal peaks for all walls in Key Research Area 1. It shows the moisture content levels of the wood sheathing (OSB or plywood) for each wall type for the entire monitoring period, from 2016 to 2017. This condensed format allows for an overview of the performance of the wall systems discussed in this section. Data from the north-facing walls usually showed the highest moisture levels.

Except for three walls with damp cellulose cavity insulation, moisture content for all walls was 16% or less throughout the monitoring period. Additional monitoring is needed to evaluate the drying performance during the first summer and moisture levels during the second winter. At many sites, the 2016–2017 winter was milder than average. Overall, the data indicate that walls with sufficient R-value exterior to the cavity (i.e., exterior insulation) are effective at controlling moisture levels of the wood sheathing. A wall with OSB exterior to the foam insulation (ZIP system) also showed stable and low levels of OSB moisture content throughout the winter.

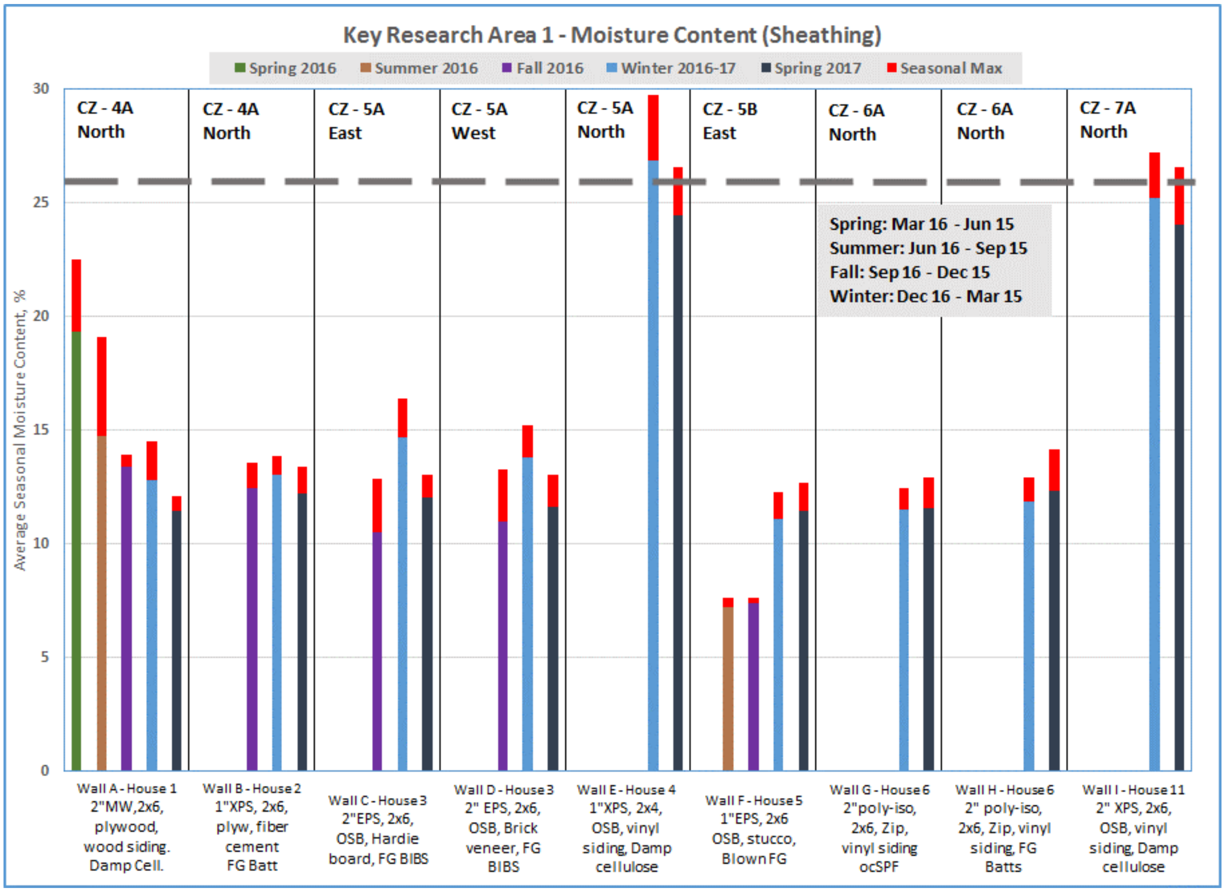


Figure 21. Key Research Area 1 summary: seasonal peak and average moisture content of wood sheathing

3.3 Key Research Area 2: Continuous Insulation, Cavity Insulation, and an Interior Vapor Retarder (Hybrid Wall)

Figure 22 shows the summary results for the OSB moisture content for House 6, located in New York, Climate Zone 6A. Note that House 6 has three different wall types: G, H, and J. Walls G and H are addressed in Key Research Area 1 (See Figure 19). Figure 22 shows walls J and H. Wall J is classified as a hybrid wall because it uses Kraft paper as an interior vapor retarder. Wall H is shown for comparative purposes: it is identical to Wall J, but it does not have Kraft paper. The following observations can be made:

- The two wall types—with and without Kraft paper—trended closely together. Both walls indicated good performance with moisture content at less than 15% for most of the monitoring period. Given that the sensors measured in wall sections at two different elevations in the building, the observed spread of measurements between the two walls types cannot be attributed to any specific wall characteristics. The more meaningful observation is that when both walls had a chance to start drying in April, the moisture content readings effectively converged around 10%. The performance of Wall J suggests that Kraft paper did not impede drying when the vapor drive reversed after the heating season was over.

- The average RH during the winter season was within the typical range, at 38%. An ERV was used to provide outdoor ventilation and was effective at controlling the RH levels in this extremely airtight house (0.52 ACH50).

- A modified WUFI simulation was overall effective at capturing the moisture content levels for Wall J.

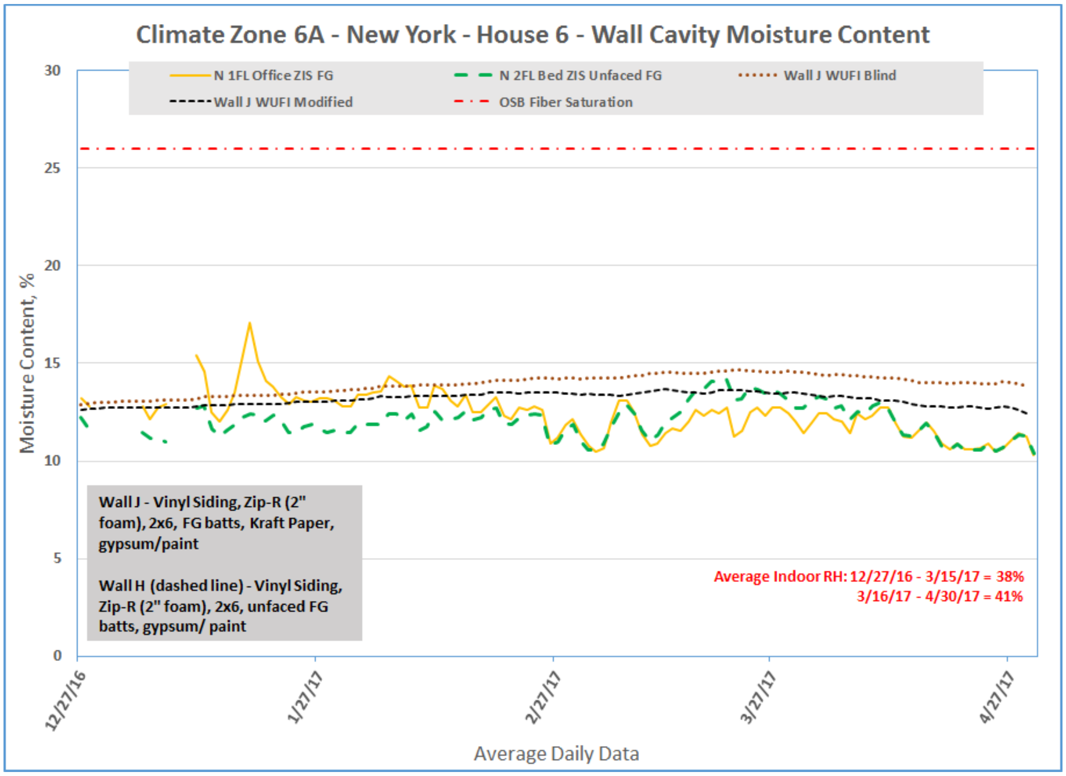


Figure 22. ZIP sheathing moisture content for Climate Zone 6A, New York (1), House 6

Figure 23 shows the summary results for the ZIP sheathing OSB moisture content for House 7, located in Pennsylvania, Climate Zone 5A. The following observations can be made:

- The moisture content of the OSB sheathing was trending slightly upward throughout the winter peaking, at about 19%, a reasonable margin from the fiber saturation point.
- Drying began around mid-March, with all sensors converging at less than 13% by the end of April, indicating good drying capacity.
- As previously discussed for House 6 with ZIP sheathing, the primary expected drying path is to the outside. A key difference between houses 6 and 7 is the cladding. Unlike vinyl siding (House 6), fiber cement siding (House 7) is not designated as vented cladding by the IRC and is expected to be less open to airflow. A drying trend was also present for House 7. It is also possible that drying to the inside was taking place because unfaced polyisocyanurate is vapor open.
- The interior humidity of the house was maintained at 40% RH for the entire monitoring period—within the expected range for this climate zone.
- As with other wall types, the south-facing wall showed the lowest moisture content throughout the monitoring period.
- The WUFI simulations showed similar trends as the measured moisture content.

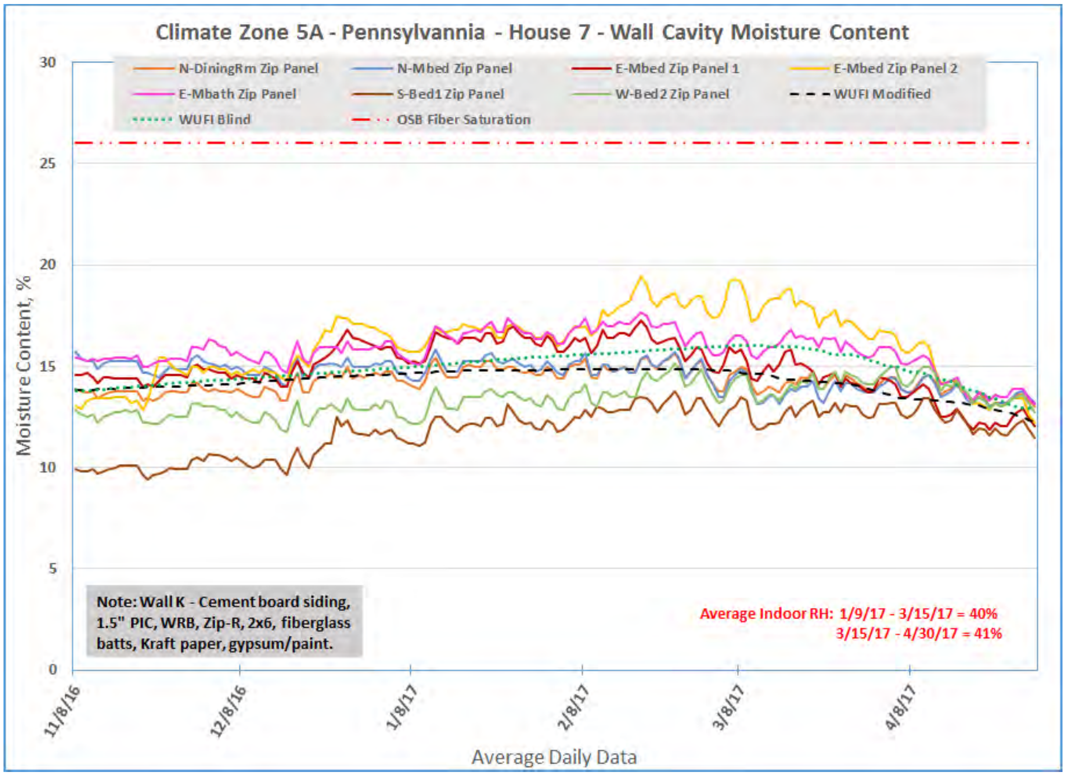


Figure 23. ZIP sheathing moisture content for Climate Zone 5A, Pennsylvania, House 7

Figure 24 and Figure 25 show the summary results for the daily OSB sheathing moisture content for House 8 and 9, respectively, located in Michigan, Climate Zone 5A. The data are reported jointly for both houses because the wall systems are the same, the houses are located in close proximity, and the observed performances were similar. Because of changes in the construction schedule, the monitoring period for House 8 and House 9 started in the middle of winter. Both houses were unoccupied for the entire monitoring period. Additional monitoring is recommended for these houses. The following observations can be made:

- The OSB moisture content levels are in the range of 8%–13% for both houses and stable for all sensors.
- The R-5 XPS exterior insulation in combination with the Kraft paper is effective at controlling interior vapor drive in the 2x6 walls in Climate Zone 5A. Note that although the house was not occupied, construction moisture typically contributes to indoor RH during the first season.
- Note that the winter temperatures at this site were somewhat mild for this location. For most of the winter, the temperatures were above 20°F, with only two short periods dropping into the 10°F range.
- The modified WUFI simulation showed good agreement with the field data throughout the entire monitoring period, confirming stable moisture performance for the system.

The initial results suggest that this wall system can be an effective and practical option for walls achieving R-24.

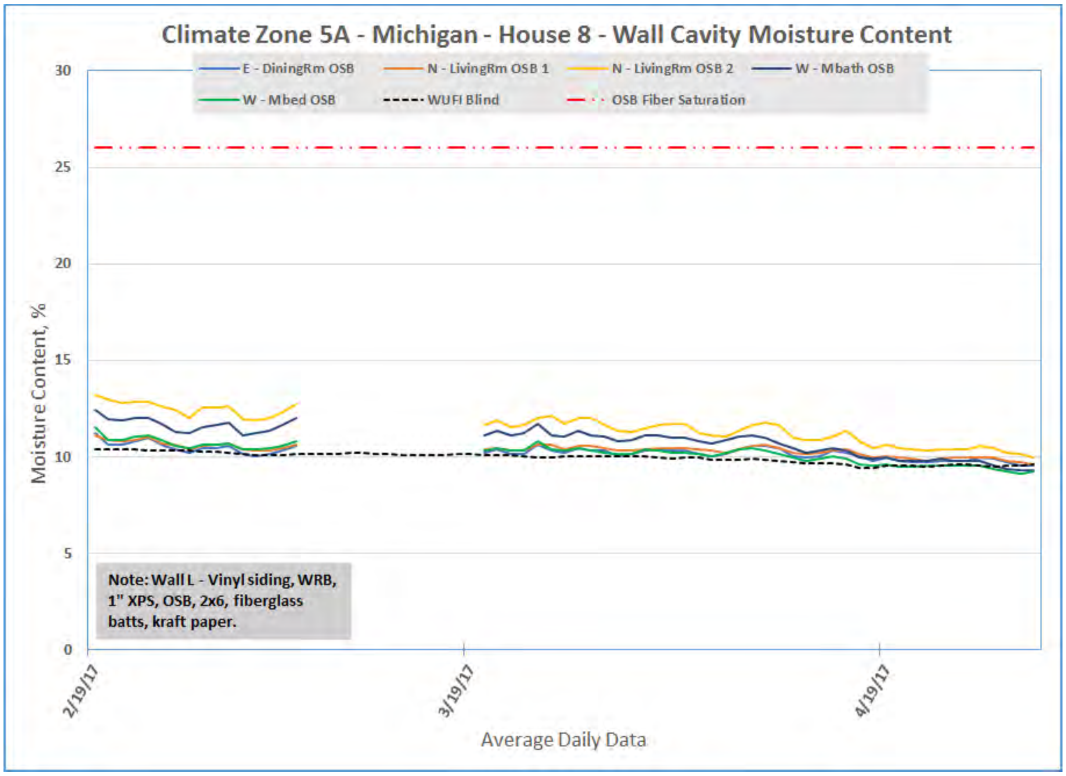


Figure 24. Oriented strand board sheathing moisture content for Climate Zone 5A, Michigan (3), House 8

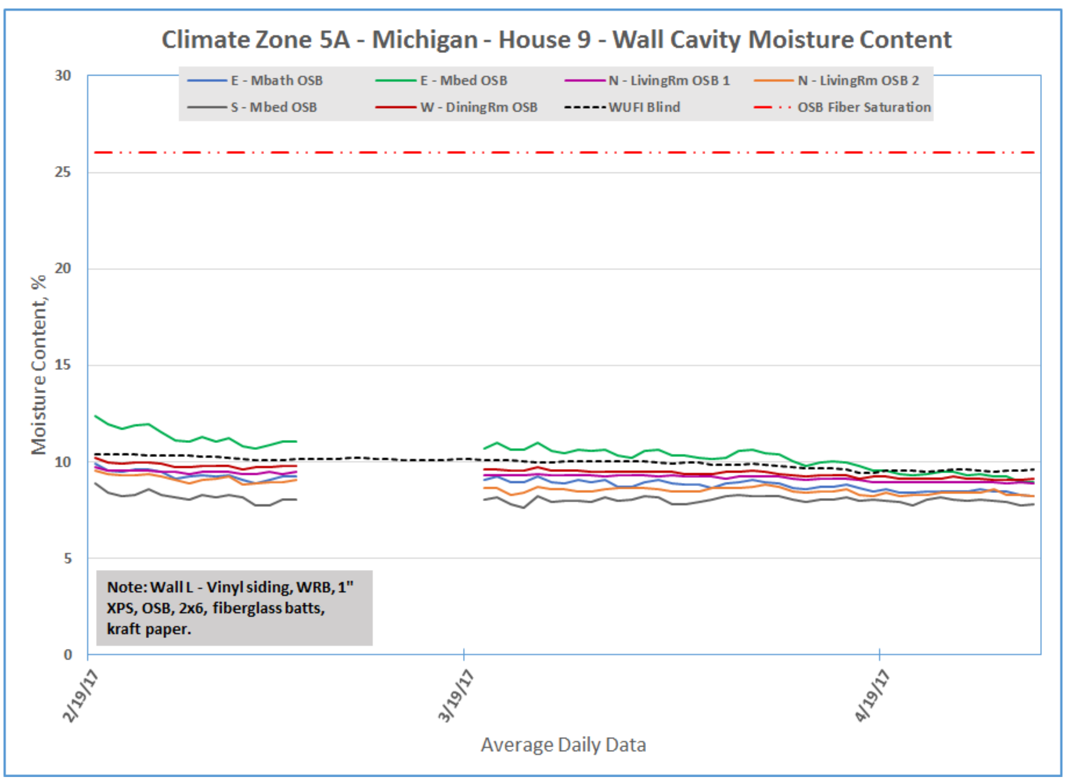


Figure 25. Oriented strand board sheathing moisture content for Climate Zone 5A, Michigan (4), House 9

Figure 26 shows the summary results for the daily OSB sheathing moisture content for House 10, located in Michigan, Climate Zone 5A. House 10 is an existing house with a newly constructed addition featuring energy-efficient walls. All sensors were installed in the addition. The house has an air leakage rate of 3.04 ACH as tested after completion of the addition—this level of air tightness meets the criteria for homes in the study. The following observations can be made:

- This wall uses 4-mil polyethylene as an interior vapor barrier and foiled-faced exterior polyisocyanurate insulation, so the assembly can be categorized as a double-vapor-barrier system. The data provide an interesting case for evaluation of the wall's performance.
- The interior RH levels remained relatively high throughout the winter, averaging 55% and peaking at 62%. The house relies on exhaust fans for ventilation. The homeowner indicated that they were running a humidifier.
- All sensors in Wall M were reading stable moisture content levels of OSB at less than 12% throughout the monitoring period. Throughout the winter and through April, the moisture content levels did not show any seasonal trend even as the interior RH remained consistently high.
- WUFI simulations accurately predicted moisture levels in Wall M throughout the monitoring period.
- A section of the wall constructed without polyethylene (Figure 27, Wall M1) showed a dramatically different performance, with moisture content levels about 10 points higher compared to wall sections with polyethylene. These results suggest that even walls with an exterior insulation R-value exceeding the code minimum (R-6.5 installed vs. R-5 minimum) can be sensitive to high levels of indoor RH; however, note that even without the polyethylene, the OSB moisture content had not reached the fiber saturation point. Wall M1 showed onset of drying beginning of April.
- For Wall M, both blind and modified WUFI simulations slightly underestimated the moisture content levels while closely replicating the flat, stable trend throughout the entire monitoring period.
- For Wall M1 (without polyethylene), the WUFI simulation was highly sensitive to the inputs. The blind model indicated a "runaway" prediction, with the moisture content levels exceeding the fiber saturation point. The modified model showed a reasonable agreement with the field measurements. These observations have a twofold implication: (1) the wall assembly is very sensitive to conditions such as RH and T and material selection; and (2) WUFI simulations for these types of wall systems should include sensitivity studies to capture the range of performance, and they should be used to identify key wall variables that can make the wall performance less sensitive to boundary conditions.

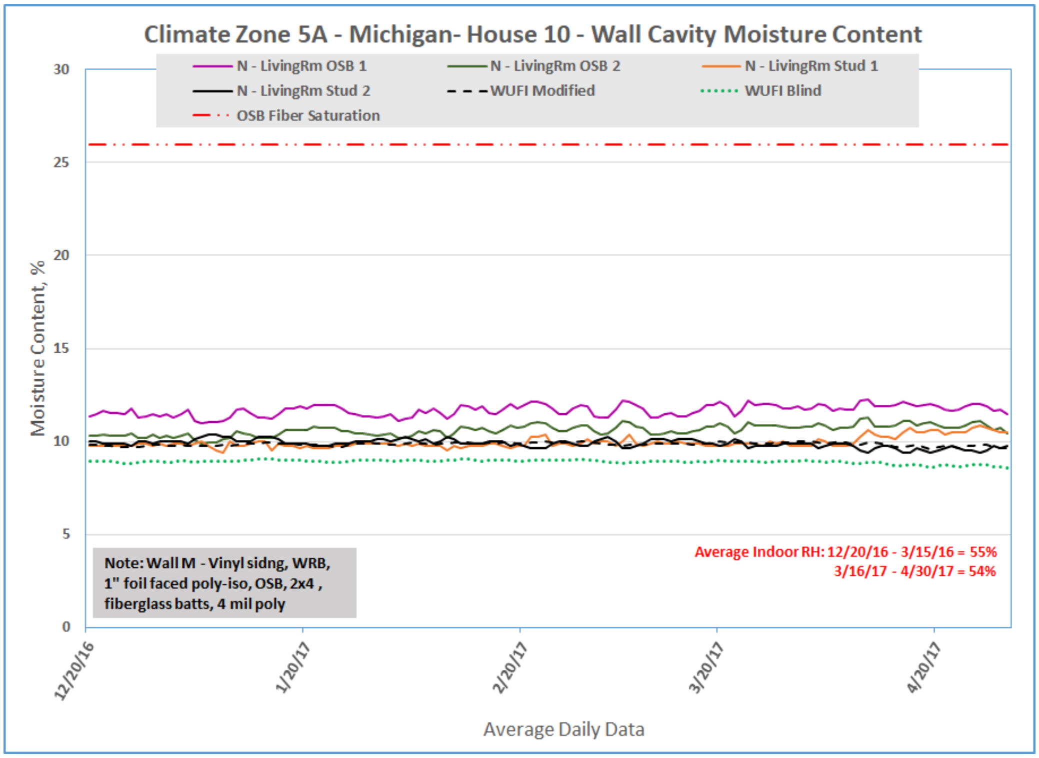


Figure 26. Oriented strand board sheathing and stud moisture content for Climate Zone 5A, Michigan (5), House 10 (Wall M)

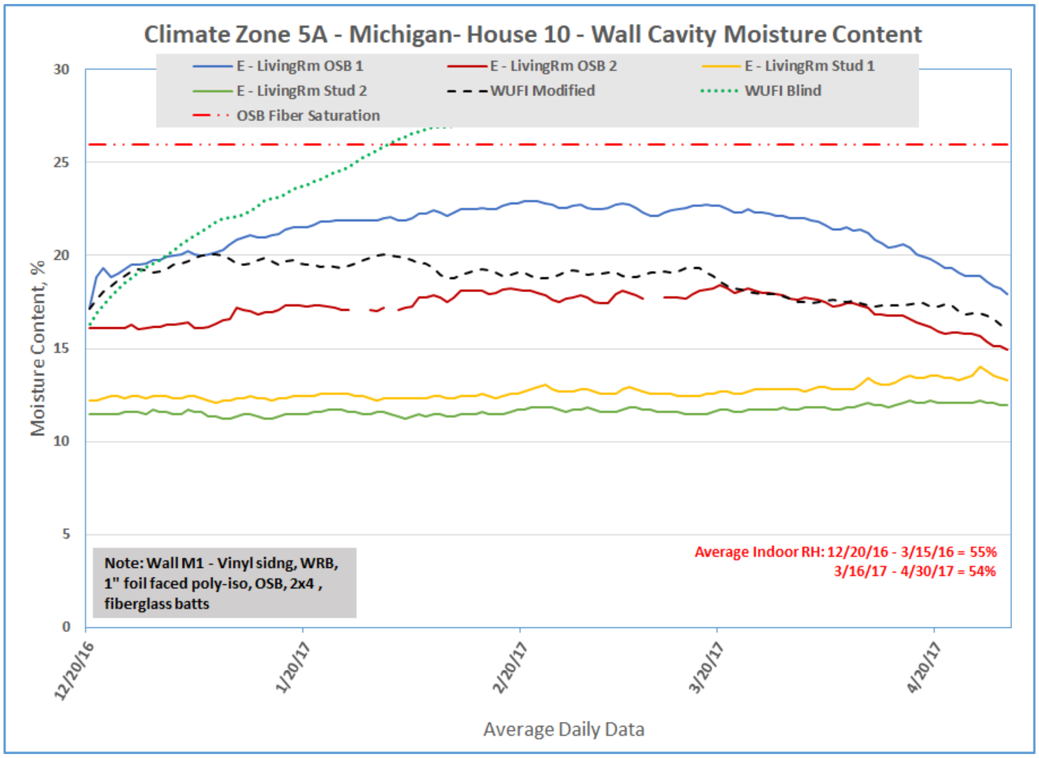


Figure 27. Oriented strand board sheathing and stud moisture content for Climate Zone 5A, Michigan (5), House 10 (Wall M1)

Figure 28 shows the summary results for the daily OSB sheathing and stud moisture content for Wall N in House 11 in Michigan, Climate Zone 7A. The wall featured a smart (i.e., variable) interior vapor retarder. The following observations can be made:

- As a result of damp-sprayed cellulose in the cavity, this hybrid wall had high initial moisture content of the OSB sheathing with several sensors at the fiber saturation point.
- The OSB moisture content remained high for a prolonged period, with two of the four sensors not showing an onset of drying as of the end of April.
- Comparing the data with Wall I (also House 11) that did not have the interior smart vapor retarder, both wall types showed similar high levels of moisture content throughout the winter and a slow drying trend even as the interior RH levels were relatively low throughout the winter and spring averaged around 30%. Continued monitoring is needed to better understand the performance of these wall assemblies.

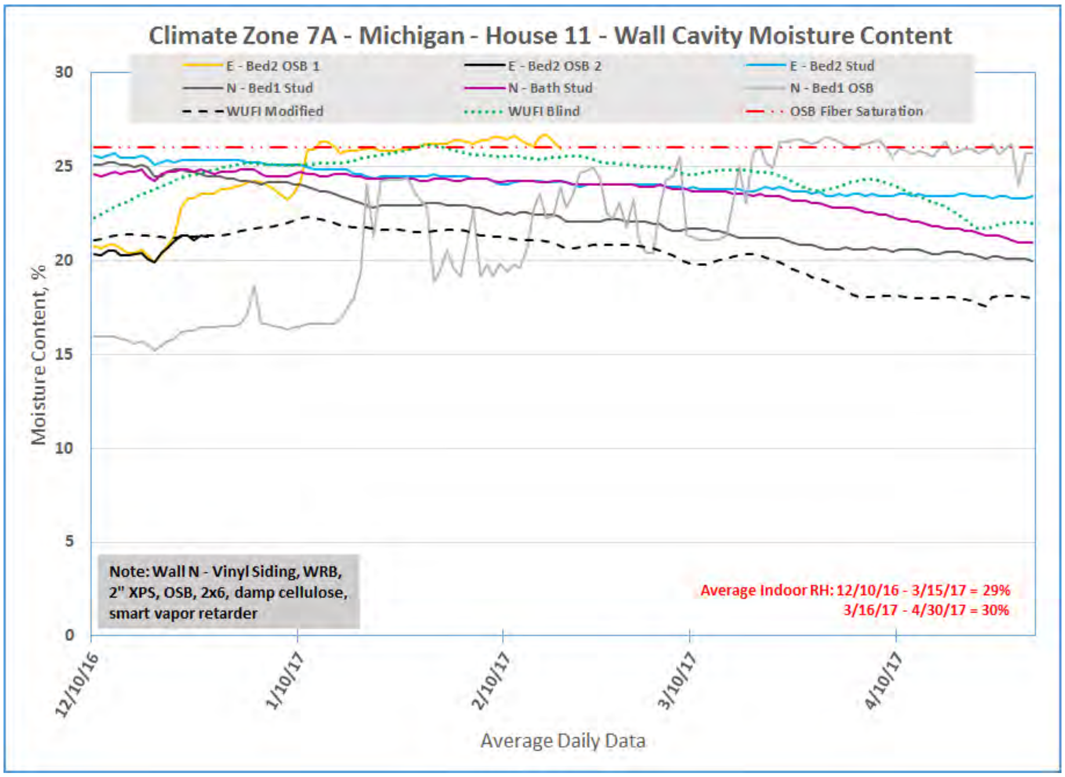


Figure 28. Oriented strand board sheathing and stud moisture content for Climate Zone 5A, Michigan (6), House 11

Seasonal Summary of Moisture Content Data for Key Research Area 2

Figure 29 provides a summary of seasonal averages and seasonal peaks for all walls in Key Research Area 2. It shows the moisture content levels of the wood sheathing (OSB or plywood) for each wall type for the entire monitoring period, from 2016 to 2017. This condensed format allows for an overview of the performance of the wall systems discussed previously in this section. Data from north- and east-facing walls usually showed the highest moisture levels.

Overall, walls with exterior insulation and an interior vapor retarder appear as a viable option for climate zones 4 and higher. Continued monitoring is recommended for all these walls. Based on the initial data set, the following generalization can be made:

- The walls with ZIP-R sheathing (Wall J and K) were consistently less than 20% moisture content, and there was a definitive drying trend toward the end of the monitoring period (beginning of spring).

- The 2x6 walls with a combination of R-5 XPS and Kraft-faced fiberglass batts (Wall L) showed stable low moisture content levels in Climate Zone 5A. This is a streamlined method for achieving R-24 walls with minimum changes to construction practices.

- A wall with a double vapor retarder (Wall M) also showed stable low moisture content levels. These types of walls are less forgiving to exterior moisture leaks. Therefore, design and construction of the exterior water control layers (cladding, WRB, flashing, etc.) and air barriers should take into consideration reduced capacity of the wall system for rapid moisture dissipation. A WUFI simulation of a water leak in this assembly showed very slow drying, with moisture persisting during a course of months.

- The presence of Kraft paper does not seem to alter the walls' ability to dry, suggesting that walls that rely on a combination of temperature control and vapor drive control strategies may be viable practical solutions for construction of energy-efficient walls.

- The effectiveness of a smart vapor retarder to manage the moisture load added by damp-sprayed cellulose needs further monitoring.

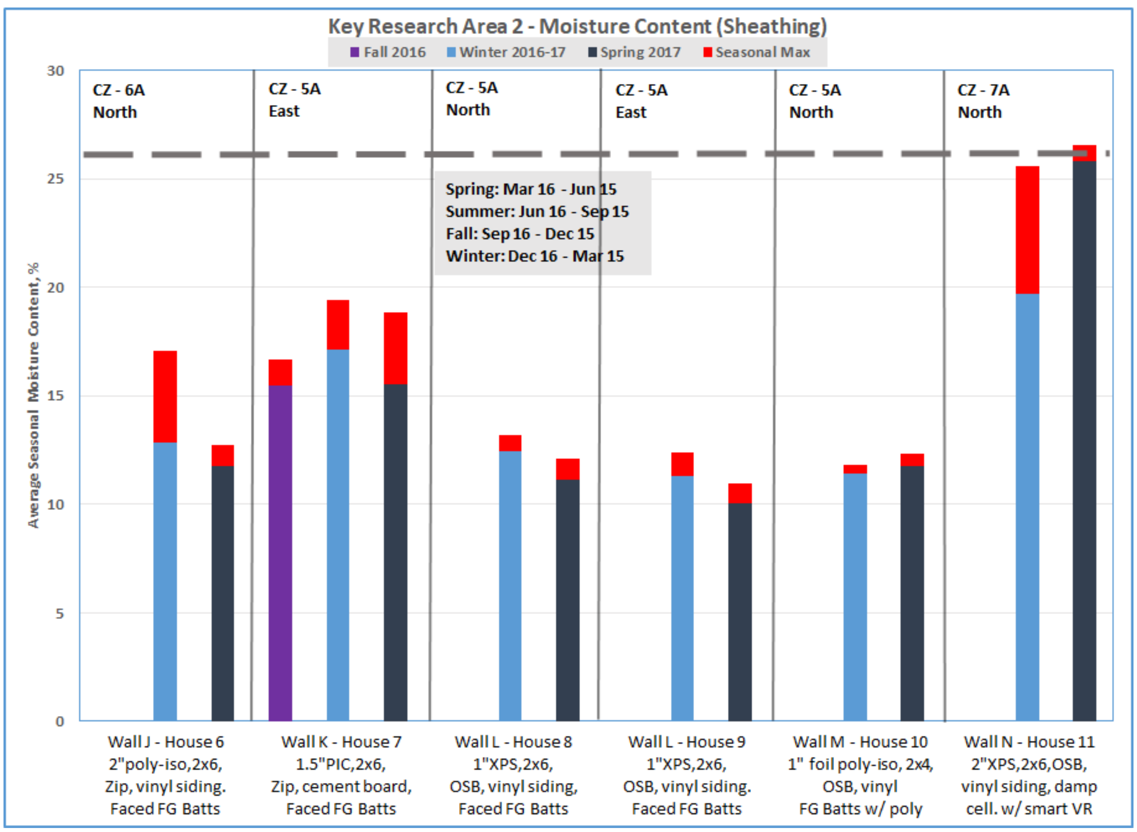


Figure 29. Key Research Area 2 summary: seasonal peak and averages moisture content of wood sheathing

3.4 Key Research Area 3: Cavity-Only Insulation

Figure 30 shows the summary results for the daily OSB sheathing moisture content for House 12, located in Indiana, Climate Zone 4A. The following observations can be made:

- Polyethylene vapor retarder (Class I) is very effective at controlling interior vapor drive. The OSB moisture content remained stable and low (less than 10%) throughout the monitoring period. This observation is consistent with other studies and other houses in this study. (Note that walls with reservoir claddings are subject to solar drive; during the summer, this adds to moisture loads in walls with Class I vapor retarders.)
- The primary drying path for this wall system is expected to be to the outside.
- Performance of this wall assembly during a cooling season should be monitored to evaluate the potential for moisture buildup in the cavity because of cooler indoor temperatures.
- WUFI simulations were effective at capturing these types of systems.

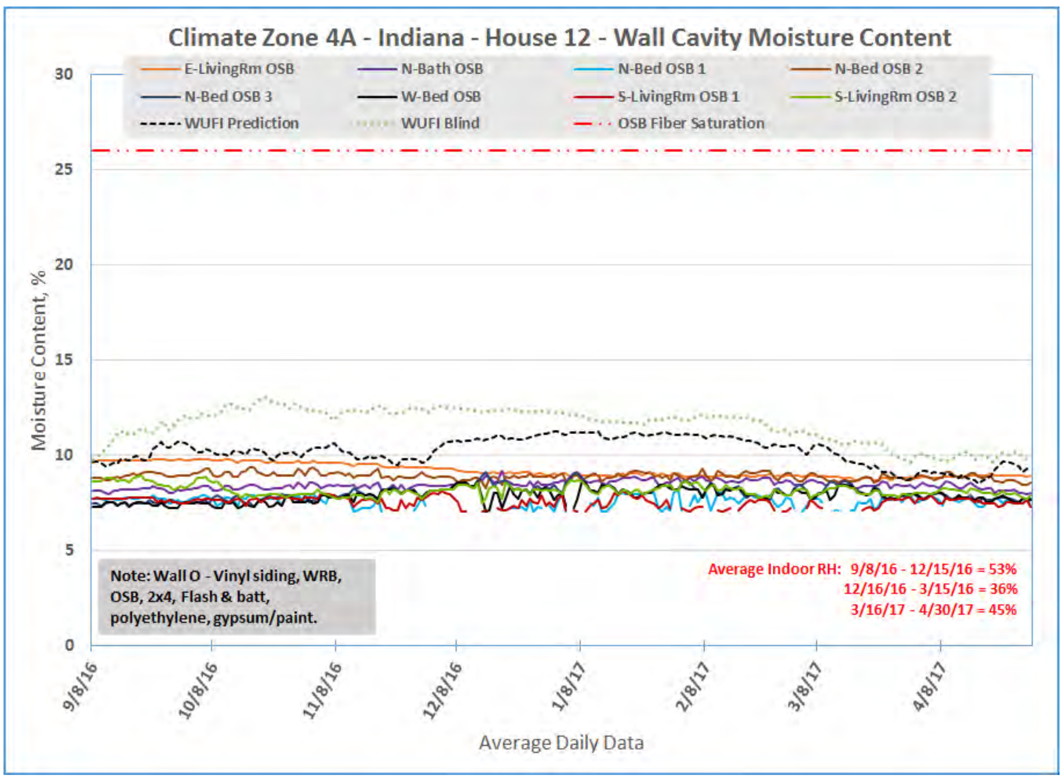


Figure 30. Oriented strand board sheathing moisture content for Climate Zone 4A, Indiana, House 12

Figure 31 shows the summary results for the OSB sheathing daily moisture content for House 13, located in Washington, Climate Zone 4C. Note that because a non-vented cladding was used, the IRC requires a Class I or Class II vapor retarder (was not used in this house) in Climate Zone 4C. The following observations can be made:

- As is typical for walls without an interior vapor retarder and/or exterior insulation, there was a noticeable trend for moisture increase during the heating season. OSB moisture content levels were elevated as much as 21%. These moisture content levels are 5% or more less than the fiber saturation point and can be considered within acceptable performance range.

- The drying for this wall assembly was expected to occur to the inside and to the outside, although the fiber cement siding will slow down drying to the outside.
- Three sensors indicated a spring drying trend.
- The interior RH levels during the winter season were 40% on average. This was somewhat less than the results of the previous monitoring study, which showed RH levels exceeding 60%.
- The WUFI simulations showed good agreement with the field measurements.
- A WUFI sensitivity study simulating a 10-point interior RH level increase to an average of 50% showed an increase in OSB moisture levels to 26%, suggesting that the interior RH levels should be controlled for homes with wall assemblies without an interior vapor retarder.
- If a wall system with reduced seasonal fluctuations was desired, the use of a Class II interior vapor retarder (e.g., Kraft paper, membranes) should be considered. Installing cladding in a vented manner can provide another mechanism for moisture dissipation to the outdoors.

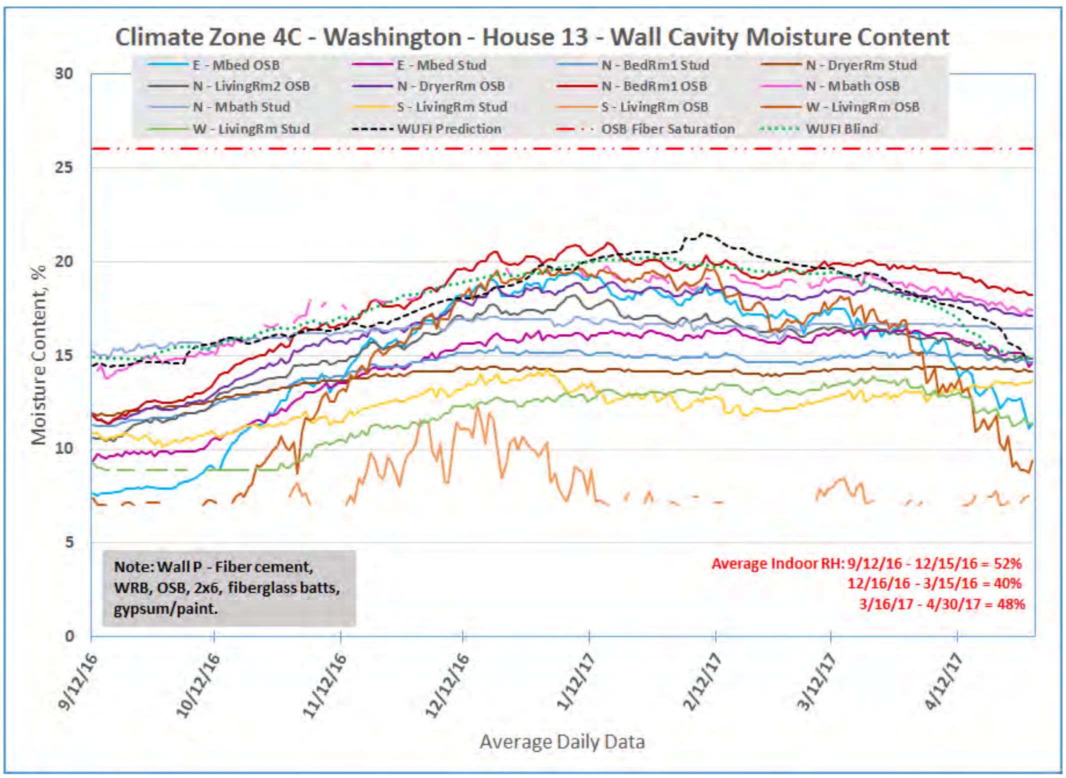


Figure 31. Oriented strand board sheathing and stud moisture content for Climate Zone 4C, Washington, House 13

Figure 32 shows the summary results for the OSB sheathing and stud daily moisture content for House 14, located in Michigan, Climate Zone 5A. Note that the monitoring did not begin until the end of January. The following observations can be made:

- Drying of OSB was observed from the beginning of the monitoring period, with the moisture content levels stabilizing less than 15% by the end of April.

- The results demonstrate the wall's ability to dry out throughout the winter and spring season, with drying likely occurring in both directions. The wall design features vinyl siding over 14 perm WRB on the exterior and a Class III vapor retarder (6 perm dry-cup paint) on the interior.
- The indoor RH levels (25% winter average) were lower than typically expected for this climate zone, contributing to the consistent drying trend indicated by the data. The winter was also relatively mild for this location, with the coldest temperatures at 19.5°F. Therefore, additional monitoring is recommended to capture more severe conditions.
- The modified WUFI simulation showed good agreement with the field results in terms of capturing the trends and the magnitudes. The blind simulation using a generic (and more severe) set of conditions suggested a much slower rate of drying.

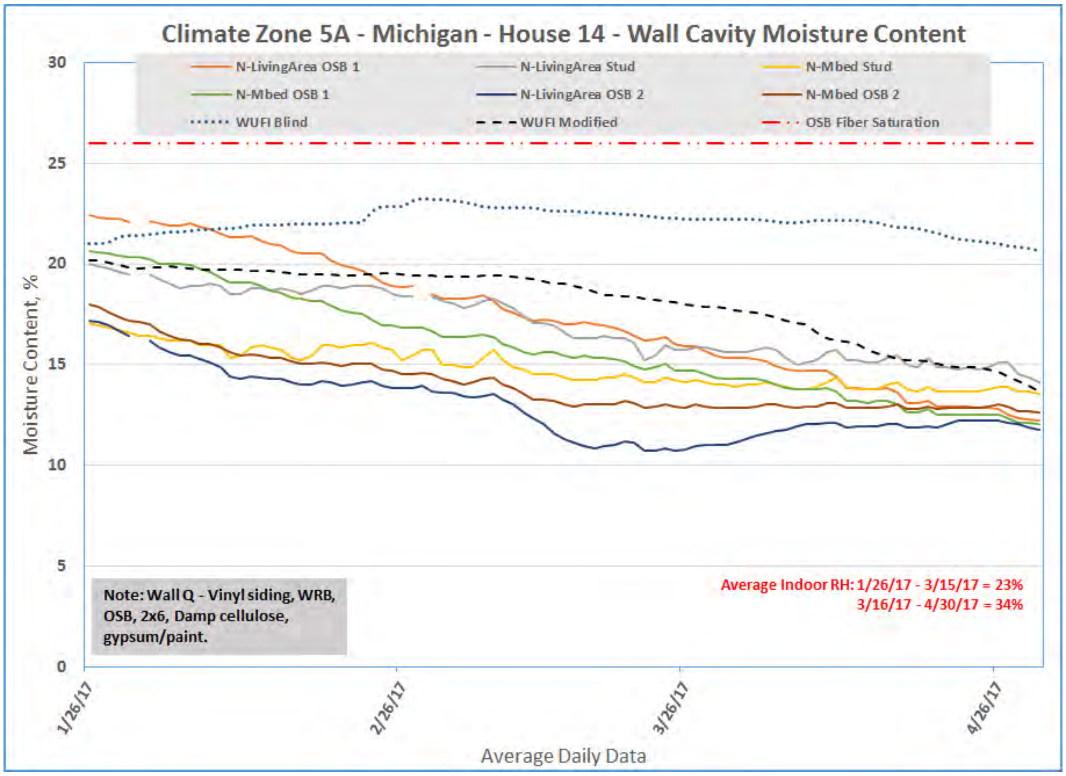


Figure 32. Oriented strand board sheathing and stud moisture content for Climate Zone 5A, Michigan (7), House 14

Figure 33 shows the summary results for the plywood daily moisture content for House 15, located in Illinois, Climate Zone 5A. The following observations can be made:

- Two of the four sensors stopped reading during the winter. Only two sensors continued to reliably provide data on OSB moisture content throughout the monitoring period. One of the sensors was installed in part of the walls with fiber cement panel cladding (panel cladding rather than lap siding was used). The other sensor was installed in a section of the wall with vinyl siding. Because Wall R is a deep-cavity wall with damp cellulose insulation, initial high moisture content levels were expected.
- The OSB initial moisture content varied between 10%–20%. The two sensors (yellow and orange lines) indicate two diverging trends. The living room sensor (fiber cement panel cladding) started at a higher moisture content, of about 20%, which began to rise at the onset of the heating season, exceeding fiber

saturation levels. The bedroom sensor (vinyl siding) started at a low moisture content (10%) and remained relatively stable, with a small (~4%) increase in the middle of winter.

- This observation suggests a definitive difference in performance based on the type of cladding. (Although north-versus-east orientation possibly played a role in the observed difference in performance, the east orientation did not experience the level of sun exposure to explain the observed difference.) The fiber cement panel cladding limited drying to the outside. Because it is a panel-type product—rather than lap siding—there was no air exchange on the outside surface of the OSB or the WRB. Even during the summer months, the drying was slow, and moisture was remaining inside the wall cavity at the onset of the heating season. With the vapor drive direction during the heating to the outside, any drying to the inside was impeded until the vapor drive was reduced or reversed (springtime).

- For this specific wall assembly in this climate zone, having a cladding that effectively blocks outward drying appears to be problematic for the following reasons:

    - It did not allow the construction moisture in the wall cavity to dry out sufficiently fast even during the drying season.

    - The absence of the interior vapor retarder exacerbated the problem during the winter when the wall continued to absorb water vapor from the inside the house, yet the wall had no ability to release the accumulated moisture

- The drying for this wall was expected to occur primarily to the inside. Given that the wall is 8-in. nominal thickness, drying of cavity moisture to the interior was expected to take time. Drying to the inside during the heating season was also counteracted by interior vapor drive that pushed the indoor moisture inside the wall cavity.

- The two diverging trends observed in this house suggest that the initial moisture content before the walls are enclosed may be more critical for deeper assemblies, particularly if the cladding or the interior finish are not vapor open.

- Another factor that contributed to the observed rise of moisture content during the heating season was low winter temperatures at this site (as low as 1°F).

- Consistent with field data, WUFI simulations for this wall assembly appeared very sensitive to the boundary conditions and initial moisture content levels. The two WUFI simulations diverged throughout the heating season, similar to the trends observed in the field.

- Continued monitoring is recommended for this wall assembly to better understand the underlying dynamics of the moisture performance.

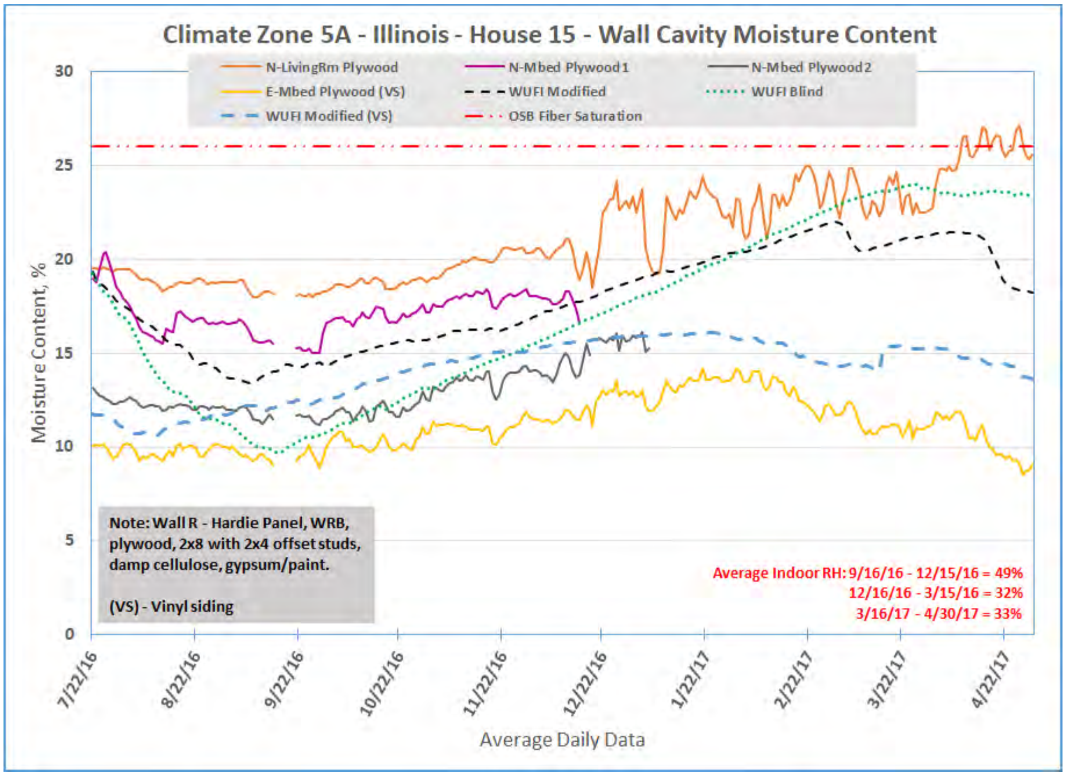


Figure 33. Plywood and stud moisture content for Climate Zone 5A, Illinois (1), House 15

Figure 34 shows the summary results for the ZIP sheathing daily moisture content for House 16, located in Illinois, Climate Zone 5A. The following observations can be made:

- The initial high moisture content levels were consistent with the installation of damp-sprayed cellulose. The moisture dried during the late spring and early summer. With the beginning of the heating season, the moisture started to rise, reaching 21%–22% in several locations. This moisture content level was 4%–5% or more less than the fiber saturation point and can be considered within acceptable performance range; however, note that large seasonal fluctuations are not the preferred response pattern.
- With fiber cement panel cladding, the primary drying path for this wall assembly was expected to be to the inside.
- The interior RH levels during the winter season were 42% on average. This is within the range observed in this and other monitoring studies for this climate zone.
- The modified WUFI simulation showed good agreement with the field measurements. A WUFI simulation with generic inputs (blind simulation) showed good initial agreement with the field data, but the model began to significantly diverge from the monitoring results during the heating season. The primary difference between the blind and modified simulations included the warmer winter temperatures and less permeable interior paint. This observation supports the notion that walls without an interior vapor retarder are more sensitive to boundary conditions. In addition, the modeling indicates that the wall may cross into a range approaching or reaching the fiber saturation point during a colder winter and/or if a more permeable interior paint were used (4.6 perm dry cup was used in House 16).
- If a wall system with reduced seasonal fluctuations is desired, use of Class II interior vapor retarders or the addition of exterior insulation should be considered.

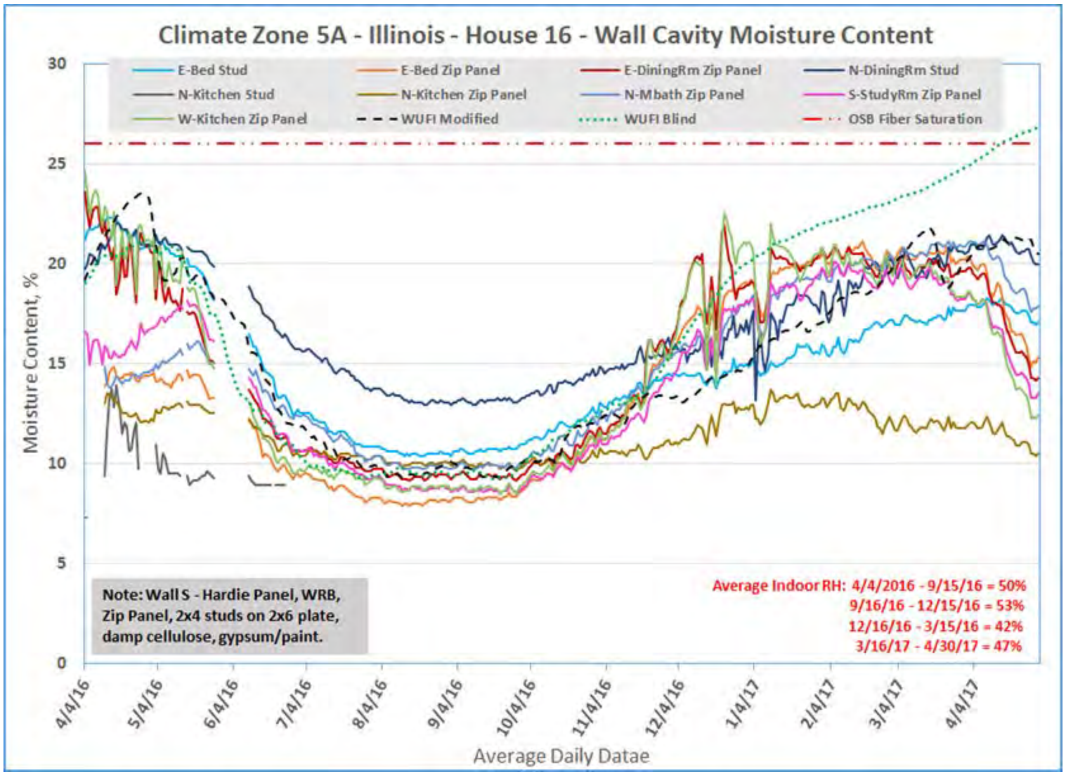


Figure 34. ZIP sheathing and stud moisture content for Climate Zone 5A, Illinois (2), House 16

Figure 35 shows the summary results for the OSB sheathing and stud daily moisture content for House 17, located in Michigan, Climate Zone 5A. The following observations can be made:

- The OSB moisture content indicated a seasonal trend, with a winter rise as high as 22%. Similar to House 16, this moisture content was a few points less than the fiber saturation point and can be considered within acceptable performance range. Note, again, that large seasonal fluctuations are not the preferred response pattern.
- This moisture content level indicated marginal performance.
- The interior RH levels during the winter season were 42% on average. This is within the range observed in this and other monitoring studies for this climate zone.
- WUFI simulations showed a limited ability to predict the observed performance for this wall system. The researchers could not identify a clear trend between the field data and the simulation results, suggesting that the wall performance depends on factors not explicitly captured by the simulation. It is likely that air leakage from the inside the house into the wall cavity is the variable that contributed to the observed behavior and resulting in the difference between the model and the several sensors that were trending higher than the predictions. A drywall air sealing solution can be recommended for this wall to complement the vapor retarder. A follow-up with the builder for this house confirmed that the air barrier was provided only at the wall's exterior, and no added measures were implemented to seal at the drywall.
- A definitive drying trend was observed in April, with moisture content rapidly dropping to levels at or near 15%. The drying path for this wall can occur to the inside and to the outside.

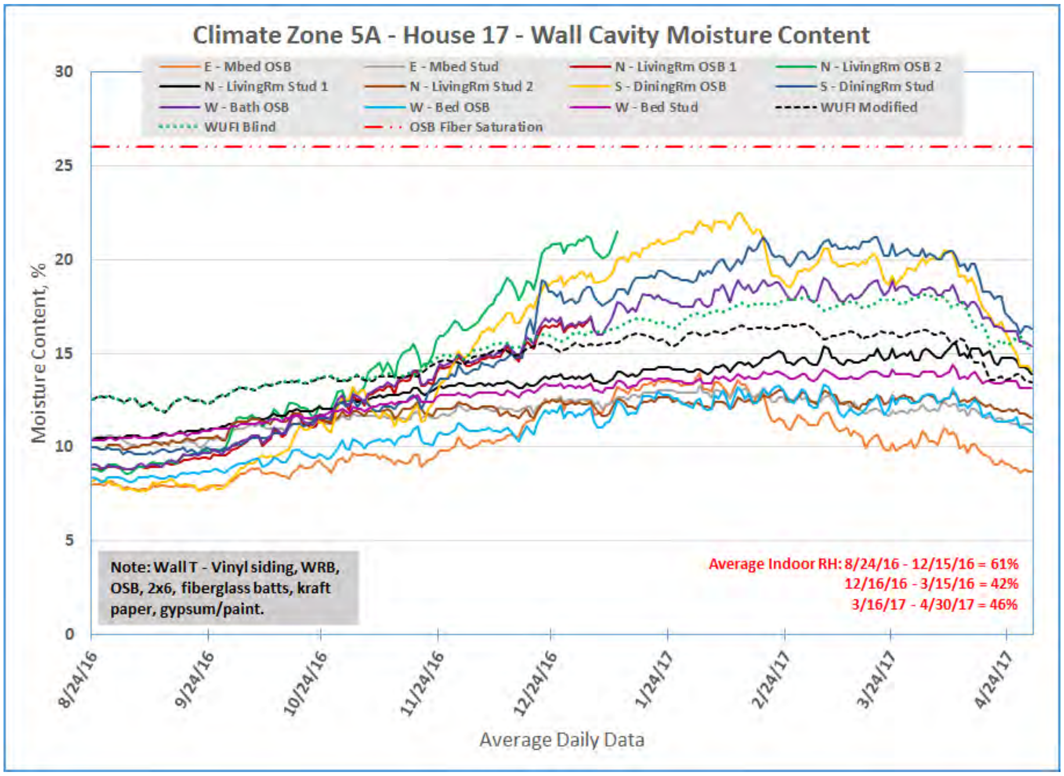


Figure 35. Oriented strand board sheathing and stud moisture content for Climate Zone 5A, Michigan (8), House 17

Figure 36 shows the summary results for the OSB sheathing and stud daily moisture content for House 18, located in Michigan, Climate Zone 5A. The following observations can be made:

- House 18 is similar to House 17 in construction and performance. The observations made for House 17 apply to House 18. The difference is that the monitoring period for House 18 began two and one-half months after House 17.

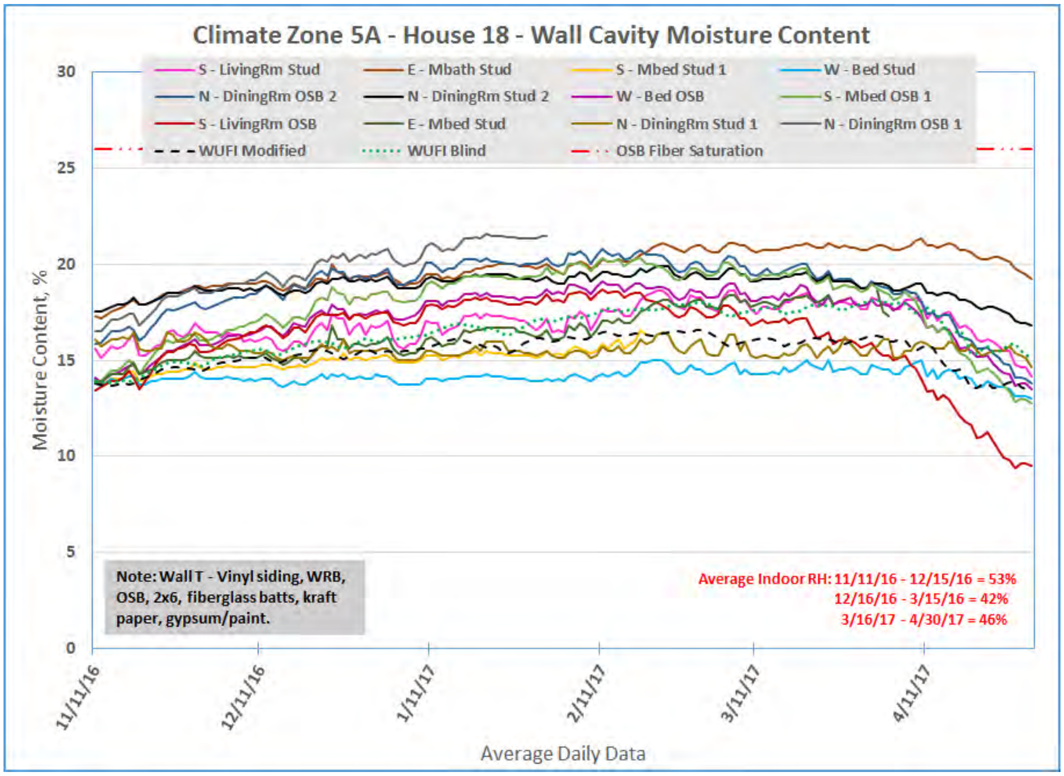


Figure 36. Oriented strand board sheathing and stud moisture content for Climate Zone 5A, Michigan (9), House 18

Figure 37 shows the summary results for the OSB sheathing and stud daily moisture content for House 19, located in New York, Climate Zone 5A. The following observations can be made:

- As with other walls with polyethene vapor retarder, the moisture content was low and stable throughout the entire monitoring period for wall sensors. Therefore, the polyethylene membrane appeared effective at controlling both vapor and air movement.
- The interior RH levels during the winter season were 42% on average. This is at the low range of the spectrum but within the range observed in this and other monitoring studies for this climate zone.
- The WUFI simulation slightly overpredicted the moisture content levels while showing the same stable trend overall. The difference is likely the result of the initial moisture content set for WUFI simulations based on the sensor with the highest moisture level.
- The drying path for this wall for any incidental moisture was to the outside. The house wrap used for this house was rated at 8 perms. Although a more vapor-open house wrap may be recommended for this wall to increase its drying capacity, the observed performance did not indicate a need for a change based on the current conditions. Note that if a reservoir cladding is used, a low-perm house wrap helped control solar vapor drive.

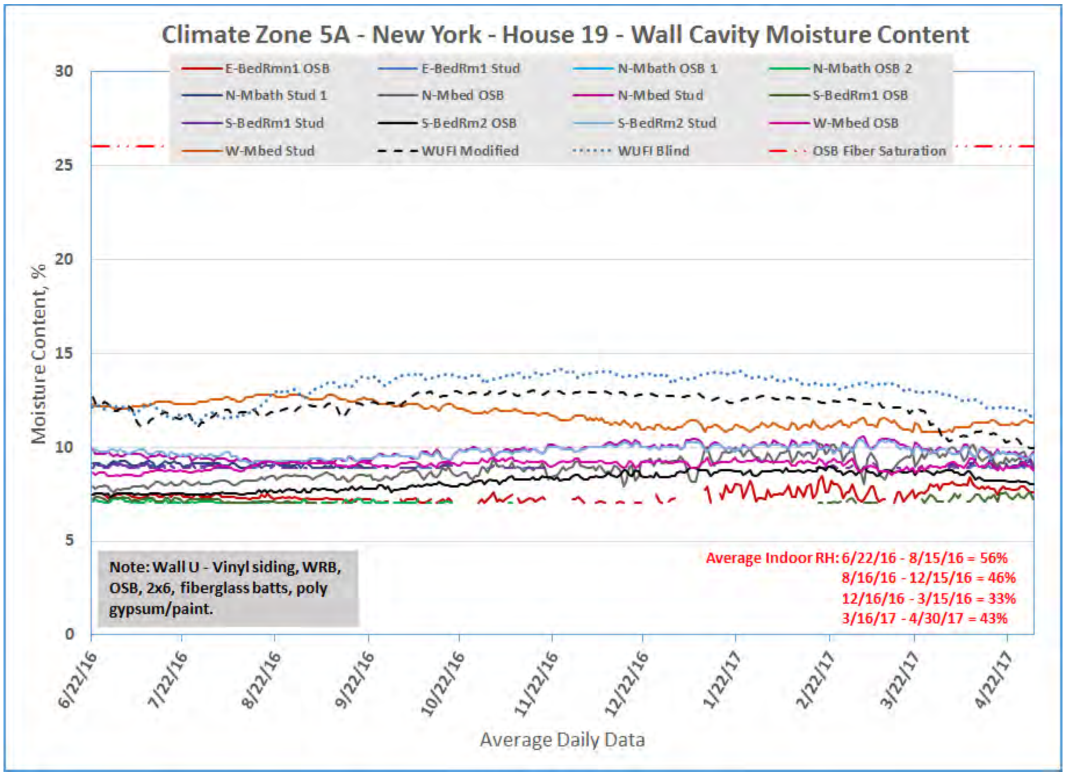


Figure 37. Oriented strand board sheathing and stud moisture content for Climate Zone 5A, New York (2), House 19

Figure 38 shows the summary results for the OSB sheathing and stud daily moisture content for House 20, located in New York, Climate Zone 5A. The following observations can be made:

- There was a distinct difference between the performance of the studs and OSB sheathing in this wall assembly. The stud moisture content was low and stable throughout the entire monitoring period, whereas OSB underwent a significant winter moisture content increase.
- The stud sensors were installed inside the cavity inboard of the spray foam insulation. Temperature inside the cavity remained above 40°F (about 20° higher than at the interior OSB surface), and RH levels remained within 70%. The RH at the inside surface of the OSB approached 100% for an extended period during the winter, which is consistent with the moisture content readings.
- The initial design information provided for the site indicated that closed-cell spray foam was specified for the walls in the house. Based on the observed performance, it is highly likely that open-cell product was installed.
- The interior RH levels during the winter season were 38% on average. This is within the range observed in this and other monitoring studies for this climate zone.
- The blind WUFI predictions were based on closed-cell spray foam in the cavity. These simulations closely followed the performance inside the cavity and diverged from the measurements of the OSB moisture content. For the modified WUFI simulations, open-cell spray foam was modeled instead. The predicted performance based on the modified simulation followed the field measurements more closely. The observed difference between the model and the field data are likely a result of the difference in the temperature conditions between the WUFI input files and the actual weather conditions at the site.

- The interior paint was at 16 perm (dry-cup)—above the upper limit for a Class III vapor retarder. The house wrap is also highly permeable (54 perm). This wall is effectively a vapor-open wall with the ability to dry toward indoors and outdoors. As a result, the OSB dried out quickly as the outdoor temperatures began to rise in March.

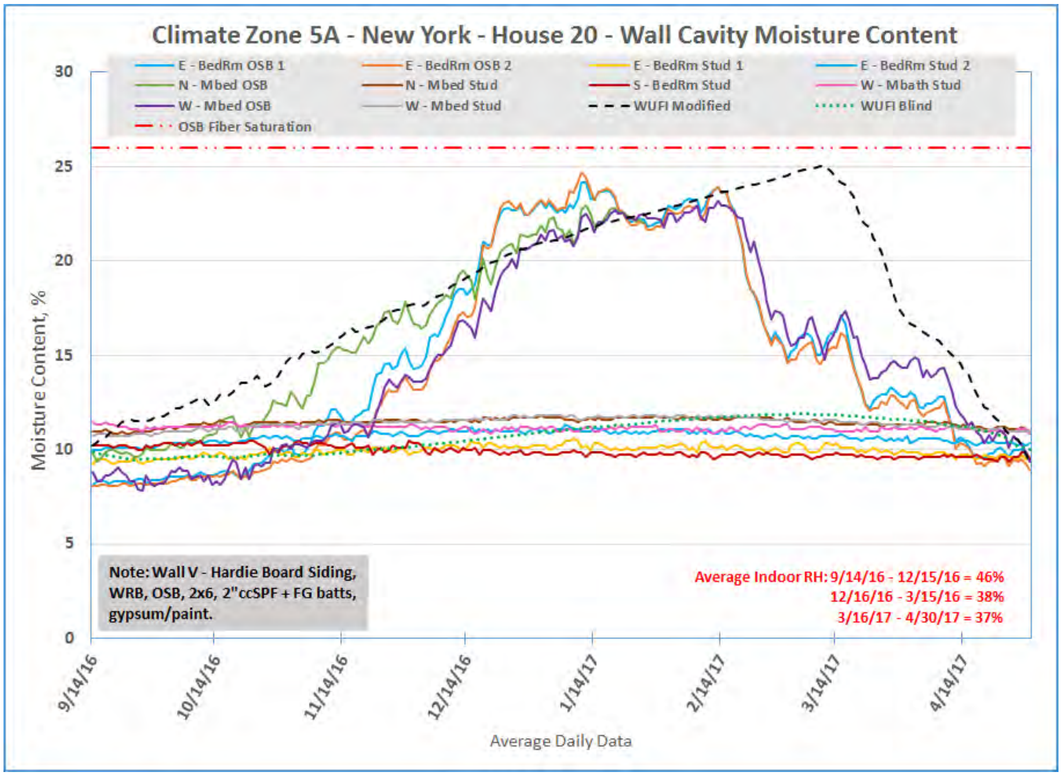


Figure 38. Oriented strand board sheathing and stud moisture content for Climate Zone 5A, New York (3), House 20

Figure 39 shows the summary results for the OSB sheathing and stud daily moisture content for House 21, located in Wisconsin, Climate Zone 6A. The following observations can be made:

- Wall W is a unique system that effectively consists of two walls—an exterior 2x6 wall and an interior 2x4 wall—separated by a sheet of a smart vapor retarder. Both walls are insulated with fiberglass batts.
- The field results were somewhat variable, and no clear trends can be distinguished; however, all sensors were at or less than the 20% limit, indicating an overall acceptable performance.
- The initial moisture levels ranged between 10%–17%, and the overall trends were relatively flat throughout the monitoring period, with a modest rise during the winter for a few sensors. A slow drying trend was also observed for a few sensors in the spring. Additional monitoring is needed to better characterize this wall's performance after all materials had an opportunity to fully equalize to house's conditions. The observed performance is likely associated with the use of the smart vapor retarder that allows some interior vapor drive and inhibits drying to the interior.
- WUFI simulations were consistent with the observed trends; however, there were significantly underpredicted moisture content levels compared to data from most sensors.

- The interior RH levels during the winter season were 35% on average. This is within the expected range for this climate zone.

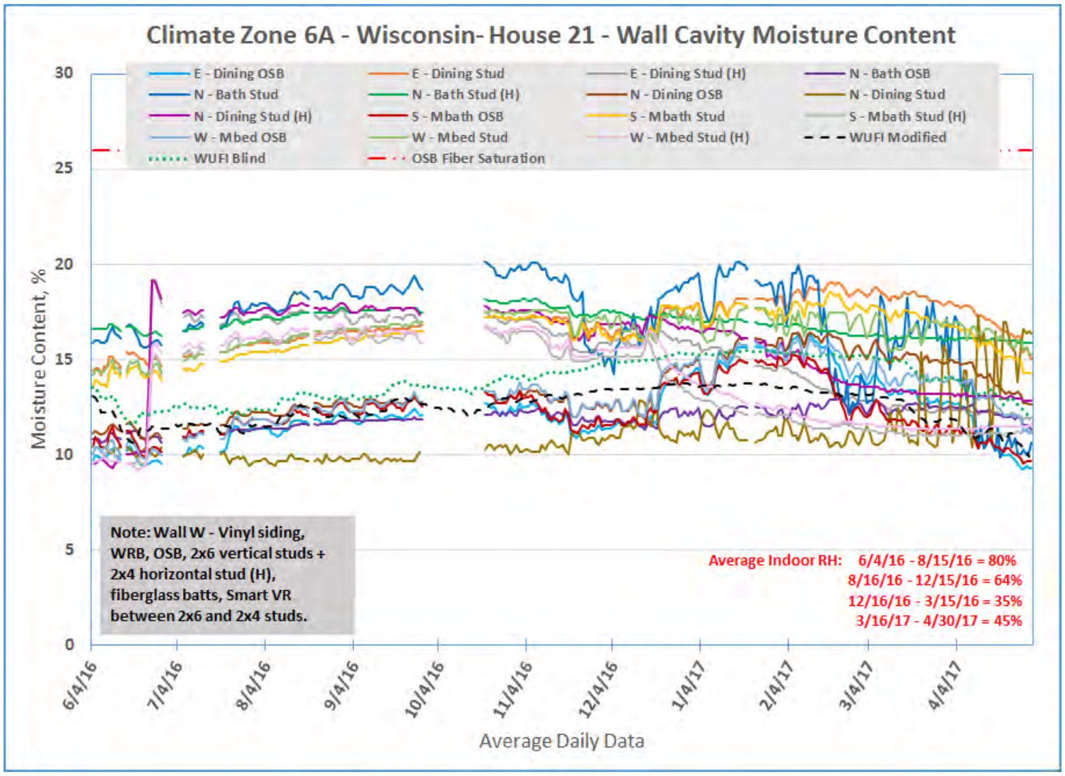


Figure 39. Oriented strand board sheathing and stud moisture content for Climate Zone 6A, Wisconsin (1), House 21

Figure 40 shows the summary results for the ZIP sheathing and stud daily moisture content for House 22, located in Wisconsin, Climate Zone 6A. The following observations can be made:

- As with other walls with polyethylene as an interior vapor retarder, the moisture content levels were very stable. No fluctuations were observed during the winter or spring in studs or ZIP panels, even as the outdoor temperatures dropped as low as -4°F in the winter.

- There is a delineation between the OSB and stud moisture levels. OSB oscillated around or less than 10%, and lumber was in the range of 12%–15%. Unlike many other wall assemblies, the OSB moisture content was lower than the framing moisture content. This behavior is likely because the wall is vapor closed and airtight and was able to keep the moisture levels of the materials at the same level as at the time of installation. Note that vapor permeability of the ZIP panels was lower than that of the OSB.

- Interior RH measurements are not available for this house.

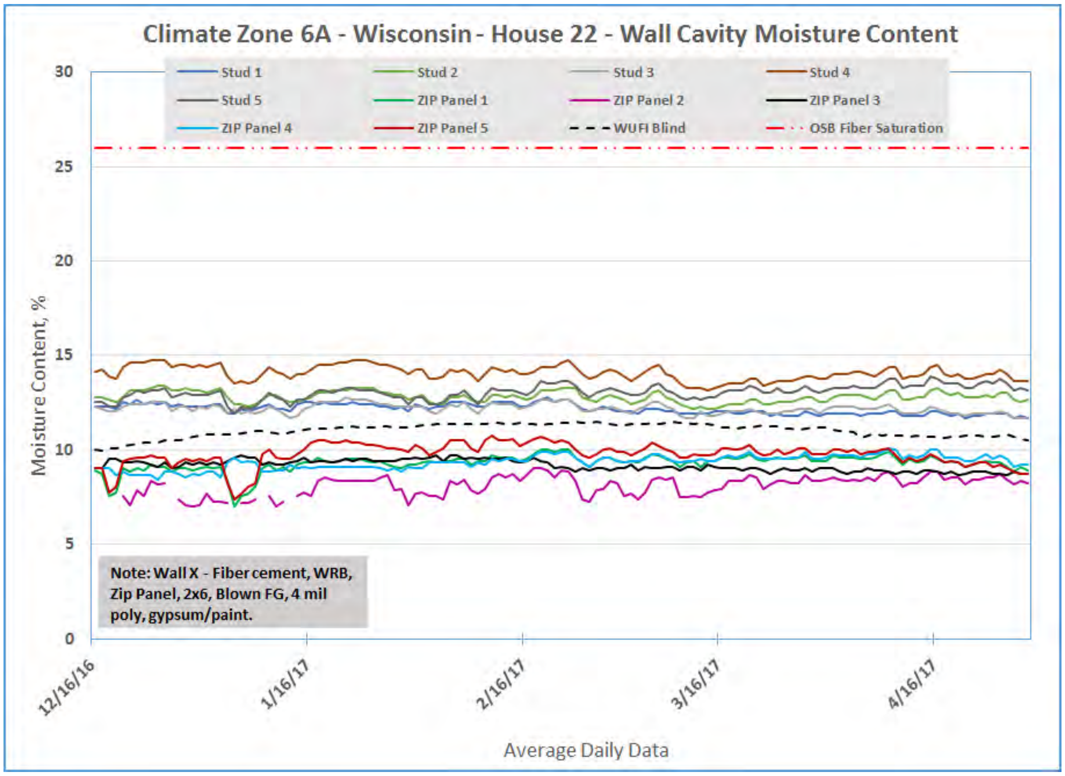


Figure 40. ZIP sheathing and stud moisture content for Climate Zone 6A, Wisconsin (1), House 22

Seasonal Summary of Moisture Content Data for Key Research Area 3

Figure 41 provides a summary of seasonal averages and seasonal peaks for all walls in Key Research Area 3. It shows the moisture content levels of the wood sheathing (OSB or plywood or ZIP) for each wall type for the entire monitoring period, from 2016 to 2017. This condensed format allows for an overview of the performance of the wall systems discussed previously in this section. Data from north-facing walls usually showed the highest moisture levels.

In summary, a wide range of performances was observed for walls in this category (no exterior insulation). As a rule, walls with an interior vapor retarder showed more stable moisture content levels. Walls without an interior vapor retarder were more sensitive to indoor and outdoor conditions. This observation is true for walls with all vapor-permeable cavity insulation types. Walls with damp-sprayed cellulose that had an opportunity to dry out after the installation showed increases in moisture content during the heating season.

Kraft paper was not as effective at controlling vapor and/or air drive into the cavity because polyethylene and walls with Kraft paper experienced increases in moisture content during the heating season; however, in Climate Zone 5A Kraft paper was able to keep the moisture level several percentage points less than the fiber saturation point. Combining Kraft paper with an interior air sealing strategy can offer an option for modulating the seasonal fluctuations.

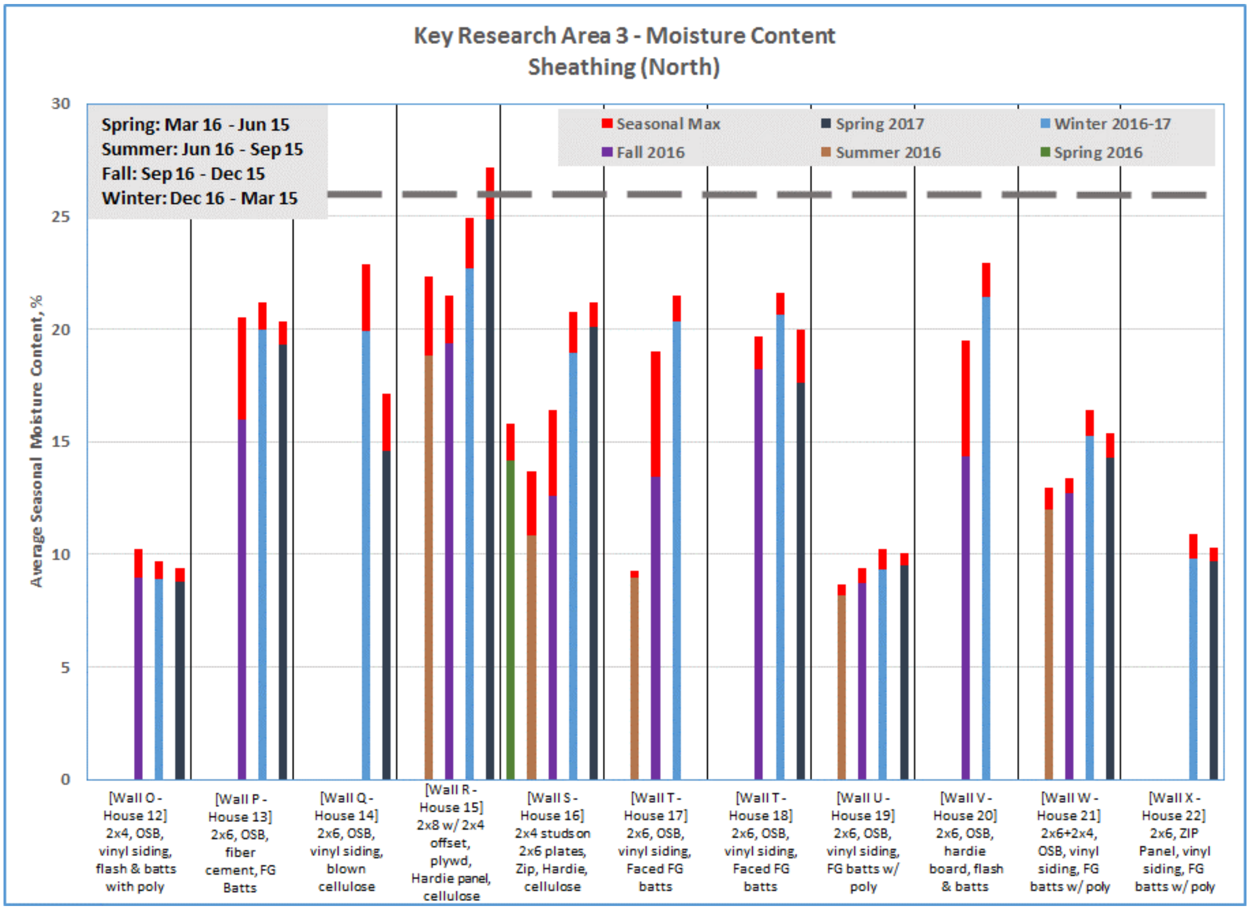


Figure 41. Key Research Area 3 summary: seasonal peak and averages moisture content of wood sheathing

3.5 Rim Joists

A total of 12 houses included moisture sensors installed at the rim joist. Figure 42 summarizes seasonal peaks and averages for each house. The results are grouped into walls with exterior insulation (blue area) and walls without exterior insulation (pink area). With one exception (House 1), a spray foam insulation was used on the interior of the rim joist. In several cases, it is not known whether open-cell or closed-cell spray foam was used.

With the exception of houses 16 and 18, rim joist moisture content was less than 20% for all houses. Based on the information available on houses 16 and 18, there is not a clear definitive reason why the moisture content reached the fiber saturation point for these two houses and yet not for other homes with open-cell spray foam insulation. It is possible that the spray foam insulation was applied at a lower thickness. The average interior RH was 42% for both House 16 and House 18.

Because the permeability of the interior insulation is not known for several houses, it is not always clear which element or combination of elements are most critical to the observed performance. The following observations can be made based on the available data:

- Walls with exterior insulation remained at low moisture levels and did not show significant seasonal fluctuations. For Climate Zone 4A (House 1), the rim area was vapor open in both directions. For climate zones 5A and 6A (houses 3, 6, 7), foam products were installed on both faces of the rim joist. For all walls with exterior insulation, the moisture content was less than 15% and did not exhibit significant seasonal fluctuations.

- For houses without exterior insulation, rim joists with open-cell spray foam showed larger seasonal fluctuations; however, these were not necessarily to the levels approaching the fiber saturation point. Those houses that did not show seasonal fluctuations (houses 19 and 22) likely used closed-cell spray foam.

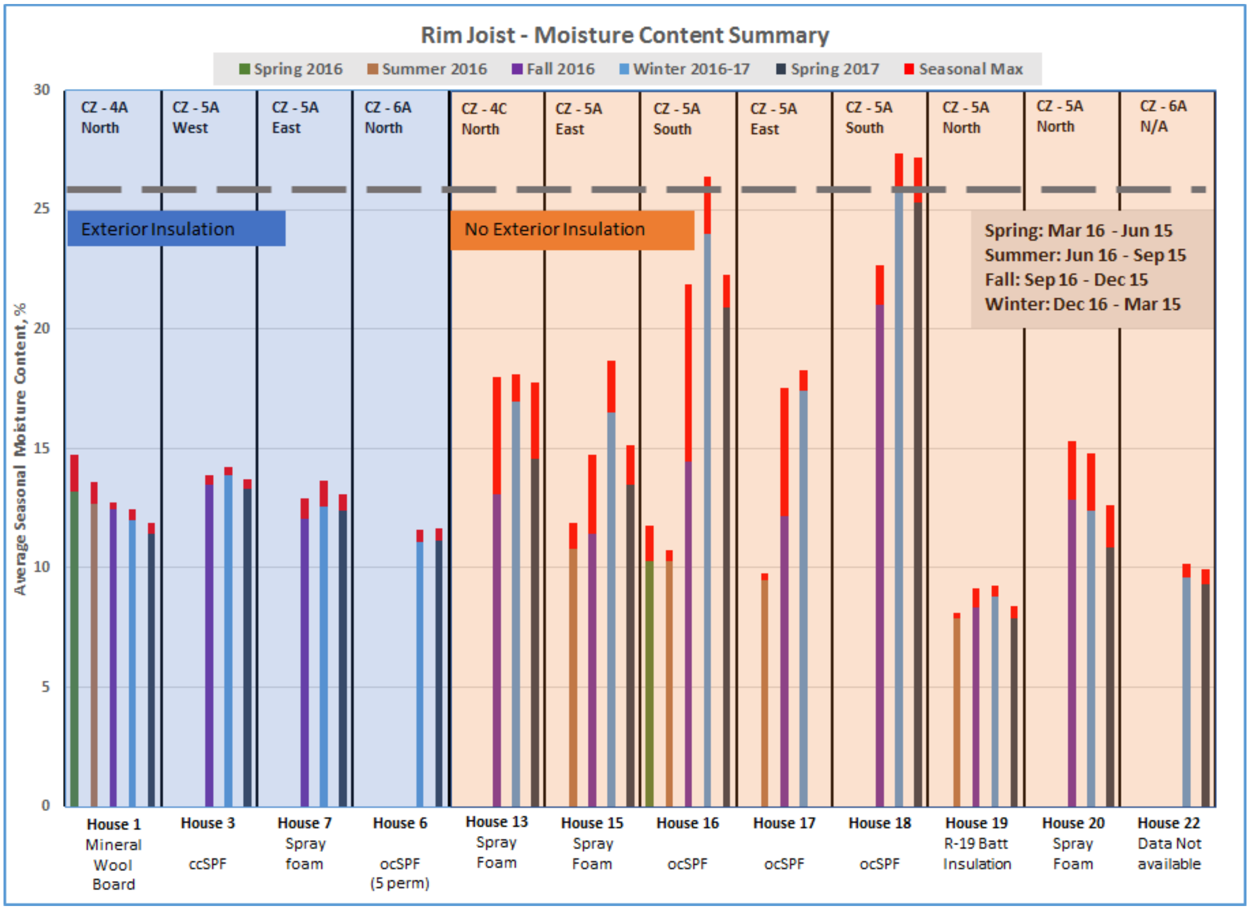


Figure 42. Summary: seasonal peak and averages moisture content of rim joists

3.6 Summary Observations of WUFI Simulation

Field observations for each house were compared to WUFI simulations conducted in two formats: (1) “blind” predictions using a general set of material properties and boundary conditions and (2) “modified” predictions that used more accurate inputs (if available) for material properties (e.g., interior paint) and interior RH levels. The blind predictions were reviewed by industry experts in WUFI modeling who did not have access to any field measurements. All simulations are included with the charts for each monitored wall in sections 3.2 through 3.4. These comparisons provide a case study for assessing the effectiveness of WUFI as a predictive tool, evaluation tool, and design tool. The following general observations can be made:

- With only a few exceptions, WUFI simulations were effective at predicting trends in observed performance. The exceptions were typically associated with walls whose performance is more sensitive to boundary conditions.

- The “modified” simulations using the more accurate, site-specific input typically provided improved accuracy of the predictions. In some cases, the improvement was substantial and changed the shape of the trend. In a few cases, the improvement was not sufficient to achieve full agreement between the model and the field observations or no improvement was observed.

- For several wall configurations, WUFI simulations appeared to overestimate the rate of drying (i.e., rate of dissipating absorbed moisture). This typically resulted in underpredicting the moisture levels observed in the field.
- When WUFI was used as a design tool and the simulation results indicated performance that was on the margins of the selected pass/fail criteria, it is recommended that sensitivity studies be conducted to evaluate whether the model is subject to significant changes in predictive behavior to any parameter or a set of parameters. If such parameters are identified and show the potential to change the result of the pass/fail evaluation, it may be recommended that the wall design be adjusted to minimize its dependency on those parameters.

3.7 Interior Relative Humidity Conditions

Figure 1 shows a summary of interior RH by climate zone, including: (1) climate zone average and (2) range of average interior RH by house. All interior RH levels are reported during the winter period from December 15 to March 15. When the monitoring period did not start until after December 15, the average was calculated from the first date of monitoring.

The average RH level remained at less than 45% for all homes. Therefore, the combinations of the building enclosure, ventilation system, and occupant behavior in all monitored homes resulted in acceptable interior RH levels. The observed levels were generally consistent with the levels measured in previous studies.

One outlier is House 10 in Climate Zone 5A. This is the only house in the study that is a renovation rather than new construction. A new addition to this existing house was monitored. The owner also indicated that they were running a humidifier. The interior RH averaged 55% during the winter and peaked at 62%. Although this is an older house, the more likely cause of the elevated RH levels is the humidifier.

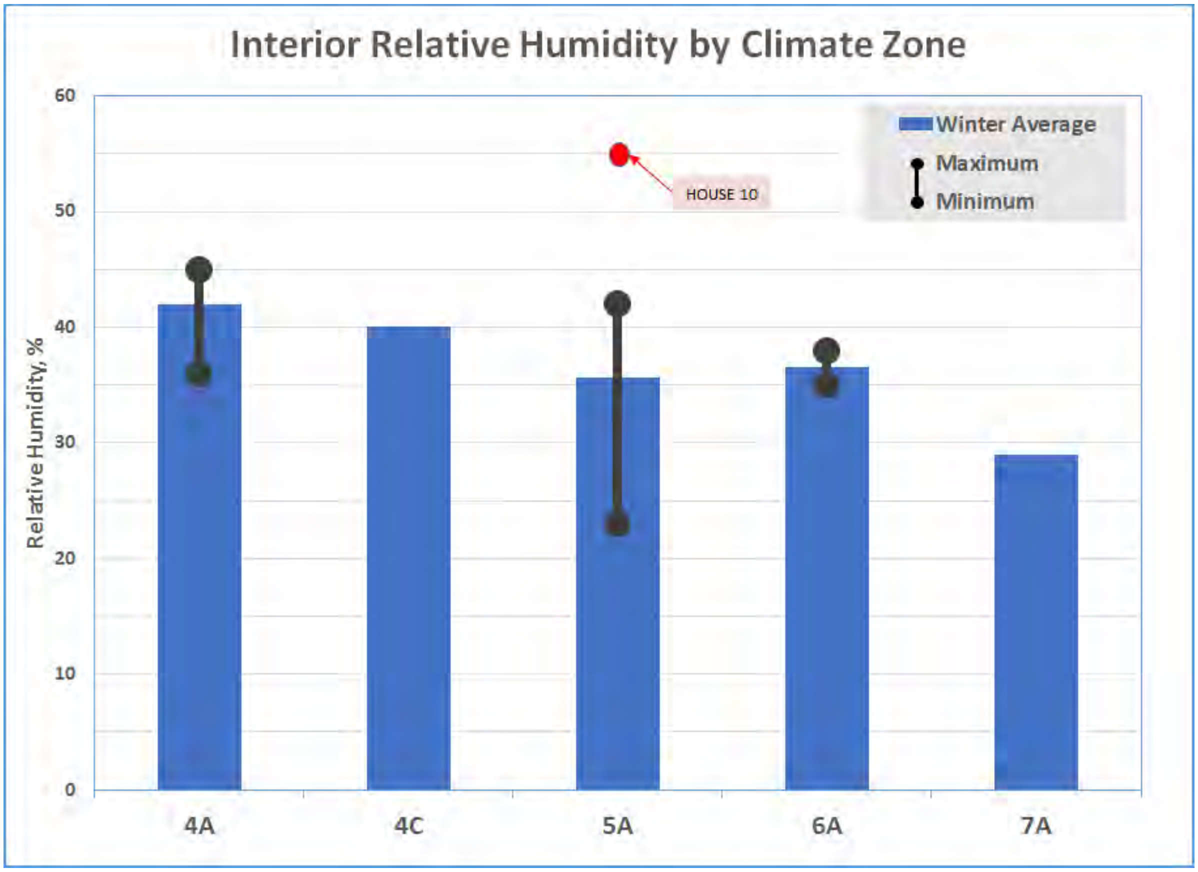


Figure 43. Winter averages for interior relative humidity by climate zone and by house

4 Summary, Conclusions, and Recommendations

The study was designed to monitor the moisture performance of energy-efficient homes in climate zones 4–7 where a substantial vapor drive to the exterior is present during the winter. The research team was not involved in the house design or construction. The overarching goal of the project is to increase builders' confidence in high-R wall systems through better understanding of the field performance. An essential element of the study is the evaluation of moisture modeling in terms of its ability to predict in-field performance. A continuation of the monitoring is planned for one more winter season to evaluate performance after the construction moisture had a chance to dissipate. Note that the past winter was somewhat mild at some sites compared to historic averages and peaks. Interestingly, other sites in the same climate zones were more representative of historic data. Monitoring for an additional year will also allow for the evaluation of variations from one year to another based on climate conditions.

4.1 General Observations

- Most walls showed moisture content levels less than the fiber saturation point during the monitoring period or following the initial drying.
- The walls with high initial moisture content typically used damp-sprayed cellulose insulation in the cavity. Depending on the wall configuration and the temperature/RH conditions, drying for these assemblies took 2–4 or more months. For homes constructed during the winter, the drying did not start until the warmer spring months. At a Climate Zone 7 site (House 11), the moisture content was above 20% through the end of April (end of reporting period).
- Exterior insulation can be an effective method for controlling the effects of the interior vapor drive. The R-value and permeability of the exterior insulation are the variables that influence a wall's moisture performance. Walls with exterior insulation that were adequately designed for the site showed stable moisture content levels (e.g., House 1, 2).
- Walls that showed an upward moisture content trend in the winter showed a drying trend in the spring. This performance pattern included walls with exterior foam sheathing, confirming that these types of walls have a capacity for drying, with this observation also applicable to walls with damp spray cellulose installed during the winter and a drying onset in April.
- Wall assemblies with ZIP-R (R-12) and vinyl siding showed stable moisture content levels at less than 15% moisture content. With the OSB sheathing exterior to the foam insulation in ZIP panels, the observed stable OSB moisture content throughout the winter suggests that exposing OSB to cold temperatures does not lead to elevated moisture levels provided that there is an adequate vapor retarder and an air barrier separating the OSB from the wall interior.
- Wall assemblies with ZIP-R (R-9) and fiber cement siding showed stable moisture content levels less than 20%, with a drying trend beginning in March.
- The 2x6 framed walls with XPS R-5 exterior foam sheathing and Kraft paper vapor retarder showed very stable moisture content levels and show promise as a practical option for achieving insulation levels as high as R-24 using standard materials with only small changes to conventional construction practices.
- Walls with a polyethylene interior vapor retarder (Class I) showed stable low moisture content levels. This observation is consistent with previous studies and applies to walls with various sheathing and cladding combinations.

- A double-vapor-barrier wall with polyisocyanurate exterior insulation and polyethylene interior vapor retarder showed stable low moisture content levels in a house with high interior RH.
- Further monitoring is needed to understand the performance of a wall with damp-sprayed cellulose cavity insulation and a smart interior vapor retarder.
- The presence of Kraft paper does not seem to alter the ability of walls with exterior foam sheathing ability to dry out.
- Walls without exterior insulation and without an interior vapor retarder in climate zones 4A or 4C can be subject to substantial seasonal moisture fluctuations (note that IRC requires a Class II or Class III vapor retarder, yet local practices may vary).
- The initial moisture content before the walls are enclosed may be more critical for deeper assemblies (e.g., 2x8) with damp-sprayed cellulose, particularly if the cladding and the interior finish are not vapor open.
- In Climate Zone 5A, walls with damp-sprayed cellulose without an interior vapor retarder and without exterior insulation are subject to large seasonal moisture fluctuations. This behavior can be exacerbated if the cladding product does not allow any level of air exchange with the outside (e.g., paneling).
- In Climate Zone 5A, walls with batt insulation and Kraft facing can be subject to seasonal fluctuations as a result of air leakage inside the wall cavity from the house interior. In contrast, polyethylene appears to serve as a more effective air barrier.
- For spray foam cavity insulation, it is critical that the product with permeability characteristics specified in the design is installed in the field. Based on the field observations, the moisture content levels can reach the fiber saturation point where the spray foam appears not to meet the design specifications.
- The evaluation of the performance of proprietary smart vapor retarders will benefit from the extended monitoring period after the construction moisture had a chance to dissipate.
- For rim joists in all walls with exterior insulation, the moisture content was less than 15% and did not exhibit significant seasonal fluctuations.
- For rim joists in walls without exterior insulation, rim joists with open-cell spray foam showed larger seasonal fluctuations; however, these were not necessarily to the levels approaching the fiber saturation point.
- Average interior RH levels in all newly constructed homes remained less than 45% during the winter season.

4.2 Modeling

- Overall, WUFI simulations can provide a valuable design and decision-making tool for the selection of wall assemblies. WUFI's ability to accurately predict in-field performance depends on the accuracy of the input parameters for material properties and boundary conditions. A broad range of predictive power was observed, with many predictions reasonably following the measured data and a few substantially diverging from the data. Further research and analysis is recommended to better understand the fundamental reasons for the observed spread in the few cases where the predictions did not track the field data.

- Using the more accurate input parameters obtained after the construction and monitoring were completed typically improved the accuracy of the models, in some cases substantially.

- Vapor-open wall designs (e.g., no interior vapor retarder) were typically more sensitive to the modeling inputs (e.g., interior RH). In contrast, vapor barrier designs (e.g., polyethylene at the interior face) were more stable and predictable.

- For several wall designs, the WUFI simulations generated as part of this project overstated the rate of drying afforded by the wall system (i.e., the wall's ability to dissipate absorbed moisture). The drying time measured in the field in these cases was substantially longer than the predictions.

- For some wall systems (e.g., House 3), blind predictions significantly diverged from field performance. This observation suggests that judgement and field experience remain a factor in understanding the long-term performance of walls.

- For walls where airflow into the cavity from the house interior may be an occurrence, the WUFI simulation may underpredict the moisture content levels by about 5 percentage points.

4.3 Recommendations

- Regarding WUFI's predictive capabilities, it is suggested that sensitivity studies be conducted for each model used in the design, particularly where the modeling results suggest performance on the cusp of the established pass-fail criteria. This recommendation is particularly important for walls with Class III or no vapor retarder.

- With continued use of polyethylene as an interior vapor retarder by builders in colder climates, it is recommended that these types of systems are accompanied with air sealing details and drainage plane details to avoid or minimize potential for water leaks or moisture accumulation. It is also important that the polyethylene does not get installed over materials with elevated moisture content, particularly if the cladding/drainage plane is not vapor open.

- "Hybrid" walls (a wall that relies on the combination of exterior insulation and a Class II vapor retarder) show promise as a technology for increased R-value with minimum changes to construction practices.

- For walls without exterior sheathing and without an interior vapor retarder in climate zones 4A or 4C, it is recommended that control of the interior RH levels be part of the overall house design strategy.

- For deep cavity walls with damp-sprayed cellulose insulation, it is particularly important that drying can occur before the walls are enclosed with drywall to allow the moisture content to reach the levels recommended by the product manufacturer.

- For walls without exterior insulation in Climate Zones 5A and higher, an air sealing strategy at the interior drywall is recommended to control airflow from inside the house into the cavity.

References

ASHRAE. 2009. ANSI/ASHRAE Standard 160-2009: Criteria for Moisture-Control Design Analysis in Buildings, Including Addendum C, June 2012. Atlanta, GA.

ASTM. 2009. Moisture Control in Buildings: The Key to Mold Prevention, 2nd Edition, Manual 19. West Conshohocken, PA.

Glass, S., V. Kochkin, S. Drumheller, and Barta L. Craig. 2015. “Moisture Performance of Energy-Efficient and Conventional Wood-Frame Wall Assemblies in a Mixed-Humid Climate.” Buildings (July).

Home Innovation Research Labs. 2014. Moisture Performance of Walls in Energy Efficient Homes. Upper Marlboro, MD.

Home Innovation Research Labs. 2014. Moisture Performance of OSB-Sheathed Walls in Homes in Climate Zone 4 and 5 Upper Marlboro, MD.

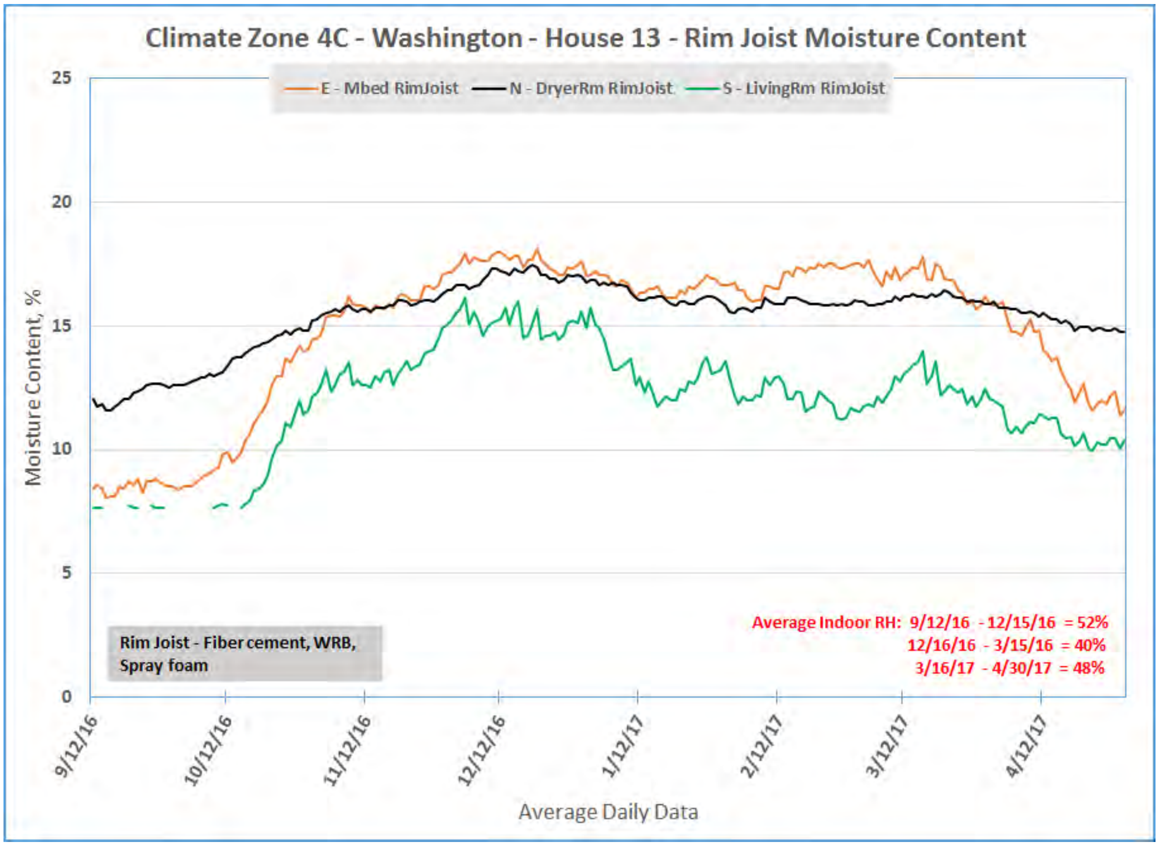
IRC 2015, International Residential Code, International Code Council (ICC), Country Club Hills, IL

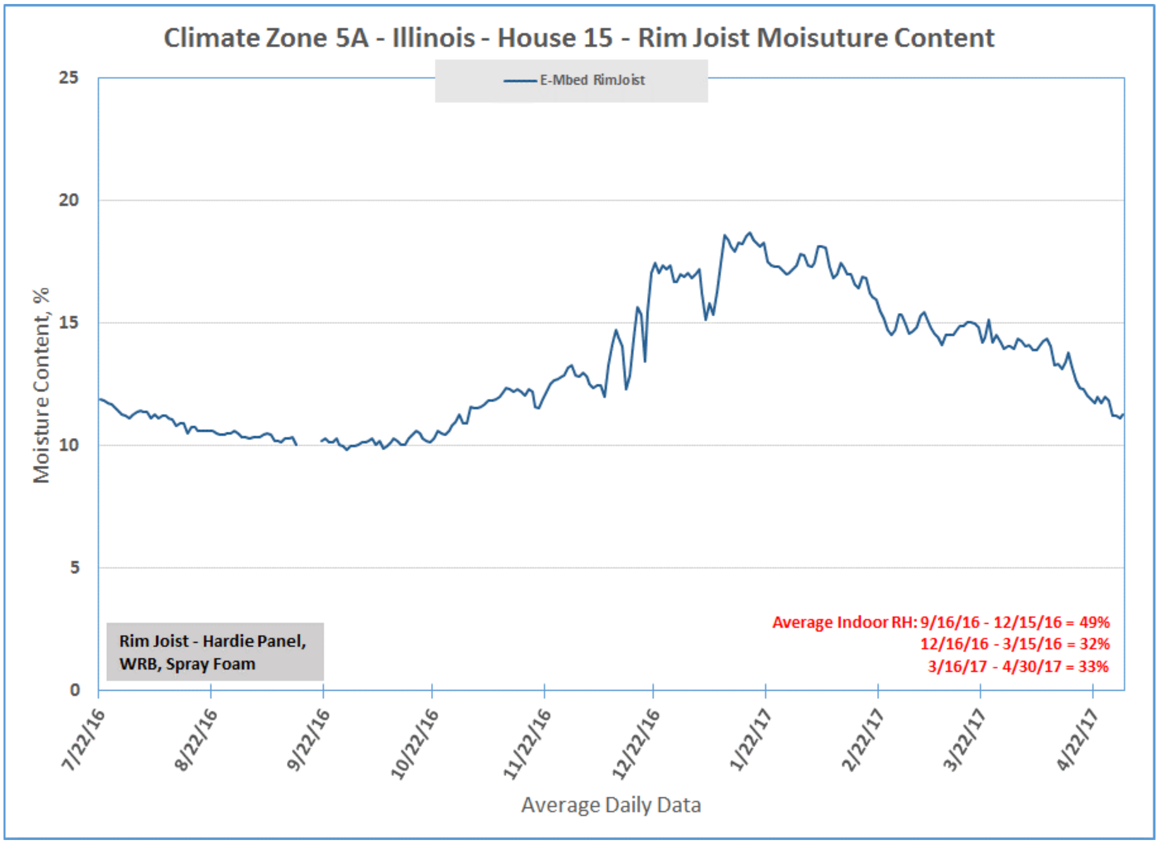
IECC 2015, International Energy Conservation Code, International Code Council (ICC), Country Club Hills, IL

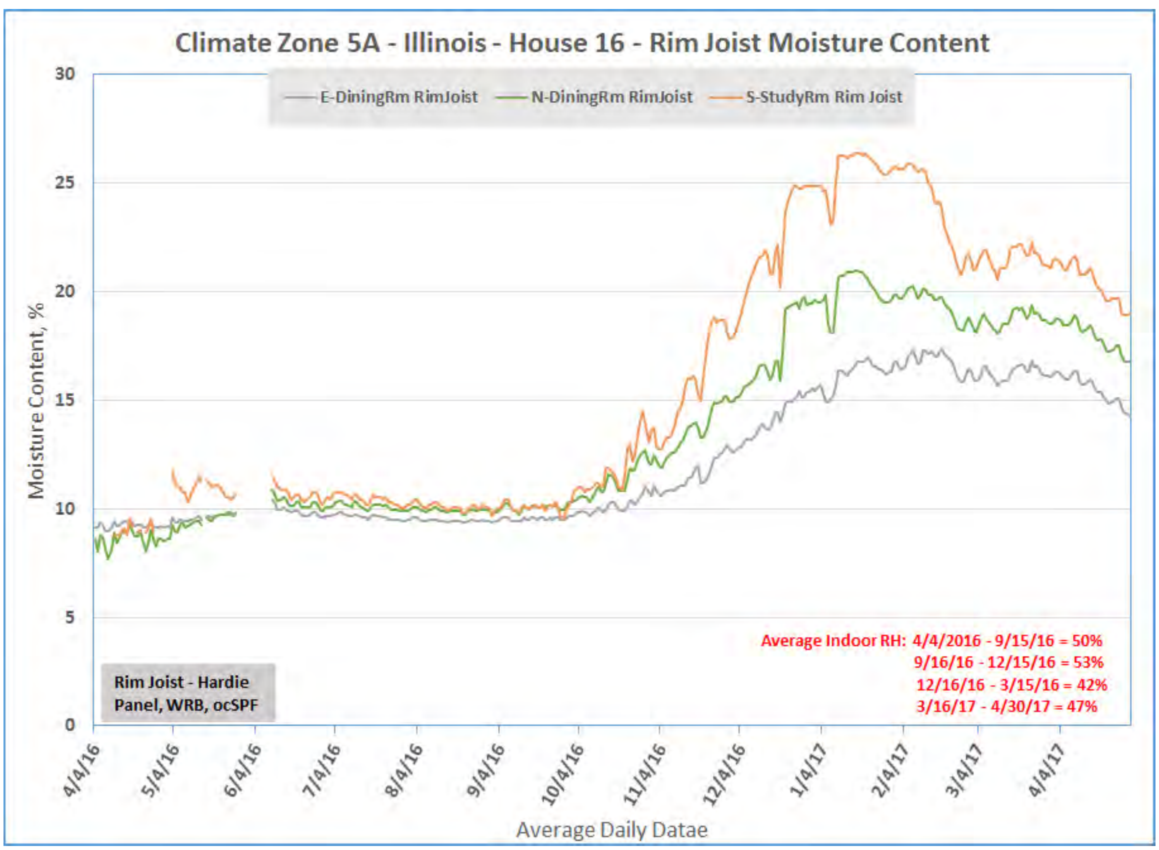
Tsongas, G. 2009. “Chapter 13: Case Studies of Moisture Problems.” In ASTM Manual 18, 2nd Edition, Moisture Control in Buildings. West Conshohocken, PA: ASTM International.

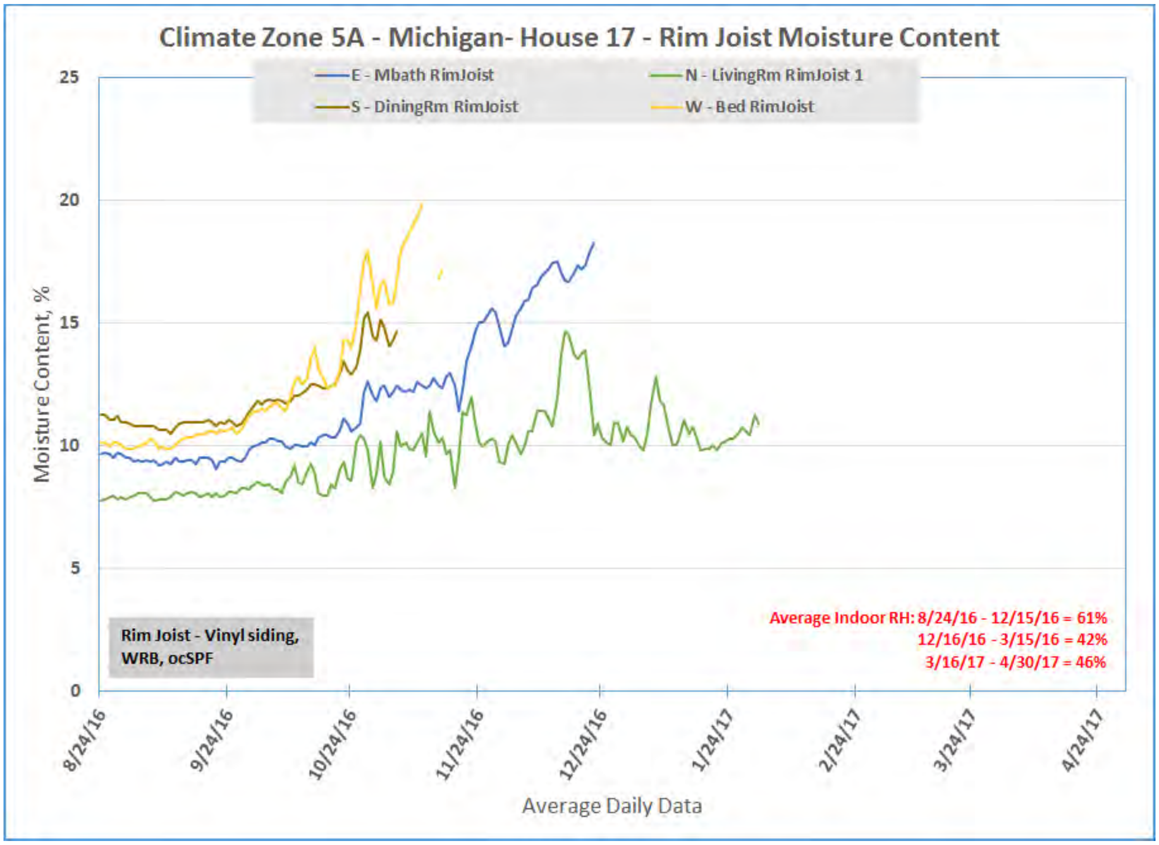
Appendix

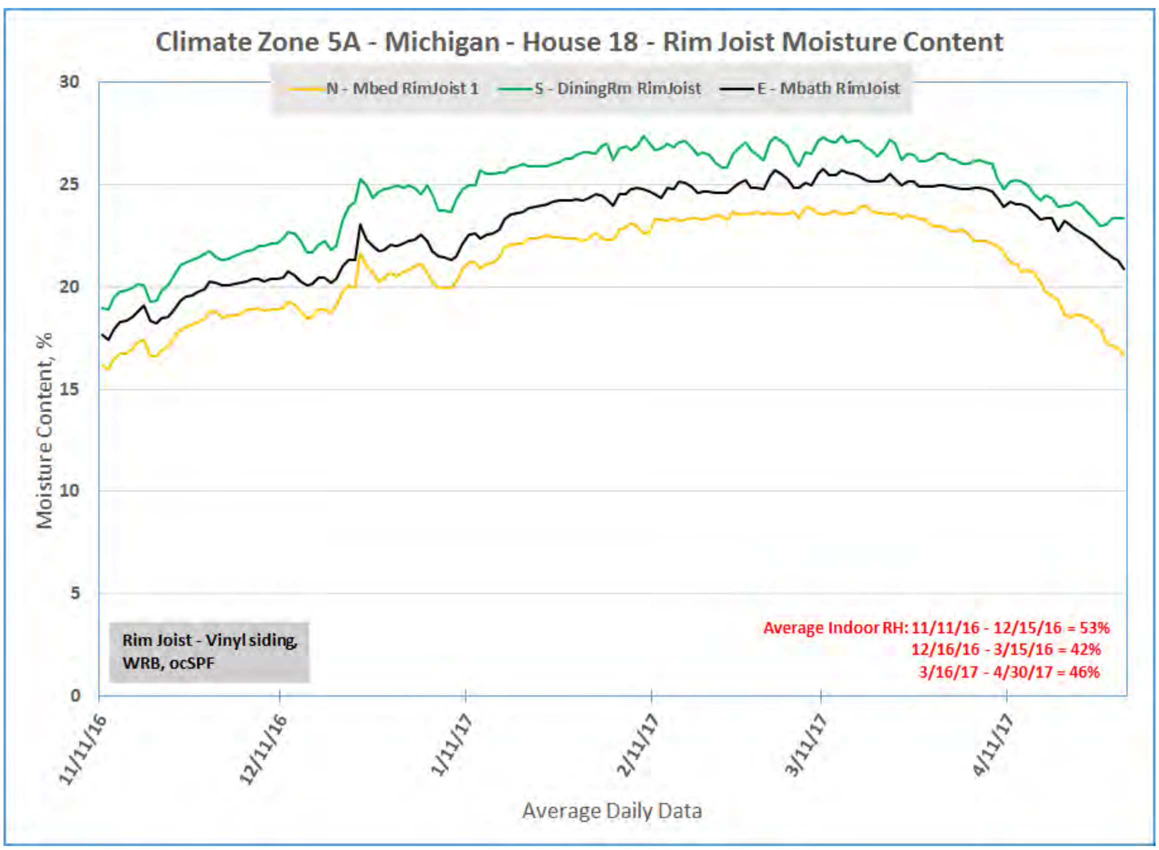
Rim Joist Moisture Content Charts

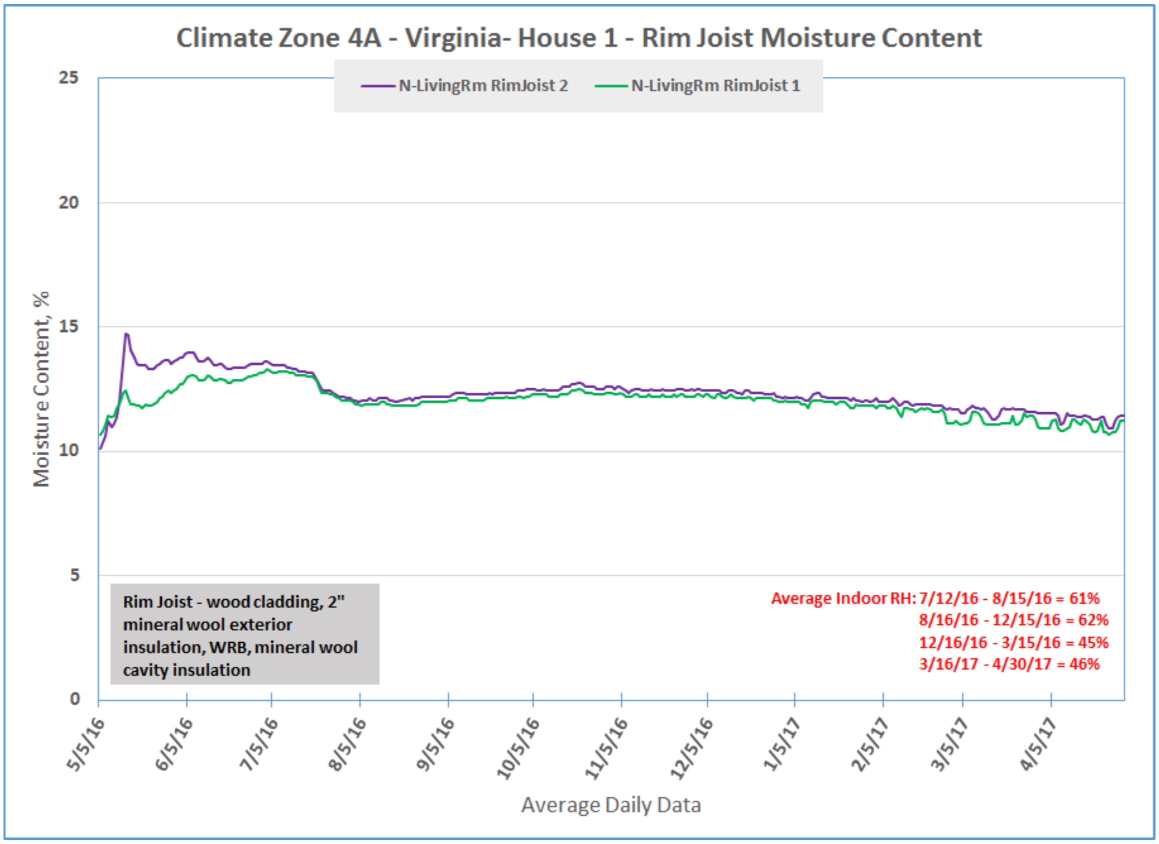


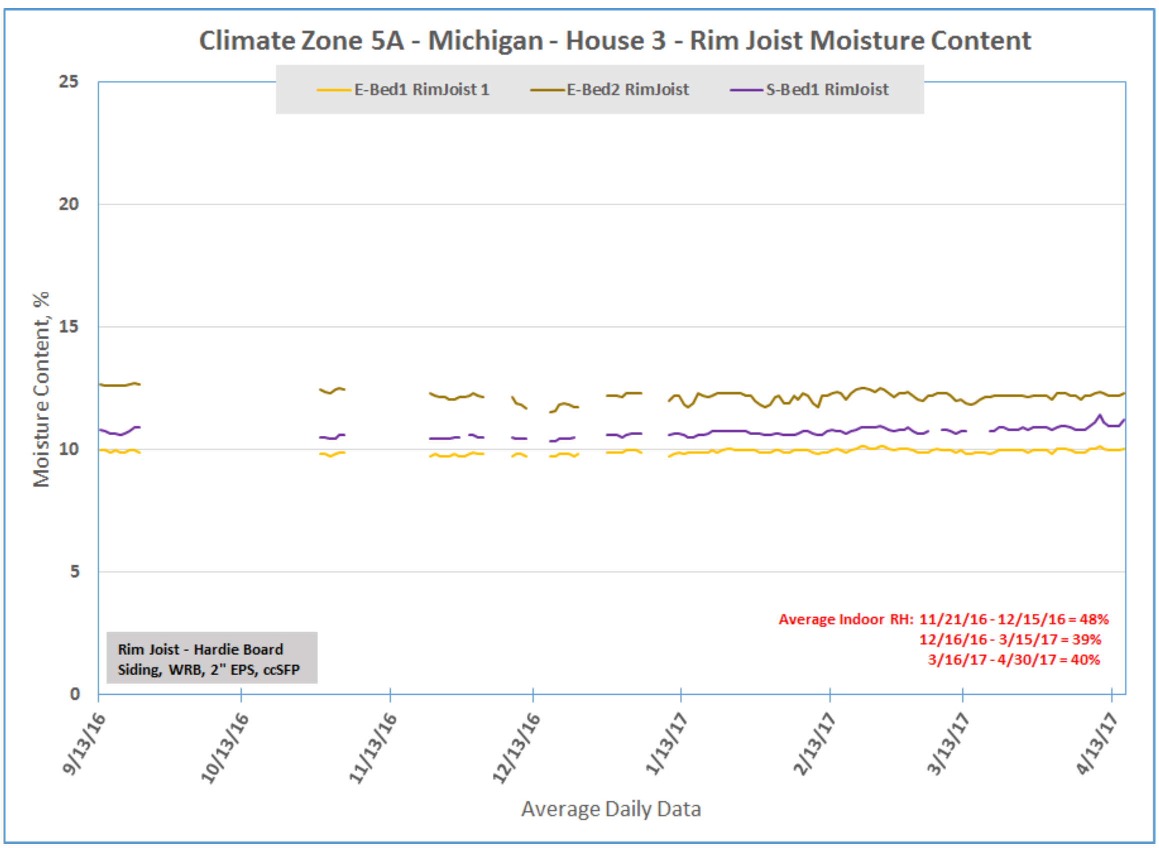

Climate Zone 5A - Illinois - House 15 - Rim Joist Moisuture Content
E-Mbed RimJoist
Moisture Content, %
25
20
15
10
5
0
Rim Joist - Hardie Panel, WRB, Spray Foam
Average Indoor RH: 9/16/16 - 12/15/16 = 49%
12/16/16 - 3/15/16 = 32%
3/16/17 - 4/30/17 = 33%
7/22/16
8/22/16
9/22/16
10/22/16
11/22/16
12/22/16
1/22/17
2/22/17
3/22/17
4/22/17
Average Daily Data

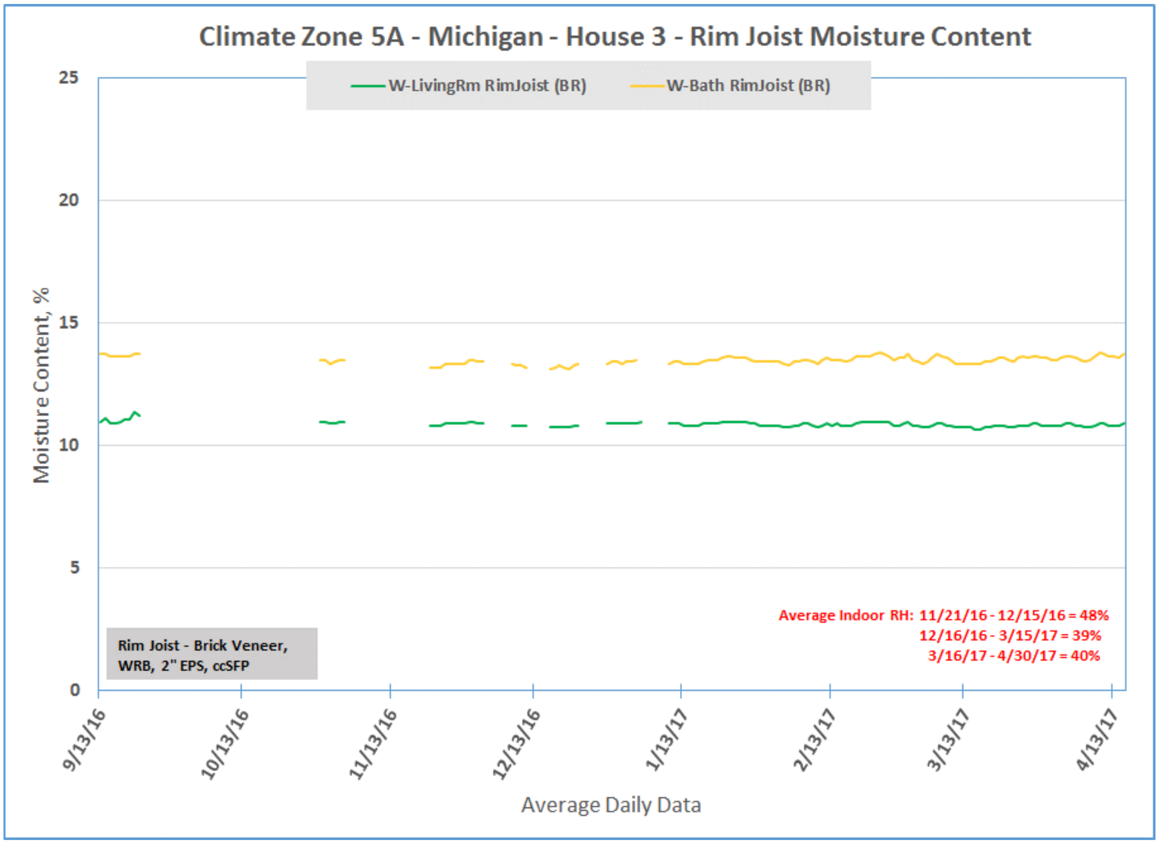

Climate Zone 5A - Illinois - House 16 - Rim Joist Moisture Content
E-DiningRm RimJoist
N-DiningRm RimJoist
S-StudyRm Rim Joist
Moisture Content, %
30
25
20
15
10
5
0
Rim Joist - Hardie Panel, WRB, ocSPF
Average Indoor RH: 4/4/2016 - 9/15/16 = 50%
9/16/16 - 12/15/16 = 53%
12/16/16 - 3/15/16 = 42%
3/16/17 - 4/30/17 = 47%
4/4/16
5/4/16
6/4/16
7/4/16
8/4/16
9/4/16
10/4/16
11/4/16
12/4/16
1/4/17
2/4/17
3/4/17
4/4/17
Average Daily Datae

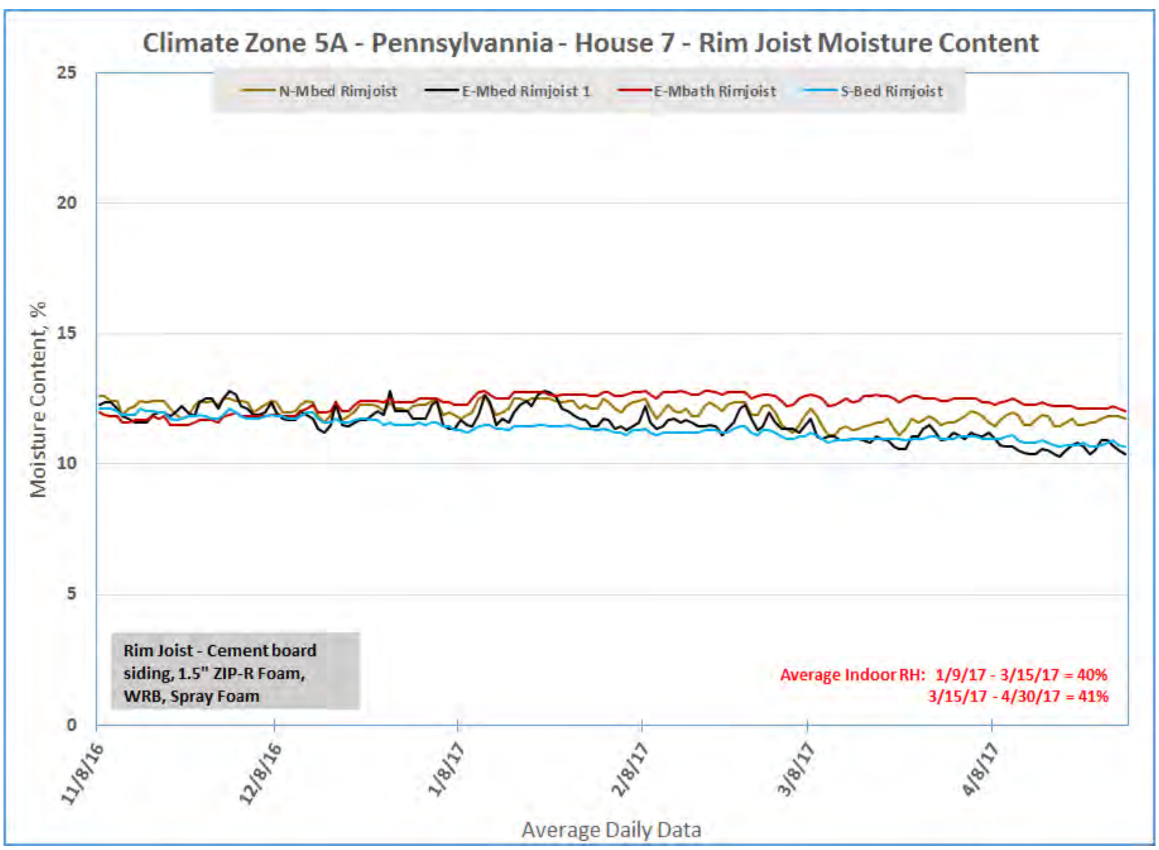

Climate Zone 5A - Michigan- House 17 - Rim Joist Moisture Content
E - Mbath RimJoist
N - LivingRm RimJoist 1
S - DiningRm RimJoist
W - Bed RimJoist
Moisture Content, %
Rim Joist - Vinyl siding, WRB, ocSPF
Average Indoor RH: 8/24/16 - 12/15/16 = 61%
12/16/16 - 3/15/16 = 42%
3/16/17 - 4/30/17 = 46%
8/24/16
9/24/16
10/24/16
11/24/16
12/24/16
1/24/17
2/24/17
3/24/17
4/24/17
Average Daily Data

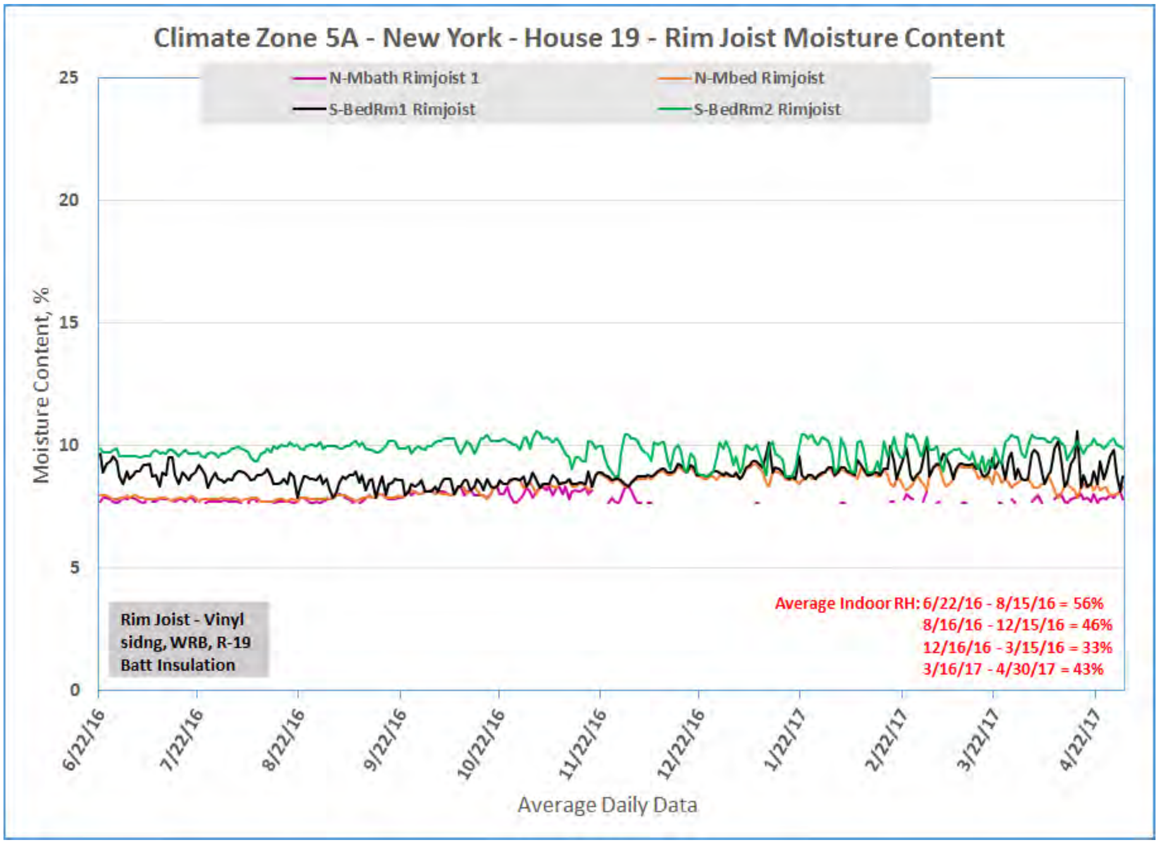

Climate Zone 5A - Michigan - House 18 - Rim Joist Moisture Content
N - Mbed RimJoist 1
S - DiningRm RimJoist
E - Mbath RimJoist
Moisture Content, %
Rim Joist - Vinyl siding, WRB, ocSPF
Average Indoor RH: 11/11/16 - 12/15/16 = 53%
12/16/16 - 3/15/16 = 42%
3/16/17 - 4/30/17 = 46%
11/11/16
12/11/16
1/11/17
2/11/17
3/11/17
4/11/17
Average Daily Data


Climate Zone 4A - Virginia- House 1 - Rim Joist Moisture Content
N-LivingRm RimJoist 2
N-LivingRm RimJoist 1
Moisture Content, %
25
20
15
10
5
0
Rim Joist - wood cladding, 2" mineral wool exterior insulation, WRB, mineral wool cavity insulation
Average Indoor RH: 7/12/16 - 8/15/16 = 61%
8/16/16 - 12/15/16 = 62%
12/16/16 - 3/15/16 = 45%
3/16/17 - 4/30/17 = 46%
5/5/16
6/5/16
7/5/16
8/5/16
9/5/16
10/5/16
11/5/16
12/5/16
1/5/17
2/5/17
3/5/17
4/5/17
Average Daily Data

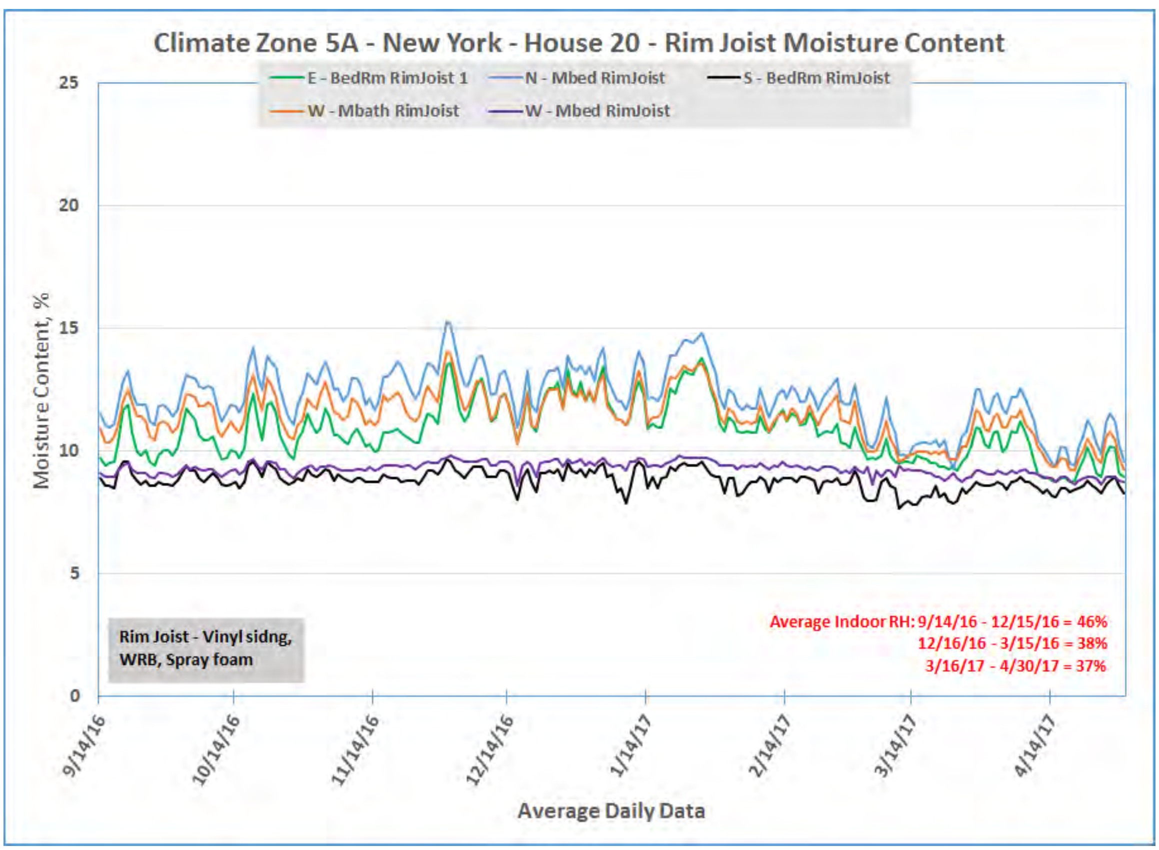

Climate Zone 5A - Michigan - House 3 - Rim Joist Moisture Content
E-Bed1 RimJoist 1
E-Bed2 RimJoist
S-Bed1 RimJoist
Moisture Content, %
25
20
15
10
5
0
Rim Joist - Hardie Board Siding, WRB, 2" EPS, ccSFP
Average Indoor RH: 11/21/16 - 12/15/16 = 48%
12/16/16 - 3/15/17 = 39%
3/16/17 - 4/30/17 = 40%
9/13/16
10/13/16
11/13/16
12/13/16
1/13/17
2/13/17
3/13/17
4/13/17
Average Daily Data


Climate Zone 5A - Michigan - House 3 - Rim Joist Moisture Content
W-LivingRm RimJoist (BR)
W-Bath RimJoist (BR)
Moisture Content, %
25
20
15
10
5
0
Rim Joist - Brick Veneer, WRB, 2" EPS, ccSFP
Average Indoor RH: 11/21/16 - 12/15/16 = 48%
12/16/16 - 3/15/17 = 39%
3/16/17 - 4/30/17 = 40%
9/13/16
10/13/16
11/13/16
12/13/16
1/13/17
2/13/17
3/13/17
4/13/17
Average Daily Data

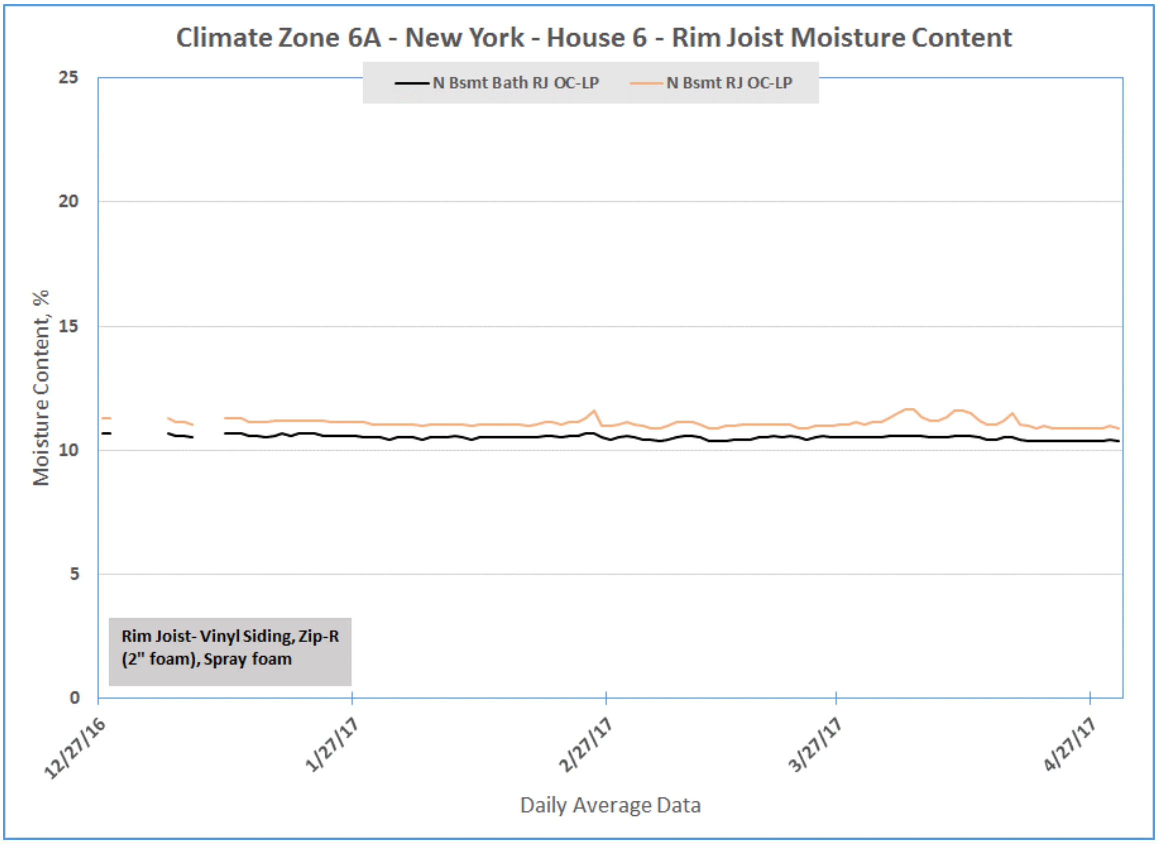

Climate Zone 5A - Pennsylvannia - House 7 - Rim Joist Moisture Content
N-Mbed Rimjoist
E-Mbed Rimjoist 1
E-Mbath Rimjoist
S-Bed Rimjoist
Moisture Content, %
25
20
15
10
5
0
Rim Joist - Cement board siding, 1.5" ZIP-R Foam, WRB, Spray Foam
Average Indoor RH: 1/9/17 - 3/15/17 = 40%
3/15/17 - 4/30/17 = 41%
11/8/16
12/8/16
1/8/17
2/8/17
3/8/17
4/8/17
Average Daily Data

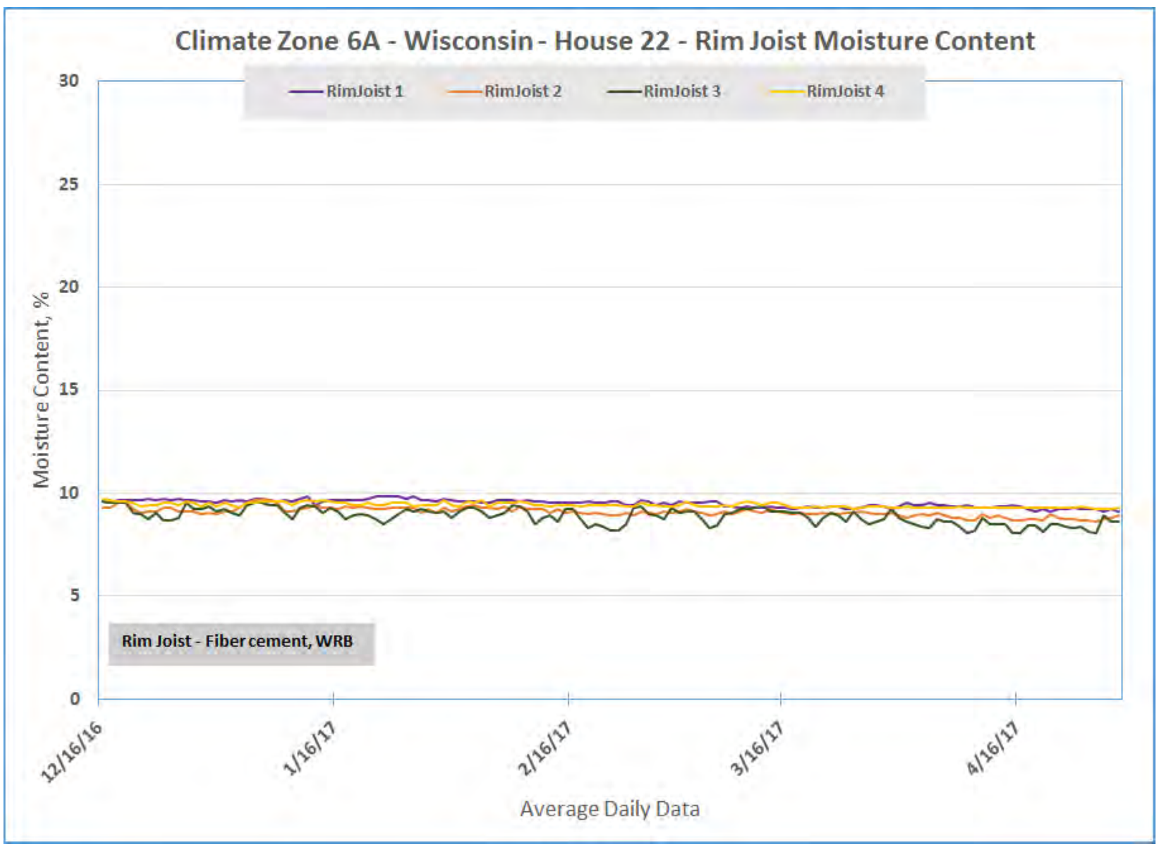


Climate Zone 5A - New York - House 19 - Rim Joist Moisture Content
N-Mbath Rimjoist 1
N-Mbed Rimjoist
S-BedRm1 Rimjoist
S-BedRm2 Rimjoist
Moisture Content, %
25
20
15
10
5
0
Rim Joist - Vinyl sidng, WRB, R-19 Batt Insulation
Average Indoor RH: 6/22/16 - 8/15/16 = 56%
8/16/16 - 12/15/16 = 46%
12/16/16 - 3/15/16 = 33%
3/16/17 - 4/30/17 = 43%
6/22/16
7/22/16
8/22/16
9/22/16
10/22/16
11/22/16
12/22/16
1/22/17
2/22/17
3/22/17
4/22/17
Average Daily Data

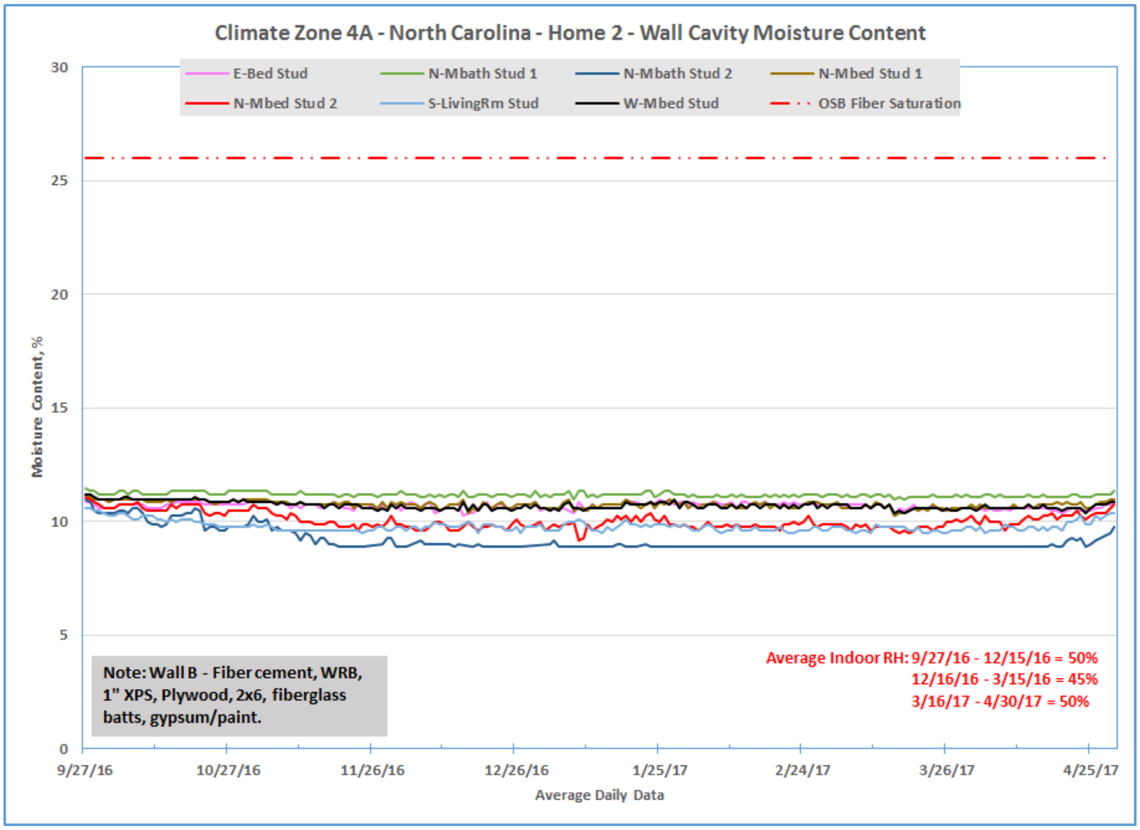


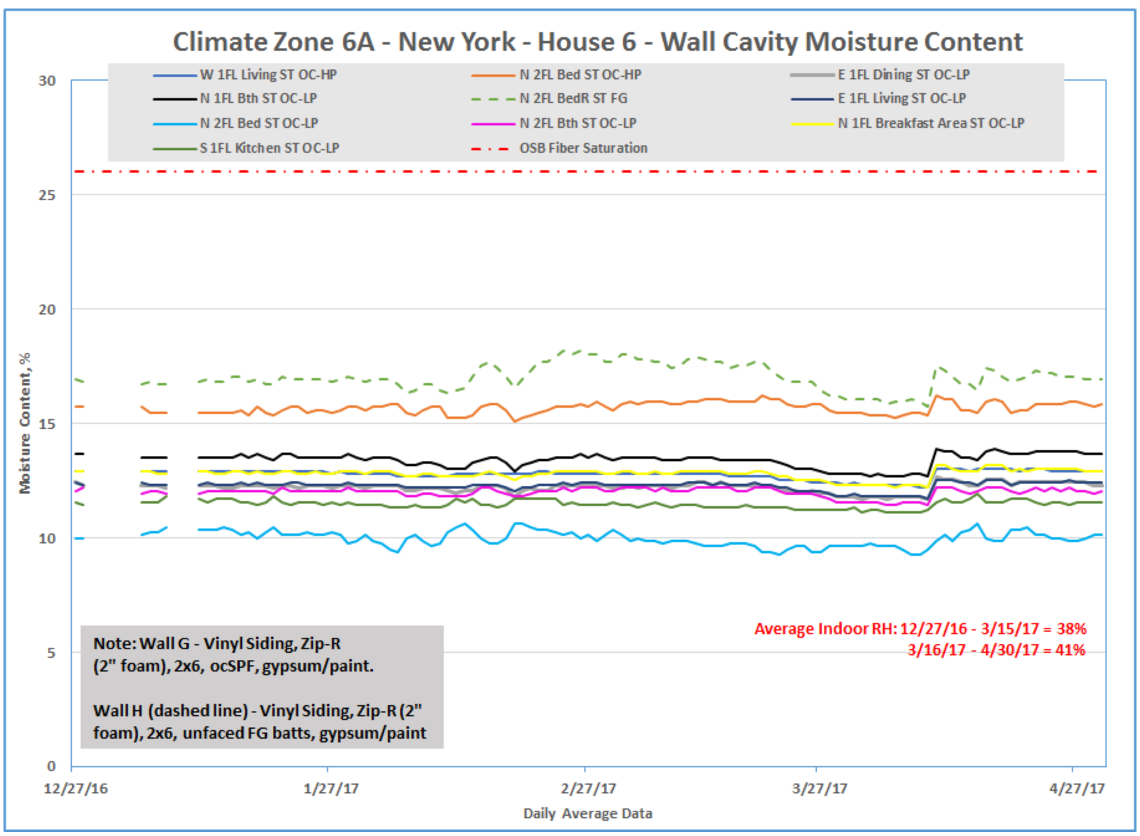
Climate Zone 5A - New York - House 20 - Rim Joist Moisture Content
E - BedRm RimJoist 1
N - Mbed RimJoist
S - BedRm RimJoist
W - Mbath RimJoist
W - Mbed RimJoist
Moisture Content, %
25
20
15
10
5
0
Rim Joist - Vinyl sidng, WRB, Spray foam
Average Indoor RH: 9/14/16 - 12/15/16 = 46%
12/16/16 - 3/15/16 = 38%
3/16/17 - 4/30/17 = 37%
9/14/16
10/14/16
11/14/16
12/14/16
1/14/17
2/14/17
3/14/17
4/14/17
Average Daily Data

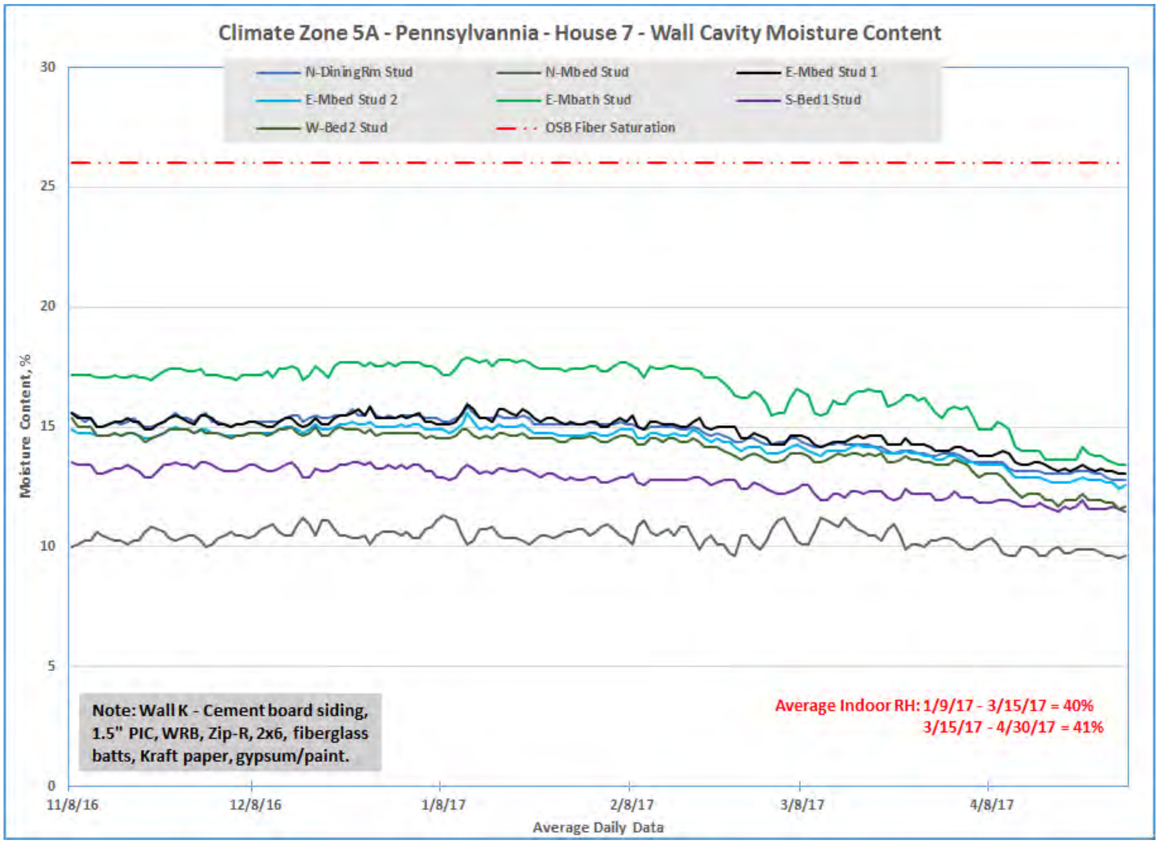

Climate Zone 6A - New York - House 6 - Rim Joist Moisture Content
N Bsmt Bath RJ OC-LP
N Bsmt RJ OC-LP
Moisture Content, %
25
20
15
10
5
0
Rim Joist- Vinyl Siding, Zip-R (2" foam), Spray foam
12/27/16
1/27/17
2/27/17
3/27/17
4/27/17
Daily Average Data


Climate Zone 6A - Wisconsin - House 22 - Rim Joist Moisture Content
RimJoist 1
RimJoist 2
RimJoist 3
RimJoist 4
Moisture Content, %
30
25
20
15
10
5
0
Rim Joist - Fiber cement, WRB
12/16/16
1/16/17
2/16/17
3/16/17
4/16/17
Average Daily Data

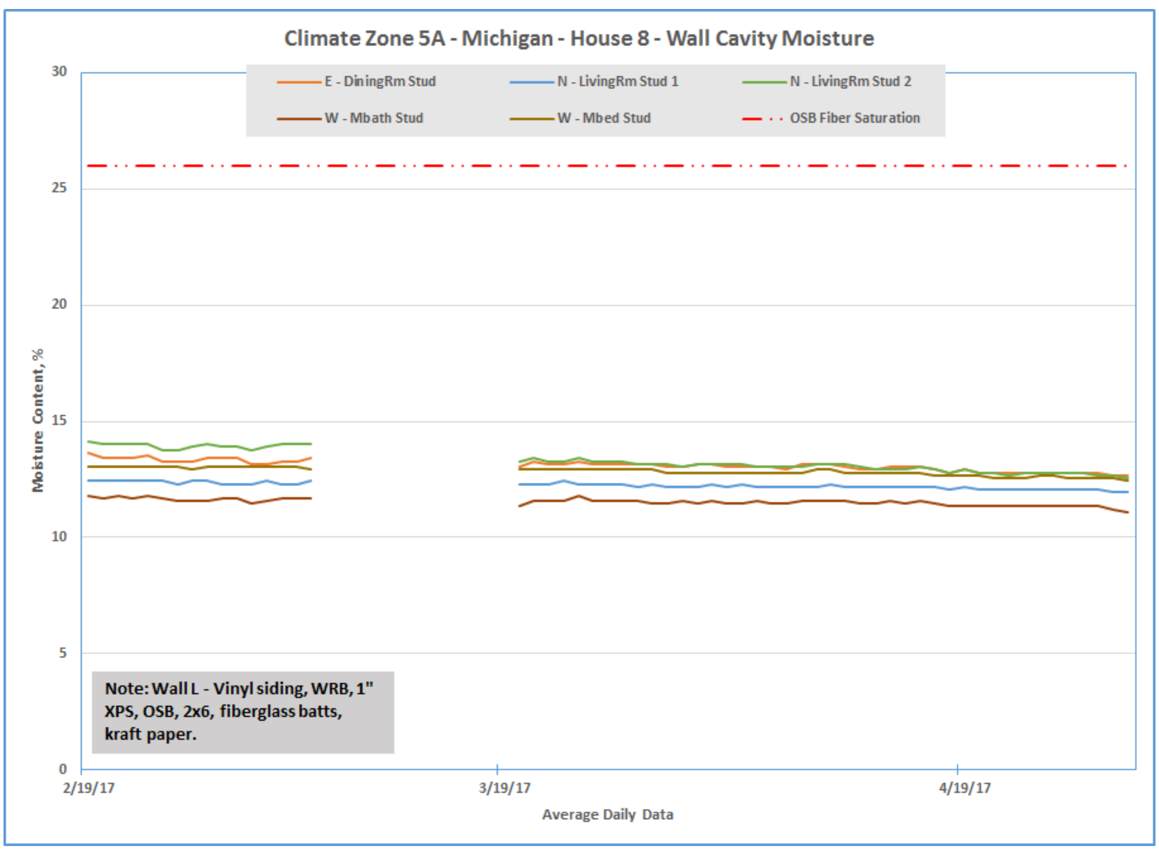
Stud Moisture Content Charts



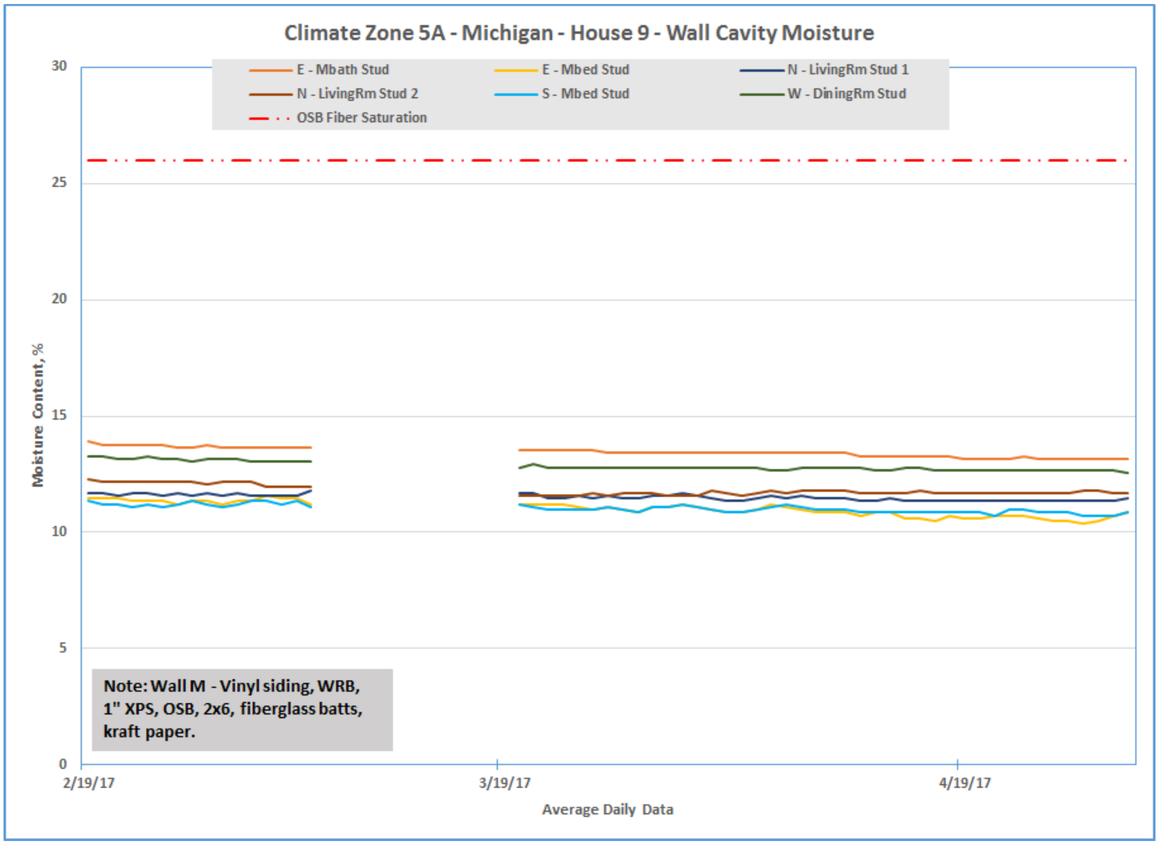


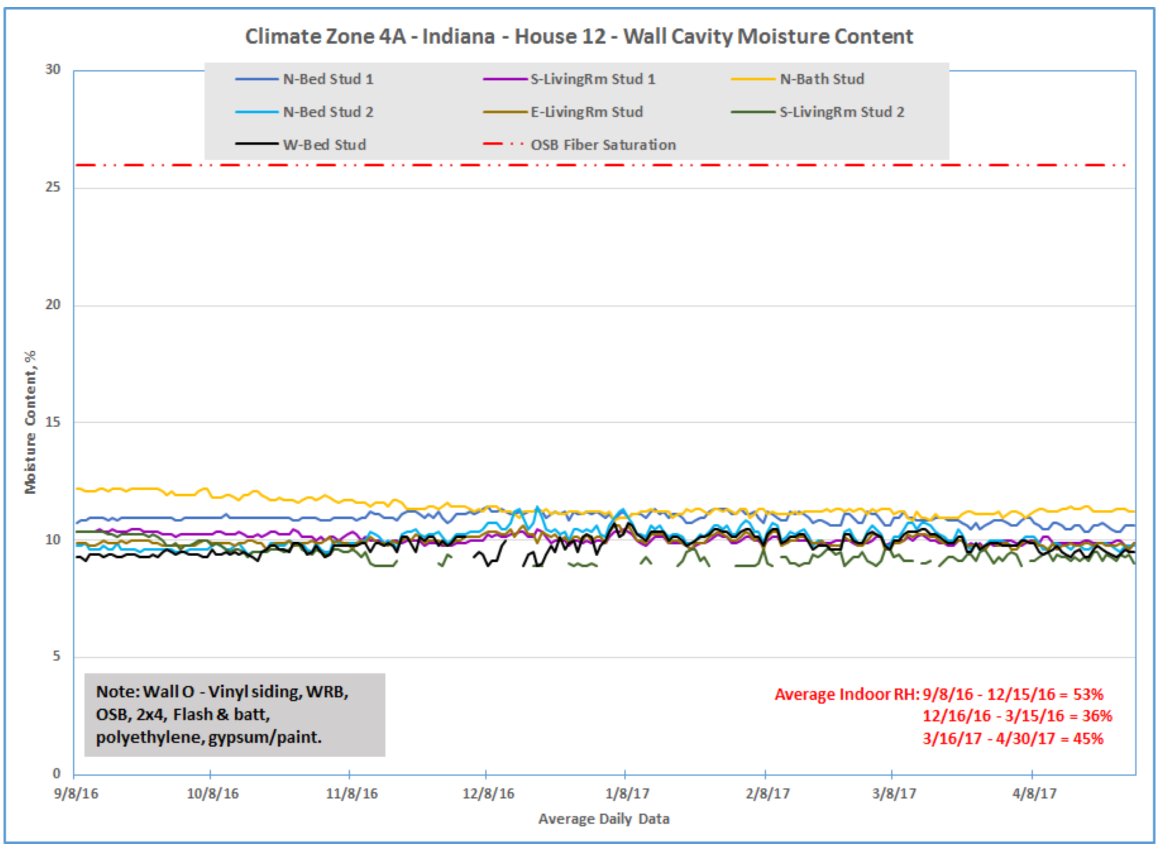


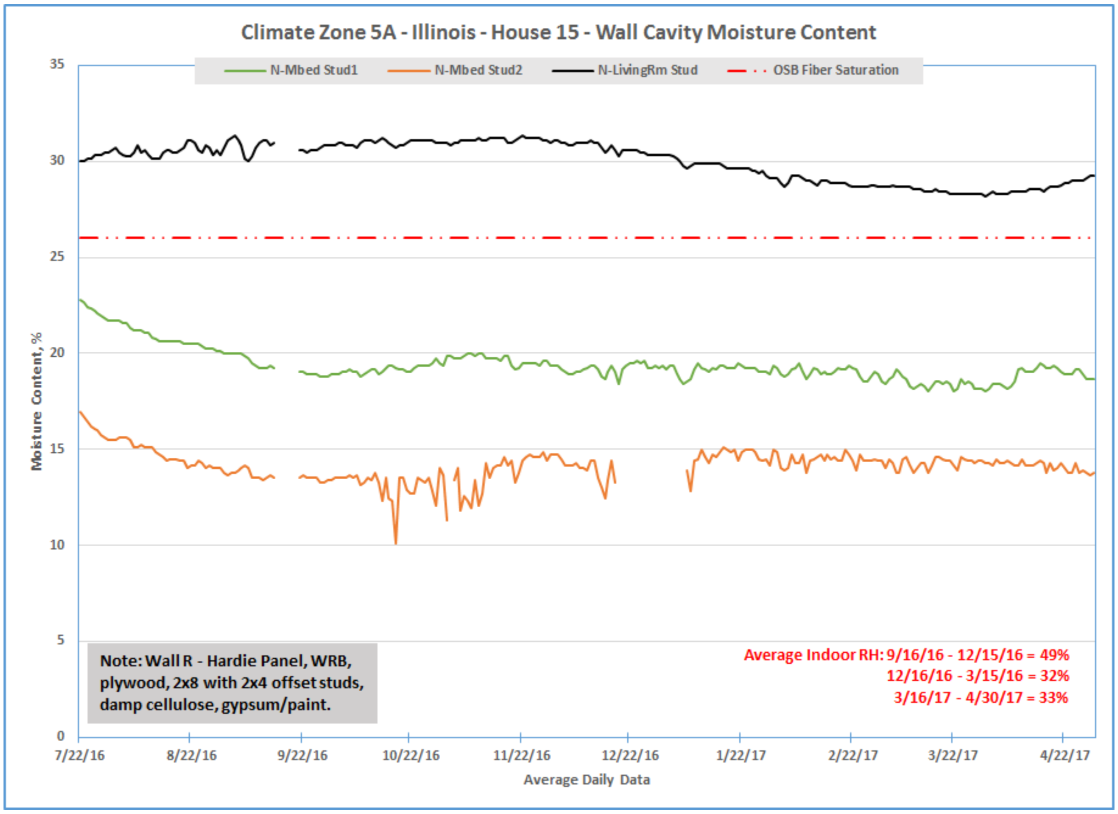
Climate Zone 5A - Pennsylvannia - House 7 - Wall Cavity Moisture Content
N-DiningRm Stud
N-Mbed Stud
E-Mbed Stud 1
E-Mbed Stud 2
E-Mbath Stud
S-Bed1 Stud
W-Bed2 Stud
OSB Fiber Saturation
Moisture Content, %
Note: Wall K - Cement board siding, 1.5" PIC, WRB, Zip-R, 2x6, fiberglass batts, Kraft paper, gypsum/paint.
Average Indoor RH: 1/9/17 - 3/15/17 = 40%
3/15/17 - 4/30/17 = 41%
11/8/16
12/8/16
1/8/17
2/8/17
3/8/17
4/8/17
Average Daily Data



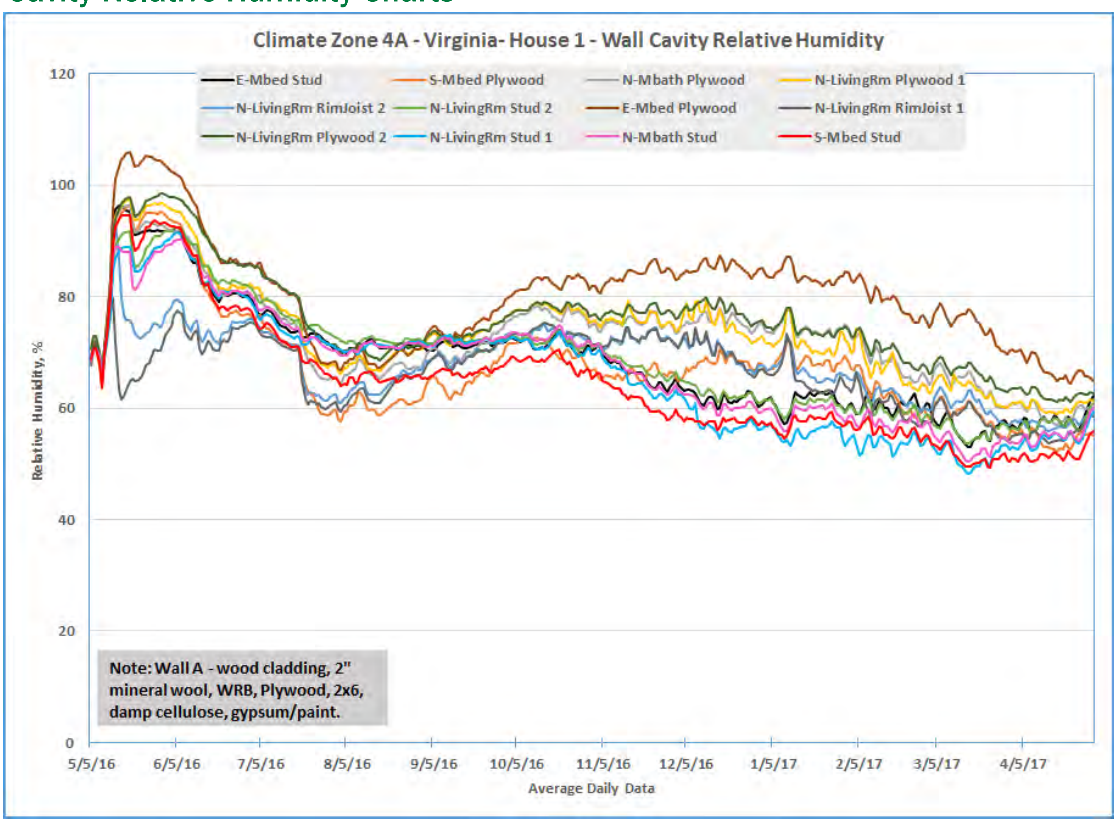
Climate Zone 5A - Michigan - House 8 - Wall Cavity Moisture
E - DiningRm Stud
N - LivingRm Stud 1
N - LivingRm Stud 2
W - Mbath Stud
W - Mbed Stud
OSB Fiber Saturation
Moisture Content, %
Note: Wall L - Vinyl siding, WRB, 1" XPS, OSB, 2x6, fiberglass batts, kraft paper.
2/19/17
3/19/17
4/19/17
Average Daily Data

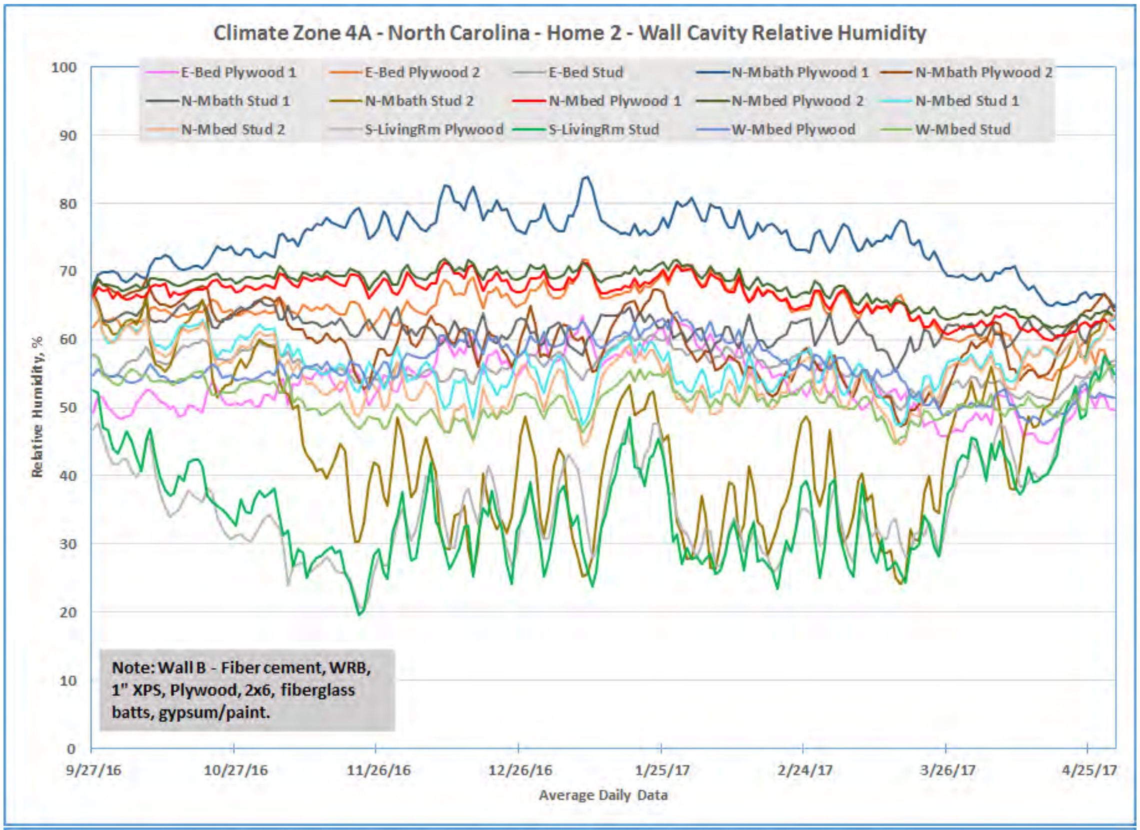

Climate Zone 5A - Michigan - House 9 - Wall Cavity Moisture
E - Mbath Stud
E - Mbed Stud
N - LivingRm Stud 1
N - LivingRm Stud 2
S - Mbed Stud
W - DiningRm Stud
OSB Fiber Saturation
Moisture Content, %
30
25
20
15
10
5
0
Note: Wall M - Vinyl siding, WRB, 1" XPS, OSB, 2x6, fiberglass batts, kraft paper.
2/19/17
3/19/17
4/19/17
Average Daily Data

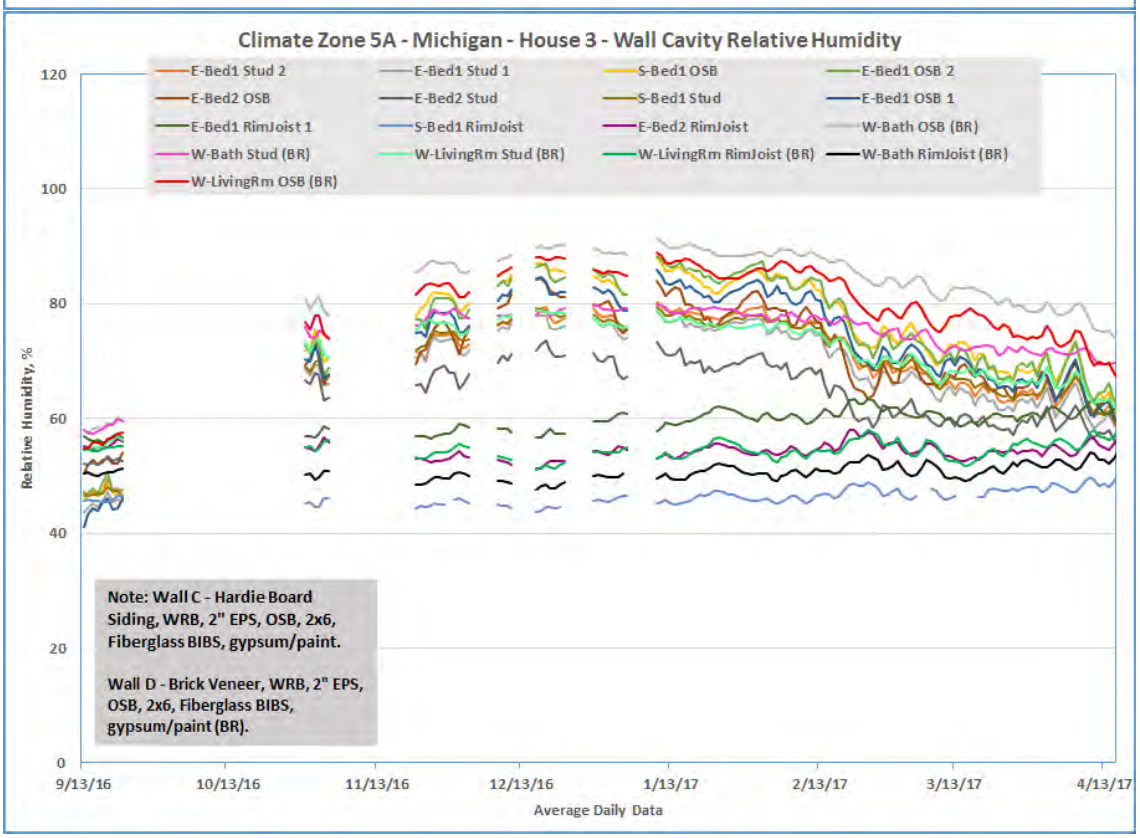

Climate Zone 4A - Indiana - House 12 - Wall Cavity Moisture Content
N-Bed Stud 1
S-LivingRm Stud 1
N-Bath Stud
N-Bed Stud 2
E-LivingRm Stud
S-LivingRm Stud 2
W-Bed Stud
OSB Fiber Saturation
Moisture Content, %
30
25
20
15
10
5
0
Note: Wall O - Vinyl siding, WRB, OSB, 2x4, Flash & batt, polyethylene, gypsum/paint.
Average Indoor RH: 9/8/16 - 12/15/16 = 53%
12/16/16 - 3/15/16 = 36%
3/16/17 - 4/30/17 = 45%
9/8/16
10/8/16
11/8/16
12/8/16
1/8/17
2/8/17
3/8/17
4/8/17
Average Daily Data

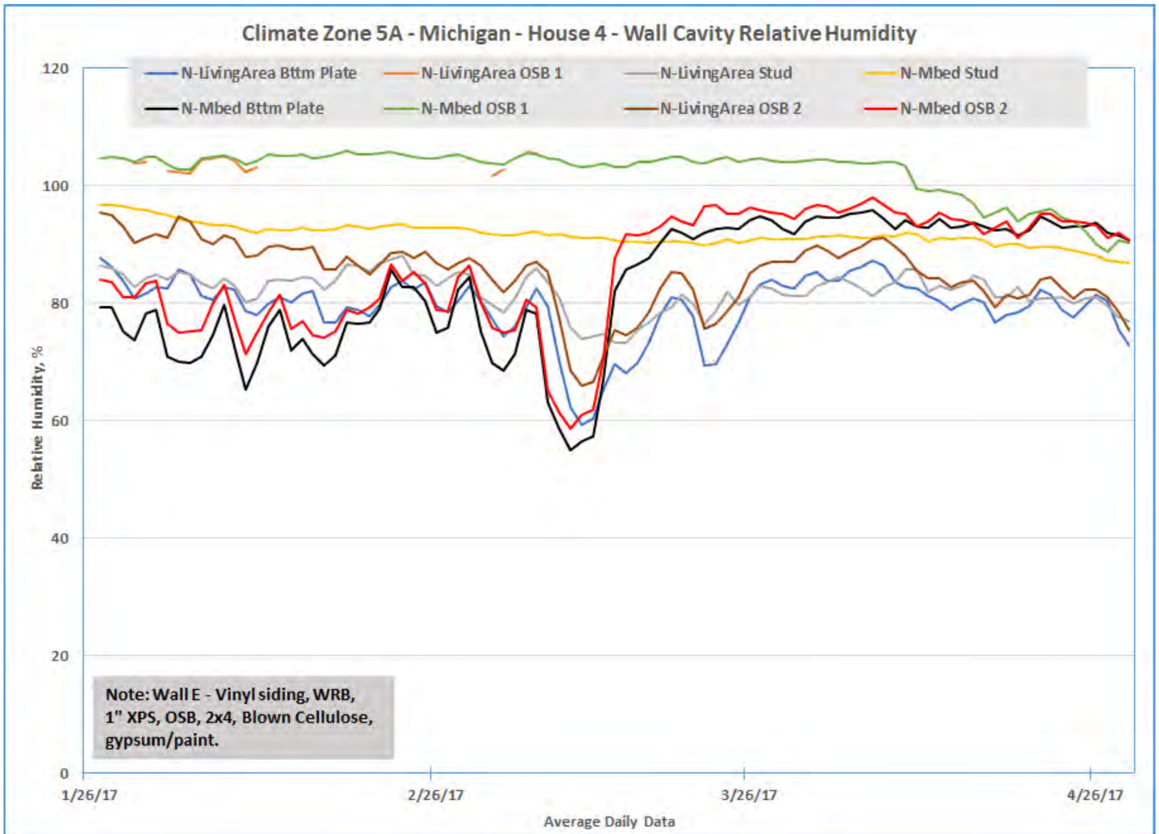


Wall Cavity Relative Humidity Charts

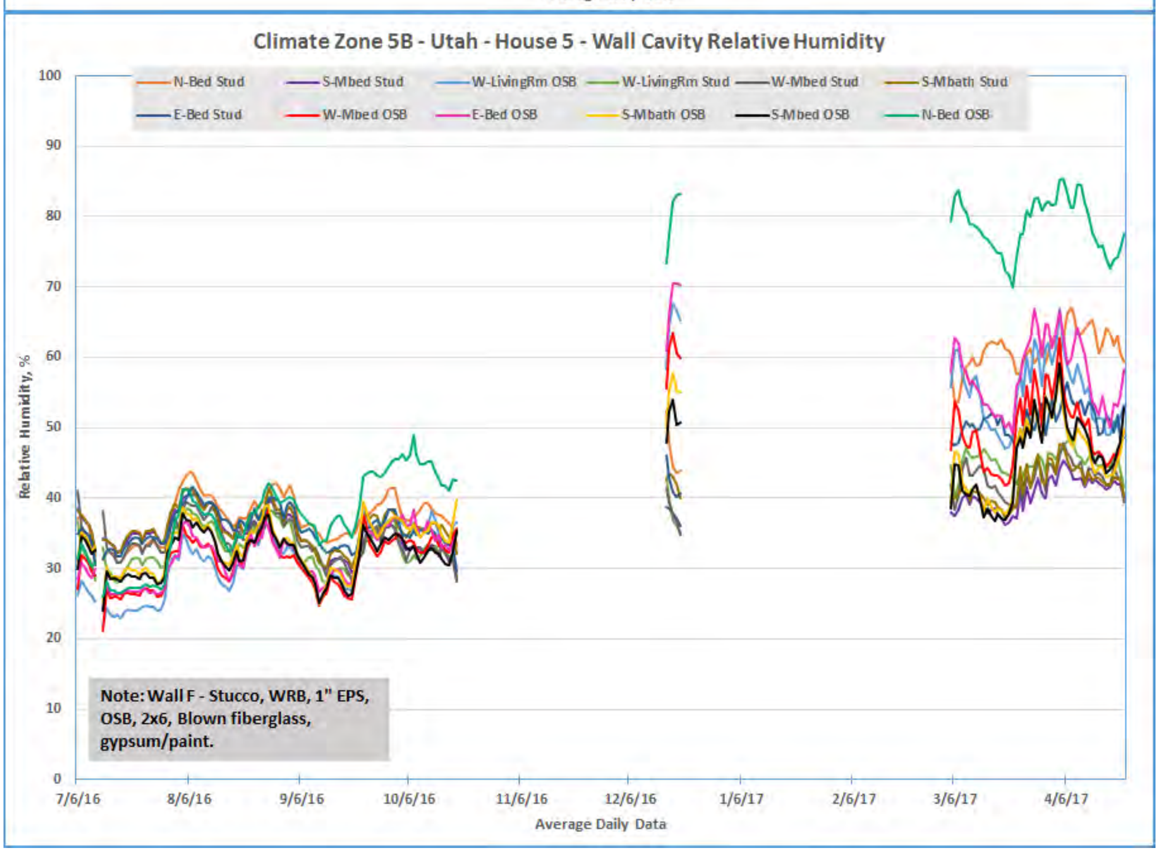



Climate Zone 4A - North Carolina - Home 2 - Wall Cavity Relative Humidity
E-Bed Plywood 1
E-Bed Plywood 2
E-Bed Stud
N-Mbath Plywood 1
N-Mbath Plywood 2
N-Mbath Stud 1
N-Mbath Stud 2
N-Mbed Plywood 1
N-Mbed Plywood 2
N-Mbed Stud 1
N-Mbed Stud 2
S-LivingRm Plywood
S-LivingRm Stud
W-Mbed Plywood
W-Mbed Stud
Relative Humidity, %
Note: Wall B - Fiber cement, WRB, 1" XPS, Plywood, 2x6, fiberglass batts, gypsum/paint.
9/27/16
10/27/16
11/26/16
12/26/16
1/25/17
2/24/17
3/26/17
4/25/17
Average Daily Data

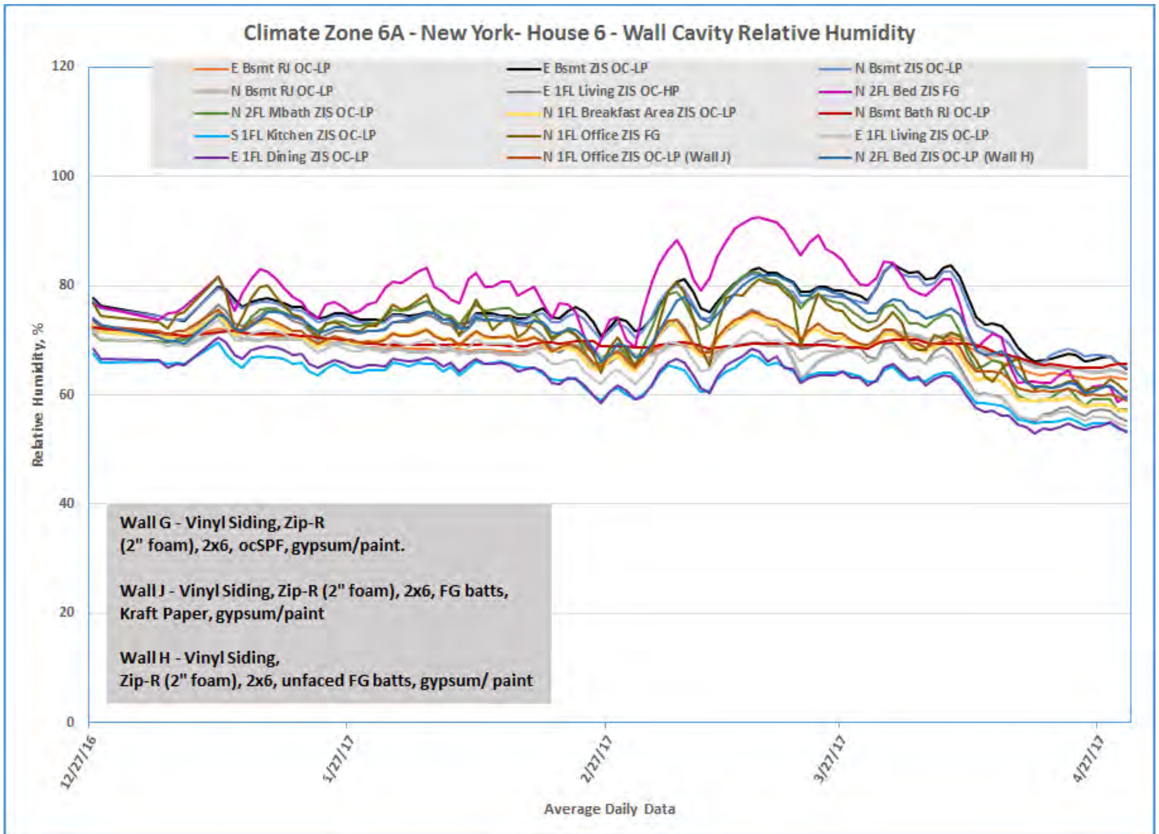

Climate Zone 5A - Michigan - House 3 - Wall Cavity Relative Humidity
E-Bed1 Stud 2
E-Bed1 Stud 1
S-Bed1 OSB
E-Bed1 OSB 2
E-Bed2 OSB
E-Bed2 Stud
S-Bed1 Stud
E-Bed1 OSB 1
E-Bed1 RimJoist 1
S-Bed1 RimJoist
E-Bed2 RimJoist
W-Bath OSB (BR)
W-Bath Stud (BR)
W-LivingRm Stud (BR)
W-LivingRm RimJoist (BR)
W-Bath RimJoist (BR)
W-LivingRm OSB (BR)
Relative Humidity, %
Note: Wall C - Hardie Board Siding, WRB, 2" EPS, OSB, 2x6, Fiberglass BIBS, gypsum/paint.
Wall D - Brick Veneer, WRB, 2" EPS, OSB, 2x6, Fiberglass BIBS, gypsum/paint (BR).
9/13/16
10/13/16
11/13/16
12/13/16
1/13/17
2/13/17
3/13/17
4/13/17
Average Daily Data

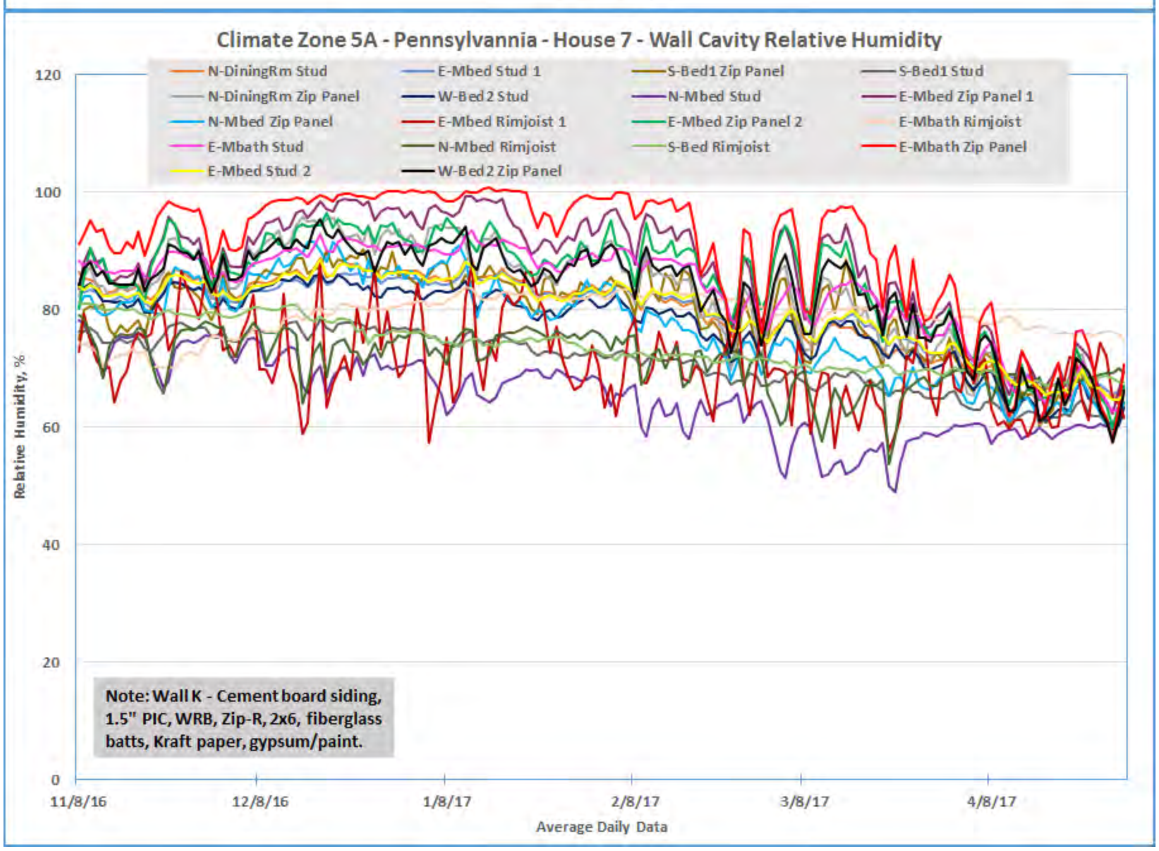


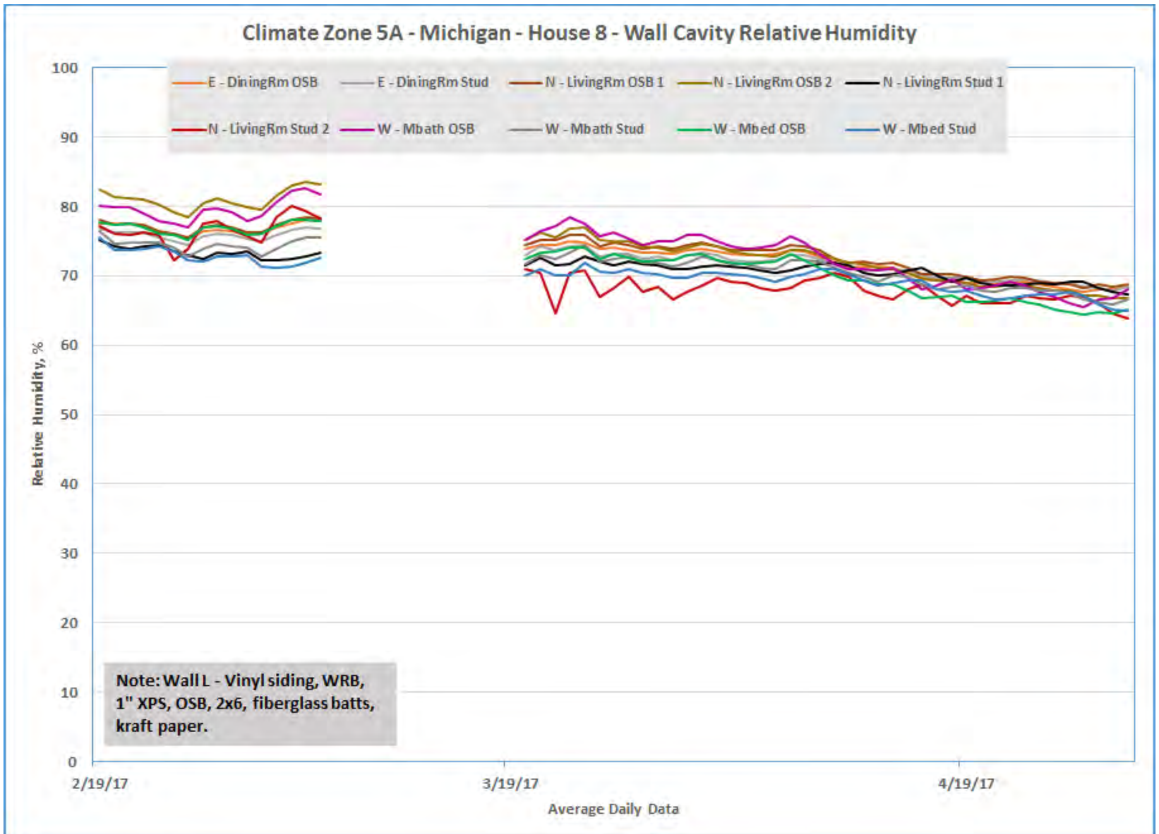
Climate Zone 5A - Michigan - House 4 - Wall Cavity Relative Humidity
N-LivingArea Bttm Plate
N-LivingArea OSB 1
N-LivingArea Stud
N-Mbed Stud
N-Mbed Bttm Plate
N-Mbed OSB 1
N-LivingArea OSB 2
N-Mbed OSB 2
Relative Humidity, %
120
100
80
60
40
20
0
Note: Wall E - Vinyl siding, WRB, 1" XPS, OSB, 2x4, Blown Cellulose, gypsum/paint.
1/26/17
2/26/17
3/26/17
4/26/17
Average Daily Data

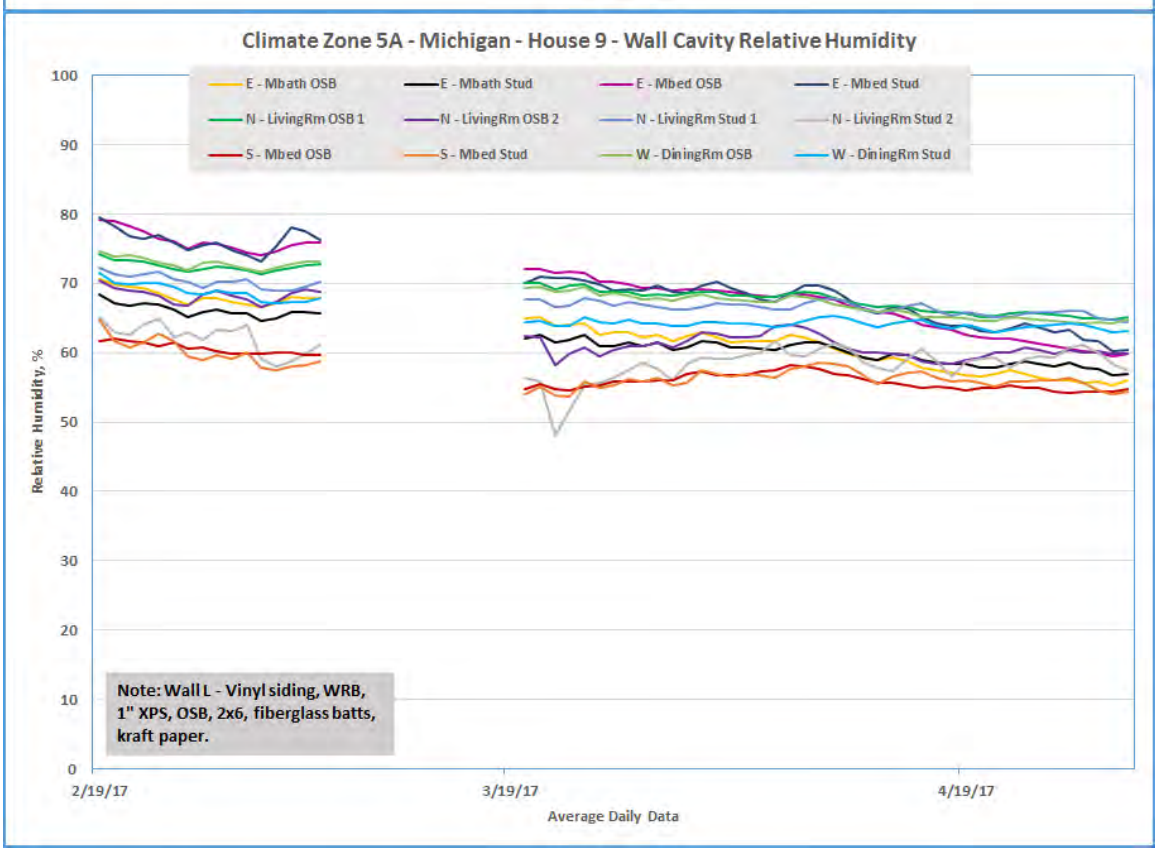


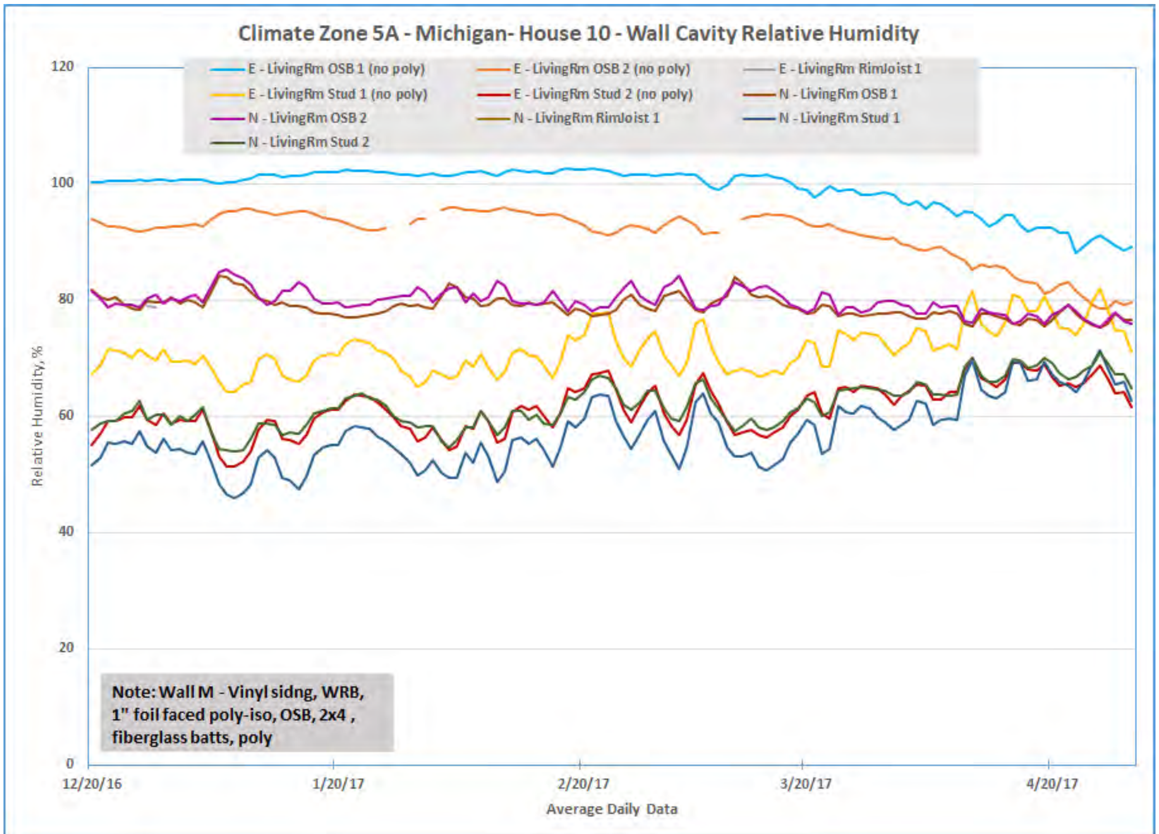
Climate Zone 5B - Utah - House 5 - Wall Cavity Relative Humidity
N-Bed Stud
S-Mbed Stud
W-LivingRm OSB
W-LivingRm Stud
W-Mbed Stud
S-Mbath Stud
E-Bed Stud
W-Mbed OSB
E-Bed OSB
S-Mbath OSB
S-Mbed OSB
N-Bed OSB
Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Note: Wall F - Stucco, WRB, 1" EPS, OSB, 2x6, Blown fiberglass, gypsum/paint.
7/6/16
8/6/16
9/6/16
10/6/16
11/6/16
12/6/16
1/6/17
2/6/17
3/6/17
4/6/17
Average Daily Data


Climate Zone 6A - New York- House 6 - Wall Cavity Relative Humidity
E Bsmt RJ OC-LP
E Bsmt ZIS OC-LP
N Bsmt ZIS OC-LP
N Bsmt RJ OC-LP
E 1FL Living ZIS OC-HP
N 2FL Bed ZIS FG
N 2FL Mbath ZIS OC-LP
N 1FL Breakfast Area ZIS OC-LP
N Bsmt Bath RJ OC-LP
S 1FL Kitchen ZIS OC-LP
N 1FL Office ZIS FG
E 1FL Living ZIS OC-LP
E 1FL Dining ZIS OC-LP
N 1FL Office ZIS OC-LP (Wall J)
N 2FL Bed ZIS OC-LP (Wall H)
Relative Humidity, %
Wall G - Vinyl Siding, Zip-R (2" foam), 2x6, ocSPF, gypsum/paint.
Wall J - Vinyl Siding, Zip-R (2" foam), 2x6, FG batts, Kraft Paper, gypsum/paint
Wall H - Vinyl Siding, Zip-R (2" foam), 2x6, unfaced FG batts, gypsum/ paint
12/27/16
1/27/17
2/27/17
3/27/17
4/27/17
Average Daily Data

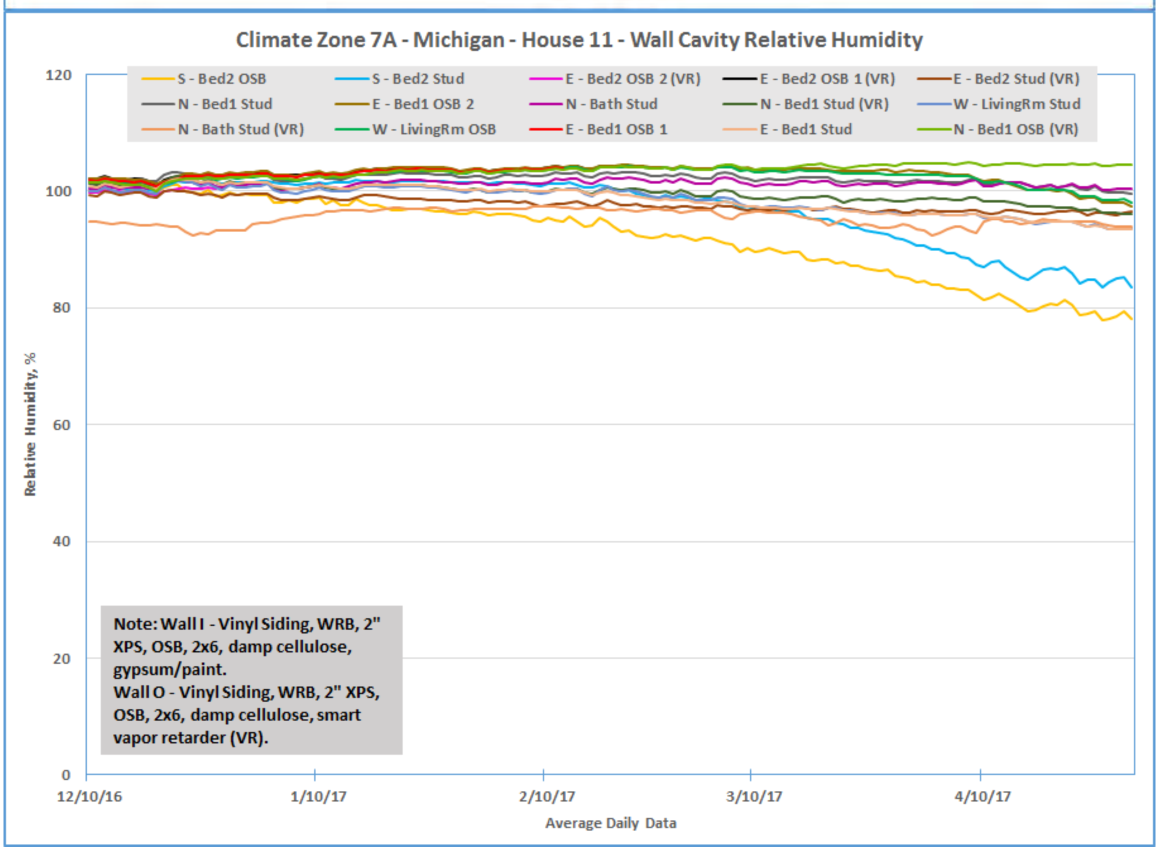

Climate Zone 5A - Pennsylvannia - House 7 - Wall Cavity Relative Humidity
N-DiningRm Stud
E-Mbed Stud 1
S-Bed1 Zip Panel
S-Bed1 Stud
N-DiningRm Zip Panel
W-Bed2 Stud
N-Mbed Stud
E-Mbed Zip Panel 1
N-Mbed Zip Panel
E-Mbed Rimjoist 1
E-Mbed Zip Panel 2
E-Mbath Rimjoist
E-Mbath Stud
N-Mbed Rimjoist
S-Bed Rimjoist
E-Mbath Zip Panel
E-Mbed Stud 2
W-Bed2 Zip Panel
Relative Humidity, %
Note: Wall K - Cement board siding, 1.5" PIC, WRB, Zip-R, 2x6, fiberglass batts, Kraft paper, gypsum/paint.
11/8/16
12/8/16
1/8/17
2/8/17
3/8/17
4/8/17
Average Daily Data


Climate Zone 5A - Michigan - House 8 - Wall Cavity Relative Humidity
E - DiningRm OSB
E - DiningRm Stud
N - LivingRm OSB 1
N - LivingRm OSB 2
N - LivingRm Stud 1
N - LivingRm Stud 2
W - Mbath OSB
W - Mbath Stud
W - Mbed OSB
W - Mbed Stud
Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Note: Wall L - Vinyl siding, WRB, 1" XPS, OSB, 2x6, fiberglass batts, kraft paper.
2/19/17
3/19/17
4/19/17
Average Daily Data

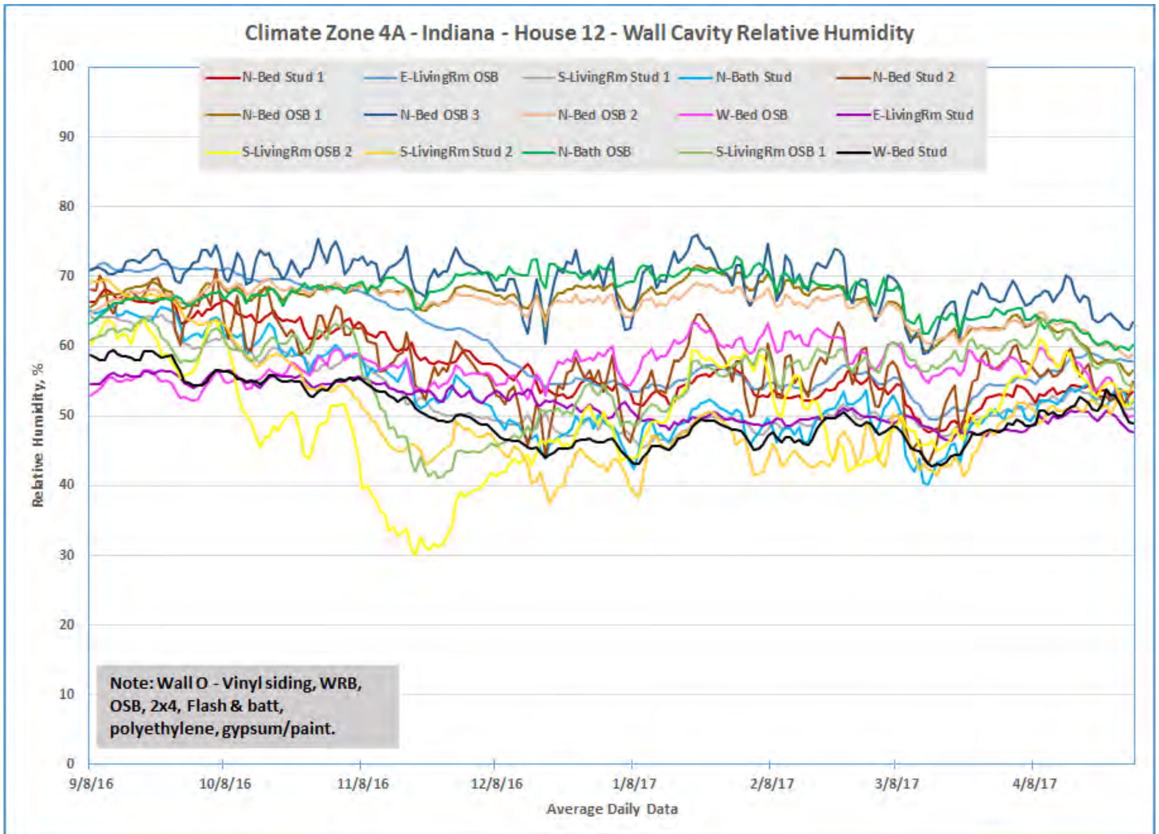

Climate Zone 5A - Michigan - House 9 - Wall Cavity Relative Humidity
E - Mbath OSB
E - Mbath Stud
E - Mbed OSB
E - Mbed Stud
N - LivingRm OSB 1
N - LivingRm OSB 2
N - LivingRm Stud 1
N - LivingRm Stud 2
S - Mbed OSB
S - Mbed Stud
W - DiningRm OSB
W - DiningRm Stud
Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
Note: Wall L - Vinyl siding, WRB, 1" XPS, OSB, 2x6, fiberglass batts, kraft paper.
2/19/17
3/19/17
4/19/17
Average Daily Data

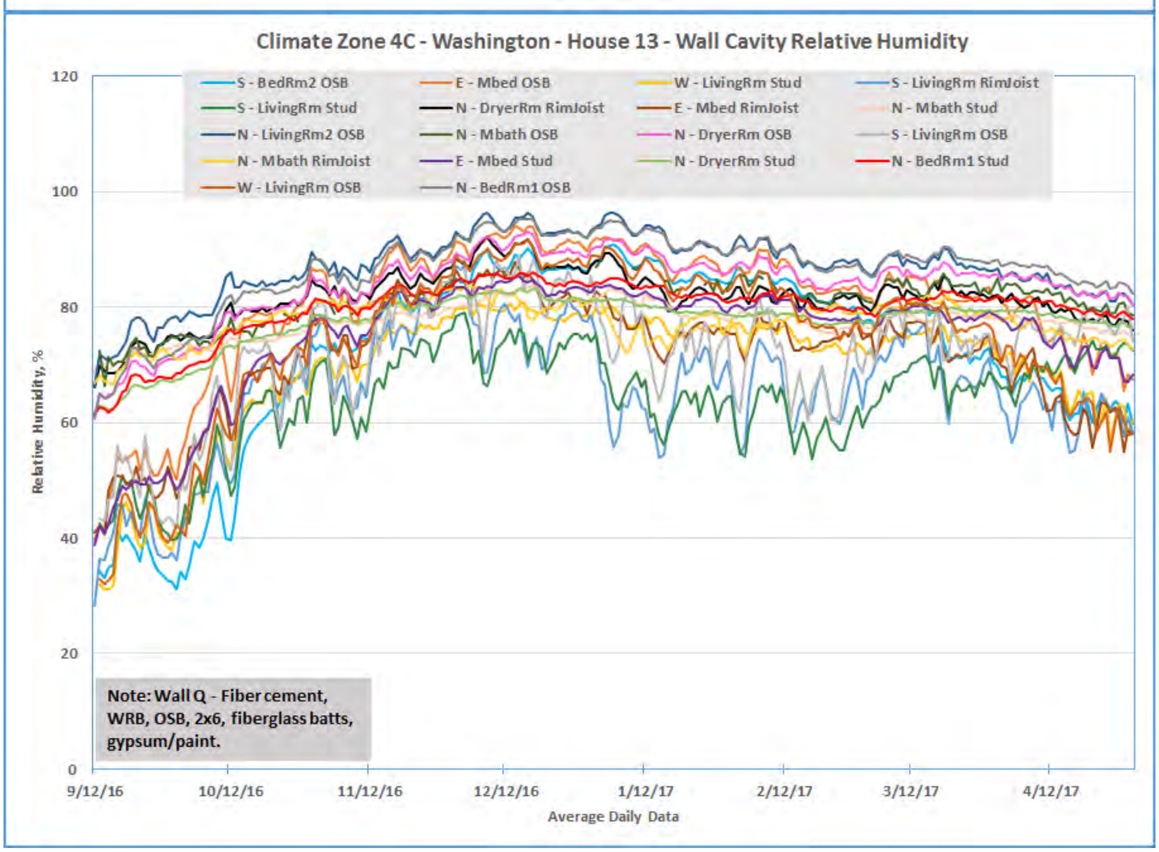


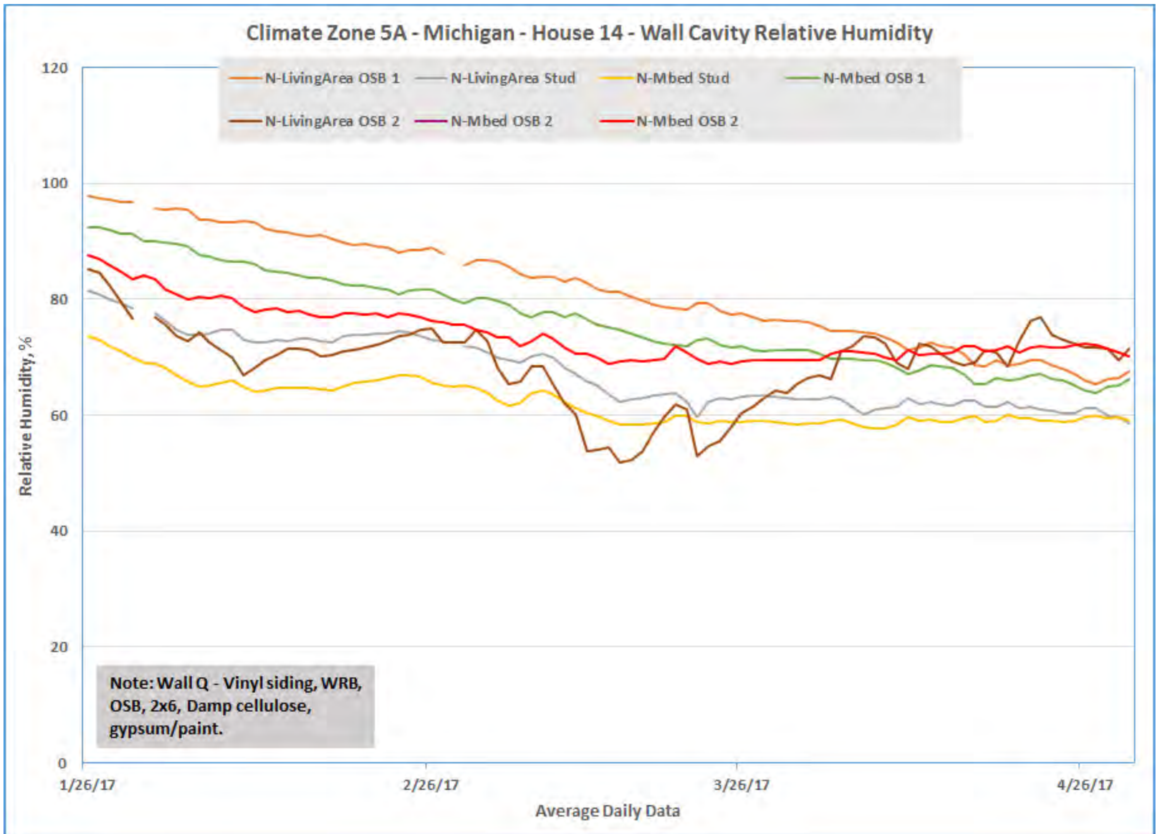
Climate Zone 5A - Michigan- House 10 - Wall Cavity Relative Humidity
E - LivingRm OSB 1 (no poly)
E - LivingRm OSB 2 (no poly)
E - LivingRm RimJoist 1
E - LivingRm Stud 1 (no poly)
E - LivingRm Stud 2 (no poly)
N - LivingRm OSB 1
N - LivingRm OSB 2
N - LivingRm RimJoist 1
N - LivingRm Stud 1
N - LivingRm Stud 2
Relative Humidity, %
Note: Wall M - Vinyl sidng, WRB, 1" foil faced poly-iso, OSB, 2x4 , fiberglass batts, poly
12/20/16
1/20/17
2/20/17
3/20/17
4/20/17
Average Daily Data

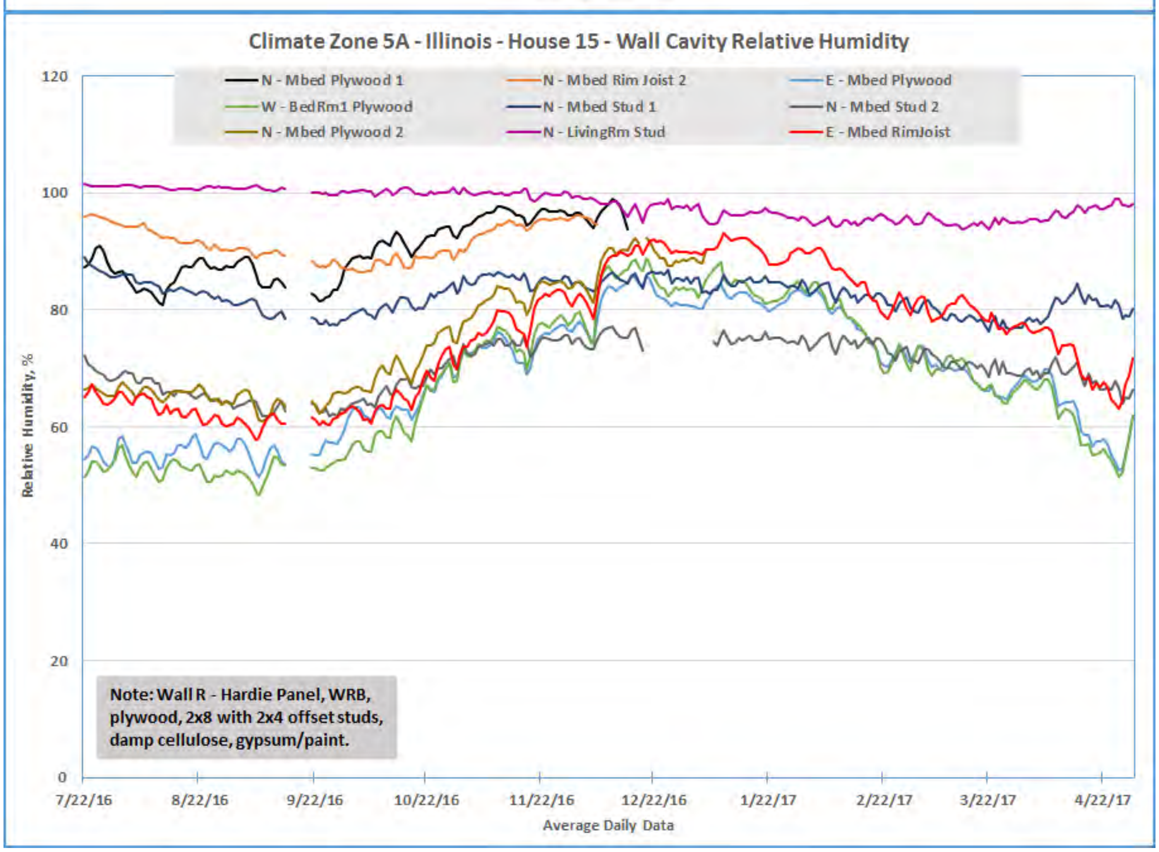


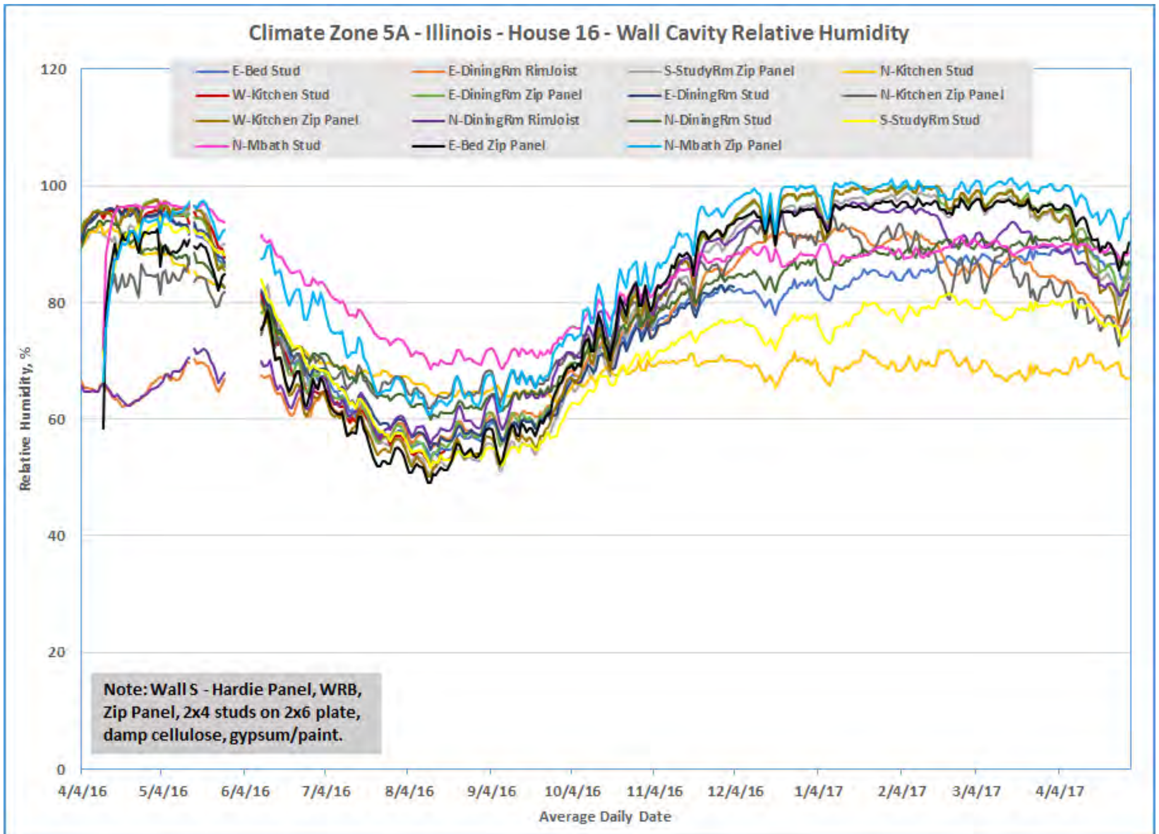
Climate Zone 7A - Michigan - House 11 - Wall Cavity Relative Humidity
S - Bed2 OSB
S - Bed2 Stud
E - Bed2 OSB 2 (VR)
E - Bed2 OSB 1 (VR)
E - Bed2 Stud (VR)
N - Bed1 Stud
E - Bed1 OSB 2
N - Bath Stud
N - Bed1 Stud (VR)
W - LivingRm Stud
N - Bath Stud (VR)
W - LivingRm OSB
E - Bed1 OSB 1
E - Bed1 Stud
N - Bed1 OSB (VR)
Relative Humidity, %
Note: Wall I - Vinyl Siding, WRB, 2" XPS, OSB, 2x6, damp cellulose, gypsum/paint.
Wall O - Vinyl Siding, WRB, 2" XPS, OSB, 2x6, damp cellulose, smart vapor retarder (VR).
12/10/16
1/10/17
2/10/17
3/10/17
4/10/17
Average Daily Data

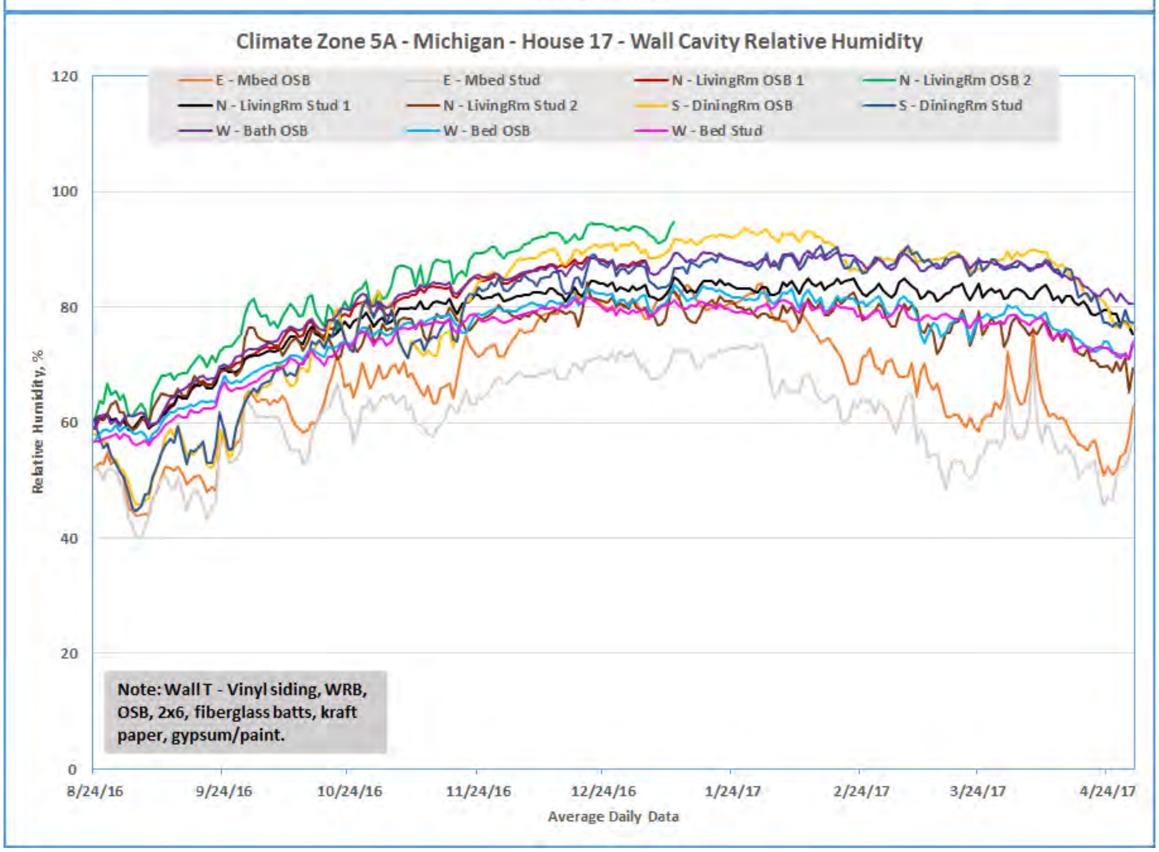

Climate Zone 4A - Indiana - House 12 - Wall Cavity Relative Humidity
N-Bed Stud 1
E-LivingRm OSB
S-LivingRm Stud 1
N-Bath Stud
N-Bed Stud 2
N-Bed OSB 1
N-Bed OSB 3
N-Bed OSB 2
W-Bed OSB
E-LivingRm Stud
S-LivingRm OSB 2
S-LivingRm Stud 2
N-Bath OSB
S-LivingRm OSB 1
W-Bed Stud
Relative Humidity, %
Note: Wall O - Vinyl siding, WRB, OSB, 2x4, Flash & batt, polyethylene, gypsum/paint.
9/8/16
10/8/16
11/8/16
12/8/16
1/8/17
2/8/17
3/8/17
4/8/17
Average Daily Data

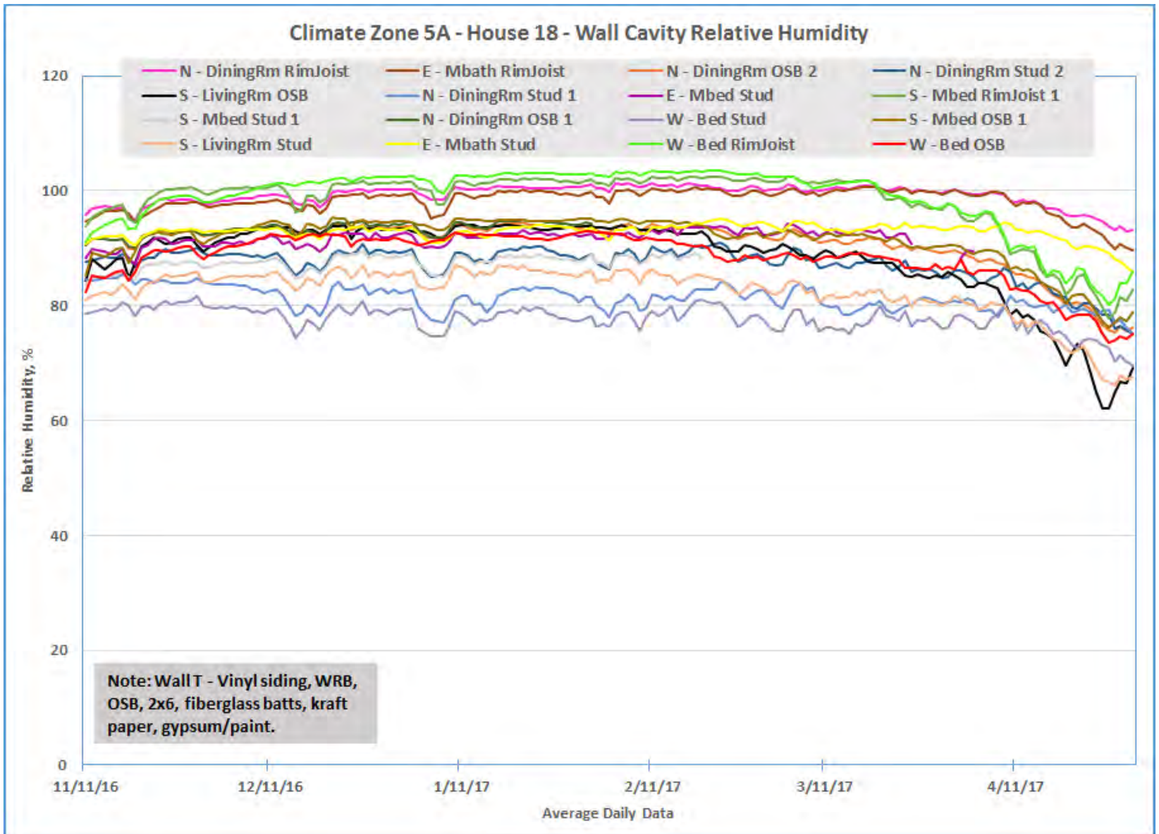

Climate Zone 4C - Washington - House 13 - Wall Cavity Relative Humidity
S - BedRm2 OSB
E - Mbed OSB
W - LivingRm Stud
S - LivingRm RimJoist
S - LivingRm Stud
N - DryerRm RimJoist
E - Mbed RimJoist
N - Mbath Stud
N - LivingRm2 OSB
N - Mbath OSB
N - DryerRm OSB
S - LivingRm OSB
N - Mbath RimJoist
E - Mbed Stud
N - DryerRm Stud
N - BedRm1 Stud
W - LivingRm OSB
N - BedRm1 OSB
Relative Humidity, %
Note: Wall Q - Fiber cement, WRB, OSB, 2x6, fiberglass batts, gypsum/paint.
9/12/16
10/12/16
11/12/16
12/12/16
1/12/17
2/12/17
3/12/17
4/12/17
Average Daily Data


Climate Zone 5A - Michigan - House 14 - Wall Cavity Relative Humidity
N-LivingArea OSB 1
N-LivingArea Stud
N-Mbed Stud
N-Mbed OSB 1
N-LivingArea OSB 2
N-Mbed OSB 2
N-Mbed OSB 2
Relative Humidity, %
120
100
80
60
40
20
0
Note: Wall Q - Vinyl siding, WRB, OSB, 2x6, Damp cellulose, gypsum/paint.
1/26/17
2/26/17
3/26/17
4/26/17
Average Daily Data

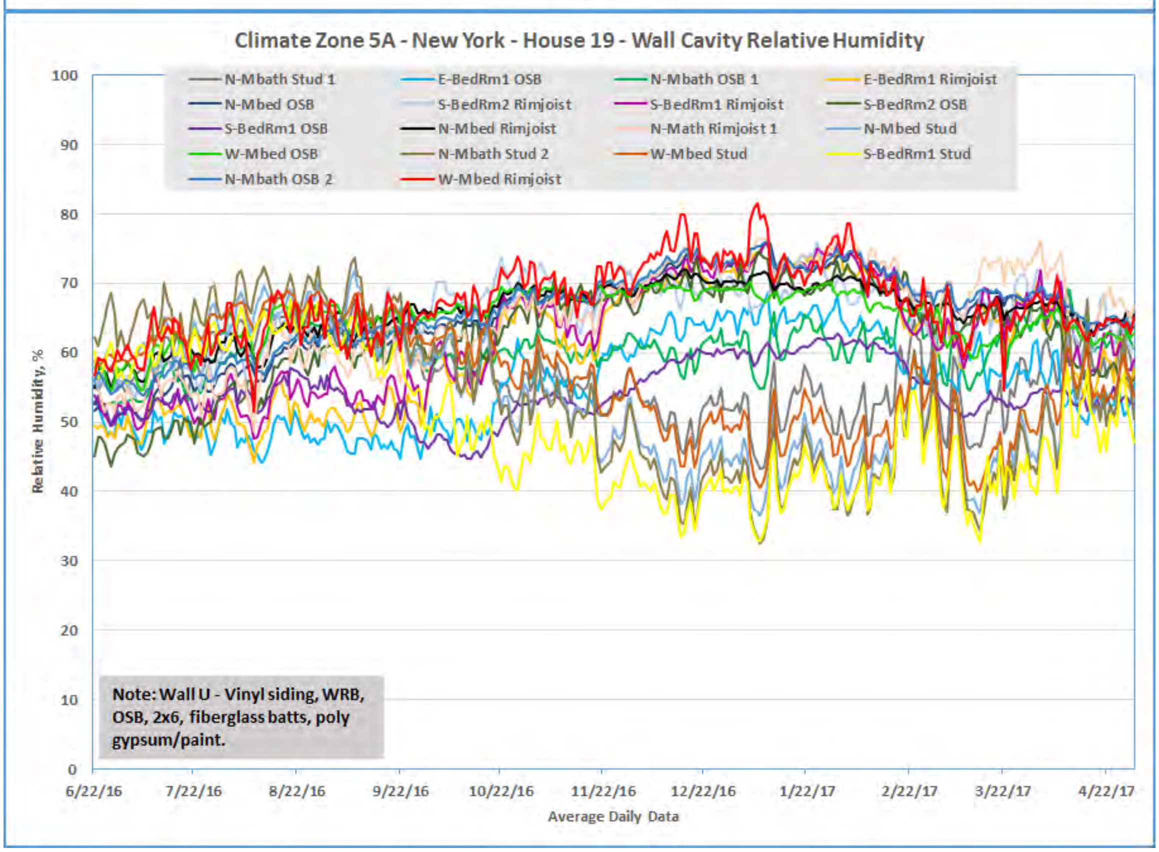

Climate Zone 5A - Illinois - House 15 - Wall Cavity Relative Humidity
N - Mbed Plywood 1
N - Mbed Rim Joist 2
E - Mbed Plywood
W - BedRm1 Plywood
N - Mbed Stud 1
N - Mbed Stud 2
N - Mbed Plywood 2
N - LivingRm Stud
E - Mbed RimJoist
Relative Humidity, %
120
100
80
60
40
20
0
Note: Wall R - Hardie Panel, WRB, plywood, 2x8 with 2x4 offset studs, damp cellulose, gypsum/paint.
7/22/16
8/22/16
9/22/16
10/22/16
11/22/16
12/22/16
1/22/17
2/22/17
3/22/17
4/22/17
Average Daily Data


Climate Zone 5A - Illinois - House 16 - Wall Cavity Relative Humidity
E-Bed Stud
E-DiningRm RimJoist
S-StudyRm Zip Panel
N-Kitchen Stud
W-Kitchen Stud
E-DiningRm Zip Panel
E-DiningRm Stud
N-Kitchen Zip Panel
W-Kitchen Zip Panel
N-DiningRm RimJoist
N-DiningRm Stud
S-StudyRm Stud
N-Mbath Stud
E-Bed Zip Panel
N-Mbath Zip Panel
Relative Humidity, %
Note: Wall S - Hardie Panel, WRB, Zip Panel, 2x4 studs on 2x6 plate, damp cellulose, gypsum/paint.
Average Daily Date

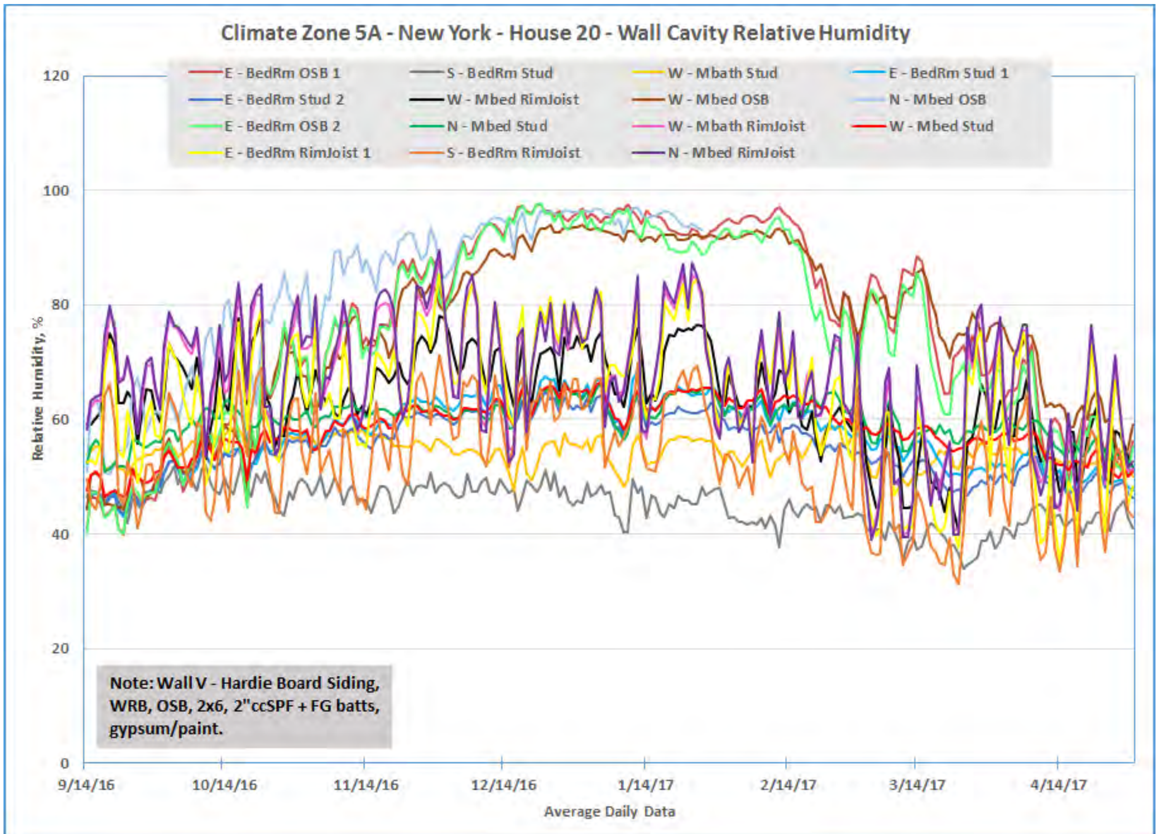

Climate Zone 5A - Michigan - House 17 - Wall Cavity Relative Humidity
E - Mbed OSB
E - Mbed Stud
N - LivingRm OSB 1
N - LivingRm OSB 2
N - LivingRm Stud 1
N - LivingRm Stud 2
S - DiningRm OSB
S - DiningRm Stud
W - Bath OSB
W - Bed OSB
W - Bed Stud
Relative Humidity, %
Note: Wall T - Vinyl siding, WRB, OSB, 2x6, fiberglass batts, kraft paper, gypsum/paint.
Average Daily Data

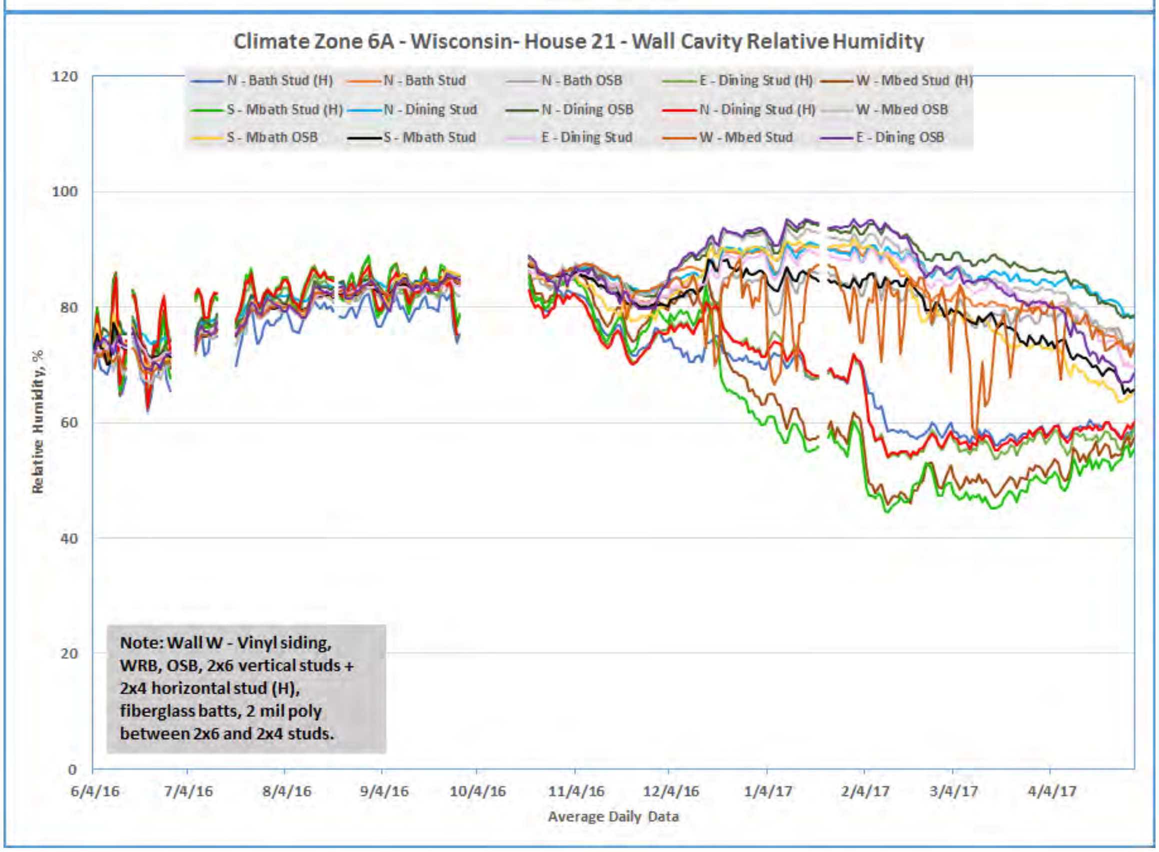


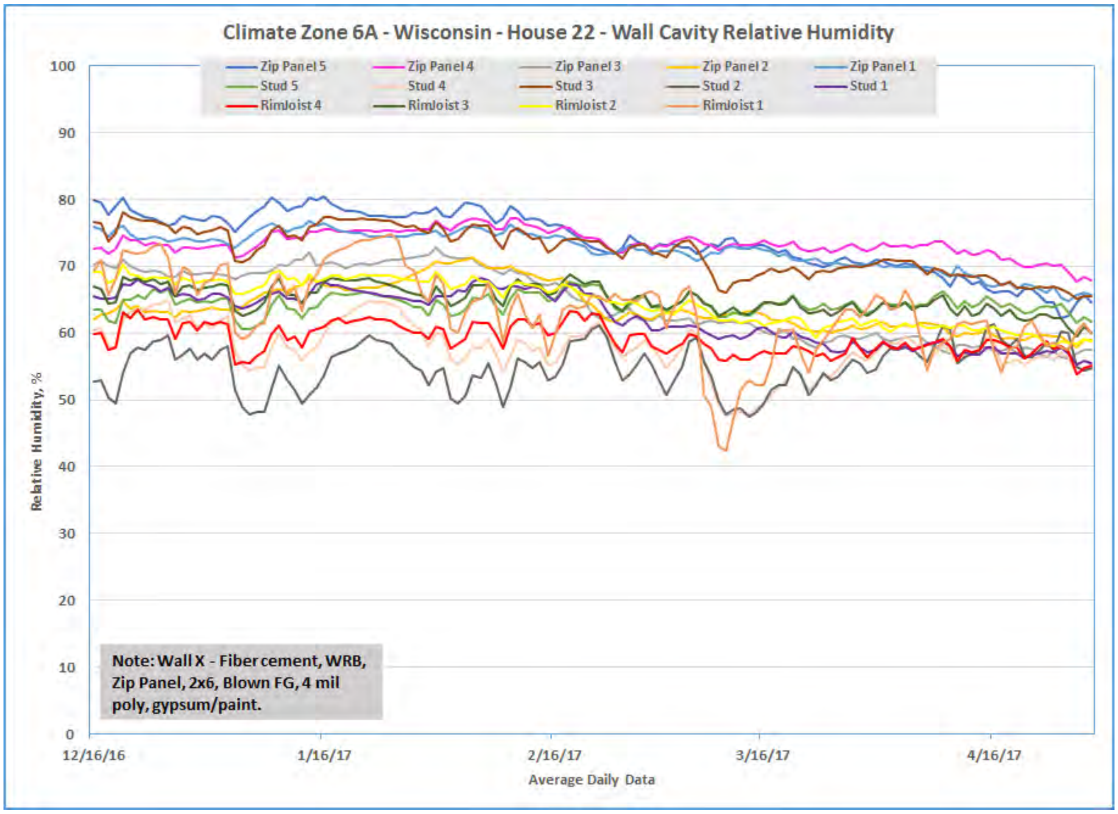
Climate Zone 5A - House 18 - Wall Cavity Relative Humidity
N - DiningRm RimJoist
E - Mbath RimJoist
N - DiningRm OSB 2
N - DiningRm Stud 2
S - LivingRm OSB
N - DiningRm Stud 1
E - Mbed Stud
S - Mbed RimJoist 1
S - Mbed Stud 1
N - DiningRm OSB 1
W - Bed Stud
S - Mbed OSB 1
S - LivingRm Stud
E - Mbath Stud
W - Bed RimJoist
W - Bed OSB
Relative Humidity, %
Note: Wall T - Vinyl siding, WRB, OSB, 2x6, fiberglass batts, kraft paper, gypsum/paint.
11/11/16
12/11/16
1/11/17
2/11/17
3/11/17
4/11/17
Average Daily Data



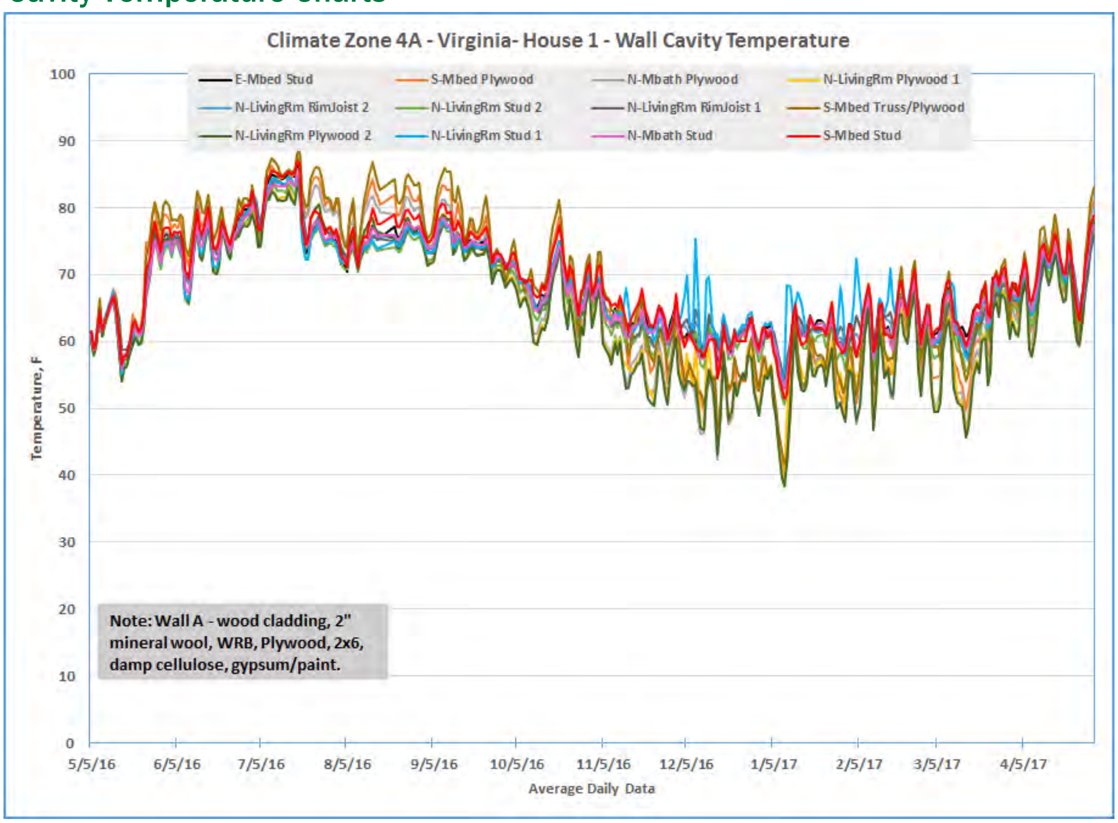
Climate Zone 5A - New York - House 19 - Wall Cavity Relative Humidity
N-Mbath Stud 1
E-BedRm1 OSB
N-Mbath OSB 1
E-BedRm1 Rimjoist
N-Mbed OSB
S-BedRm2 Rimjoist
S-BedRm1 Rimjoist
S-BedRm2 OSB
S-BedRm1 OSB
N-Mbed Rimjoist
N-Math Rimjoist 1
N-Mbed Stud
W-Mbed OSB
N-Mbath Stud 2
W-Mbed Stud
S-BedRm1 Stud
N-Mbath OSB 2
W-Mbed Rimjoist
Relative Humidity, %
Note: Wall U - Vinyl siding, WRB, OSB, 2x6, fiberglass batts, poly gypsum/paint.
6/22/16
7/22/16
8/22/16
9/22/16
10/22/16
11/22/16
12/22/16
1/22/17
2/22/17
3/22/17
4/22/17
Average Daily Data

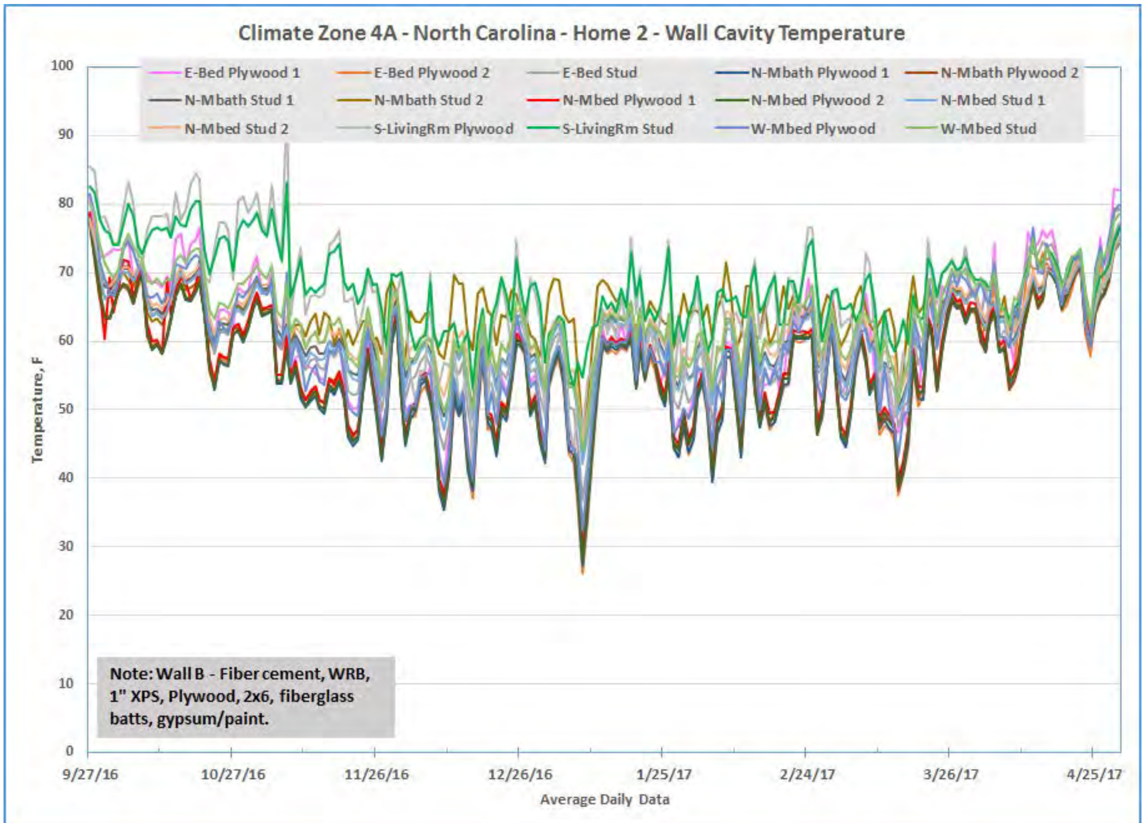

Climate Zone 5A - New York - House 20 - Wall Cavity Relative Humidity
E - BedRm OSB 1
S - BedRm Stud
W - Mbath Stud
E - BedRm Stud 1
E - BedRm Stud 2
W - Mbed RimJoist
W - Mbed OSB
N - Mbed OSB
E - BedRm OSB 2
N - Mbed Stud
W - Mbath RimJoist
W - Mbed Stud
E - BedRm RimJoist 1
S - BedRm RimJoist
N - Mbed RimJoist
Relative Humidity, %
120
100
80
60
40
20
0
Note: Wall V - Hardie Board Siding, WRB, OSB, 2x6, 2"ccSPF + FG batts, gypsum/paint.
9/14/16
10/14/16
11/14/16
12/14/16
1/14/17
2/14/17
3/14/17
4/14/17
Average Daily Data


Climate Zone 6A - Wisconsin- House 21 - Wall Cavity Relative Humidity
N - Bath Stud (H)
N - Bath Stud
N - Bath OSB
E - Dining Stud (H)
W - Mbed Stud (H)
S - Mbath Stud (H)
N - Dining Stud
N - Dining OSB
N - Dining Stud (H)
W - Mbed OSB
S - Mbath OSB
S - Mbath Stud
E - Dining Stud
W - Mbed Stud
E - Dining OSB
Relative Humidity, %
120
100
80
60
40
20
0
Note: Wall W - Vinyl siding, WRB, OSB, 2x6 vertical studs + 2x4 horizontal stud (H), fiberglass batts, 2 mil poly between 2x6 and 2x4 studs.
6/4/16
7/4/16
8/4/16
9/4/16
10/4/16
11/4/16
12/4/16
1/4/17
2/4/17
3/4/17
4/4/17
Average Daily Data

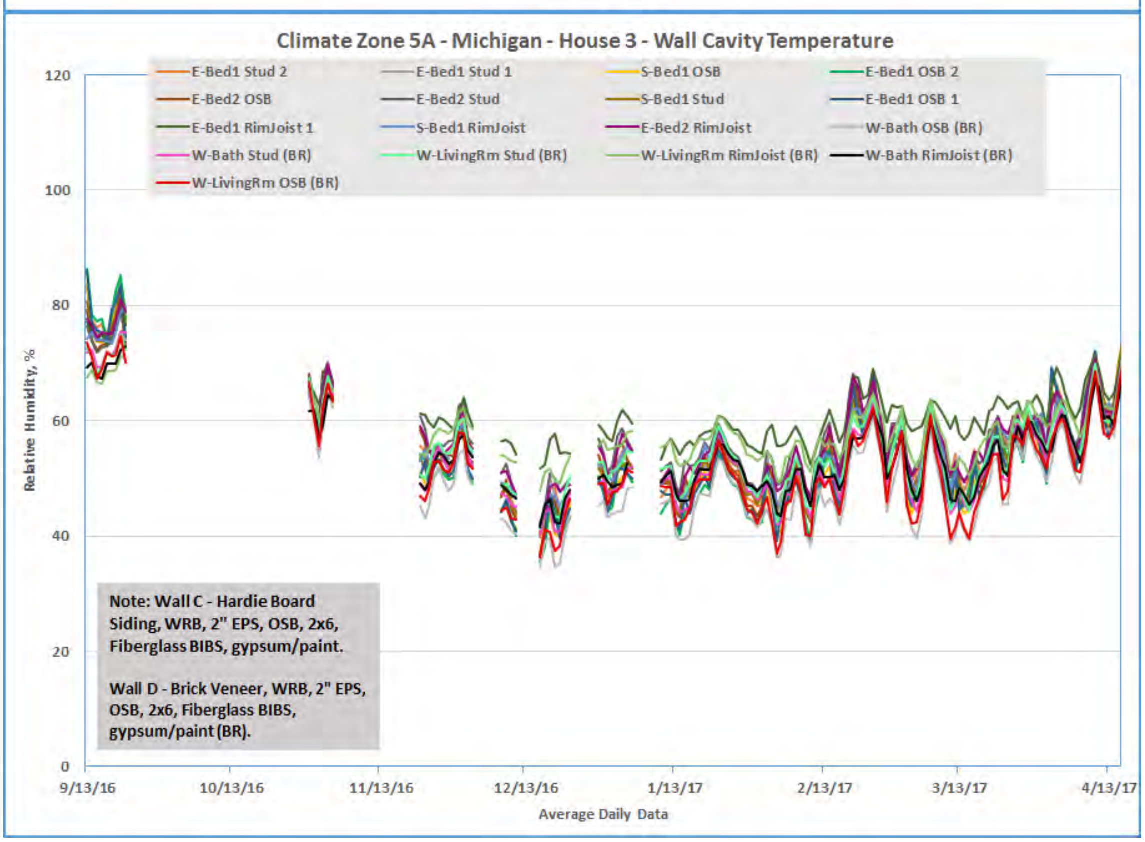


Wall Cavity Temperature Charts

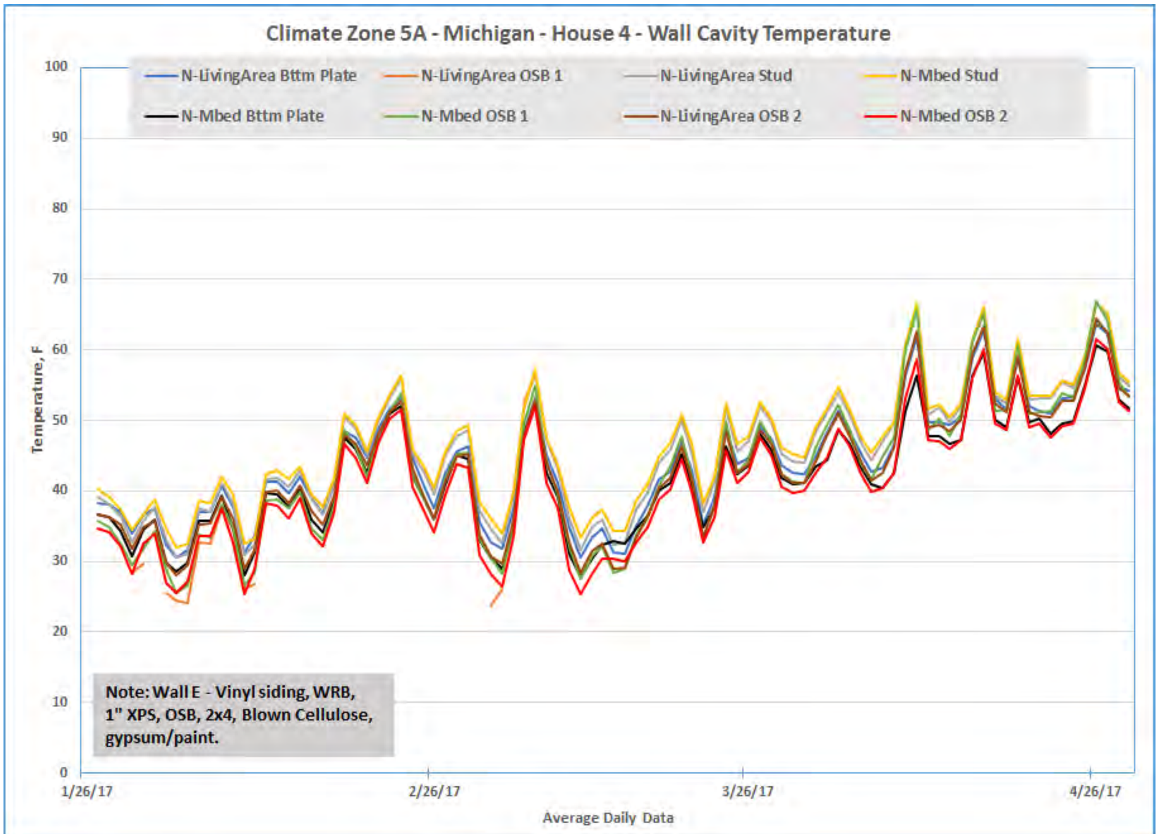




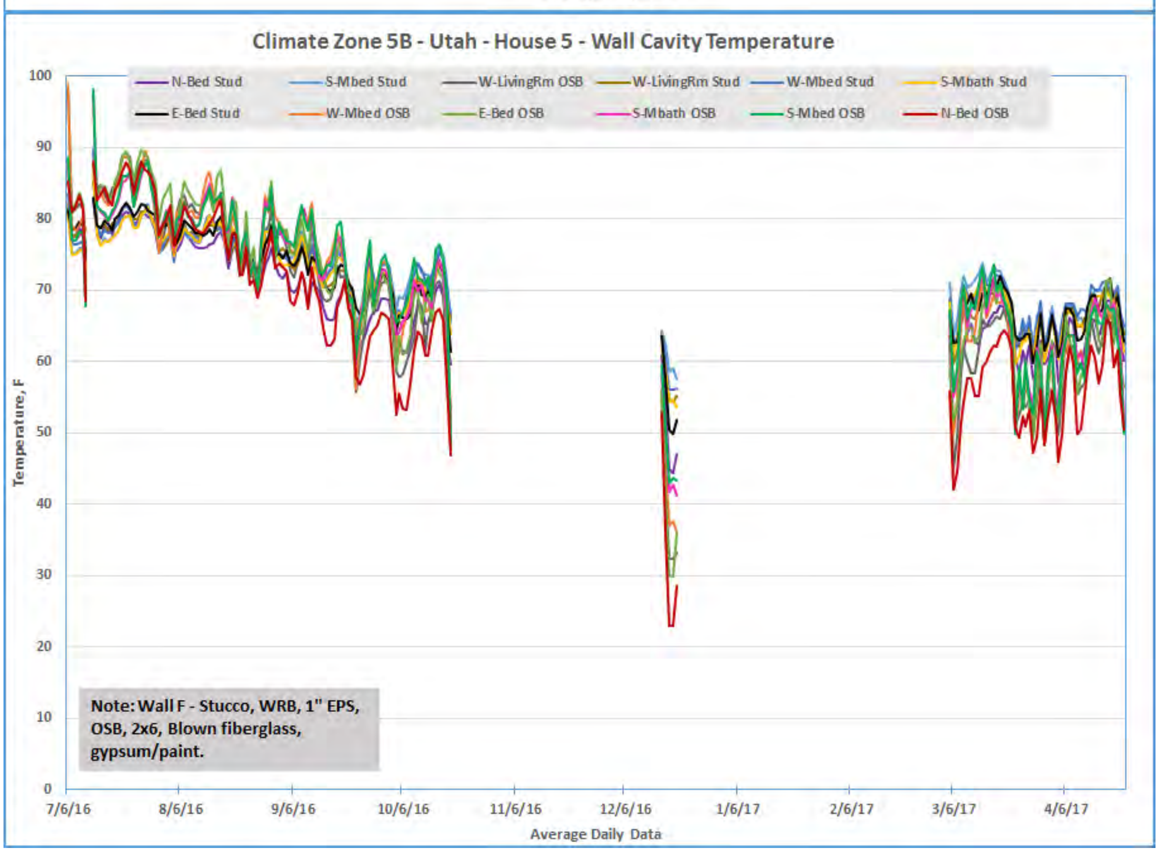
Climate Zone 4A - North Carolina - Home 2 - Wall Cavity Temperature
E-Bed Plywood 1
E-Bed Plywood 2
E-Bed Stud
N-Mbath Plywood 1
N-Mbath Plywood 2
N-Mbath Stud 1
N-Mbath Stud 2
N-Mbed Plywood 1
N-Mbed Plywood 2
N-Mbed Stud 1
N-Mbed Stud 2
S-LivingRm Plywood
S-LivingRm Stud
W-Mbed Plywood
W-Mbed Stud
Temperature, F
Note: Wall B - Fiber cement, WRB, 1" XPS, Plywood, 2x6, fiberglass batts, gypsum/paint.
9/27/16
10/27/16
11/26/16
12/26/16
1/25/17
2/24/17
3/26/17
4/25/17
Average Daily Data



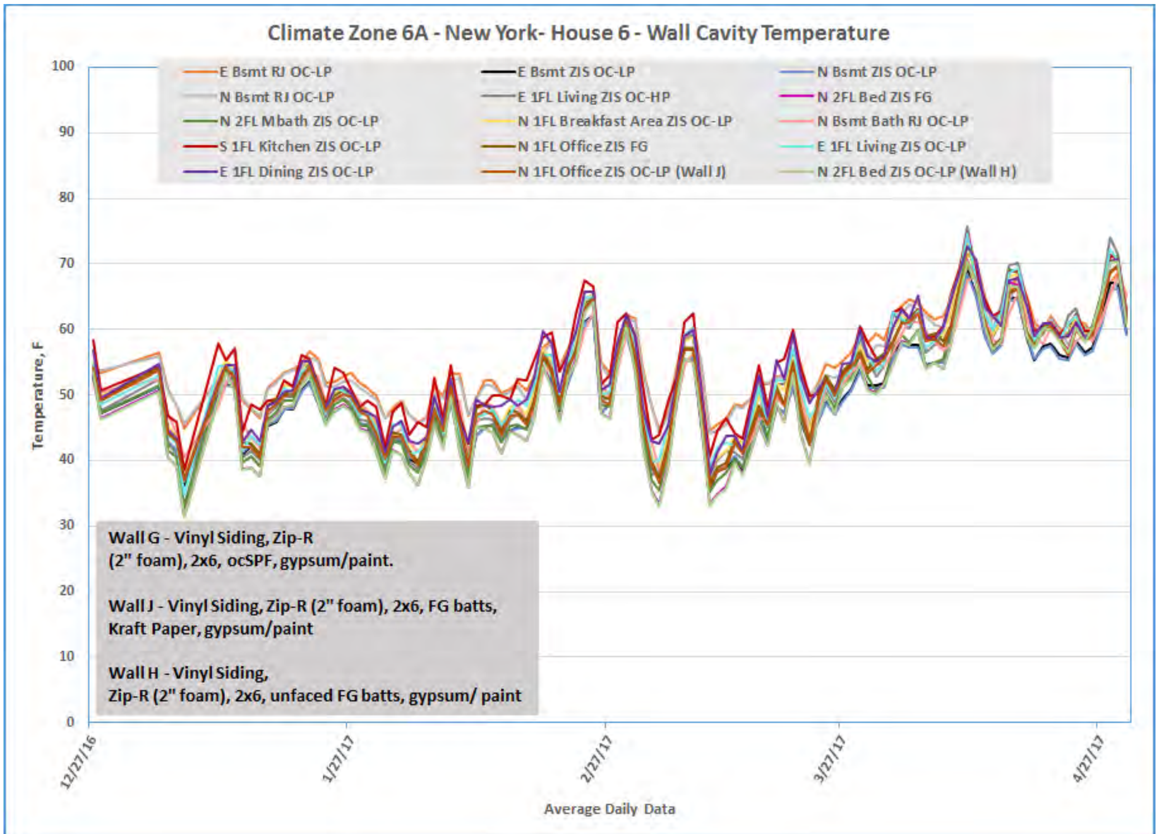
Climate Zone 5A - Michigan - House 3 - Wall Cavity Temperature
E-Bed1 Stud 2
E-Bed1 Stud 1
S-Bed1 OSB
E-Bed1 OSB 2
E-Bed2 OSB
E-Bed2 Stud
S-Bed1 Stud
E-Bed1 OSB 1
E-Bed1 RimJoist 1
S-Bed1 RimJoist
E-Bed2 RimJoist
W-Bath OSB (BR)
W-Bath Stud (BR)
W-LivingRm Stud (BR)
W-LivingRm RimJoist (BR)
W-Bath RimJoist (BR)
W-LivingRm OSB (BR)
Relative Humidity, %
Note: Wall C - Hardie Board Siding, WRB, 2" EPS, OSB, 2x6, Fiberglass BIBS, gypsum/paint.
Wall D - Brick Veneer, WRB, 2" EPS, OSB, 2x6, Fiberglass BIBS, gypsum/paint (BR).
9/13/16
10/13/16
11/13/16
12/13/16
1/13/17
2/13/17
3/13/17
4/13/17
Average Daily Data



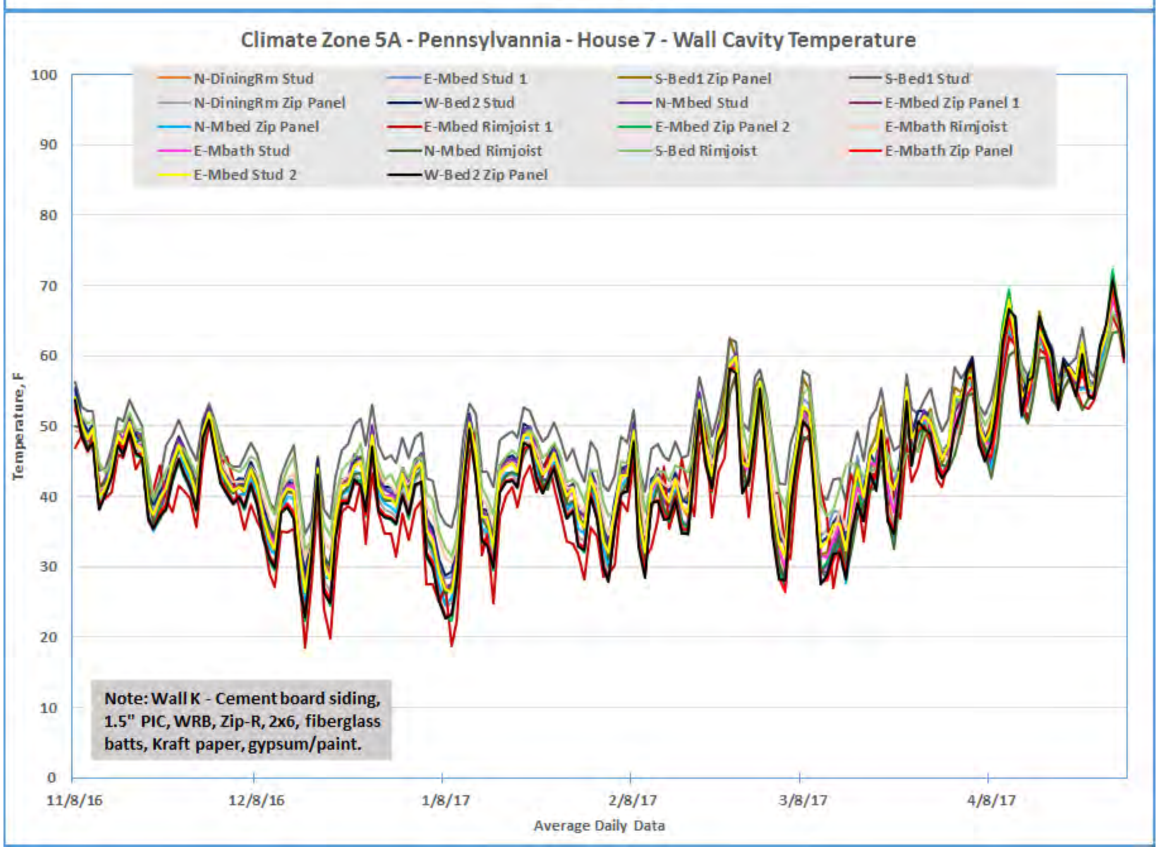
Climate Zone 5A - Michigan - House 4 - Wall Cavity Temperature
N-LivingArea Bttm Plate
N-LivingArea OSB 1
N-LivingArea Stud
N-Mbed Stud
N-Mbed Bttm Plate
N-Mbed OSB 1
N-LivingArea OSB 2
N-Mbed OSB 2
Temperature, F
Note: Wall E - Vinyl siding, WRB, 1" XPS, OSB, 2x4, Blown Cellulose, gypsum/paint.
1/26/17
2/26/17
3/26/17
4/26/17
Average Daily Data



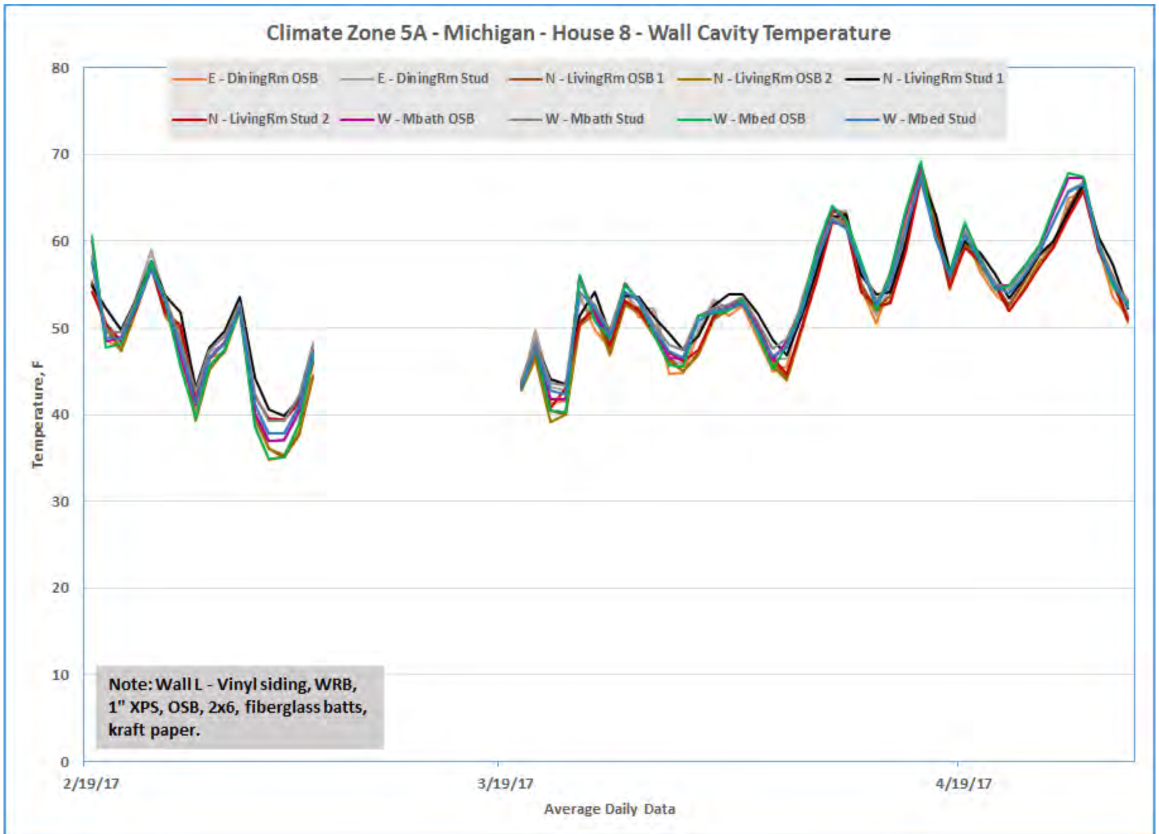
Climate Zone 5B - Utah - House 5 - Wall Cavity Temperature
N-Bed Stud
S-Mbed Stud
W-LivingRm OSB
W-LivingRm Stud
W-Mbed Stud
S-Mbath Stud
E-Bed Stud
W-Mbed OSB
E-Bed OSB
S-Mbath OSB
S-Mbed OSB
N-Bed OSB
Temperature, F
Note: Wall F - Stucco, WRB, 1" EPS, OSB, 2x6, Blown fiberglass, gypsum/paint.
7/6/16
8/6/16
9/6/16
10/6/16
11/6/16
12/6/16
1/6/17
2/6/17
3/6/17
4/6/17
Average Daily Data



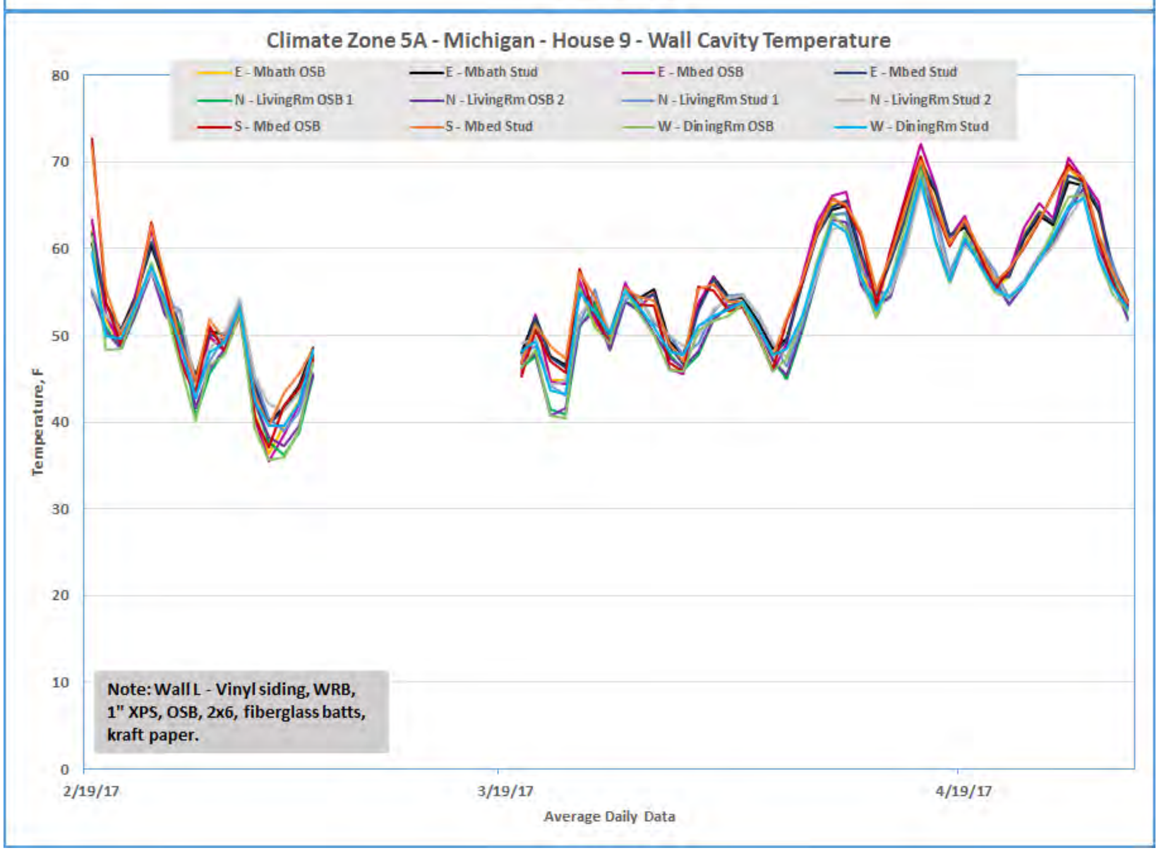
Climate Zone 6A - New York- House 6 - Wall Cavity Temperature
E Bsmt RJ OC-LP
E Bsmt ZIS OC-LP
N Bsmt ZIS OC-LP
N Bsmt RJ OC-LP
E 1FL Living ZIS OC-HP
N 2FL Bed ZIS FG
N 2FL Mbath ZIS OC-LP
N 1FL Breakfast Area ZIS OC-LP
N Bsmt Bath RJ OC-LP
S 1FL Kitchen ZIS OC-LP
N 1FL Office ZIS FG
E 1FL Living ZIS OC-LP
E 1FL Dining ZIS OC-LP
N 1FL Office ZIS OC-LP (Wall J)
N 2FL Bed ZIS OC-LP (Wall H)
Wall G - Vinyl Siding, Zip-R (2" foam), 2x6, ocSPF, gypsum/paint.
Wall J - Vinyl Siding, Zip-R (2" foam), 2x6, FG batts, Kraft Paper, gypsum/paint
Wall H - Vinyl Siding, Zip-R (2" foam), 2x6, unfaced FG batts, gypsum/ paint
Temperature, F
Average Daily Data
12/27/16
1/27/17
2/27/17
3/27/17
4/27/17



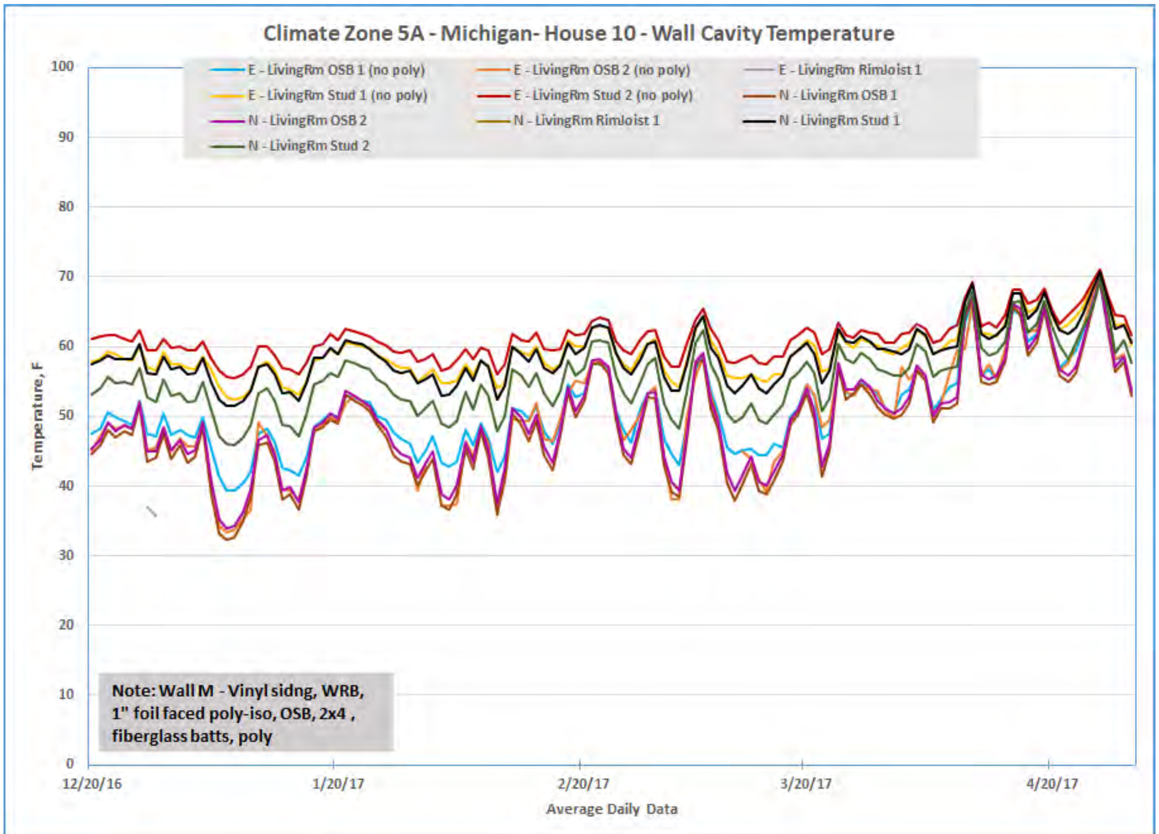
Climate Zone 5A - Pennsylvannia - House 7 - Wall Cavity Temperature
N-DiningRm Stud
E-Mbed Stud 1
S-Bed1 Zip Panel
S-Bed1 Stud
N-DiningRm Zip Panel
W-Bed2 Stud
N-Mbed Stud
E-Mbed Zip Panel 1
N-Mbed Zip Panel
E-Mbed Rimjoist 1
E-Mbed Zip Panel 2
E-Mbath Rimjoist
E-Mbath Stud
N-Mbed Rimjoist
S-Bed Rimjoist
E-Mbath Zip Panel
E-Mbed Stud 2
W-Bed2 Zip Panel
Note: Wall K - Cement board siding, 1.5" PIC, WRB, Zip-R, 2x6, fiberglass batts, Kraft paper, gypsum/paint.
Temperature, F
Average Daily Data
11/8/16
12/8/16
1/8/17
2/8/17
3/8/17
4/8/17



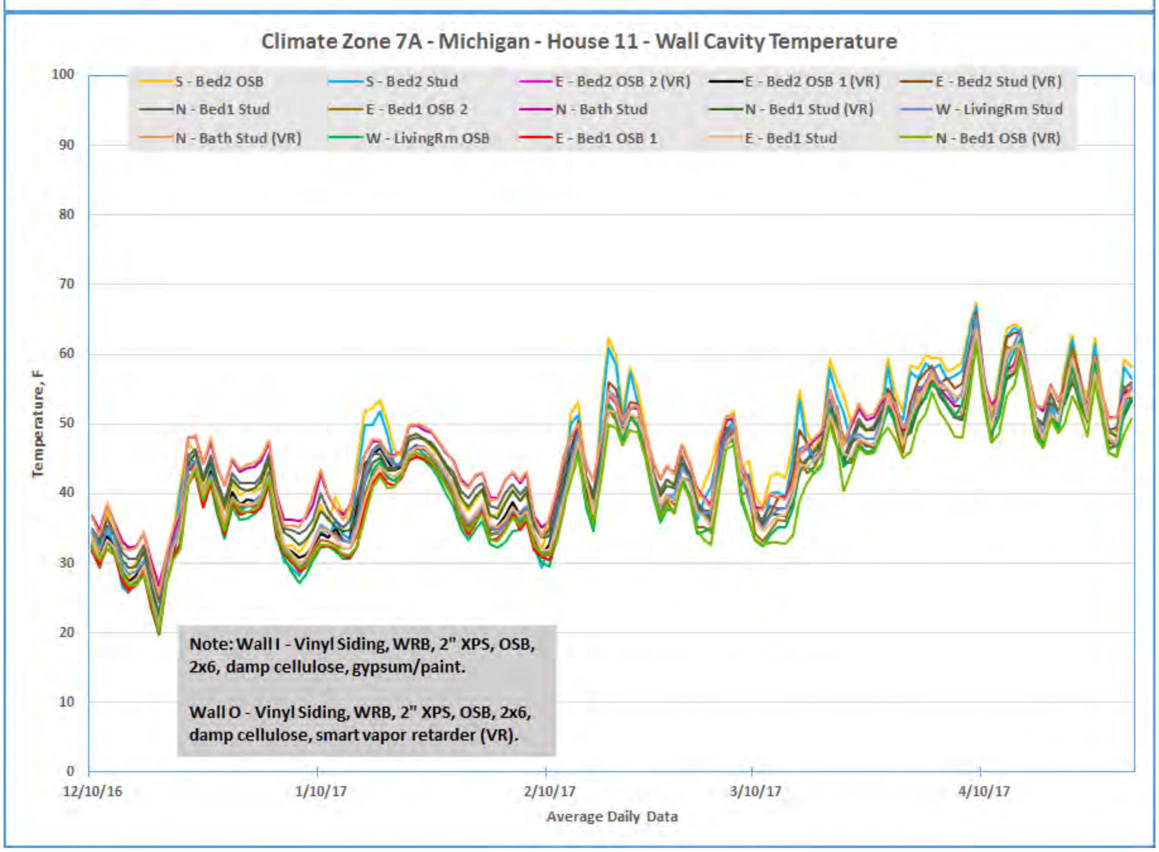
Climate Zone 5A - Michigan - House 8 - Wall Cavity Temperature
E - DiningRm OSB
E - DiningRm Stud
N - LivingRm OSB 1
N - LivingRm OSB 2
N - LivingRm Stud 1
N - LivingRm Stud 2
W - Mbath OSB
W - Mbath Stud
W - Mbed OSB
W - Mbed Stud
Temperature, F
80
70
60
50
40
30
20
10
0
Note: Wall L - Vinyl siding, WRB, 1" XPS, OSB, 2x6, fiberglass batts, kraft paper.
2/19/17
3/19/17
4/19/17
Average Daily Data



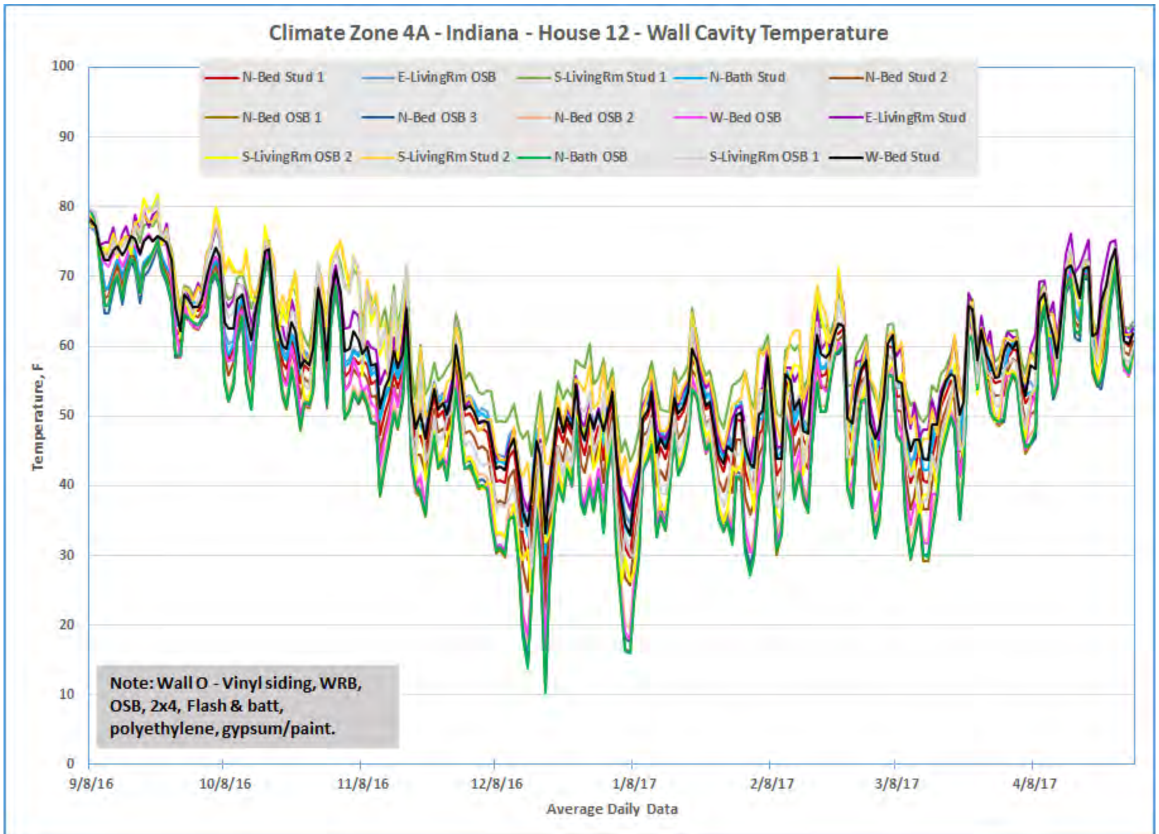
Climate Zone 5A - Michigan - House 9 - Wall Cavity Temperature
E - Mbath OSB
E - Mbath Stud
E - Mbed OSB
E - Mbed Stud
N - LivingRm OSB 1
N - LivingRm OSB 2
N - LivingRm Stud 1
N - LivingRm Stud 2
S - Mbed OSB
S - Mbed Stud
W - DiningRm OSB
W - DiningRm Stud
Temperature, F
80
70
60
50
40
30
20
10
0
Note: Wall L - Vinyl siding, WRB, 1" XPS, OSB, 2x6, fiberglass batts, kraft paper.
2/19/17
3/19/17
4/19/17
Average Daily Data

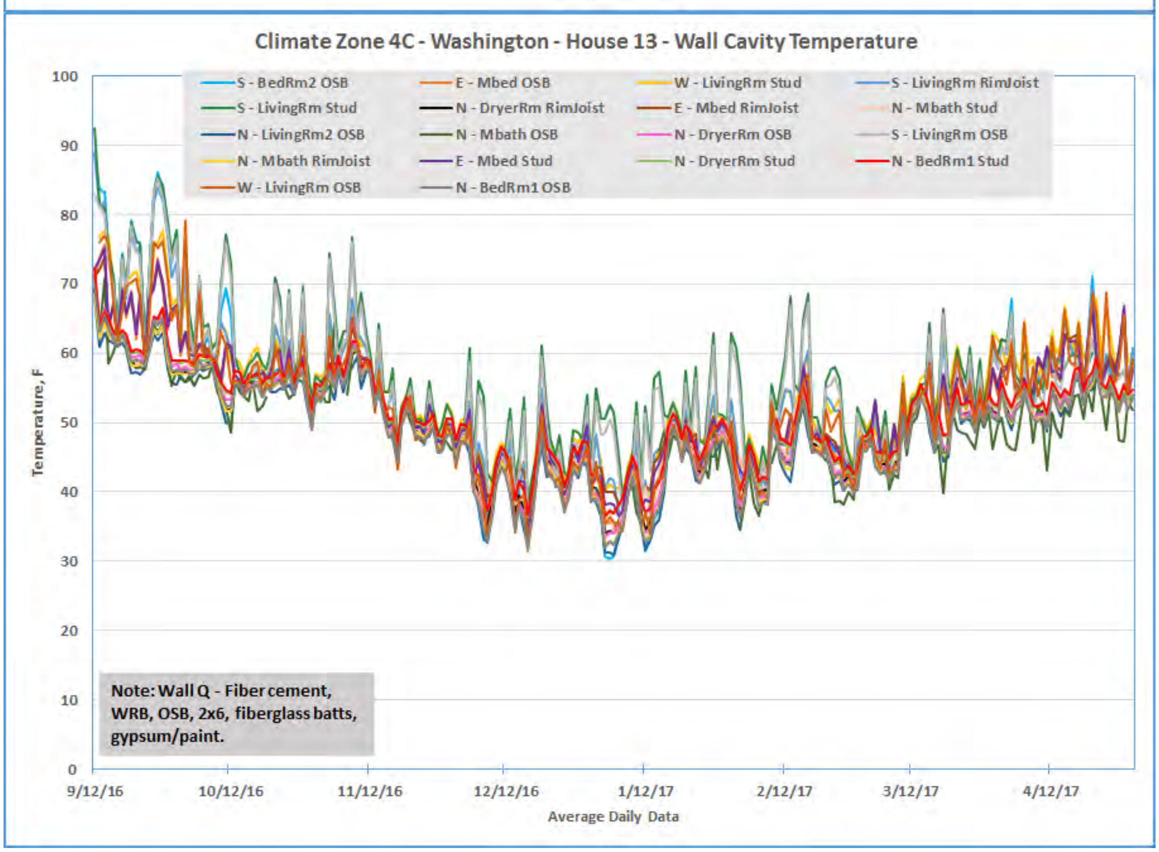


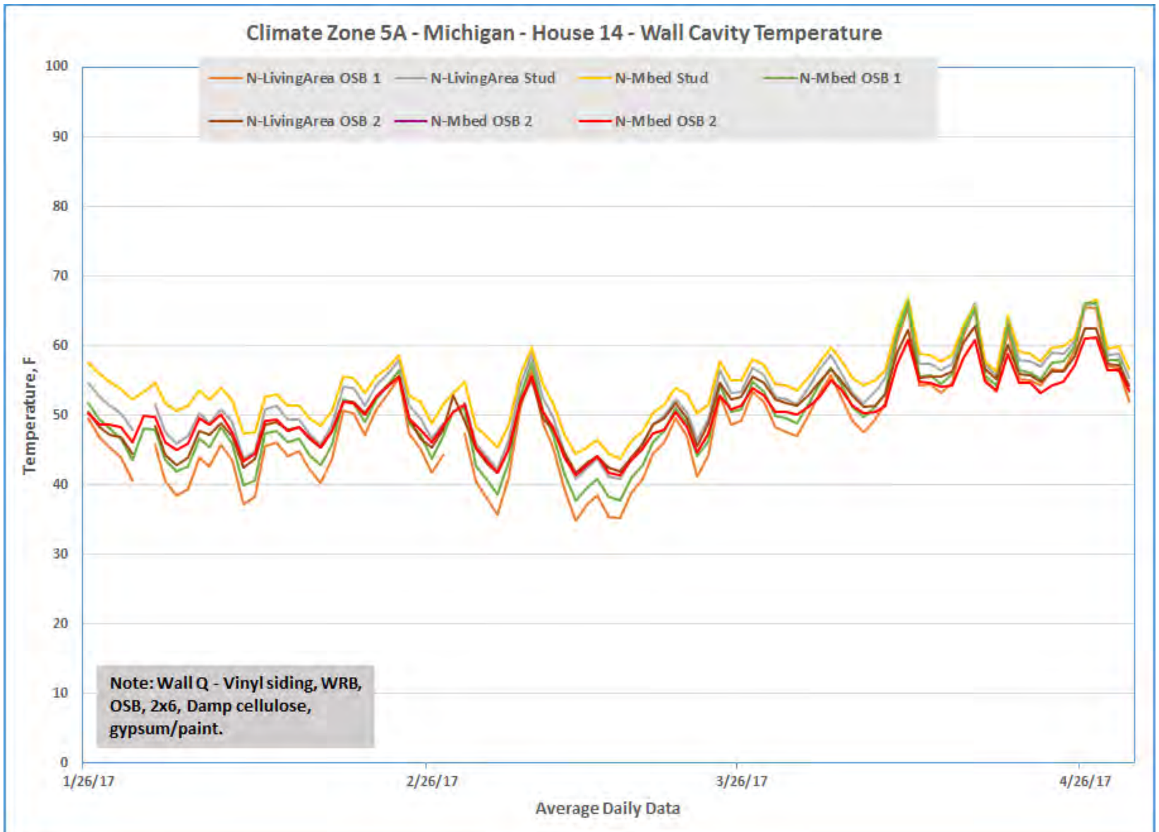
Climate Zone 5A - Michigan- House 10 - Wall Cavity Temperature
E - LivingRm OSB 1 (no poly)
E - LivingRm OSB 2 (no poly)
E - LivingRm Rimloist 1
E - LivingRm Stud 1 (no poly)
E - LivingRm Stud 2 (no poly)
N - LivingRm OSB 1
N - LivingRm OSB 2
N - LivingRm Rimloist 1
N - LivingRm Stud 1
N - LivingRm Stud 2
Temperature, F
100
90
80
70
60
50
40
30
20
10
0
Note: Wall M - Vinyl sidng, WRB, 1" foil faced poly-iso, OSB, 2x4 , fiberglass batts, poly
12/20/16
1/20/17
2/20/17
3/20/17
4/20/17
Average Daily Data

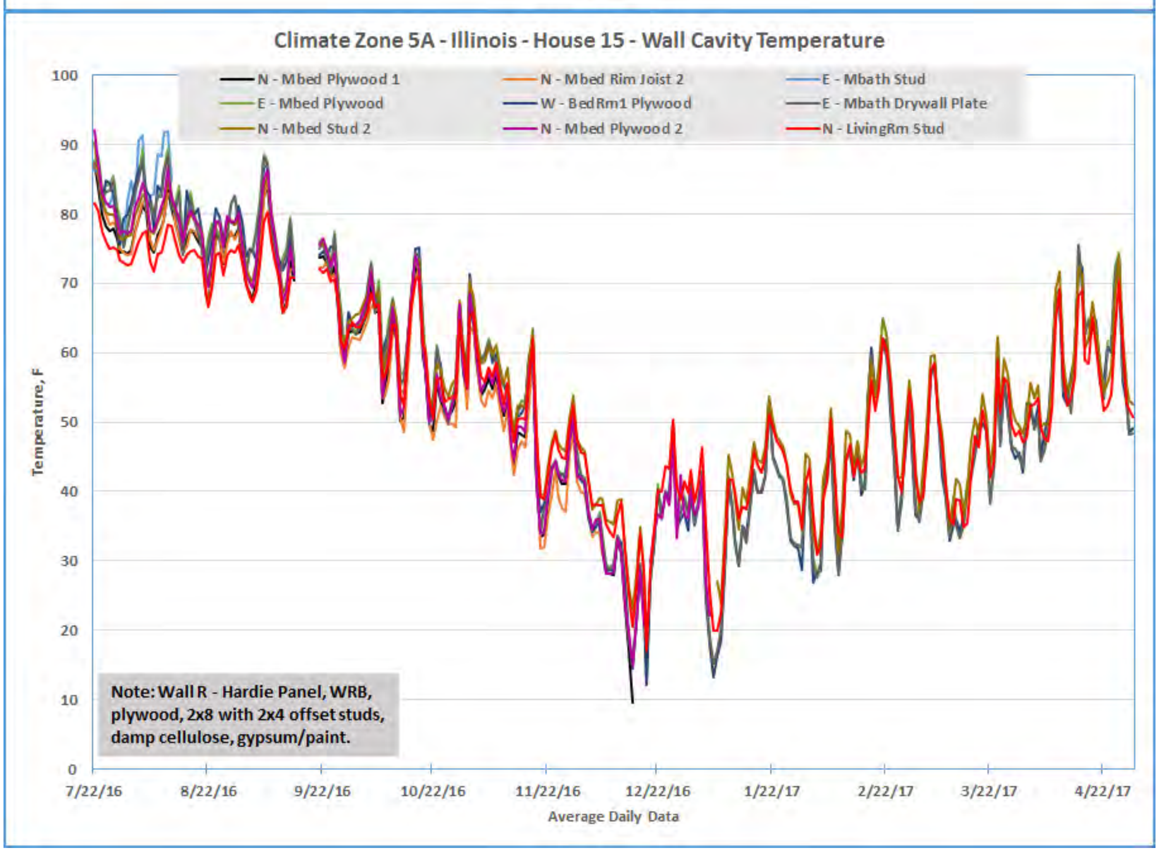


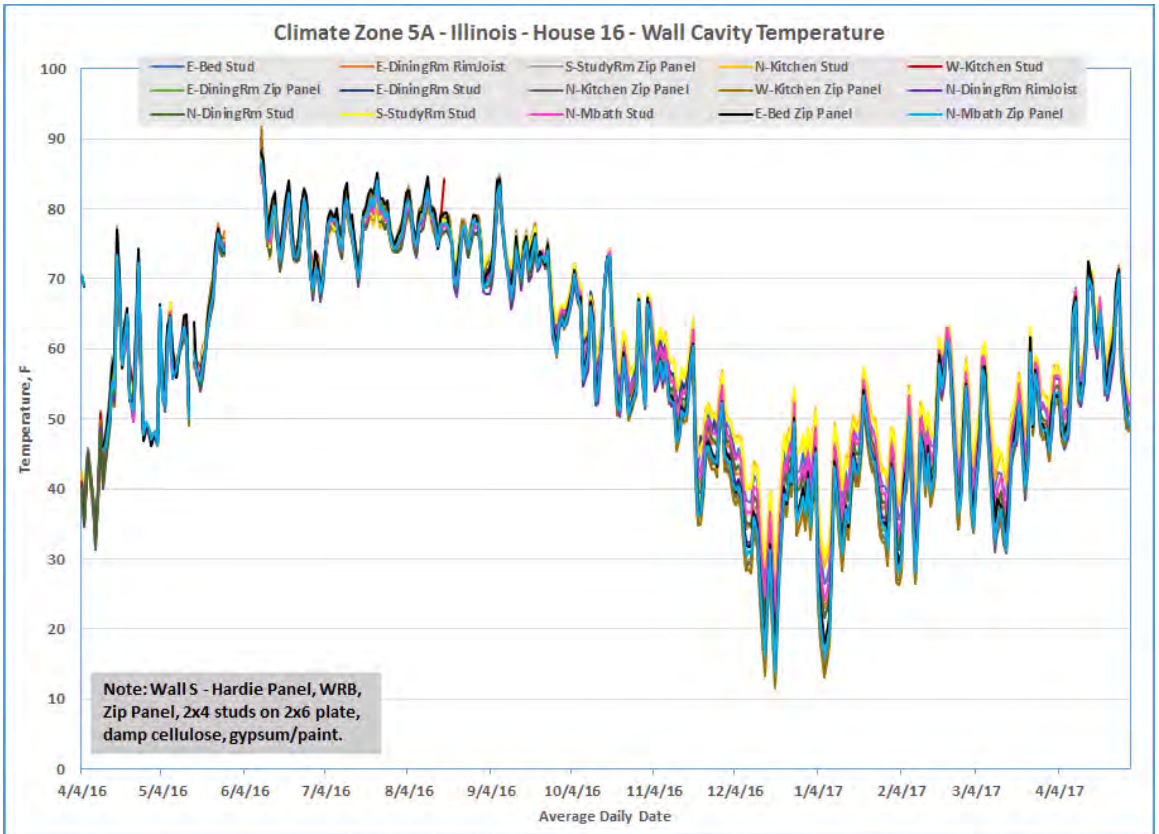
Climate Zone 7A - Michigan - House 11 - Wall Cavity Temperature
S - Bed2 OSB
S - Bed2 Stud
E - Bed2 OSB 2 (VR)
E - Bed2 OSB 1 (VR)
E - Bed2 Stud (VR)
N - Bed1 Stud
E - Bed1 OSB 2
N - Bath Stud
N - Bed1 Stud (VR)
W - LivingRm Stud
N - Bath Stud (VR)
W - LivingRm OSB
E - Bed1 OSB 1
E - Bed1 Stud
N - Bed1 OSB (VR)
Temperature, F
100
90
80
70
60
50
40
30
20
10
0
Note: Wall I - Vinyl Siding, WRB, 2" XPS, OSB, 2x6, damp cellulose, gypsum/paint.
Wall O - Vinyl Siding, WRB, 2" XPS, OSB, 2x6, damp cellulose, smart vapor retarder (VR).
12/10/16
1/10/17
2/10/17
3/10/17
4/10/17
Average Daily Data

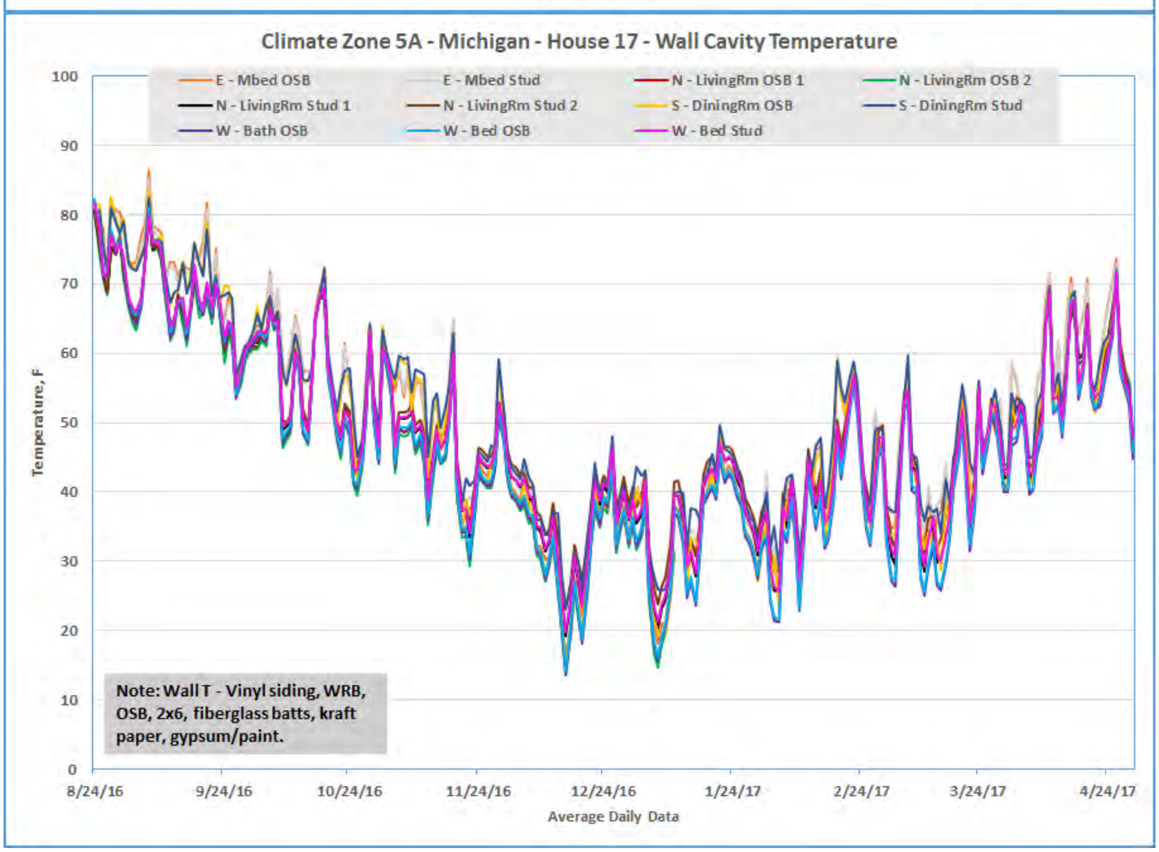

Climate Zone 4A - Indiana - House 12 - Wall Cavity Temperature
N-Bed Stud 1
E-LivingRm OSB
S-LivingRm Stud 1
N-Bath Stud
N-Bed Stud 2
N-Bed OSB 1
N-Bed OSB 3
N-Bed OSB 2
W-Bed OSB
E-LivingRm Stud
S-LivingRm OSB 2
S-LivingRm Stud 2
N-Bath OSB
S-LivingRm OSB 1
W-Bed Stud
Temperature, F
Note: Wall O - Vinyl siding, WRB, OSB, 2x4, Flash & batt, polyethylene, gypsum/paint.
9/8/16
10/8/16
11/8/16
12/8/16
1/8/17
2/8/17
3/8/17
4/8/17
Average Daily Data

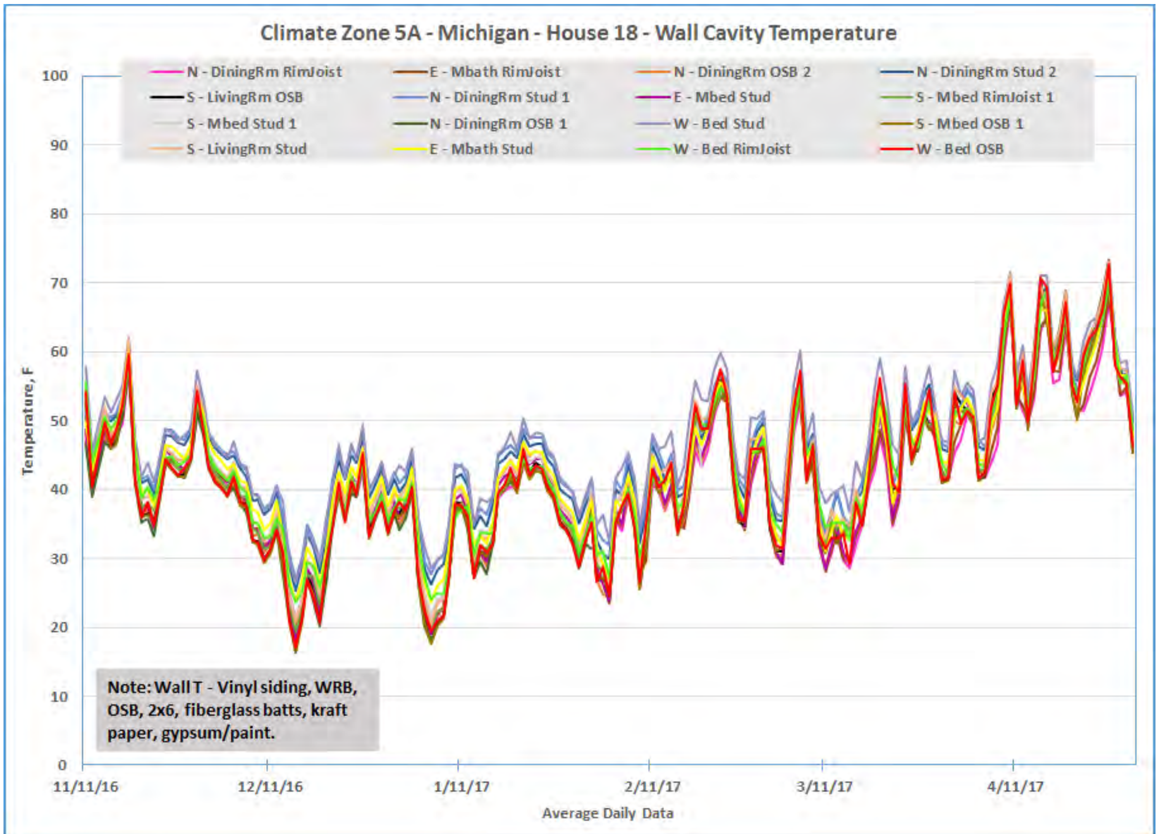

Climate Zone 4C - Washington - House 13 - Wall Cavity Temperature
S - BedRm2 OSB
E - Mbed OSB
W - LivingRm Stud
S - LivingRm RimJoist
S - LivingRm Stud
N - DryerRm RimJoist
E - Mbed RimJoist
N - Mbath Stud
N - LivingRm2 OSB
N - Mbath OSB
N - DryerRm OSB
S - LivingRm OSB
N - Mbath RimJoist
E - Mbed Stud
N - DryerRm Stud
N - BedRm1 Stud
W - LivingRm OSB
N - BedRm1 OSB
Temperature, F
Note: Wall Q - Fiber cement, WRB, OSB, 2x6, fiberglass batts, gypsum/paint.
9/12/16
10/12/16
11/12/16
12/12/16
1/12/17
2/12/17
3/12/17
4/12/17
Average Daily Data

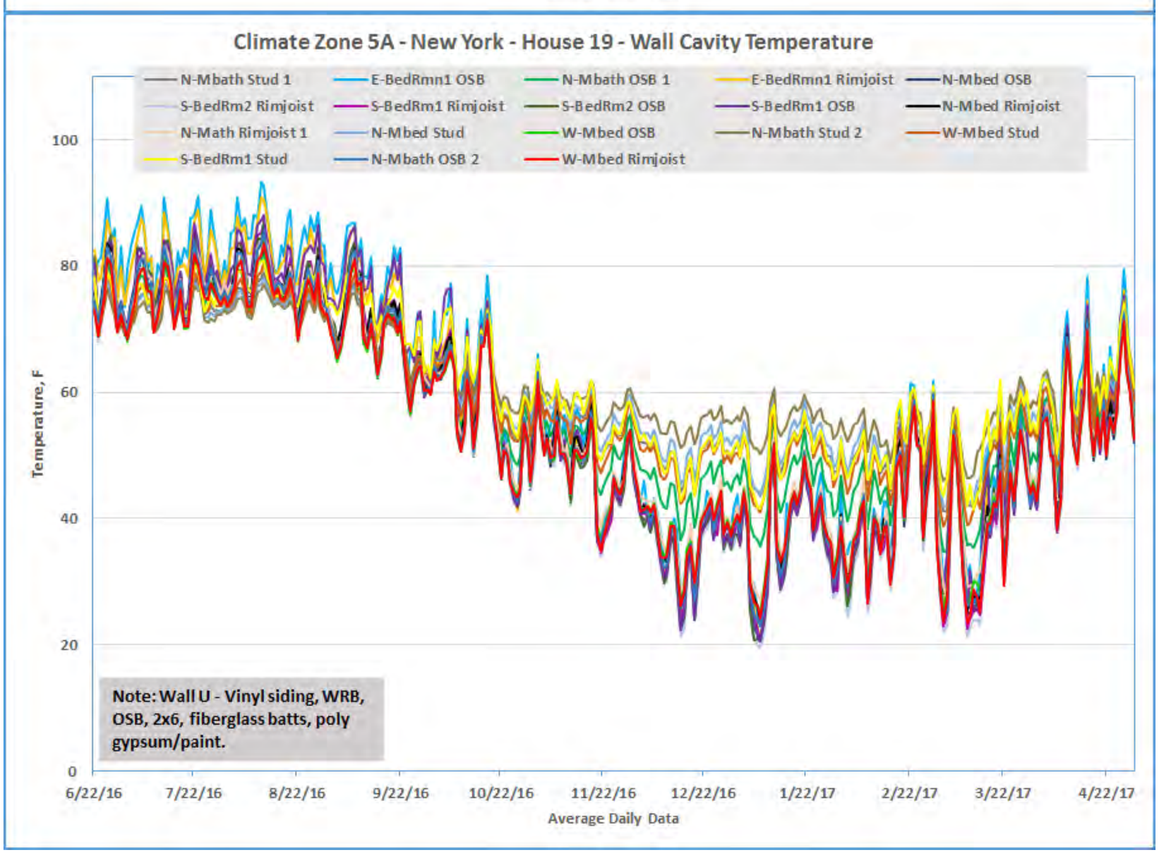

Climate Zone 5A - Michigan - House 14 - Wall Cavity Temperature
N-LivingArea OSB 1
N-LivingArea Stud
N-Mbed Stud
N-Mbed OSB 1
N-LivingArea OSB 2
N-Mbed OSB 2
N-Mbed OSB 2
Temperature, F
100
90
80
70
60
50
40
30
20
10
0
Note: Wall Q - Vinyl siding, WRB, OSB, 2x6, Damp cellulose, gypsum/paint.
1/26/17
2/26/17
3/26/17
4/26/17
Average Daily Data

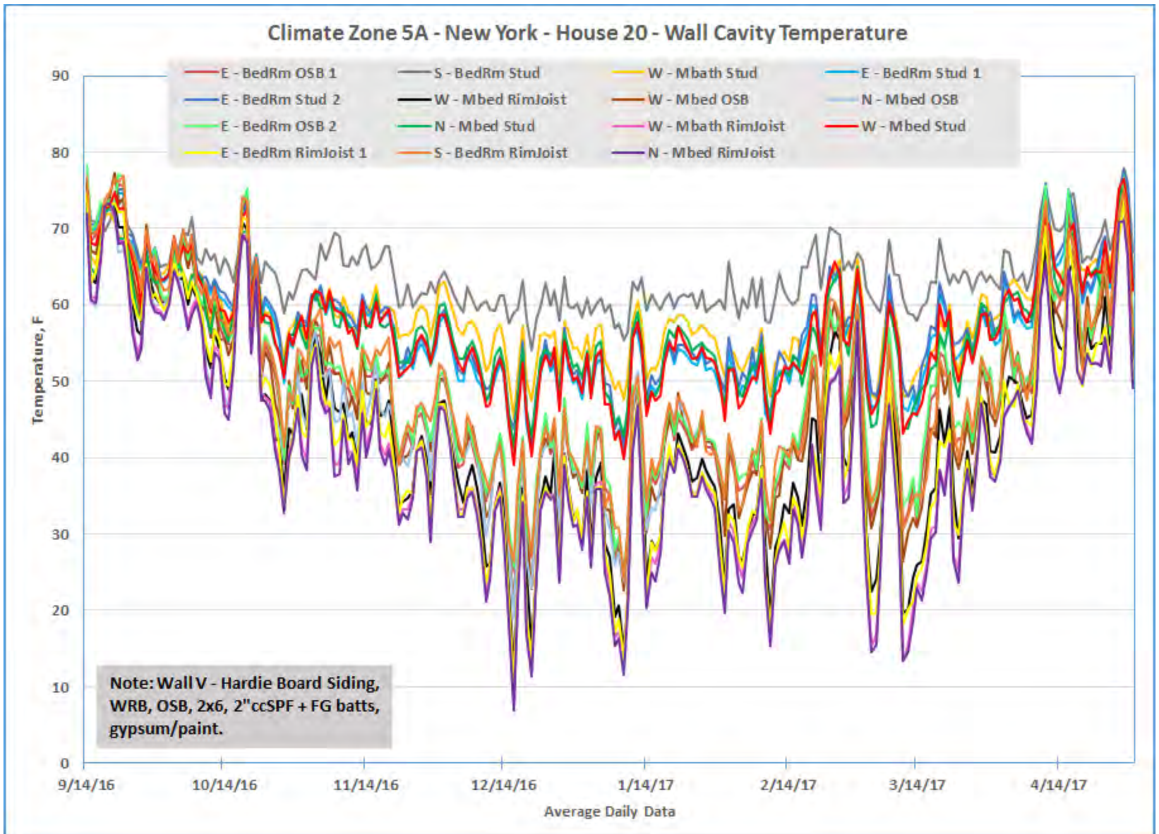

Climate Zone 5A - Illinois - House 15 - Wall Cavity Temperature
N - Mbed Plywood 1
N - Mbed Rim Joist 2
E - Mbath Stud
E - Mbed Plywood
W - BedRm1 Plywood
E - Mbath Drywall Plate
N - Mbed Stud 2
N - Mbed Plywood 2
N - LivingRm Stud
Temperature, F
100
90
80
70
60
50
40
30
20
10
0
Note: Wall R - Hardie Panel, WRB, plywood, 2x8 with 2x4 offset studs, damp cellulose, gypsum/paint.
7/22/16
8/22/16
9/22/16
10/22/16
11/22/16
12/22/16
1/22/17
2/22/17
3/22/17
4/22/17
Average Daily Data

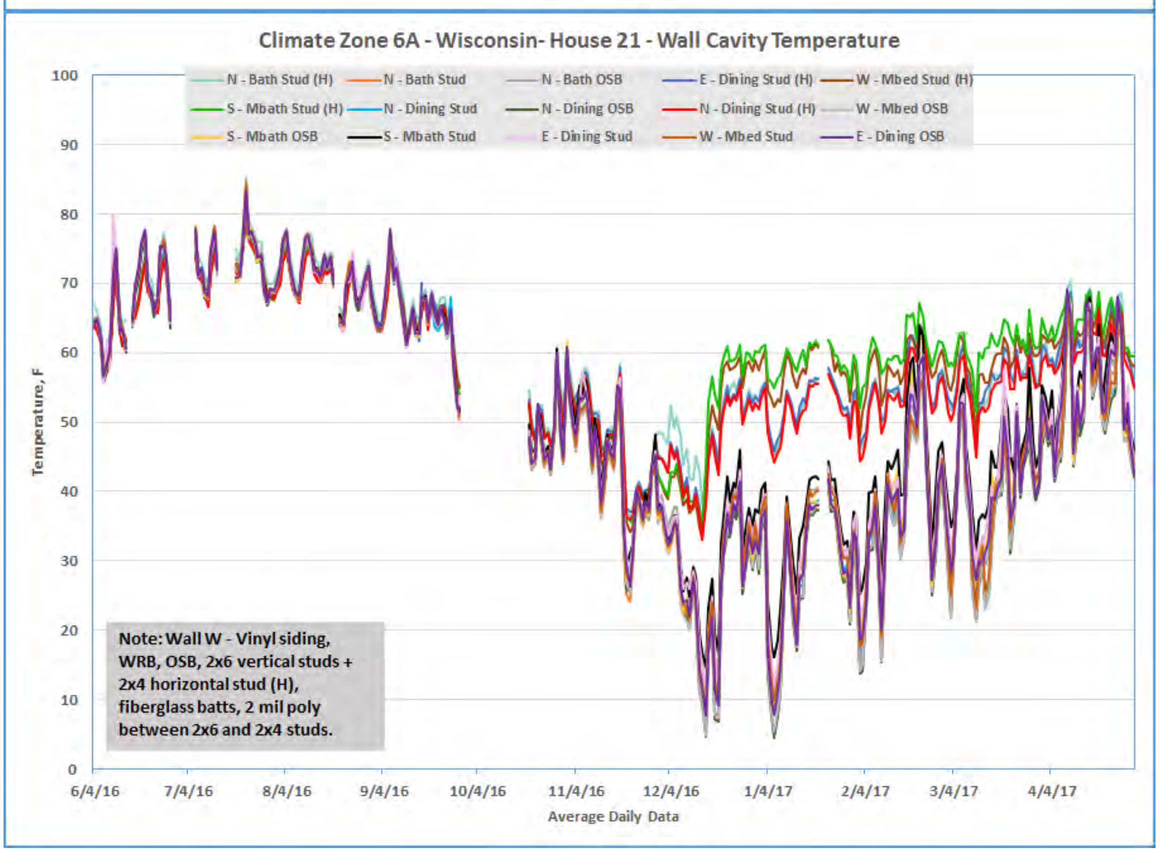

Climate Zone 5A - Illinois - House 16 - Wall Cavity Temperature
E-Bed Stud
E-DiningRm RimJoist
S-StudyRm Zip Panel
N-Kitchen Stud
W-Kitchen Stud
E-DiningRm Zip Panel
E-DiningRm Stud
N-Kitchen Zip Panel
W-Kitchen Zip Panel
N-DiningRm RimJoist
N-DiningRm Stud
S-StudyRm Stud
N-Mbath Stud
E-Bed Zip Panel
N-Mbath Zip Panel
Temperature, F
Note: Wall S - Hardie Panel, WRB, Zip Panel, 2x4 studs on 2x6 plate, damp cellulose, gypsum/paint.
Average Daily Date

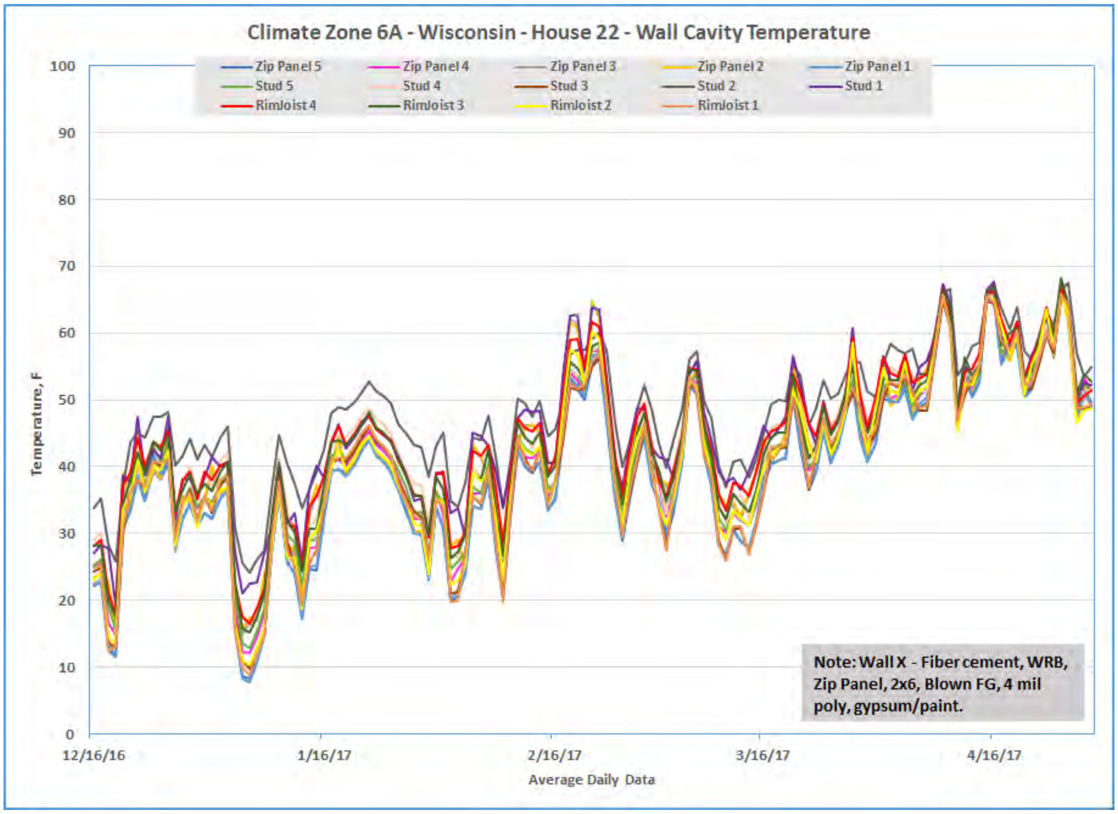

Climate Zone 5A - Michigan - House 17 - Wall Cavity Temperature
E - Mbed OSB
E - Mbed Stud
N - LivingRm OSB 1
N - LivingRm OSB 2
N - LivingRm Stud 1
N - LivingRm Stud 2
S - DiningRm OSB
S - DiningRm Stud
W - Bath OSB
W - Bed OSB
W - Bed Stud
Temperature, F
Note: Wall T - Vinyl siding, WRB, OSB, 2x6, fiberglass batts, kraft paper, gypsum/paint.
Average Daily Data


Climate Zone 5A - Michigan - House 18 - Wall Cavity Temperature
N - DiningRm RimJoist
E - Mbath RimJoist
N - DiningRm OSB 2
N - DiningRm Stud 2
S - LivingRm OSB
N - DiningRm Stud 1
E - Mbed Stud
S - Mbed RimJoist 1
S - Mbed Stud 1
N - DiningRm OSB 1
W - Bed Stud
S - Mbed OSB 1
S - LivingRm Stud
E - Mbath Stud
W - Bed RimJoist
W - Bed OSB
Temperature, F
Note: Wall T - Vinyl siding, WRB, OSB, 2x6, fiberglass batts, kraft paper, gypsum/paint.
11/11/16
12/11/16
1/11/17
2/11/17
3/11/17
4/11/17
Average Daily Data

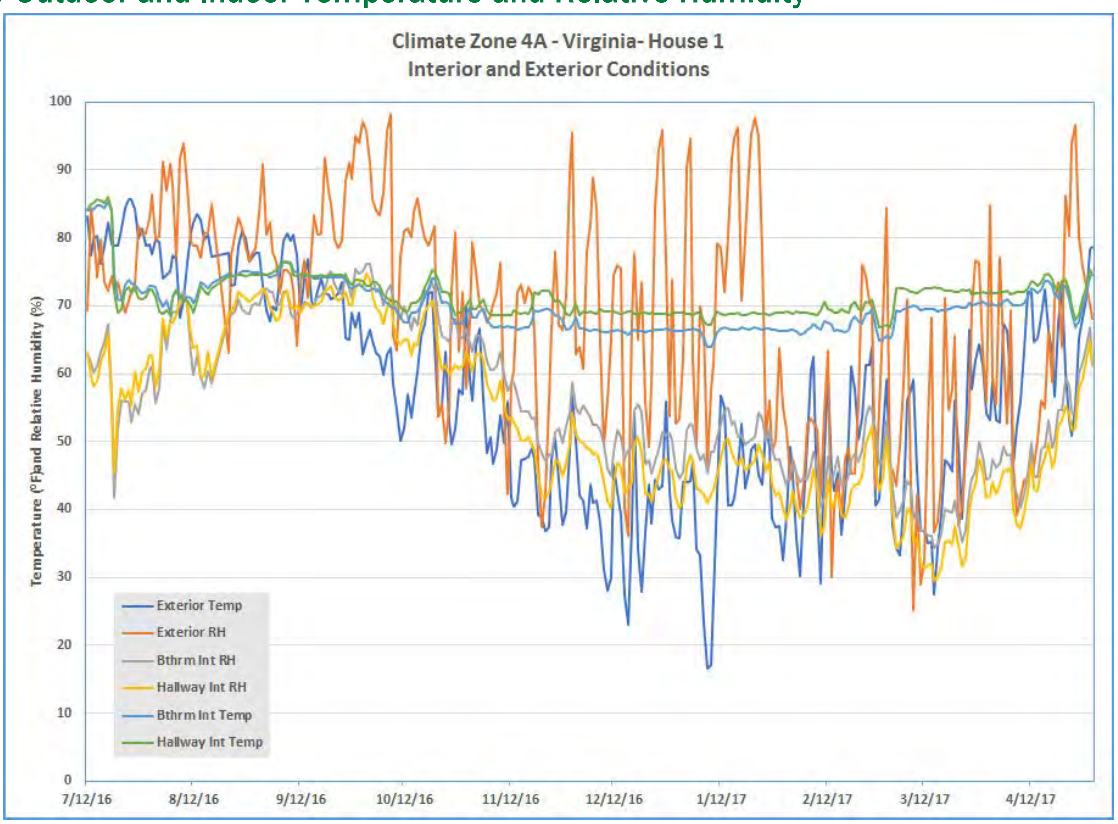

Climate Zone 5A - New York - House 19 - Wall Cavity Temperature
N-Mbath Stud 1
E-BedRmn1 OSB
N-Mbath OSB 1
E-BedRmn1 Rimjoist
N-Mbed OSB
S-BedRm2 Rimjoist
S-BedRm1 Rimjoist
S-BedRm2 OSB
S-BedRm1 OSB
N-Mbed Rimjoist
N-Math Rimjoist 1
N-Mbed Stud
W-Mbed OSB
N-Mbath Stud 2
W-Mbed Stud
S-BedRm1 Stud
N-Mbath OSB 2
W-Mbed Rimjoist
Temperature, F
Note: Wall U - Vinyl siding, WRB, OSB, 2x6, fiberglass batts, poly gypsum/paint.
6/22/16
7/22/16
8/22/16
9/22/16
10/22/16
11/22/16
12/22/16
1/22/17
2/22/17
3/22/17
4/22/17
Average Daily Data

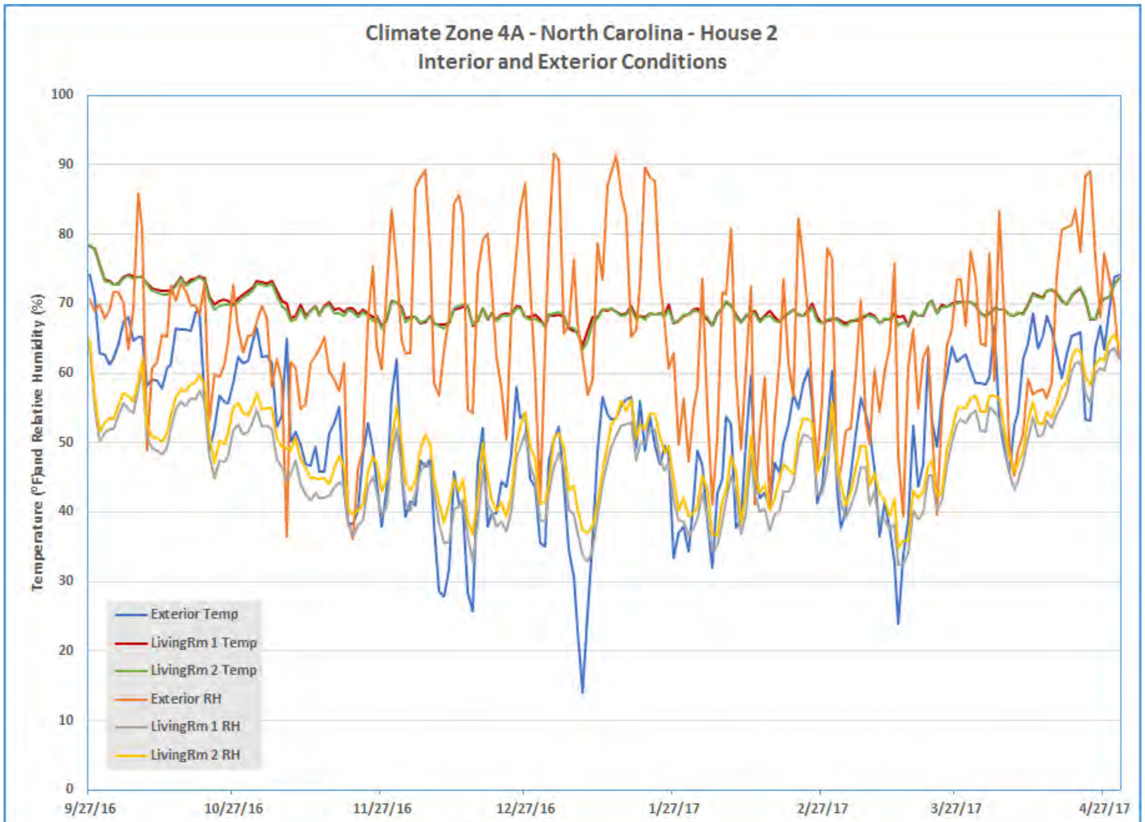

Climate Zone 5A - New York - House 20 - Wall Cavity Temperature
E - BedRm OSB 1
S - BedRm Stud
W - Mbath Stud
E - BedRm Stud 1
E - BedRm Stud 2
W - Mbed RimJoist
W - Mbed OSB
N - Mbed OSB
E - BedRm OSB 2
N - Mbed Stud
W - Mbath RimJoist
W - Mbed Stud
E - BedRm RimJoist 1
S - BedRm RimJoist
N - Mbed RimJoist
Temperature, F
Note: Wall V - Hardie Board Siding, WRB, OSB, 2x6, 2"ccSPF + FG batts, gypsum/paint.
9/14/16
10/14/16
11/14/16
12/14/16
1/14/17
2/14/17
3/14/17
4/14/17
Average Daily Data

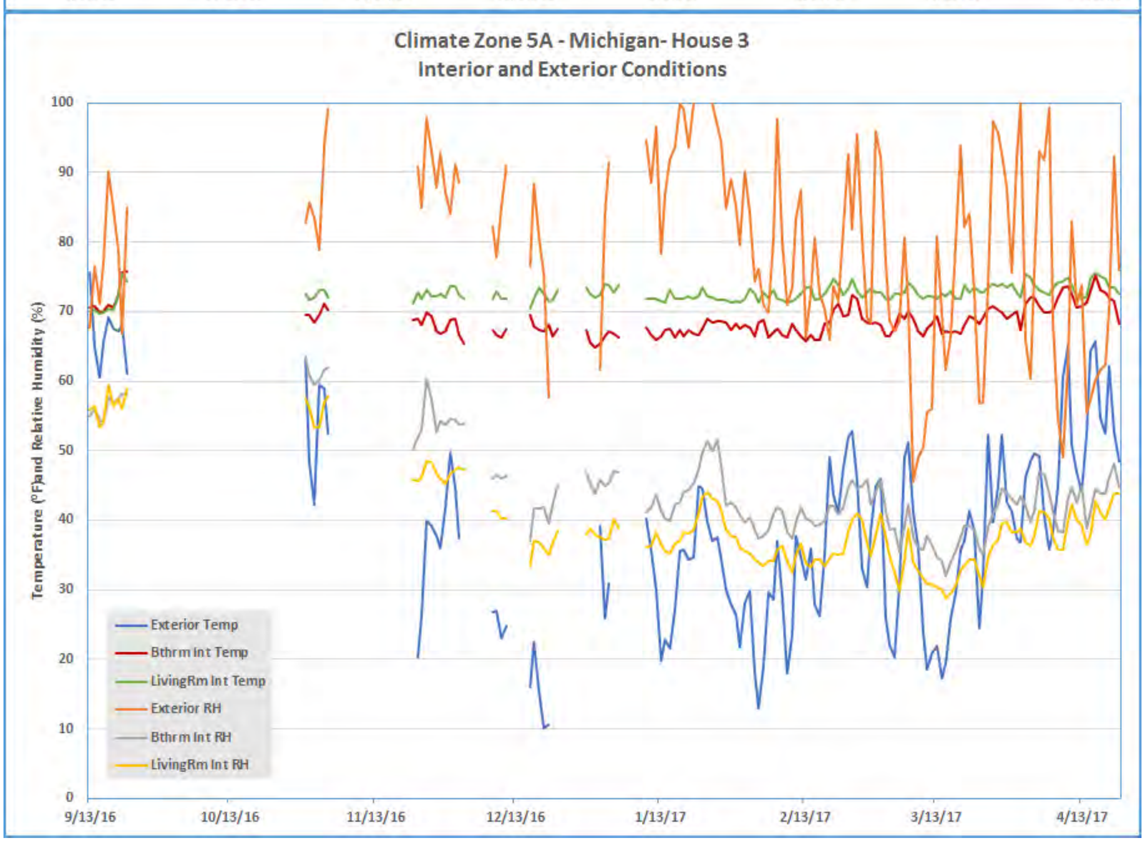

Climate Zone 6A - Wisconsin- House 21 - Wall Cavity Temperature
N - Bath Stud (H)
N - Bath Stud
N - Bath OSB
E - Dining Stud (H)
W - Mbed Stud (H)
S - Mbath Stud (H)
N - Dining Stud
N - Dining OSB
N - Dining Stud (H)
W - Mbed OSB
S - Mbath OSB
S - Mbath Stud
E - Dining Stud
W - Mbed Stud
E - Dining OSB
Temperature, F
Note: Wall W - Vinyl siding, WRB, OSB, 2x6 vertical studs + 2x4 horizontal stud (H), fiberglass batts, 2 mil poly between 2x6 and 2x4 studs.
6/4/16
7/4/16
8/4/16
9/4/16
10/4/16
11/4/16
12/4/16
1/4/17
2/4/17
3/4/17
4/4/17
Average Daily Data

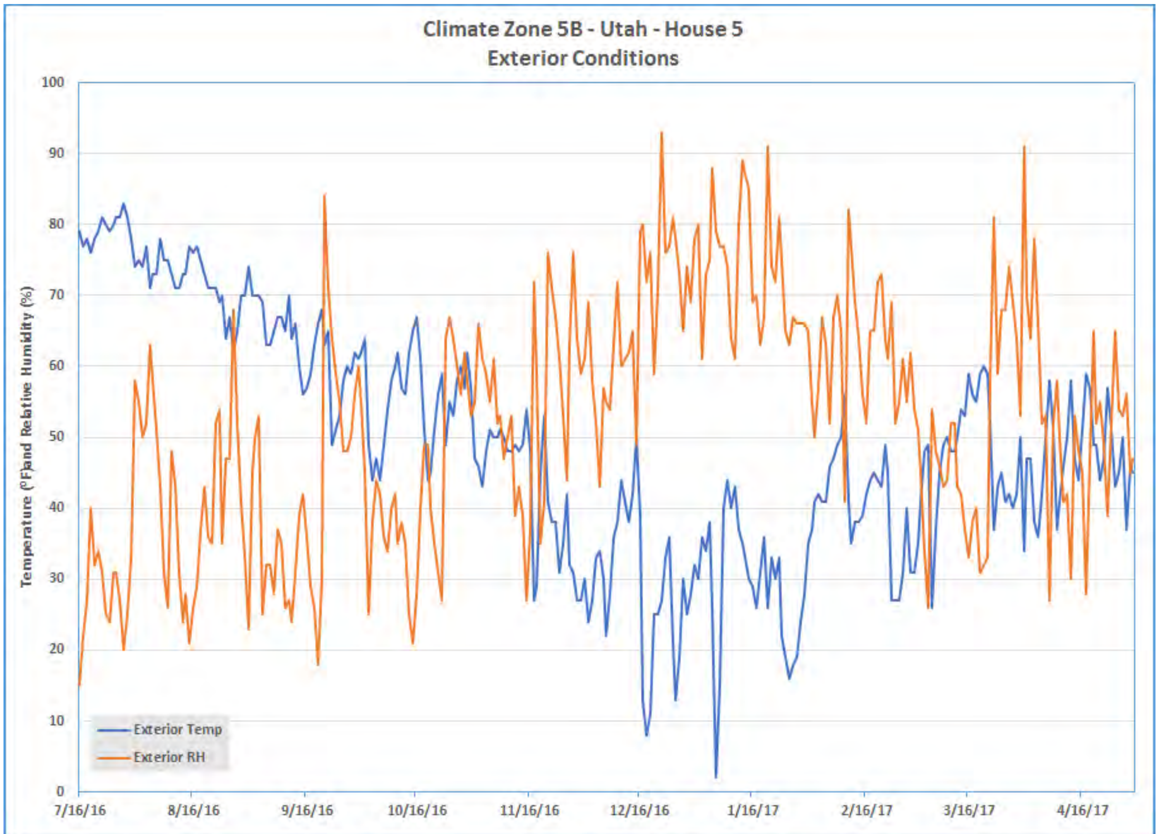


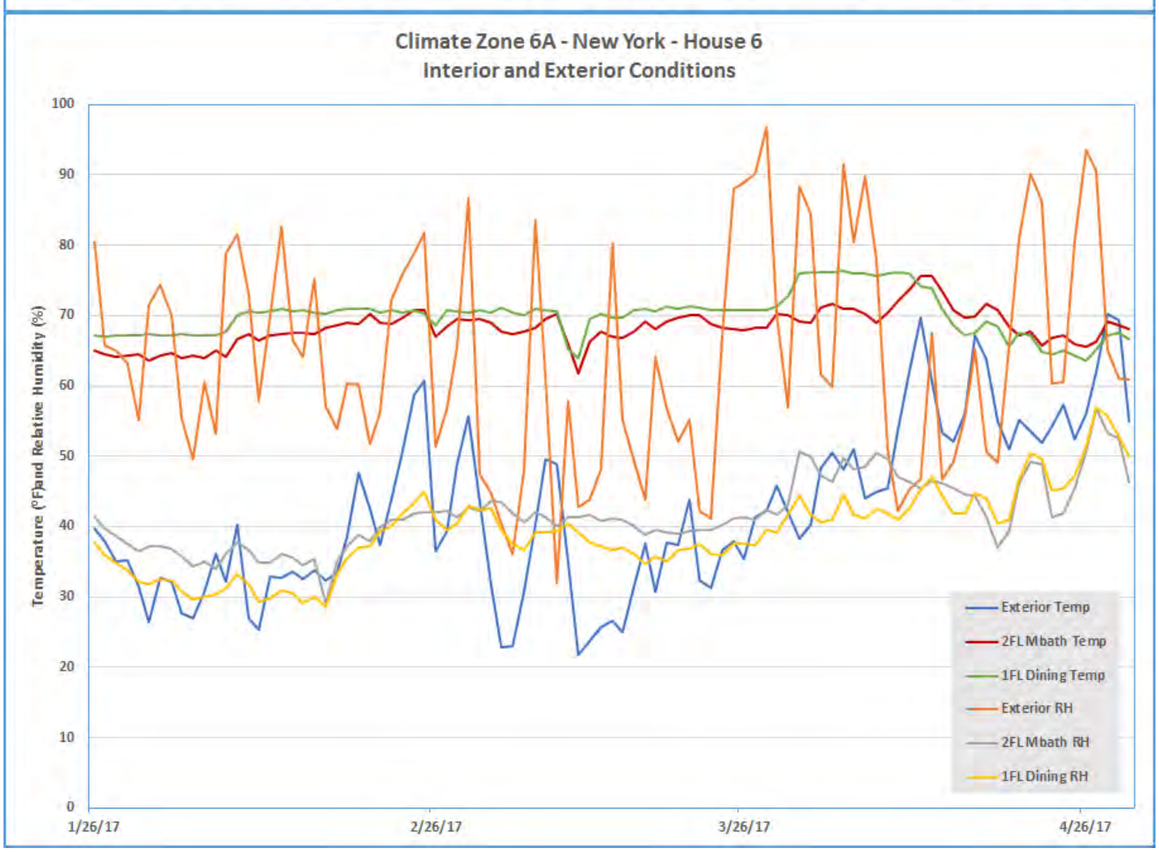
Daily Outdoor and Indoor Temperature and Relative Humidity

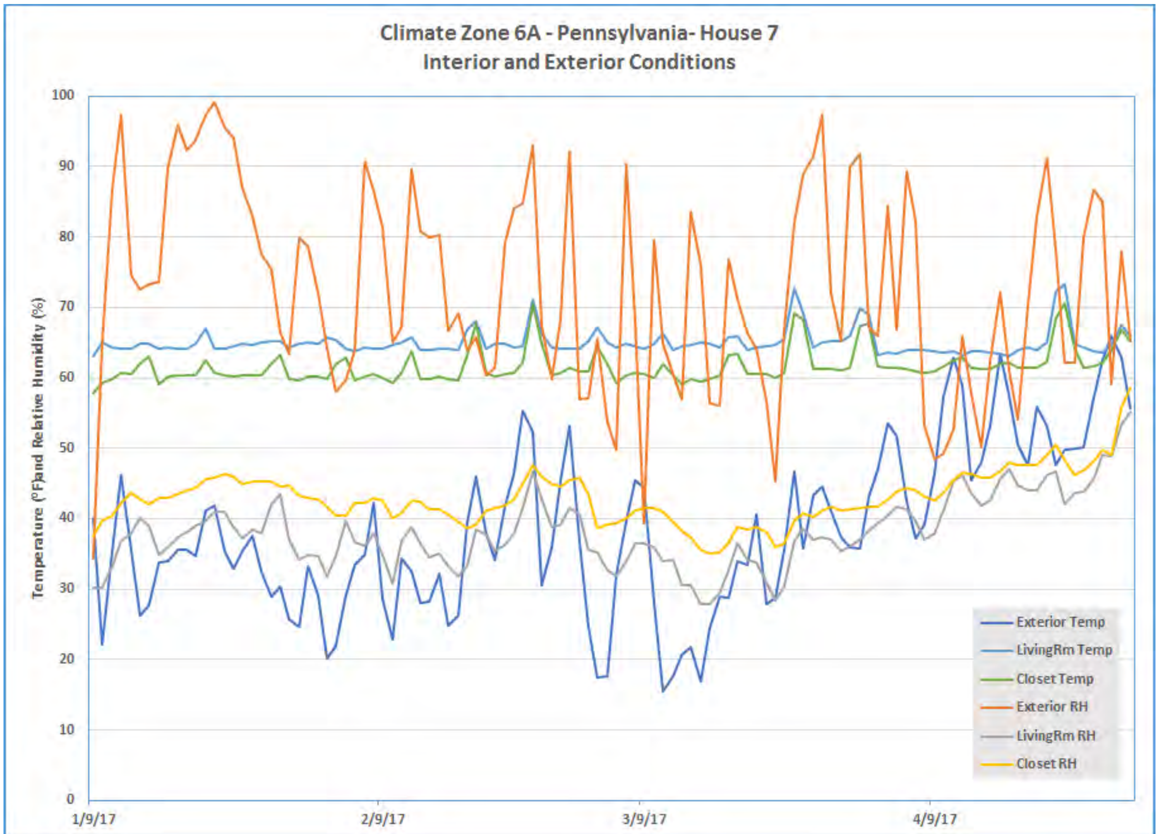


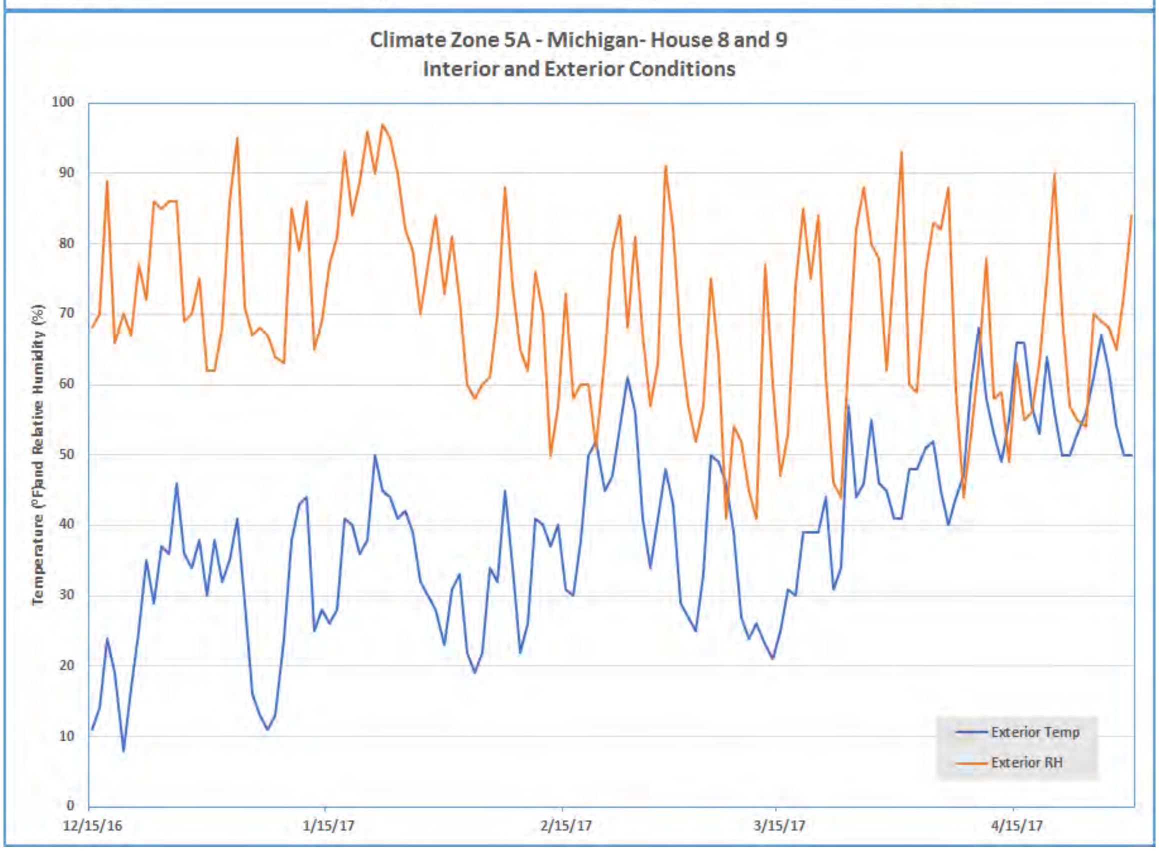

Climate Zone 4A - North Carolina - House 2
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
100
90
80
70
60
50
40
30
20
10
0
9/27/16
10/27/16
11/27/16
12/27/16
1/27/17
2/27/17
3/27/17
4/27/17
Exterior Temp
LivingRm 1 Temp
LivingRm 2 Temp
Exterior RH
LivingRm 1 RH
LivingRm 2 RH

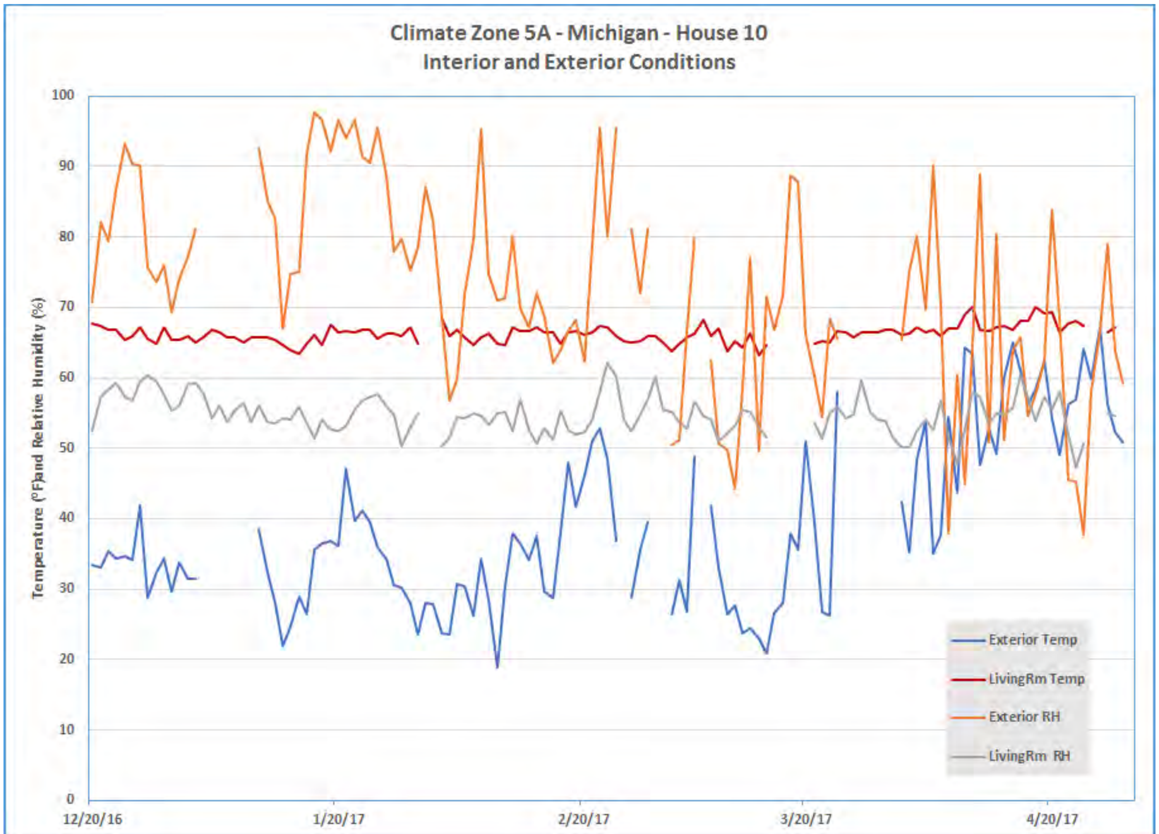

Climate Zone 5A - Michigan- House 3
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
100
90
80
70
60
50
40
30
20
10
0
9/13/16
10/13/16
11/13/16
12/13/16
1/13/17
2/13/17
3/13/17
4/13/17
Exterior Temp
Bthrm Int Temp
LivingRm Int Temp
Exterior RH
Bthrm Int RH
LivingRm Int RH

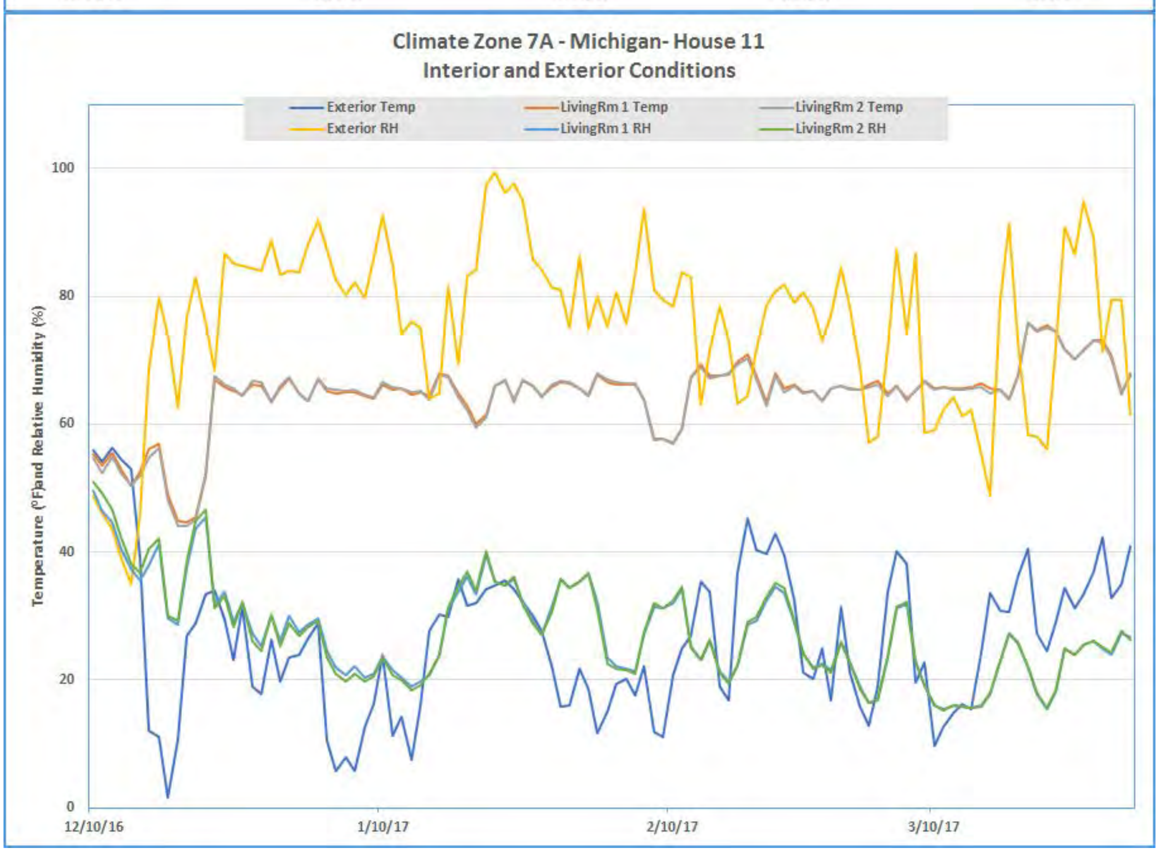

Climate Zone 5B - Utah - House 5
Exterior Conditions
Temperature (°F)and Relative Humidity (%)
Exterior Temp
Exterior RH
7/16/16
8/16/16
9/16/16
10/16/16
11/16/16
12/16/16
1/16/17
2/16/17
3/16/17
4/16/17

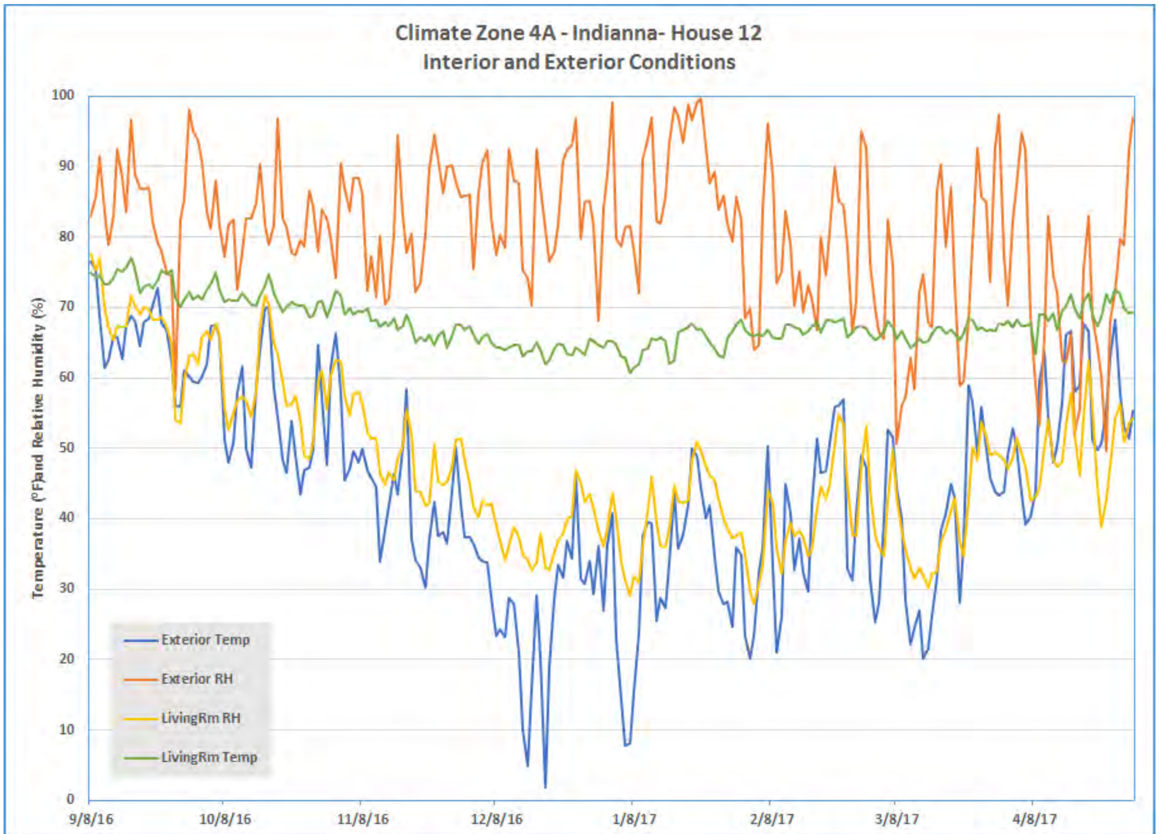

Climate Zone 6A - New York - House 6
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
Exterior Temp
2FL Mbath Temp
1FL Dining Temp
Exterior RH
2FL Mbath RH
1FL Dining RH
1/26/17
2/26/17
3/26/17
4/26/17

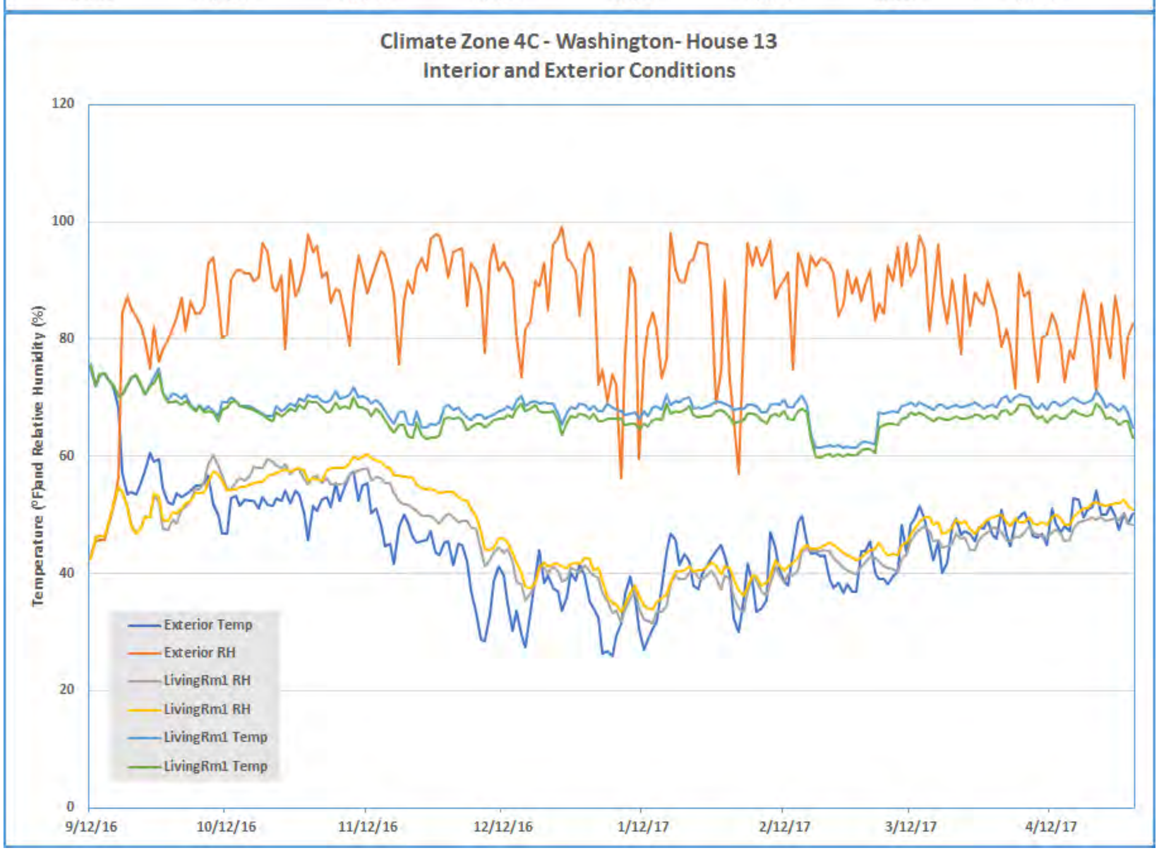

Climate Zone 6A - Pennsylvania- House 7
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
100
90
80
70
60
50
40
30
20
10
0
1/9/17
2/9/17
3/9/17
4/9/17
Exterior Temp
LivingRm Temp
Closet Temp
Exterior RH
LivingRm RH
Closet RH

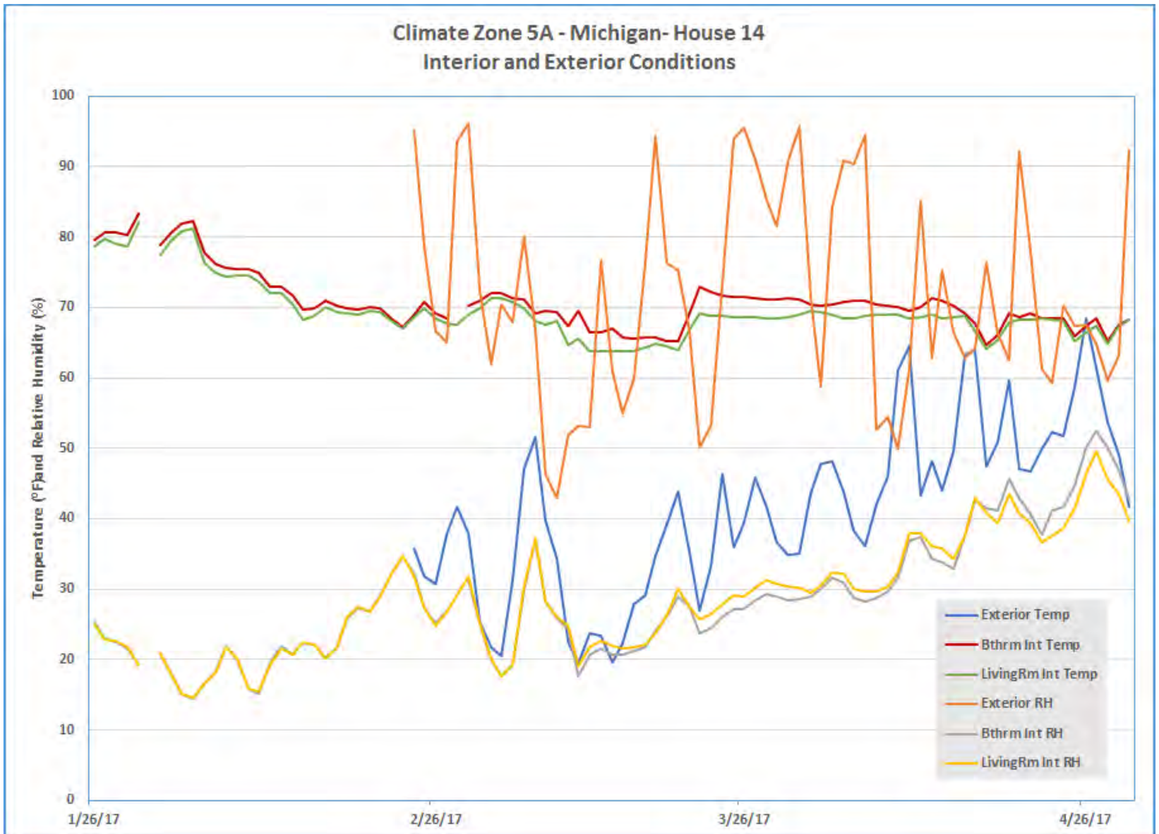

Climate Zone 5A - Michigan- House 8 and 9
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
100
90
80
70
60
50
40
30
20
10
0
12/15/16
1/15/17
2/15/17
3/15/17
4/15/17
Exterior Temp
Exterior RH

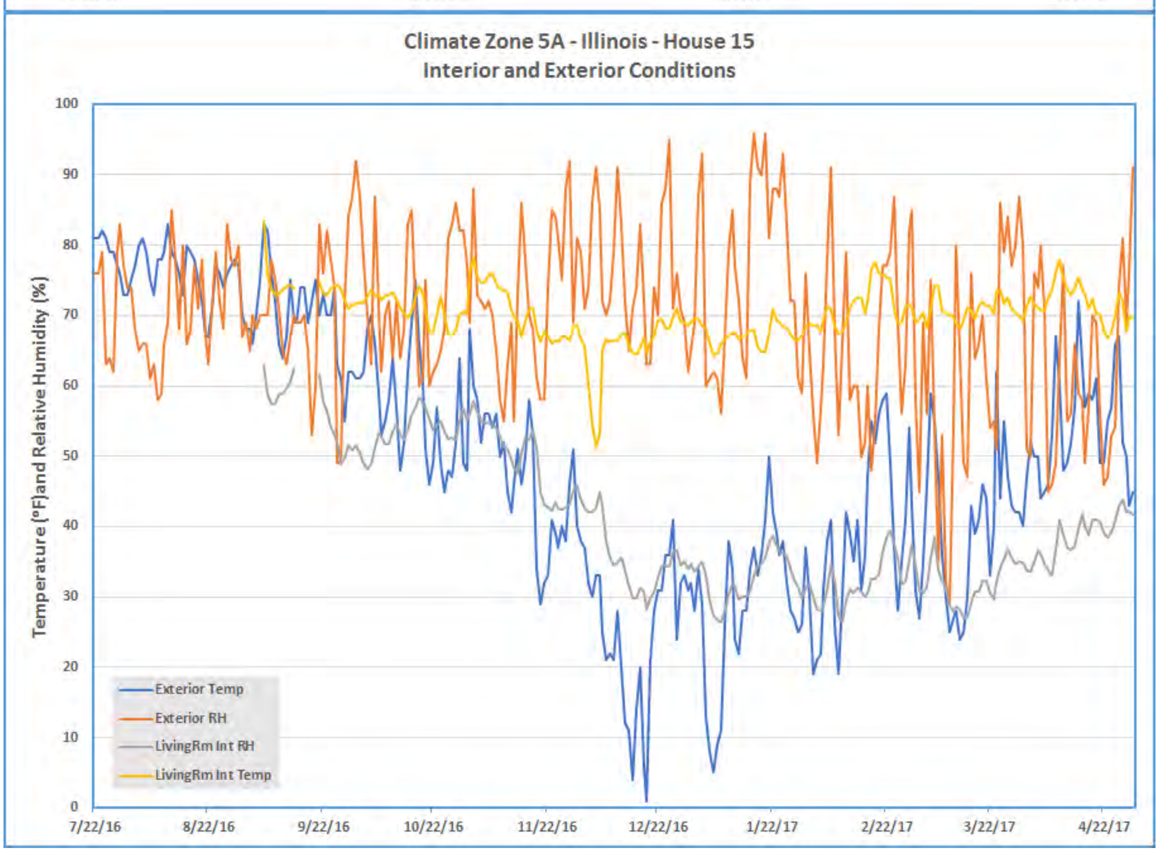

Climate Zone 5A - Michigan - House 10
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
100
90
80
70
60
50
40
30
20
10
0
12/20/16
1/20/17
2/20/17
3/20/17
4/20/17
Exterior Temp
LivingRm Temp
Exterior RH
LivingRm RH

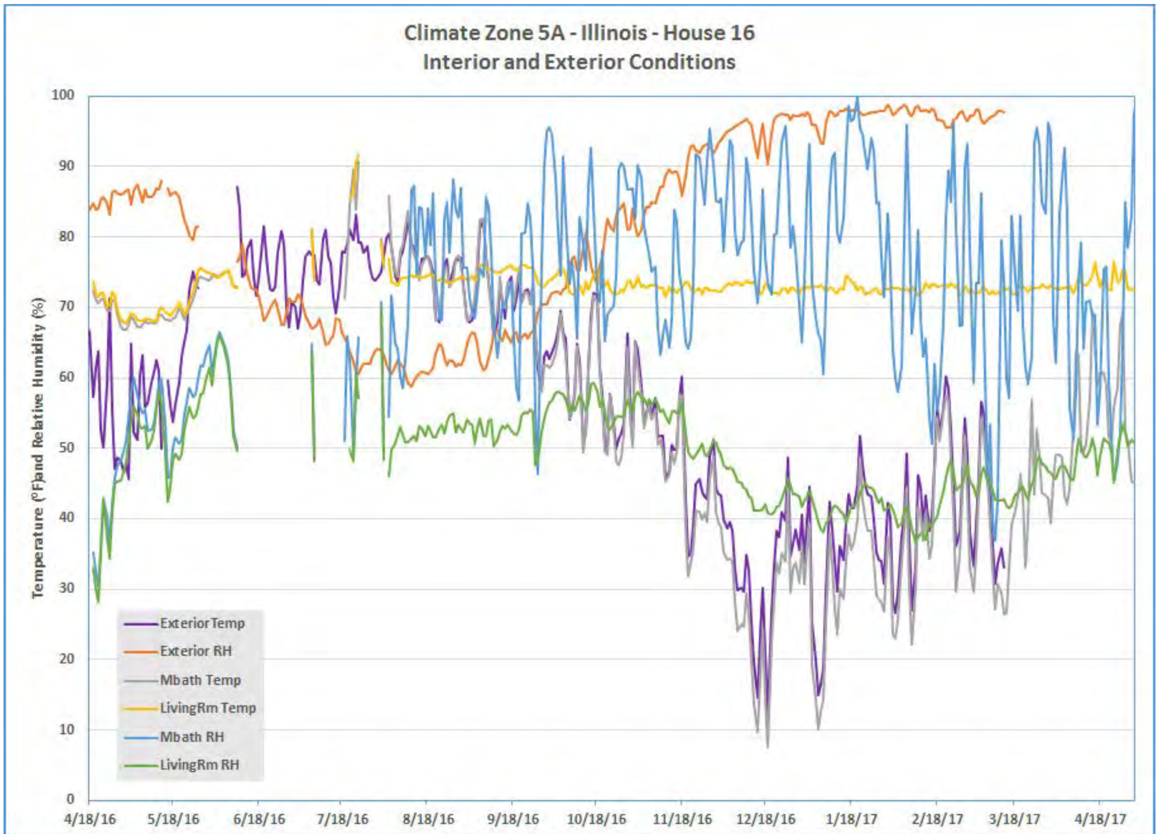

Climate Zone 7A - Michigan- House 11
Interior and Exterior Conditions
Exterior Temp
LivingRm 1 Temp
LivingRm 2 Temp
Exterior RH
LivingRm 1 RH
LivingRm 2 RH
Temperature (°F)and Relative Humidity (%)
100
80
60
40
20
0
12/10/16
1/10/17
2/10/17
3/10/17

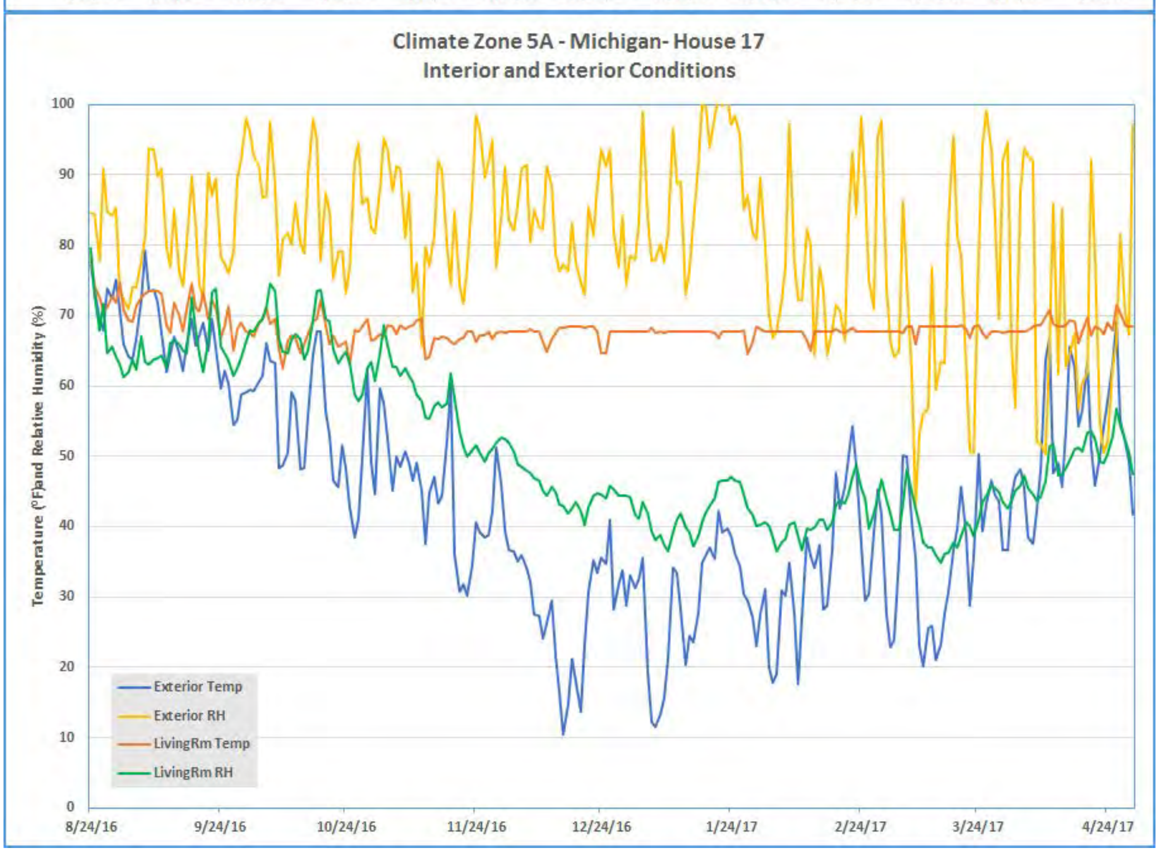

Climate Zone 4A - Indianna- House 12
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
100
90
80
70
60
50
40
30
20
10
0
9/8/16
10/8/16
11/8/16
12/8/16
1/8/17
2/8/17
3/8/17
4/8/17
Exterior Temp
Exterior RH
LivingRm RH
LivingRm Temp

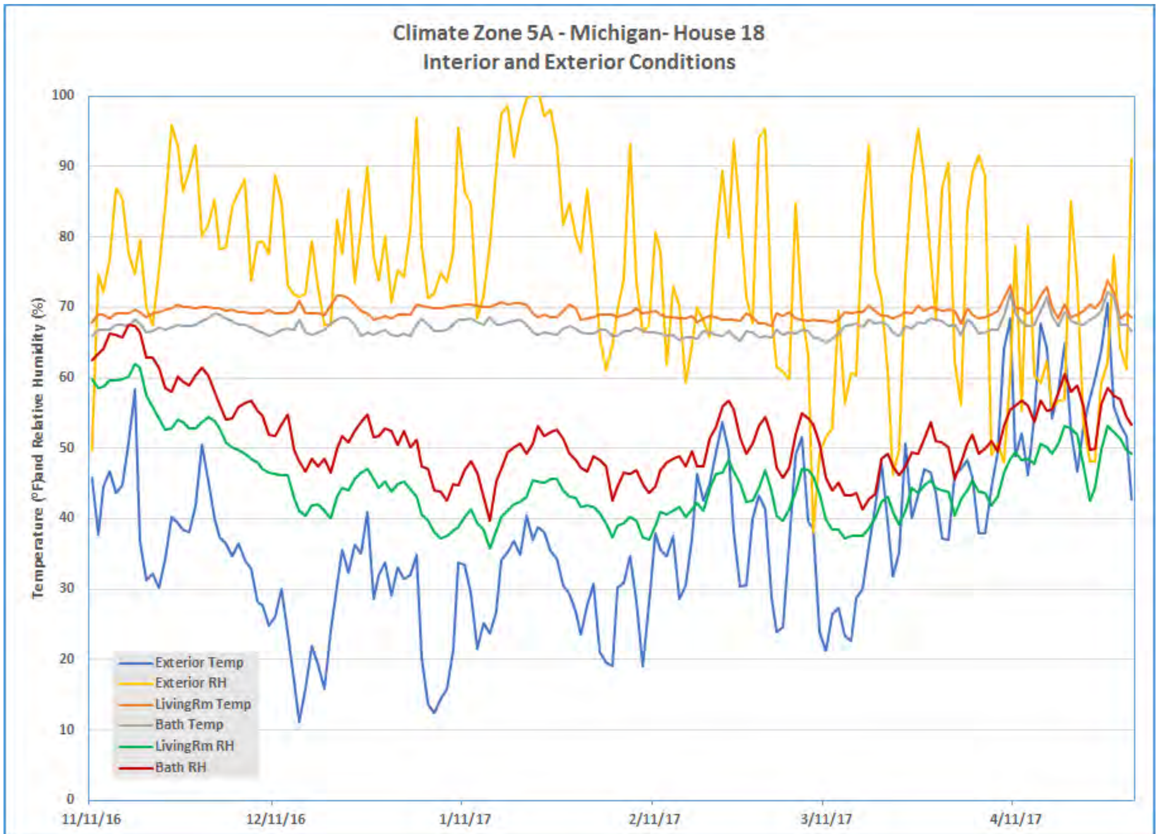

Climate Zone 4C - Washington- House 13
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
120
100
80
60
40
20
0
9/12/16
10/12/16
11/12/16
12/12/16
1/12/17
2/12/17
3/12/17
4/12/17
Exterior Temp
Exterior RH
LivingRm1 RH
LivingRm1 RH
LivingRm1 Temp
LivingRm1 Temp


Climate Zone 5A - Michigan- House 14
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
1/26/17
2/26/17
3/26/17
4/26/17
Exterior Temp
Bthrm Int Temp
LivingRm Int Temp
Exterior RH
Bthrm Int RH
LivingRm Int RH

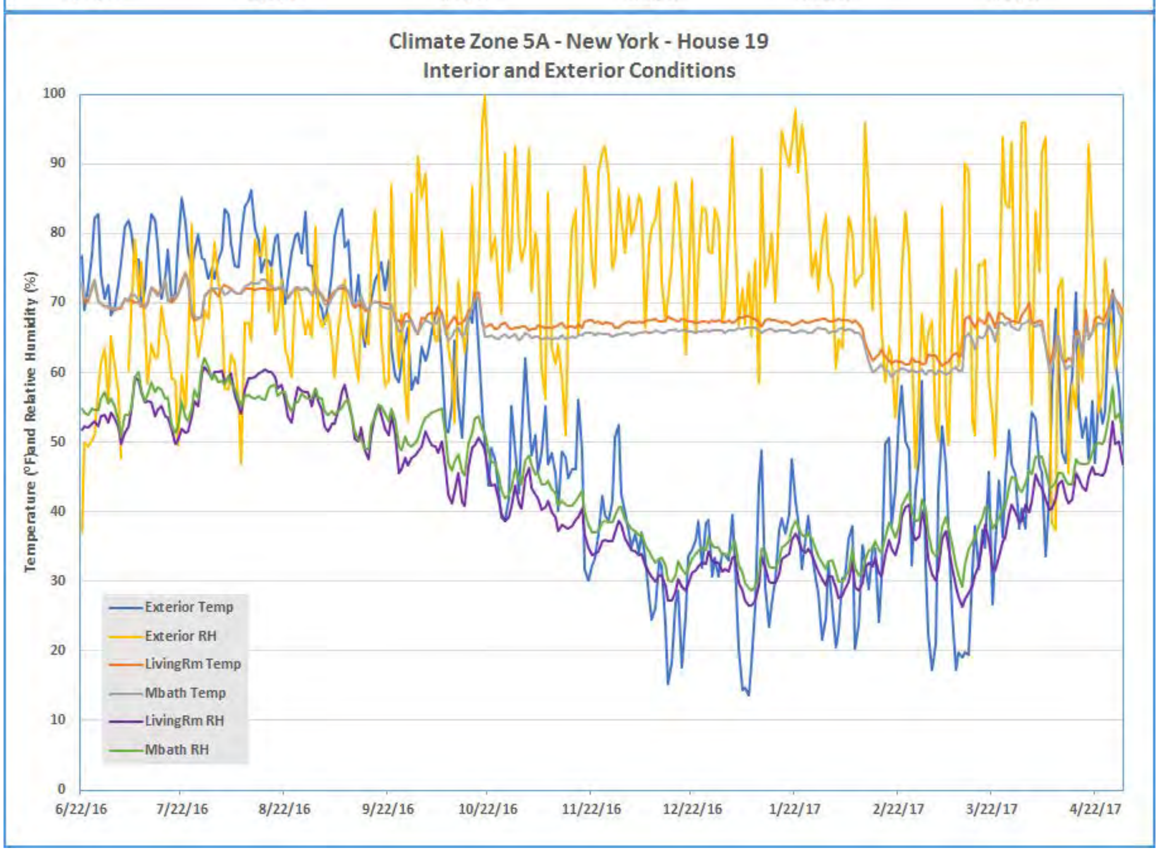

Climate Zone 5A - Illinois - House 15
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
7/22/16
8/22/16
9/22/16
10/22/16
11/22/16
12/22/16
1/22/17
2/22/17
3/22/17
4/22/17
Exterior Temp
Exterior RH
LivingRm Int RH
LivingRm Int Temp


Climate Zone 5A - Illinois - House 16
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
100
90
80
70
60
50
40
30
20
10
0
4/18/16
5/18/16
6/18/16
7/18/16
8/18/16
9/18/16
10/18/16
11/18/16
12/18/16
1/18/17
2/18/17
3/18/17
4/18/17
Exterior Temp
Exterior RH
Mbath Temp
LivingRm Temp
Mbath RH
LivingRm RH

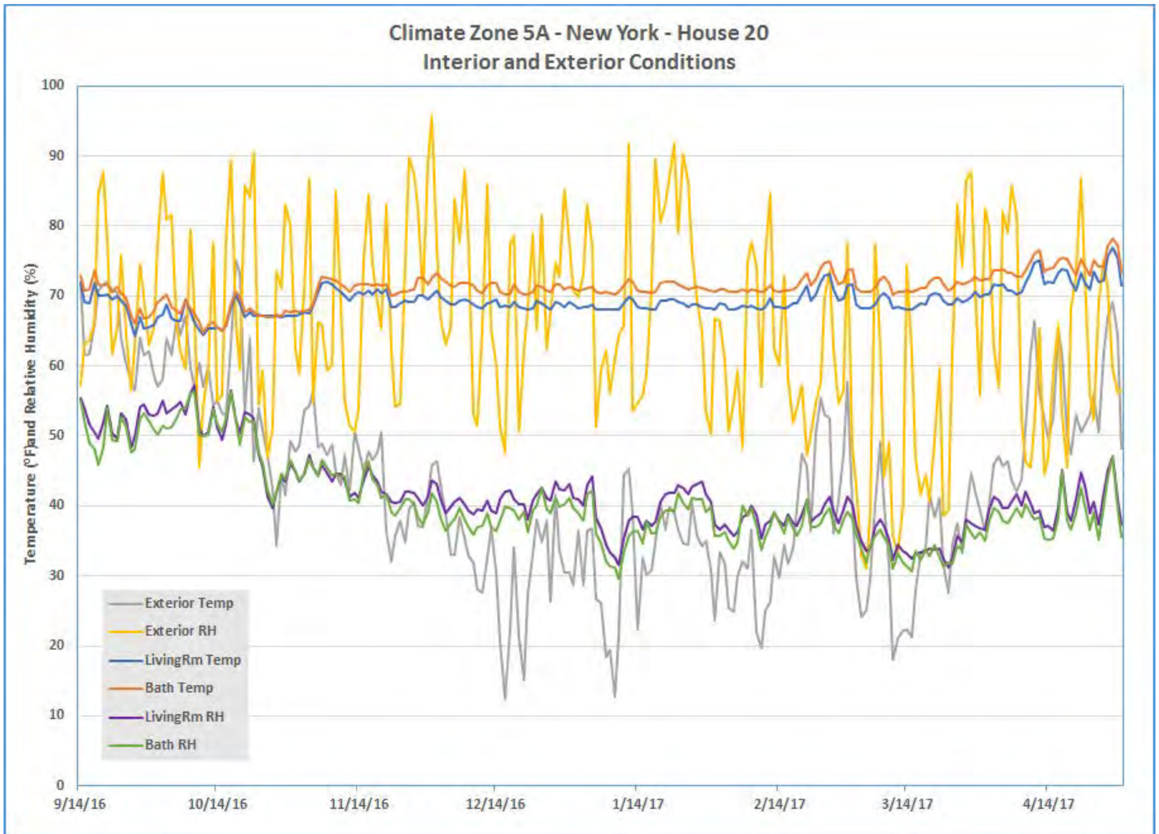

Climate Zone 5A - Michigan- House 17
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
100
90
80
70
60
50
40
30
20
10
0
8/24/16
9/24/16
10/24/16
11/24/16
12/24/16
1/24/17
2/24/17
3/24/17
4/24/17
Exterior Temp
Exterior RH
LivingRm Temp
LivingRm RH

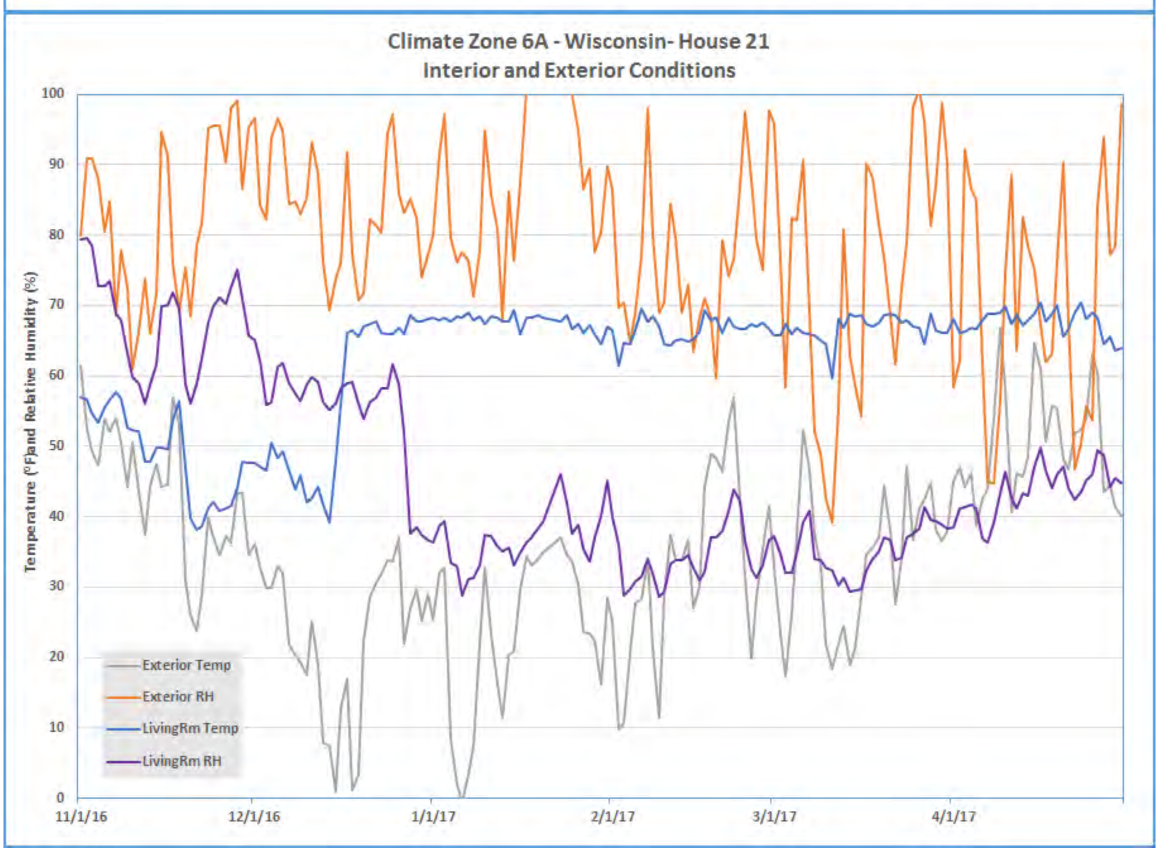


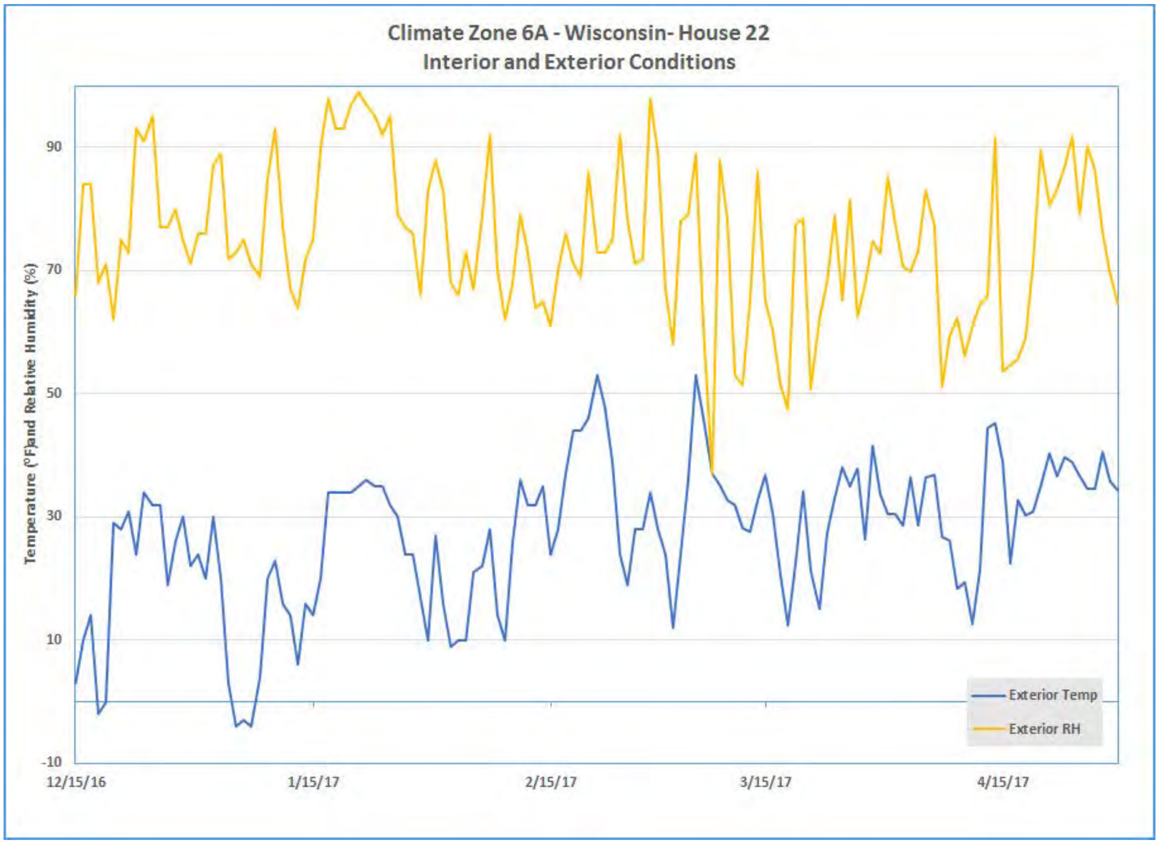
Climate Zone 5A - Michigan- House 18
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
100
90
80
70
60
50
40
30
20
10
0
11/11/16
12/11/16
1/11/17
2/11/17
3/11/17
4/11/17
Exterior Temp
Exterior RH
LivingRm Temp
Bath Temp
LivingRm RH
Bath RH



Climate Zone 5A - New York - House 19
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
100
90
80
70
60
50
40
30
20
10
0
6/22/16
7/22/16
8/22/16
9/22/16
10/22/16
11/22/16
12/22/16
1/22/17
2/22/17
3/22/17
4/22/17
Exterior Temp
Exterior RH
LivingRm Temp
Mbath Temp
LivingRm RH
Mbath RH


Climate Zone 5A - New York - House 20
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
100
90
80
70
60
50
40
30
20
10
0
9/14/16
10/14/16
11/14/16
12/14/16
1/14/17
2/14/17
3/14/17
4/14/17
Exterior Temp
Exterior RH
LivingRm Temp
Bath Temp
LivingRm RH
Bath RH


Climate Zone 6A - Wisconsin- House 21
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
100
90
80
70
60
50
40
30
20
10
0
11/1/16
12/1/16
1/1/17
2/1/17
3/1/17
4/1/17
Exterior Temp
Exterior RH
LivingRm Temp
LivingRm RH



Climate Zone 6A - Wisconsin- House 22
Interior and Exterior Conditions
Temperature (°F)and Relative Humidity (%)
90
70
50
30
10
-10
12/15/16
1/15/17
2/15/17
3/15/17
4/15/17
Exterior Temp
Exterior RH

Building AMERICA
U.S. Department of Energy

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

For more information, visit: buildingamerica.gov

DOE/EE-1784 · May 2018