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High-R Walls for Remodeling: Wall Cavity Moisture Monitoring

J. Wiehagen and V. Kochkin
NAHB Research Center

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High-R Walls for Remodeling: Wall Cavity Moisture Monitoring

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Definitions

ACH_{50}	Building air changes per hour at a 50 pascal interior pressure differential with respect to the exterior
AFUE	Annual fuel utilization efficiency
BA	Building America
DOE	U.S. Department of Energy
DP	Dew point
HSPF	Heating season performance factor, representative of the efficiency rating of electric heating equipment
ICC	International Code Council
IECC	International Energy Conservation Code
MC	Moisture content; relating to wood properties, the moisture content is defined as the weight of the water contained in the wood expressed as a percentage of the oven dry weight of the wood.
NAHB	National Association of Home Builders
OSB	Oriented strand board
PS2	Performance standard for wood-based structural-use panels
RH	Relative humidity
SEER	Seasonal energy efficiency ratio, a measure of the efficiency of consumer central air-conditioning systems
SPF	Spruce-Pine-Fir
T	Temperature
Vinyl	Vinyl siding used as the outermost exterior finish
WRB	Weather-resistive barrier

Executive Summary

The National Association of Home Builders (NAHB) Research Center Industry Partnership team monitored six homes constructed in 2009 for wall cavity moisture characteristics. Five of the homes were constructed in climate zone 5 and one in climate zone 4. The monitoring program was initiated from an experience of oriented strand board (OSB) sheathing problems (buckling and siding displacement) in similar homes constructed in the same geographic area to characterize the wall moisture. The homes under test were constructed using code-compliant wall construction practices and materials using an exterior weather-resistive barrier on the exterior of the wood structural sheathing. The homes were all tested to air infiltration levels of fewer than four air changes per hour at 50 Pa. The monitoring program was designed to identify seasonal moisture characteristics that might indicate the potential for problems as well as produce a baseline set of data for comparison to homes constructed with higher performing (better insulated) wall systems.

One suspected interaction that might lead to moisture problems, including sheathing buckling, was increased winter moisture levels in the cavity because of a combination of lower infiltration rates (of colder, drier air in winter) resulting from a combination of air sealing strategies and interior winter moisture levels that raise humidity levels in the home. The wall cavity and sheathing monitoring results presented here provide empirical data on the cyclic moisture characteristics of wall cavities in higher efficiency homes that are a precursor to subsequent data from high performance wall systems in homes constructed to building energy code levels at or exceeding those outlined in the *International Energy Conservation Code* (International Code Council 2012). The monitored data in particular include the moisture content of the wood structural sheathing, a primary indicator of OSB expansion.

The results of the monitoring period reported for each home indicated a wide range of cavity moisture characteristics that are generally seasonal and directional, with the colder periods and the east and north walls showing the higher instances of moisture content (MC). All wall cavities measured show a cyclic behavior for the OSB MC but with a wide variation in the both the peak moisture content and the duration of higher levels of MC measured. Often, wide variations occur within the same home.

Results of this study will help create a baseline for the next study that is currently under way, focusing on the moisture performance of high R-value wall systems in energy efficient homes throughout multiple climate zones. The next phase of this research will look at a range of wall systems and construction configurations, upgraded to meet or exceed the minimum insulation levels and airtightness requirements of current energy codes. The focus of the study is on the performance of wall systems and, in particular, the moisture characteristics inside the wall cavity and in the wood sheathing. Furthermore, although this research will initially address new home construction, the goal is to resolve potential moisture issues in wall cavities of existing homes when insulation and air sealing improvements are made.

1 Purpose

This study, which was performed by the National Association of Home Builders (NAHB) Research Center Industry Partnership, was initiated to characterize indoor humidity levels and wall cavity moisture performance in standard constructed wall systems in homes air sealed beyond standard building code requirements. This initial work will also support ongoing efforts to address the moisture performance of much higher efficiency wall systems. Furthermore, although this research will initially examine new home construction, the goal is to resolve potential moisture issues in wall cavities of existing homes when insulation and air sealing improvements are made in older homes.

The objectives of the study were to document seasonal wall cavity moisture characteristics, document oriented strand board (OSB) moisture characteristics and indoor humidity levels in homes with substantially lower infiltration rates, and with sufficient data, isolate the variables or a combination of variables that can result in unsatisfactory moisture performance of standard acceptable wall system construction.

The purpose of this initial effort was to document construction practices and obtain wall cavity moisture performance data for occupied homes framed in the fall of 2009 in the same geographical areas and by the same builders that experienced buckling of OSB wall sheathing in the winter of 2008–2009. The specific buckling issue raised concerns for builders that combining higher efficiency home features might lead to more wall cavity moisture problems. Based on the unexpected wall sheathing failures in homes constructed according to current code practices and similarly to many homes that apparently do not have moisture problems, this study was organized to investigate the cyclic moisture characteristics in the wall cavity. Documenting the moisture characteristics in wall cavities of these standard wall details and operating in uncontrolled but common field conditions was deemed necessary to correlate wall construction methods and materials with the cavity moisture performance. This documentation is important to not only uncover potential problems but also to correlate similar characteristics in other, more efficient wall system designs.

2 Introduction

Overall, the goal of the U.S. Department of Energy's (DOE) Building America (BA) program is to "demonstrate how cost-effective strategies can reduce home energy use by up to 50%, for both new and existing homes, in all climate regions by 2017." To this end, the BA teams conduct research to "design, test, upgrade, and build high performance homes using strategies that significantly cut energy use." (DOE 2012a).

The changes in the moisture performance of the wall system can have serious negative effects on the building durability, indoor environmental quality, and even comfort without immediate signs to the home occupant. The NAHB Research Center's moisture research is designed to yield information on the moisture performance of upgraded existing and new energy efficient homes with higher performing wall systems. The testing detailed in this report provides baseline data for standard home construction with lower infiltration levels than standard homes. The next phase of this research will look at wall systems upgraded to meet or exceed the minimum insulation levels and airtightness requirements of the *International Energy Conservation Code* (IECC; International Code Council [ICC] 2012). The focus of the study is on the performance of wall systems and, in particular, the moisture characteristics inside the wall cavity and in the wood sheathing. Furthermore, this study will initially consider new home construction, but the goal is to resolve potential moisture issues in wall cavities of existing homes when insulation and air sealing improvements are made.

Increasing insulation levels in wall systems is a key element in achieving current and new BA goals for energy performance. Technologies and construction methods to accommodate higher levels of insulation are often based on typical construction methods that serve multiple purposes, including structural and fire safety. At the same time, walls constructed using these methods are expected to last for many decades and to function as a neutral aspect to the environmental quality of the indoor air (e.g., not contribute to mold and decay).

This field testing parallels other BA research in that higher R-value walls must be demonstrated to perform satisfactorily as a material and to last for the life of the home. Higher R-value wall systems are expected to perform thermally as designed; this research focuses on ensuring that the changes to the wall system design and their construction will continue to perform like the wall systems used successfully for generations.

The monitoring details outlined here in climate zone 4 and the ongoing expanded research will analyze wall moisture performance in multiple climate zones except for hot-dry climates. The data obtained through this monitoring effort are expected to serve as empirical evidence of the wall system moisture performance throughout multiple seasons, climate zones, and houses with lower infiltration. In addition, for some test homes, these data will be combined with energy consumption data and ventilation data to give an overall characterization of the whole-house energy and moisture performance that can then be used to compare with models that predict such results.

3 Background

3.1 Field Observations

Some builders in the midwestern states and Pennsylvania reported an apparent increase in OSB wall sheathing buckling was reported during the winter season of 2009. The homes with reported OSB buckling are located in cold climates (climate zones 5 and 6) or at the boundary between the cold and mixed-humid climates (zone 4).

The team interviewed several builders who experienced this problem. The problem manifested itself as “wavy” vinyl siding (Figure 1 through Figure 4). The repairs typically involve removing the siding and replacing buckled OSB panels. Evidence of the panels having elevated moisture levels was observed during the repairs, including in some cases observations of a “mold-like substance” on the interior face of the panel. During repairs made in the winter months, in some cases, frost was also observed on the exterior face of the panel.

Figure 1. Wavy lap siding resulting from buckled OSB panels on the rear wall of a house

Figure 2. Wavy siding resulting from buckled OSB panels on a side wall of a house

Figure 3. Removed buckled OSB panel

Figure 4. Wall with buckled OSB panels (siding removed exposing the weather-resistive barrier)

3.2 OSB Sheathing Characteristics

OSB panels are made of wood strands oriented and glued together. Because wood changes dimensions as it releases or gains moisture, the OSB panels expand as the moisture content (MC) of wood increases in response to the ambient conditions. All OSB panels are required to meet the linear expansion limits of Product Standard PS-2 (1) (NIST 2004) for a maximum average expansion of 0.5% in either panel direction (machine and cross machine) when subjected to a controlled laboratory MC change of about 19%.

OSB panels typically arrive at the jobsite at low MC (e.g., 5%). The OSB manufacturers' installation instructions require a ⅛-in. gap between the vertical panel joints to allow limited expansion of the panels. If the expansion of the panel exceeds the provided gap, the panels are prone to buckling in the direction perpendicular to the wall's plane. For a 48-in.-wide panel with a linear expansion of 0.5%, installed with a ⅛-in. gap, the calculated maximum MC change for panels to come into full contact without additional room to expand is about 10%. As the team observed during this study, MCs of OSB above 20% and even above 25% are not uncommon in walls in the initial months following the construction process (and in some cases later in service)—resulting in a total potential moisture fluctuation of 15%–20% relative to the initial starting point of 5%. Sheathing fasteners help restrain the expansion of panels in a wall assembly. A follow-up laboratory study is planned to investigate the relationship between the panel properties and the panel expansion and buckling behavior when attached to wall framing.

4 Research Methodology

The research methodology includes the following primary steps:

1. Identifying new homes built in fall 2009 by the same builders in the same geographical areas that experienced OSB buckling in spring 2009
2. Observing OSB installation on each selected home
3. Collecting relevant design, construction, and material data for each selected home
4. Installing sensors in walls to measure temperature, dew point (DP), and relative humidity (RH) inside the cavity and MC of OSB sheathing
5. Measuring air exchange rates through blower door testing for each selected home
6. Collecting and analyzing data
7. Developing conclusions based on the documented performance.

This report summarizes results of steps 1 through 5 on six homes, and the remaining steps on five of the homes. An analysis of the available wall cavity measured moisture performance data collected is included. Conclusions are drawn based on the analysis completed to date.

4.1 Research Homes

Three homebuilders in three different states made six homes/jobsites in climate zones 4 and 5 (Figure 5) available to the NAHB Research Center. A site visit was conducted for each home during the construction process. A Site Inspection Data Sheet (see Appendix) was completed for each home/jobsite to document construction details, home design, and material characteristics. Table 1 summarizes key characteristics for each home. Table 2 contains wall assembly details.

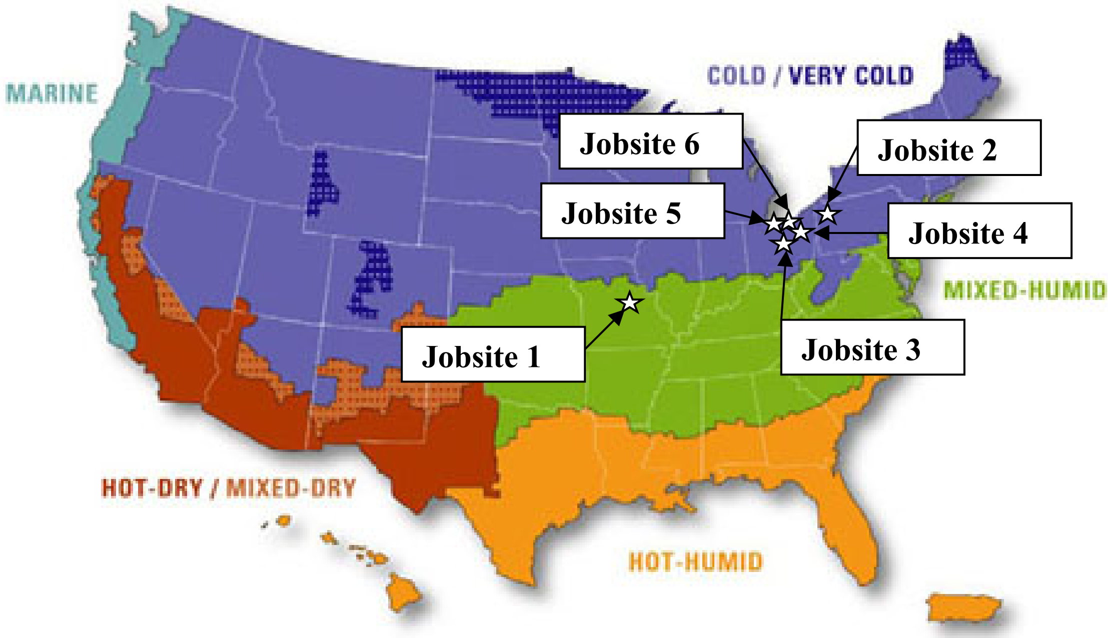

Figure 5. Jobsite geographical locations overlay on the DOE climate and hygrothermal map (Source: Building America website - DOE 2012b)

Because the building's airtightness is important to its moisture performance, blower door tests were conducted on each home to measure the amount of air changes per hour at 50 Pa (ACH_{50}). The blower door tests were performed after completion of construction and before occupancy. Table 1 includes results of the blower door tests.

Table 1. Jobsite and Home Details

Jobsite Number	City	State	Climate Zone	ENERGY STAR	Blower Door ACH_{50}[a]	Square Footage[b] (ft^2)	Number of Occupants	Basement		Attached Garage		Heating System	Cooling System	Ventilation	Fire-place
								Conditioned	Finished	Conditioned	Finished				
1	Chesterfield	MO	4	Yes	2.49	5,700	Model Home	Yes	Yes	Yes	Yes	Gas (92.1 AFUE)	Electric (SEER-14)	Unknown[c]	Gas
2	Valencia	PA	5	Yes	2.41	5,300	3	Yes	No	No	Yes	Electric (8.0 HSPF)	Electric (SEER-13)	Kitchen/Bathrooms	Wood
3	Mansfield	OH	5	No	2.12	4,000	4	Yes	No	No	Yes	Electric (8.1 HSPF)	Electric (SEER-13)	Kitchen/Bathrooms	No
4	Wadsworth	OH	5	Yes	3.71	3,000	2	Yes	No	No	Yes	Gas (93 AFUE)	Electric (SEER-14)	Whole-house	No
5	Lorain	OH	5	No	3.27	2,800	4	Yes	No	No	Yes	Gas (92.3 AFUE)	Electric (SEER-13)	Kitchen/Bathrooms	No
6	North Ridgeville	OH	5	No	2.83	3,000	3	Yes	Partial	No	Yes	Gas (92.3 AFUE)	Electric (SEER-13)	Kitchen/Bathrooms	No

Notes: AFUE, annual fuel utilization efficiency; SEER, seasonal energy efficiency ratio; HSPF, heating season performance factor
a. Depressurization blower door test results reported. The blower door test results are developed from multipoint depressurization test results.
b. Home square footage includes the basement.
c. The information provided by the builder on this house is inconsistent with the plan specifications.

Table 2. Wall Details

Jobsite Number	City	State	Framed Stories	Framing Size[a,b]	Stud Material/ Grade	Stud MC[c] (%)	Air Sealing	Wall Insulation/ Vapor Retarder	WRB (Perms[d])	Finish
1	Chesterfield	MO	2	2 × 4	SPF/Stud	9-17	Sill, Rim Joist	R-13/ Kraft paper	Brand 1 (46.6)	Brick and Cement Fiber Board
2	Valencia	PA	3	2 × 6	SPF/Stud	11-15	Plates (top, bottom, and sill), Rim Joist	R-19/ Kraft paper	Brand 2 (56)	Brick, Stone, and Vinyl
3	Mansfield	OH	2	2 × 4	SPF/Stud	9-15	Plates (top, bottom, and sill), Rim Joist	R-13/ Kraft paper	Brand 2 (56)	Vinyl
4	Wadsworth	OH	1	2 × 4	SPF/Stud	10	Plates (top, bottom, and sill), Rim Joist	R-15/ Kraft paper	Brand 2 (56)	Vinyl
5	Lorain	OH	2	2 × 4	SPF/2	12-13	Bottom Plate	R-13/ Kraft paper	Brand 3 (63)	Vinyl
6	North Ridgeville	OH	1	2 × 4	SPF/Stud	8-14	Bottom Plate	R-13/ Kraft paper	Brand 3 (63)	Vinyl

a. Spruce-Pine-Fir (SPF) typical wood species for all jobsites
b. Stud spacing of 16 in. on center used for all jobsites
c. Framing MC measured during site visit
d. Perm ratings for WRBs obtained from product specifications physical properties data sheets [Dow, 2010], [DuPont 2007]

Table 3 gives specific dates for construction of each home. All homes were framed primarily in November. Occupancy of the homes began in January and February 2010. Figure 6 shows the total precipitation by month during the time of construction for each site, including historical monthly averages for comparison. Generally, total precipitation during the observation period measured below historical monthly averages except for October and January, when precipitation levels were higher than average. Table 3 also includes the dates of the NAHB Research Center site visits. NAHB Research Center staff was present at the time of the wall framing only for jobsite 1 (Chesterfield, Missouri). For the other five sites, the visit was conducted a few days after the framing had been completed and the wall framing was still exposed.

Table 3. Home Construction Dates

Jobsite Number	Foundation Start	Framing Start	Roof Enclosed	House Enclosed	Occupancy Start	NAHB Research Center Site Visit
1[a]	10/23/09	11/03/09	11/12/09	11/13/09	12/22/09	11/04/09
2	10/29/09	11/17/09	12/10/09	12/10/09	1/18/10	11/20/09
3	10/22/09	11/10/09	11/11/09	11/12/09	1/6/10	11/12/09
4	10/19/09	11/5/09	11/09/09	11/10/09	2/22/10	11/12/09
5	10/20/09	11/10/09	11/18/09	11/24/09	01/19/10	11/12/09
6	10/14/09	10/30/09	11/12/09	11/19/09	01/25/10	11/12/09

[a] Home is a model home, occupancy date is the date the home became open for display.

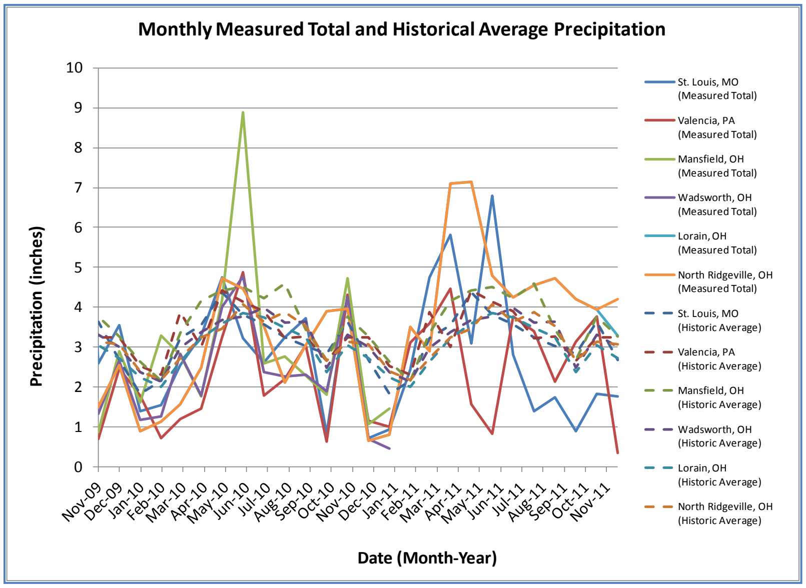

Figure 6. Comparison of precipitation amounts for each jobsite location

The walls being monitored represent the most common wall assemblies being constructed in the United States. Figure 7 shows a general representation of the wall detail for the homes being monitored. Table 2 contains a complete list of the wall configuration and materials. All of the homes were constructed with interior kraft-faced batt facing. Figure 8 through Figure 13 show first-story plans and photographs of each home. In each home, a "test wall" was selected for detailed documentation of the OSB installation process and monitoring of the moisture performance. The test walls were selected based on (1) wall orientation and (2) the amount of openings (i.e., doors or windows) in the wall. Because the MC in the OSB panels is the driving factor for panel expansion and possibly buckling, sidewalls with a northward orientation were the primary choice for investigation. These walls were selected because of higher expected MCs from reduced sun exposure, which leads to lower wall temperatures and decreased drying potential. The walls with fewer openings are expected to be more prone to buckling because of increased amounts of sheathing and cumulative expansion across the face of the wall. The test wall is always a first-floor side wall (left or right side elevation) with few openings and the majority of the wall adjacent to livable space. Panel dimensions, gapping between installed panels, and panel attachment details were observed and documented for each test wall (Table 4).

The OSB panels used in wall construction of the six homes came from six different mills from five manufacturers. Because panel linear expansion properties vary by mill based on the materials used in panel fabrication (e.g., wood species, strand orientation, resin type and content, and wax), panels are classified by manufacturer (1 through 5) and mill location (A or B).

OSB samples were taken from wall sheathing panels at each of the jobsites for testing linear expansion properties. Researchers at the NAHB Research Center's laboratory conducted the testing in accordance with PS-2 (National Institute of Standards and Technology, 2004). Table 4 contains the results from the linear expansion testing. Linear expansion in the machine grain direction was substantially below the 0.5% limit for all six mills. Linear expansion in the cross direction varied substantially between the mills, from as low as 0.22% to as high as 0.57%. Panels from Mill 2-B consistently exceed the PS-2 0.5% limit. Panels from Mill 1 and Mill 5 were at or near the 0.5% limit.

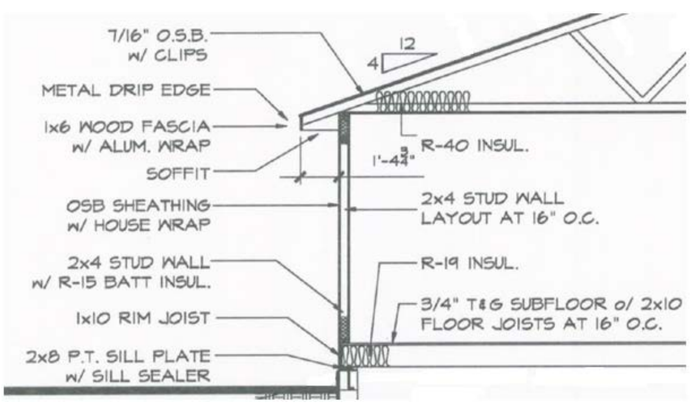

Figure 7. Common wall detail for monitored homes

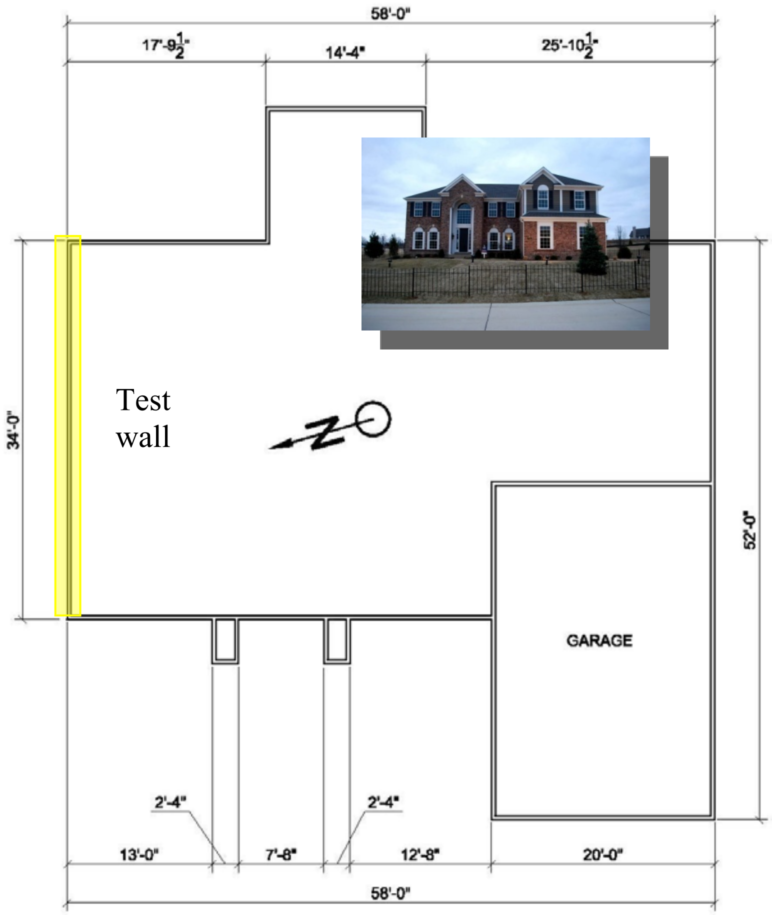

Figure 8. Jobsite 1 test wall location and orientation

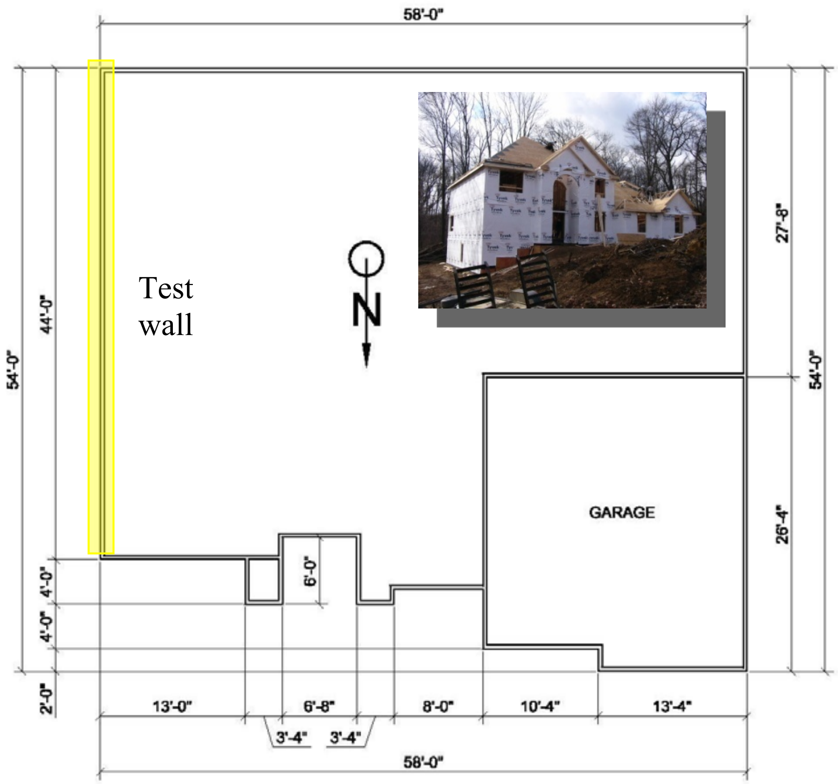

Figure 9. Jobsite 2 test wall location and orientation

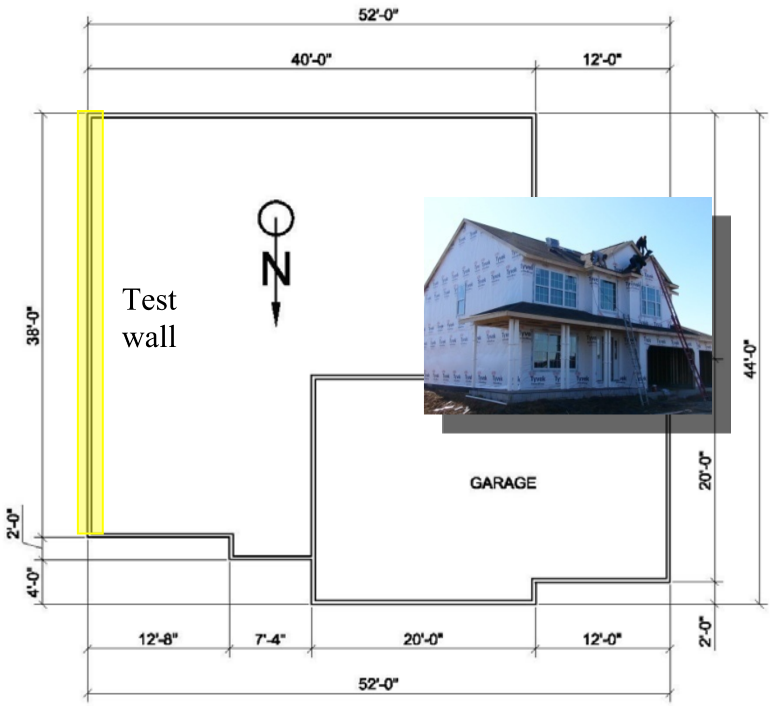

Figure 10. Jobsite 3 test wall location and orientation

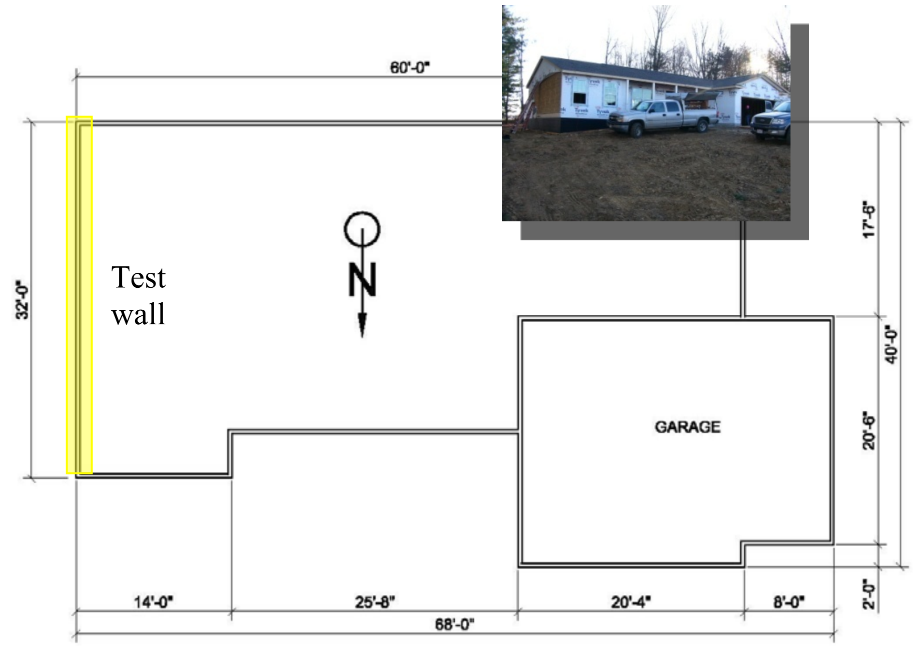

Figure 11. Jobsite 4 test wall location and orientation

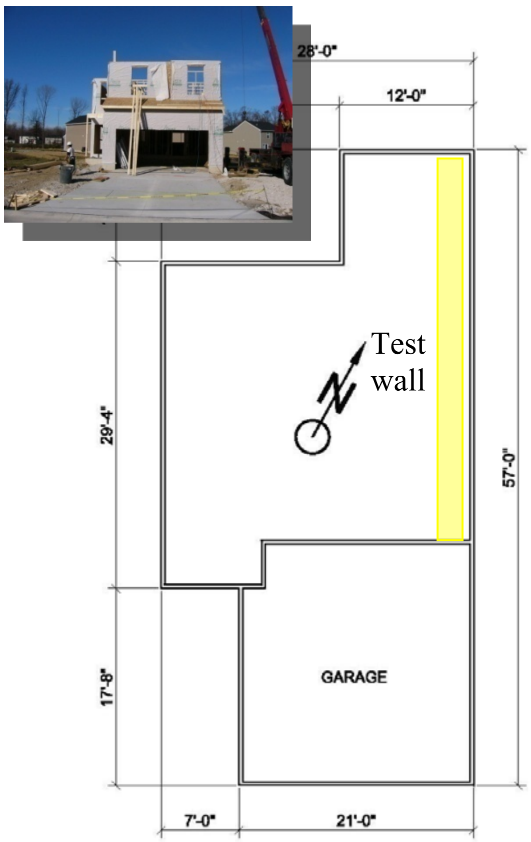

Figure 12. Jobsite 5 test wall location and orientation

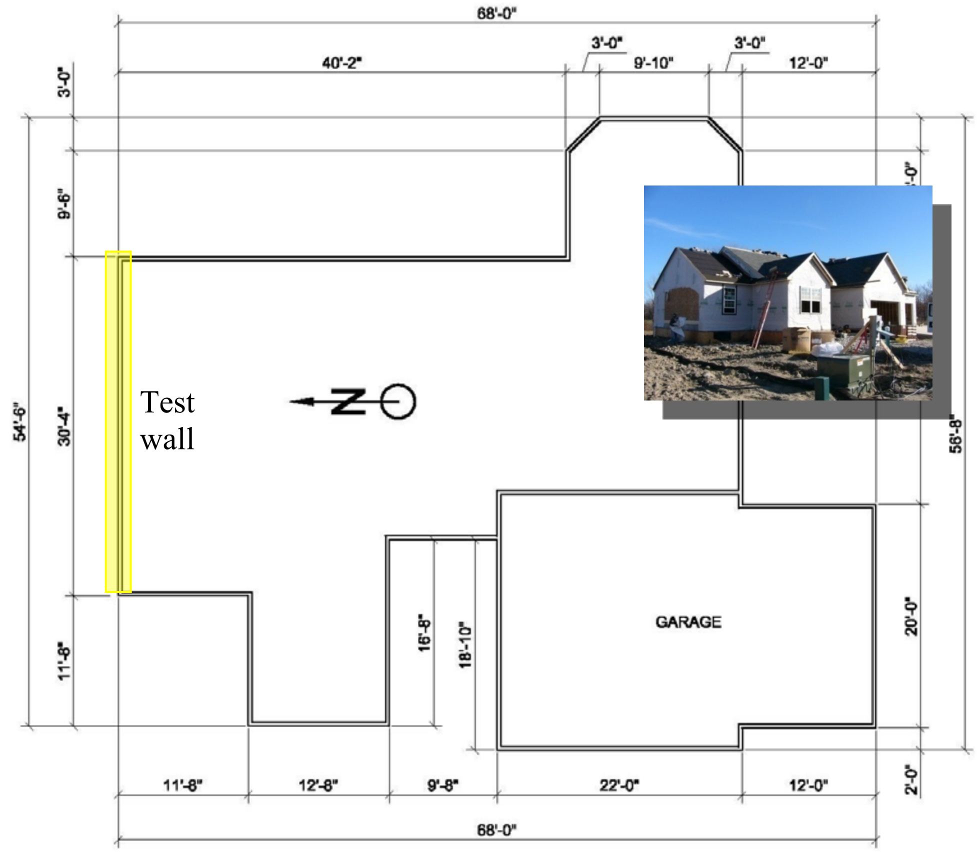

Figure 13. Jobsite 6 test wall location and orientation

Table 4. OSB Panel Properties and Installation Details

Jobsite	OSB Mill	Floor	Average MC at Inspection	Panel Dimension		Installed Vertical Edge Gap (in.)	Panel Orientation	Fasteners			Linear Expansion	
				Mean	Deviation			Edge Distance (in.)	Orientation to Adjoining Panel Edge	Over-driven	Grain Direction	Mean
1	Mill 1	1	<6%	47.910	0.027	0–3/16	Vertical	0–1/2	Perpendicular	Partial	Machine	0.13
											Cross	0.50
	Mill 2-A	2	<6%	47.934	0.023	-		-	-	-	Machine	0.07
											Cross	0.22
2	Mill 3	1	11%	48.036	0.048	0–1/8		*(Footnote a)*			Machine	0.10
											Cross	0.25
	Mill 2-B	2	10%	47.881	0.013	-		-	-	-	Machine	0.16
											Cross	0.56
3	Mill 4	1	9%	47.948	0.0210	0–5/32		1/16–1/2	Parallel	Yes	Machine	0.16
											Cross	0.27
	Mill 2-B	2	8%	47.931	0.0342	-		-	-	-	Machine	0.23
											Cross	0.49
4	Mill 3	1	7%	47.972	0.025	1/32–1/8		1/2	Parallel	Yes	Machine	0.13
											Cross	0.28
5	Mill 5	1	9%	48.060	0.009	1/16–1/8		0–1/2	Varies	Partial	Machine	0.20
											Cross	0.47
	Mill 2-B	2	<6%	47.866	0.026	-		-	-	-	Machine	0.16
											Cross	0.57
6[b]	Mill 2-B	1	9%	95.938	0.030	0–1/8	Horizontal	>1/2	Parallel	No	Machine	0.16
											Cross	0.57

a. At the time of the jobsite visit, OSB sheathing was covered with WRB and sheathing fasteners were not accessible for detailed inspection.
b. Linear expansion results from OSB sheathing obtained at Jobsite 5 (panels used were from the same mill and had the same manufacture date).
"-" indicates that data is not available for the panels from that mill. Panel separation measurements were taken from a defined test wall section in the test home with panels from a specific mill. In some jobsites wall panels in other wall sections than the test wall were from two different mills.

The home located in Valencia, Pennsylvania (Jobsite 2) had a wood framed walk-out basement such that one end of the home had three framed stories. The test wall for this home was at the second level as shown in Figure 14.

Figure 14. Jobsite 2 east wall (test wall highlighted), three stories framed

The framing on Jobsites 4 and 6 was completed before the NAHB Research Center staff visited. As a result, all excess OSB sheathing panels were removed from the site before the visits. For Jobsite 4, the builder was able to obtain OSB panels from the same manufacturer and mill; the unique difference between panels installed on the walls and the panels used for linear expansion testing was the manufacture date (installed panels manufactured September 9, tested panels manufactured September 3). No linear expansion samples were obtained from Jobsite 6 because the OSB panels were identical to those used on Jobsite 5.

5 In-Service Environmental Conditions Monitoring

Because increased moisture in the OSB panels is the primary driver for panel expansion, sensors were installed inside the wall cavity of the test wall and in several other reference locations of each house to measure the MC of the OSB panels and environmental conditions inside the wall cavity. In addition, one or two sensors were installed inside of each home to monitor the temperature and RH inside the house. The ambient weather data were obtained from local weather stations. This section discusses details of the environmental monitoring system and presents the available data for each of the jobsites.

5.1 Monitoring System

Small wireless sensors (Omnisense S-900-1, Figure 15) were installed in walls in the home to measure the following parameters:

- Cavity temperature (–40°F to 185°F)
- Cavity RH (0% to 100%)
- Cavity DP temperature
- OSB sheathing moisture content (7% to 40%).

The temperature and RH are measured by an internal sensor located inside the plastic housing. The wood MC is determined using two screw pins driven into the sheathing and is based on the measured resistivity of the OSB material. The sensors transmit measurements at set intervals (in most cases, 30 min) wirelessly to a gateway (router). The gateway then uploads the measurements to a central website location for storage and acquisition. Figure 16 shows a typical installation of a sensor before enclosing with insulation.

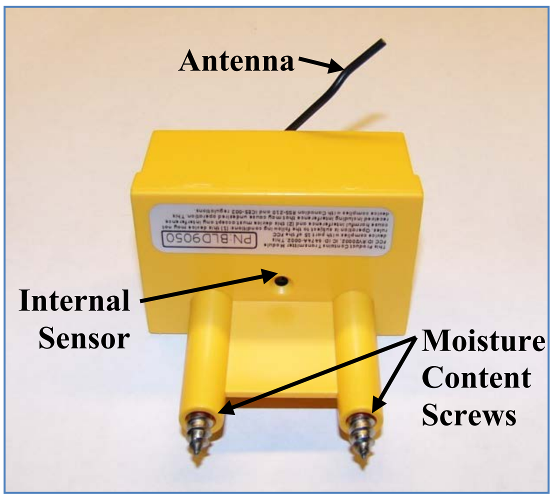

Figure 15. Omnisense S-900-1 sensor

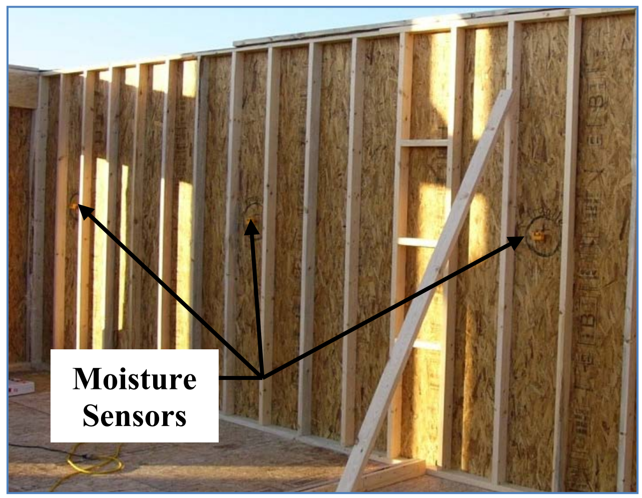

Figure 16. Installed test wall moisture sensors

The manufacturer states that the sensor accuracy for the models used is ±2.0% RH and ±0.3°C. The NAHB Research Center has performed numerous calibrations to verify both sensor accuracy and the correlations with the MC. MC correlations have been performed comparing to readings on handheld electrical conductance type moisture meters as well as comparing MC readings with wet/oven dry sample measurement calculations. The wood MC value reported through the sensor technology is a wood moisture equivalent and is the water content of wood as a percentage of dry weight. The sensor manufacturer calibrates its devices based on wood species and temperature compensation relationships outlined by the U.S. Department of Agriculture (James 1988).

5.2 Monitoring Sensor Locations

On average, eight sensors were installed in the one-story homes and 14 sensors were installed in the two-story homes. Sensors were attached to the inside face of the exterior OSB panel in the center of the wall cavity. The sensors were located at an elevation of 5 ft above the subfloor. A minimum of one sensor per wall orientation (i.e., north, west, east, and south) was installed with three sensors installed in each test wall. In two-story homes, a minimum of three sensors were installed in the second floor exterior wall above the test wall.

Table 5 describes individual sensor locations and associated wall orientation for each of the six jobsites. During the planning stages of this study, based on discussions with builders, the NAHB team determined that there was no consistency between OSB buckling and interior room use (e.g., bathrooms with higher humidity). Therefore, sensor locations were not predetermined based on adjacent interior room use.

One sensor was located in the interior of the home to monitor temperature and RH inside the house. Although the intention was to locate the interior sensor as near to the home's thermostat as possible, because of aesthetics and homeowner preferences, the interior sensors in five of the six homes were located in the kitchen above cabinets. In addition, exterior daily average ambient temperature, RH, and DP were obtained from weather stations located near each home.

Table 5. Sensor Locations by Jobsite

Adjacent Interior Room Use	Number of sensors (wall orientation)					
	Jobsite Number					
	1	2	3	4	5	6
Kitchen	2 (Interior, East)	1 (Interior, East)	1 (Interior, West)	1 (Interior, South)	1 (Interior)	1 (South)
Full Bath	1 (South)	1 (East)			1 (East)	
Half Bath			1 (East)		1 (East)	
Living room	3 (2-North, West)		2 (North, East)			
Family room	1 (North)		2 (East, South)			
Dining room		2 (North, East)			1 (East)	
Great room				1 (North)	2 (North, West)	1 (Interior)
Bedroom/Office	5 (3-North, West, South)	5 (1-North, West, 2-East, South)	4 (North, 2-East, South)	4 (West, 3-East)	4 (North, West, East, South)	5 (3-North, East, South)
Breakfast		1 (South)			1 (East)	
Laundry					1 (East)	1 (South)
Closet/Pantry	1 (East)	2 (East)	2 (West, East)		1 (East)	
Garage	1 (North)	1 (North)	1 (West)	1 (East)	1 (East)	1 (North)

6 Results of In-Service Environmental Conditions Measurements

The available recorded measurements for each home are presented by jobsite, floor level, and exterior wall orientations in various charts in this section. All results are reported as daily averages calculated based on the measurements recorded every half hour. Because the primary observation is the OSB MC level, RH and temperature plots are given for only the first-floor locations. The measurements recorded by the sensors installed in garage walls are included for each home. It should be noted that garages are constructed as unconditioned space in five of the six homes.

Based on visual observations of the siding in the spring of 2010, none of the six homes exhibited buckling to the degree that would be visible through the siding. The OSB MC increased from less than 6% to 11%, however, at the time of the site visit. The OSB MC ranged from 10% to 25% at the time of first measurements after initial occupancy that started in January and February. Table 6 lists the calculated OSB panel expansions, which are based on these changes in MCs and the results of the linear expansion tests. OSB buckling potential is highest for Jobsite 5 with installed panel gaps of ⅛ in. and a maximum calculated expansion of 5/16 in. Maximum potential panel expansions in the other homes all are in the range of the provided gaps; therefore, buckling potential is low. In all homes, the MC started trending down in the spring months as the average daily temperature increased. These observed decreases in OSB MC ranged from about 5% to as much as 20%.

Table 6. Potential OSB Panel Expansion

Jobsite	OSB Mill	Maximum Moisture Content Increase[a]	Maximum Calculated Panel Expansion (in.)	Vertical Edge Gap as Installed (in.)
1	Mill 1	16	3/16	0–3/16
	Mill 2-A	14	1/16	-
2	Mill 3	14	1/16	0–1/8
	Mill 2-B	13	3/16	-
3	Mill 4	8	1/16	0–5/32
	Mill 2-B	6	1/16	-
4	Mill 3	-	-	1/32–1/8
5	Mill 5	23	5/16	1/16–1/8
	Mill 2-B	20	5/16	-
6	Mill 2-B	9	1/16	0–1/8

a. The maximum MC increase reported in this table is estimated relative to the MC at the time of the visit to allow for direct comparison of the calculated expansion with the gap measured at the time of the visit. It is likely that the OSB MC at the time of panel installation was lower and the overall change in MC was greater.

Based on the available data, Table 7 and Figure 17 through Figure 21 show the daily average OSB MCs for each jobsite. Figure 27 through Figure 51 show in-service home interior and wall cavity measurements of temperature, RH, DP, and a comparison of MC. In-service conditions are given for five of the six homes for the following performance periods (data for Jobsite 4 are not available because of the lack of an agreement with the homeowner):

- Jobsite 1 – Late January 2010 to early December 2011
- Jobsite 2 – Late March 2010 to November 2011
- Jobsite 3 – Mid-March 2010 to mid-January 2011
- Jobsite 4 – No data available
- Jobsite 5 – Late January 2010 to November 2011
- Jobsite 6 – Mid-January 2010 to mid-September 2011.

Table 7. Summary Wall Cavity Moisture Characteristics for Latest Annual Period

Job Site	Extended Monitoring Period	Interior Conditions		Days[a]	Peak OSB MC (Most Recent Year Data) Wall Orientation: N	W	E	S	Annual Range Cavity MC Temperature (T) DP	
1	1/28/2010 12/11/11	Average RH Maximum RH Minimum RH Average Temp Winter RH[b]	33.2% 40.0% 22.4% 73.1°F 27.3%	365	15%	14%	9%	9%	Minimum MC Average MC Average T Average DP	7%–9% 7%– 2% 62°F–68°F 40°F–48°F
2	3/22/2010 12/11/11	Average RH Maximum RH Minimum RH Average Temp Winter RH[b]	46.1 60.3 29.5 72.6°F 35.9%	355	17%	16%	30%	14%	Minimum MC Average MC Average T Average DP	8%–10% 9%–16% 57°F–60°F 47°F–50°F
3	3/16/2010 1/31/11	Average RH Maximum RH Minimum RH Average Temp Winter RH[b]	51.0 69.8 35.7 72.4°F 41.0%	304	14%	14%	17%	14%	Minimum MC Average MC Average T Average DP	7%–10% 8%–11% 64°F–68°F 48°F–53°F
4	No Data Available									
5	1/29/2010 12/11/11	Average RH Maximum RH Minimum RH Average Temp Winter RH[b]	52.4 68.8 35.2 71.8°F 44.7%	365	23%	18%	33%	16%	Minimum MC Average MC Average T Average DP	9%–12% 12%–22% 55°F–58°F 48°F–52°F
6	1/13/2010 9/15/11	Average RH Maximum RH Minimum RH Average Temp Winter RH[b]	49.7 69.8 34.4 71.7°F 40.1%	365	13%	n/a	12%	21%	Minimum MC Average MC Average T Average DP	7%–9% 8%–12% 63°F–65°F 49°F–50°F

[a] In most recent annual measurement period
[b] Winter RH is the average interior RH for the period from December through March (if available)

Table 7 lists the initiation date of in-service condition monitoring and peak OSB MCs for each house. Also included in Table 7 is the range of interior RH over the most recent available annual monitoring period for each site. Daily average interior temperatures were approximately 70°F over the monitoring period for each house. The average wintertime interior RH is also included.

The trends in OSB MC demonstrate that during the initial stages of home occupancy as well as the subsequent winter period, MCs are elevated or elevating. As ambient temperatures increase in the spring, however, the MC in OSB panels decreases. This drying out of the panels is most accentuated during the first half of April, with a drop in OSB MC observed in all of the homes except one during this period. The MC of the OSB sheathing decreases to less than 12% over the summer for all homes.

Figure 17 through Figure 21 chart the change in the OSB sheathing MC for each test site based on daily averages. The data come from all wall cavities with available moisture sensor readings, including the unconditioned garage wall cavity. The radial chart begins and ends at the 12 o'clock position regardless of the total range of dates for the plot. In all cases, the starting point is within a few months of construction completion. The same data are included in Section 7.4, but charted using a linear plot line.

As would be expected, the MC of the OSB sheathing increases in the winter months, peaking in late winter. In the colder months, and more generally in occupied homes with lower air infiltration rates, the moisture drive is from the interior to the exterior. The moisture drive would include exfiltration and diffusion. In most cases, the drop-off to lower MC levels occurs in early spring through the summer and into the fall, when the cycle repeats.

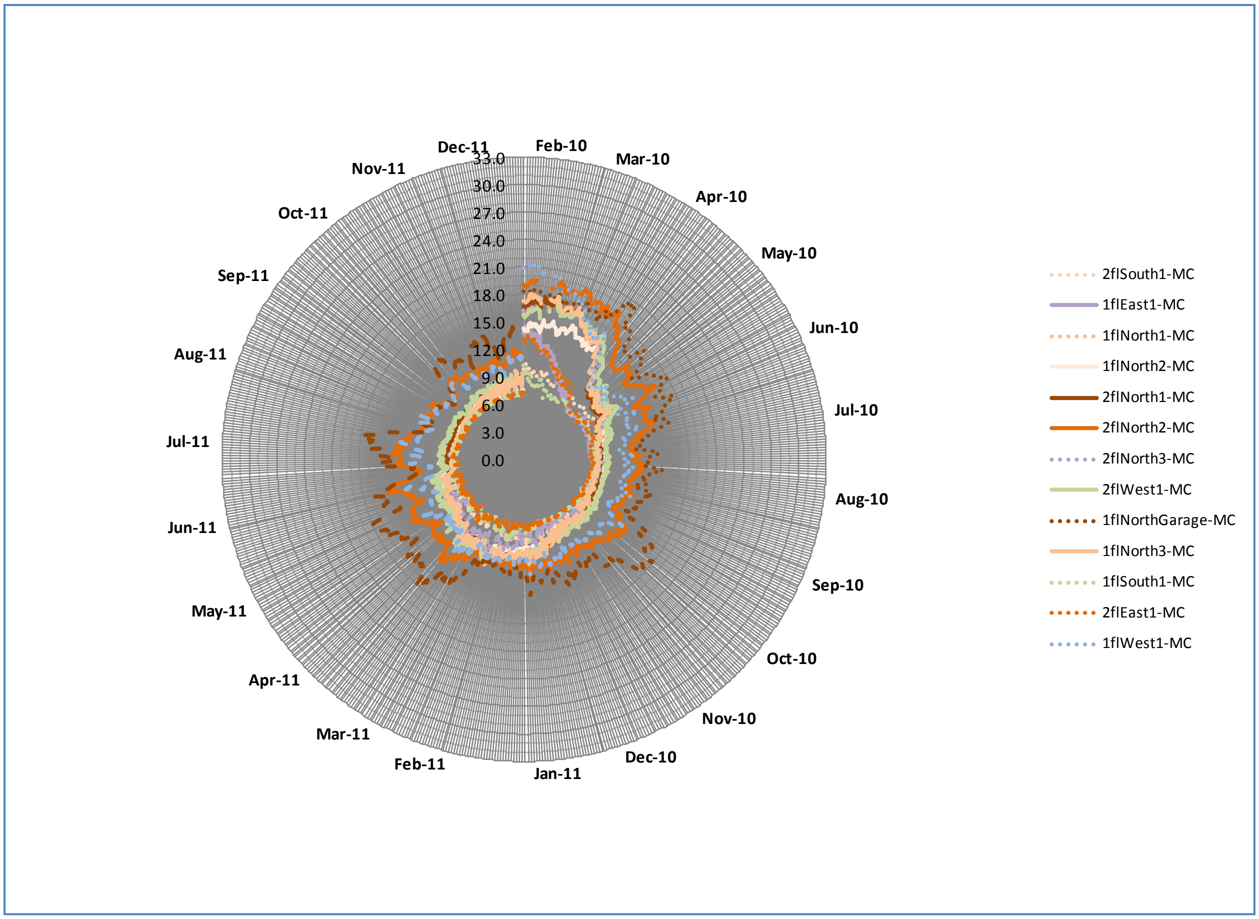

Figure 17. Jobsite 1 OSB MC, all available data

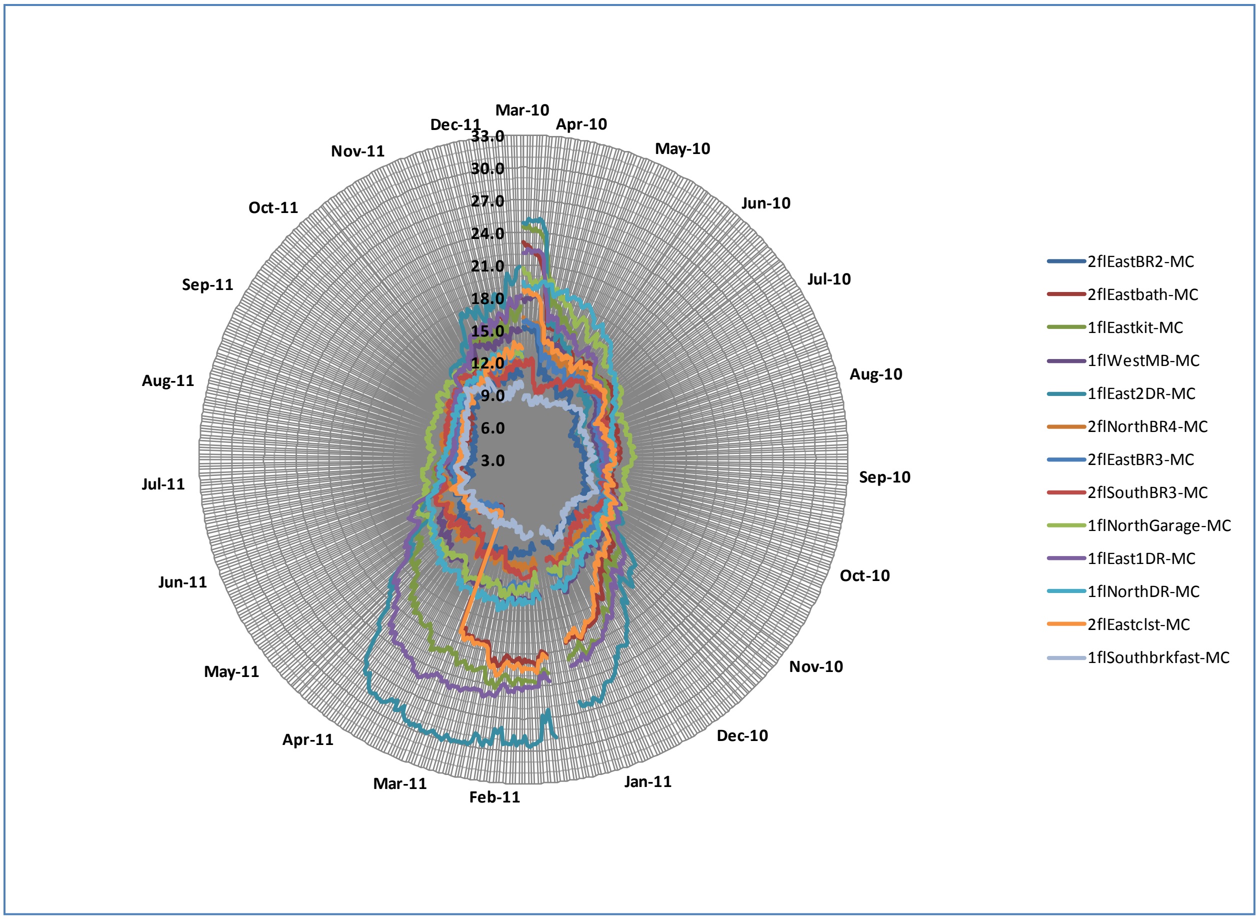

Figure 18. Jobsite 2 OSB MC, all available data

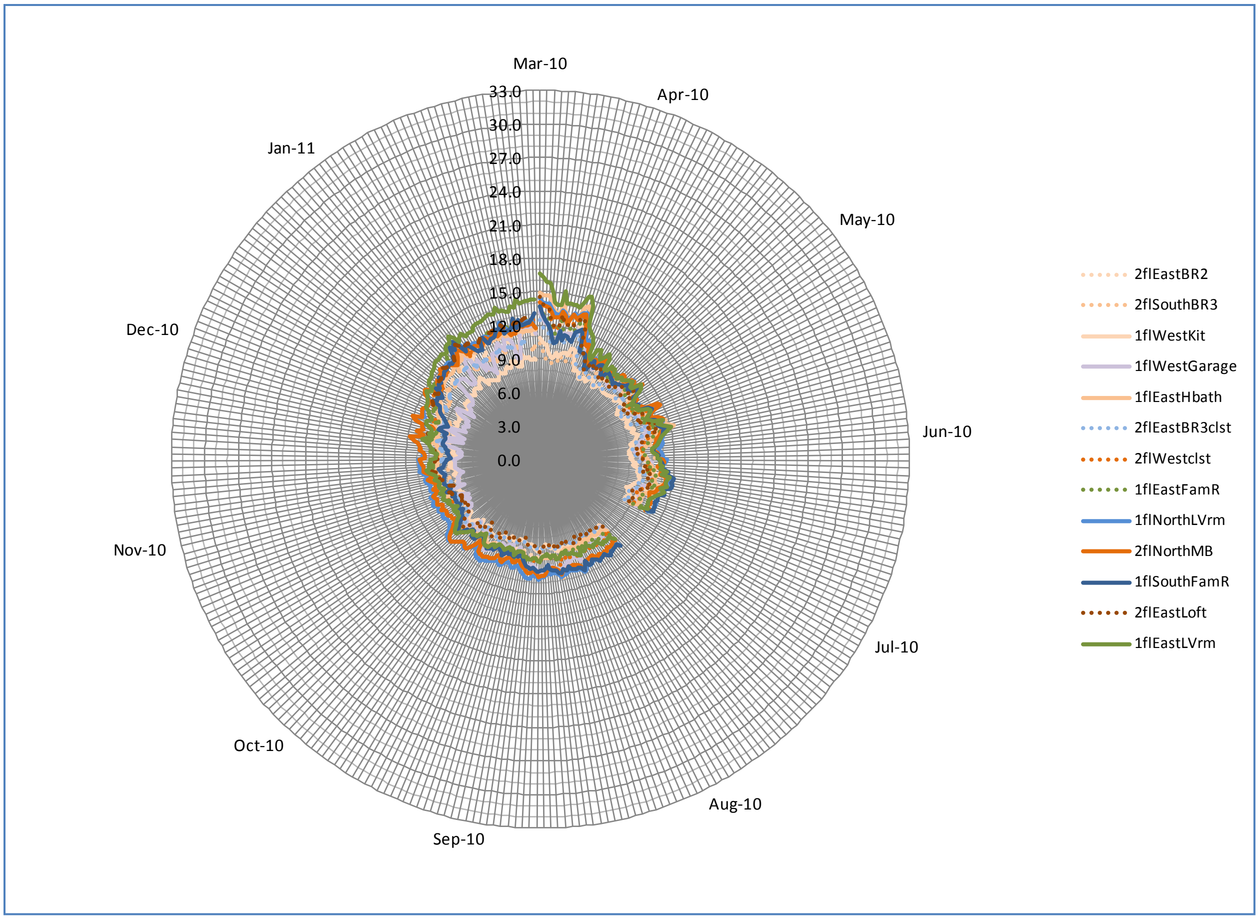

Figure 19. Jobsite 3 OSB MC, all available data

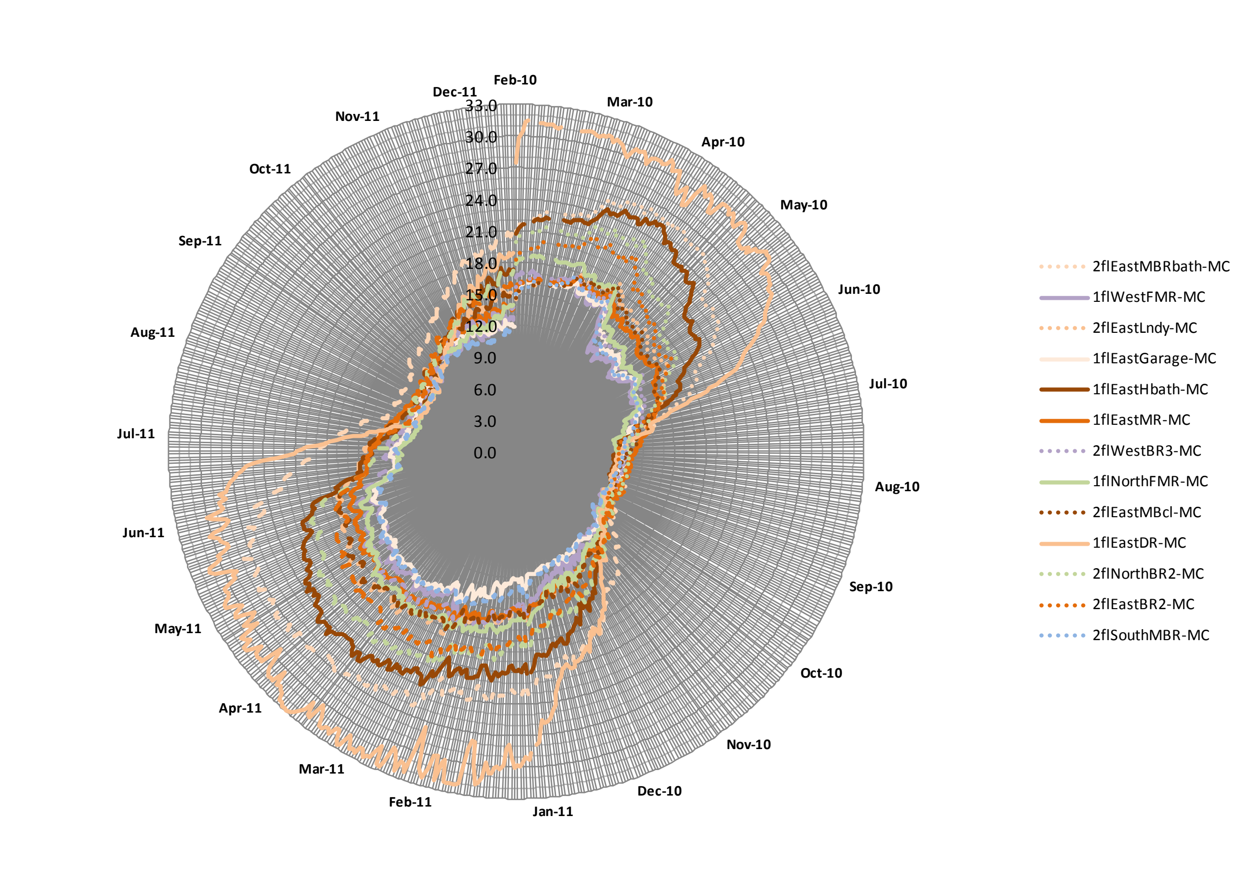

Figure 20. Jobsite 5 OSB MC, all available data

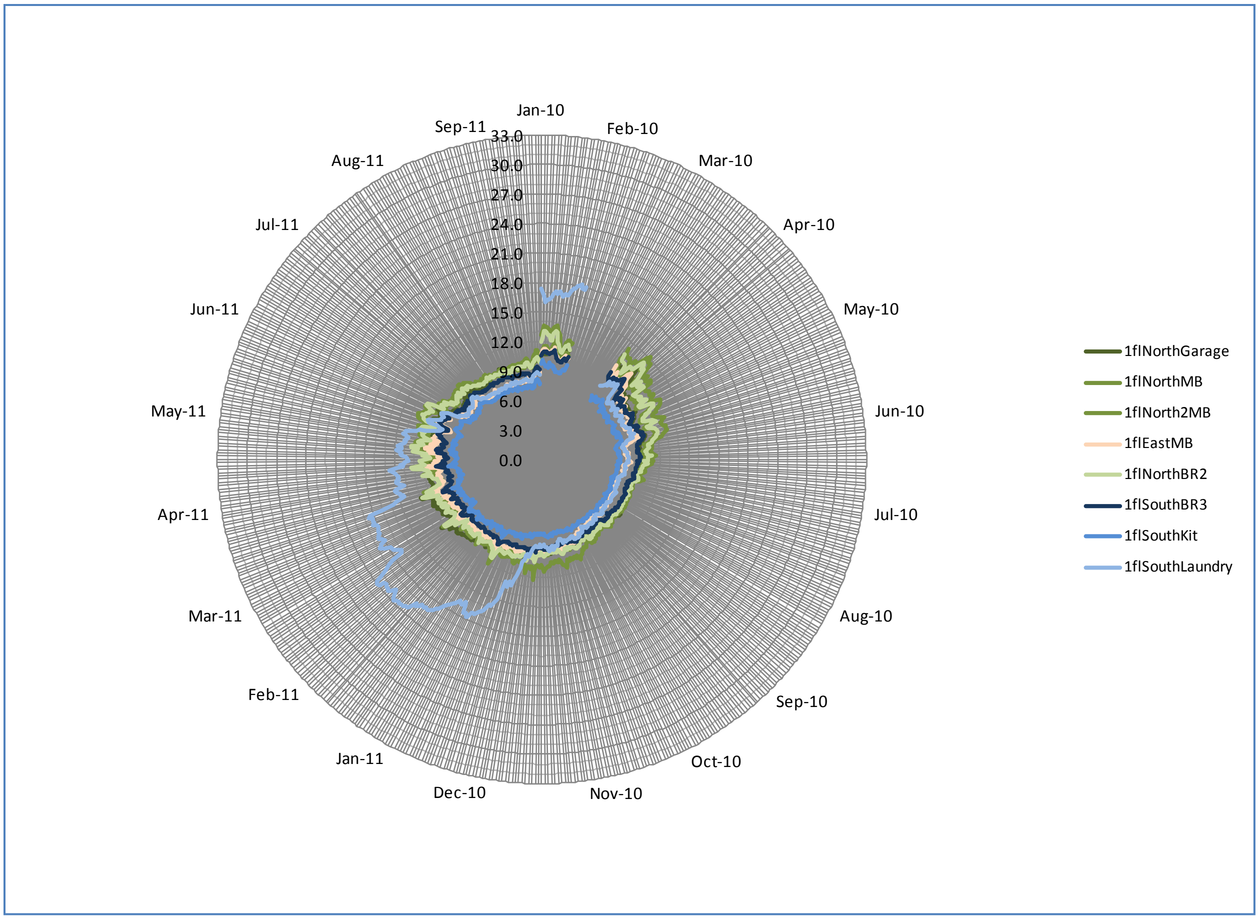

Figure 21. Jobsite 6 OSB MC, all available data

As seen in the previous charts, Jobsites 2 and 5 show elevated MC in some wall cavities. The MC measurements indicate levels reaching to slightly greater than 30% in a few wall cavities. This level of MC suggests a fiber saturation point state of the OSB panels.

A number of wall cavities in Jobsite 5 show elevated MC readings for an extended time period, lasting into the early summer when the MC readings drop off quickly. Figure 22 represents data for a 1-year period in a wall cavity comparing the MC to the cavity temperature. The cyclic nature of the MC is clearly shown as well as the relationship between the cavity temperature and the MC where the MC levels greater than 20% span both warm and cold seasons (and cavities). This result is unique among the five jobsites where data are available for an extended period.

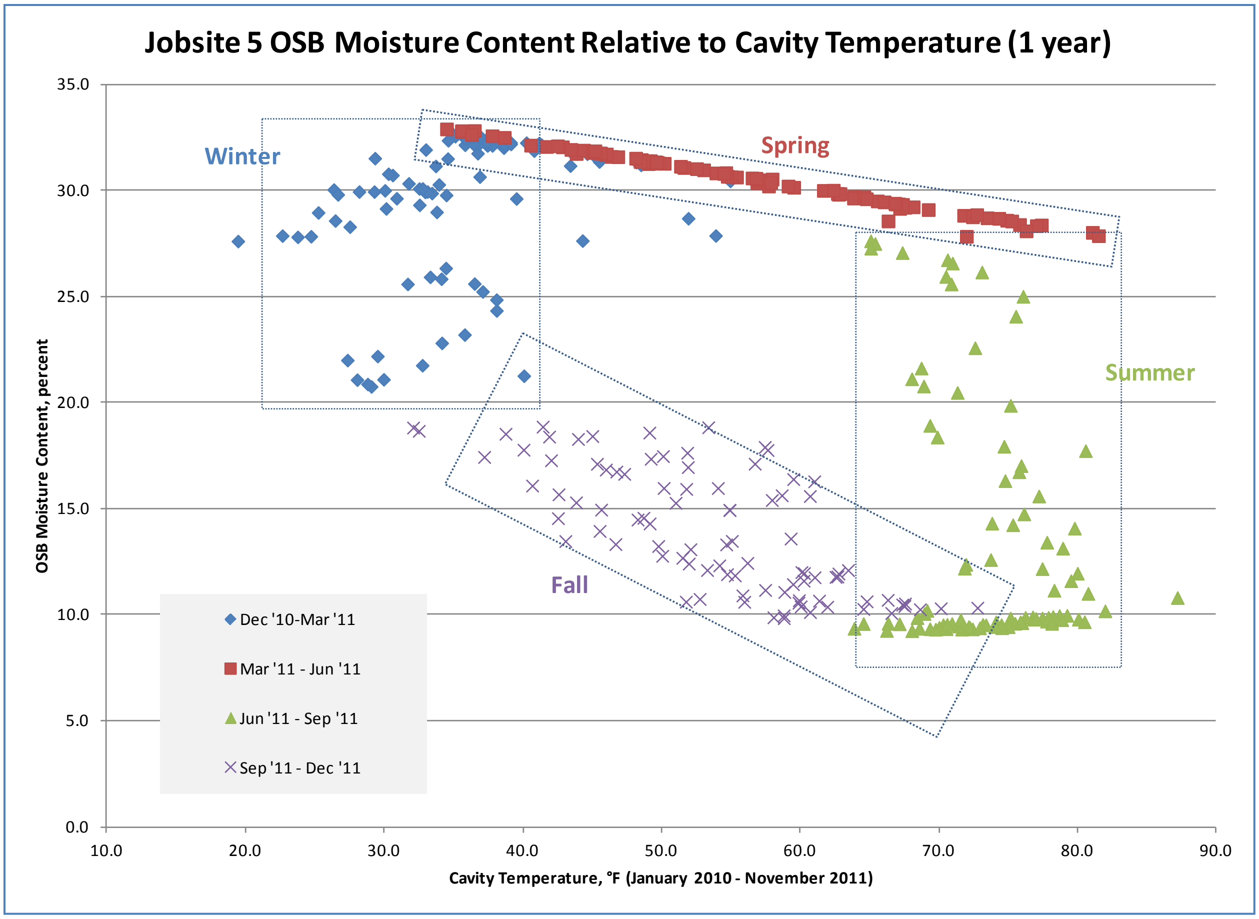

Figure 22. Example of an elevated OSB MC in one wall section showing seasonal changes in MC

As RH increases in a wall cavity, the potential for condensation of water on the interior surface of OSB panels also increases. Figure 23 and Figure 24 are comparison plots for the test wall cavity temperature difference between the cavity temperature and the DP temperature for Jobsites 2 and 5. Negative values indicate a higher cavity DP than cavity air temperature near the OSB sheathing, resulting in the potential for condensation. Jobsite 2 has the most significant difference and Jobsite 5 has a much lesser degree of difference. The other jobsites have little or no calculated potential for condensation as measured.

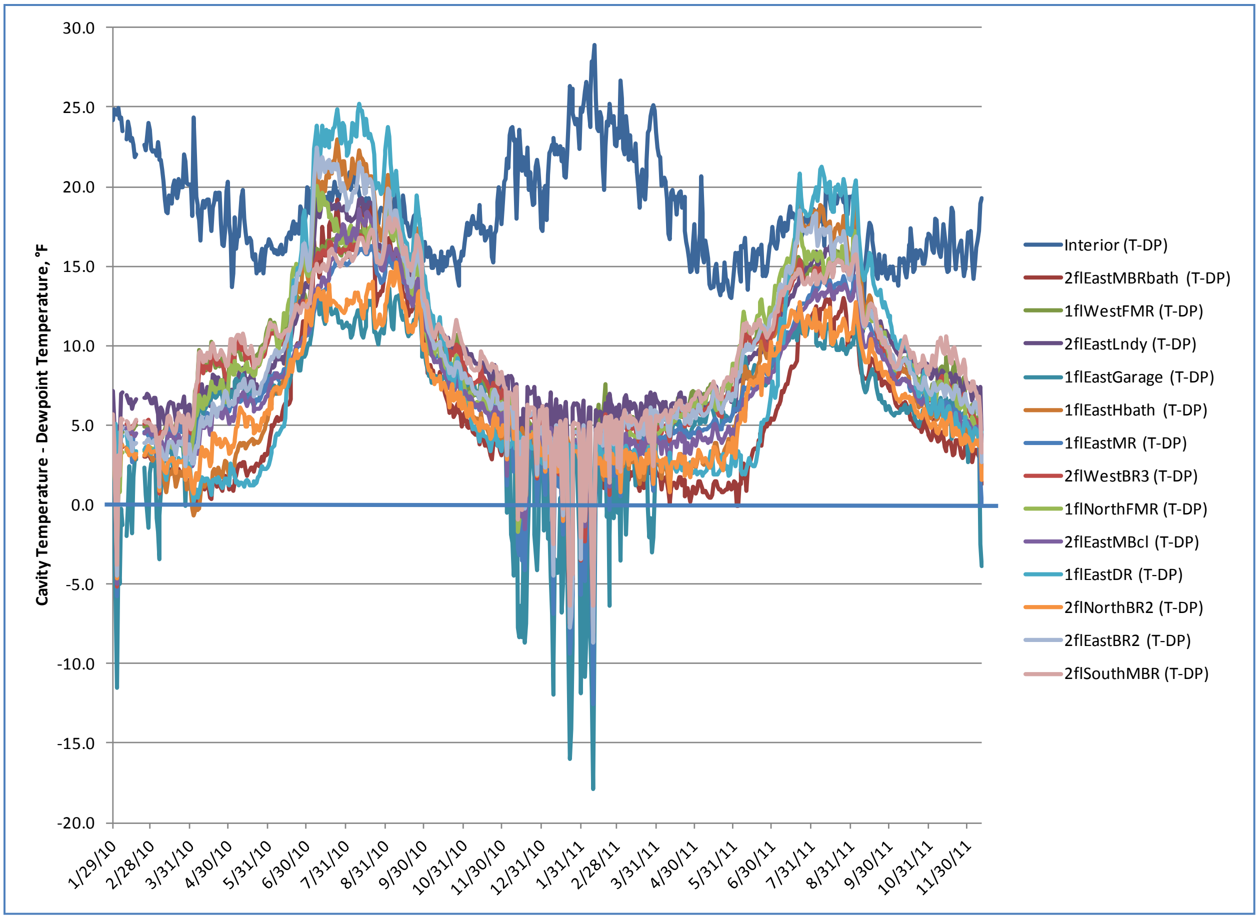

Figure 23. Jobsite 2 delta cavity temperature minus DP temperature (negative values indicate condensation potential)

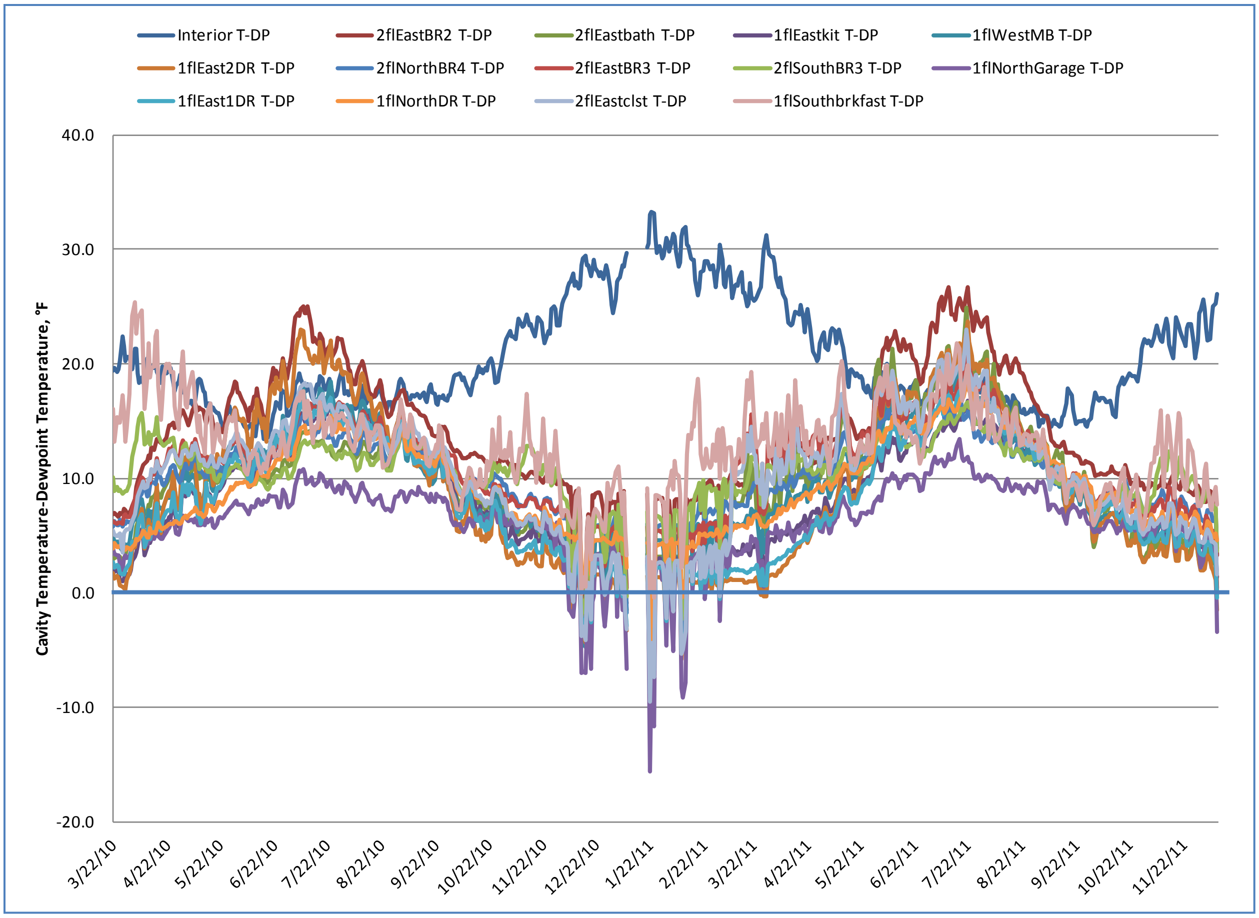

Figure 24. Jobsite 5 delta cavity temperature minus DP temperature (negative values indicate condensation potential)

When evaluating the condensation potential (negative values for the air–DP temperatures) compared to the MC, the graphical results show an interesting relationship in which the higher levels of MC measured do not coincide directly with the calculated condensation potential (refer to Figure 25). In fact, the wall sections with the higher levels of MC appear to have lower overall instances of condensation potential.

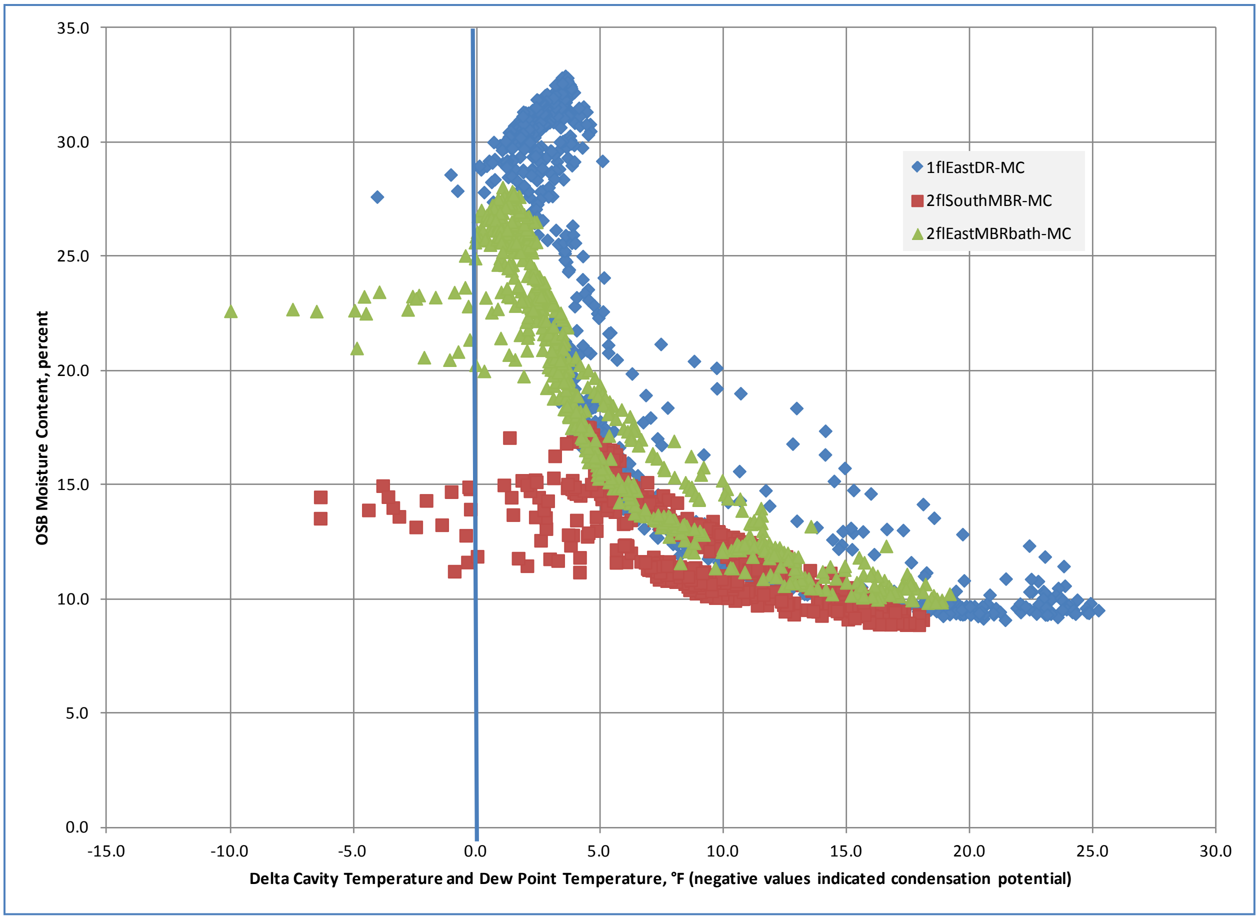

Figure 25. Jobsite 5 comparison of MC and DP

Furthermore, as shown in Figure 26, in this home where some cavities have higher levels of MC, the overall trends of all sections appear to track each other, although with different absolute levels of OSB MC. It does appear, however, that one or two cavities might have a source for air leakage (assumed from the interior), resulting in a much higher level of MC readings.

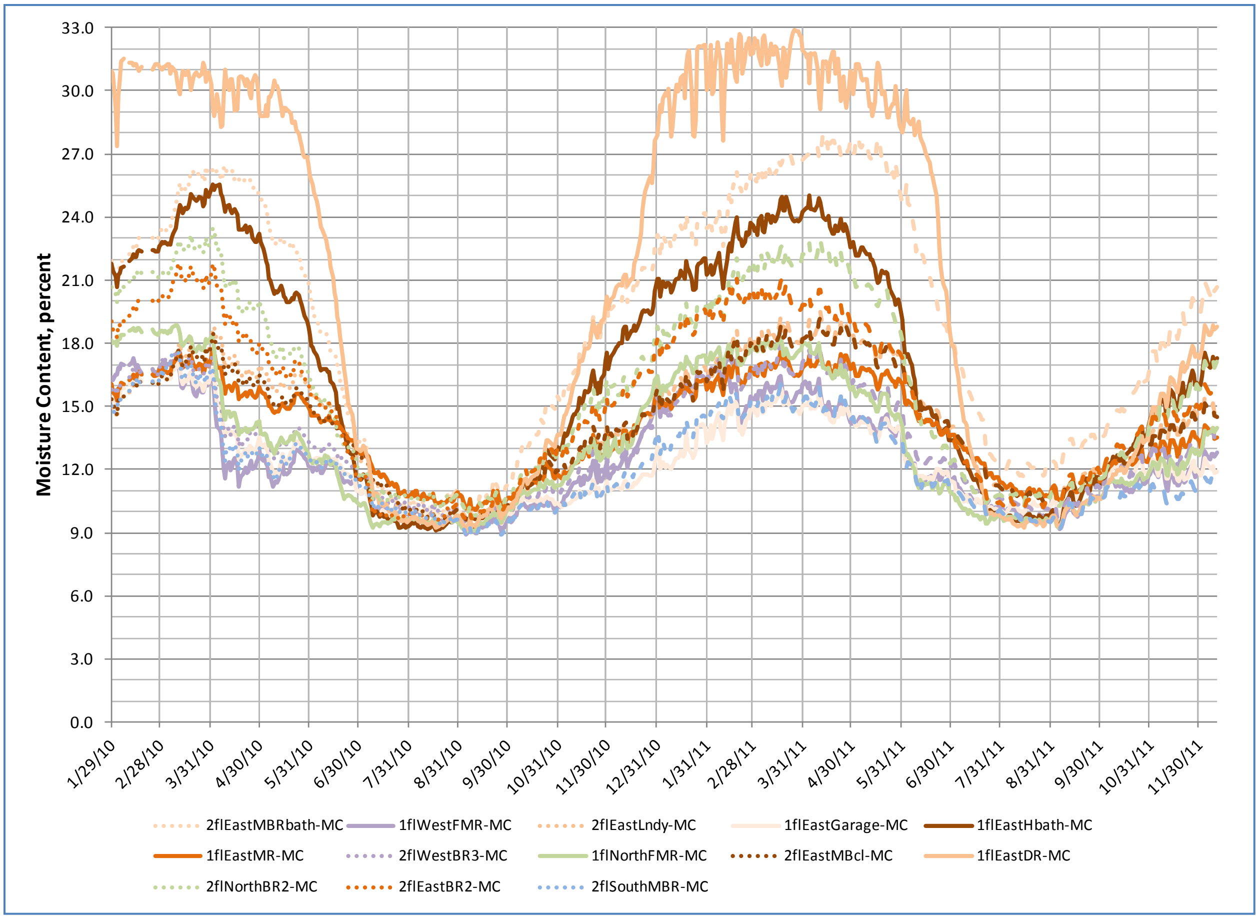

Figure 26. Jobsite 5 MC comparison of all wall cavities

7 Data Comparisons

The next sections review the trends in the various moisture performance characteristics for the wall systems. All available data are plotted to indicate the trends from the construction completion through a period of occupancy. Refer to Table 1 for the individual characteristics of the homes for which wall cavity moisture data are available. The cavity moisture characteristics include the following:

- Air temperature near the OSB sheathing
- RH near the OSB sheathing
- DP temperature near the OSB sheathing
- MC of the OSB sheathing.

Other related characteristics include the indoor air temperature and RH as well as the ambient air temperature and RH (from a nearby weather station).

7.1 Cavity Temperatures

Figure 27 through Figure 31 show cavity temperatures near the OSB sheathing for each of the jobsites.

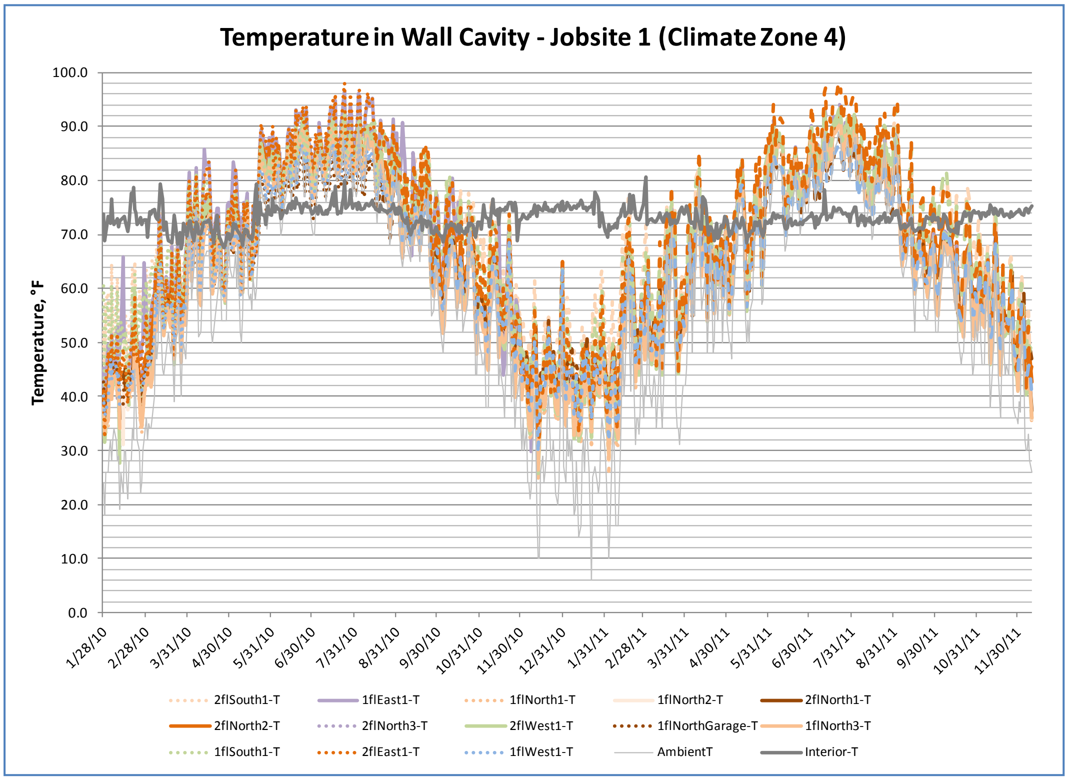

Figure 27. Jobsite 1 temperatures

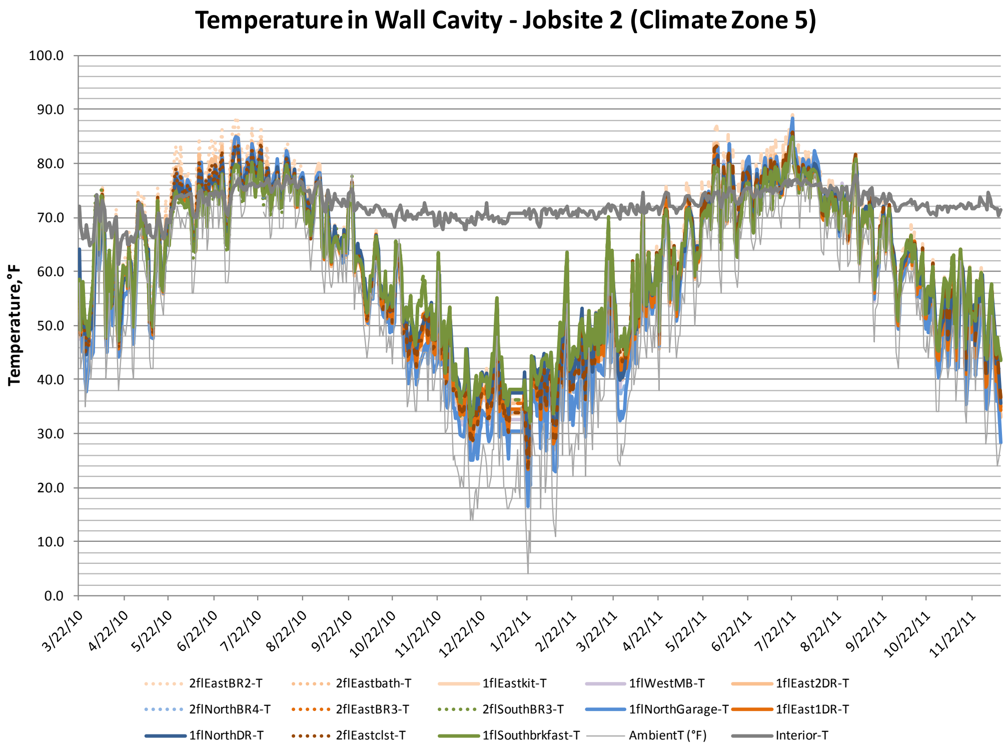

Figure 28. Jobsite 2 temperatures

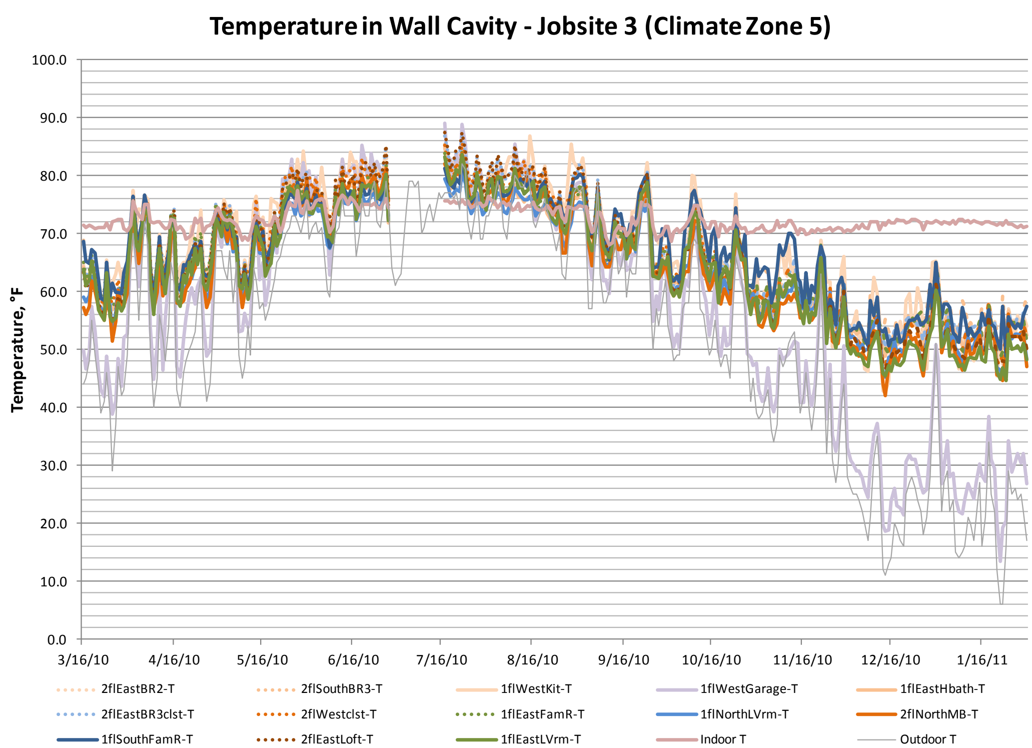

Figure 29. Jobsite 3 temperatures

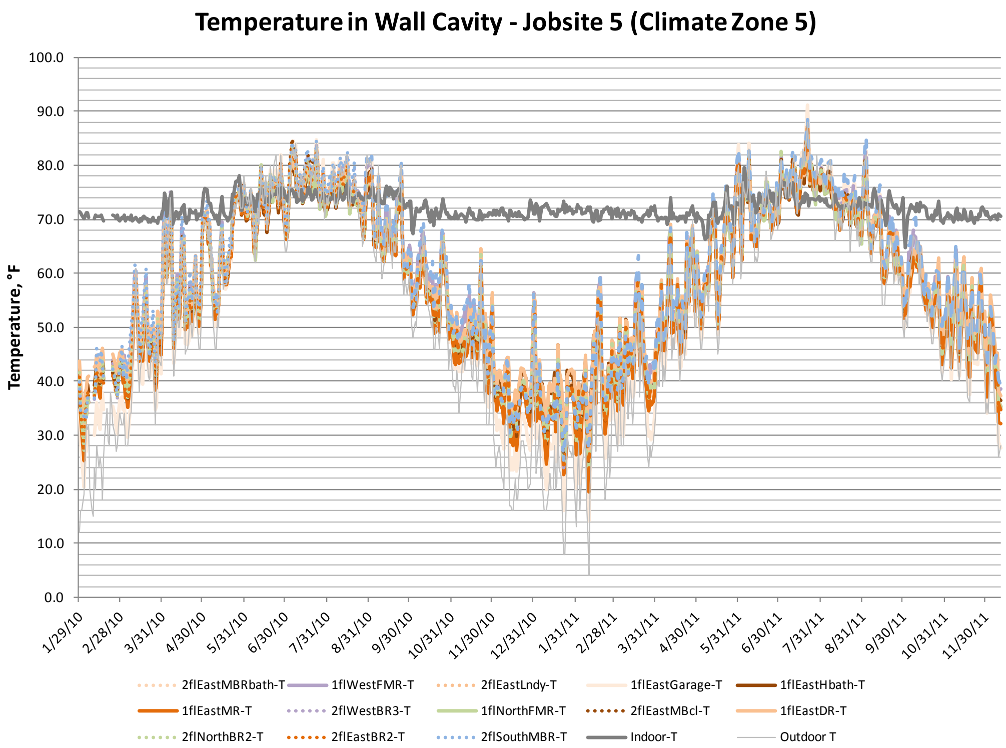

Figure 30. Jobsite 5 temperatures

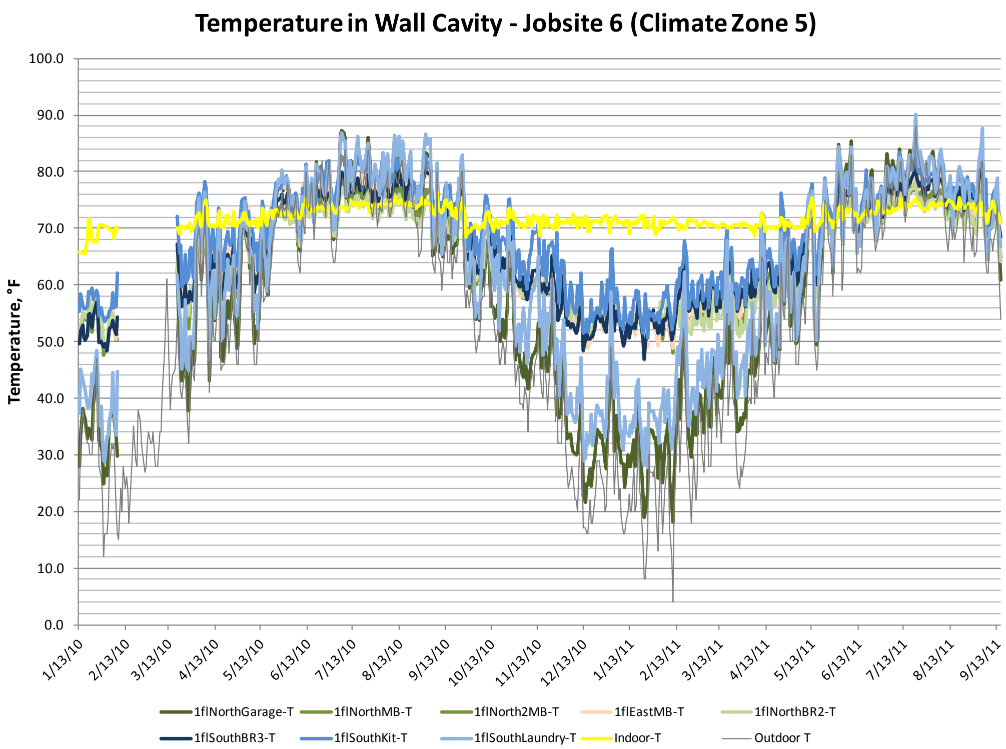

Figure 31. Jobsite 6 temperatures

7.2 Cavity Relative Humidity

Figure 32 through Figure 36 show cavity relative humidity near the OSB sheathing for each of the jobsites.

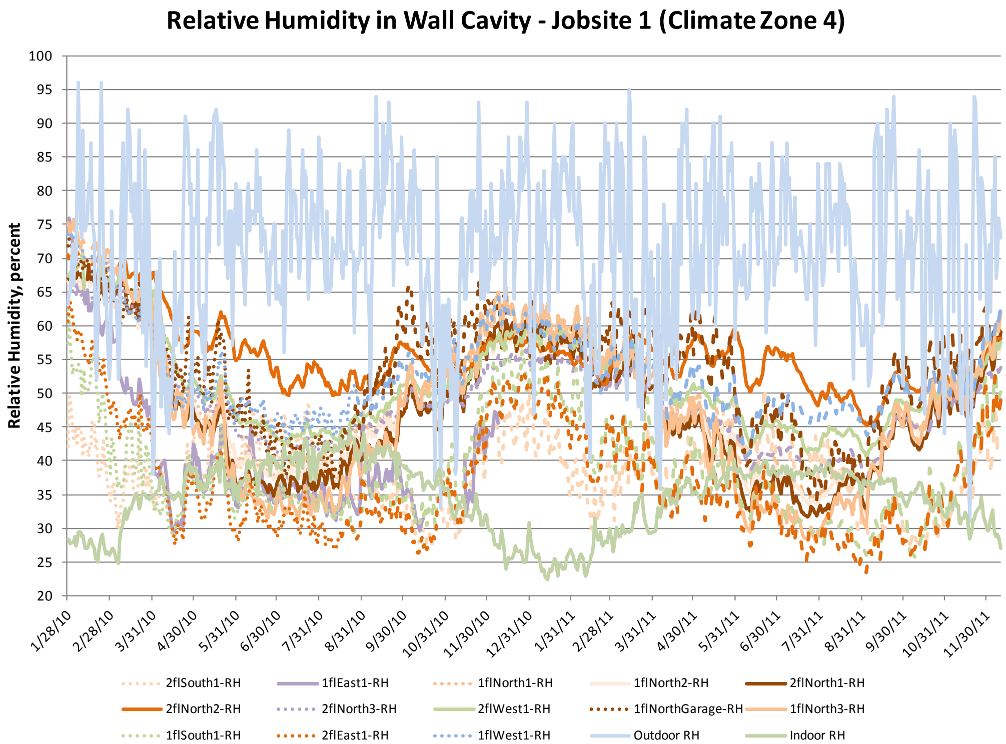

Figure 32. Jobsite 1 RH values

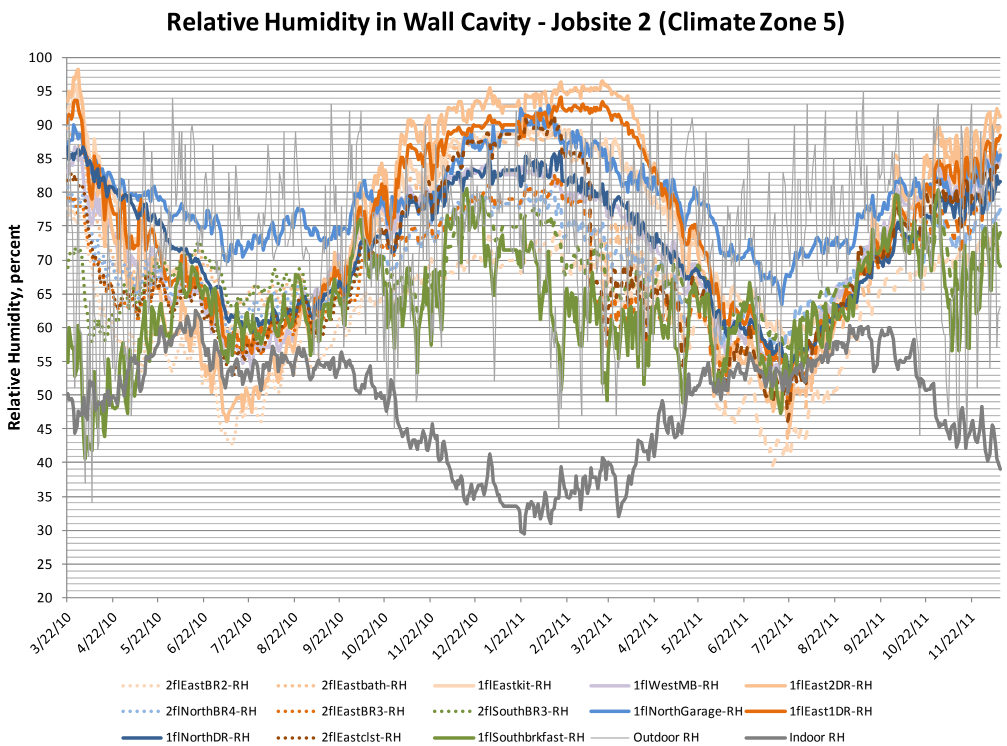

Figure 33. Jobsite 2 RH values

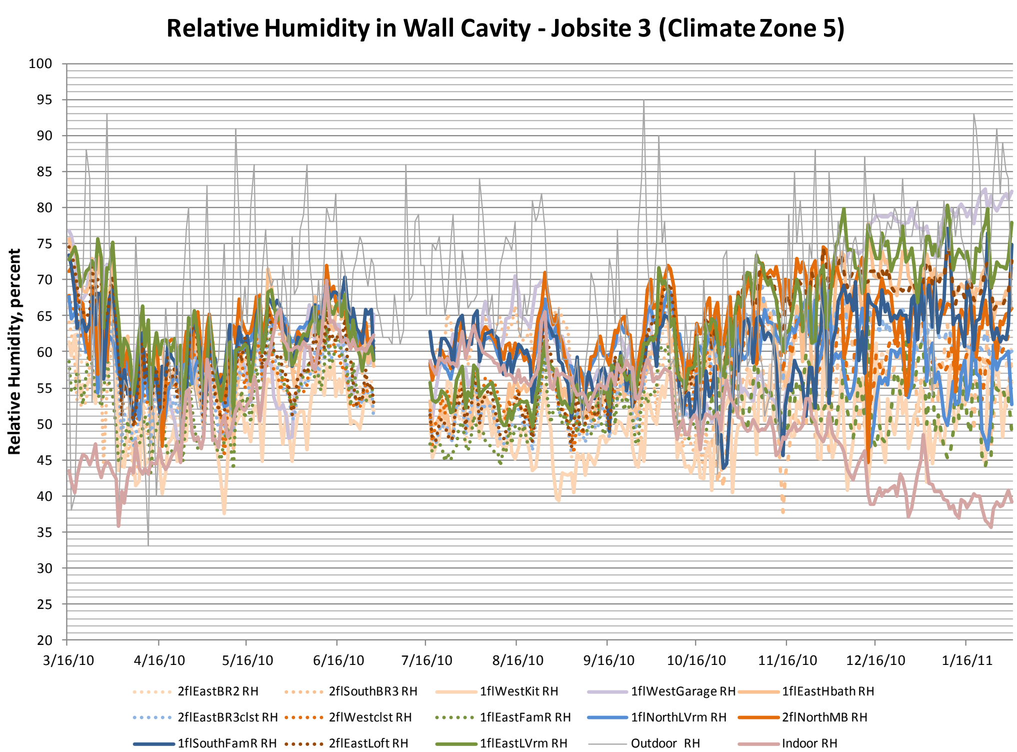

Figure 34. Jobsite 3 RH values

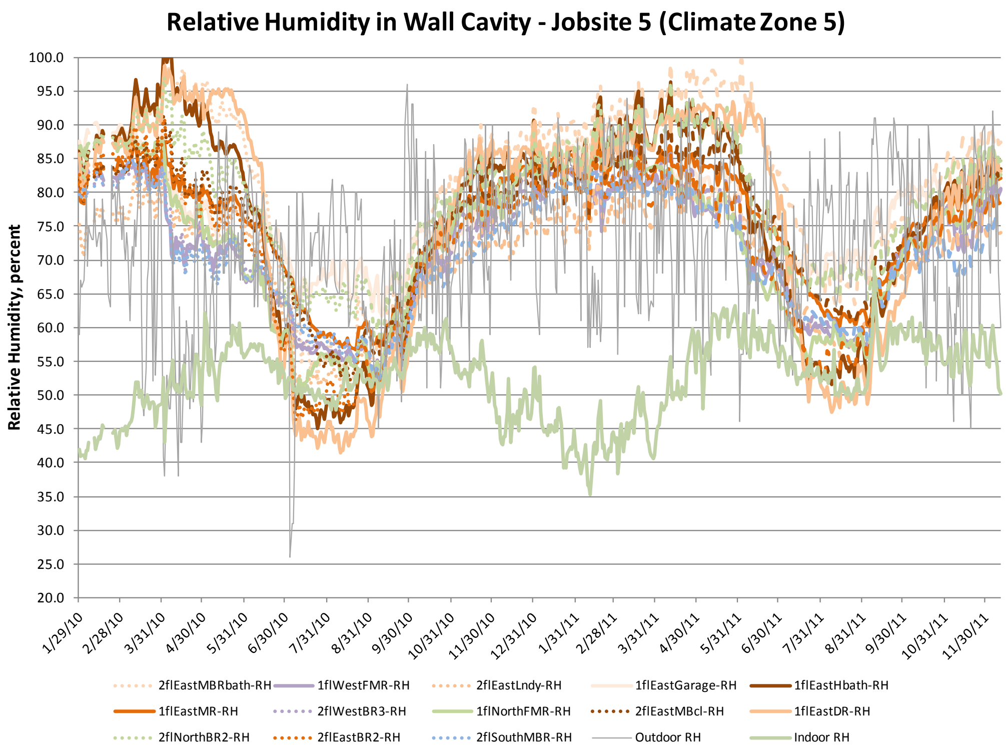

Figure 35. Jobsite 5 RH values

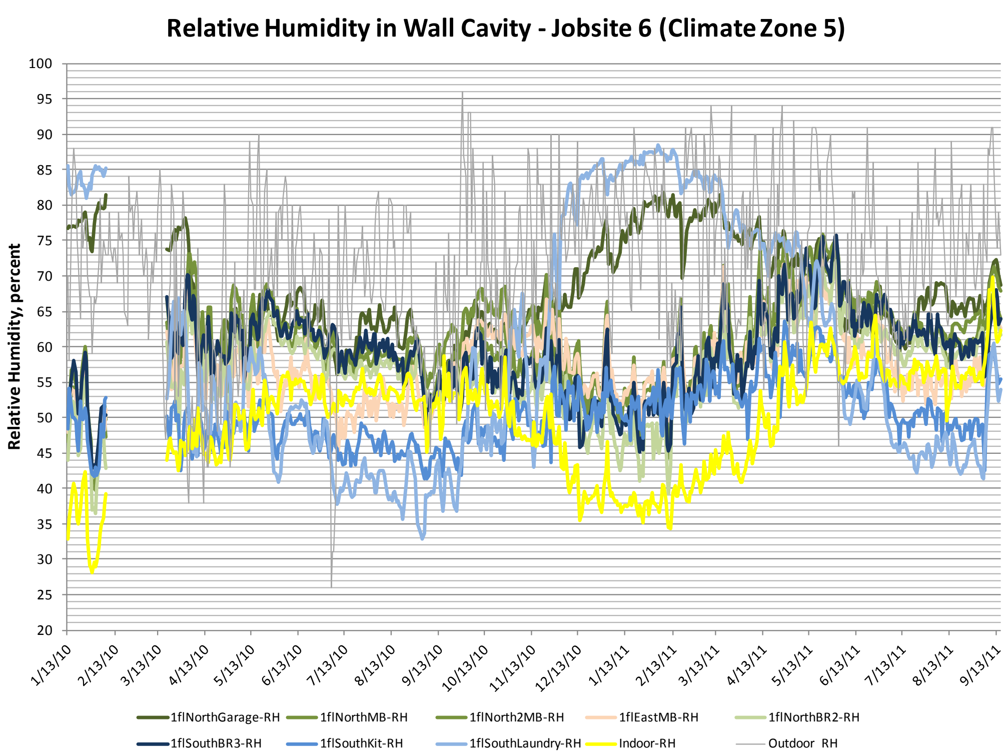

Figure 36. Jobsite 6 RH values

7.3 Cavity Dew Point Temperatures

Figure 37 through Figure 41 show cavity DP temperatures near the OSB sheathing for each of the jobsites.

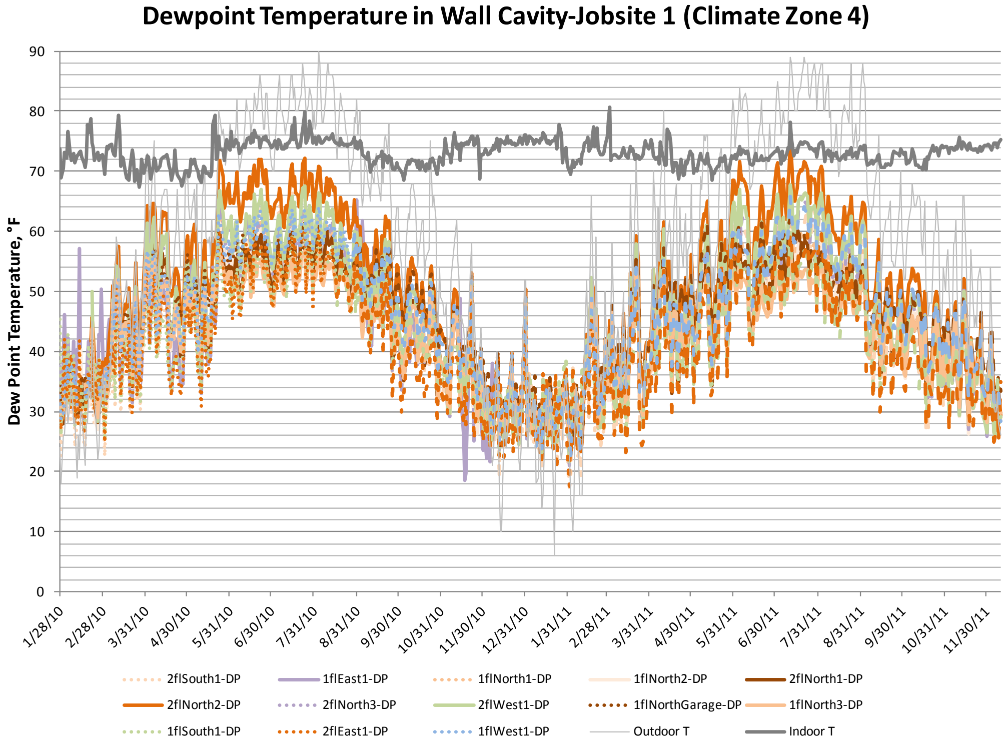

Figure 37. Jobsite 1 DP temperatures

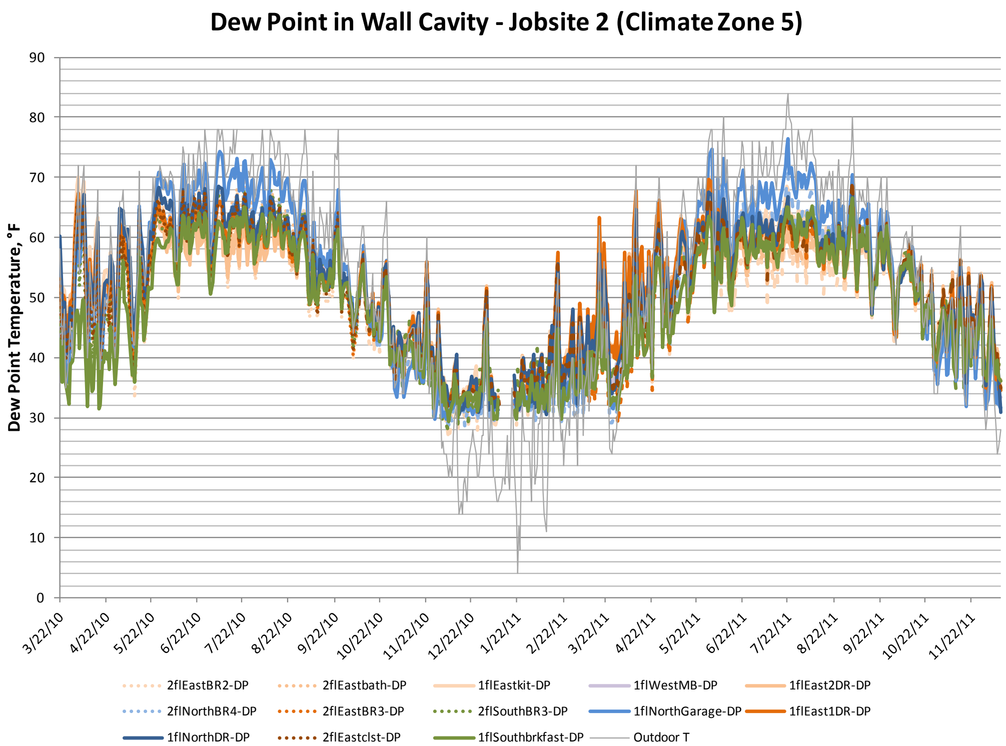

Figure 38. Jobsite 2 DP temperatures

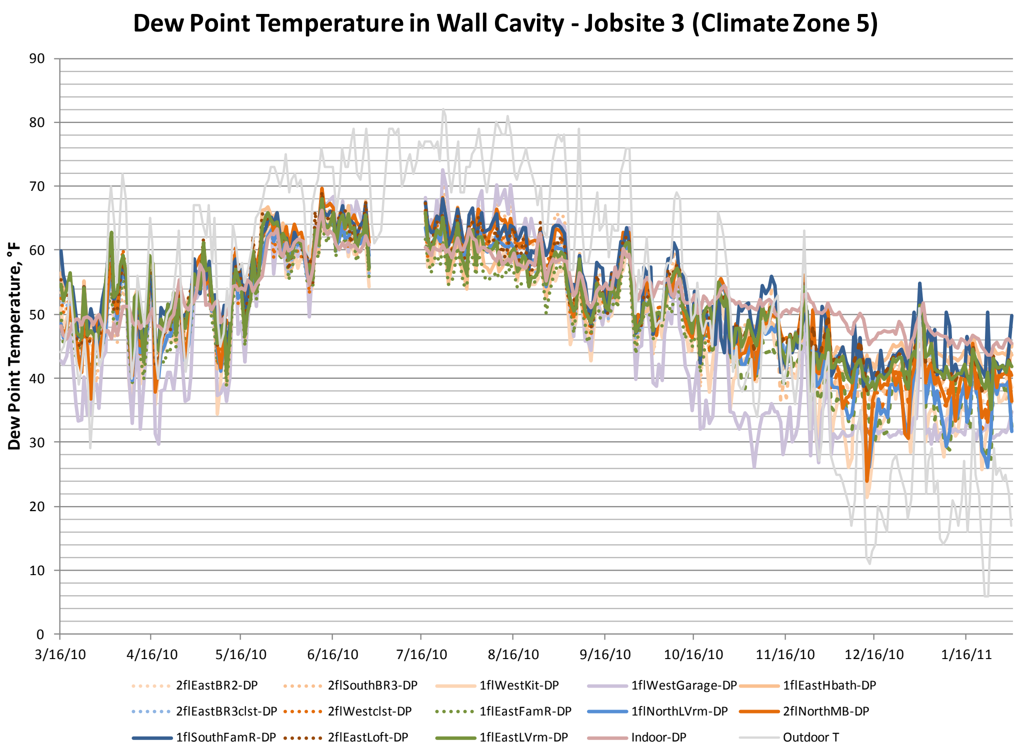

Figure 39. Jobsite 3 DP temperatures

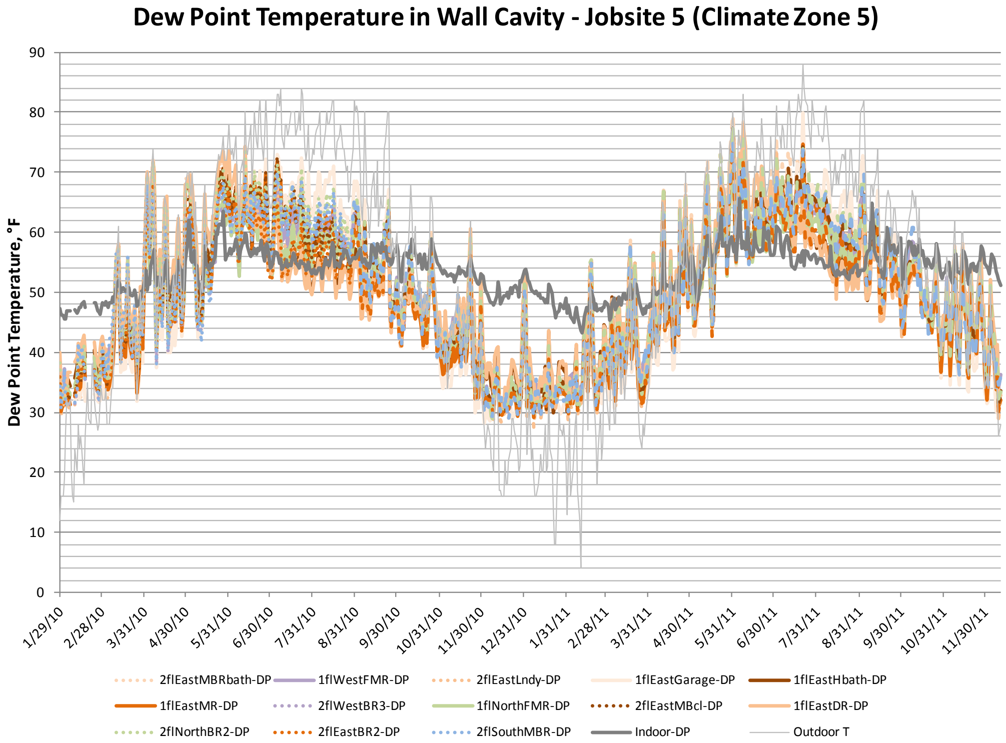

Figure 40. Jobsite 5 DP temperatures

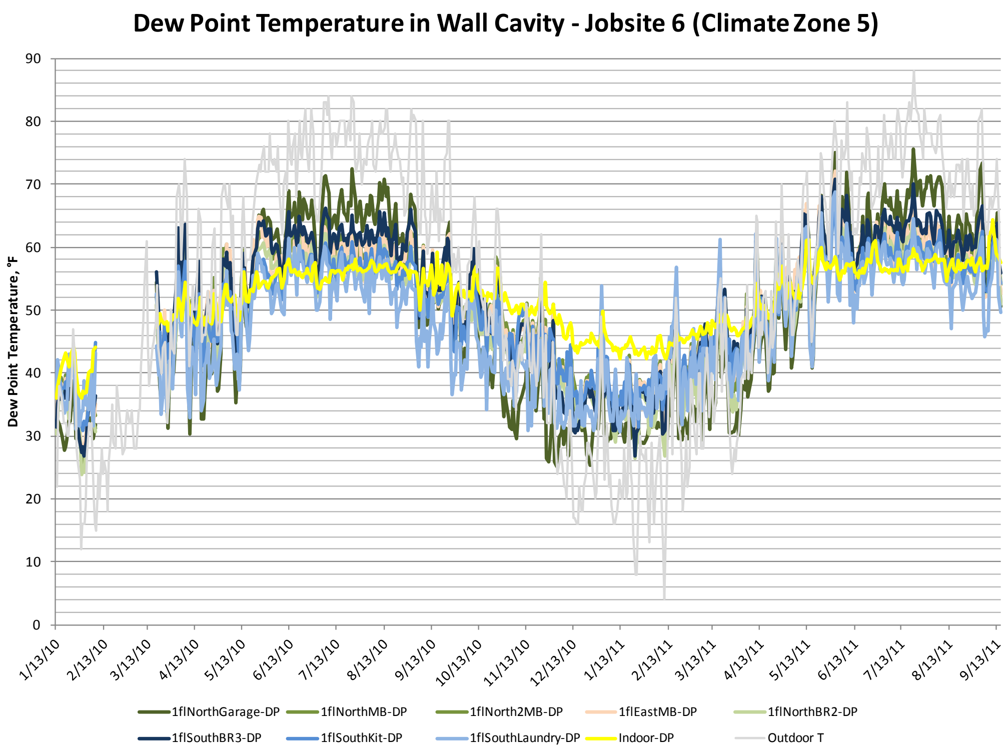

Figure 41. Jobsite 6 DP temperatures

7.4 Oriented Strand Board Moisture Content

Figure 42 through Figure 46 show the OSB MC for each of the jobsites.

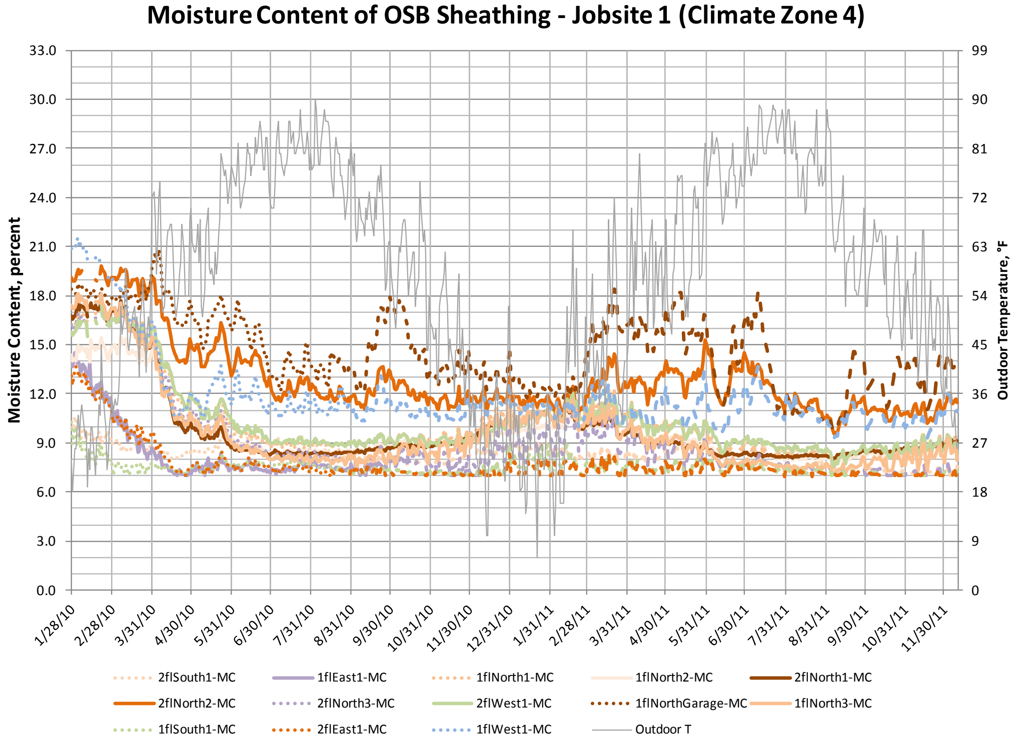

Figure 42. Jobsite 1 MC

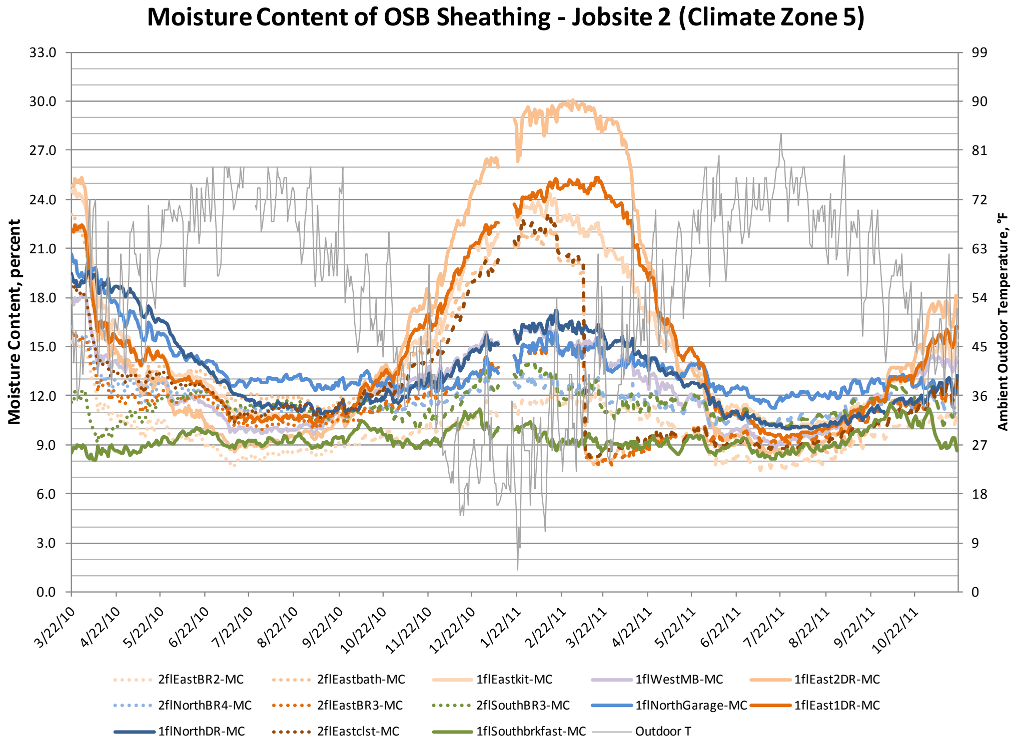

Figure 43. Jobsite 2 MC

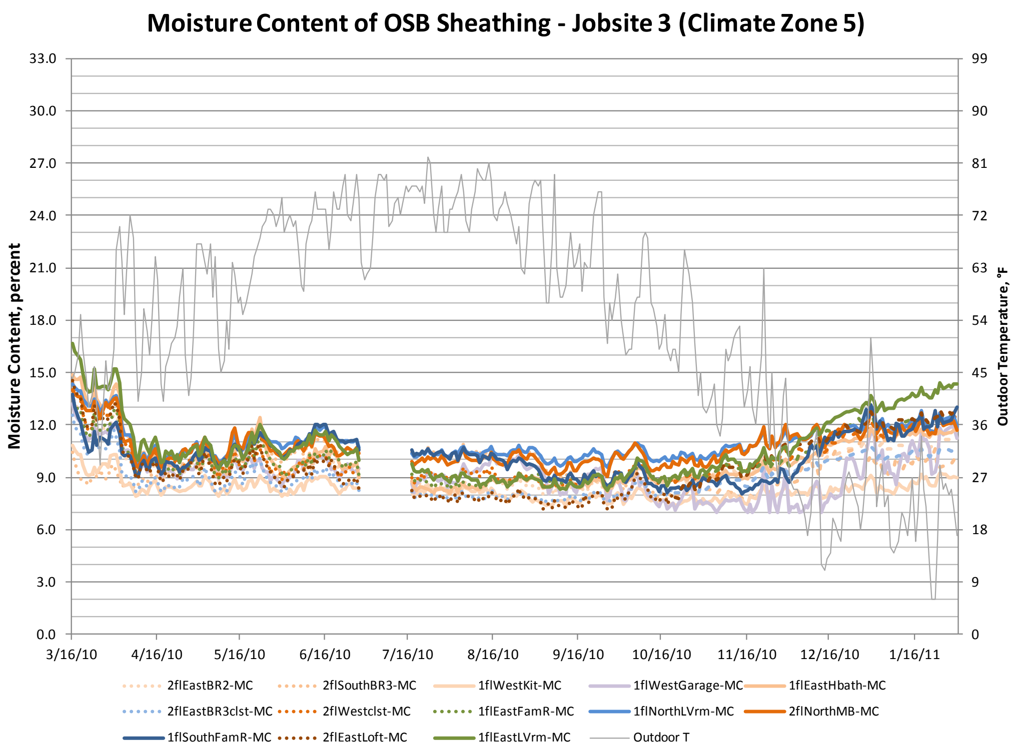

Figure 44. Jobsite 3 MC

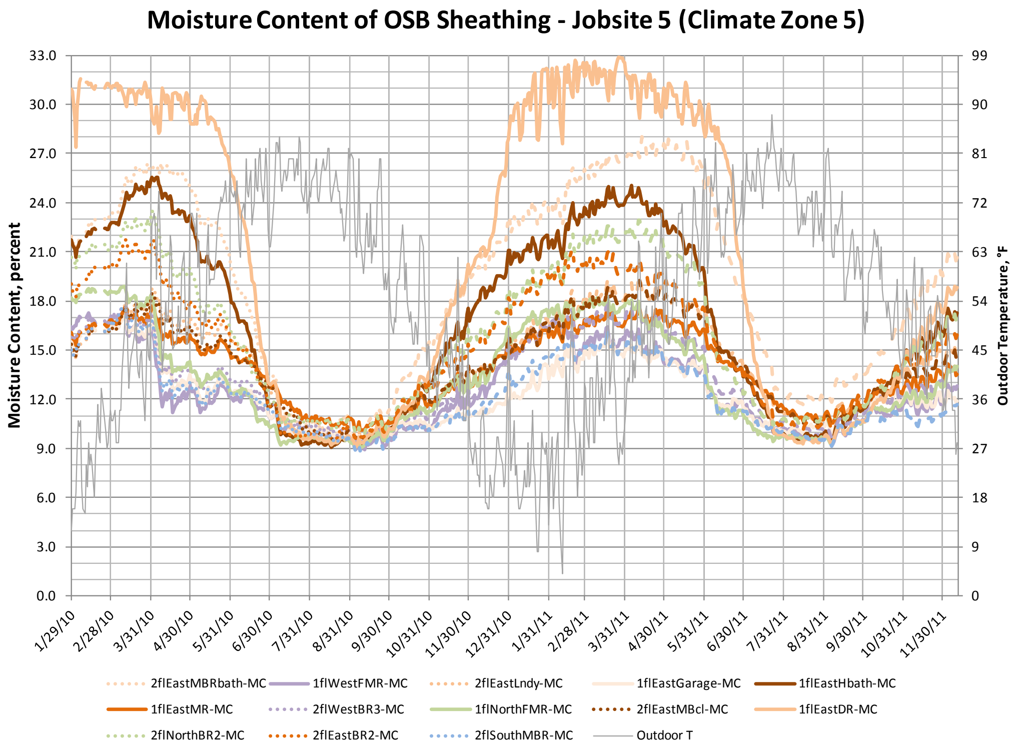

Figure 45. Jobsite 5 MC

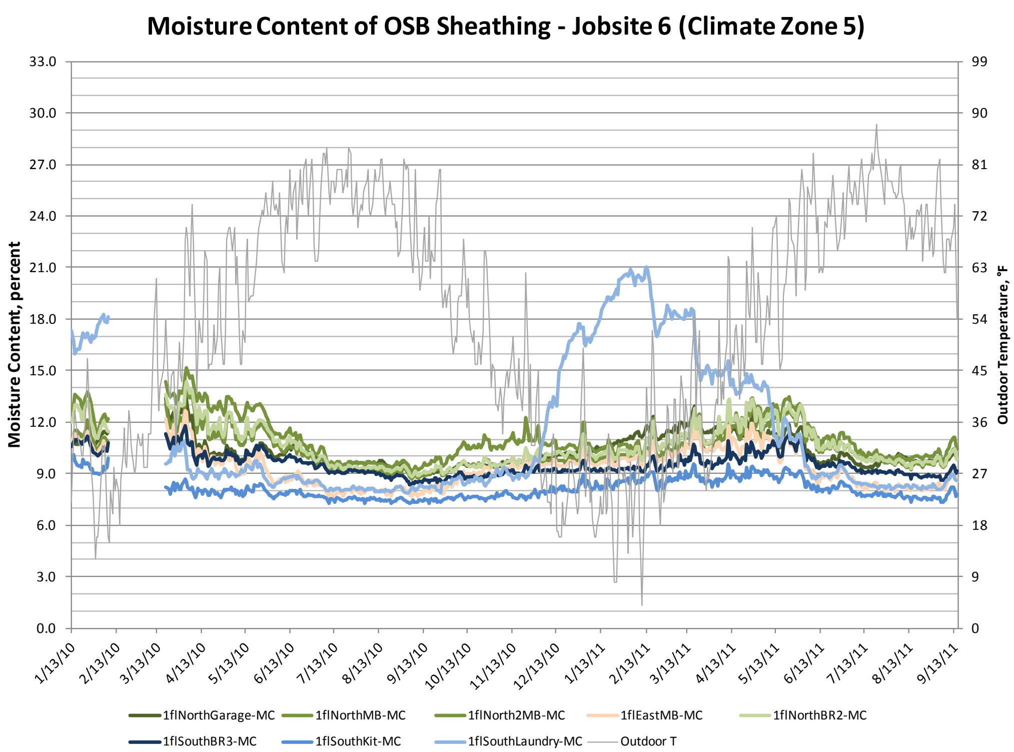

Figure 46. Jobsite 6 MC

7.5 Oriented Strand Board Moisture Content and Relative Humidity

Figure 47 through Figure 51 show the relationship between the OSB MC and the RH in the wall cavity for each of the jobsites. Wall cavities with higher level MCs are selected for the comparison.

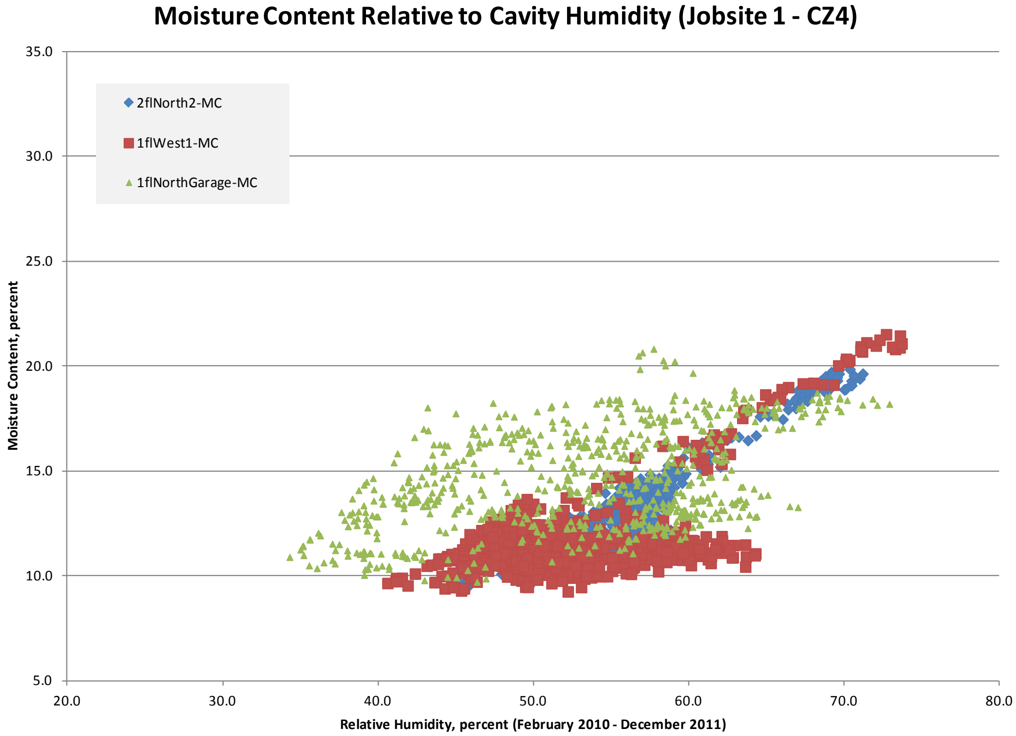

Figure 47. Jobsite 1 MC relative to humidity

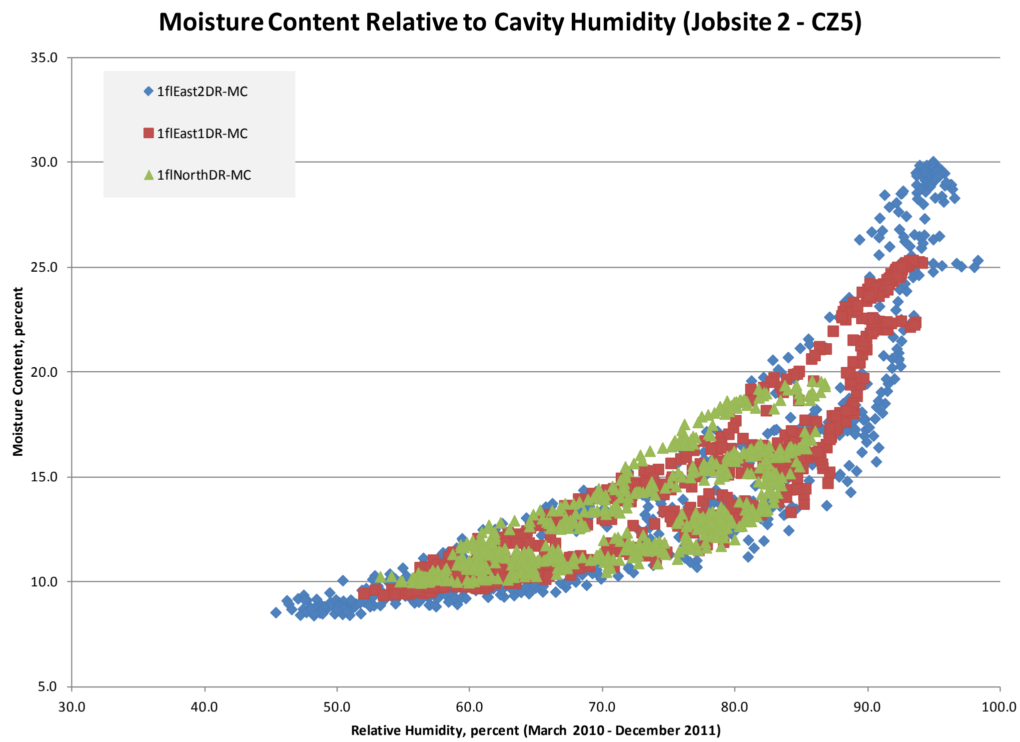

Figure 48. Jobsite 2 MC relative to humidity

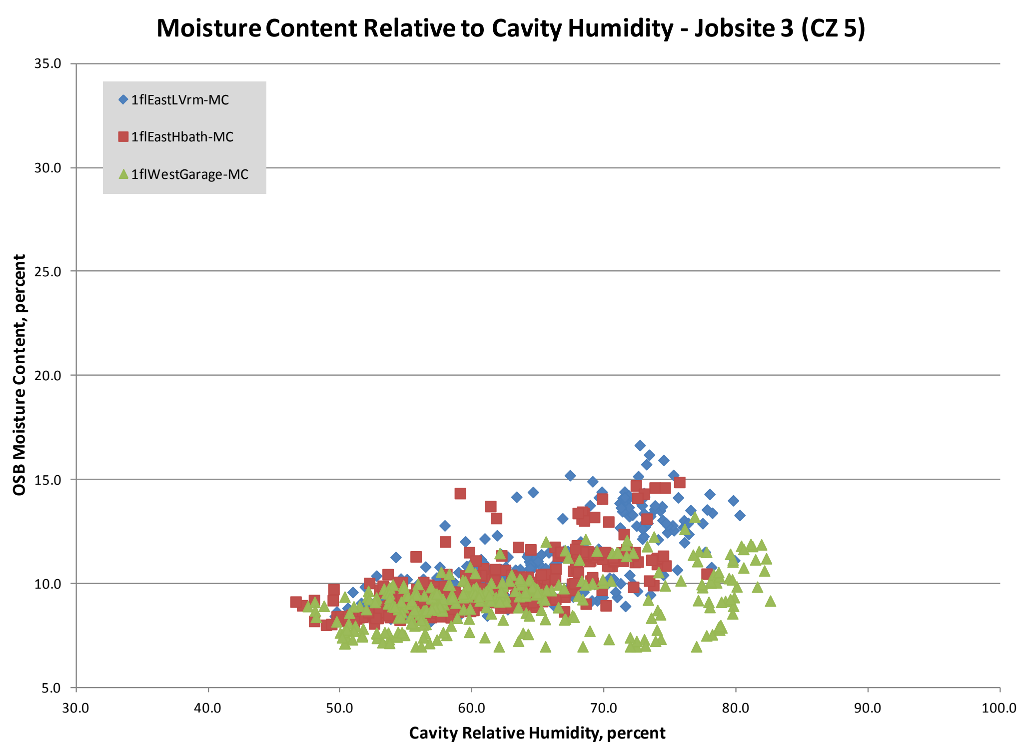

Figure 49. Jobsite 3 MC relative to humidity

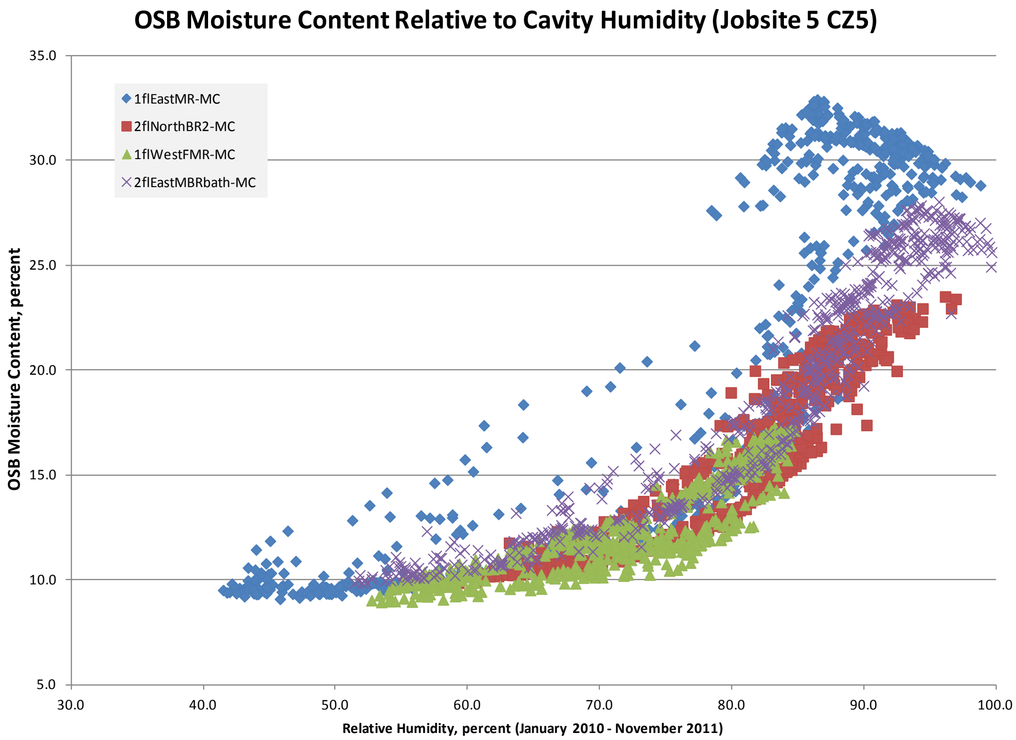

Figure 50. Jobsite 5 MC relative to humidity

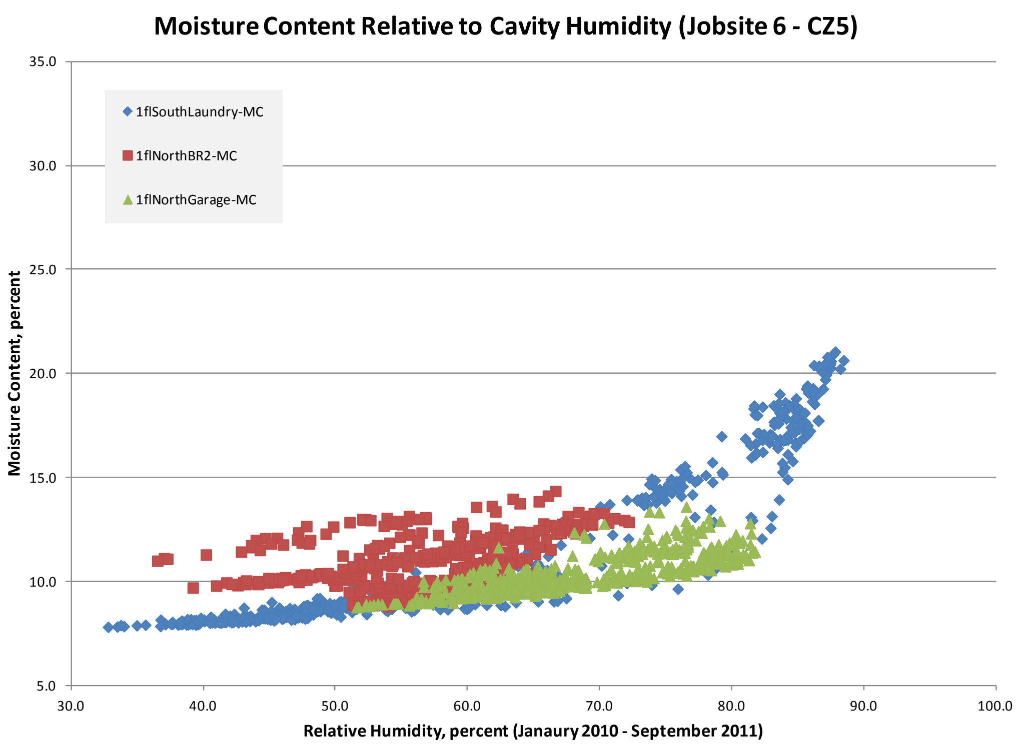

Figure 51. Jobsite 6 MC relative to humidity

8 Analysis Based on ASHRAE 160-2009

Before this study began, one of the home builders in Ohio reported that, while repairing walls with buckled OSB following the winter of 2009, a mold-like substance was often present on the interior face of the OSB panels. To investigate the potential for mold growth in the test homes monitored in this study, the observed environmental conditions of the wall cavity are evaluated using the threshold established by ASHRAE Standard 160-2009 "Criteria for Moisture-Control Design Analysis in Buildings" (ASHRAE, 2009). Standard 160 provides temperatures and associated RH ranges that minimize mold growth on the surfaces of components of building envelope assemblies (Table 8).

Table 8. Standard 160 Condition Criteria Necessary to Minimize Mold Growth

Criteria	Duration	RH when Temperature is in Range	
A	30 days	<80% RH	
B	7 days	<98% RH	41°F < T < 104°F
C	24 hours	<100% RH	

The wall cavity temperatures and RH levels are evaluated according to these criteria for the homes, with results shown in Table 9.

Table 9. Wall Cavity Analysis of Standard 160 Criteria

Jobsite	Days in Analysis	Range of Days in Which Criteria Exceeded in any Wall Cavity Number of Monitored Wall Cavities in Which Criteria Exceeded		
		Criteria A	*Criteria B*	*Criteria C*
1	655	0	0	0
2	600	8–157 11 of 13 test cavities	0	0
3	293	0	0	0
4	n/a	n/a	n/a	n/a
5	653	88–324 12 of 13 test cavities	3–7 2 of 13 test cavities	6 1 of 13 test cavities
6	582	37 1 of 8 test cavities	2–50 2 of 8 test cavities	0

Note: n/a, data not available
[a] For example, in Jobsite 2, criteria A was exceeded between 8 and 157 days in 11 of the 13 wall cavities under test

The Jobsite 5 home appears to have the greatest potential for moisture-related problems; however, no problems have been reported. It is not known how the cyclic behavior of the wall cavity moisture characteristics is representative of long-term problems. Moreover, the ASHRAE 160 criteria appear to be intended as a lower bound set to ensure that mold growth does not occur rather than as an indicator of a trigger at which mold growth does occur. Particularly, criterion A of 80% RH appears to be very conservative for wall cavities and would disqualify typical wall assemblies that have been used for many decades without reported problems.

9 Summary

This study documents construction methods and materials used by builders that experienced OSB buckling problems in previously constructed homes during the winter of 2008–2009. These builders and newly constructed homes were selected for a more focused analysis of the wall cavity moisture conditions because the construction methods are very typical of building code practices and most met more stringent requirements of efficiency programs. The selected test homes all had air infiltration rates less than four ACH_{50}, substantially lower than many new homes. Sensors installed in exterior wall cavities of six subject homes measure the cavity temperature and humidity and through a screw pin attachment, the MC of the wood structural sheathing. One sensor location within the interior of the home records indoor temperature and humidity. The data collected by the sensors provide objective moisture characteristics for the sheathing panels within the selected wall cavities over annual periods when the sensor receiver has Internet access. Samples of wall sheathing material were also taken from the construction sites and evaluated in terms of the moisture properties and expected expansion limits.

Successful data collection for five homes ranged from 11 to 22 months (no data were available for one home). Over the first winter season of the study (November 2009 through May 2010), buckling of OSB wall sheathing was not observed in any of the six homes (the walls were visually inspected in April and May 2010). No subsequent reports indicated any continued problems with OSB buckling in these or other homes in the neighborhood.

For an annual period, average cavity temperatures for all wall orientations were within 3°F in the same house and the average DP temperatures were within 5°F. In all homes, the MC started trending down in the spring (early to mid-April) as the average daily temperature increased. A typical observed drop of OSB MC ranged from 5% to 10%. Summertime sheathing MC in all monitored walls decreased to less than 12% regardless of the winter peak MC.

Periods of elevated MC in some wall sheathing panels were recorded in each of the homes. The OSB MC increased from less than 6% to 11% at the time of panel installation or jobsite visit to anywhere from 10% to more than 30% in some cases. In three of the homes, the OSB MC levels exceeded 15% for an extended period of time. In two of those three homes, MC peaked at more than 25%, with the highest measured MC at more than 30% (one sensor only).

An analysis of the wall cavity conditions against a set of mold growth criteria based on temperature, RH, and their duration suggests that in two of the six homes there were periods when there was potential for mold growth based on the ASHRAE Standard 160. Of the three primary criteria (A, B, and C), criterion A was exceeded as much as half the time in one test cavity, criterion B was exceeded 10% of the time in one test cavity, and criterion C was exceeded 1% of the time in one test cavity. No further cavity investigation analysis is planned.

10 Initial Results and Observations

The objectives of the study were to document cyclic wall cavity moisture characteristics; document wall sheathing moisture characteristics in homes with substantially lower infiltration rates; and, with sufficient data, isolate the variables or a combination of variables that might result in unsatisfactory moisture performance of standard acceptable wall system construction.

The overall MC records, although somewhat limited, indicate the following for the structural sheathing:

- Post construction sheathing MC increase was common in all monitored homes.
- Periods of high MC (more than 15%) occurred at some time during the year for most of the homes.
- A cyclic nature to sheathing MC was common in all homes; however, the level of swing (amplitude) can be significantly different among homes in the same climate.
- Colder months had the highest levels of sheathing MC, as expected.
- Based on the limited data set, interior average RH appears not to be a good indicator of increased sheathing MC.
- The sample with the lowest interior average RH did correlate with the lowest average sheathing MC, as expected.
- Typical annual average interior RH levels were more than 45%.
- A calculation of the periods when there is condensation potential near the sheathing does indicate increased MC in the sheathing, but the peak level of elevated MC varies significantly.

As an unexpected result, analysis of the expansion of OSB panels based on the measured linear expansion properties and the measured peak MC levels suggests a significant potential for OSB buckling in the period following the construction process for one of the test homes (Jobsite 5). Based on calculations of expected linear expansion, the recommended gapping and panel expansion properties for the other four homes are adequate to prevent OSB buckling. Because the wavy siding was not observed in Jobsite 5, it should be noted that limited amount of buckling would not show through vinyl siding because the siding strips are capable of spanning over minor imperfections in the wall sheathing.

Analysis of a correlation between the results of blower door tests and the OSB MC in walls does not indicate a strong trend. To draw more definitive conclusions, this study needs to be expanded to include homes with a wider range of airtightness characteristics.

Among other observations, the walls with a southern orientation had the lowest sheathing MCs because of the higher cavity temperatures from the longer period of exposure to direct sunlight, leading to higher drying potential.

11 Ongoing Moisture Research and Next Steps

Results of this study will serve as a baseline for the next study (already underway), which focuses on the moisture performance of high R-value wall systems in energy efficient homes. The next phase of this research will look at wall systems upgraded to meet or exceed the minimum insulation levels and airtightness requirements of the 2012 IECC (ICC 2012). The focus of the study is on the performance of wall systems and, in particular, the moisture characteristics inside the wall cavity and in the wood sheathing. Furthermore, while this research will initially address new home construction, the goal is to address potential moisture issues in wall cavities of existing homes when insulation and air sealing improvements are made.

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Appendix: Site Inspection Data Sheet

Project #: (internal use only)

1. Site Location

Street	City	State
Zip	**Climate Zone**	**Local Weather Station**
Notes:		

2. Dates of Construction/Weather

	Date	Rain data (total inches)
Foundation Start		
Framing Start		
Roof enclosed by		
House enclosed by		
Occupancy start on		

3. House

Number of Stories (do not include basement)			
Basement	Yes☐	No☐	
Basement Conditioned/Unfinished	Yes☐	No☐	N/A☐
Basement Finished	Yes☐	No☐	N/A☐
Attached Garage	Yes☐	No☐	
Garage Finished	Yes☐	No☐	N/A☐
Ventilation System:			
Code minimum (bathrooms, kitchen)	Yes☐	No☐	
Whole-house ventilation	Yes☐	No☐	

ERV	Yes ☐ No ☐
HRV	Yes ☐ No ☐
Whole-house humidifier	Yes ☐ No ☐
Whole-house dehumidifier	Yes ☐ No ☐

Heating System Type	

Heating System:	
Electric (HSPF)	☐ ______________
Gas (AFUE)	☐ ______________
Other	________________

Cooling System Type	

Cooling System:	
Electric (SEER)	☐ ______________
Other	________________

Ducts, duct location, duct insulation:

Hot Water System Type	

Hot Water System:	
Electric (EF)	☐ ______ Tank ☐ Tankless ☐
Gas (EF)	☐ ______ Tank ☐ Tankless ☐
Other	________________

Energy Star House	Yes ☐ No ☐

Other:

4. Wall framing and sheathing

WALL CONSTRUCTION	
Stick-built	☐
Panelized on site	☐
Panelized off site	☐

FRAMING

2 x 4 walls ☐
2 x 6 walls ☐

Studs at 16" oc ☐
Studs at 24" oc ☐

Framing same all stories Yes ☐ No ☐ ______________________

Double To Plate ☐
Single To Plate ☐

Framing Species and Grade ______________________

Framing moisture content when being sheathed ______________________

OSB WALL SHEATHING		**Note:** all measurements on a min of 5 panels per house
Panel Thickness	______________	
Panel Width	______________	
Panel Length	______________	
Panel Brand and Certification Agency	______________	
Panel Span Rating	______________	
Gap between Panels	______________	
Panel MC at installation	______________	
Continuously Sheathed	Yes ☐ No ☐	______________
TO BE COMPLETED IN THE LAB:		
Linear expansion properties	______________	

5. Thermal/Moisture/Air Barriers

WRB Brand	____________________
WRB Taped	Yes☐ No☐
WRB Perm Rating	____________________
Flashing Material	____________________
Flashing Details	____________________
Exterior Rigid Foam	Yes☐ No☐
Wall Cavity Insulation	____________________
Band Joist Insulation	____________________
Attic Insulation	____________________
Basement Insulation	____________________
Raised Heel Truss	Yes☐ No☐
Attic Eave Baffles	Yes☐ No☐
Wall Vapor Retarder	____________________
Wall Paint	____________________
<u>Air Sealing Details</u>	____________________
Top Plates	____________________
Bottom Plates	____________________
Sill Plates	____________________
Rim Joists	____________________
Roof Heel	____________________
Recessed Lights	____________________
Shower/Tub	____________________
Garage	____________________

Basement	____________________
Blower Door Test Results (if available)	
Fill Out Energy Star Thermal Bypass Checklist as applicable and attach to this checklist	☐Complete ☐N/A

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