Addendum
to the May 2018 Report "Moisture Performance of High-R Wall Systems" by Home Innovation Research Labs

September 2018

This Addendum and the main report are posted at www.homeinnovation.com/moisturestudies

Purpose

This Addendum summarizes the results of extended monitoring that continued through April of 2018. The goal of the extended monitoring is to capture the performance through an additional winter season, after the construction moisture had an opportunity to dissipate, so that the observed results are representative of expected longterm trends in wall performance. Monitoring through an additional year also provides data for a different set of climatic and indoor conditions.

Addendum and Main Report

This addendum is intended to complement the main report. The research methodology and definiton of test homes and materials described in the main report are fully applicable to this Addendum. Several key tables are included in the addendum to facilitate the review of the results. The Addendum includes moisture content charts for each house over the entire monitoring period with a respective set of observations for each house. The observations are carried over from the main report and then augmented or modified as appropriate based on analysis of results of the 2017-2018 extended monitoring period. These changes are shown using underline/strikethrough format for easy review and comparison with the original set of oberservations. One key difference is that the Addendum does not inlcude WUFI modeling. The extended monitoring period is not modeled and the WUFI models representing the initial monitoring period are not carried over into the Addendum. Observations related to WUFI modeling have been removed from the contents of the Addendum for clarity. The reader is referred to the main report for information on WUFI modeling.

Monitored Sites

A total of 22 houses were included in the monitoring study. In several cases throughout the duration of the study, some of the sensors discontinued functioning or were removed by the occupant. Those instances are noted where applicable in the observations. Figure A1 shows the location of the 22 houses.

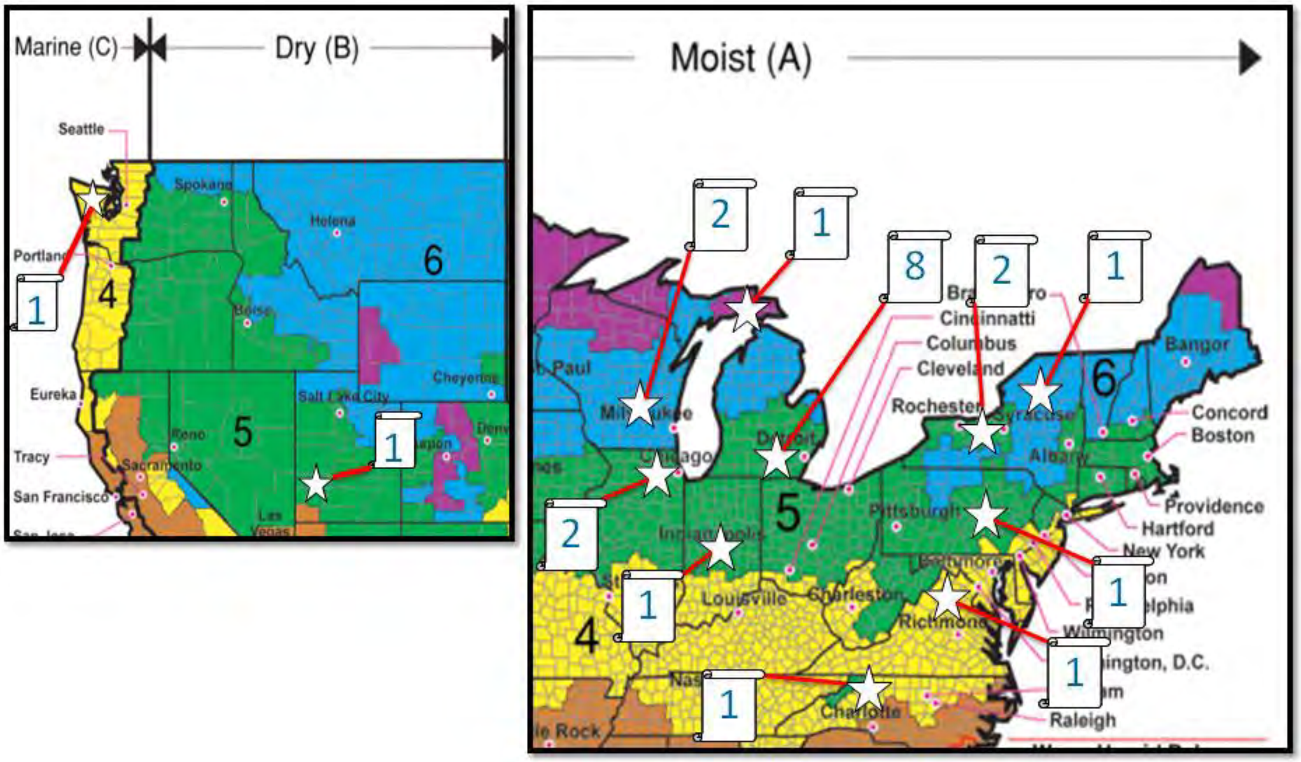

Figure A1. Map showing the location and number of houses by state and climate zone

Table 1 provides a summary of the house locations and other key relevant parameters. Table 2 sumarizes wall configurations and Table 3 provides permenace data for materials used in the houses. Table 4 provides a summary of winter temperatures for the 2016-2017 and 2017-2018 winter seasons. The data indicates a colder 2017-2018 winter season for most sites, with exception of Site 13 in Washington state. For some sites, the differences in the coldest temperature between the last two winters exceeded 20°F. The difference in the average winter temperature was as high as 7°F.

Table 1. Summary of Test Sites

Test Site	State + ID	Climate Zone	Conditioned Floor Area, ft²	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

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).

Table 3. 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

Table 4. Winter Temperatures at Test Sites

Test Site	State + ID	Climate Zone	Winter 2016-17 Minimum Temp.	Winter 2016-17 Average Temp.	Winter 2017-18 Minimum Temp.	Winter 2017-18 Average Temp.
1	VA	4A	16.6	43.2	13.1	38.7
2	NC	4A	14	45.1	16	41.1
3	MI1	5A	10.1	31.6	-2.8	25.4
4	MI2	5A	19.5	32	-3.1	25.2
5	UT	5B	2	30	-3	31
6	NY1	6A	20.9	36.2	8.3	31.9
7	PA	5A	15.5	32.9	1.4	28.6
8	MI3	5A	8	32	-6	27
9	MI4	5A	8	32	-6	27
10	MI5	5A	18.8	33.5	-2.2	26.5
11	MI6	7A	1.6	23.3	-1.4	19.2
12	IN	4A	1.8	33.4	-3	29
13	WA	4C	25.9	38.9	29.6	41.3
14	MI7	5A	19.5	32	-3.1	25.2
15	IL1	5A	1	30	-9	26
16	IL2	5A	12.3	33	-10	29
17	MI8	5A	10.5	30.6	0.1	26.9
18	MI9	5A	11.1	31	0.1	27.6
19	NY2	5A	13.7	32.5	2.9	29.1
20	NY3	5A	12.5	32.6	4	29.5
21	WI1	6A	-0.5	27.2	-5.1	22.7
22	WI2	6A	-4	26	-9	21

Wood Sheathing Moisture Content Results by Key Research Area and Test Site

Following the main report format, the analysis is organized by key research area. Within each key research area, test sites are organized by climate zone.

Key Research Area 1: Continuous Insulation and Cavity Insulation

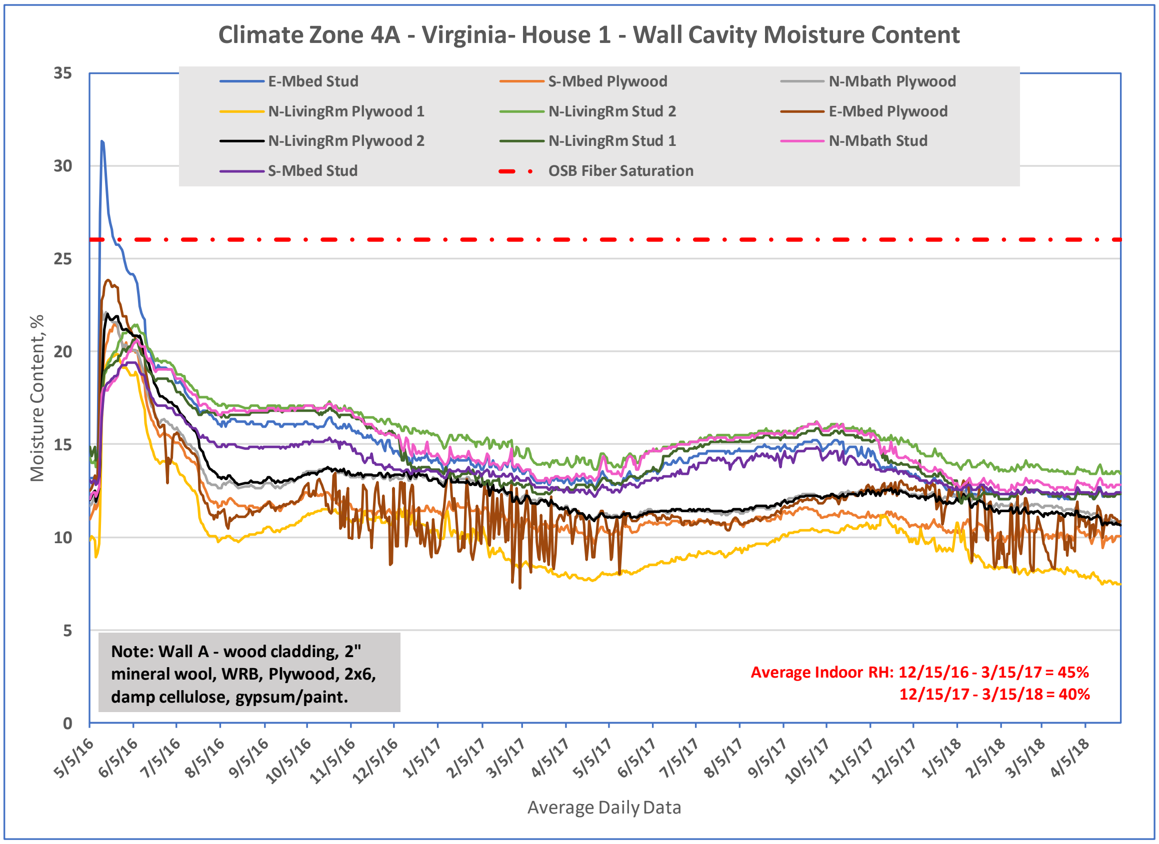

Figure A2. Plywood sheathing and stud moisture content for Climate Zone 4A, Virginia, House 1

Figure A2 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 of 2016, 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%–1~~5~~6%, throughout the ~~following three seasons~~remainder of the monitoring period.
- 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. After the initial drying, moisture content

remained stable over the next two years. Therefore, the wall was effective at controlling vapor drive from the interior during the winter with temperatures as low as 16°F in 2017 and 13°F-in 2018. 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) in 2017 and reduced to about 40% in 2018. 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).

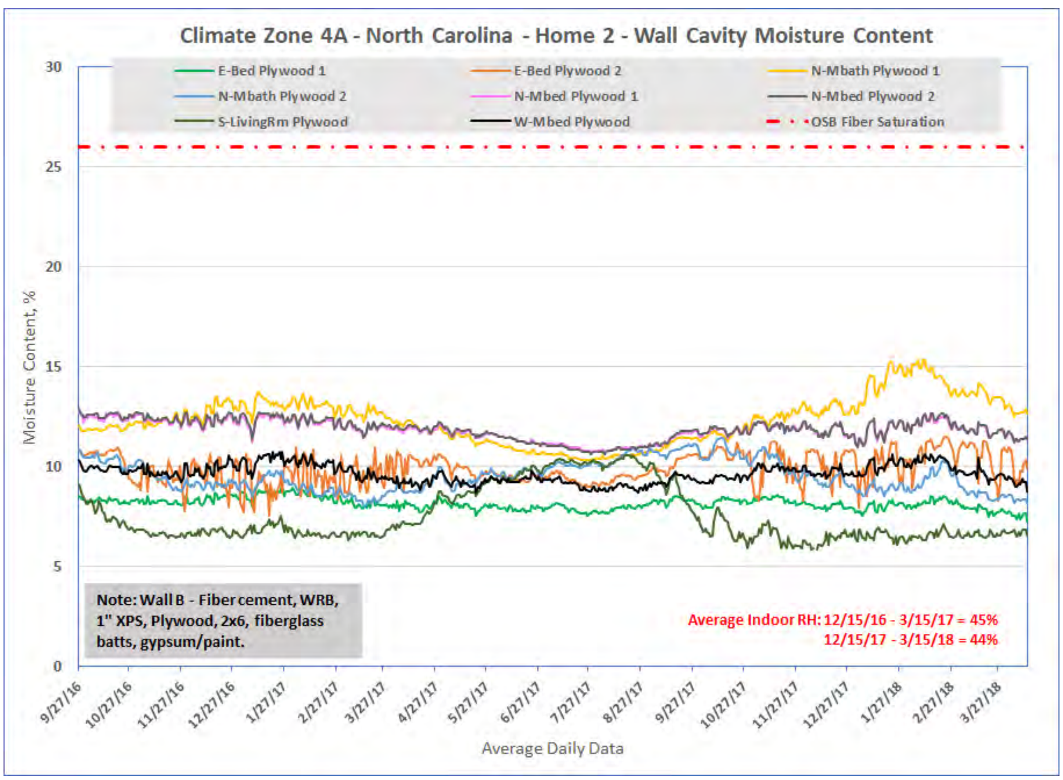

Figure A3. Plywood sheathing moisture content for Climate Zone 4A, North Carolina, House 2

Figure A3 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~~did not exceed 145% 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~~19-month monitoring season, from September 2016 through April of ~~2017~~2018, the moisture content remained stable and low. This observation is consistent with solid wood members (studs)~~, as shown in Appendix~~ . Therefore, this wall assembly was effective at controlling the interior vapor drive during the winter with temperatures as low as 14°F in January of 2017 and 16°F in 2018.

- Interior RH averaged 44-45% during ~~the~~ winter seasons. 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 1~~3~~5%) compared to walls facing south (as low as ~~7~~6%). 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).

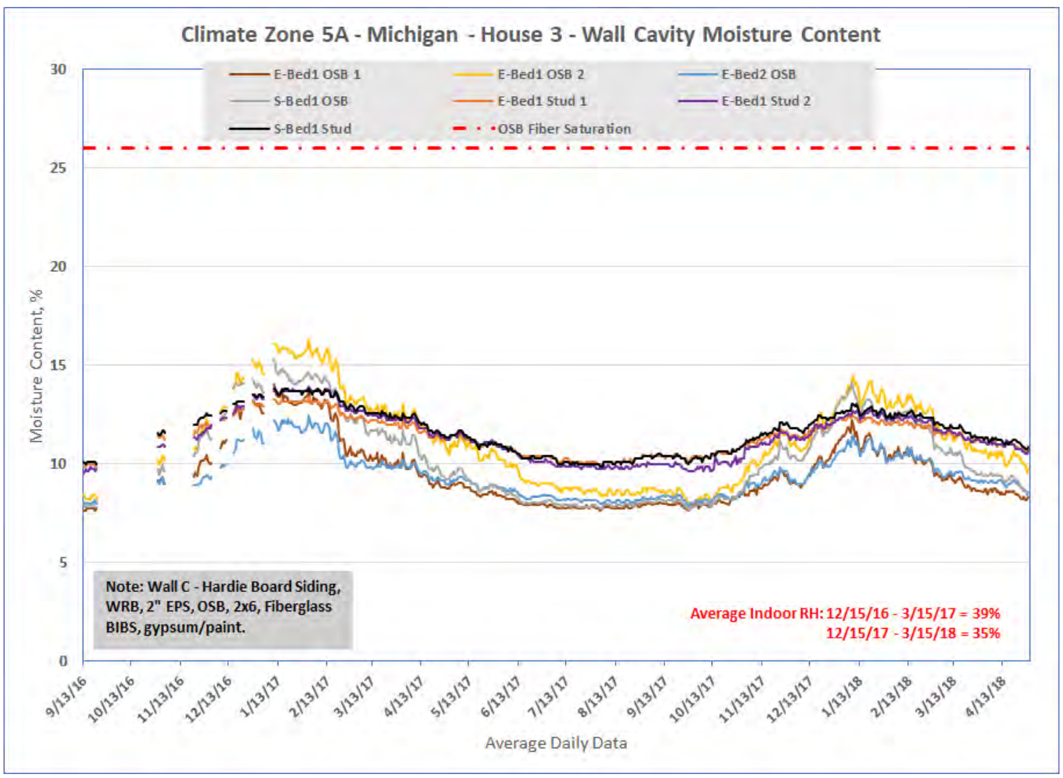

Figure A4. OSB sheathing and stud moisture content for Climate Zone 5A, Michigan (1), House 3 (Wall C)

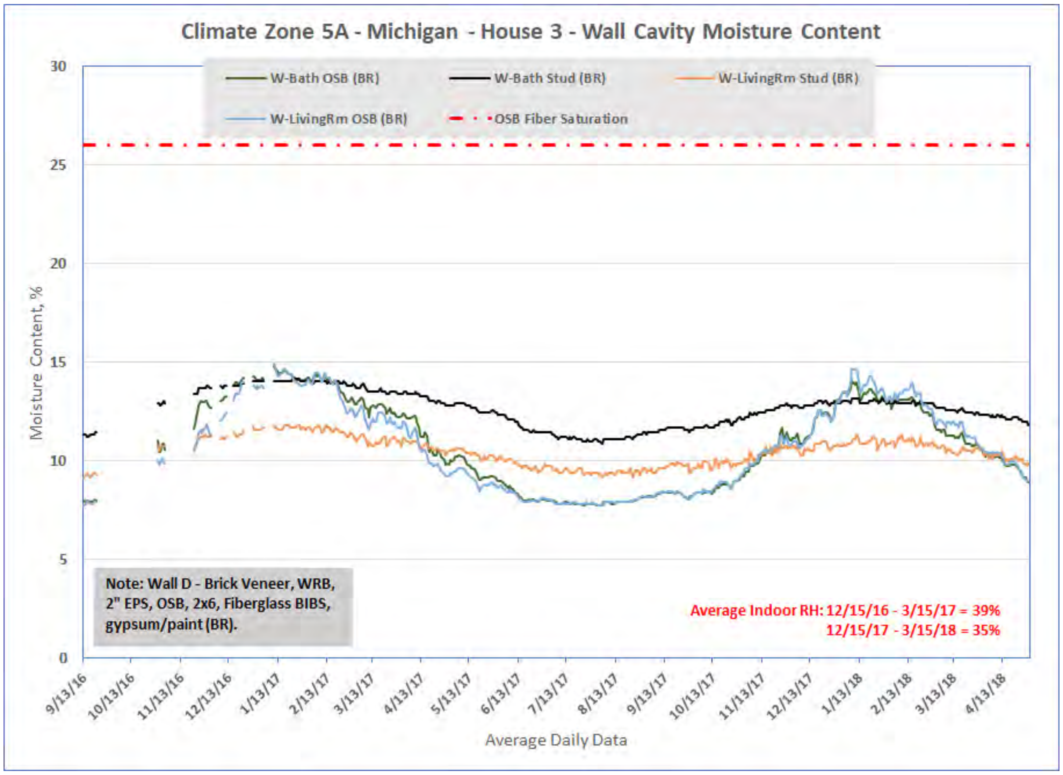

Figure A5. OSB sheathing and stud moisture content for Climate Zone 5A, Michigan (1), House 3 (Wall D)

Figure A4 and Figure A5 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 2017) 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 entire monitoring period, with the highest recoded levels of 16% during the first winter season (outdoor temperatures as low as 10°F). The second winter showed nearly identical trend with the moisture levels 1-2 percent lower. With outdoor temperatures as low as -2.8°F compared to 10°F a year before, the results suggest that the wall performance is less sensitive to the winter conditions – an attribute of walls with exterior insulation.

- Both walls experienced a mild upward trend in moisture content during the heating season. During the first winter, ~~T~~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~~ During the second winter, the walls performed nearly identically.

- The interior RH averaged 40% in the first winter ~~period~~and 35% in the second winter, 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.

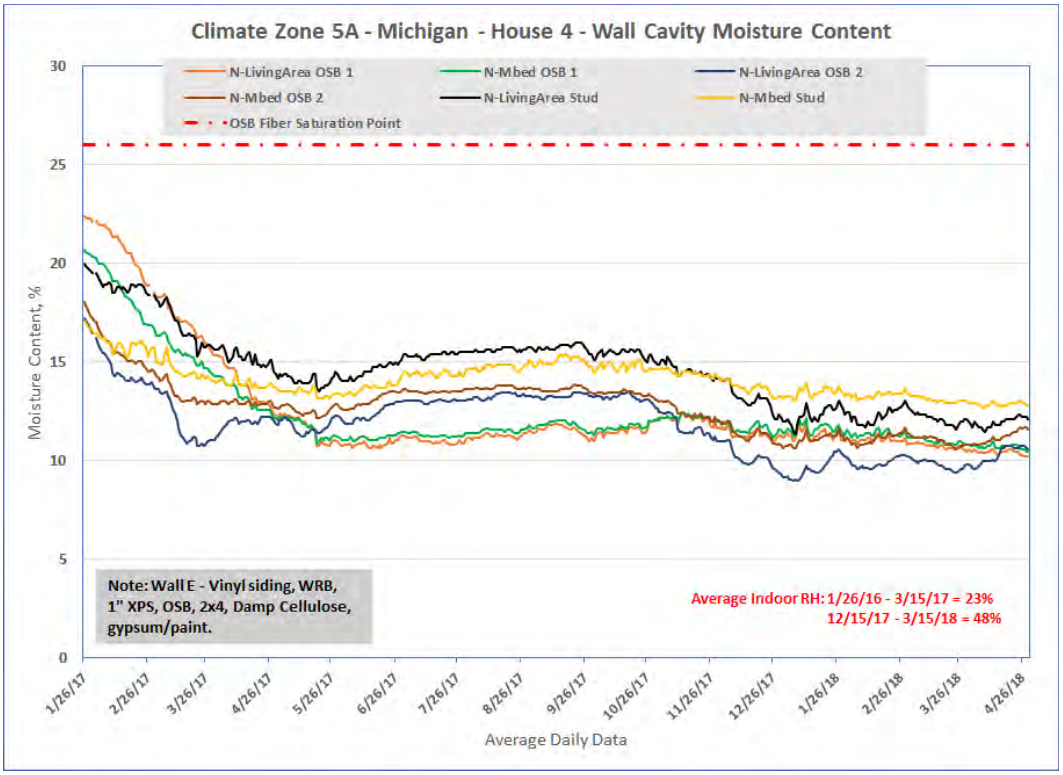

Figure A6. OSB sheathing and stud moisture content for Climate Zone 5A, Michigan (2), House 4

[Note: House 4 and House 14 were transposed in the main report. This error is corrected in this Addendum.]

Figure A6 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~~reached or exceeded 20%~~–25%~~ at three sensor locations. ~~These high moisture content levels were sustained throughout the winter, with a~~A drying trend ~~starting in April~~was observed from the beginning of the monitoring period. The drying was most likely to the inside of the house. The low indoor RH level (23%) facilitated the drying and was added by warmer temperatures in the cavity.

- The house was not occupied during the first winter, and the interior RH was low, averaging 2~~5~~3%. ~~A longer monitoring period is needed to better understand the long-term moisture-management characteristics of the wall, particularly d~~During the second~~a~~ winter season when the house is occupied, the RH level increased to nearly 50%. This townhouse relies on exhaust fans for ventilation. A combination of occupant activities with this type of ventilation lead to levels of RH that represent the upper range for Climate Zone 5 based on observations from previous studies. A more typical average RH for Climate Zone 5 is in the 30-40% range.

- The elevated interior RH level in the second winter didn't lead to an increase in OSB moisture content. The combination of exterior foam sheathing and cellulose cavity insulation was effective at keeping OSB moisture content levels at or below 15% throughout the winter. The second winter was substantially colder than the year before with outdoor temperatures dropping to -3.1°F.

- ~~Initial~~Early 2017 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.

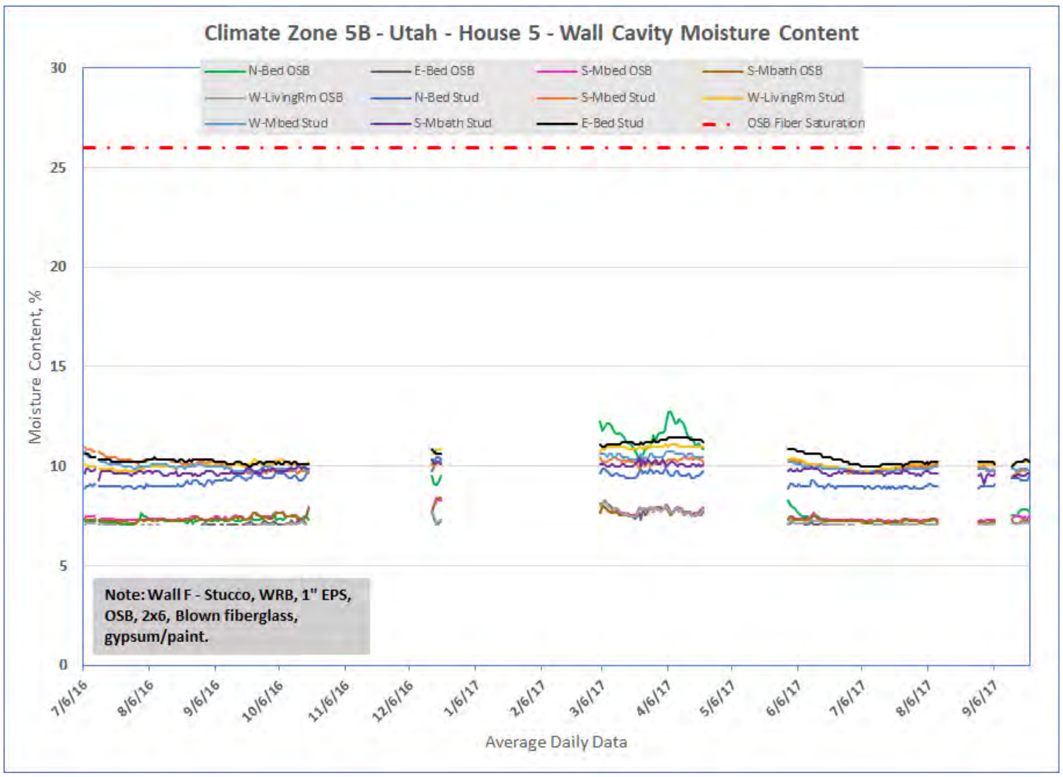

Figure A7. OSB sheathing and stud moisture content for Climate Zone 5B, Utah, House 5

[Note: House 5 was disconnected by the occupant. No new data is available for this house. The analysis from the Main Report is shown below without modifications.]

Figure A7 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.

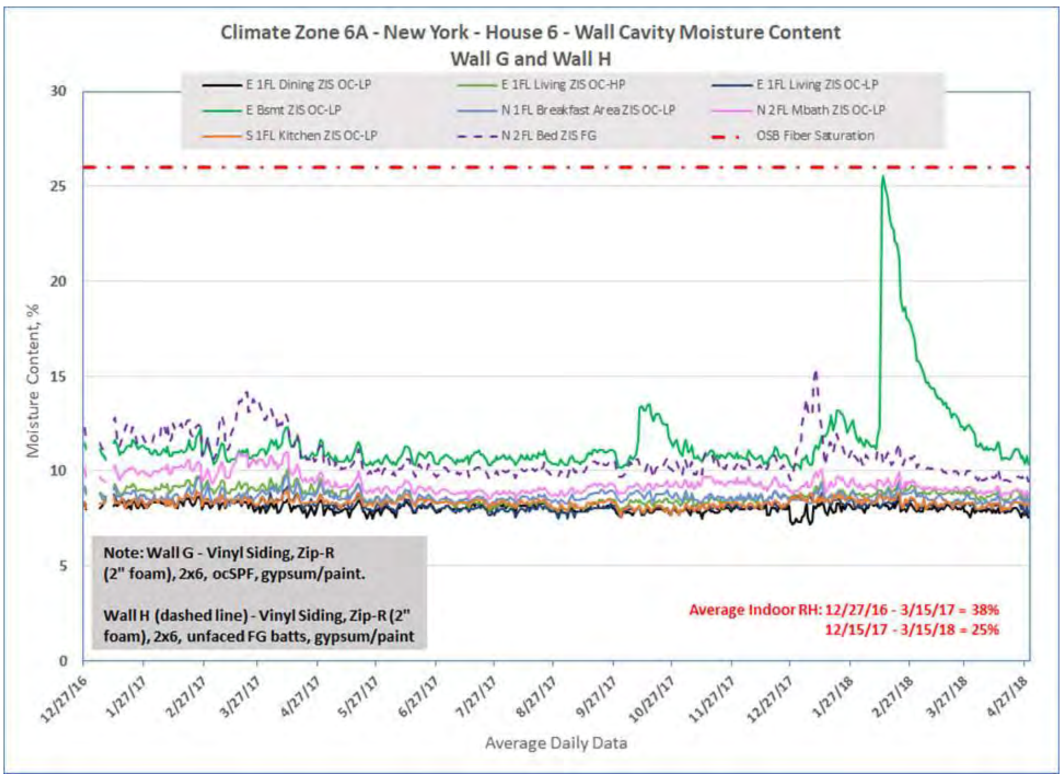

Figure A8. ZIP sheathing moisture content for Climate Zone 6A, New York (1), House 6

Figure A8 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. Note that two types of open-cell spray foam was used with Wall G: low-perm (LP) with specified permeance of 5 perm at total thickness and high-perm (HP) with specified permeance of 30 perm at total thickness. The type of spray foam used is noted for each sensor on the graph legend. The following observations can be made:

- The OSB moisture content was trending primarily flat at ~~less than~~ 145% or less for ~~all~~ most sensors in all orientations with many trending below 10%. One conspicuous exception was a sensor in the walk-out basement wall that spiked precipitously during the second winter season reaching the fiber saturation level for a short period of time. Given the rate of increase, this spike was mostly likely caused by a short-term water leak event from the outdoors. Two moderate spikes in October and January at the same sensor suggest that this location is associated with a minor breach in the water resistive barrier that gets penetrated when events reach a certain level of intensity. It's noted that this wall is below a deck and it's possible that the observed vulnerability is at the deck-to-wall joint area. It is less likely that the moisture spikes were caused by an air leak from the indoors because the uptake in moisture would have been slower and the supply of moisture would have been more persistent. The data also shows that the moisture began drying immediately after the wetting event—an indicator of the wall's capacity for dissipating moisture. While the initial rate of drying was high, it took two months for the moisture content to return to its pre-spike level. Drying in this wall can occur in both directions, but the primary drying path is expected to be to the inside.

- -The coldest outside temperature in 2016-2017 winter was 21°F, suggesting a relatively mild winter for the climate zone. The second winter was colder with the lowest temperature at 8°F. The second winter spike for the walk-out basement sensor is unlikely to be related to the lower outdoor temperatures.
- 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 dashed line in Figure A8). The moisture content at this location (sensor in the second-floor bedroom) trended slightly higher than most sensors. It showed 4-6% short-term spikes in OSB moisture content; as with the basement sensor, the moisture was able to dry out quickly.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 first winter season was within the typical range at 38% and somewhat lower 25% for the second season. 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 Because the wall system does not contain any low-perm materials, drying can occur in either direction and will depend on the season and direction of vapor drive. The ZIP panel is the material with the lowest permeability in the assembly.

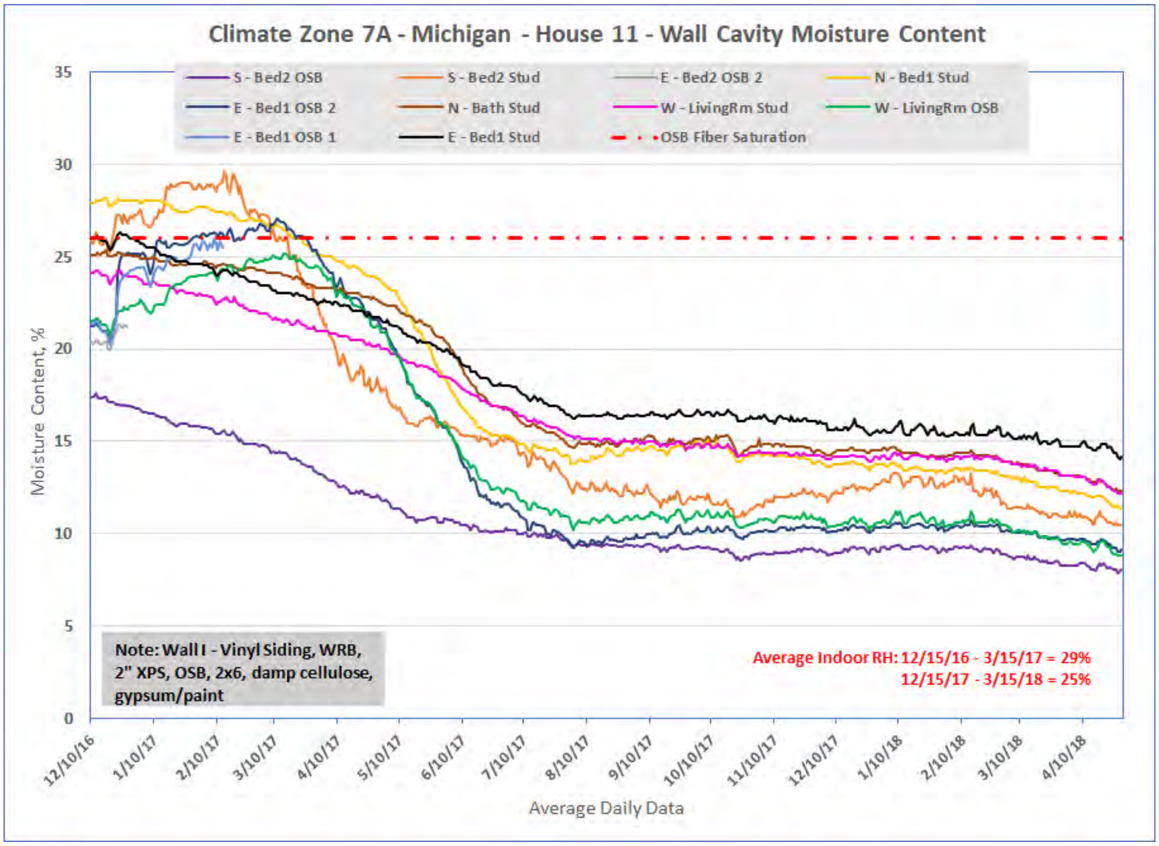

Figure A9. OSB sheathing and stud moisture content for Climate Zone 7A, Michigan (6), House 11

Figure A9 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.~~
- All sensors dropped to below 20% by middle of June of 2017. Drying was complete by the end of July of 2017 as evidenced by the inflexion points on the moisture content chart for both OSB and lumber.
- The direction of drying is expected to be primarily toward the indoors. The permeability of paint is not known for this house.
- Moisture levels remained stable and below 16% for all sensors for the remainder of the monitoring period through April of 2018. The second heating season did not lead to any upward trends in moisture content indicating that 2 inches of XPS was sufficient to keep the wall cavity warm (outdoor temperatures as low as 1°F).
- The interior RH remained low (25-29% on average) throughout the winter seasons. The ventilation system has not been reported for this house. WUFI simulations can be performed in the future to test the sensitivity of this wall assembly to higher interior RH levels.

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

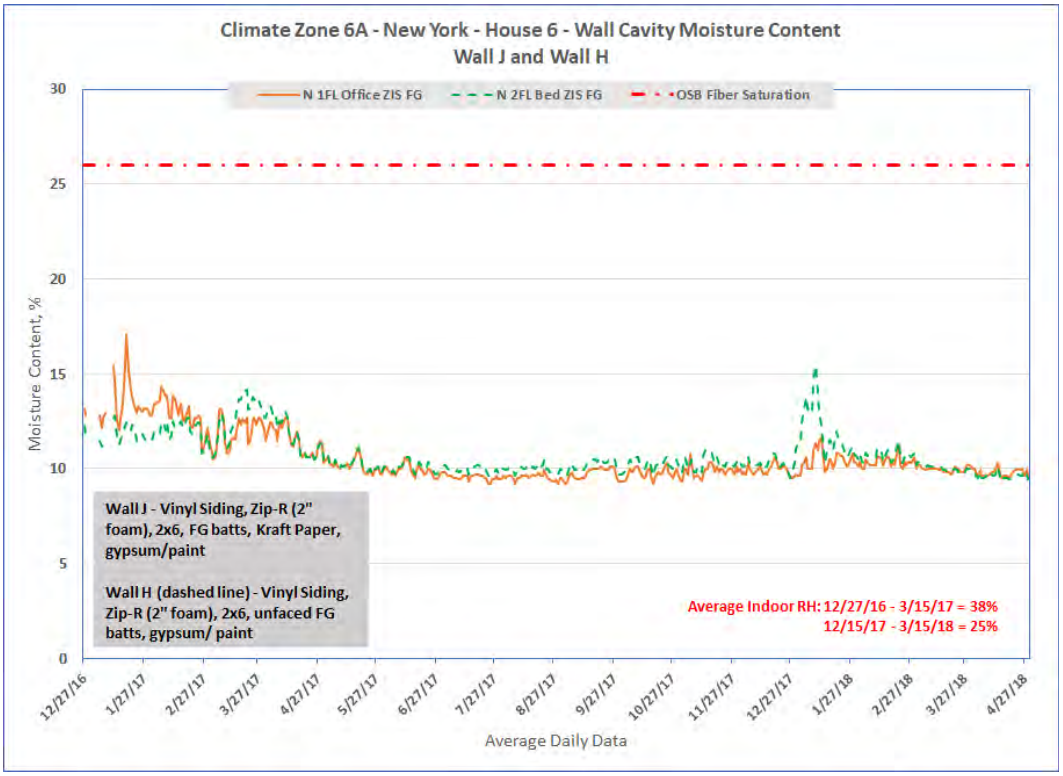

Figure A10. ZIP sheathing moisture content for Climate Zone 6A, New York (1), House 6

Figure A10 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 A8). Figure A10 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 throughout the monitoring period. Both walls indicated good and stable performance with moisture content at less than 15% after initial drying and at about 10 percent 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 of 2017, 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 first winter season was within the typical range, at 38% in 2017 and somewhat lower at 25% for the second season. An ERV was used to provide outdoor ventilation and was effective at controlling the RH levels in this extremely airtight house (0.52 ACH50).

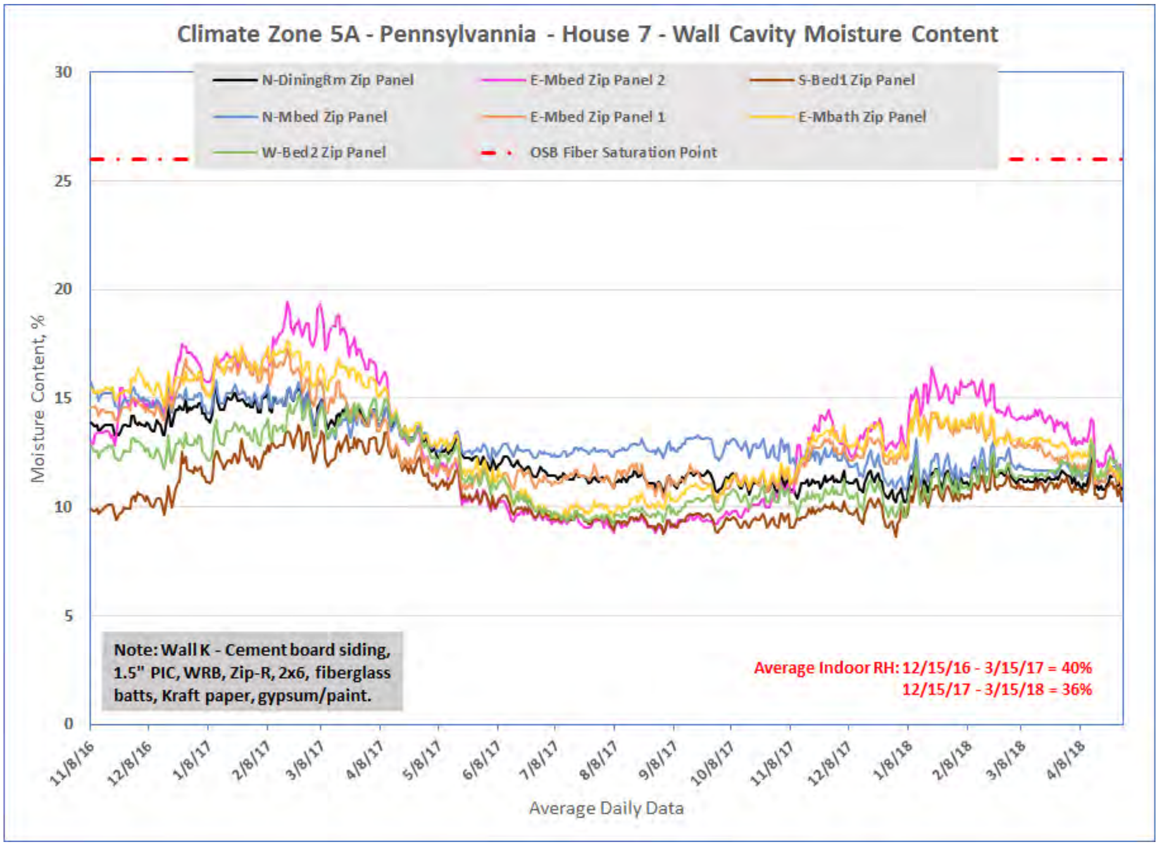

Figure A11. ZIP sheathing moisture content for Climate Zone 5A, Pennsylvania, House 7

Figure A11 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 first 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.
- Moisture content remained flat and stable throughout the summer at below 13%. The second winter uptick was lower in amplitude and absolute value, peaking at or below 16%. This reduction in the second winter was observed despite lower winter temperatures (15°F in 2017 and 1°F in 2018). The key difference was the starting moisture level at the beginning of the heating season.
- 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 36-40% RH for the entire monitoring periodboth winter seasons—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.

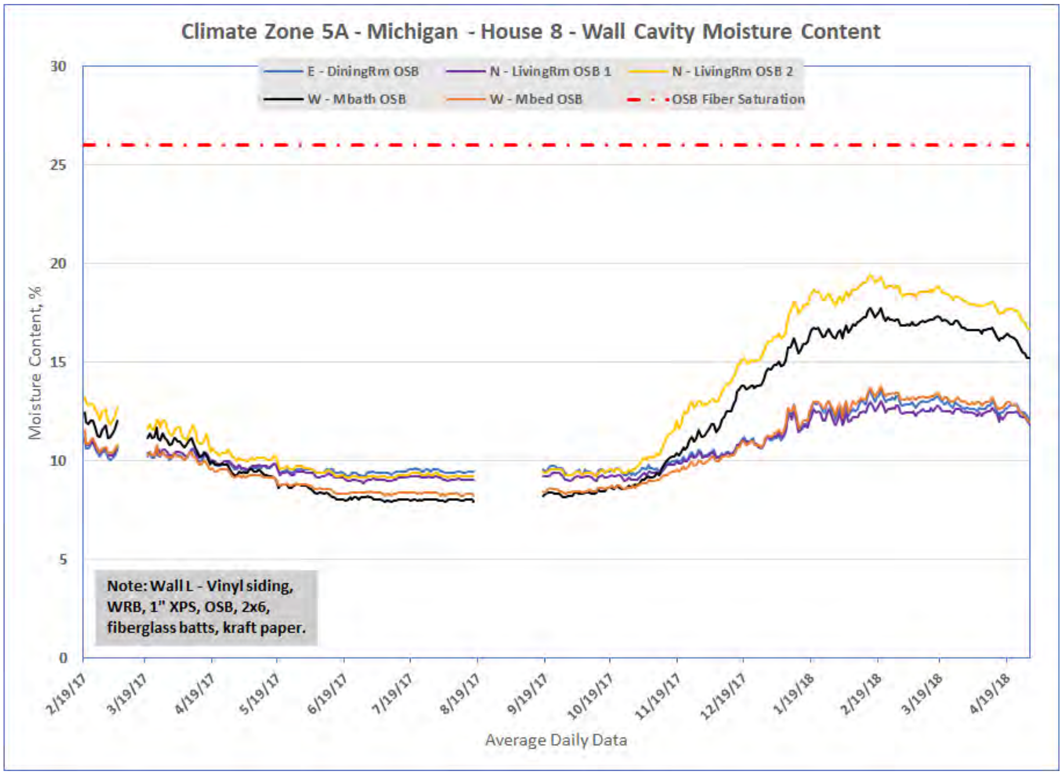

Figure A12. OSB sheathing moisture content for Climate Zone 5A, Michigan (3), House 8

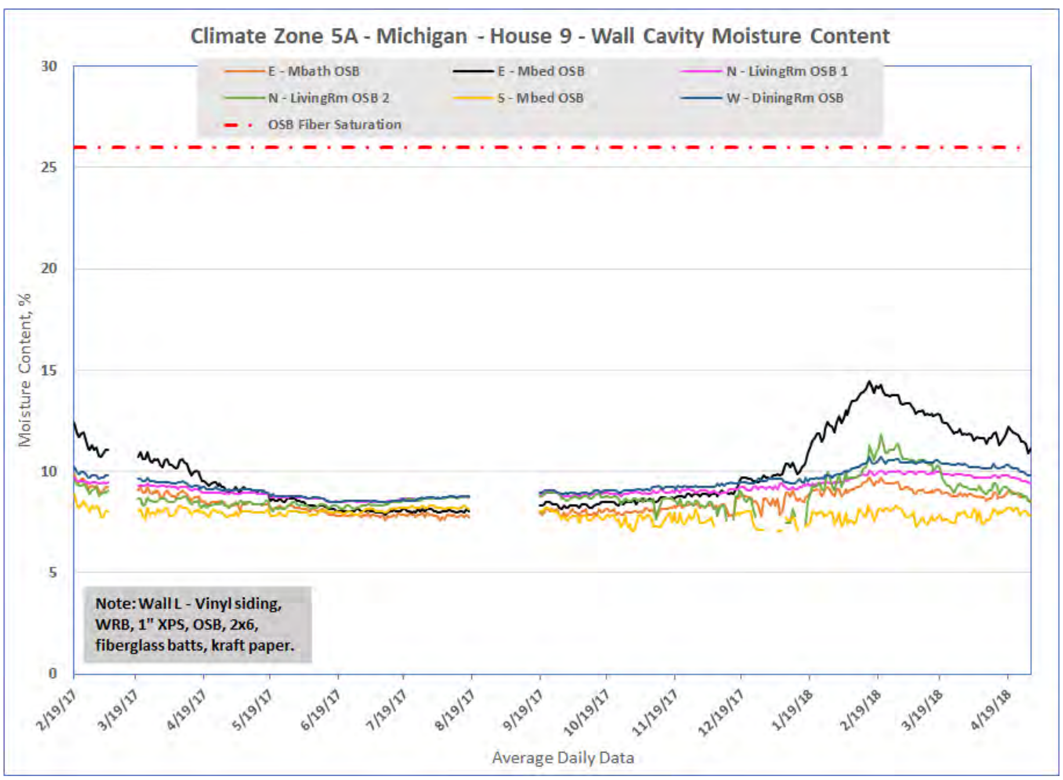

Figure A13. OSB sheathing moisture content for Climate Zone 5A, Michigan (3), House 9

Figure A12 and Figure A13 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~~during the first winter. ~~Additional monitoring is recommended for these houses.~~ Indoor relative humidity data for these houses was not available. 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 through the fall of 2017. At the beginning of the 2017-2018 heating season, there is a trend for moisture content increase across all sensors, with the trend more prominent for House 8. The moisture content does not exceed 20% for House 8 and 15% for House 9 – all well below the fiber saturation point.

- For House 8, there are two sensors that are distinctively higher during the 2018 winter than the remaining three sensors. One of these sensors is on the north wall where drying is the slowest and the other is in a master bathroom where the relative humidity may be elevated. For House 9, there is only one sensor trending distinctively higher from the rest of the set. The observed selective pattern with only some of the sensors showing a distinct winter trend suggest that air leakage is a likely contributing factor in those three cases.

- ~~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 first winter temperatures at this site were somewhat mild for this location:~~.~~ ~~F~~for most of the first winter, the temperatures were above 20°F, with only two short periods dropping into the 10°F range. The second winter was more typical with temperatures reaching -6°F.

- 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. The ~~initial~~ results ~~suggest~~ indicate that this wall system can be an effective and practical option for walls achieving R-24. Where an additional margin of safety is sought to further minimize the amplitude of the heating season moisture content cycles, air sealing at the interior sheathing can be implemented to control the flow of air into the cavity from the indoors.

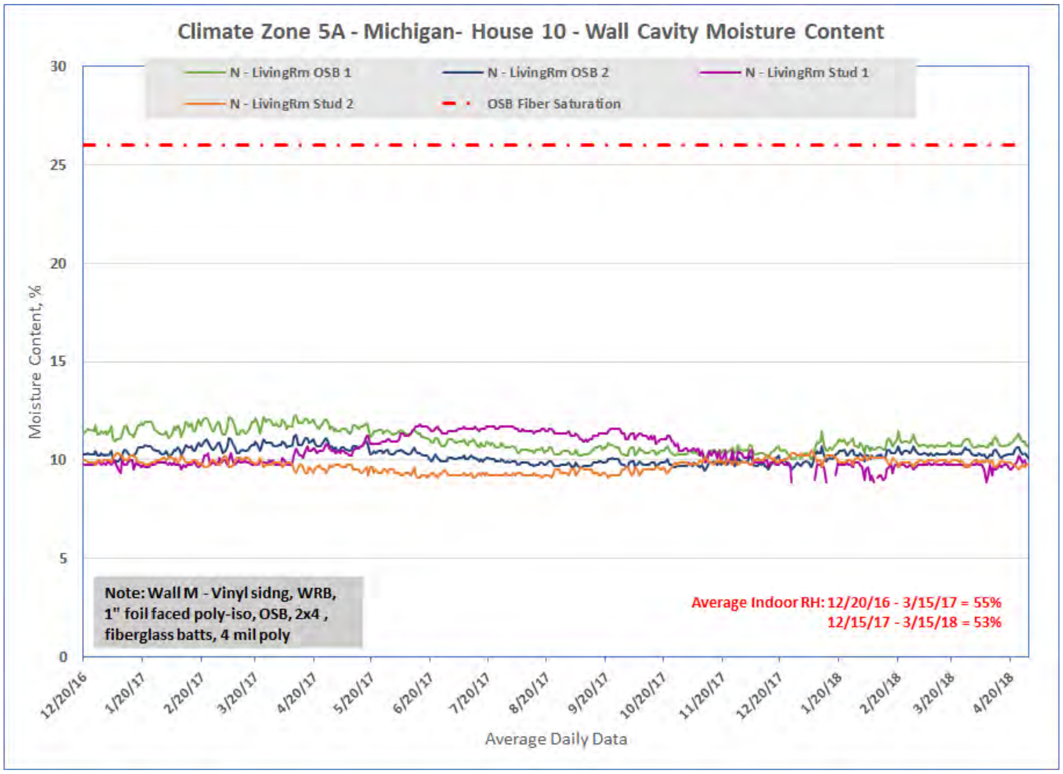

Figure A14. OSB sheathing and stud moisture content for Climate Zone 5A, Michigan (5), House 10 (Wall M)

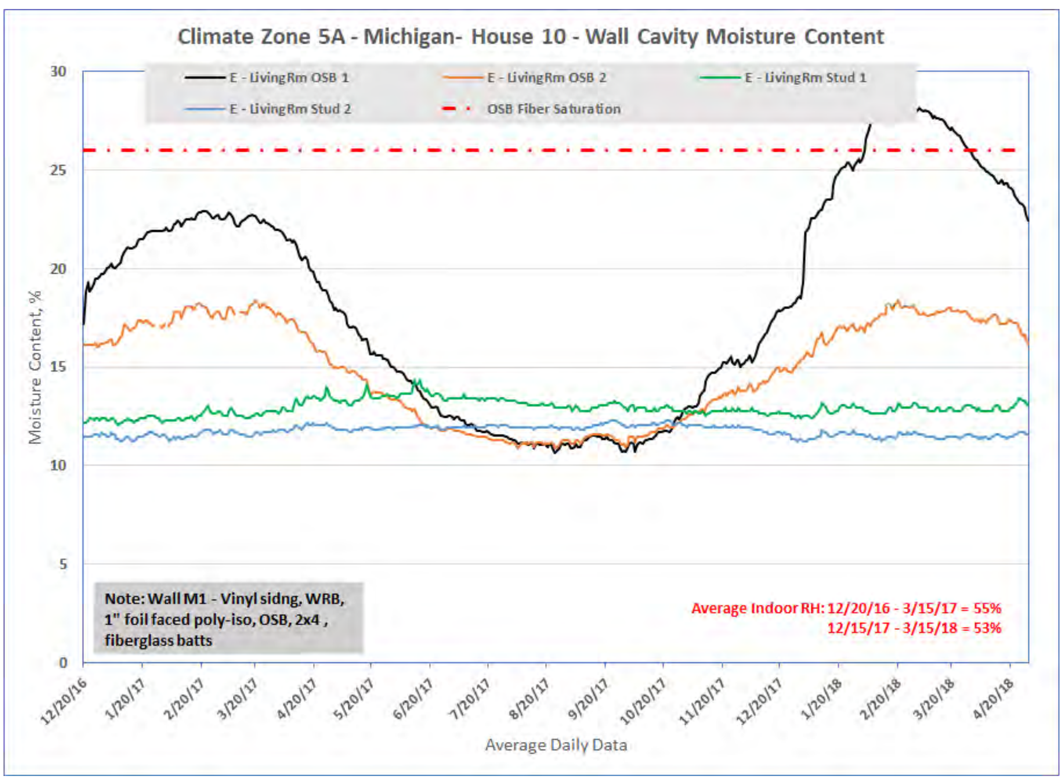

Figure A15. OSB sheathing and stud moisture content for Climate Zone 5A, Michigan (5), House 10 (Wall M1)

Figure A14 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 w~~Wall M 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% during the first heating season and averaging 53% and peaking at 60% during the second heating season. 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, t~~The moisture content levels did not show any seasonal trend even as the interior RH remained consistently high.
- A section of the wall constructed without polyethylene (Figure A15, Wall M1) showed a dramatically different performance, with moisture content levels ~~about 10 points higher compared to wall sections with polyethylene~~reaching the fiber saturation point. These results suggest that even walls with an exterior insulation R-value exceeding the code minimum (R-6.5 installed vs. R-5 code minimum) can be sensitive to high levels of indoor RH~~;~~. The impact of the outdoor temperature was also evident: ~~however, note that even without the polyethylene~~the OSB moisture content had not reached the fiber saturation point in the first heating season (minimum temperature 18.8°F) but remained at or near fiber saturation for an extended period of time during the second heating season (minimum temperature -2.2°F). Wall M1 showed onset of drying ~~beginning of April~~early spring both years.

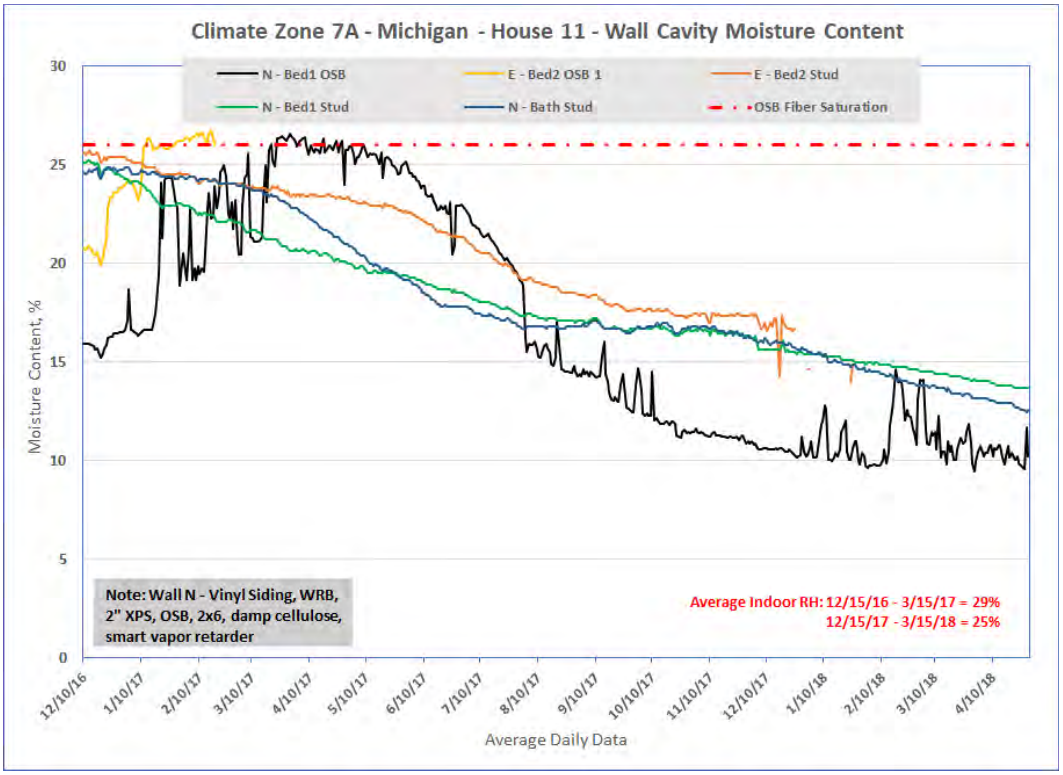

Figure A16. OSB sheathing and stud moisture content for Climate Zone 7A, Michigan (6), House 11

Figure A16 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~~until early May of 2017~~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.~~ The onset of drying was delayed and the rate of drying was somewhat slower for Wall N compared to Wall I. For Wall I, most sensors plateaued around mid-July. For Wall N, the sensors were trending down for the majority of the monitoring period.
- The data suggests that the smart vapor retarder has a moderate impact on drying rate. However, this wall configuration represents the most severe condition – a significant internal moisture load at the construction phase. All sensor readings for Wall N reached below 20% by end of July – about a two-month delay compared to Wall I. After the moisture was dissipated, it remained stable for the remainder of the monitoring period.
- As evidenced by flat trending of Wall I during the second heating season, 2-inch XPS was sufficient to control interior vapor drive even as the outdoor temperatures reached -1.4°F. Therefore, the contribution

of the smart vapor retarder to controlling winter vapor drive cannot be definitively evaluated – it's presence was not critical to the performance of this wall assembly.

1.2 Key Research Area 3: Cavity-Only Insulation

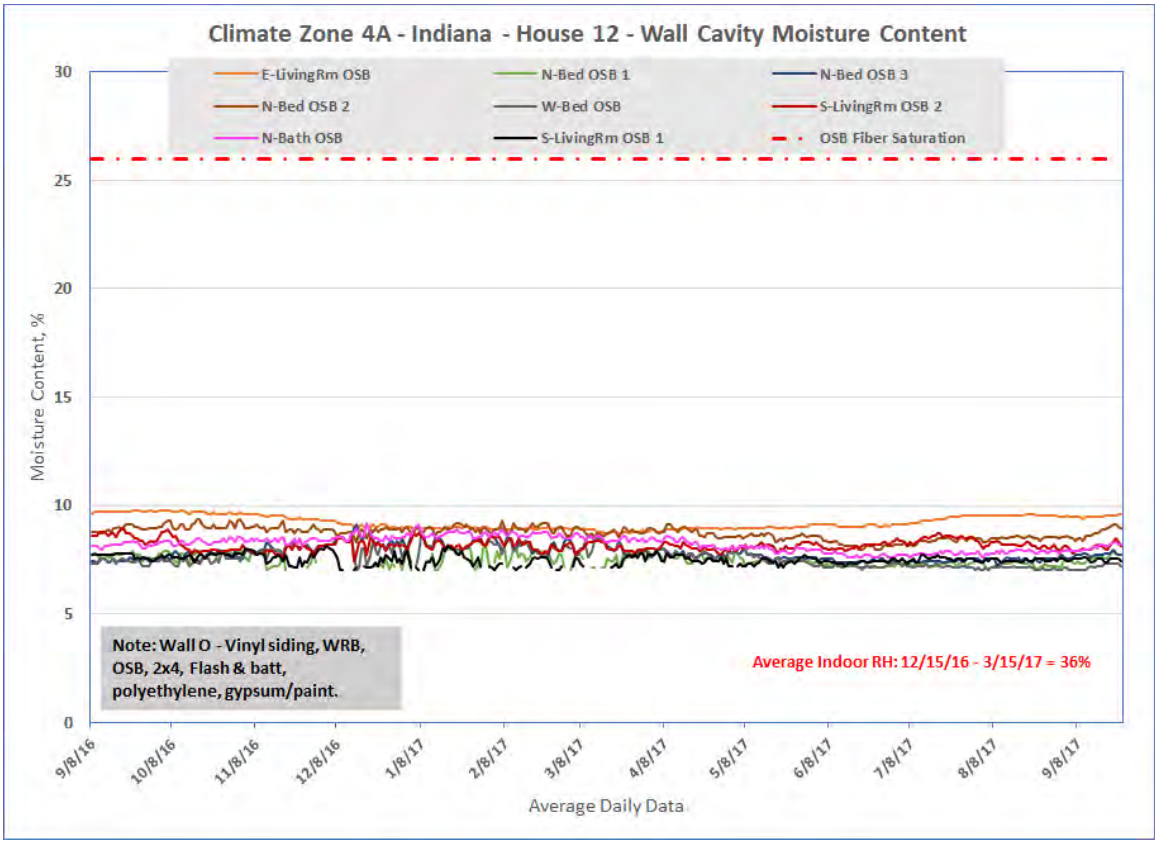

Figure A17. OSB sheathing moisture content for Climate Zone 4A, Indiana, House 12

Figure A17 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 entire 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~~the cooling season ~~should be monitored to evaluate~~did not indicate ~~the~~ any~~potential for~~ moisture buildup in the cavity~~ because of cooler indoor temperatures~~.

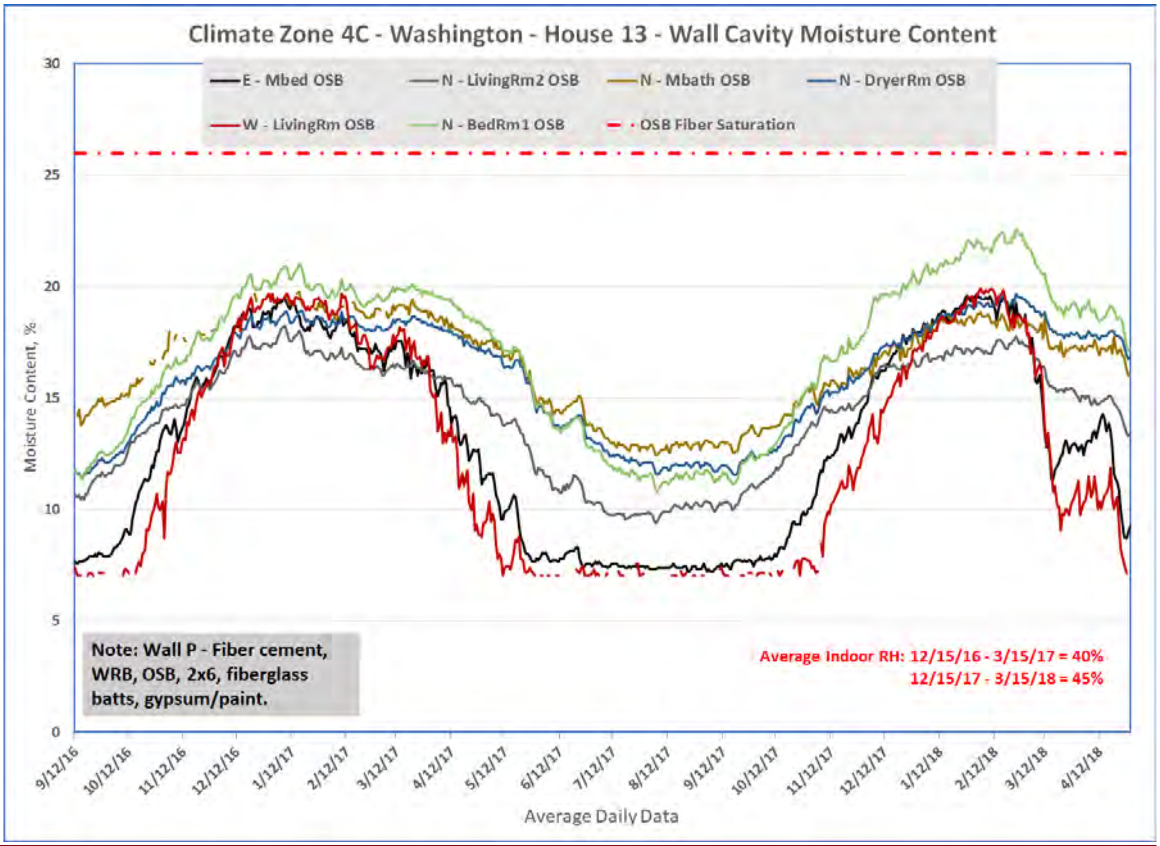

Figure A18. OSB sheathing moisture content for Climate Zone 4C, Washington, House 13

Figure A18 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~~22% for one of the sensors with the rest of the sensors at or below 20%. These moisture content levels are ~~5~~4% or more ~~less than~~below the fiber saturation point and can be considered within acceptable performance range.

- A consistent moisture built up trend during the heating season was observed in three of four cardinal directions (there were no sensors in south-facing walls). Solar drive was not sufficient in any of the three directions to alter the moisture build-up profile. This observation in part can be attributed to the climate.

- A drying trend initiated late march to early April with the east and west orientations drying at a faster rate and reaching lower moisture levels compared to north-facing walls. The west and east walls completed their drying by mid-May, whereas some of the north-facing walls showed a downward drying trend until July. Difference in solar drive is the primary reason for this difference in behavior.

- 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 seasons were ~~40% on average~~40-45%. This was ~~somewhat less~~not far from than the results of the previous monitoring study, which showed RH levels exceeding 60%. This is one of the few sites where the second winter outdoor temperatures were a few degrees higher that the first winter (minimum temperature 25.9°F in 2016-2017 vs 29.6°F in 2017-2018).

- 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.

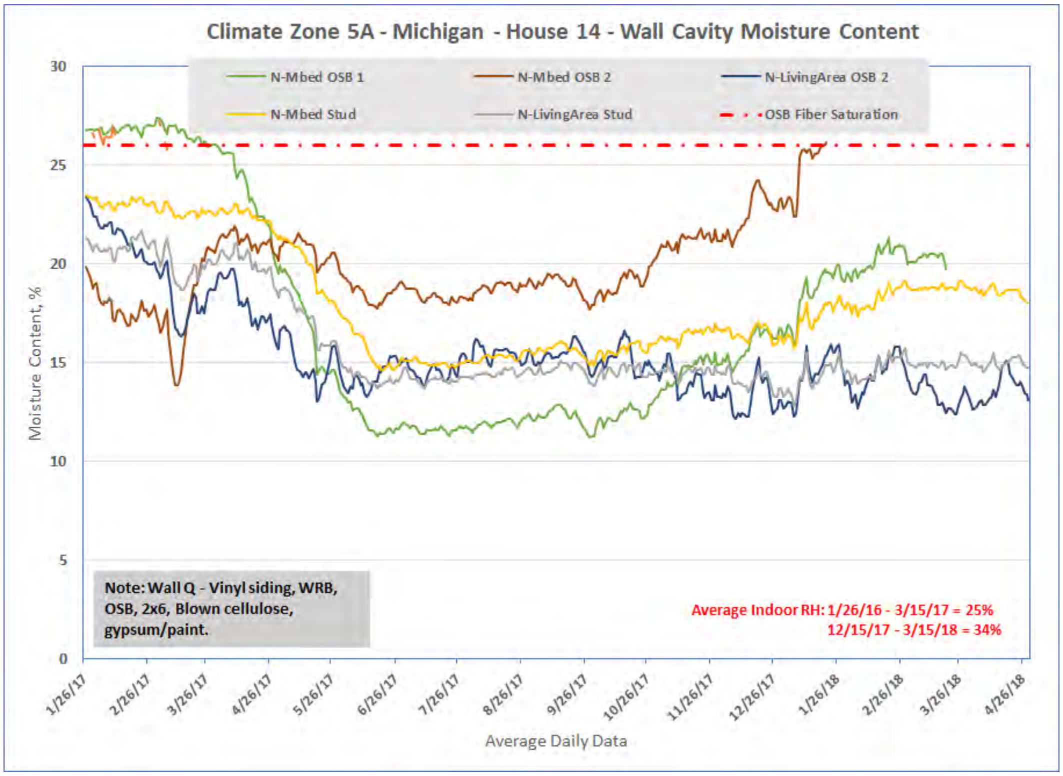

Figure A19. OSB sheathing and stud moisture content for Climate Zone 5A, Michigan (7), House 14

[Note: House 4 and House 14 were switched in the main report. This error is corrected in this Addendum.]

Figure A19 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 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. 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 reached or exceeded 20% for all five sensor locations. A definitive drying trend was not observed until April. The drying could be to the inside or to the outside of the house.

- Although all sensors are in the north-oriented wall, a range of performances is observed. The sensor with the lowest summer moisture content dropped to as low as 11%, whereas the sensor with the highest summer moisture content oscillated around 19%.

- Two of the sensors did not exhibit the typical upward trend during the second heating season. Two other sensors show a modest increase of 4-6% during the same period and one sensor reached the fiber saturation point leading to its malfunction.
- This scatter in drying and seasonal trends may be explained by the narrow wall segments in a wall with a large openings-to-opaque-wall ratio. It's likely that a smaller cavity near a window had less drying potential and the localized conditioned were impacted by the window or door.
- Compared to House 4 – a house of the same configuration built by the same builder, the performance of Wall Q was more unpredictable and, in several cases, with amplified seasonal fluctuations. Moisture content trends for Wall E (House 4) during the second heating season were more stable and flat.
- 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.

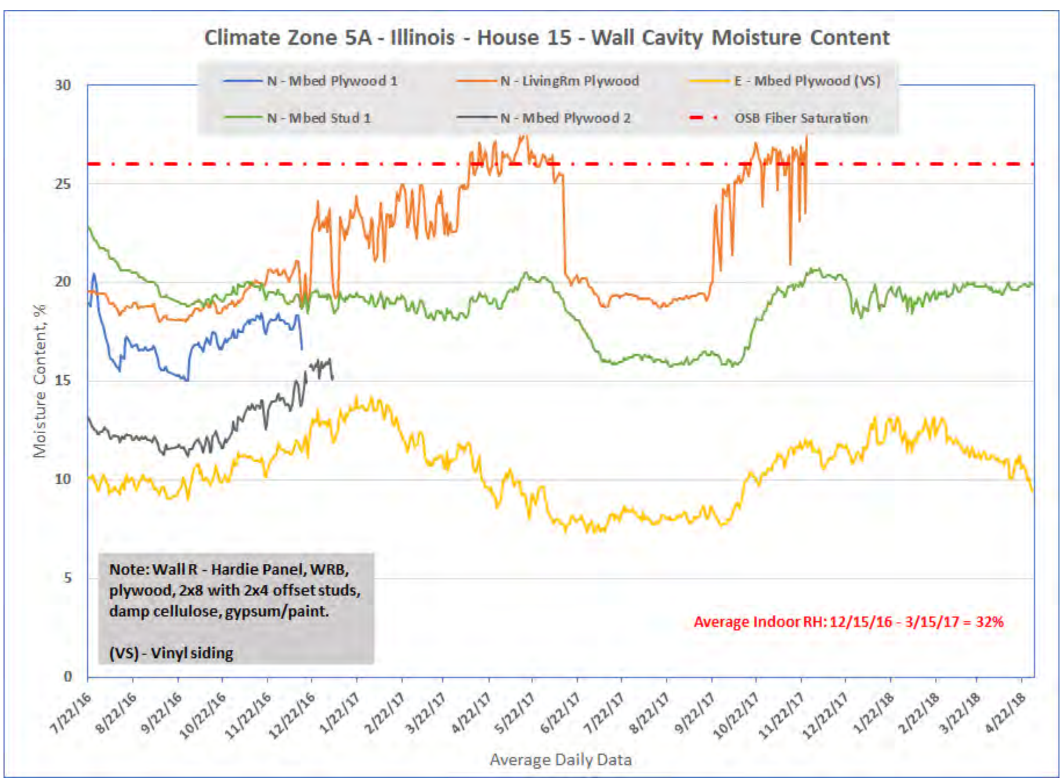

Figure A20. Plywood sheathing and stud moisture content for Climate Zone 5A, Illinois (1), House 15

Figure A20 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~~ plywood 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~~ plywood 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 trend repeated itself during the second heating season until the sensor stopped reading (typically a result of long-term exposure to high moisture levels or condensation).
- 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 the first winter. The trend closely repeated itself during the second 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~~ plywood 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 first 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). Even during the summer time the drying was slow and moisture content dropping to just below 20%. Moisture content started to climb back up rapidly in September leading to a failure of the sensor.
- 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 hygric inertia attributed to this wall is also evidenced by the moisture content of the stud that oscillates between 16% and 21% for the majority of the monitoring period.
- 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 in the first heating season and -9°F in the second heating season).

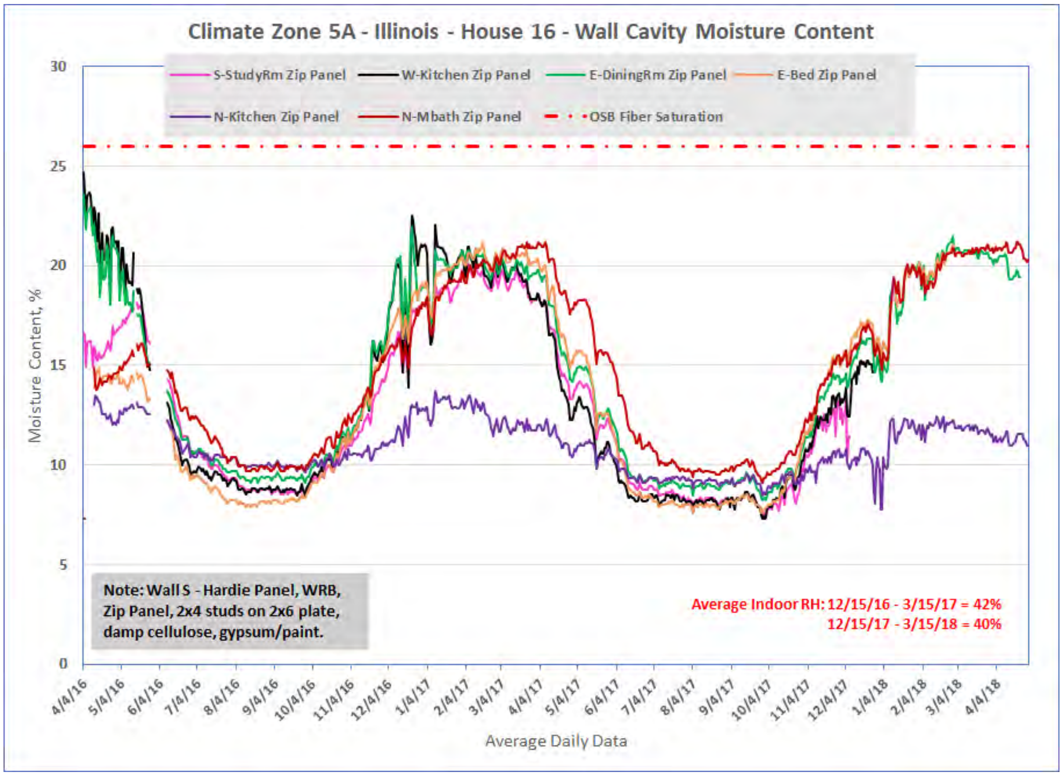

Figure A21. ZIP sheathing moisture content for Climate Zone 5A, Illinois (2), House 16

Figure A21 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. The trend repeated itself during the second heating season. 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 seasons were in the 40-42% 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 (see the main report for details on modeling) and also ~~. 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~~ indicateds 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). The data from the second winter did not support the notion of the exterior temperature effect – the moisture content peaked at about the same level even though the minimum exterior temperatures were substantially lower (12.3°F in 2016-2017 vs. -10°F in 2017-2018). However, it is noted that while the peak temperatures were lower, the averages over the winter season were lower only by only 4 degrees (33°F and 29°F, respectively). It is likely that the Class III paint at 4.6 perm dry cup also helped to mitigate the effects of the lower temperatures.

- 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.

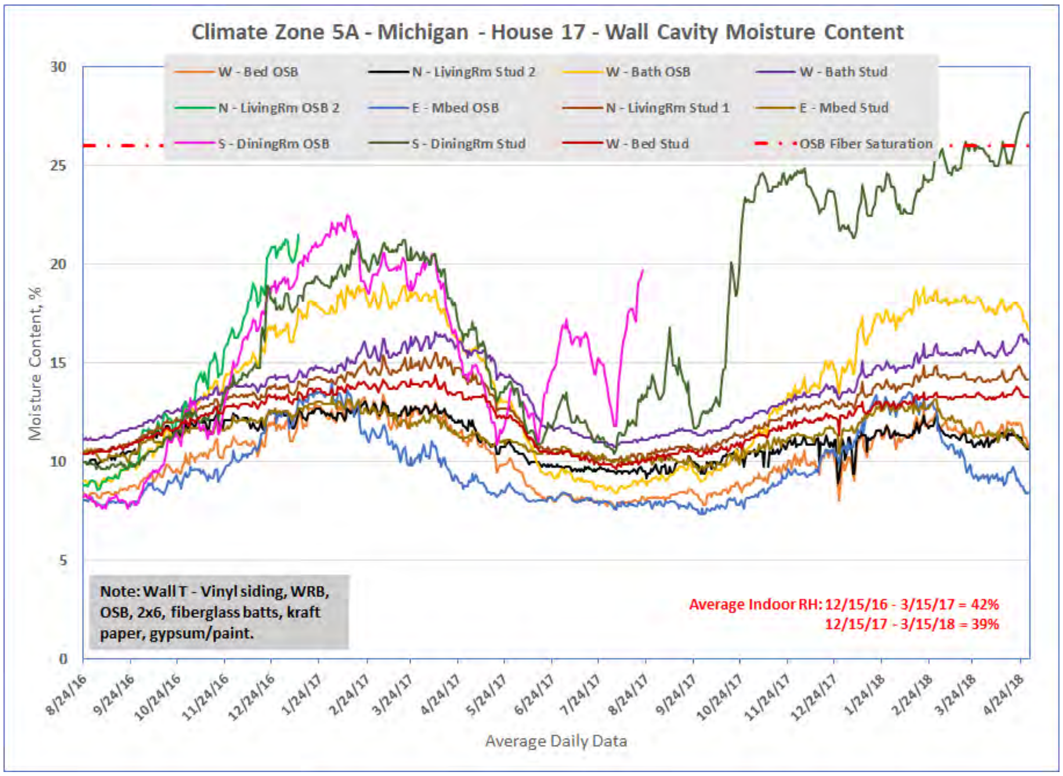

Figure A22. OSB and stud moisture content for Climate Zone 5A, Michigan (8), House 17

Figure A22 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 the OSB moisture content rising each winter and drying out in the summer. Most sensors were below 16% percent in the winter. A bathroom sensor elevated to 19% each winter, likely due to slightly higher interior relative humidity levels.

- There are two sensors with distinctly different behavior from the rest of the set – both in dining room south. The sensors fluctuate throughout and either reach fiber saturation or malfunction after exhibiting amplified spikes. Although the sensors are in the south wall (typically lowest risk orientation), review of the plan reveal that the cavity where these two sensors are located is between the entry door and a window in a wall section shaded by an adjacent garage protruding about 12 feet beyond the face of the monitored wall. It is likely that the sensors that are near the window are subject to colder temperatures due to thermal bridging and/or a small air or water leak that the wall cannot overcome due to lack of solar exposure at this location. Another potential reason is inadequate installation of the batts leading to ineffective performance of the Kraft paper as a vapor retarder.

- The behavior of a living room sensor (N-LivingRm-OSB2) is similar, likely for the same reasons as described above.
- a winter rise as high as 22%. Similar to House 16, The majority of sensors this moisture content waswere 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.
- However, observations from three sensors that showed higher levels of moisture content suggest that quality of installation of wall materials is an important aspect for these types of walls in colder climate where interior vapor drive is significant and sustained for an extended period. This moisture content level indicated marginal performance.
- The interior RH levels during the winter season were 42% and 39% on average between first and second winter, respectively. 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.

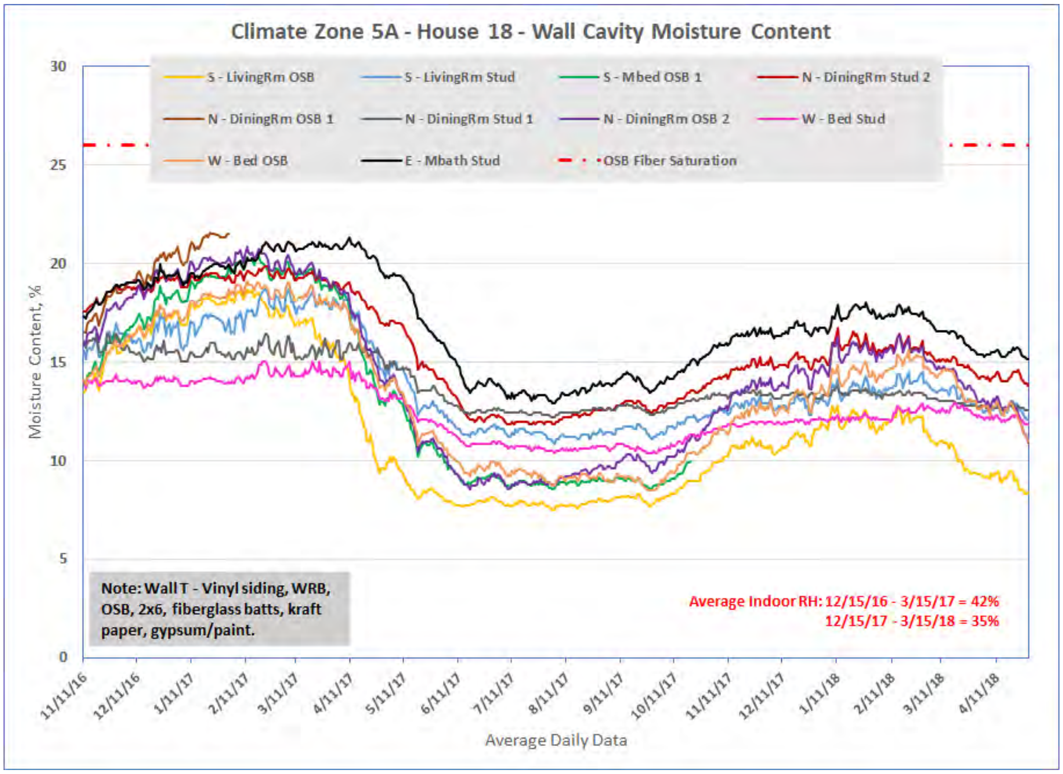

Figure A23. OSB and stud moisture content for Climate Zone 5A, Michigan (9), House 18

Figure A23 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 p~~Performance is also similar with exception of those three sensors in House 17 that showed amplified seasonal trends. ~~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.~~ In House 18, the upward amplitude during the second winter is about 4-6% lower compared to the first winter, which is likely due to the lower interior relative humidity levels.

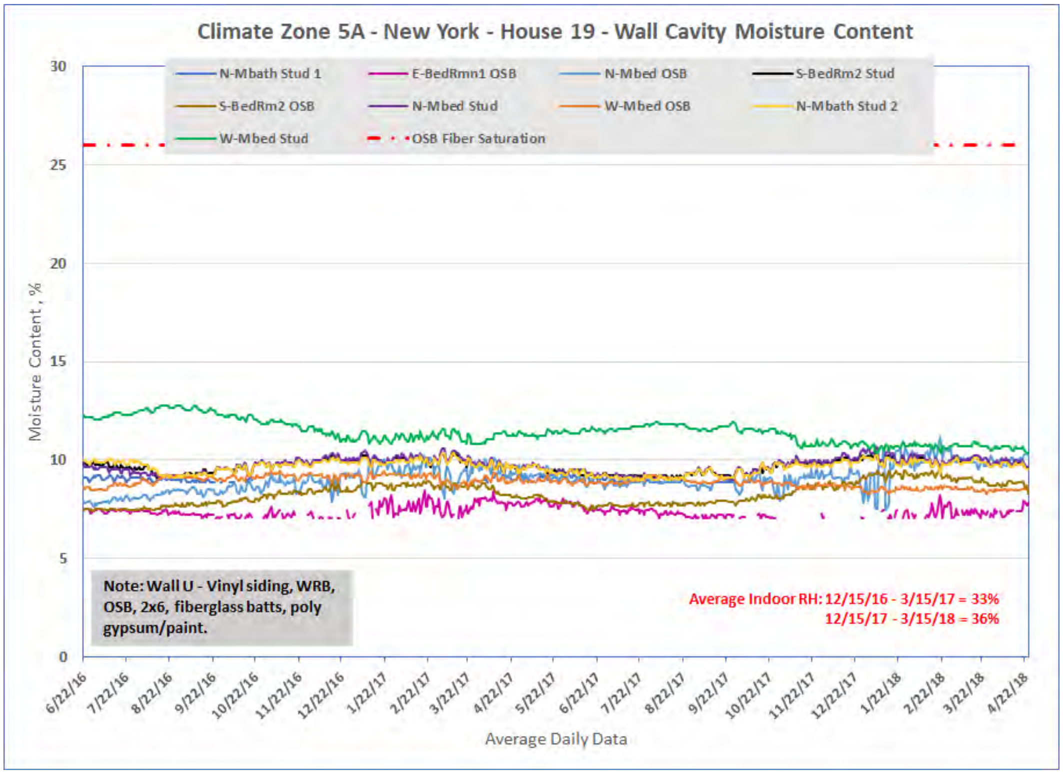

Figure A24. OSB and stud moisture content for Climate Zone 5A, New York (2), House 19

Figure A24 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 wall didn't indicate sensitivity to exterior temperature during the heating season (13.7°F in 2016-2017 vs. 2.9°F in 2017-2018) as there was no winter uptake in moisture content either year.

- The interior RH levels during the winter seasons were in the 4233-36% range 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 would have helped control solar vapor drive.

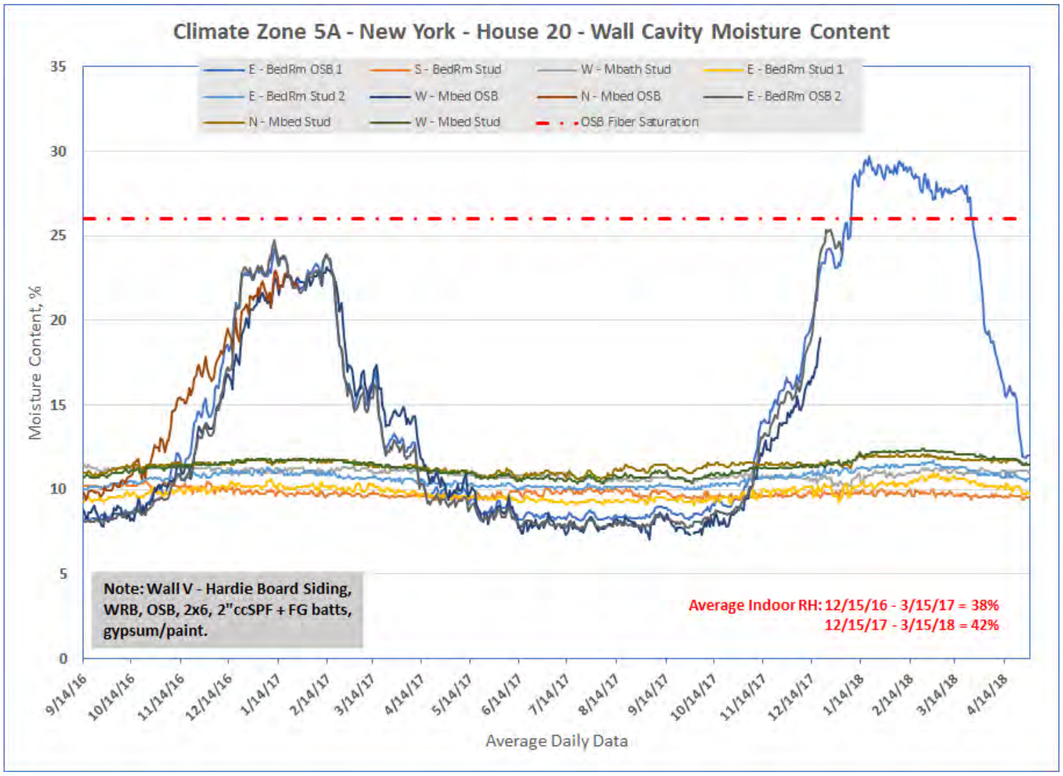

Figure A25. OSB and stud moisture content for Climate Zone 5A, New York (3), House 20

Figure A25 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 each of the two years, approaching or reaching the fiber saturation point. The extended moisture load appeared to lead to failure of several OSB sensors with only one of the four sensors operational at the end of the monitoring period.
- 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 for the first winter and 42% for the second winter. This is within the range observed in this and other monitoring studies for this climate zone.
- 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.

- Field quality control measures are recommended to ensure that the specified spray foam product is installed. Although spray foam is often selected for its insulative and air sealing characteristics, its vapor permeability is an important property for the entire wall or roof system.

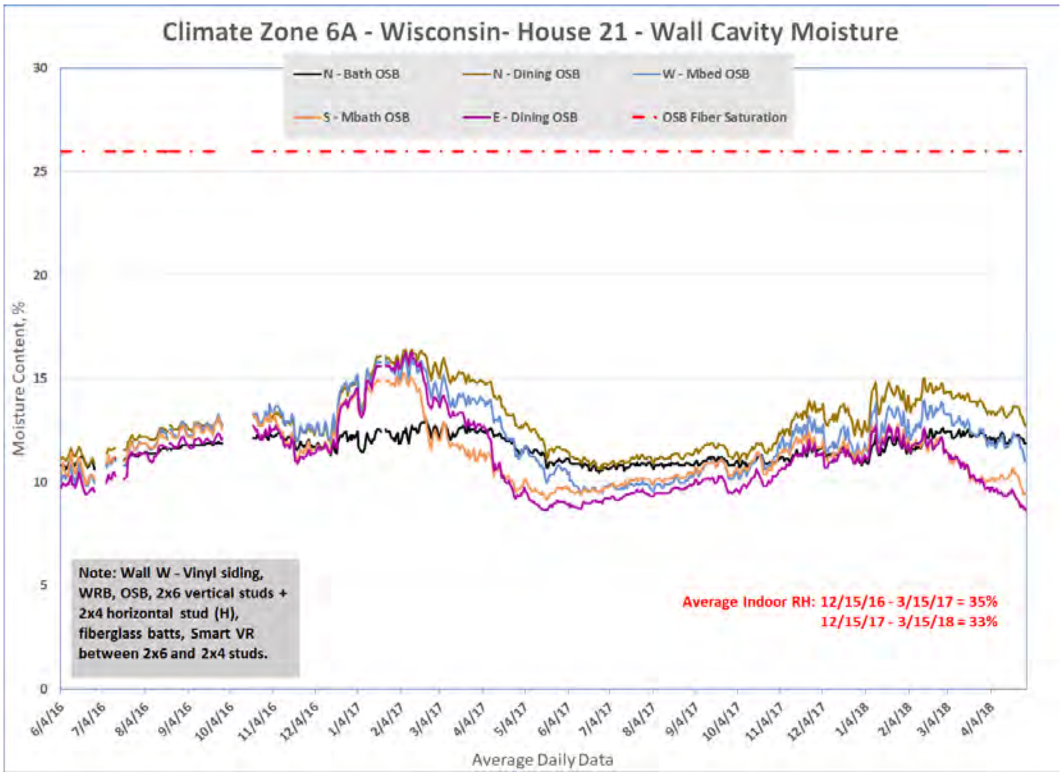

Figure A26. OSB sheathing moisture content for Climate Zone 6A, Wisconsin (1), House 21

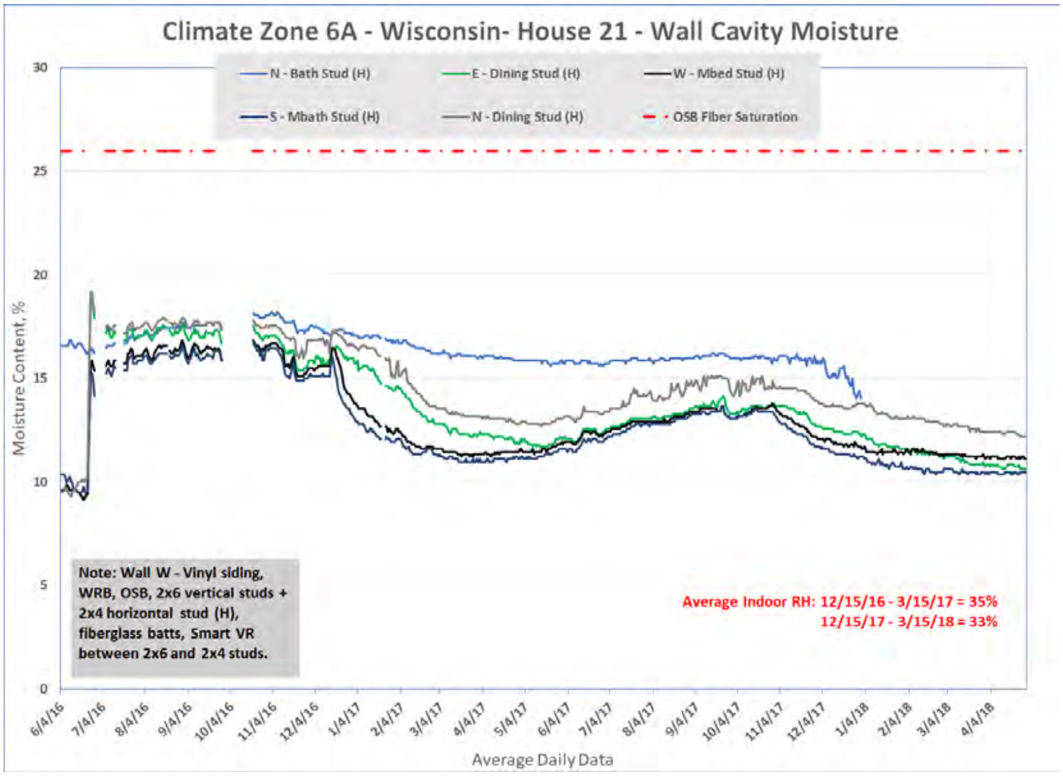

Figure A27. Studs (outside of the vapor retarder) moisture content for Climate Zone 6A, Wisconsin (1), House 21

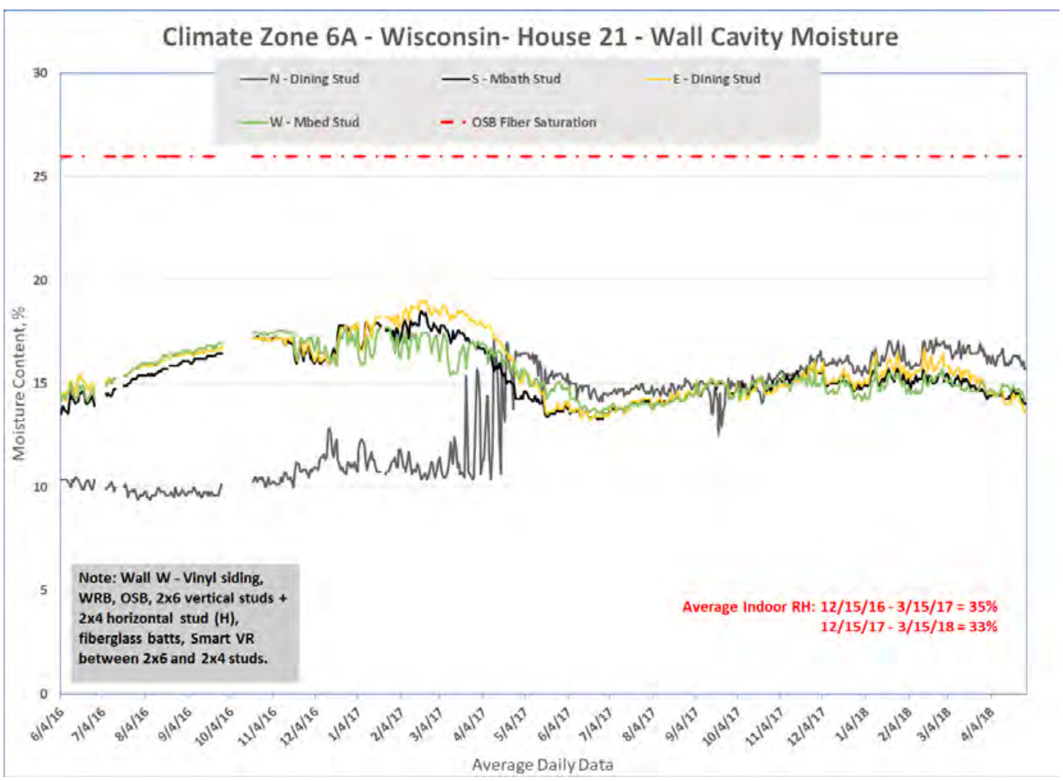

Figure A28. Studs (inside of the vapor retarder) moisture content for Climate Zone 6A, Wisconsin (1), House 21

~~Figure 26~~ 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. To facilitate review of the data, measured moisture content is graphed across three separate charts: exterior OSB (Figure A26), studs out of the vapor retarder (Figure A27), and studs inside the vapor retarder (Figure A28). The charts show~~s~~ 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:

- The OSB moisture content is stable with a muted seasonal trend raising from 9-11% summer levels to as high as 15-16% during heating seasons.
- The moisture content of studs located outside of the smart vapor retarder ranges trending down over the entire course of the monitoring period from about 16-18% initially to 10-12% following a somewhat unique pattern. The observed shape of the curve is likely the result of the smart vapor retarder limiting drying to the inside that would be present in a more traditional wall. The sensors in the south and west orientation indicate quickest drying – due to solar drive promoting drying to the outside.
- The moisture content of framing located inside of the smart vapor retarder ranges fluctuates between 14% and 19% following a more typical seasonal pattern with upward trends during the heating season. This performance is consistent with the framing reacting to the vapor drive from the inside of the building.
- Overall, this unique wall shows stable behavior with moisture levels well below the fiber saturation point.
- ~~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.

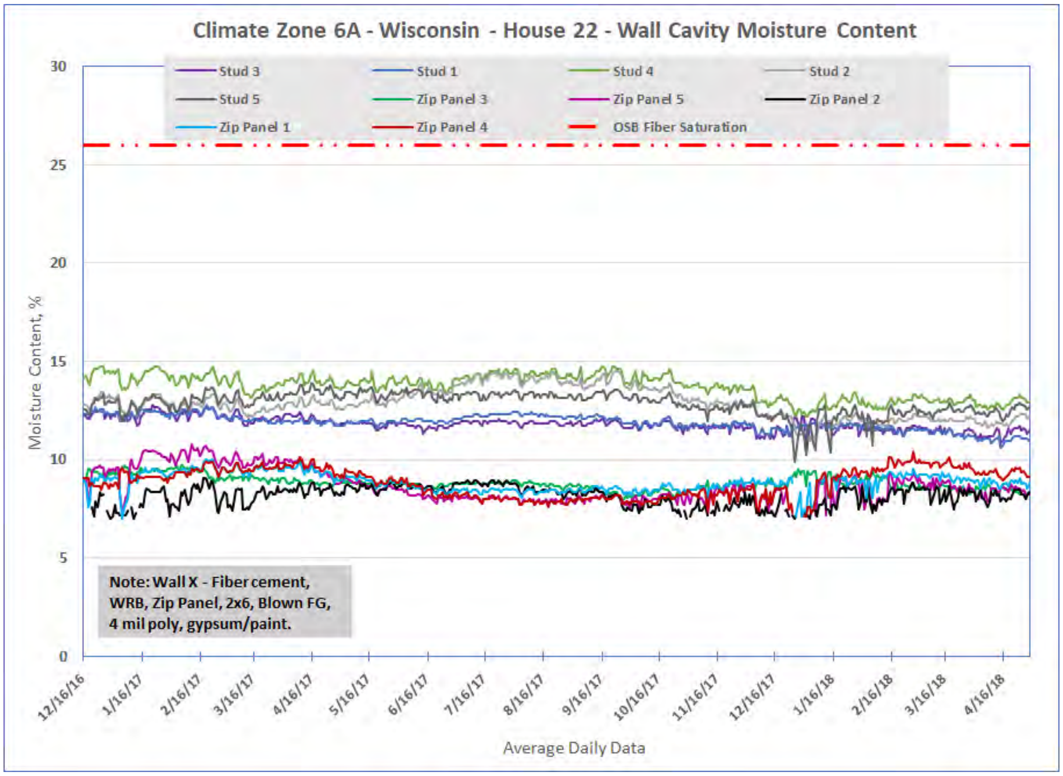

Figure A29. OSB sheathing and stud moisture content for Climate Zone 6A, Wisconsin (2), House 22

Figure A29 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 throughout the entire monitoring. No fluctuations were observed during the winter or spring in studs or ZIP panels, even as the outdoor winter temperatures dropped as low as -94°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 is lower than that of the OSB and fiber cement is an unvented cladding.
- The data indicates that the materials were not subjected to moisture during installation. At the time when walls were enclosed and the monitoring period began all sensors were at below 15% moisture content. This is an important consideration for this wall assembly. Enclosing this wall assembly after a rain event would likely lead to extended period of elevated moisture levels inside the wall as there is no clear drying path.
- Interior RH measurements are not available for this house.

Performance of Rim Joists

A total of 12 houses included moisture sensors installed at the rim joist. Figure A30 summarizes summer and winter 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 during the first heating season 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 during the first heating season and somewhat lower at 40% and 35%, respectively, for the second heating season. The moisture content was also lower during the second heating season for both houses (17% peak for House 16 and 22% peak for House 18 – both below the fiber saturation point).

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 (~~h~~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 and most houses showed lower moisture content levels during the second heating season even though the outdoor temperatures were lower. Those houses that did not show seasonal fluctuations (Houses 19 and 22) likely used closed-cell spray foam.

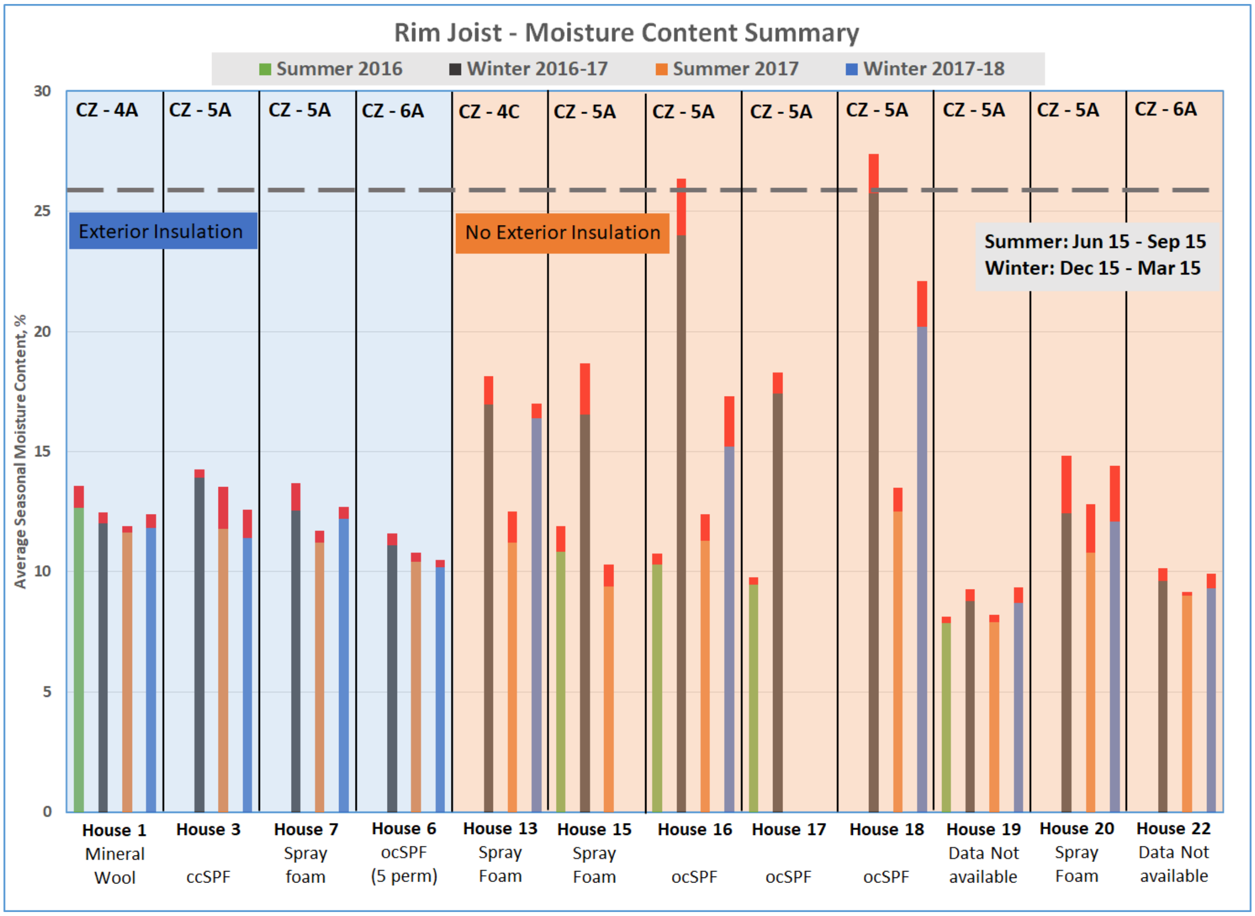

Figure A30. Summary: seasonal peak and averages moisture content of rim joists

Interior Relative Humidity Conditions

Figure A31 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 with each winter shown separately. 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 450% for all homes with the majority of homes at below 45%. 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 in the low to mid 550s% during the winter and peaked at 62% each time. Although this is an older housea renovation, the more likely cause of the elevated RH levels is the humidifier.

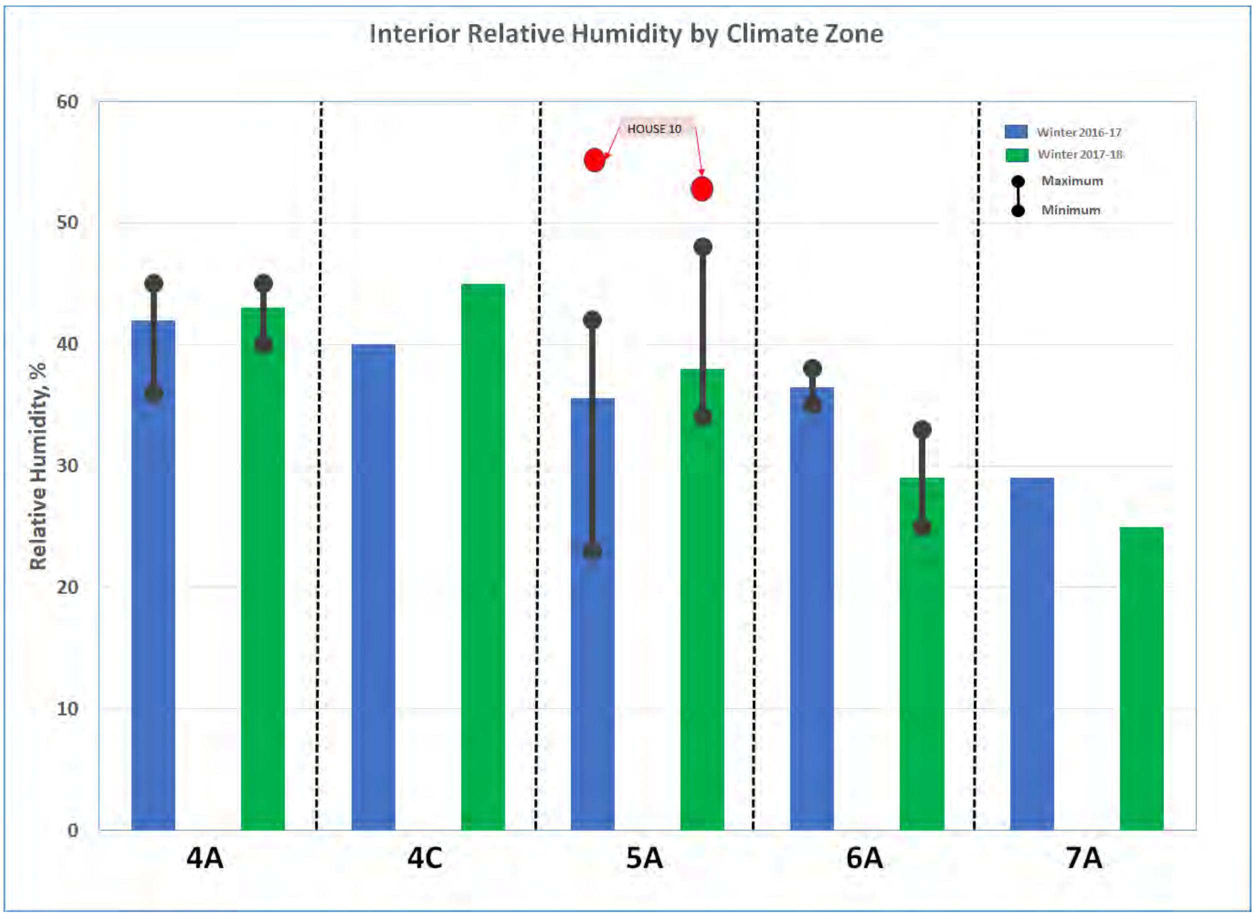

Figure A31. Summary: seasonal peak and averages moisture content of rim joists

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.

The conclusions and recommendations provided in the main report have been validated and expanded upon by the additional monitoring results through April of 2018. The conclusions and recommendations are reproduced below with minor adjustments and additions. The reader is referred to the main report for information on WUFI simulations.

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/humidity 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.
- 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 there is an adequate vapor retarder and an air barrier separating the OSB from the wall interior.
- Wall assemblies with ZIP-R (R-9), fiber cement siding, and Kraft paper vapor retarder showed stable moisture content levels less than 20% during the first heating season and less than 16% during the second heating season. The wall exhibited a definitive drying trend at the onset of the first spring, indicating that Kraft paper did not impede drying in a substantial manner.
- The 2x6 framed walls with XPS R-5 exterior foam sheathing and Kraft paper vapor retarder showed stable moisture content levels with moderate seasonal fluctuations. This wall provides 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 without exception. 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.

- The presence of Kraft paper does not seem to alter the ability of walls with exterior foam sheathing ability to dry.
- 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., panel cladding). One such wall reached fiber saturation point during winter and dried out only to about 19% in the summer that was followed by a rapid moisture uptake at the beginning of the next heating season.
- 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. In some cases, quality of installation of batt insulation with Kraft paper was identified as a potential reason for outlier behavior of individual sensors in a house. Excessive thermal bridging and proximity to openings were also identified as risk factors.
- 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.
- When used in a wall with damp cellulose cavity insulation, a smart vapor retarder (i.e., variable vapor retarder) slowed down the drying of the cavity.
- 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 and appeared to be more stable during the second heating season.
- Average interior RH levels in all newly constructed homes remained less than 50% during the winter season.
- House 4 provided a case study for comparing unoccupied versus occupied indoor relative humidity levels in the same house. During the first winter the house was unoccupied with 23% average relative humidity, whereas during the second winter when the house was occupied the average relative humidity approached 50%. This observation confirms the potentially significant impact of the occupant behavior on interior relative humidity. As a point of comparison, a paired house of similar construction and in proximity (House 14) exhibited relative humidity levels in the mid 30% range during the second winter.
- Results of House 6 that overall showed very stable moisture content levels suggest that interface with exterior features such as a deck can be vulnerable to exterior moisture.

- As the second winter was associated with colder temperatures at most test sites, the effect on the wall moisture content varied between homes. In some cases, elevated moisture content levels were observed as a result. In other cases, the effect was offset by lower interior relative humidity levels or the wall assembly showed to be less sensitive to the outdoor temperature levels (those walls typically have exterior insulation or a Class I vapor retarder).

Recommendations

- 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 or for any walls that rely on a Class II or III vapor retarder as a moisture control mechanism 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.
- Quality of installation of Kraft paper batts can be a potential factor in moisture performance of walls.