Measured Performance of an R-40 Double-Stud Wall in Climate Zone 5A

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ABSTRACT

Moisture problems within the building shell can be caused by a number of factors including excess interior moisture, bulk water intrusion, capillary action from concrete to wood connections, and through wetted building materials such as siding wetted from rain splash back. Depending on the temperature of the surfaces and the permeability of the materials, that moisture may get trapped inside of the walls and could potentially lead to mold growth and/or decay of the buildings materials.

High-R wall assemblies are gaining popularity due to programs promoting high performance building shells for both new construction and retrofit activities. While the reduction in heat transfer is desirable from an energy standpoint, decreased heat transfer also results in decreased drying potential. With the increasing thickness of walls, moisture related failures could become much bigger problems.

To evaluate the potential for moisture problems in high R-value walls, the project team conducted a combination of modeling and field monitoring. Climate Zones 4A, 5A, 6A, and 7 were the focus of the modeling exercise. This paper presents the results of the modeling compared to data collected from a double cellulose wall in Climate Zone 5A. Several different failure criteria and their validity are discussed.

INTRODUCTION

Moisture problems within the building shell can be caused by a number of factors including excess interior moisture which is transported into the wall through air leakage and vapor drive, bulk water intrusion from leaks and wind driven rain, capillary action from concrete to wood connections, and through wetted building materials such as siding wetted from rain splash back. Depending on the temperature of the surfaces and the permeability of the materials, moisture may get trapped inside of the walls and could potentially lead to mold growth and/or decay of the buildings materials.

High-R wall assemblies and assemblies employing a combination of insulation products are gaining popularity in the market due to programs like Passive House (PH) and Net Zero Energy Home (NZEH) challenges in several states and highly incentivized retrofit programs. New insulation products, code changes, and the desire to reduce costs to achieve these new efficiency levels are also factors behind the various assemblies available today.

While several researchers have been conducting hygrothermal analysis for years, there are few published works on high R-value walls, and there has been even less field research to validate the results. Climate zones of the greatest interest are 4A, 5A, 6A, and 7 as defined in the 2009 *International Energy Conservation Code* (ICC 2009). These zones experience both cooling and heating seasons as well as considerable humidity during the summer, which will likely reduce the drying potential of the wall assemblies. The research presented here is intended to fill some of these gaps.

The first phase of this research project involved extensive modeling (Arena and Mantha 2012). Several different failure criteria were used to analyze the hygrothermal performance of the assemblies, including condensation potential,

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moisture content thresholds, drying capacity of the assembly, and potential for mold growth.

The goals of the second phase of this study were to monitor an R-40, double-stud cellulose assembly in Climate Zone 5A to determine the accuracy of the moisture modeling and make recommendations to ensure durable, efficient assemblies. Results of the field monitoring are presented here along with a comparison to predicted results.

MODELING

Hygrothermal modeling of the test home wall assembly was conducted using WUFI 5.2. Wall construction consisted of double-stud framing, full depth dense-packed cellulose insulation, an exterior sheathing with an integrated weather resistant barrier (WRB), and vinyl siding (Figure 1).

The hygrothermal properties for the exterior sheathing were provided by the manufacturer. The permeability of the WRB increases with increasing RH, thereby, acting like a smart vapor retarder (SVR). According to the manufacturer's data, the permeance ranges from 0.3 perms at 0% rh to 13 perms at 100% rh. SVRs are typically installed on the interior of the wall just behind the drywall in cold climates to prevent warm moist interior air from entering the wall in the winter while still allowing the wall to dry to the interior in the summer. Even though the main benefits of this type of product are lost due to its placement on the exterior of the wall assembly being studied, its location shouldn't result in poor hygrothermal performance because it will become more vapor open as RH increases.

The exterior vinyl siding is applied directly to the sheathing and is considered by code to be a vented cladding. Therefore, an air change rate of 10 ach per hour was assumed behind the siding. This value was chosen based on results from ASHRAE research report 1091 which states that the equivalent permeance of the wall assembly is drastically increased once the minimum threshold of 10 ach is reached. Since vinyl siding is considered by code to act as a vented cladding, this minimum threshold was used.

The interior of the drywall was coated with a vapor retarder primer. The manufacturer's specifications state that this product results in a film with a water vapor permeance of

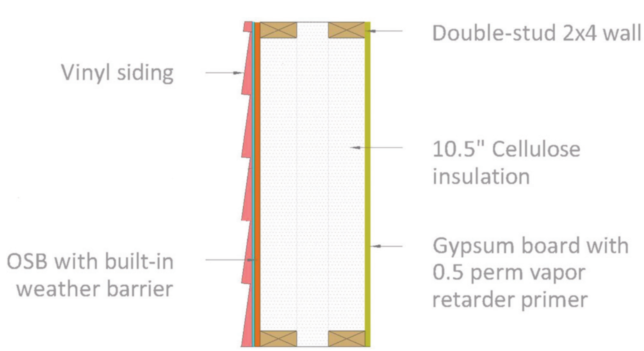

Figure 1 *Typical double stud high-R wall with cellulose insulation.*

0.5 perms when the coating has dried. For the purposes of the initial modeling, it was assumed that the coating was uniform and that this permeance was achieved. Therefore, this value was applied to the interior side of the sheetrock in the model.

The interior conditions were determined in accordance with the criteria for design parameters (intermediate method) as outlined in ASHRAE Standard 160 (2009) and all current, applicable addenda. Interior and exterior boundary conditions are displayed in Table 1.

Experimental Method

The test house was a new construction project located in Climate Zone 5A. Two test bays were identified: one on the north and one on the south facade. Data recorded during this study included: (1) temperature, relative humidity (RH), and moisture content (MC) of the studs at different heights and depths within the exterior walls; (2) MC, temperature, and RH of the sheathing in the center of the bay as well as temperature and RH in the center of the wall cavity and just behind the sheetrock; (3) interior temperature and RH; (4) exterior temperature and RH; and (5) insolation on the south wall. All interior sensors and wall sensors were hard wired to a data logger located in the basement, which was in turn connected to a wireless modem for data collection. The data logger was programmed to read temperature, relative humidity, and wood resistance data every 5 minutes and output the average of those readings every hour. The data was filtered for zero and negative values and the remaining outputs were averaged hourly (Karagiozis and Childs 2006). Data from the pyranometer and exterior temperature/RH sensors were downloaded manually every couple of months.

Table 1. Boundary Conditions

Parameter	Setting
Wall Orientation	North (worst-case scenario) and South
Initial Temperature and RH	68°F and 80%
Heating Setpoint	70°F
Cooling Setpoint	75°F
Floating Indoor Temperature Shift	5°F
RH	Generated in WUFI per ASHRAE Standard 160 criteria for design
Moisture Generation Rate (lb/h)	0.83 (2 bedrooms)
Air Exchange Rate (1/h)	0.2 (equivalent of standard construction)
Climate Zone	5A: Boston, MA
Simulation Start Date	10/1/2011
Initial MC of OSB (lb/ft^3)	5.62 (≈14% MC)
Rain Penetration	1% of driving rain deposited on exterior of WRB

Initial Conditions

During the sensor install in March of 2012, a handheld Delmhorst BD 2100 moisture meter was used to take multiple measurements of the studs and sheathing. According to these tests, initial MC in the sheathing ranged from 7.5%–9.0% and averaged 9.5% in the above grade studs, indicating that the materials were very dry and had been protected from getting wet during construction.

In July 2012, the data logging equipment was installed and interior conditions recorded (Table 2). The interior RH was elevated because the house had been closed up since completion of construction, and the air conditioner was not running. No additional dehumidification equipment was present to remove foundation moisture.

Sensors Types, Calibration, and Accuracy

A total of fifty-six temperature, relative humidity, and moisture content sensors were installed. A description of each of the sensors installed for this study along with its function, accuracy, and model number is located in the Appendix.

To verify temperature sensor accuracy prior to installation, all thermistors were connected to a Campbell Scientific CR10X data logger, allowed to settle to room conditions, and then tested and compared to a high accuracy Omega Engineering thermistor (model 44031) sensor which was used as the reference temperature sensor. The Omega 44031 element is rated at ±0.1°C (0.18°F) interchangeability.

Pre-installation testing of the moisture content sensors and measurement circuit was accomplished by measuring known, fixed resistance values which included both very low (shorted pins) and high resistances. The high resistance values chosen were lower than desired, but were limited by the in-house verification equipment's measurement range.

Sensor Placement

Two test bays were identified: one bay under the window facing north (hereafter referred to as the north bay), while the second bay is located next to a window in the south facing wall (hereafter referred to as the south bay). Both test bays were located on the first floor of the house.

Table 2. Measured Initial Indoor Conditions

Level	Parameter Measured	Result
1st Floor	Interior Temperature	78°F
	RH	69%
	Drywall MC	0.5% to 1%, no mold visible
Basement	Temperature	72°F
	RH	83%
	Stud MC	18%, mold visible

Because windows have been known to be a source of bulk moisture leakage in wall assemblies, a test bay under a window was chosen. Even if best practice methods were applied, damage to flashing or failure of materials could result in leaks. If there was a bulk water leak, the effects of that leak on the assembly's hygrothermal performance would be captured.

In the north bay, sensors were clustered in 11 different locations (four clusters total directly under the window) within the bay [Figure 2]). At each of these locations temperature, RH, and moisture resistance data was collected. The locations are shown in Figure 2. Configuration was similar for the south bay sensors.

The temperature sensors were held firmly against the stud or OSB with a zip tie base so that they would not be pulled away from the wood during installation of the blown-in insulation. The RH sensors were covered with moisture permeable house wrap to prevent dust and bulk moisture from damaging them while allowing moisture vapor to penetrate for accurate readings of operating conditions. The house wrap product used has a moisture vapor permeance of 58 perms (Figure 3).

Before installation, heat shrink tape was installed over the length of the moisture pins, leaving only approximately ¼ in. of the tip exposed and the very top where the wires had been soldered. They were gently tapped into the wood studs and the sheathing to a depth of approximately ½ in. in the direction of the grain and were spaced 1 in. apart. A template was used to ensure consistent spacing. To prevent short circuiting of the pins, electrical tape was secured over the portion of the pin not embedded in the wood.

The interior temperature/RH sensor was installed in the living room on the first floor to record indoor operating conditions. This sensor is located at the same height as the thermostat on a wall in the center of the room. An exterior

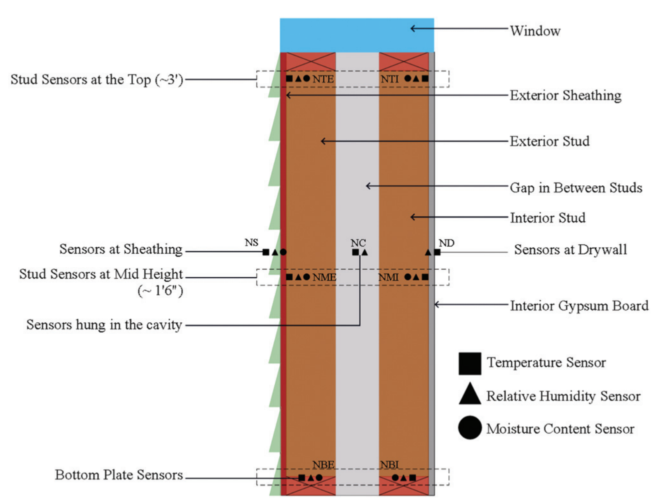

***Figure 2** Sectional view showing typical sensors locations for each bay.*

temperature and relative humidity sensor was installed on the south side of the house along with a pyranometer to collect solar radiation data (Figure 4). The data logging equipment that collects data from the pyranometer and the external HOBO was located on the underside of the front porch overhang to protect it from the elements.

MATHEMATICAL METHODS

Wood resistance based sensors were used to measure moisture content in the sheathing and wood studs. Moisture measurements using wood electrical resistance sensors have been in practice for years and have been well documented (Pfaff 1986; Garrahan 1988; Carll 1996; Ueno 2008; Straube et al. 2002).

An error analysis was performed on previously published resistance and MC data for Douglas fir provided by the Forest Products Laboratory (FPL). It was discovered that, due to the logarithmic relationship between the measured resistance and the corresponding MC, the resulting error in the calculated MC is rather small, especially in the range of 8%–20% MC, which is the range of concern for this study. A 20% error in a resistance measurement results in a 2% to 3% error in the resulting MC value. These accuracies are highly acceptable.

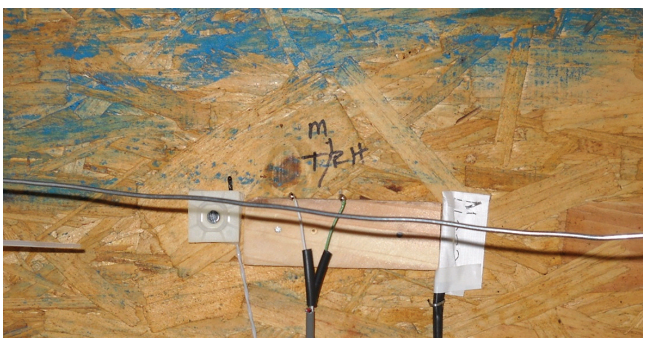

Figure 3 *North bay OSB sensors: temperature, moisture content pins, and RH from left to right.*

To convert the electrical resistance field measurements to MC values, a regression was performed on the data from the FPL listed in James (1988). The resulting equation from the curve fit is as follows:

$$MC = (-0.1071)\log(R)^3 + (1.3325)\log(R)^2 - (7.2625)\log(R) + 22.298 \qquad (1)$$

where

MC = Douglas fir moisture content in % mass

R = electrical resistance in ohms (Ω)

Most DC resistance sensors are calibrated or designed for Douglas fir and a correction factor is applied to that measurement to correct for species as well as temperature. Because the studs in the test home were labeled “SPF” (spruce/pine/fir), it was assumed that the studs were Fir, and therefore, no correction factor was applied.

Though a wide range of correction factors are available for wood species from the FPL, this is not the case with wood products like OSB and plywood. In this study, correction factors for sheathing were obtained from Straube et al. (2002). It should be noted that these factors were developed over a very limited number of samplings from one supplier.

Sensor readings must also be corrected for temperature of the material when using resistance based sensors. The resistance of the wood is dependent on temperature, and as the temperature of the material rises, the resistance decreases. According to Straube et al. (2002), the electrical conductivity of wood approximately doubles for every 10°C temperature change. Affected moisture content is in the range of 0.10%–0.15% MC/°C. Equation 3 was used (Pfaff and Garrahan 1986) to correct for both species and temperature of the sheathing. In Equation 3, constants a and b are specific to each species.

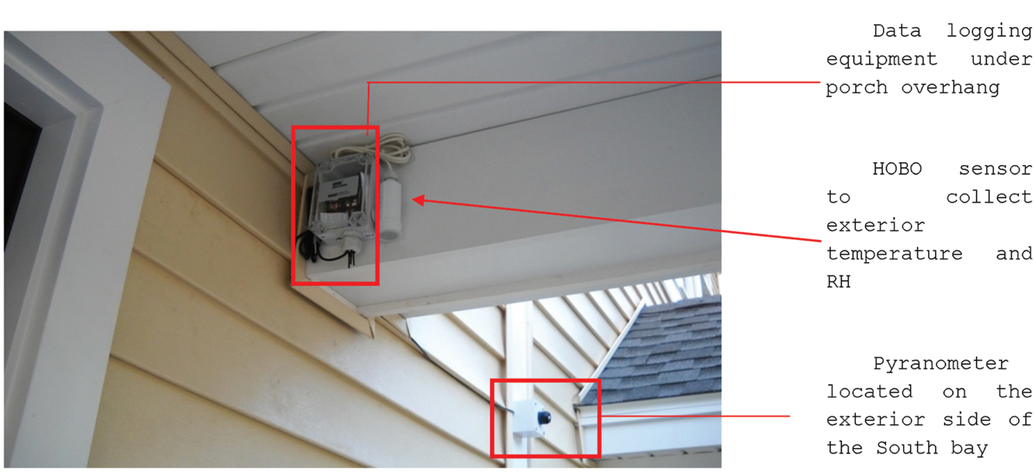

Figure 4 *Location of exterior HOBO, pyranometer, and associated data logger.*

$$MC_c = \left[\frac{MC + (0.567 - 0.0260t) + 0.000051t^2}{0.881(1.0056)^t} - b\right] + a \quad (2)$$

where

MC_c = corrected moisture content

MC = moisture content in megaohms

t = temperature of material at the same depth as the MC reading in °C

a = 1.1114

b = 0.366

It is also recommended that the temperature (t) in Equation 3 be the temperature of the material at the same depth as the moisture pins. However, in this study the temperature at the surface of the sheathing was used. THERM models were run for measured conditions to verify accuracy of the installed temperature sensors and to identify temperature at the depth of the moisture pins. It was found that the temperature varied less than half a degree at 0°F outside. This difference lessened as the exterior temperature increased. Therefore, the surface temperature of sheathing was deemed sufficient for the corrections.

MONITORING RESULTS AND DATA ANALYSIS

This section presents analysis of the measured data and draws comparisons between the measured and predicted modeling results. The model was first compared to the measured performance without calibration for differences in actual vs. modeled weather conditions. This was done to draw conclusions about the accuracy of the modeling software if a user does not have access to measured data to perform such calibrations. The model was then run using actual measured interior and exterior boundary conditions as well as the measured initial sheathing MC.

Boundary Conditions

The weather file for Boston, MA was used in the modeling. Table 3 compares the average monthly outdoor temperature, RH, and corresponding humidity ratio from the measured data and WUFI's weather file for the monitoring period (mid July 2012 through mid April 2013). In general, the monitoring period was warmer and more humid than that represented by Boston's cold year weather file. The average monthly humidity ratios show that the moisture content in the exterior air was higher for most of the monitoring period than presented in the weather file.

The interior conditions for both the predicted and actual cases are shown in Figures 5 and 6. It should be noted that the home was unoccupied until the middle of September and the cooling system was not running until the beginning of August.

Solar radiation on the south façade of the test home was also monitored. To prevent damage to they vinyl siding, the sensor was attached to a piece of wood trim to the right of the entry instead of directly over the test bay. This resulted in a situation where the pyranometer would be shaded more than the actual test bay.

The shading function in SketchUp was used to determine the extent to which the pyranometer was shaded, as compared to the test bay (Figure 7). July and August show little to no additional shading. As the sun gets lower in the sky from September to December it appears that the pyranometer gets about an hour to an hour and a half less sun than the test bay during the afternoon between 2:30 and 4 pm. Based on solar intensity values for Boston generated with Solrad, a solar position and solar radiation calculator from the Washington

Table 3. Comparison of Measured Outdoor Temperature and RH to Predicted Values from WUFI and TMY2 Data.

	WUFI			Measured		
	Temperature, °F	RH, %	Humidity Ratio, lb_W/lb_{da}	Temperature, °F	RH, %	Humidity Ratio, lb_W/lb_{da}
July	70	69	0.0110	76	63	0.0122
August	69	74	0.0104	78	64	0.0132
September	62	66	0.0077	67	69	0.0097
October	53	67	0.0057	56	75	0.0072
November	41	66	0.0036	41	65	0.0042
December	29	65	0.0024	36	76	0.0034
January	28	59	0.0019	30	64	0.0022
February	27	72	0.0020	31	65	0.0026
March	39	65	0.0033	38	63	0.0032
April	46	57	0.0037	48	55	0.0038

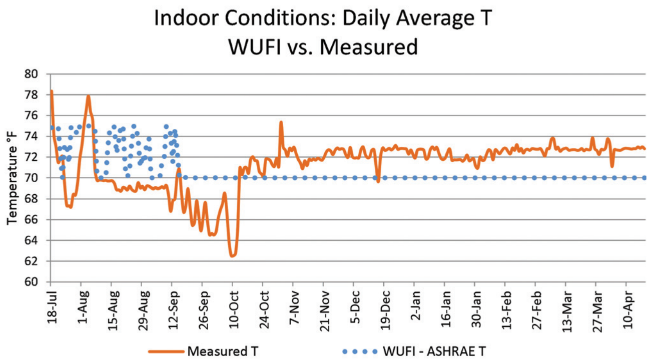

Figure 5 *Measured and predicted interior temperature in the test house.*

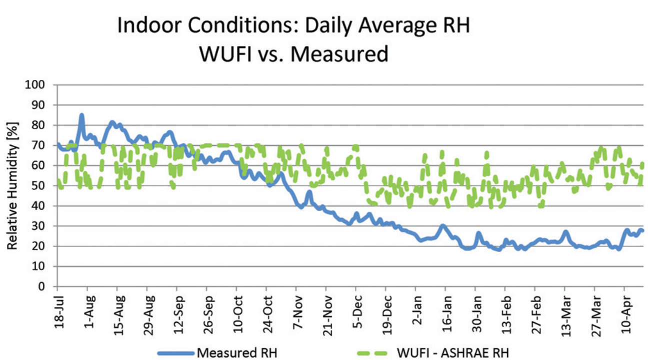

Figure 6 *Measured and predicted interior RH in the test house.*

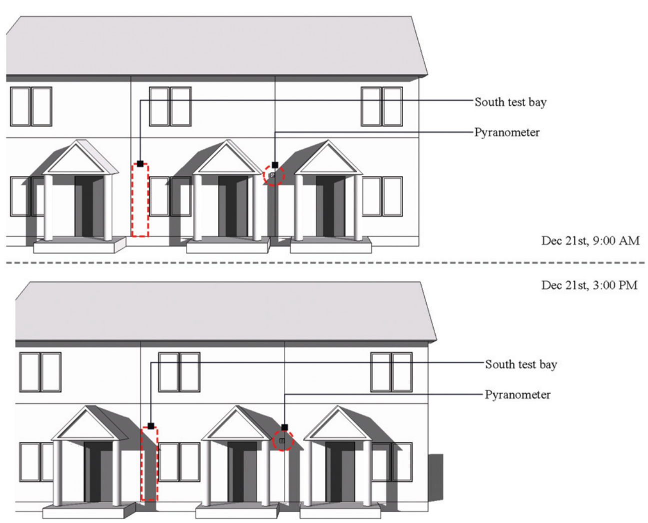

Figure 7 *Solar shadow analysis for pyranometer located on the south wall.*

State Department of Ecology (Pelletier 2013), the amount of radiation hitting the pyranometer is estimated to be 10% to 15% lower from September to December respectively than the that reaching the façade of the south test bay.

Table 4 lists the average daily solar radiation by month for Boston as assumed by WUFI and PVWatts compared to the measured data.

This comparison of measured and predicted data shows that the actual insolation was less than that in the WUFI data file and the PVWatts predictions during the monitored period. This is logical since no shading was assumed on the vertical surface for either the WUFI or PVWatts analysis, while the porches on the south façade definitely shade the sensor and the test bay in the morning and afternoon.

Hygrothermal Performance of the Assembly

Several failure criteria were identified against which wall assemblies should be evaluated. The criteria evaluated for this study include condensation potential, moisture content thresholds, drying potential of the assembly, and the potential for mold growth as determined by ASHRAE Standard 160, *Criteria for Moisture-Control Design Analysis in Buildings* (2009).

Moisture Content

It is often quoted that the minimum moisture content (MC) requirement for the growth of fungi is approximately 20% in wood, corresponding to about 80%–90% rh (Siau 1984). MC values were calculated for each pair of moisture pins installed in the studs and sheathing and evaluated against this threshold.

As of mid-April 2013, the sheathing MC in the south bay has remained below the 20% threshold peaking at approximately 16% (Figure 8). In the north bay, the MC rose slightly

Table 4. Comparison of Actual and Predicted Solar Radiation on the South Wall

Month	Solar Radiation, kWh/m^2 per day		
	WUFI	PVWatts	Actual*
July	2.75	2.76	1.99
August	2.81	3.27	2.64
September	3.33	3.59	2.49
October	2.90	3.92	1.55
November	2.82	2.96	2.50
December	2.77	3.06	1.41
January	3.08	3.27	2.22
February	3.24	4.19	2.02
March	3.54	3.60	2.17
April	3.13	3.03	2.43

*Actual solar radiation reaching the test bay on the south façade is estimated to be approximately 10% to 15% higher than the values shown in the table.

above 20% during most of February and a portion of March. The difference in these moisture levels was anticipated since the south bay receives direct solar radiation which should result in enhanced drying potential. Measured temperature and RH levels confirm that the sheathing in the south bay was warmer and had a lower RH than the sheathing in the north bay supporting the MC results. Predicted differences in MC between the two walls also supports these findings. Figure 8 shows the predicted MC using the WUFI weather file and the ASHRAE Standard 160 method for generating the boundary conditions versus the MC predictions using the measured boundary conditions. The predictions using the measured conditions map the measured MC values slightly better at the beginning of the monitoring period, but neither set of assumptions result in the same MC peaks, nor do the peaks occur at the same time of the year as the measured values in the south bay.

To investigate the reasons for these differences, several different parameters in the model were altered, including permeance of the VR paint, permeance of the WRB on the exterior sheathing, moisture penetration into the wall assembly, and various combinations of these values. The values analyzed include:

- Constant permeance of the sheathing using the upper and lower boundaries of the permeability curve: 0.3 and 13 perm.
- Increased permeance of the VR paint, assuming it was not applied per the manufacturer's recommendations: 10 perm.
- A rain leak into the OSB layer behind the WRB equal to 1% of the driving rain.

Thirteen different combinations of these parameters were modeled and analyzed. Five different curves have been presented in Figure 9 and are compared to the measured data and the predicted MC using the ASHRAE Standard 160 boundary conditions. Combinations that did not appear to change the predictions when compared to the results using the original material properties and measured boundary conditions have been eliminated. The most significant match appears to be the case where a 1% moisture leak was assumed in the north bay. Those assumptions result in a much closer matching of the curves, peak MC, rate of moisture increase, and a closer match of the timing of the peak MC. Considering these sensors are located directly under a window, a moisture leak could be very possible.

A similar study was conducted for the south bay (Figure 10). The results displayed in Figure 10 show that the measured MC peaks in January at approximately 17% MC and begins to dry out again in February. The modeling results show peaks of 14% in March and drying beginning in April.

To validate the MC results for the sheathing, the MC values for the stud sensors were also calculated and evaluated. Figures 11 and 12 show the MC readings for all the moisture

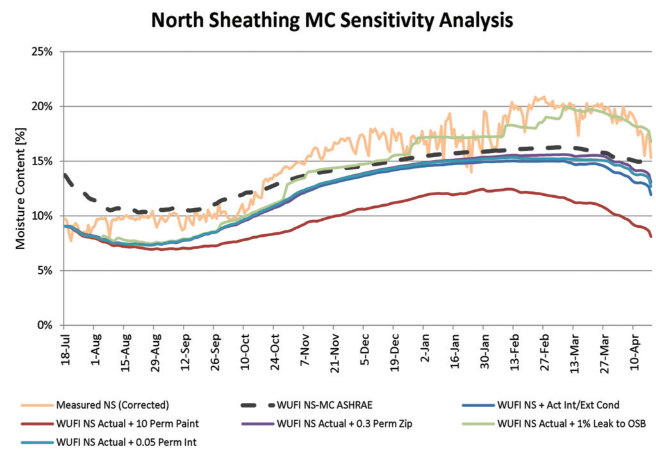

Figure 9 *Comparison of predicted MC levels in the north bay using different boundary conditions.*

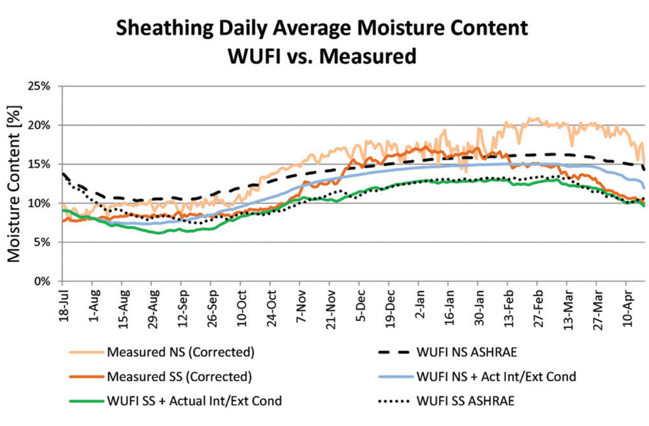

Figure 8 *Measured and predicted daily MC for the north and south sheathing.*

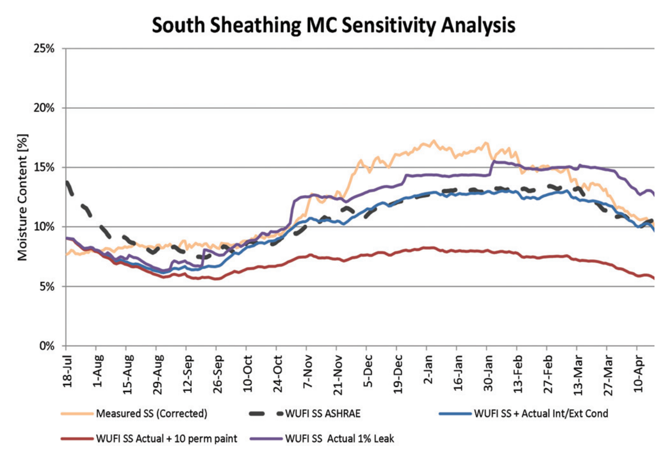

Figure 10 *Comparison of predicted MC levels in the south bay using different boundary conditions.*

pins in the south and north bays respectively. The north bay exterior stud MC readings are elevated like the sheathing MC and follow a similar pattern. In the south bay, most of the sensors show decreasing MC levels, except for the lower exterior stud position. Since it follows the same pattern as the north bay sensors, this could indicate a leak or concentrated drainage pattern at the corner of the window bordering that bay.

Measurements from both bays support the findings from the sheathing analysis and showed several consistent trends. In general, the monitored locations in the walls appear to be drying out from July until the end of September, at which time the sensors located in the sheathing and exterior studs show an increase in MC. The sensors on the interior studs show a decrease in MC in both bays during the entire monitoring period. Lastly, the bottom plate sensors (exterior and interior) were the wettest of all the locations at the beginning of the monitoring period.

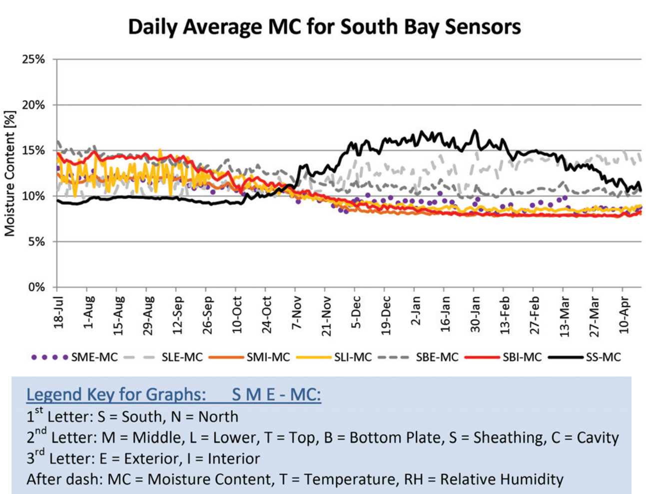

Figure 11 *Daily average MC readings for the sensors in the south test bay.*

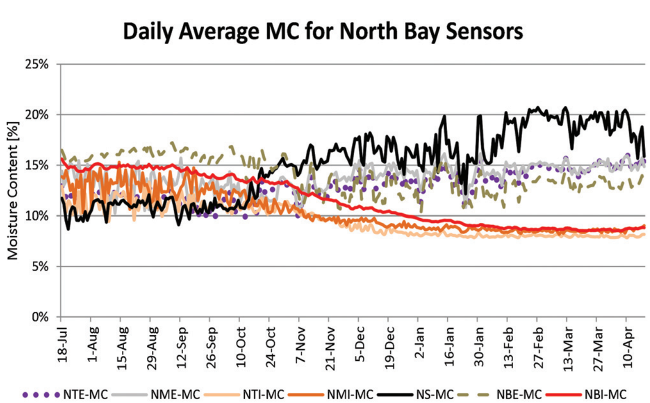

Figure 12 *Daily average MC readings for the sensors in the north test bay.*

Condensation Potential

Condensation potential within the wall was evaluated by comparing the interior air dew-point temperature to the surface temperature of the potential condensing surface. This method generally represents a worst case scenario as it assumes that moisture through air leakage enters the wall assembly from the interior. If the surface temperature of the material is lower than the dew-point temperature of the air (Straub et al. 2009), condensation is likely to occur: the longer the period during which the surface temperature falls below the air dew-point temperature, the greater the risk for damage. The critical juncture analyzed was the inside surface of the exterior sheathing in both bays.

As shown in Figure 13, the measured north and south sheathing temperatures started to drop below the indoor dew point in September. According to the predicted model (Figure 14) the sheathing surface temperature should start to drop below the indoor dew point in late October. The duration of time the surface temperatures stay below the dew point increases as the weather gets colder.

As with MC, condensation potential was also evaluated at the studs. The interior studs in both bays are consistently above the dew point, however, the exterior studs in both bays

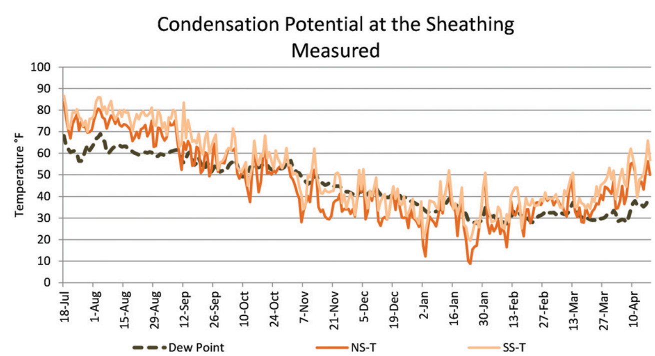

Figure 13 *Condensation potential in the north and south sheathing.*

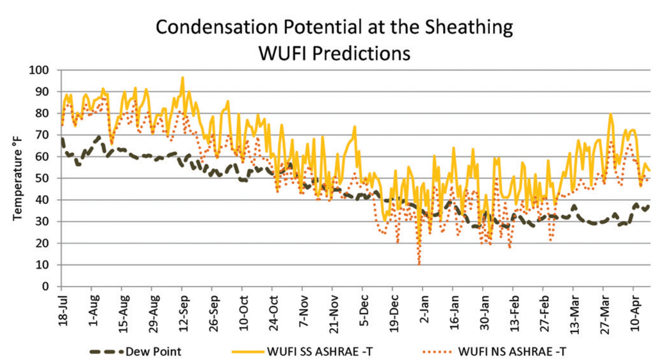

Figure 14 *Predicted condensation potential in the sheathing.*

fall below, closely mapping the sheathing and further validating the results.

Based on the indoor boundary conditions, the dew point was calculated on an hourly basis for the monitoring period for both the predicted (ASHRAE Standard 160 conditions) and measured data. The actual and predicted surface temperatures of the sheathing were then compared to the respective dew points. The percentage of time that the surface temperature fell below the dew point was calculated and tabulated for each bay. A summary of the results is shown in Table 5.

Because the predicted interior RH using ASHRAE Standard 160 is higher than the measured data, the calculated condensation potential is significantly higher than that of the measured data.

ASHRAE Standard 160 Criteria

ASHRAE recently published ASHRAE Standard 160, *Criteria for Moisture-Control Design Analysis in Buildings* which sets the performance criteria to minimize problems associated with moisture in building envelope assemblies. The standard specifies that the following conditions be met: the 30 day running average surface RH must be less than 80% when the 30-day running average surface temperature is between 41°F and 104°F. This threshold applies to all materials and surfaces in the building envelope except the exterior surface. If just one 30-day average fails to meet these conditions, the assembly is considered to have failed.

Table 5. Condensation Potential for Exterior Sheathing—Measured vs. Predicted

Orientation	Case	Hours of Potential Condensation (Jul–April)[1]	% of Collection Period
North	Measured	2866	44%
	Predicted	4776	61%
South	Measured	2255	34%
	Predicted	4777	44%

[1]Collection period consisted of 6573 hours.

Table 6. Analysis Results for ASHRAE Standard 160 Criteria for Double Stud Walls with Cellulose Insulation: Measured vs. Predicted

Orientation	Case	% of 30-Day Averages that Fail (Jul–Mar)[1]	Pass/Fail
North	Measured	23%	Fail
	Predicted	36%	Fail
South	Measured	18%	Fail
	Predicted	54%	Fail

[1]Collection period resulted in 244 30-day averages.

The interior face of the sheathing was chosen as the surface to be evaluated with this criterion. Surface temperature and RH of the sheathing was averaged over a 30-day period and compared to the above limits. A summary of the results can be found in Table 6. Even though it only takes one noncompliant 30-day period to result in failure, the magnitude or number of failures should be considered. Therefore, the percentage of 30-day averages for the monitoring period that have failed these criteria have been presented for both the measured data and the predicted results using the ASHRAE Standard 160 boundary conditions. According to the data, both the north and south wall fail to meet this criterion, but as discovered in the first phase of this research (Arena and Mantha 2012), most walls with sheathing outside the insulation will fail if the interior face of the sheathing is the surface evaluated.

Note that the initial assumptions for the sheathing RH start at 80% when using the ASHRAE Standard 160 design criteria. The actual RH of both bays was lower than this, resulting in fewer 30-day failures from the measured data compared to the predicted data. RH levels recorded for each of the sensors on the studs show agreement with the sheathing values. The south sheathing sees a higher potential for mold growth according to the predicted data because the predicted south sheathing temperatures stay above 41°F for the majority of the monitored period whereas the north sheathing temperatures are predicted to fall below 41°F for several months.

DISCUSSION

Moisture Content

The difference between the measured results of the two facades is significantly different and is supported by the modeling predictions, however predicted peaks in MC are lower than actual for both walls. The south bay sheathing shows the MC values peaking around 17%. Drying of the assembly starts around January and continues gradually through the end of the modeling period where it ends up at about 10% MC. The north bay sheathing peaks at just over 21% MC. Drying of the assembly didn't begin until late March. At the end of the monitoring period, the MC was still above 15%.

Except for the beginning of the monitoring period, predictions from WUFI using the ASHRAE Standard 160 design criteria closely mapped the predictions when using the actual measured boundary conditions. The difference at the beginning of the period is due to the materials being drier than is assumed when using the Standard 160 criteria. However, neither resulted in peak MC levels as high as was measured in the field.

Based on the parametric study conducted, it appears that the elevated MC in the north wall could be due to a moisture leak under the window. When modeled with a 1% leak to the OSB, the predicted results very closely mapped the measured performance. Little effect was seen from varying the perm rating of the WRB or from decreasing the perm rating of the interior VR paint to 0.05 perm. Assuming a 10 perm VR paint, on the other hand, resulted in even lower MC predictions and, therefore, was determined not to be likely, considering the measured results.

When evaluating this assembly over a three year period using the initial modeling assumptions and the ASHRAE Standard 160 method, it is predicted that the sheathing will dry out seasonally and peak MC levels will decrease over time (Figure 15). The monitored results from the south bay support this conclusion. The results from the north bay are not so definitive. While the sheathing does appearing to be drying out at the rate and time shown in Figure 15, the measured MC levels exceed the predictions by about 4%, rising above the 20% MC threshold for mold growth. Another concern is that several of the positions in the exterior studs show slightly increasing MC levels through the end of the monitoring period. Additionally, introducing a 1% rain leak to the OSB layer resulted in much better agreement of the predicted and measured results. These three factors raise concerns about the durability of the north wall.

Condensation Potential

When using the ASHRAE Standard 160 boundary conditions, the measured condensation potential for the monitoring period is lower than predicted. This is due to the fact that the interior RH is significantly lower than that generated by that method. The Standard 160 method of generating RH resulted in values ranging from 70% rh in the summer to 40% rh in the winter. This home's actual interior RH dropped under 30% from January through March, while the Standard 160 method produced RH levels of 50% to 60% for the same time period. This has a drastic affect on calculation of the dew point and hence, condensation potential. Even though the percentage of hours of potential condensation is lower for the actual assemblies than predicted, it is still very high at 34% for the south wall and 44% for the north.

ASHRAE Standard 160 Criteria

Both the north and south walls fail the ASHRAE Standard 160 30-day criterion using the monitored data or the predicted results. When comparing actual versus predicted results the north and south sheathing failure rate for the measured data was significantly lower than that predicted with the modeling. This is because the starting RH of the materials as recommended in Standard 160 was 80% when the actual measured RH started at approximately 70% for the north wall and 60% for the south. All the temperature and RH sensors in the bays support the readings captured for the sheathing.

Past modeling work in this area has indicated that very few walls in cold climates will pass this criterion if the inside face of the exterior sheathing is evaluated. It is even less likely if the modeling period is started in October and the ASHRAE recommendations for initial surface temperature and RH are assumed. Although the probability of mold growth should be evaluated, there should be further investigation into whether failing this criterion does actually result in mold growth. One instance of failure of all the 30-day averages through the year appears to be much too restrictive of a metric.

When the failures occur is also important. Did they take place at the very beginning of the modeling period due to the assumptions for the initial conditions and then not again? Do they occur if the modeling is started at a different time of year? Has there been any forensic proof that exceeding these conditions on the interior of the exterior sheathing does in fact result in mold growth? Do the thousands of homes constructed with the sheathing outside of the insulation in cold moist climates have mold problems?

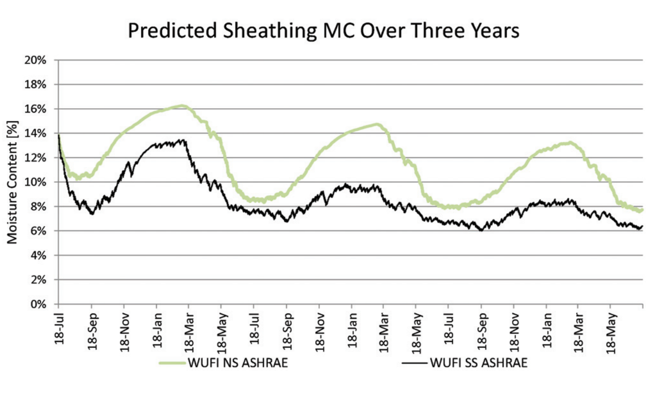

Figure 15 *Predicted sheathing MC over a three year period.*

CONCLUSIONS

The main focus of this study was to evaluate the predicted performance of the specified wall assemblies against the measured performance. The goals were to monitor an actual high R-value wall assembly to determine the accuracy of the moisture modeling and make recommendations to ensure durable, efficient assemblies. The wall assembly monitored and analyzed in this report was an R-40, double-stud cellulose assembly in Climate Zone 5A.

Several failure criteria were analyzed including MC, condensation potential, drying potential, and the potential for mold growth. No one failure criteria should be evaluated on its own. Several key performance metrics need to be evaluated before making a decision on the performance of a particular assembly. The most useful combination of criteria will look at long term and short term drying potential. Overall assembly moisture content should never increase over time and should ideally decrease. Each component in a given assembly should dry out to a safe level every year. The condensation potential and thresholds for mold growth should be evaluated. If hydrophobic materials exist in the assembly, condensation potential should be minimized at all costs, while materials with moisture absorption capabilities will be more forgiving. Finally, the thresholds for decay should be avoided entirely.

Data collected from July to mid-April of 2013 indicates reasonable agreement with the modeling and shows the following:

- Long term modeling results indicate that this assembly should dry out over the course of the year and experience decreasing peak moisture content levels for the following years. These are major indicators that a wall is durable and shows good hygrothermal performance.
- Measured data for the south wall shows good agreement with predicted peak MC levels using the ASHRAE Standard 160 design criteria. The increase and decrease of MC over the monitoring period was faster for the actual wall than predicted, resulting in less time spent at elevated moisture conditions than predicted.
- Measured data for the north bay indicates a similar rate of response for moisture build up and drying compared to predicted response. However, peak MC levels were higher than predicted and reached approximately 21%.
- Condensation potential, while high, is lower than that predicted, due primarily to indoor assumptions used during the modeling.
- Both walls fail the ASHRAE Standard 160 30-day criterion for mold growth. Although it is important to evaluate the potential for mold, this criterion may be too restrictive and may not be appropriate for all surfaces of the assembly. Further investigation into its validity is recommended.
- A parametric study indicates that the north bay may be experiencing moisture intrusion from driving rain.
- A more vapor open interior surface (10 perm) on this high-R assembly results in lower predicted peak MC levels and faster drying than the initial assumption of 0.5 perm for the VR paint.

Overall, the wall assembly is predicted to perform well. Measured data in the south wall supports these findings, while measured data in the north wall suggests the performance is marginal to fair.

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APPENDIX—SENSOR TYPE AND DESCRIPTIONS

All monitoring equipment specifications and sensor accuracies are provided in Table A1. The temperature sensor used was an Omega Engineering TH-44006-40-T fast-response, 10KΩ thermistor with an exposed element and an interchangeability of ±0.2°C (0.36°F).

The measurement circuit was a DC half-bridge circuit. The two resistors making up the half-bridge consisted of the TH-44006-40-T thermistor and a fixed-value 10KΩ, 0.1% precision resistor. An excitation voltage of 2.5VDC was used.

To verify temperature sensor accuracy prior to installation, all thermistors were connected to a Campbell Scientific CR10X data logger, allowed to settle to room conditions, then tested and compared to a high accuracy Omega Engineering thermistor (model 44031) sensor which was used as the reference temperature sensor. The Omega 44031 element is rated at ±0.1°C (0.18°F) interchangeability.

The humidity sensor used was a Honeywell HIH-4021 RH sensor. It contains a thermoset polymer capacitive sensing element with on-chip integrated signal conditioning. The sensing element is covered and is condensation resistant. As a

Table A1. Equipment Used for Measurements

Measurement	Equipment and Specification
Moisture Content: Studs and Sheathing	Custom Wood Moisture Sensors Manufactured from: GE Protimeter Moisture Meter Replacement Pins, 1 in. Long, Grainger P/N 3YYE5, Insulated with Heat Shrink, Soldered to Shielded, Stranded, 22AWG Sensor Cable
Relative Humidity: Inside Walls	Honeywell Humidity Sensor Model HIH-4021-002 Measurement Range = 0%–100% rh, Accuracy = ±3.5%, Sensor Is Covered and Condensation Resistant, Supply Voltage = 5Vdc, Device is Calibrated at 5Vdc and 25°C
Temperature: Inside Walls	Omega Engineering P/N TH-44006-40-T, Fast Response Thermistor Sensor with Exposed Element, Operating Range = –80°C 120°C, Interchangeability = ±0.2°C, 10K-Ohm Bead, Equipped with 40 in. of 26AWG PFA Insulated Cable
Interior Temperature/RH	Humirel HTM2500LF Temperature and Relative Humidity Module, 0–100% rh, ±3% from 10%–95% rh Typical
Exterior Temperature/RH	HOBO U23-002 Exterior T/RH Data Logger
Incident Solar Radiation	HOBO Micro Station Logger, H21-002, HOBO S-LIB-M003 Silicon Pyranometer
One-Time Moisture Content Reading of Building Materials	Delmhorst BD 2100 Moisture Meter

further means of protecting the sensor, the HIH-4021 was enclosed in a small bag made from house wrap prior to its installation in the wall assembly. The sensor's tight, laser-trimmed interchangeability helps to reduce or eliminate calibration requirements.

The HIH-4021 humidity sensor requires a supply voltage of between 4 and 5.8Vdc. The supply voltage used was 5Vdc (the sensor is calibrated at 5 V dc and 25°C). Sensor output is a near linear DC voltage. At higher humidity levels the output voltage exceeds the data logger's 2.5Vdc maximum input voltage. A voltage divider reduced the data logger's input voltage to an acceptable level and consisted of two 2MΩ, 0.1% precision resistors which also helped satisfy the sensor's high input impedance measurement circuit requirement.

To verify humidity sensor accuracy, prior to installation all sensors were connected to a Campbell Scientific CR10X data logger, allowed to settle to room conditions then tested and compared to both an Onset Computer Corporation U14-001 Temperature/Relative Humidity Data Logger (±2.5% rh from 10%–90% typical) as well as a Humirel HTM2500LF (calibrated within ±2% at 55% rh).

Each moisture content sensor consisted of two one-inch, stainless steel, GE moisture meter replacement pins soldered to stranded, shielded, 22AWG sound and security cable. The pins were insulated except for the tip to eliminate measuring the highest moisture content over the pin's length and were driven into clear wood at a distance of 1 in. from each other.

The measurement circuit used was a DC half-bridge circuit similar to that used for the wall temperature sensor measurements. The two resistors making up the half-bridge circuit consisted of the moisture content pin-pair and a fixed-value 2MΩ, 0.1% precision resistor. An excitation voltage of 2.5Vdc was used and a two second delay allowed the resistance reading to stabilize before measurement.

The data logger program's scan rate (execution interval) was originally set to fifteen minutes but was subsequently changed to five minutes to provide for more data points due to the need to filter random negative values from the final resistance averages.

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