The Hygrothermal Performance of Wood-Framed Wall Systems Using Spray Polyurethane Foam Insulations and a Smart Vapor Retarder in the Pacific Northwest

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ABSTRACT

The US Pacific Northwest building codes require vapor retarders or barriers used in residential building walls to prevent moisture-related damages due to the moderate temperatures and high moisture levels caused by precipitation and relative humidity throughout the year. Research on wood-framed wall systems with exterior stucco and cavity spray polyurethane foams is being conducted in this climate zone. Two stucco-clad wall systems have been installed side by side in a natural-exposure testing facility in the Seattle, WA, area. One wall is insulated with a hybrid insulation system comprised of 2 in. spray polyurethane closed-cell foam and unfaced fiberglass batts. The closed-cell foam works in place of a separate vapor retarder due to its low water vapor transmission property, and at the same time offers good airtightness and thermal resistance. The other wall is insulated with 6 in. of open cell foam and has a variable-vapor-resistance "smart vapor" retarder attached to the interior surfaces of the foam and gypsum layer. Contrary to common building practice, the application of interior wall cavity foam requires careful moisture design. The results from the field tests confirm the critical role of the highly absorptive cladding and at the same time the use of cavity spray foam insulations. The results are being extended using a hygrothermal simulation tool. The field test data are compared to the simulation tool for both walls. This paper will describe the performance of these two walls and the need for clear design guidance for application in the Pacific Northwest.

INTRODUCTION

Pacific Northwest region is identified as a marine climate, with a unique combination of high precipitation and relative humidity that creates a challenge to the building envelope systems as far as moisture performance is concerned. Historical failures of the building envelopes in this region taught designers and builders to conduct a moisture study before implementing a design. A modern moisture engineering analysis is deployed by system design engineers and architects that incorporate hygrothermal modeling into the design process to optimize the systems under consideration.

Hygrothermal modeling tools such as WUFI® (2008) Pro 4.2 have been extensively used in the building industry for the purpose of building envelope design and performance comparison. As these tools are getting more sophisticated and at the same time more user friendly, designers can incorporate the modeling into the decision-making process more easily. Making the right choice of the best-performing system for the job in a specific location is much easier than before (Karagiozis et al. 2004; Straube and Schumacher 2002). These models incorporate vapor diffusion, capillary transport, sorption and suction capacities, and phase change such as vapor to liquid, ice to water, and vice versa. Equally useful is the identification of potential moisture-related problems with a specific building envelope in a specific location through hygrothermal modeling. In both cases, the accuracy of the modeling results is not as critical as the investigation and comparison of moisture performance of the building envelope (Straube and Schumacher 2002). When comparing the modeling results with field test data, however, a discrepancy exists due to the assumptions, ideal construction (e.g., completely

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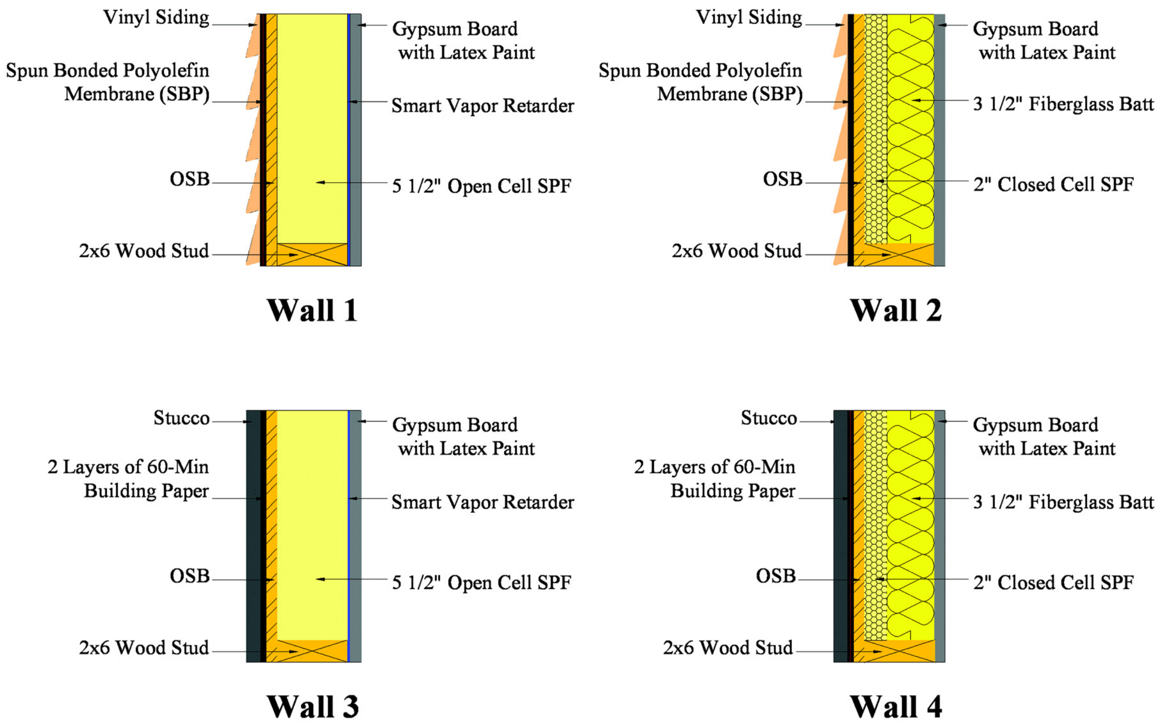

Figure 1 *Cross sections of modeled wall systems (wood studs not modeled).*

airtight), and materials properties used in the modeling (Karagiozis 2005).

Among the building envelope systems, residential light framing walls with fiberglass insulation have been studied extensively over the last few years. Walls insulated using spray polyurethane foams (SPF) also have been investigated by both modeling and field testing. For example, in 2007, Finch et al. (2007) presented hygrothermal modeling and 6-month field test data for four SPF walls with bricks installed in Waterloo, ON, Canada. In that specific climate, their results showed the closed-cell SPF had sufficient vapor resistance to maintain the oriented strand board (OSB) sheathing moisture content below 20%, while the open-cell SPF had insufficient vapor resistance. Their research also showed that the change of indoor relative humidity had little effect on the closed-cell SPF walls but great impact on open-cell SPF walls. Thus, a vapor-retarding layer was suggested for open-cell SPF walls. Smith (2009) confirmed that the closed-cell SPF walls with vinyl siding performed well in seven Canadian climates, whereas the open-cell SPF walls with no vapor retarders or barriers did poorly. This modeling investigation was validated with a number of simple, small-scale, controlled laboratory chamber testing results. The study concluded that a vapor retarder is needed for open-cell SPF walls but not for the closed-cell SPF walls for the specific vinyl cladding wall.

The purpose of this paper is to investigate the hygrothermal performance of residential SPF walls in the Pacific Northwestern US climate zone using a combination of hygrothermal modeling and field test. Through modeling, two types of cladding were studied in the 2 × 6 wood framing walls: vinyl siding and stucco with no air gaps. For both exterior claddings, two insulation systems were incorporated in the models: the open-cell SPF and closed-cell SPF with R13 fiberglass batts. Following recommendations from researchers, including those mentioned above, and building code requirements, the open-cell SPF walls incorporated a vapor-retarding layer on the interior while the closed-cell SPF walls did not have any vapor retarder. The vapor-retarding layer used was a smart vapor retarder with a relative-humidity–dependent water vapor permeance (Gatland et al. 2007). In addition to the modeling activities, two wall systems modeled were installed in a specific Puyallup, WA, location for field testing to compare with modeling results.

RESIDENTIAL SPRAY FOAM WALL MODELS

Four walls using two types of cladding and insulations were modeled (Kuenzel et al. 2001). These walls, as shown in Figure 1, consisted of the following layers (from exterior to interior):

- Wall 1: vinyl siding, spun-bonded polyolefin membrane (SBP), 1/2 in. OSB sheathing, 2 × 6 wood framing, 5 1/2 in. open cell SPF, one layer of smart vapor retarder, and

Table 1. SPF Materials Properties Used in Modeling

Material Property	Open-Cell SPF	Closed-Cell SPF
Density	0.5 pcf	2.0 pcf
Thermal conductivity (aged)	0.278 Btu·in/h·ft^2·°F	0.172 Btu·in/h·ft^2·°F
Thermal resistivity (aged)	3.6 h·ft^2·°F/Btu·in	5.8 h·ft^2·°F/Btu·in
Water vapor permeability (RH_{mean}=25%)	23.8 perm·in	1.51 perm·in

Table 2. Initial and Boundary Conditions Used in the Modeling

Condition	Item	Value
Initial conditions	Temperature	68°F
	Relative humidity	80%
Boundary conditions	Orientation	South
	Exterior surface (film) thermal resistance	0.334 h·ft^2·°F/Btu
	Interior surface (film) thermal resistance	0.334 h·ft^2·°F/Btu
	Surface (film) thermal resistance	0.71 h·ft^2·°F/Btu
	Rain water absorption factor	0.7
	Interior temperature	68 ± 2°F sinusoidal
	Interior relative humidity	50 ± 10% sinusoidal
	Exterior weather data (30-yr 10th percentile warm year)	Seattle, WA

1/2 in. gypsum plaster board with one layer of primer and one layer of latex paint

- Wall 2: vinyl siding, spun-bonded polyolefin membrane (SBP), 1/2 in. OSB sheathing, 2 × 6 wood framing, 2 in. closed-cell SPF, 3 1/1 in. fiberglass batt (R13), and 1/2 in. gypsum plaster board with one layer of primer and one layer of latex paint
- Wall 3: stucco, two layers of 60-minute building paper, 1/2 in. OSB sheathing, 2 × 6 wood framing, 5 1/2 in. open-cell SPF, one layer of smart vapor retarder, and 1/2 in. gypsum plaster board with one layer of primer and one layer of latex paint
- Wall 4: stucco, two layers of 60-minute building paper, 1/2 in. OSB sheathing, 2 × 6 wood framing, 2 in. closed cell SPF, 3 1/2 in. fiberglass batt (R13), and 1/2 in. gypsum plaster board with one layer of primer and one layer of latex paint

One-dimensional hygrothermal modeling was conducted on these four walls for a three-year duration beginning October 1.

Materials Properties

All wall components except SPF insulations are generic materials in the hygrothermal modeling software Generic North America Materials Database (WUFI 2008). The polyamide (PA) membrane was used for the smart vapor retarder in the open cell SPF models. The SPF insulations used in the models are supplied by a major US building insulation manufacturer. Table 1 summarizes the main materials properties used in the modeling and obtained from the product specification sheets. The water vapor permeability values are based on the dry cup measurements.

Initial and Boundary Conditions

Table 2 summarizes the initial and boundary conditions used for all four walls. All wall components were assumed to have the initial constant moisture content under the initial temperature and relative humidity as shown in Table 2. The exterior boundary conditions were imposed to the walls using the weather data file in the software for Seattle, WA. This file was created based on 30-year 10th percentile warm-year weather data from the software's climate database, and the 10th percentile warm year was chosen.

HYGROTHERMAL MODELING RESULTS

Each of the four walls was modeled for Seattle, WA. The modeling criteria followed *ANSI/ASHRAE Standard 160, Criteria for Moisture Design Analysis in Buildings*. The modeling results for these walls were compared to each other for hygrothermal performance. Wood components in the walls are most likely subject to mold growth. Thus, the OSB sheathing water content was evaluated. The temperature and relative humidity results for the OSB sheathing also are important factors that impact condensation in the wall structure. In this paper, the wall moisture performance evaluation criteria for wood components are as follows:

Table 3. Moisture Content Modeling Results for OSB for Seattle, WA Climate (1/2 in. [13 mm] from exterior surface of OSB)

	Wall 1-OSB	Wall 2-OSB	Wall 3-OSB	Wall 4-OSB
Moisture Content	12%	12%	15%	15%

Table 4. Modeled Wall Moisture Performance Based Upon OSB Temperature and RH*

	Wall 1		Wall 2		Wall 3		Wall 4	
	7 days	30 days	7 days	30 days	7 days	30 days	7 days	30 days
Moisture Content	Pass	Pass	Pass	Pass	Pass	Fail	Pass	Pass

* *Notes:* "7 days" refers to the moisture performance based on OSB 7-day running average temperature and RH results. "30 days" refers to the moisture performance based on OSB 30-day running average temperature and RH results.

- OSB or wood stud cavity moisture content is less than 20% (not referenced in *ANSI/ASHRAE Standard 160*)
- 7-day running average surface RH is less than 98% when the 7-day running average surface temperature is between 40°F and 100°F
- 30-day running average surface RH is less than 80% when the 30-day running average surface temperature is between 40°F and 100°F

Moisture Content

The moisture content results for OSB sheathing for each wall are summarized in Table 3. The moisture content values listed in the table are annual maximum percentage values by dry mass of the specific layer. Any values greater than 20% are considered hazardous conditions that could allow mold growth on the wood. Lower than 20% moisture content values are highlighted in green, and no mold growth potential is predicted. As a 1-D model was used for the analysis, wood studs were not modeled.

Table 3 showed that all four walls modeled had less than 20% moisture content in the OSB sheathing. As the largest potential for moisture accumulation would be the sheathing board, the modeling results predicted no potential failures for the Seattle climate.

Seven-Day Average Relative Humidity and Temperature

All four walls modeled had highest moisture content and relative humidity levels at OSB sheathing layer compared to other components in the same wall system. The 7-day moving average values of OSB relative humidity, as shown in Figure 2, are less than 90%. Thus, these results predict no danger of moisture problems for the OSB sheathing. Therefore, all four walls in these three locations met the proposed moisture performance criterion for the 7-day moving average values of relative humidity. The location plotted for Figure 2 is 13 mm in the OSB board from the exterior.

Thirty-Day Average Relative Humidity and Temperature

Figure 3 shows the 30-day average RH and temperature results for the walls modeled in Seattle climate. Wall 3 (stucco with open-cell SPF and smart vapor retarder) was predicted to have mold growth potential on the OSB due to the high levels of RH in the temperature rage of 40°F to 80°F. Walls 1, 2, and 4 might have high RH for the initial months in the first year, but can dry out in the subsequent months. It should be pointed out that walls 1, 2, and 4 do not exceed 80% RH in years 2 and 3 of the simulation.

Table 4 summarizes these results regarding mold growth potentials for each wall in accordance to the moisture performance evaluation criteria used in this paper. Only wall 3 is predicted by modeling to have potential moisture problems.

FIELD TEST WALLS

Two walls (i.e., walls 3 and 4, shown in Figure 1) were constructed in the summer of 2008 in the Washington State University Natural Exposure Testing (NET) facility (originally constructed by Tichy and Murray [2003] and Karagiozis and Desjarlais [2007]) through a collaborative research contract (Dr. Carolyn Roos, WSU investigator) with the Oak Ridge National Laboratory (Dr. Karagiozis, principal investigator). The NET facility is located in Puyallup, WA, approximately 30 miles south of Seattle, WA.

Walls 3 and 4 were installed on the southern side of the facility. Figure 4 shows location of the two walls in the NET facility. Figure 5 shows the two walls under construction (after SPF spray). The relative humidity in the NET facility was kept constant at 45% while the temperature at 20°C.

In each wall, the following sensors were instrumented:

- 7 relative humidity (RH) sensors
- 7 moisture content (MC) sensors
- 15 temperature thermocouples
- 1 heat flux meter

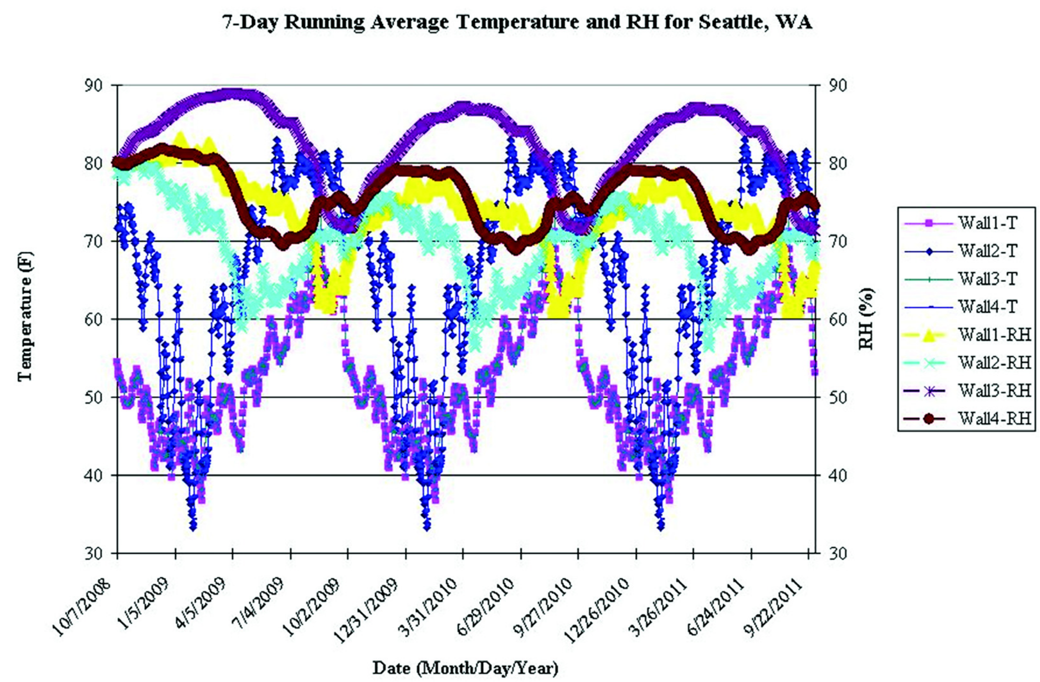

Figure 2 *OSB 7-day running average temperature and RH for Seattle, WA.*

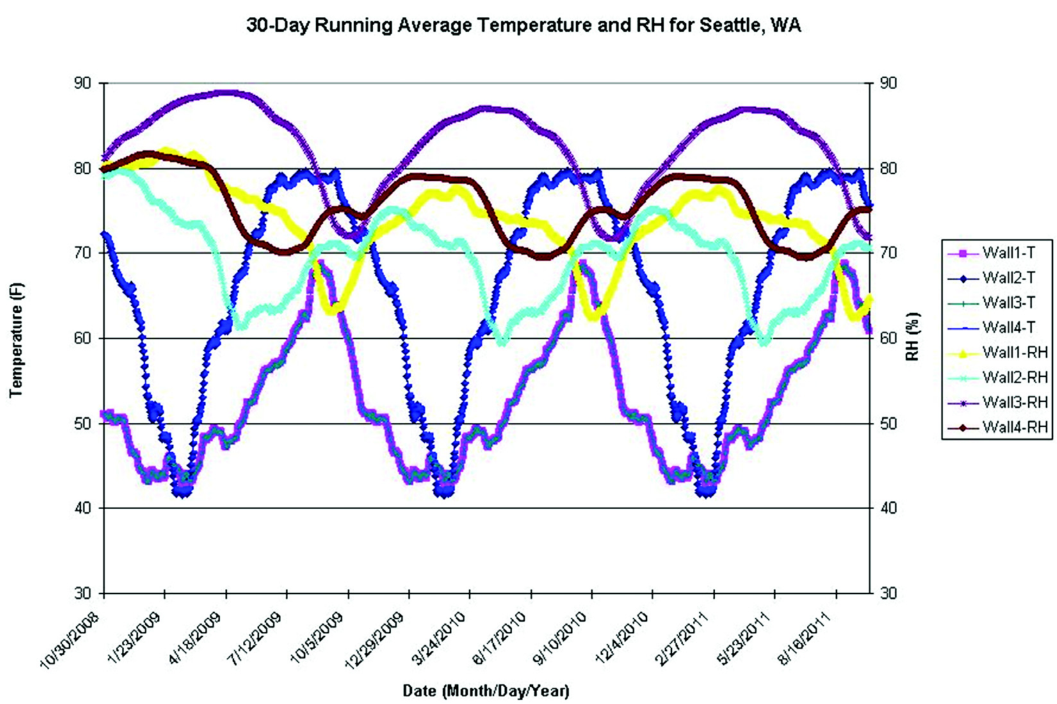

Figure 3 *OSB 30-day running average temperature and RH for Seattle, WA.*

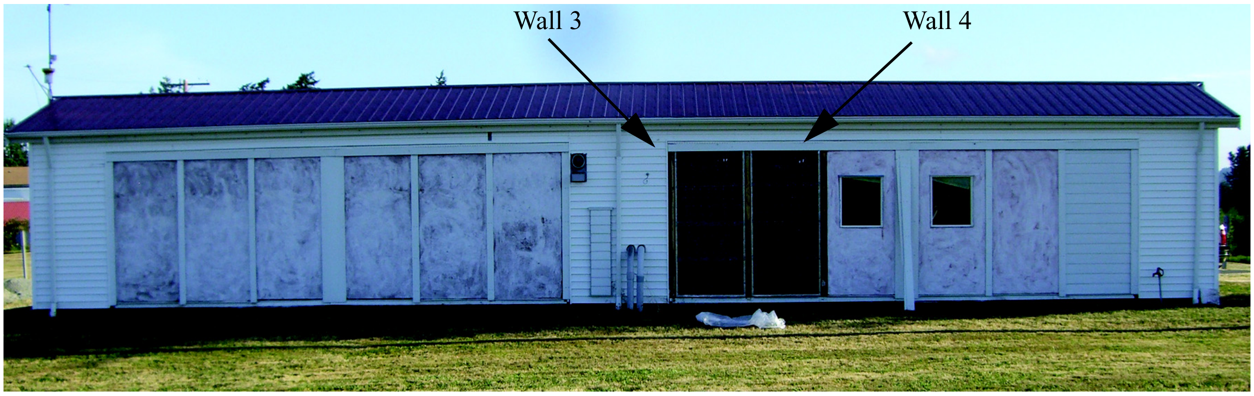

Figure 4 *Location of walls in the NET facility.*

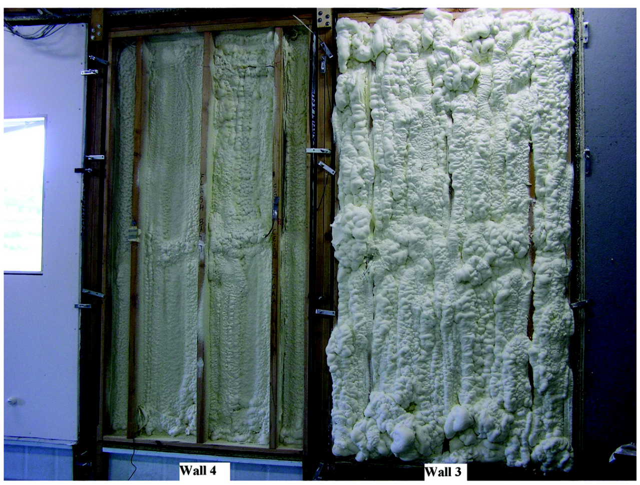

Figure 5 *Interior of walls 3 and 4 (prior to addition of fiberglass insulation) under construction.*

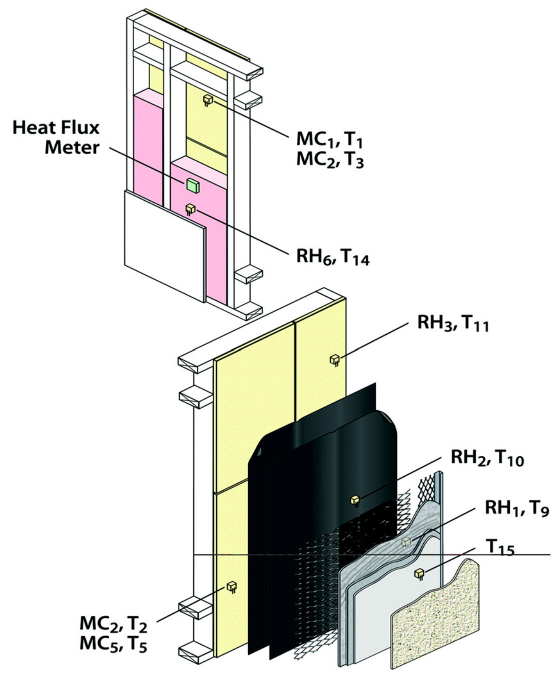

Figure 6 *Field walls instrumentation diagram.*

Figure 6 shows the instrumentation. All sensors are connected to the data acquisition system that records and stores hourly data that can be analyzed for the test walls.

FIELD TEST RESULTS

Both MC and RH test data obtained so far represent a field test period of approximately 10 months. Figure 7 shows the hourly moisture content data for the OSB of both walls. The sensor is located approximately 1/8 in. (3 mm) from the exterior most of the OSB layer. For the late winter through spring period, the OSB moisture content levels for both walls exceeded 20% threshold, indicating potential mold growth in the OSB.

Figures 8 to 9 show the moving average test data for the RH and temperature of the OSB for both walls. The data for these figures are from the RH and temperature sensors (not shown in Figure 6) on the interior side of the OSB sheathing (opposite to the RH_3 / T_{11}, as shown in Figure 6). For the majority of whole field test period recorded, the OSB for both walls had temperatures between 40°F to 80°F, matching the modeling results. The 7-day moving average OSB RH for wall 3 (with the maximum RH being 99.7%) did not meet *ASHRAE Standard 160*, while wall 4 did (with the maximum RH being 96.5%), as shown in Figure 8. The 30-day moving average of OSB RH, shown in Figure 9, however, shows that neither wall 3 nor wall 4 met the moisture performance evaluation criteria used in this paper following *ASHRAE Standard 160*. The OSB

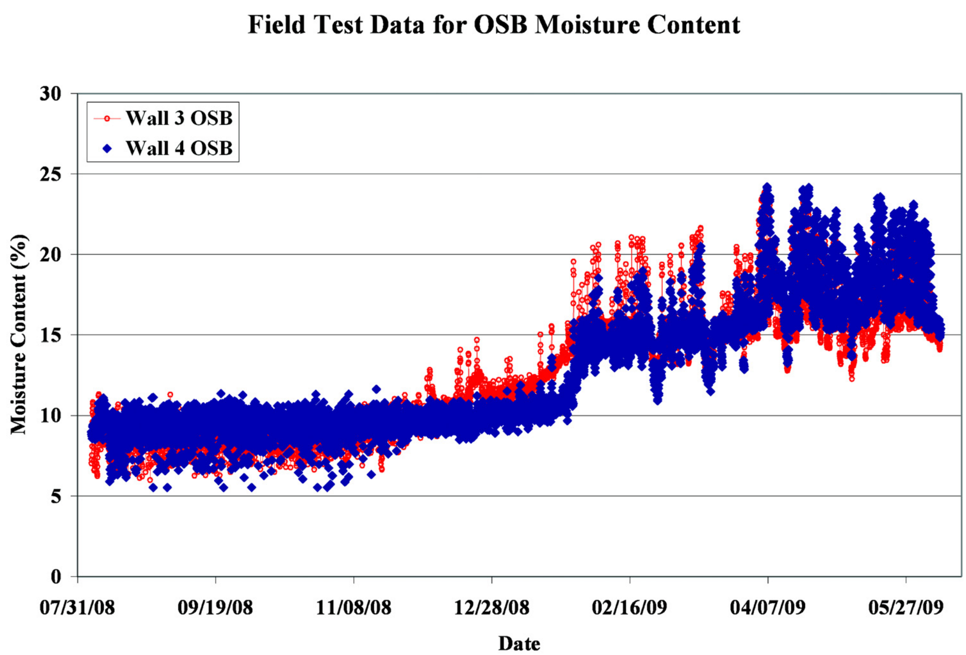

Figure 7 *OSB moisture content field test data for walls 3 and 4.*

RH data for both walls, as shown in Figure 9, reached to between 80% to 100% and stayed at this dangerously high level for more than half of the data period, which is approximately 6 months.

Comparing with modeling results for walls 3 and 4 in Seattle (Tables 3 and 4), the field test data showed more severe potentials for mold growth on the wood components in walls with stucco finishing. Not only are the RH levels in the field walls more severe than the modeling results, but the OSB also had much higher moisture contents. This may be caused by four main discrepancies between modeling and field testing:

1. Water penetration through the field of the stucco layer was not included in the analysis. A detailed study performed by Karagiozis and Desjarlais (2007) using the same test facility on stucco walls suggested that modeling accuracy may be improved when correctly accounting for the water penetration. This should be examined in the future work.
2. The material properties of wall components used in the modeling may be different than those used in the field walls. The difference of material properties may cause a significant difference in modeling results (Karagiozis 2004).
3. The weather data for year 2008–2009 were more severe than the moisture reference year in the hygrothermal modeling software. This could have a lesser impact than the previous two items. A further study should be conducted to examine the difference between the actual weather data and the weather file used in the modeling. Also the modeling should be repeated using the actual weather data if significant differences are determined.
4. The inward vapor drives that result due to the presence of solar heating on the exterior surface of the cladding, especially from stucco cladding, can further increase the moisture accumulation in the OSB sheathing for these types of wall systems.

CONCLUSIONS AND RECOMMENDATIONS

Hygrothermal performance modeling for building envelopes can provide quick and comparative results to evaluate system moisture performance in specific climate zones. This approach was used to evaluate walls finished with stucco and vinyl siding on the exterior and insulated with open- and closed-cell SPF materials. Modeling results showed moisture performance failure for the open-cell spray-foam–insulated wall finished with stucco in Seattle, WA, area. The modeling results also showed that the two stucco walls had higher potential mold growth on OSB than the two vinyl siding walls. This is due to the moisture storage capacity of the exterior cladding. Relative humidity together with surface temperature data presented more information regarding the moisture performance than wood component moisture content.

Comparing with ongoing field testing, modeling showed less severe levels of moisture content and relative humidity for OSB sheathing layer. For the stucco walls modeled, neither the OSB layer moisture contents nor 7-day average relative humidity data showed potential problems. The field test data, however, showed serious problems, with a very high level of OSB moisture content and relative humidity at moderate

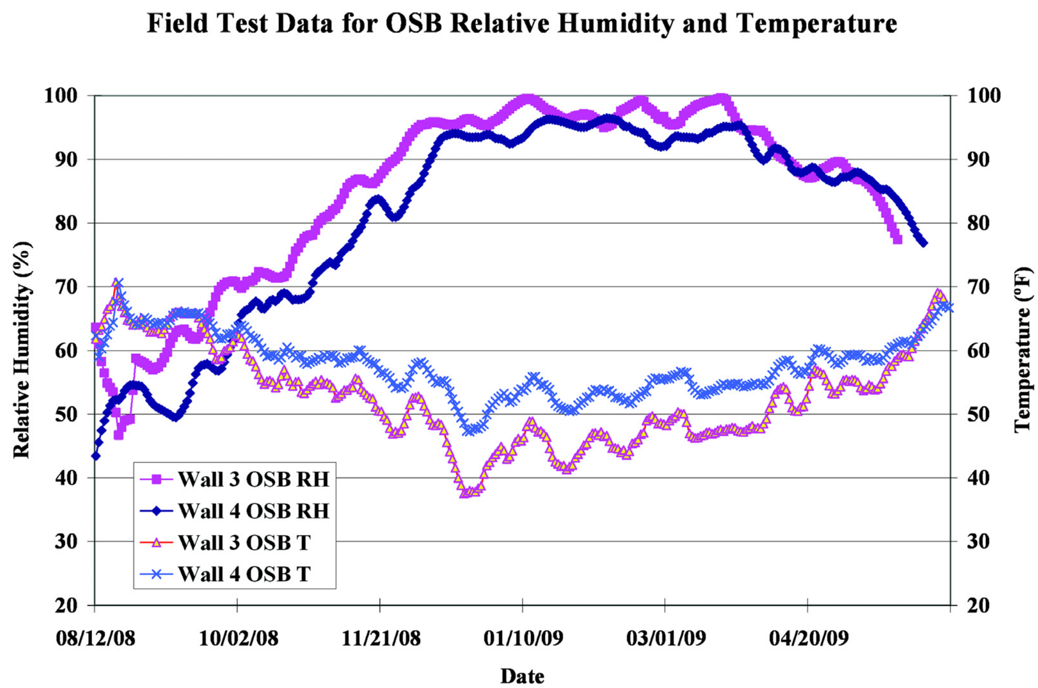

Figure 8 *Field test data of 7-day moving average for OSB relative humidity and temperature for walls 3 and 4.*

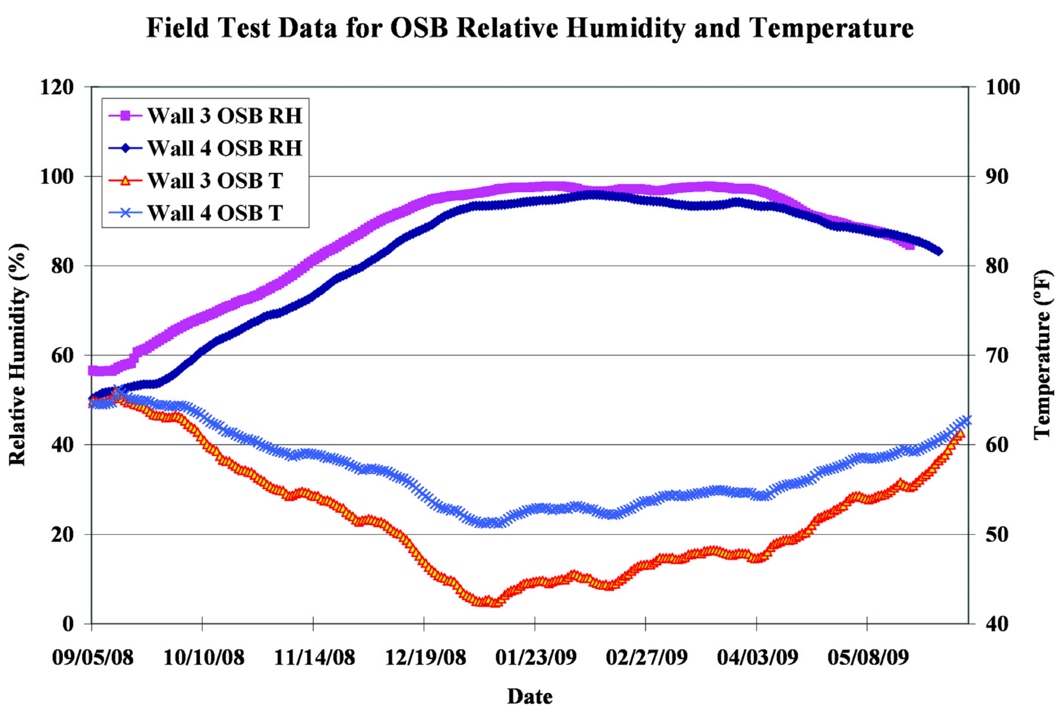

Figure 9 *Field test data of 30-day moving average for OSB relative humidity and temperature for walls 3 and 4.*

temperatures at which mold can grow. This may be caused by the idealized system models where water leakage due to cracks not being taken into account. The impact of water penetration through the stucco cracks was not included in the analysis. Some impact, but less significant, may be from the use of a rather severe weather year. Therefore, it is concluded that a parametric sensitivity hygrothermal modeling analysis is needed and guidelines needed to be validated by real field test results.

The recommended solution to the moisture problems with stucco walls in Northwest Pacific climates is to change the wall design. A ventilated air gap between the stucco and building paper attached to the OSB layer may be added to allow moisture to flow with air out of the wall instead of penetrating and accumulating in the OSB and wood studs (Tichy and Murray 2003). This would reduce the impact of water penetration through the cladding and also solar-driven moisture. This design change is recommended for the field stucco walls in the Seattle area, and data on the renovated walls are to be used for comparison and verification. A new series of field tests is currently being conducted, and these results will be presented in another scientific paper in 2011. Another recommendation is to test the materials used in the field test walls for moisture properties. The models should be rerun to verify the field test results using the measured material properties and actual weather data. Also, the water penetration should be included in the models to further improve modeling accuracy.

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