COLD CLIMATE HOUSING RESEARCH CENTER

CCHRC

Evaluating the Need for Vapor Retarders with Open Cell Polyurethane and Cellulose Insulation in Extreme Cold Climates

February 3, 2014

Special thanks to: Demilec, Icynene, and Thermo-Kool Alaska

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Introduction

Increasing the energy efficiency of houses in Alaska often involves enhancing the building envelope. Enhanced envelopes have higher R-values and are more tightly sealed than typical older envelope construction methods. With past construction methods, it has been necessary to keep interior relative humidity levels below the optimal range (40 - 60%) for occupant comfort and health (Sterling et al., 1985), in order to avoid problems caused by mold and moisture accumulation. However, advances in envelope design for new and retrofit construction may allow for a shift from prior assumptions.

Recent experiments conducted by the Cold Climate Housing Research Center (CCHRC) on exterior insulation systems (Craven, Garber-Slaght, 2012) indicate that certain building envelope systems can withstand sustained periods of up to 40% relative humidity and positive pressurization in a severe climate such as Fairbanks, whereas others may be at risk for condensation and mold growth at 25% relative humidity and neutral pressure. Another approach for improving hygrothermal performance over conventional construction practices is using stud-fill insulation that reduces air flow through or increases the hygric buffering capacity in the building envelope. The CCHRC Mobile Test Lab (MTL) was used to study the hygrothermal performance of several wall sections with open cell spray polyurethane foam (ocSPF), cellulose, and fiberglass insulations and varying levels of vapor control. The study was designed to answer the following:

- What level of vapor control is necessary to use open cell spray polyurethane foam or cellulose as cavity insulation in a severe cold climate like IECC climate zone 8?
- Does open cell spray polyurethane foam improve hygrothermal performance relative to fiberglass batts as cavity insulation in Fairbanks?
- Does dense-pack cellulose improve hygrothermal performance relative to fiberglass batts as cavity insulation in Fairbanks?
- Does open cell foam present a new option for rim joist insulation in an extreme cold climate?

Study Methods

A combination of physical testing of walls and hygrothermal modeling were used to study the various wall systems.

Mobile Test Lab

CCHRC's MTL is a road-worthy trailer with nine test wall bays. The interior temperature and relative humidity of the trailer can be maintained over a broad range and a Heat Recovery Ventilator (HRV) circulates air and allows for variations in pressure. During this study, CCHRC maintained the lab at 72°F (22°C) and 40% relative humidity throughout the winter test period with near neutral pressure with respect to ambient conditions (0 to 1 Pascals). A period of increased positive pressure (about 5 Pa) occurred for the last three months of the study in order to simulate pressurization from the stack effect above the neutral pressure plane or unbalanced mechanical systems. Figure 1 shows the exterior of the MTL under construction. The test wall configurations are labeled with numbers as shown in Figure 2.

Figure 1. The MTL under construction. The walls for the MTL were constructed inside the building and then the trailer was moved outside to a clearing to the south of the building.

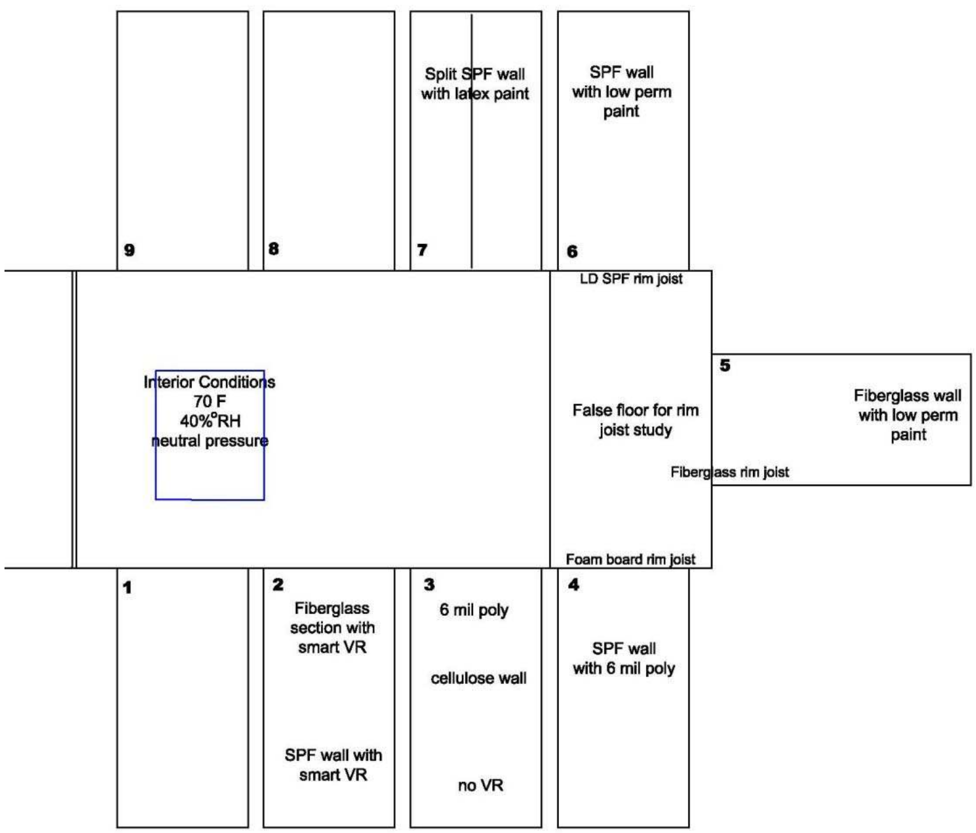

Figure 2. The layout of the MTL. The MTL was set in a clearing with wall #1 facing eastward and wall #5 facing to the north. Walls 1, 8 and 9 were not part of this study and are not discussed in this report.

Envelope Configurations

Four MTL bays were designed in coordination with insulation manufacturers Demilec and Icynene using open cell spray polyurethane foam (ocSPF). A fifth wall was insulated with dense-pack cellulose, and a control wall was insulated with fiberglass batts (see Table 1). The three remaining walls in the MTL are part of another research project and will be reported on in a separate document. All test walls had a weather barrier (e.g. Tyvek) on the exterior of the plywood sheathing and vinyl lap siding on the exterior, and the interior was finished with painted gypsum drywall.

Table 1. Wall Constructions

Wall	Framing	Vapor Control*	Stud Cavity
2 lower	2x4	Smart Vapor Retarder (Class II)	R-13 ocSPF
2 upper	2x4	Smart Vapor Retarder (Class II)	R-11 Fiberglass
3 upper	2x6	6 mil polyethylene (Class I)	R-21 Cellulose
3 lower	2x6	Latex paint (Class III)	R-21 Cellulose
4	2x6	6 mil polyethylene (Class I)	R-21 ocSPF
5	2x6	Low perm paint (Class II)	R-21 Fiberglass
6	2x6	Low perm paint (Class II)	R-21 ocSPF
7	2x6	Latex paint (Class III)	R-21 ocSPF

*The vapor retarder classifications shown in Table 1 follow the definitions from the 2012 International Residential Code (IRC) published by the International Code Council (ICC).

Five 2x6 walls were sheathed with ½-inch plywood on the exterior and ½-inch gypsum board on the interior. The exterior plywood had a horizontal cut across each wall to mimic the joint where two sheets of plywood come together. Each test wall had gypsum board sealed to the perimeter studs and top plate with acoustical sealant to minimize edge effects; the gypsum board was not sealed to the bottom plate since this edge of the test wall is considered representative of typical construction. Three of the test walls were set upon simulated subfloor assemblies with 2x10 lumber used for the rim and floor joists and ¾-inch plywood as the floor. These three test walls were installed in the back of the MTL so that a complete floor was made between the three MTL walls, and sealed to the MTL floor. Any air gaps between the false floor and MTL walls or floor were sealed with one-component spray foam (can foam).

Each of the five test walls had a plastic duplex electrical outlet box attached to a center stud and a $^{5}/_{8}$-inch hole was cut in the stud next to the box per ASTM Standard Specification E 1677-05. No electrical wiring was run through the test wall or placed in the outlet box, but the sensor wires were routed through the stud cavity and through the outlet box to allow for connections to the data logging system.

Each of the five 2x6 test walls had a simulated window built approximately in the middle of the test wall. Simulated windows were used in order to study the annular space around a window but to avoid the problems introduced by condensation on windows in a high humidity environment. A window buck was built using 2x6 framing filled with an insulated framed box made with plywood, 2x2 wood framing, and fiberglass insulation. The insulated box was installed like a window leaving an approximate ½-inch annular space between the window buck perimeter and the insulated box was filled with spray foam or fiberglass insulation, depending on the test wall scenario. A detailed illustration is provided in Figure 3.

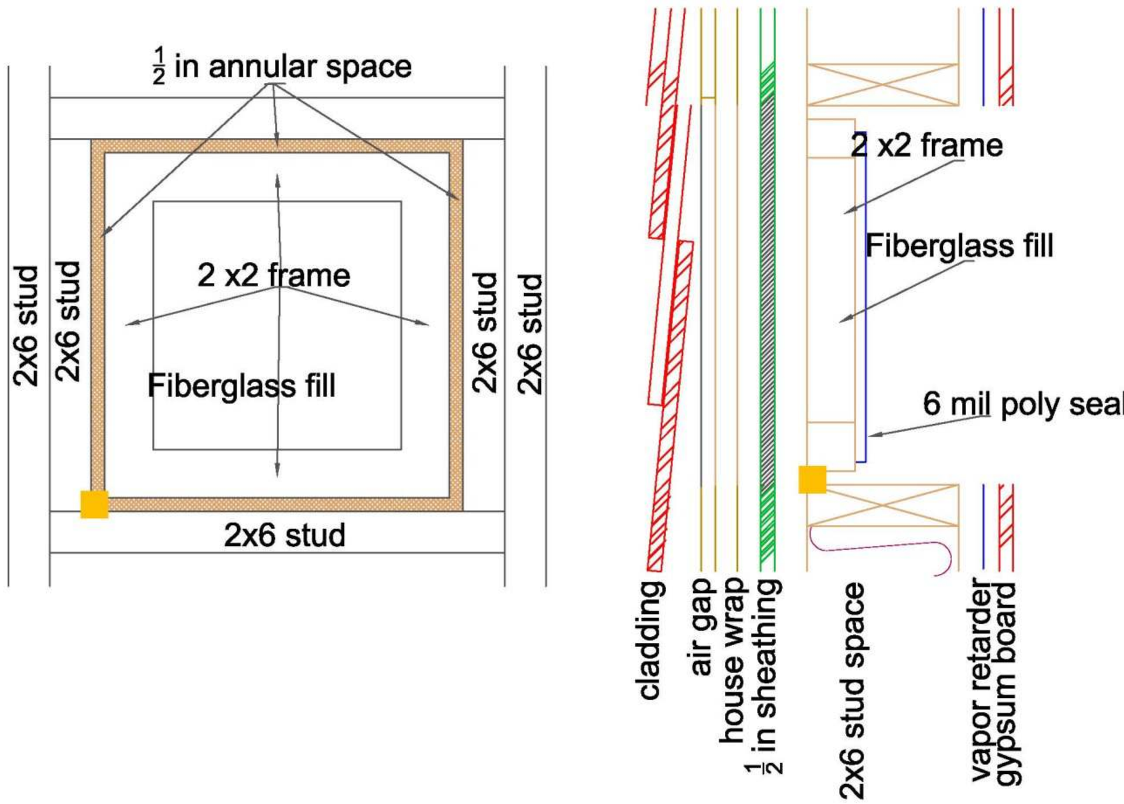

Figure 3. Simulated window. Three of the SPF walls, the cellulose wall, and the control wall had a simulated window, which allowed for study of water vapor infiltration into the annular space with different insulations.

Three test walls were fully filled with Demilec or Icynene ocSPF insulation with differing methods of finishes for the vapor control layer, while the fourth test wall was insulated with dense-pack cellulose and the control wall was insulated with fiberglass batts. Detailed descriptions of each scenario are given later in this report and are illustrated in the figures provided.

A fourth ocSPF test wall had nominal 2x4 studs with exterior ½-inch plywood (with the horizontal cut on the exterior) and ½-inch gypsum board on the interior. One stud bay was filled with fiberglass batts. Each stud bay had the horizontal cut in the plywood and an outlet box penetration. This test wall did not have a window.

Test Wall #2, Smart VR with ocSPF (Figure 4)

This wall had a 2x4 stud bay filled ocSPF with a two-mil Nylon vapor retarder (smart vapor retarder) (ICC class II vapor retarder) sealed at the test wall perimeter (plates and studs) with acoustical sealant. The smart vapor retarder has a water vapor permeance of < 1 perm at low relative humidity, and a permeance of >10 at high relative humidity (60%). The penetrations for the electrical outlets were not sealed. The gypsum board received one coat of primer and one coat of latex paint as a finish. The upper cavity had fiberglass batt in place of ocSPF.

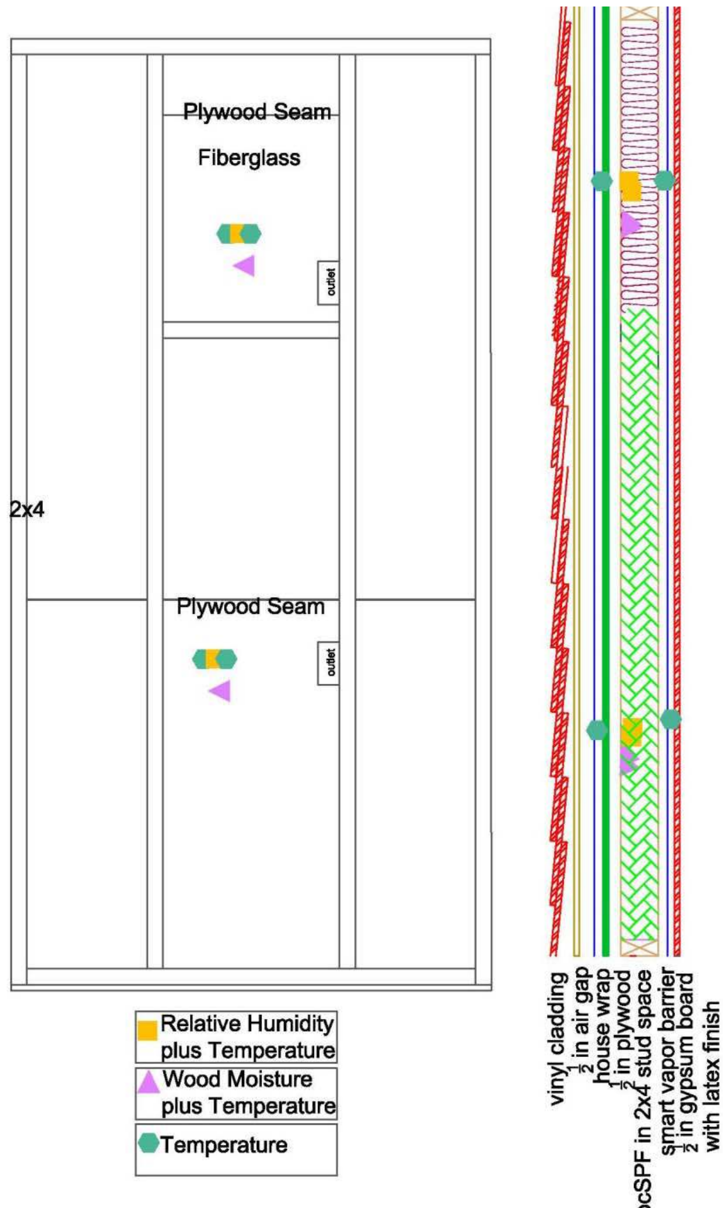

Figure 4. Elevation drawing of Wall 2. Approximate sensor locations are included in the drawing.

Test Wall #4, ocSPF with a six-mil polyethylene vapor retarder (Figure 5)

The 6-mil polyethylene vapor retarder (ICC class I vapor retarder) was sealed at the test wall perimeter (plates and studs) with acoustical sealant. The penetration for the window was attached to the face of the window-buck studs with staples, and the annular space between the window and the framing was filled with one-component spray foam. The penetration for the electrical outlet was not sealed. The gypsum board received one coat of primer and one coat of latex paint as a finish. The rim joist underlying the test wall was insulated with approximately 6 inches of ocSPF.

Test Wall #5, Control Wall (Figure 5)

This is the control wall, which was insulated with R-21 friction-fit fiberglass batts. The gypsum board exterior was painted with one coat of latex primer and one coat of low permeance paint (< 1 perm) (ICC class II vapor retarder) as the finish. The penetration for the electrical outlet was not sealed. The annular space between the window and the framing was filled with fiberglass batt scraps. The rim joist underlying the test wall was insulated with R-21 fiberglass batts cut to fit the perimeter of each rim joist bay without any method of air sealing.

Test Wall #6, ocSPF with one coat of low permeance paint (Figure 5)

This wall had a coat of primer paint and a coat of low permeance paint (< 1 perm) (ICC class II vapor retarder) on the gypsum board. The penetration for the electrical outlet was not sealed. The annular space between the window and the framing was filled with one-component spray foam. The rim joist underlying the test wall was insulated with 4 inches of extruded polystyrene (XPS) boards cut to roughly fit and sealed to the perimeter of each rim joist bay with one-component spray foam.

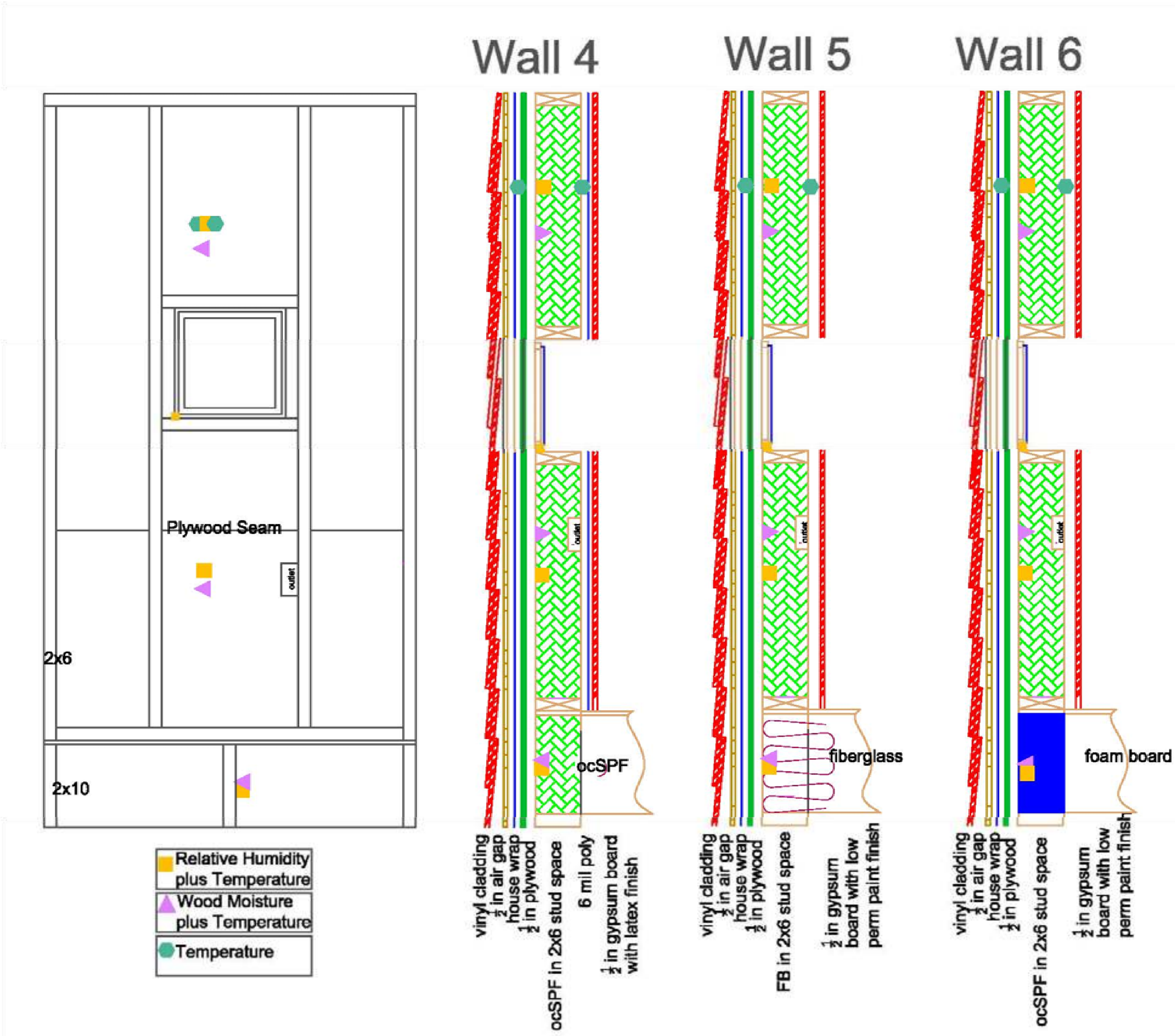

Figure 5. Elevations for spray foam walls. These three walls were at one end of the MTL and shared a false floor, which allowed for three different types of insulation against the rim joist.

Test Wall #7, ocSPF with latex paint (Figure 6)

This test wall was split in half vertically, with ocSPF from Demilec on one side and ocSPF from Icynene on the other. The divider between the two partitions was a two-inch thick piece of extruded polystyrene insulation sealed to the sheathing, plates, and drywall. The gypsum board received one coat of primer and one coat of latex paint (an ICC class III vapor retarder) as a finish. The window and outlet penetrations repeated on each side of the test wall. The penetrations for the electrical outlet were not sealed. The annular space between the windows and the framing was filled with one-component spray foam.

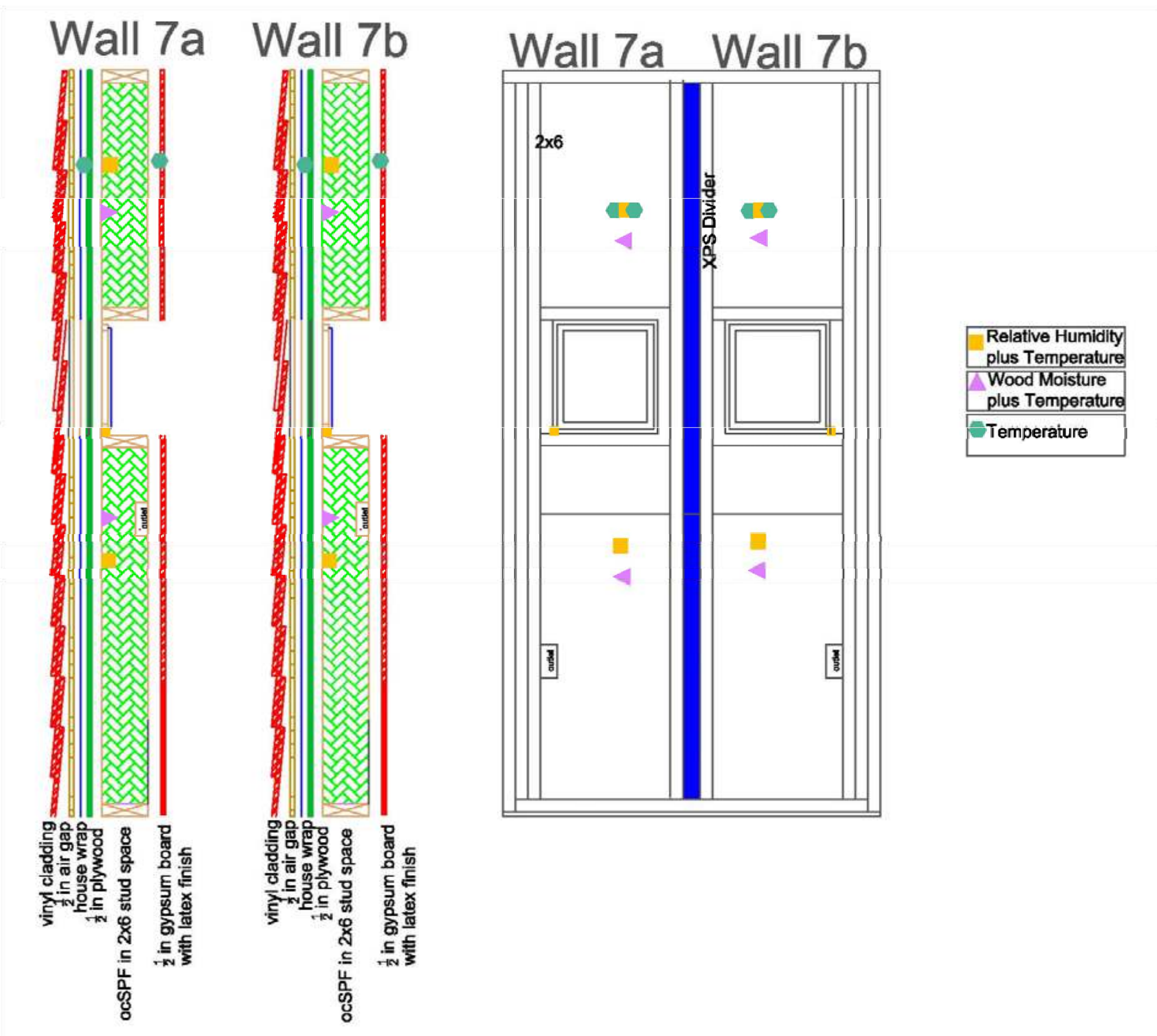

Figure 6. Elevation of Wall 7. Sides A and B had the same configuration, each with a different brand of ocSPF. Wall 7 had no vapor retarder at all.

Test Wall #3, Dense-Pack Cellulose *(Figure 7)*

Wall 3 was sheathed with ½-inch plywood and insulated with dense-pack cellulose covered with a six-mil polyethylene vapor retarder (an ICC class I vapor retarder) sealed at the test wall perimeter (plates and studs) with acoustical sealant. The stud bay below the window only had latex paint (ICC class III) as its vapor retarder. The penetration for the window was adhered to the face of the window buck studs with staples, and the annular space between the window and the framing was filled with one-component spray foam. The penetration for the electrical outlet was not sealed. The gypsum board on the interior face received one coat of primer and one coat of latex paint as a finish.

Figure 7. The cellulose wall. All of the wall but the space below the window had a 6 mil vapor retarder.

Instrumentation

Each test wall was built with a combination of temperature, relative humidity, wood moisture content, and heat flux sensors. Knowing the relative humidity and temperature allows for the assessment of humidity relative to the dew point (i.e. condensation potential), while knowing the moisture content allows for the assessment of moisture accumulation in solid phase materials. The heat flux sensors were used in a trial attempt to measure the R-value of building assemblies in-situ. The locations and types of these sensors are shown in Figures 4 through 7. Table 2 presents information on the particular sensors.

Table 2. Sensors in the MTL Walls

Sensor	Brand/Model	Range	Accuracy
Relative Humidity	Honeywell HIH4010	-40°C to 85°C 0% to 100%	±3.5%
Temperature	Honeywell S&C /Fenwall NTC Thermistors	-60°C to +150°C	±1°C
Moisture Content	Resistance pins	7% to 25%*	±2% *
Heat Flux Transducers	REBS HFT3 Huskeflux HFP01	-40°C to 55°C, ±100 W/m^2 -30°C to +70°C, ±2000 W/m^2	±5% -15% to +5%

*These values are for Douglas fir, there is less accuracy for plywood. (Straube, Onysko, Schumacher, 2002)

The thermistors were soldered to 22 gauge communication wire and wired to a Campbell Scientific CR1000 using a 10Kohm resistor in a bridge circuit. The relative humidity sensors were soldered to the communication wire along with a thermistor and put in a polyolefin bag.

The moisture content resistance pins are small brass rods soldered to the end of wires. The two rods were embedded in plywood sheathing, 1 inch apart, to the same depth. A thermistor was also embedded in the plywood near the pins. The two pins along with a 3 Mohm resistor formed a bridge circuit. The resistance of the wood between the pins was recorded and translated into moisture content using equations 1 and 2. The sensors were attached to the interior face of the plywood sheathing (Figure 8).

$$Log_{10}(MC) = 2.99 - 2.113(Log_{10}(Log_{10}(R1))) \qquad (1)$$

Where R1 is the reading in ohms and MC is the moisture content percentage for Douglas fir.

This moisture content was then corrected for temperature (Garrahan, 1988).

$$MC\% = \frac{\left[\frac{MC+0.567-(0.026*Temp)+(0.000051*Temp^2)}{0.881*(1.0056^{Temp})}-B\right]}{A} - 2 \qquad (2)$$

Where Temp is the temperature at the sensor in °C and MC is the uncorrected moisture content percentage from equation 1. For Douglas fir/plywood A=1 and B=0, and -2% is the correction for plywood (Straube, Onysko, Schumacher, 2002).

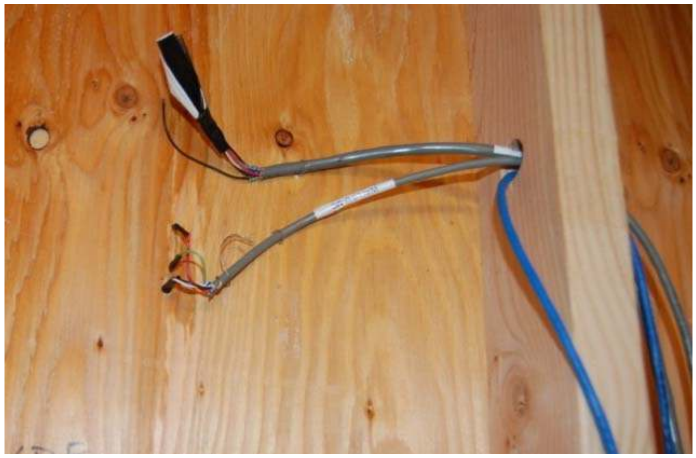

Figure 8. Sensors installed on the plywood sheathing. The relative humidity/temperature sensor is on the top. Below it the moisture content sensor is embedded directly into the plywood.

In addition to sensors embedded in each wall, two relative humidity/temperature sensors monitored the interior conditions of the MTL. A Setra 265 pressure transducer was used to monitor the pressure inside the MTL with respect to the outside. A weather station on the roof of the CCHRC Research and Testing Facility was used to monitor ambient conditions.

In-Situ R-value Testing

CCHRC performed in-situ R-value testing of each of the test walls following ASTM standard C1046. The heat flux transducers were calibrated using a LaserComp, Fox314 thermal conductivity analyzer before and after the testing. They were placed on the inside surface of the walls, fully covered with tape and adhered to the wall with thermal conductivity paste. Figure 9 shows the placement of the heat flux sensor on Wall 5.

Figure 9. Heat flux transducers. The two transducers in this photo were installed on the same wall in order to compare data. The blue tape was used to minimize air currents directly on the sensors.

The heat flux transducers output a mV signal that is converted to a heat flux in BTU/hr*ft^2, using multipliers calibrated from the Fox314 tests. The R-value of the cavity insulation is then determined using equation 3.

$$R - value = \frac{Temperature\ back\ of\ the\ gypsum\ board - Temperature\ at\ sheathing}{Heat\ flux} = \frac{hr \cdot ft^2 \cdot {}^\circ F}{BTU} \quad (3)$$

Heat flux data were collected for three months as the process and readings were refined to produce consistent results. The final R-values were calculated using 12-hour averages for a 3-day time segment in January 2013. The data were analyzed using the convergence test from ASTM C1046.

MTL Tear Down

At the conclusion of the 17 month test, the MTL walls were taken apart and the process was documented. Visual observations and pictures of the tear-down were used to document any mold within the wall cavities.

WUFI Hygrothermal Modeling

WUFI 5.2 is one-dimensional hygrothermal modeling software. It evaluates the thermal and moisture performance of a wall cross-section based on boundary conditions and physical properties of the wall materials. WUFI was used to model the walls for a 10-year period to see if there are long-term moisture effects that were not apparent in the 17 month MTL study. In addition to vapor diffusion, the model allows for moisture to be introduced into the wall as part of an air infiltration model. For this project, air infiltration was set to air tightness class B which is equivalent to approximately 3 ACH50. This tightness was used to demonstrate the leakage from the unsealed outlet penetrations.

The walls were created in WUFI using a combination of WUFI generic materials and material-specific properties culled from manufacturer websites. A number of pertinent properties are presented in Table 3. Each material was modeled to be as close to reality as possible with readily available information. When the information was not readily available the default WUFI values were used.

Table 3. WUFI Properties

Material	Bulk Density (lb/ft^3)	Porosity (ft^3/ft^3)	Heat Capacity* (Btu/lb•°F)	Thermal Conductivity* (Btu/hr•ft•°F)	Permeability* (perm in)
Vinyl Siding	149.827	0.001	0.239	0.289	0.001
Air Gap (1/2 in)	0.081	0.999	0.239	0.041	176.438
Weather Barrier	27.968	0.001	0.358	1.387	0.392
Plywood (1/2 in)	37.457	0.96	0.449	0.058	0.5
R-11 Fiberglass Batt	1.873	0.99	0.201	0.023	99.077
Open Cell Spray Polyurethane Foam	0.468	0.99	0.351	0.021	22.0[1]
Dense Pak Cellulose (5.5 in)	3.25[2]	0.99	0.449	0.022	69.247
6 mil Poly	8.116	0.001	0.549	1.329	0.004
Smart Vapor Retarder	8.116	0.001	0.549	1.329	0.002 to 0.05[3]
Gypsum Board (1/2in)	53.0	0.65	0.208	0.094	21.467

*These are the values for the dry material; some materials have moisture dependent data in the model as well.

[1]From data sheet for Demilec Sealection 500, http://www.demilecusa.com/wp-content/uploads/2013/08/Sealection-500-TDS.pdf

[2]From data sheet for Thermo-Kool Mono-Therm, http://www.thermo-koolofalaska.com/wp-content/uploads/2012/07/WallDensity.pdf

[3]From data sheet for CertainTeed MemBrain, www.certainteed.com/resources/3028097.pdf

The boundary conditions were set to be as close to the MTL study as possible. An ASHRAE year 3 (third most severe year) for Fairbanks, Alaska was used for the exterior condition. The interior conditions were set to average 40% relative humidity and 70°F for the entire year. Each simulated wall was set up with an air leakage path to mimic the outlet hole, air tightness class B (3 air changes per hour at 50 Pa).

Findings and Discussion

The test results indicate that in a severe cold climate like Fairbanks, Alaska, ocSPF in above-grade walls should be used in conjunction with a strong vapor control layer. A class I vapor retarder (i.e. 6 mil polyethylene) provided adequate control of moisture infiltration attributable to water vapor diffusion and air leakage. Class II vapor retarders (i.e. smart vapor retarder and low perm paint) produced varying results in this study, which could be the result of their different installation and detailing. Further research is needed to determine whether a class II vapor retarder can provide effective moisture protection for ocSPF-insulated walls in extreme cold climates. Class III vapor retarders (i.e. latex paint) resulted in high relative humidity at the sheathing plane and moisture content in the plywood sheathing in excess of common risk thresholds during the winter test periods, as well as limited visible mold growth on the plywood surface. Dense-pak cellulose in a nominal 2x6 stud cavity also demonstrated a need for a strong vapor control layer on the warm side of the wall. The study did not look at class II retarders with cellulose.

Overall Wall Performance: SPF Walls

Moisture content of 16% is the point where surface mold can start to develop (Lstiburek, 2002). The moisture content of the plywood sheathing of the ocSPF walls hovered around the threshold of concern during the first winter but only one wall approached the 16% threshold during the second winter. Figure 10 shows the moisture content of the sheathing in the cavity above the window for the ocSPF walls. The moisture content in one of the SPF walls with latex paint (purple line, Wall 7b) increased dramatically during the second winter just before pressure was applied; however it dried to the level of the other walls quickly once exterior temperatures rose. In prior MTL studies these drastic spikes in moisture content have corresponded to sudden leakage events, usually from the windows. The cause of this spike is unknown, and was not replicated in Wall 7a. It is possibly the result of voids in the spray foam (see figure 24) increasing convective loops which carried more moisture into the wall.

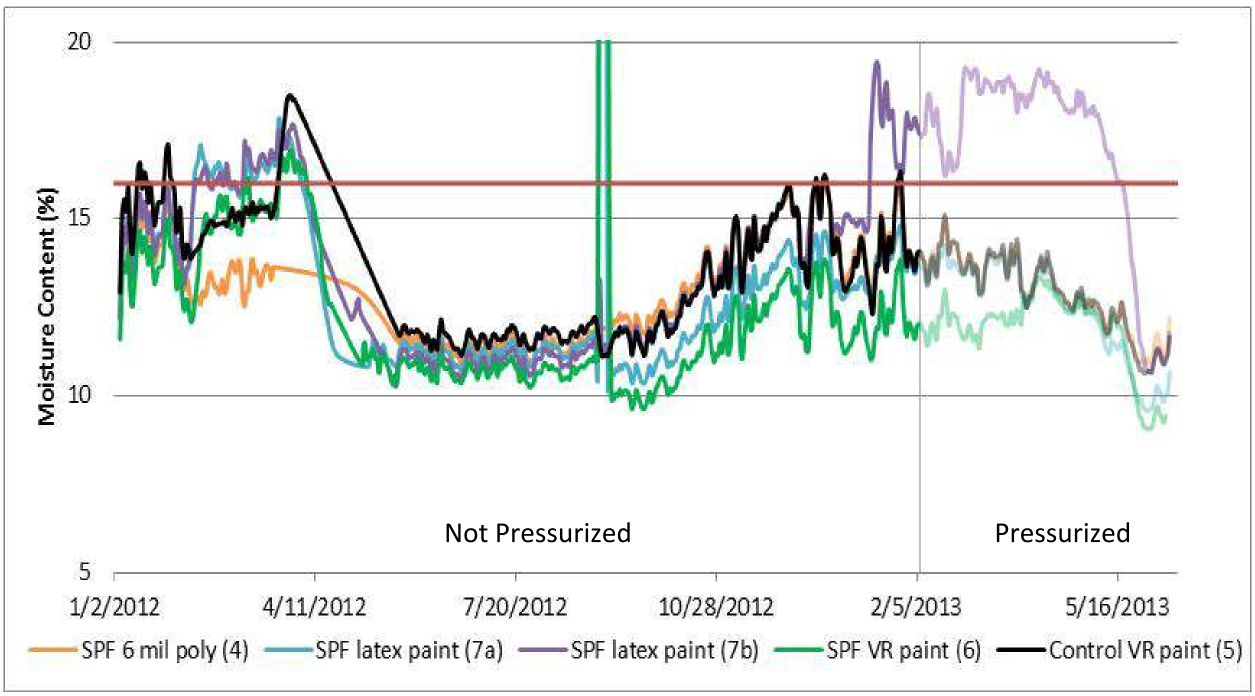

Figure 10. Moisture content in the upper cavity of the ocSPF walls. The red line is the line of 16% moisture content; where there is a cause for concern. There was a sensor error in April 2012 that results in the straight line interpolations of the data from April 1 to May 2, 2012. Wall numbers are in parentheses.

Relative humidity and temperature at the sheathing plane is more indicative of the potential for mold growth. Humidity above 80% with corresponding temperatures above 41°F (5°C) is the danger zone for mold growth (Hukka and Viitanen, 1999). Figure 11 shows relative humidity over the course of the study. Walls with only latex paint had humidity at the sheathing plane above 80% for most of both winters. The increase in pressure did not create much difference in the humidity of the walls in a way that is readily discernable from the variations from the ambient temperature.

Walls 6 and 5 both had low perm paint as their vapor control layer; low perm paint is considered a class II vapor retarder. There was more moisture infiltration into the stud cavity with the low perm paint than the class I 6 mil polyethylene. The ocSPF wall fared better than the fiberglass wall hovering around 80% relative humidity even when pressurized (Figure 11). This difference may be due to the air tightness qualities of the ocSPF.

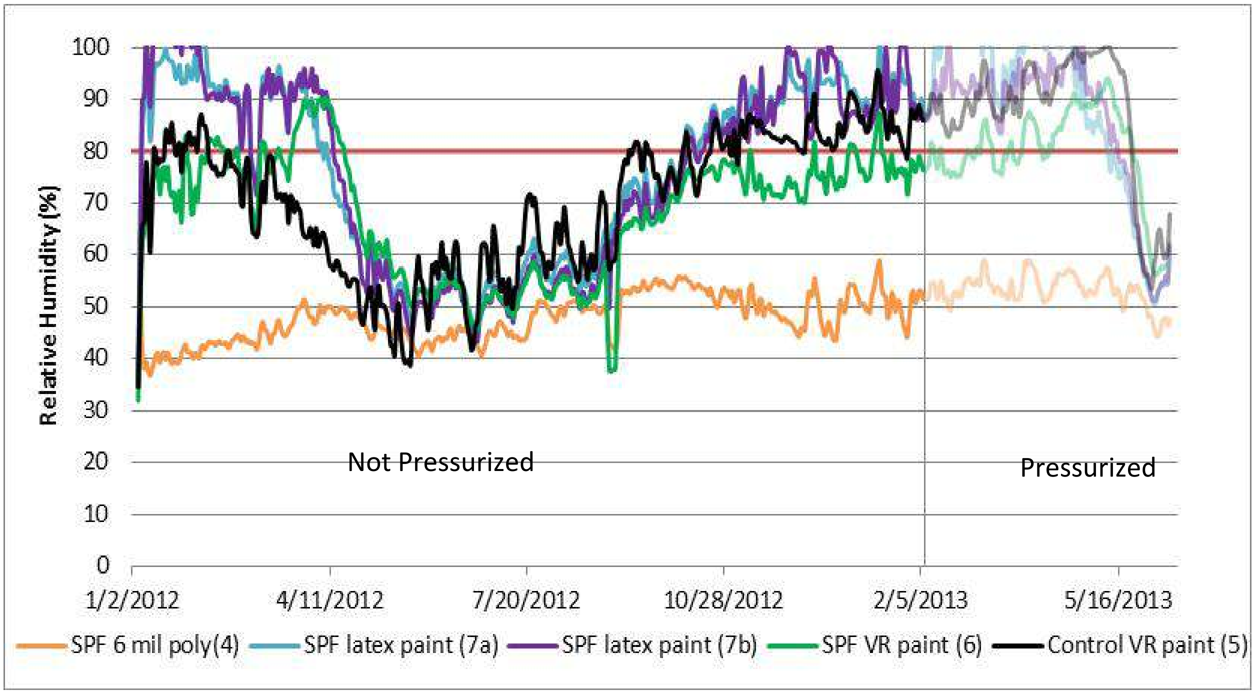

Figure 11. Relative humidity in the outlet cavity of the ocSPF walls. Walls with strong vapor retarders had humidity values below the 80% threshold for mold (the red line) for a majority of the study. Wall numbers are in parentheses.

A common way to estimate the potential for moisture problems in a wall is to compare the dew point within the conditioned space to calculated or measured temperatures at the sheathing plane (Lstiburek and Carmody, 1994). Figure 12 shows this comparison for the MTL, where the dew point is calculated using the measured interior temperature and relative humidity in the MTL. The actual dew point at the sheathing plane can be seen in Figure 11 when the relative humidity reaches 100%; discrepancies are due to the amount of vapor that gets through or around the vapor retarder. If the temperature at the sheathing plane falls below the dew point, moisture in the air within the stud cavity will condense onto the plywood. The orange (Wall 4), black (Wall 5), and purple (Wall 7a) lines in Figure 12 show the temperature at the sheathing plane in three walls. During the coldest months the temperature at the sheathing was below the dew point in all three walls. However, most of that time the temperature at the sheathing was also below the freezing point (blue line). Condensation at below freezing temperatures leads to the deposition of frost on the interior of the sheathing, limiting absorption of moisture into the plywood. Liquid moisture was only present at the sheathing when temperature was above freezing. These liquid moisture events did not last for extended periods of time and the moisture content sensors did not show any significant increases in moisture in the sheathing that would be attributed to condensing events.

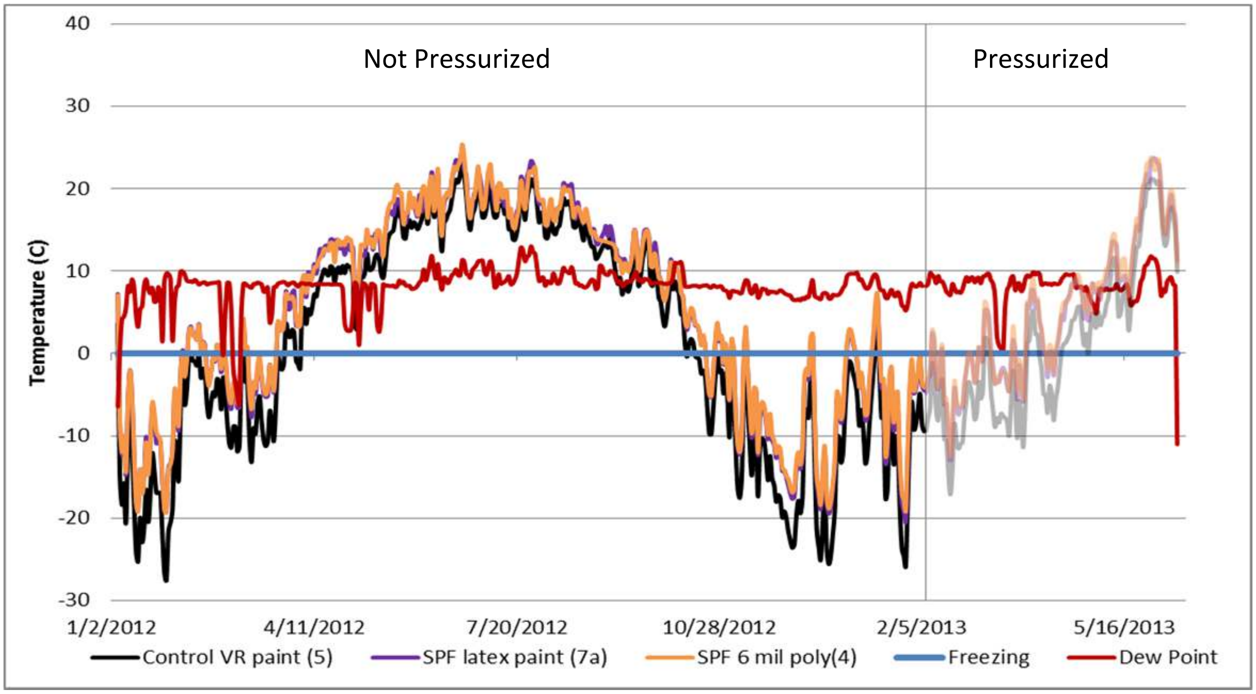

Figure 12. Temperature and dew point at the sheathing plane. When temperatures fall between the dew point and freezing line, condensation in liquid form will occur. Wall numbers are in parentheses.

A plot of relative humidity versus temperature can provide a better estimate of whether a wall is in danger of mold growth (Figure 13). When a certain number of hours (usually more than 2 weeks) are spent above the critical relative humidity/temperature function, the wall is in danger of growing mold. The critical function comes from equation 4 for critical mold conditions developed by Hukka and Viitanen (1999).

$$RH_{crit} = \begin{cases} -0.00267T^3 + 0.160T^2 - 3.13T + 100.0 & when\ T \leq 20°C \\ 80\% & when\ T > 20°C \end{cases} \quad (4)$$

Each data point (represented by x) in the chart represents 1 hour. In addition to critical temperature and relative humidity, a certain amount of continuous time at the critical conditions is required to initiate mold growth. The plots do not necessarily show continuous time above the critical line; the points above the line might have been spread over the course of the 17-month study.

The plots provide more insight into the difference between the unpressurized and pressurized walls. There are fewer data points for the pressurized data, but the humidity is higher in those three months.

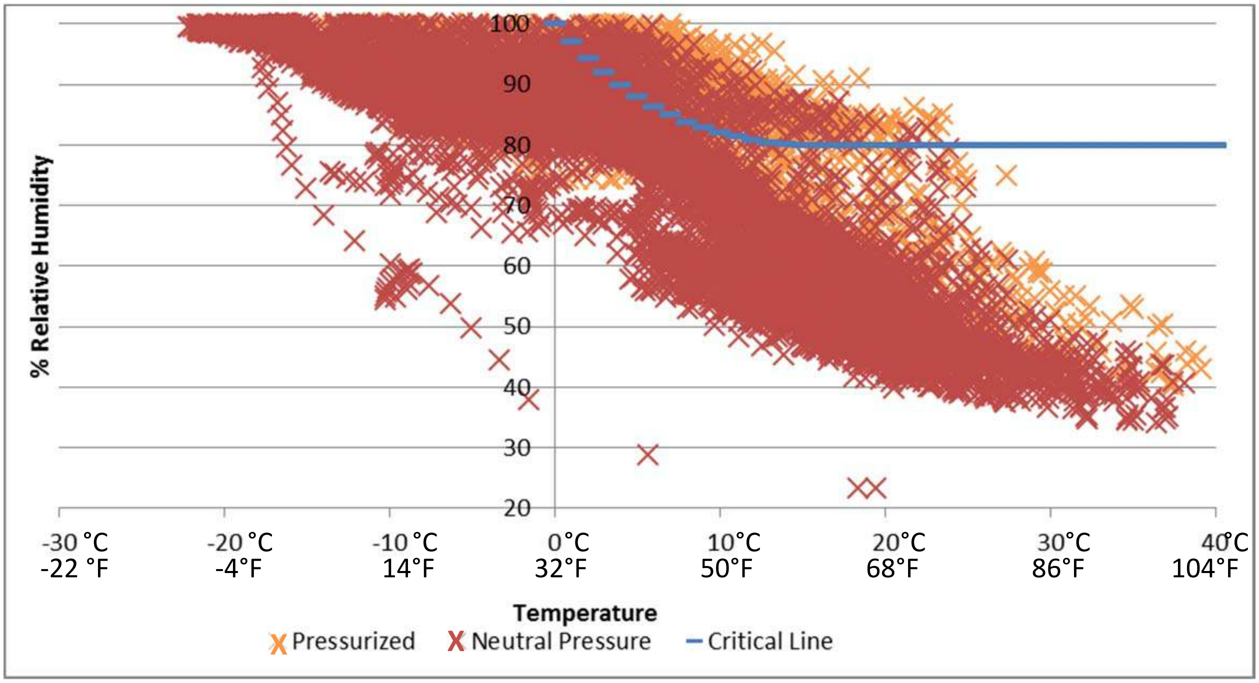

Figure 13. A plot assessing the mold growth potential on the plywood sheathing of the outlet stud cavity of Wall 7b. This wall had ocSPF insulation and latex paint as its vapor retarder, however a majority of the high humidity happened when the temperature was too low for mold growth. This test wall had one spot of visible mold at the sheating.

The fiberglass-insulated test wall with the smart vapor retarder (Wall 2 upper) had a larger change with the addition of pressure (Figure 14) when compared to the ocSPF-insulated test wall (Wall 2 lower) with the same vapor retarder (Figure 15). In the fiberglass test wall there are no hours above the critical line prior to pressurization, after pressurization was added the hours quickly accumulate. The ocSPF test wall with the smart vapor retarder did not have any hours above the critical line. This suggests that ocSPF is more resistant to air leakage than the fiberglass. However, the comparison of test Walls 5 and 6 (see Appendix) do not show the same trend for test walls with low-perm paint. Plots for all of the walls studied are available in the Appendix.

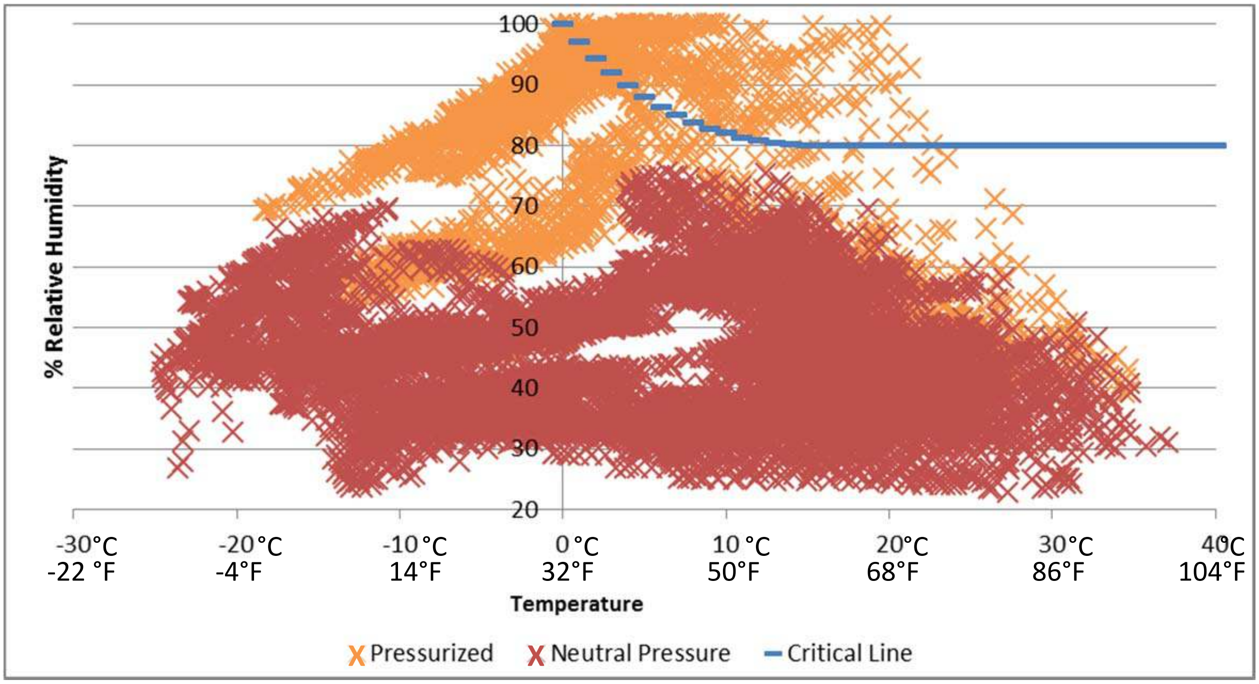

Figure 14. A plot of the upper cavity of Wall 2. This part of the wall had fiberglass batt behind a "smart" vapor retarder.

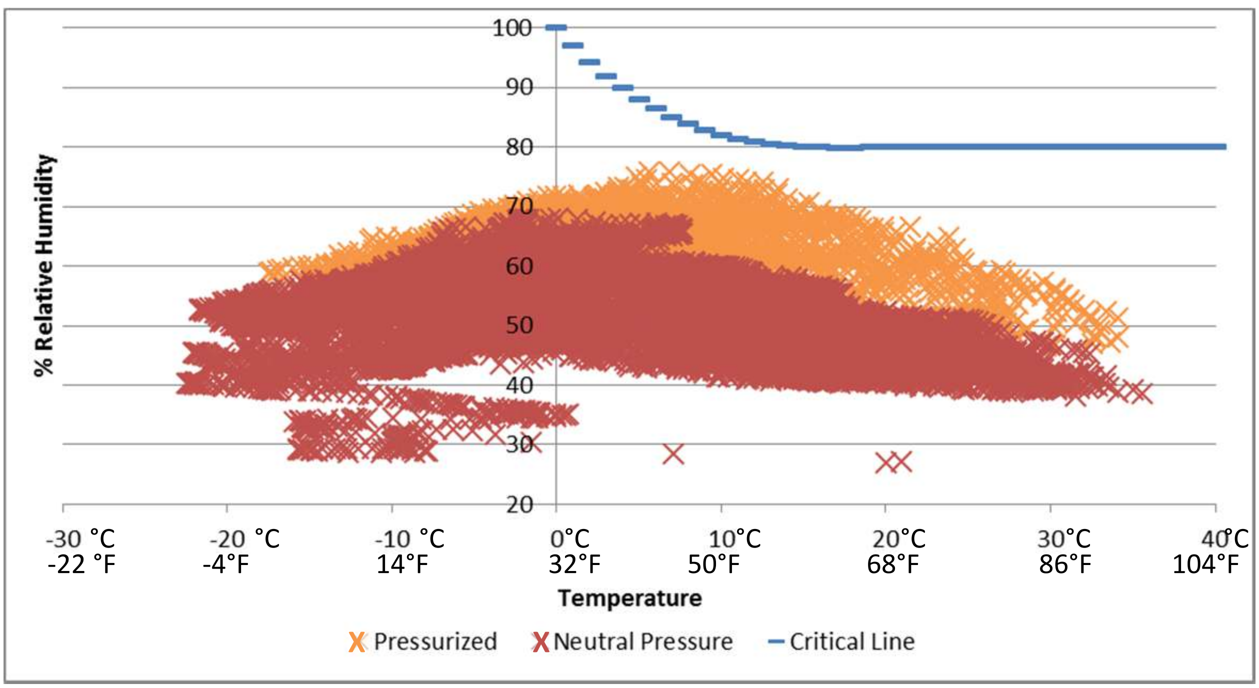

Figure 15. A plot of the lower cavity of Wall 2. This part of the wall had ocSPF behind a "smart" vapor retarder.

The pressurization of the MTL gave the most insight into the airtightness of ocSPF versus fiberglass. Wall 2 had ocSPF in the lower cavity and fiberglass in the upper cavity, both cavities had a smart vapor retarder (class II) behind the gypsum board. The relative humidity of both cavities stayed low and fairly comparable until the MTL was pressurized. The relative humidity inside the fiberglass wall increased dramatically with the pressurization of the lab (Figure 16). Figure 17 shows the discoloration on the back of the fiberglass at the split in the plywood, another indication of air leakage through the fiberglass.

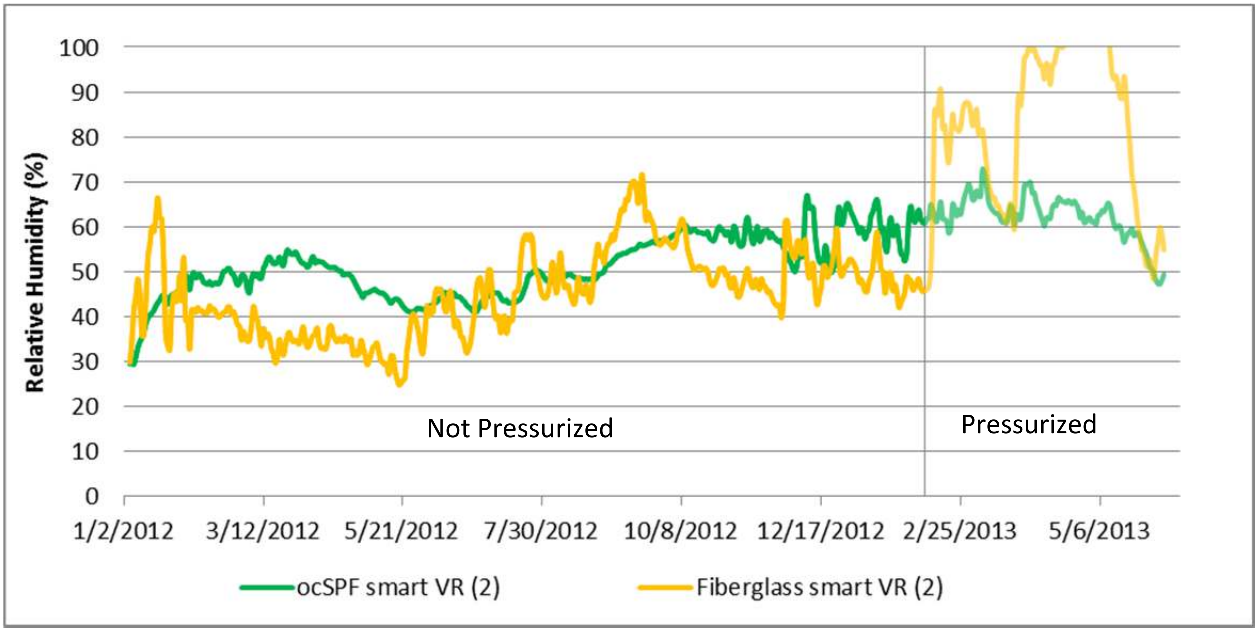

Figure 16. Relative humidity in Wall 2. The dip in humidity of the fiberglass wall after pressurization corresponds with a 2-week period of no pressurization.

Figure 17. Back of fiberglass from Wall 5. The line in the fiberglass is from the cut that was made in the plywood during construction. The grey discoloration around the line is most likely due to air leakage around the gap in the plywood. Photo courtesy of Randy Nicklas of Icynene.

These test results indicate that some level of vapor retarder is required when using ocSPF as insulation for walls in extreme cold climates. The 6 mil polyethylene and the smart vapor retarder both provided adequate vapor control for the ocSPF walls. The low perm paint did not perform as well as the vapor retarders, but did slightly better than the wall with latex paint. The wall with latex paint had high relative humidity levels through most of the winter, and at least one spot of black mold growing on the plywood sheathing (Figure 18).

Figure 18. Mold in the upper cavity of Wall 7b. The spot of mold is less than 1 in^2.

The smart vapor retarder and the low perm paint have a similar permeance, less than 1 perm, making them class II vapor retarders. However, the smart vapor retarder performed much better than the low perm paint (Figure 19). The smart vapor retarder was sealed to the outer studs with acoustical sealant and the gypsum board was screwed over the retarder, compressing the vapor retarder to the studs wherever it was not sealed. The paint was applied to the gypsum board, which was sealed to the outer studs with silicone caulk. Around the air leakage areas (the window, the outlet, and along the base plate) the paint was not as well sealed as the smart vapor retarder and possibly allowed for larger leakage paths than the smart vapor retarder behind the gypsum board.

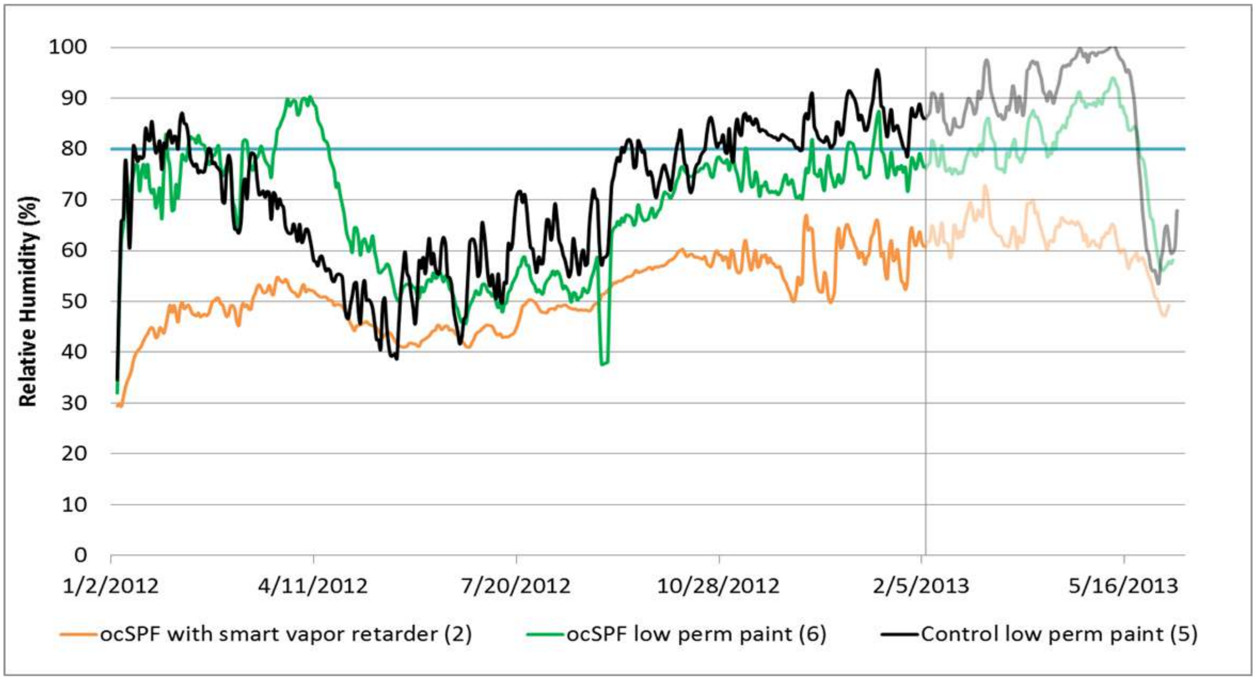

Figure 19. Comparison of walls with class II vapor retarders. The class II vapor retarders showed different moisture performance from each other. Wall numbers are in parentheses.

Overall Wall Performance: Cellulose Walls

The hygrothermal performance of the cellulose walls is shown in Figures 20 and 21. The portion of the cellulose wall with only latex paint (Wall 3 lower) went above 16% moisture content. The portion with a 6-mil polyethylene vapor retarder (Wall 3 upper) performed similarly to the fiberglass control wall with low perm paint. When the MTL was pressurized, the cellulose wall with a vapor retarder outperformed the fiberglass wall with low perm paint.

The relative humidity in the cellulose wall at the sheathing plane followed a similar pattern as the moisture content. The wall with a strong vapor retarder performed well, with the humidity staying below the 80% threshold. The wall with only latex paint had higher relative humidity, especially during the end of the study when the MTL was pressurized.

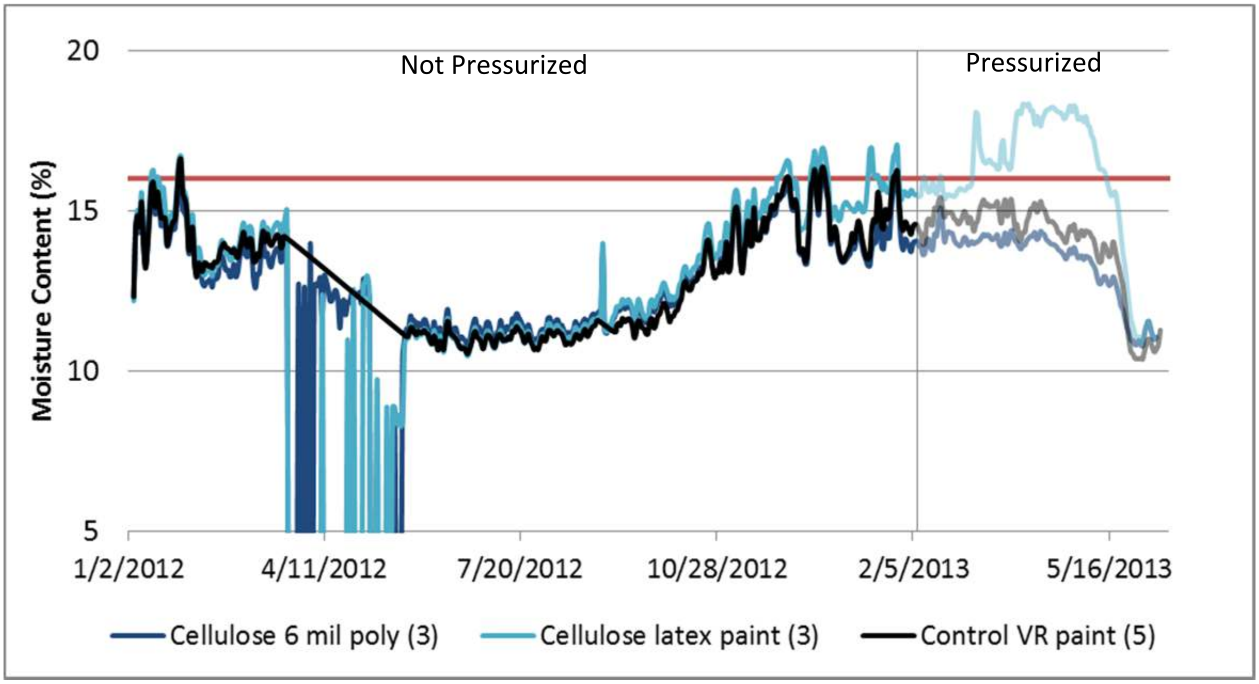

Figure 20. The moisture content of the cellulose wall. Cellulose with a strong vapor retarder performed slightly better than the fiberglass wall with the low perm paint. The straight line in April 2012 is due to errors in all of the moisture content sensors. The red line is the 16% line of concern for moisture content. Wall numbers are in parentheses.

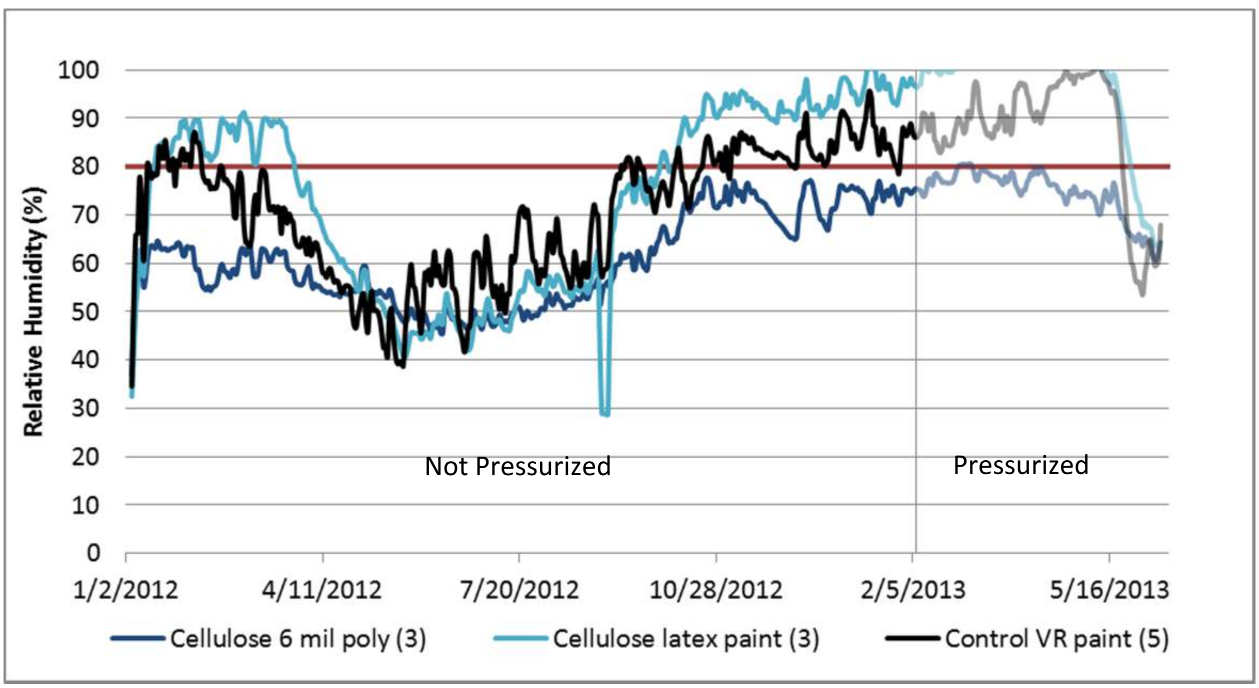

Figure 21. The relative humidity of the cellulose wall. Cellulose with a strong vapor retarder performed slightly better than the fiberglass wall with the low perm paint. The red line is the 80% relative humidity line of concern. Wall numbers are in parentheses.

Dense-pack cellulose in this wall configuration requires some form of vapor retarder in the cold Fairbanks climate. A class I retarder provided adequate control of moisture infiltration attributable to water vapor diffusion and air leakage. This study did not address a class II vapor retarder for cellulose.

Window Annular Space Hygrothermal Performance

The annular space around each mock window was monitored for relative humidity. Five of the walls had one-component spray foam (can foam) in the annular space and one had fiberglass insulation. Figure 22 shows the difference in relative humidity between the foam (Walls 7a and 6 were used to represent the average) and the fiberglass (Wall 5). The fiberglass-filled annular space shows slightly elevated humidity during the winter months relative to the annular spaces filled with foam. With pressurization the humidity in the fiberglass and foam-filled annular spaces rose above the 80% threshold. The spray foam shows improvement over fiberglass, but the elevated humidity with pressurization reinforces the need for an additional method of sealing the annular space (i.e. caulking with backer rod).

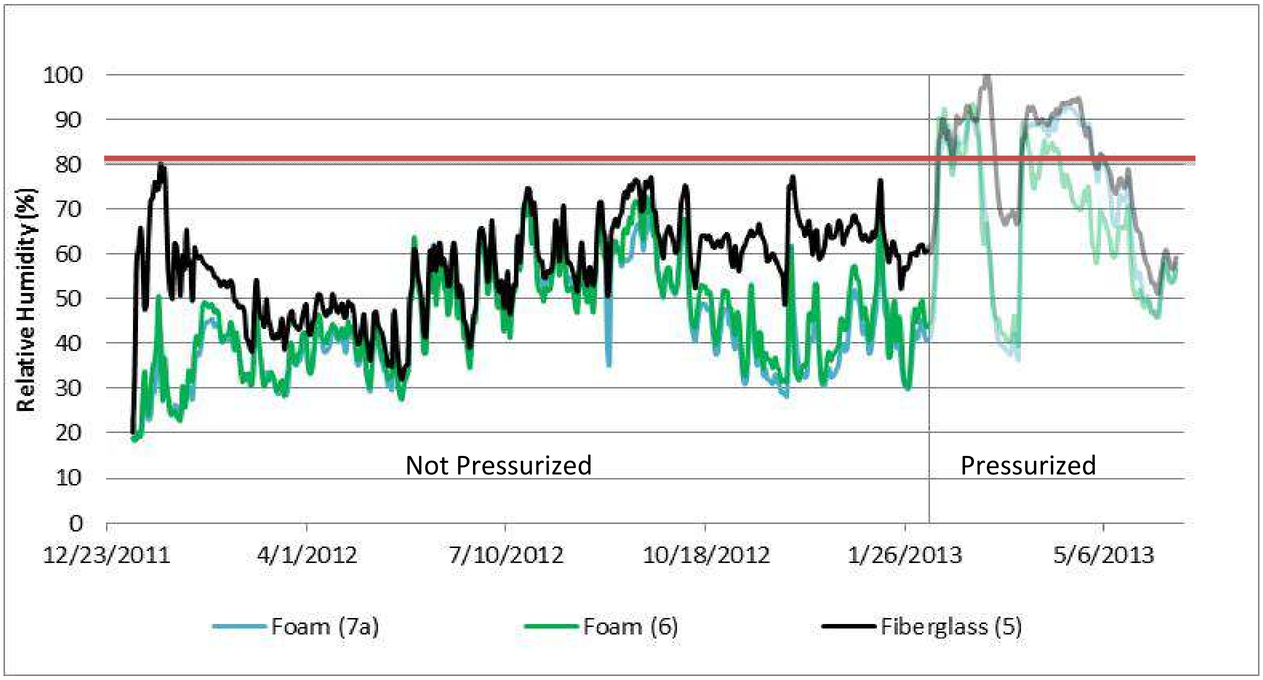

Figure 22. Relative humidity in the window annular space. Walls 7a and 6 represent the average trend in humidity in the spray foam within the space. Wall numbers are in parentheses.

Sub-floor Hygrothermal Performance

A comparison of the humidity under the sub-floor is presented in Figure 23. Without pressurization, all of the subfloor rim joists stayed below the danger threshold although the relative humidity behind the fiberglass was approaching 80% just before pressurization. With pressurization only the XPS insulated rim joist sealed with one-component spray foam stayed below the risk threshold.

Using fiberglass or XPS in the rim joist area are common techniques in cold climate residential construction. This study reaffirms that if fiberglass is used it needs to be sealed with an air and vapor retarder. The XPS/can spray foam combination appears to be a good option for the rim joists. Another common cold climate construction technique is to use closed-cell polyurethane to insulate rim joists. These findings suggest that substituting open-cell polyurethane would present a potential risk for mold growth if a vapor retarder (less than 1 perm) is not applied over the ocSPF. This risk would be greater in the higher levels of multi-story structures due to the additional pressure created by the stack effect.

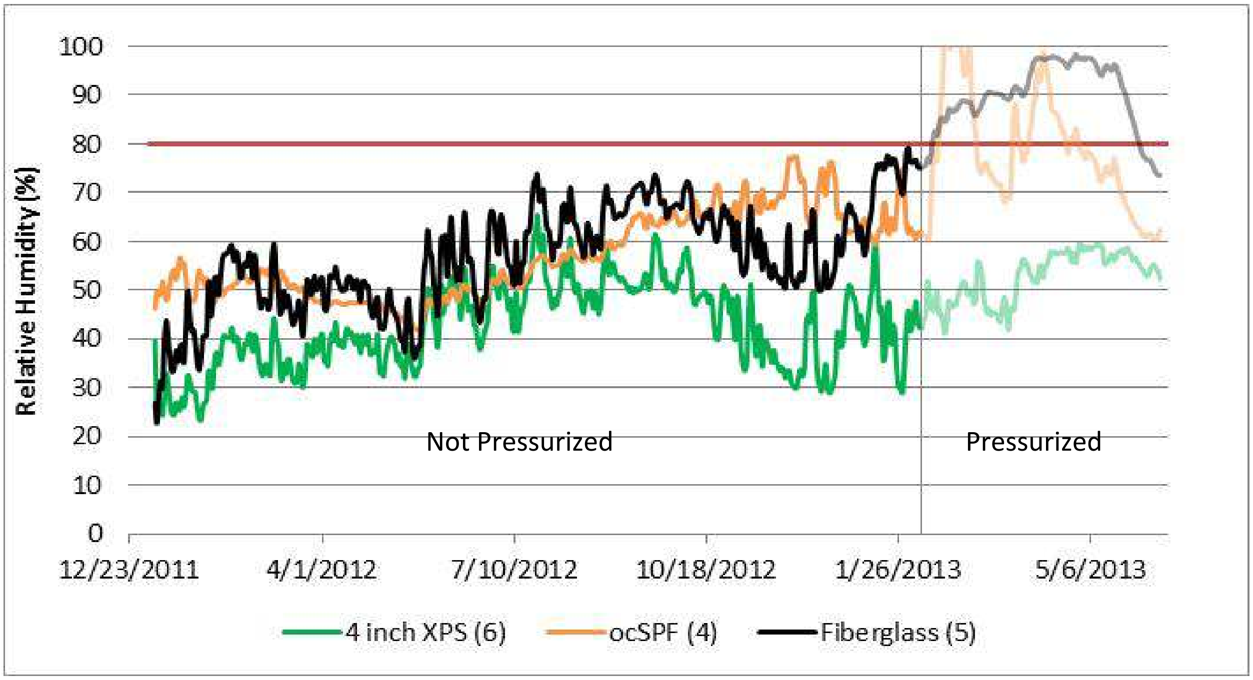

Figure 23. Relative humidity in the rim joist under the false floor. Four inches of extruded polystyrene sealed around the edges with one-component spray foam was the most effective at moisture control. The red line marks the bottom of the risk zone. Wall numbers are in parentheses.

In-Situ R-value Testing

The in-situ R-value analysis of the test walls found large variation in the wall R-values. The variations are hard to specify and are likely due to a variety of factors. For example there were voids found in some of the ocSPF walls when they were taken apart, resulting from less-than-perfect spraying conditions (Figure 24). The walls were sprayed inside; however the spraying equipment was in a truck outside in late December when the ambient temperature was around 4°F. The spray foam contractor had problems with faulty drum heaters. There were problems keeping the lines and the barrels at the correct temperature, which may have contributed to the voids. Another source of variation in the in-situ R-values is the air movement inside the MTL which introduced convective heat transfer that the sensors cannot read. In aggregate, these factors lead to the in-situ R-values being provisional data.

Figure 24. Voids in the ocSPF of Wall 7a. Instead of adhering to the plywood, the ocSPF created an air pocket throughout the lower cavity of Wall 7a. This photo shows the full span of the 15-inch stud cavity.

Due to the variations in R-value across the walls and over time CCHRC decided to focus the R-value analysis on the fiberglass wall (Wall 5). The R-value per inch for the fiberglass is 3.81 hr ft^2 °F/BTU based on the manufacturers specifications. The in-situ R-values for the fiberglass insulation in Wall 5 ranged from 2.64 to 3.78 hr ft^2 °F/BTU per inch over the course of the 3 month R-value testing.

The two months of the R-value testing, conducted during November and December 2012, recorded very noisy heat flux data which was difficult to use to calculate a consistent R-value. Figure 25 shows a portion of the R-value data for the fiberglass in Wall 5. The overall fiberglass R-value swings from 14 to 30 hr ft^2 °F/BTU over the course of 16 days. There is a brief window then the data is less noisy when the exterior temperature rose well above 0°F (when the electric heaters were not interfering with the signal). The average fiberglass R-value for this period is 18.7 hr °F ft^2/BTU, close to the specified R-21 for fiberglass. However, when the data is averaged from November 2012 to January 2013 the fiberglass R-value is 14.2 hr °F ft^2/BTU.

In mid-January CCHRC discovered a problem with the grounding of the data logger. After providing a better ground connection, subsequent in-situ R-value data had less noise. The R-value data in Figure 26 has a smooth line but has some variations that cannot be explained by the external temperature fluctuations. During this period the overall fiberglass R-value ranged from 7 to 17 hr ft^2 °F/BTU.

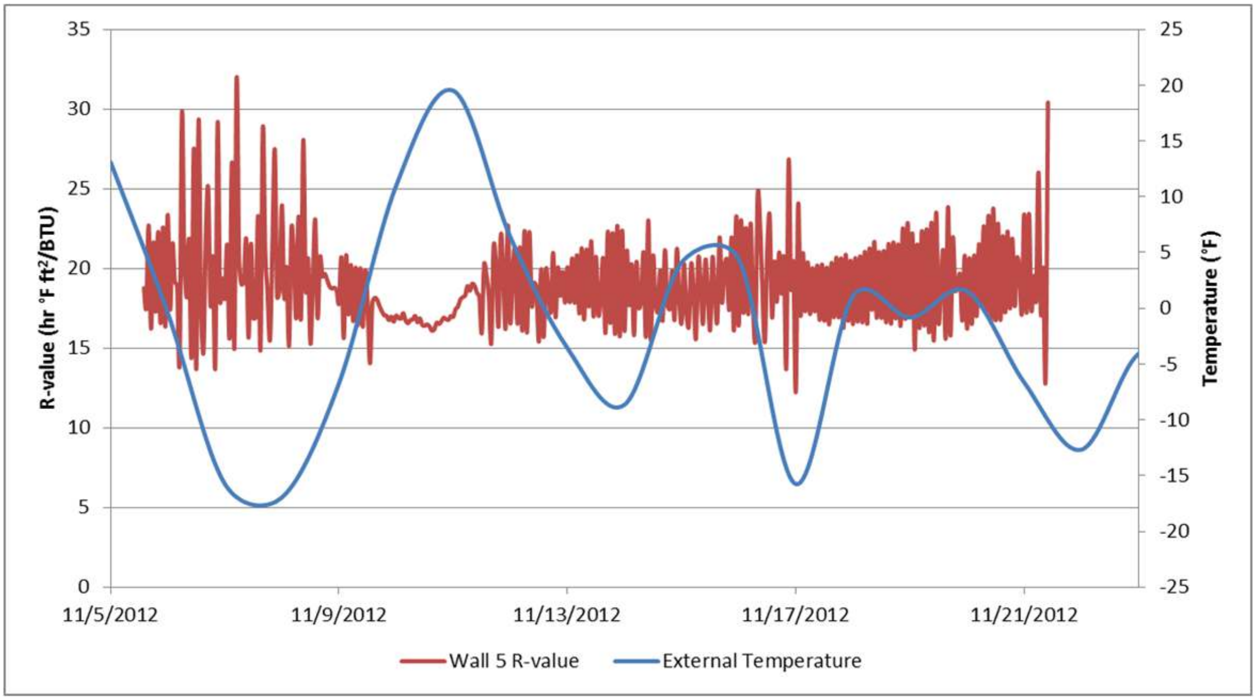

Figure 25. Early in-situ R-value data. Later data were less noisy with the logger better grounded.

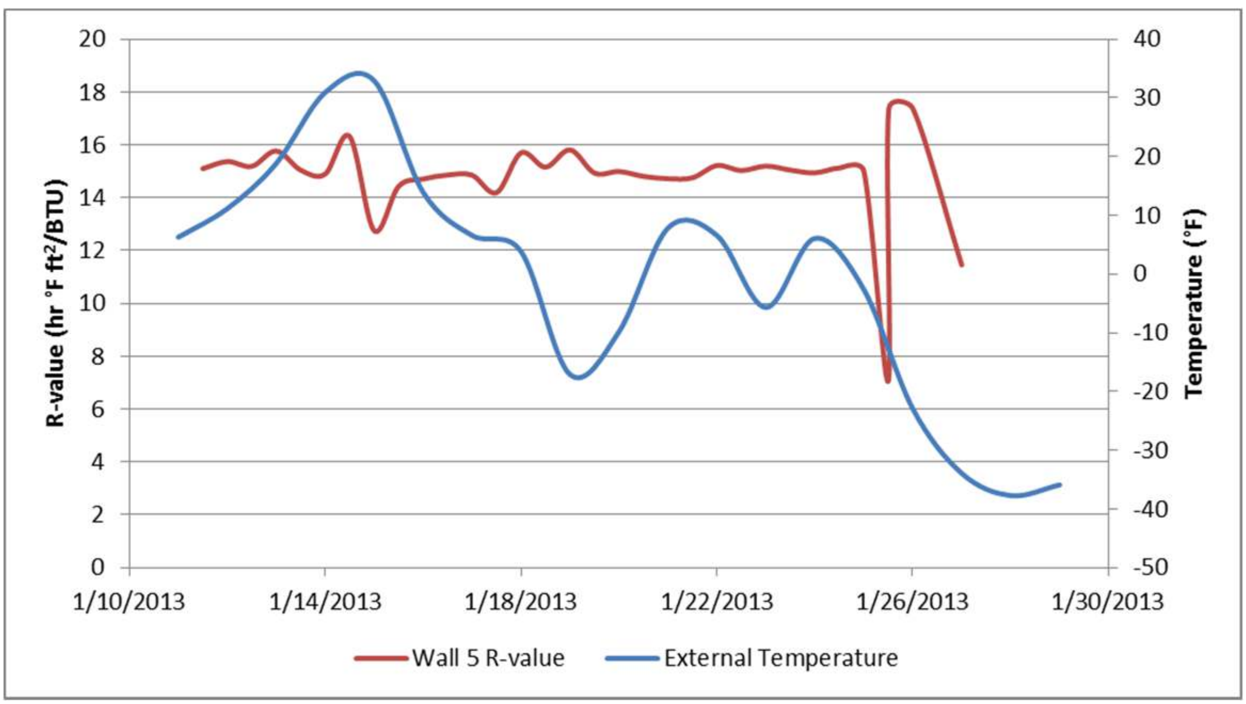

Figure 26. R-value and external temperature for a well-grounded logger. All of the heat flux sensors showed similar patterns during this period. A few of the deviations correspond with temperature changes but some do not and remain unexplained.

The heat flux sensors were all recalibrated after the R-value testing and were found to be close to their original calibration. A final test was run on Wall 5 to determine if variations were the result of a single sensor. All of the heat flux sensors were placed on Wall 5 and the R-value was calculated for 3 days. Figure 27 shows the results of this test. The R-value averages 20 across all the sensors but the individual sensor averages range from 18 to 25 hr ft^2 °F/BTU. Further testing showed that no single sensor was a constant outlier; it is assumed that the variation in the sensors had more to do with the sensor location on the wall, small variations in the wall construction, and combined heat and mass transfer phenomena occurring within the wall assembly, than variability in the sensors.

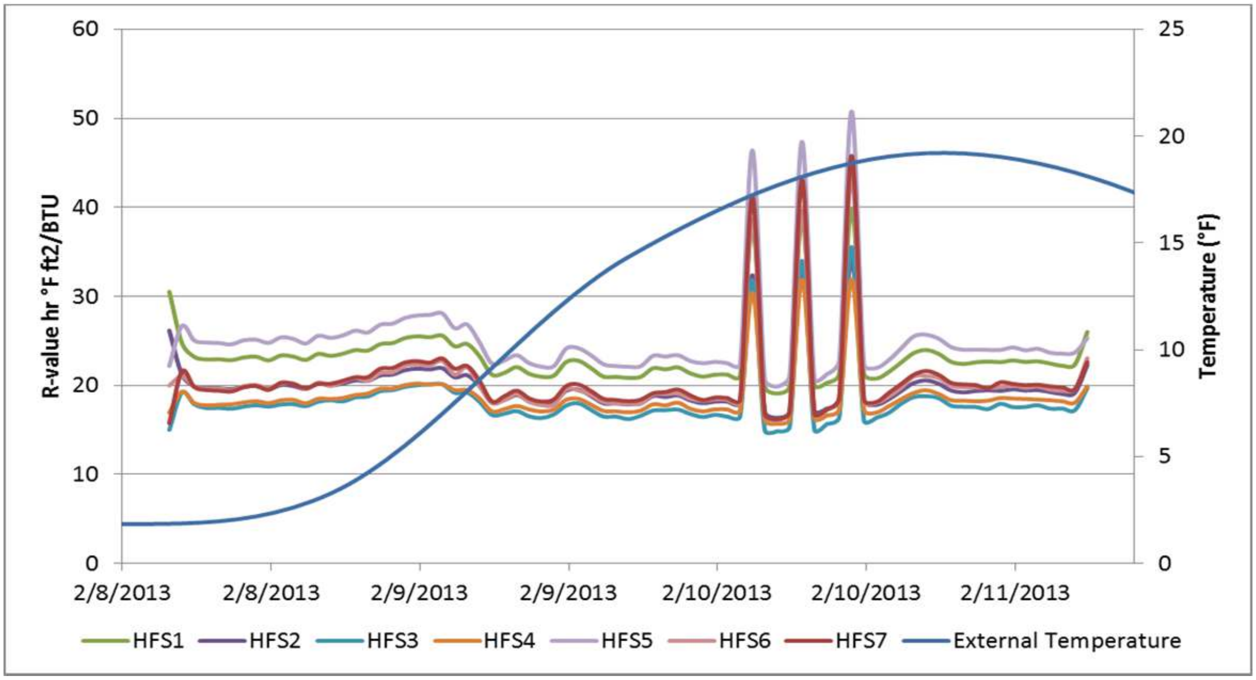

Figure 27. All heat flux sensors deployed on Wall 5 for 3 days. The effect of the temperature can be seen as the R-value drops with the increase in exterior temperature. The causes of the three spikes in this data are unknown but could be the result of electrical interference.

The sensors all follow the same pattern, but with substantial offset, illustrating that the heat flux sensors provided reasonable accuracy when viewed in aggregate but had poor precision relative to standard lab methods for determining R-value. The three spikes in the data all happened on the same day, four hours apart. The physical phenomena that created the spikes are unknown, however for such a short timeframe the spikes have an effect the average R-value.

The increase in external temperature during this period shows the effects the outside temperature has on the R-value which fluctuates as the exterior temperature changes. While variations in the insulation R-values were expected in the in-situ analysis, the large variations per wall over-time were unexpected. Future studies under more controlled conditions are required to better access the causes of such variation before this type of analysis is used in the future.

Modeling

WUFI Pro 5.2 was used to extend performance predictions beyond the 17-month MTL assessment. Empirical data from the unpressurized MTL were compared with models from WUFI. The WUFI model output compared well with the ocSPF test wall data in terms of relative humidity (Figures 28 and 29). WUFI shows walls with only latex paint drying at a slower rate in the spring than was found in the test walls (see Figure 29). This slower drying leads to an increase in modeled moisture content for these walls (Figure 31).

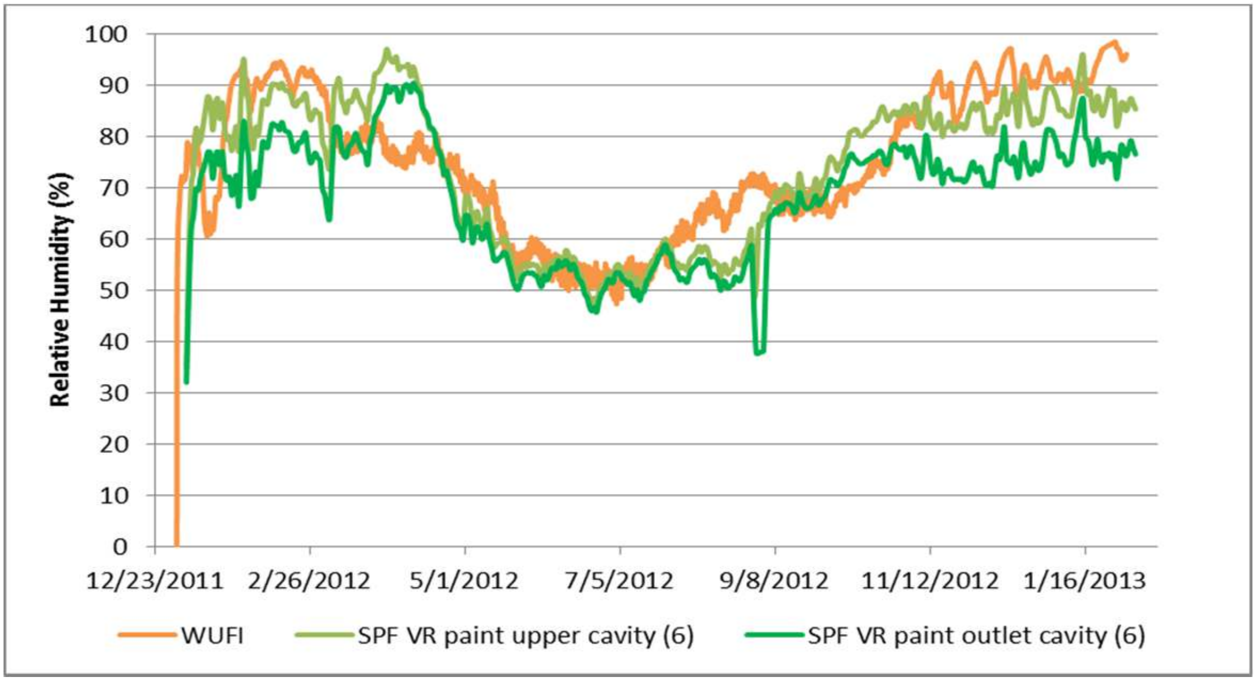

Figure 28. Comparision of WUFI relative humidity at the sheathing plane data to Wall 6. Walls with a strong vapor retarder compared well to the WUFI model. Wall numbers are in parentheses.

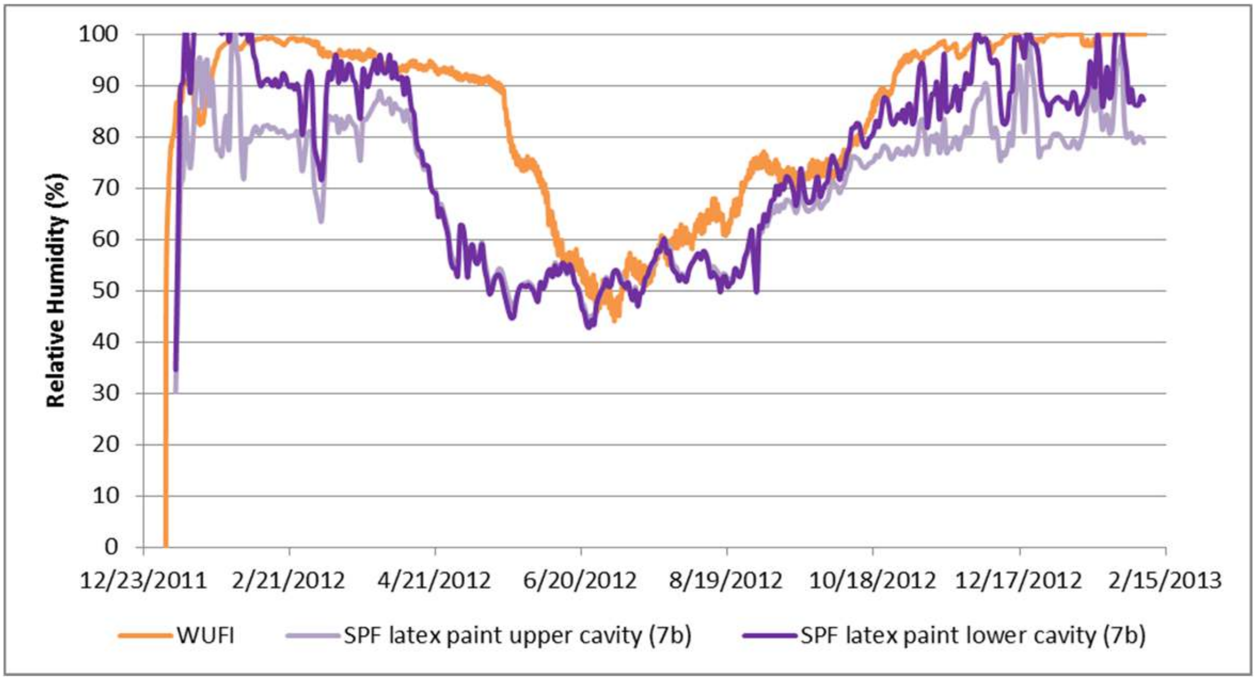

Figure 29. Comparision of WUFI relative humidity at the sheathing plane data to Wall 7b. Notice the lag in the drying time in the WUFI model for walls with latex paint vapor retarder. Wall numbers are in parentheses.

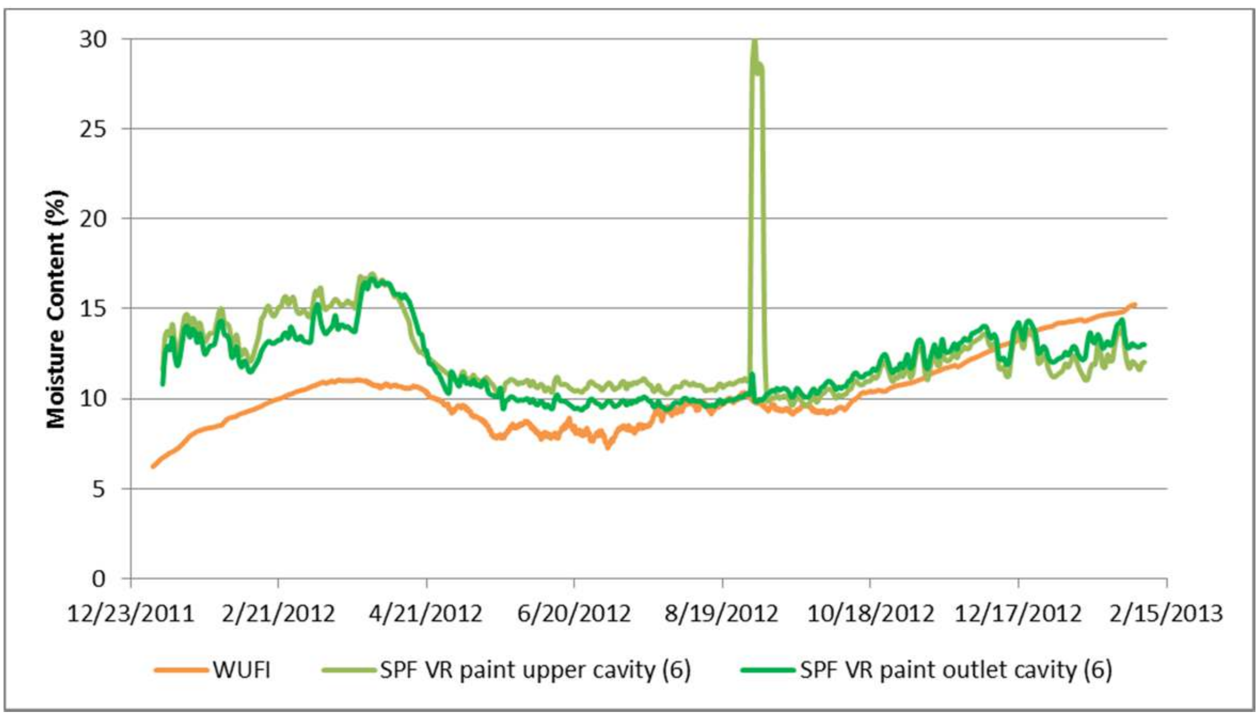

Figure 30. Comparison of WUFI sheathing moisture content to the MTL Wall 6. The green spike is likely an error in the data collection system. Wall numbers are in parentheses.

In terms of moisture content, the WUFI model predicted lower moisture content than was measured in the MTL walls with a class II vapor retarder (Figure 30). Some of this can be explained by the fact that the moisture content sensors cannot measure very low moisture contents (below 7%). The walls with only latex paint do not agree with the modeled moisture content, showing lower moisture content than WUFI predicted (Figure 31). The walls hit a modeled maximum of 35% moisture content in late March of the second winter. The model shows the plywood sheathing drying back to 8% moisture content by late June; however, it rises to 35% toward the end of every winter. This discrepancy may be due to the slower drying trend in the model, which allows for higher humidity and temperature for a longer time in the spring than the test walls actually encountered.

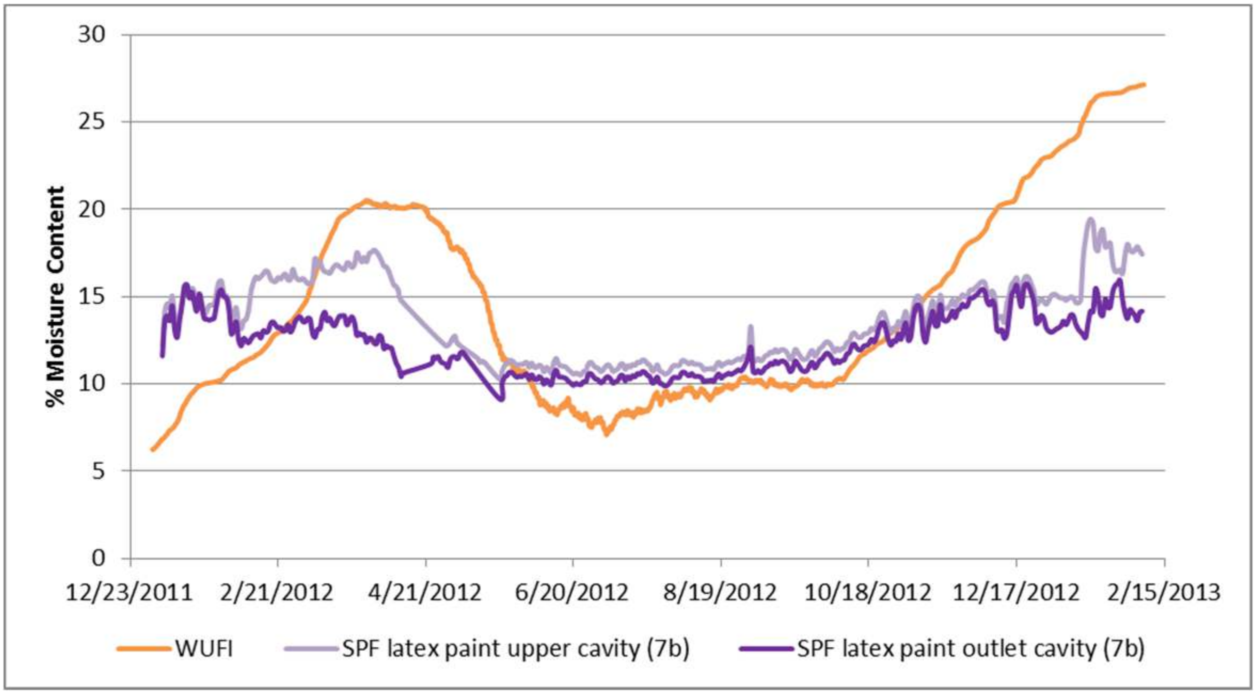

Figure 31. Comparison of WUFI sheathing moisture content to Wall 7b. WUFI predicted that the moisture content will reach 35% toward the end of every winter. Wall numbers are in parentheses.

WUFI had a similar correlation in the cellulose walls (Figures 32 and 33). The model slightly underestimated the relative humidity in the wall with only latex paint and slightly overestimated the humidity in the wall with a strong vapor retarder. However, the lag in drying found in the ocSPF walls is less drastic in the cellulose walls and much closer to the MTL walls. In the 10-year model, the cellulose wall with only latex paint bordered on having mold problems.

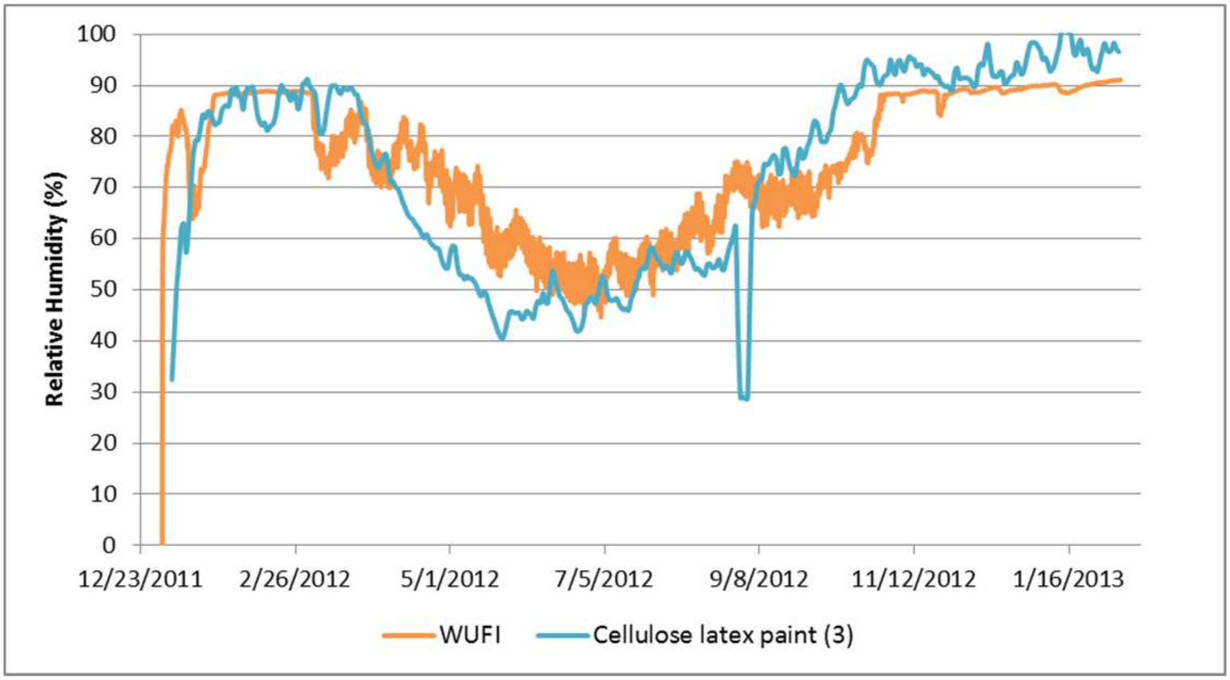

Figure 32. Comparison of WUFI sheathing relative humidity to the cellulose-insulated test wall (Wall 3). This portion of the wall had latex paint as its vapor retarder. Wall numbers are in parentheses.

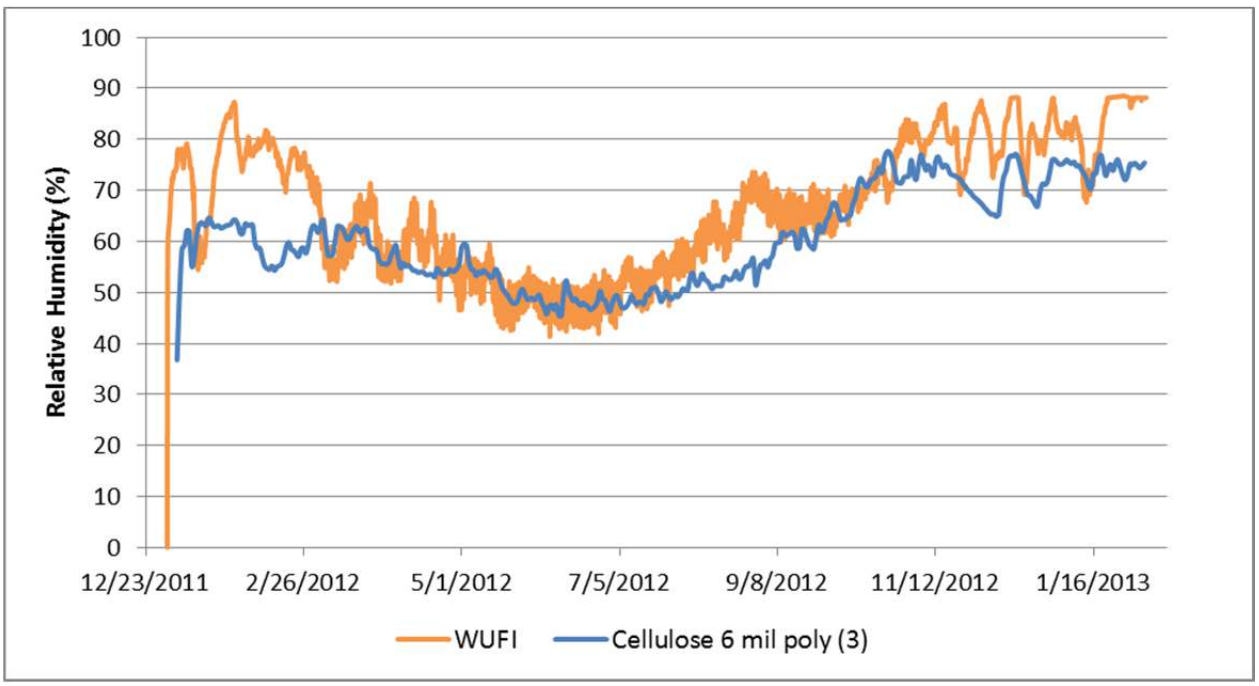

Figure 33. Comparison of WUFI sheathing relative humidity to cellulose-insulated test wall (Wall 3). This portion of the wall had a 6 mil polyethylene vapor retarder. Wall numbers are in parentheses.

WUFI predicted that the ocSPF walls with only latex paint would show signs of moisture related problems, whereas a low perm layer (less than 1 perm) creates walls largely free of moisture-related problems. Table 4 presents some of the results of the 10 year model for the MTL walls. A rating of green means the wall does not have the conditions that allow mold to develop at the sheathing. Yellow is a cautionary color, meaning that there are sometimes conditions for mold but in these cases only in the worst conditions (i.e. the optimal culture medium, combined with high initial spore moisture content). The WUFI Bio-output does not completely agree with the MTL teardown data. Wall 5, in particular had several spots of mold on the sheathing when it was taken apart (Figure 34) and Wall 7 only had one small spot of mold (Figure 18). WUFI Bio did not predict the growth of mold in Wall 5 over the 10 year model, yet the test wall developed mold within its first year and a half.

Table 4. WUFI Bio results.

	WUFI Bio 10 year result	MTL results
Wall 2, R-13 ocSPF with a smart vapor retarder	Green	No visible mold
Wall 2, R-11 Fiberglass with a smart vapor retarder	Green	No visible mold
Wall 3, R-21 Cellulose with latex paint	Yellow at worst conditions	No visible mold
Wall 3, R-21 Cellulose with 6 mil polyethylene	Green	No visible mold
Wall 4, R-21 ocSPF with 6 mil polyethylene	Green	No visible mold
Wall 5, R-21 Fiberglass with low perm paint	Yellow at worst conditions	Isolated spots of mold
Wall 6, R-21 ocSPF with low perm paint	Yellow at worst conditions	No visible mold
Wall 7, R-21 ocSPF with latex paint	Red	Isolated spot of mold

Figure 34. Mold behind the fiberglass of Wall 5. This wall had a several spots of mold on the sheathing that WUFI Bio does not predict.

Conclusions

The hygrothermal performance of open cell spray polyurethane foam and dense-pak cellulose is better than fiberglass batts if the insulations are used in conjunction with a class I vapor retarder. This finding is based on the measured relative humidity at the sheathing plane, plywood sheathing moisture content, and visible mold growth in the test walls. A class II vapor retarder, like the smart vapor retarder and the low perm paint, was somewhat effective with ocSPF in this short-term study for providing moisture control. Whether a class II vapor retarder can protect ocSPF and cellulose-insulated walls adequately in an extreme cold climate was not resolved in this study. Both the ocSPF and cellulose had high levels of relative humidity at the sheathing when only a class III vapor retarder was present. These high levels of humidity tended to correspond with below-freezing temperatures at the sheathing, which kept the moisture content of the sheathing low as moisture was not absorbed by the plywood.

The in-situ R-values for the test walls were too variable to provide enough information on the thermal performance. Insulation installation variation, large temperature differentials, and unknown sources of interference resulted in measurements that are substantially different than R-values measured in controlled laboratory conditions. Further analysis of the method in a more controlled situation is necessary to improve future in-situ R-value testing.

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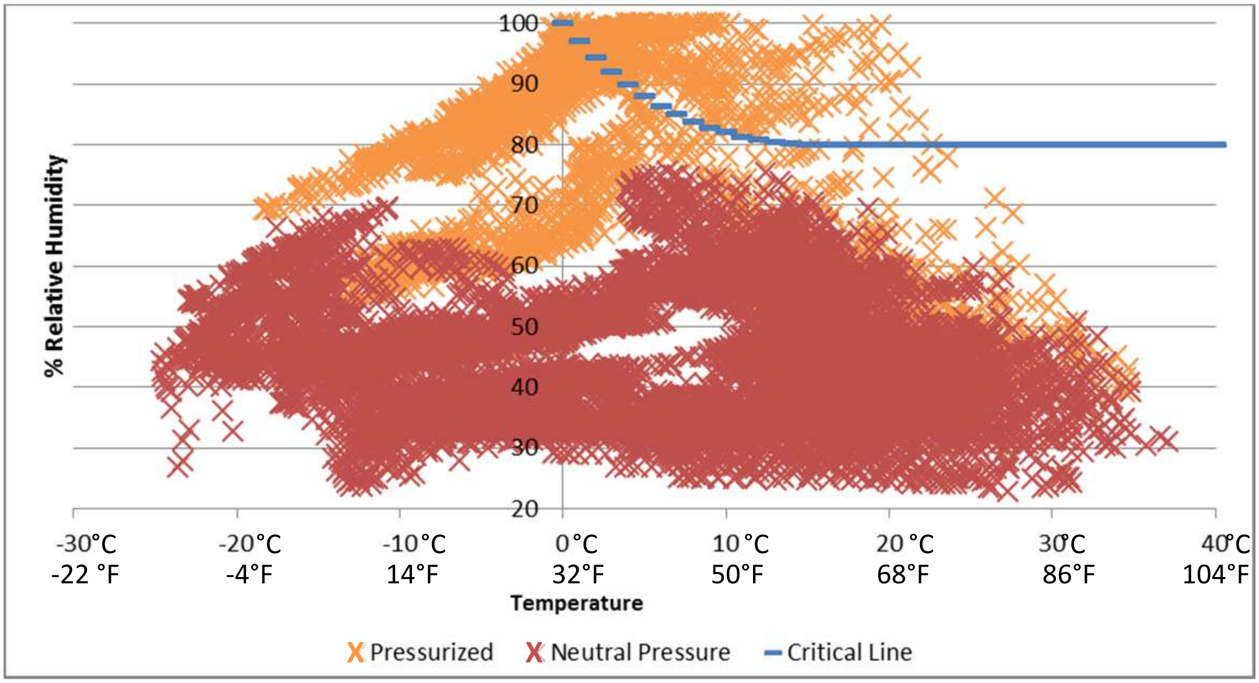
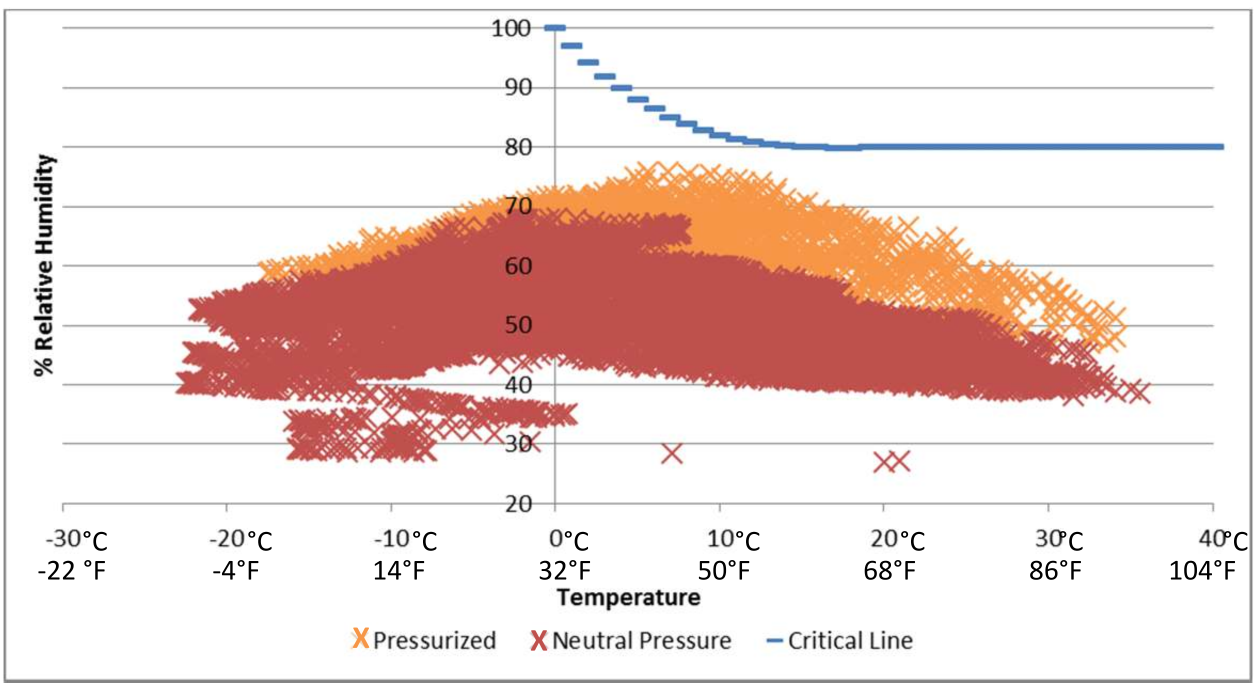
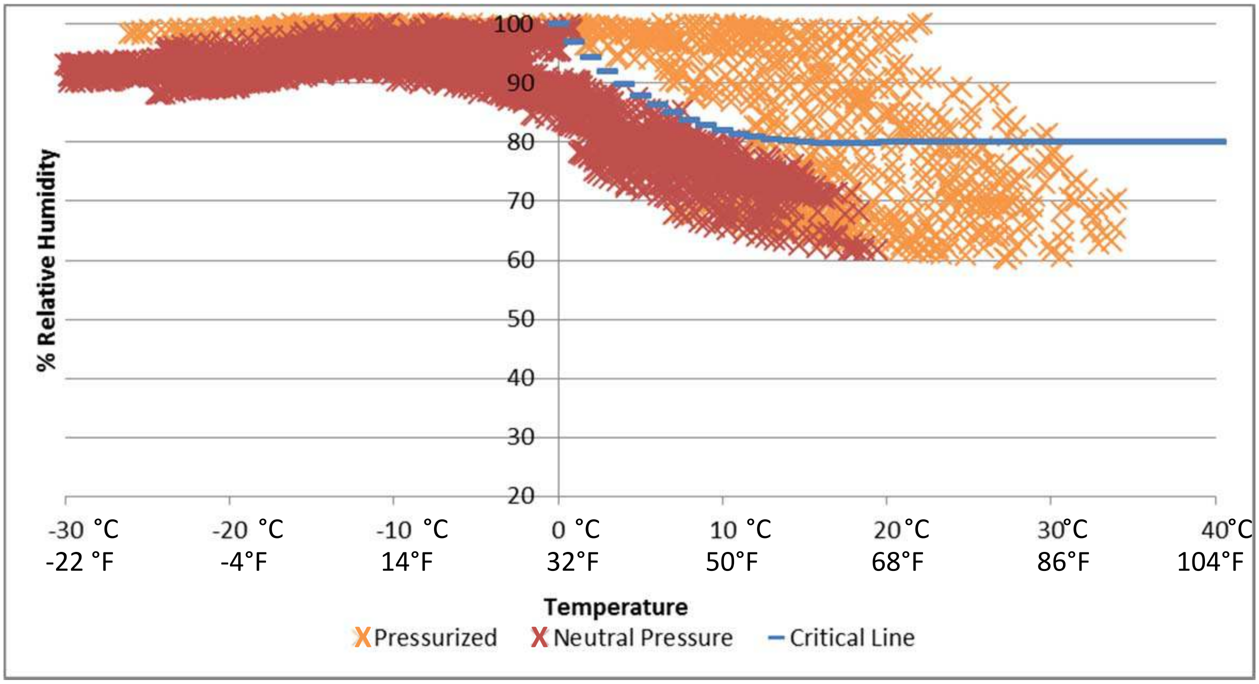
Appendix A – Scatter Plots for all Walls



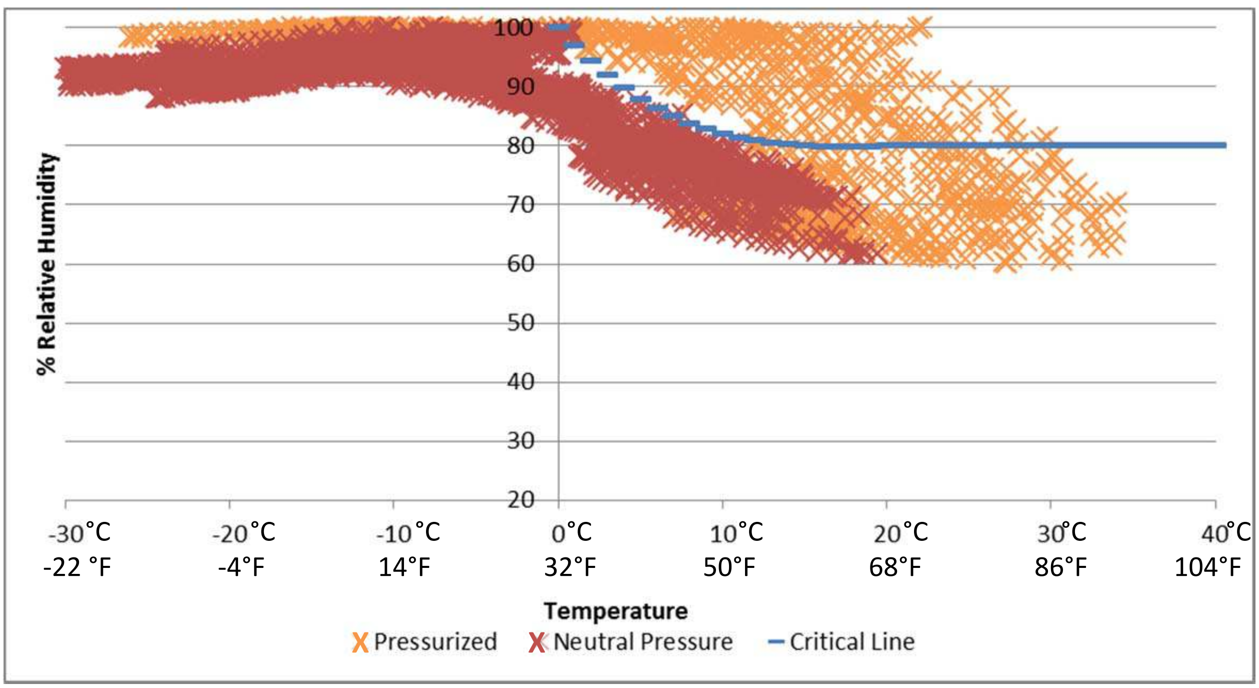
Wall 2 upper cavity, fiberglass with a smart vapor retarder



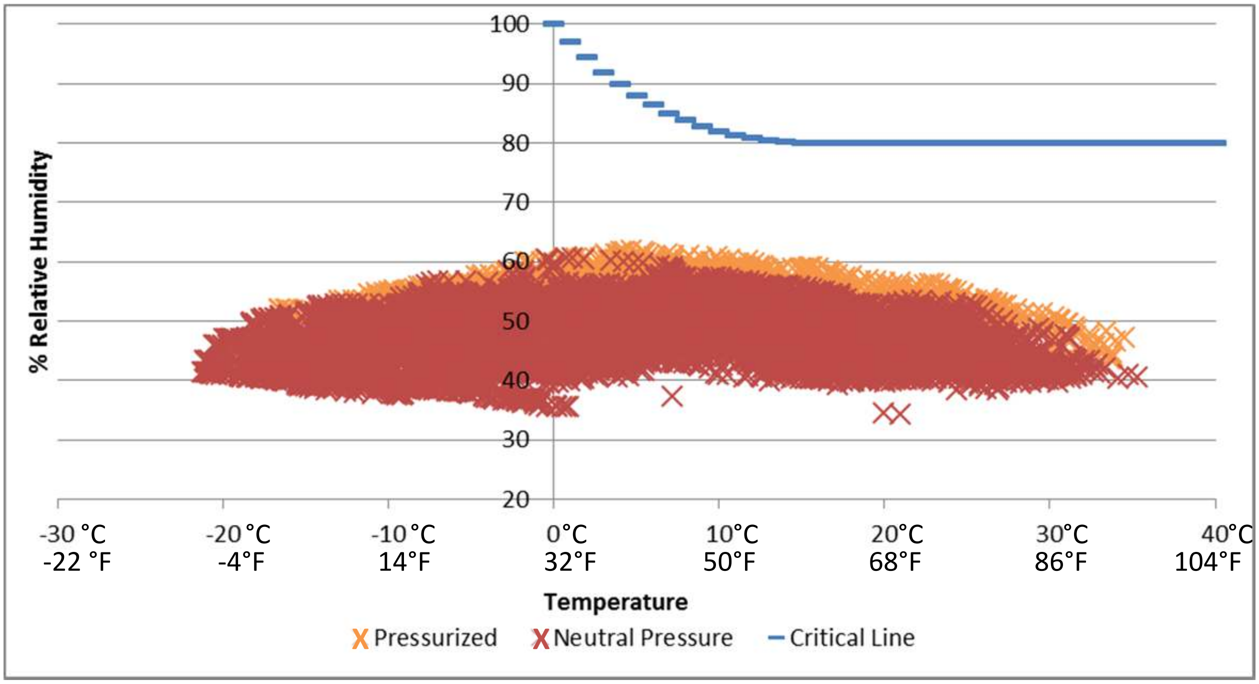
Wall 2 lower cavity, ocSPF with a smart vapor retarder



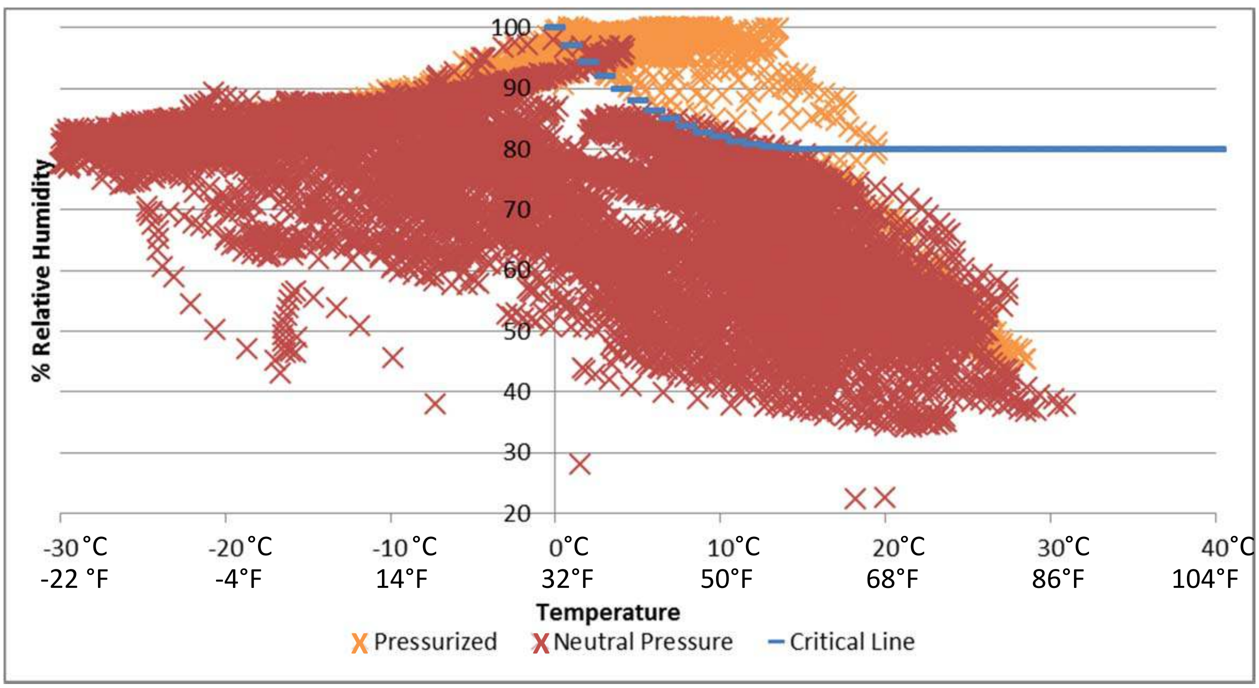
Wall 3 lower cavity, cellulose with latex paint



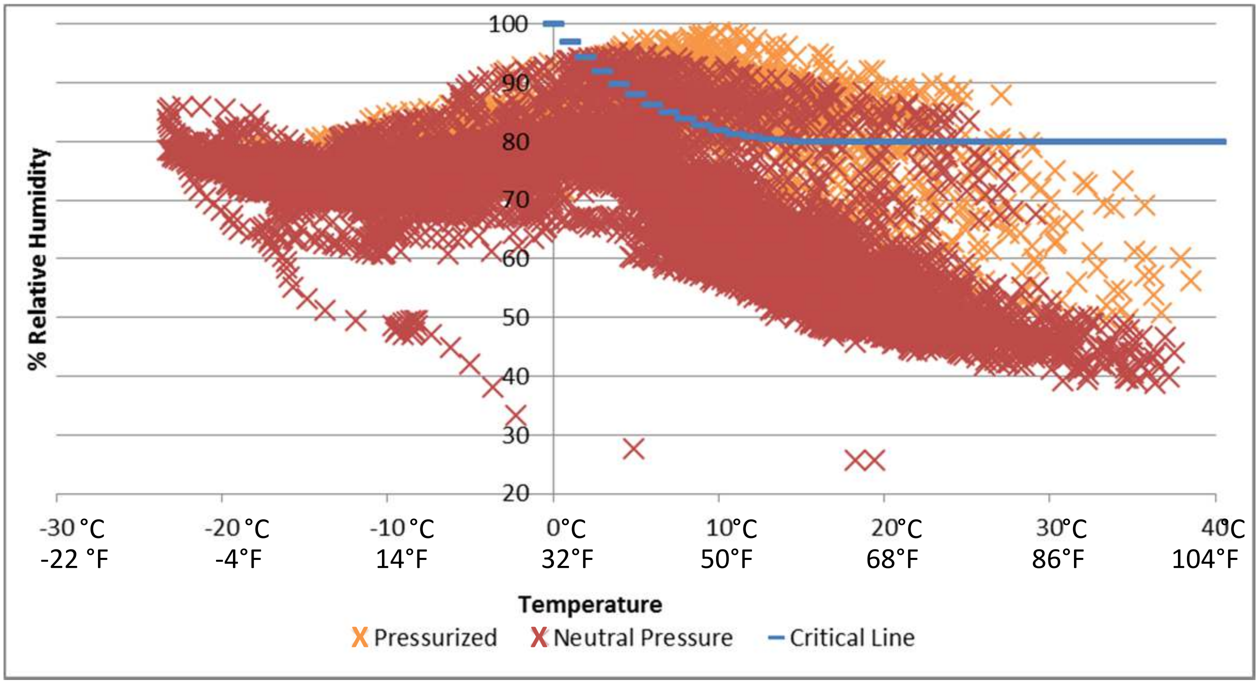
Wall 3 upper cavity, cellulose with a 6 mil polyethylene vapor retarder



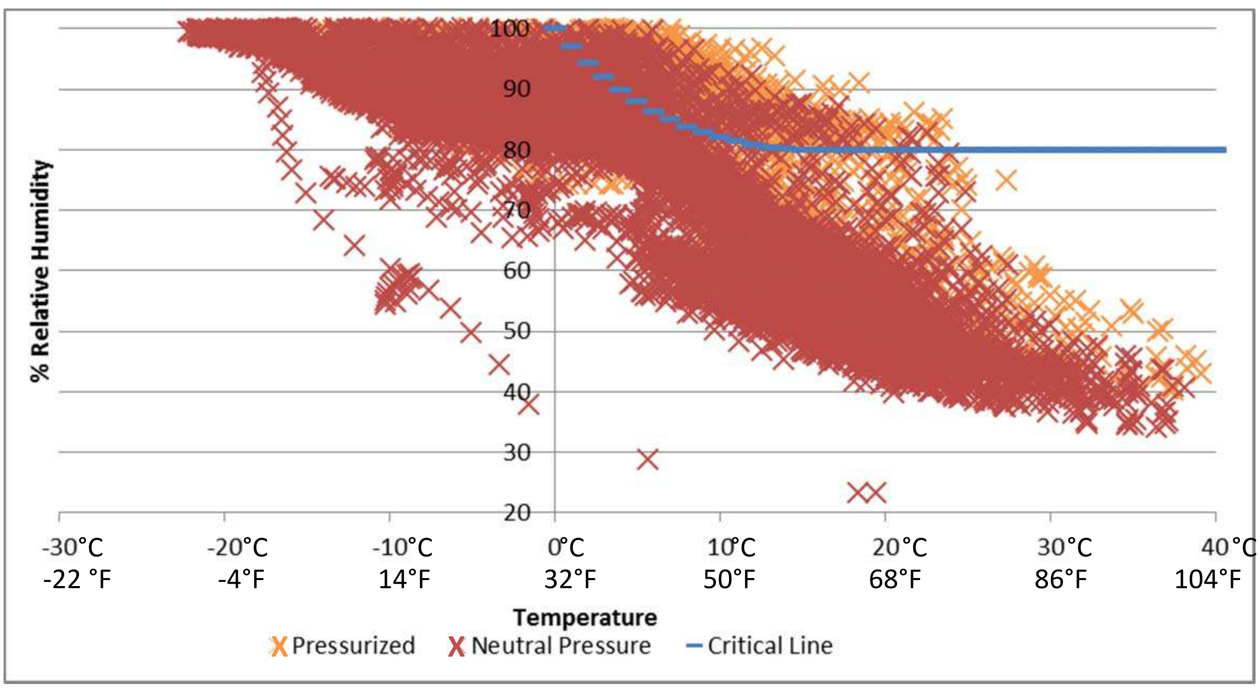
Wall 4 lower cavity, ocSPF with a 6 mil polyethylene vapor retarder



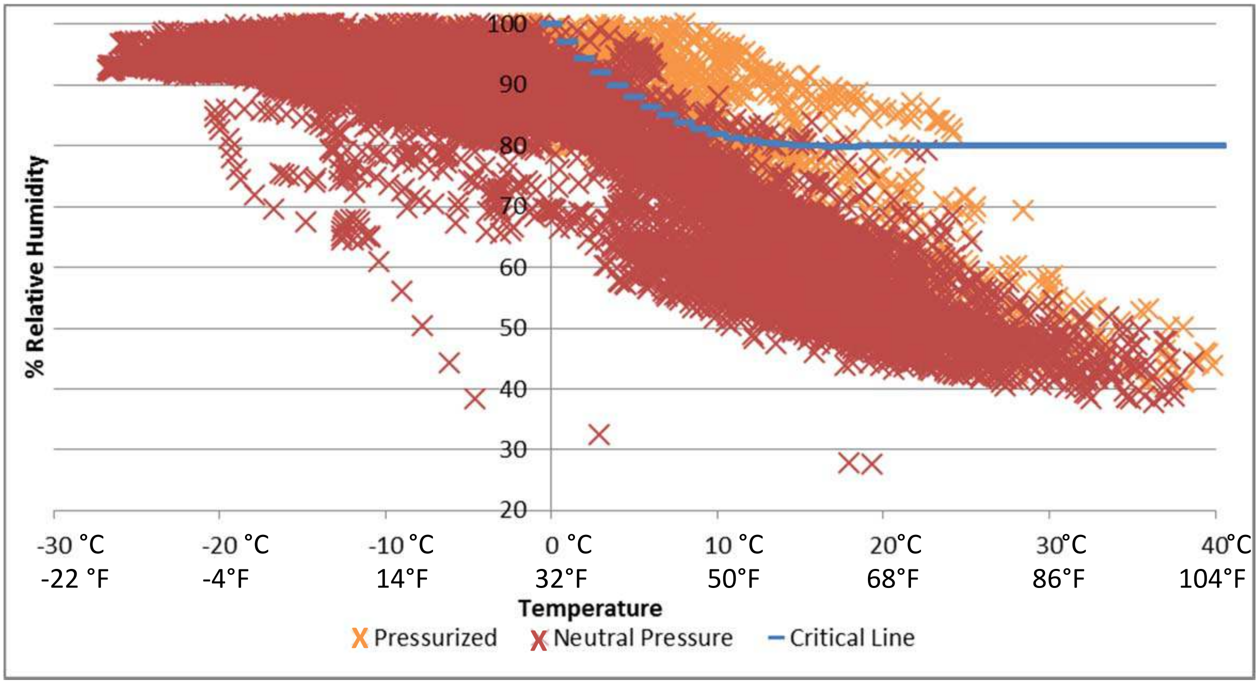
Wall 5 lower cavity, fiberglass with low perm paint



Wall 6 lower cavity, ocSPF with low perm paint



Wall 7a lower cavity, ocSPF with latex paint



Wall 7b lower cavity, ocSPF with latex paint