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Exterior Insulation Envelope Retrofits in Sub-Arctic Environments

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ABSTRACT

A common practice in residential construction is retrofitting above-grade walls with foam insulation to reduce heating demand. Structures in sub-arctic environments typically have an air/vapor retarder on the interior framing surface, therefore the addition of relatively water vapor impermeable exterior foam insulation on the exterior has the potential to significantly reduce the drying ability of wall systems. The reduced drying ability is problematic if the retrofit does not adequately prevent condensation within the wall framing. These retrofits may induce mold growth, thereby increasing susceptibility to indoor air quality problems and reduced service life of retrofitted structures.

To investigate the likelihood of this retrofit strategy causing moisture accumulation in wood-framed structures in sub-arctic environments, nine nominal four ft (1.2 m) by eight ft (2.4 m) test wall sections were constructed using varying ratios of stud-fill fibrous insulation and foam insulation exterior to the wall sheathing. The use of a polyethylene air/vapor retarder varied; each test wall with an air/vapor retarder had unsealed penetrations common to past construction practices. The wall sections were tested in Fairbanks, Alaska over two winters under varying interior relative humidity and air pressure conditions and were monitored for temperature, relative humidity, and wood moisture content.

Test walls with less than approximately 68% of the nominal wall R-value on the exterior performed poorly in terms of wood framing moisture content and relative humidity at the sheathing interior surface. Wall systems without a polyethylene air/vapor retarder had widespread visible mold growth at the end of the two-year empirical test. Wall systems with a polyethylene air/vapor retarder tended to have lower humidity at the sheathing surface and visible mold growth only near penetrations in the air/vapor retarder, but had higher wood moisture contents well into the summer drying season. Moisture accumulation and mold were largely absent from test wall sections that had 68% or more of the total wall R-value on the exterior, regardless of whether an interior air/vapor retarder was present.

INTRODUCTION

Many commercial buildings and new residential construction in cold climates rely on continuous insulation exterior to the sheathing to reduce thermal bridging through structural framing and to attain thermal performance goals. Residential building code allows for typical interior finishes to be used as a vapor retarder when a sufficient amount of R-value is added as insulated sheathing; for example, R-10 (RSI-1.8) or more over a 2x4 wall, and R-15 (RSI-2.6) or more over a 2x6 wall in climate zones 7 and 8 (ICC, 2010). This method is also being used for residential retrofits in cold climates; for example, 3,482 homes in Alaska had documented insulation upgrades to above-grade walls from 2008 to 2011 (AHFC 2012) while

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more presumably have happened without formal documentation.

Residential structures in sub-arctic environments such as Alaska and northern Canada are typically wood framed and have an air/vapor retarder installed immediately behind the finished interior surface, such as 6-mil polyethylene sheeting. Past construction practices did not ensure that penetrations in this air/vapor retarder were sealed, allowing air from the conditioned space to exfiltrate during winter creates a source of moisture within the building envelope. Barring other sources, such as the infiltration of precipitation, this moisture typically evaporates during the summer months, establishing an approximate balance between moisture sources and sinks. The addition of a relatively water vapor impermeable layer, such as rigid foam insulation exterior to the wood sheathing, is a commonly recognized technique to keep framing warmer than the dew point. However, the use of foam insulation may also significantly reduce the drying ability of wall systems. This reduction in drying ability is problematic if it is not offset by a reduction in wetting. These retrofit scenarios may induce mold growth, thereby increasing the possibility of indoor air quality problems and reduced service life of retrofitted structures.

McFadden (1989) conducted a field study of 39 structures in Interior Alaska with and without exterior foam insulation to determine if moisture was accumulating within wall insulation, but concluded that no substantial problems were found beyond isolated areas of high moisture in specific structures. Derome and Desmarais (2006) studied leaky wood frame envelopes subjected to simulated Montreal winter conditions, finding that test walls with exterior foam insulation had higher sheathing moisture contents compared to test walls without foam insulation and test walls with interior foam insulation. A significant finding from Derome and Desmarais (2006) was that only the exterior insulation strategy resulted in a gravimetric sheathing moisture content over 28%, representing potential for mold growth and rot initiation.

The two primary metrics for evaluating moisture in wood within the built environment are relative humidity and moisture content. Relative humidity controls moisture levels in wood below the fiber saturation point, which ranges from 20 – 30% moisture content; higher moisture contents require a liquid water source (Anagnost, 2007). Wood is at risk for mold growth if it reaches equilibrium with air at approximately 75% relative humidity or greater (Anagnost, 2007). For non-equilibrium conditions variation is introduced depending on temperature, substrate type, and duration of exposure, amongst other factors (Viitanen, 1994; Viitanen and Ojanen, 2007). Most notably, at temperatures approaching freezing, the relative humidity where mold growth initiates increases (Viitanen, 1994). For rot, 40 – 80% moisture content represents optimal conditions, while 20 – 30% represents the lower range of concern (Anagnost, 2007). Correspondingly, 75% relative humidity and 20% moisture content represent conservative thresholds for concern with respect to mold growth and rot initiation, respectively.

The main objective of this work was to determine if exterior foam insulation retrofits of residential structures in sub-arctic climates can be conducted without presenting an unacceptable risk for moisture accumulation. The primary variables studied were the presence or absence of a polyethylene air/vapor retarder, ratio of R-values between exterior and stud cavity insulation, interior relative humidity, and pressure within the conditioned space.

METHODOLOGY

The mobile test lab (MTL) is a nine-panel test trailer located outside the Cold Climate Housing Research Center facility in Fairbanks, Alaska (99% design temperature -38.1°F (-38.9°C), 13,528°F (7,515°C) heating degree days (ASHRAE 2009)). The lab has four nominal 4 by 8 ft (1.2 by 2.4 m) test bays on each of its two long sides and one test bay on the opposite end of the trailer door. The interior of the trailer can be climate controlled to mimic a home's interior climate. An HRV can be used to control the air pressure within the conditioned space relative to ambient conditions.

The retrofit study ran from October 2009 to July 2011. The interior conditions varied between the two winters (see Table 1). The 40% relative humidity maintained during the first winter is the lowest limit of the optimum zone for human health (Sterling, et al. 1985). The 25% relative humidity maintained during the second winter corresponds approximately to a dew point of 36°F (2°C), the lower limit recommended by ASHRAE (2009). The MTL was not mechanically humidified over the two summers, but the interior relative humidity averaged the same as ambient, around 50%.

Air pressure differences across the building envelope in cold climates during the heating season tend to be negative at lower floors and positive near the top of the envelope with respect to ambient conditions due to stack effect. These pressure differences are highly dynamic due to flux in environmental conditions and occupant behavior. Since interior moisture flux through the envelope is the focus of this study, positive pressure was maintained during the first winter; the range of 1 to 7 Pa (0.004 to 0.03 in. water) positive pressure was chosen to represent the expected range within the upper reaches of single to multi-story residential structures (Schmid 1999). Near neutral pressures were maintained during the second winter test period to minimize the influence of air flow through the test wall assemblies. The pressure was measured on a monthly basis using a digital manometer. Humidity and pressure within the MTL were raised individually to the levels maintained during the first winter in January through February 2011 to examine the influence of temporary changes in interior conditions.

Table 1. Interior Conditions in the Mobile Test Lab

	Temperature	Relative Humidity	Pressurization
First Winter (2009-2010)	70°F (21°C)	40%	1 to 7 Pa (0.004 to 0.03 in. water)
Summer (2010)	Ambient	Ambient	Neutral
Second Winter (2010-2011)	70°F (21°C)	25%	-0.3 to 1 Pa (0.001 to 0.004 in. water)
Summer (2011)	Ambient	Ambient	Neutral

Nine different walls were tested in the MTL (see Table 2). They varied according to the percentage of insulation inside and outside of the sheathing and whether they had an interior 6 mil polyethylene air/vapor retarder. The control wall was a 2x4 frame filled with R-11 (RSI-1.9) fiberglass batts, the two outer cavities served as buffers between the lab structure and the sensored test area. The insulation ratios expressed in Table 2 are based on the insulated portions of the test wall only and neglect the effect of framing on wall R-values. The exterior sheathing was 0.5 in. (13 mm) plywood installed flush with the exterior of the test lab. Each test wall had a spun-bonded polyolefin weather barrier attached to the sheathing and 0.5 in. (13 mm) gypsum wall board as an interior sheathing. The gypsum wall board was left unpainted. Expanded polystyrene (EPS) insulation was added over the long sides of the MTL to different thicknesses and the MTL was then clad with vinyl lap siding over a 0.75 in. (19 mm) air gap. An outlet box was installed on each wall to allow for sensor wire passage and to create an air leakage path. The stud cavity and 6 mil polyethylene sheeting were installed to mimic the quality of construction typically found in older homes in Alaska. The outlet penetrations were left unsealed, while the outer and window perimeter of each test wall with 6 mil polyethylene was sealed with acoustical sealant. See Figure 1 for a cross section of a sample wall.

Table 2. Test Wall Make-up

Wall	Nominal Framing	6 mil Poly	Stud Cavity	% of total	Exterior Insulation	% of total
1	2x4	Yes	R-11 (RSI-1.9)	58.8%	EPS (R-7.7, RSI-1.4)	41.2%
2	2x4	No	R-11 (RSI-1.9)	58.8%	EPS (R-7.7, RSI-1.4)	41.2%
3	2x6	Yes	R-19 (RSI-3.3)	71.2%	EPS (R-7.7, RSI-1.4)	28.8%
4	2x4	No	R-11 (RSI-1.9)	41.7%	EPS (R-15.4, RSI-2.7))	58.3%
5	2x4	Yes	R-11 (RSI-1.9)	100%	none	0%
6	2x6	Yes	R-19 (RSI-3.3)	34.4%	SPF* (R-36.3, RSI-6.4)	65.6%
7	2x4	No	R-11 (RSI-1.9)	32.3%	EPS (R-23.1, RSI-4.1)	67.7%
8	2x4	Yes	R-11 (RSI-1.9)	32.3%	EPS (R-23.1, RSI-4.1)	67.7%
9	2x4	Yes	R-11 (RSI-1.9)	41.7%	EPS (R-15.4, RSI-2.7)	58.3%

*SPF = Spray applied polyurethane foam insulation

Each wall in the MTL had 13 sensors embedded within it. The sensors monitored temperature, wood moisture content, and relative humidity within the wall. They were placed in the same locations in each wall (see Figure 1). A

Campbell Scientific CR1000 datalogger recorded data at an hourly interval. The NTC thermistors (accuracy ±0.36°F (0.2°C)) and Honeywell HIH4000 relative humidity sensors (range 0 to 100%, ±8% between 60 and 100% relative humidity) were used with factory calibrated data to determine temperature and relative humidity. Long term accuracy is a known problem for relative humidity sensors, particularly when exposed to humidity levels near the dew point for extended periods (Straube et.al. 2002). All of the relative humidity sensors were paired with a NTC thermistor in a small bag made of spun-bonded polyolefin. These were attached to both sides of the sheathing in the cavity below the window. Moisture content was monitored using resistance pins (range of 7 to 40%) made of brass rods embedded one inch apart into the studs of each test wall; such sensors are generally expected to have an approximate accuracy of ±2% (Straube et.al. 2002).

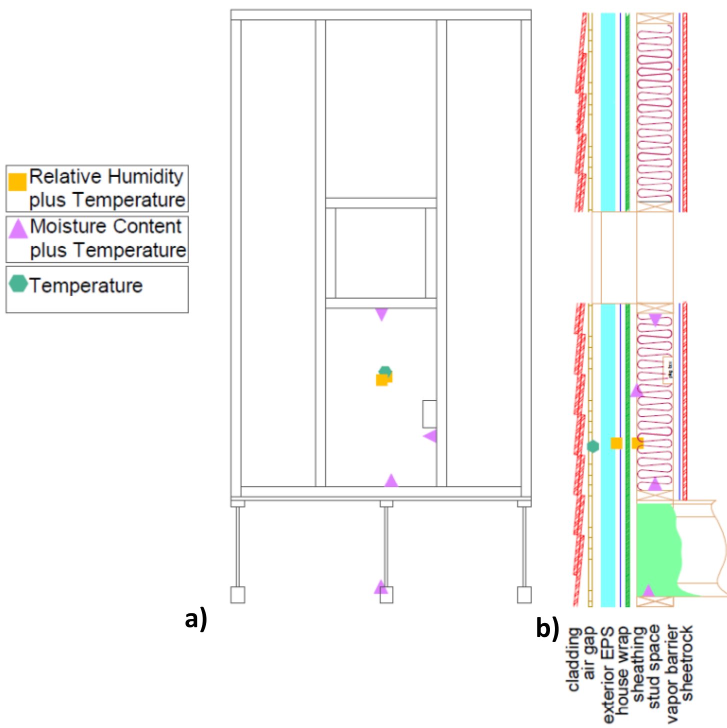

Figure 1*. (a) An elevation view of the basic construction of each wall and (b) a cross section of wall 3. All nine walls had similar construction and the same sensor layout.*

RESULTS

Relative humidity data within the test walls without a polyethylene air/vapor retarder (Figure 2a) illustrate a consistent and expected trend: test walls with more exterior insulation had consistently lower relative humidity at the interior side of the sheathing. Note that all of these walls (walls 2, 4 and 7) experienced relative humidity well above the threshold for mold risk for extended durations during the first winter, whereas only the wall with the least amount of exterior insulation (wall 2) remained consistently above 75% relative humidity during the second winter. This had a rough correlation to visual observation of mold growth during test wall disassembly. Walls 2 and 4 had abundant mold covering the sheathing interior surface, whereas wall 7 had no mold discernible by visual observation.

Trends in the humidity levels were similar for the test walls with a polyethylene air/vapor retarder (Figure 2b), but the response time of the walls to changes in interior and ambient conditions was considerably delayed. This is well illustrated by the response to the temporary spikes in interior humidity and pressure in January and February 2011. The walls with an air/vapor retarder required several months to lower from a relative maximum reached in the winter to more moderate levels in the following summer and fall, considerably more time than the corresponding walls without a polyethylene air/vapor retarder. The exception to this observation is the wall with a polyethylene air/vapor retarder and no exterior insulation (control wall), which dropped from 100% relative humidity at the sheathing plane to ~60% after winter over the course of a month. The slower decline in relative humidity from winter to summer for walls 1, 3, 8, and 9 demonstrates the limited ability of walls with both a polyethylene air/vapor retarder and exterior insulation to release moisture.

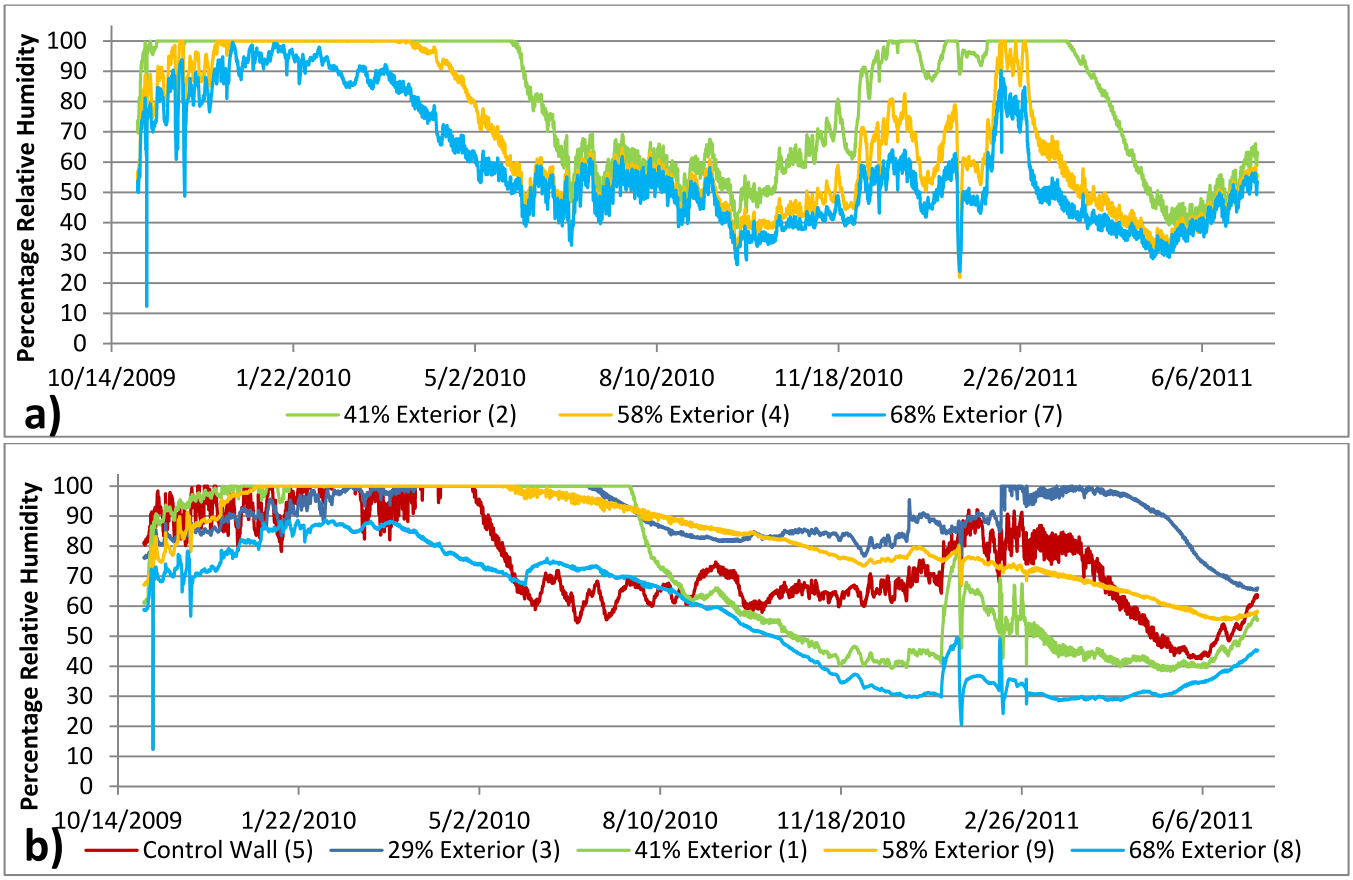

Figure 2 *(a) The relative humidity at the sheathing for walls without interior air/vapor retarders and (b) the relative humidity in the walls with air/vapor retarders. Data were recorded over 100%, however since that is over the range of the sensors that data were evaluated at 100%. Wall numbers are in parenthesis.*

Visible mold for the walls with a polyethylene air/vapor retarder was largely relegated to the sheathing in immediate vicinity of the unsealed penetration in the polyethylene around the electrical outlet box. Walls with the least or intermediate thickness of exterior insulation (walls 1, 3 and 9) had a similar amount of mold in this region, however, wall 3 appeared to show initial signs of mold growth in multiple locations. The wall with the most exterior insulation (wall 8) had no visually discernible mold growth.

The moisture content in the wood framing shows more complex behavior. Figure 3 shows the moisture content of the base plate under the window for each wall; the moisture content sensor was located immediately adjacent to the sheathing. The trend seen with the relative humidity data persist, where greater amounts of exterior insulation serve to maintain lower moisture content in the wood framing, when grouping walls with or without polyethylene air/vapor retarders.

The walls with an air/vapor retarder illustrate a strong dependence on insulation thickness. The wall with the most exterior insulation (wall 8) had moisture contents consistently below the 20 – 30% rot risk lower threshold, while the walls with the least exterior insulation (walls 1 and 3) had moisture contents within or above this threshold for several months of the first winter and summer monitoring period. The behavior of wall 3 was similar to the wall with no exterior insulation (control wall), except wall 3 took several months longer to dry during the summer. The walls with no polyethylene air/vapor retarder showed a weaker dependence on the amount of exterior insulation. The walls with the most exterior insulation (wall 7) and the least exterior insulation (wall 2) approached but never reached the 20% moisture content threshold. Wall 2 may have remained below the 20% threshold because the wall in the location of the sensor was below freezing, whereas wall 4 the wall between 2 and 7 was above the 20% threshold for the first winter.

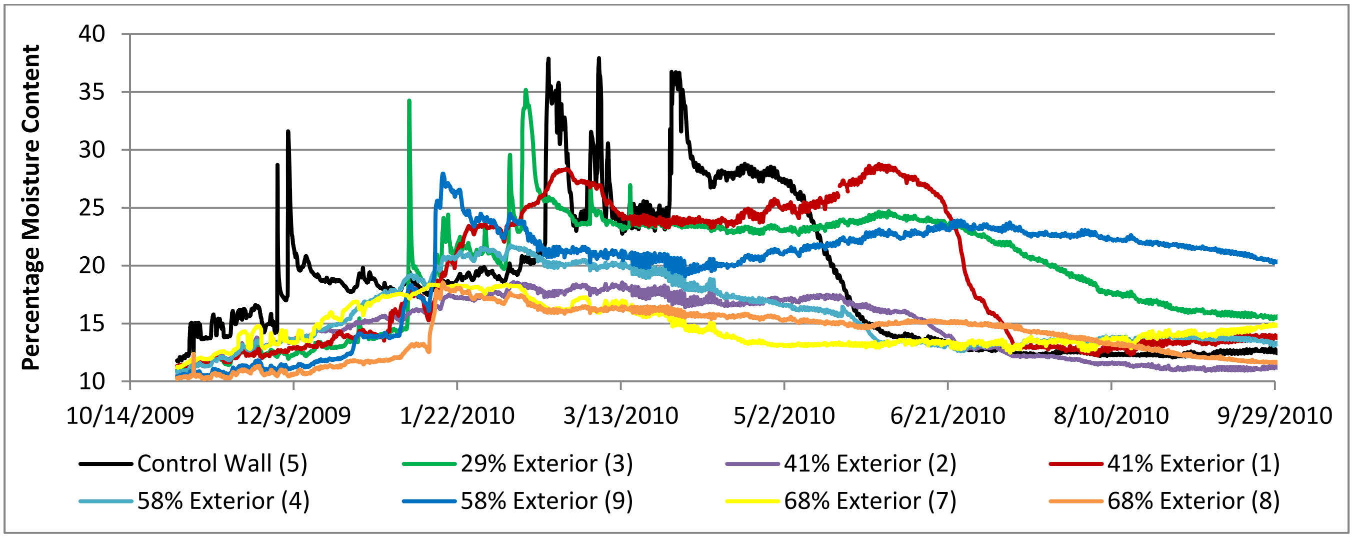

Figure 3 *The moisture content of the base plate. These data are only for the first winter and summer drying season. The erratic spikes and dips in the winter for the walls 1 and 3 are due to freezing of the moisture in the stud, changing the signal of the sensor. Wall numbers are in parenthesis.*

The moisture content at the base plate appears to indicate that the walls with a polyethylene air/vapor retarder were susceptible to wetting from a sudden introduction of moisture, such as condensation drainage, as shown by the sharp spikes in moisture content in January 2010. In contrast, the walls without polyethylene show more gradual changes in moisture content. The spikes in moisture content during this timeframe correspond to a period of extreme cold that led dew point or colder temperatures for most walls, however, the dew point was not reached for the wall with the most exterior insulation (wall 8). It is unlikely that these moisture spikes can be fully attributed to condensation drainage along the sheathing plane.

Wall 9 had base plate moisture contents and sheathing plane relative humidity levels that appear anomalously high in comparison to walls with an air/vapor retarder and different amounts of exterior insulation. There was some evidence of slight wetting from the wall exterior during MTL disassembly. Wall 2 had extensive wetting from the exterior due to a leak in the flashing above the wall, however, this moisture is not readily discernible from the relative humidity and moisture content monitoring data. This may be partially attributable to the moisture content readings corresponding to a small sample area, where as wetting is presumably not uniform in the walls.

DISCUSSION

The relative humidity and wood moisture content monitoring data in addition to the visual observations of mold summarized above indicate some potential benefits and risks for exterior foam insulation retrofits. In sub-arctic environments such as Fairbanks, when approximately 68% of the total wall R-value was exterior to the sheathing (e.g. 6 in. (152mm) of EPS over a 2x4 wall), the benefits dominated. With a polyethylene air/vapor retarder, this retrofit method consistently kept the sheathing plane above the dew point and the wood framing moisture content below the rot initiation threshold, even under humidity and pressure conditions considered to be challenging for building envelopes in a cold climate. Without a vapor retarder the wall performance was similar, however, the relative humidity at the sheathing plane was slightly higher and occasionally reached the dew point. Hygrothermal performance was substantially improved relative to the control wall (i.e. no exterior insulation) for this retrofit method.

In contrast, the retrofit methods with a polyethylene air/vapor retarder and 29% to 58% of the total wall R-value exterior to the sheathing demonstrated little benefit. While condensation potential was reduced under relatively moderate humidity and pressure conditions relative to the control wall, summer drying rates were substantially lengthened both in terms of humidity at the sheathing plane and wood framing moisture content. Visually discernible mold growth was not substantially different between the walls with these retrofit methods and the control wall.

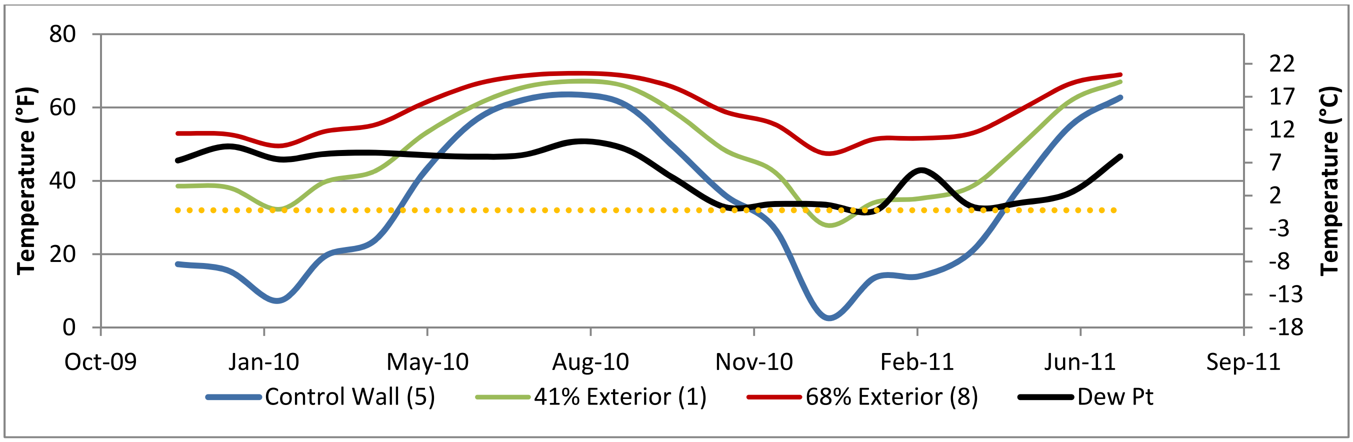

Figure 4 *Average monthly temperatures on the interior surface of the sheathing plane. The three walls presented were 2x4 construction with R-11 (RSI-1.9) fiberglass batt. Wall numbers are in parenthesis.*

A common analysis framework for evaluating the risk for condensation in wall assemblies involves comparison of sheathing temperatures to the dew point for interior conditions over time (Handegord, 1985). This comparison is shown in Figure 4 for walls 1, 8 and the control wall. Based on this framework, the less time the sheathing temperature remains below the dew point, the better the hygrothermal performance of a wall assembly. While this analysis can explain why wall 8 outperformed the control wall, it doesn't account for the relatively poor performance of wall 1. In other words, the significant reduction in condensation potential for wall 1 from the addition of exterior insulation did not lead to demonstrated improvements in hygrothermal performance. It is worth noting that this observation could also be extended to walls 2, 3, 4 and 9 relative to the control wall.

There are many factors that may contribute to this behavior. One factor is that the control wall had substantially less resistance to water vapor transmission due to the lack of exterior foam insulation, allowing for faster drying of accumulated moisture in the summer. A second factor is that the consistent subfreezing temperatures of the control wall sheathing reduced mold growth risk, despite the control wall having consistently higher humidity conditions at the sheathing plane the second winter and often above the general mold growth risk threshold. An additional factor is that condensation for the control wall may have been deposited as frost for the majority of both winters because the sheathing temperature was well below the freezing point for most of the winter. This would limit the ability of the sheathing and framing to absorb condensation, as noted previously by Derome and Desmarais (2006). In comparison, wall 1 remained under the dew point and above freezing for several months during the first winter, allowing for condensation deposition as liquid water.

The walls without a polyethylene air/vapor retarder tended to have higher relative humidity at the sheathing plane during the winter and to have lower in the summer relative to the walls with an air/vapor retarder. Drying during the transition into summer was appreciably faster for the walls without an air/vapor retarder. The difference in exterior insulation between walls 4 and 7 was modest (58% and 68% of the total wall R-value, respectively). However, the effect was very significant in terms of mold growth risk, as wall 4 had abundant mold on its sheathing whereas wall 7 had no visually discernible mold growth. While the interior finish for the walls did not meet specifications for a class III vapor retarder (ICC 2010), these observation indicate that the code prescribed amount of insulated sheathing may be inadequate for areas of climate zone 8.

CONCLUSIONS

The addition of exterior insulation is a commonly deployed construction technique targeted at reducing heat loss and condensation within wall assemblies. The results of this study indicate that both these goals can be met for sub-arctic environments if a substantial fraction of the wall R-value is shifted to the exterior, as was done for walls 7 and 8 (68% of the total wall R-value exterior to the sheathing). The balance of exterior and stud cavity insulation ratios was a stronger influence on hygrothermal performance than the presence of a polyethylene air/vapor retarder. While achieving this R-value balance with exterior foam can often be challenging in terms of cost and practicality, if less exterior foam insulation is used in a retrofit, the goal of reducing condensation potential can be undermined for sub-arctic environments. Walls 1, 2, 3, 4 and 9 in this study (29 – 58% of the total wall R-value exterior to the sheathing) demonstrated an inadequate ability to prevent moisture infiltration into the wall assembly during the winter and a reduced ability to release moisture in the summer relative to the control wall. The retrofit methods for these walls show a risk for mold and rot based on the sheathing plane relative humidity and wood framing moisture content monitoring data, respectively, as well as visual observations of mold growth.

The specific insulation ratios from this study are highly specific to the test environment. Fairbanks is an arid climate in the sub-arctic, which creates hygrothermal conditions substantially different than other cold climate regions. Further research would help establish the necessary insulation ratios in different cold climate regions in order to acceptably manage hygrothermal performance.

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