COLD CLIMATE HOUSING RESEARCH CENTER
CCHRC

Safe, Effective & Affordable Retrofits for Cold Climates

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Disclaimer: The products were tested using the methodologies described in this report. CCHRC cautions that different results might be obtained using different test methodologies. CCHRC suggests caution in drawing inferences regarding the products beyond the circumstances described in this report.

Abstract

The high cost of energy in Alaska often drives homeowners to improve the energy efficiency of their homes. A common retrofit technique is to add foam board insulation to the exterior of the walls. This technique improves the insulation value of the walls and limits the thermal bridging loss of the studs; however, if not done correctly, it changes the moisture dynamics of the wall, which can lead to mold and rot inside the walls. In cold climates, general guidance for moisture-safe walls is to place a significant amount of exterior insulation (2/3 of the total wall R-value in Fairbanks, AK) to ensure the dew point does not fall inside the stud wall and create condensation. Foam board insulation is a plastic material that has a low permeance (vapor does not travel though it readily). Moisture that enters a retrofit wall with foam board on the exterior does not dry as readily; if the drying process is too slow, then moisture levels can accumulate over time, leading to mold growth and rot. This study looks at higher permeance exterior insulation options in order to evaluate if these kinds of retrofits are more moisture-safe than those using foam board.

Keywords: insulation, retrofit, walls

Safe, Effective, and Affordable Retrofits for Cold Climates

Nearly half of all homes in Alaska were built during the oil pipeline boom of the 1970s and 80s (Wiltse & Madden, 2018). Now 30 to 50 years old, these homes are energy inefficient and lack modern ventilation systems. It is this type of home that is largely responsible for the high energy costs plaguing Alaska, where the average annual energy cost is twice the cost in cold regions of the western United States and three times more than the national average (Wiltse & Madden, 2018). Given that the average life of a home in the U.S. is 61 years (Aktas & Bilec, 2012), many poorly built homes would benefit from reduced energy costs and improved comfort of energy efficiency efforts; indeed, many Alaska homeowners seek ways to lower high energy costs through home energy retrofits.

A common retrofit technique for residential buildings in Alaska is the addition of rigid foam board insulation on exterior walls, typically performed as part of a residing project. Adding exterior foam board insulation to reduce heating demand can also change the moisture flow through the wall. This change in moisture dynamics is typically either ignored or misunderstood in the design, which has often resulted in compromised indoor air quality and damage to the structure due to moisture accumulation, mold, and rot in the building envelope.

Best practice retrofit guidelines consider both energy savings and moisture management, but such guidelines are rarely followed due to the high cost of construction and impracticality in implementation. For example, when retrofitting a 2x6 wall following the moisture-safe rule of thumb for Fairbanks (1/3 of the wall's total installed R-value inside the sheathing; 2/3 outside the sheathing), eight to ten inches of exterior foam insulation would be necessary. Resistance to installing this amount of exterior insulation has led to a pattern of insulation practices that may meet initial cost savings objectives but introduce risks associated with inadequate moisture control.

There are potential alternatives to exterior foam board retrofits. A recent Cold Climate Housing Research Center (CCHRC) project found that more vapor-permeable exterior insulations (like fiberglass) can be affordable, effective, and safe (Garber-Slaght et al., 2015). Hygrothermal models pinpointed certain wall designs that required further field testing to determine if they have acceptable moisture performance. This followup study used the CCHRC Mobile Test Lab (MTL) to test potential wall retrofits for moisture durability. Ten different walls were tested over the 2017-2018 and 2018-2019 winters. The data from the study was used to inform further hygrothermal models of wall retrofits. This study found that some vapor-permeable exterior insulation retrofits that do not meet the $^{1}/_{3}$ to $^{2}/_{3}$ rule can be moisture-safe in some retrofit cases.

Background

The high cost of energy in Alaska often drives homeowners to implement energy retrofits on their homes. The Alaska Housing Finance Corporation (AHFC) has been tracking energy retrofits in Alaska since 1996. Energy retrofits often include improvements to the building envelope via additional insulation and air tightening practices. Table 1 shows the number of homes in four regions around the state that have added insulation to their homes and how those retrofits have improved the air tightness (Air Changes per Hour (ACH), is a measure of air tightness). Tighter homes can lead to higher interior moisture as a result of lower accidental ventilation; if there are no changes to the intentional ventilation system, it can create serious indoor air quality and building envelope problems.

Table 1. Exterior Wall Retrofits by Region (Alaska Retrofit Information System, Unpublished raw data. CCHRC Analysis, 2015).

Region[1]		**Exterior Wall Retrofits**[2]	**Air Tightness Improvement**[3]
Interior (Doyon)	600 homes	61% used 2 inches or less foam board	from 8.5 to 6.3 ACH 50
South Central (CIRI)	1,200 homes	48% used 2 inches or less foam board	from 8.2 to 5.6 ACH 50
Northern (ASRC and NANA)	80 homes	96% used 2 inches or less foam board	from 7.9 to 5.4 ACH 50
Western (Calista)	217 homes	99% used 2 inches or less foam board	from 11.4 to 7 ACH 50

[1] Doyon, Cook Inlet Regional Corporation, Inc. (CIRI), Arctic Slope Regional Corporation (ASRC), NANA, and Calista Corporation are all Alaska Native Settlement Claims Act (ANCSA)-based regions. For a map, please visit http://ancsaregional.com/ancsa-map/
[2] The remaining percentage received more than two inches.
[3] The initial number is the average tested pre-retrofit air leakage; the second number is the average tested air leakage after the exterior wall retrofit.

Literature Review

Residential buildings in Alaska are commonly 2x6 frame construction with R-19 fiberglass batts between the studs, an interior Class I vapor retarder (6 mil polyethylene), and interior gypsum wallboard (see Figure 1). Older homes usually have a leaky vapor retarder system, if they have one at all. The vapor retarder serves two purposes: to prevent water vapor from entering the stud cavity and to limit moist air flow through the building envelope. A leaky vapor retarder allows moisture and air to exit the building through the walls. These wall assemblies do not typically experience moisture-related issues because the outside sheathing is below freezing in winter, so any moisture that condenses on the sheathing surface freezes and does not cause mold problems (Straube, 2011). Without exterior insulation, the frozen moisture thaws and dries to the outside quickly in the spring, creating minimal mold (Craven & Garber-Slaght, 2014).

Older homes are often retrofitted with exterior rigid insulation on the walls (see Figure 1). This technique offers many potential benefits, including increasing the effective R-value of the walls and reducing thermal bridging through the framing. A sufficient amount of insulation will reduce the chance of condensation within the wall cavity (Holladay, 2011) and correctly installed external retrofits will also increase the durability of the structure (Osser, Neuhauser, & Ueno, 2012).

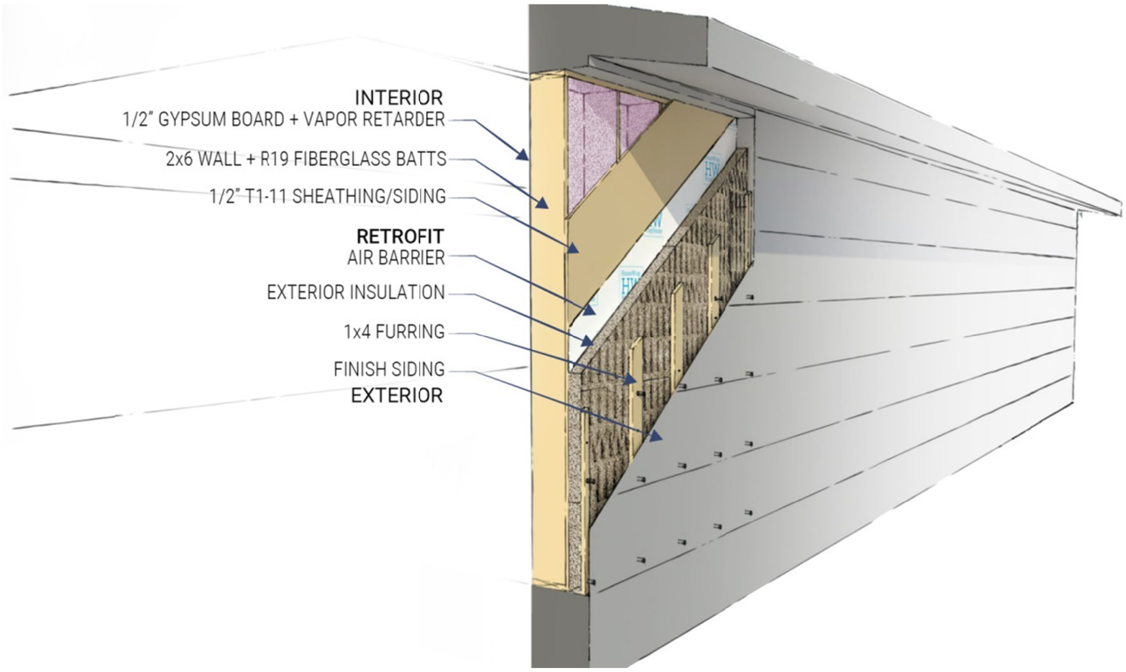

Figure 1. A typical wall retrofit in Fairbanks, Alaska. The 1x4 furring creates a drainage/ventilation area for any liquid water or water vapor that might get behind the siding, also called a rain screen.

In cold climate retrofits, it is important to install a sufficient amount of external insulation to keep the sheathing and framing above the dew point temperature so that any escaping warm moist indoor air does not condense inside the wall cavities. In Interior Alaska, this means following the $^1/_3$ to $^2/_3$ rule, or making sure that at least $^2/_3$ of the total wall R-value is outside of the sheathing (for this project, the advertised R-value is always used, even though insulation R-value can change with temperature). One example of a wall built using this concept is the Residential Exterior Membrane Outside-insulation TEchnique (REMOTE) wall, described for new walls in “Installing Exterior Insulation in Cold Climates” by Chlupp (2009). The REMOTE wall also illustrates another important guideline for cold-climate retrofits: walls need a way to self-dry. In the case of REMOTE walls, the drying path is toward the inside. The $^1/_3$ to $^2/_3$ rule helps prevent condensation from occurring within wall cavities, however creating a pathway for drying ensures that any moisture entering the wall cavity will also have a chance to leave (Lepage & Lstiburek, 2012; Holladay, 2010). In a retrofit with an interior vapor retarder where there is minimal drying to the inside, the $^1/_3$ to $^2/_3$ rule becomes important for reducing moisture problems, especially when low permeability foam board is added to the outside.

Builders and researchers have been experimenting with insulations for external wall retrofits other than the traditional choice of rigid foam board. Insulations such as cellulose and stone wool offer the potential for better moisture protection than rigid foam and the ability to deviate from the $^1/_3$ to $^2/_3$ rule, potentially lowering retrofit costs. While using less exterior insulation than called for by the $^1/_3$ to $^2/_3$ rule increases the condensation potential at the sheathing, cellulose and stone wool are more forgiving because they are vapor-open, providing greater drying potential via diffusion toward the outside. This reduces peak moisture content (MC) within the framing and accelerates drying times–two key elements of moisture control. However, these hypotheses are theoretical and there is currently little experimental verification to support them in extreme cold climates.

Trainor et al. modeled several walls in various locations across Canada and found that a wall with three inches of exterior stone wool will have limited mold growth when compared to plastic insulations (i.e. rigid foam boards) in a climate like Yellowknife (13,860 Heating Degree Days$_{65°F}$) (2016). However, at a higher interior relative humidity (RH), between 40-60%, the wall will be over 28% moisture content (Trainor et al., 2016). Craven & Garber-Slaght (2014) found that test wall sections with exterior cellulose insulation had better moisture performance than those with exterior expanded polystyrene (EPS) foam, but did not determine a minimum thickness of cellulose for adequate moisture protection. Holladay (2011) summarized research on stone wool, noting that stone wool boards could be installed in a similar manner to rigid foam and that they are strong enough to support vertical furring strips and siding. Stone wool is more vapor-permeable than an equivalent thickness of rigid foam but, similar to cellulose insulation, a minimum thickness for its use in exterior insulation retrofits has not been established for cold climate regions such as Interior Alaska.

Methodology

This project used two methods to evaluate retrofit walls for moisture safety: in-situ testing in the Mobile Test Lab (MTL) and hygrothermal modeling using WUFI Pro. The MTL was located in Fairbanks, Alaska for the entire testing period. Data from the MTL was used to verify the WUFI models. The models were then evaluated in varying climates around the state: Fairbanks, Anchorage, and Juneau.

Mobile Test Lab

The CCHRC MTL is a movable test lab with nine test wall bays. The interior can be maintained at a set temperature, relative humidity, and pressure, and can be moved to any location and orientation in order to get the desired outdoor conditions. Test walls are monitored for moisture infiltration and conditions that may develop mold. The MTL has been used for a variety of wall moisture studies since 2003. In this study, 2x6 test walls were retrofit with vapor-open exterior insulations to determine if alternative insulations that do not meet the $^1/_3$ to $^2/_3$ rule would improve moisture performance of retrofit walls. The walls were individually pressurized using the interior MTL air to a variable positive pressure (the target air leakage was 5 air changes per hour at 50 Pascals (ACH50)). The interior relative humidity and temperature were maintained at 40% and 70°F respectively. RH of 40% is high for cold climates, but is the lower threshhold of what is considered healthy for occupants (Sterling et al., 1985).

Each wall was constructed of new materials and the walls were as alike as possible given the variation in materials. The walls had ½-inch painted gypsum board on the interior, 6 mil polyethylene sheeting behind the gypsum, 2x6 stud cavities with R-19 fiberglass batts, and ½-inch exterior plywood sheathing (this study did not look at Oriented Strand Board (OSB) which has very different moisture behavior). The retrofit included a house wrap over the plywood with varying exterior insulation, (the fiberglass and cellulose retrofits were held in place with a second layer of house wrap), a ½ inch rain screen gap, and vinyl siding. Table 2 explains the exterior insulation of each wall. Best practice for exterior insulation in the Fairbanks climate is to have $^2/_3$ of the total wall R-value outside of the plywood wall sheathing. Walls 3 and 9 were special product tests that are addressed in separate reports. None of the vapor-open retrofit walls met the Fairbanks best practice of $^2/_3$ exterior insulation.

Table 2.MTL Exterior Insulation.

Wall #	Exterior Insulation	Exterior insulation permeance	% exterior R-value	Complies with $^{1}/_{3}$ to $^{2}/_{3}$ rule?
Wall 1	1.5 inches of stone wool board	78 perm	20.67%	no
Wall 2	2 inches of unfaced EPS board	2.5 perm	29.63%	no
Wall 3*	2 inches of bio based insulation	unknown	24.00%	no
Wall 4	3 inches of stone wool board	39 perm	34.26%	no
Wall 5	None-control wall	None		yes
Wall 6	3.5 inches of blown-in cellulose	20 perm	39.20%	no
Wall 7	3.5 inches of blown-in fiberglass	28 perm	39.20%	no
Wall 8	4 inches of unfaced EPS board	1.25 perm	45.71%	no
Wall 9*	Lower 4 inches of bio based insulation	unknown	38.71%	no
Wall 9*	Upper 1 inch of Vacuum insulated panels	unknown	100.00%	yes

*The results for these walls are addressed in separate reports.

The vapor retarders were sealed with acoustical sealant and every penetration was taped. Air was introduced into the wall via a central fan and piping system with metered air (shown in Figure 2). The air was metered individually at each wall to mimic an air leakage rate of 5 ACH50 based on the work of Trainor (2014). This translated to approximately 34 cubic feet per hour (CFH) passing through each wall for the first year. During the first year of the study the fan ran every other week until February when it was turned on and left running until April. The pressure difference between the wall and the main room on the MTL was monitored as was the pressure difference between the main room and outside.

Because the pressure developed by the air injection system was higher than expected in the first year, a second year of study was conducted. During the second year, the fan was set to maintain as close to a 1 Pa pressure differential between the wall stud cavity and the interior room of the MTL, comparable to +2Pa of pressure caused by the stack effect on the second floor of a Fairbanks house in the winter. The overall differential pressure from inside the MTL to the outside was designed to be neutral, although there were variations due to ventilation and exterior conditions.

Figure 2. Inside of the completed MTL. The ABS black piping was used to create a constant and controlled air leakage.

The walls were monitored for hygrothermal performance using 16 to 17 sensors in each wall. Figure 3 shows the sensor layout for typical walls, and Table 3 lists specific information on each type of sensor. The in-wall RH and temperature sensors were placed against the inner face of the plywood sheathing.

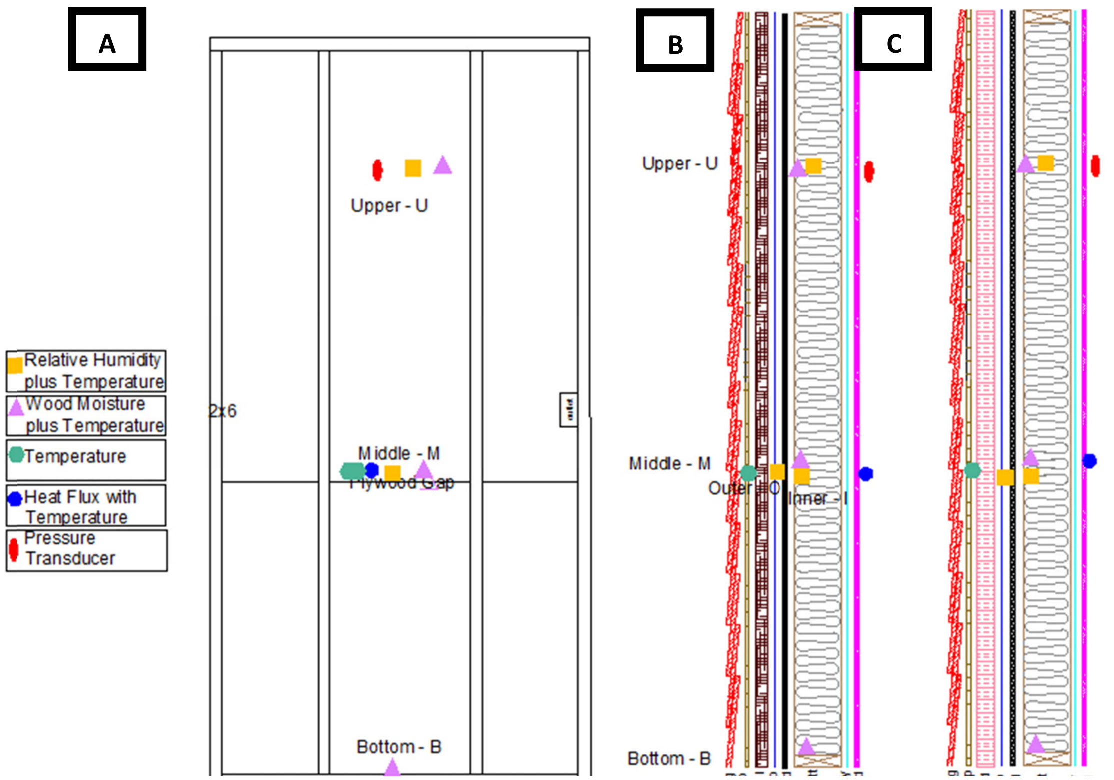

Figure 3. Sensor layout. Some walls had more sensors than others based on their make-up and the material that was being studied. ***A*** *wall elevation shows sensor combinations for all walls;* ***B*** *is the section profile for Wall 1 and* ***C*** *is the section profile for Wall 2.*

Table 3. Sensor Specifications.

Sensor Type	**Relative Humidity**	**Temperature**	**Moisture Content**	**Pressure Transducer**	**Heat Flux Transducers**
Specific Sensor	Honeywell HIH4010	US Sensor PS103J2 NTC Thermistors	Resistance pins	Setra Pressure Transducer 265	REBS HFT3, Huskeflux HFP01
Operating Conditions	-40°C to 85°C 0% to 100%	-80°C to 150°C	7% to 40%*	0 to 249 Pa	-40°C to 55°C, ±100 W/m^2 -30°C to +70°C, ±2000 W/m^2
Error	±3.5%	±0.1°C	±2% *	±1%	±5% -15% to +5%

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

Hygrothermal Modeling

WUFI Pro 6 is a one-dimensional hygrothermal modeling program that evaluates the thermal and moisture performance of a wall cross-section based on boundary conditions and physical properties of wall materials. The model allows for moisture to be introduced into the wall by water vapor diffusion and air infiltration. The interior conditions were modeled at 40% relative humidity and 70°F; a typical cold weather year for Fairbanks was used initially to model external conditions (based on 30-year weather data). Data from the MTL study (internal and external) was used to verify the Fairbanks models and allow for extrapolation to varying insulation thicknesses and other locations in Alaska.

Mold danger was assessed at the inner plywood sheathing surface, which is the most likely component of the envelope to encounter mold growth. Material with MC less than 20% has little mold growth risk, 20 to 28% has the potential for mold growth and rot depending on length of time at these moisture contents, and moisture content greater than 28% will have moisture related problems (Smegal et al., 2013). The relative humidity and temperature were also analyzed. Figure 4 shows the threshold for mold risk based on temperate and humidity that is built in to the hygrothermal model. These results were also compared to the physical investigation of the MTL walls at the end of the 2 year study.

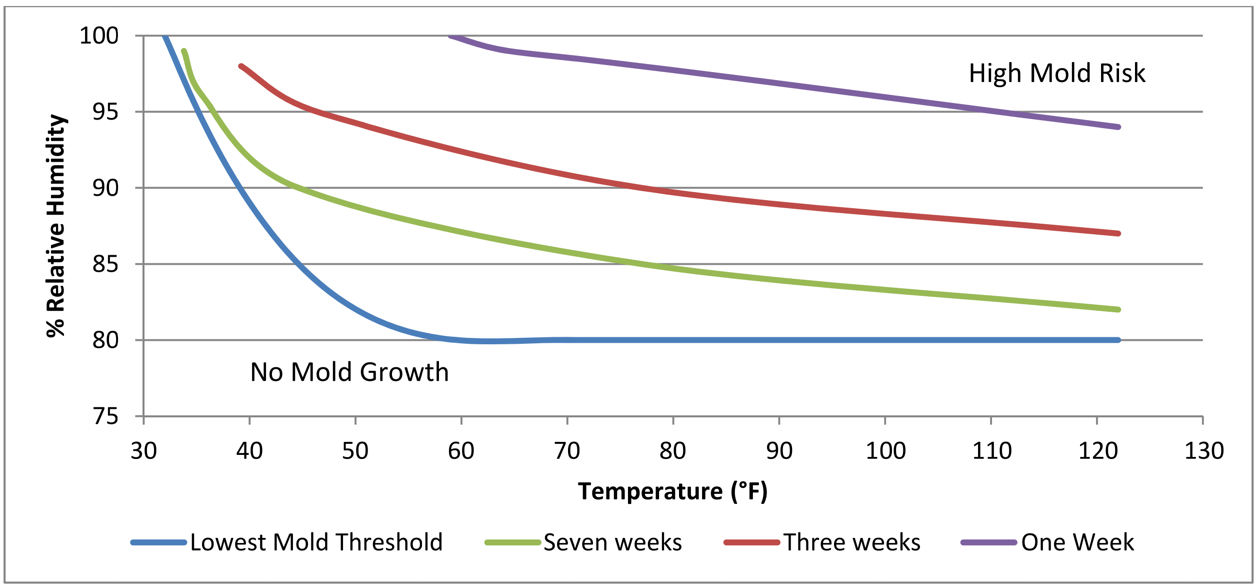

Figure 4. Mold growth conditions for wood. The purple, red, and green lines estimate the conditions that will initiate mold growth within one, three, and seven weeks. Time estimates come from Hukka & Viitanen (1999).

Results

MTL Moisture Content

Moisture content in plywood and studs are an indication of potential rot. To capture data indicating rot, moisture content sensors were embedded in the plywood in two locations per wall and also in the base plate 2x6 lumber. Moisture content above 20% places the material at risk for rot and mold (Carll & Wiedenhoeft, 2009).

The moisture content of the plywood and base plate for each wall was evaluated over the full two years of the study. The moisture rose when air movement from the conditioned space was introduced (air was only injected during the winter). Air was introduced at a low point in the wall near the base plate, but all three moisture content sensors within each specific wall registered similar moisture content. Figures 5 through 7 show representative moisture content of the plywood sheathing from each wall.

Figure 5 shows how too little exterior insulation can allow moisture to build up in the wall and stay there longer into the summer drying season. The 2-inch EPS wall reached 50% moisture content the first year and took two months longer to dry than the control wall with no exterior insulation. In the second winter it reached 35% moisture content and took more than 3 months longer to dry. The stone wool walls performed better in the first winter with the 1.5 inch wall exceeding 30% moisture content for a short period; however the walls dried much quicker in the spring than the EPS or control wall (Figure 6). The higher moisture content in the 1.5-inch stone wool wall during the second year is surprising and could hint at accumulation over time. Figure 7 shows that both the fiberglass and cellulose exterior insulation walls had low moisture content.

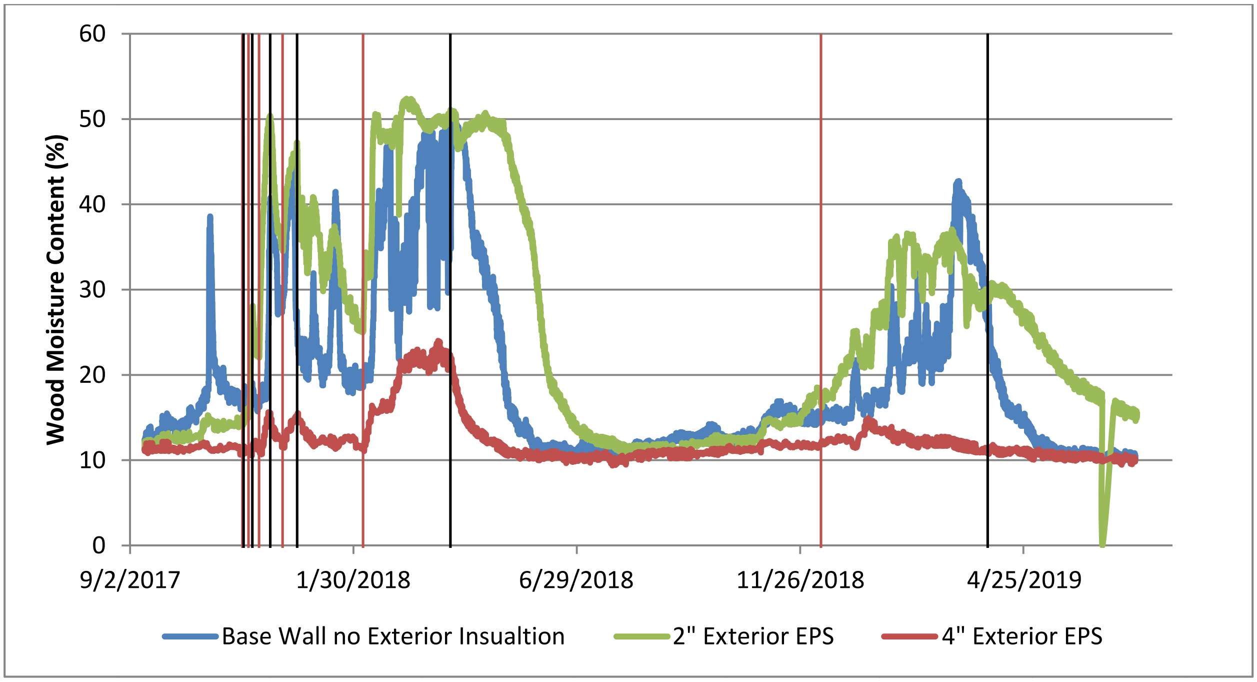

Figure 5. Moisture content of the EPS walls. The wall with two inches of exterior EPS was above the 20% moisture content danger line both winters. The red vertical lines indicate when the air injection system was turned on and the black lines indicate when it was turned off.

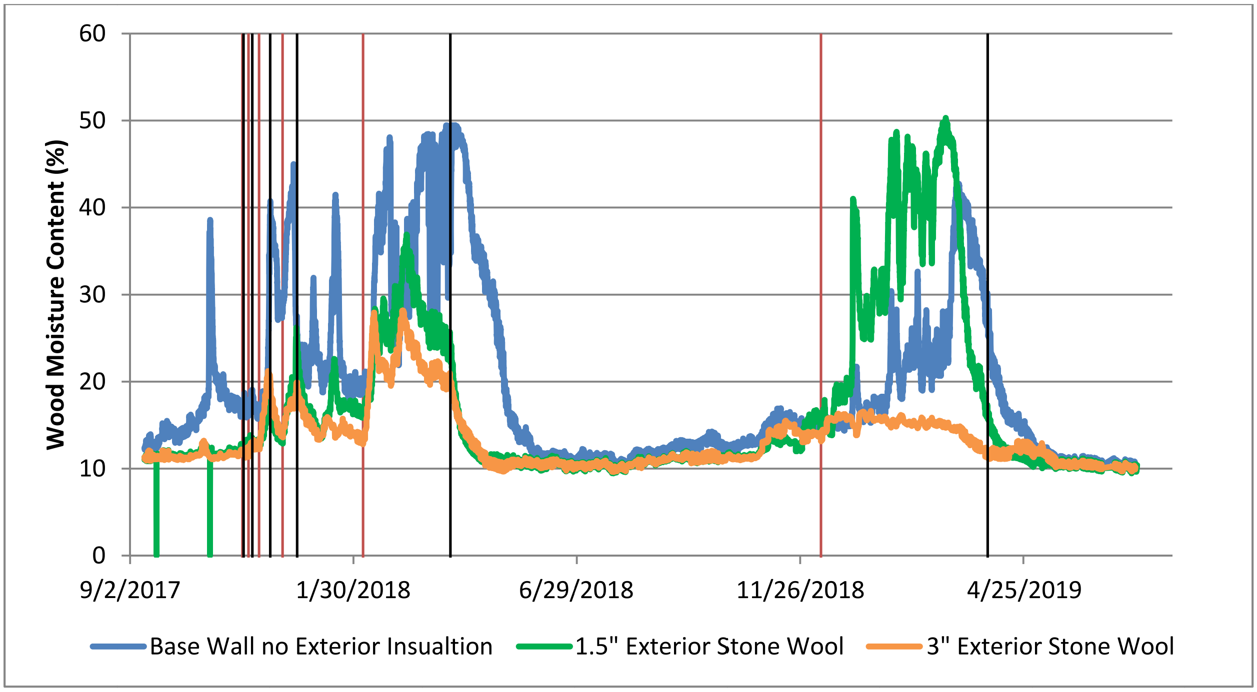

Figure 6. Moisture content of the stone wool walls. The 1.5-inch stone wool had moisture contents above the 20% threshold both winters. The 3-inch wall was above 20% for a month during the first winter. The red vertical lines indicate when the air injection system was turned on and the black lines indicate when it was turned off.

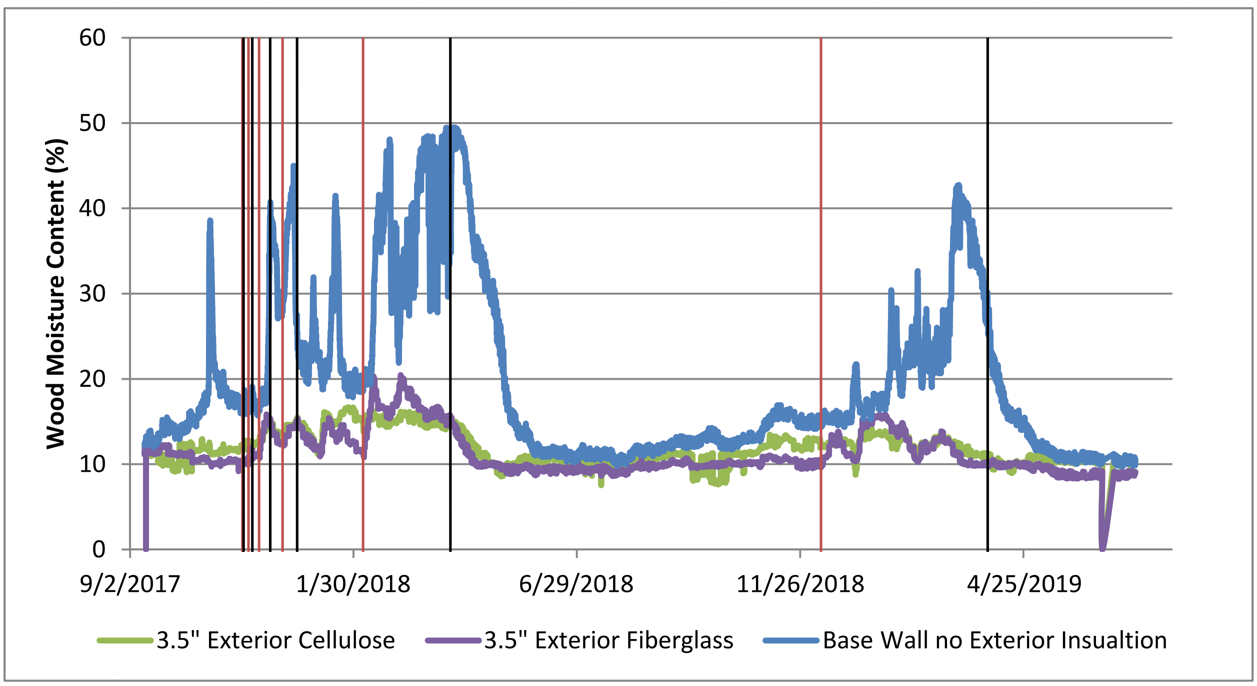

Figure 7. Moisture content of exterior blown-in materials walls. The fiberglass wall did not exceed 20% except for 2 brief periods in the first winter. The cellulose wall never exceeded 20% moisture content. The red vertical lines indicate when the air injection system was turned on and the black lines indicate when it was turned off.

MTL Relative Humidity

Relative humidity, temperature, and time are the defining variables for the development of mold. In general, mold can develop on a building material surface if RH is 80% or higher, the temperature is above freezing, and those conditions remain for a sufficient length of time. Figure 4 shows four curves for mold growth and estimated time to growth. The analysis of the MTL focused on the lowest threshold in Figure 4, which is the curve for RH critical from equation 1 (Hukka & Viitanen, 1999). The hours above the critical RH and temperature were logged and the consecutive hours evaluated. Depending on how high above the RH critical line, mold can develop in 4 to 8 weeks of consecutive hours.

$$RH_{critical} = \begin{cases} -0.00267T^3 + 0.160T^2 - 3.13 + 100 \; when \; 0 \leq T \leq 20°\text{C} \\ 80\% \qquad\qquad\qquad\qquad when \; T > 20°\text{C} \end{cases} \tag{1}$$

The MTL walls were analyzed for relative humidity vs. temperature over each hour. The isopleths show a dot for the conditions inside the stud wall for each hour. If enough consecutive hours are above the RH critical line, mold can grow. The higher the RH and temperature, the fewer number of consecutive hours it will take to develop mold. Figure 8 shows why typical walls in Fairbanks do not develop mold in the winter; most of the hours above 80% RH are also below freezing.

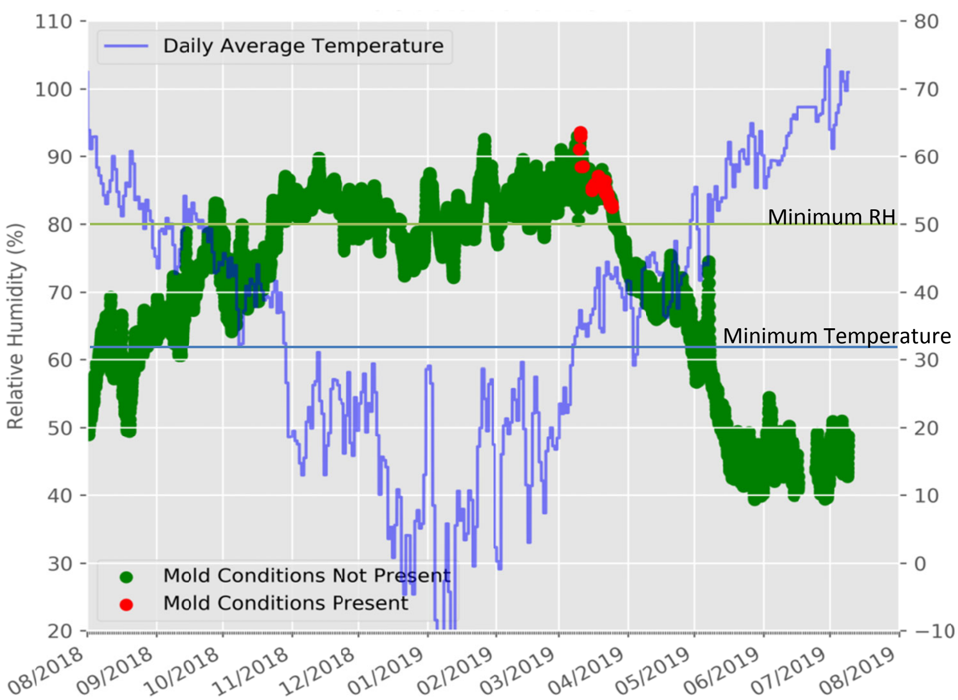

Figure 8. Base wall isopleth for Year 2. This is the pre-retrofit wall that is typical in most homes in Fairbanks. Very few consecutive hours are in the mold danger zone. When the temperature and RH are both above the minimum lines, the wall is in the red dot danger zone.

The stud bays in the cellulose and fiberglass retrofit walls did not have many days above the RH critical line during Year 2 (just three days for the cellulose wall and none for the fiberglass wall). Even under the harsh conditions of the first year, the two blown-in walls performed well. The fiberglass wall had 42 days above RH critical, while the cellulose wall was 75 days above. However, those days were not all consecutive, the cellulose wall had the maximum of 34 consecutive days (more than 4 weeks) in RH critical. During those 4 consecutive weeks the temperature in the wall low enough that visible mold did not develop.

Wall 1 with 1.5 inches of exterior stone wool had only 24% of its R-value outside the plywood sheathing, an extreme violation of the $^{1}/_{3}$ to $^{2}/_{3}$ rule for Interior Alaska. Wall 4 was also in violation with three inches of stone wool, or 39% R-value, on the exterior. However, Wall 4 is potentially moisture-safe despite this. Figures 9 and 10 show the mold potential of Walls 1 and 4 during the second year of the study (with lower air leakage rates). The longest consecutive time in the mold potential zone for Wall 1 was 35 days in Year 1, and it hit RH/temperate critical 100 days out of the entire 2-year study (this wall had small visible spots of mold after Year 1). For Wall 4, however, the longest consecutive time in the mold potential zone was 33 days in Year 1, and it hit RH/temperature critical 50 days out of the entire 2-year study.

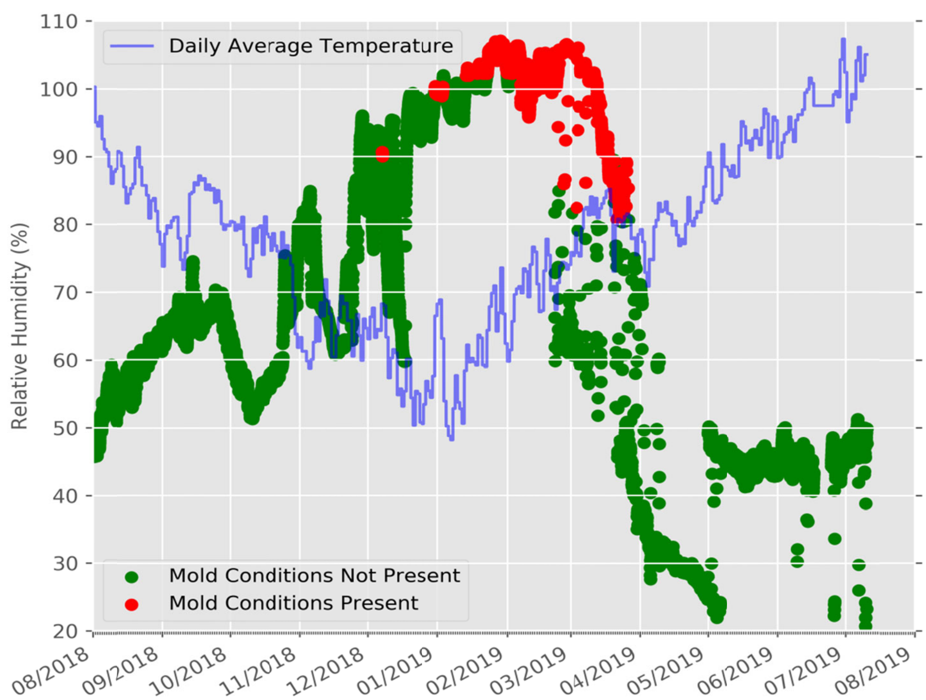

Figure 9. Wall 1 isopleth Year 2. This wall had a 1.5-inch stone wool retrofit on the outside. It was above RH and temperate critical for 65 days in Year 2. RH data points over 100% are considered 100%, the upper limit of the sensors.

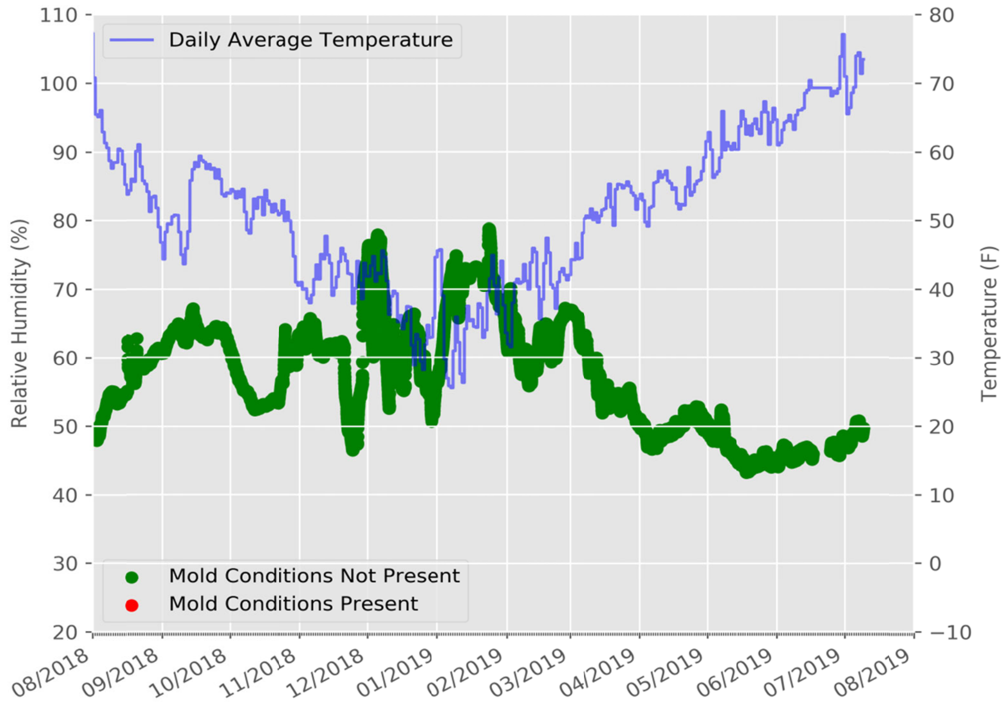

Figure 10. Wall 4 isopleth for Year 2. This wall had a 3-inch stone wool retrofit on the outside. It did not reach mold conditions during year 2.

The EPS walls were retrofit with lighter density EPS (compared to the typical Fairbanks EPS with facers on both sides, 0.9 perm inch based on manufacturer's specifications) to see if a slightly higher permeability (5 perm inch) would aid in the moisture performance. Wall 2 with two inches of EPS did not perform well in either year, developing mold on the inner face of the plywood sheathing over the 2-year study (Figure 11). Wall 8 with four inches of EPS performed better the second year, but did not perform very well in Year 1 with the higher air leakage, with 84 days in the critical RH and temperature zone. Figures 12 and 13 show the RH and temperature critical times for the EPS walls during Year 2. Wall 2 was in the mold potential zone for 153 days during Year 1. It was in danger of mold for 17.5 consecutive weeks in Year 1 (visual inspections at the end of year 1 verified mold growth). Wall 8 had 84 days above RH critical in Year 1 and 9.5 consecutive weeks.

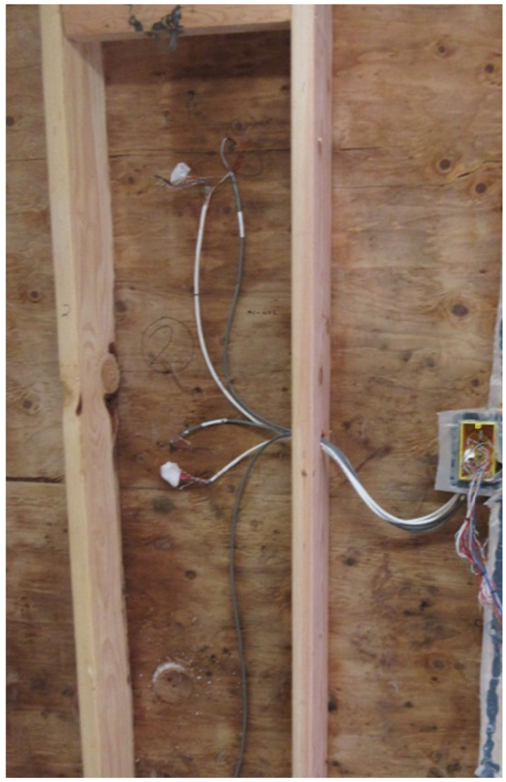

Figure 11. Wall 2 with a 2-inch EPS retrofit at the end of Year 2. Mold grew on the plywood and the studs during the first winter and expanded during the second winter.

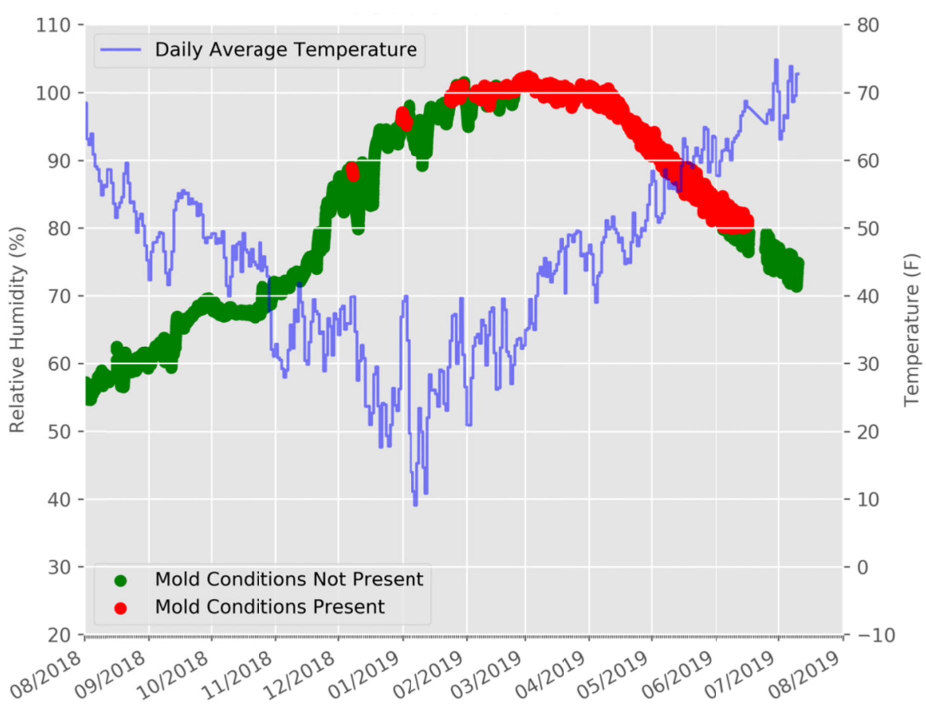

Figure 12. Wall 2 with a 2-inch EPS retrofit isopleth for Year 2. This wall was over the RH critical line 135 days in Year 2.

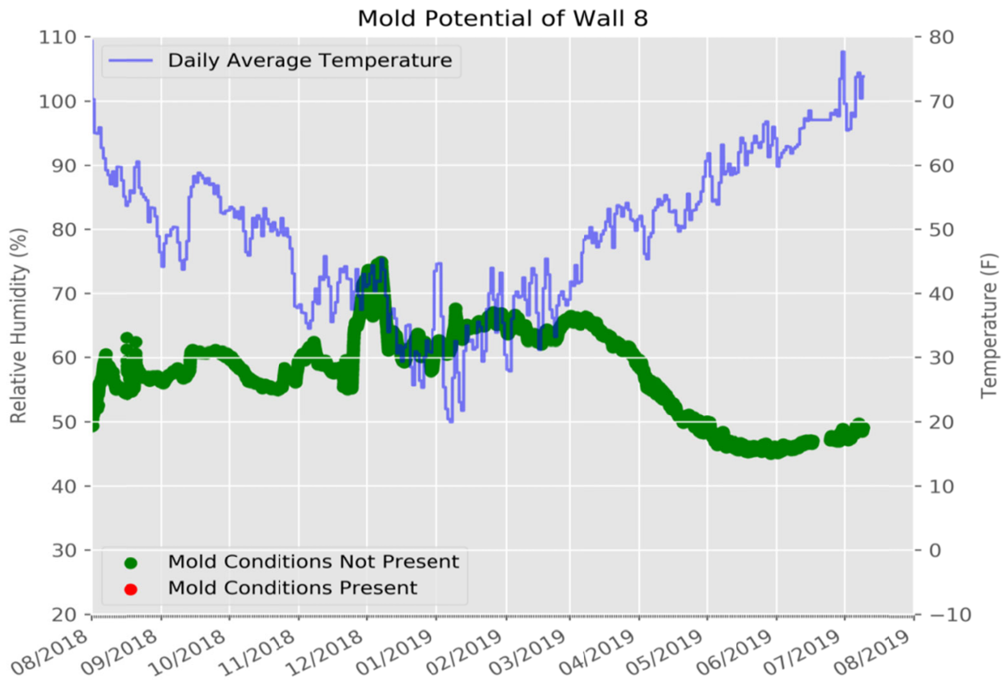

Figure 13. Wall 8 isopleth for Year 2. This wall had four inches of exterior EPS insulation. It did not have mold conditions in year 2.

WUFI Correlation

WUFI models were made of each wall and correlations were developed between the MTL walls and the WUFI models (using weather and interior temperature from the 2 year MTL study). Temperature correlations at the inner plywood/fiberglass interface were accurate for all walls (Figure 14).

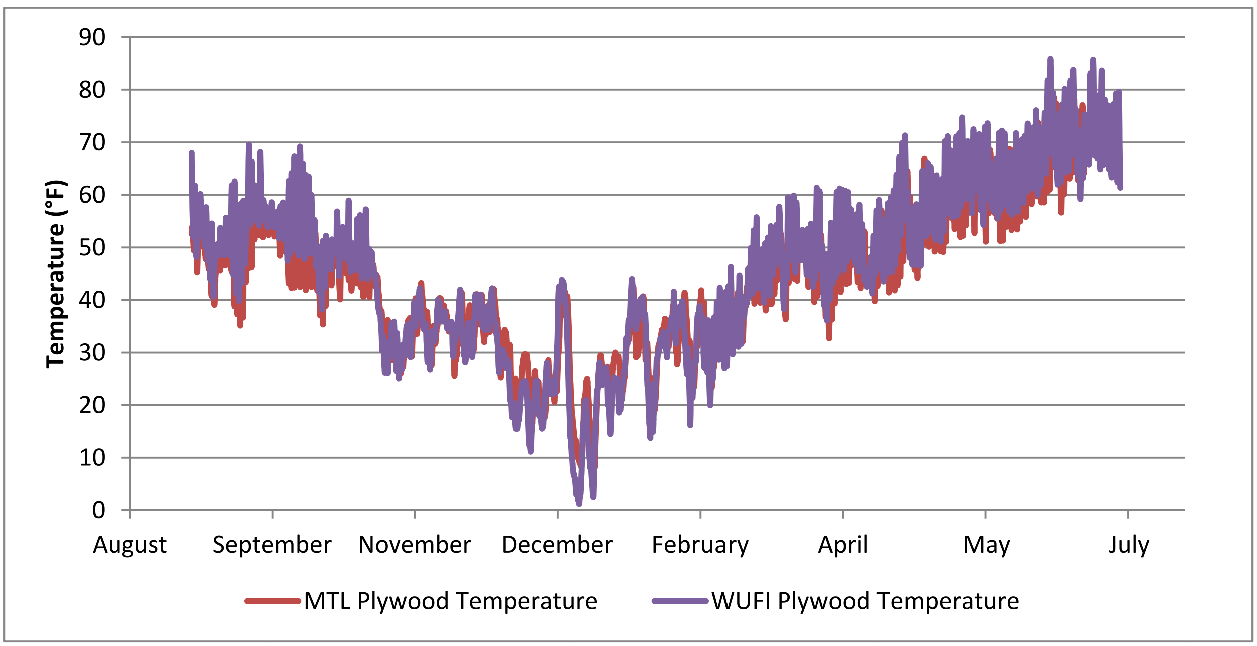

Figure 14. WUFI and MTL temperature correlation for Wall 2. This is a sample graph of the correlation between the MTL and WUFI on temperature. All the walls correlate well with the WUFI model on temperature at the plywood sheathing.

In general, the MTL walls with thicker exterior insulation had better RH and moisture content correlations with the WUFI model, but the base wall had the closest correlations. Table 4 summarizes the correlations. WUFI tends to have better RH correlations, being only about 10% lower than the MTL walls in most cases. WUFI moisture content correlations are not as consistent, ranging from within 2% to to 40% below the MTL data. This could be due to a variety of reasons: the moisture parameters for the wall materials were not measured but taken from WUFI generic properties and manufacturer's information, the air leakage metering in the MTL was not precise, and the frozen moisture in the walls affects the moisture content pin readings.

Table 4. WUFI and MTL Correlation Summary.

	Moisture Content Correlation	**RH Correlation**	**WUFI Conditions**
Wall 1 **1.5 inch stone wool**	WUFI 40% lower than the MTL on average	WUFI 10% lower than the MTL on average	9 ACH50 +2 Pa
Wall 2 **2 inch EPS**	WUFI 15% lower than the MTL on average	WUFI 10% lower than the MTL on average	9 ACH50, +2 Pa
Wall 4 **3 inch stone wool**	WUFI 6% lower than the MTL on average	Within 10%	9 ACH50, +2 Pa
Wall 5	Within 2% on average	Within 6% WUFI dries slower	5 ACH50, +2 Pa
Wall 6 **3.5 inch cellulose**	WUFI 3% lower than the MTL on average	WUFI 10% lower than the MTL on average	5 ACH50, +2 Pa
Wall 7 **3.5 inch fiberglass**	WUFI 6 to 2% lower than the MTL on average	Within 10% WUFI dries slower	5 ACH50, +2 Pa
Wall 8 **4 inch EPS**	Good within 2% on average	WUFI 20% high	5 ACH50, +2 Pa

The WUFI conditions that most influence the correlation are the air leakage rate and the pressurization of the model; they are presented in the final column of Table 4. These conditions are part of the WUFI air infiltration model. The model was developed for relatively airtight homes in cold and moderate climates (Kunzel, Zirkelbach & Schafaczek, 2012). The WUFI air infiltration model is not well-vetted for 5 ACH50, and leakier buildings (9 ACH50) have not been evaluated in the model. All models started with 5 ACH50 and positive 2 Pa of pressure, which was the design goal for the MTL. The thicker walls correlated well with 5 ACH50 and +2 Pa. The thinner walls required modeling at 9 ACH50 and +2 Pa to get a near correlation, and Wall 1 still does not correlate for moisture content. This is potentially due to the moisture content pins in the thinner walls being affected by below freezing temperatures. Figure 15 shows the poor correlations between WUFI and the MTL for Wall 1, the 1.5-inch stone wool retrofit.

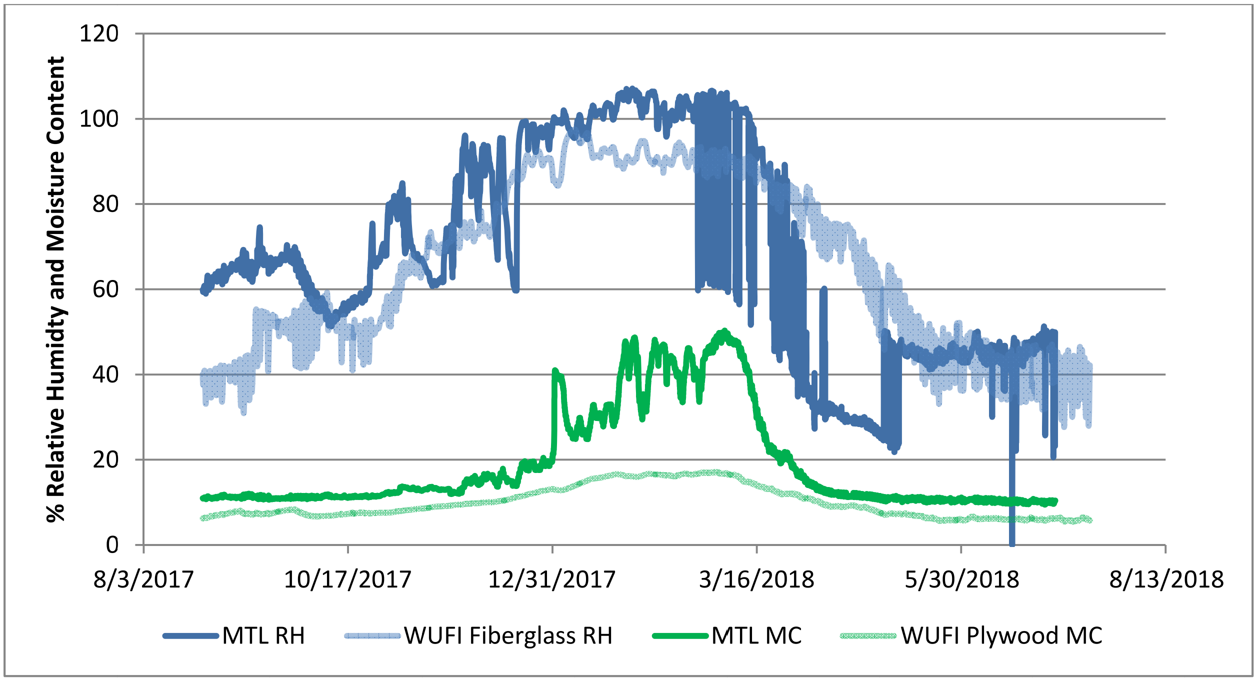

Figure 15. Wall 1 WUFI and MTL correlation. This WUFI model used 9ACH50 and +2Pa to try to bring the moisture readings more in line with the MTL.

Figure 16 shows a better positive correlation between WUFI and the MTL. This figure refers to the baseline wall with no exterior insulation. Figure 17 shows the fiberglass wall correlation, which is one of the more positive correlations in this study.

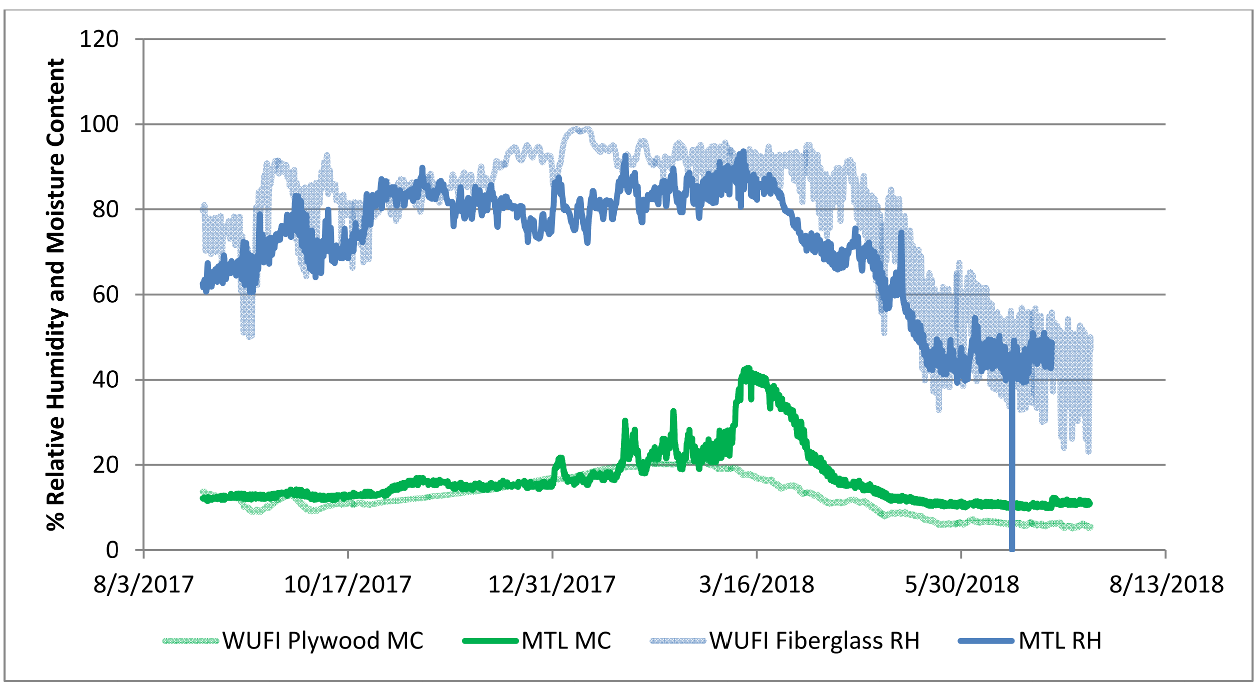

Figure 16. Wall 5 WUFI and MTL Correlation. This WUFI model used 5 ACH50 and +2Pa which was the design air leakage rate for the MTL.

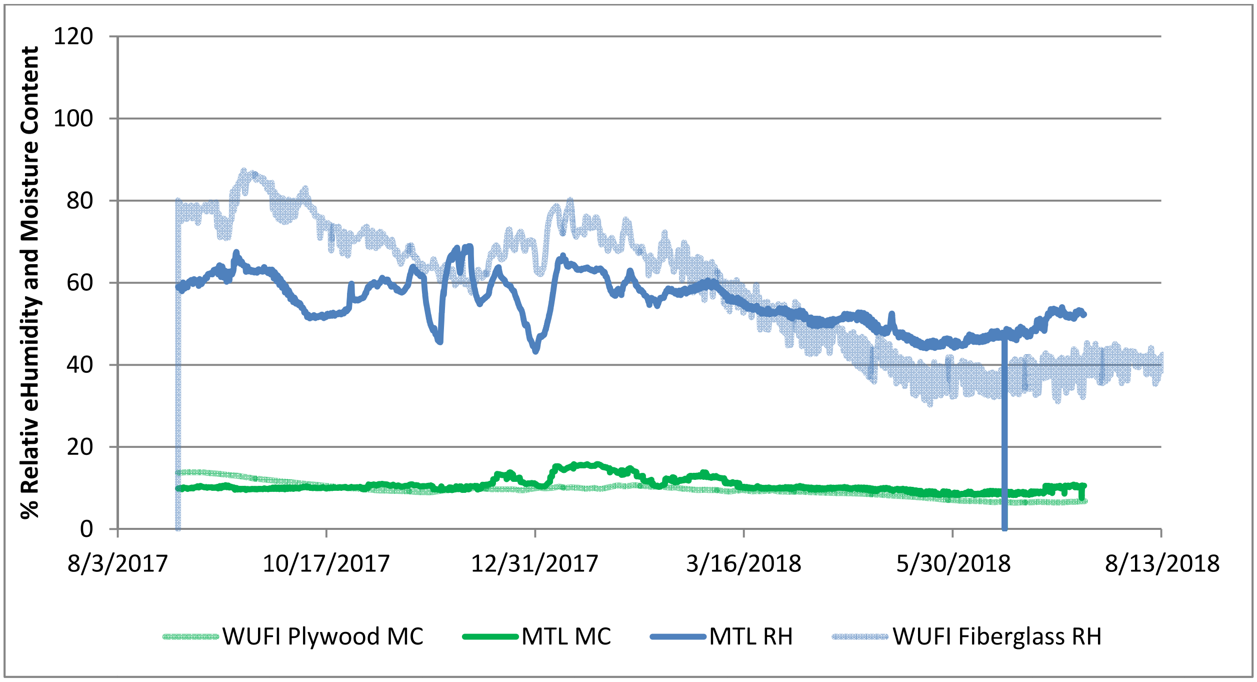

Figure 17. Wall 7 WUFI and MTL Correlation. This is the exterior fiberglass retrofit wall. This WUFI model used 5 ACH50 and +2Pa which was the design air leakage rate for the MTL.

WUFI Projections

Assuming the poor correlations were due to lack of precise air leakage data and problems with freezing moisture content sensors, the wall systems that were found to be at high risk for moisture problems in the MTL and WUFI were evaluated for ten years and in different climate areas around Alaska. Moisture problems may not become visually obvious in the first year or two after construction or renovation. The WUFI models allow for extrapolation beyond the 2-year study. Table 5 provides climate summary data for the three locations.

Table 5. Climate data for WUFI models.

	Heating Degree Days$_{65°F}$	Mean Annual Temperature	Average Annual Precipitation	
Fairbanks	13,940	28.3°F	10.8 in. rain	65 in. snow
Anchorage	10,570	33.4°F	16.6 in. rain	74.5 in. snow
Juneau	8,897	41.9°F	62.3 in. rain	86.7 in. snow

2-inch EPS retrofit

CCHRC looked at a higher-permeablity EPS (5 perm inch) for these models. These results are very specific to the moisture performance of the higher permeablity EPS and should not be extrapolated to other types of EPS board. The lower permeablity (0.9 perm inch) EPS with facers on both sides will have poorer moisture performance (Craven & Garber-Slaght, 2014).

Fairbanks 10-year data

As Figures 11 and 12 show with measured data, a 2-inch EPS retrofit is not a moisture-safe option for Fairbanks. Deconstruction of MTL Wall 2 showed mold growth on the plywood sheathing after the first winter and more mold after the second winter (see Figure 11). The WUFI model agrees; showing mold growth within the first year post-construction. Figure 18 shows the accumulation of moisture in the wall over a 10-year period. The plywood moisture content exceeds 20% each winter and dries each summer. However, the high moisture content in the winter will lead to rot over time. The high constant relative humidity will result in mold. This wall does not manage moisture safely for the health of the home occupants and the building structure.

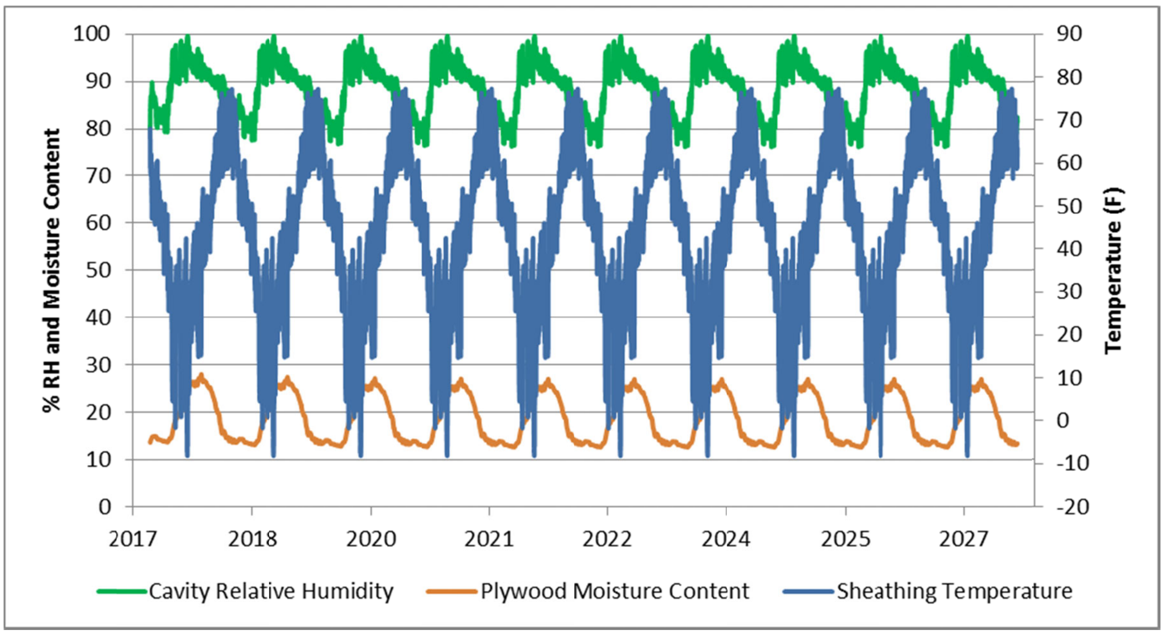

Figure 18. Fairbanks 10-year WUFI projections for Wall 2 with two inches of EPS. The above freezing temperatures at the sheathing and the high relative humidity lead to mold.

Anchorage 10-year data

The 2-inch retrofit performs better in the warmer climate of Anchorage; however, there is still risk associated with this retrofit. If there are areas of high air leakage, there is the potential of mold and rot. The plywood moisture content does not rise as quickly as the Fairbanks model, but the relative humidity remains in the mold danger zone most of time (Figure 19).

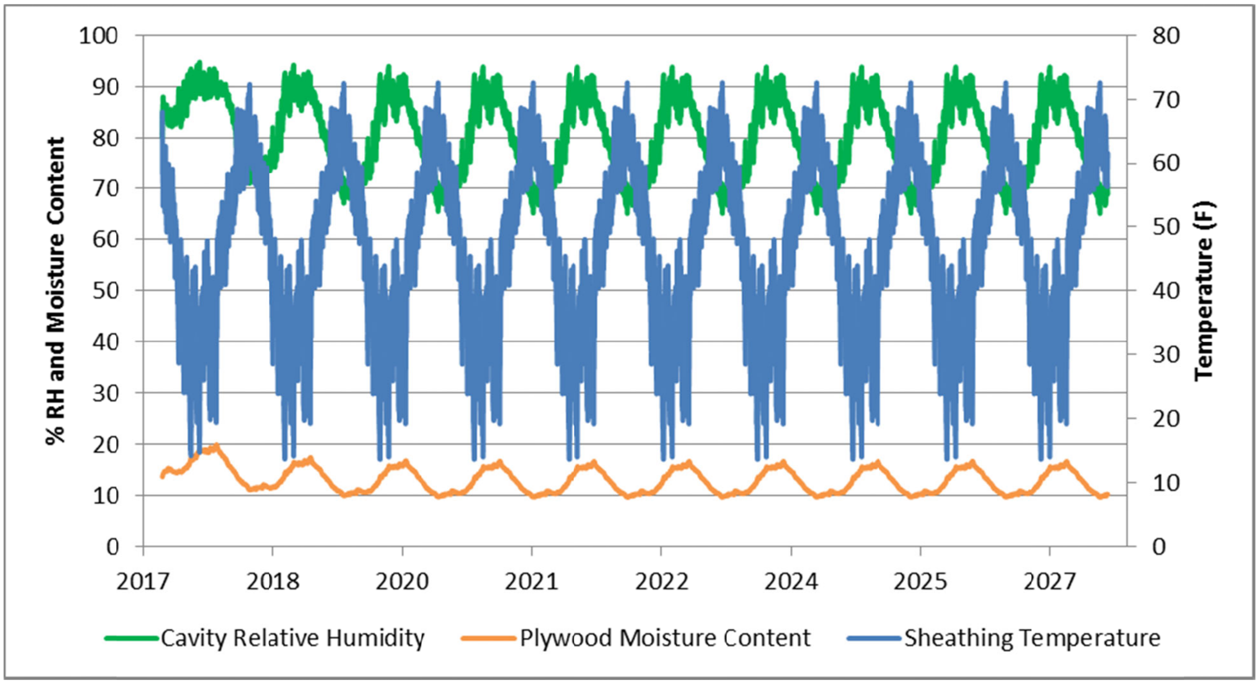

Figure 19. Anchorage 10-year data for a 2-inch exterior EPS retrofit. Above freezing temperatures and relative humidity above 80% will lead to mold danger at the plywood sheathing.

Juneau 10-year data

The model finds that this retrofit does not seem to develop any moisture issues in Juneau over the course of a 10-year period (Figure 20), due to the warmer winter temperatures in Juneau.

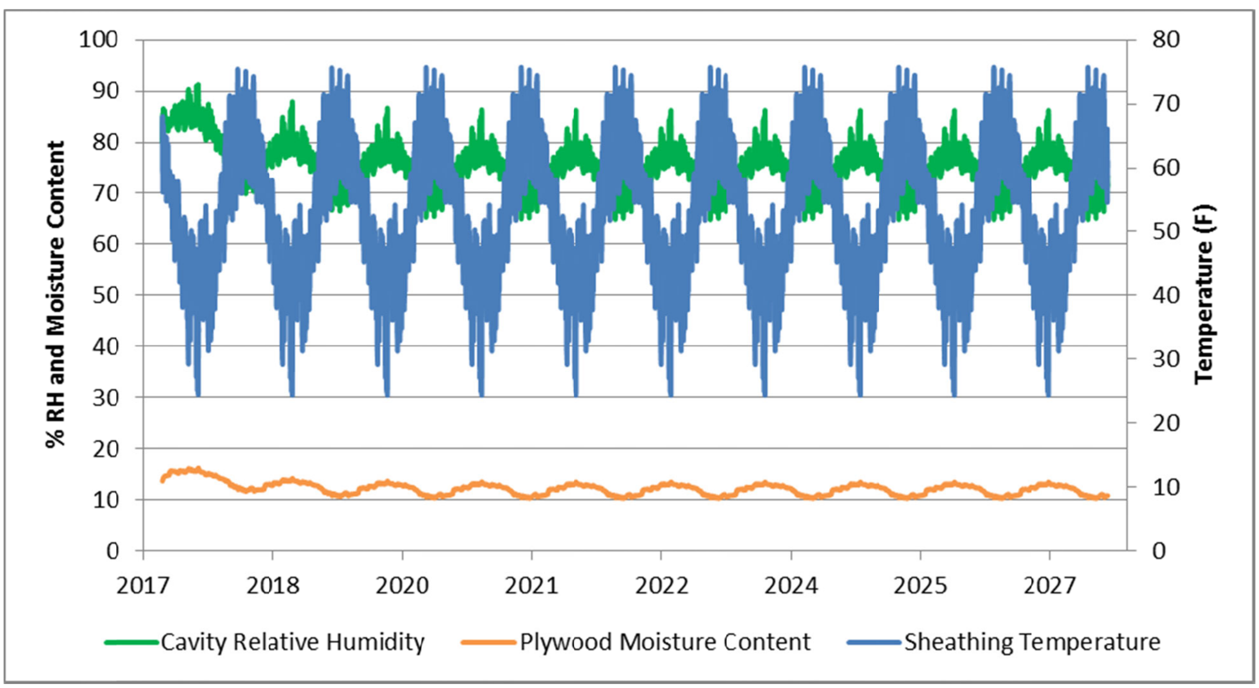

Figure 20. The 2-inch EPS retrofit in Juneau. Juneau's milder temperature makes this retrofit a safe option.

Other EPS retrofit options

Two inches of unfaced EPS is not an option for a Fairbanks retrofit, so other levels of insulation were considered. Three inches of foam is still not enough to avoid high levels of mold risk at the sheathing in the first two years after construction, and remains in the caution zone for the duration of the 10-year model. Table 6 presents options for EPS retrofits to existing R-19 2x6 fiberglass walls with interior vapor retarders (R-21 stud walls will have different results). WUFI's mold postprocessor outputs a danger level based on color: red is not acceptable with mold growth greater than 200 mm/year, yellow shows mold growth between 50 and 200 mm/year requiring caution and additional study, and green is reserved for mold growth less than 50 mm/year.

The modeled walls have a leaky interior 6-mil polyethylene vapor retarder, a vented exterior rain screen, a higher permeability (5 perm inch) unfaced EPS, and have a maximum air leakage of 5 ACH50. Increasing the air leakage or neglecting the exterior rain screen changes the results dramatically. For example, without the drying path provided by a vented exterior rain screen, the 4-inch EPS retrofit moves into the yellow caution range.

Table 6. Summary of WUFI Results at Plywood Sheathing.

	Fairbanks	Anchorage	Juneau
1-inch High Perm EPS	Unacceptable	Unacceptable	Caution
2-inch High Perm EPS	Unacceptable	Strong Caution	Acceptable
3-inch High Perm EPS	Strong Caution	Caution	Acceptable
4-inch High Perm EPS	Acceptable	Acceptable	Acceptable

Exterior cellulose retrofits

The plywood sheathing with an exterior 3.5-inch cellulose retrofit appears to be moisture-safe in Fairbanks, Anchorage, and Juneau. A modeled 2-inch cellulose retrofit is also moisture safe, but the amount of cellulose added to the existing wall should depend on the cost effectiveness of the labor versus the potential savings. Too little cellulose will not have the savings over the high cost of installation. From a practical standpoint, a wall with blown-in insulation will be at least 3.5 inches thick as framing lumber provides an economical solution to building up wall thickness.

The walls were modeled with a leaky interior 6-mil polyethylene vapor retarder and a vented exterior rain screen. They have a maximum air leakage of 5 ACH50. Increasing the overall house air leakage or neglecting the exterior rain screen changes the results dramatically. Without a vented exterior rain screen the cellulose retrofit moves into the yellow "caution" area at the sheathing, and the outer edge of the cellulose is in constant danger of mold growth.

Exterior fiberglass retrofits

The 3.5-inch blown-in fiberglass retrofit is moisture-safe in Fairbanks, Anchorage, and Juneau. A 2-inch retrofit is an option as well; however, there is a loss in thermal performance that will likely negate any cost savings if thinner amounts of fiberglass are used instead. Additionally, it is more cost effective to have at least 3.5 inches of blown-in insulation to match the typical size of framing lumber. The walls were modeled with a leaky interior 6-mil polyethylene vapor retarder and a vented exterior rain screen, and have a maximum air leakage of 5 ACH50. Like the exterior cellulose retrofit model, changing the air leakage or neglecting the exterior rain screen changed the results dramatically. For example, without a vented exterior rain screen the outer edge of the fiberglass is in danger of mold growth.

Stone wool Retrofits

Stone wool is a highly permeable material. It has a permeablity of 107 perm inch versus faced EPS which is only 0.9 perm inch. This high permeablity makes the wall more forgiving in high moisture events. The 10-year models of stone wool walls show that having more than R-8 (2 inches) of outer stone wool insulation on a 2x6 wall with an interior vapor retarder makes the wall more robust from moisture damage. Figure 21 shows the moisture content in the plywood based on the amount of exterior stone wool. The model with the least exterior insulation (1 inch) has climbing moisture content over 10 years. The 1.5-inch model doesn't climb but does get above the 20% danger threshold every winter; this is verified by Wall 1 in the MTL, which had 36 consecutive days in the RH critical zone and small patches of visible mold on the sheathing.

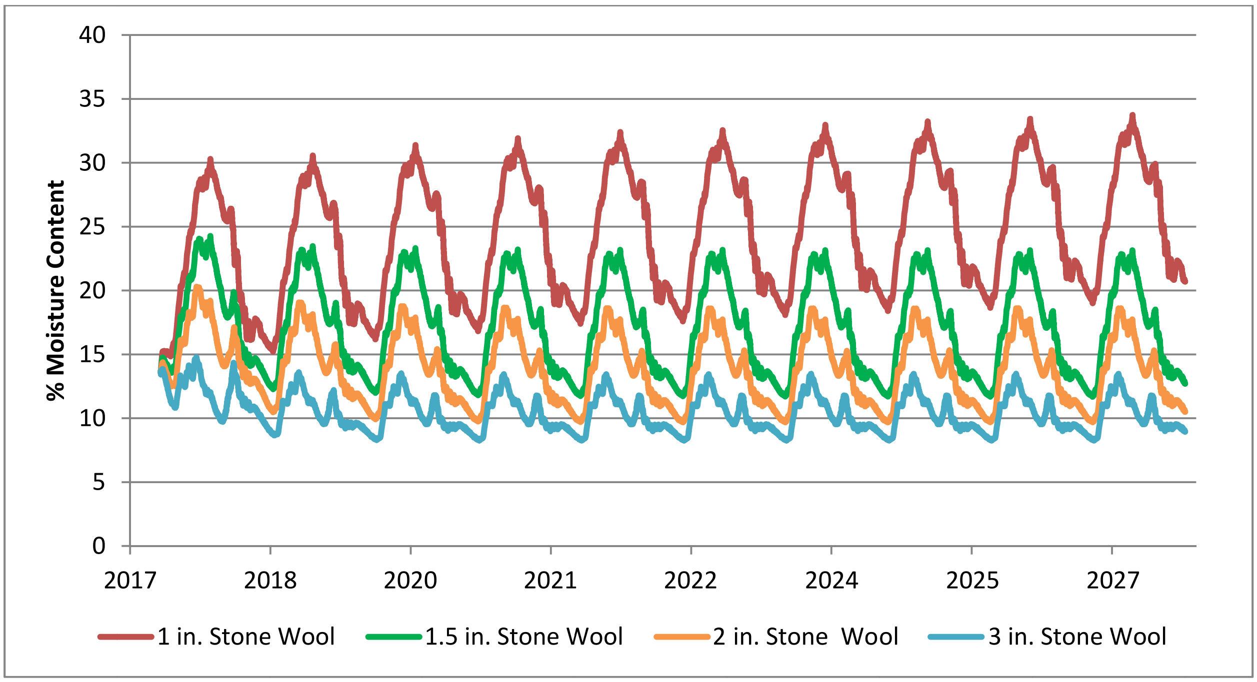

Figure 21. Plywood sheathing moisture content for stone wool exterior insulation in Fairbanks. The 1.5-inch model is the same as Wall 1 from the MTL study. It is in the critical zone enough hours each winter to cause concern.

Figures 22 and 23 show the variation in relative humidity and inner sheathing temperature with varying levels of exterior stone wool. The 1-inch model is always in the mold danger zone while the 1.5-inch model tends to have lower humidity in the summers. This is due to the lower temperature at the plywood sheathing with less exterior insulation; the RH will be higher at lower temperature. The model shows that 1.5 inches of exterior stone wool puts the wall at risk of mold growth; adding more insulation would be a wise choice. The test wall in the MTL showed some visible mold growth in select areas of the plywood sheathing over the 2-year study.

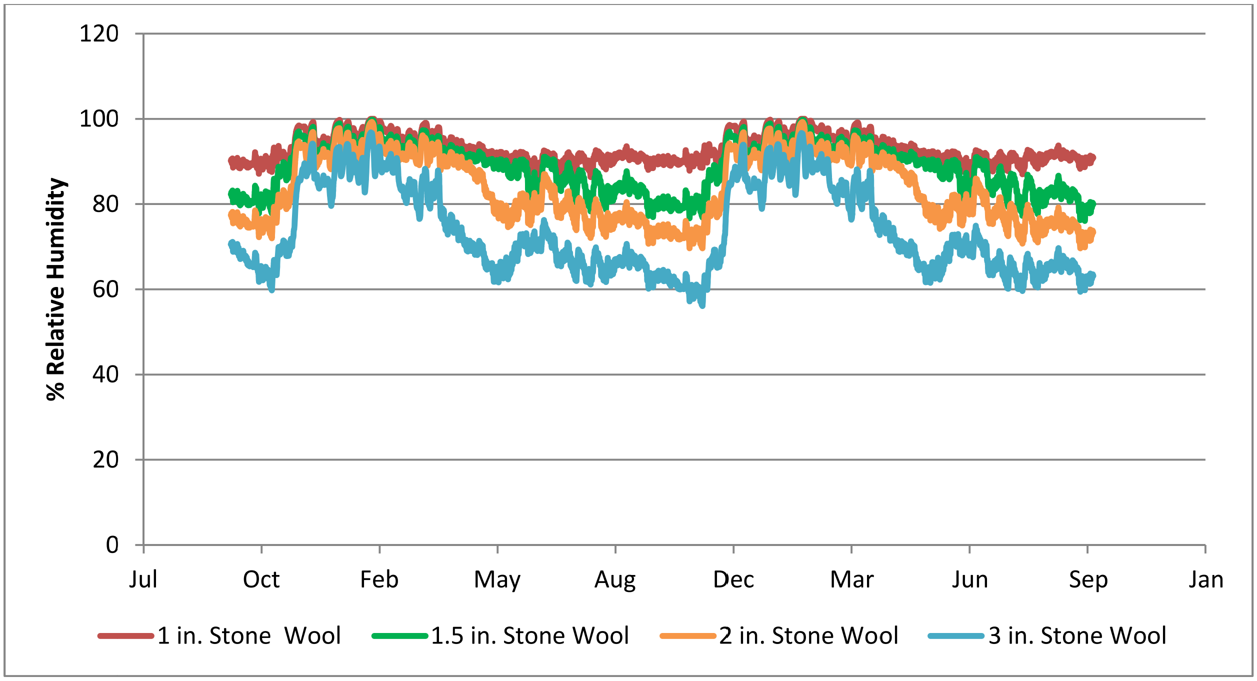

Figure 22. Stud cavity relative humidity for stone wool exterior insulation in Fairbanks. The relative humidity of the thinner stone wool retrofits is much higher than the thicker retrofits.

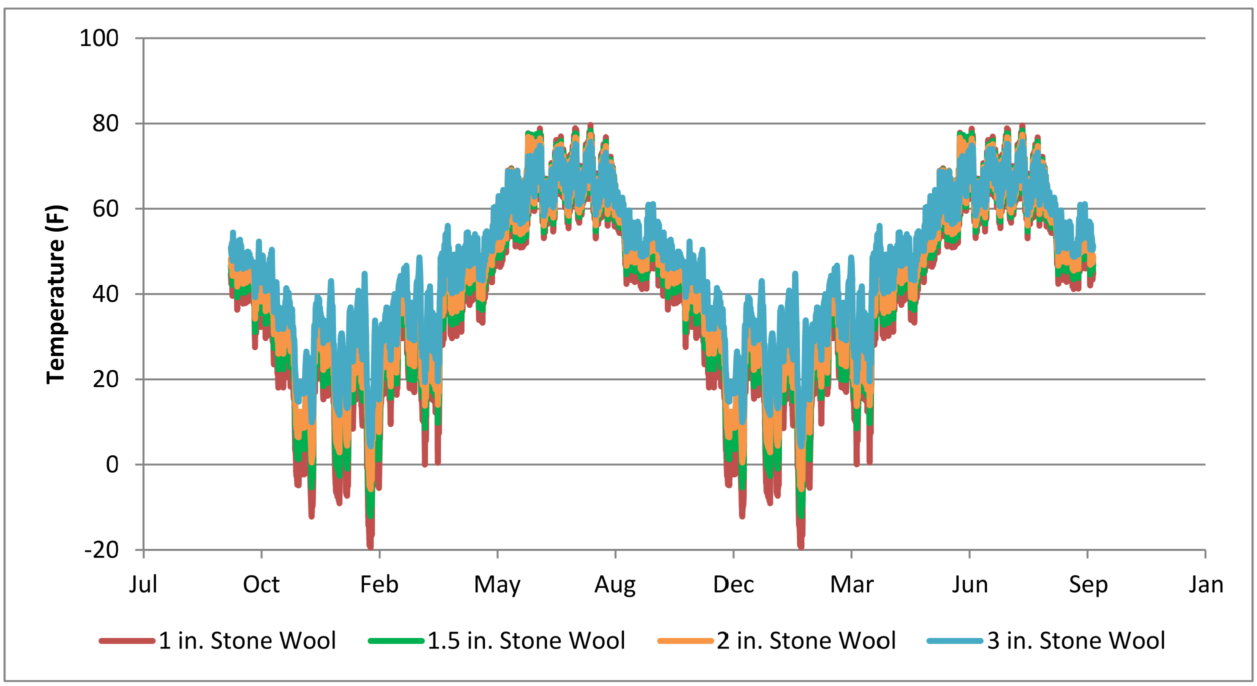

Figure 23. Plywood sheathing temperature for stone wool exterior insulation in Fairbanks. This shows that more exterior insulation keeps the plywood warmer.

Discussion

Exterior insulation improves the energy performance of walls. Figure 24 shows the measured temperature at the plywood sheathing for the retrofits in this study. The wall with no exterior insulation is warmer than the outside air but noticeably colder than all walls with exterior insulation retrofits.

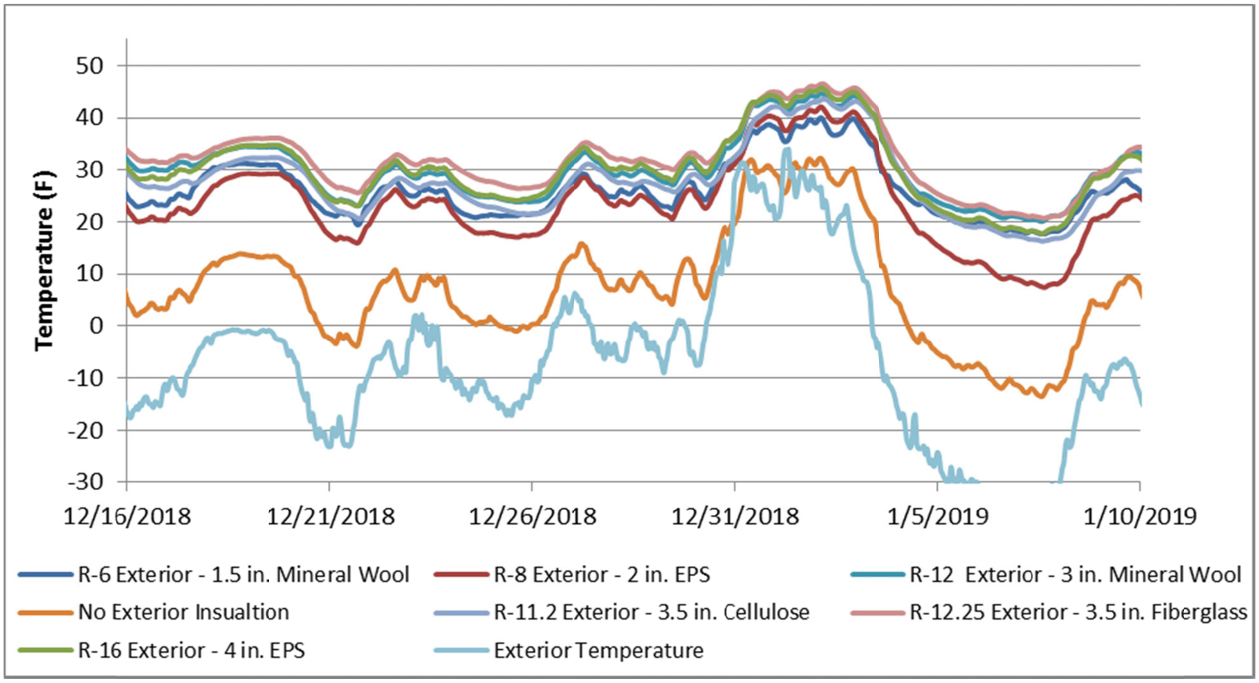

Figure 24. MTL Inner plywood sheathing temperatures. All of the walls with exterior insulation show significantly warmer sheathing temperatures than the control wall with no exterior insulation.

The cost savings versus the capital costs of wall retrofits are presented in Garber-Slaght et al., 2015 and summarized in Table 7. In general, wall retrofits are not as cost effective as other energy efficiency retrofits; homeowners should talk to a home energy rater before embarking on an expensive wall retrofit (Garber-Slaght, et al., 2015).

Table 7. The Economics of wall retrofits in Fairbanks, AK at $3.05/gallon heating fuel (used with permission from Garber-Slaght et al., 2015).

Wall	Annual space heating cost	Installed Cost	Annual Savings	SIR[1]	Adjusted Payback[2]	NPV @ 13 years[3]
Base Wall	$3,839					
Air Barrier Only	$3,321	$5,885	$518	2.1	12.4	$283
4-inch unfaced EPS	$2,749	$14,939	$1,090	1.7	15.2	-$1,960
1.5-inch Stone wool	$2,976	$13,642	$863	1.5	17.8	-$3,366
2-inch Stone wool	$2,908	$14,698	$931	1.5	17.8	-$3,613
3-inch dense pack cellulose	$2,848	$17,485	$991	1.3	20.3	-$5,685
3-inch dense pack fiberglass	$2,822	$18,223	$1,017	1.3	20.7	-$6,113

[1] Savings-to-Investment Ratio, the present value of savings over its life divided by its initial cost. A SIR of 1 is the breakeven point; any SIR over 1 is considered cost-effective.

[2] Years for investment to pay back taking into account energy cost increases over time and a 3% real discount rate (which has already been adjusted for inflation).

[3] Net Present Value of the investment after 13 years, the average length of time that a buyer lives in a home. Negative values indicate the investment will not be fully paid back within the 13-year period.

Wall retrofits have the potential to change the moisture dynamics in drastic ways. The study in the MTL used high interior relative humidity (40% is high for Interior Alaska due to low outdoor ambient humidity, but is considered a healthy RH level) and average air leakage (the target leakage was 5 ACH50 the average of existing post retrofit homes) in order to demonstrate what happens in the walls if they are under stressed conditions. The most typical Fairbanks exterior wall retrofit of two inches of EPS produced mold inside the wall in the first year, even with the unfaced more permeable EPS. Table 8 shows a summary of how many days each wall was in the mold danger zone over the 2-year study. Depending on the RH and temperature, mold tends to grow within four to eight weeks. The 2-inch EPS wall spent 17 consecutive weeks in the danger zone in Year 1, and 16 consecutive weeks in Year 2. The 1.5 inch stone wool wall had 36 consecutive days in the potential mold zone and developed spots of mold. The 4-inch EPS wall spent 9.5 weeks during Year 1 in the mold danger zone, but did not develop visible mold. This could be due to lower RH and temperatures that would require a longer time for mold to grow, or the mold growth was so small as to not be visible to the naked eye. None of the other walls spent nearly as much consecutive time in the danger zone, which was verified by no visible mold in the walls at the end of construction.

Table 8. Summary of critical temperature and RH for mold growth.

Wall #	Exterior Insulation	% exterior R-value	Total Days in RH critical (Year 1)	Total Days in RH critical (Year 2)	Max consecutive days in RH Critical
Wall 1	1.5 inches of stone wool board	20.67%	64	65	36 (spots of visible mold)
Wall 2	2 inches of unfaced EPS board	29.63%	153	135	122 (visible mold)
Wall 4	3 inches of stone wool board	34.26%	50	0	33
Wall 5	none		25	8	5
Wall 6	3.5 inches of cellulose	39.20%	75	3	34
Wall 7	3.5 inches of fiberglass	39.20%	42	0	17
Wall 8	4 inches of unfaced EPS board	45.71%	84	0	67

Conclusion

Retrofitting walls with exterior insulation can be a tricky energy efficiency solution. Special care needs to be paid to the moisture dynamics of the retrofit wall design as existing walls usually have a leaky plastic vapor barrier directly behind the inner gypsum wall board. Sticking to the $^1/_3$ to $^2/_3$ insulation ratio rule for Interior Alaska is a fail-safe way to prevent moisture problems that could arise from adding vapor-impermeable insulation to the outside a wall (for Anchorage 60% of the R-value should be exterior of the sheathing, for Juneau 43%. Refer to the online calculator for more information: http://dewpointcalc.cchrc.org/).

There is potential to use vapor-open exterior insulation in violation of the $^1/_3$ to $^2/_3$ rule if the existing building envelope has:

- an interior 6-mil polyethylene vapor retarder that is not very leaky (this is very difficult to determine, and will probably require a professional to inspect the walls), or

- the overall post-retrofit house air leakage is less than 5 ACH 50, and
- the exterior retrofit includes an exterior vented rain screen that is at least ½ inch wide.

Air control is critical in wall retrofits. Air leakage through the building envelope can account for 18% of the total home space heating loss (Garber-Slaght et al., 2015). Air leakage is also the major source of moisture infiltration into the walls. In any home retrofit, special detail needs to be paid to the air control layer for energy savings but also moisture control. However, there is still a minimum insulation thickness based on the material, the energy savings target, and the house location. Table 9 provides a summary of potential options for Fairbanks.

Table 9. Wall retrofit options for Fairbanks, AK.

	Stone wool	Blown-in Fiberglass	Blown-in Cellulose	5 perm inch EPS
Necessary amount of exterior insulation for an R-19 wall retrofit	At least 2 inches	At least 2 inches	At least 2 inches	At least 4 inches

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