COLD CLIMATE HOUSING RESEARCH CENTER
CCHRC

Safe
Effective &
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RETROFITS

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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

Adding rigid foam to the exterior of a house is a common energy retrofit in Alaska. This technique has the potential to improve a home's energy performance but it can also change the moisture dynamics of the wall. This change in moisture movement can result in compromised indoor air quality and reduced durability of the structure due to moisture accumulation in the building envelope. CCHRC looked into alternative exterior insulation retrofit designs that are moisture safe, energy efficient, and affordable to homeowners. The research included a literature review, interviews with contractors, and hygrothermal modelling. Five potential wall retrofits have been chosen for further study: an air barrier only retrofit, 2 inches of mineral wall board, 4 inches of high permeability EPS, 3 inches of spray in fiberglass, and 3 inches of spray in cellulose.

Keywords: walls, energy efficiency, retrofits

Safe, Effective, and Affordable Retrofits

More than half of homes in Alaska were built during the pipeline construction boom of the 70s and 80s. These homes are now 25-45 years old, are generally energy inefficient, and lack modern ventilation systems. This is part of the reason the average annual energy cost for homes in Alaska is more than twice the national average, exceeding more than four times the national average in some regions (Wiltse, Madden, & Valentine, 2014).

While the Alaska Housing Finance Corporation's (AHFC) Home Energy Rebate and Weatherization Assistance programs have helped many Alaskans reduce their energy costs through energy efficient retrofits, many homes have not benefited from such upgrades. There are approximately 115,000 housing units in Alaska built in the 1970s and 1980s that have not undergone such retrofits. Nearly 20,000 homes in Alaska are estimated to have One Star energy ratings (i.e. these homes use at least four times as much energy as a new home built to Alaska's Building Energy Efficiency Standard (Alaska Housing Finance Corporation, 2013)).

Walls are a significant source of energy loss in buildings and are often one of the most difficult areas to retrofit as there is typically limited space for additional insulation and the existing insulation is usually difficult to access. An analysis of more than 25,000 "As-Is", or pre-retrofit, home energy ratings in Alaska showed that an average 23% of the space heating loss was through the walls (Alaska Housing Finance Corporation, 2015; CCHRC estimates derived using the Alaska Retrofit Information System (ARIS) database). In addition to this conductive heat loss through the walls, older walls are often leaky, contributing to heat loss through air movement. Heat loss due to air leakage through all parts of the building accounts for an additional 18% of the total space heating loss.

A common retrofit technique for residential buildings in Alaska is the addition of foam board insulation on exterior walls. This popular retrofit is typically performed as part of a re-siding project for a house. While these retrofit designs include foam board insulation to reduce heating demand, these designs also change the moisture flow through the wall. This change in moisture dynamics is typically not considered in the design or is frequently misunderstood. This is significant because retrofit designs can potentially result in compromised indoor air quality and reduced durability of the structure due to moisture accumulation in the building envelope.

Best practice retrofit guidelines consider both energy savings and moisture management, but such retrofits are almost never done 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 R-value inside the sheathing 2/3 outside the sheathing), eight to ten inches of exterior foam insulation would be necessary. This has led to a pattern of exterior insulation practices that may meet initial cost savings objectives but introduce risks associated with inadequate moisture control.

This project was designed to identify affordable wall retrofit ideas that do not compromise wall durability and which are effective at improving the thermal performance of the envelope. Because envelope designs need to consider climate as an important variable, the initial evaluation was conducted specific to Interior Alaska. It was set up four distinct phases:

1. A review of pertinent literature of wall retrofits in cold climates,
2. Interviews with several local builders for wall retrofit ideas, feedback, and cost estimates as well as internal CCHRC meetings to develop wall retrofit ideas,
3. Hygrothermal modeling to determine which wall ideas are robust to moisture, and
4. An economic assessment of the cost of wall retrofits and the payback.

Background

The high cost of energy in Alaska often drives homeowners to implement energy retrofits on their homes. The AHFC has been tracking energy retrofits in Alaska since 1996. Often energy retrofits include improving the building envelope via additional insulation and air tightening practices. Table 1 shows the number of homes in 4 regions around the state that have had a wall retrofit where insulated sheathing was added and how those retrofits have improved the air tightness.

Table 1. Exterior Wall Retrofits by Region.

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

In the Doyon region alone there are several thousand homes that would benefit from envelope energy retrofits. There are approximately 43,730 homes in the region built in the 1990s or earlier. These older homes use an average of 50 to 100 million BTUs more energy annually than a home built in 2005. About 10% of these older homes have undergone a recent energy retrofit which leaves about 40,000 homes in the Doyon region that have not recently had an energy retrofit. Of the 4,000 homes in the Doyon region that have had an energy retrofit, 15% (or 600) of those retrofits had some sort of insulated sheathing added to the envelope.

Literature Review

The addition of external insulation to the outside walls offers many potential benefits, including increasing the R-value of the walls, reducing thermal bridging through the studs, and improving air tightness. 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).

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 moisture does not condense on these surfaces. In Interior Alaska this means following the "$^1/_3$ to $^2/_3$ rule," or making sure that at least $^2/_3$ of the R-value of the wall is outside of the sheathing when using rigid foam board for the external insulation. One example of a wall built using these concepts is the REMOTE wall, described for new walls in "Installing Exterior Insulation in Cold Climates" by Chlupp (2009). The REMOTE wall also illustrates another guideline that is important to durable external wall retrofits in cold climates, walls need a way to self dry (in the case of REMOTE the drying path is toward the inside). The $^1/_3$ to $^2/_3$ rule helps to prevent condensation from occurring within wall cavities, however creating a pathway for drying is extra insurance that any moisture entering the wall cavity will also have a chance to leave (Lepage & Lstiburek, 2012; Holladay, 2010).

Recently, 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 mineral wool offer the potential for better moisture protection than rigid foam and the ability to vary from the $^1/_3$ to $^2/_3$ rule, potentially making for a less expensive retrofit. 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 mineral wool, which are water vapor open, provide greater drying potential via diffusion. This reduces peak moisture contents within the framing and accelerates drying times, two key elements of moisture control. However, there is currently little experimental verification to support these claims. Craven & Garber-Slaght (2014) found that test wall sections with exterior cellulose insulation had better moisture performance than those with exterior EPS foam but did not determine a minimum thickness of cellulose for adequate moisture protection. Holladay (2011) summarized research on mineral wool, noting that mineral wool boards could be installed in a similar manner to rigid foam and that it was strong enough to support vertical furring strips and siding. Mineral 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 Alaska.

A complete annotated bibliography is available in Appendix A.

Walls Studied

CCHRC developed wall retrofit concepts for a base 2x6 wall that has an unsealed interior vapor retarder, R-19 fiberglass batts in the stud cavities and T1-11 plywood siding. This base wall is typical of walls built in Interior Alaska during the pipeline construction boom of the late 1970s and early 1980s. These homes are often retrofitted with exterior foam board insulation, installed directly over the T1-11. These retrofits tend to use 1 to 2 inches of faced EPS, which create the potential for moisture problems in the walls. Prior research suggests that a wall retrofit that is more vapor permeable could be an affordable and safe alternative. With this in mind, several wall retrofit scenarios were developed using cellulose, fiberglass, and rigid mineral wool board insulations. Table 2 lists the first 11 retrofits that were studied using hygrothermal software, WUFI. The foam retrofits were included for comparison.

Table 2. Walls Studied.

	Air Barrier	Exterior Insulation	Air Barrier	Siding Ventilation*	Siding
Air Barrier Retrofit	Housewrap	None	None	¾ inch ventilated rain screen	Vinyl siding
Foam Retrofit #1	None	2 inches EPS	None	none	Vinyl siding
Foam Retrofit #2	Housewrap	2 inches EPS	None	¾ inch unvented rainscreen	Vinyl siding
Foam Retrofit #3	Housewrap	6 inches EPS	None	¾ inch unvented rainscreen	Vinyl siding
Mineral wool panel Retrofit #1	Housewrap	2 inches mineral wool panels	None	¾ inch ventilated rain screen	Vinyl siding
Mineral wool panel Retrofit #2	Housewrap	4 inches mineral wool panels	None	¾ inch ventilated rain screen	Vinyl siding
Mineral wool panel Retrofit #3	Housewrap	6 inches mineral wool panels	None	¾ inch ventilated rain screen	Vinyl siding
Cellulose Retrofit #1	Housewrap	5.5 inches dense pack cellulose	Housewrap	¾ inch ventilated rain screen	Vinyl siding
Cellulose Retrofit #2	Housewrap	3.5 inches dense pack cellulose	Housewrap	¾ inch ventilated rain screen	Vinyl siding
Blown Fiberglass Retrofit #1	Housewrap	5.5 inches dense pack fiberglass	Housewrap	¾ inch ventilated rain screen	Vinyl siding
Fiberglass Batt Retrofit	Housewrap	R-21 fiberglass batt	Housewrap	¾ inch unvented rainscreen	Vinyl siding

*Ventilated refers to a rain screen with openings at the top and bottom to allow the free movement of air from outside. An unvented rain screen has an air gap but the gap is blocked at the top and/or bottom with wooden “nailers.”

After initial study and interviews with residential contractors in Fairbanks, a few more wall retrofit scenarios were analyzed in WUFI. These additional scenarios added unfaced EPS as another insulation option since it is more water vapor permeable than EPS with plastic facers. Table 3 lists the follow-up wall retrofits analyzed with WUFI.

Table 3. Follow-up Walls Studied.

	Air Barrier	Exterior Insulation	Air Barrier	Siding Ventilation	Siding
Foam Retrofit #4	Housewrap	7 inches EPS	None	¾ inch unvented rainscreen	Vinyl siding
Unfaced Foam Retrofit #1	None	2 inches unfaced EPS	None	None	Vinyl siding
Unfaced Foam Retrofit #2	Housewrap	2 inches unfaced EPS	None	¾ inch unvented rainscreen	Vinyl siding
Unfaced Foam Retrofit #3	Housewrap	6 inches unfaced EPS	None	¾ inch unvented rainscreen	Vinyl siding
Unfaced Foam Retrofit #4	Housewrap	4 inches unfaced EPS	None	¾ inch unvented rainscreen	Vinyl siding
Mineral wool panel Retrofit #4	Housewrap	1.5 inches mineral wool panels	None	¾ inch ventilated rain screen	Vinyl siding
Cellulose Retrofit #3	Housewrap	3 inches dense pack cellulose	Housewrap	¾ inch ventilated rain screen	Vinyl siding
Cellulose Retrofit #4	Housewrap	3 inches dense pack cellulose	Housewrap	¾ inch unvented rainscreen	Vinyl siding
Blown Fiberglass Retrofit #2	Housewrap	3 inches dense pack fiberglass	Housewrap	¾ inch unvented rainscreen	Vinyl siding
Blown Fiberglass Retrofit #3	Housewrap	3 inches dense pack fiberglass	Housewrap	¾ inch ventilated rain screen	Vinyl siding

Based on WUFI analysis and contractor feedback, five retrofit walls became the focus of this project: the air barrier only wall, unfaced foam retrofit #4, mineral wool panel retrofit #1, unfaced foam retrofit #4, , fiberglass retrofit #3 and blown cellulose retrofit #3 (Figures 1-5). These specific combinations were chosen because they:

- provide acceptable hygrothermal performance based on the WUFI simulations, discussed below, and
- use the minimum amount of exterior insulation for each insulation choice to minimize the cost of retrofit construction.

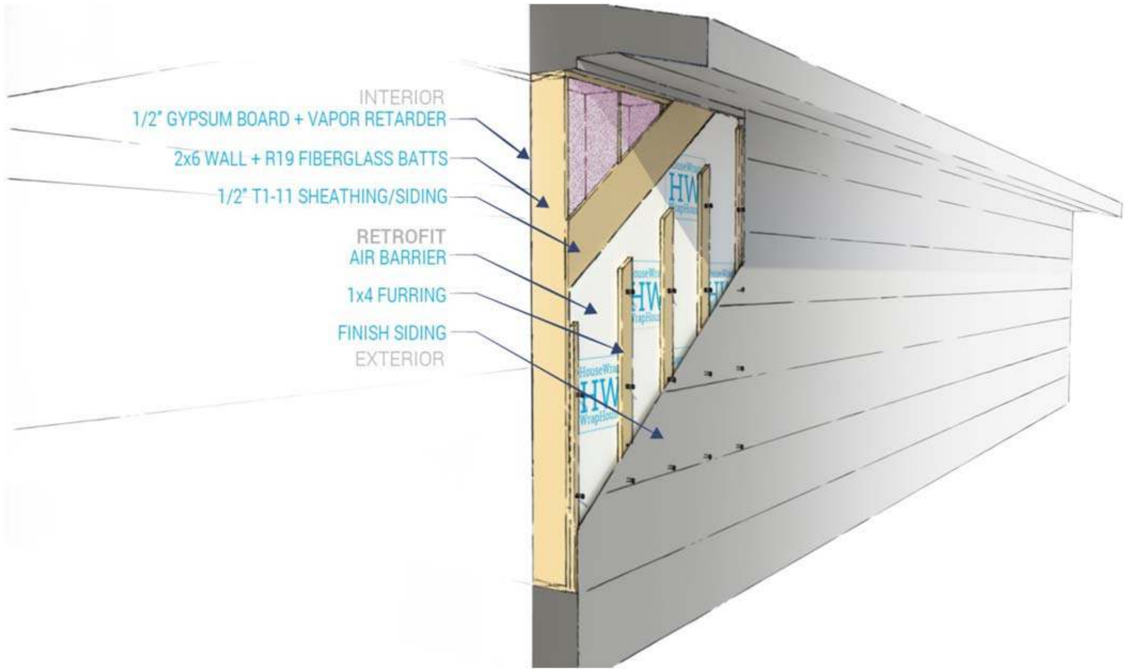

Figure 1. Air barrier only retrofit. An exterior house wrap is added to inhibit air leakage from the house.

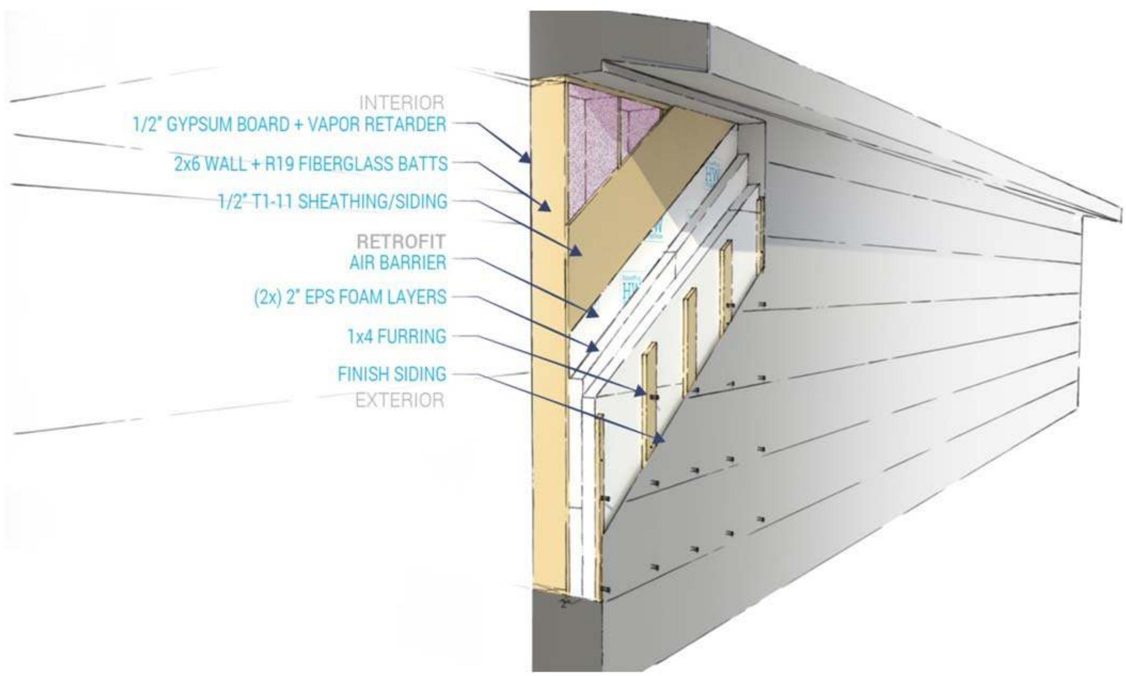

Figure 2. Four inches of permeable EPS. This wall has 4 inches of EPS with a higher permeability (5 or more perms) than the typical faced EPS.

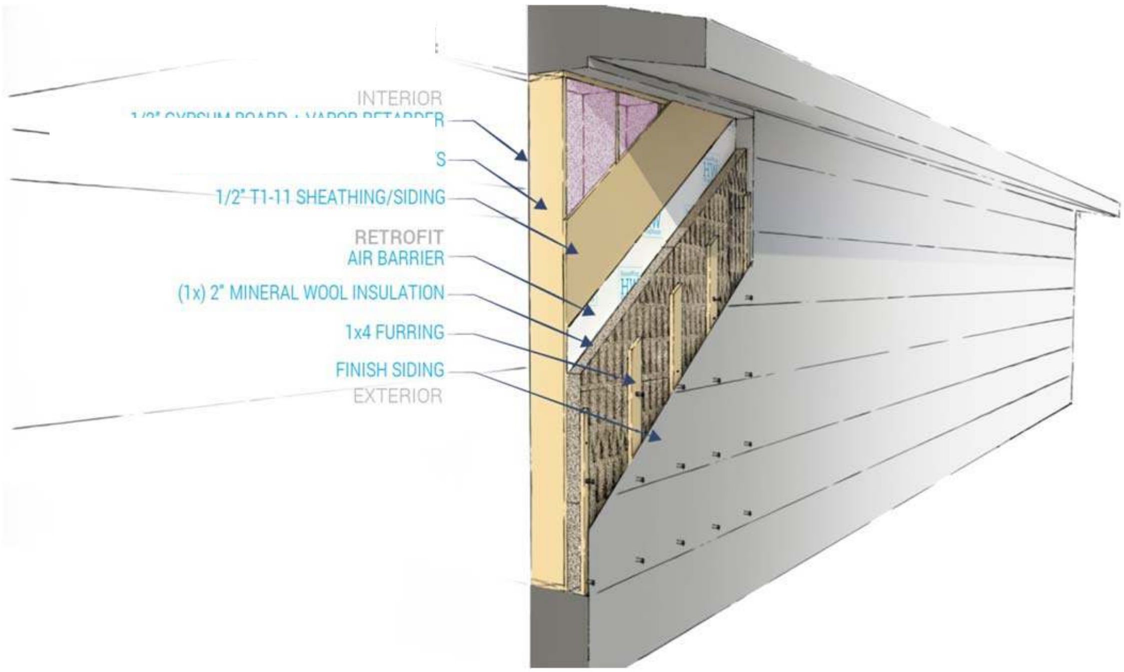

Figure 3. Two inches of mineral wool. This wall has highly permeable mineral wool insulation.

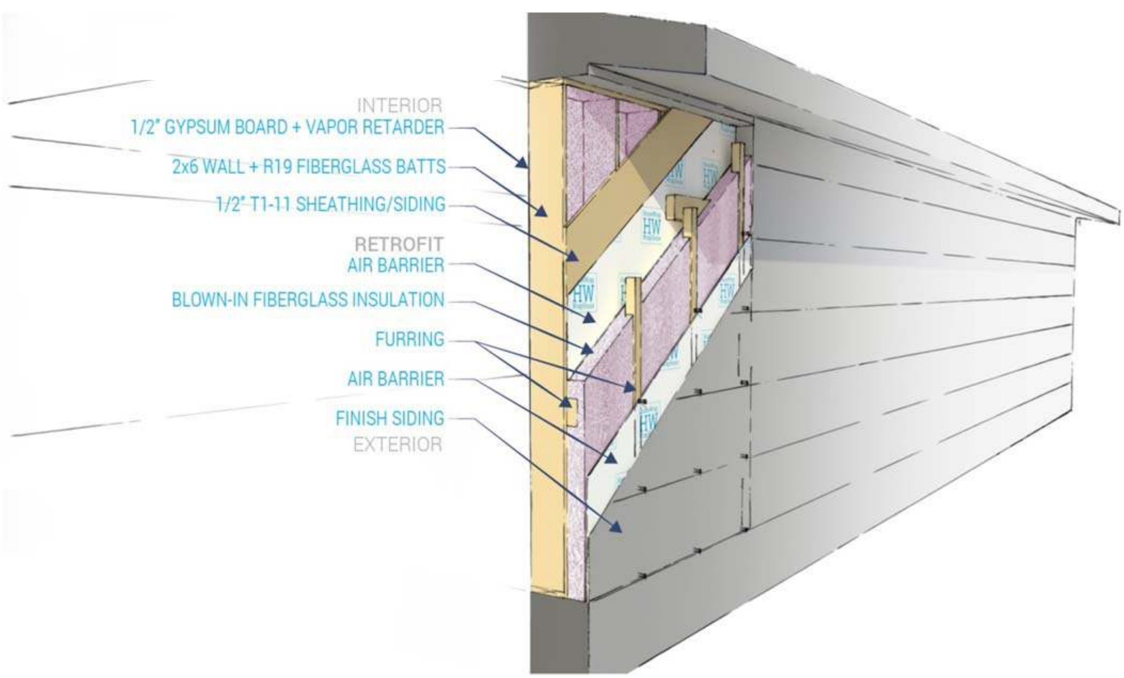

Figure 4. Fiberglass curtain wall. This wall has an exterior curtain frame to contain 3 inches of fiberglass.

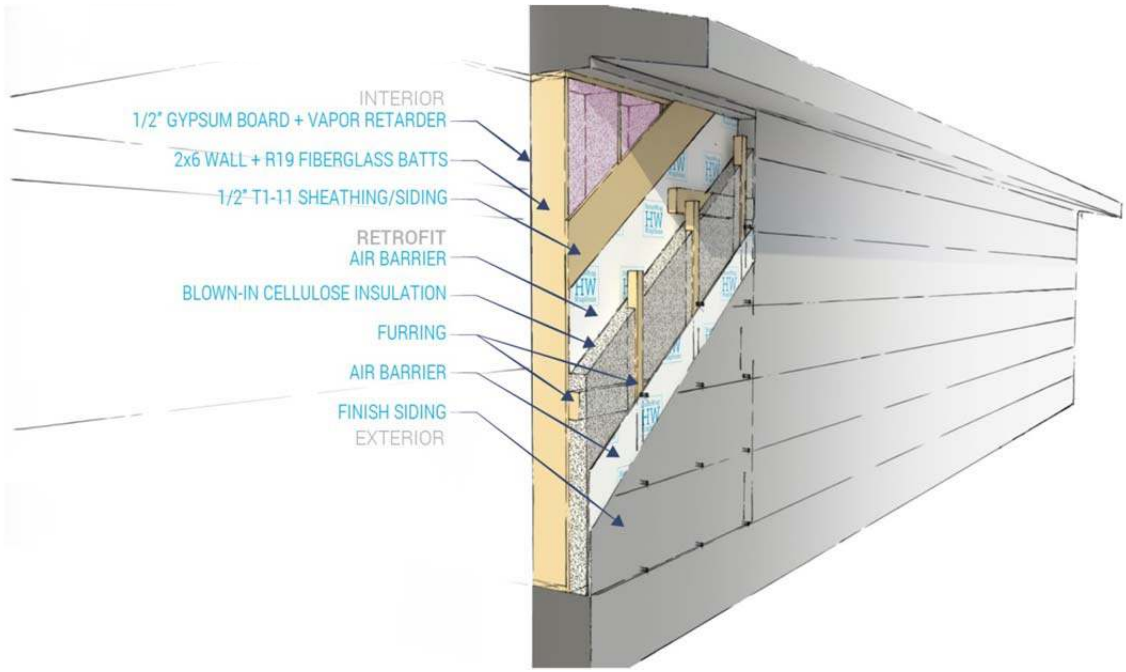

Figure 5. Cellulose curtain wall. This wall has an exterior curtain frame to contain 3 inches of cellulose.

Hygrothermal Modeling

WUFI Pro 5.3 is a one-dimensional hygrothermal modeling computer program. It evaluates the thermal and moisture performance of a wall cross-section based on boundary conditions and physical properties of the wall materials. The model allows for moisture to be introduced into the wall by water vapor diffusion and air infiltration. For this study the interior conditions were set to 40% relative humidity and 70°F, a typical cold weather year for Fairbanks was used for the external conditions. Table 7 offers a summary of the WUFI outputs. The mold danger is categorized by color: green for safe (less than 50mm of mold growth per year), yellow for further study (50mm to 200mm of mold growth per year), and red for extensive mold growth (more than 200mm/year). Output that falls between the clear boundaries of these three categories is described using two colors. Mold danger is assessed at the plywood sheathing surface as the most likely component of the wall to encounter mold growth. The notes column reflects the results when the plywood is replaced with OSB sheathing.

It is interesting to note that the base wall has a yellow “caution” result. This is the typical wall construction of a majority of homes in Interior Alaska. Most of these homes do not show moisture failure, in part because Fairbanks has a dry climate and interior relative humidity does not reach 40% in most homes. Additionally, this wall configuration is frozen at the sheathing most of the winter and when the condensation thaws it is able to dry to the outside quickly.

Table 7. WUFI results for retrofit options

	Retrofit Option	Mold Danger at the Plywood	Notes
	Base Wall	yellow	yellow to red with OSB
	Air Barrier Only	yellow	
Foam Retrofits	2 inch EPS unvented	red	
	2 inch EPS unvented	red	
	6 inch EPS unvented	red	
	7 inch EPS unvented	yellow to green	
	2 inch unfaced EPS no air gap	red	
	2 inch unfaced EPS ventilated	yellow	
	4 inch unfaced EPS ventilated	yellow to green	yellow to green with OSB, but a little worse off
Mineral Wool Panel Retrofits	1.5 inch mineral wool panel	yellow to green	
	2 inch mineral wool panel	green	yellow to green with OSB
	4 inch mineral wool panel	green	
	6 inch mineral wool panel	green	
Cellulose Retrofits	5.5 inch dense pack	green	green with OSB
	3.5 inch dense pack	green	yellow to green with OSB
Fiberglass Retrofits	5.5 inch dense pack	green (yellow at outside edge of fiberglass)	green with OSB
	R-21 batt	green (yellow at outside edge of fiberglass)	green with OSB

A full report of the modeling is available in Appendix B.

Contractor Interviews

CCHRC developed a list of potential wall retrofits and shared them with local Fairbanks contractors. The contractors provided feedback which helped guide the wall retrofit designs. After the initial WUFI modeling, CCHRC went back to some of the contractors for cost estimates to retrofit a hypothetical 2x6 wall rectangular house (Figure 6).

The retrofit options can be generally categorized into two construction types: rigid boards and curtain walls. The rigid board method included unfaced EPS and semi-rigid mineral wool insulation options which are mechanically fastened with battens. The curtain wall method included cellulose and fiberglass insulation options; filling a framework created by 2x4 strapping attached horizontally to the sheathing followed by 2x2 vertical attachments to create a 3-inch insulation cavity.

Both retrofit insulation methods included the installation of a water-resistive barrier over the sheathing. The curtain wall insulation method also had a second water resistive barrier installed over the vertical 2x2s which was reinforced by 1x4 battens that are fastened to the 2x2s. For both insulation methods, the battens allow for a vented airspace between the exterior insulation and the siding.

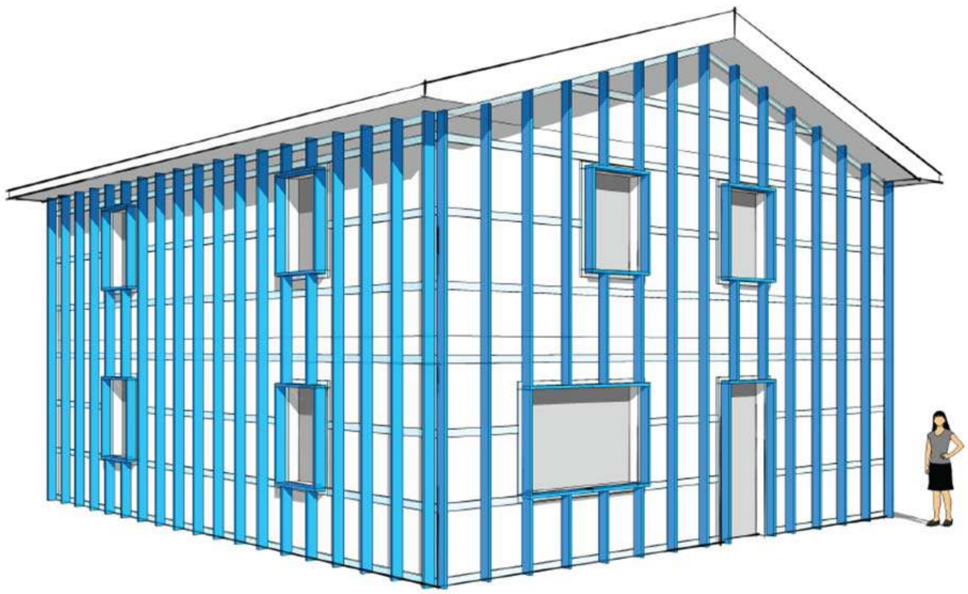

Figure 6. House mockup for the curtain wall retrofit scenario. The curtain wall has horizontal members attached to the T-111 siding and then vertical members attached to the horizontals. Housewrap is affixed to the vertical members and the entire cavity is filled with a dense pack insulation.

All contractors interviewed preferred the retrofit options using unfaced EPS and mineral wool boards over creating an exterior curtain wall and adding blown in fiberglass or cellulose. Several contractors were quite concerned with having cellulose on the exterior of the building due to potential wetting problems from exterior weather; of the two, blown-in fiberglass was the preferred option. Three contractors offered labor estimates on retrofitting the walls with mineral wool board or four inches of unfaced EPS, and two estimates were received for the curtain wall approach. Material costs were estimated by CCHRC and added to the contractor quotes for labor. None of the estimates included adding siding to the wall, as that would be the same for all retrofits. Table 4 shows the average costs based on these estimates.

Table 4. Contractor cost estimates

Retrofit Concept	Average Cost Estimates
Air Barrier only	$5,890
4 inch unfaced EPS	$14,940
1.5 inch mineral wool panel	$13,640
2 inch mineral wool panel	$14,700
3 inch cellulose	$17,480
3 inch blown fiberglass	$18,220

Energy Modeling

AKwarm is energy modeling software designed specifically for Alaska. A hypothetical 2 story 2,000 sq. ft. house was created using the program (illustrated in Figure 6). It had a conventional oil boiler and generic electric hot water heater. The attic had R-38 batts and the floor was a conventional heated crawlspace with an approximate R-value of 20 on the foundation wall.

The base house had a 2x6 stud wall insulated with R-19 fiberglass batts and an air leakage of 7 ACH50. Each wall retrofit was modeled separately, only the construction of the exterior walls and air leakage was changed. The air leakage for the retrofits was set to 5 ACH 50. Table 5 shows the R-value of the walls based on the AKwarm models.

Table 5. R-Value of retrofit walls

	Wall	R-Value
	Base Wall	R-16
	Air barrier only	R-16
Foam Retrofits	4 inch unfaced EPS furring with venting	R-34
Mineral Wool Panel Retrofits	1.5 inch mineral wool panel	R-24
	2 inch mineral wool panel	R-26
Cellulose Retrofits	3 inch dense pack	R-29
Fiberglass Retrofits	3 inch dense pack	R-30

Table 6 compares the annual space heating savings from each of the retrofit options, based on a heating fuel price of $3.05 per gallon.

Table 6. Annual savings for retrofits

	Wall	Annual Cost	Annual Savings	Energy Use
	Base Wall	$3,839	---	118.5 MMBtu
	Air Barrier Only	$3,321	$518	102.5 MMBtu
Foam Retrofits	4 inch unfaced EPS	$2,749	$1,090	84.9 MMBtu
Mineral Wool Panel Retrofits	1.5 inch mineral wool panel	$2,976	$863	91.9 MMBtu
	2 inch mineral wool panel	$2,908	$931	89.8 MMBtu
Cellulose Retrofits	3 inch dense pack	$2,848	$991	88.0 MMBtu
Fiberglass Retrofits	3 inch dense pack	$2,822	$1,017	87.1 MMBtu

Economic Assessment

Over the long-term, all of the wall retrofits modeled in this study are considered cost-effective because they have a Savings-to-Investment Ratio (SIR) of greater than 1.0. The SIR is the present value of the savings of the energy efficieny measure over its life divided by the initial cost, so an SIR of 1.0 is where the savings equal the initial investment cost. For example, retrofitting a wall with 4 inches of unfaced EPS foam is estimated to have an SIR of 1.7. This means that over the estimated 30 year life of the improvement, the energy savings are worth nearly twice as much as the original cost of the retrofit in 2015 dollars. The SIR includes an estimated increase in fuel prices over time, the effects of inflation, and a discount rate.

While all of these retrofits are cost-effective in the long-term, many people are still not choosing to perform them. One potential reason for this is that many people will not live in their home long enough to reap the full benefits of the retrofit. According to a 2013 study by the National Association of Home Builders, home buyers will occupy a house for 13 years on average (Emrath, 2013). The American Community Survey data provides a more detailed look at the length of time homeowners have lived in their current home in the Fairbanks North Star Borough, shown in Figure 7 (U.S. Census Bureau, 2013).

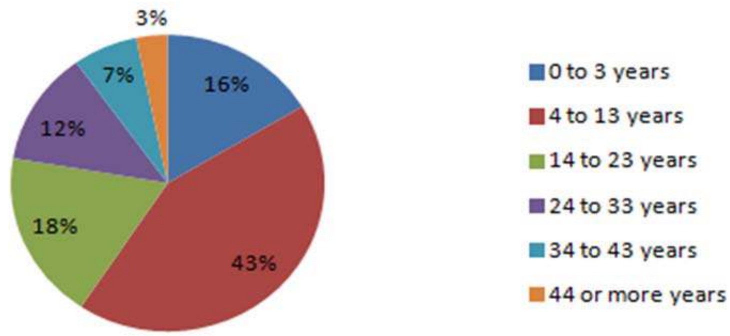

Figure 7.Fairbanks North Star Borough homeowner length of time in current home. Few people remain in their homes for longer than 13 years.

The adjusted payback for the wall retrofits shows that only the air barrier retrofit will pay itself off during the 13-year average occupancy of a home owner. This payback has been adjusted to take into account projected fuel price increases over time, inflation, and a discount rate. However, a more energy efficient wall will continue to provide the benefits of decreased energy costs for future occupants. While these future savings could be incorporated into the sale price of the home, research (Doyle and Bhargava, 2012) has shown that energy efficiency measures are not usually properly valued in appraisals. The Net Present Value at 13 years column in Table 8 shows the value of the wall retrofit to a homeowner after 13 years in today's dollars. A positive number means that the 13 years of energy savings were worth more than the initial cost of retrofit, and a negative number signifies that the initial cost of the wall retrofit have not yet been paid back by the 13 years of energy savings. Another way to think of this number is this is that negative numbers are the amount of additional value that the home would have to sell for in order for the retrofitter to fully recoup their money. For example, if a homeowner retrofitted their home with 4 inches of EPS foam, they would need to sell the house for an additional $1,960 in 13 years in order to recover their costs.

Table 8. The Economics of Wall Retrofits in Fairbanks, AK at $3.05/ gallon of fuel oil

Wall	Annual space heating cost	Installed Cost	Annual Savings	SIR	Adjusted Payback[1]	NPV @ 13 years[2]
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 mineral wool panel	$2,976	$13,642	$863	1.5	17.8	-$3,366
2 inch mineral wool panel	$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] 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).

[2]This is the Net Present Value of the investment after 13 years, the average length of time that a homeowner lives in their home.

It is important to note that this analysis is highly dependent upon the price of fuel oil. For example, before global oil prices fell in 2013, heating fuel was nearly one dollar per gallon higher than it was in Fairbanks 2014. An analysis of wall retrofit economics using $4.00 per gallon heating fuel prices shows higher SIRs and quicker paybacks for all walls involved, with a 4 inch EPS retrofit now showing a net savings during the average period of occupancy for homeowners. These estimates are shown in Table 9.

Table 9. The Economics of Wall Retrofits in Fairbanks, AK at $4.00/ gallon of fuel oil

Wall	Annual space heating costs	Installed Cost	Annual Savings	SIR	Adjusted Payback	NPV @ 13 years
Base Wall	$5,012		---			
Air Barrier Only	$4,336	$5,885	$677	2.7	9.3	$2,176
4 inch unfaced EPS	$3,589	$14,939	$1,423	2.3	11.4	$2,005
1.5 inch mineral wool panel	$3,885	$13,642	$1,127	2.0	13.2	-$222
2 inch mineral wool panel	$3,796	$14,698	$1,216	2.0	13.2	-$218
3 inch dense pack cellulose	$3,719	$17,485	$1,293	1.8	14.9	-$2,089
3 inch dense pack fiberglass	$3,685	$18,223	$1,328	1.7	15.2	-$2,410

An additional consideration is that energy retrofits are not selected solely on the basis of expected payback. One contractor characterized client motivations for re-siding and exterior insulation retrofits as improving the appearance of the house, reducing maintenance needs, and reducing heating demand. In this context, reducing energy costs is one factor amongst several that inform decisions relating to retrofits that include exterior insulation.

Conclusions

The current retrofit practice of adding 1.5 to 2 inches of rigid foam board exterior to the sheathing is commonly done because the labor is relatively quick and the cost is affordable. However, such small amounts of water vapor impermeable exterior insulation change the moisture dynamics of the wall and have the potential to cause moisture problems within the wall.

The water vapor permeability of the exterior insulation is a very important variable for moisture control. Rigid foam board is fairly vapor impermeable, meaning that moisture cannot pass though it easily and may remain trapped inside the wall. Installing a more vapor permeable exterior insulation may help to mitigate moisture problems, as evidenced by the WUFI simulations of water vapor permeable exterior insulation options. Mineral wool in rigid board form is one potential insulation that is highly vapor permeable, as are cellulose and fiberglass. Some unfaced EPS foam boards have a moderate vapor permeability (5 perm and higher) compared to other foam boards. Correspondingly, more insulation is necessary to achieve acceptable moisture performance (4 inches EPS at 5 perm in Fairbanks), but substantially less than conventional EPS (7 inches).

In addition to the water vapor permeability of the exterior insulation, venting of the siding is an important variable for moisture control. Unvented siding can create problems even if the exterior insulation has a high permeability. Ideally, a retrofit wall will have a ¾ to 1 inch vertical rain screen behind the siding that is vented at the top and the bottom

Builders expressed concerns that building a curtain wall to use dense pack cellulose or exterior fiberglass might be too complex and labor intensive approach relative to retrofit concepts that use rigid insulation boards. The cost estimates for the curtain wall retrofit concept varied, presumably because this retrofit method is not common practice. The adjusted payback on these types of retrofits ranged from 14 to 15 years (at $4/gallon fuel), which are not appealing when homeowners tend to stay in a house for 13 years or less.

The mineral wool panel (1.5”) and unfaced EPS (4”) retrofit concepts were most promising in terms of cost and builder preference for implementation. The adjusted payback at $4/gallon fuel was 11.4 years for 4 inches of unfaced EPS and 13.2 years for the mineral wool panels. This payback is more tolerable for homeowners.

This project set out to develop wall retrofit ideas that are safe, effective and affordable. Several ideas have been found to be effective and affordable, they have modeled out as safe but need physical testing to verify their moisture performance. Past experience with comparing hygrothermal simulations to experimental data has shown the importance of performing physical tests to refine results. The next step is to test the mineral wool panel and unfaced EPS walls physically to determine how they perform over the course of a Fairbanks winter.

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Chlupp, T. (2009). Installing exterior insulation in cold climates. *Journal of Light Construction*, 27(8), 31-38.

Craven, C. and Garber-Slaght, R. (2014). Cellulose insulation moisture performance in cold climate construction. Retrieved from Cold Climate Housing Research Center website: http://www.cchrc.org/sites/default/files/docs/CelluloseSnapshotFinal.pdf

Doyle, V. and Bhargava, A. (2012). The Role of Appraisals in Energy Efficiency Financing.. National Renewable Energy Laboratory. Retrieved from http://www.nrel.gov/docs/fy12osti/54329.pdf

Emrath, P. (2013). Latest study shows average buyer expected to stay in a home 13 years. National Association of Home Builders. Retrieved from http://eyeonhousing.org/2013/01/latest-study-shows-average-buyer-expected-to-stay-in-a-home-13-years/?_ga=1.80624919.1452188703.1431555458

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Holladay, M. (2011, September 30). How to install rigid foam sheathing [Web log comment]. Retrieved from http://www.greenbuildingadvisor.com/blogs/dept/musings/how-install-rigid-foam-sheathing

Lepage, R. & Lstiburek, J. (2012). Moisture durability with vapor permeable insulating sheathing. Retrieved from Building Science Corporation website: http://www.buildingscience.com/documents/bareports/ba-1313-moisture-durability-with-vapor-permeable-insulating-sheathing

Osser, R., Neuhauser, K., & Ueno, K. (2012). Proven performance of seven cold climate deep retrofit homes. U.S. Department of Energy. Retrieved from: http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/seven_cold_climate_homes.pdf

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Appendix

Appendix A: Annotated Bibliography

Cold Climate Housing Research Center. (2014). Evaluating the need for vapor retarders with open cell polyurethane and cellulose insulation in extreme cold climates. Retrieved from Cold Climate Housing Research Center website http://www.cchrc.org/sites/default/files/docs/DurableEnvelopesReport.pdf

Motivation: The study addressed the following questions.

What level of vapor control is necessary to use open cell spray polyurethane foam (ocSPF) 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, Alaska?

Does dense-pack cellulose improve hygrothermal performance relative to fiberglass batts as cavity insulation in Fairbanks, Alaska?

Does open cell foam present a new option for rim joist insulation in an extreme cold climate?

Methods: Researchers used hygrothermal modeling and physical testing of walls in test wall bays in Fairbanks, AK. The test walls were subjected to interior conditions of 72°F, 40% RH, and a period of positive pressure. The test walls featured different vapor retarders, interior insulations, and exterior insulations. They were instrumented for temperature, RH, wood moisture content, and heat flux.

Findings: In a severe cold climate, ocSPF should be used with a strong vapor control layer, such as a class I vapor retarder. The hygrothermal performance of ocSPF and cellulose is better than that of fiberglass batts if used with a class I vapor retarder. The question of their moisture performance with a class II vapor retarder is unresolved.

Chlupp, T. (2009). Installing exterior insulation in cold climates. *Journal of Light Construction*, 27(8), 31-38.

Motivation: Typical 2 x 6 frame construction presents problems in cold climates when moisture can become trapped between the interior vapor retarder and the exterior OSB sheathing.

Discussion: The REMOTE wall system is one solution to this problem. The exterior membrane provides an air seal, and the exterior insulation keeps the sheathing and framing above the dew point temperature so that moisture cannot condense inside the wall. The key to using this method is to ensure that there is enough insulation on the outside of the house to keep the sheathing membrane warm. The rule of thumb practice is that 1/3 of the total R-value of the wall can be inside the vapor retarder. The wall is allowed to dry to the interior if moisture does condense because there is no interior vapor retarder.

Findings: In the author’s experience, the higher cost and extra labor for using the REMOTE method are offset by reduced energy use and a longer building life cycle.

Craven, C. and Garber-Slaght, R. (2014). Cellulose insulation moisture performance in cold climate construction. Retrieved from Cold Climate Housing Research Center website: http://www.cchrc.org/sites/default/files/docs/CelluloseSnapshotFinal.pdf

Motivation: Cellulose insulation has several properties that could facilitate better envelope moisture management when used to increase wall R-value.

Methods: Researchers built 5 test walls with different configurations of vapor retarders, interior insulation, and exterior insulation. Walls with exterior insulation deliberately did not follow the 2/3 rule for exterior insulation for the climate in Fairbanks. Researchers monitored the temperature, RH, and moisture content of the wall cavities for 18 months while maintaining an interior climate of 72°F and 40% RH.

Findings: The wall with exterior cellulose insulation had better moisture performance than the wall with exterior EPS but still spent time with RH above 80%. Both test walls did not have a polyethylene vapor barrier, but instead had an interior class III vapor retarder. Using dense pack cellulose as an exterior insulation in Interior Alaska has the potential to provide better moisture protection than an equivalent R-value of rigid foam but more study is needed to determine the minimum amount of cellulose necessary for adequate moisture protection.

Craven, C. and Garber-Slaght, R. (2014). Exterior insulation envelope retrofits in cold climates: Implications for moisture control. *HVAC&R Research,* 20(4), 384-394.

Motivation: To investigate the potential for exterior rigid foam retrofits in subarctic climates to cause moisture accumulation in wood-framed structures.

Method: Researchers built 9 test walls with varying ratios of stud-fill and exterior insulation, and vapor retarder or no vapor retarder. The wall cavities were monitored for temperature, RH, and moisture content over two winters in Fairbanks, AK. The interior RH and air pressure were varied over the study period.

Findings: The test walls with less than 2/3 of the total wall R-value on the exterior performed poorly in terms of wood moisture content and RH at the sheathing regardless of whether or not they had a vapor retarder. The presence of a vapor retarder did reduce the envelope wetting and drying rates.

Gibson, S. (2010, June 23). Can exterior foam insulation cause mold and moisture problems [Web log comment]? Retrieved from http://www.greenbuildingadvisor.com/blogs/dept/qa-spotlight/can-exterior-foam-insulation-cause-mold-and-moisture-problems

Motivation: Thick layers of rigid foam insulation form a vapor retarder on the exterior of a home. Will this trap moisture and lead to rot?

Discussion: In a cold climate, moisture vapor is driven outwards into exterior walls. It condenses into a liquid where it encounters a material surface below the dew point, usually the back side of the exterior sheathing. Foam board on the exterior prevents moisture from drying to the exterior, and can lead to mold.

Findings: Suggestions to avoid this problem include adding enough foam board to keep the sheathing above the dew point, using a different material such as cellulose in a double-framed wall that allows drying to the outside, and, in the case of foam, leaving a path for the wall to dry to the interior.

Holladay, M. (2010, October 15). Calculating the minimum thickness of rigid foam sheathing [Web log comment]. Retrieved from http://www.greenbuildingadvisor.com/blogs/dept/musings/calculating-minimum-thickness-rigid-foam-sheathing

Motivation: How thick should exterior rigid foam insulation be?

Discussion: The IRC contains a table, N1102.5.1 that lists the minimum exterior foam R-value for different climate zones.

Findings: Thick foam is better than thin foam because thin foam reduces the ability of a wall to dry to the outside without warming the interior enough to prevent moisture accumulation. The minimum thickness depends on the wall design and the climate. The other important wall construction detail is to avoid a vapor retarder on the interior to allow the wall to dry to the inside.

Holladay, M. (2010). Deep-Energy Retrofits. *Fine Homebuilding,* #213, 56-60.

Motivation: Deep energy retrofits focus on reducing heating and cooling loads, rather than upgrading appliances or lighting. The cost of such a retrofit can be very high – so this article studies the methods for practical and cost-effective measures that can make any home more efficient.

Discussion: All retrofits should follow these steps: begin with an energy audit, perform air-sealing, install mechanical ventilation, start insulating from the top, insulate the interior side of basement walls, install dense-pack cellulose into any empty stud-bays, install rigid foam on the exterior, then replace windows and the heating system. One home profiled in the case studies for this article used a wall retrofit of a 2x2 frame on the exterior filled with 4 inches of closed-cell spray foam.

Findings: There are a number of smaller, less expensive measures that homeowners can take instead of a deep energy retrofit. These measures have shorter paybacks.

Holladay, M. (2011, September 30). How to install rigid foam sheathing [Web log comment]. Retrieved from http://www.greenbuildingadvisor.com/blogs/dept/musings/how-install-rigid-foam-sheathing

Motivation: Green Building Advisor receives frequent questions about installing rigid foam sheathing on exterior walls.

Discussion: This article provides an overview of installing foam on the exterior of a home, addressing topics such as the type of foam to use, how to brace the wall, how to fasten the foam to the wall, where the water-resistive barrier goes, how to install windows, and retrofits. It contains links to several articles providing more details on these topics.

Findings: Exterior rigid foam improves air tightness, adds R-value, reduces the chance of condensation in wall cavities, and reduces thermal bridging through studs.

Holladay, M. (2011, August 26). Installing mineral wool insulation over exterior wall sheathing [Web log content]. Retrieved from http://www.greenbuildingadvisor.com/blogs/dept/musings/installing-mineral-wool-insulation-over-exterior-wall-sheathing

Motivation: Can mineral wool insulation be used as an alternative to rigid foam insulation on the exterior side of wall sheathing?

Discussion: Exterior insulation keeps wood warm and dry, reduces condensation potential, and reduces thermal bridging. Mineral wool is vapor permeable insulation made from basalt rock. Denser varieties can be installed like foam board while the less dense types are more fluffy, like fiberglass. Building Science Corporation conducted tests using Roxul mineral wool to study if Roxul was strong enough to support vertical furring strips and siding without squash blocks.

Findings: Mineral wool can be strong enough to support siding using vertical furring strips. Advantages to using it as exterior insulation include that insects don't eat it, it doesn't absorb water, it dries quickly, and it is dense enough to resist wind-washing.

Joyce, D. (2009). Retrofitting Exterior Insulation. *Journal of Light Construction* 28(2), 1-8.

Motivation: The author's company needed to do an energy retrofit on an 80 year old home near Boston.

Methods: The company replaced the roofing, siding, and windows. They also wrapped the entire exterior with rigid foam insulation. The retrofit plan included a layer of housewrap over the existing sheathing, two layers of 2-inch thick foam, a layer of vertical strapping, and finally PVC clapboards nailed to the strapping to create a rain-screen wall.

Findings: Occupants described the house as draft-free and warm. There were no ice dams on the roof and new HRVs that were installed provided ventilation. The retrofit was still young at the time of the article so author didn't comment on long-term issues.

Lepage, R. & Lstiburek, J. (2012). Moisture durability with vapor permeable insulating sheathing. Retrieved from Building Science Corporation website: http://www.buildingscience.com/documents/bareports/ba-1313-moisture-durability-with-vapor-permeable-insulating-sheathing

Motivation: To address the uncertainty of the effects of inward driven moisture and the interaction of increased sheathing temperatures on the moisture durability of the edifice when exterior sheathing insulation is added to a building.

Method: Researchers conducted hygrothermal modeling for cities in different climate zones. The modeling varied the thickness of the exterior insulation (mineral board), permeance of the water resistive barrier, presence of interior vapor control, type of structural sheathing, and the air exchange rate of the gap behind the brick cladding. They modeled 2x4 walls with R-9 to R-13 batts in the cavity

Findings: Researchers identified vapor permeable (above 5 perms) insulations for retrofits to include mineral board, glass insulations.

A water resistive barrier permeance in the range of 1 to 10 perms is sufficient in all climate zones (1 to 7) with at least one inch of exterior insulation. For less than one inch of insulation, the permeance should be less than 1 perm.

For cold climate zones (6 and above) the authors recommend at least 2 inches of exterior insulation.

In rainy climates, high permeance water resistive barriers should not be combined with vapor-permeable exterior insulation.

Low permeance interior vapor control layers should be avoided. The authors recommend using latex paint to inhibit outward flowing moisture when exterior insulation is used.

Lstiburek, J. (2002). Moisture Control for Buildings. *ASHRAE Journa,l* 44(2), 36-41.

Motivation: Moisture engineering can be used to design a building envelope that meets moisture-related performance objectives.

Discussion: Moisture loads on the wall are rain exposure and interior climate. Moisture storage capacity of the wall depends on time, material properties, and temperature. Mold isn't a problem until moisture accumulates beyond a safe storage limit. Strategies to control moisture include controlling entry, controlling accumulation, removing moisture, and combinations of all three. This includes controlling groundwater entry below grade, rainwater entry above grade, air transport of moisture, and vapor diffusion.

Findings: The article concludes with general and climate-specific requirements for walls. For cold climates, avoid vapor retarders towards the exterior, limit air movement from interior to exterior, control the temperature of condensing surfaces in the heating season, keep the interior dew point above 35°F, and allow the wall to dry to the outside.

Maref, W., Armstrong, M., and Rousseau, M.Z. (2009). Workshop on moisture management and energy rating in building envelopes / Part I: characterization of hygrothermal performance of wall systems. 12th Canadian Conference of Building Science and Technology (Montreal, QC). Retrieved from: http://c.ymcdn.com/sites/www.nibs.org/resource/resmgr/BEST/BEST2_049_EE13-4.pdf

Motivation: To investigate the hygrothermal response of two retrofitted wood-frame walls. The experiment objectives were to test:

1) If the properties of the exterior insulation will affect the wetting and drying potential of the wall assembly,
2) If the air leakage through an assembly is a potent factor in transporting moisture to and from enclosed cavities,
3) If increases in interior RH can result in higher wetting of the stud cavity, and
4) If walls with exterior insulation are less prone to condensation in the cavities.

Methods: Three walls were assembled for testing in Ottawa, Canada. One wall, a 2 x 6 with an R-value of 20, served as the control and was not retrofitted. The other two walls represented two different types of retrofits: adding XPS or mineral fiber insulation to the exterior. The walls were exposed to varying levels of RH and pressure on the interior, and weather on the exterior. Challenges were introduced both in terms of opening an air leakage path and increases in the interior RH and air pressure. Researchers monitored the temperature, RH, pressure, and surface liquid on each layer of the wall assembly from fall 2007 to summer 2008.

Findings: Adding exterior thermal insulation can reduce the duration of the potential for condensation within a wall, but condensation can still take place during the coldest part of winter. Exterior insulation materials not only affect the flow of moisture to the outside during winter but also the flow of moisture inwards during the humid summer. For example, the XPS foam allowed less moisture through to the outside than the mineral fiber. The study findings particular to the four objectives listed above are as follows:

1) Both walls with exterior insulation dried by spring with no damage, but the wetting event was short-lived.
2) Air leakage is a large factor in transporting moisture into a wall.
3) Strong winds prevented the study from answering this objective.
4) Walls with exterior insulation are less prone to condensation due to the insulation raising the temperature of the stud cavity. However, this has limits, in that colder outdoor temperatures lower the benefit of the exterior insulation to reduce condensation potential.

Osser, R., Neuhauser, K., & Ueno, K. (2012). Proven performance of seven cold climate deep retrofit homes. U.S. Department of Energy. Retrieved from: http://apps1.eere.energy.gov/buildings /publications/pdfs/building_america/seven_cold_climate_homes.pdf

Motivation: This report presents 7 case studies for examining energy savings and occupant comfort improvements.

Methods: This report discusses seven homes in Massachusetts. Each home underwent major renovations. Authors compared pre- and post-airtightness and utility bills and also presented the costs of the retrofits and occupant feedback. The walls in the 7 homes were all retrofitted using the same method. First, existing 2 x 4 cavities were filled with fibrous, cellulose, or spray foam insulation. House wrap was then applied over the existing sheathing, and then 4 inches of polyisocyanurate insulation (polyiso) in two 2-inch layers was applied over the house wrap. Finally, vertical strapping applied over the polyiso allowed cladding to be attached. The primary water control layer was the exterior face of the polyiso.

Findings: Retrofits need to result in energy savings, improved durability, and improved occupant comfort. It is important to quantify these qualities through data collection before and after retrofits.

Shepard, M. (2011). Tightening the Shell from Outside. *Journal of Light Constructio,n* 29(9), 1-6.

Motivation: The author’s construction company needed to do an energy retrofit and major remodel of a home in Vermont.

Methods: On previous jobs, they wrapped houses in two layers of blue board, but they pointed out the following disadvantages: hard to flash windows to the drainage plane, and furring strips have to be screened to keep bugs out and be flat. They chose a different method of wrapping the house with 4-inch polyiso roofing panels, followed by continuous OSB sheathing, then housewrap, flashing, and siding. The roofing panels increased the wall R-value, minimized thermal bridging, and helped air-seal the home. On the inside, spray foam was used to fill in the truss bays over exterior walls, 18 inches of cellulose were added to the existing fiberglass batts, and where possible, the fiberglass was replaced entirely with cellulose.

Findings: The article was published before the interior portion of the retrofit was complete, but an initial blower door test showed that air leakage had been reduced. The estimated cost of the exterior insulation, sheathing and labor, and labor was $7.45 per square foot, less than the author's estimated costs for wrapping the house with blue board ($8/square foot) or using SIPs to retrofit the home ($10/square foot).

Smegal, J. & Lstiburek, J. (2013). Hygric redistribution insulated assemblies: retrofitting residential envelopes without creating moisture issues. U.S. Department of Energy. Retrieved from: http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/hygric_redistribution.pdf

Motivation: The authors wanted to address the following questions:

How much water is stored in the drainage cavity, and does it pose a moisture-related durability threat?

If water becomes trapped in the drainage cavity, where does it go and what impact does it have on the wall system?

Why is there a discrepancy between hygrothermal analysis of vapor impermeable, low R-value exterior insulations, and field performance? In other words, why do these retrofits not result in the predicted moisture problems?

Are there alternative solutions to energy retrofits that decrease the risk of moisture-related durability problems?

Methods: The authors did a literature review of previous research, laboratory testing programs, and test wall monitoring in climate zone 4C. The lab test wall and field test walls measured the effects of subjecting a wall with a drainage gap to wetting.

Findings: The team found that there is no moisture durability risk when water is drained in the gap between exterior insulation and the sheathing membrane. The water mostly diffused into the wall cavity and dried to the interior. The researchers felt this was the reason that homes with exterior insulation do not experience moisture problems – water is able to drain when it forms on the interior side of the exterior insulation. Some strategies to safely prevent moisture problems with exterior insulation are to add width to a drainage gap and to drain penetrations to the front of the insulation. Future work could address the point at which moisture becomes a problem, and the thermal losses associated with the size of the drainage gap.

Ueno, K. (2010). Residential exterior wall superinsulation retrofit details and analysis. Retrieved from Building Science Corporation website: http://www.buildingscience.com/documents/confpapers/cp-1012-residential-exterior-wall-superinsulation-retrofit

Motivation: Existing housing stock represents a large opportunity for energy retrofits. Part of a retrofit can consist of "superinsulating" above-grade walls.

Methods: This paper analyzes 3 cold climate retrofit projects in Massachusetts. It presents the enclosure strategies, case-specific solutions to problems including windows and air barriers, economic analyses, and hygrothermal simulations. The projects added 4 inches of rigid foam to the outside of above-grade walls to increase insulation and decrease thermal bridging.

Findings: The retrofits kept 2/3 of the insulation on the outside of the existing sheathing to reduce condensation risk. Moisture damage risk was addressed by redundant drainage planes, a drained and ventilated cavity, properly flashing windows and other penetrations, and elevation of the condensing surface temperature.

Appendix B: Hygrothermal Evaluation for Safe, Effective, and Affordable Retrofits

WUFI Pro is one-dimensional hygrothermal modeling software. It evaluates the thermal and moisture performance of a wall cross-section based on the interior and exterior conditions and physical properties of the wall materials. The WUFI software makes it possible to evaluate the relative humidity and moisture content of the wall components as they interact with interior and exterior environments. The moisture performance of a wall can be projected out over the course of years. This can be a powerful tool in making design decisions regarding the exterior envelope when building in specific areas of Alaska. The program can tabulate the progressive risk of moisture condensing in a wall assembly, using a specific location's weather patterns. WUFI was used in this project to evaluate multiple wall scenarios for their ability to maintain safe levels of moisture in the wooden structure of the walls.

Boundary Conditions

The interior conditions for the scenarios were a constant relative humidity of 40% and a constant temperature of 70°F. The exterior was simulated as a cold winter (-51°F minimum winter temperature) in Fairbanks, Alaska. A slight overpressure of +2Pa was simulated to mimic the positive pressure at the top of a 2-story house. The base wall was modeled with an air leakage of 7 ACH50, the retrofit scenarios were modeled with 5 ACH50 air leakage. These ACH50 values came from average values for pre- and post- retrofits in Interior Alaska that were part of the Alaska Housing Finance Corporation's Energy Rebate Program (Alaska Housing Finance Corp, 2015).

Walls Studied

The base wall for all the scenarios was 2x6 wooden stud frame construction. The interior wall was painted ½ inch gypsum board. It had an interior, leaky vapor retarder of 6 mil polyethylene. The wall cavities were filled with R-19 fiberglass batts. The exterior of the wall was painted ½ inch T1-11 plywood siding. For each retrofit it was assumed that the T1-11 would remain in place and be covered with an exterior retrofit. Table B-1 lists the different combinations of walls studied. In a few cases T1-11 OSB siding was substituted for the plywood T1-11, these are not listed in Table B-1 but are evaluated in the results.

Table B-1. Walls Studied

	Air Barrier	Exterior Insulation	Air Barrier	Siding Ventilation*	Siding
Air Barrier Retrofit	Housewrap	None	None	¾ inch ventilated rain screen	Vinyl siding
Foam Retrofit #1	None	2 inches EPS	None	None	Vinyl siding
Foam Retrofit #2	Housewrap	2 inches EPS	None	¾ inch unvented rainscreen	Vinyl siding
Foam Retrofit #3	Housewrap	6 inches EPS	None	¾ inch unvented rainscreen	Vinyl siding
Foam Retrofit #4	Housewrap	7 inches EPS	None	¾ inch unvented rainscreen	Vinyl siding
Unfaced Foam Retrofit #1	None	2 inches unfaced EPS	None	None	Vinyl siding
Unfaced Foam Retrofit #2	Housewrap	2 inches unfaced EPS	None	¾ inch unvented rainscreen	Vinyl siding
Unfaced Foam Retrofit #3	Housewrap	6 inches unfaced EPS	None	¾ inch unvented rainscreen	Vinyl siding
Unfaced Foam Retrofit #4	Housewrap	4 inches unfaced EPS	None	¾ inch unvented rainscreen	Vinyl siding
Mineral Wool Panel Retrofit #1	Housewrap	2 inches mineral wool panels	None	¾ inch ventilated rain screen	Vinyl siding
Mineral Wool Panel Retrofit #2	Housewrap	4 inches mineral wool panels	None	¾ inch ventilated rain screen	Vinyl siding
Mineral Wool Panel Retrofit #3	Housewrap	6 inches mineral wool panels	None	¾ inch ventilated rain screen	Vinyl siding
Mineral Wool Panel Retrofit #4	Housewrap	1.5 inches mineral wool panels	None	¾ inch ventilated rain screen	Vinyl siding
Cellulose Retrofit #1	Housewrap	5.5 inches dense pack cellulose	Housewrap	¾ inch ventilated rain screen	Vinyl siding
Cellulose Retrofit #2	Housewrap	3.5 inches dense pack cellulose	Housewrap	¾ inch ventilated rain screen	Vinyl siding
Cellulose Retrofit #3	Housewrap	3 inches dense pack cellulose	Housewrap	¾ inch ventilated rain screen	Vinyl siding
Cellulose Retrofit #4	Housewrap	3 inches dense pack cellulose	Housewrap	¾ inch unvented rainscreen	Vinyl siding
Blown Fiberglass Retrofit #1	Housewrap	5.5 inches dense pack fiberglass	Housewrap	¾ inch ventilated rain screen	Vinyl siding
Blown Fiberglass Retrofit #2	Housewrap	3 inches dense pack fiberglass	Housewrap	¾ inch unvented rainscreen	Vinyl siding
Blown Fiberglass Retrofit #3	Housewrap	3 inches dense pack fiberglass	Housewrap	¾ inch ventilated rain screen	Vinyl siding
Fiberglass Batt Retrofit	Housewrap	R-21 fiberglass batt	Housewrap	¾ inch unvented rainscreen	Vinyl siding

*Ventilated refers to a rain screen with openings at the top and bottom to allow the free movement of air from outside. An unvented rain screen has an air gap but the gap is blocked at the top and/or bottom with wooden "nailers."

Results

WUFI outputs a variety of results for each wall. The summarized results are presented in Table B-2.

This summary used the WUFI postprocessor program called Bio. Bio outputs a mold risk assessment based on the relative humidity and temperature at the location of interest. If the location has a relative humidity and temperature above the threshold for mold for an appropriate amount a time the danger for mold grows. Bio tracks the relative humidity, temperature, and time over the course of the model and determines if the location in the wall is in danger of mold. A green output deems the wall construction relatively safe. A yellow output means that that location in the wall is in danger of mold, but that it is right on the edge. A red output means the wall is in danger of mold.

Table B-2. WUFI Results

	Retrofit Option	Mold Danger at the Plywood	Notes
	Base Wall	yellow	yellow to red with OSB
	Air Barrier Only	yellow	
Foam Retrofits	2 inch EPS no air gap	red	
	2 inch EPS unvented	red	
	6 inch EPS unvented	red	
	7 inch EPS unvented	yellow to green	
	2 inch unfaced EPS unvented	red	
	2 inch unfaced EPS ventilated	yellow	
	4 inch unfaced EPS ventilated	yellow to green	yellow to green with OSB, but a little worse off
Mineral Wool Panel Retrofits	1.5 inch mineral wool panels	yellow to green	
		green	yellow to green with OSB
	2 inch mineral wool panels		
	4 inch mineral wool panels	green	
	6 inch mineral wool panels	green	
Cellulose Retrofits	5.5 inch dense pack	green	green with OSB
	3.5 inch dense pack	green	yellow to green with OSB
Fiberglass Retrofits	5.5 inch dense pack	green (yellow at outside edge of fiberglass)	green with OSB
	R-21 batt	green (yellow at outside edge of fiberglass)	green with OSB

The walls that were borderline in in the WUFI Bio analysis were studied further. Figures B-1 though B-5 provide further details on the borderline yellow/green walls. The basic threshold for mold is RH above 80% and temperatures above 40°F. Rot is another problem that can occur when moisture develops inside the walls. The threshold surface mold is 16% moisture content, above 20% moisture content rot initiates. The graphs show the trends for the first five years of the wall construction. In most cases the first year is wetter than the subsequent years; this is due to the drying out of initial construction moisture during the first year.

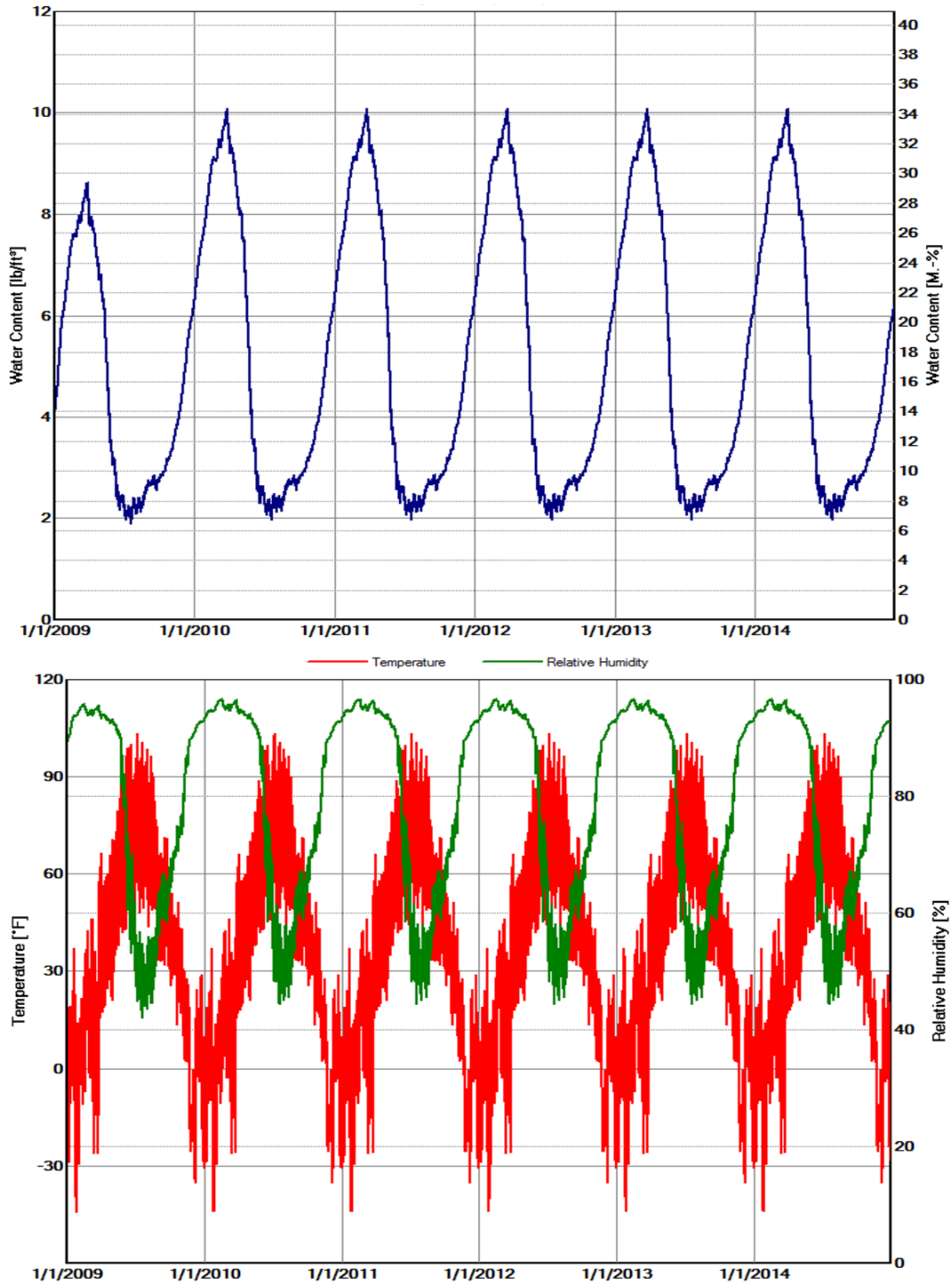


Figure B-1. The base wall. The base 2x6 wall shows high RH and high moisture content in the winter months; however the wall was yellow in the WUFI Bio analysis. This is because most of the high moisture events happen in the winter when the wall is well below freezing.

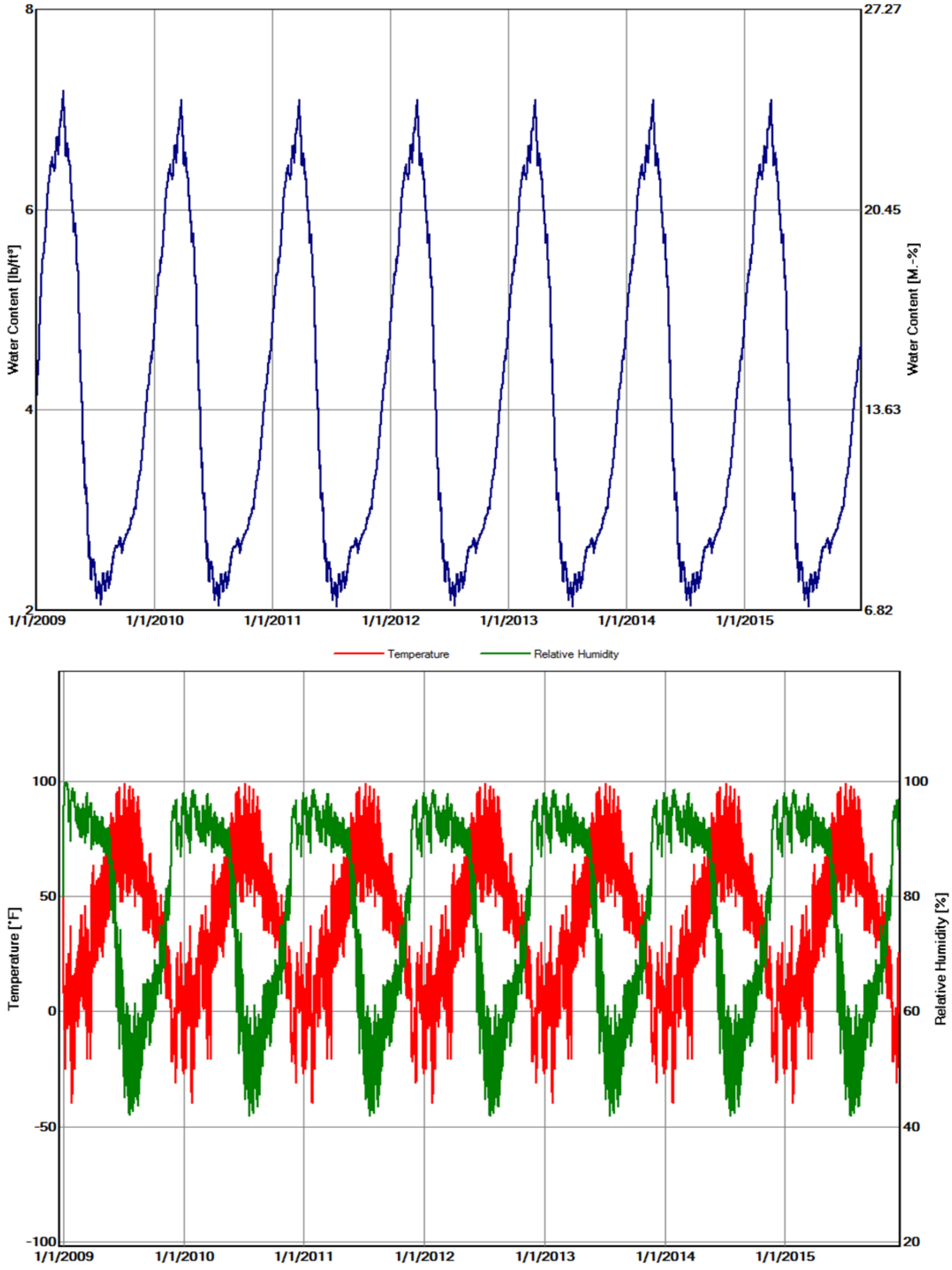


Figure B- 2. Air barrier only retrofit. The air barrier only retrofit has slightly lower RH and moisture content than the base wall, but the values are elevated. This wall performs moisture-wise due to below freezing winter temperatures and the ability to dry to the outside.

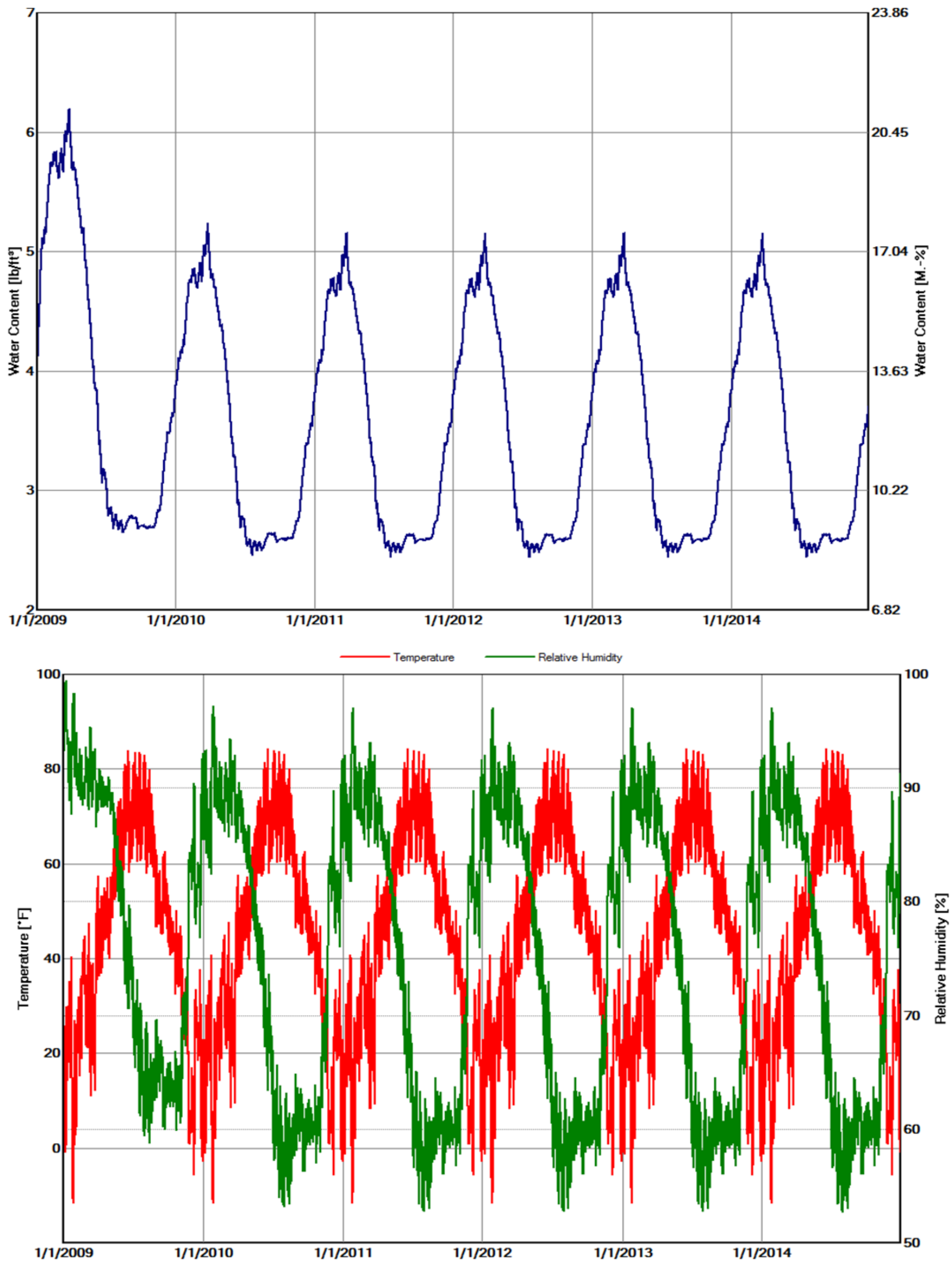
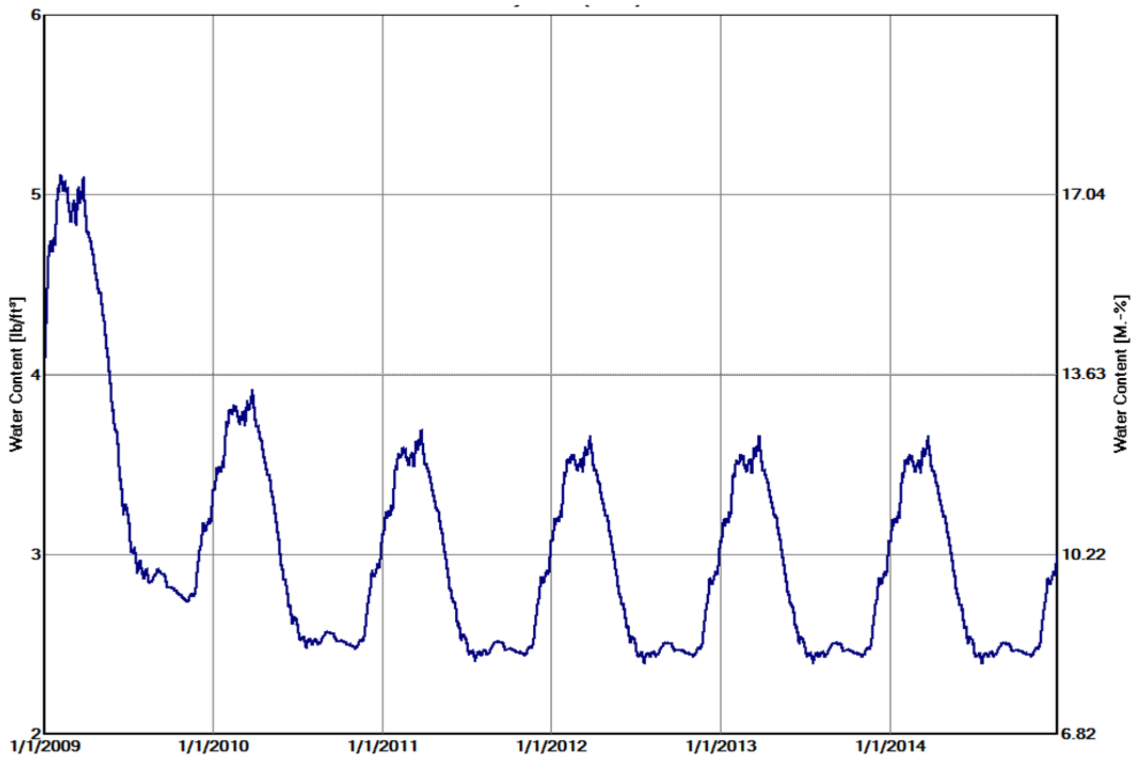


Figure B-3. Foam retrofit with 2 inches unfaced EPS and ventilated siding. Unfaced EPS has a higher perm rating (5) than faced EPS (less than 1). However, two inches of unfaced EPS is still not enough to keep moisture out of the stud cavity. The ventilated wall is yellow in WUFI Bio; the unvented version is red in Bio. The two graphics are for the ventilated wall, it shows the moisture accumulation in the wall that is right on the edge of danger. This is a wall that needs further testing.



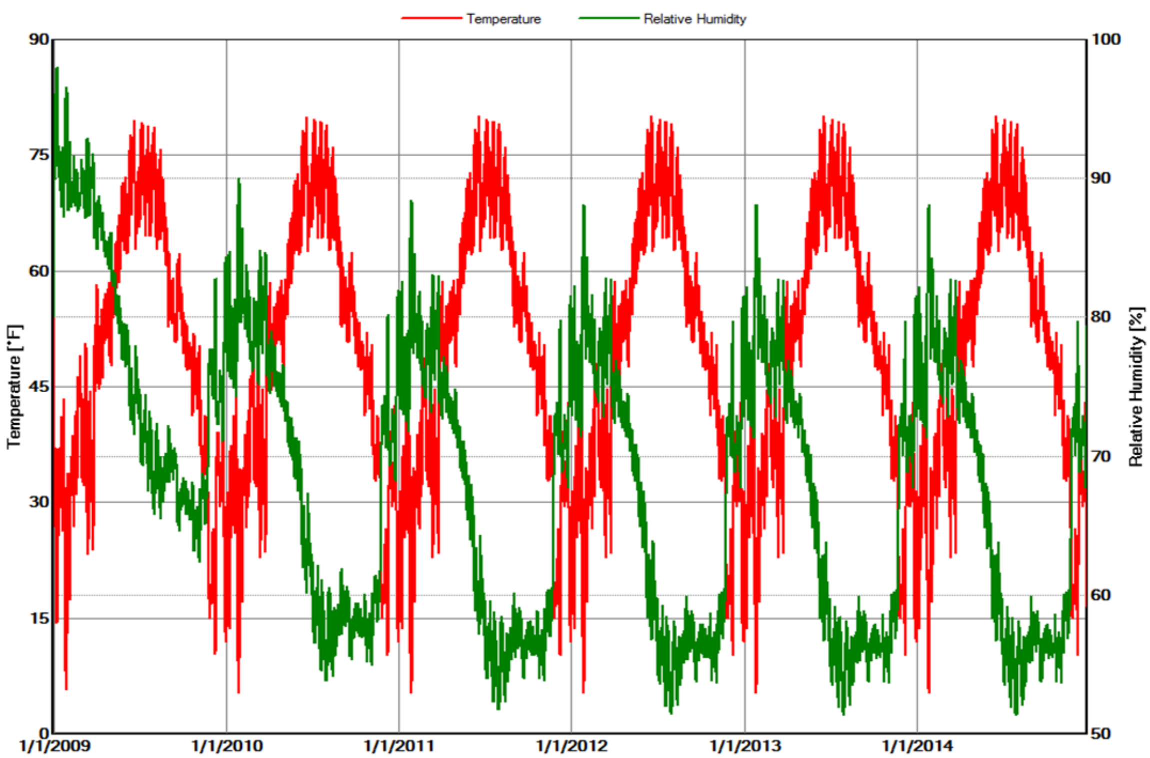
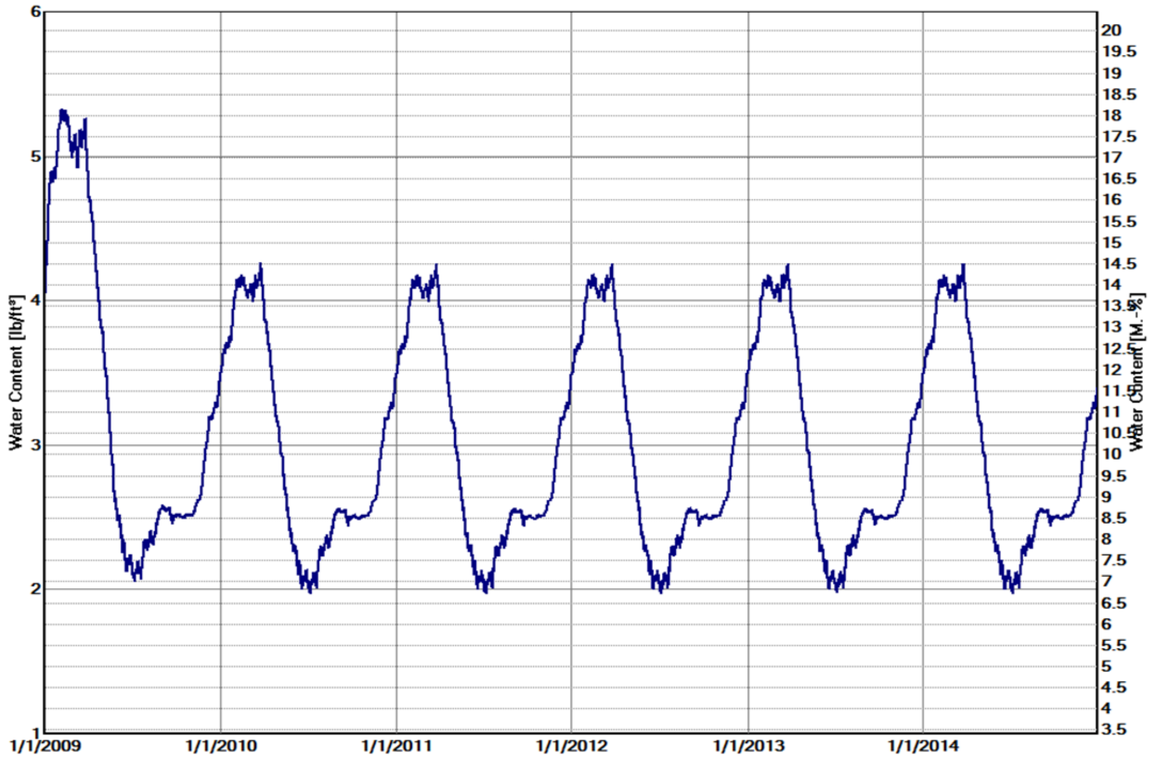


Figure B-4. Foam retrofit with 4 inches unfaced EPS and ventilated siding. Four inches of the higher perm unfaced EPS shows potential as a safe retrofit option. The moisture content in the plywood stayed below 13.6% after its first year. The RH in the wall occasionally creeps above the 80% threshold for mold problems, but for short and cold periods of time.



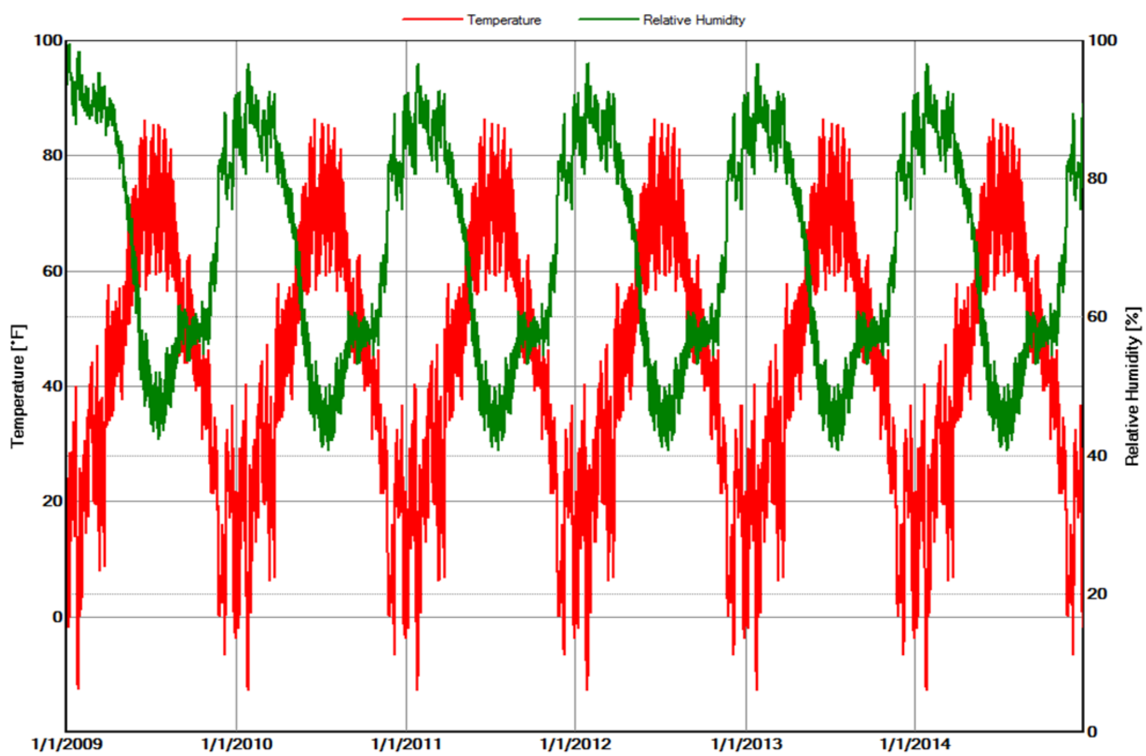


Figure B-5.One and one-half inch mineral wool panel retrofit. One and a half inches of mineral wool panel is in the yellow to green range in WUFI Bio. It has a high moisture spike its first year but evens out below 14.5% moisture content after the first year. The high humidity is not for a long enough duration to have much mold growth. This wall requires more testing.