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Hygric Redistribution in Insulated Assemblies: Retrofitting Residential Envelopes Without Creating Moisture Issues

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Definitions

BEopt	Building Energy Optimization
Btu	British thermal unit
DOE	U.S. Department of Energy
ffpic	Foil-faced polyisocyanurate
fl oz	Fluid ounce
ft^2	Square foot
g	Gram
L	Liter
lb	Pound
m^2	Square meter
MBtu	Million Btu
MC	Moisture content
mL	Milliliter
Ng	Nanogram
Pa	Pascal
RH	Relative humidity
o.c.	On center
OSB	Oriented strand board
XPS	Extruded polystyrene
Yr	Year

Executive Summary

This research report was prepared by the Building Science Corporation Building America Research Team as part of the Energy Efficient Housing Research Partnerships project. The project title is Hygric Redistribution in Insulated Assemblies.

The exterior retrofit of frame assemblies can be risky when impermeable insulating sheathings of relatively low thermal resistance are used. For example, basic hygrothermal analysis demonstrates that removing the existing cladding and installing a board foam insulation with low vapor permeance (such as ½-in. foil faced rigid insulation) directly over the sheathing membrane under a replacement cladding (such as vinyl siding) is likely to cause moisture problems in cold climates. One such problem is known as a "cold sided vapor barrier." Tens of thousands of such retrofit and renovation projects have been completed, however, without apparent problems. There is also a perception that when water is intentionally drained in a drainage cavity between exterior insulation and the existing structure following an energy retrofit, moisture-related durability concerns exist for the sheathing and wood structure.

This experimental program includes a literature review of previous research, laboratory testing programs, and an analysis of full-scale test wall performance in the U.S. Department of Energy's climate zone 4C.

The following four questions were proposed to determine the level of risk associated with adding drained exterior insulation to the exterior of an existing home during an energy retrofit:

1. How much water is stored in the drainage cavity, and does it pose a moisture-related durability threat?
2. If water becomes trapped in the drainage cavity, where does the water go, and what impact does it have on the durability of the wall system?
3. Why is there a discrepancy between the basic hygrothermal analysis of vapor impermeable, relatively low R-value exterior insulations, and field performance?
4. Are there alternative solutions to energy retrofits that decrease the risk of moisture-related durability problems?

The team found that there is virtually no moisture durability risk to the sheathing when water is drained repeatedly in the drainage gap between the exterior insulation and the sheathing membrane, provided there are no other moisture-related issues unrelated to the drainage cavity such as air leakage condensation, or bulk rain water leakage.

1 Problem Statement

1.1 Introduction

Many thousands of homes in the United States, particularly in cold climates, need an energy retrofit to reduce the energy consumed for space conditioning and increase occupant comfort. Straightforward insulation strategies that do not increase the risk of moisture-related durability issues to the enclosure are needed.

The most straightforward solution is adding insulation to the exterior during an energy retrofit, especially where it is preferred not to disrupt the interior. Potential complications with enclosure and cladding details resulting from the increased thickness of the enclosure wall must be considered. Typically, insulation thicknesses of 1 in. and less do not require modifications to other details, but insulation thicknesses of 2 in. and greater will require modifications to window detailing and cladding attachment. When exterior insulation between 1 and 2 in. is installed, modifications to the enclosure depend on the specified construction details and material and cladding selection, and must be considered on a case-by-case basis.

1.2 Background

The exterior retrofit of frame assemblies appears to be risky when impermeable insulating sheathings of relatively low thermal resistance are used. The most typical of these is foil-faced polyisocyanurate (ffpic). Basic hygrothermal analysis, using hygrothermal simulation software or mathematically derived procedures, demonstrates that wrapping the exterior of a wood frame house with a sheathing membrane, followed by installing ½-in. foil-faced rigid insulation under a replacement cladding (such as vinyl siding), is likely to lead to moisture problems in cold climates. This problem is referred to as a "cold sided vapor barrier."

The Building Science Corporation (BSC) Building America Research Team examined this potential problem as part of the Energy Efficient Housing Research Partnerships project. In its experience prior to this research project, though, the BSC team had seen many such retrofit and renovation projects completed in cold climates without apparent problems.

The research team hypothesized that such retrofit applications actually work because the relatively cold exterior vapor barrier acts as a dehumidifier for the wall. The BSC team believes that the condensate on the back of the condensing surface—the interior facing side of the impermeable insulating sheathing—does not cause damage because this condensate drains harmlessly to the outside. This condensing surface is exterior to the water management layer (the previous cladding or sheathing membrane) (Figure 1). The drainage that will occur is not reflected in hygrothermal simulations. This research also assumes that the wall did not suffer durability issues before the retrofit, which means there was not enough moisture movement (through vapor diffusion or air leakage) from the interior to result in condensation on the interior surface of the exterior structural sheathing. This condensation is likely to have caused moisture-related durability issues without exterior insulation. Adding any amount of insulation to the exterior will increase the durability of the wood sheathing by increasing the surface temperature and decreasing the potential for condensation, as long as condensation that can occur to the exterior of the sheathing is adequately drained.

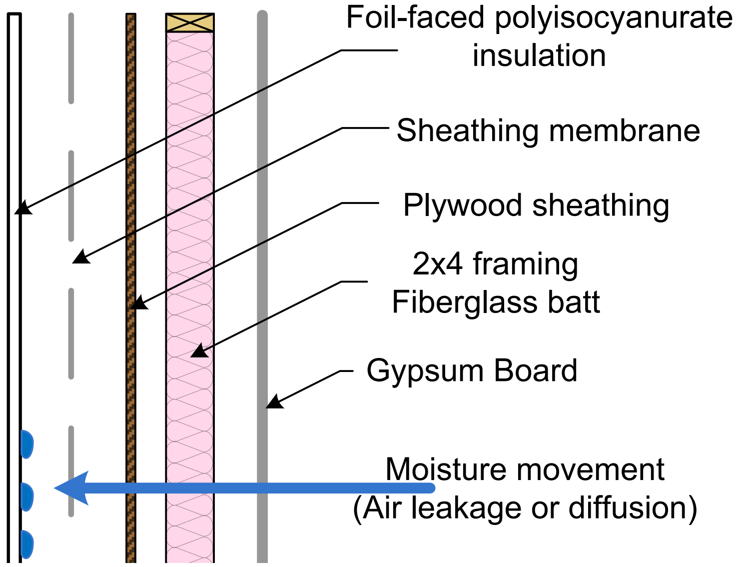


Figure 1. Moisture movement and condensation on interior surface of exterior insulation

This has huge positive implications for the retrofit of frame walls. It makes available a less costly approach to exterior insulation approaches where risk from moisture damage is low. The effectiveness of the drainage needs to be determined, however, as well as the reduction (penalty) in thermal resistance resulting from an air gap that facilitates drainage. This research examined only the effectiveness of the drainage gap and the moisture-related durability of the enclosure. The BSC team did not investigate the potential loss of thermal resistance resulting from a drainage cavity.

1.3 Relevance to Building America's Goals

Overall, the goal of the U.S. Department of Energy (DOE) Building America Program is to reduce home energy use by 30%–50% (compared to 2009 energy codes for new homes and pre-retrofit energy use for existing homes). To this end, BSC conducts research to "develop market-ready energy solutions that improve efficiency of new and existing homes in each U.S. climate zone, while increasing comfort, safety, and durability."

This research project explores retrofit insulation strategies to existing buildings, particularly in cold climates. The main goals of adding the exterior insulation are to reduce the energy consumption and increase the occupant comfort. There is also evidence of significantly decreasing the condensation potential on the interior of the sheathing by using exterior insulation (Smegal and Straube 2009). Once the information from this research project is disseminated, along with appropriate cladding attachment details and finishing details, the results from this research could be quickly scalable to all retrofit projects.

The Building Energy Optimization (BEopt) tool was used to optimize the amount of exterior insulation installed as a retrofit on the exterior of the house strictly from a cost and source energy perspective without analyzing increased occupant comfort and increased moisture durability benefits. The simulated house is approximately 2,300 ft^2, with a window area of 410 ft^2, which is approximately 18% of the exterior wall area. For the benchmark, it was assumed that the 2 × 4 walls are uninsulated because of the age of the house for retrofit. The first analysis point for all simulations was installing R-13 cavity insulation. It is assumed for prediction purposes that the interior living space could be disrupted to install the cavity insulation. In reality, in some cases, it might not be possible to not affect the interior spaces during relatively simple retrofits.

After adding the cavity insulation, five different thicknesses of exterior polyisocyanurate board insulation were simulated. Polyisocyanurate was chosen because it has the highest R-value per inch of all foam board insulations, and is less expensive than extruded polystyrene (XPS) (Grin and Lstiburek 2011).

Table 1 summarizes the results of this analysis, and the appendix includes a copy of the analysis bar charts and optimization curves. For each city (Boston, Massachusetts; Duluth, Minnesota; Kansas City, Missouri; and Dallas, Texas), the optimized solution (based strictly on energy and cost) is indicated in bold. In climate zone 4 and above, BEopt showed that the optimized solution for retrofit is using 1.5 in. of exterior insulation. An attempt was made to estimate other construction related costs such as wood strapping, fasteners, and window boxes,among others, for thicker exterior insulation installation.

Table 1. Total Energy Savings for Each Retrofit Strategy at Various Locations (MBtu/yr)

	Boston, Massachusetts	Duluth, Minnesota	Kansas City, Missouri	Dallas, Texas
DOE Climate Zone	5	7	4	3
Benchmark Uninsulated	0	0	0	0
R-13 Cavity	69	100	65	**46**
1-in. Exterior Insulation	88	128	82	57
1.5-in. Exterior Insulation	**92**	**135**	**87**	60
2-in. Exterior Insulation	96	141	90	62
3-in. Exterior Insulation	101	148	94	97
4-in. Exterior Insulation	104	153	97	66

1.4 Cost Effectiveness

Adding exterior insulation not only increases the installed insulation R-value, but also increases the whole-wall R-value and improves the insulative performance of the stud space insulation because it minimizes the thermal bridging through the framing (Smegal and Straube 2009). The cost of adding exterior insulation depends on the type of insulation added, the thickness, and any other changes to the enclosure resulting from increased thickness, such as modifying the window and door installations. At an exterior insulation thickness of 1 in. or less, there are no significant changes to any of the other enclosure detailing.

BEopt predicted that for DOE climate zones 4, 5, and 6, the maximum total energy savings occurred with 1.5 in. of exterior insulation. From *RSMeans CostWorks2011* (Reed Construction Data, May 2011), the incremental cost of adding 1.5 in. of exterior ffpic to the wall system is $1.56/ft^2. Monetary savings based on decreased energy for space conditioning will depend on the type and thickness of exterior insulation, the climate, and the type of fuel used for space conditioning. Table 2 gives the BEopt predictions of the amount of money saved. These savings are predicted when a house with an enclosure with R-13 batt has 1.5 in. of ffpic installed to the exterior. The house in the simulation is a Building America benchmark house and might not accurately reflect the condition of older homes, so the savings might be underestimated. Also, in some areas, old homes are sometimes uninsulated in the walls. Adding 1.5 in. of ffpic to an uninsulated wall assembly was not calculated, but the savings can be expected to be about $1,000/yr for the simulated building in a cold climate. This analysis also did not account for airtightness changes, but applying a drainage membrane and continuous exterior insulation could improve the airtightness of the building as well.

Table 2. Predicted Annual Savings

Representative City	DOE Climate Zone	R-13 Cavity	1.5-in. (R-9.75) Exterior Insulation	Savings
Boston, Massachusetts	5	6,031	5,879	$152
Duluth, Minnesota	7	5,741	5,603	$138
Kansas City, Missouri	4	4,965	4,874	$91

It cannot be ignored that an initially slightly more expensive system might have to be implemented to save a significant amount of energy over the entire life of the structure, which will be much longer than a standard mortgage. Research has shown that walls exceeding an R-value of 35 can financially pay back during the life of the initial mortgage through energy savings while reducing greenhouse gases (Grin 2008). Because the building enclosure is designed to use less energy, the energy and greenhouse gas emissions savings extend for the life of the building, not just the initial mortgage.

1.5 Tradeoffs and Other Benefits

Adding exterior insulation will result in a more comfortable living space, but this significant benefit is difficult to quantify in terms of dollars. Also, by adding exterior insulation, the temperature of the condensation plane in cold climates (the interior surface of the exterior sheathing) will become warmer, which will decrease the risk of condensation and moisture-related durability risks such as mold. By increasing the durability of the enclosure, the sustainability of the building is also increased. By doubling the life of a building using the same amount of resources to construct it, the building is twice as resource efficient.

Also, note that it is possible to improve the airtightness of the enclosure during a retrofit like this, which will result in further energy savings. A ventilation strategy, however, might be required to bring adequate fresh air to the interior space.

2 Experiment

2.1 Research Questions

The key research question is this: How risky is adding drained exterior insulation in an energy retrofit of an existing home? Drained exterior insulation in this project refers to exterior board foam insulation that is installed over a sheathing membrane, with the intentional drainage cavity of the wall between the insulation and sheathing membrane. The durability in question is the durability of the wood sheathing. Some perceive that adding exterior insulation to the exterior of the wood sheathing will cause moisture-related durability problems with the wood sheathing.

To answer the key question, the mechanisms of wetting and drying will be examined:

- How much water can be stored in the drainage cavity, and does it pose a moisture-related durability threat?
- If water becomes trapped in the drainage cavity, where does the water go, and what impact does it have on the durability of the wall system and the moisture content (MC) of the sheathing?
- Are there alternative solutions to energy retrofits that decrease the risk of moisture-related durability problems?

2.2 Technical Approach

This research project was divided into several areas of work.

A literature review was conducted before testing, to determine what testing has been conducted and what research has been published on moisture-related issues with exterior insulation retrofits. There is no specific literature review section in this report, but the relevant information is discussed in each section.

Laboratory testing was conducted to determine the amount of water drained and stored in the drainage cavity of various wall systems by measuring the amount of water stored after water is poured into the drainage cavity. The sheathing MC was monitored during and following water application to the drainage cavity to see what effect, if any, the stored water had on the MC of the sheathing.

In a similar test, water was intentionally stored between the exterior insulation and drainage plane to determine what impact that had, if any, on the MC of the sheathing and wall cavity. Moisture stored in the drainage cavity is widely perceived to cause moisture-related durability issues for the sheathing.

Full-scale comparative field testing of exterior insulated walls in DOE climate zone 4C with other more traditional wall construction strategies has been completed. This testing focused on determining moisture-related durability risks caused by exterior wetting between the wood sheathing and exterior low permeance insulation. The conclusions from this testing are relevant to all climate zones, particularly cold climates.

3 Testing and Analysis

The experimental testing program was designed to assess the moisture-related risks of draining the enclosure wall system between the insulation and the sheathing on various drainage plane materials. Testing was designed to compare various drainage plane materials, and to determine if certain materials altered, either positively or detrimentally, the inherent moisture-related risk.

Field tests were conducted on full-scale test walls that compare side-by-side, exterior insulated walls with more standard construction techniques. In the full-scale field testing, a known volume of water was injected using a wetting apparatus directly against the exterior surface of the sheathing, simulating a deficiency in the drainage plane.

3.1 Drainage and Drying Testing

Drainage and drying testing is important in determining the amount of water that can be drained from the enclosure system, and to quantify the amount of stored water following initial drainage. This moisture could be drained intentionally from flashed openings in the enclosure or as a result of diffusion condensation through the enclosure. Typically there are two options. The water can evaporate and diffuse away in six possible directions, or be dried by ventilation (air movement). Determining the drying rates of various wall systems is important because the drying rate is related to the moisture durability and moisture storage capacity of a wall system. In this case, drying rates were not analyzed because the temperature and relative humidity (RH) conditions around the test wall, which affect the drying rate, could not be tightly controlled. Tight control is important because fluctuations in the ambient RH will affect hygroscopic materials in the wall system and the weight of the wall will change with changes in RH (Smegal 2006). In future testing, an enclosure could be built around the testing apparatus to tightly control the temperature and RH so walls can be compared with the same boundary conditions. Drying rates of different walls will depend on their construction and material properties. Drying rates of test walls during field testing for exterior insulated walls and more typical construction are illustrated in Section 3.3.

Previous research conducted at Pennsylvania State (Schumacher et al. 2003) and the University of Waterloo (Smegal 2006) used a similar testing technology of a balance that gravimetrically measures the mass of water in a 4 ft × 8 ft wall panel during drainage testing. This research was limited, however, to total moisture storage in the drainage cavity and did not address the manner or rates of hygric redistribution. Further, the effects of repeated wetting were not investigated. No literature was found that indicates that the MC of the sheathing was measured during drainage and drying testing. This research project extends previous research by measuring the impact of drainage and storage on the MC of the wood-based sheathing.

3.1.1 Research Goal/Questions To Be Answered

There is a perceived concern in the industry that designing the enclosure wall system with the sheathing membrane and drainage plane between the exterior insulation and the sheathing might result in moisture-related issues for the wood-based sheathing. Moisture-related issues are caused by wetting that exceeds the drying capacity of the system and overcomes the safe storage ability (Figure 2). Measuring the amount of water that drains, and how much is stored, after one wetting or several wettings will help determine which enclosure assemblies decrease the exposure to moisture and reduce the risk even further.

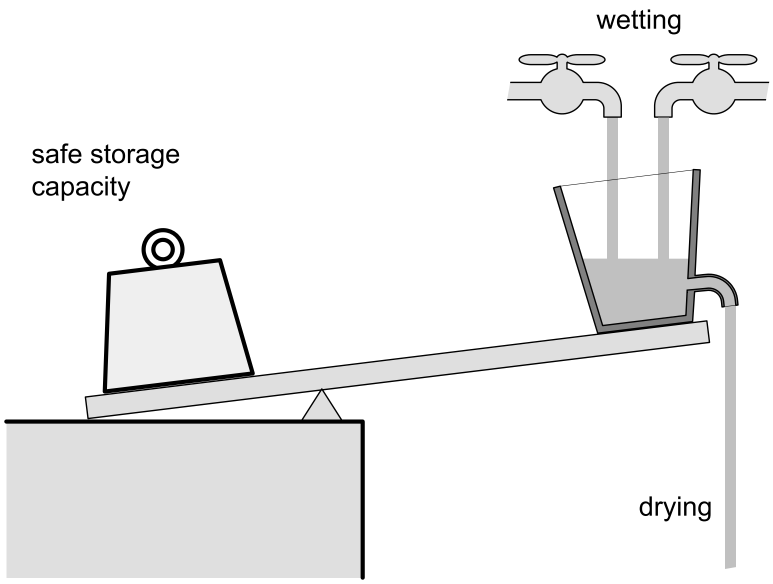


Figure 2. Moisture balance of wetting and drying

This testing was done with no temperature gradient across the wall. It is well documented that solar heating of the cladding will drive moisture into the enclosure (solar inward vapor drives) (Straube 2009; Smegal 2006; Straube and Burnett 2005). Future testing could incorporate simulated inward solar drives that would determine the effects on drying and hygric redistribution in the drainage cavity and enclosure wall.

3.1.2 Testing System

Figure 3 shows the schematic of the wall balance used for testing. The test wall was nearly balanced with counterweights so the mass on the 25-lb load cell was approximately 5 to 10 lb. By using a smaller load cell, the precision of the load cell can be increased with limited cost.

Figure 4 depicts the actual balance used in the laboratory. The test balance is a steel structure that is self contained so that it can be moved around the laboratory. It is not anchored to the floor. Test walls were outfitted with nine wood MC sensors to continuously monitor the wood MC of the sheathing. Figure 5 shows the layout of all nine sensors, and Figure 6 illustrates an individual wood MC sensor and thermistor. The sensors were continuously monitored using a Campbell Scientific CR1000 data logger and multiplexer. The MC sensors measure a resistance across the wood that correlates to an MC. As the MC increases, the electrical resistances of the wood decrease (Straube et al. 2002).

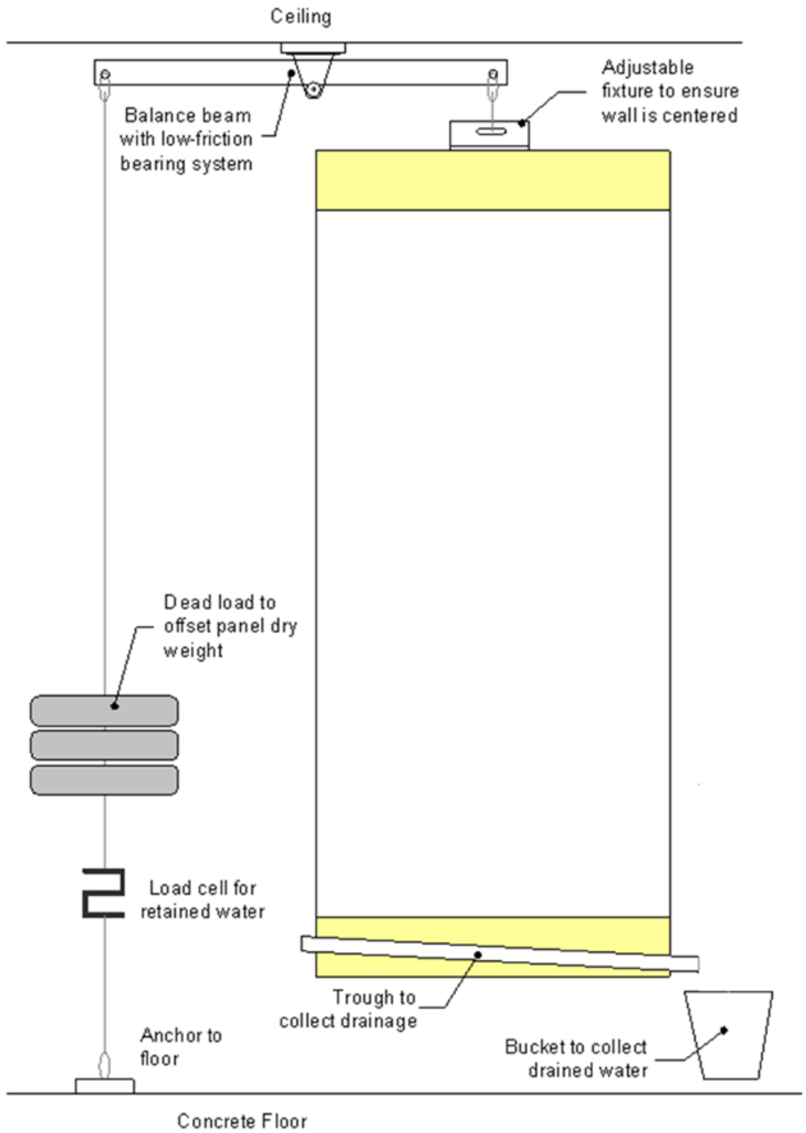


Figure 3. Wall balance schematic

Figure 4. Drainage and drying balance

Figure 5. Location of wood MC sensors

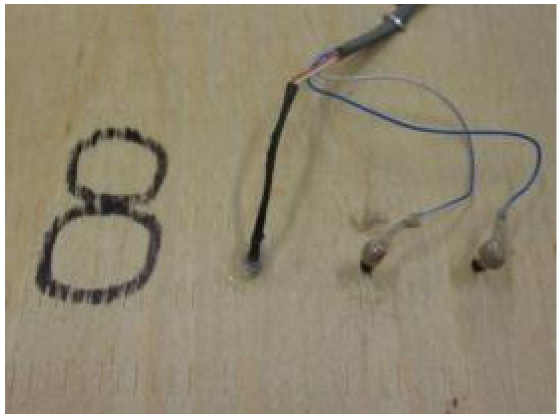


Figure 6. Installed wood MC sensor and thermistor

Wood MCs of plywood are a close approximation, and should not be judged with a pass/fail criterion. When MC measurements are analyzed in the laboratory or in the field, the reading should be kept in context and good building science judgment is required to determine the moisture risk to the plywood. For example, elevated wood MCs in the cold winter months are much safer from a mold growth perspective than similar MCs in the summer, when mold will grow more quickly. Also, a high MC for a short period followed by drying is not necessarily risky, as wood-based materials are able to manage high MCs for short periods without exceeding the safe storage capacity of the assembly.

In general, decay will not occur unless the MC is greater than fiber saturation for a prolonged period of time (Steffen 2000). Fiber saturation is commonly reached at an MC of approximately 25% to 30% (Baker 1969). Sustained MCs above 28% for more than 4 weeks would generally be cause for concern.

All of the test walls (Figure 7) were 4 ft in width and 8 ft in height, consisting of a 2 × 4 wood framed cavity at 16-in. o.c., plywood sheathing with a ⅛-in. horizontal seam, a 6-mil polyethylene air and vapor barrier on the interior (Figure 8), a sheathing membrane, and ¾-in. ffpic insulation on the exterior (Figure 9). Installing the ffpic on the exterior and polyethylene on the interior means that drying of the entire system can occur only through ventilation and diffusion of the drainage cavity to the top and bottom of the drainage space. Moisture can still redistribute into the sheathing and stud space, but that will not result in any change of mass of the system.

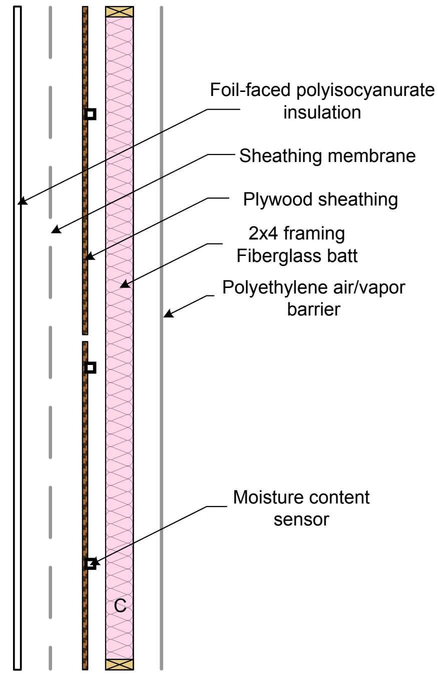


Figure 7. Typical test wall schematic

Figure 8. Interior surface of typical test wall

Figure 9. Exterior surface of typical test wall

This testing is in support of retrofit applications, and in many cases, retrofits may not have a polyethylene vapor barrier on the interior to limit the flow of water vapor. This testing, then, might be conservative. Historically, however, oil-based paints that acted as a vapor control layer were used. On most walls in retrofit situations, there are likely several layers of paint depending on the age of the building and occupant behavior. Having a vapor control layer on the interior decreases the ability of inward drying in laboratory testing and will result in the highest sheathing MC possible under the test conditions. This means that it is the worst case scenario for sheathing wetting under the specific test conditions.

3.1.3 Matrix for Testing

Tests have been conducted on a smooth plastic housewrap and a corrugated plastic housewrap. A wall with liquid applied membrane will also be tested. While designing the testing program, multiple tests were conducted on the smooth and corrugated housewraps, and on different wall balances in an attempt to show repeatability of the testing procedure. Repeatability of testing results was shown to be quite good previously when similar tests were conducted numerous times or in different laboratories (Smegal 2006).

Table 3. Testing Matrix for Drainage and Drying Testing

Test	Equipment	Sheathing Membrane
1	BSC Wall Balance	Smooth Plastic Housewrap
2	BSC Wall Balance	Corrugated Plastic Housewrap
3	BSC Wall Balance	Smooth Plastic Housewrap
4	Alternative Wall Balance	Corrugated Plastic Housewrap

3.1.4 Testing Protocol

The testing program was designed based on the testing and research conducted at the University of Waterloo on dozens of different wall configurations. A drainage trough at the top of the wall was constructed using plastic housewrap. Five narrow 2-in.-long spacers (Figure 10) were inserted into the top of the drainage space to ensure that water entered the drainage space (Figure 11).

Figure 10. Two-inch-long plastic spacers

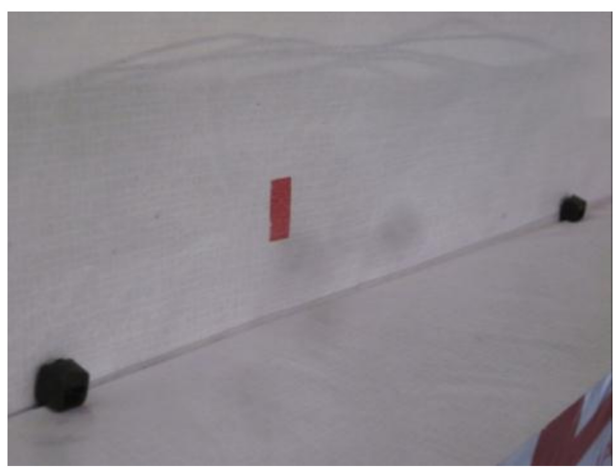


Figure 11. Spacers installed in top of drainage gap

In the case of the smooth plastic housewrap, the top edge of the ffpic was pressed tight against the housewrap, and water could not easily enter the drainage cavity. Once water penetrated the top edge, water drained to the bottom quickly and uniformly.

Before the test began, a wall calibration procedure was undertaken. Calibration weights were added and removed to ensure that results could be verified during the data analysis that followed the testing. Calibration weights were also used at the end of the test before the wall was detached from the balance. Calibration is required to zero the balance and determine the linear relation to the system as built. It is completed at the start of every test to verify the system parameters once the wall has been hung. The readings on the load cell were taken continuously but the output was a 15-min average during drying.

Based on previous research and testing, the BSC team decided to follow the same testing protocol as Smegal (2006). The first application of water was 1.5 L (50 fl oz) into the drainage space. This volume was chosen because it is a manageable amount that ensures that the drainage space is wetted as much as possible. Approximately 15 min after the first application was complete, the drainage space received a second injection of 1.5 L (50.7 fl oz). Fifteen minutes was used based on previous tests of dozens of wall systems. The drainage appeared to stop for all walls at the 15-min mark, but minimal drying of stored moisture had occurred. The second application was used to determine if water is being absorbed into the wall system. With nonhygroscopic materials on both surfaces of the drainage cavity, the team expected that the first and second applications of water would result in approximately the same amount of storage. Fifteen minutes after the second application of water, the free drainage had generally stopped. This is referred to as the storage amount.

3.1.5 Results/Analysis

Two tests were conducted on smooth plastic housewrap, stapled to the sheathing, with ffpic applied directly to the surface. It should be noted that the housewrap manufacturer recommends using cap staples to attach the housewrap. Otherwise, any warranty is voided. Field observations have demonstrated, though, that the housewrap is often installed with standard staples without caps.

The installation of housewrap without cap staples will give a worst case scenario for drainage and drying. The gap provided by the caps, especially against a relatively hard surface such as the surface of board foam insulation has been shown to be large enough to improve drainage and ventilation drying (Smegal 2006). A future drainage test may be conducted using smooth plastic housewrap installed with cap staples to quantify differences in both drainage and drying.

Figure 12 shows the initial drainage test. It starts with two calibration weights that were added, 100 g and 200 g (3.5 oz and 7 oz). At the 100-g (3.5-oz) weight, the measurement is within 2 g (0.07 oz), or 0.67 g/m^2 (0.002 oz/ft^2). Fifteen minutes after the first pour, the storage was approximately 80 g (2.8 oz), and 15 min after the second pour (indicated by the vertical dashed line), the amount stored was 85 g (3 oz) or 28.8 g/m^2 (0.09 oz/ft^2). Because the gap was so small, it does appear that there was still some drainage from the cavity at the 15-min mark. The two storage amounts were nearly identical. This was expected because neither drainage plane surface was absorptive.

As a comparison to add perspective, when water was spray applied to a single nonabsorptive polyethylene sheet or a sheet of Plexiglas, the surface storage amounts were consistently 35 g/m^2 (0.11 oz/ft^2) and 65 g/m^2 (0.21 oz/ft^2), respectively. Drainage tests conducted on a 1-mm gap with both sides constructed of Plexiglas stored 24 g/m^2 (0.08 oz/ft^2) (see Table 4). More was stored on a single sheet than in the narrow drainage cavity because the cavity was too narrow to allow the moisture to form beads of water (Smegal 2006).

Table 4. Values of Maximum Storage Amounts on Nonabsorptive Surfaces for Context to Testing Storage Amounts

	Maximum Storage g/m^2 (oz/ft^2)
Water Sprayed Against Smooth Polyethylene Sheet	35 (0.11)
Water Sprayed Against Plexiglas Sheet	65 (0.21)
Water Poured Between Two Layers of Plexiglas Approximately 1 mm Apart	24 (0.08)

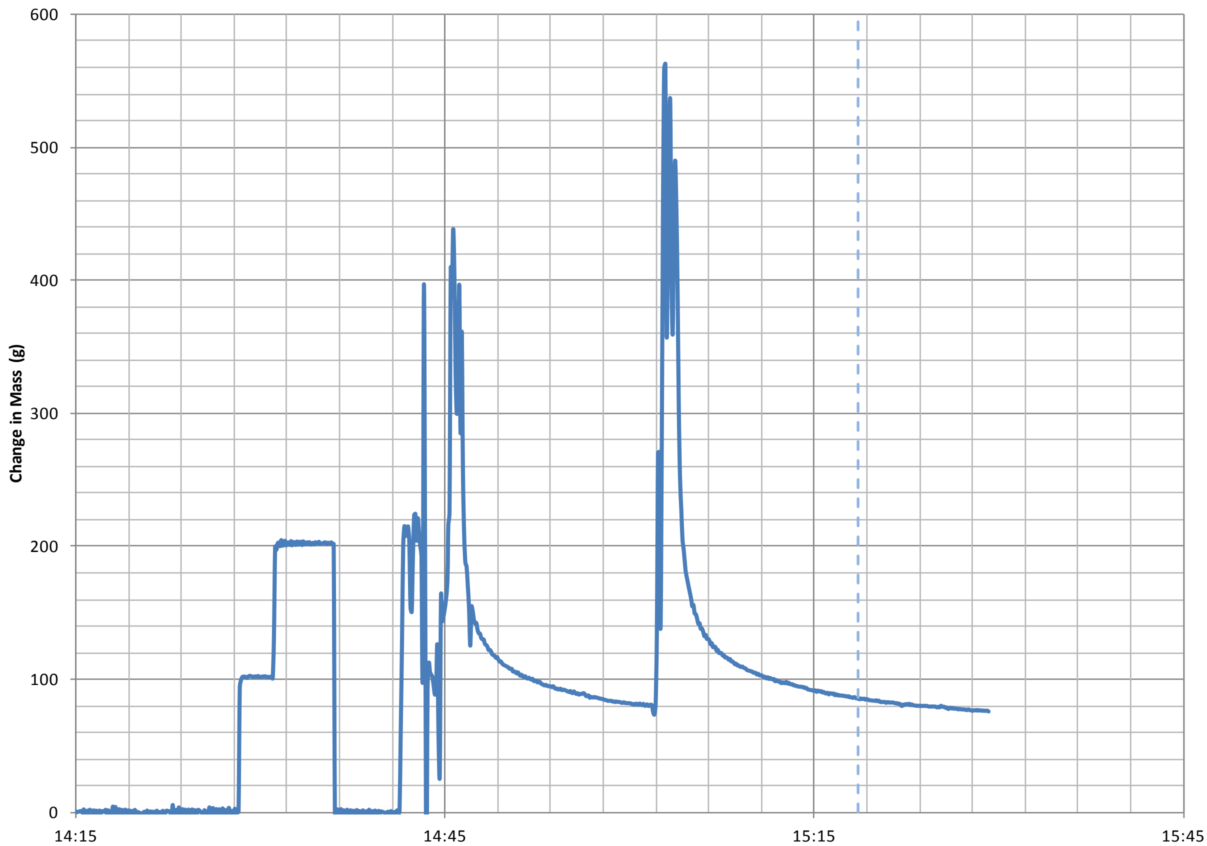


Figure 12. Smooth plastic housewrap drainage test

After the initial drainage and drying test, the drainage cavity was subjected to repeated wettings over a few days, to help determine if repeated wettings in the drainage gap to the interior of exterior insulation would result in any moisture-related durability issues. It was found that there was a correlation between the sheathing MC and repeated wettings, as shown in Figure 13, but the scale of the MC is between 9% and 12% as an average for all nine MC locations. This scale is used to show the correlation, but it should be noted that moisture durability is generally not an issue until the MC is greater than 20%. The average ±1 standard deviation of all the MC readings is also shown on the series of MC sensors.

The total increase in the weight of the wall following the six wettings was approximately 200 g (7 oz). This is equivalent to approximately 67 g/m^2 (0.22 oz/ft^2). The surfaces of the drainage cavity are nonhygroscopic, which means that the increase in the weight of the wall was a result of redistributed moisture into the sheathing and stud cavity.

Calculations show that an increase of 200 g (7 oz) of water, assuming that the added water is entirely in the plywood sheathing (which is likely not the case because some is stored in the drainage cavity), would correspond to an MC increase in the plywood of approximately 1.3%. This also assumes that the moisture is evenly distributed in the sheathing and is not stored in the stud space cavity as vapor. No RH sensors were installed in the cavity for this test, although there is evidence of moisture vapor increases during cavity wetting in the hygric redistribution test discussed later.

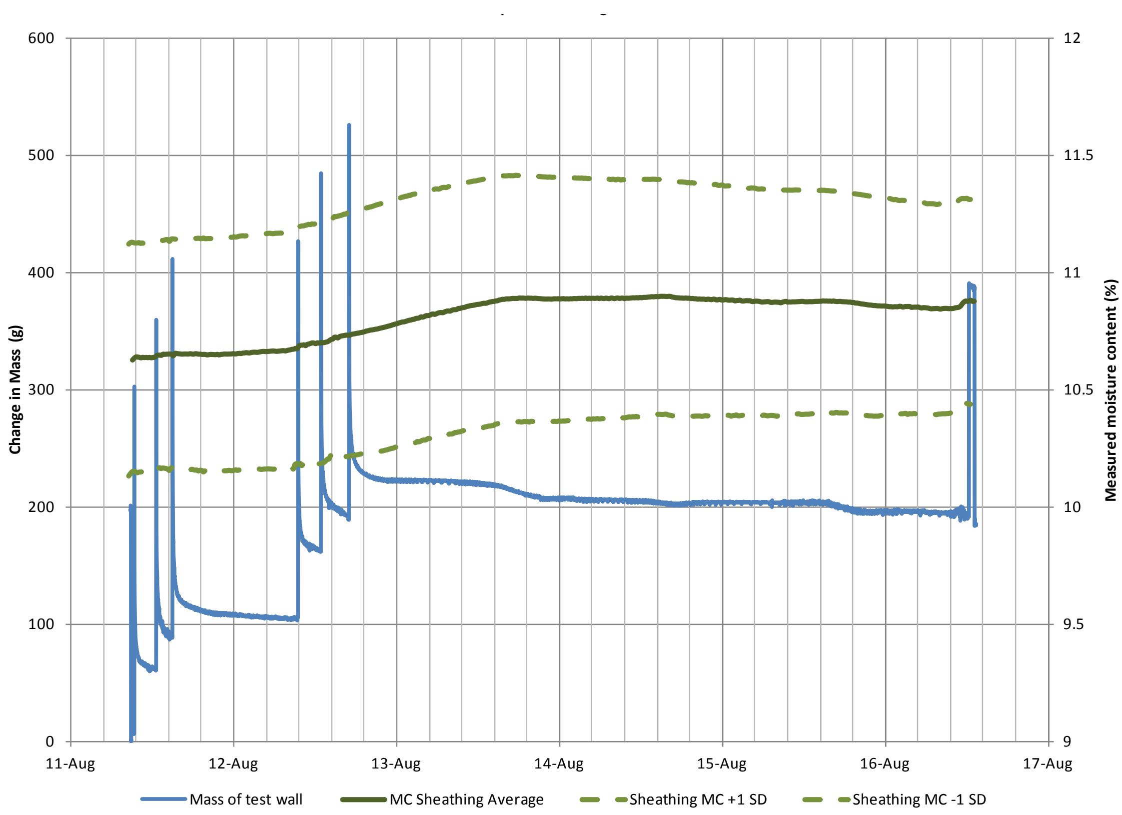


Figure 13. Repeated drainage gap wetting analysis, smooth housewrap

A second drainage test was conducted on smooth plastic housewrap to test the repeatability of the testing program. The results of the storage following the first and second cavity wettings are shown in Table 5, along with the results from the previous test. Using a sample size of two, the difference in results was nearly half. It is expected that with a greater number of tests, the repeatability would show a small standard deviation in the storage amounts. The repeatability is also expected to improve when there is some absorptivity and a more significant amount of water is stored. The amount of water stored during these drainage tests is quite small, even smaller than the amount of water that can be stored when sprayed against a polyethylene sheet.

Table 5. Comparison of Drainage Tests on Smooth Plastic Housewrap

	Initial Storage g/m^2 (oz/ft^2)	Final Storage g/m^2 (oz/ft^2)
Test 1 – Initial Drainage Test on Smooth Plastic Housewrap	26 (0.09)	28 (0.09)
Test 3 – Second Test on Smooth Plastic Housewrap for Repeatability	15 (0.05)	19 (0.06)

Two tests were also conducted on a wall with a corrugated plastic housewrap. Intuitively, this material will store more water because there is more surface area for drainage and available surface for water storage. The gap is also wider, and previous testing (Table 4) demonstrated that a very small gap will store less water when the water is not able to form beads of water on the surface. One test was conducted at the BSC laboratory in Waterloo, and the second test was conducted at the laboratory of an industry partner on a different balance apparatus.

Table 6 shows the results from the two tests. The final storage results were the same for each test and very similar to the amount of water stored when water is sprayed against a polyethylene sheet to add context to the storage amounts. This is a very small storage amount, and shows there is no absorptivity of the materials in the drainage cavity. It is unclear why the initial storage was higher than the final storage for the first test. The corrugated plastic housewrap did store more water than the flat plastic housewrap, although the results are still quite similar with respect to the moisture loading on the wall and the effects of moisture on durability.

As stated previously, by confirming with calibration weights, the total weight of the wall is accurate to approximately 2 g, which is equivalent to 0.67 g/m^2. In the case of the corrugated plastic housewrap tests, this represents approximately 2% of the final storage amount.

Table 6. Comparison of Drainage Tests on a Corrugated Plastic Housewrap

	Initial Storage g/m^2 (oz/ft^2)	Final Storage g/m^2 (oz/ft^2)
Test 2 – Initial Drainage Test on Corrugated Plastic Housewrap	42 (0.14)	36 (0.12)
Test 4 – Second Test on Corrugated Plastic Housewrap on a Different Balance Apparatus	35 (0.11)	36 (0.12)

The BSC team observed that the drainage did occur more quickly using the corrugated housewrap, but both wall types were able to drain quite quickly and effectively. In a smaller gap, a large amount of water will be pushed laterally to the edges, but in a larger gap, the water will drain straight down in the path that it was poured into the wall. This was made evident by a very small amount of leakage out the sides of the flat plastic housewrap wall, through the tape, and onto the exterior face of the ffpic.

A repeated wetting test was also conducted on the corrugated plastic housewrap wall, and the results are shown in Figure 14 (with the same scale as the previous test depicted in Figure 13). There were two extra wetting events compared to the flat plastic housewrap (Figure 13), but the entire wall system with corrugated plastic housewrap gained more than twice the mass as the smooth plastic housewrap. The drainage cavity materials are nonhygroscopic, which means that more than twice the water vapor diffused into the sheathing and stud cavity from the drainage space. This happens because more water is stored after each wetting event, and the vapor can very easily move into the plywood sheathing through the vapor permeable drainage plane. The increase in MC from repeated wettings is still less than 20%, the minimum threshold for moisture-related durability concerns.

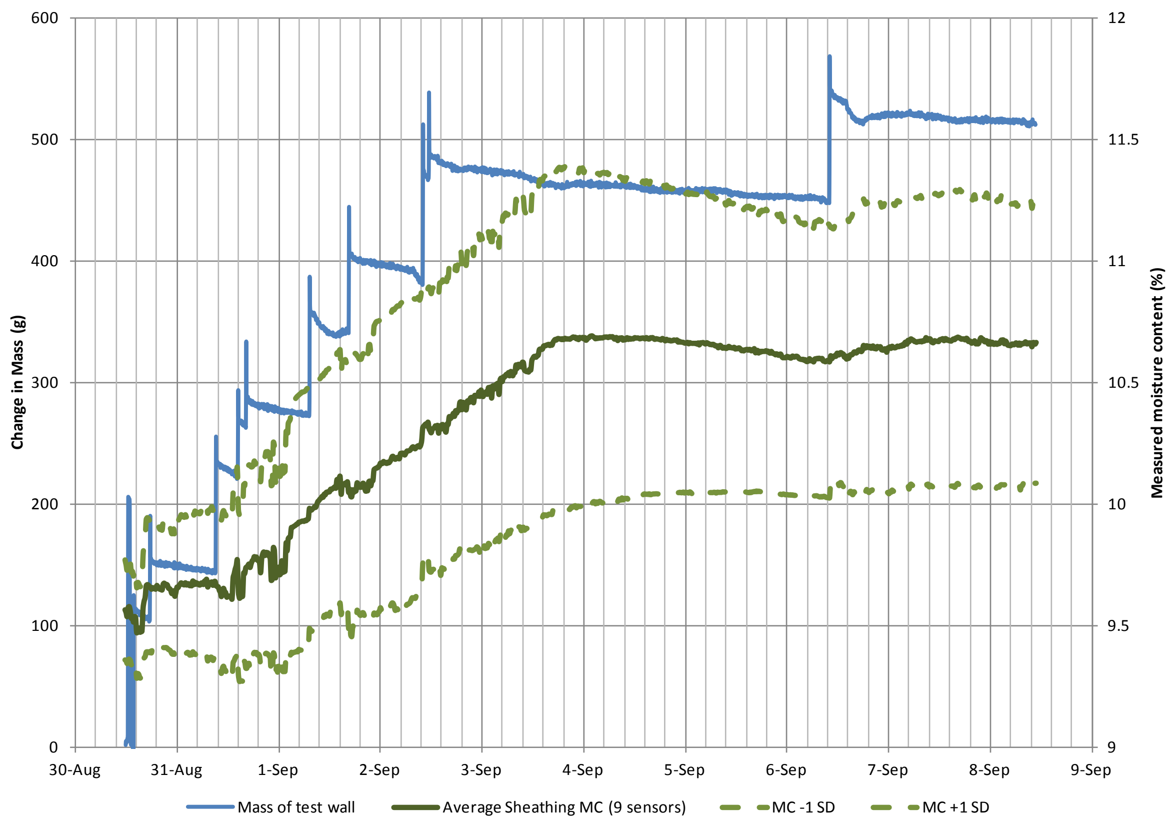


Figure 14. Repeated drainage gap wetting analysis, corrugated housewrap

3.1.6 Summary

The larger gap provided by the corrugated plastic housewrap allowed more rapid drainage than the flat plastic housewrap; however, it did store nearly twice as much water following drainage. To keep that in perspective, the corrugated plastic housewrap stored approximately the same amount of water as a sheet of polyethylene with water sprayed against it, and only approximately half as much as a sheet of Plexiglas with water sprayed against it.

Following repeated wettings of the entire drainage cavity, there were no moisture-related durability issues of the sheathing under laboratory conditions.

The repeated wetting events on the corrugated plastic housewrap resulted in a higher adsorption to the plywood sheathing because more water is stored following each wetting event, likely because of the increased surface area for water deposition.

It is likely that using cap staples as recommended by the product manufacturer to install the smooth housewrap will result in quicker, more vertical drainage similar to the corrugated housewrap. Because there is not significantly more surface area resulting from corrugations of the housewrap, though, storage would likely have been similar to that of the smooth plastic housewrap.

This test can be used to compare the performance of different wall systems in the laboratory, but it is difficult to correlate the results to leaks that occur in real buildings. The volume and the frequency of water that might leak in the field are based on many variables and entirely unpredictable.

3.2 Hygric Redistribution

This testing program was designed to more accurately determine what happens to water that becomes trapped in the drainage cavity behind vapor impermeable exterior insulation, or sustained long-term wetting in the drainage cavity. The potential improvements resulting from a corrugated housewrap instead of a smooth housewrap will be investigated. The hypothesis was that a corrugated housewrap could allow more hygric redistribution (diffusion) of water vapor in all directions in the drainage cavity.

3.2.1 Research Goal/Question To Be Answered

Here, the main question is what happens to water and the hygroscopic wall materials during sustained long-term wetting in the drainage cavity behind vapor impermeable exterior insulation. Does the water evaporate and move in all directions through the cavity? Is there a risk to the moisture durability of the wall system? Do the results differ if a different corrugated housewrap is used?

3.2.2 Testing System

The same balance used for drainage and drying testing, described earlier in the report, was used to hold the 8-ft-tall by 6-ft, 8-in.-wide test wall, so that it could be monitored gravimetrically. Both MC and RH sensors were used to measure the amount of moisture in the stud spaces, sheathing, and drainage cavity. The wall section is the same as the previously described test (refer to Figure 7) using a corrugated plastic housewrap as the sheathing membrane.

To accurately measure the RH in the drainage space without affecting the drainage gap, the RH sensors were installed from the exterior of the ffpic in a pocket that was formed on the interior so that it did not affect the drainage cavity (Figure 15). Figure 16 shows the distribution of the RH sensors, and Figure 17 depicts the layout of both the RH sensors and the sheathing MC sensors.

A wetting apparatus was installed on the interior surface of the exterior insulation to allow a known amount of water to be injected at a controlled time and location. The wetting apparatus consisted of a storage medium 11 in. wide by 20.5 in. tall installed directly against the surface of the ffpic as shown in Figure 16 and indicated by the blue square in Figure 17. A perforated tube connects the storage medium to the exterior of the wall for water injections. This enables wetting to a known area in the drainage cavity without disturbing the wall system.

The test wall was built of 2 × 4 framing on standard 16-in. centers and insulated with fiberglass batt insulation. To mimic standard cold-climate construction and to limit immediate drying of the injected moisture, a Class I vapor retarder was installed on the interior side of the framing. A ½-in. plywood sheathing was installed because this would most likely be used in a retrofit situation instead of oriented strand board (OSB).

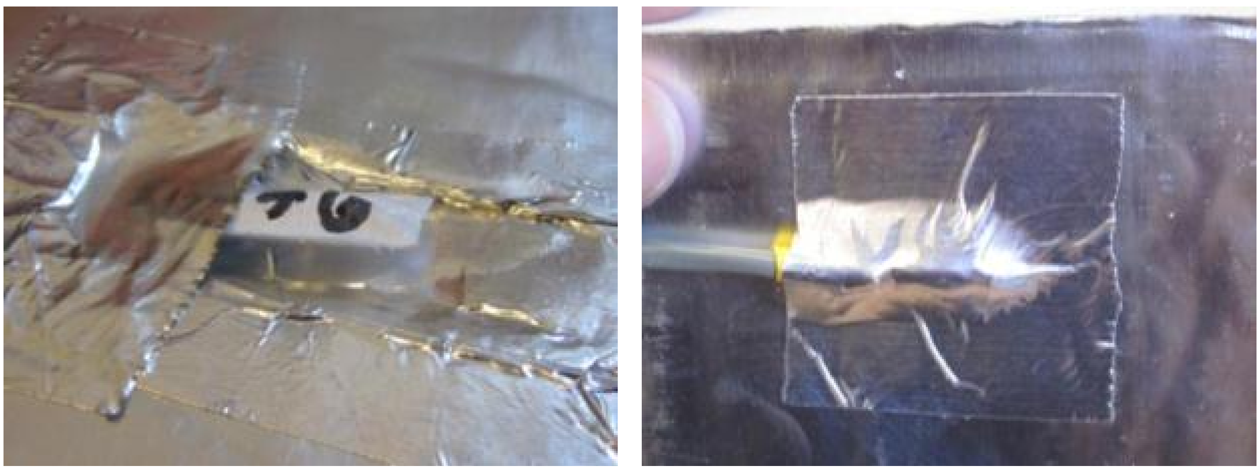


Figure 15. RH sensor in the drainage space

Figure 16. Wetting system and drainage space RH sensors

Intentional wetting was conducted on the schedule shown in Table 7. Initially 1 oz was injected twice daily, but this was increased to 1.5 oz twice daily. The volume was increased for two reasons: (1) it was unclear if maximum storage was being reached because no water was draining out during injection; and (2)1.5 oz, injected twice daily, is a standard intentional wetting volume during the full-scale field testing discussed in Section 3.3. The total amount of water injected over 7 days was 13 oz (390 mL). A small amount of water did drain within a few minutes of injecting1.5 oz of water, but water was injected slowly to maximize the water stored in the wetting system prior to any drainage.

Table 7. Hygric Redistribution Wetting Schedule

Date (2011)	Amount	Time
Wednesday, September 14	1 oz (30 mL)	Morning and afternoon
Thursday, September 15	1 oz (30 mL)	Morning and afternoon
Friday, September 16	1.5 oz (45 mL)	Morning and afternoon
Sunday, September 18	1.5 oz (45 mL)	Morning
Monday, September 19	1.5 oz (45 mL)	Morning and afternoon
Tuesday, September 20	1.5 oz (45 mL)	Morning and afternoon
Wednesday, September 21	1.5 oz (45 mL)	Morning

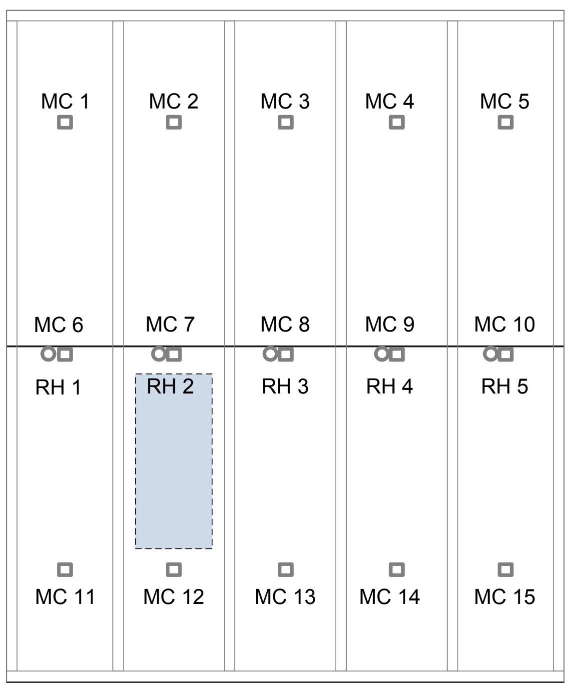


Figure 17. Layout for sheathing MC sensors and stud space RH sensors as shown from the "interior"

3.2.3 Matrix for Testing

The initial test was conducted with a corrugated housewrap, and subsequent testing parameters were determined based on the analysis results. Initially the BSC team thought that there would be significant measurable redistribution in the drainage cavity of water vapor, so a second test would be conducted with a smooth plastic housewrap of similar vapor permeance to demonstrate the advantages of a corrugated housewrap. The test results, however, show very little measured lateral redistribution of water vapor in the drainage cavity.

The team proposed using a drainage mesh (Figure 18) to increase the depth of the drainage cavity and to minimize the barriers to vapor diffusion or potentially a "bumpy" housewrap (Figure 19). This also minimizes barriers to lateral diffusion but keeps the drainage space smaller.

The time frame of this research project, however, did not allow further tests to be conducted on these proposed materials.

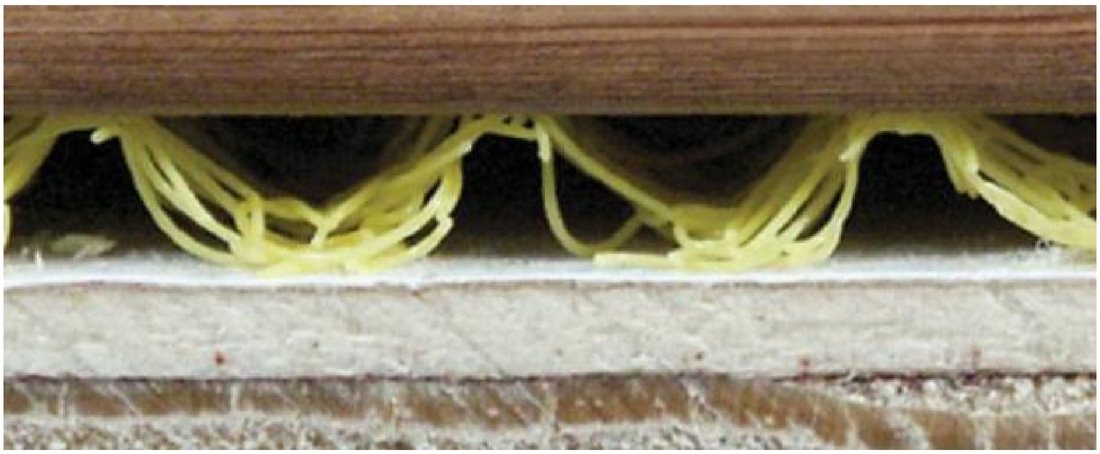


Figure 18. Example of drainage mesh between two sheet materials

Figure 19. Example of a bumpy housewrap

3.2.4 Results/Analysis

Testing began on September 13, 2011 with 1 day of data before wetting to establish the background levels of moisture in the test wall. Wetting began on September 14. There were no variations in the RH sensors in the drainage cavity (Figure 20), which was contrary to expectations, although the drainage space RH sensors did appear to trend with the laboratory RH. Because this was the first test of this kind, it is unclear if there was a sensor-related issue resulting from the method of RH installation, or if there was no hygric redistribution in the drainage cavity. In future tests simulated solar energy could be added to the test wall to see if the increased energy load will help distribute moisture.

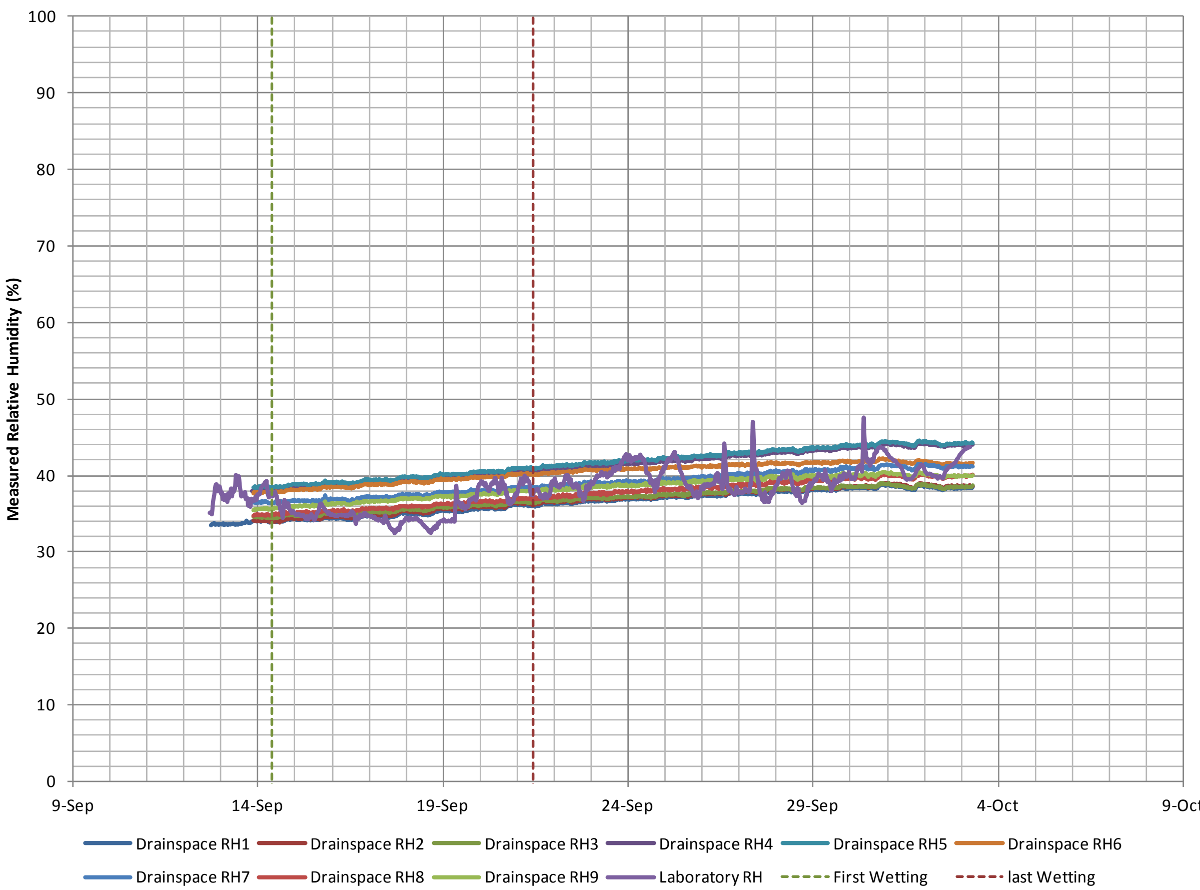


Figure 20. Measured RH at nine locations in the drainage space

Because there was no apparent lateral diffusion, moisture physics principles were more closely examined in an attempt to understand the behavior.

First, it became apparent that the amount of surface area for diffusion through the face of the housewrap was significantly higher (225 in^2) compared to the effective area of diffusion from the edges of the wetting paper (12.6 in^2) (Figure 21).

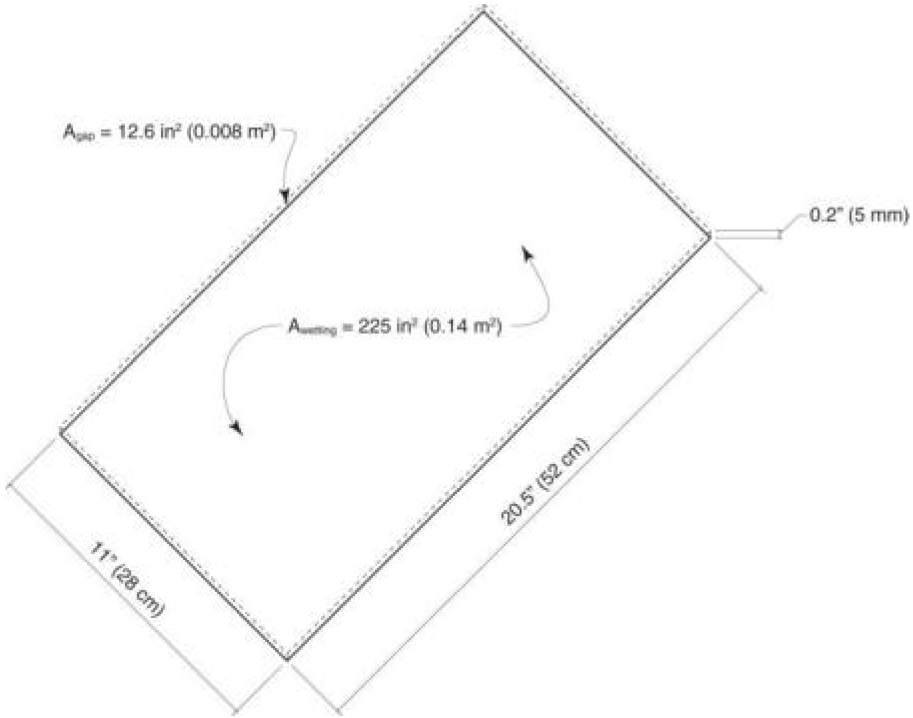


Figure 21. Comparison of surface areas for diffusion from wetting system

When considering vapor permeability properties, the following two values are of significant importance:

- Permeability of air = 185 ng/Pa·s·m
- Permeance of the housewrap = approximately 1,800 ng/Pa·s·m^2

Therefore, the thickness of air required to have the same vapor resistance as the housewrap is

- Permeability of air/permeance of material = 0.103 m or 4.0 in.

This means that for every water vapor molecule that moves through the housewrap, to dry to the air gap, a water vapor molecule has to move 4 in. through the air in the gap around the wetting paper. This is further complicated by the fact that the gap is not full of air, but rather repetitive layers of corrugated housewrap, decreasing the permeance even further.

The two factors of increased surface area for diffusion, along with the comparatively low vapor permeance of the housewrap, mean that water vapor will move through the housewrap into the plywood very easily relative to diffusing through the drainage gap. Plywood is a very adsorptive material for water vapor, and becomes significantly more vapor permeable as the RH increases (ASTM E96 wet cup test).[1]

Several conclusions can be drawn from this analysis:

[1] ASTM Standard E96 is available for purchase at http://www.astm.org/Standards/E96.htm.

- Measuring significant RH increases in the drainage gap is unlikely with this testing setup.
- Changing the gap material, the thickness of the gap, and the amount of water might allow measurement of more diffusion in the drainage gap.
- Using a smaller scale test setup with RH sensors installed much closer to the wetting system might be required to show what hygric redistribution does occur.

Analysis of the RH sensors in the each of the five stud spaces (Figure 22) shows that the stud space directly behind the wetting system (RH2) does experience increased RH starting 2 days after the first wetting. The maximum RH measured at RH2 is approximately 72%. On September 22, there is a slight increase in the RH in both adjacent stud spaces (RH1 and RH3), but only of 4% to 5%. This percentage range is comparatively insignificant.

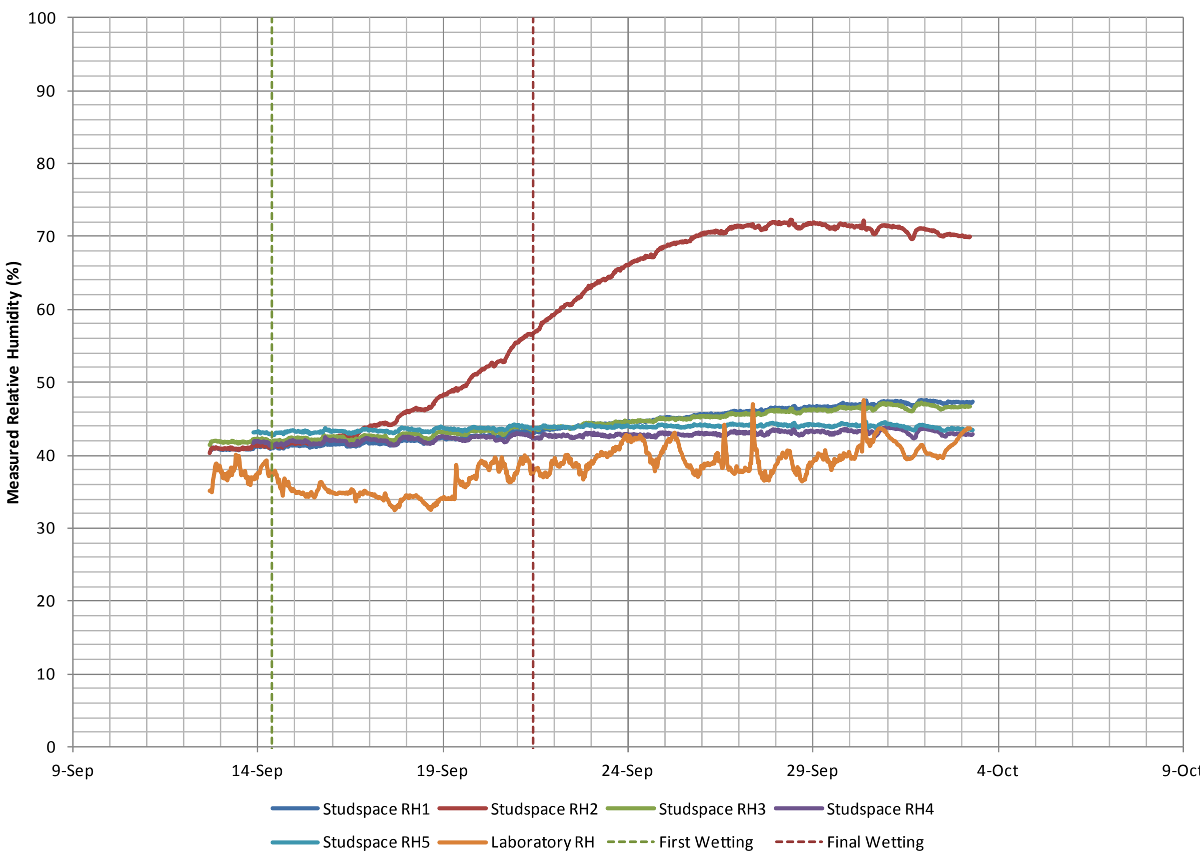


Figure 22. Measured RH in the five stud spaces

There were no MC sensors in the sheathing directly adjacent to the wetting system. MC 7 was approximately 1 in. above the top edge of the wetting system, and MC 12 was approximately 7 in. below the bottom edge of the wetting system.

The MC at the measurement location MC7 started increasing 1 day after the first wetting and increased to a maximum of approximately 13% (Figure 23). At MC12 beneath the wetting system, there was also an increase, but it was much more modest, with a maximum of approximately 11%. It started to increase almost 3 days after the first wetting (Figure 24). These MCs are very low and do not indicate any risk of moisture-related durability issues.

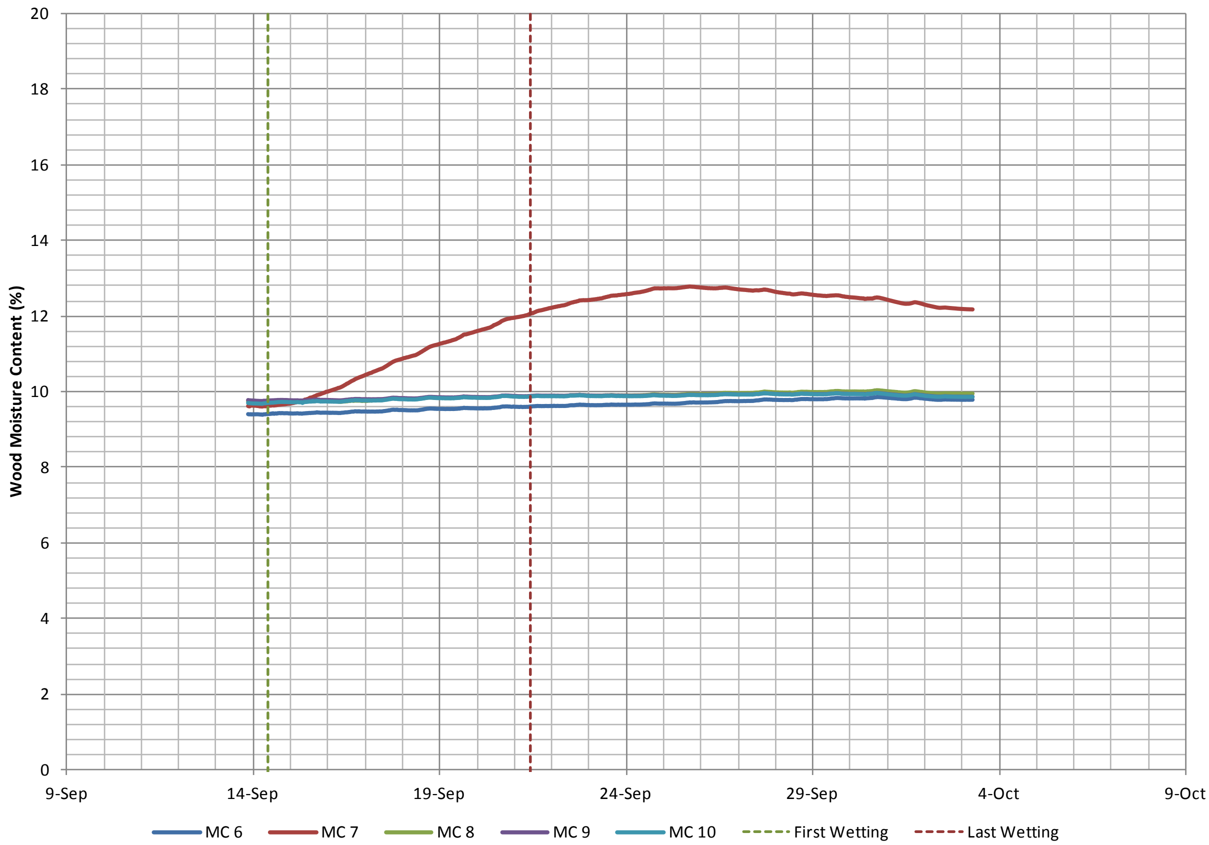


Figure 23. Measured MC sensors in all five stud spaces at the mid height of the wall

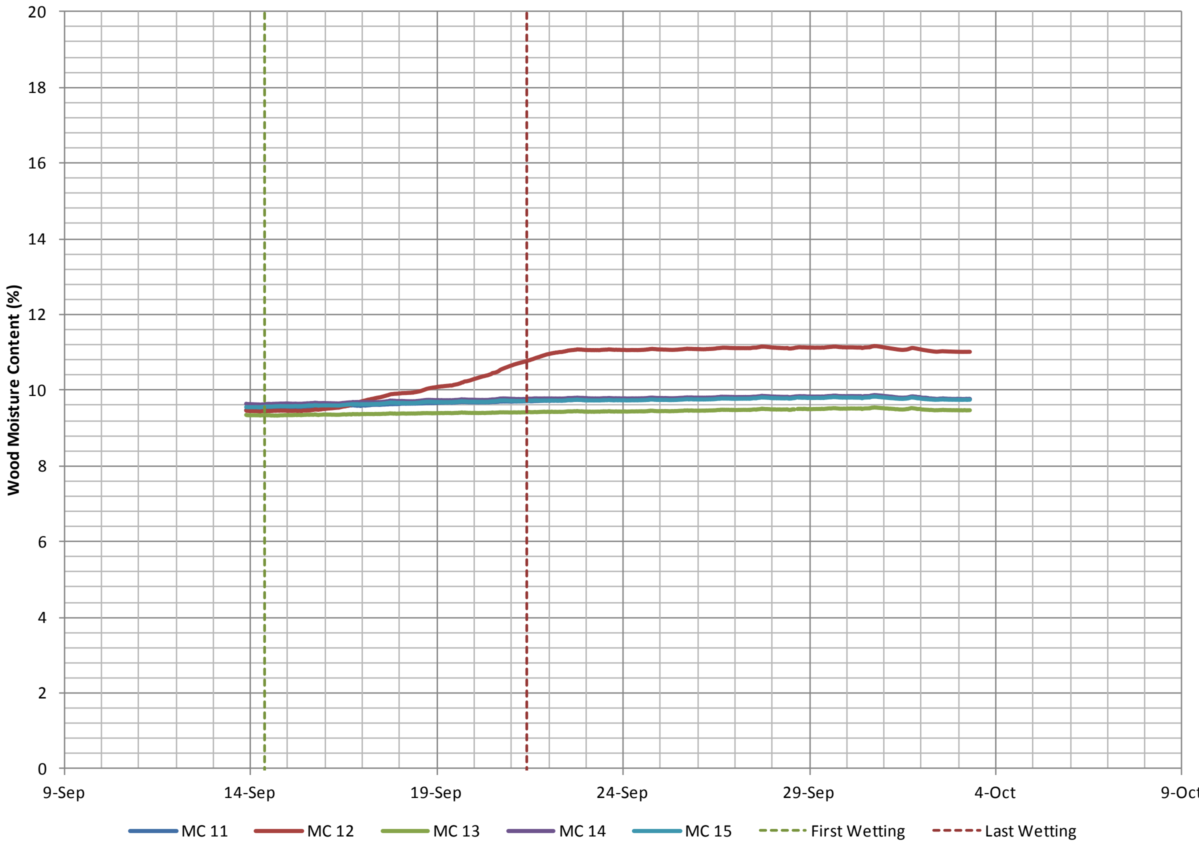


Figure 24. Measured MC sensors in all five stud spaces 16 in. from the bottom of the wall

3.2.5 Summary

After adding a total of 13 oz (390 mL) of water to the wetting system, the maximum measured MCs just above and below the wetting system in the plywood sheathing were 13% and 11%, respectively. There was an increase in the stud space RH (RH2) corresponding to the placement of the wetting system, to a maximum of 72% and a slight increase of the stud space RH sensors in the adjacent stud spaces. This correlates with increased vapor permeability of the plywood sheathing with increased RH.

There did not appear to be an increase in the drainage space RH sensors corresponding to the wetting events, which was initially unexpected. Further analysis showed that, in fact, it is much easier under these test conditions for water vapor to move into the plywood than move significant distances in the drainage cavity.

Several ideas might improve and further this testing for successive tests:

- Smaller test walls with a higher density of RH and MC sensors can be used to further investigate hygric redistribution.
- Conducting a test with a polyethylene sheet behind the housewrap will prevent moisture transport into the wall and control one of the boundary conditions for this testing.

- Potentially, more water, longer wetting, a larger gap, and less material in the gap might increase the potential for diffusion of water laterally through the drainage gap.
- Simulated solar energy could be used to add energy (drive) to the system, although this might only complicate matters because it will be difficult to achieve a constant temperature and energy input across the wall.

3.3 Field Testing

Full-scale comparative field testing of exterior insulated walls in DOE climate zone 4C for comparison with other more traditional wall construction strategies is complete. This testing focused on determining the hygric redistribution of water applied between the sheathing and low permeance exterior insulation to assess the moisture-related durability risks to the enclosure. The performance of an exterior insulated wall (Wall A) shown in Figure 25 was compared to a more standard construction practice, direct applied stucco (Wall B), shown in Figure 26.

The two comparison walls were constructed on all four orientations of the test hut and were exposed to natural environmental conditions.

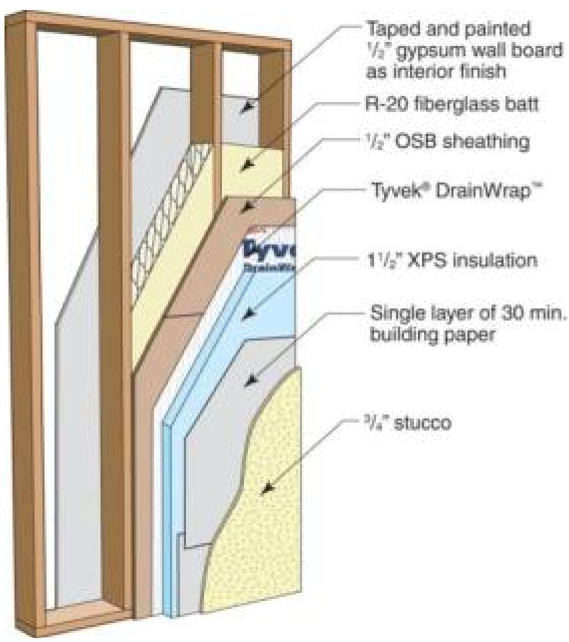


Figure 25. Exterior insulated wall on all four orientations (Wall A)

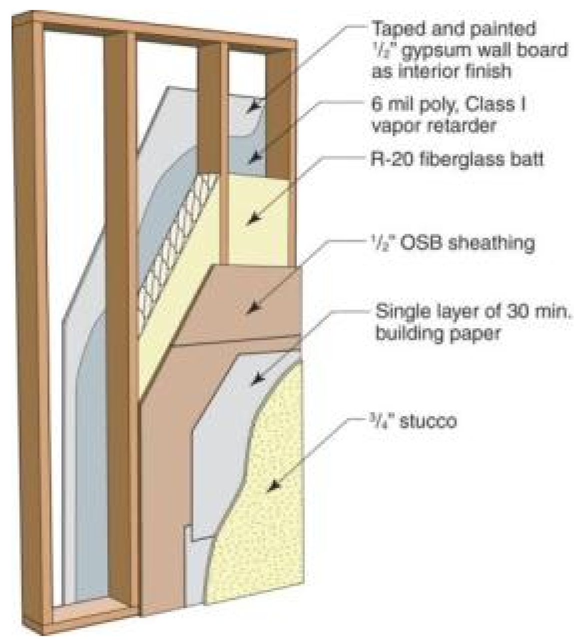


Figure 26. Direct applied stucco wall on all four orientations (Wall B)

3.3.1 Enclosure Wetting Systems

A wetting apparatus was installed on both the interior and exterior of each test wall to allow a known amount of water to be injected at a controlled time and location. The wetting apparatus consisted of storage media 11 in. wide by 20.5 in. tall installed directly against the interior and exterior surface of the sheathing (Figure 27). A perforated tube connected each of the storage media to the interior of the test hut to allow access for water injections. This enables wetting to either the interior or exterior independently without opening and disturbing the wall system. The wetting system was designed to simulate a window leak, and was used to help determine the drying potential of a wall system. On the analysis graphs the exterior wetting events are indicated by red vertical dashed lines and the interior wetting events are indicated by blue vertical dashed lines. When an intentional wetting event occurred repeatedly over multiple days, only one line is shown, indicating the first wetting. There were five intentional wetting events as shown in Table 8. For each wetting event, 1.5 oz (45 mL) was injected twice a day for 5 days. This is a total of 15 oz (~450 mL) into the wetting apparatus directly against the sheathing. For the entire test period 60 oz (~1.8 L) was injected against the exterior of the sheathing, and 15 oz (~450 mL) was injected against the interior surface of the sheathing.

Figure 27. Exterior wetting apparatus

Table 8. Intentional Wetting Event Schedule and Location

	Location	Start Date	Amount
Wetting Event 1	Exterior	July 5, 2010	15 oz (450 mL)
Wetting Event 2	Exterior	August 30, 2010	15 oz (450 mL)
Wetting Event 3	Interior	January 19, 2011	15 oz (450 mL)
Wetting Event 4	Exterior	May 9, 2011	15 oz (450 mL)
Wetting Event 5	Exterior	August 9, 2011	15 oz (450 mL)

3.3.2 Instrumentation

Each of the test walls was outfitted with a series of temperature, RH, and wood MC sensors. These sensors were continuously monitored and recorded throughout the testing period using a data acquisition system. Photographs of the individual sensors are shown in Figure 28 and 29. Variations on a "typical" sensor package (illustrated in Figure 30) were used for each test panel.

MC pins were installed in the framing lumber and the sheathing (from the interior) in all wall systems (Figure 28). Wood MCs can be determined from the electrical resistance of wood based on the Garrahan equation (Onysko et al. 2010; Garrahan 1988). These pins can be used to measure MC at any depth chosen because the pins are electrically insulated except for the tips.

Measurements are most commonly taken at ¼-in. (6-mm) tip depth. In this study, MC measurements were taken at two depths on the lower OSB near the wetting system so the moisture gradient could be determined. The wood MC pins were installed in combination with a temperature sensor in all locations. To correct the MC readings for temperature effects, a hole was drilled to the same depth as the MC pins and a temperature sensor was installed inside.

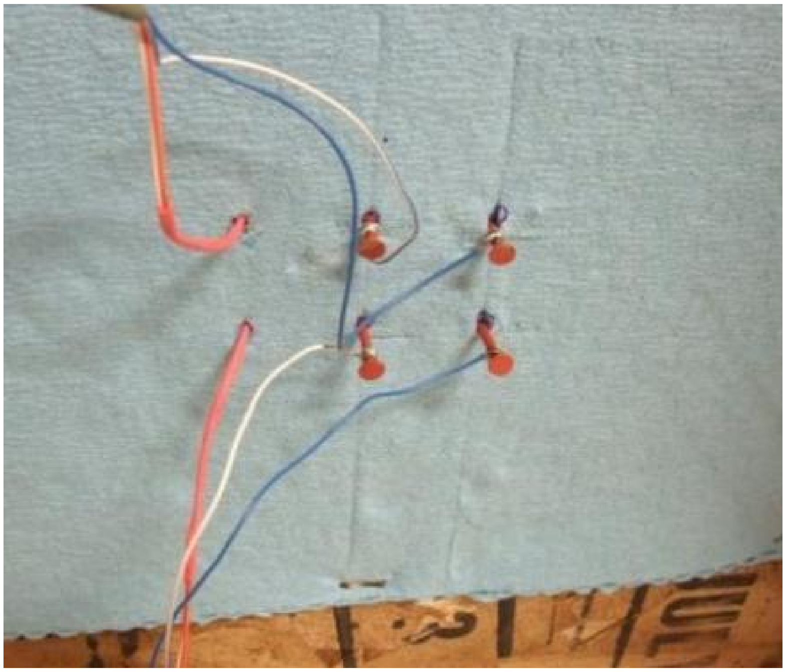
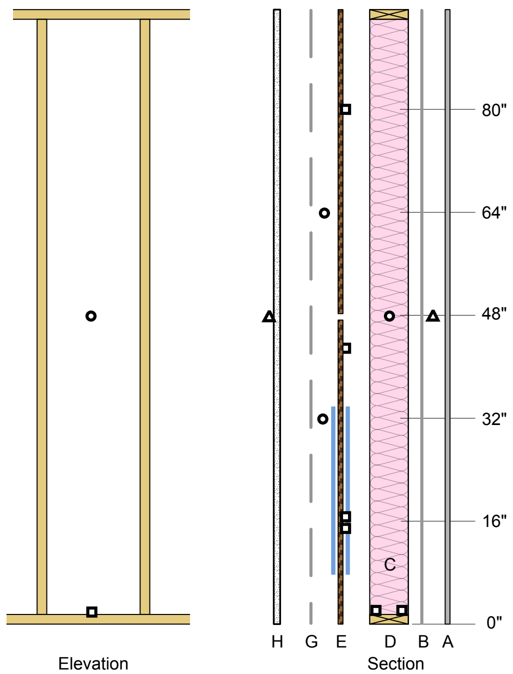


Figure 28. MC pins installed in plywood sheathing through the wetting system

RH sensors were installed in the middle of each stud cavity, and in the drainage space of each wall. The RH sensor was always installed in combination with a temperature sensor, both of which are protected by a vapor permeable, water resistant cover (see Figure 29). RH and temperature sensors were installed at the midpoint of the stud space, between the drywall and the sheathing, as well as in some drainage cavities.

Figure 29. RH and temperature sensor installed in a stud bay (with MC pins installed below)



Assembly

Layer	Function	Description
A	Interior Finish	gypsum wall board
B	Vapor Control	poly
C	Studspace	fiberglass batt
D	Framing	2x6
E	Sheathing	½" OSB
F	Sheathing Membrane	#15 felt
G	Drainage Gap	none
H	Cladding	stucco

Sensor Package

Layer	Code	Location
A	taem	Interior finish, exterior face, 48"
C	r/tcnm	Studspace, interstitial, 48"
D	m/tdeb	Framing, exterior edge, bottom plate
D	m/tdib	Framing, interior edge, bottom plate
E	m/teem	Sheathing, exterior, 16"
E	m/teim	Sheathing, interior, 16"
E	m/tenm	Sheathing, interstitial, 48"
E	m/tenm	Sheathing, interstitial, 80"
G	r/tgnw	Drainage space, interstitial, 32"
G	r/tgne	Drainage space, interstitial, 64"
H	them	Cladding, exterior surface, 48"

- ○ Relative Humidity and Temperature Sensor Package
- □ Moisture Content Pins and Temperature Sensor Package
- △ Temperature Sensor
- ⧅ Moisture Content Wafer and Temperature Sensor Package
- 〓 Moisture Content Pins

Figure 30. Typical wall construction and sensor configuration

One of the most significant advantages to using a test hut with removable/replaceable walls for analysis compared to instrumenting walls in existing buildings is that the experimenter can deliberately and easily stress the walls with high moisture loads, either in terms of vapor (e.g., ≥50% interior RH) or liquid water (e.g., intentional wetting systems). In most cases, building owners are not interested in participating in research conducted on their enclosure walls by adding moisture. In addition, it is often difficult to determine the performance of a wall system without stressing the moisture tolerances of a wall to determine the comparative risk of certain construction techniques.

3.3.3 Observations and Data Analysis

This analysis contained is limited to observations and data collected during the monitoring period (December 17, 2009, to November 3, 2011) for the exterior insulated Wall A (refer to Figure 25) and a traditional stucco Wall B (directly applied to building paper over wood sheathing; see Figure 26). Four analysis criteria were used to compare the performance of the test walls:

- Sheathing wood MC measurements under normal operating conditions
- Sheathing wood MC measurements during wetting and drying from an interior wetting event
- Sheathing wood MC measurements during wetting and drying from an exterior wetting event
- Dew point analysis and potential air leakage condensation at the condensation plane (interior surface of the exterior sheathing)
- Qualitative visual observations during deconstruction.

For this report, the focus was on the measured MC of the sheathing at the four measurement locations. The four sheathing moisture measurements are as follows:

- 16 in. from the bottom of the bottom plate at the interior edge of the sheathing
- 16 in. from the bottom of the bottom plate at the exterior edge of the sheathing
- 48 in. from the bottom of the bottom plate at the center of the sheathing
- 80 in. from the bottom of the bottom plate at the center of the sheathing

The two MC sensors at 16 in. were used to evaluate the performance after wetting events because they were installed in the sheathing in direct contact with the wetting system (Figure 28). The MC sensors at 48 in. and 80 in. from the bottom plate were not affected by either the interior or exterior wetting events, and are a good indication of how the sheathing MC is affected by the construction assembly under normal operating conditions.

Sheathing moisture is used as the performance criterion because this is the first location where vapor diffusion condensation would occur in a cold climate during the heating season. In the case of these test walls, the most significant moisture risks were at the locations of the wetting systems, allowing comparison of the sheathing moisture performance under significant moisture stresses. MCs of the sheathing are used as a comparison instead of pass/fail criteria for the wall assembly. Generally, under normal conditions, the following criteria are used to assess the risk of various test wall assemblies:

- Peak sheathing with an MC < 20%, no mold growth, very little risk
- Peak sheathing with an MC of 20%–28%, potential for eventual mold growth, depending on frequency and length of wetting and temperatures during wetting. This design can be successful but conservative assessments usually require corrective action to be taken.
- Peak sheathing with an MC >28%, moisture-related problems are expected and this design is not recommended.

Predicted wood MCs of wood-based sheathing are generally assessed with respect to relative risk instead of judged on pass/fail criteria. The predicted MC should be kept in context and good scientific judgment is required to determine the moisture risk to the sheathing. For example, elevated wood MCs in the cold winter months when the wood substrate is on the cold side of the assembly are much safer from a mold growth perspective than similar MCs in the summer, when the temperatures are in the correct range for optimal mold growth. Also, high MCs for a short period followed by drying are not necessarily risky, because wood-framed structures are able to manage high MCs for short periods without exceeding the safe storage capacity of the assembly.

The safe storage capacity is the amount of moisture an assembly is able to manage without suffering any moisture-related issues. The baseline wood MC is a factor in the safe storage capacity because the lower the wood MC is during normal operation (without wetting events), the more moisture the wood can handle before reaching any durability risks. If the measured wood MC is consistently higher, even if there are no moisture durability risks, there is less moisture buffering capacity in the wood before reaching moisture-related durability risk levels.

3.3.4 Comparison of Walls A and B

Comparing the overall MC measurements at the lower measurement location (both interior and exterior) indicates that the MC was higher on Wall B relative to Wall A for the same sensor (interior edge compared to interior edge, and exterior edge compared to exterior edge) for the entire monitoring period (all four orientations on Figure 31, Figure 33, Figure 35, and Figure 37). The only exception is on North Wall B, where the interior edge MC sensor did not appear to respond to the first two wetting events. The reason for this is unknown.

Even though the research focused on exterior wetting events, one interior wetting event was conducted to compare the moisture-related durability performance of the two walls. Following the intentional interior wetting event (January 2011), Wall A dried more quickly in all cases than Wall B. This is because there is very little drying potential to the exterior in both Wall B and Wall A. Wall B was constructed with Class I polyethylene vapor control (<0.1 perms) on the interior, so drying to the interior is not possible. Wall A has a Class III interior vapor control layer (<1 perms < 10, latex paint on the drywall) and is thus able to dry to the interior. Table 9 shows the amount of time, in days, following the interior wetting event until the measured MC was less than 20%. The next wetting event was May 5, 2011, so if the measured sheathing MC was still above 20% MC at that time, a value of >106 days was used.

Table 9. Comparison of Drying Rates for Wall A and Wall B Following Interior Wetting Event in January 2011

	Wall B (Direct Applied Stucco)	Wall A (XPS Exterior Insulation)
North	>106 days	68 days
East	>106 days	53 days
South	68 days	29 days
West	95 days	47 days

At the midheight and upper MC measurement locations (all four orientations on Figure 32, Figure 34, Figure 36 and Figure 38), which are largely unaffected by the intentional wetting events, the MC measurements on Wall A on all orientations does not exceed 11%, and is always less than Wall B. Wall B measurements do not exceed 17%, which is also considered a safe level of moisture in the OSB sheathing.

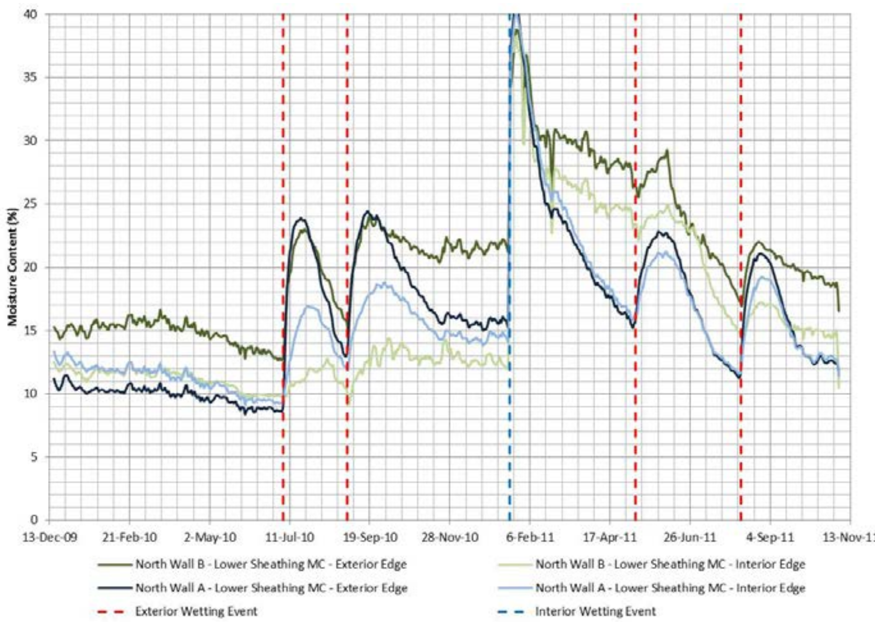


Figure 31. Lower OSB sheathing measured MC comparison between north Wall B (direct applied stucco) and north Wall A (exterior insulation)

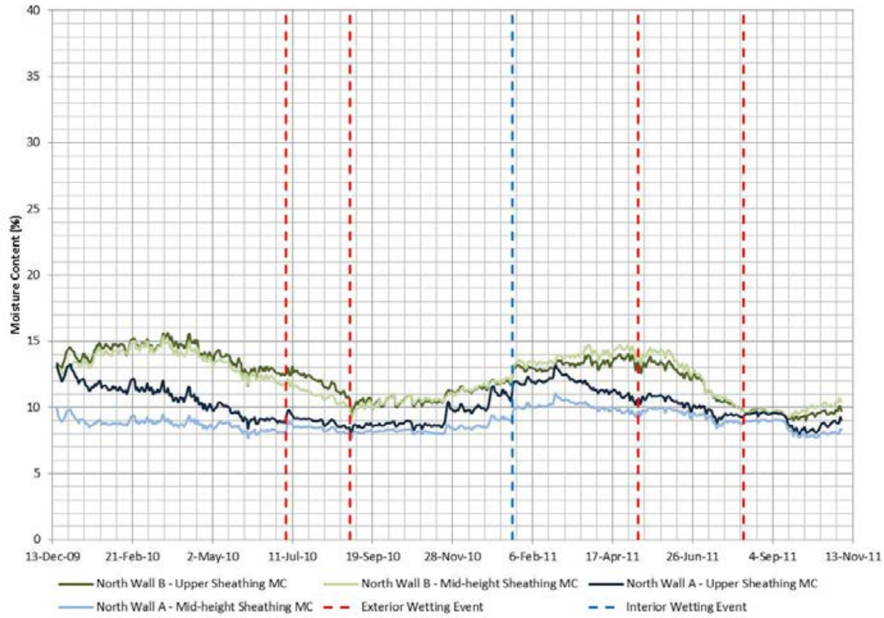


Figure 32. Middle and upper OSB sheathing measured MC comparison between north Wall B (direct applied stucco), and north Wall A (exterior insulation)

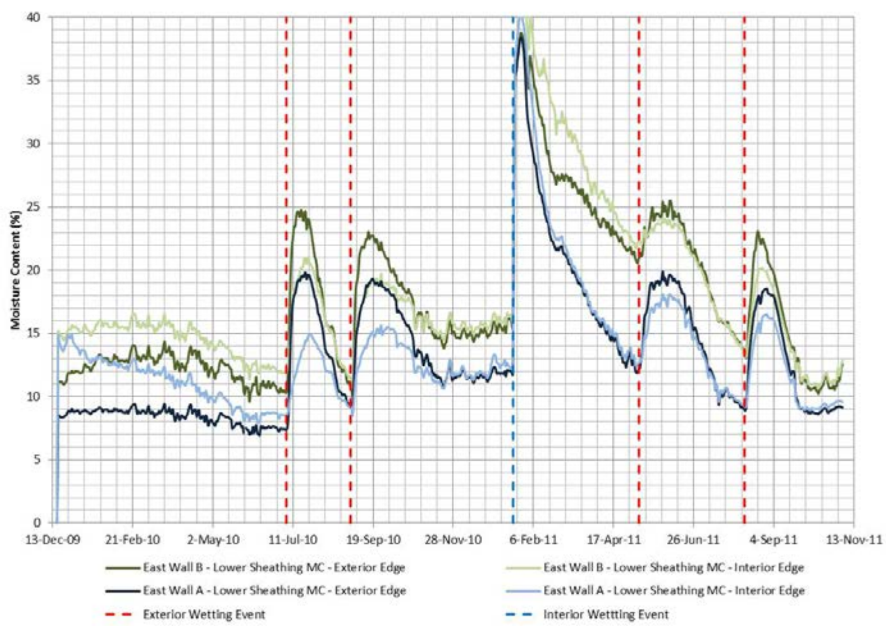


Figure 33. East Wall B (direct applied stucco) and east Wall A (insulating sheathing) lower OSB sheathing measured MC

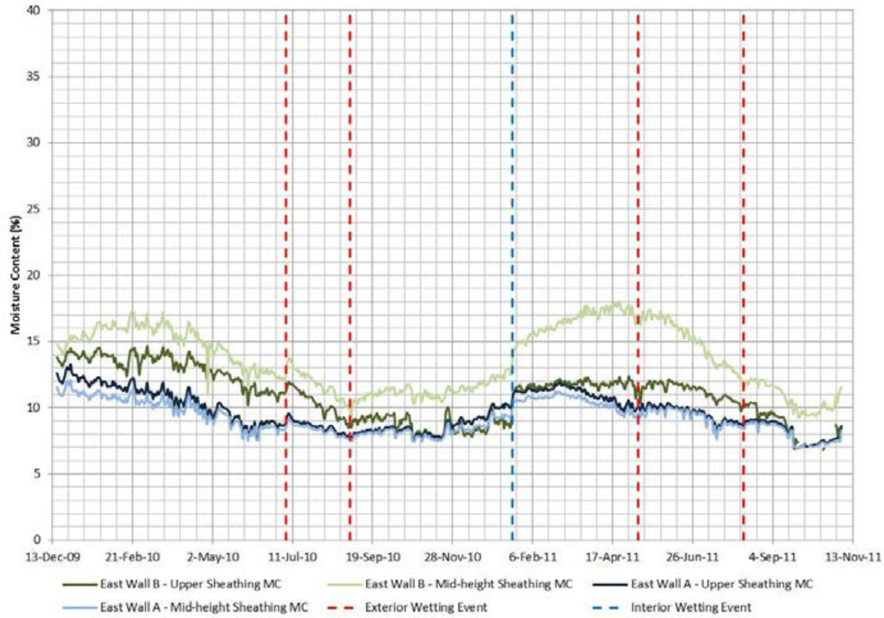


Figure 34. East Wall B (direct applied stucco) and east Wall A (insulating sheathing) middle and upper OSB sheathing measured MC

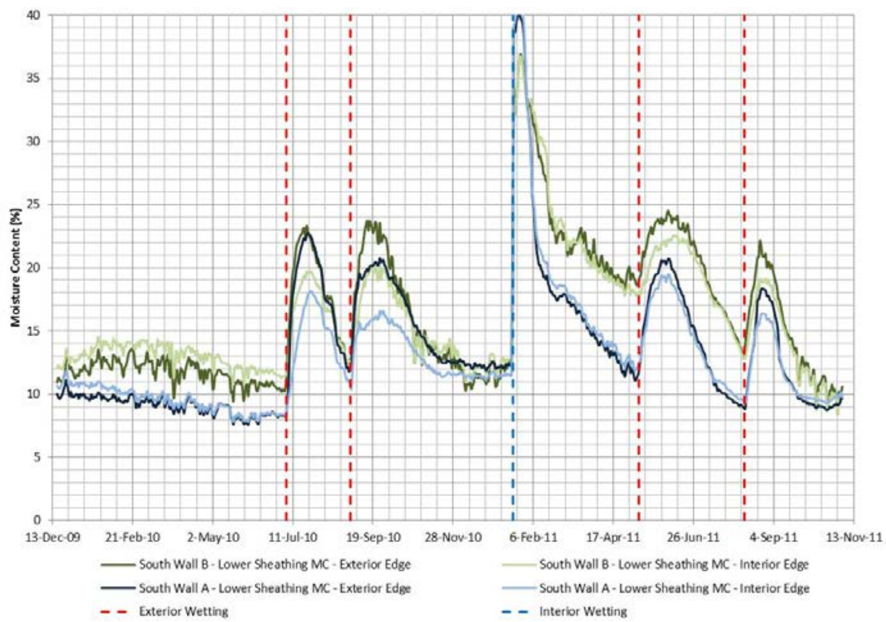


Figure 35. South Wall B (direct applied stucco) and south Wall A (exterior insulation) lower OSB sheathing measured MC

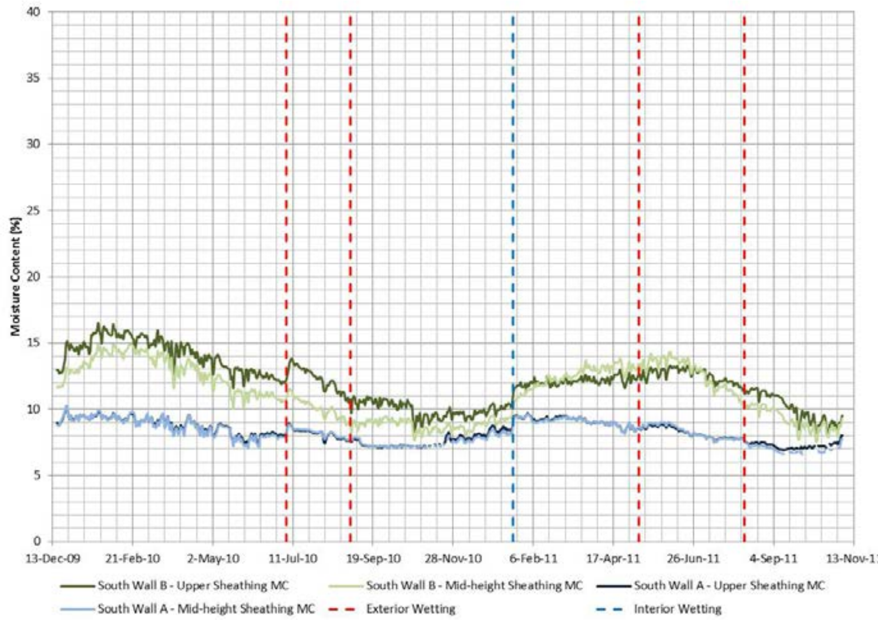


Figure 36. South Wall B (direct applied stucco) and south Wall A (exterior insulation) middle and upper OSB sheathing measured MC

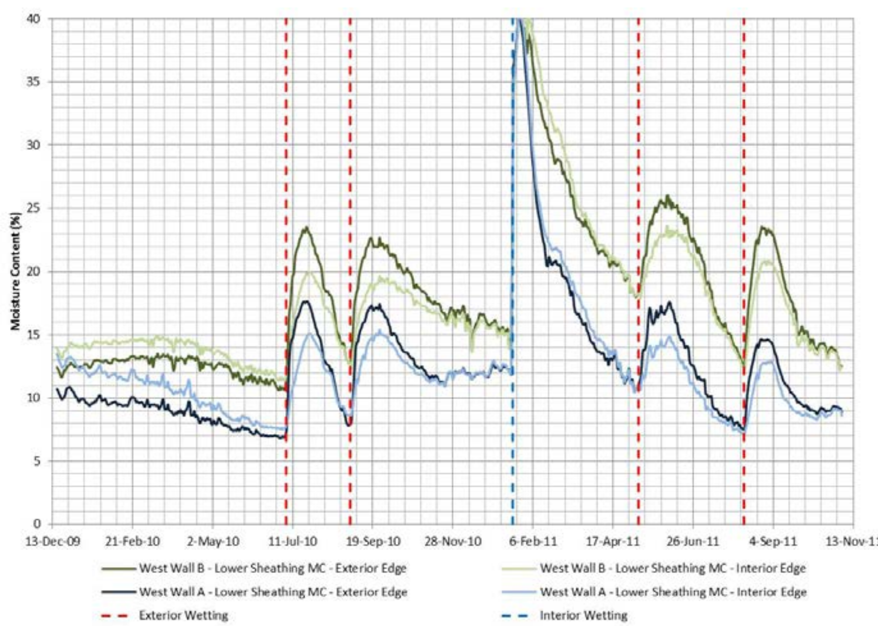


Figure 37. West Wall B and south Wall A lower OSB sheathing measured MC comparing exterior insulation

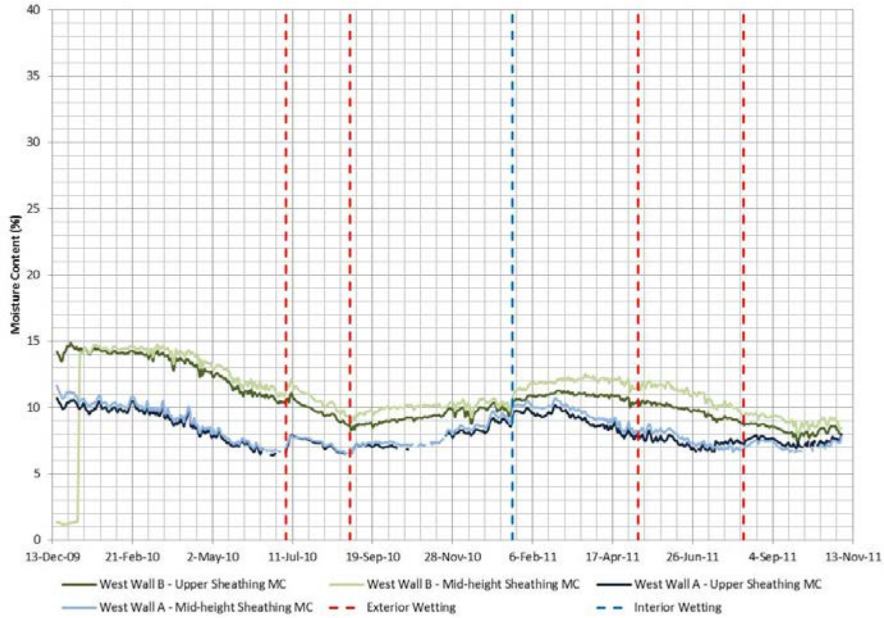


Figure 38. West Wall B and south Wall A middle and upper OSB sheathing measured MC comparing exterior insulation

3.3.4.1 Comparison of Sheathing Temperatures and Interior Dew Point

The measured and calculated performance improvements to the building enclosure using exterior insulation are not new ideas. In 1964, Hutcheon demonstrated how the temperature gradients across a masonry wall changed when the insulation was moved from the interior of the structure to the exterior of the structure (Hutcheon 1964). He showed that condensation issues at 35% interior RH were solved by moving the insulation to the exterior. These same principles have been more recently illustrated by Straube using more current construction practices (Straube 2011).

The analysis in this report discusses the potential for interior air leakage condensation based on the measured interior air dew point and the measured sheathing temperature. This analysis is a measure of moisture durability **risk**, not actual moisture durability. This is because it is assumed that the vapor control of the enclosure is adequate and condensation will occur only if there is a path for air leakage from the interior to the sheathing and the sheathing is below the dew point of the air.

Field experience with airtightness and blower door testing has demonstrated that the enclosure will always have some air leaks, and their location and size depend on the type and quality of construction. It is not uncommon to find air leakage pathways through electrical outlets, switches, and other interior finish penetrations. This means that with air permeable cavity filled insulation, which is the most commonly used, evidence of moisture condensation on the interior surface of the exterior OSB behind penetrations can be found. Figure 39 shows an example of an air leakage condensation problem behind an electrical outlet in a 6-year-old house with an interior poly vapor barrier. The OSB and framing are stained and dark with surface mold and the nails are corroding.

Figure 39. Example of air leakage condensation durability issues

The condensation potential is directly related to the interior conditions and the sheathing temperature. Generally speaking, dry air has less moisture available to condense so there will be less concern for lower humidity interior conditions. For this analysis, two time periods were used over the colder winter months, and these two periods are shown on both the temperature (Figure 40) and RH (Figure 41) graphs. The interior temperature was approximately 20°C for the entirety of both comparison periods, with some small variations. The interior RH was set to 40% for the winter months and maintained with a humidifier controlled by the data acquisition system.

The temperature and RH are used to calculate the hourly dew point of the interior air for comparison to the sheathing temperature. The temperature of the sheathing is taken at the midheight midthickness of the sheathing and not at the interior surface, but the difference in temperature is negligible over half the thickness of the OSB.

The comparison results of this analysis are summarized numerically in Table 10 for both comparison time periods, and graphically in Figure 42 and Figure 43 for the individual analysis time periods. The results show a significant decrease in the number of measured potential hours of air leakage condensation when 38 mm (1½ in.) of XPS is installed as exterior insulation.

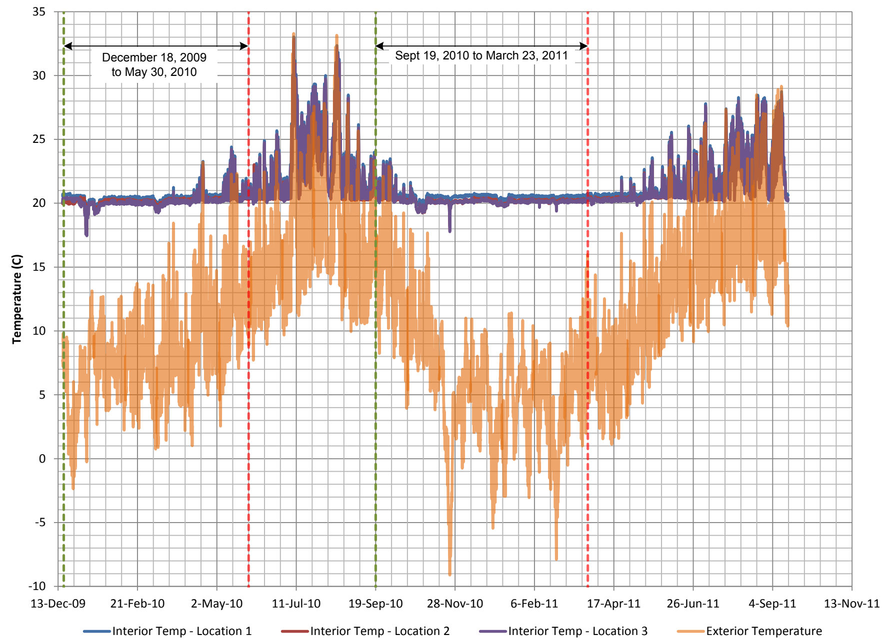


Figure 40. Measured interior and ambient temperatures

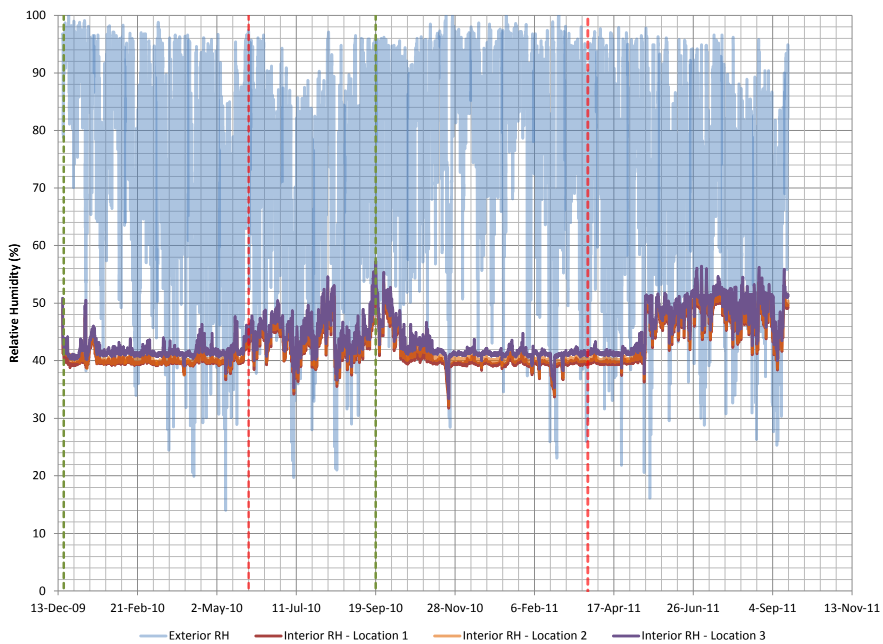


Figure 41. Measured interior and ambient RH

Table 10. Number of Hours of Potential Air Leakage Condensation Based on the Interior Dew Point and Sheathing[a]

	Potential Hours of Condensation Between December 18, 2009, and May 30, 2010 (3,936 Total hours)	Potential Hours of Condensation Between September 19, 2010, and March 23, 2011 (4,441 Total hours)
North Wall B	1,252	2,417
North Wall A (XPS)	91	551
East Wall B	1,165	2,293
East Wall A (XPS)	72	478
South Wall B	1,050	1,980
South Wall A (XPS)	51	320
West Wall B	741	2,011
West Wall A (XPS)	94	518

[a] Temperature measure of moisture-related durability risk, not moisture-related durability

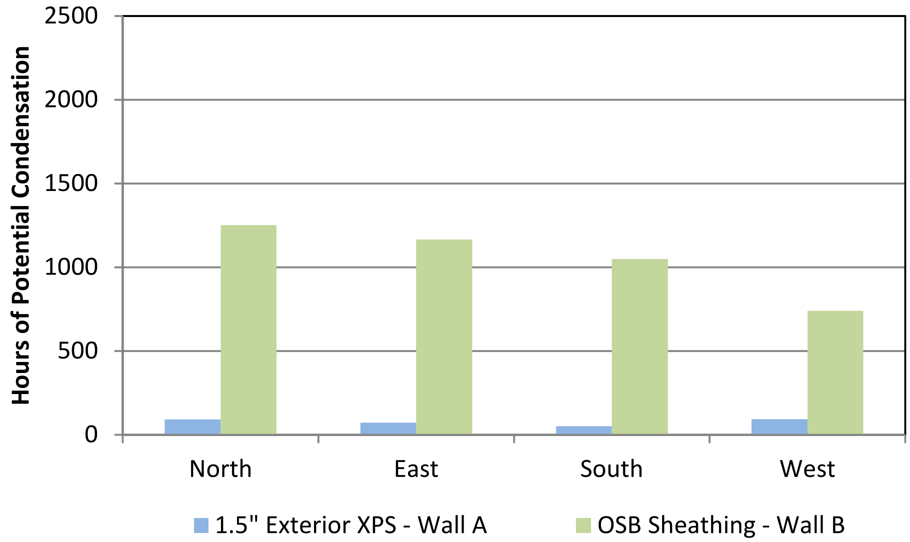


Figure 42. Comparison of the hours of potential condensation between Wall B and Wall A from December 18, 2009, to May 30, 2010, using measured interior dew point and sheathing temperature

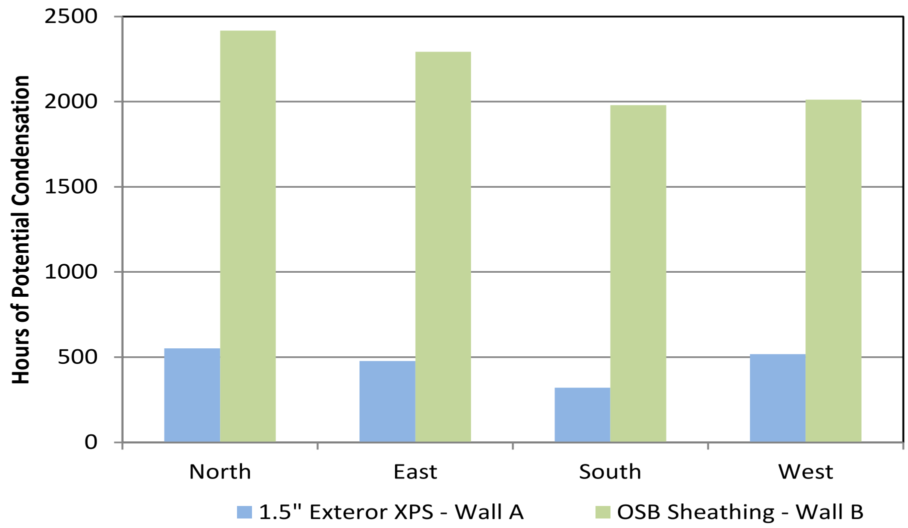


Figure 43. Comparison of the hours of potential condensation between Wall B and Wall A from September 19, 2010, to March 23, 2011, using measured interior dew point and sheathing temperature

The degree of potential risk in terms of vapor diffusion and air leakage moisture condensation is proportional to the length of time that the sheathing temperature is continuously below the dew point without any drying potential, and the magnitude of the difference between the dew point and the sheathing temperature. This means that a sheathing temperature 10° below the dew point will condense more water than a sheathing temperature 2° below the dew point, all other factors being equal. If the temperature of the sheathing is below freezing, condensation will occur as frost or ice, and then melt when the sheathing temperature increases.

Figure 44 and Figure 45 show the measured interior dew point and simultaneous measured sheathing temperature for walls A and B for both analysis time periods on the north orientation. The green line is the measured sheathing temperature of Wall A, and the blue line is the measured sheathing temperature of Wall B, depending on the comparison graph.

The black line is the measured interior dew point. When the sheathing temperature falls below the dew point temperature, condensation will occur if the interior air contacts the interior surface of the sheathing.

These two figures show that the sheathing temperature for Wall B was much lower than Wall A for extended periods of time, which correlates with the numerical results of Table 10. This means that even with 1.5 in. of exterior XPS insulation, there is still a potential for a small amount of condensation, but significantly less than most building code minimum approved wall systems. If condensation does occur in Wall A, it will be able to dry much more quickly to the interior because latex paint is the only form of vapor control, compared to Wall B with a Class I polyethylene vapor barrier.

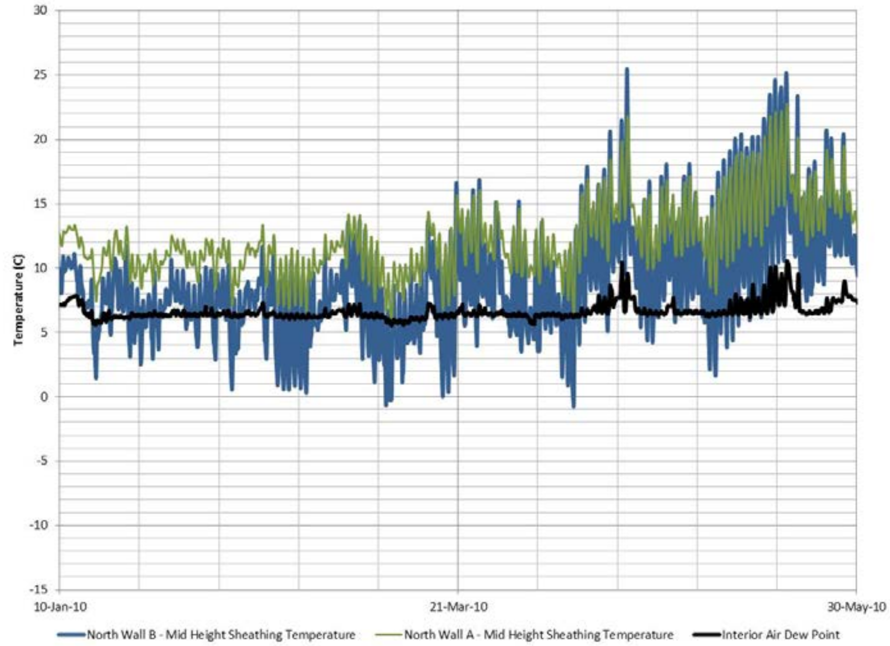


Figure 44. Comparison of condensation potential between north walls A and B, January to May 2010

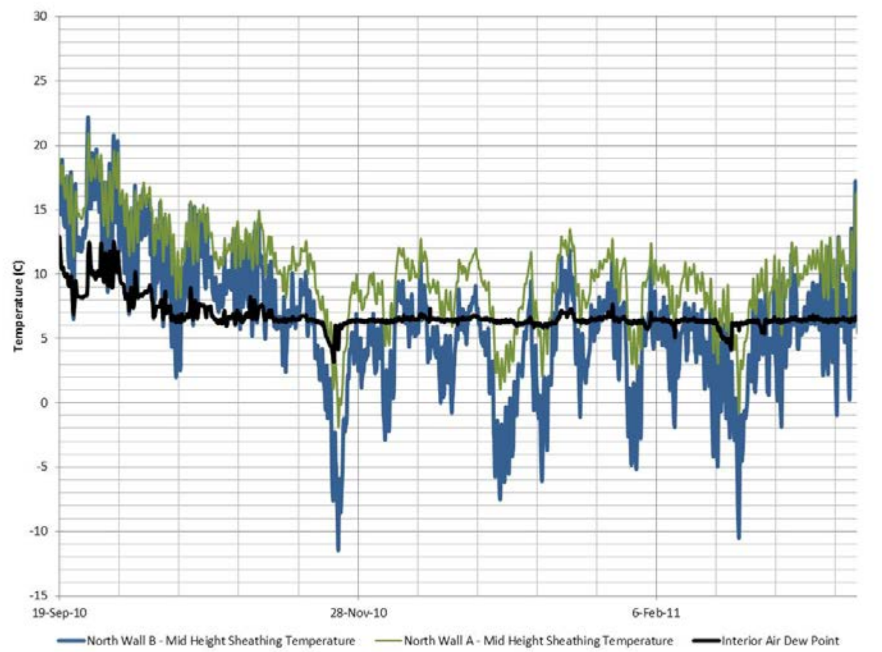


Figure 45. Comparison of condensation potential between north walls A and B, September to March 2010

3.3.5 Test Wall Deconstruction

The test walls were deconstructed on November 2 and 3, 2011. The deconstruction was conducted carefully and systematically so that each component of each wall system could be photographed, examined, and compared. Disassembly was critical because inspecting all aspects of all layers of the test walls was very informative. It was important to see if the visual observations correlated to and validated the measured results (Lstiburek and Parthenon 2011).

With this qualitative comparison analysis it is important to keep in mind the boundary conditions that the walls were subjected to, both on the interior and exterior. Figure 40 and Figure 41 show the interior and exterior temperature and RH, and Table 8 shows the amount of water added to the surface of the sheathing.

The testing was conducted for approximately 2 years, so the conditions required extrapolation to determine what the OSB might look like after many years in service.

On all orientations, the exterior of the OSB on Wall A looked like new except for the immediate vicinity of the wetting apparatus where water was held between the XPS and sheathing directly against the OSB. The exterior of the sheathing on Wall B on all four orientations was considerably darker and stained over a much greater area. These observations show that measurements of lower MCs in Wall A correspond to a much cleaner and newer looking OSB sheathing on all four orientations.

Photos of the north orientation are shown in Figure 46 and Figure 47 from two different directions. Photos of the east and south orientation are shown in Figure 48 and Figure 49, respectively. Unlike the other orientations, there was no photo taken of the entire west elevation immediately following deconstruction.

Figure 46. Exterior OSB sheathing on the north orientation immediately following deconstruction

Figure 47. Exterior OSB sheathing on the north orientation immediately following deconstruction (photo taken from the opposite direction of Figure 46)

Figure 48. Exterior OSB sheathing on the east orientation immediately following deconstruction

Figure 49. Exterior OSB sheathing on the south orientation immediately following deconstruction

3.3.6 Summary

The following list is a point form summary of the conclusions of full scale wall testing of an exterior insulated wall assembly compared side-by-side with a more traditional wall assembly without exterior insulation in a DOE 4C climate zone typical of the Pacific Northwest. These conclusions are based on measured data over the test period as well as qualititave observations during the deconstruction that occurred on November 2, and 3, 2011.

- MC monitoring of the midheight and upper sheathing showed that the sheathing MC of Wall B was always higher than Wall A, but did not exceed criteria for moisture-related durability concerns.
- Following the interior wetting event, Wall A dried more quickly to safe levels than Wall B, because the vapor control layer on Wall A was Class III and the vapor control layer on Wall B was Class I, which eliminated drying to the interior.
- Following the exterior wetting events, the drying rates were relatively similar between Walls A and B. Generally the MC was higher on Wall B, so even though the drying rates were similar, the MC of the sheathing on Wall B remained elevated compared to Wall A.
- In dew point analysis, Wall B had significantly higher moisture durability risks with respect to interior air leakage condensation than Wall A. This is because the exterior insulation in Wall A keeps the sheathing at a higher temperature, reducing the number of hours that the sheathing is below the interior air dew point. This is not a durability problem unless interior air reaches the surface of the sheathing.
- Observations from the wall deconstruction showed that the exterior surface of the OSB for Wall B was quite stained behind and around the wetting apparatus. There was also

staining on the upper portion of the OSB on Wall B, as well as a general overall darker appearance to the entire OSB sheet compared to Wall A. The OSB on Wall A looked like new except directly behind and under the wetting apparatus.

Data analysis and wall deconstruction demonstrated that there were no moisture-related durability concerns of the wood structural sheathing in climate zone 4C when 1.5 in. of exterior XPS insulation was installed to the exterior of OSB structural sheathing and Tyvek DrainWrap. Water was intentionally placed in direct contact with the exterior surface of the sheathing behind the low vapor permeance XPS exterior insulation four times through the monitoring period, no moisture-related durability concerns were measured or observed. The overall performance of the exterior insulated wall was better under all comparison criteria than that of the direct applied stucco wall.

3.4 Conclusions

Four research questions were presented at the start of this report to help determine any moisture-related durability risks of adding drained exterior insulation to the existing sheathing in an energy retrofit of an existing home.

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

Laboratory tests were conducted on a drainage balance of drained exterior insulation on a stud wall, using both smooth and corrugated plastic housewrap. The range of water amounts stored in these drainage tests was 19 g/m^2 to 36 g/m^2 when the entire surface area of the drainage cavity was wetted. This amount of water in the drainage cavity after a large wetting event proved insignificant to the moisture durability of the wall system.

Repeated wettings of the drainage cavity (6–8 times) did increase the overall mass of the wall and the MC of the sheathing (less than 2%). This shows that it is unlikely for any amount of water that is stored in the drainage cavity to result in moisture durability risks of the sheathing, assuming there are no other simultaneous moisture sources such as air leakage condensation on the sheathing.

Even when water was directly applied to the sheathing (simulating a deficiency in the sheathing membrane) during field testing, the exterior insulated wall performed better than the direct applied stucco wall in side-by-side comparisons on all four orientations in climate zone 4C.

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

During hygric redistribution testing in the laboratory, water was injected into storage media in the drainage cavity to simulate water trapped in the drainage cavity (not in direct contact with the plywood sheathing). This water appeared to mostly diffuse across the sheathing membrane and adsorb into the plywood sheathing. The RH in the stud space increased during wetting. Mathematical analysis also confirmed that most of the moisture diffused into the wall relative to redistribution in the drainage cavity. After injecting 13 oz of water over a week, there was no risk of any moisture-related durability issues.

During field testing when water was trapped against the sheathing, the water was able to dry to the interior because there was no Class I vapor control layer on the interior, resulting in a more quickly drying plywood sheathing and overall lower sheathing wood MC than the comparison standard stucco construction wall.

3. Why is there a discrepancy between the basic hygrothermal analysis of vapor impermeable, relatively low R-value exterior insulations and field performance?

For the purposes of this report and analysis, the BSC team assumed that the discrepancy in field performance and hygrothermal analysis was based on the fact that hygrothermal analysis does not take into account the effects of drainage that occurs when any moisture condenses on the interior surface of the exterior insulation. Further study in this might be conducted in the future.

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

Initial testing has shown that even with a flat plastic housewrap with no extra drainage gap, there is little risk of any moisture-related durability issues from water being drained through or trapped in the cavity. That being said, it is always beneficial to design the system with a factor of safety, assuming that there will be unanticipated design deficiencies. Adding more width to the gap will ensure that water drains easily and some ventilation will occur, but that could also lead to decreasing the energy gains of exterior insulation. Also, it is good practice to drain penetrations to the front of the insulation to minimize the water draining behind the insulation.

3.5 Future Work

Within the Building America Program, there are currently no plans or budget to expand on the knowledge and information included in this report. The BSC team, however, feels that a greater understanding of the potential moisture-related durabiltiy issues could be gained through further testing in the following areas:

- With all tests, a greater moisture load should be added to see at what point the wall will experience moisture-related durabilty issues. This will help constrain the upper bounds of the moisture durability for the wall system. It could be argued that the added water used in this testing program is not representative of moisture loads in the field in some cases. It is known, though, that the amount of water that enters a drainage cavity is related to many variables, including amount of driving rain, enclosure moisture management details, and the quality of workmanship.
- Other sheathing membranes and drainage mats could be tested to improve the understanding of how various wall system compontents affect the moisture-related durability of wall systems. Other test variables such as temperature gradients across the wall or solar heating of the cladding could also be added to more closely simulate field conditions.
- Thermal losses for drained exterior insulation should be measured and correlated to the size of the drainage gap to determine if there is any measurable effect on performance.

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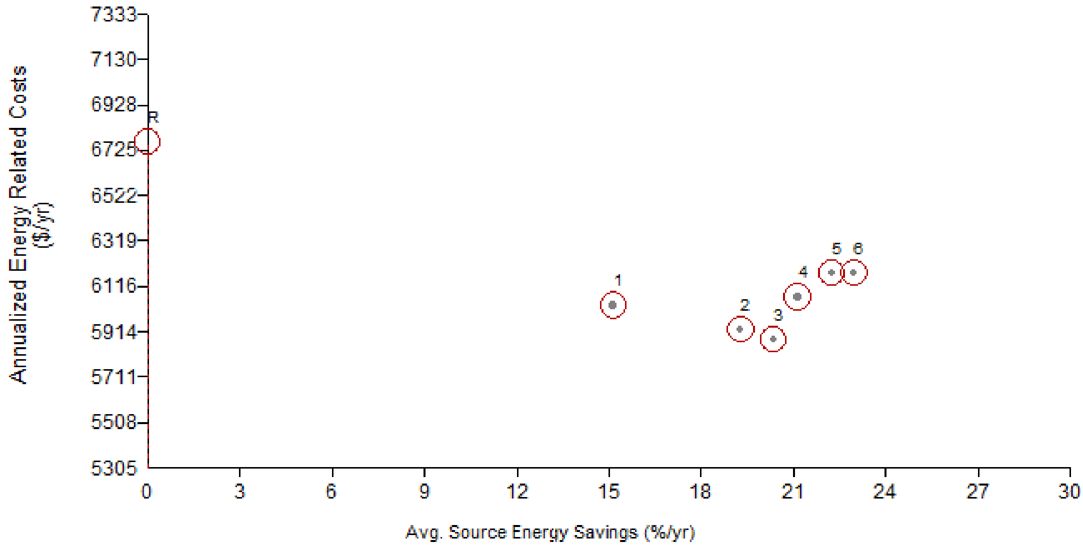
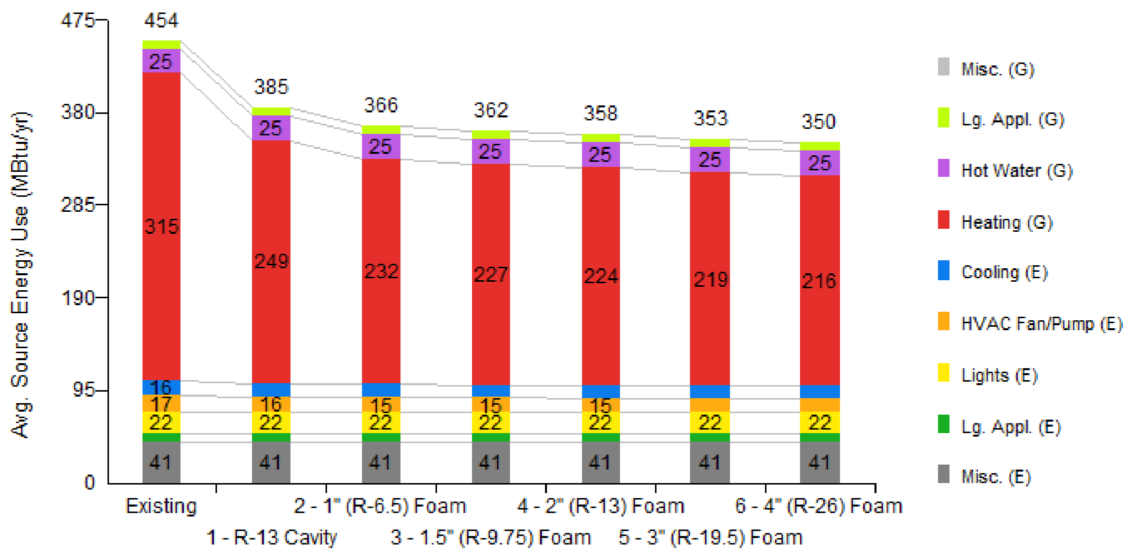
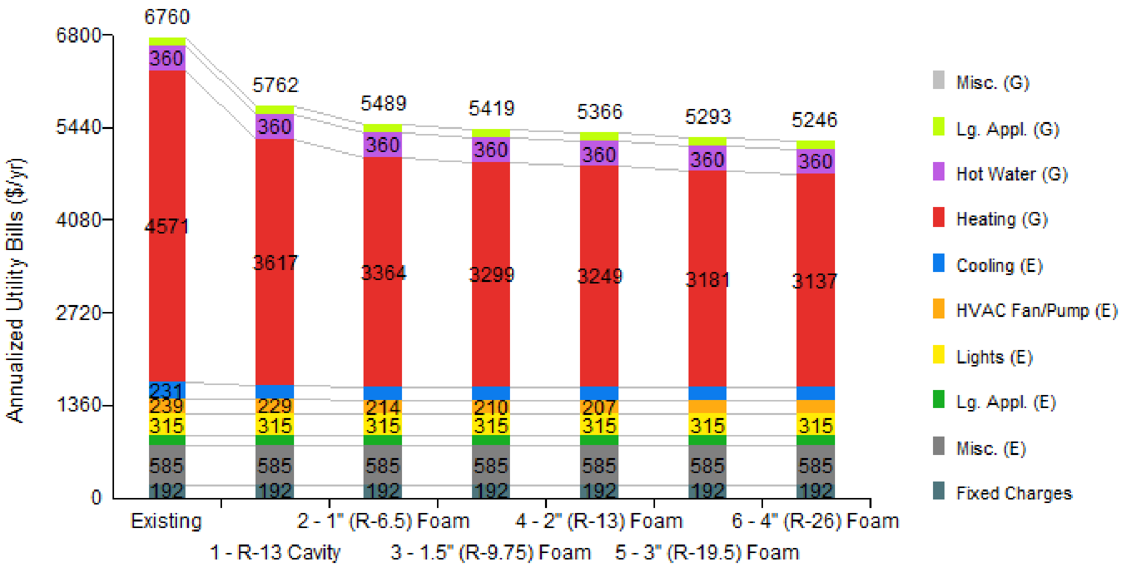
Appendix: BEopt Output Graphs

Boston



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1360
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6760
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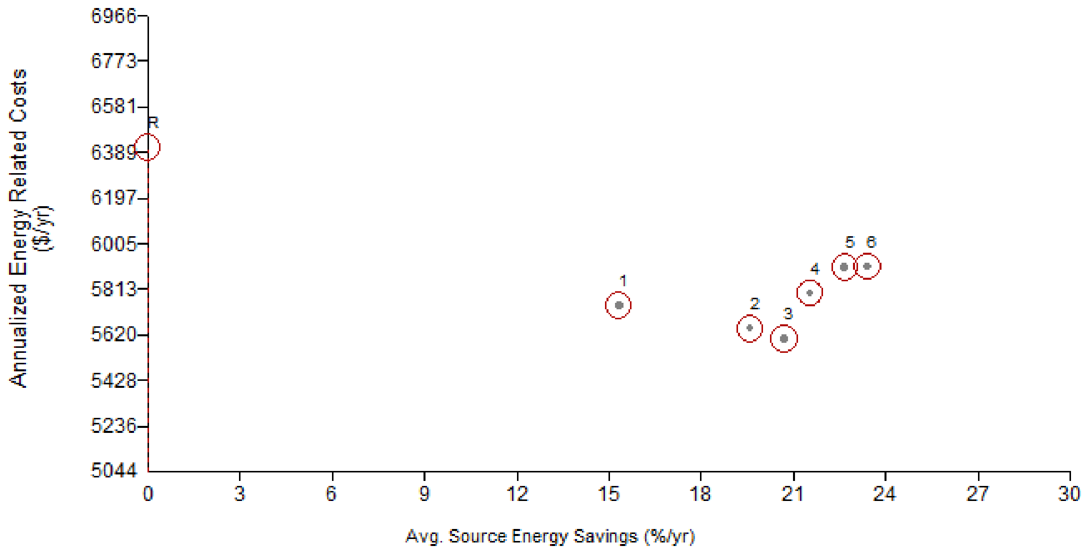
5419
5366
5293
5246
360
4571
3617
3364
3299
3249
3181
3137
231
239
229
214
210
207
315
585
192
Existing
1 - R-13 Cavity
2 - 1" (R-6.5) Foam
3 - 1.5" (R-9.75) Foam
4 - 2" (R-13) Foam
5 - 3" (R-19.5) Foam
6 - 4" (R-26) Foam
Misc. (G)
Lg. Appl. (G)
Hot Water (G)
Heating (G)
Cooling (E)
HVAC Fan/Pump (E)
Lights (E)
Lg. Appl. (E)
Misc. (E)
Fixed Charges

Duluth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2
3
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6
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9
12
15
18
21
24
27
30
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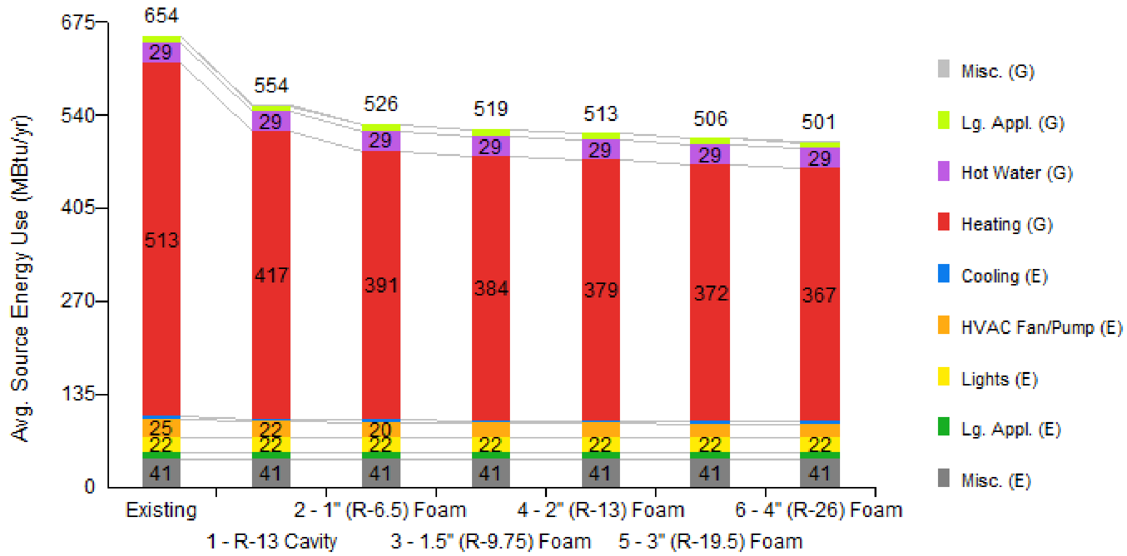
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135
0
654
554
526
519
513
506
501
29
513
417
391
384
379
372
367
25
22
20
41
Existing
1 - R-13 Cavity
2 - 1" (R-6.5) Foam
3 - 1.5" (R-9.75) Foam
4 - 2" (R-13) Foam
5 - 3" (R-19.5) Foam
6 - 4" (R-26) Foam
Misc. (G)
Lg. Appl. (G)
Hot Water (G)
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Cooling (E)
HVAC Fan/Pump (E)
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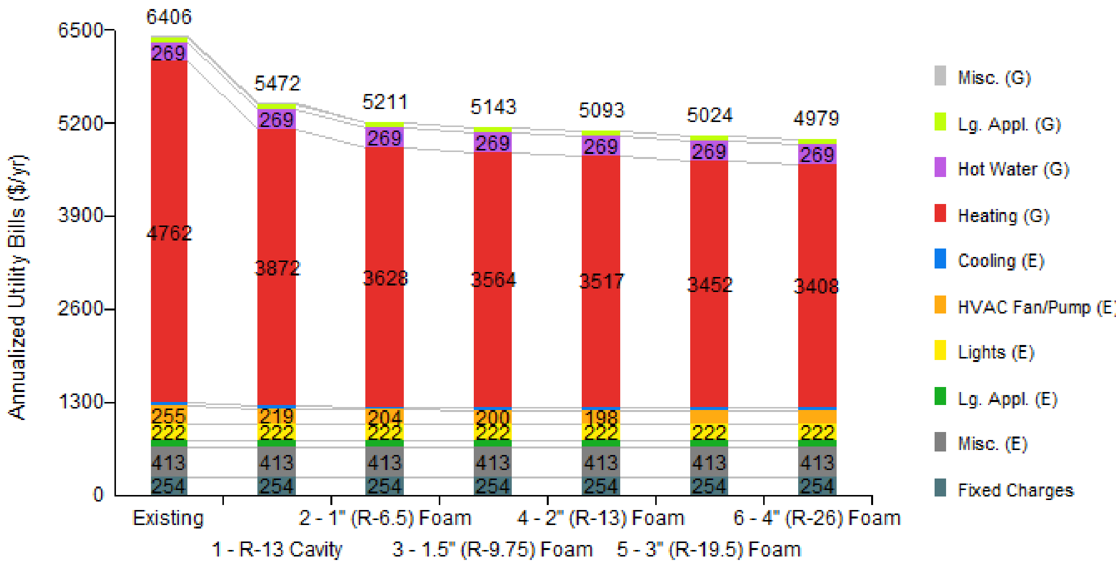
Lg. Appl. (E)
Misc. (E)



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5143
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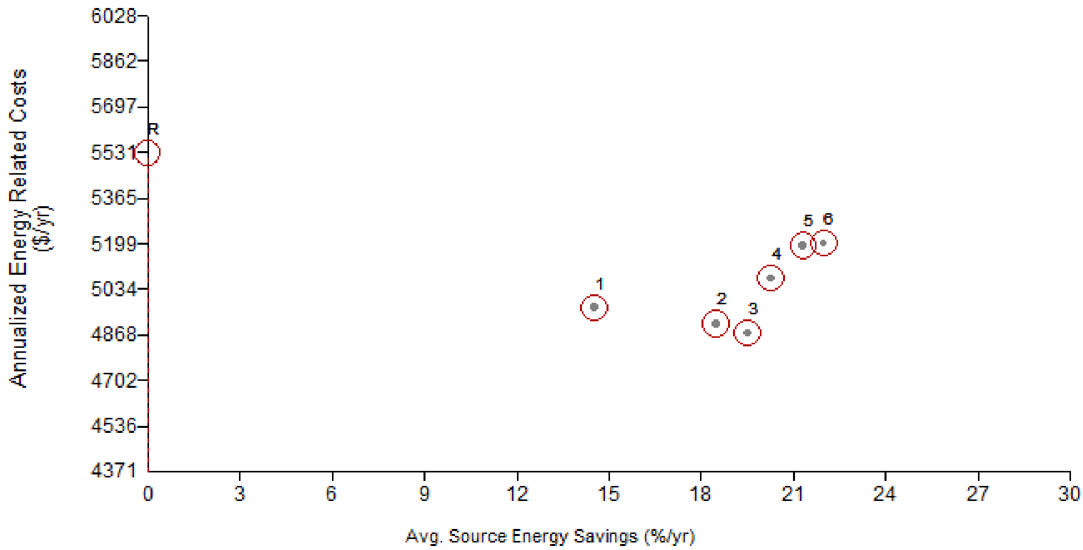
5024
4979
269
4762
3872
3628
3564
3517
3452
3408
255
219
204
200
198
222
413
254
Existing
1 - R-13 Cavity
2 - 1" (R-6.5) Foam
3 - 1.5" (R-9.75) Foam
4 - 2" (R-13) Foam
5 - 3" (R-19.5) Foam
6 - 4" (R-26) Foam
Misc. (G)
Lg. Appl. (G)
Hot Water (G)
Heating (G)
Cooling (E)
HVAC Fan/Pump (E)
Lights (E)
Lg. Appl. (E)
Misc. (E)
Fixed Charges

Kansas City



Annualized Energy Related Costs ($/yr)
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4868
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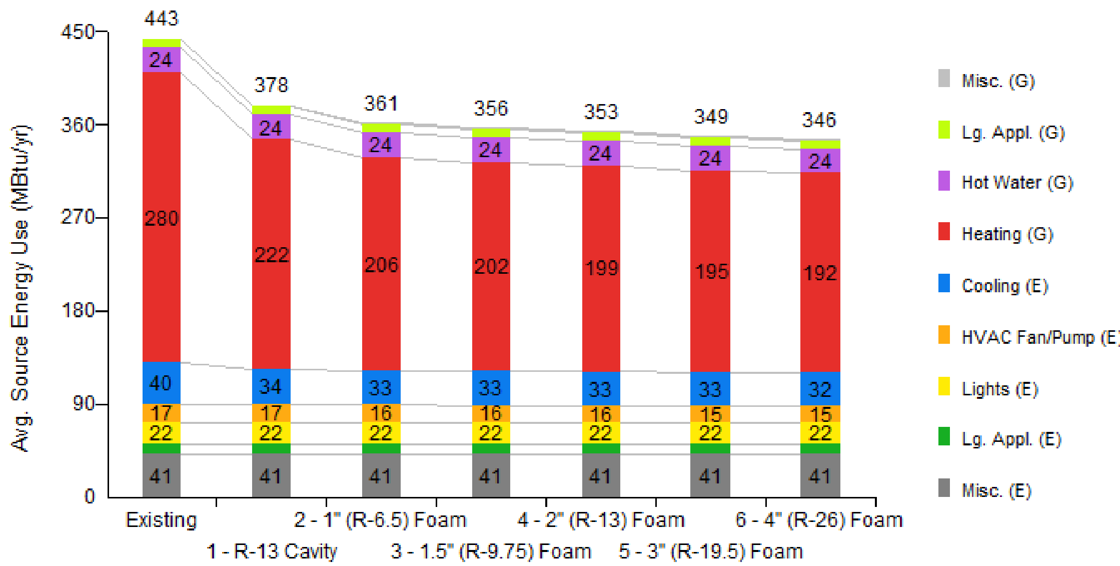
4536
4371
R
1
2
3
4
5
6
0
3
6
9
12
15
18
21
24
27
30
Avg. Source Energy Savings (%/yr)



Avg. Source Energy Use (MBtu/yr)
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360
270
180
90
0
443
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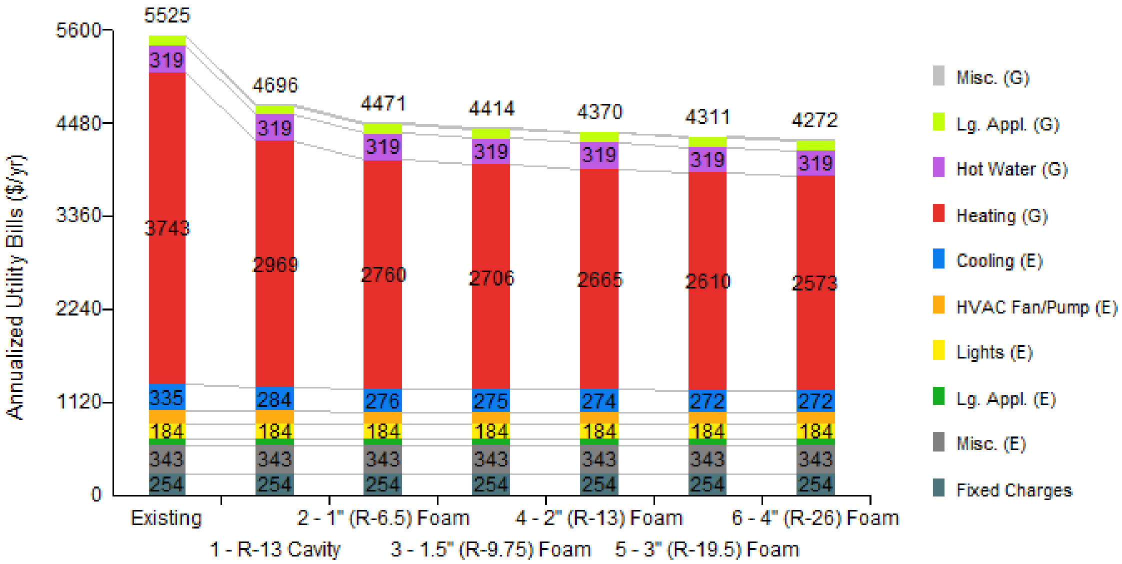
361
356
353
349
346
24
280
222
206
202
199
195
192
40
34
33
32
17
16
15
22
41
Existing
1 - R-13 Cavity
2 - 1" (R-6.5) Foam
3 - 1.5" (R-9.75) Foam
4 - 2" (R-13) Foam
5 - 3" (R-19.5) Foam
6 - 4" (R-26) Foam
Misc. (G)
Lg. Appl. (G)
Hot Water (G)
Heating (G)
Cooling (E)
HVAC Fan/Pump (E)
Lights (E)
Lg. Appl. (E)
Misc. (E)



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1120
0
Annualized Utility Bills ($/yr)
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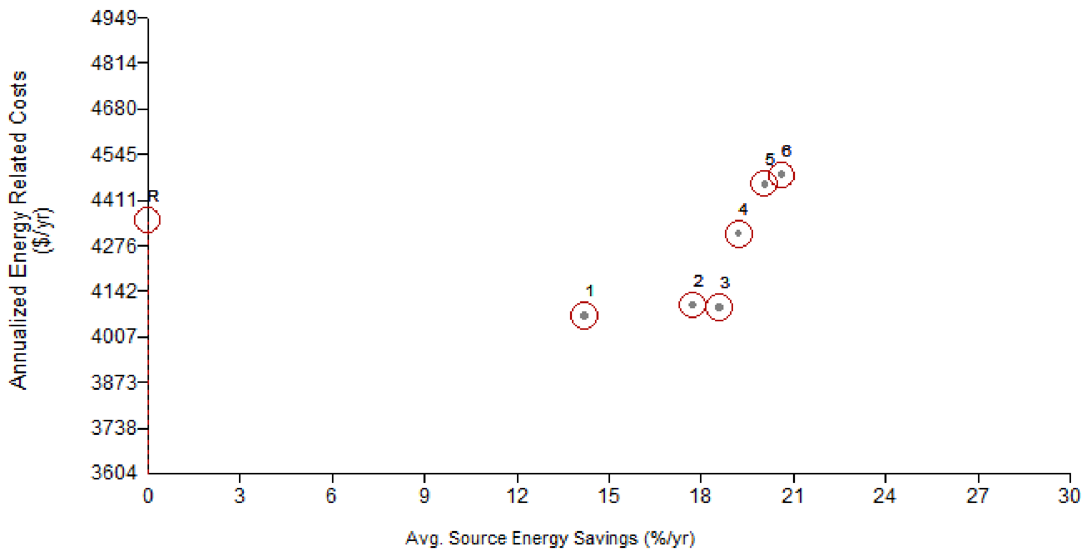
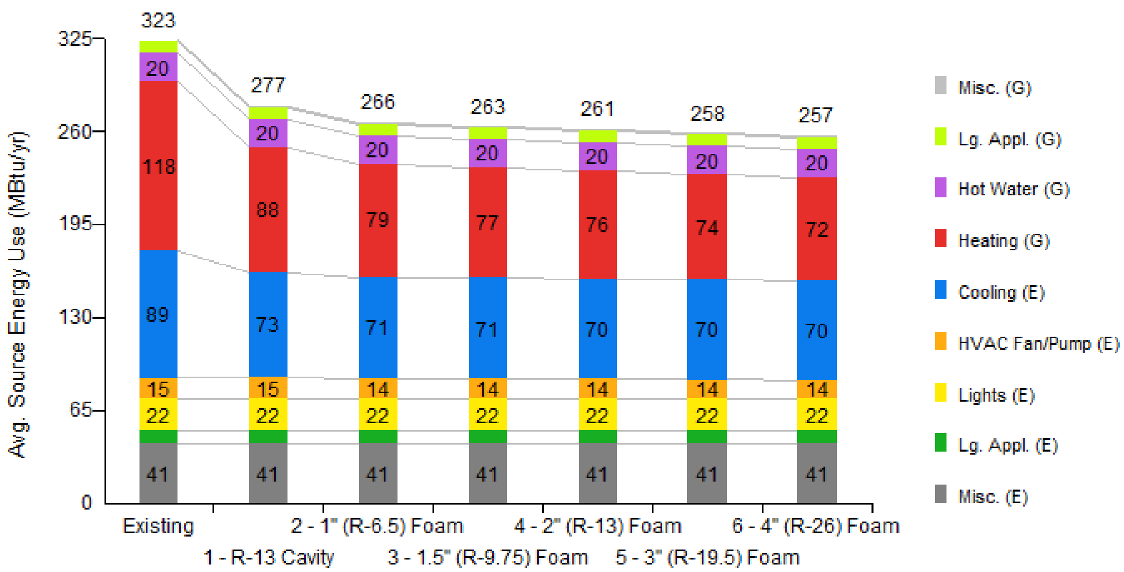
4471
4414
4370
4311
4272
319
3743
2969
2760
2706
2665
2610
2573
335
284
276
275
274
272
184
343
254
Existing
1 - R-13 Cavity
2 - 1" (R-6.5) Foam
3 - 1.5" (R-9.75) Foam
4 - 2" (R-13) Foam
5 - 3" (R-19.5) Foam
6 - 4" (R-26) Foam
Misc. (G)
Lg. Appl. (G)
Hot Water (G)
Heating (G)
Cooling (E)
HVAC Fan/Pump (E)
Lights (E)
Lg. Appl. (E)
Misc. (E)
Fixed Charges

Dallas



Annualized Energy Related Costs ($/yr)
4949
4814
4680
4545
4411
4276
4142
4007
3873
3738
3604
R
1
2
3
4
5
6
0
3
6
9
12
15
18
21
24
27
30
Avg. Source Energy Savings (%/yr)



Avg. Source Energy Use (MBtu/yr)
325
260
195
130
65
0
323
277
266
263
261
258
257
20
118
89
15
22
41
20
88
73
15
22
41
20
79
71
14
22
41
20
77
71
14
22
41
20
76
70
14
22
41
20
74
70
14
22
41
20
72
70
14
22
41
Existing
1 - R-13 Cavity
2 - 1" (R-6.5) Foam
3 - 1.5" (R-9.75) Foam
4 - 2" (R-13) Foam
5 - 3" (R-19.5) Foam
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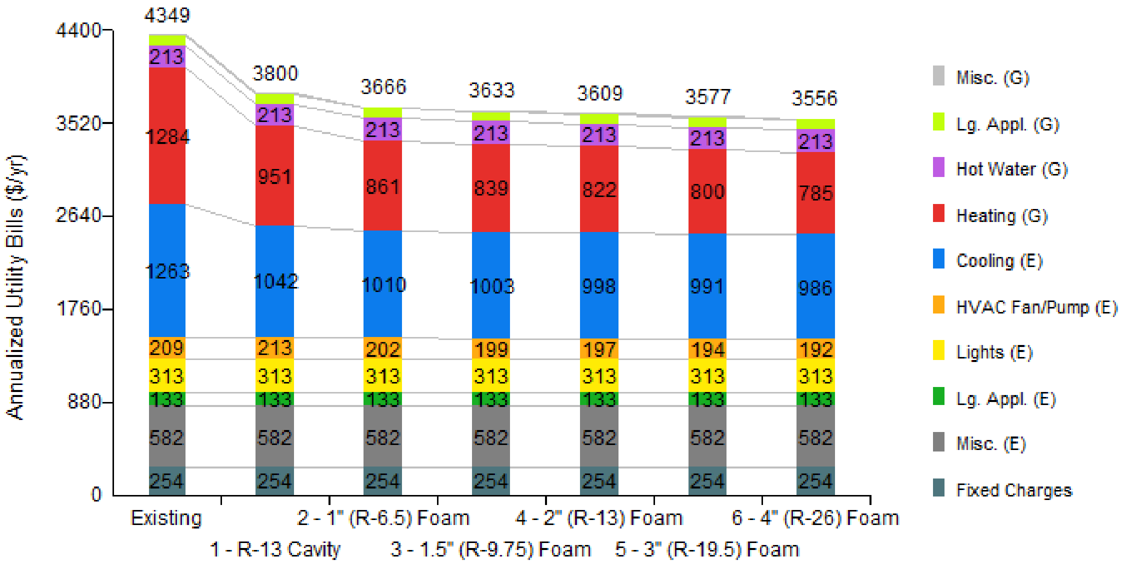
Misc. (G)
Lg. Appl. (G)
Hot Water (G)
Heating (G)
Cooling (E)
HVAC Fan/Pump (E)
Lights (E)
Lg. Appl. (E)
Misc. (E)


Annualized Utility Bills ($/yr)
4400
3520
2640
1760
880
0
4349
3800
3666
3633
3609
3577
3556
213
1284
1263
209
313
133
582
254
951
1042
213
861
1010
202
839
1003
199
822
998
197
800
991
194
785
986
192
Existing
1 - R-13 Cavity
2 - 1" (R-6.5) Foam
3 - 1.5" (R-9.75) Foam
4 - 2" (R-13) Foam
5 - 3" (R-19.5) Foam
6 - 4" (R-26) Foam
Misc. (G)
Lg. Appl. (G)
Hot Water (G)
Heating (G)
Cooling (E)
HVAC Fan/Pump (E)
Lights (E)
Lg. Appl. (E)
Misc. (E)
Fixed Charges

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