Moisture-Related Durability of In-Service High-R Wall Assemblies in Pacific Northwest Climates

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ABSTRACT

The Passive House program is becoming increasingly well-known in North America. This program aims to produce a superior thermal enclosure such that the space conditioning systems may be minimized, if not appreciably eliminated. Many Passive House designs use double-stud or thick wall enclosures. By adding significant thicknesses of cavity insulation, this approach provides a high level of thermal performance (R-value). However, the decreased heat flow through these walls reduces drying and can therefore place colder building components at risk of moisture damage. Constructing walls with exterior continuous insulation is a method that helps minimize these effects by warming critical layers, reducing potential condensation and moisture concerns.

This paper reports on two ongoing projects to assess the durability of these assemblies by comparing a 2 × 10 wood-framed wall with nominal exterior insulation in Portland, Oregon to a 2 × 10 wood-framed wall with an interior insulated service cavity in Victoria, British Columbia. Both walls are instrumented to measure temperature and moisture profiles through the assembly, for both the north and south orientations. Historical data from previous research programs will be discussed and compared to measurement data from the current ongoing project. The threshold of performance for these assemblies will be discussed along with solutions to address potential concerns. Analysis of preliminary data shows that it is consistent with past research, and supports the conclusion that exterior insulation can improve durability relative to double-stud walls.

INTRODUCTION

Passive House construction is growing in popularity in North America. The Passive House standard includes an ultra-low energy consumption target that is achieved through measures such as a high-R-value enclosure, passive solar heating, heat recovery ventilation, and seasonal shading (Passive House Institute 2014). More specifically, enclosures are specified and constructed to be well-insulated and airtight, with minimal thermal bridging. To supplement the limited maximum R-value of cavity insulation between dimensional lumber, additional insulation is sometimes required. This additional insulation is commonly added by building and insulating a thick wood-framed wall (e.g., using a double-stud wall, wood I-joists, or similar) or by adding exterior insulation (i.e., continuous insulation on the exterior of a more conventional, dimensional lumber wall). The positioning of this additional insulation will affect the hygrothermal behavior of the wall assembly by affecting the structural sheathing temperature, and thus the potential for durability concerns.

This paper reports on two Passive House projects that use different high R-value wall enclosure strategies to help achieve their low energy consumption targets. The two projects are in the Pacific Northwest, International Energy Conservation Code (IECC) Climate Zone 4C: one in Victoria, British Columbia (using a double-stud approach) and the other in Portland, Oregon (using exterior insulation). Both locations have approximately 2500 heating degree days at 18°C (4500 heating degree days at 65°F).

The Pacific Northwest was chosen for this comparison and analysis to address a gap in the research of high-R wall performance. Exterior-insulated and thick wood-framed wall assemblies have been studied and compared in IECC Climate

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Zones 5 and 6, and builders continue to gain experience with these systems in dry climates. However, there remains a need to study and compare the performance of these systems in more humid coastal climates like those of the Pacific Northwest.

To meet the energy requirements of the Passive House program, the building in Victoria was constructed with a thick stud wall with an interior insulated service wall, and the building in Portland was constructed with a thick stud wall with continuous exterior insulation. Both of these strategies increase the overall effective R-value from standard construction, and decrease thermal bridging through the clear-wall portion of the enclosure. Enclosure monitoring sensor packages were installed in both projects to monitor the conditions of the assembly and compare durability performance. Detailed wall assembly drawings and measured monitoring data from both of these assemblies are presented further in the report. Preliminary data is analyzed and compared to previous research on double-stud and exterior insulation wall assemblies.

BUILDING ENCLOSURE

The building enclosure is designed to separate the interior space from the exterior on every surface of the building both above and below ground. The most important function of the enclosure, with respect to long-term durability, is the control of liquid water, including rainwater, surface water, and ground water. For the purposes of this study, it is important to note that failure to adequately control liquid water will eventually result in the failure of almost any wall system, regardless of the design. This means that monitored enclosure walls that show good measured performance are not immune from failure should the critical water management details be missed. Air control across the enclosure is also important in terms of energy consumption and the movement of water vapor into and out of the enclosure. Failure to control air leakage and subsequent vapor movement can result in long-term durability problems and moisture-related failures as a result of condensation on surfaces within the enclosure. The Passive House program requires airtightness testing to ensure that air leakage is below a specified limit. This reduces the risk of cold weather air leakage condensation but does not eliminate it.

An air barrier must be continuous. Its components (i.e., materials and systems) should be air impermeable, strong, stiff, and durable. When dealing with airtightness, it is also important to consider both windwashing and re-entrant looping. If the air barrier is located near the interior of the enclosure, it is possible for wind-driven air to flow from the exterior into any cavities and back to the exterior. This can reduce the effective R-value of the insulation and may add moisture to the enclosure. Similarly, if the air barrier is located near the exterior of the enclosure it is possible for interior air to move into the enclosure and then return to the interior. This also results in increased energy demands, and in colder climates, will add moisture to the enclosure that could potentially be detrimental. It is important to note that neither windwashing nor re-entrant looping can be measured by an air leakage test. It is very difficult to measure the effects of re-entrant looping or windwashing within wall constructions being monitored. Controlling vapor movement by diffusion is also important, but does not move as much water vapor as quickly as air leakage.

Air and vapor control can be achieved with a single material (such as polyethylene sheeting), but it is not necessary to combine these functions in one layer. Some insulation materials such as spray foam may be part of an air barrier system, whereas some materials such as dense-packed cellulose retard air flow but are too air permeable to be considered part of an air barrier system. With respect to this study, the air barrier in Portland was the plywood sheathing, taped at the joints, using transition membranes at penetrations such as windows and doors and also at the transition to the foundation. The interior vapor control was a continuous layer of a smart vapor retarder material (not taped at the edges, since the vapor control layer was not also the air control layer). A smart vapor retarder has a relative humidity (RH) dependent vapor permeance which means that at the low relative humidities (e.g., ~50% rh) that would be expected in the interior space, the vapor permeance is low (≤1 Perm), but at the higher relative humidities (e.g., ~80% rh) that could be expected if there was water in the wall cavity, or strong inward vapor drives, the permeance increases significantly (>10 Perms) to allow moisture to pass. In Victoria, the vapor and air barrier were the same material, a trilaminate polyolefin/polypropylene membrane installed at the interstitial layer between an exterior and interior framing layer so that services could be run on the interior without penetrating the membrane and allowing air leakage. The membrane was well sealed to all transitions and any penetrations.

LITERATURE REVIEW

Neil Hutcheon was one of the first to address the benefits of exterior insulation. He explained that moving the insulation from the interior of a masonry wall to the exterior surface increases the temperature of the structure during cold weather and can increase the minimum temperature of the condensation plane above the dew point of the interior air, which minimizes the risk of condensation and improves the durability of the wall assembly (Hutcheon 1964). Others (Handegord 1985, Straube 2011) built on Hutcheon's work, adding simple numerical analysis to determine the ratio of insulation R-value required on each side of the condensation plane to minimize the risk of condensation based on the interior dew point and exterior temperature.

Measured performance bears out these analyses. Past published research on high-R wall assemblies in cold climates, including measurement of moisture content, has been conducted in a variety of locations, on many different types of wall assemblies. This review highlights several studies with particular relevance to double-stud wall assemblies and exterior-insulated wall assemblies. All of the reviewed studies were conducted in IECC Climate Zones 5–7.

Tsongas (1991) investigated the performance of wall assemblies in 86 homes in Montana and Washington State in Climate Zones 5 and 6. There was a range of construction types, vapor control layers, and insulation types (with varying vapor permeance) through the monitored regions. The study houses included some exterior insulating sheathing construction and some double-stud wall construction. The exterior insulating sheathing was either foil-faced polyisocyanurate, extruded polystyrene (XPS) or expanded polystyrene (EPS). It was found that building walls with more cavity insulation led to increased moisture levels in the wall assemblies, and that walls with exterior insulating sheathing were significantly drier than walls without exterior insulating sheathing. These walls were believed to be drier because the insulating sheathing kept the wall cavity wood members warmer and also because the insulated sheathing was an excellent exterior moisture barrier that prevented wet siding from transmitting or wicking moisture into the wall cavity.

Arena et al. (2013) monitored the performance of a double-stud wall in Boston, MA, in Climate Zone 5A. A hygrothermal model was used to correlate the measured data. The results showed that the hygrothermal simulation predicted lower sheathing moisture contents than were measured, even though the simulated RH in the model was 20%–30% higher than the measured RH. This means that the measured performance of the double-stud wall assembly was worse than predicted, even with much lower risk factors such as significantly decreased interior relative humidity. Ueno (2015) also found that in Devens, MA (Climate Zone 5), monitoring of a dense-packed cellulose wall assembly showed measured moisture contents greater than 30% with elevated interior relative humidity levels, and measured moisture contents greater than 20% with controlled interior relative humidity levels.

In 2014, at the University of Waterloo in Waterloo, Ontario, Canada (Climate Zone 5), a research program was conducted on a field test hut with several different wood-framed high-R wall assemblies side by side (Fox et al. 2015). Test walls consisted of thick cavity walls such as double-stud walls, I-joist walls with dense-packed cellulose, walls with three different types of exterior continuous insulation (with varying vapor permeance), and a typical 2 × 6 wall assembly with R-22 fiberglass batt and no exterior insulation. All of the test walls were challenged with intentional controlled water and air leakage at different times. It was concluded that the oriented strand board (OSB) sheathing in the exterior-insulated walls was warmer and reduced the risk of moisture-related issues, especially near the location of the controlled air leak. The sheathing in the exterior-insulated walls was consistently below 16% moisture content. The deep-cavity cellulose-insulated walls had the highest moisture content levels in both the framing plates and OSB sheathing throughout the duration of the study period. These walls also had the highest number of condensation hours and were slower to dry in comparison with the exterior-insulated walls.

In 1987, Robert Kane and Guy Titley designed a research program to address the concern that the use of an exterior low vapor permeance foam sheathing allows an accumulation of moisture between the vapor barrier and the exterior sheathing. Walls in occupied buildings in four Canadian cold-climate cities were chosen. The primary method of analysis was moisture content readings of the wood framing in all cases, in combination with temperature measurement and moisture measurements at the sheathing/insulation interface. It was concluded that XPS used as exterior sheathing does not cause moisture accumulation in the wood studs and that XPS sheathing will warm the batt/sheathing interface, thereby controlling the amount of possible air leakage or vapor-driven condensation. It was also concluded that regardless of the design and materials chosen, the importance of installing a proper air barrier to control the moisture cannot be overemphasized.

From the reviewed papers on the measurement of both thick and exterior-insulated wall assemblies, it is clear that there is a general pattern of findings. Monitoring of exterior-insulated walls indicates lower measured moisture contents and higher condensing plane temperatures. The exterior-insulated wall results do not appear to depend on the vapor permeance of the exterior insulation. These walls have a reduced risk for moisture problems, whether caused by vapor diffusion or air leakage. Monitored thick walls with dense-packed cellulose often showed higher measured moisture contents, and a greater risk of moisture-related durability issues, although it was noted in at least one paper that all of the elevated measured moisture contents dried to safe levels in the summer months (Ueno 2015).

MONITORING

The buildings in the current study are wood-framed multi-unit residential buildings (MURBs), 3 to 4 stories in height. Instrumentation was installed on both the north and south orientations. It is the authors' experience that the north and south orientations can have very different experimental outcomes because of the solar influence on the south orientation. Hence, both the north and south orientations are instrumented whenever possible during monitoring. Both of the monitoring locations were instrumented with a series of temperature, relative humidity, and wood moisture content sensors at strategic locations in the enclosure to measure and record the hygrothermal conditions on an hourly basis. The monitoring techniques are based on those described by Straube et al. (2002). The interior and exterior temperature and RH (boundary conditions) are critical to understanding the wall performance and temperature and moisture gradients across the enclosure. The exterior conditions were derived from nearby meteorological station data.

Wood moisture content was determined by measuring the electrical resistance across a sample of wood and correlating the electrical resistance with a wood moisture content according to the Garrahan equation (Onysko et al. 2010).

Dryability of water in the enclosure is often used as a comparison criterion for different wall assemblies, but this is difficult to do in real building enclosures due to the risk of moisture damage by intentionally injecting water. Using dryability is only practical in test huts, where walls can be stressed with moisture without affecting a building. Analysis of enclosure dryability is beyond the scope of this study because real buildings are used for comparison.

Exterior-Insulated Assemblies and Instrumentation (Portland)

In Portland, four walls in four different suites were instrumented, two on the north orientation, and two on the south orientation, as shown in Figure 1.

The interior conditions in every suite were measured immediately inside the continuously-operated heat recovery ventilator (HRV) exhaust fan. A detailed cross section of the Portland wall assembly, showing the typical monitoring locations, is shown in Figure 2. The sensors were installed at the mid-point between framing members, at the mid-height of the wall. The data acquisition system was installed above the ceiling in the corridor between the suites.

Thick Double-Stud Wall Assemblies and Instrumentation (Victoria)

In Victoria, two walls in two different suites were instrumented, for a total of four locations, two on the north orientation, and two on the south orientation (Figure 3). The units, and thus the walls, are stacked one above the other. The interior conditions in every suite were measured in both the common area and the master bedroom, at ceiling height. A detailed cross section of the Victoria wall assembly, showing the typical monitoring locations, is shown in Figure 4.

Evaluation Criteria

In colder climates, accumulation of moisture in the sheathing or elevated sheathing surface RH are used as key performance criteria because the sheathing is typically the first location where water vapor condensation would occur in a cold climate during the heating season as a result of air leakage

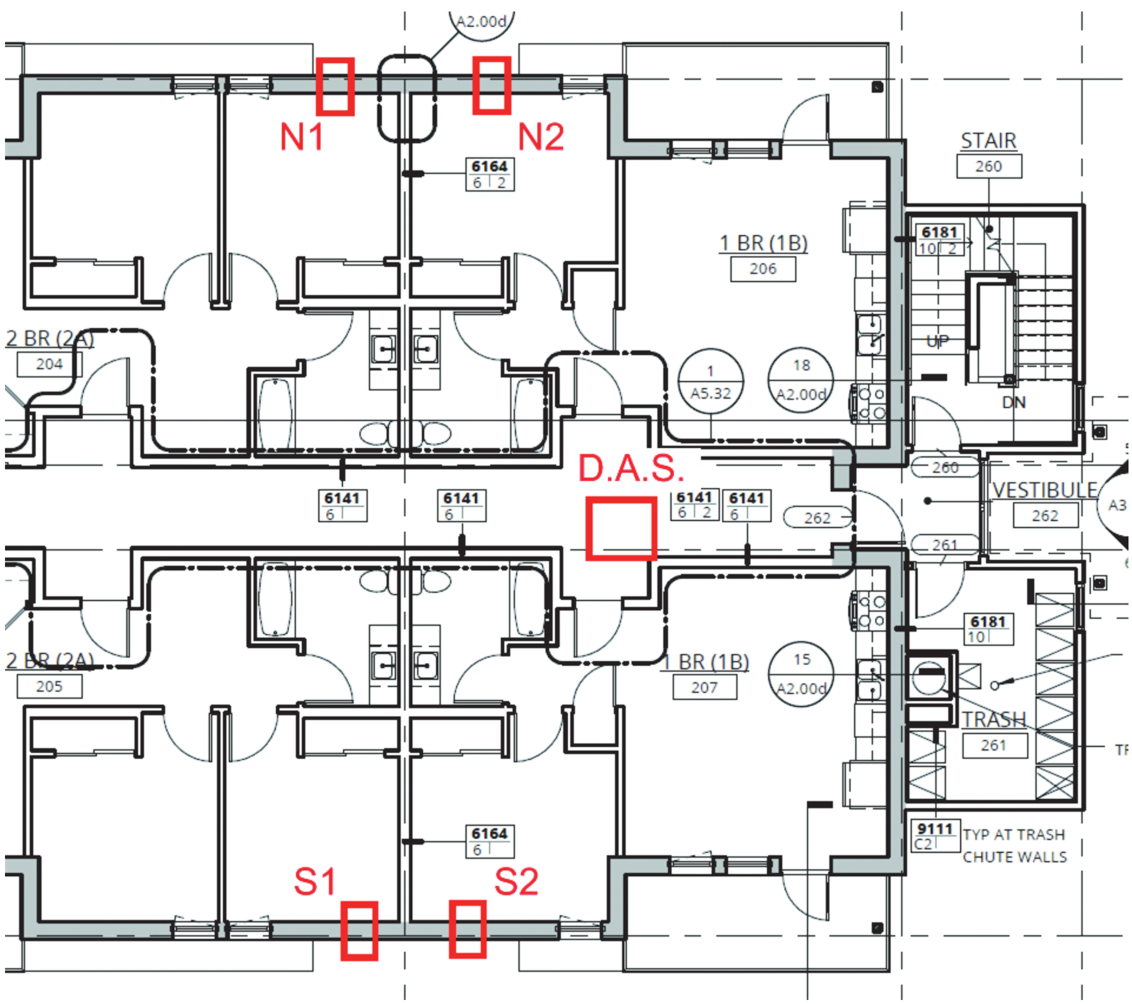

Figure 1   Four monitoring locations and the location of the data acquisition system on the third floor (Portland).

or vapor diffusion from the interior. The sheathing may also experience moisture accumulation from the exterior in wet climates.

There are several ways to assess moisture accumulation and the moisture-related durability of structural wood sheathing. ASHRAE Standard 160, *Criteria for Moisture-Control Design Analysis in Buildings*, Addendum A (ASHRAE 2009), uses a pass-fail evaluation based on the IEA Annex 14 standard (IEA 1991) to minimize mold growth. Specifically, the criteria for low mold risk is a 30-day running average surface RH <80% when the 30-day running average surface temperature is between 5°C and 40°C (41°F and 104°F)

However, the ASHRAE 160 criteria have been found to poorly correlate to actual biological growth risk (Lstiburek et al. 2015). To help provide more accurate analysis, the results will be compared using the Finnish VTT Technical Research

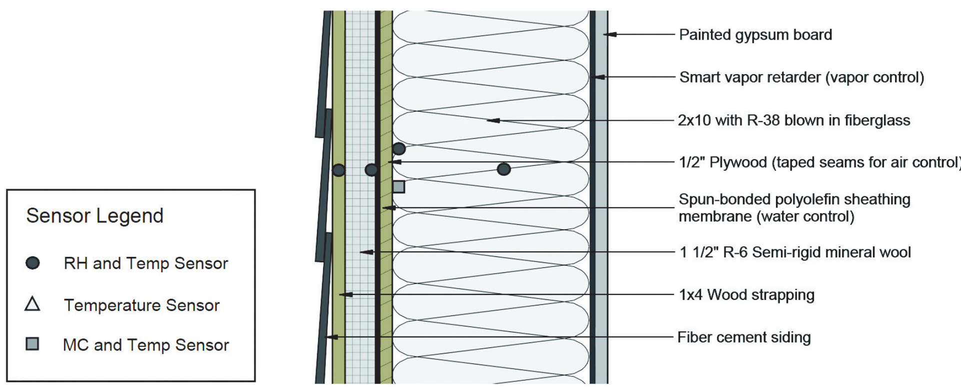

Figure 2 *Detailed assembly and typical monitoring locations (Portland).*

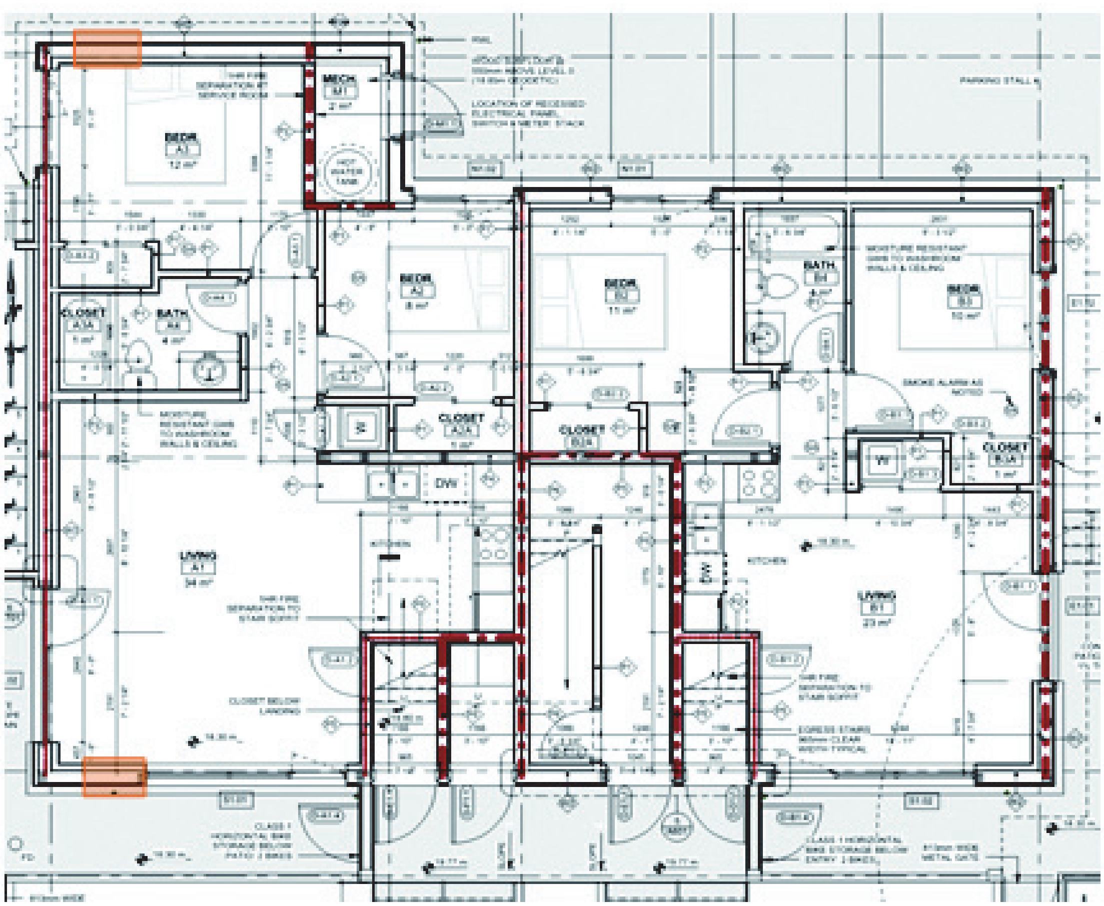

Figure 3 *Plan view showing monitoring locations (Victoria).*

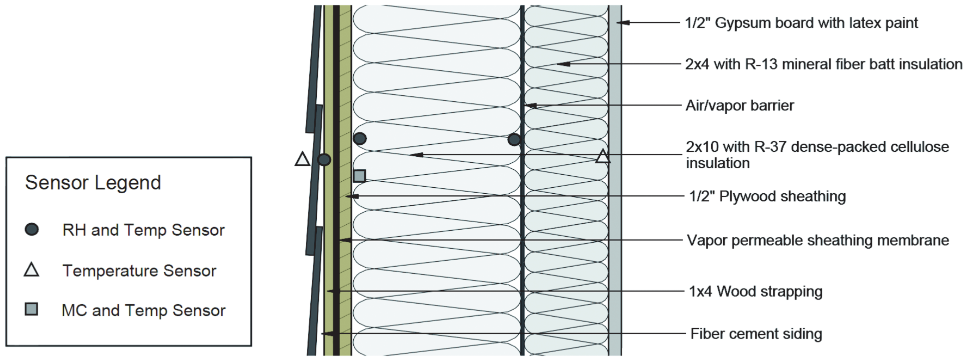

Figure 4 *Detailed assembly and typical monitoring locations (Victoria).*

Centres' Improved Model to Predict Mold Growth in Building Materials (Viitanen and Ojanen 2007). This model is based on empirical regressions of actual mold growth on building materials in varying climatic conditions. While the VTT model results do not necessarily guarantee the presence of mold, they do provide a greater degree of reliability than categorical limits. The VTT model output is a mold index, summarized in Table 1. Mold index values less than 3 are generally not visible to the naked eye, and therefore mold indices greater than 3 are considered a fail.

Table 1. Mold Index for the VTT Model (Viitanen and Ojanen 2007)

Index	Growth Rate	Description
0	No growth	Spores not activated
1	Small amounts of mold on surface (microscope)	Initial stages of growth
2	<10% coverage of mold on surface (microscope)	—
3	10%–30% coverage of mold on surface (visual)	New spores produced
4	30%–70% coverage of mold on surface (visual)	Moderate growth
5	>70% coverage on mold on surface (visual)	Plenty of growth
6	Very heavy and tight growth	Coverage around 100%

MONITORING DATA AND ANALYSIS

Monitoring at the Portland location (exterior-insulated assemblies) began during construction in November 2014, but the suites were not occupied until June of 2015. The data for this analysis begins on June 4, 2015 and finishes in June of 2016, for one full year of data. Monitoring will continue until at least 2017.

The interior and exterior relative humidity and temperature boundary conditions are shown in Figure 5. The interior conditions are an average of all four suites, and all four suites were quite similar in their conditions. The interior average temperature was relatively constant at 20°C–22°C (68°F–72°F), and the interior relative humidity fluctuated between 45% and 65% but had a trend to the lower threshold throughout the coldest months, because cool humid exterior fresh air was brought into the building and heated, reducing the relative humidity of the ventilation air. The interior relative humidity trend is correlated to changes in the exterior temperature, as well as occupancy behavior. There was no elevated interior relative humidity at the start of the research program that would indicate a source of construction moisture in the suites.

Monitoring of the Victoria location (double-stud assemblies) was delayed and began in December 2015, four months after the suites were instrumented and occupied in September of 2015. The data for this analysis begins on December 19, 2015 and will continue until 2017.

The interior and exterior relative humidity and temperature are shown in Figure 6. The interior average temperature was relatively constant at 21°C (71°F), and the interior relative humidity fluctuated between approximately 35% and 55%.

The sheathing temperature and relative humidity used to calculate the mold index results (see the Conclusions section) are shown in Figures 7 and 8. Results are provided for both monitored buildings with a running 24 h average. The start of monitoring was delayed in Victoria, and only overlapping data is shown in this comparison between December 2015 and June 2016. Portland results are colored in blue, whereas Victoria results are colored red, with the north elevation in a lighter shade for both buildings. All of the average temperatures are similar, but there are peaks on the south orientation in Portland (dark blue) that have higher measured temperatures through the monitoring period as a result of solar heating in Portland.

The measured relative humidity at the sheathing in Victoria (Figure 8) is higher on both the north and south in comparison to the Portland measurements even though the exterior ambient relative humidity was very similar in both Portland and Victoria. The measured differences in sheathing RH from Figure 8 is further analyzed later in the paper.

Figure 9 compares the exterior temperature and sheathing temperature of each building and Figure 10 compares the exterior relative humidity and sheathing relative humidity for each building. These comparisons were conducted between December 22, 2015, and February 29, 2016. Only the coldest months of the year were used because the effect of the exterior insulation on wall performance is more significant to the durability of the enclosure during the coldest months when there is

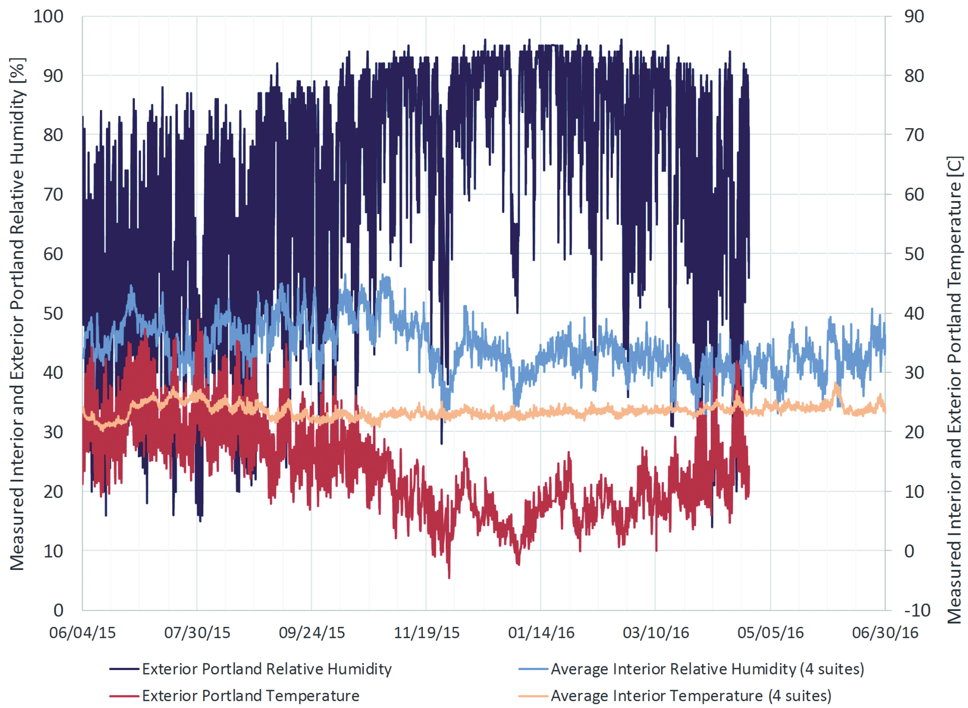

Figure 5 *Interior and exterior temperature and relative humidity (Portland).*

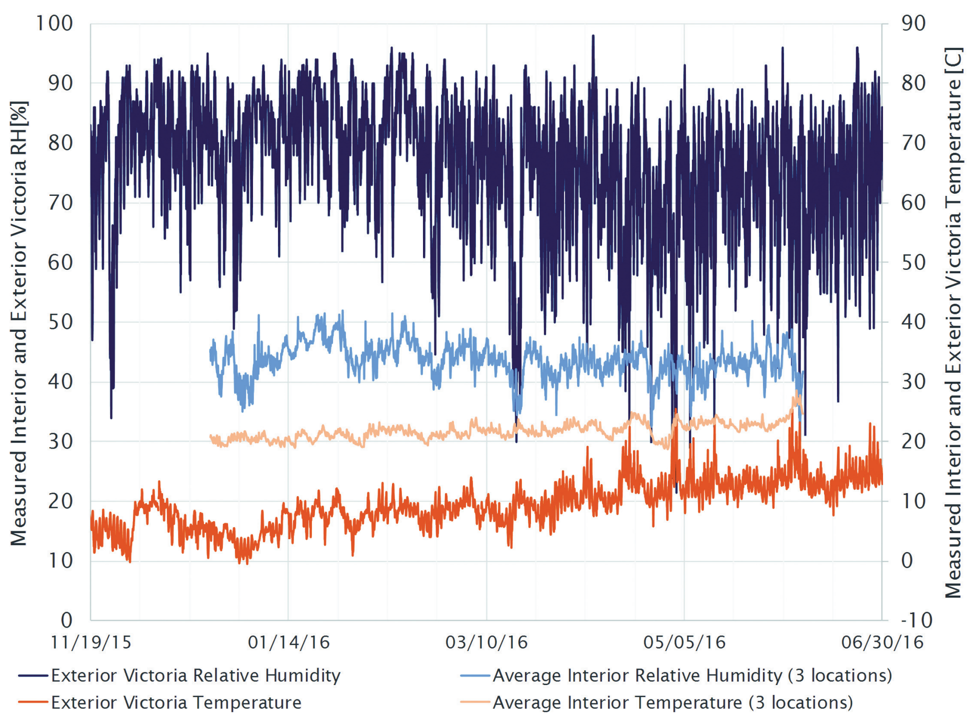

Figure 6 *Interior and exterior temperature and relative humidity (Victoria).*

a risk of moisture accumulation. Because the two cities have similar climates, these figures can be used to demonstrate the effect on the enclosure of the two wall construction strategies. For example, the blue dashed lines of Figure 9 show that, at an exterior temperature of 3°C (37.5°F) in either city, the sheathing without exterior insulation (Victoria) will be approxi-

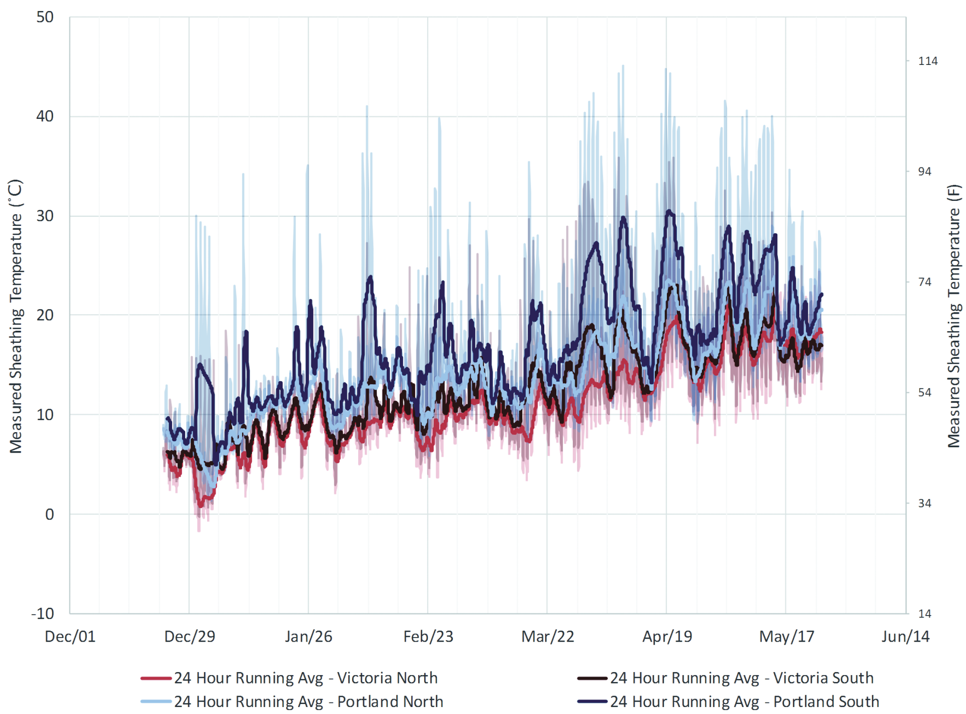

Figure 7 *Sheathing temperature and 24 h running average for Portland (blue) and Victoria (red), north and south orientations.*

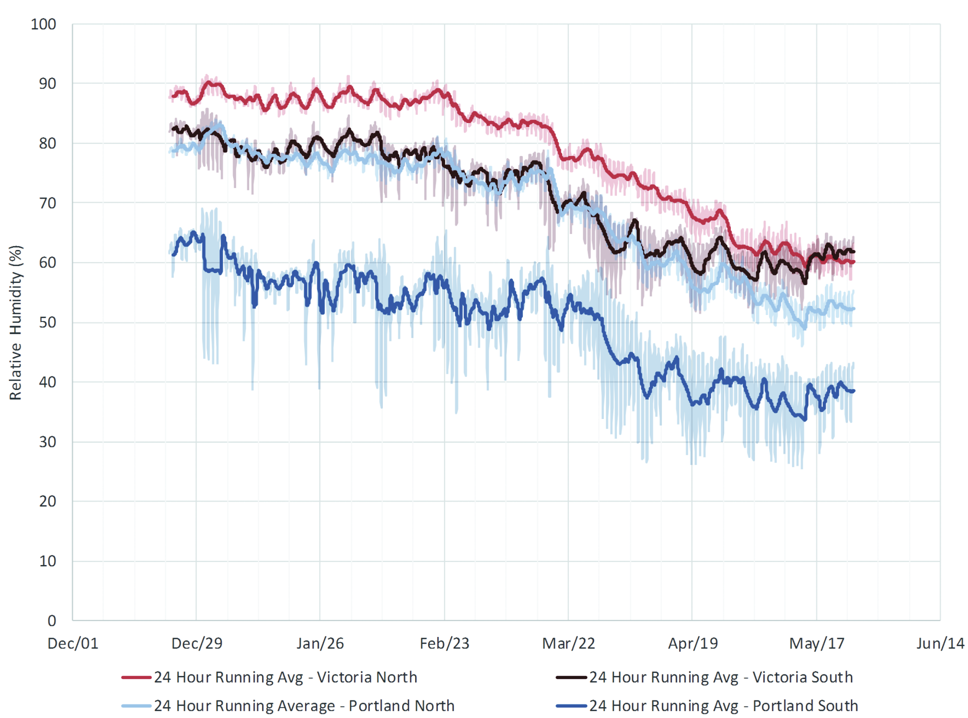

Figure 8 *Sheathing relative humidity and 24 h running average for Portland (blue) and Victoria (red), north and south orientations.*

mately 4.5°C (40°F) on average and the sheathing with exterior insulation (Portland) will be approximately 7.5°C (45.5°F) on average. The exterior insulation is clearly shown to have a warming effect on the sheathing as indicated by warmer average sheathing temperatures in Portland for the same exterior temperature. This effect would be more pronounced in colder climates, or with a more significant

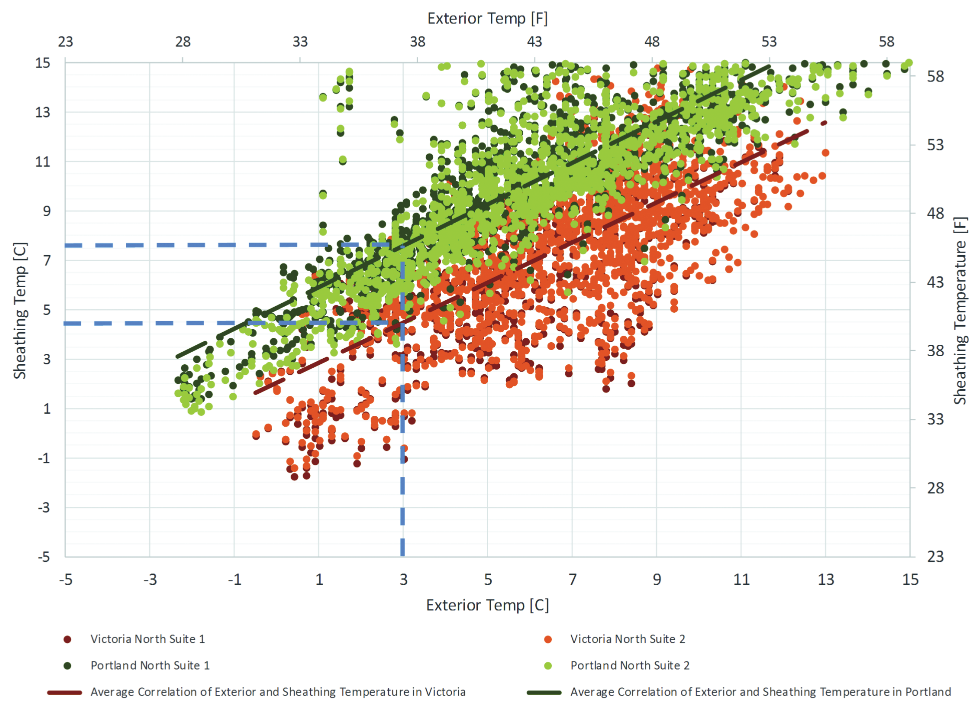

Figure 9 *Distribution of exterior temperatures and sheathing temperatures for Victoria (orange) and Portland (green), on the north orientation.*

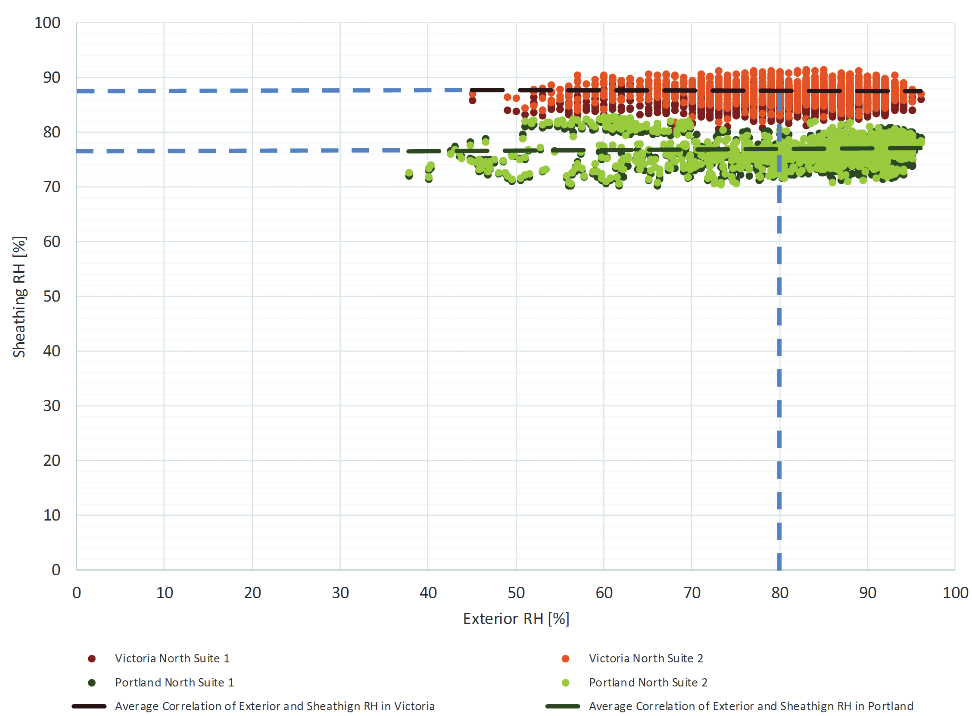

Figure 10 *Distribution of sheathing relative humidity for Victoria (orange) and Portland (green), on the north orientation.*

portion of the insulation R-value on the exterior of the sheathing relative to the total R-value of the wall.

As a result of the increased sheathing temperatures in the exterior-insulated (Portland) building demonstrated in Figure 9, Figure 10 shows that the relative humidity is decreased at the sheathing layer in Portland. For example, at a measured exterior RH of 80%, the average measured RH at the interior surface of the sheathing of the double-stud walls (Victoria) is approximately 88%, while in the exterior-insulated walls (Portland), the average measured sheathing RH is 76%.

Plotting the measured sheathing surface temperature and relative humidity and applying the VTT model under a sensitive moisture class (typical for wood board products), with a decline coefficient of 0.3, the mold indices for all eight evaluated walls are shown in Figure 11.

Using a mold index criterion of 3 as explained earlier, the results indicate no appreciable risk of mold growth on the sheathing based on measured temperature and relative humidity in either of the monitored buildings, despite the north walls of the Victoria building experiencing 30-day running average relative humidities and temperatures sufficient for concerns of mold growth. Most importantly, none of the exterior-insulated walls suggest the ability to harbor even microscopic levels of mold growth.

CONCLUSIONS

A literature review of field research results found that there were greater moisture-related durability risks with thick double-stud walls compared to exterior-insulated wall assemblies. It was concluded there were no increases to the moisture durability risks as a result of the addition of exterior insulation. This finding is supported by decades of field experience.

In this research program, analysis of the measured sheathing temperature and RH compared to exterior temperature and RH showed that the sheathing of the exterior-insulated wall assembly (Portland) had higher sheathing temperatures and lower sheathing RH for a given exterior temperature and RH, compared to the double-stud assembly (Victoria). Increasing the R-value ratio of exterior insulation to cavity insulation would further increase these effects.

Analysis using the VTT mold index model showed that neither wall assembly experienced measured conditions that show a risk of mold growth on the sheathing during the monitored period. The mold index was 0 for all four monitored locations on both orientations in Portland and on the south orientation in Victoria. On the north orientation in Victoria, the mold index reached approximately 0.4, which is very low. Initial stages of microscopic mold start at a mold index of 1.

Both of the monitored buildings in the current study meet very strict airtightness levels to achieve the Passive House certification, so the workmanship and attention to detail of the air barrier system was higher than in standard construction practices. As well, it is important to note that failure to adequately control precipitation will eventually result in the failure of almost any wall system, regardless of the design. This means that monitored enclosure walls that show good

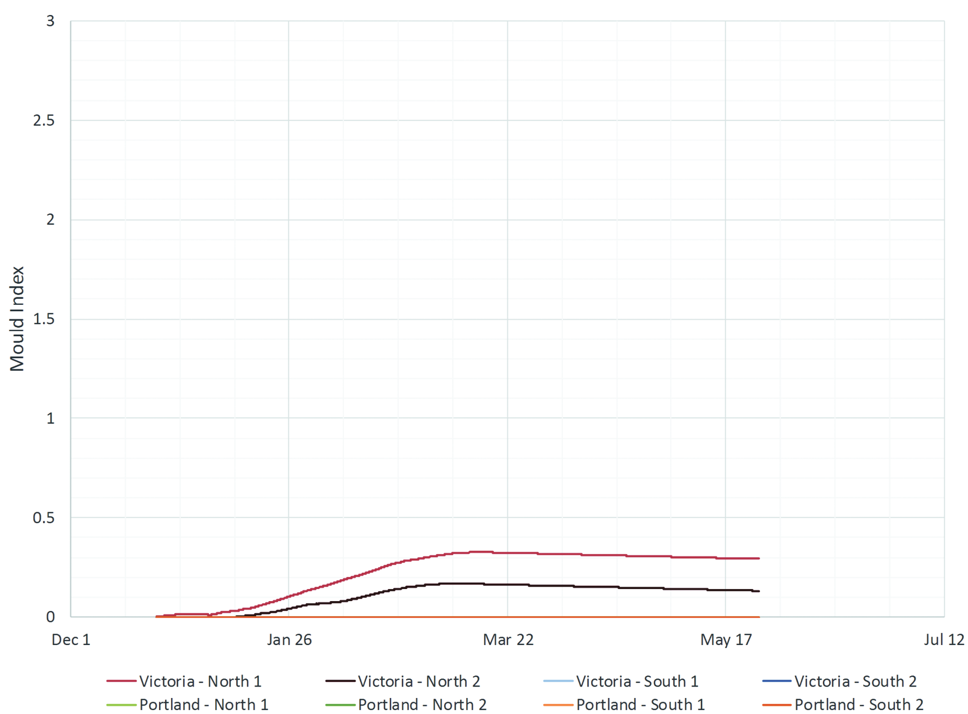

Figure 11 *Mold index results for Victoria and Portland, modeled from December 2015 to May 2016. The mold index was 0 for all four monitored locations in Portland and on the south orientation in Victoria.*

performance are not immune from failure should important rainwater management details be missed.

Moisture-related durability also relates to the drying ability of the assembly, which was not addressed in this research program because determining drying ability requires intentionally wetting the wall systems. Intentional wetting of wall systems is typically done on test hut walls, rather than real buildings, because of the potential for damage.

The results of this study support the substantial body of research suggesting that exterior-insulated assemblies can be used without increasing moisture-related durability risks.

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