PASSIVE HOUSE WALL ASSEMBLY PERFORMANCE – A CASE STUDY

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ABSTRACT

Improvements in building efficiency can significantly reduce carbon emissions and are an intrinsic component in greenhouse gas reduction targets. The Passive House concept provides a framework for high-performance building that is growing in popularity in Canada, and particularly in the Pacific Northwest. The Passive House standard requires its buildings to achieve specific performance values for heating energy use intensity, total energy use intensity, spatial temperature variation, heat recovery ventilation performance and air leakage rate. The promised co-benefits of Passive Houses include superior thermal comfort and indoor air quality.

Passive House design is not prescriptive and can incorporate many different design aspects. The wall assembly is no exception. This paper evaluates the hygrothermal performance of a deep-stud wall assembly of a Passive House in Victoria, BC, with regards to moisture durability. The concern with deep or double-stud wall assemblies is the combined effects of reduced drying with wall configurations that place moisture sensitive materials in riskier locations. Consequently, enclosure monitoring was undertaken in an occupied six-plex over the period of one year.

The enclosure monitoring sensor packages were installed in strategic locations in the wall assembly to monitor the conditions of the assembly. The assemblies were evaluated based on the results of an empirical mould risk index. The wall assembly appears to perform acceptably, with minor concerns of mould growth on the North wall. Air leakage is a significant concern for cavity insulated walls, but the airtightness requirements of Passive house minimize this risk.

INTRODUCTION

Buildings, representing around 40% of total carbon emissions (EPA 2017), are an important focus for meeting regional, national, and international carbon emission reduction targets. Many standards and regulations have been created to provide both incentive and deterrent forces to reduce carbon footprints and increase energy efficiency. The Passive House concept provides a framework for high-performance building that is growing in popularity in Canada, and particularly in the Pacific Northwest.

The Passive House standard requires its buildings to achieve specific performance values for space conditioning energy use intensity, total energy use intensity, spatial temperature variation, ventilation performance, and air leakage rate. The promised co-benefits of Passive Houses include superior thermal comfort and indoor air quality. These performance targets necessitate super-insulated enclosure assemblies. The assembly type, choice of materials, and their position within the assembly can affect the long-term performance of the enclosure. Inadequately designed enclosures may restrict moisture flow, leading to accumulation and biodeterioration, further compounded by decreased heat flow, which minimizes drying potential. High-performance assemblies are therefore predisposed to durability risks if not appropriately designed.

This paper will summarize the hygrothermal performance of a deep-stud wall assembly with an interior service wall in the Pacific Northwest climate. This assessment was completed for a new spec-built, six-unit Passive House complex located in Victoria, BC, known as the North Park Passive House (North Park). The building was constructed in 2014/2015 and was occupied in September 2015. The moisture durability of the sheathing was of principle interest, followed by other parameters such as the impact of solar heating and inward driven moisture. Enclosure monitoring sensor packages were installed to monitor the conditions of the assembly. The results were analyzed using the VTT *Improved Model to Predict Mold Growth in Building Materials* (Viitanen and Ojanen 2007).

BACKGROUND

The building enclosure is a system of materials designed to physically separate the interior space from the exterior on every surface of the building, both above and below ground. The enclosure must provide control over heat, air, and moisture, in both its gaseous and liquid forms. The building enclosure should control liquid water (including rain, surface water, and ground water) from entering the building, moisture vapour from traveling through building materials, and moisture laden air from transporting and condensing moisture onto building materials. Failure to adequately control any of these three forms of moisture can result in long-term durability problems and moisture-related failures.

Liquid water for wall assemblies is typically deterred by a water shedding surface and a water resistive barrier. For this study, the North Park Passive house used a drained and ventilated (“rainscreen”) cladding system with fibre cement siding and a permeable sheet-applied sheathing membrane (wall assembly details are shown in Figure 3).

An air barrier is used to eliminate the passage of air between the interior and the exterior environments. A secondary function is to deter moisture laden air from condensing on surfaces within the enclosure. A proper air barrier system must be continuous across the entire enclosure, air impermeable, strong, stiff, and durable. Some insulation materials, such as spray foam, may also be part of an air barrier system; whereas some materials, such as dense-packed cellulose (which was used in this study assembly), retard air flow but are too air permeable to be part of an air barrier system.

When dealing with air tightness, it is also important to consider both wind-washing 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 convect in the interstitial spaces of the wall assembly and re-enter into the interior. It is important to note that neither wind-washing nor re-entrant looping can be measured by an air tightness test.

A vapour barrier or retarder is used to control vapour from traveling through building materials by diffusion. Air and vapour control can be achieved with a single material or as separate materials. With respect to this study, a polyolefin membrane with polypropylene fibres was used as both the air and vapour barrier and was installed at the interface between the exterior deep studs and an interior framed wall. This was done so that services could be run on the interior without penetrating the air barrier layer.

With most experimental programs involving measurements of moisture profiles in wall assemblies, air and vapour control are the most critical to the monitoring results. It is important to note, however, that failure to adequately control precipitation will eventually result in the failure of almost any wall system, regardless of the design. This means that enclosure monitoring results that show good performance are not immune from failure should critical water management details be missed.

LITERATURE REVIEW

There is a collection of past published research on High-R wall assemblies in cold climates including measurement data of moisture in various wall assemblies. This research was conducted in a variety of locations, on many different types of wall assemblies. This review will highlight 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 2-7 and featured vented cladding systems.

Tsongas (1991) investigated the performance of wall assemblies in 86 homes in Montana and Washington State in climate zones 4, 5 and 6. There was a range of construction types, vapor control layers, and insulation types through the monitored regions. The study houses included some exterior insulated sheathing construction and some double stud wall construction. The exterior insulation 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 insulated sheathing were significantly drier than walls without exterior insulated sheathing. These walls were found to be drier because the insulated 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 in the wall cavity.

Arena et al (2013) monitored the hygrothermal performance of a high R-value, dense-packed cellulose, double stud wall in Boston, MA (climate zone 5A). Hygrothermal modelling was compared to measured data of a test house. The results showed that the hygrothermal simulation predicted lower sheathing moisture contents than were measured, even though the simulated relative humidity 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. Moisture content in the south walls of the test house remained below 20% throughout the year; however, peak moisture content in the north walls reached approximately 20% and had significant periods above 16%.

Lepage et al (2013) conducted a parametric hygrothermal study of high-performance wall assemblies in climate zones 2 to 7, representing a broad range of North American climates. The study used calibrated hygrothermal models to compare the moisture durability of high-R walls when subjected to various moisture loads, including air leakage and bulk water leaks. It found that under ideal circumstances, double-stud or deep-stud wall assemblies can perform well, but for even small amounts of induced air leakage, the moisture content can rapidly increase, resulting in compromised durability.

Ueno (2015) monitored a high R-value, dense-packed cellulose, double stud wall assembly in Devens, MA (climate zone 5). Field monitoring showed measured moisture contents greater than 30% with elevated interior relative humidity levels (40-50% RH) and measured moisture contents greater than 20% with controlled interior relative humidity levels (10-30% RH).

Smegal et al. (2016) compared the deep-stud wall assembly of the North Park Passive House to an exterior insulated wall assembly of a Passive House in Portland, Oregon. It was determined that all the measured moisture contents of the deep-stud wall assembly were higher than those of the exterior insulated wall assembly. The difference between the measured sheathing temperatures and the exterior temperatures were also much higher in the exterior insulated wall assembly compared to the deep-cavity wall assembly.

Trainor et al. (2016) conducted a field study on four full scale high R-value wall assemblies using both exterior insulated and deep-cavity wall systems in Waterloo, ON (border of climate zones 5 and 6). The walls were tested under as-built conditions along with simulations to test air leakage from the interior and rain leakage from the exterior. For the as-built conditions, the moisture content readings were measurably higher in the double-stud wall than the other test walls, but maintained below 20%. During the air leakage simulation, the double-stud wall reached a peak moisture content of approximately 30%. The exterior insulated walls did not appreciably change in moisture content after induced air leakage (<10% MC). During the rain leakage simulation, it was demonstrated that the double-stud wall was quicker to dry to pre-wetting moisture content levels in comparison with the exterior insulated walls. The mineral fiber exterior insulated wall dried at only a slightly slower rate than the datum 2x6 wall or the double-stud wall.

From the reviewed papers, it can be determined that deep-cavity or double-stud wall assemblies can have much higher moisture contents than other walls, which corresponds to a greater risk of moisture related durability issues. This is only slightly off-set by faster drying rates. Should wetted condition persists for a sufficiently long period, the safe moisture storage threshold may be surpassed, leading to biodeterioration.

MONITORING

North Park is a three-storey, multi-unit residential wood-framed building (MURB). The building was instrumented on both the north and south orientations on the second and third storeys to record the hygrothermal behaviour of the wall assemblies. North and south orientations often have very different experimental outcomes because of the solar influence on the south orientation.

Monitoring locations were instrumented with temperature, relative humidity and wood moisture content sensors at strategic locations to capture the hygrothermal behaviour of the wall assembly. The sensors were wired into a data acquisition system (Campbell Scientific CR1000) measured on 5 minute intervals and averaged hourly. The temperature sensors were 10k NTC glass-encapsulated thermistors (±0.2 °C); the relative humidity sensors were thermoset polymer capacitive sensors with onboard conditioning (±3.5%, from 10%–90% RH); and the moisture content sensors were corrosion-resistance and electrically insulated pins (± 3%, with temperature and wood species correction in accordance with the Garrahan equation (1988)). The techniques of installation are described by Straube et al (2002). The outdoor environmental conditions were derived from nearby meteorological station data.

Wall Assembly and Instrumentation

Two walls in two different suites were instrumented on the second and third levels, two on the north orientation (N2 and N3), and two on the south orientation (S2 and S3). Figures 1 and 2 show the approximate locations of the instrumentation. The interior conditions in each suite were measured in the common area and inside the master bedroom at ceiling height. A detailed cross section of the wall assembly showing the typical monitoring locations is shown in Figure 3.

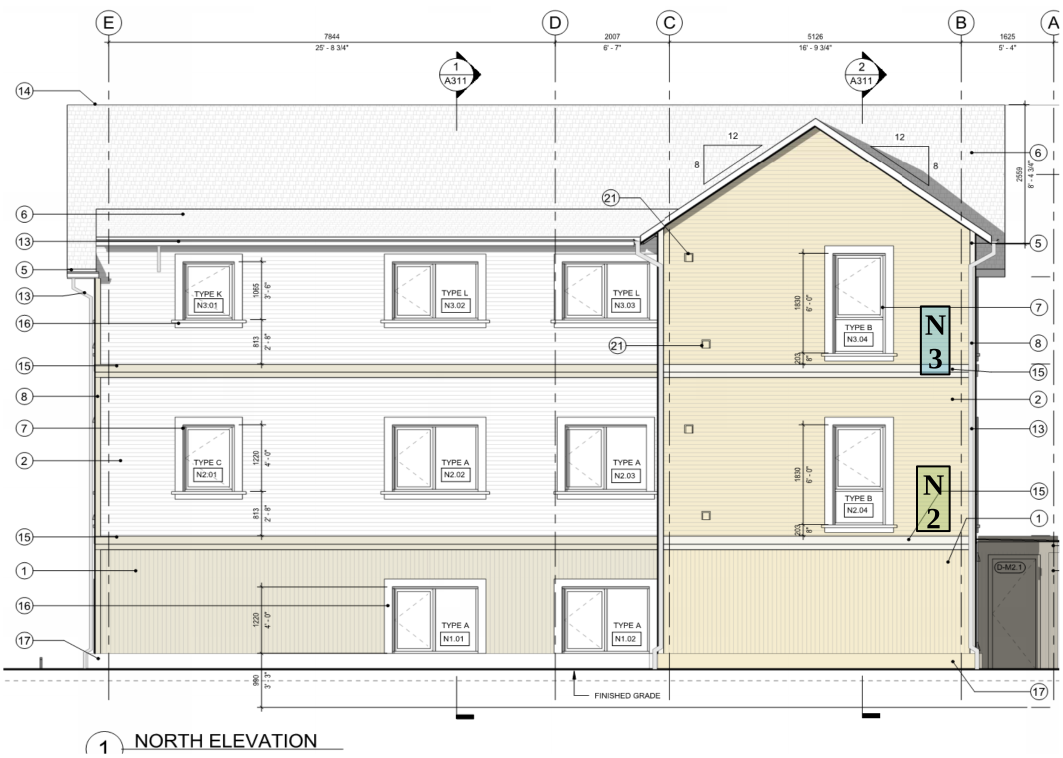

Figure 1: North elevation showing approximate locations for the instrumented enclosure sections. [1]

[1] The nomenclature for the assemblies follows the orientations (N or S) for the walls, followed by the floor level (2 or 3).

Figure 2: South elevation showing approximate locations for the instrumented enclosure sections. [1]

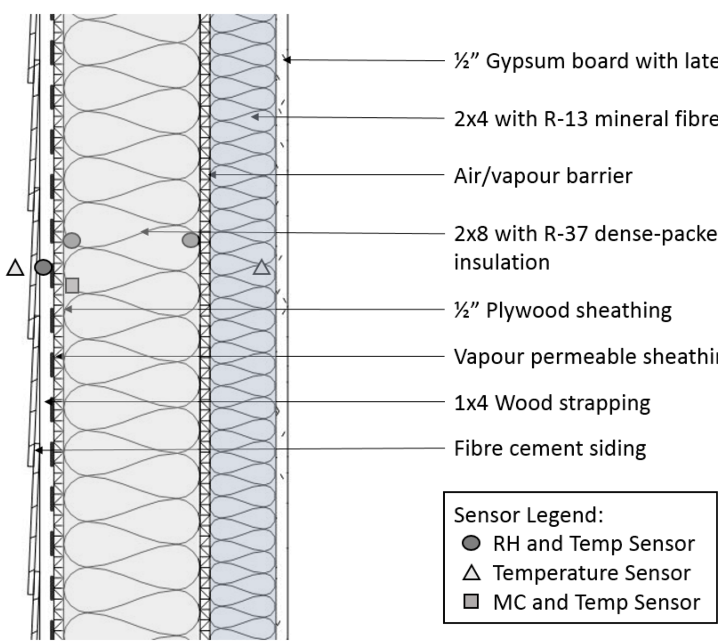

Figure 3: Detailed assembly and typical monitoring locations

RESULTS

Results were aggregated into the respective study locations (N2, N3, S2, and S3) and reviewed for broad level performance behaviour. Data were taken from January 1, 2016 until December 31, 2016 to form an entire 'study year', which was warmer and wetter than average. The critical relative humidity and temperature profiles for the four analyzed wall segments are provided in Figures 4 to 7. The sheathing temperature, vapour barrier temperature, and interior drywall temperatures provide the through-wall temperature profile and correlate proportionally to the level of insulation. By comparing the interior dew point temperature to the sheathing and vapour barrier temperatures, condensation risk and associated potential moisture damage can be estimated. The exterior and interior relative humidity across the deep-stud wall provides a general indicator of the risk of moisture related damage.

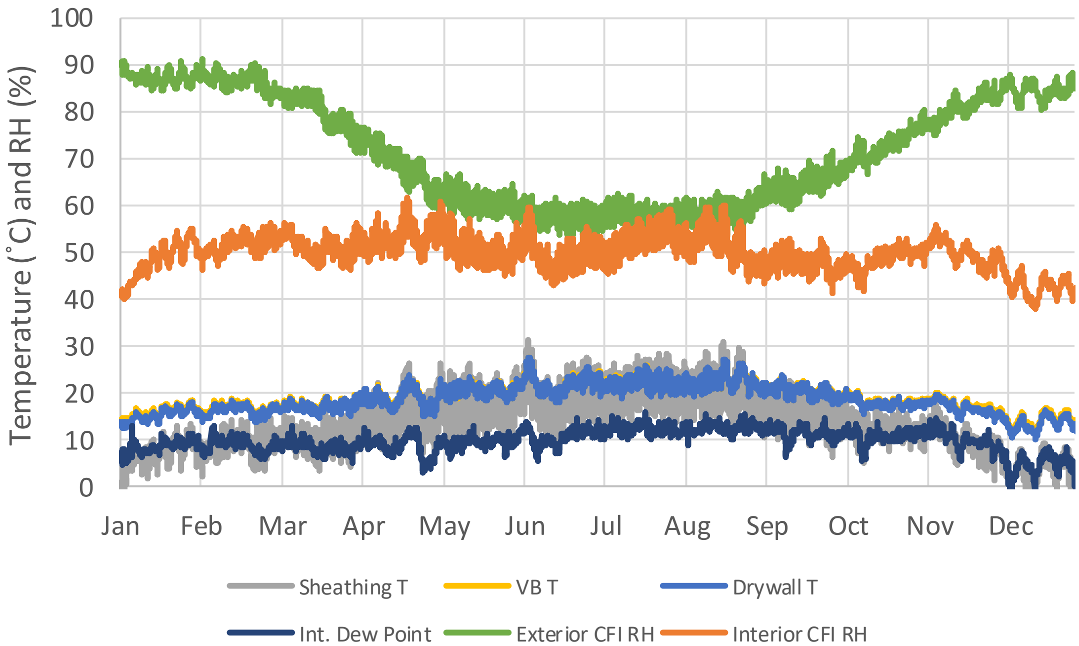

Figure 4: N2 wall data for Sheathing, Vapour Barrier (VB) and Drywall temperatures, including indoor air dew point temperature, and the exterior/sheathing and interior cellulose fibre insulation relative humidity from January to December, 2016.

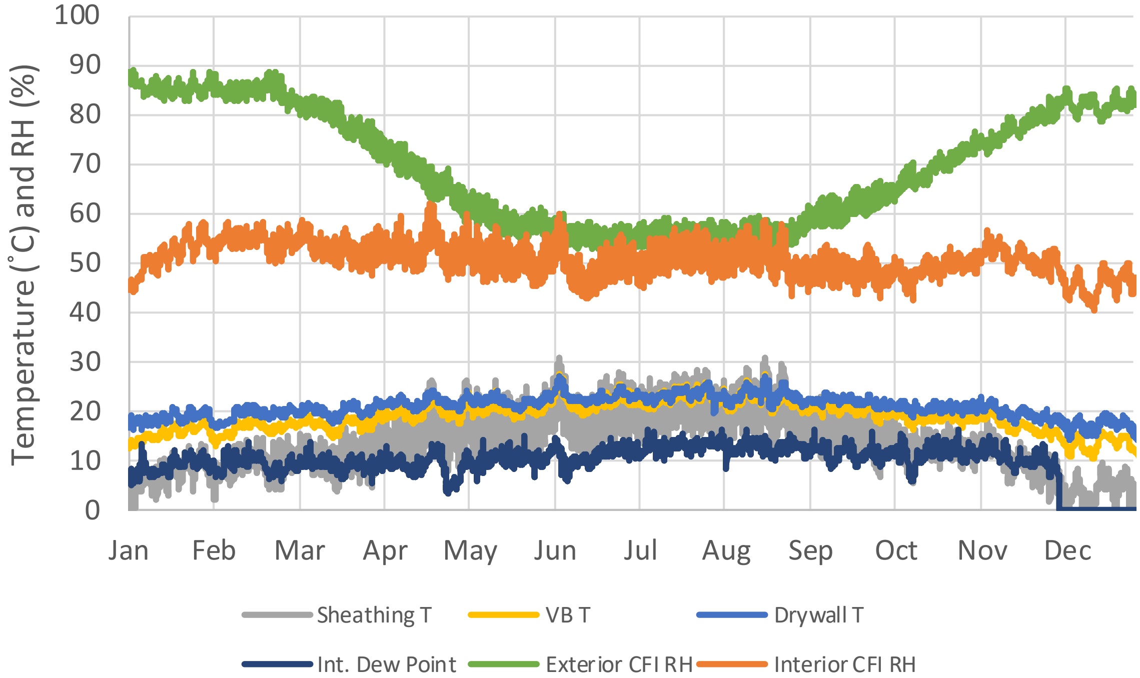

Figure 5: N3 wall data for Sheathing, Vapour Barrier (VB) and Drywall temperatures, including indoor air dew point temperature, and the exterior/sheathing and interior cellulose fibre insulation (CFI) relative humidity from January to December, 2016.

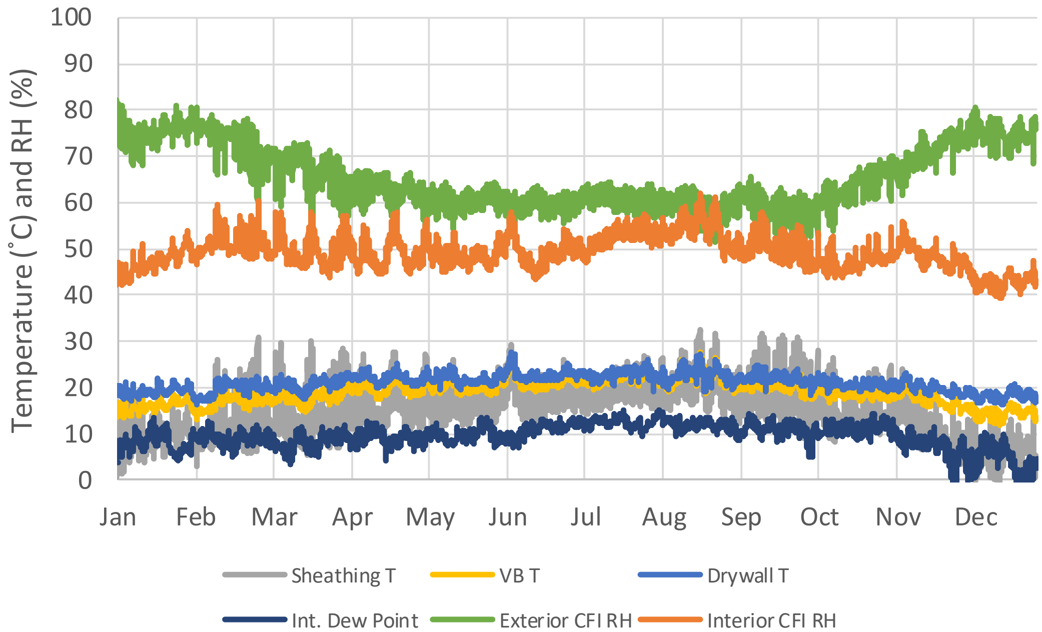

Figure 6: S2 wall data for Sheathing, Vapour Barrier (VB) and Drywall temperatures, including indoor air dew point temperature, and the exterior/sheathing and interior cellulose fibre insulation (CFI) relative humidity from January to December, 2016.

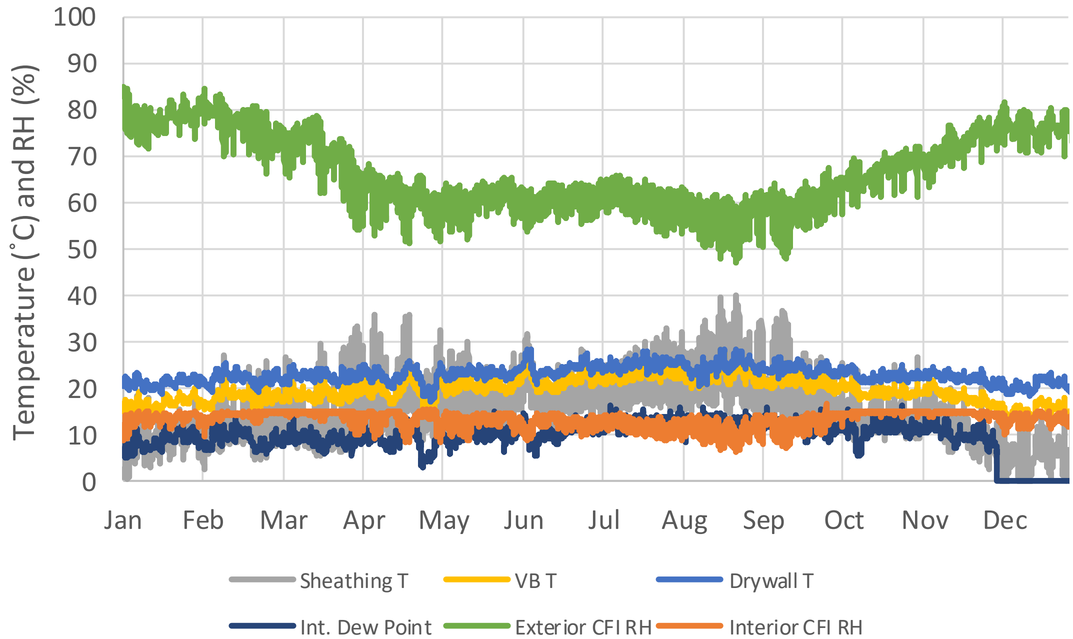

Figure 7: S3 wall data for Sheathing, Vapour Barrier (VB) and Drywall temperatures, including indoor air dew point temperature, and the exterior/sheathing and interior cellulose fibre insulation (CFI) relative humidity from January to December, 2016. The Interior CFI RH sensors is malfunctioning.

From Figures 4 to 7, the temperature of the vapour barrier remains above the interior dew-point at all times throughout the year. This indicates that there would be no risk of condensation from indoor moisture at the vapour barrier. The sheathing temperature however, does dip below the dew point temperature, particularly on the north walls. This indicates that there is potential for condensation to develop on the sheathing from exfiltrating air through the enclosure. However, the rigorous air leakage testing requirements of Passive House and the location of the air barrier within the assembly mitigate concerns of air leakage condensation.

From Figures 4 to 7, it can be seen that the relative humidity on the exterior of the insulation is higher in the north walls and that it is susceptible to higher variation in the south walls. These observations hint at the effects of inward driven moisture (e.g. moisture driven into the wall assembly by high outdoor vapour pressures) and to the general drying effect of a solar heated south elevation (i.e. with drier cellulose insulation on the south orientation).

By investigating the water vapour pressure across vapour absorbing or retarding materials (e.g. the plywood, cellulose, or vapour barrier) the direction of drying and wetting can be identified. The vapour pressure for the interior and exterior relative humidity sensors on either side of the cellulose insulation are shown in Figure 8. The sub-plot below shows the gradient, with negative values indicating an inward gradient, and positive values showing an outward gradient of flowing moisture.

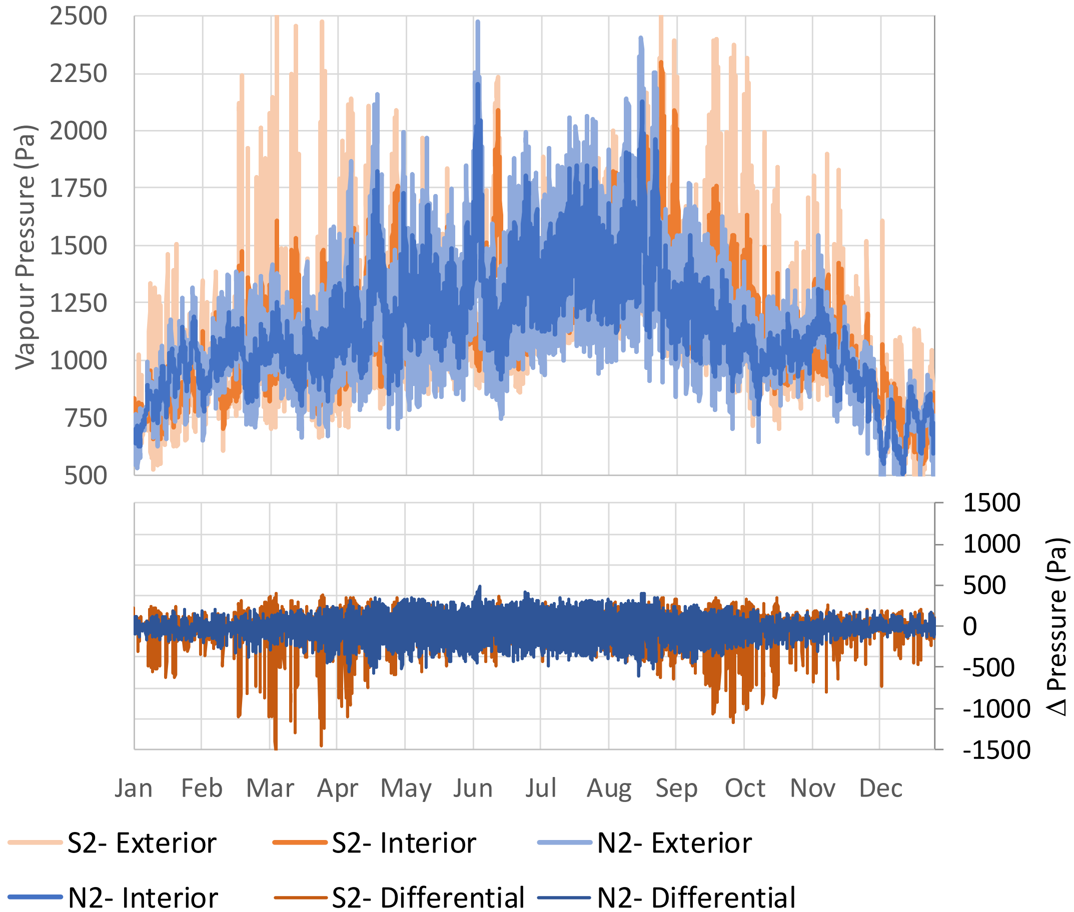

Figure 8: Cellulose Insulation Vapour Pressure and Vapour Pressure Gradients, for North and South Walls on Level 2.

The south walls experience significantly higher vapour pressure peaks than the north walls. This translates into higher peak inward vapour drives into the cellulose insulation, which appears to be abated by the hygroscopicity of the cellulose. Review of the pressure gradients provides an indication of direction of drying. In the swing seasons, the south orientation appears to have strong inward vapour gradients. These correspond to wetting events followed by sunny periods, which create high vapour pressures differentials forcing water through the sheathing and into the cellulose insulation. Despite a ventilated drainage cavity on light coloured cladding, vapour pressures drives exceeding 1500Pa were observed. The north elevation tends to a neutral pressure gradient, with a slight diurnal variation likely caused by temperature differences. These drying and wetting patterns affect the plywood sheathing moisture levels, and consequently the durability of the assembly.

The structural durability for wood sheathing is typically evaluated based on moisture content. Moisture contents exceed 25% are susceptible to rot and decay. A plot of the sheathing moisture content, for both the north and south orientation, is provided in Figure 9.

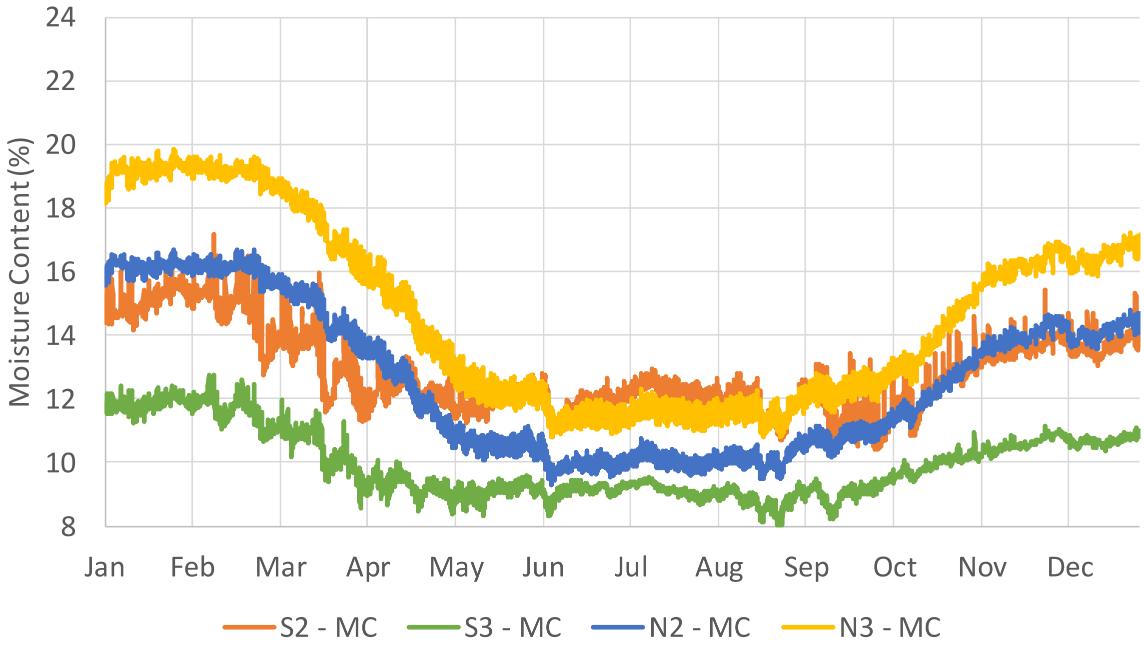

Figure 9: Sheathing Moisture Content (MC) for North and South Walls, on Levels 2 and 3.

The sheathing moisture contents are generally less on the south orientation than the north. This is due to higher temperatures caused by solar heating, which permits increased drying rates. An exception to this is the S2 assembly, which may experience greater cladding precipitation run-off from the S3 wall above that is subsequently driven in by solar vapour drives. The lowest threshold for superficial mould growth is around 16%, whereas the structurally damaging rot is known to occur when the plywood reaches the fibre saturation point, at around 25-28%. The sheathing moisture content of all locations fell below 20% for the entirety of the year and therefore does not appear to be at risk of rot. The sheathing moisture content on both the north orientation sensors did, however, have periods above 16%, which is above the lowest threshold for mould growth.

DISCUSSION

In colder climates, sheathing moisture contents or surface relative humidity are used as the performance criteria for mould growth. This is because it is the first possible location for surface condensation. There are several ways to assess moisture related durability of structural wood sheathing. The ASHRAE 160 "Criteria for Moisture-Control Design Analysis in Buildings" (ASHRAE 2009) uses a pass-fail evaluation, based on the IEA- Annex 14 standard (IEA, 1991), to minimize mould growth based on three criteria:

1) 30-day running average surface RH < 80% when the 30-day running average surface temperature is between 5˚C and 40˚C.

2) 7-day running average surface RH<89% when the 7-day running average surface temperature is between 5˚C and 40˚C.

3) 24-hour running average surface RH<100% when the 24-h running average surface temperature is between 5˚C and 40˚C.

However, these criteria have been found to poorly correlate to actual biological growth risk (Lstiburek, 2015). To help provide more accurate analysis, the results will be compared using the Finnish VTT Technical Research Centre's Improved Model to Predict Mold Growth in Building Materials (Viitanen, 2007). The recently revised ASHRAE 160-2016 has adopted a modified VTT approach. This model is based on empirical regressions of actual mould growth on building materials in varying climatic conditions. While the model results do not necessarily guarantee presence of mould, it does provide a greater degree of reliability than categorical limits. The VTT model output is a mould index, the extent summarized in Table 1. Mould index values less than 3 are generally not visible to the naked eye, and therefore mould indices greater than 3 are considered a fail.

Table 1 – Mould Index for the VTT Model (Viitanen, 2007)

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

A mould index of less than 1 would be deemed acceptable, as this constitutes only microscopic levels of mould which are not likely to generate spores that can affect human health. Figure 10 was produced by incorporating the temperature and relative humidity data and assuming pristine plywood (mould growth index of 0).

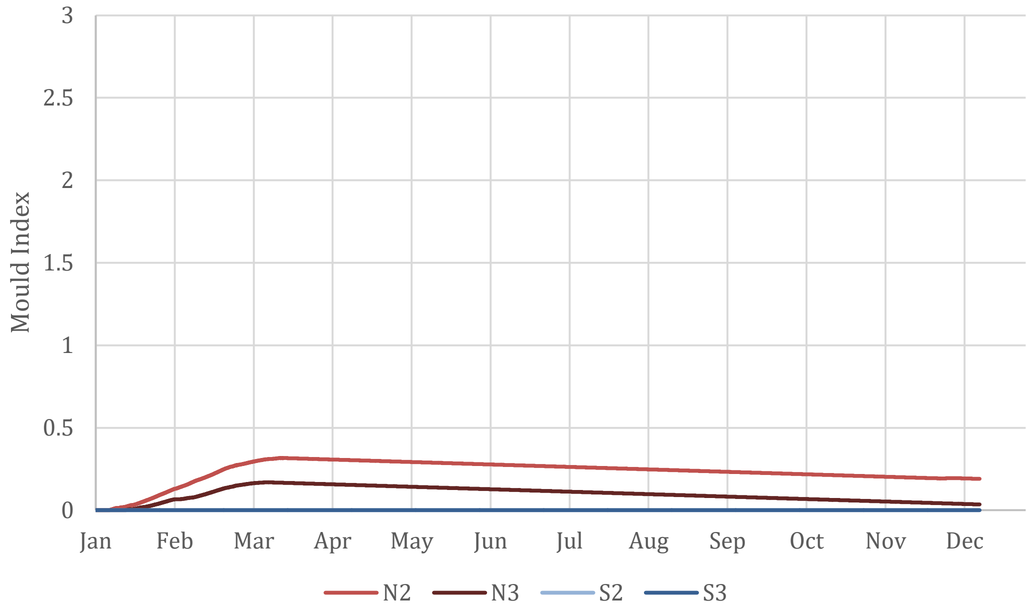

Figure 10: VTT Mould Index for N2, N3, S2, and S3 walls

From Figure 10, models for the S2 and S3 walls were shown to have no mould growth due a lack of moisture. The north walls, however, were modeled to be sufficiently cool and humid that microscopic mould growth could occur. Over the one year monitoring period, a slight increase in predicted microscopic growth was calculated during the spring season as the humidity increases concurrently with temperatures creating conditions suitable for mould growth. Despite the N3 wall having a higher moisture content, the combination of temperature and relative humidity in the N2 wall were both sufficiently high that the N2 wall appears to have a marginally higher mould index. In the model, the summers were sufficiently dry that the plywood sheathing in both N2 and N3 dried out and the mould went into stasis. To determine the maximum mould growth condition the model was run iteratively until the starting and final mould indices for the modeled year were approximately equal. The results, including the number of iterations (i.e. years), are provided in Figure 11.

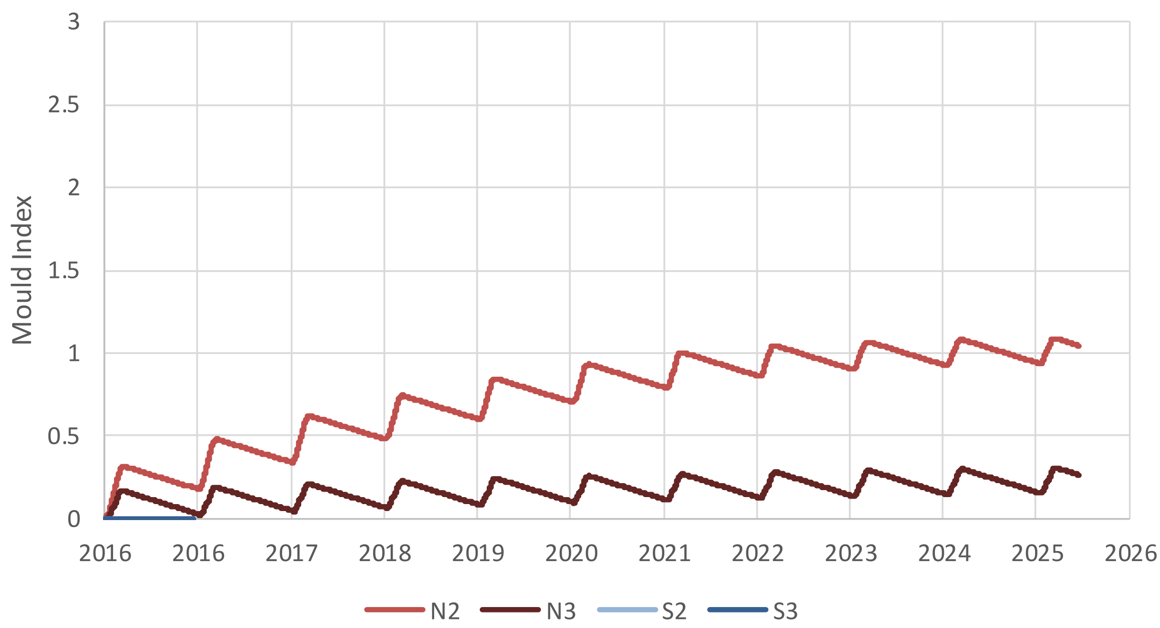

Figure 11: Maximum Supportable Mould Conditions for North and South Walls on the 2nd and 3rd Storeys

The iterative simulations suggest that after about a decade, a mould growth index of around 1 could be anticipated for the N2 wall and around 0.25 for the N3 wall. This assumes that each year is identical to the measured year. This suggests that localized initial stages of growth may be found microscopically, but would not pose a durability risk to the structure. Risks to human health would also be limited, as the air barrier system of a Passive House is rigorously tested and would thus significantly inhibit any spore or fungal cell laden air movement across the air barrier assembly.

A strategy to help further minimize this risk of mould growth is to keep the sheathing slightly warmer. The slight temperature increase of the south elevation was sufficient to have virtually zero risk of mould growth. This could be accomplished by adding insulation to the exterior of the sheathing. This was investigated and supported in a research paper by Smegal et al. (2016). Despite the vapour resistance of the plywood sheathing, the effects of inward driven moisture were measurable on the exterior side of the vapour barrier. A more permeable exterior layer would therefore permit greater inward vapour flows, which could result in condensation against the exterior side of the vapour barrier.

CONCLUSIONS

The hygrothermal performance of the deep-stud wall assembly of the North Park Passive House was evaluated based on numerous factors. It was determined that the temperature of the vapour barrier remained above the interior dew-point at all times throughout the year; however, the sheathing temperature dropped below the dew point temperature at various points throughout the year. This indicates that there is potential for condensation to develop on the sheathing from exfiltrating air. The moisture content of the sheathing for all walls was maintained below 20% at all times throughout the year. This indicates that the walls are not at risk of rot. The moisture contents of the north walls did have periods above 16% which is above the lowest threshold for mould growth. Fungal modelling estimates that after about a decade, a maximum mould index of around 1 is anticipated for the north wall. This means that localized initial stages of growth may be found microscopically, but would likely not pose a durability risk to the structure or an appreciable risk to human health.

REFERENCES

Arena, L., Owens, P., & Mantha, P. 2013. Measured performance of an R-40 double-stud wall in climate zone 5A. Thermal Performance of the Exterior Envelopes of Whole Buildings XII International Conference, Clearwater, FL.

Environmental Protection Agency (EPA). 2017. “Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2015.” EPA 430-P-17-001. https://www.epa.gov/sites/production/files/2017-02/documents/2017_complete_report.pdf.

Fox, M., Straube, J., Ge, H., and Trainor, T. 2014 Field test of hygrothermal performance of highly insulated wall assemblies. Presented at the Canadian Conference on Building Science and Technology, Toronto, ON, October 28-30.

Garrahan, Peter. 1988. “Moisture Meter Correction Factors.” In In-Grade Testing of Structural Lumber. Madison, WI.

Handegord, G.O.P., “Prediction of the Moisture Performance of Walls”, ASHRAE Transactions Vol 91, Part 2, 1985.

IEA. 1991. Sourcebook, Report of Annex XIV, Volume 1. Leuven, Belgium: International Energy Agency

Kane, R., and Titley, G. 1987. Case histories of moisture monitoring in residential walls. Thermal Insulation: Materials and Systems, ASTMSTP 922, 615-629.

Lepage, R., Schumacer, C., Lukachko, A., 2016. Moisture Management for High R-Value Walls, Building America Report. Golden, CO: National Renewable Energy Laboratory

Lstiburek, J, Ueno, K, Musunuru, S. 2015. Modeling Enclosure Design in Above Grade Walls, Building America Report, Gaithersburg, MD: National Renewable Energy Laboratory

Smegal, J., Lepage, R., Schumacher, C., 2016. Moisture-Related Durability of In-Service High-R Wall Assemblies in Pacific Northwest Climates, Thermal Performance of the Exterior Envelope of Buildings XIII, Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc.

Straube, John. "BSD-163: Controlling Cold-Weather Condensation Using Insulation". Building Science Digests. Building Science Corporation., 2011.

Straube, J.F. , Onysko, D., and Schumacher, C. "Methodology and Design of Field Experiments for Monitoring the Hygrothermal Performance of Wood Frame Enclosures" J. Of Thermal Insulation and Building Envelopes. Vol 26, No. 2, October, 2002, pp. 123-151.

Trainor, T.M., Smegal, J., Straube, J., and Parekh, A. 2016. Measured and Predicted Moisture Performance of High-R Wall Assemblies in Cold Climates. Thermal Performance of the Exterior Envelopes of Whole Buildings XIII International Conference, Clearwater, FL.

Ueno, K. 2015. Monitoring of double-stud wall moisture conditions in the northeast. Building America Report. Gaithersburg, MD: National Renewable Energy Laboratory.

Viitanen, H. and T. Ojanen; 2007. Improved Model to Predict Mold Growth in Building Materials. Proceedings: Thermal Performance of the Exterior Envelopes of Buildings X. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2007.