ABSTRACT
This study aimed to generate hygrothermal and durability-related performance data for light-wood-frame walls meeting the RSI 3.85 (R-22) requirement for buildings up to six storeys in the City of Vancouver. Twelve wall panels in six types of assemblies and three orientations were tested, using a test hut in FPInnovations' Vancouver laboratory. These six walls consisted of different insulation strategies/materials and interior vapour control layers. Walls No. 1 and No. 2 represented deep cavity walls, insulated in their stud cavities with glass fibre batt and open-cell spray foam, respectively. Walls No. 3 – No. 6 were split-insulated assemblies, using exterior insulation of rigid stone wool, extruded polystyrene, foil faced-polyisocyanurate, and expanded polystyrene, respectively. Walls No. 1, 3, and 4 had sheet polyethylene and walls No. 2 and 5 used a vapour-retarding paint for interior vapour control. Aside from vapour diffusion, water injection was conducted to stress the walls to investigate their moisture-related behaviour.

Data collected from October 2018 to May 2020 are presented in this paper. The test confirmed that the split-insulated walls had warmer OSB sheathing and were therefore less likely to have vapour condensation; vapour-permeable exterior insulation facilitated drying towards the exterior and may therefore reduce durability risks. For walls No. 2 and No. 5, the interior vapour-retarding paint coupled with the wall's drying capacity did not provide sufficient protection against wetting caused by outward vapour migration under the test conditions. No OSB sheathing showed visible mould growth resulting from outward vapour diffusion, although the mould prediction based on the standard ASHRAE 160 suggests walls No. 2 and No. 5 in the north orientation should have shown mould growth by the end of the test. Wall No. 5 (in north/south orientations) showed mould growth on the exterior surface of its OSB sheathing in and around the wetting pad, suggesting poor drying after water injection.

HYGROTHERMAL PERFORMANCE TESTING OF R-22 WOOD-FRAME WALLS IN THE VANCOUVER CLIMATE

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INTRODUCTION

New building energy regulations are being implemented at an accelerated pace across Canada to meet the mandates of governments to reduce energy consumption and greenhouse gas emissions. In the Province of British Columbia, the BC Energy Step Code was enacted in April 2017 to transform the new construction of both Part 9 and Part 3 buildings with the aim of achieving net-zero energy ready buildings by 2032. Given the adoption of the overall "envelope first" approach, the building envelope must be built to be highly airtight and thermally efficient to meet the new energy code requirements. The City of Vancouver has required RSI 3.85 (R-22 effective) for above-grade and foundation walls of residential buildings up to six storeys (BC Housing 2017). This would require additional insulation, often exterior insulation over a traditional wood-frame wall, or a deeper stud or double-stud wall. While measures of increasing the overall thermal resistance of exterior walls and the general impact of adding insulation (e.g., cavity insulation, exterior insulation) on the hygrothermal performance of conventional wood frame walls were well understood, moisture-related performance data about RSI 3.85 (R-22) walls in the Vancouver climate were needed to identify potential negative consequences of added thermal insulation and various vapour control measures, confirm acceptance of designs under current building code requirements, validate design tools, and improve specifications. FPInnovations therefore initiated in 2018 a test of six types of light wood-frame walls that meet the RSI 3.85 (R-22) requirement using a test hut located at its Vancouver site. The work primarily aimed to improve the designs of R-22 wood-frame walls, which can be used in both Part 9 and Part 3 buildings and to ensure their long-term durability performance in service. Nineteen months' data, together with implications for wall designs are presented in this paper.

MATERIALS AND METHODS

In this study, a total of 12 light-wood-frame test wall panels, each measuring 1200 mm (4 ft.) wide and 2400 mm (8 ft.) tall, were installed at the test hut. One replicate of the walls (No. 1-No. 5) was installed north-facing (i.e., wall panels N1-N5), while a second replicate was installed south-facing (i.e., wall panels S1-S5). Walls No. 3 (wall panel E1) and No. 6 (E2) were installed to face east, with wall No. 3 serving as a reference wall for these three orientations (Figure 2). Installation took place from June to August 2018.

FIGURE 1: Exterior of the Finished Test Hut

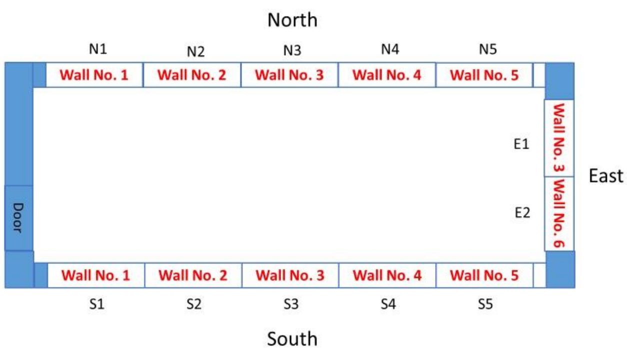

FIGURE 2: Layout of 12 Test Wall Panels, in Six Wall Assemblies and Three Orientations at the Test Hut

Among the six test wall assemblies, the thermal insulation type(s) and location(s) as well as the coupled interior vapour control layers were the major variables. The details of the wall assemblies are summarized in Table 1. Walls No. 1 and No. 2 represented deep-stud walls. No. 1 was similar to a traditional wall with its 38 mm by 184 mm (nominal 2 in. by 8 in.) stud cavities filled with RSI 4.9 (R-28) glass fibre batt insulation. No. 2's double-stud wall cavities were filled with a highly vapour-permeable, 8 kg/m^3 (0.5-pcf) open-cell spray polyurethane foam (ocSPF). The other four types of walls were split-insulated assemblies, differing only in the exterior insulation, which was rigid stone wool (38 mm (1.5 in.) thick) in wall No. 3, extruded polystyrene (XPS, 25 mm (1 in.)) in No. 4, foil faced-polyisocyanurate (polyiso, 25 mm (1 in.)) in wall No. 5, and expanded polystyrene (EPS, 38 mm (1.5 in.)) in No. 6. They all meet Clause 9.25 of Division B of the National Building Code of Canada on outboard to inboard thermal insulation ratio requirement (0.2) to prevent vapour condensation for the climate of Vancouver. The vapour permeance decreases from the stone wool, EPS, XPS, to the foil faced-polyiso. For controlling outward vapour diffusion, a vapour-retarding paint was applied on walls No. 2 and No. 5 and a 6-mil polyethylene (poly) vapour barrier was installed on the interior side in the other four walls. The test walls had the same drywall (12.7 mm (1/2 in.) in thickness), oriented strand board (OSB) exterior sheathing (11 mm (7/16 in.) in thickness), exterior water-resistive barrier (a plastic membrane permeable to water vapour), and cladding (painted hardboard siding), which was installed on 19 mm by 38 mm (nominal 1 in. by 2 in.) battens to create a rainscreen cavity.

<table>
<tr><th>Wall No.</th><th>Interior vapour control</th><th>Framing</th><th>Stud cavity insulation</th><th>Exterior insulation</th><th>Effective RSI (R)</th></tr>
<tr><td>1</td><td>Poly vapour barrier</td><td>38 mm x 184 mm @ 400 mm o.c. (2x8 @ 16" o.c.)</td><td>RSI 4.9 (R-28) glass fibre batt</td><td>--</td><td>3.9 (22.4)</td></tr>
<tr><td>2</td><td>Vapour-retarding paint on foam, on drywall*</td><td>38 mm x 89 mm @ 400 mm o.c. (2x4 @ 16" o.c.) double stud with a 6 mm (¼") gap</td><td>ocSPF</td><td>--</td><td>3.9 (22.4)</td></tr>
<tr><td>3</td><td rowspan="2">Poly vapour barrier</td><td rowspan="4">38 mm x 120 mm @ 400 mm o.c (2x6 @ 16" o.c.)</td><td rowspan="4">RSI 3.5 (R-20) glass fibre batt</td><td>Rigid stone wool (RSI 1.1 (R-6)), vapour permeance of 1200 ng/(Pa·s·m^2) (21 US perm)</td><td>4.1 (23.0)</td></tr>
<tr><td>4</td><td>XPS (RSI 0.88 (R-5)), vapour permeance of 87 ng/(Pa·s·m^2) (1.5 US perm)</td><td>3.9 (22.0)</td></tr>
<tr><td>5</td><td>Vapour-retarding paint on drywall</td><td>Foil faced-polyiso (RSI 1.1 (R-6.2)), vapour permeance near 0</td><td>4.1 (23.2)</td></tr>
<tr><td>6</td><td>Poly vapour barrier</td><td>Type 2 EPS (RSI 1.1 (R-6)), vapour permeance of 130 ng/(Pa·s·m^2) (2 US perm)</td><td>4.1 (23.0)</td></tr>
</table>

TABLE 1: Summary of Six Test Wall Assemblies

(Note: "o.c." means "on centre". For wall panels N2 and S2, there was a vapour-retarding paint initially applied on the foam and another vapour-retarding paint was applied on the drywall on November 26, 2019 to increase the wall's resistance to outward vapour diffusion after the initial test results.**)**

The performance evaluation focused on the OSB sheathing as it was the most sensitive component to moisture accumulation in this study. Considerable effort was made to measure the OSB's moisture content (MC) and service environment (i.e., temperature and relative humidity (RH)). Six pairs of resistance-based moisture pin sensors, labelled from O1 to O6, were inserted into the OSB sheathing from its interior surface to measure the MC. The pins were installed at six heights (from top to bottom): 2250 mm (90 in.), 1200 mm (48 in., i.e., at mid-height), 580 mm (23 in.), 475 mm (19 in.), 360 mm (14 in.), and 150 mm (6 in.) from the bottom, respectively. The moisture pins were uncoated stainless screws and each pair had a combined temperature probe to measure the local temperature for correcting the MC readings. A small calibration study was conducted to compare the MC measurements to oven dry-based gravimetric MC under four humidity conditions for the batch of OSB used. Due to the large variation between and within OSB panels, it was later decided to use a calibration equation generated for OSB by the US Forest Products Laboratory based on very large sample sizes that took into account the effects of both temperature and humidity (Boardman et al. 2017). In addition to the moisture sensors, four RH/T sensors, labeled from RH/T1 to RH/T4, were installed to measure changes in temperature and RH across each wall assembly. Sensor RH/T1 was installed at mid-height in the rainscreen cavity, RH/T2 (at mid-height) and RH/T3 (at a height of 600 mm (24 in.)) were on the interior surface of the OSB sheathing, and RH/T4 (at mid-height) was behind the drywall. Further information about the test can be found in the final report of this study (Wang 2021).

The test hut was maintained at a relatively high indoor RH of around 50% at a temperature of 21°C. The walls were further stressed by injecting water through a small tube into a wetting pad pre-built on the exterior surface of each OSB sheathing, based on a method originally developed by Dr. John Straube and his team at the University of Waterloo (Smegal et al. 2012). Fixed amounts of water were injected in the 1st summer (July) and the 2nd winter (November, January) to assess the wall's drying capacity. Conditions in the service environment control the wood's MC and provides implications about its long-term durability. For example, fungi will thrive on many materials including wood under warm and damp conditions; an RH of 80% in a warm environment (e.g., 20-30°C) is commonly taken as the threshold for initiation of mould growth on wood-based products (Viitanen and Paajanen 1988). Prolonged dampness may even cause wood decay and corrosion of fasteners, compromising structural integrity. A study by FPInnovations showed that the MC of kiln-dried lumber, plywood, and OSB needed to rise to approximately 26% for decay fungi to initiate at the temperature of 20°C; it then took months at this MC level for detectable strength loss to occur (Wang et al. 2010).

RESULTS AND DISCUSSION

EFFECT OF ORIENTATION

Orientation has a large effect on a building envelope's hygrothermal performance. The measurements of temperature and RH from the OSB sheathing's interior surface of wall No. 3 confirmed that the sheathing remained the warmest and driest in the south-facing wall panel (S3) and the coldest and dampest in the north-facing wall panel (N3), with the east between these two orientations (Figure 3). This is due to the north-facing assemblies receiving lower levels of solar irradiance. As a result, they are most likely to experience durability-related issues.

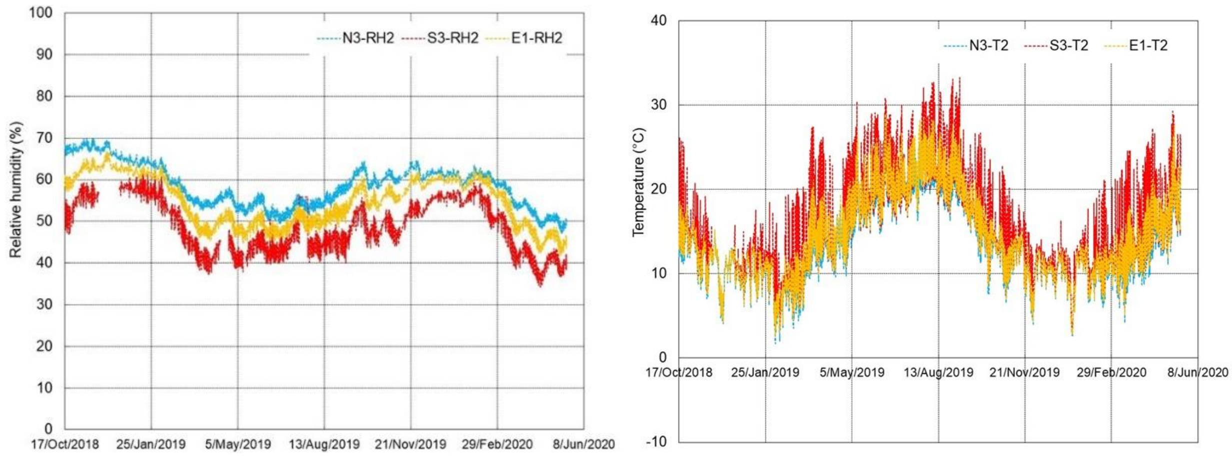

FIGURE 3: Relative Humidity (RH2, left) and temperature (T2, right) on OSB's Interior Surface of Wall No. 3 (North-Facing N3 (Blue), South-Facing S3 (Red), and East-Facing E1 (Yellow))

EFFECT OF EXTERIOR INSULATION ON SHEATHING TEMPERATURE

Exterior insulation keeps the sheathing warmer. Comparing a split-insulated test wall (e.g., wall No. 3) to a deep-cavity wall without exterior insulation (e.g., No. 1), both in the north orientation, the OSB sheathing of wall panel N3 was warmer than that of wall panel N1 by approximately 2-4°C in the winter. As a result, exterior insulation may reduce vapour condensation potential when there is air exfiltration from the indoor humid space. Comparing the temperature of the sheathing (interior) with the dew point of the indoor air, Figure 4 shows walls No. 1 and No. 2, without exterior insulation, would have very high potential of vapour condensation, which could occur approximately 40% of the year in the north orientation if there is air exfiltration. The condensation potential is the highest in the winter when the sheathing is the coldest. By comparison, the split-insulated walls (e.g., No. 3 thru No. 6) had greatly reduced vapour condensation potential (10-20%) due to their warmer sheathing.

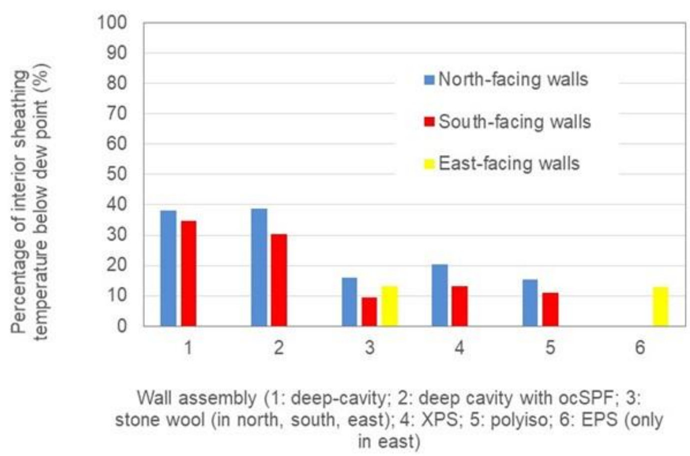

FIGURE 4: Percentages of Sheathing's Interior Surface Temperature Falling below the Indoor Air's Dew Point for Six Test Walls in Three Orientations over the Year of 2019

RELATIVE HUMIDITY AT SHEATHING

The test showed the indoor vapour control method (i.e., poly vapour barrier or vapour-retarding paint used in this test) had a large impact on the RH in the service space next to the sheathing by controlling outward vapour diffusion. In addition, the vapour permeance of exterior insulation also matters since it influences the drying capacity towards the exterior. Among the five north-facing wall panels (Figure 5 showing the RH measured at the sheathing's interior surface of both north-facing and south-facing walls), wall panel N2's sheathing overall had the highest RH, followed by wall panel N5. The RH levels in these two walls consistently remained above 80% during the two winter seasons, indicating a high risk of mould growth on the sheathing. The vapour-retarding paints used in these two walls did not appear adequate in controlling outward vapour diffusion. By comparison, the other three wall panels (N1, N3, and N4), all with poly vapour barriers, had RH measurements consistently below 80%. The humidity levels in the five south-facing counterparts showed a similar pattern but were generally lower and had larger fluctuations. The two east-facing walls (No. 3 and No. 6) both showed RH measurements below 80%. This test confirmed an adequate interior vapour control layer would remain important for the building envelope in Vancouver's mild climate, particularly for relatively humid buildings (e.g., with an indoor RH of around or above 50% in the winter).

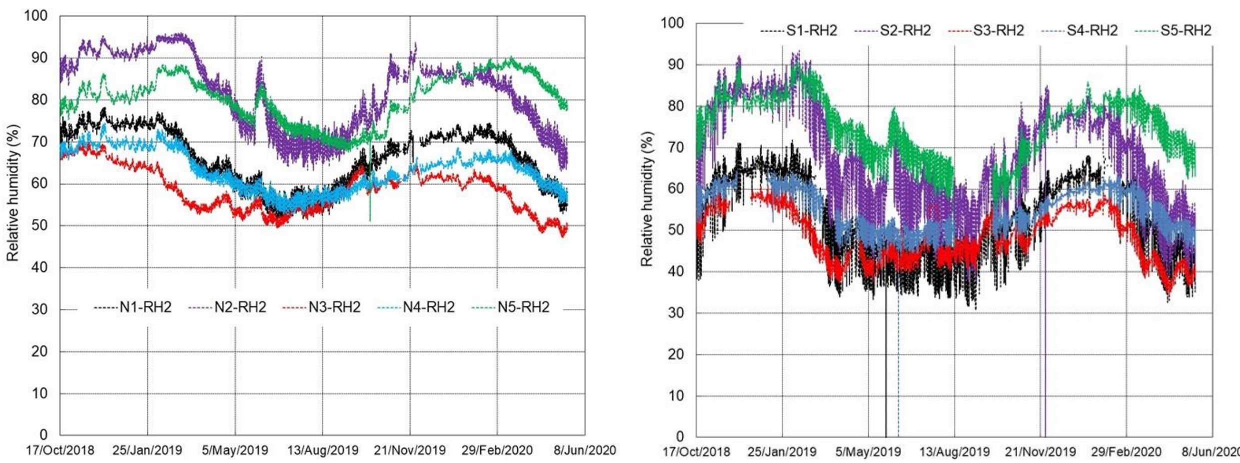

FIGURE 5: Relative Humidity (RH2) Measured at Sheathing's Interior Surface in Five North-Facing (left) and South-Facing (right) Wall Panels (N1 (Black), N2 (Purple), N3 (Red), N4 (Blue), and N5 (Green))

WOOD MOISTURE CONTENT

The MC of wood provides a direct indication about durability risk. In the test, the OSB sheathing's MC was measured using moisture pins installed from its interior surface to the mid-depth to avoid direct impact of liquid water when water was injected into the wetting pad on the sheathing's exterior surface. The MC measurements based on three sensors (i.e., sensors O3, O4, and O5) installed in the same area where the wetting pad was installed are used in Figure 6 to show the drying performance of the selected four wall panels. For test wall panel N1, its OSB sheathing had MC readings just slightly above 11% in the 1st winter when there was no water injection. It dried quickly when water was injected in the summer. Its MC mostly remained below 16% after water was injected in the 2nd winter. Being built airtight together with the interior poly vapour barrier, this deep wall assembly had good drying performance towards the exterior following water injection during both summer and winter, indicating an acceptable level of tolerance against exterior moisture ingress, typically caused by rain penetration in field. Wall panel N3's sheathing had MC below 8% in the 1st winter. Its peak MC readings remained below 16%, followed by quick drying after each phase of water injection. With the interior poly vapour barrier to prevent wetting from the high indoor humidity and the highly vapour-permeable stone wool exterior insulation to facilitate drying towards the exterior, this wall is expected to be durable and tolerant of extra moisture loads in building service.

For wall panel N4, its OSB sheathing's MC remained below 10% in the 1st winter. Its peak MC measurements approached 18% following each phase of water injection. The drying was slower in the winter than in the summer, and slower than wall panel N1 or N3 but remained acceptable. The 25 mm (1 in.) thick XPS has a dry-cup vapour permeance, according to the manufacturer, of about 87 ng/(Pa•s•m²) (about 1.5 US perm), above the threshold of 60 ng/(Pa•s•m²) (about 1 US perm) specified by the Canadian building codes for a vapour barrier material. However, in wall No. 5 with a vapour-retarding paint on the drywall and vapour-impermeable foil-faced polyiso exterior insulation, the test showed moisture accumulation with the MC reaching almost 16% in the 1st winter. When water was injected in the 1st summer, the highest MC exceeded 22% but the sheathing dried slowly in warm weather. Following the two water injections in the 2nd winter, the peak MC reached about 20% and then remained stable, not showing drying until May, when it was warmer. Note there was difficulty in injecting water into this wall panel in the 2nd winter; otherwise, the MC measurements would very likely have been higher.

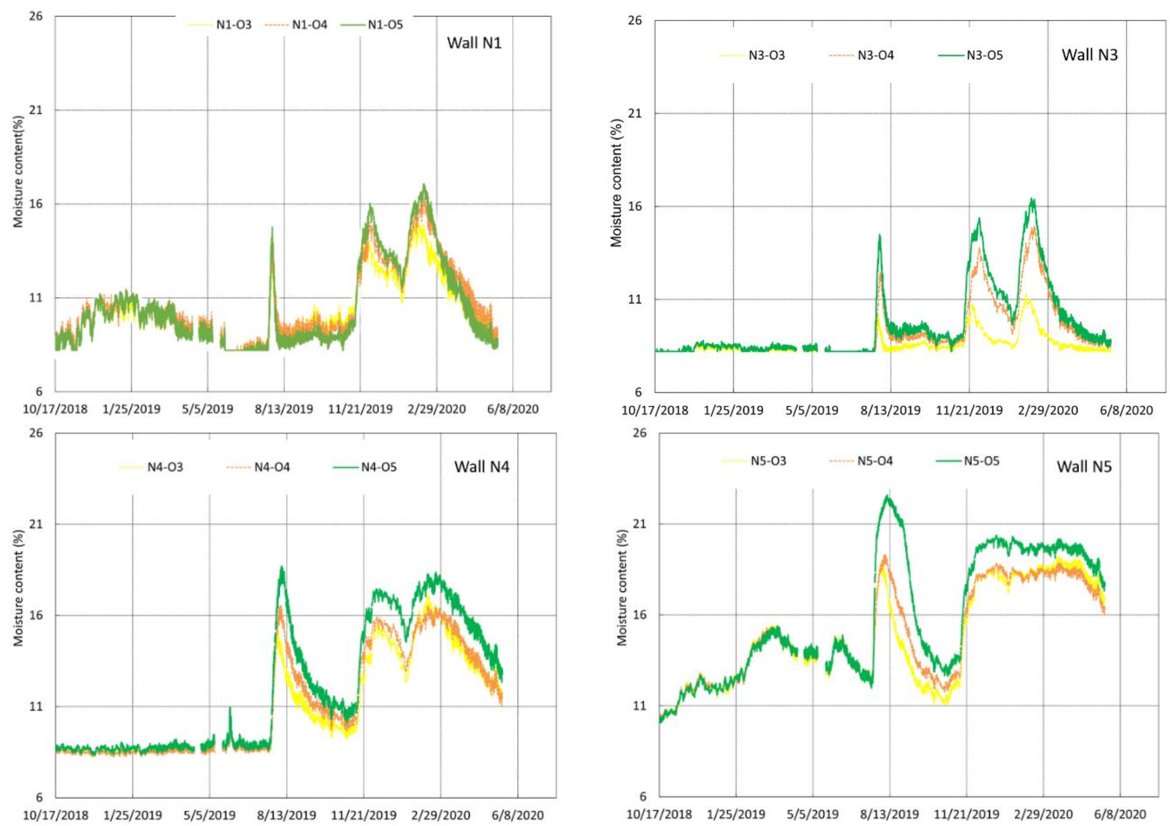

FIGURE 6: Moisture Content Measured from OSB Sheathing's Wetting Pad Area based on Three Sensors (labelled as O3, O4, and O5) in Wall Panels N1, N3, N4, and N5

MOULD GROWTH PREDICTION AND OBSERVATION

A mould index (MI) was calculated based on the measurements to predict mould growth potential of the OSB sheathing of these test walls according to the standard ASHRAE 160 (2016). The MI is designed to range from 0 (i.e., no mould growth) to 6 (i.e., with the surface fully covered with mould), and a rating of 3 indicates visible mould growth on the surface. The standard classifies building materials into four sensitivity classes: Very Sensitive (e.g., untreated wood), Sensitive (e.g., wood-based boards), Medium

Resistant (e.g., cement or plastic), and Resistant (e.g., glass or metal) as different levels of susceptibility to mould growth (Viitanen and Paajanen 1988).

Using hourly temperature and RH measurements from the OSB sheathing's interior surface (from its mid-height to exclude impact of the intentional water injection) during the 19-month test and assuming the OSB sheathing was either "Very Sensitive" or "Sensitive", the MI calculations found that only walls No. 2 and No. 5 had calculated MI over 0, indicating their service environments were favourable for mould growth at least for some time during the test. However, a MI rating exceeding 3.0 was found only in the case of wall panel N2 when the sheathing was assumed to fall into the "Very Sensitive" class (Figure 7). The MI value of wall panel N2 increased almost linearly after the test started in October and exceeded 4.0 after the 1st winter. It then dropped slowly in warmer and drier weather. The continued decrease in the 2nd winter, in contrast to quick increase in the 1st winter, was likely attributable to the increased vapour resistance of the wall's interior side after its drywall was repainted with another vapour-retarding paint in November 2019. In terms of wall panel N5, its MI exceeded 2.9 when the test was finished in May 2020. It is likely its MI would have exceeded 3.0 if the test had lasted longer.

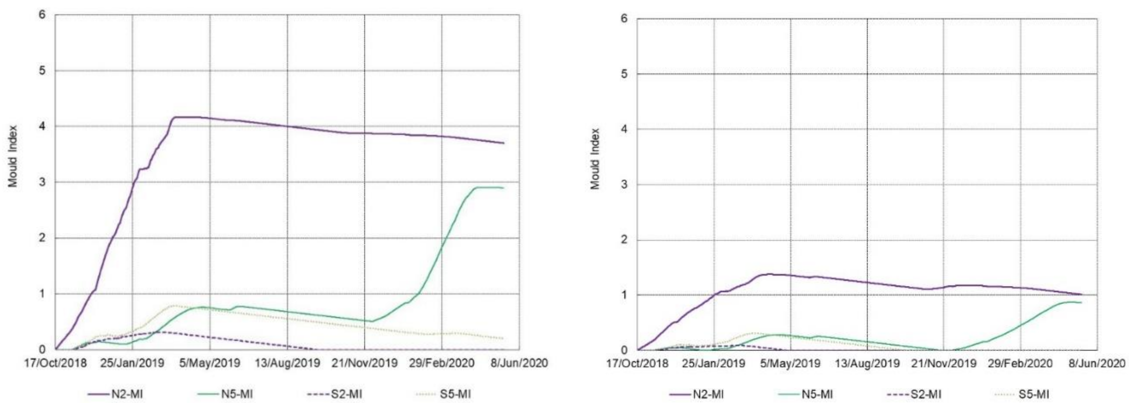

FIGURE 7: Calculated Mould Index, Assuming "Very Sensitive" (Left) and "Sensitive" (Right) as the Sensitivity Class and Using Temperature/Relative Humidity Measured from the Sheathing (Interior Surface) of Walls No. 2 and No. 5 (Wall Panels N2 (Purple, Solid), S2 (Purple, Broken), N5 (Green Solid), and S5 (Green, Broken))

When the wall panels were carefully checked upon deconstruction in July-August 2020, the interior surface of each OSB sheathing including that of wall panels N2 and N5 was clean, without visible mould growth. For wall No. 2, the spray foam appeared to seal the entire interior surface of the sheathing and may have prevented mould growth by reducing oxygen supply. On the exterior surface of each OSB sheathing, no mould indicative of outbound or inbound vapour diffusion was observed. This indicates that mould prediction methods may need to be further improved. However, mould was found around and below the wetting pads of wall panels N5 and S5, with more severe mould growth on wall panel N5, proving again the foil-faced polyiso exterior insulation in this wall did not allow drying to occur towards the exterior.

CONCLUSIONS AND IMPLICATIONS FOR WALL DESIGN

The hygrothermal performance of these six test walls is summarized in Table 2, based on this test. The following conclusions provide implications to improve wall design and construction.

- Split-insulated walls have warmer sheathing and are much less likely for the sheathing temperature to fall below the dew point and therefore have lower vapour condensation potential, compared to deep-cavity walls with similar effective R-values. Deep-cavity assemblies need to be built super airtight to prevent vapour condensation due to their colder sheathing.

- When exterior insulation is used, the type has little impact on its capacity to keep the sheathing warm at a given RSI-value (R-value). However, its vapour permeance will greatly affect the wall's drying performance and needs to be carefully assessed in design. Vapour-permeable exterior insulation facilitates drying towards the exterior; impermeable exterior insulation minimizes the drying capacity and may trap moisture.
- The interior vapour control of building envelope remains important in Vancouver's mild climate, especially for humid residential buildings (e.g., with RH of around or above 50% during wintertime). The poly vapour barrier in walls No. 1, No. 3, and No. 4 appears to be effective in preventing outward vapour diffusion and the related wetting. The vapour-retarding painting used in walls No. 2 and No. 5, coupled with the wall's drying capacity does not sufficiently protect these two walls from wetting caused by outward migration of the indoor humidity.

ACKNOWLEDGEMENTS
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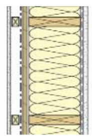
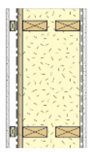
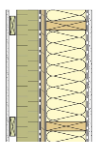
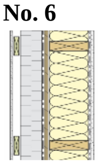
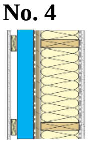
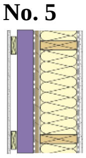
Wall assembly	RH on OSB's interior surface in winter	Moisture accumulation risk on OSB due to outward vapour diffusion from humid indoor space	Drying capacity after incidental water leaks behind sheathing membrane	Overall long-term durability performance
No. 1 	Below 80%	Low risk	Good drying (Drying occurs towards the exterior.)	Acceptable when it is built to be airtight
No. 2 	Exceeding 90% with the initial vapour-retarding paint on the foam; above 80% with another interior vapour-retarding paint on drywall	Considerable moisture accumulation risk due to high indoor RH in winter	Good drying (Drying occurs towards both interior and exterior.)	Mould growth potential and not suitable for buildings with a high indoor moisture load; better interior vapour control will help.
No. 3 	Below 80%	Low risk	Good drying (Drying occurs towards the exterior.)	Good
No. 6 	Below 80%	Low risk	Good drying (Drying occurs towards the exterior.)	Good
No. 4 	Below 80%	Low risk	Acceptable drying performance (It dries slowly towards the exterior through the exterior insulation.)	Acceptable
No. 5 	Persistently above 80%	Considerable moisture accumulation risk due to high RH in wintertime	Poor drying (Very limited drying may occur towards the interior when conditions permit.)	Serious durability risk from outward vapour diffusion when there is a high indoor moisture load; or exterior water ingress.

TABLE 2: Summary of Hygrothermal Performance of Six Test Walls in Vancouver's Climate