FIELD EVALUATION OF HYGROTHERMAL PERFORMANCE AND CONSTRUCTABILITY OF A VACUUM-INSULATED, THIN WOOD-FRAME WALL ASSEMBLY

Mark Carver, CanmetENERGY, Natural Resources Canada
Anil Parekh, CanmetENERGY, Natural Resources Canada
Christopher Baldwin, Mechanical and Aerospace Engineering, Carleton University
Brock Conley, Mechanical and Aerospace Engineering, Carleton University

ABSTRACT

High performance housing (R-2000, Net-Zero Energy, Passive House) standards in Canada require high levels of insulation compared to code-built homes. Homebuilders have traditionally employed thick wall assemblies that are often twice as deep as conventional walls to achieve the necessary thermal resistance [typically RSI 5.0-8.8 (R 28-50)]. Because walls cannot protrude beyond zoning setbacks, these thick walls negatively affect the livable area. This has a real cost to buyers (as high as $25,000 per home in some markets,) on top of the additional materials and labour necessary. This has been identified as a barrier to adoption of such housing.

To help address this, CanmetENERGY in partnership with Owens Corning and Carleton University developed and evaluated an extruded polystyrene/vacuum insulation panel insulating system for thin, high R-value wood-framed walls. Prototype assemblies were constructed and installed in a test hut. The thermal resistance of the test assemblies was determined to be between RSI 7.6 to 9.0 (R-43 to R-51), twice that of today's code built homes. Moisture content of the wall sheathing was measured over a 1-year period. Potential for resilience issues were observed in both intact and compromised vacuum insulation panels when high interior relative humidity was present. The experimental tests showed it is imperative to control interior relative humidity in dwellings to prevent failure from accumulated moisture within a vacuum-insulated wall assembly.

INTRODUCTION

Residential buildings in Canada currently account for over 18% of the total secondary energy consumption in Canada, with 62% of this being for space heating (NRCan, 2013). To reduce this demand, residential buildings are now being built with more insulation and to a higher level of air tightness. Additionally, an increasing number of residences are being built to voluntary performance standards, including R-2000 (NRCan, 2017), Net Zero and Net Zero Ready (CHBA, 2017), and PHIUS+ 2015 (PHIUS, 2015). When built in Canada, buildings built to these standards require significantly higher levels of insulation and air-tightness compared to code-built homes. Homes built to these standards often have twice as much insulation compared to typical new construction. To meet the needs of the next generation of residential

buildings, significant research is required on high thermal resistance building envelopes, including their optimization in terms of reduced costs, reduced thickness and increased durability and buildability.

To satisfy this demand for high thermal resistance, low profile wall assemblies, the use of vacuum insulation panels (VIPs) show significant potential. VIPs consist of a porous core, wrapped in a membrane and placed under vacuum. This eliminates or significantly reduces convective and conductive heat transfer within the panel. Literature (Mukhopadhyaya et. al, 2014) has shown that a VIPs can obtain thermal conductivities as low as 0.0034 W/m·K, at the centre of panel. However, VIPs face several integration challenges before they can be implemented into Canadian residential construction, namely:

1) Fragility: If the membrane is compromised, the vacuum and associated thermal resistance is substantially (~75%) reduced.

2) Constructability: Due to the fragility, VIPs are likely not suitable for a construction site. They need to be incorporated into a system that protects them and does not impose labour intensive installation.

3) Thermal bridging: Structural members to support fasteners can lead to significant thermal bridging.

4) Drying potential: VIPs are vapour impermeable. This needs to be considered in the design of the assembly to mitigate moisture related issues.

To address these challenges, CanmetENERGY and Owens Corning have incorporated VIPs within a commercial insulated sheathing product. This system helps to protect the VIPs. While additional care is necessary to ensure that an errant nail doesn't penetrate the VIPs, installation is otherwise standard. The integration of the VIPs within the insulated sheathing product however, could introduce a second, undesired moisture barrier, preventing the wall's drying potential to the exterior. This is of particular concern in cold climates. To determine how the composite insulation/VIP layer impacts moisture transfer, two vacuum-insulated wall assemblies were exposed to the elements for one year in an in-situ test facility. This paper outlines the current state of high performance housing in Canada, the proposed wall assemblies incorporating VIPs, the testing methodology and results. A discussion of the hygrothermal testing and constructability evaluation of and recommendations for further development and implementation are included.

RECENT TRENDS IN CANADIAN HIGH PERFORMANCE HOUSING CONSTRUCTION

Over the past five years, CanmetENERGY has been using computer optimization coupled with cost data and building energy simulation software to identify cost-optimal pathways for constructing net-zero energy and net-zero ready homes in Canada. CanmetENERGY developed a Housing Technology Assessment Platform (H-TAP) to conduct this analysis. The findings from this research have contributed to significant cost savings to achieve Net-Zero Energy Housing (NZEH) performance, compared to the first generation of Canadian NZEH. One of the clear H-TAP recommendations, is that significantly reducing space-heating demand is a key to cost-effective net-zero energy designs. H-TAP recommends high RSI above grade wall assemblies in order to accomplish this. In some climate zones, the cost-optimal level of thermal resistance is twice that required by code.

The H-TAP research findings have had a direct impact on the most recent NZEH built in Canada. These include those built and rated as part of the R-2000 Net Zero Energy Pilot (NRCan, 2013) and the Owens Corning Net-Zero ecoEII project entitled: Integrating Renewables and Conservation Measures in a Net-Zero Energy Low-Rise Residential Subdivision (NRCan, 2016).

Table 1: Above grade wall assemblies and associated thermal resistance of recent Canadian Net-Zero Energy homes. Comparative 2012 NBC code requirement is RSI 3.24 (R-18.4) in all of these locations.

Location	**Guelph**	**Calgary**	**Edmonton**	**Ottawa**	**Montreal**
Form	Detached	Detached	Detached	Attached	MURB
Year built	2015	2015	2015	2015	2015
HDD [18°C]	3890	5000	5120	4500	4200
Wall assembly	R24 batt + R15 XPS (3")	R24 + R22.5 XPS (4.5")	2x4 double stud c/w 12" cellulose	R24 + R10 XPS (2")	R24 + R10 XPS (2")
Effective thermal resistance [K·m²/W (ft²·°F·h/Btu)]	RSI 6.5 (R37)	RSI 7.5 (R43)	RSI 7.0 (R40)	RSI 5.5 (R31)	RSI 5.1 (R29)
Assembly thickness [mm (inches)]	216 (8.5)	254 (10)	305 (12)	190 (7.5)	190 (7.5)

Table 1 above summarizes the wall assemblies used in some of Canada's most recent NZEH. Homebuilders seeking to build to these standards have traditionally employed thick wall assemblies that are sometimes twice as deep as conventional walls to achieve necessary thermal resistance [RSI 5.0-8.8 (R 28-50)]. For production builders who are increasingly required to build on tighter lots, this has a real cost. Because walls cannot protrude beyond zoning setbacks, these thick walls negatively affect the livable area in the home. For example, if building-in from plates, a 405 mm (16") thick double stud wall contributes to a 7% loss of floor area compared to a code-built 165mm (6.5") thick wall, in a typical 225 m2 (2400 ft2) new home. This has a real cost to buyers which is reported to be as high as $25,000 per home in some markets (Sachs, 2014) on top of the additional materials and labour necessary to construct these assemblies. This has been identified as a barrier to adoption of high-performance housing.

To help address this barrier, CanmetENERGY is developing and evaluating High-R, Thin Wall systems. Compared to conventional code-built wall assemblies, this research aims to:

1) Double the thermal resistance of a conventional code-built wall [ie, RSI 7.9 (R-45)] in a similar thickness [ie,180 mm (7") thick];

2) Not introduce any additional moisture-related durability risks; and

3) Ensure similar "buildability" of the assembly and not introduce excessive labour requirements.

This paper describes two design variations of a vacuum-insulated wood frame wall assembly. This assembly has been evaluated to exceed the thermal resistance target in a 150 mm (6") depth (from the inside of studs to the inside of the ventilated rainscreen). Results of the assessment of moisture-related risk and buildability are discussed.

DESIGN OF WALL ASSEMBLIES

To meet the requirements demanded by industry for High-R, thin walls, the following principles were applied in the conception and design of wall assembly incorporating VIPs:

1) 2x4 structural framing ought to be used. The thermal benefit of 2x6 framing is minimal. The extra 2 inches of thickness can be put to much better use providing high resistivity, continuous insulation. Structural requirements can be met with 2x4s. In Canada, under Part 9 of the National Building Code (Housing and Small Buildings), 38x89mm (2x4") framing with 400mm (16") stud spacing is suitable for 2 storey construction. 38x89mm (2x4") framing with 300mm (12") stud spacing can be used up to 3 storeys (NRC, 2015).

2) Weather and air barrier and continuous exterior insulation ought to be placed outside of the structural framing in order to protect it.
3) Sufficient conventional insulation must be present that in the event of VIP failure, condensation will not occur within the structural layer.
4) To minimize thermal bridging:
    a. The VIPs should be positioned directly over the framing members where possible.
    b. VIP coverage should be as close to 100% as practically feasible.
    c. Materials surrounding the VIPs should have low thermal conductivity.
5) Due to their fragility, VIPs ought to be sandwiched between and protected by other materials, and ideally installed in a factory environment.
6) The handling of VIPs on site should be minimal and assembly details should be conventional and well understood by trades.

With these principles in mind, the assembly shown in Figure 1 was conceived, described from interior to exterior:

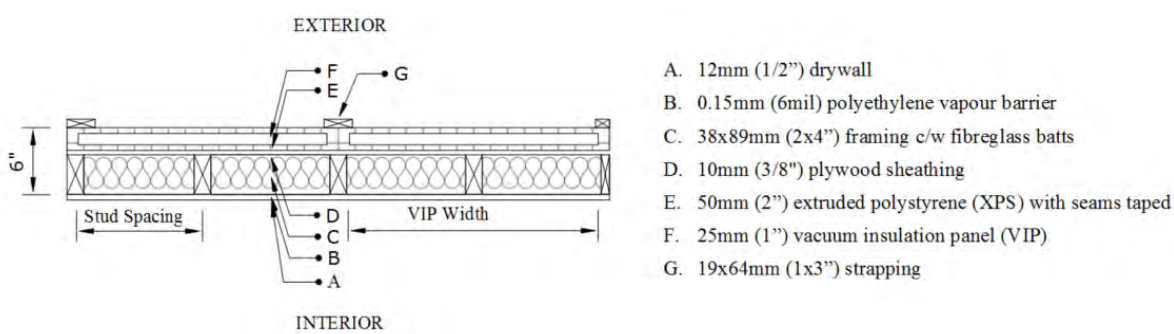

Figure 1: Schematic of developed wall system using VIPs

This is a fairly conventional assembly and doesn't require any special construction techniques or complicated detailing. The insulated sheathing could serve the role of an exterior air barrier system.

VIP Insulated Sheathing Design Evolution

If the seal on a VIP is compromised, so is the majority of its insulation value. Consequently, it's critical that VIPs are not cut or punctured in the construction process. To protect the VIPs, an insulated sheathing layer has been designed that uses rigid foam (extruded polystyrene) to encapsulated the VIPs, providing the VIPs some protection, while also creating nailing strips at standard construction spacing (12 in, 16 in, 24 in). Normally, rigid foam used as insulated sheathing would be fastened to framing (studs and plates) with cap nails at 6 inches on centre around the perimeter of the board and 8 inches on centre in the field. In this case, VIPs would only be safe from nails if they were aligned with the stud cavities.

A disadvantage of this approach is that if VIPs are aligned with the cavities, thermal bridging through the studs and the XPS joints would become significant. This is depicted in Figure 2 below. This increases condensation risk associated with high localized heat flux which results in lower local temperatures and consequently lower dew points. This increases the chance of condensation forming on the structural and wood sheathing surfaces

A secondary downside to this approach is that the panels can only be used for very specific stud spacing. If a builder uses 19" or 24" stud spacing, this panel design will not work. A different panel design would be required.

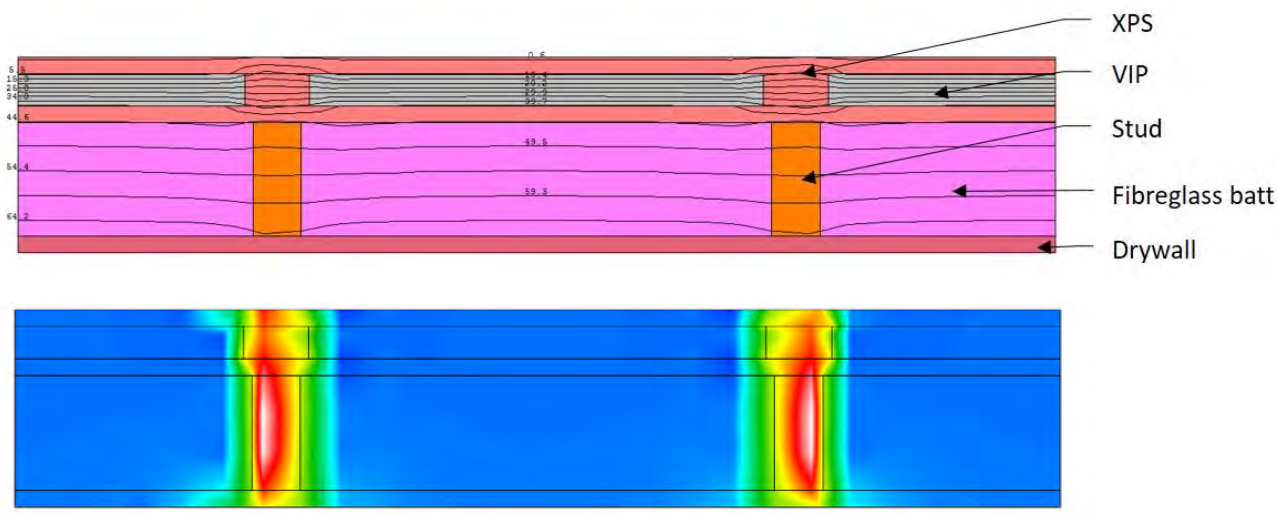

Figure 2: Isotherms and heat flux through thermal bridges

To minimize thermal bridging, while allowing flexibility to frame on 12, 16, 19 or 24" centres, a different approach was taken. The composite panel pictured below (Figure 3) would be applied horizontally to 16" or 19" centre framing or vertically on 12" or 24" centres. It features a 25mm (1") nailing strip XPS surround around the perimeter.

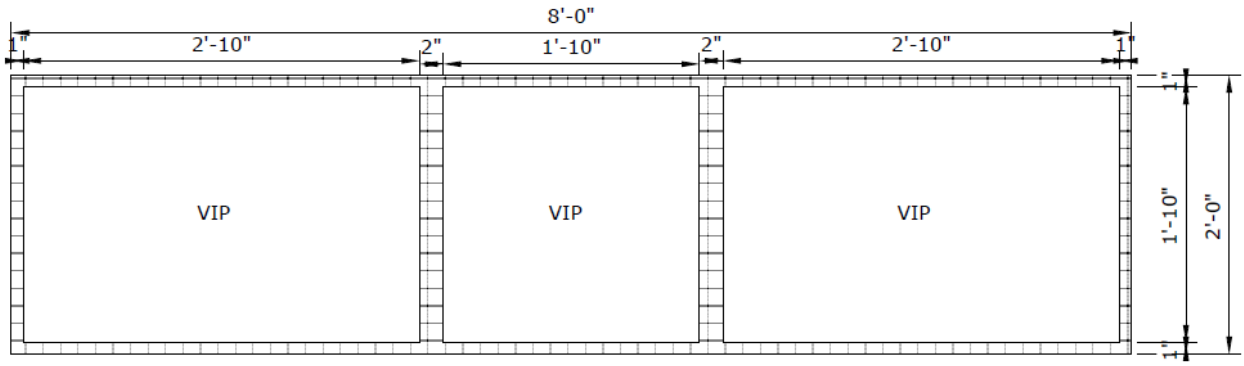

Figure 3: XPS / VIP composite panel layout schematic – location of smaller VIP is variable and based on design requirements of the application

Two different configurations (walls B and C) were designed and constructed. The first wall (Wall B) consists of 2x4 studs placed at 16" OC. This wall would be suitable for a single family bungalow or two storey home, still the most prevalent form of new housing start in Canada. The use of 2x4 studs as opposed to the more common 2x6 studs reduces the in cavity insulation, but with the large outboard insulating value, this loss in thermal resistance is a very small percentage of the overall thermal performance. The 50 mm (2") reduction in wall thickness provides a significant increase in usable area. The second wall (Wall C) follows the same design principles but has 2x4 studs framed at 12" OC. This allows for 3-storey building to be constructed, common in today's multi-unit residential buildings (MURBs). Key metrics, including framing factor (percentage of the wall that is wood framing), VIP coverage and the overlap of XPS and framing, for each of the wall designs, based on a 2.44 m (8') clear wall section are provided in Table 2. Schematics of the two wall sections as tested are shown in Figure 5 below.

Table 2: Key metrics of Wall B and Wall C

Measurement	Wall B (16" OC Framing)	Wall C (12" OC Framing)
Framing Factor	13.7%	16.7%
VIP Coverage	85.9%	85.9%
Aligned XPS and Stud Coverage	4.7%	9.0%

EXPERIMENTAL METHODOLOGY

To experimentally evaluate the performance of the developed wall designs, full-scale test specimens were constructed and installed in CanmetENERGY's Building Envelope Test Hut (CE-BETH). This facility has been designed to experimentally determine both the thermal performance and moisture transfer occurring within a building envelope. To experimentally determine the thermal resistance of the wall, a test procedure outlined in ASTM C1155 (ASTM, 2013) was utilized. The interior temperature of the test hut was kept constant at 21°C ±1°C while the exterior of the wall specimens were exposed to the natural elements and subject to daily cyclical exterior temperature cycles. Using a 4-month (January to April) average of the measured interior and exterior temperatures and point heat fluxes through the wall, the thermal resistance of each measurement point, representing a unique cross section, was determined. The 4 unique cross sections for each wall can be seen in Figure 5. The overall thermal resistances of the wall specimens were then calculated using a weighted average by area. These values were then compared to guarded hot box testing conducted at Carleton University of the same wall specimens. The complete thermal analysis and comparison between the testing methods can be found in (Conley et.al. 2016), and a summary of the overall

effective thermal resistance of the two walls being tested is shown in Table 3.

Table 3: Summary of Overall Thermal Resistances measured In-Situ and by Guarded Hot Box

Assembly	In-Situ		Guarded Hot Box	
	(K·m2/W)	(ft2·°F·hr/Btu)	(K·m2/W)	(ft2·°F·hr/Btu)
Wall A (baseline)	4.3±0.4	24.2±2	N/A	N/A
Wall B	8.61±0.6	48.9±3	8.97±0.25	50.9±1.4
Wall C	7.68±0.6	43.6±3	8.97±0.25	50.9±1.4

In addition to determining the thermal performance of the wall specimens, moisture transfer through the wall specimens was also measured. To maintain a constant internal boundary condition, temperature and relative humidity (RH) were held at 21°C ±1°C and 45% ±5% respectively. During the summer months, only the interior temperature was controlled, and humidity floated in response. Consequently, interior RH peaked in July and was 54% on average for that month. Although higher than usual in Canadian homes in the winter, an RH of 45% was selected to represent a worst case scenario. This level of RH is observed in cases with very high airtightness, very high occupancy or other moisture loads. Towards the end of the testing period, the relative humidity inside the test hut was lowered to 35%, and the impact of this change in boundary conditions was noted.

To measure moisture transfer within the wall, a number of sensors were installed. These include relative humidity sensors in the internal cavities of the wall, and moisture content sensors (MCS) in the structural members and the plywood sheathing between the structural members and the exterior insulation. Readings from these sensors were taken every 5 minutes and recorded using an automated data logger. The MCS measure the resistance between 2 stainless steel screws installed at a fixed distance apart and depth in the wood. As the moisture content of the wood decreases, the resistance measured between the pins increases. The combination of the MCS and the data acquisition systems were able to measure percent moisture content down to ~13%, however as moisture content dropped below this, the resistance between the screws exceeded the maximum value that could be read by the system (1 giga-Ohm). As the primary concern in monitoring the moisture content within the wall was to ensure high moisture was not observed, it was assumed that if the channel read >1 giga-Ohm, no potential existed for either rot or mold growth.

A total of nine MCS were installed within each wall, with four in the structural members (2x4 framing) and five installed within the plywood sheathing. In the sheathing, two MCS were installed inline with the edge of the VIPs, one in the middle of the seam between with two VIPs and the last two installed behind the VIP, with the first 100 mm (4") from the VIP edge and the second dead center of the VIP. Sensor placement can be seen in Figure 5 below.

A number of VIPs had obviously lost their vacuum once delivered. This was immediately apparent, as they had lost rigidity and the foil film was no longer taught. Instead of discarding these VIPs, they were incorporated into a special composite panel and instrumented. The thermal and moisture data from this panel would provide insight into the performance and potential for condensation behind a punctured VIP. Since the R-value is significantly diminished outboard of the framing, the dew-point could be moved into the framing layer. Monitoring the moisture levels and temperatures would allow a determination of the risk of condensation occurring within this layer and the potential for rot and mold growth. To examine this scenario, the MCS in Wall C were installed behind the punctured VIPs.

To compare the moisture transfer observed in the experimental vacuum-insulated walls, a wall constructed to current building code performance and representing common industry practice was built and labelled as Wall A. This wall was used as a baseline to compare how a standard wall and the experimental VIP walls react to changes in the boundary conditions. The baseline wall assembly is shown in Figure 4 below:

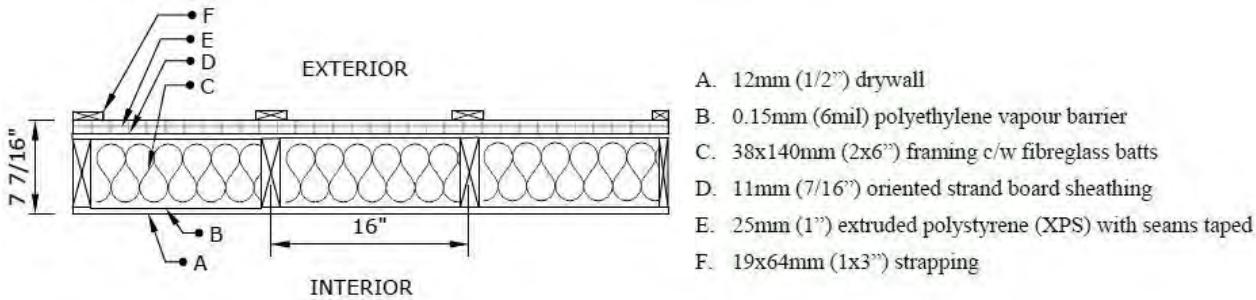

Figure 4: Schematic of the baseline wall assembly built to current building codes

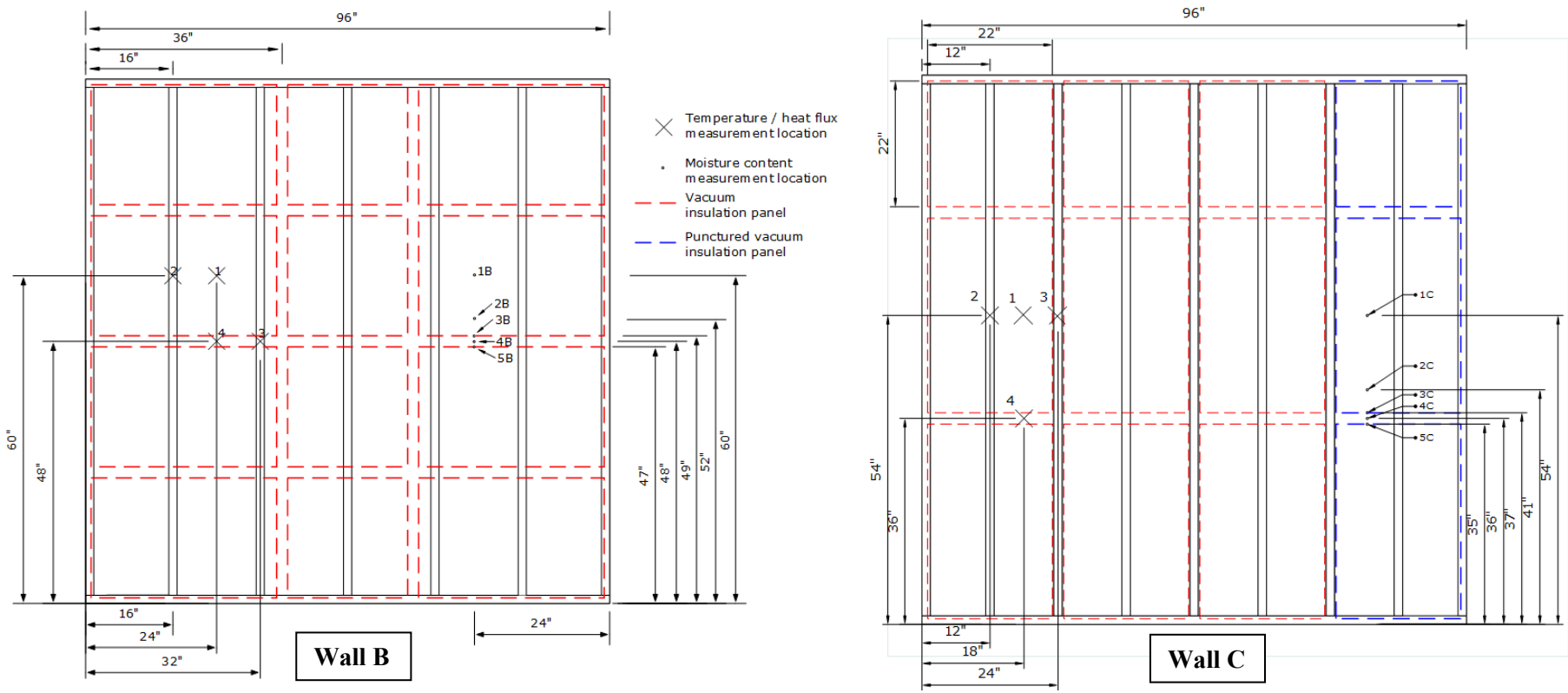

Figure 5: Schematic of the two designed wall sections as experimentally evaluated using framing at 16" OC (Wall B - left) and 12" OC (Wall C - right)

MOISTURE PERFORMANCE ASSESSMENT CRITERIA

In order to be considered a durable assembly, conditions that may lead to mold growth or rot of organic materials within the assembly must be avoided. The following criteria were established to evaluate results. Criterion 2 and 3 are based on ASHRAE 160-2009 (ASHRAE, 2009). It is recognized that ASHRAE 160-2016 supersedes the 2009 revision. However, at project imitation, the 2009 version was most recent. The authors submit that the results are still valid, given that the 2009 version of Section 6.1 "*Conditions necessary to Minimize Mold Growth*" is generally viewed to be more stringent.

1) The surface RH and moisture content of the structural members of the experimental walls should not be significantly higher than those of the baseline assembly when subjected to the same interior and exterior boundary conditions over the course of a year;

2) To minimize the potential for mold growth:

    a. 30-day running average surface RH should be < 80% when the 30-day running average surface temperature is between 5°C (41°F) and 40°C (104°F), and,

    b. 7-day running average surface RH should be < 98% when the 7-day running average surface temperature is between 5°C (41°F) and 40°C (104°F), and,

    c. 24-h running average surface RH should be < 100% when the 24-h running average surface temperature is between 5°C (41°F) and 40°C (104°F); and

3) To avoid structural damage due to moisture, for wood and wood products, recurring moisture contents above the fiber saturation point for longer than one week shall be avoided (ASHRAE, 2016). The average fibre saturation point for the wood framing and OSB or plywood sheathing is assumed to be 28% (CWC, 2017).

If any of these conditions are not met, the potential for failure within the wall system is present, and steps to mitigate the moisture accumulation should be examined.

MOISTURE MONITORING

No specific wetting mechanisms were designed into the experiment. Interior relative humidity and air temperature were controlled and held constant at the following set-points:

- 21°C temperature, 45% relative humidity during the 2016 winter;
- 22°C temperature, uncontrolled humidity (allowed to float) during the summer;
- 22°C temperature, 35% relative humidity during the 2017 winter.

The 1-day running average of measured interior conditions over the duration of the test are plotted in Figure 6. The conditions were selected to represent a "worst-case" scenario of high interior humidity over the winter. The exterior of the assemblies were exposed to the elements. Consequently, the assemblies were subject to all of the real-world moisture transfer phenomena, including vapour diffusion, air infiltration / exfiltration, wind driven rain and solar vapour drive. The exterior of the walls face North-east. This orientation historically receives the most wind-driven rain in the Ottawa, Ontario climate as per the ASHRAE design year 2.

Relative humidity within the stud cavity and moisture content of the sheathing and bottom plates were monitored continuously at a sampling period of 5 minutes. Monitoring was carried out from January 2016 to February 2017 for Wall A and Wall B and until November 2016 for Wall C. This prolonged testing period provides insight into the annual wetting and drying cycle experienced within the assemblies being tested. The resistance read by the MCS installed within the structural members for both walls B and C exceeded the maximum measurable. This indicated that no significant moisture accumulation occurred. The 5 sensors installed within the sheathing however did indicate measurable change in moisture content within the plywood. The precise location of each of these sensors for Wall B and Wall C is shown in Figure 5. The sheathing moisture content is plotted and the results are discussed in further detail in the following section.

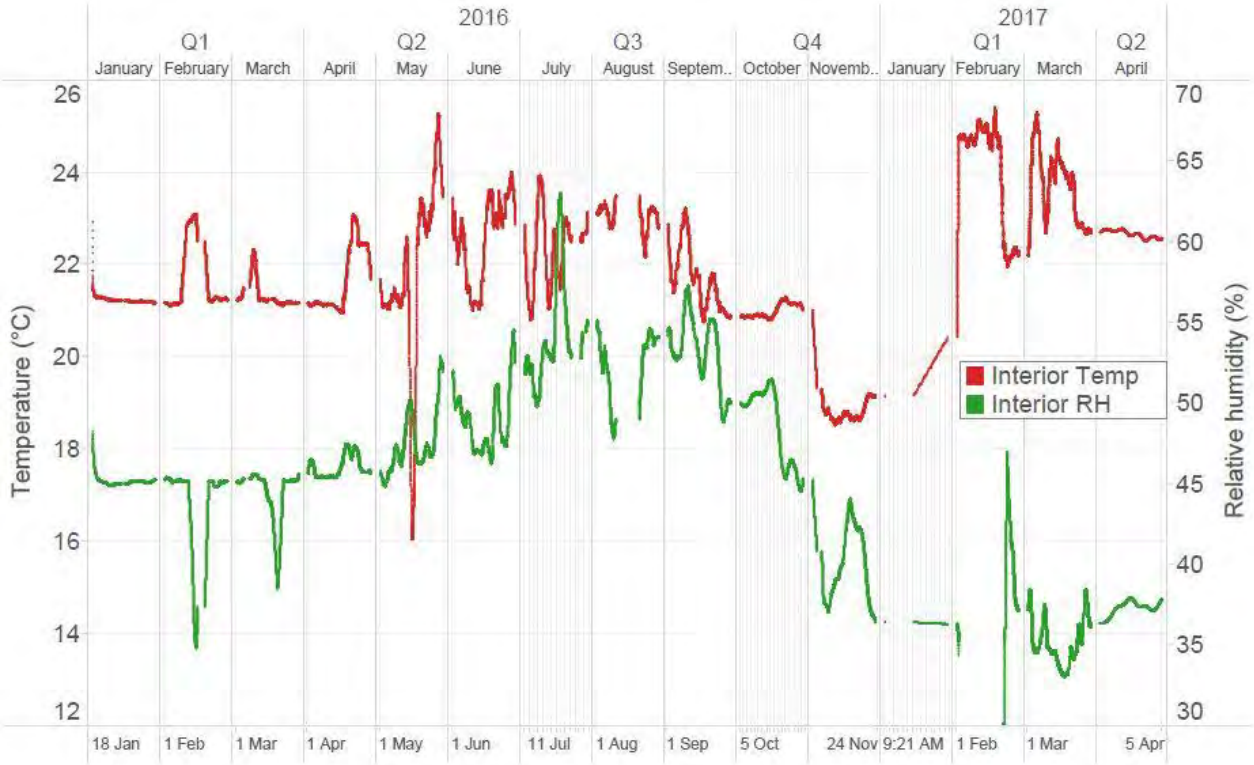

Figure 6: 1-day running average of Interior Temperature and Relative Humidity

Wall A

Two moisture content sensors were installed within the baseline wall. The first (1A) was installed within the bottom plate of the test wall, while the second sensors (2A) was installed in the OSB sheathing. The results of these two sensors have been plotted in Figure 7. When testing began in January 2016, Wall A had a low moisture content (<15%) in both the sheathing and the structural members. Moisture content of the sheathing did increase over the course of the winter, but only exceeded 20% for a period of less 3 days. These spikes were the result of control failures within the test hut, where interior temperatures exceeded the set points, briefly approaching 40°C. The humidifier released very large amounts of water vapour in response to try and maintain the RH setpoint. This introduced a high moisture load (but relatively low RH due to the moisture capacity of the air at 40°C) into the air that then transferred into each of the wall components. Although the response of the wood members in the wall to this large moisture load was immediately apparent, once control was restored, the walls quickly returned to their previous moisture levels. The sheathing began to dry at the end of the heating season and continued to dry throughout the summer. The baseline wall was removed in the fall of 2016, once a moisture content and surface RH baseline over a complete heating and cooling season

established. Interior surface RH of the sheathing never approached 80%. The moisture content of framing and sheathing never exceeded 28%. Moisture content readings are plotted below in Figure 7.

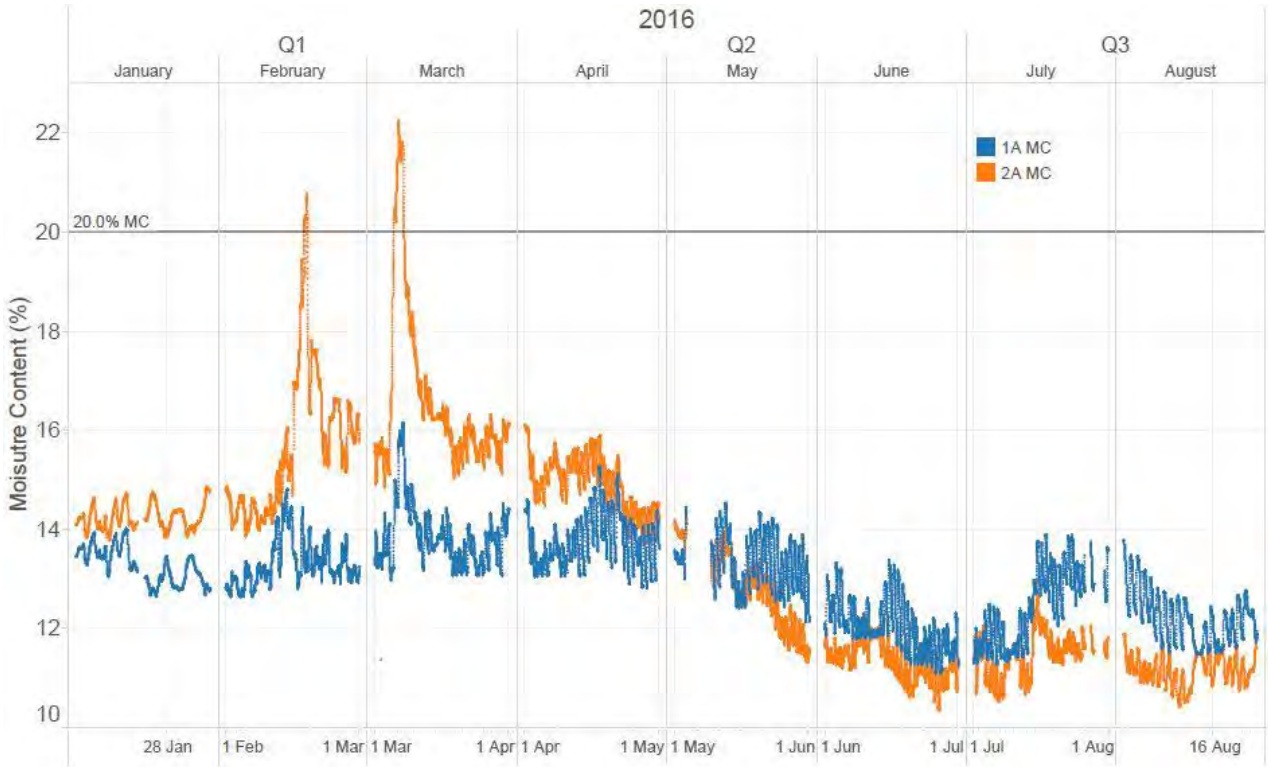

Figure 7: Moisture content of the framing (1A) and sheathing (2A) of wall A

Wall B

Nine MCS were installed within wall B, however four of those were installed in the structural members and showed no measurable moisture content change as a result of the maxed out sensors. The remaining 5 MCS, as shown in Figure 5, were installed in the sheathing. Measured moisture content is plotted and the results are shown in Figure 8. The exterior of Wall B was clad and closed to the elements over the winter 15/16 holidays. However, the batts, vapour barrier and drywall were not installed until mid January 2016. This allowed the bare cavities and interior of the sheathing to be exposed to the high humidity and moisture load of CE-BETH. Despite the VIPs, the interior surface of the plywood sheathing became cold (especially at the VIP seams) causing an even larger increase in local relative humidity at the sheathing surface. This resulted in local moisture content of the sheathing behind the VIP seam (points 3B, 4B, and 5B) to exceed 30% at the outset of testing. This likely exceeded the fibre saturation point, however as soon as the cavities were insulated and the vapor barrier was installed, these locally high readings began to drop.

While the moisture content 100 mm from the edge of the VIP initially started at a lower moisture content, it increased to the point where all five points read in excess of 20%. Drying to <20% MC took 43 days. Sheathing moisture increased over the summer, but the mean of the 5 readings within the sheathing remained below 20% MC save for a period of about 20 days from July 14th to August 3rd. This showed that with the VIPs, the area between the panels is much more susceptible to moisture accumulation. This is likely the result of the lower temperatures of the sheathing when compared to the center of panel; despite the relatively higher vapour permeance of the composite panel at the VIP seam. When compared to the baseline wall, Wall B

accumulated additional moisture, showing greater potential for long term problems (criterion 1 failed). It should be noted, however, that interior surface RH of the sheathing never approached 80% (criterion 2 passed). The moisture content of framing and sheathing did not exceed 28% for more than a week (criterion 3 passed).

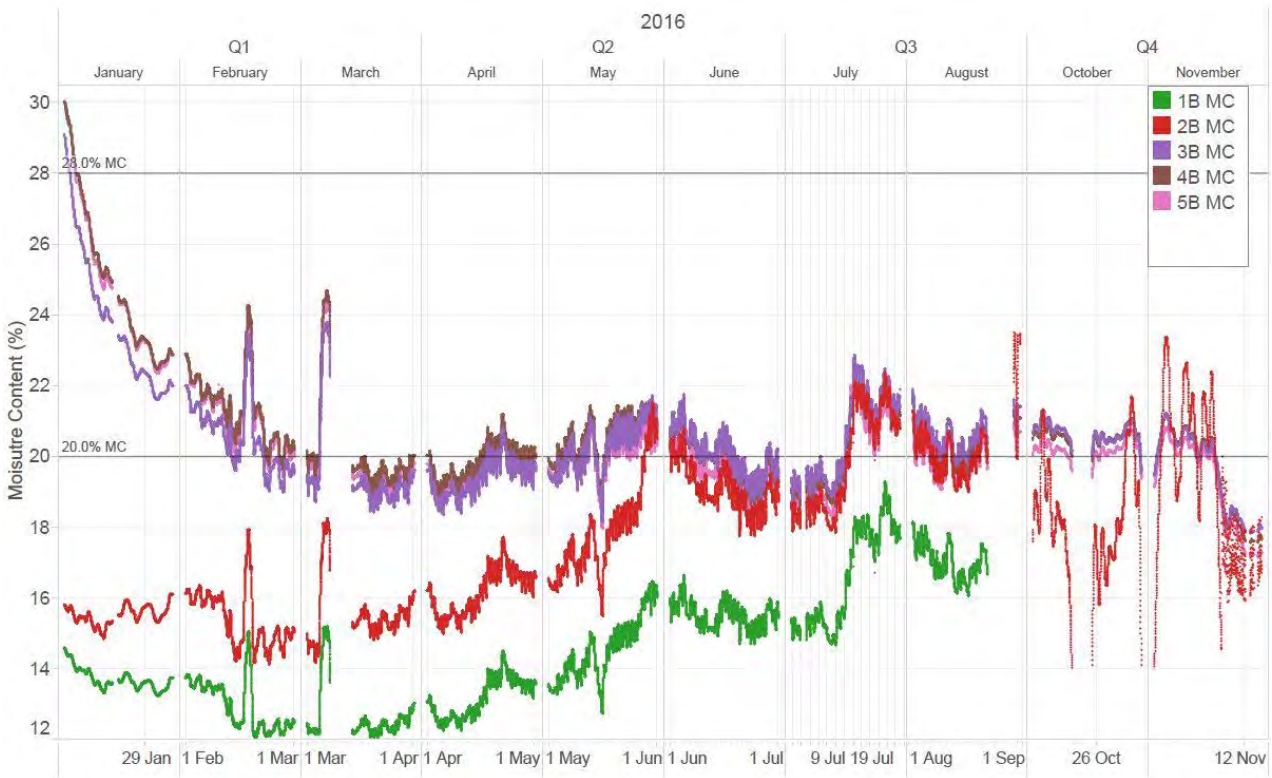

Figure 8: Moisture content of sheathing in Wall B

Wall C

Nine MCS were also installed within wall C, however, like Wall B, four of those were installed in the structural members and showed no measurable moisture content change as a result of the maxed out sensors. The remaining five MCS, as shown in Figure 5, were installed in the sheathing behind the punctured VIP panels, and the results are shown in Figure 9. Wall C was insulated and the vapour barrier and drywall were finished prior to Wall B. This significantly slowed the rate of wetting of the sheathing from the interior. A general wetting trend was observed from January to April 2016. This was likely a result of the higher relative humidity being experienced by the sheathing due to its colder temperature behind the failed VIPs compared to the intact VIPs in Wall B.

The mean moisture content of the sheathing exceeded 20% for a period of approximately 51 days (March 4 – April 24). This is considered to be an excessive period of elevated moisture content. It is difficult to attribute this elevated moisture to a specific wetting mechanism. Air infiltration is assumed to have been insignificant, as the panels were well sealed on the exterior. However, infiltration was not measured. Pressure differential across the assemblies was not measured, but no differential was mechanically induced. Given the orientation, the ventilated cavity and the cladding and its lack of moisture storage, the effect of solar moisture drive is assumed to be minimal as well. Wind driven rain is expected to have had a minor effect as there were no

penetrations, all seams were sealed with tape and the XPS forming the rainscreen is hydrophobic (maximum water absorption of 0.10% by volume). Consequently, this wetting is presumed to be the result of vapour pressure drive from the interior and air exchange with the interior (the air barrier was located on the exterior). By mid-April, moisture content in the sheathing had peaked and drying to the exterior continued until the interior RH was reduced.

When compared to the baseline wall, Wall C accumulated additional moisture, showing greater potential for long term problems (criterion 1 failed). It should be noted, however, that interior surface RH of the sheathing never approached 80% (criterion 2 passed). The moisture content of framing and sheathing did not exceed 28% for more than a week (criterion 3 passed).

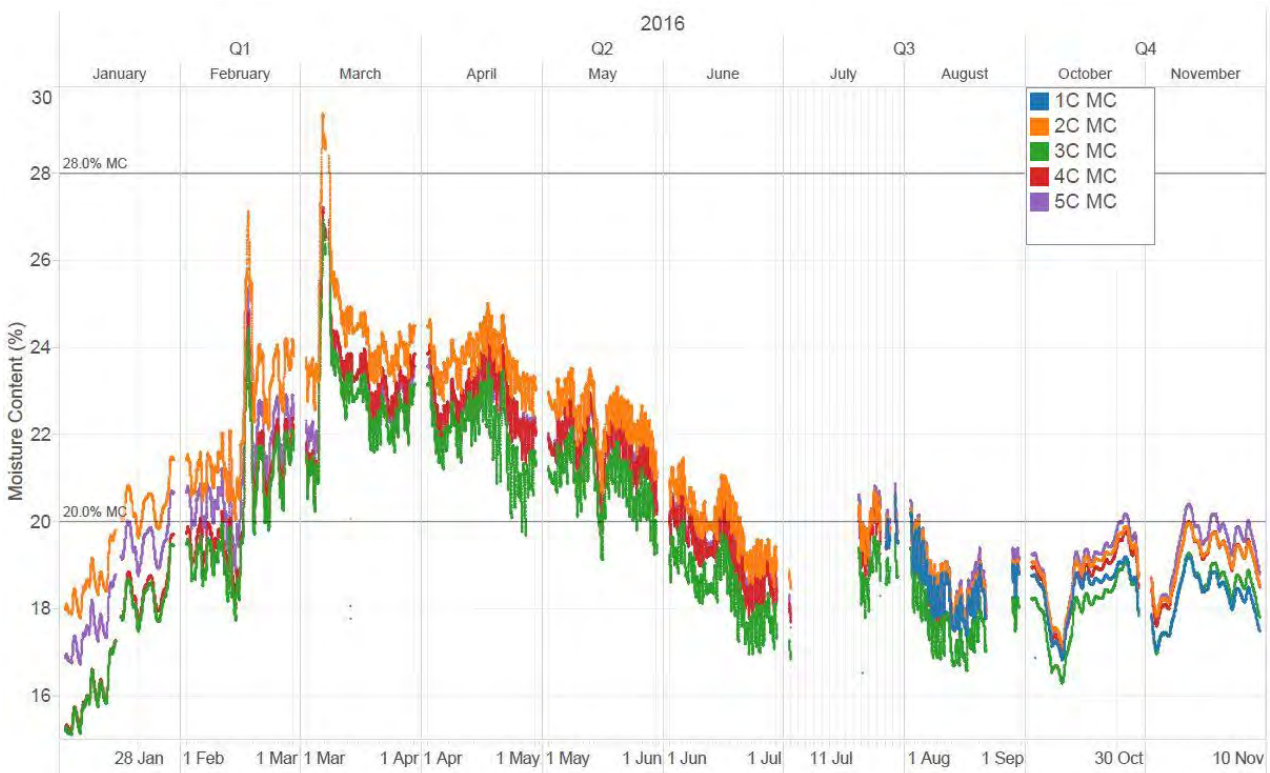

Figure 9: Moisture content of sheathing in Wall C, behind compromised VIPs

DISCUSSION

Composite Panel Performance

The composite XPS/VIP panels were designed to provide a very high thermal resistance insulation layer outboard of framing, with the goal of keeping the sheathing warm in a thin, high-R wall. Through thermal testing, these assemblies were found to have RSI values ranging from 7.6 to 9 (R-42 to 51). The goal of doubling R-value in a wall no thicker than current code was therefore achieved. This was the principal focus. The second goal was to ensure that the designs were resilient and would not introduce moisture-related risk.

Through the moisture measurements, it was found that both VIP-insulated walls exceeded the 1st failure criterion outlined in the test methodology. That is, the surface RH and moisture content of the sheathing in the experimental walls was significantly higher than those of the baseline assembly when subjected to the

same interior and exterior boundary conditions over the course of a year. This is not necessarily an indication that these assemblies would fail under these conditions. It is, however, an indication that the risk is higher compared to the code-built baseline assembly.

It was also observed that the interior moisture content of the air in the test hut has the greatest correlation to the moisture content present in the wall assemblies. The moisture content of the VIP insulated walls exceeded 20% during the winter months, when warm, moist air migrated through the wall. As the temperature profile dropped, the RH profile rose contributing to elevated moisture content. The primary driver of this was high humidity levels of 45% over the first winter. When the humidity level was reduced during the second winter to 35%, substantial drying of the wall assemblies occurred. This showed that one of the most influential ways to prevent failure within such assemblies that do not allow significant outward drying is to closely control the humidity present within the dwelling through mechanical methods. The ability to control humidity levels during winter months is imperative to the resiliency of wall assemblies with VIPs on the exterior. A passive strategy may be to increase the R-value outboard of the sheathing, in order to keep it warmer. The RH in most Canadian houses would not approach the levels introduced in the test. However in specific locales, and in homes built to a very high level of air tightness, these levels of RH are observed. In these applications, an energy recovery ventilator or dehumidifier should be installed to regulate the relative humidity level. It is presumed that eliminating the interior vapour barrier to allow some inward drying would not aid in this scenario, given the high interior moisture load.

Buildability

The design of an exterior insulated sheathing panel with embedded VIP must strike a balance between maximizing VIP insulated areas, minimizing risk of punctured VIPs and providing sufficient space for fastening.

The composite XPS/VIP panels built and tested for this project featured a 25mm (1”) strip of solid XPS around the perimeter, and a 50mm (2”) strip of solid XPS between VIPs. This allowed for a narrow nailing strip for attaching panels to framing or sheathing. The researchers installed the panels themselves and went to painstaking lengths to ensure that VIPs weren’t punctured. Though they don’t swing hammers for a living, they were likely far more careful than could be expected by typical framing crews. The researchers observed that a 25mm (1”) nailing strip is likely insufficient for stick-built applications. In this case, a minimum nailing strip width of 38mm (1-½”) is likely called for. However, the larger nailing strip will reduce the effective area insulated by VIP and will have a negative effect on overall thermal resistance.

It would be prudent to print lines on the exterior surface of the composite panels to denote what areas are safe to nail or cut through and which areas cannot be compromised.

Though encasing VIPs in XPS provides some protection from puncture, the composite panels are still relatively fragile and likely not suited for field application. An errant fastener could easily penetrate 13mm (½”) of foam and puncture the underlying VIP. Any unintended load, such as standing on the panels could snap the XPS surround. A framer may decide to cut through or trim a panel. Furthermore, if such panels are stored on site, there is always a risk they may be damaged by excavation or hoisting equipment. For these reasons, they are likely best handled and installed in a factory environment where better quality assurance protocols can be implemented. The use of a CNC galley nailer would also allow far tighter tolerances on

nailing patterns, and consequently a smaller nailing strip could be used.

Due to the standard sizing of VIP and the inability to cut them, their use would be best suited to modular construction. A recommendation for future study would be to optimize panel designs and sizes to accommodate typical residential wall modules.

CONCLUSIONS

1) Through the use of a composite XPS/VIP outboard insulation panel, thermal resistances in excess of RSI 8 were obtained in 150 mm thick wall assemblies. This represents a greater than 100% improvement on current code built homes. Such assemblies have significant potential to deliver required thermal resistance in thin profiles in future homes built to R-2000, Net-Zero, Net-Zero Ready or Passive House standards.

2) Although promising thermal benefits exist, durability risks in the form of potential for decay and mold growth need to be further studied and reduced. Through the long term experimental evaluation of moisture content in the wall assemblies, when high interior humidity is present, moisture content in the sheathing of vacuum-insulated walls was considerably higher than the code-built wall. This high moisture content was mitigated when the interior humidity within the test hut was reduced. The ability to control humidity levels during winter is imperative to the resiliency of wall assemblies with VIPs on the exterior. Increasing the R-value outboard of the sheathing, consequently keeping it warmer would also likely reduce moisture accumulation. This risk increases if the VIPs are punctured. In this situation, controlling relative humidity though mechanical means and ensuring sufficient thermal resistance is even more important. These initial results indicate that more work is required to better understand the effects of boundary conditions and design strategies to mitigate risk.

3) The evaluation of the constructability of the vacuum-insulated assemblies concluded that in order to control costs, the process for assembling and fabricating VIP composite panels needs to be simple and streamlined. The installation of such panels ought to be done in the factory. Even protected with XPS, VIPs are not suited for field installation.

ACKNOWLEDGMENTS

This authors would like to acknowledge:

- Funding support from Natural Resources Canada's Program for Energy Research and Development.
- Technical expertise, advice and product contributions from Owens Corning

REFERENCES

ANSI/ASHRAE Standard 160. 2009. Criteria for Moisture Control Design Analysis in Buildings.

ASTM C1155-95 (2013), Standard Practice for Determining Thermal Resistance of Building Envelope Components from the In-Situ Data, ASTM International, West Conshohocken, PA, 2013

Canada Wood Council (2017), About Moisture and Wood. Accessed June 1, 2017. http://cwc.ca/design-with-wood/durability/durability-hazards/about-moisture-and-wood/

Conley, B.; Baldwin, C.; Cruickshank, C.A.; Carver, M. (2016) Comparison and Validation of Modelling Methods for Non-Homogenous Walls Incorporating Vacuum Insulation Panels. 2016. International High Performance Buildings Conference, West Lafayette, Indiana.

CHBA, 2017.. Net Zero Home Labelling Program Technical Standard – Version 1. (April 1, 2017). Canadian Home Builders' Association. Ottawa, ON

Mukhopadhyaya, P., MacLean, D., Korn, J., van Reenen, D., & Melleti, S. (2014). Building applications and thermal performance of vacuum insulation panels (VIPs) in Canadian subarctic climate. Energy and Buildings, 85, 672-680.

National Research Council of Canada. (2015). National Building Code of Canada 2015 (NBC) Volume 2. Table 9.23.10.1

NRCan, 2013. Natural Resources Canada. R-2000 Net Zero Energy pilot. Accessed June 1, 2017. https://www.nrcan.gc.ca/energy/efficiency/housing/new-homes/5067

NRCan, 2016. Natural Resources Canada. (2016). National Energy Use Handbook: 1990 to 2013. Ottawa: Office of Energy Efficiency, Natural Resources Canada.

NRCan, 2016. Natural Resources Canada. Integrating Renewables and Conservation Measures in a Net-Zero Energy Low-Rise Residential Subdivision, ecoEnergy Innovation Initiative demonstration project. Accessed June 1, 2017. https://www.nrcan.gc.ca/energy/funding/current-funding-programs/eii/16140

NRCan, 2017. Natural Resources Canada. The R-2000 Standard (2012 Edition). Accessed June 1, 2017. http://www.nrcan.gc.ca/energy/efficiency/housing/new-homes/5089

Sachs, M. 2014. The Business of Green Housing. Carleton University Lecture Series. November 18, 2014. Slides accessed May 29, 2017. https://carleton.ca/cserc/20142015-lectures/business-green-housing-people-want-arent-willing-pay/

PHIUS, 2015. Passive House Institute US. PHIUS + 2015 Passive Building Standard – North America