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Evaluation of thermal and moisture response of highly insulated wood-frame wall assemblies: Part I: experimental trials in the field exposure of walls test facility

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**Evaluation of Thermal and Moisture
Response of Highly Insulated Wood-
Frame Wall Assemblies – Part I:**

**Experimental trials in the
Field Exposure of Walls test Facility**

Report A1-006035

*Bartko, M., Lacasse, M. A., G. Ganapathy and
M. Nicholls*

31 October, 2016

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Also, the authors wish to thank NRC-Construction for providing the funding to enable researchers to build, operate and maintain a state-of-the-art Field Exposure of Walls Facility (FEWF) that was used in this project.

Executive Summary

Over the years, the energy efficiency of the North American housing stock has significantly improved mainly due to higher insulation levels, more efficient windows and, more importantly, adoption of various energy efficiency measures by building codes. The increased insulation levels of building envelopes for homes leads to a multitude of opportunities as well as challenges. A major opportunity is to reduce heat losses and thereby significantly reducing the space heating loads. However, there are many challenges that necessitate changes in the current construction process, durability of products, and more importantly, the effect of higher insulation levels on the overall moisture performance and expected long-term performance of the building envelope. A major barrier to the uptake of highly insulated homes is the lack of proven evidence of reliable thermal and moisture performance of these homes as might be achieved in various climates of Canada.

The National Research Council of Canada (NRC) has undertaken field monitoring and computer modelling to investigate the risk of condensation in wall assemblies having different combinations of increased thermal resistance (R-value) of cavity insulation and of selected exterior insulation products. A set of three wall assemblies with different types of exterior insulation systems were chosen for the field study. The set of three wall assemblies range from total insulation value of RSI-4.96 to RSI 7.57 (R-29 to R-43). Full-scale testing included 8 months performance monitoring. These wall specimens were installed in a side-by-side test bay and were subjected to local climate conditions of Ottawa, Canada; on the interior of the specimens conditions were nominally maintained at 21°C and 35% RH. This report provides results of field trials of the three wall assemblies in terms of their hygrothermal performance and risk for condensation over a year of operation.

Building Regulations for Market Access Program

**Evaluation of Thermal and Moisture Response of Highly Insulated
Wood-Frame Wall Assemblies – Part I:**

Experimental Trials in the Field Exposure of Walls Test Facility

Authored by:

M. Bartko, M. A. Lacasse, G. Ganapathy and M. Nicholls

**A Report for the
Canadian Wood Council**

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31 October, 2016

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1. Introduction

1.1 Overview

The Canadian market for new residential home construction and existing retrofits was about 79 million m², which represents an investment of about CDN \$9.7 billion in 2012 [**Error! eference source not found.**]. Conservatively assuming a 25% market share by 2025, highly-insulated (enhanced) envelopes could save 11.6 PJ of energy and 1.2 Mt of Green House Gas per year [1]. This represents a significant economic opportunity for the housing industry within Canada and for value-added exports such as manufactured panelized wall systems. This project is needed to provide the scientific data and analysis necessary to characterize the thermal and moisture performance of advanced residential wall systems. Such information is needed to update any considerations for further energy efficiency improvements to building codes and technical requirements of nay voluntary residential energy efficiency programs. Evidence is needed to guide the development of highly energy efficient, cost-effective, durable and buildable solutions that are well-integrated with current practices used for wall assemblies of Canadian housing.

Given the heightened interest of homebuilders to provide homes that met or exceeded Energy Star requirements, and their voiced concerns regarding “super-insulated” homes, the intent of this work was to demonstrate compliance of a set of highly-insulated wall assemblies as compared to a code compliant reference wall in respect to their anticipated thermal and hygrothermal performance when subjected to Canadian climate extremes. On the basis of providing useful information to building practitioners, the National Research Council Canada (NRC) undertook field monitoring and numerical modelling to investigate the risk of condensation in wall assemblies having different combinations of increased thermal resistance (R-value) of insulation for selected insulation products.

To achieve higher wall insulation levels in wood-frame wall assemblies, it has been commonplace to apply rigid, or semi-rigid, board insulation over the inside or outside of the framing. Alternatively, double wall or deep wall construction assemblies can be used to attain the desired level of insulation. However, concerns had been expressed in the building community regarding the use of progressively higher levels of insulation in wall assemblies as a means of attaining greater energy savings. It was felt that the use of higher insulation levels would increase the risk of incurring moisture problems given the perceived effect that highly insulated walls have on the wetting and drying characteristics of walls.

To help address the development of such unintended consequences, a collaborative research project, with government and industry participation, was initiated to explore, develop, test and document the energy performance and moisture response of highly insulated residential wall systems. The information derived from the project will be used to guide the development of durable new wood frame wall assemblies.

1.2 Objectives

The intent of the project was to develop information on the moisture and thermal performance of progressively higher insulated wood-frame wall assemblies. The information is to be used to: (1) Support the evaluation of future code proposals regarding energy efficiency improvements to building envelope systems; (2) Support the development of knowledge, details and practices for advanced wall systems for voluntary residential energy efficiency programs; (3) Help the housing industry meet near- and net-zero energy targets, and; (4) Promote the deployment of highly energy efficient wall details for new and retrofitted existing wood-frame construction. In essence, the primary outcome from this project is to facilitate the widespread adoption of high performance residential wood-frame wall systems (Energy Guide rating: EGH-83 and 86) that are practical, buildable, durable, energy efficient and affordable.

To achieve these objectives, the project focused on investigating the moisture and energy performance of thermally enhanced wood-frame walls with progressively higher levels of insulation from a base line (2010 National Building Code minimum (RSI 3.27 – 4.13) to new R-2000 performance levels (RSI 7.04 – 7.92). It permitted comparing the heat, air and moisture response of the advanced wall systems to the base line code-compliant wall and thereafter complete the necessary analysis to develop meaningful information outputs that could be used to address and thereby alleviate industry concerns regarding the unintended consequences of enhanced wall insulation systems on the moisture performance of the wall assemblies over time.

In collaboration with the Canadian Wood Council (CWC), NRC-Construction developed proposals for 3 wall assemblies to be tested in NRC-Construction's Field Exposure of Walls (FEWF) test facility, shown in FIGURE 1, over a period of 8-months in a yearly cycle where the walls were exposed to outdoor conditions.

As it was of importance to ensure that the results of the research were meaningful in all regions of Canada, the analysis was extended through the use of simulation tools to representative cities in the Atlantic and Prairie regions of Canada, the lower coastal mainland of BC and in the North. Given that conducting experimental tests to determine the hygrothermal performance of different wall systems in different Canadian locations is time consuming and expensive, an advanced hygrothermal modeling tool was used to develop this part of the project. The modeling tool (hygIRC-2D) was benchmarked against experimental data obtained from field test of the project. Once the benchmarking of the modeling tool was completed, it was then used to investigate the effect of different outdoor and indoor conditions, as may be found in the different regions of Canada, on the moisture and thermal performance of the wall assemblies; results from the numerical simulation part of the project can be found in the companion report [3].

In this report, results are provided of the monitoring of the hygrothermal response of a set of three highly insulated wall assemblies to local climate conditions of Ottawa and when subjected to forced exfiltration conditions.

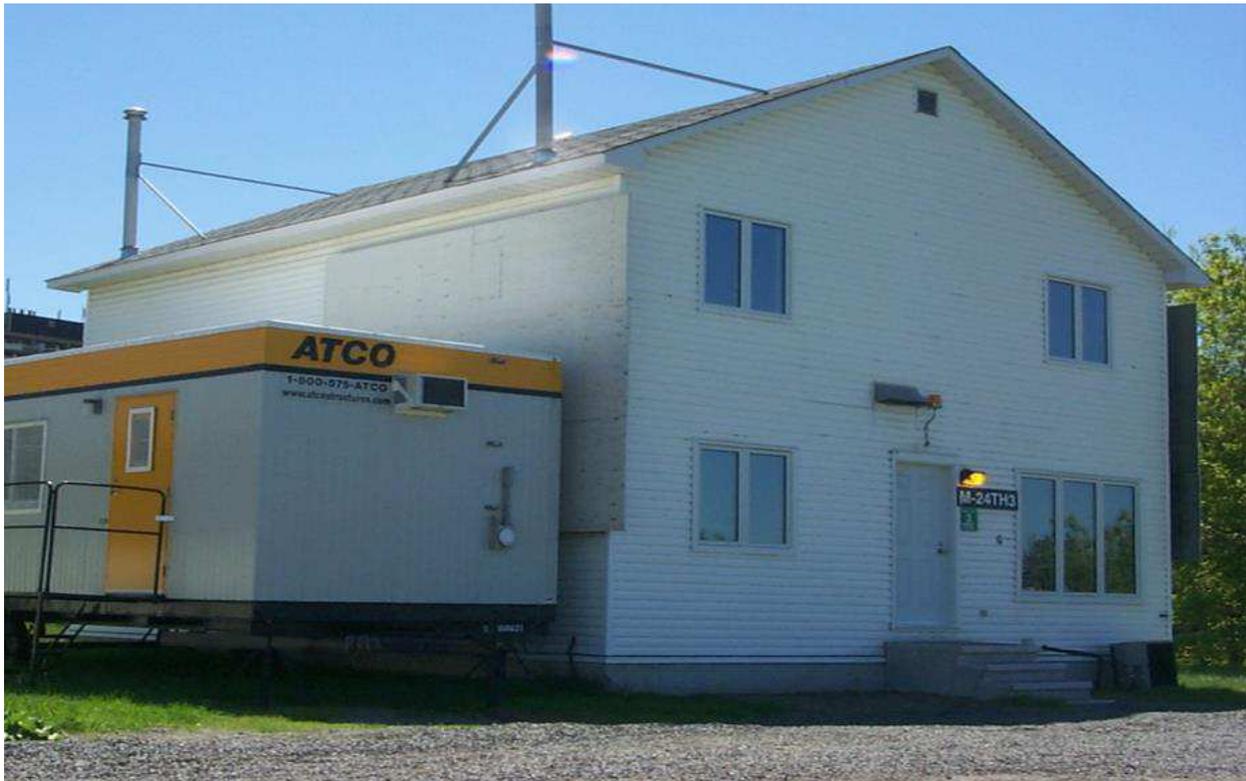


Figure 1. NRC-Construction's Field Exposure of Walls (FEWF) test facility, located at the NRC Montreal Road campus in Ottawa

2.0 Research Approach

2.1 Scope of Testing

The field monitoring of the three (3) different wall assemblies was undertaken in the NRC's Field Exposure of Walls Facility (FEWF), located at the NRC campus in Ottawa. The research approach was similar to that used in previous projects where there was interest in knowing the hygrothermal response of wall assemblies subjected to local climate conditions as described by Lacasse et al. [4], Armstrong et al. [11], Maref et al. [11, 13] and Saber et al. [5, 14].

Field monitoring of the test specimens was conducted from February 2016 to October 2016; this allowed an 8-month period over which test specimens were subjected to a broad range of weather conditions for each set of experiments.

2.2 Description of Wall Specimens

Test specimens

Two wall test specimens with size of 4 x 6 ft. (1220 x 1790 mm) consisted of 2x6-in. (38 x 140 mm) wood-frame walls and another having a 2x10-in. (38 x 230 mm) wood-frame were installed side-by-side in the FEWF (Figure 2). The different material layers and the dimensions of the wall specimens are given in Figure 3 to Figure 5.

The common elements of three wall test specimens included vinyl siding attached to 0.75 in. thick furring strips (which created an air space) on the exterior side of the assemblies, and painted gypsum wallboard (GWB) on the interior of the assembly.

Wall 1 (W1 XPS) and Wall 3 (W3 OSB) used similar components throughout, resulting in identical thermal resistance, but the components were rearranged primarily to see the effect of using a variable permeance vapour retarder (sometimes called a "smart" vapour retarder). An OSB panel was used in Wall W3 as a "smart" vapour retarder; in W1 this same panel was used on the exterior of the assembly, and vapour barrier in that wall was a polyethylene sheet (6 mil).

A continuous exterior insulation layer of wall W1 (XPS; Figure 3) was created by adding a 25 mm (1 in.) thick extruded polystyrene (XPS) panel onto the 11 mm (7/16 in.) thick oriented strand board (OSB), the OSB being overlaid with a polymer-based sheathing membrane. The OSB board was attached to the 38 x 140 mm (1.5 x 5.5 in.) wood-frame wall and friction-fit glass fibre batt insulation of R-24 was added to the interior wall cavity between the vertical studs. The interior side of wall W1 consisted of polyethylene air and vapour barrier (6 mil thick), and 12.7 mm (0.5 in.) thick interior drywall. The total nominal thermal resistance for W1 (XPS) was R29.

Wall 3 (W3 OSB), deviated from standard construction by not having a polyethylene sheet as vapour barrier, but instead, an OSB panel; this arrangement of layers for W3 is given in Figure 5. Similar to that which was installed in W1, a 25 mm (1 in.) thick continuous layer of extruded polystyrene (XPS) was installed to the wood frame from exterior side. Glass-fibre batt insulation of R-24 was installed in the wood-frame cavity, and installed inboard of the stud cavity, was an 11 mm (7/16 in.) thick OSB (taped joints) as a "smart" vapour retarder. Interior

drywall 12.7 mm (0.5 in.) thick was installed as the interior finish as in all other wall assemblies. The total nominal thermal resistance for wall W3 was R29.

The level of insulation used in Wall 2 (W2 PH) was increased to levels typically used in Passive Haus (PH) design (Figure 4) and in which a much deeper cavity (9.25 in. + 3.5 in.) is required to accommodate R 43 batt insulation. The materials used for insulation were wood fibre batt placed between the 2x10-in. (38 x 230 mm) wood studs against a 25mm (1 in.) wood fibre exterior diffusion board; both products being novel to North America and imported from the UK. The secondary interior wood frame 2x4-in. (38 x 89 mm), was offset from the primary 2x10-in. frame to eliminate thermal bridging; the secondary frame was also filled with wood fiber batt insulation. As was used in wall W3, an 11 mm (7/16 in.) OSB was used as a smart vapour barrier in lieu of a polyethylene sheet, the sheet being placed between the two stud-walls. A 12.7mm (0.5 in) thick interior drywall formed the interior side. For wall W2 the wood fiber insulation provided a nominal R-value of R43.

The sequence of installation of the primary wall components forming the interior portion of the respective test specimens and inboard of the 2x6-in. (38 mm x 140 mm) wood framing is illustrated in Figure 6 to Figure 9. In Figure 6 is shown the state of fabrication where the exterior sheathing panel (OSB) has been installed for wall specimen W1, followed by the glass fibre batt insulation and the polyethylene vapour barrier installed from the interior side. As evident in Figure 7, the sequence of installation of wall components is shown from left to right in the Figure. The left-most figure shows the wood-based diffusion board installed on the exterior side of the 2x10-in. wood frame; thereafter, wood fiber insulation is placed in the stud cavity; an OSB panel is installed as vapour barrier atop of which can be seen a 2x4-in. wall; in this interior wall is installed wood fiber insulation towards the interior.

The construction of specimen W3 is given in Figure 8 where XPS sheathing has been installed to the wood frame from the exterior side; glass fibre batt insulation is installed in the stud cavities and; the interior side includes the OSB panel as smart vapor barrier to which is affixed the interior finish consisting of gypsum drywall panel.

The final sequence, provided in Figure 9, shows the installation of wood furring strips to which was affixed the exterior cladding.

Additional installation details for each of the test specimens can be found in Appendix 1 Test Specimen Fabrication and Installation details .

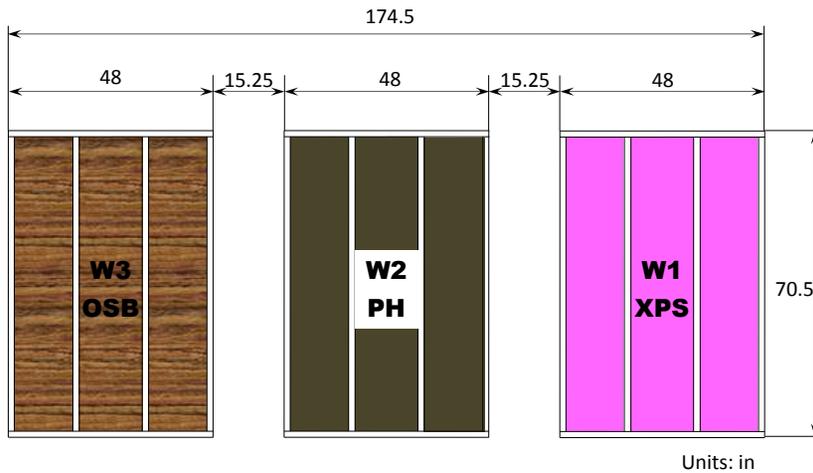
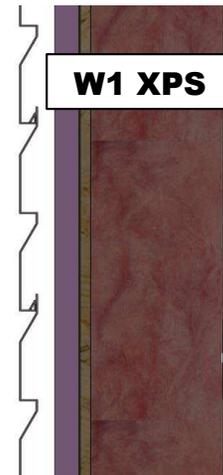


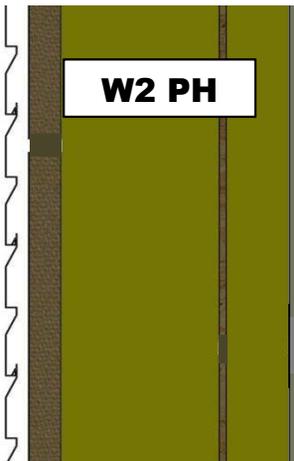
Figure 2. Schematic of three 2x6-in. (38 mm x 140 mm) wood-frame wall (residential) test specimens installed side-by-side in FEWF



Total R-29

- Vinyl siding
- 3 x 0.75 in. nominal vertical furring strip
- 1 in. XPS rigid foam insulation (R5)
- Sheathing membrane
- 11 mm OSB wood-sheathing
- 1.5 x 5.5 in. nominal wood stud cavity
- R24 glass fiber batt insulation for 6 in. cavity
- 6 mil poly air/vapour barrier
- 0.5 in. painted drywall

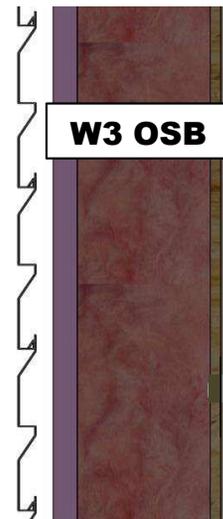
Figure 3. Wall 1 (W1: XPS) - Horizontal cross-section through XPS wall assembly



Total R-43

- Vinyl siding
- 3 x 0.75 in. nominal vertical furring strip
- Sheathing membrane
- 24mm Diffusion board
- 1.5 x 9.25 in. nominal wood stud cavity
- R30 Wood fibre insulation for 10 in. cavity
- 11 mm OSB wood-sheathing; joints taped
- 1.5 x 3.5 in. studs (Service wall interior)
- R13 Wood fibre insulation for 4 in. cavity
- 0.5 in. painted drywall

Figure 4. Wall 2 (W2: PH) - Horizontal cross-section through Passive Haus wall assembly



Total R-29

- Vinyl siding
- 3 x 0.75 in. nominal vertical furring strip
- 1 in. XPS rigid foam insulation (R5)
- 1.5 x 5.5 in. nominal wood stud cavity
- R24 glass fiber batt insulation for 6 in. cavity
- 11 mm OSB wood-sheathing; joints taped
- 0.5 in. painted drywall

Figure 5. Wall 3 (W3: OSB) - Horizontal cross-section through wall assembly with OSB as smart vapor barrier



Figure 6. Wall 1 (XPS) – (i) Stud wall wood frame with OSB, (ii) GF batt insulation in stud cavities, (iii) poly vapour barrier



Figure 7. Wall 2 (PH) - (i) Stud wall wood frame with diffusion board, (ii) wood fiber insulation in stud cavities, (iii) OSB smart vapour retarder (iv) interior wood fiber insulation



Figure 8. W3 (OSB) – (i) Stud wall wood frame with external XPS board, (ii) GF batt insulation in stud cavities, (iii) OSB smart vapour retarder



Figure 9. Installation of W1, W2, & W3 in FEFW showing (i) exterior layers under air cavity, furring strips & (ii) exterior cladding (vinyl siding)

Instrumentation

For the characterization of the hygrothermal response of the walls, the test specimens were instrumented with different sensors to permit determining the degree of heat transfer across the specimens, to establish values for surface temperature and local relative humidity as well as the presence of moisture accumulation and pressure differences across the different layers; the different sensors used in this study are listed in Table 1.

For each test specimen, an array of sensors was deployed in a grid at each layer of the assembly; an example of the array of sensors deployed within wall assembly of test specimen W1 is shown in Table 2, the broader set of sensors for all test specimens are provided in



Vaisala Model WXT

Appendix 2

Test Specimen Sensor Installation Details).

A local weather monitoring device (Vaisala Model WXT 510) that included a rain gauge, sensors for air temperature, relative humidity, air pressure, wind speed and wind direction, was installed in close proximity to the wall specimens and provided information on hourly ambient exterior conditions. The combined package permitted determining the response of the respective wall assemblies to changing weather conditions over hourly, daily and seasonal periods.

Each of the three test specimens was isolated from each other by a vertical chase that provided effective control of heat, air and moisture flow (Figure 2) and as well provided room for running wires for instrumentation (Figure 9). The test specimens were also isolated from the surrounding building envelope of the test house with effective heat, air and moisture control materials (e.g. thermal insulation and self-adhered airtight membranes were used), as well as flashings where warranted.

As a part of the test protocol all heat flux transducers (HFTs) used in the test specimens were calibrated according to ASTM C-1130 “Standard Practice for Calibrating Thin Heat Flux Transducers” [6]; the uncertainty of the heat flux measurements was $\pm 5\%$. The locations of the HFTs in the respective test specimens are shown in Figure 2 to Figure 4.

Table 1. List of sensors used to determine hygrothermal response of test specimens to changing local exterior and interior conditions

Sensors	Manufacturer / Supplier	Model	Range	Accuracy
Thermocouple	Omega	TT-T-24-SLE	-100°C to +200°C	0.5°C or 0.4% FS
Relative Humidity & Temperature	Vaisala	HMP-60	RH: 0 to 100%; Temp.: - 40°C to +60°C	RH : $\pm 5\%$ Temp.: $\pm 0.6^\circ\text{C}$
Pressure	Setra	C264	$\pm 0.25''\text{WC}$ & $\pm 2.5''\text{WC}$	$\pm 1\%$ FS
Heat flux sensors	Hukseflux	PU11T & PU32T	-20°C to + 60°C	$\pm 5\%$ at 20°C
Moisture tapes	Detec & SMT	N/A	Up to 40% moisture content	

2.3 Test Protocol

The test protocol was conceived to ensure that the wall assemblies were monitored to assess their vapour diffusion characteristics over an 8 month period, the initial period (A) covering the coldest period of the year.

The test protocol consisted of exposing the wall specimens to:

- Exterior weather conditions prevalent at the FEWF test site;
- A set of indoor controlled temperature and humidity conditions.

Indoor controlled conditions were based on that provided in ASHRAE standards [7] as these relate to indoor winter and summer conditions (21°C; 35% RH). To attain these conditions, an indoor climatic chamber was installed and sealed against the perimeter of the test opening, thereby allowing control of indoor conditions to which test specimens were subjected.

Test Periods – The monitoring program was set-up in four (4) periods (A, B, C and D) as provided in

Table 3. The length of periods varied, but in essence the initial period, Period A, was intended

Period	Interior conditions				Exterior conditions	
	Temperature (°C)	RH (%)	Pressure (Pa)	Deficiency (3mm slit)	Deficiency (3mm slit)	Temperature / RH
A (20 days)	21	35	0	Closed	Open	Ambient local
B (20 days)	21	55	20	Open	Open	Ambient local
C (190 days)	21	Variable / natural	0	Open	Open	Ambient local
D (20 days)	21	Variable / natural	0	Closed	Open	Ambient local

as a period over which the fluctuations of heat flow, temperature, relative humidity and pressure differences within the assembly were monitored to gain an appreciation of the response of the wall to local weather conditions and when the interior conditions were nominally maintained at 21°C and 35% RH. Period B was meant to subject specimens to conditions where warm moist air (21°C; 55% RH) exfiltrated through intended deficiencies in the test specimens; exfiltration was induced by applying a 20 Pa pressure across the test specimens from the interior enclosure. In this instance, there was interest in bringing about condensation on cold surfaces within the wall. The subsequent period, period C, provided a period over which the deficiencies remained in the assembly but no exfiltration pressure was applied to the enclosure and interior RH conditions were not controlled to a set RH level as they were for periods A and B. As such, the wall might recover from moisture deposition within the wall and in essence, “dry out”. In this way, the propensity for the wall to dry out following occurrences of moisture deposition within the wall provided a means to assess the robustness of the moisture management ability of the wall assembly. The final period (Period D), was again intended as a period over which to gain an understanding of the response of the wall to increasingly cooler periods following the summer months; the deficiencies were not present in this instance and neither was the RH in the interior enclosure maintained to a set level.

Table 2 – Selected array of sensors deployed within wall assembly of test specimen W1

W1 – Location of thermocouples		Designation	
Exterior temperature	B1_TC_01	+	
Exterior (stud) temperature	B1_TC_02	+	
XPS at top	B1_TC_03	+	
XPS at bottom	B1_TC_04	+	
Sheathing membrane at top	B1_TC_09	+	
OSB interior surface top	B1_TC_10	+	
OSB interior surface bottom	B1_TC_11	+	
Drywall exterior top	B1_TC_16	+	
Interior surface temperature	B1_TC_17	+	
Interior surface (stud) temperature	B1_TC_18	+	

W1 – Location of RH sensors		Designation	
Exterior	B1_RHT_01	x	
XPS at top	B1_RHT_02	x	
XPS at bottom	B1_RHT_03	x	
Sheathing membrane at top	B1_RHT_04	x	
Sheathing membrane at bottom	B1_RHT_05	x	
OSB interior surface top	B1_RHT_06	x	
OSB interior surface bottom	B1_RHT_07	x	
Drywall exterior top	B1_RHT_08	x	
Interior surface	B1_RHT_09	x	

W1 – Location of ΔP transducers		Designation	
Exterior air pressure	B1_DP_01	▲	
Mid stud air pressure	B1_DP_02	▲	
Interior air pressure	B1_DP_03	▲	

W1 – Location of thermocouples		Designation	
Middle XPS at top	B1_TC_05	+	
Mid-height XPS – left cavity	B1_TC_06	+	
Mid-height XPS – right cavity	B1_TC_07	+	
Middle XPS at bottom	B1_TC_08	+	
Middle stud cavity at top	B1_TC_12	+	
Mid-height stud– left cavity	B1_TC_13	+	
Mid-height stud– right cavity	B1_TC_14	+	
Middle stud cavity at bottom	B1_TC_15	+	
Mid-height drywall – right cavity	B1_TC_19	+	

Table 3. - Test protocol over monitoring period (2016)

Period	Interior conditions				Exterior conditions	
	Temperature (°C)	RH (%)	Pressure (Pa)	Deficiency (3mm slit)	Deficiency (3mm slit)	Temperature / RH
A (20 days)	21	35	0	Closed	Open	Ambient local
B (20 days)	21	55	20	Open	Open	Ambient local
C (190 days)	21	Variable / natural	0	Open	Open	Ambient local
D (20 days)	21	Variable / natural	0	Closed	Open	Ambient local

Deficiencies in the wall assembly — Each test specimen included a deficiency through which air from the interior was meant to exfiltrate through the test specimens. The size and location of the respective deficiencies are shown in Figure 10. Pressure differences across the assemblies, occurring either naturally or through forced air flow from the interior enclosure, induced the flow of air through the deficiencies as suggested in the schematic on the right of the photos in Figure 10. The location of the deficiencies at the interior of the test specimens and at the exterior sheathing panel, in principal, permitted a path for air to flow. The air leakage rate at several different enclosure pressures for each of these deficiencies was determined the results of which are given in Table 4. These are given as the air leakage rate (L/sec m²). Of importance are the values of air leakage at the exfiltration mode when the deficiencies were present in the walls (Period B-“Deficiency state”).

Table 4 – Air leakage Q (L/sec m²) of test specimens at 75Pa

Wall	Q (L/sec m ²)
W1	6.59
W2	1.91
W3	6.66

2.4 Monitoring

Data was gathered continuously over an 8-month period and data analysis consisted of reviewing relevant sensors within the assembly and determining whether there was risk to the formation of condensation within the respective assemblies over the evaluation period.



Figure 10 – Deficiencies in wall test specimens showing location & size of deficiency in W1 (XPS)

On the basis of results obtained from monitoring the response of the respective wall assemblies to local climate conditions, the numerical hygrothermal model hygIRC-2D was benchmarked against selected experimental data. Thereafter, the model was used to conduct a parametric analysis to investigate the risk of condensation and mould growth in the respective wall assemblies subjected to different climatic conditions for a select set of locations in Canada; this report is provided in [3], whereas, a description of the hygIRC-2D numerical hygrothermal simulation model and record of benchmarking exercises are available in [4].

3.0 Results

In this section, the hygrothermal response of wall test specimens to local climate conditions is described and those instances when moisture from condensation within the wall assembly was observed are discussed. The information acquired from the monitoring program is quite considerable and additional details of this can be found in

Appendix 3.

3.1 Response of Walls assemblies

The hygrothermal response of the test specimens over the monitoring period of 8 months is shown in Figure 11 for the respective test specimens: (i) W1-with XPS exterior insulation; (ii) W2-PH with wood fibre insulation, and; (iii) W3-with OSB as a smart vapour retarder. The location of the temperature and relative humidity sensors for which values are provided in the figure are shown in the diagram adjacent to the plots. In the plot, values recorded for the 3 periods of the test protocol (i.e. A, B and C) include the: (i) interior surface temperature (black lines); (ii) temperature (T / blue lines) and relative humidity (RH / red lines) of the sheathing panel (OSB for W1, wood fiber based diffusion board for W2, and XPS for W3) at mid-height of the wall, and (iii), the same T and RH in proximity to the 3 mm slit through which air could exfiltrate the wall.

The daily fluctuations in temperature of both the exterior surface of the thermal insulation as well as the interior dew point temperature are superimposed on the seasonal variations.

It can be generalized for all three types of walls tested, that the temperature at the interior surface of the respective sheathing panels gradually rise from below -10°C in February to upwards of 35°C , with maximum values attaining $> 40^{\circ}\text{C}$ in Period C (May -August). The relative humidity (RH) at the interior surface of the respective sheathing panels varies over the monitoring period between 30% and 60% RH, with significant increase in values up to 90% RH recorded during period B of the monitoring program (i.e. induced air exfiltration). The corresponding temperatures at this same location were quite low, reaching -10° ; as such, the propensity to the formation on condensation was high.

Period B of the monitoring program was intended to bring about occurrences of condensation within the wall assembly. This was the “deficiency state” when warm moist air from the interior was to exfiltrate to the exterior of the test specimens under forced flow conditions. Period B was completed over a three week period during the month of March (i.e. 7 to 28 March 2016). As is perhaps obvious from Figure 12 to Figure 14, significant moisture uptake occurred for all three wall assemblies during the deficiency state, period B, this period being defined by the slits being open to air movement. The response of the moisture detection strips to the presence of moisture is marked with a decrease in electrical resistance which manifests itself by an increase in the value for conductivity. The increase in values for conductivity during period B denotes the presence of condensation.

Whereas after the indoor pressure was reduced to 0Pa at the beginning of the period C (28 March 2016), all wall assemblies started to dry out. At this stage both internal and external slits remained open. The dissipation of moisture from the same locations in Period C is evident from decreases in moisture content values over time; no moisture was detected towards the end of Period C. The moisture sensors in the W2 test specimen stopped recording the presence of moisture after approximately 30 days, at end of April 2016; and in assemblies W1 and W3 no moisture presence was recorded after a period of approximately 60 days, the end of May 2016. This implies that all moisture that was deposited in the walls over period B could gradually dissipate from the wall assemblies.

The propensity for the growth of mould inside the three test walls is shown in Figure 15. Here, values of mould index are given as a function of the monitoring period, in days. The mould index value is based on a mathematical relationship developed by Hukka and Viitanen [8], Viitanen and Ojanen [9], and Ojanen et al. [10] in which values for relative humidity (RH) and temperature (T) and information on the type of surface onto which mould may grow permits establishing the susceptibility to mould growth; values for mould index may range between 0 and 6, where 0 represents no mould growth and 6, very heavy (100% coverage) and tight growth. Its application to providing information on wall performance is more fully described in [4]; additional details regarding the mould index is provided in Appendix 4.

Given the relative humidity and temperatures on the sheathing surface were rising during the Period B, the propensity for mould growth towards the end of Period B increased significantly attaining maximum values of 6 in all three tested assemblies. With lower levels of RH over the Period C, the mould index values slowly abated. However it would be premature to exclude the risk of the occurrence of mould entirely at this stage of testing.

It is the opinion of authors that to determine the behavior of the wall specimens, it would be beneficial to continue data acquisition for a period over the winter of 2016/2017 and thereafter perform a visual inspection of each of the test specimens.

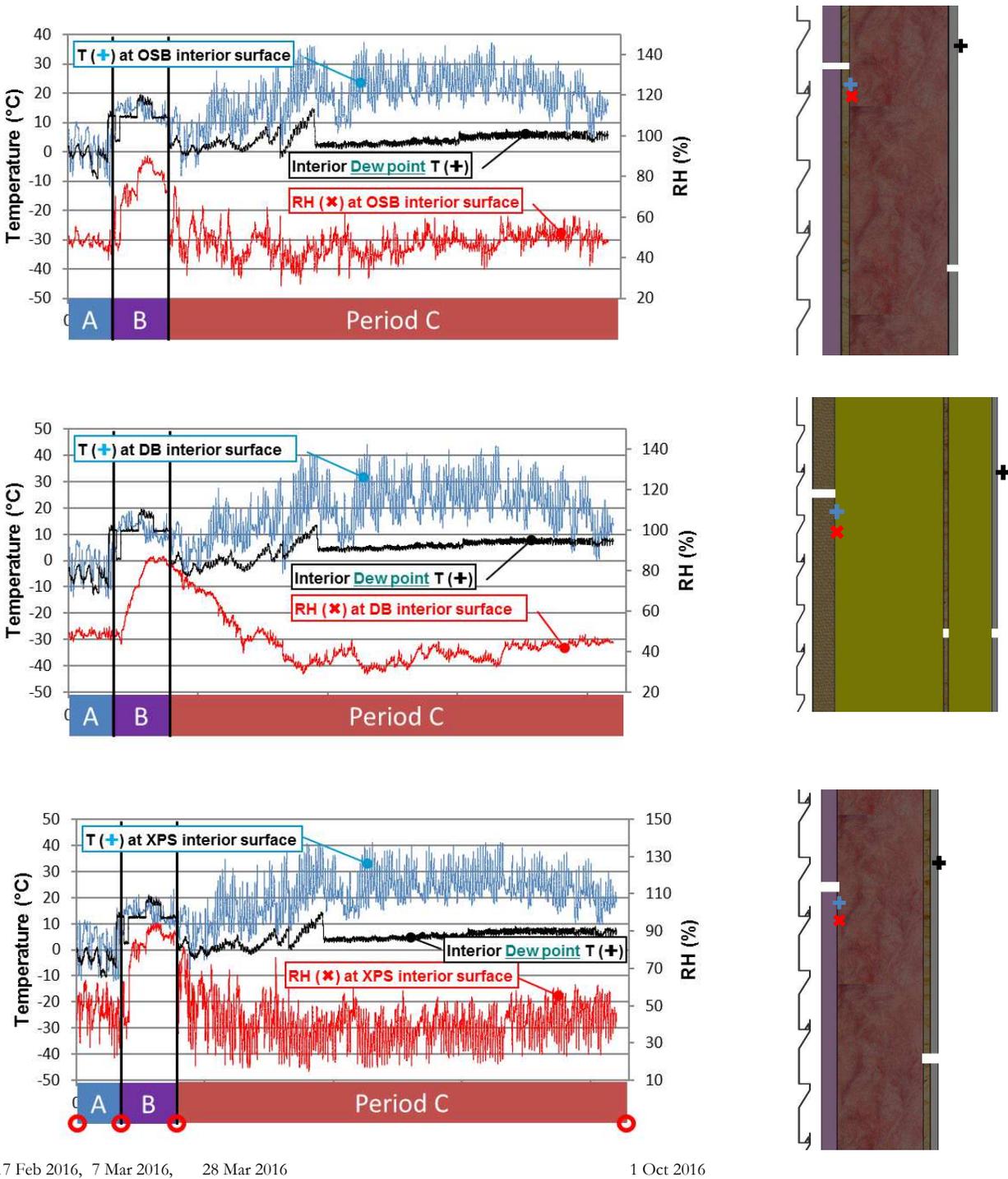


Figure 11– Response of respective wall assemblies (Temperature [T]; RH at exterior insulation surface and dew point T) over monitoring period (2016); (i) W1 (XPS); (ii) W2 (PH); (iii) W3 (OSB)

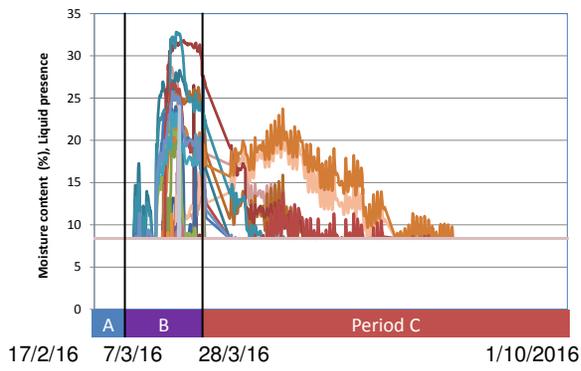


Figure 12 – W1 : Response of moisture detection strip to the presence of moisture in the wall

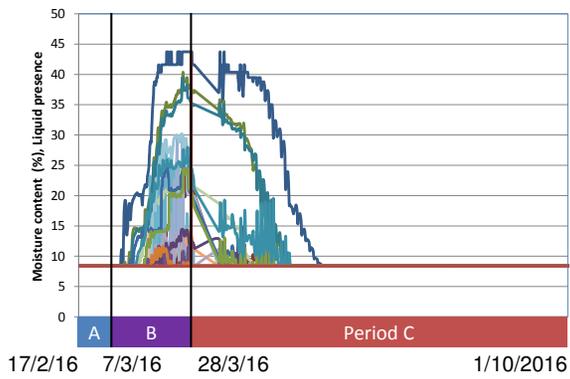


Figure 13 – W2: Response of moisture detection strip to the presence of moisture in the wall

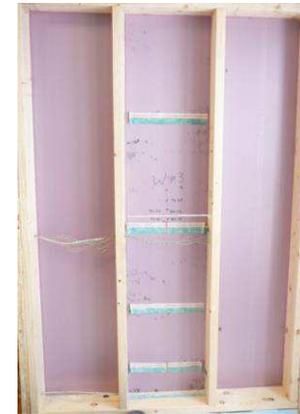
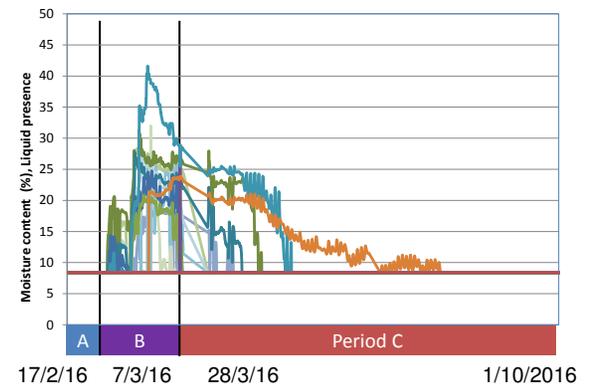


Figure 14 – W3: Response of moisture detection strip to the presence of moisture in the wall

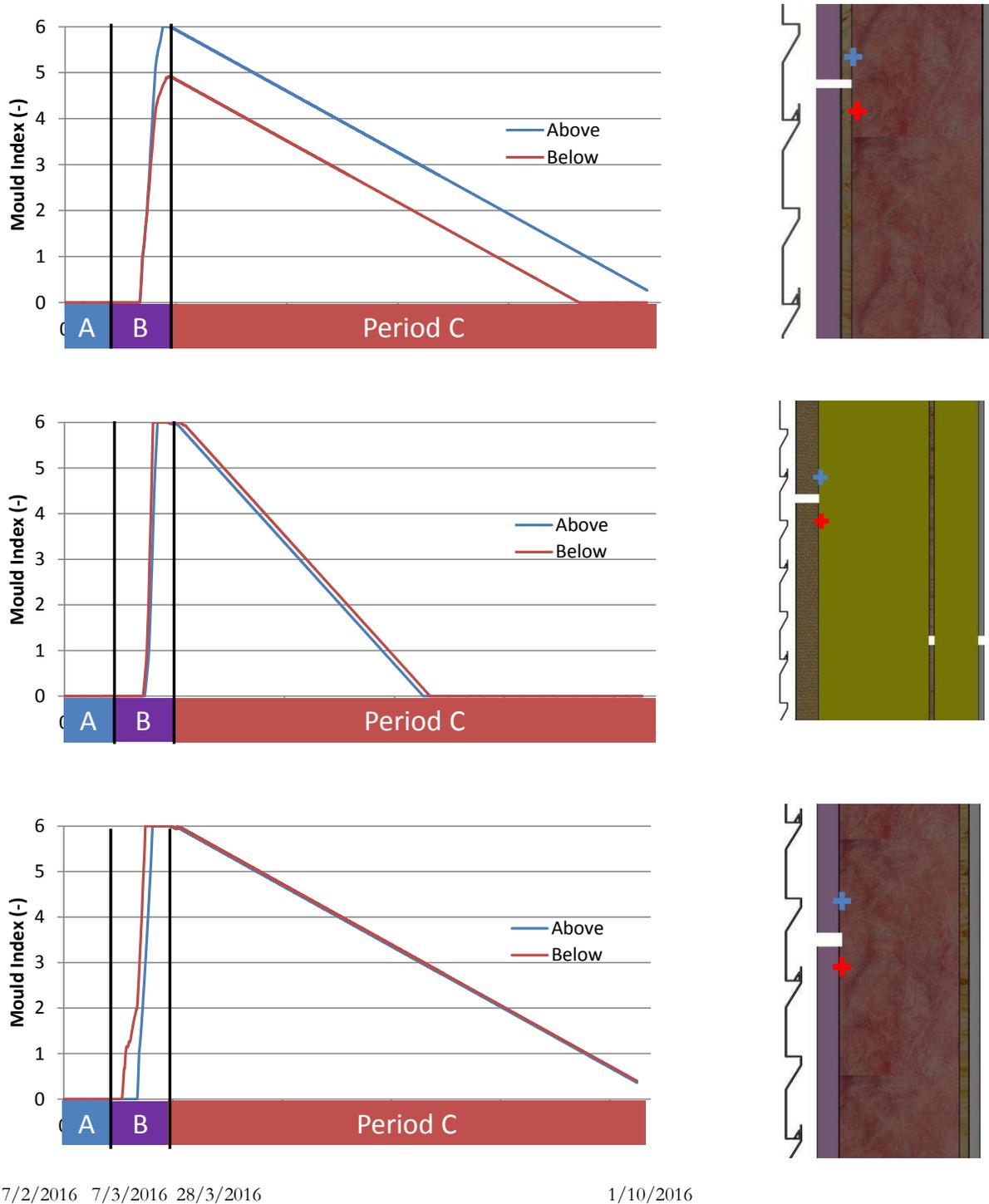


Figure 15 – Mold Index calculation results by Viitanen for monitoring period (2016) above and below the deficiency slits on exterior side; (i) W1 (XPS); (ii) W2 (PH); (iii) W3 (OSB)

4.0 Summary of Response of Walls assemblies

The hygrothermal response of 3 highly insulated wood frame wall assemblies was monitored over an 8 month period to determine whether any of these walls were susceptible to moisture problems that might accrue from inadvertent condensation in the wall assemblies. The walls were subjected to local climate conditions of Ottawa, ON. To determine the vulnerability of the wall test specimens and to assess their robustness to moisture ingress from air leakage, all assemblies were configured to include openings in the air barrier and exterior sheathing panel to permit the passage of air exfiltration from or infiltration to an interior conditioned enclosure. It is important to emphasise that such openings are not standard in wall assemblies and in usual in-service conditions, much lower levels of moisture would be expected to exfiltrate through a typical wall assembly. The summary of the hygrothermal responses of the respective test walls are given below; a definition of the mould index is provided in Appendix 4.

Response of W1 (XPS)

Given that the exterior OSB sheathing panel is located towards the exterior of the wall assembly it is evidently exposed to cold temperatures in winter; as such, the OSB sheathing panel together with the wood studs are the most susceptible components of the assembly. The detection of moisture by sensors (Figure 12 top) together with high values calculated for the mould index (Figure 15 top) permits one to assume that in instances where air exfiltration is permitted to occur across the assembly there is a higher risk to the formation of condensation and in turn, a risk to premature deterioration. The presence of an air cavity behind the vinyl cladding enabled the assembly over a period of 5 months to gradually dry out whilst the value of the mould index diminished. It should be noted that the degree of air exfiltration that was permitted was one that was imposed on the wall assembly by forcing air through purposely made deficiencies. This is not a situation that would normally occur in-service; no condensation issues would arise for this particular wall assembly provided it was properly constructed using accepted practice to ensure control of air and water vapour transfer across the wall.

Response of W2 (PH)

The rate of moisture dissipation (Figure 13) and degree of reduction in value for the mould index (Figure 15 center) over time are considerably greater (approximately two-fold decrease) than that of wall W1; hence this assembly if properly constructed, is quite robust as compared to wall W1 in respect to managing moisture deposition with the wall assembly.

Response of W3 (OSB)

The layer of OSB used as a smart vapour retarder in the assembly of wall W3 allows for higher RH fluctuations on interior side of the XPS board; the overall performance of this assembly is similar to that of wall W1, given it contains identical components (glass fiber thermal insulation, external XPS board, dry wall) with the exception of a 6 mil polyethylene vapour barrier. During the deficiency period condensation of moisture was observed at the location of the slits and high values for mould index we likewise reported; following the deficiency period mould index values declined over a period of 2 months (Figure 14) and after 5 months the mould risk index (Figure 15 bottom) also diminished. No condensation issues would arise for this particular wall assembly provided it was properly constructed using accepted practice to ensure control of air and water vapour transfer across the wall.

Final commentary

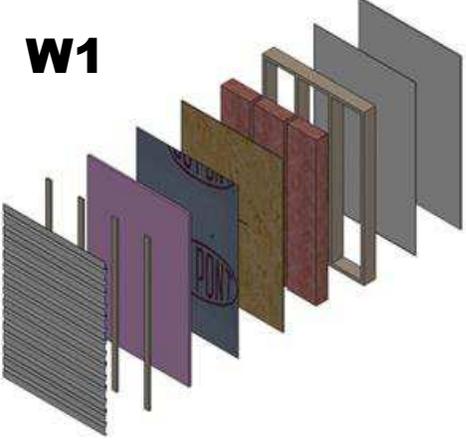
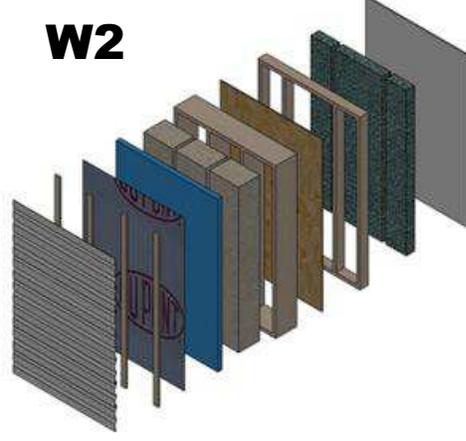
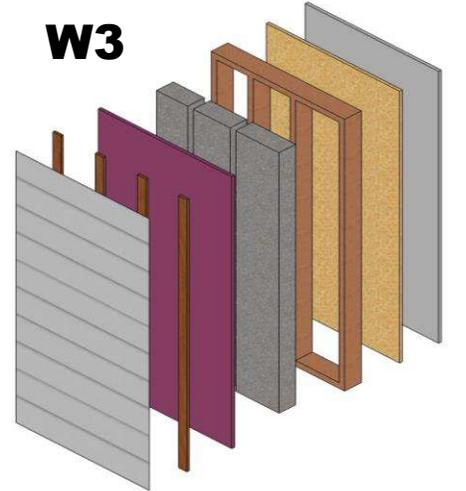
Results from this study show that in instances where openings for air leakage exist, there is a considerable risk to condensation in wall assemblies. The risk to the formation of mould (Viitanen mould index value = 6) on the interior surface of the sheathing panels of all tested walls is significant in instances where forced air exfiltration was imposed on the wall test specimen during cold periods. However, these openings were introduced to induce condensation in the wall and to determine the ability of the wall assemblies to “dry out”, i.e. dissipate any accumulated moisture within the wall. It was shown that all walls tested had the ability to dissipate moisture from within the wall in a 1-2 month period; this is a positive observation. Under normal in-service conditions in which the vapour barrier is not assumed to be breached, none of these walls would be at risk to the formation of condensation, nor mould.

5.0 References

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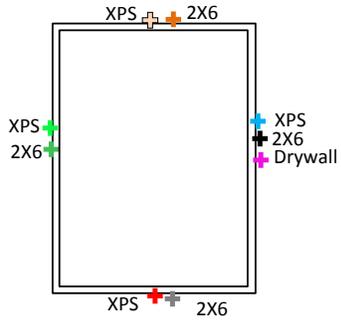
Appendix 1 Test Specimen Fabrication and Installation details

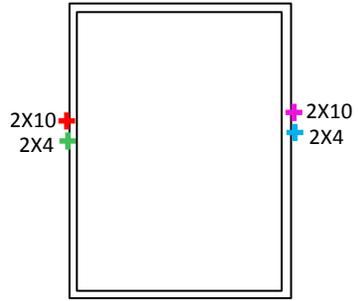
<p>W1</p> 	
<p>W2</p> 	
<p>W3</p> 	

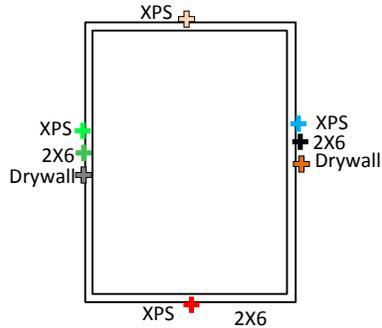
Appendix 2 Test Specimen Sensor Installation Details

Test specimens - Location of temperature thermocouples (TC)

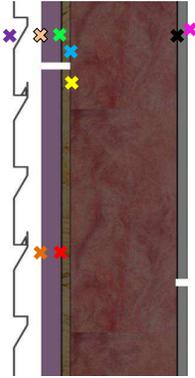
<p>W1 – Location of thermocouple (T)</p> <ul style="list-style-type: none"> — Exterior Vinyl siding top temperature B1_TC_01 — Exterior Vinyl siding top(stud) temperature B1_TC_02 — Exterior XPS insulation top temperature B1_TC_03 — Exterior XPS insulation bottom temperature B1_TC_04 — Exterior sheathing membrane top temperature B1_TC_09 — Interior OSB 1" above slit temperature B1_TC_10 — Interior OSB 1" below slit temperature B1_TC_11 — Exterior drywall top temperature B1_TC_16 — Interior drywall top temperature B1_TC_17 — Interior drywall top(stud) temperature B1_TC_18 	
<p>W2 – Location of thermocouple (T)</p> <ul style="list-style-type: none"> — Exterior vinyl siding top temperature B2_TC_01 — Exterior vinyl siding top(stud) temperature B2_TC_02 — Exterior sheat.membrane top temperature B2_TC_03 — Exterior sheat.membrane bott. temperature B2_TC_04 — Exterior diff.board top temperature B2_TC_05 — Exterior diff.board bottom temperature B2_TC_06 — Interior diff.board top temperature B2_TC_07 — Interior diff.board 1" above slit temperature B2_TC_08 — Interior diff.board 1" below slit temperature B2_TC_09 — Exterior OSB top temperature B2_TC_10 — Exterior OSB bottom temperature B2_TC_13 — Interior OSB top temperature B2_TC_14 — Exterior drywall top temperature B2_TC_17 — Interior drywall top temperature B2_TC_18 — Interior drywall top(stud) temperature B2_TC_19 	
<p>W3 – Location of thermocouple (T)</p> <ul style="list-style-type: none"> — Exterior vinyl top temperature B3_TC_01 — Exterior vinyl top(stud) temperature B3_TC_02 — Exterior XPS top temperature B3_TC_03 — Exterior XPS bottom temperature B3_TC_04 — Interior XPS top temperature B3_TC_09 — Interior XPS 1" above slit temperature B3_TC_10 — Interior XPS 1" below slit temperature B3_TC_11 — Interior OSB top temperature B3_TC_14 — Interior drywall top temperature B3_TC_16 — Interior drywall top(stud) temperature B3_TC_17 	

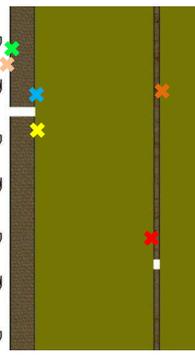
W1 – Location of thermocouple (T)	Designation	
<ul style="list-style-type: none"> — Mid XPS insulation top middle temperature B1_TC_05 — Mid XPS insulation left middle temperature B1_TC_06 — Mid XPS insulation right middle temperature B1_TC_07 — Mid XPS insulation bottom middle temperature B1_TC_08 — Mid 2X6 stud top middle temperature B1_TC_12 — Mid 2X6 stud left middle temperature B1_TC_13 — Mid 2X6 stud right middle temperature B1_TC_14 — Mid 2X6 stud bottom middle temperature B1_TC_15 — Interior drywall right middle temperature B1_TC_19 		

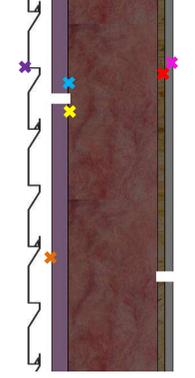
W2 – Location of thermocouple (T)	Designation	
<ul style="list-style-type: none"> — Mid 2X10 right middle temperature B2_TC_11 — Mid 2X10 left middle temperature B2_TC_12 — Mid 2X4 left middle temperature B2_TC_15 — Mid 2X4 right middle temperature B2_TC_16 		

W3 – Location of thermocouple (T)	Designation	
<ul style="list-style-type: none"> — Mid XPS top middle temperature B3_TC_05 — Mid XPS left middle temperature B3_TC_06 — Mid XPS right middle temperature B3_TC_07 — Mid XPS bottom middle temperature B3_TC_08 — Mid 2X6 stud left middle temperature B3_TC_12 — Mid 2X6 stud right middle temperature B3_TC_13 — Interior drywall left middle temperature B3_TC_15 — Interior drywall right middle temperature B3_TC_18 		

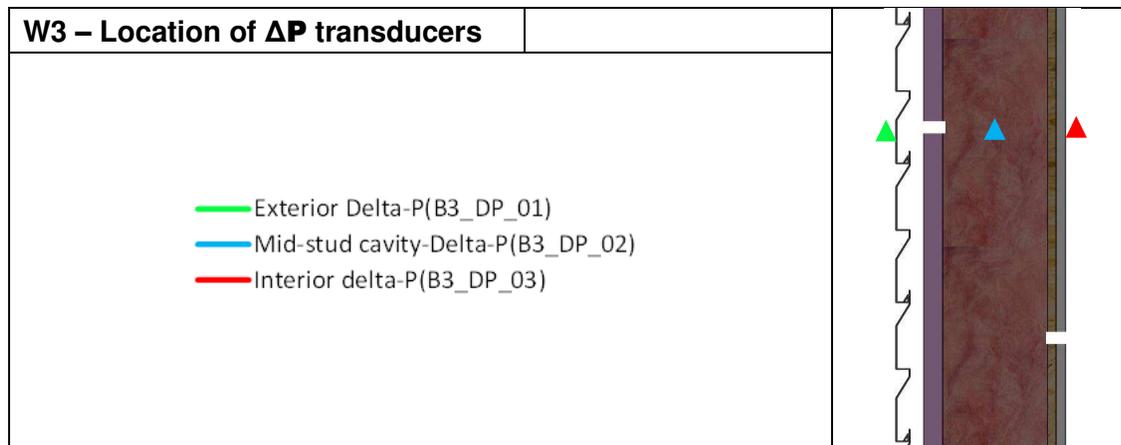
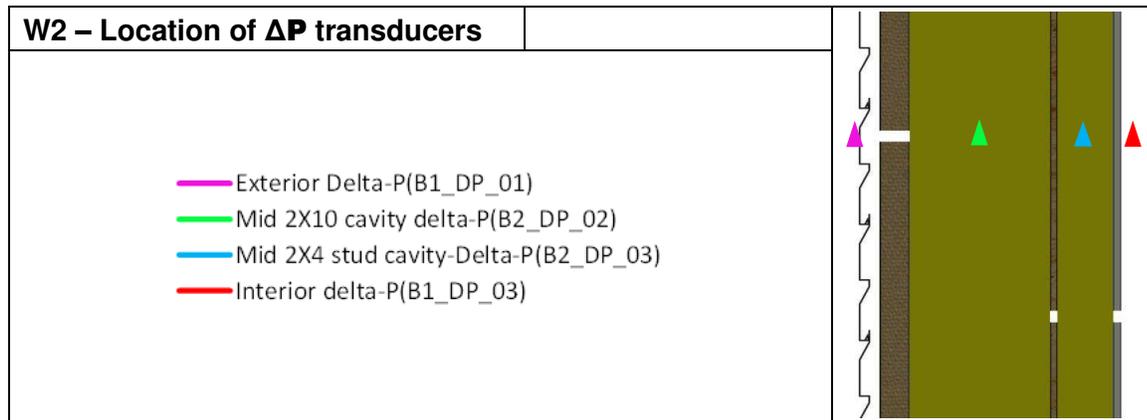
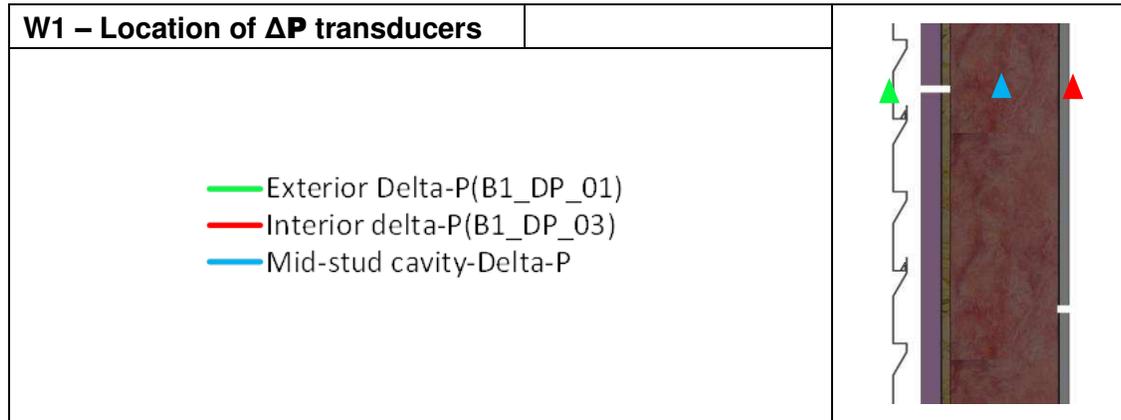
Test specimens - Location of relative humidity sensors (RH)

W1 – Location of RH sensors	Designation	
<ul style="list-style-type: none"> — Exterior vinyl siding top RH B1_RHT_01_RH — Exterior XPS insulation top RH B1_RHT_02_RH — Exterior XPS insulation bottom RH B1_RHT_03_RH — Exterior sheathing membrane top RH B1_RHT_04_RH — Exterior sheathing membrane bottom RH B1_RHT_05_RH — Interior OSB 1" above slit RH B1_RHT_06_RH — Interior OSB 1" below slit RH B1_RHT_07_RH — Exterior drywall top RH B1_RHT_08_RH — Interior drywall top RH B1_RHT_09_RH 		

W2 – Location of RH sensors	Designation	
<ul style="list-style-type: none"> — Exterior vinyl siding top RH B2_RHT_01_RH — Exterior sheathing membrane top RH B2_RHT_02_RH — Exterior diff. borad top RH B2_RHT_03_RH — Interior diff. board 1" above slit RH B2_RHT_04_RH — Interior diff. board 1" below slit RH B2_RHT_05_RH — Exterior OSB bottom RH B2_RHT_06_RH — Interior OSB top RH B2_RHT_07_RH — Exterior drywall top RH B2_RHT_08_RH — Interior drywall top RH B2_RHT_09_RH 		

W3 – Location of RH sensors	Designation	
<ul style="list-style-type: none"> — Exterior vinyl siding top RH B3_RHT_01_RH — Exterior XPS insulation top RH B3_RHT_02_RH — Exterior XPS insulation bottom RH B3_RHT_03_RH — Interior XPS insulation 1" above slit RH B3_RHT_04_RH — Interior XPS insulation 1" below slit RH B3_RHT_05_RH — Interior OSB top RH B3_RHT_06_RH — Interior drywall top RH B3_RHT_07_RH 		

Test specimens - Location of Pressure transducers



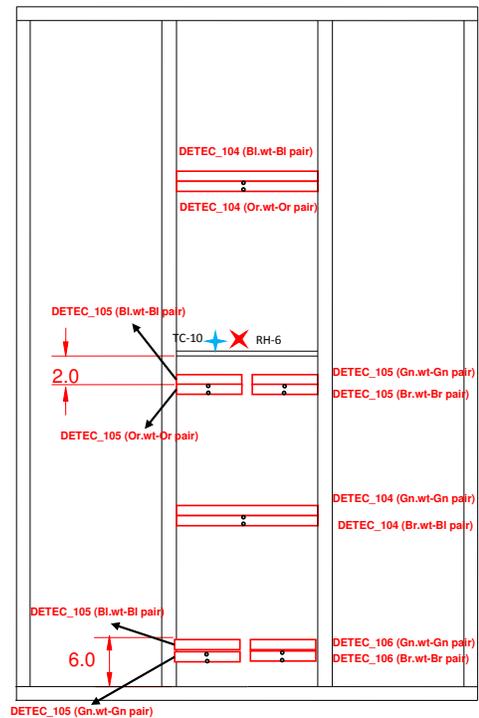
Test specimens - Location of moisture and liquid sensing tapes

W1 - Location of DETEC moisture sensing tapes in stud cavity

- 103-Liq_Outside XPS Insulation@bottom
- 103-Liq_Outside TYVEK@Bottom
- 104-Liq_Outside OSB@Top left
- 104-Mois_Outside OSB@top left
- 105-Liq_Outside OSB@Top right
- 105-Mois_Outside OSB@Top right
- 106-Liq_Outside OSB@Bottom left
- 106-Mois_Outside OSB@Bottom left
- 107-Liq_Outside OSB@Bottom right
- 107-Mois_Outside OSB@Bottom right
- 108-Liq_Inside OSB@Top
- 108-Mois_Inside OSB@Top
- 109-Liq_Inside OSB@Mid-Bottom
- 109-Mois_Inside OSB@Mid-Bottom
- 110-Liq_Inside OSB-under Slit@left
- 110-Mois_Inside OSB-Under Slit@left
- 111-Liq_Inside OSB-Under Slit@right
- 111-Mois_Inside OSB-Under Slit@right
- 112-Liq_Inside OSB@Bottom left
- 112-Mois_Inside OSB@Bottom left
- 113-Liq_Inside OSB@Bottom right
- 113-Mois_Inside OSB@Bottom right
- 114-Liq_Mid cavity_ On left side Stud under Slit
- 114-Mois_Mid cavity_ On left side Stud under Slit
- 115-Mois_Mid cavity_ On right side Stud under Slit
- 115-Liq_Mid cavity_ On right side Stud under Slit
- 116-Liq_Bottom Stud Track
- 116-Mois_Bottom Stud Track
- 117-L Inside Stud
- 117-M Inside Stud
- 101-Liq_Outside XPS Insulation@Top
- 102-Liq_Outside Tyvek@Top



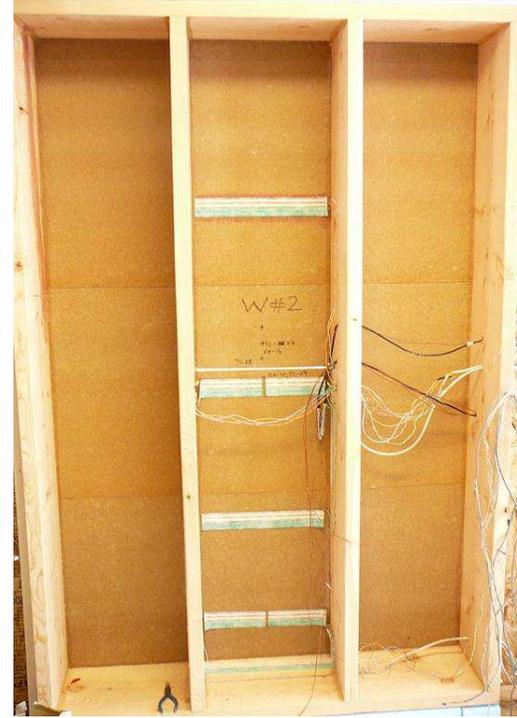
LAYER 5 - Interior Face of OSB



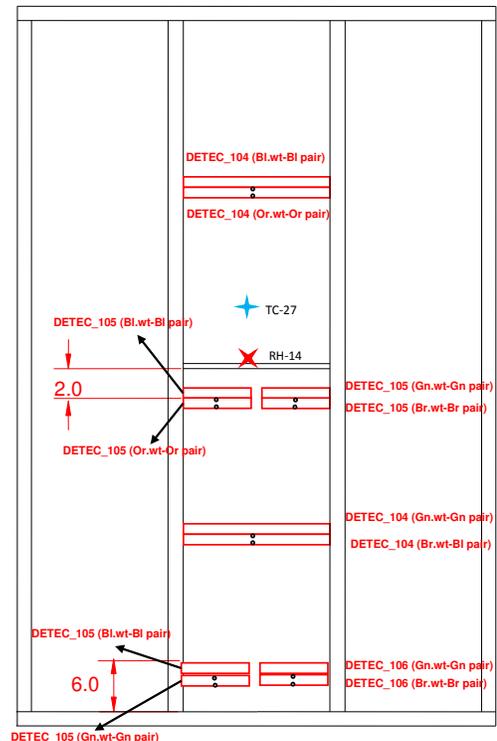
View from interior of specimen.
All dimensions in inches.

W2 - Location of DETEC moisture sensing tapes in stud cavity

- 203-Liq_ Inside Diff.Board@Mid-Bottom
- 203-Mois_ Inside Diff.Board@Mid-Bottom
- 204-Liq_ Outside Diff.Board@Top right
- 204-Mois_ Outside Diff.Board@Top right
- 205-Liq_ Outside Diff.Board@Top left
- 210-Liq_ Inside Diff.Board-Under Slit@left
- 210-Mois_ Inside Diff.Board-Under Slit@left
- 211-Liq_ Inside Diff.Board-Under Slit@right
- 211-Mois_ Inside Diff.Board-Under Slit@right
- 212-Liq_ Inside Diff.Board@Bottom left
- 212-Mois_ Inside Diff.Board@Bottom left
- 213-Liq_ Inside Diff.Board@Bottom right
- 213-Mois_ Inside Diff.Board@Bottom right
- 214-Liq_Mid cavity_ On left Stud under Slit
- 214-Mois_Mid cavity_ On left side Stud under Slit
- 215-Liq_Mid cavity_ On right side Stud under Slit
- 215-Mois_Mid cavity_ On right side Stud under Slit
- 216-Liq_Bottom Stud Track
- 216-Mois_Bottom Stud Track
- 202-Mois_ Inside Diff.Board@Top



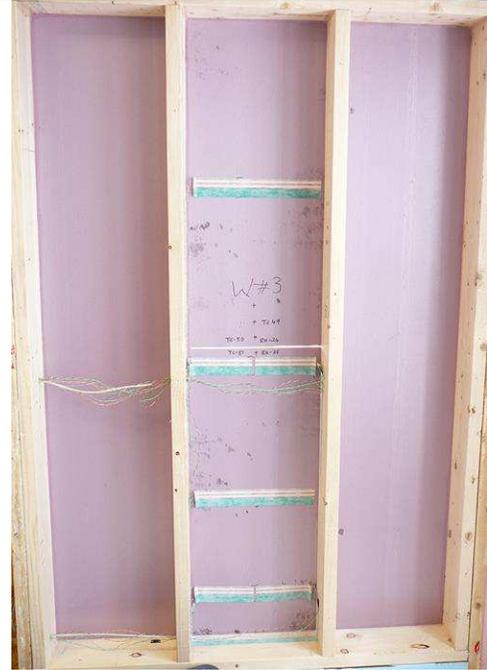
LAYER 4 - Interior Face of diffusion board



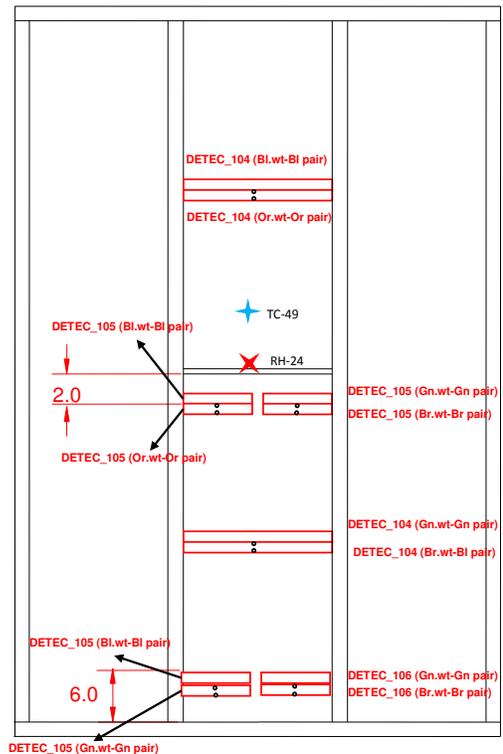
View from interior of specimen.
All dimensions in inches.

W3 - Location of DETEC moisture sensing tapes in stud cavity

- 301-Liq_ Outside RigidFoam@Bottom right
- 303-Liq_ Outside RigidFoam@Bottom left
- 303-Mois_ Outside RigidFoam@Bottom left
- 304-Liq_ Inside RigidFoam@Top
- 305-Liq_ Inside RigidFoam@ Mid-Bottom
- 307-Liq_ Outside TYVEK@Top
- 307-Liq_ Outside TYVEK@Bottom
- 308-Liq_ Outside RigidFoam@Top right
- 308-Mois_ Outside RigidFoam@Top right
- 309-Liq_ Outside RigidFoam@Top left
- 309-Mois_ Outside RigidFoam@Top left
- 310-Liq_ Inside RigidFoam-Under Slit@left
- 311-Liq_ Inside RigidFoam-Under Slit@right
- 312-Liq_ Inside RigidFoam@Bottom left
- 313-Liq_ Inside RigidFoam@Bottom right
- 314-Liq_ Mid cavity_ On left side Stud under Slit
- 314-Mois_ Mid cavity_ On left side Stud under Slit
- 315-Liq_ Mid cavity_ On right side Stud under Slit
- 315-Mois_ Mid cavity_ On right side Stud under Slit
- 316-Liq_ Bottom Stud Track
- 316-Mois_ Bottom Stud Track
- 317-L Inside Stud
- 317-M Inside Stud



LAYER 3 - Interior Face of XPS insulation

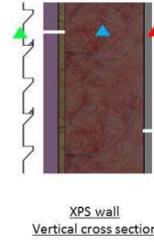
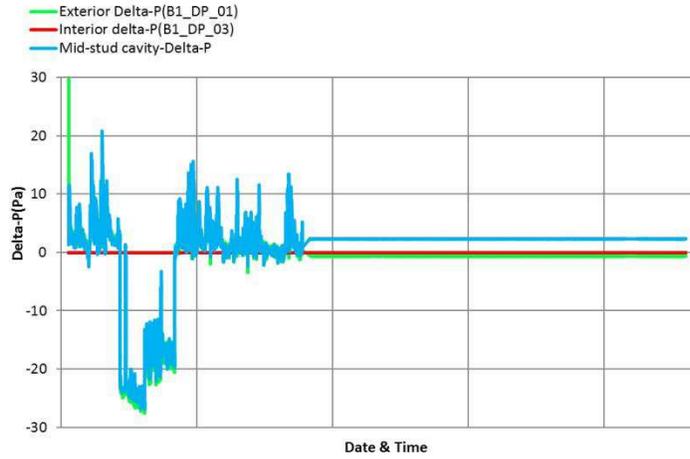


View from interior of specimen.
All dimensions in inches.

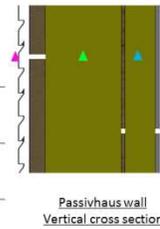
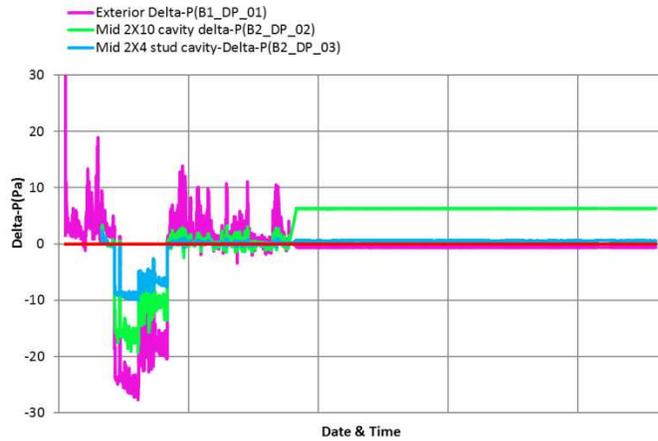
Appendix 3

Pressure variations over monitoring period

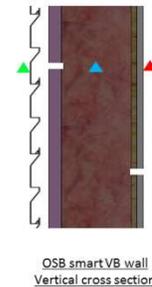
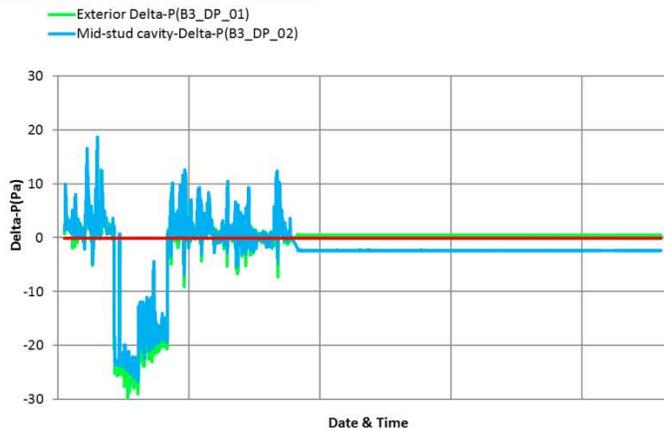
Wall-1 Delta-P across interior chamber



Wall-2 Delta-P across interior chamber



Wall-3 Delta-P across interior chamber



17 Feb 2016

7 Mar 2016

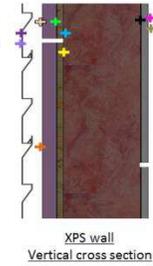
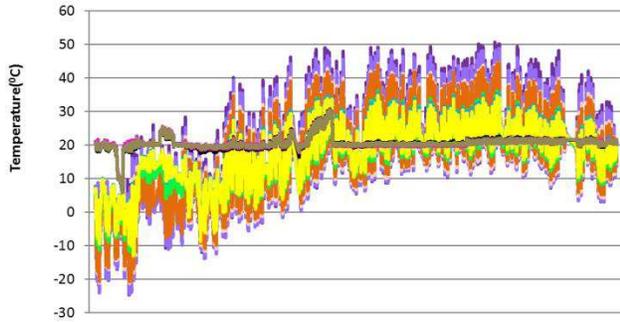
28-Mar 2016

1 Oct 2016

Temperature variations over monitoring period

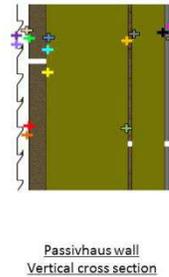
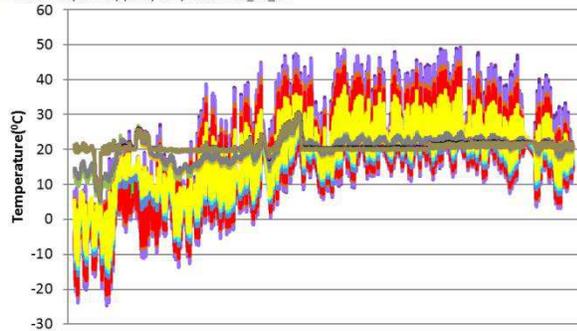
Wall-1 Temperature(TC)

- Exterior Vinyl siding top temperature B1_TC_01
- Exterior XPS insulation top temperature B1_TC_03
- Exterior sheathing membrane top temperature B1_TC_09
- Interior OSB 1" below slit temperature B1_TC_11
- Interior drywall top temperature B1_TC_17
- Exterior Vinyl siding top(stud) temperature B1_TC_02
- Exterior XPS insulation bottom temperature B1_TC_04
- Interior OSB 1" above slit temperature B1_TC_10
- Exterior drywall top temperature B1_TC_16
- Interior drywall top(stud) temperature B1_TC_18



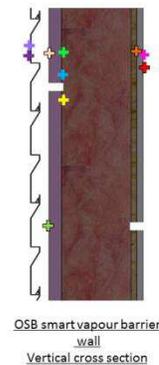
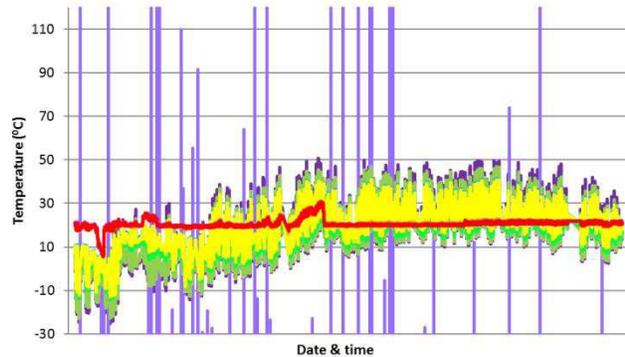
Wall-2 temperature

- Exterior vinyl siding top temperature B2_TC_01
- Exterior sheat.membrane top temperature B2_TC_03
- Exterior diff.board top temperature B2_TC_05
- Interior diff.board top temperature B2_TC_07
- Interior diff.board 1" below slit temperature B2_TC_09
- Exterior OSB bottom temperature B2_TC_13
- Exterior drywall top temperature B2_TC_17
- Interior drywall top(stud) temperature B2_TC_19
- Exterior vinyl siding top(stud) temperature B2_TC_02
- Exterior sheat.membrane bott. temperature B2_TC_04
- Exterior diff.board bottom temperature B2_TC_06
- Interior diff.board 1" above slit temperature B2_TC_08
- Exterior OSB top temperature B2_TC_10
- Interior OSB top temperature B2_TC_14
- Interior drywall top temperature B2_TC_18



Wall-3 temperature

- Exterior vinyl top temperature B3_TC_01
- Exterior XPS top temperature B3_TC_03
- Interior XPS top temperature B3_TC_09
- Interior XPS 1" below slit temperature B3_TC_11
- Interior drywall top temperature B3_TC_16
- Exterior vinyl top(stud) temperature B3_TC_02
- Exterior XPS bottom temperature B3_TC_04
- Interior XPS 1" above slit temperature B3_TC_10
- Interior OSB top temperature B3_TC_14
- Interior drywall top(stud) temperature B3_TC_17



17 Feb 2016

7 Mar 2016

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1 Oct 2016

Appendix 4

Mould Index and Hygrothermal Performance

Results were expressed using the mould index (M) criteria developed by Hukka and Viitanen [8], Viitanen and Ojanen [9], and Ojanen et al. [10]. The most recent mould model by Ojanen et al. [10] was used in this study to determine the mould index of different materials of the wall assemblies. In that model [10], the sensitivity of different construction materials for mould growth was classified in four sensitivity classes, namely, very sensitive, sensitive, medium resistant and resistant (see Table). Table provides the assumed correspondence of sensitivity class for materials located within the wall assembly of this study. More specifically, the sensitivity class for the top and bottom plates, OSB and foam was considered “Sensitive”, whereas the sensitivity class of the materials for cavity insulation (fiber-based), drywall and membranes was considered “Medium Resistant”.

Table 5. Description of Mould Index (M) levels [8, 9, 10]

M	Mould Index (M) Description of Growth Rate
0	No growth
1	Small amounts of mould on surface (microscope), initial stages of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, < 10% coverage, or < 50% coverage of mould (microscope)
4	Visual findings of mould on surface, 10%–50% coverage, or > 50% coverage of mould (microscope)
5	Plenty of growth on surface, > 50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

Table 6. Mould growth sensitivity classes and some corresponding materials [10]

Sensitivity Class	Materials	RH _{min} (%) [*]
Very Sensitive	Pine sapwood	80
Sensitive	Glued wooden boards, spruce	80
Medium Resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool	85
Resistant	PUR with polished surface	85

^{*} Minimum relative humidity needed for mould growth

Table 7. Mould growth sensitivity classes for materials of wall assemblies listed in Table 2

Sensitivity Class	Material Layers of Wall Assemblies	RH _{min} (%) [*]
Very Sensitive	Wood fibre insulation	80
Sensitive	Top plate, bottom plate, OSB, foam	80
Medium Resistant	Fiberglass insulation, gypsum, membranes	85
Resistant		85

^{*}Minimum relative humidity needed for mould to grow