Evaluation of thermal and moisture response of highly insulated wood-frame wall assemblies, phase 2: Part II: numerical modelling

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Evaluation of Thermal and Moisture Response of Highly Insulated Wood-Frame Wall Assemblies — Phase 2

Part II: Numerical Modelling

Report A1-000444.6

Hamed H. Saber and G. Ganapathy

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Executive Summary of Entire Project

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 insulation products. This project consisted of two phases. This section provides a summary of the results of Phase 1 and Phase 2.

In Phase 1 of this project, the field monitoring of residential 38 mm x 140 mm (2 x 6 in) wood-frame wall systems that had been constructed using different types of exterior insulation products were undertaken at the Field Exposure of Walls Facility (FEWF) of NRC-Construction, located in Ottawa; the primary intent was to investigate the risk of condensation and mould growth in three mid-scale (1219 mm x 1829 mm / 4 ft x 6 ft) wall specimens installed in the FEWF. The first specimen was constructed by installing 25 mm (1 in) thick EPS insulation panels (EPS Wall); the second specimen was constructed with 51 mm (2 in) thick XPS insulation panels (XPS Wall); whereas the third specimen was constructed by installing 76 mm (3 in) thick mineral fibre batt insulation (Mineral Fibre Wall); all insulation products were installed outboard of the sheathing membrane. The overall nominal R-values of the EPS Wall, XPS Wall, and Mineral Fibre Wall were RSI-4.92 (R-27.9), RSI-5.98 (R-34.0), and 6.42 (R-36.5), respectively. The three wall specimens were installed side-by-side in the FEWF and subjected to local climate conditions of Ottawa over a period of one year (August 11, 2013 – October 1, 2014).

In Phase 2 of this project, another three mid-scale 1219 mm x 1829 mm (4 ft x 6 ft) wood-frame wall specimens were installed side-by-side in the FEWF. These walls are named in this report as XPS Wall, SPF Wall and CEL Wall. The XPS Wall consisted of 38 mm x 140 mm (2 x 6 in) wood-frame; the SPF Wall consisted of 38 mm x 229 mm (2 x 6 in + 2 x 4 in (i.e. 2x10 in)) wood-frame; whereas the CEL Wall consisted of 38 mm x 279 mm (three 2 x 4 in (i.e. 2 x 12 in)) wood-frame. The primary insulation materials for XPS Wall were RSI-4.23 (R-24) glass fiber batt insulation over which and towards the interior was installed 51 mm (2 in) of XPS rigid foam insulation; the overall nominal thermal resistance for this wall was RSI-5.98 (R-34.0). For the SPF Wall, the primary insulation materials were 61 mm (2.4 in) thick of Spray Polyurethane Foam (SPF) of RSI-2.87 (R-16.3) applied on the interior surface of the OSB sheathing panel and 168 mm (6.6 in) of same type of glass fiber batt insulation as in the XPS Wall (RSI-5.05 / R-28.7); the overall nominal thermal resistance for SPF Wall was RSI-7.92 (R-45). For the CEL Wall, the insulation product that filled the entire wall cavity consisted of cellulose fiber insulation providing a nominal R-value of RSI-6.96 (R-39.5). The field monitoring of the test specimens was conducted from January 2015 to September 2015. This allowed a 9-month period over which test specimens were subjected to a broad range of weather conditions of Ottawa.

For both Phase 1 and Phase 2 of this project, the first stage of the work program included the experimental design, installation of test specimens, commissioning of instrumentation, operation of the test facility, collection and monitoring of data, and data analyses. The second stage of the work program included conducting: material characterization of the insulation products (EPS, XPS, mineral fibre insulation, SPF and cellulose fiber insulation), model benchmarking, and thereafter, parametric model simulation study to predict the thermal and hygrothermal performances of different wall systems, subjected to different climates in Canada.

The hygrothermal model, hygIRC-C, was benchmarked against the measured data for wall systems of Phase 1 (see reference [13]) and Phase 2 as presented in this report. Results showed that the model predictions were in good agreement with the experimental data obtained from the different wall specimens. Thereafter, the hygrothermal model was used to conduct parametric analyses to predict the risk of condensation and mould growth in full-scale wall assemblies Phase 1 [13] and Phase 2 that incorporated different insulation products when these walls were subjected to climate conditions of Ottawa (ON), Edmonton (AB) Vancouver (BC), St. John's (NL), and Yellowknife (NT).

Similar to the previous NRC project that has led to code changes of Part 9 of the "2015 National Building Code Canada" [17], the simulation parameters that were used in this project for the six wall assemblies of Phase 1 and Phase 2 (indoor conditions, outdoor conditions, air leakage rate, and other simulation parameters) were the same as that recommended by the Task Group (TG) on Properties and Position of Materials in the Building Envelope*. The hygrothermal performance of all walls was compared to the National Building Code of Canada's prescribed reference wall (REF Wall). The REF Wall consists of interior drywall ((12.7 mm / 0.5 in) thick), polyethylene membrane air and vapour barrier (6 mil thick), 38 mm x 140 mm (2 x 6 in) wood-frame with friction-fit glass fibre batt insulation of RSI-4.23 (R-24), and oriented strand board (OSB) (11 mm / 7/16 in thick).

The performance was expressed using the mould index criteria, which allowed sufficient resolution to assess the risk of moisture condensation and related risk of mould growth in the wall assemblies. The development of the mould index has been on-going for several years with the most recent mould model having being provided by Ojanen et al. [27]. This mould model was used in this project and the previous NRC project [17]. Briefly, the mould index levels range in value from 0 to 6, with 0 being equivalent to no growth and 6 indicating 100% coverage of either heavy or tight mould growth. The visual identification of mould growth on surfaces is given an index level value of 3 [27].

For each climatic location, the weather data was analyzed to identify the orientation of the wall assembly with the highest exfiltration rate. Note that a higher exfiltration rate would result in a greater risk to the formation of condensation and mould growth within the wall. As such, for each climatic condition, all numerical simulations were conducted for the wall assemblies that faced the predominant direction that would provide the highest exfiltration rate. Furthermore, it was determined that walls of the third storey were subjected to higher exfiltration rates as compared to walls in lower stories. Thus, all wall assemblies investigated in this project were walls of the third storey of low-rise buildings; this was assumed to represent the worst case scenario.

After conducting the numerical simulations for all wall assemblies, and based on the air leakage paths considered in this study, the different wall locations at risk for the formation of condensation and mould growth were identified and for which the corresponding value for mould index was calculated. It is important to point out that the wall locations at risk of mould growth would change by considering different air leakage paths within the wall assembly.

To compare the hygrothermal performance of different wall systems with that for the National Building Code of Canada's prescribed reference wall, the simulation results were summarized in a simple form using the following two parameters:

- Overall average mould index, and
- Overall maximum mould index.

* TG acting on behalf of the NBCC Standing Committee on Housing and Small Buildings (SCHSB).

The two above parameters were determined for a two year simulation period (i.e. average year followed by a wet year, selected from long-term meteorological data for each location).

For the wall assemblies of Phase 1 [13], the results showed that the values for the overall average mould index and overall maximum mould index in these walls with different types of exterior insulations (EPS Wall, XPS Wall, Mineral Fibre Wall) were lower than that of the reference, NBC-compliant wall (REF Wall). Regarding the effect of the climatic locations on the performance of the REF Wall, EPS Wall and XPS Wall, the location of St. John's appeared to have the most severe climate in comparison to the other four locations investigated (Vancouver, Ottawa, Edmonton and Yellowknife); the greatest values of the overall average mould index of the wall configurations amongst the five locations occurred at this location. For the wall having mineral fibre insulation, however, the values of overall average mould index were approximately the same for St. John's and Vancouver.

For the wall assemblies of Phase 2, the results showed that the values of the overall average mould index and the overall maximum mould index of the SPF Wall and CEL Wall were lower than those of the code-compliant reference wall (REF Wall). However, and unlike the XPS Wall of Phase 1, the values of the overall average mould index and the overall maximum mould index of the XPS Wall of Phase 2 were greater than those of the REF Wall. It is important to note that the XPS Wall of Phase 1 [13] is similar to the XPS Wall of Phase 2 except that the XPS layer of 51 mm (2 in) thick in the former was located outboard, on the sheathing membrane, while the same XPS layer of 51 mm (2 in) thick in the latter was located inboard (between the vapour barrier and the cavity insulations).

Also, similar to the wall assemblies of Phase 1 [13], the climatic condition of St. John's (NL) appeared to have the most severe climate for all wall systems of Phase 2 (REF Wall, XPS Wall, SPF Wall and CEL Wall) in comparison to the other four locations investigated (Vancouver (BC), Ottawa (ON), Edmonton (AB) and Yellowknife (NT)); the greatest values of the overall average mould index in these walls amongst the five locations occurred in this location.

Finally, the hygrothermal performances of all wall systems of Phase 1 and Phase 2 of this project, excluding the XPS Wall of Phase 2, are higher than those of the code-compliant reference wall, when these walls were subjected to different climatic conditions of Canada. Furthermore, as expected, increasing the R-value of the wall systems of Phase 1 and Phase 2 resulted in an enhancement of the energy performance by decreasing both heat losses and heat gains through the wall systems.

Evaluation of Thermal and Moisture Response of Highly Insulated Wood-Frame Wall Assemblies ─ Phase 2

Part II: Numerical Modelling

Authored by:

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Ottawa ON K1A 0R6 Canada

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Evaluation of Thermal and Moisture Response of Highly Insulated Wood-Frame Wall Assemblies ─ Phase 2 Part II: Numerical Modelling

Hamed H. Saber and Gnanamurugan Ganapathy

1. Introduction

A review of literature is provided on the moisture performance of the building envelope of housing and small buildings in cold climates [1-12]. The details of this literature review are available in the previous report of Phase 1 [13]. In this report, the hygIRC-C model was benchmarked against the test data of wall assemblies of Phase 2. Thereafter, this model was used to conduct a parametric study that formed the basis for an investigation of the energy performance and risk of formation of condensation and resulting mould growth in highly insulated wood-frame wall assemblies of Phase 2 when these walls are subjected to different climatic conditions of Canada.

2. Project Overview

NRC has undertaken field monitoring and numerical 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 insulation products. The field monitoring of different wall assemblies was undertaken in the NRC's Field Exposure of Walls Facility (FEWF). Three wall assemblies were tested in Phase 1 and another three wall assemblies were tested in Phase 2. A description of the wall assemblies of Phase 1 and Phase 2 is provided in Table 1.

In Phase 1 [13, 14], three 1219 mm x 1829 mm (4 ft x 6 ft) having 38 mm x 140 mm (2 x 6 in) wood-frame wall test specimens were constructed using different types of exterior insulation products that included: 25 mm (1 in) thick EPS; 51 mm (2 in) thick XPS, and, 76 mm (3 in) thick mineral fibre insulation. The three test specimens were installed side-by-side in the FEWF and exposed to local climate conditions of Ottawa over a one year period; the test period started on August 11, 2013 and ended on October 1, 2014.

In Phase 2, another three 1219 mm x 1829 mm (4 ft x 6 ft) wood-frame walls were constructed, as shown in Figure 1 to Figure 4; as was the case in Phase 1, the test specimens were installed side-by-side in the FEWF (Figure 1). The common elements of all three test specimens were, starting from the exterior of the assemblies, the vinyl siding, polymer-based sheathing membrane, and 11 mm OSB wood-sheathing panel; for the interior finish, a 6 mil polyethylene air and vapor barrier and a 12.5 mm drywall panel. The three walls of Phase 2 are named in this report as XPS Wall (extruded polystyrene as insulation), SPF Wall (spray polyurethane foam as insulation) and CEL Wall (cellulose fibre as insulation) . All walls were of wood-frame construction, the difference being that the frame of the XPS Wall nominally consisted of 38 mm x 140 mm (2 x 6 in) wood framing (Figure 2), that for the SPF Wall, 38 mm x 229 mm (2 x 6 in + 2 x 4 in (i.e. 2x10 in)) wood framing (Figure 3), and that for the CEL Wall, 38 mm x 279 mm (three 2 x 4 in (i.e. 2 x 12in)) wood framing (Figure 4).

The primary insulation materials for the XPS Wall were: RSI-4.23 (R-24) glass fiber batt insulation over which and towards the interior was installed 51 mm (2 in) of XPS rigid foam insulation; the overall nominal thermal resistance for the XPS Wall was RSI-5.98 (R-34). For the SPF Wall, the primary insulation materials were: ca. 61 mm (2.4 in) of Spray Polyurethane Foam (SPF, RSI-2.87 (R-16.3)) applied on the interior surface of the OSB sheathing panel and 168 mm (6.6 in) of same type of glass fiber batt insulation as in XPS Wall (RSI-5.05 (R-28.7)); the overall nominal thermal resistance for the SPF Wall was RSI-7.92 (R-45). For the CEL Wall, the insulation products consisted of cellulose fiber insulation providing a nominal R-value of RSI-6.96 (R-39.5). Whereas for the XPS Wall and the SPF Wall the full depth of the vertical studs was used across the wall assembly, for the CEL Wall, 2 x 4 in framing was used in the central stud cavity on the exterior and interior of the wall; this arrangement is more clearly evident from the horizontal sectional view provided in Figure 4.

The scope of work of Phase 1 and Phase 2 included the experimental design, installation of test specimens, commissioning of instrumentation, operation of the test facility, collection and monitoring of data, data analyses, material characterization of the insulation products (EPS, XPS and Mineral Fibre (MF), Spray Polyurethane Foam (SPF), and Cellulose fibre (CEL)), and finally numerical modelling.

The previous report of this project focused on the results of the three wall assemblies of Phase 1 [13]. Whereas this report focuses on the numerical modelling where the NRC's hygrothermal model, hygIRC-C, was benchmarked against the FEWF test data of the different wall specimens of Phase 2. Thereafter, the model was used to conduct parametric analyses to permit investigating the energy performance, and the risk of condensation and mould growth in different wall assemblies, when subjected to different climatic conditions of a selected set of locations in Canada. The hygIRC-C model description and record of benchmarking are available in reference [13].

3. Model Benchmarking

Having previously benchmarked the present model to several tests undertaken in controlled laboratory conditions as described previously in reference [13], a subsequent and important step was to benchmark the present model against the field measurements for the three wall systems of Phase 2 (Table 1). A brief description of the constructed wall specimens of Phase 2 is provided in the previous section and more details are available in reference [14]. Information is provided below regarding assumptions, and initial and boundary conditions that were used in conducting model benchmarking.

Table 1. Descriptions of walls for Phase 1 and Phase 2 (Yr 2013-2015)*

Phase	Wall-1 4 ft x 6 ft	Wall-2 4 ft x 6 ft	Wall-3 4 ft x 6 ft
Phase 1: **2 x 6 in wood framing with exterior insulation [13, 14]**	• Vinyl siding • 1.5 in wide x 7/16 in thick furring strip installed vertically • 1 in EPS rigid foam insulation **(exterior insulation)** • Sheathing membrane • 11 mm OSB wood-sheathing • 2x6 nominal stud cavity with R24 glass fiber insulation batts • 6 mil poly air/vapour barrier • ½ in painted drywall	• Vinyl siding • 1.5 in wide x 7/16 in thick furring strip installed vertically • 2 in XPS rigid foam insulation **(exterior insulation)** • Sheathing membrane • 11 mm OSB wood-sheathing • 2x6 nominal stud cavity with R24 glass fiber insulation batts • 6 mil poly air/vapour barrier • ½ in painted drywall	• Vinyl siding • 1.5 in wide x 7/16 in thick furring strip installed vertically • 3in semi-rigid mineral fibre insulation **(exterior insulation)** • Sheathing membrane • 11 mm OSB wood-sheathing • 2x6 nominal stud cavity with R24 glass fiber insulation batts • 6 mil poly air/vapour barrier • ½ in painted drywall
	Wall-4 (XPS Wall) **4 ft x 6 ft**	**Wall-5 (SPF Wall)** **4 ft x 6 ft**	**Wall-6 (CEL Wall)** **4 ft x 6 ft**
Phase 2: **Different wood framing with interior insulation [14]**	• Vinyl siding • Sheathing membrane • 11 mm OSB wood-sheathing • 2x6 nominal stud cavity with R24 glass fiber insulation batts • 2 in (2 layers of 1 in thick) XPS rigid foam insulation (interior insulation) • 6 mil poly air/vapour barrier • ½ in painted drywall	• Vinyl siding • Sheathing membrane • 11 mm OSB wood-sheathing • 2x10 nominal stud cavity (2x6 and 2x4 studs together) with 2 in spray foam insulation on interior side of the OSB + glass fiber filling the rest of the cavity • 6 mil poly air/vapour barrier • ½ in painted drywall	• Vinyl siding • Sheathing membrane • 11 mm OSB wood-sheathing • 2x12 nominal stud cavity (2x4 stud + 2x4 gap + 2x4 stud) with cellulose insulation filling in entire cavity • 6 mil poly air/vapour barrier • ½ in painted drywall

*** Layers listed from exterior to interior**

3.1 Wall Specimens

The three (1219 mm x 1829 mm / 4 ft x 6 ft) residential wood-frame wall test specimens of Phase 2, and described earlier, were installed side-by-side in the Field Exposure of Walls Facility (FEWF). The different material layers and the dimensions of the wall specimens are provided in Table 1 and shown in Figure 1 to Figure 4. As a part of the test protocol, fully described in [14], all Heat Flux Transducers (HFTs) used in the three test specimens were calibrated according to the ASTM C-1130 “Standard Practice for Calibrating Thin Heat Flux

Transducers" [15]. The uncertainty of heat flux measurements was ± 5%. Also, the uncertainty of the thermocouple measurements was ± 0.1°C. The locations of the HFTs are shown in Figure 2 (XPS Wall), Figure 3 (SPF Wall), and Figure 4 (CEL Wall).

3.2 Transient Numerical Simulations

This section presents the assumptions, and initial and boundary conditions that were used in conducting the numerical simulations for different wall specimens of Phase 2 (Table 1). The hygrothermal properties of insulation products of these walls (XPS, SPF and cellulose fibre) were measured in this project. These assumptions and initial and boundary conditions are similar to those of the wall specimens of Phase 1 [13].

3.2.1 Assumptions

It was assumed that all material layers were in direct contact with one another (i.e. the interfacial thermal resistances between all material layers were neglected). The emissivity of all surfaces that bounded the airspaces (i.e. airspaces between the vinyl siding and building membrane) was taken equal to 0.9 [16]. The effects of heat transfer by conduction, convection and radiation within these airspaces on the thermal performance of wall assemblies were also determined.

3.2.2 Initial and Boundary Conditions

The initial temperature in all material layers of the respective wall specimens (XPS Wall, SPF Wall, and CEL Wall) was assumed uniform and equal to 10.0°C. Since this initial temperature was not the same as in the test, it was anticipated that the predicted dynamic response of the different wall specimens in the first period of the test (e.g. the first 24 – 48 hr) would be different from that obtained in the test itself. The boundary conditions on the top and bottom surfaces of the wall systems were assumed to be adiabatic (i.e. no edge heat losses). The outdoor surface of the vinyl siding for all wall systems was subjected to a temperature boundary condition. Similarly, the indoor surface of the gypsum board for all wall systems was subjected to a temperature boundary condition. The temperatures on the outdoor and indoor surfaces of different wall specimens, and that changed over time, were taken equal to that measured on these surfaces.

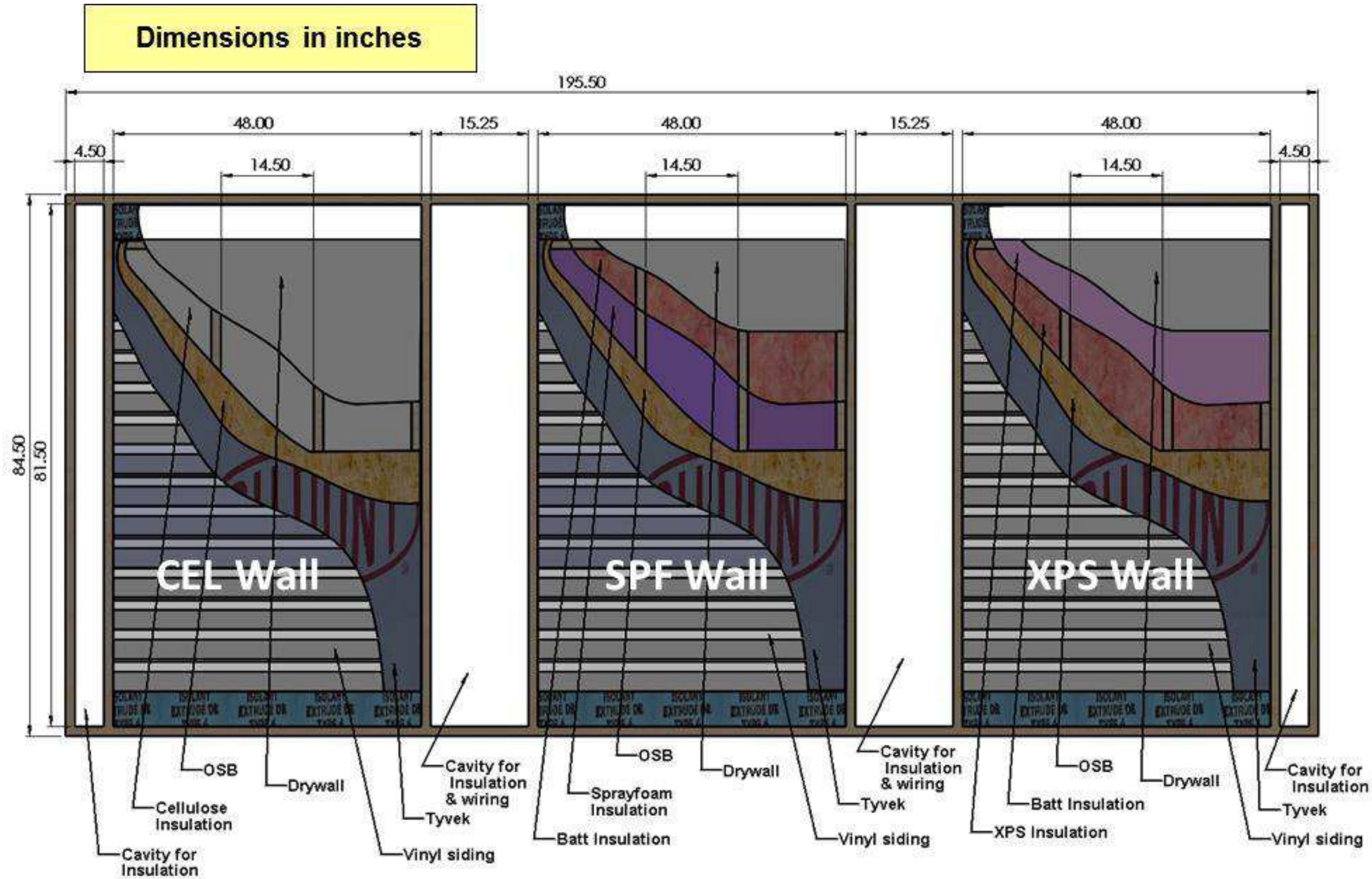


Figure 1. Schematic of three residential wood-frame wall test specimens installed side-by-side in the FEWF

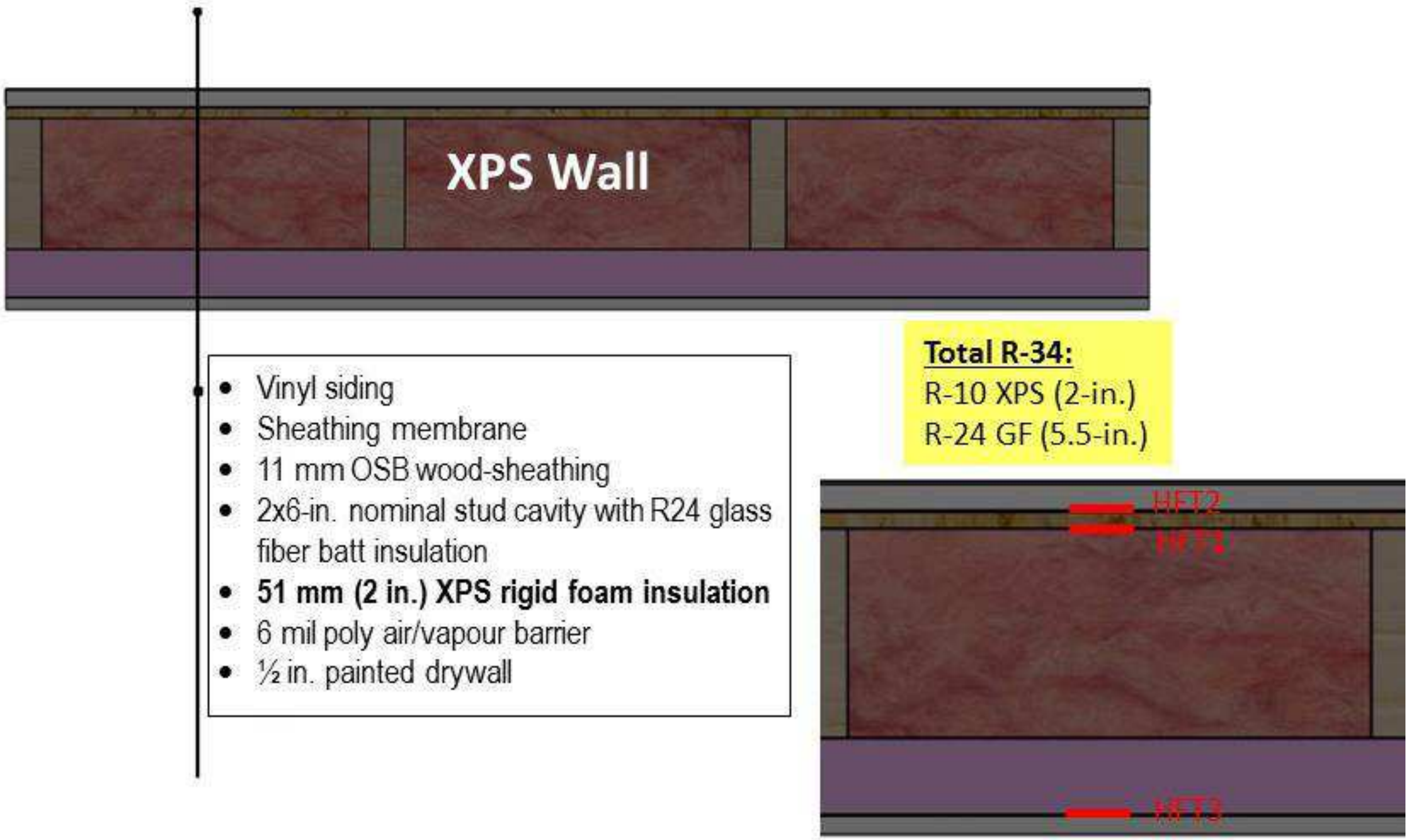


Figure 2. Horizontal cross-section through XPS Wall assembly showing locations of Heat Flux Transducers, HFTs (Wal-4)

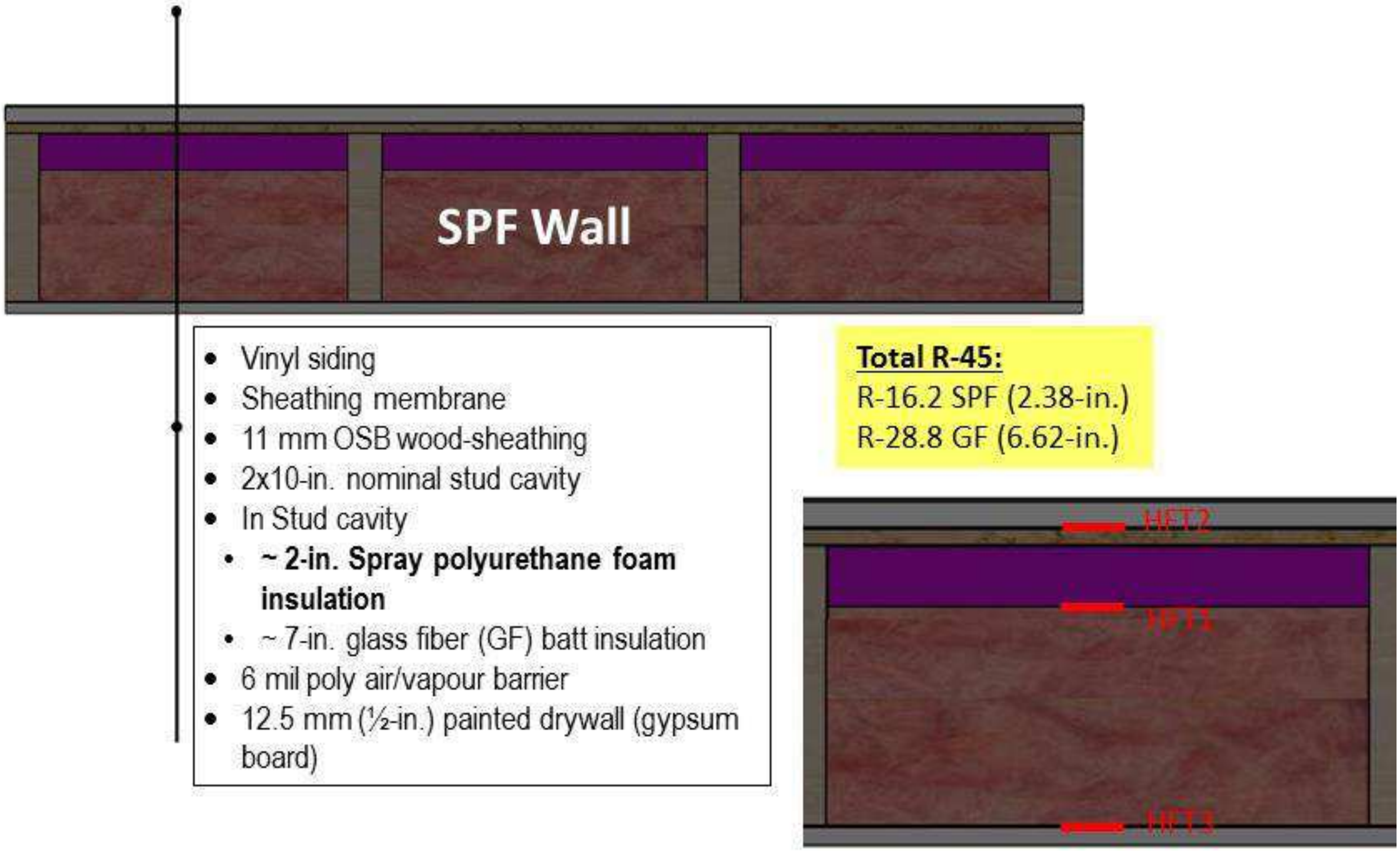


Figure 3. Horizontal cross-section through SPF wall assembly showing locations of Heat Flux Transducers, HFTs (Wall-5)

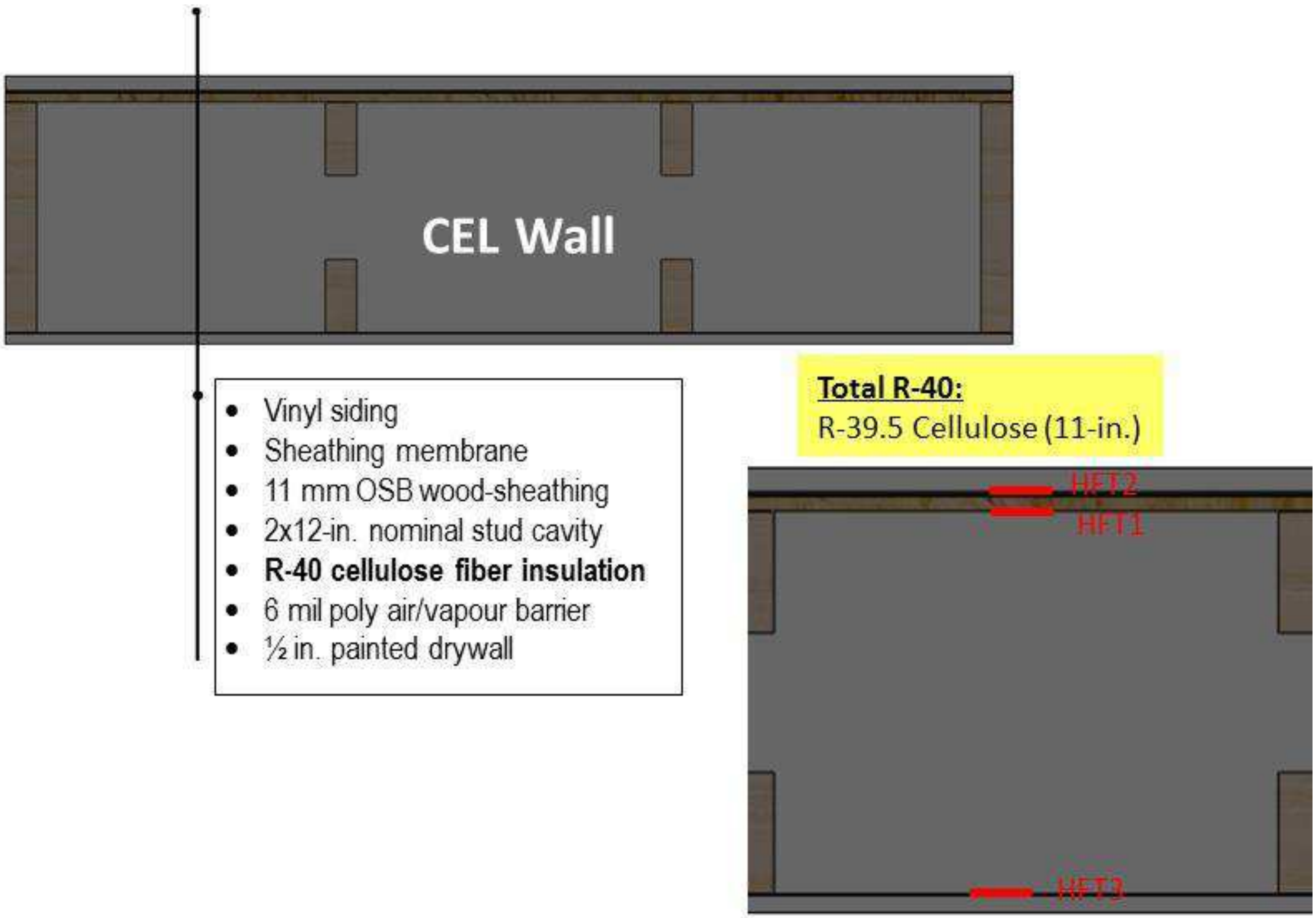


Figure 4. Horizontal cross-section through cellulose fibre wall assembly showing locations of Heat Flux Transducers, HFTs (Wall-6)

3.4 Comparison between Model Predictions and Measurements

The hygIRC-C model was previously benchmarked against the test data of the three wall specimens of Phase 1 [13]. Similarly, to benchmark the model against the test data of the three wall specimens of Phase 2, transient numerical simulations were conducted for these wall specimens (Figure 1). The full description of all instrumentation (i.e. thermocouples, Heat Flux Transducers (HFTs), Pressure (P) sensors, and Relative Humidity (RH) sensors) and experimental data are available in [14]. In each wall system, three Heat Flux Transducers (HFTs) were used to measure the heat flux at the middle (mid-height and mid-width, see the inserts in Figure 2, Figure 3 and Figure 4) of each wall at three interfaces, namely:

(a) HFT1 at OSB – mineral (glass) fibre insulation interface of XPS Wall, at SPF – mineral (glass) fibre insulation interface of SPF Wall, and OSB – cellulose fibre insulation interface of CEL Wall;
(b) HFT2 at sheathing membrane – airspace (inside the vinyl siding) interface for the three wall systems, and;
(c) HFT3 at the polyethylene air barrier membrane – gypsum interface for the three wall systems.

For the XPS Wall, Figure 5-i, Figure 5-ii and Figure 5-iii show comparisons between the measured and the predicted values of heat flux during the test period. In these figures, time = 0 at which experimental data was collected corresponded to January 1, 2015 at 00:14 AM. Figure 5-i shows that the measurements of HFT1 located at the OSB – mineral fibre insulation interface are in good agreement with that predicted by the hygIRC-C model. As shown in Figure 5-ii, the predicted heat fluxes at the sheathing membrane – airspace interface are in good agreement with measurements taken from HFT2. Similarly, Figure 5-iii shows that the predicted heat fluxes at the poly – gypsum interface are in good agreement with measurements from HFT3.

Figure 6-i, Figure 6-ii and Figure 6-iii show comparisons between the measured and predicted values of heat flux during the test period at different locations for the SPF Wall. As shown in these figures, the predicted values of heat flux are in good agreement with the measured values at each of the respective interfaces, specifically at the SPF – mineral fibre insulation interface (Figure 6-i), sheathing membrane – airspace interface (Figure 6-ii), and the poly – gypsum interface (Figure 6-iii).

Finally, for the wall specimen cellulose fibre insulation (CEL Wall), comparisons are provided in Figure 7-i, Figure 7-ii and Figure 7-iii and in which are shown the predicted values of heat flux that are in good agreement with the measured values at each of the respective interfaces, specifically at the: OSB – cellulose fibre insulation interface (Figure 7-i), the sheathing membrane – airspace interface (Figure 7-ii), and the poly – gypsum interface (Figure 7-iii).

In summary, the results presented in this section show that the predicted values of heat flux at different locations in the wall assembly are in good agreement with the measured values of heat flux for the three wall systems, namely the: XPS Wall (Figure 5), SPF Wall (Figure 6), and CEL Wall (Figure 7).

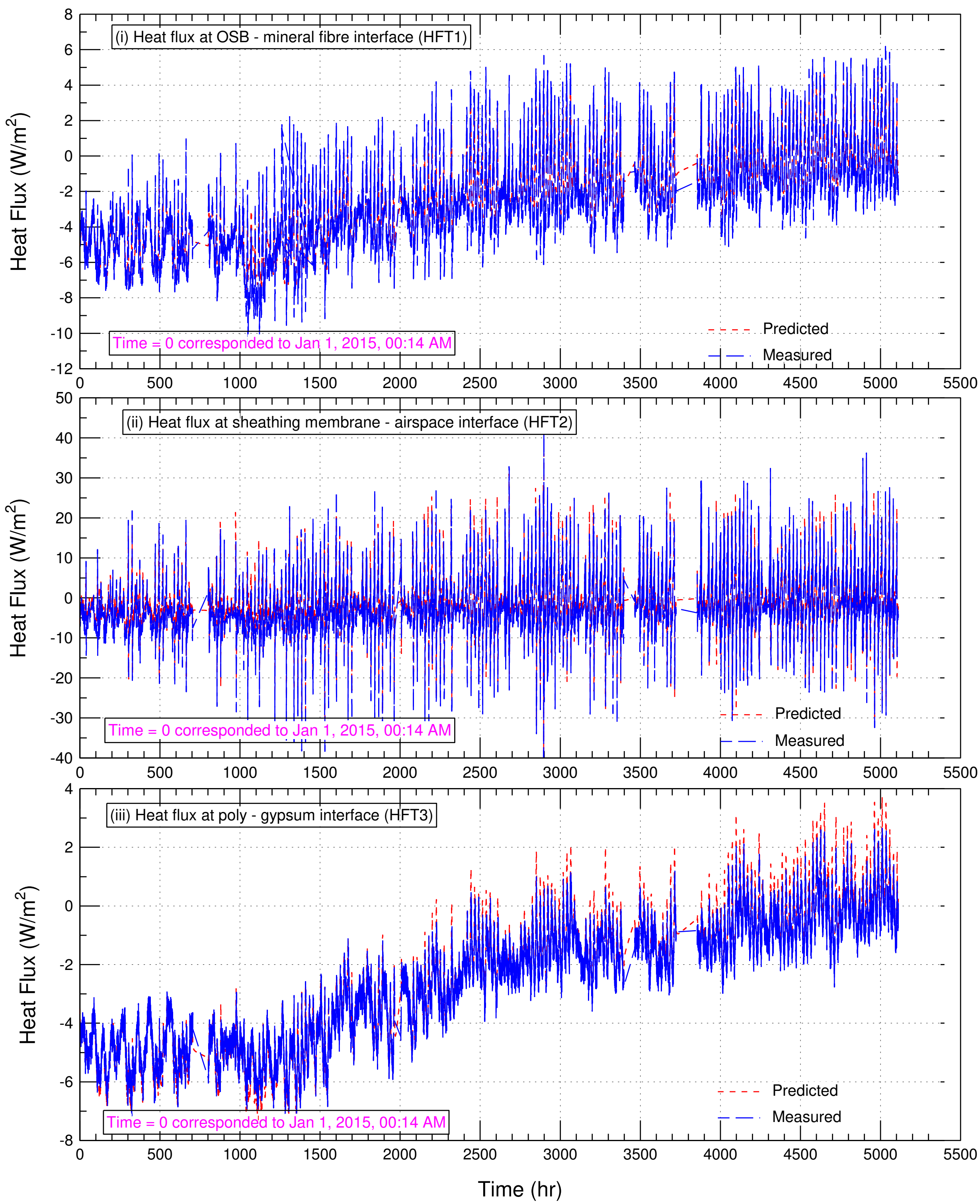


Figure 5. XPS wall (Wall 4) — Comparison between predicted and measured heat fluxes at interface: (i) OSB – mineral fibre; (ii) sheathing membrane – airspace; (iii) poly – gypsum

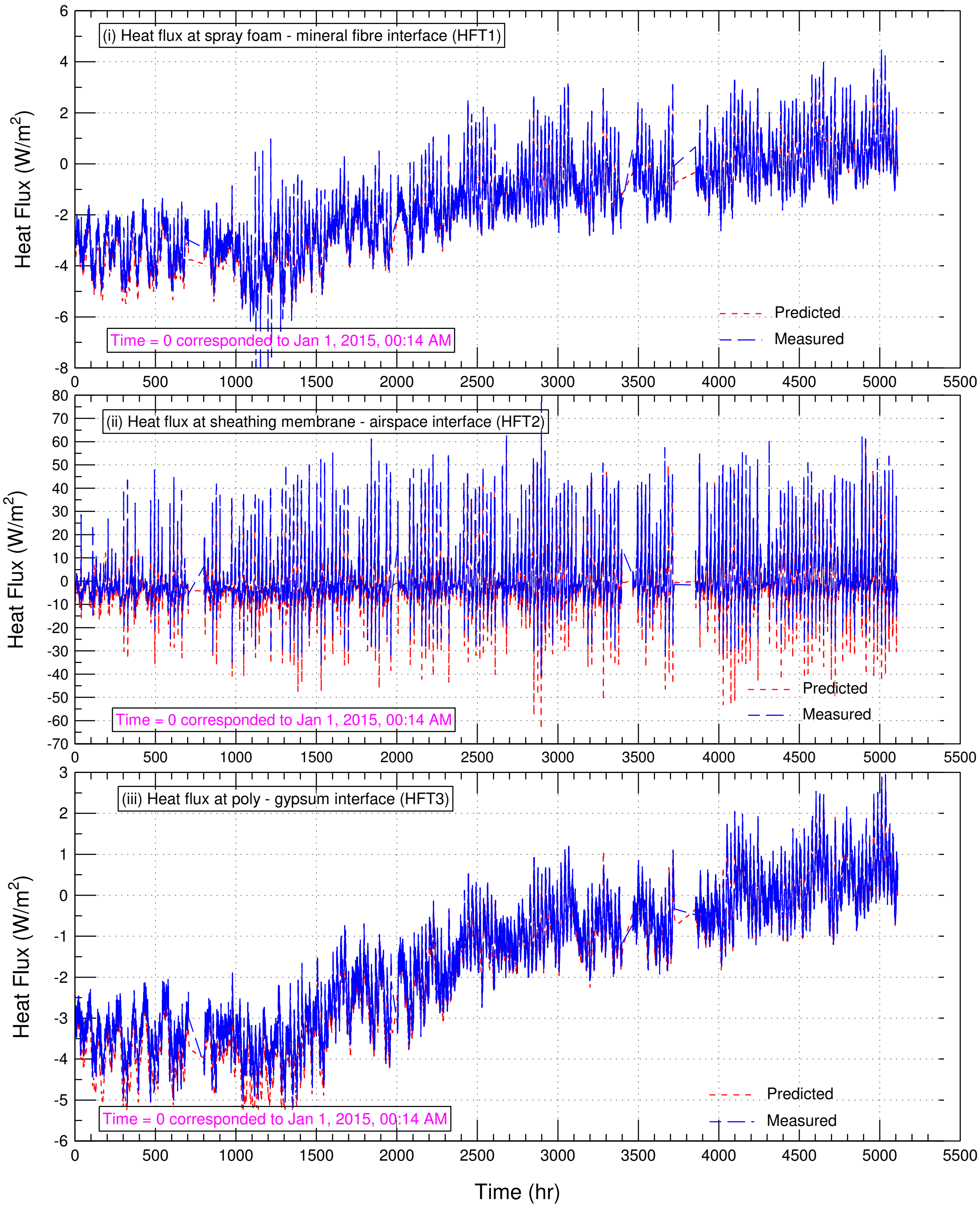


Figure 6. SPF wall (SPF Wall) — Comparison between predicted and measured heat fluxes at interface: (i) spray foam – mineral fibre; (ii) sheathing membrane – airspace; (iii) poly – gypsum

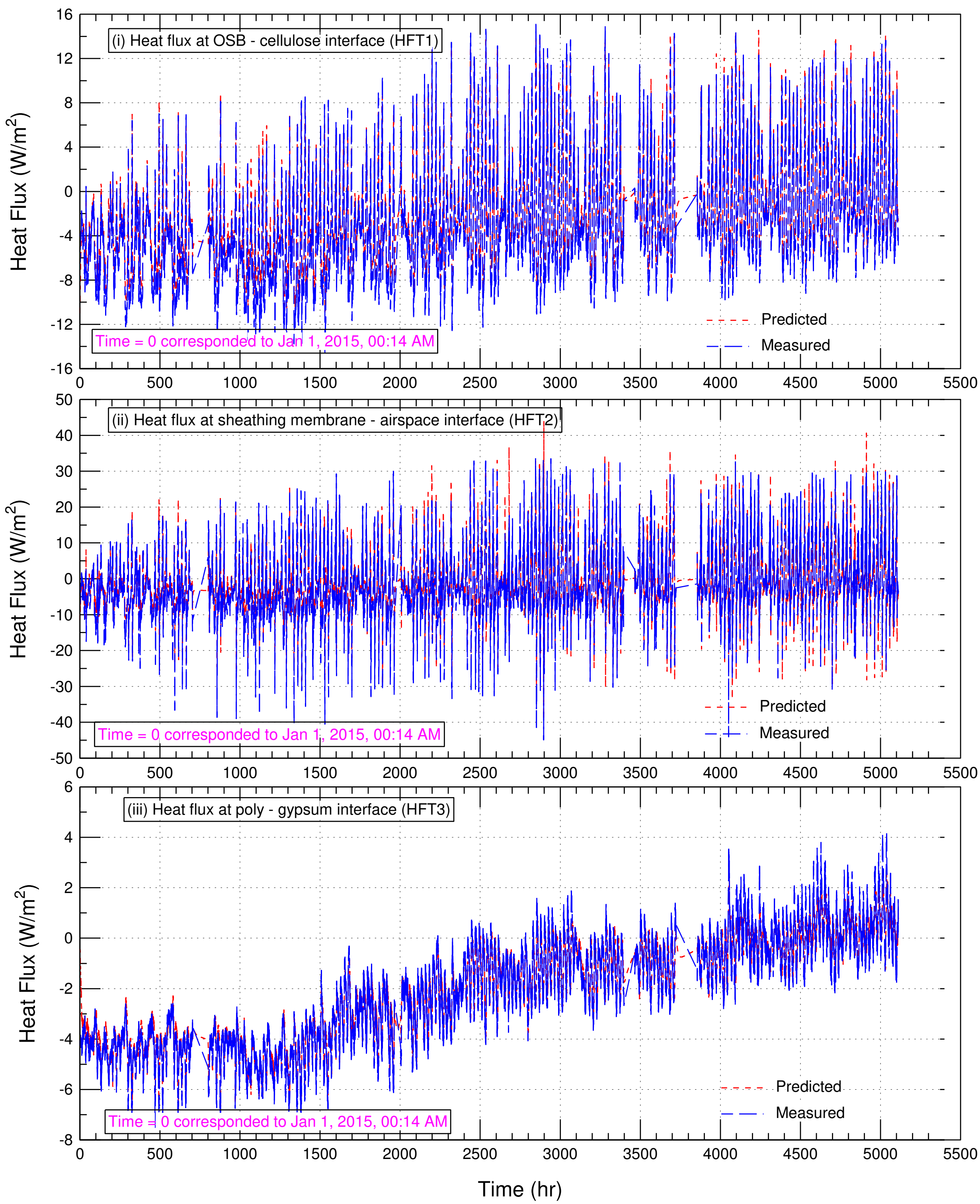


Figure 7. Cellulose fibre wall (CEL Wall) — Comparison between predicted and measured heat fluxes at airspace interface: (i) OSB - cellulose; (ii) sheathing membrane - airspace; (iii) poly-gypsum

It is not possible to complete the benchmarking of the model in respect to moisture transport on the basis of the field trials undertaken in the FEWF. This requires conducting experiments in a controlled environment after first conditioning the test specimens to known levels of moisture content in each layer of the wall specimen. In fact the model has previously been benchmarked in controlled conditions as provided in the appendix of reference [13]. Thus, after benchmarking the present model in this project in respect to heat flux, and having previously benchmarked the model to several tests undertaken in field and controlled laboratory conditions as indicated in [13], this model was used with confidence in this study to investigate the energy performance and the risk of condensation and mould growth in the wall assemblies when these walls were subjected to a selected set of Canadian climatic conditions.

3.5 Wall Assembly Configurations and Simulation Parameters

Similar to the previous NRC project [17, 18] and the wall assemblies of Phase 1 of this project [13], the hygrothermal simulations of all wall assemblies were conducted using the hygIRC-C model and using the construction details common to all wall assemblies to be modelled as listed in Table 2. For each of the materials or components specified, the rationale for the selection of specific materials is also given in this table.

Table 2. Construction details common to all wall assemblies to be modelled [13, 17, 18]

Material selection	Rationale
An exterior finish consisting of vinyl cladding installed on 19 mm strapping	To minimize the impact of exterior water ingress
A weather-resistive barrier (WRB) with a WVP of 1400 ng/(Pa•s•m²) (25 US perm) such as spun bonded polyolefin membrane	Common construction and highly permeable so as not to limit the application of insulation materials for which the selection of a more vapour tight material might otherwise affect the intent of the project
2 x 6 in wood-frame construction using framing members at 16 in on center	Currently, most common construction framing used in housing
A vapour barrier with a WVP of 60 ng/(Pa•s•m²)	NBCC 2010 minimum requirement 9.25.4.2. (see reference [19])
An interior finish consisting of 12.5 mm gypsum board	Currently the most common construction method for interior finish

Figure 8 shows a schematic of the code-compliant reference wall assembly. For the three wall systems of Phase 2, schematics of these wall assemblies are shown in Figure 9 for the XPS Wall, Figure 10 for the SPF Wall, and Figure 11 for the CEL Wall. The measurement of the water vapour permeabilities and thermal conductivities of the respective insulation products as well as the nominal R-values of these walls are listed Table 3. The dependence of the water

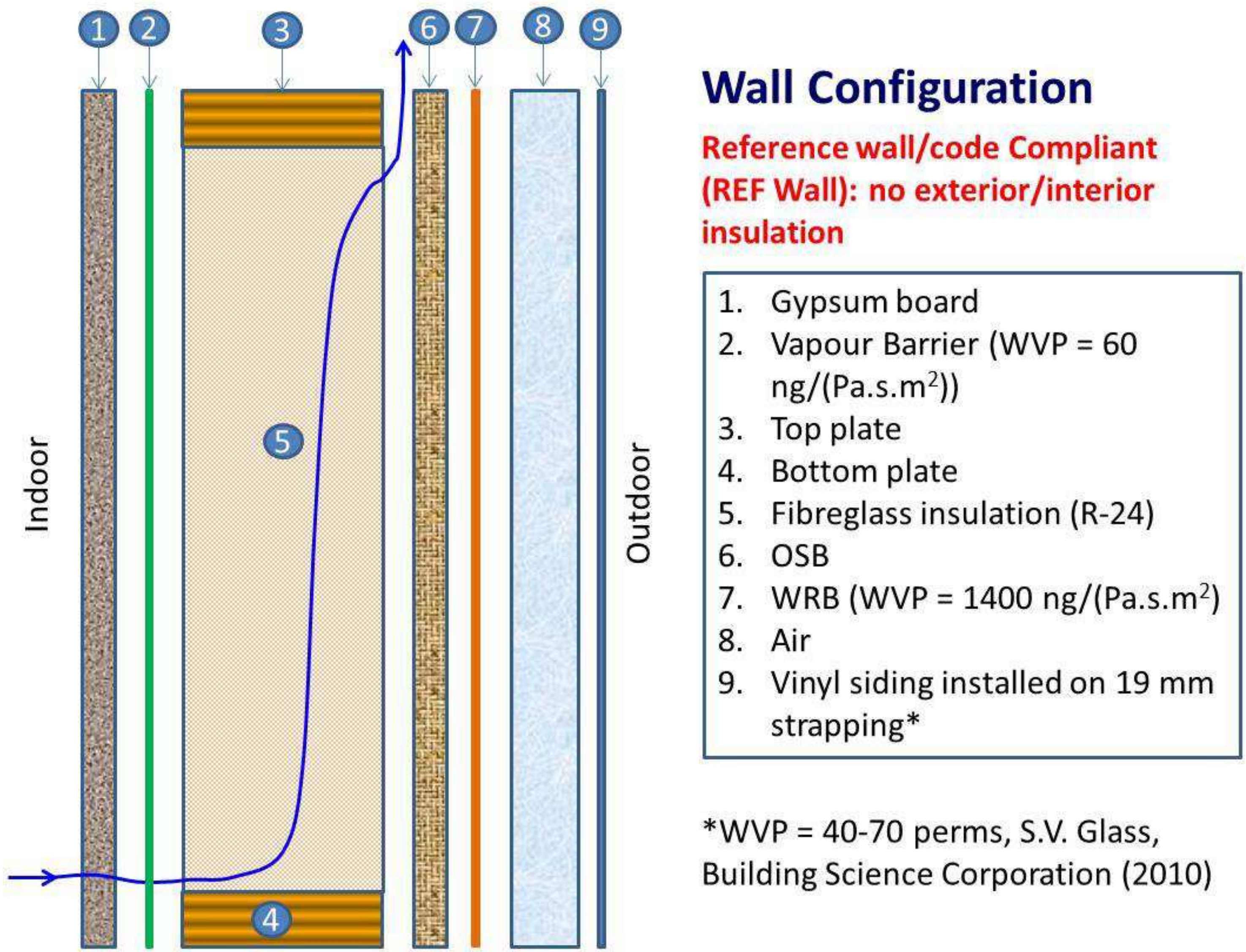


Figure 8. Schematic of reference wall assembly/code compliant configuration showing different component layers and assumed path of air flow through assembly (no exterior/interior insulation, REF Wall)

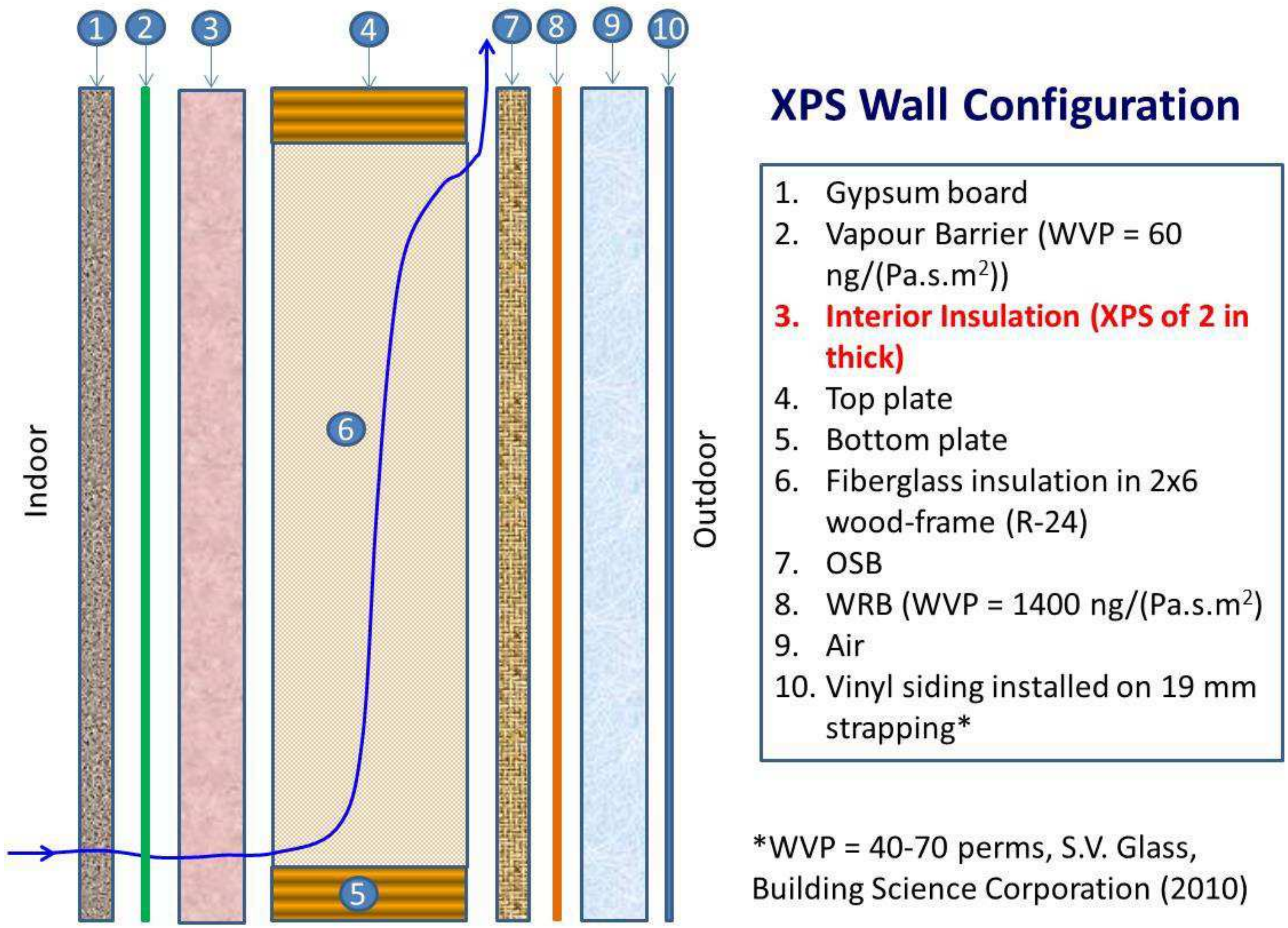


Figure 9. Schematic of the wall assembly configuration with interior XPS insulation showing different component layers and assumed path of air flow through assembly (XPS Wall)

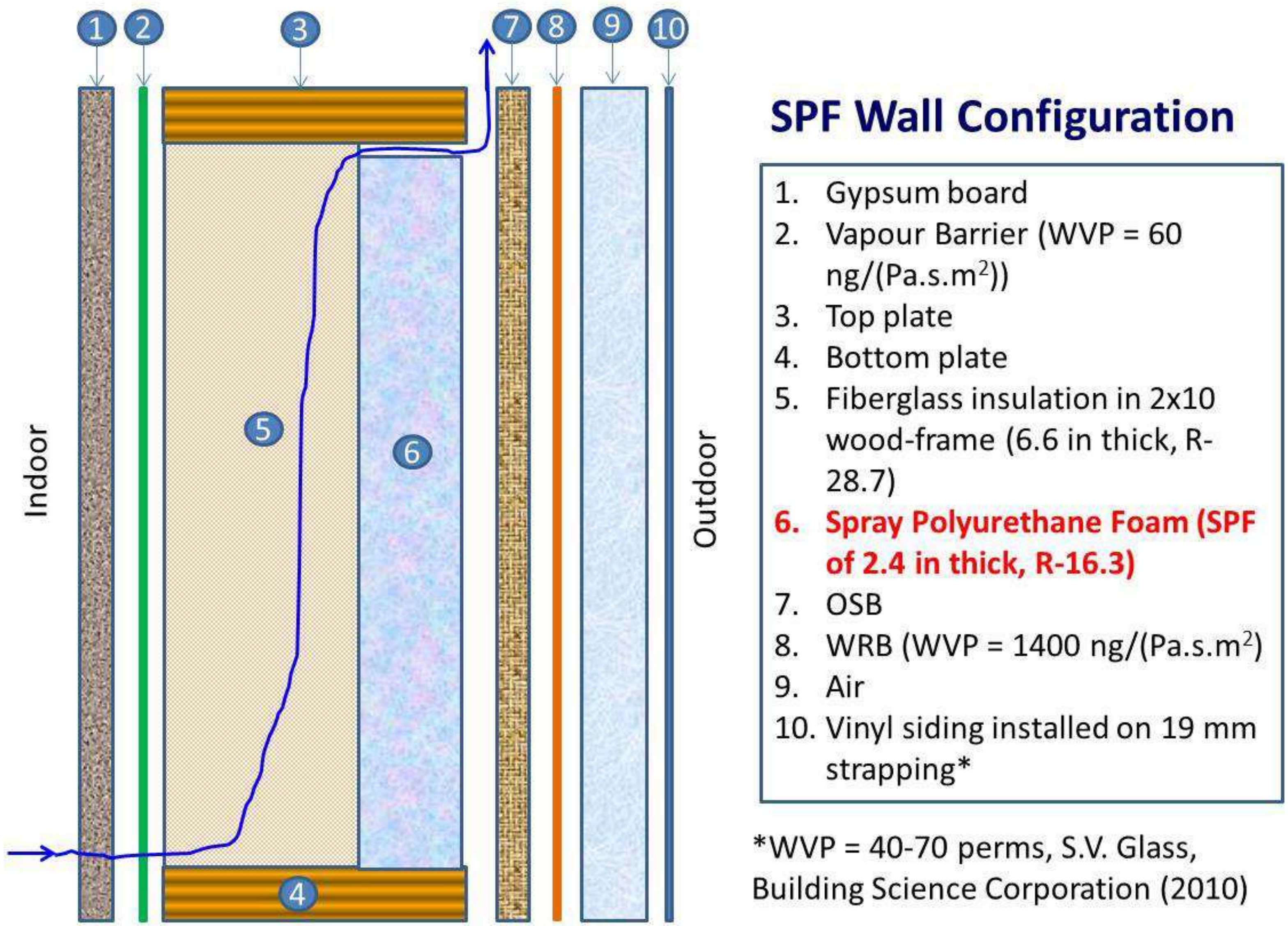


Figure 10. Schematic of the wall assembly configuration with Spray Polyurethane Foam (SPF) insulation showing different component layers and assumed path of air flow through assembly (SPF Wall)

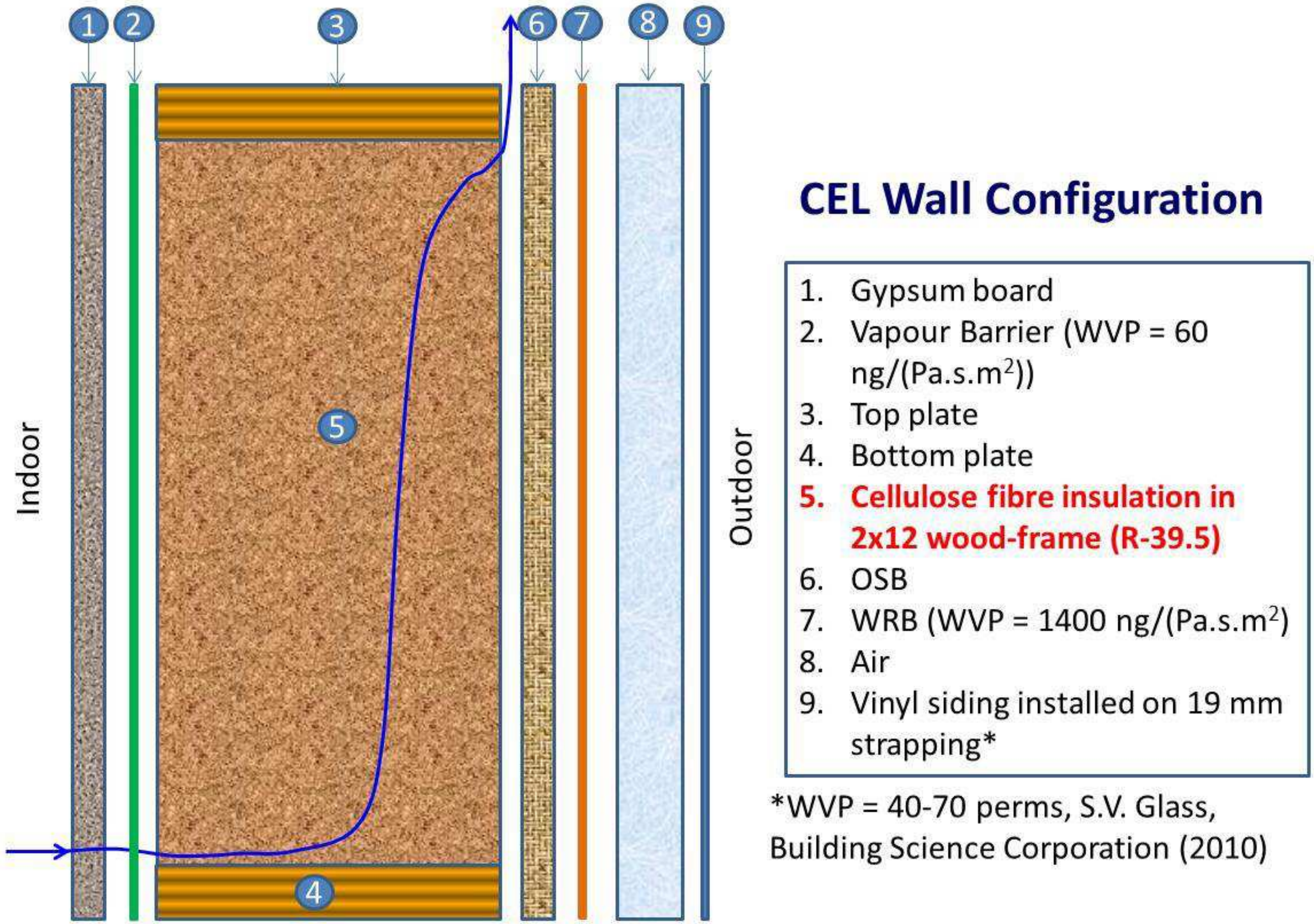


Figure 11. Schematic of the wall assembly configuration with cellulose fibre insulation (CEL) showing different component layers and assumed path of air flow through assembly (CEL Wall)

vapour permeability on the relative humidity of different insulations (XPS, Cellulose and SPF) is shown in Figure 12. The locations in these wall assemblies at risk of condensation and mould are listed in Table 4.

Whereas the simulated results for moisture content and temperature are produced for every location within the wall system and at every 1 hr interval, an analysis of results was performed to establish which locations in the wall showed the greatest susceptibility to risk of condensation for the assemblies studied; this permitted rationalising the presentation of results. Post-processing of simulation results and reporting thus focussed on the locations reported in Table 4.

Table 3. Water vapour permeabilities and thermal conductivities of the insulations, and nominal R-values of the wood-framed wall systems

Parameter	**XPS Wall**	**SPF Wall**	**CEL Wall**
Wood-Framing Cavity Insulation	Mineral fibre (5.5 in thick)	Mineral fibre (6.6 in thick)	Cellulose fibre (11 in thick)
Wood-Framing size	38x140 mm (2x6 in)	38x229 mm (2x10 in)	38x279 mm (2x12 in)
Insulation Details			
Type	**XPS**	**SPF**	**Cellulose**
Thickness (in/mm)	**2/51**	**2.4/61**	**11/279**
Dry Density (kg/m^3)	26	40	60
Dry Thermal Conductivity (W/(m•K))	0.0290	0.0212	0.0402
Vapor Permeability (kg•m/(s•m^2•Pa))*	1.39E-12	6.75E-13	1.075E-10
Total Vapor Permeance (ng/(s•m^2•Pa))*	27.4	11.1	384.6
Vapor Permeance ((ng/(s•m^2•Pa))/25.4 mm)*	54.9	26.6	4232.3
RSI-value (m^2•K/W)	1.75	2.88	6.95
R-value (ft^2•hr•^{o}F/BTU)	9.95	16.33	39.47
RSI-value ((m^2•K/W)/25.4 mm)	0.88	1.20	0.63
R-value ((ft^2•hr•^{o}F/BTU)/in)	4.97	6.80	3.59
Total nominal RSI-value (m^2•K/W)	**5.97**	**7.94**	**6.95**
Total nominal R-value (ft^2•hr•^{o}F/BTU)	**33.90**	**45.07**	**39.47**

*** At dry-cup condition**

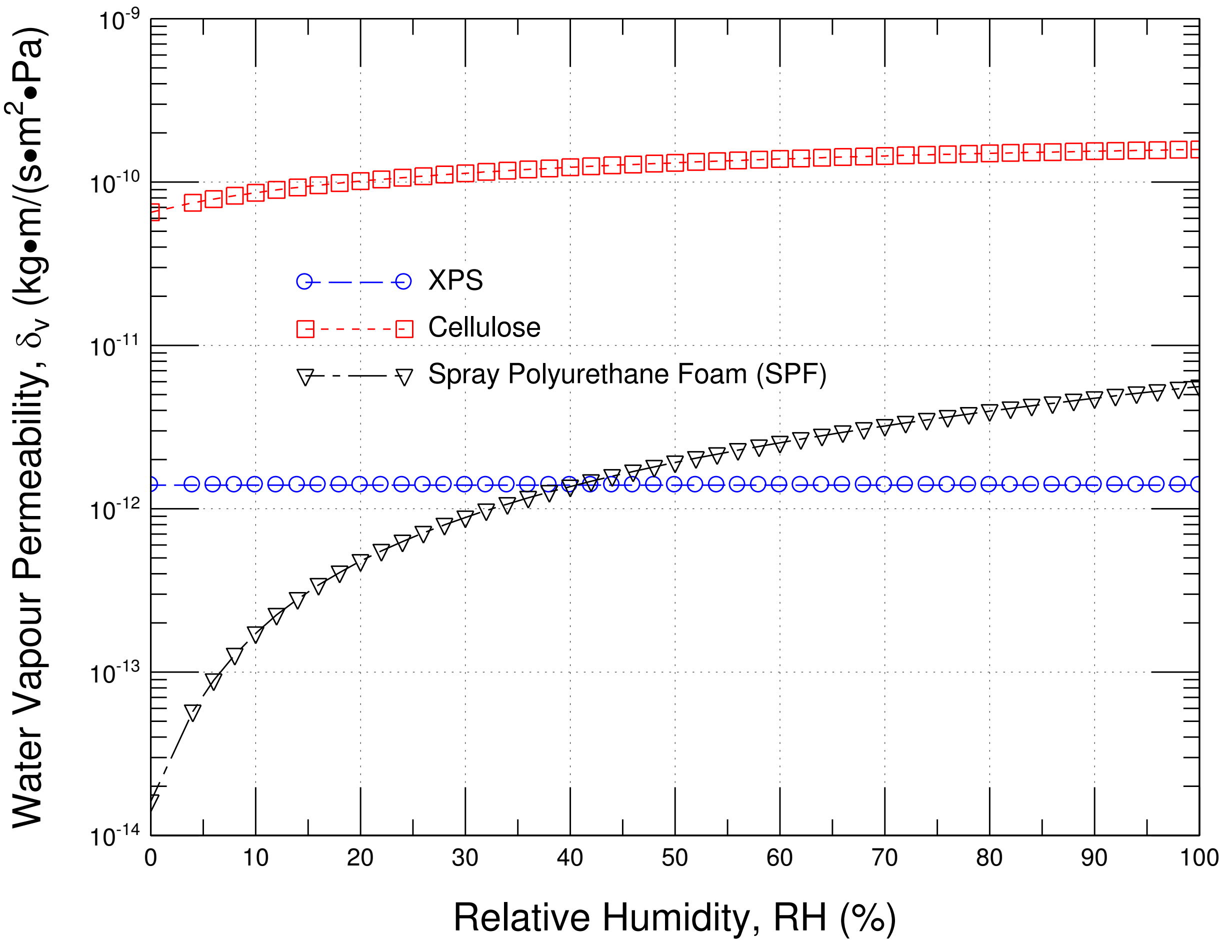


Figure 12. Dependence of water vapour permeability on the relative humidity for XPS, Cellulose and SPF insulations

Table 4. Locations in wall assembly at risk of condensation and mould growth

Location (see Figure 13)	Depths and heights
Top plate layer	51 mm (2 in) and 63 mm (2.5 in)
Insulation at top plate	10 mm (0.4 in) by 51 (2 in) and 63 mm (2.5 in)
Interface between top plate and insulation	63 mm (2.5 in)
Insulation at base of wall assembly	10 mm (0.4 in) deep by heights of 152 (6 in), 305 (12 in), 457 mm (18 in)
Interface between sheathing panel and insulation	152 (6 in) and 305 mm (12 in)

4. Simulation Conditions for Parametric Study

The full details of the simulation conditions for the parametric study are provided in [13, 17], and summarized in this section for the wall assemblies shown in Figure 8 through Figure 11 (see Table 3).

4.1 Vapour Barrier Conditions

As provided in Subsection 9.25.4 of the NBCC [19], the current maximum allowable WVP value for vapour barriers is 60 ng/(Pa•s•m²). This parametric study was conducted using a vapour barrier with a WVP of 60 ng/(Pa•s•m²) as provided in Table 2.

4.2 Air Leakage Conditions

The air leakage rate for all cases in all locations was set to 0.1 L/(s•m²) at 75 Pa, which was an assumption used in at least one previous study (see [17, 18, 20]). These air leakage conditions are those assumed for the wall components of a home and would be roughly an order of magnitude smaller than the whole house air leakage of an R-2000 qualified home as provided by NRCan[†]. As the hourly total pressure difference (ΔP), due to wind pressure and stack effect, across the wall assembly changed with time for each climatic condition, the hourly air leakage rate (ξ) changed with time as well, and was calculated as to satisfy the condition of $\xi = 0.1$ L/(s•m²) at $\Delta P = 75$ Pa. The dependence of the air leakage rate on time for each climatic condition is available in reference [13]. Furthermore, the full details for calculating the air leakage are available in reference [17].

The modelling assumed that the path for air movement is initiated at the interior and is introduced at the bottom of the wall and thereafter moisture is deposited along the interior face of the sheathing panel and exits through the top of the wall. This air leakage path was one of the scenarios used in the study by Ojanen and Kumaran [20] in which it was assumed that air would move through imperfections that existed at the wall top plate and the joint between the interior face of the exterior sheathing and the exterior of the top plate. For the code-compliant reference wall (REF Wall), this air leakage path is shown Figure 8, and that for other walls is shown in Figure 9 (XPS Wall), Figure 10 (SPF Wall), and Figure 11 (CEL Wall).

All wall assemblies shown in Figure 8 through Figure 11 represent wall assemblies of the third storey of low-rise buildings and facing the direction of the highest exfiltration rate. These walls were assumed to be shaded to minimize the impact of solar-driven moisture ingress into the assembly and to minimize the solar drying effect on the wall. However, diffuse radiation was taken into consideration. This represents the worst case scenario for the risk of formation of condensation and mould growth within the wall assemblies [17, 18].

[†] http://www.nrcan.gc.ca/energy/efficiency/housing/new-homes/5089: R-2000 Standard - 2012 Edition; Natural Resources Canada's Office of Energy Efficiency; 16 p; § 4.3 Airtightness Requirements: The building envelope shall be constructed sufficiently airtight such that either the air change rate at 50 Pascals is no greater than 1.5 air changes per hour; 1.5 ACH @ 50 Pa is equivalent to 0.61 L/s-m^2 @ 50 Pa and would necessarily be higher at 75 Pa.

4.3 Climatic Conditions

Similar to Phase 1 of this project [13], the wall assemblies shown in Figure 8 through Figure 11 were subjected to different climatic conditions of five different locations within Canada and having differing values of Heating Degree Days (HDD) and Moisture Index (MI), namely:

- **Vancouver, BC** (mild, wet, HDD18 = from 2600 to 3100, MI = 1.44),
- **St. John's, NL** (cold, wet, HDD18 = 4800, MI = 1.41),
- **Ottawa, ON** (cold, dry, HDD18 = 4440 - 4500, MI = 0.84),
- **Edmonton, AB** (cold, dry, HDD18 = 5120, MI = 0.48), and
- **Yellowknife, NT** (cold, dry, HDD18 = 8170, MI = 0.58).

The weather data of the locations listed above were obtained from the NRC's weather database. For each wall system, the numerical simulations were conducted for a period of two years where the first year corresponded to an average year and the second year corresponded to a wet year [13].

4.4 Indoor Conditions

As in Phase 1 of this project [13], the indoor relative humidity (RH_{ind}) corresponded to water vapour pressure differential ($\Delta P_v = P_{v,indoor} - P_{v,outdoor}$) of 700 Pa, but the value of RH_{ind} was capped at 70%. The indoor temperatures were set according to that provided in the ASHRAE Standard 160 [21] with respect to recommendations for conditioned space. The rationale for selecting these indoor conditions are available in [13, 17].

4.5 Initial Conditions

The initial temperature in all layers of the wall assemblies were taken equal to 21°C and the initial moisture content of all material layers corresponded to a relative humidity of 50%.

4.6 Material Properties

The hygrothermal properties for the XPS (XPS Wall), spray polyurethane foam (SPF Wall), and cellulose fibre insulation (CEL Wall) were measured and used in the numerical simulations. The recommended WVP by Glass [22] for the OSB layer (11 mm thick) as a function of RH were used in the numerical simulations. Whereas, the hygrothermal properties of the other material layers shown in Figure 8 through Figure 11 were obtained from the NRC's material database [23, 24]. A summary of the simulated conditions for all wall assemblies are provided in Table 5.

Table 5. Summary of simulated conditions

Criteria	Assumptions/Conditions
Predominant wall orientation	Facing the highest exfiltration rate
ΔP for stack effect	Top storey of a 3-storey building to maximize the effect of exfiltration
ΔP for ventilation	Assume depressurization/pressurization from ventilation source is negligible
Air leakage rate	Corresponds 0.1 L/(s•m^2) at 75 Pa (see [17] for details)
Interior moisture load	Constant water vapour pressure differential, ΔP_v = 700 Pa; capped at 70% RH
Water vapour permeance of OSB	Function of RH ranging from 0-100% as recommended by Glass [22]
Modelling period	Two years – Jan to Dec: one average year followed by one wet year
Geographical locations	Ottawa (ON), Edmonton (AB), Vancouver (BC), St. John's (NL), and Yellowknife (NT)

5. Acceptable Performance

Similar to Phase 1 of this project [13] and a previous NRC study [17, 18], the modelling results for wall assemblies were expressed using the mould index (M) criteria developed by Hukka and Viitanen [25], Viitanen and Ojanen [26], and Ojanen et al. [27]. Table 6 lists the mould index levels ranging from 1 to 6. The most recent mould model by Ojanen et al. [27] was used in this study to determine the mould index of different materials in the wall assemblies. As provided in Table 7 [27], the sensitivity of different construction materials for mould growth was classified in four sensitivity classes, namely, very sensitive, sensitive, medium resistant and resistant. Table 8 provides the sensitivity class for materials located within the different wall assemblies.

Defining which level of mould index listed in Table 6 as a "critical level", i.e. the threshold of mould index, is not available at this time. However, the values of the mould index of the client's walls were compared against the value of the mould index of the reference, and code-compliant wall to determine whether or not the performances of the client's walls were as good as the reference wall. Currently, the TC of ASHRAE SSPC 160 is working to implement the mould index in ASHRAE 160. One of the tasks of the TC is to consult with the researchers from Finland and Germany who developed the mould index criteria in order to define the threshold values for mould index.

Table 6. Description of Mould Index (M) levels [25, 26, 27]

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 7. Mould growth sensitivity classes and some corresponding materials [27]

Sensitivity Class	Materials	RH_{min} (%)*
Very Sensitive	Pine sapwood	80
Sensitive	Glued wooden boards, PUR with paper surface, 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 8. Mould growth sensitivity classes for materials of wall assemblies listed in Table 3

Sensitivity Class	Material Layers of Wall Assemblies	RH_{min} (%)*
Very Sensitive		80
Sensitive	Top plate, bottom plate, OSB	80
Medium Resistant	SPF, cellulose fibre, fiberglass, gypsum, membranes	85
Resistant		85

*Minimum relative humidity needed for mould to grow

6. Approach for Assessing the Overall Performance

As was the case of wall assemblies of Phase 1 of this project [13], the numerical results showed that the primary locations within the wall assemblies of Phase 2 (see Figure 8 through Figure 11) at risk of formation of condensation and possible mould growth were identified as those located at the top portion and bottom portion of the wall assemblies. These locations are listed Table 9 and also identified in Figure 13.

Close examinations for the numerical results at the bottom portions of the wall systems of Phase 2 as shown in Figure 14 indicating that there are more locations at risk of condensation and mould growth. These locations are listed in Table 10. Comparisons of the mould index in these locations (see Table 10) for different wall assemblies, subjected to different climatic conditions are shown in Figure 15, Figure 16, Figure 17, Figure 18, and Figure 19 for the climates of Ottawa, Edmonton, Vancouver, St. John's and Yellowknife, respectively. As shown in these figures, there is risk of condensation and mould growth in the XPS wall system. However, the values of the mould index in these locations are approximately negligible for the other wall systems (i.e. REF Wall, SPF Wall, and CEL Wall).

Table 9. List of locations at risk of condensation and at which mould index evaluated

#	Figure 13a	Top Portion of Wall Components at Risk of Mould Growth:
1		Whole top plate layer
2		Whole top plate - cavity insulation interface
3		Top plate layer (51 mm (2 in) long)
4		Top plate layer (64 mm (2.5 in) long)
5		Top plate -cavity insulation Interface (51 mm (2 in) long)
6		Top Plate -cavity insulation Interface (64 mm (2.5 in) long)
7		Top cavity insulation of 10 mm (0.4 in) high (51 mm (2 in) long)
8		Top cavity insulation of 10 mm (0.4 in) high (64 mm (2.5 in) long)
9		Top cavity insulation of 10 mm (0.4 in) high - cavity insulation interface (51 mm (2 in) long)
10		Top cavity insulation of 10 mm (0.4 in) high - cavity insulation interface (64 mm (2.5 in) long)
	Figure 13b	**Bottom Portion of Wall Components at Risk of Mould Growth:**
11		cavity insulation (10 mm (0.4 in) thick, 457 mm (18 in) high)
12		cavity insulation (10 mm (0.4 in) thick, 305 mm (12 in) high)
13		cavity insulation (10 mm (0.4 in) thick, 152 mm (6 in) high)
14		OSB-cavity insulation Interface (305 mm (12 in) high)
15		OSB-cavity insulation interface (152 mm (6 in) high)

Table 10. List of bottom location in wall assembly at risk of condensation and at which mould index evaluated

1	Figure 14a,b,c,d	Exterior portion of bottom plate of 51 mm (2 in) long
	Figure 14a,b,c,d	Exterior "L" shape of cavity insulation of 51 mm (2 in) long, 76 mm (3 in) high, 10 mm (0.4 in) thick:
2		Cavity insulation of 51 mm (2 in) long, 10 mm (0.4 in) thick
3		Cavity insulation of 76 mm (3 in) high, 10 mm (0.4 in) thick
4	Figure 14a,b,c,d	OSB of 76 mm (3 in) high
5	Figure 14a,b,c,d	Exterior surface of cavity insulation of 76 mm (3 in) high
6	Figure 14a,b,c,d	Cavity insulation – bottom plate interface of 51 mm (2 in) long

It is important to point out that there is no risk of condensation and mould in the locations listed in Table 10 for the wall systems of Phase 1 with exterior/outboard insulations [13].

To compare the performance of different wall assemblies, the mould results are presented on basis of a simplified form using the following two parameters [13, 17, 18]:

- M_{AVG}: Overall average value of mould index at different locations in the wall.
- M_{MAX}: Overall maximum value of mould index at different locations in the wall.

For the purpose of comparison of the hygrothermal performance of the wall systems of Phase 1 with those of Phase 2 (Table 1), the two parameters above were determined based on a simulation period of two years (i.e., simulation of the average year followed by the wet year) for the locations shown in Figure 13a, b and listed in Table 9.

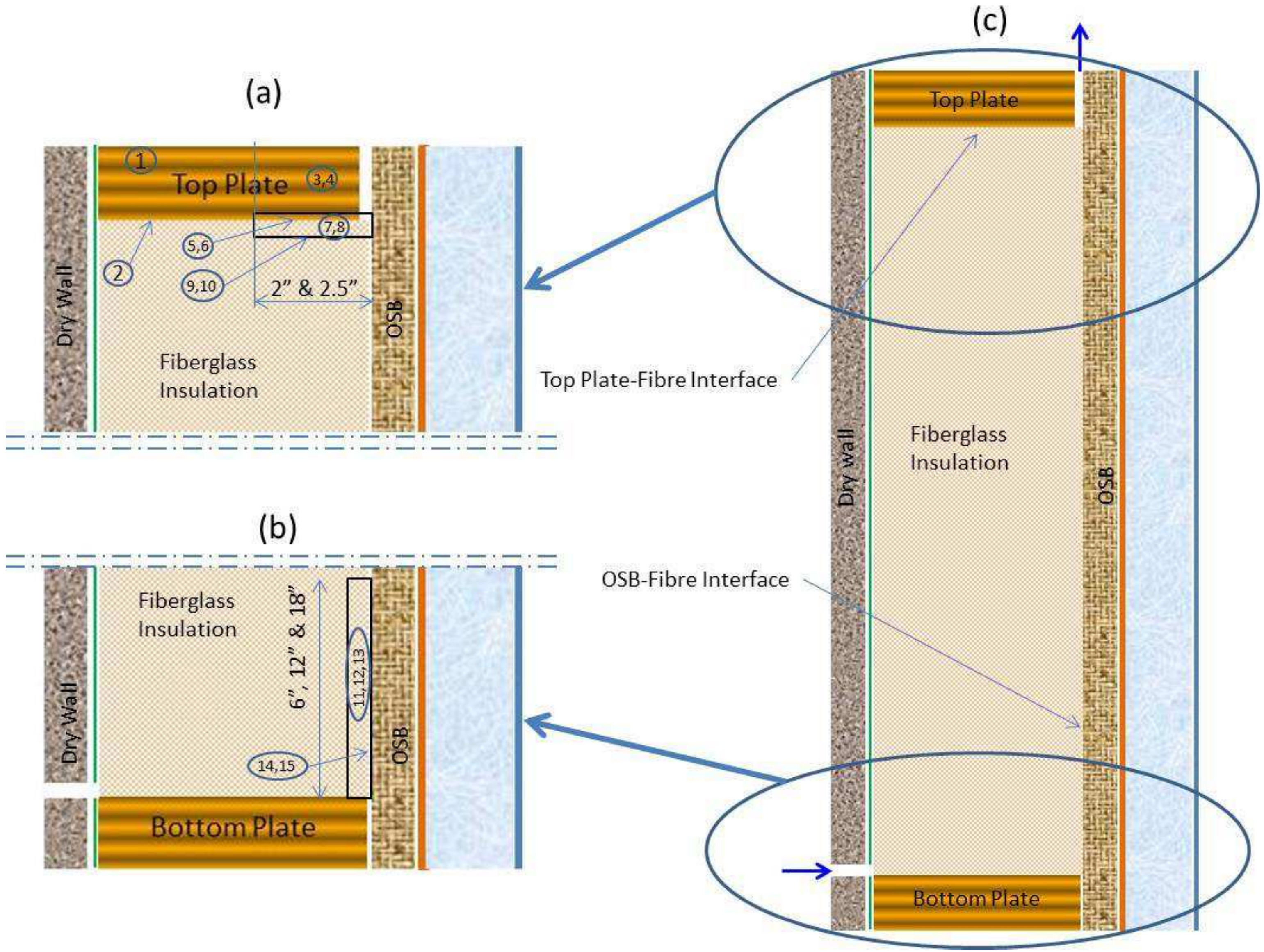


Figure 13. Locations in wall assembly at risk of formation of condensation and mould growth: (a) Location at top plate and in the top plate, the insulation, and along interface between top plate and insulation layers; (b) at base plate of wall assembly in insulation and along interface between sheathing panel and insulation

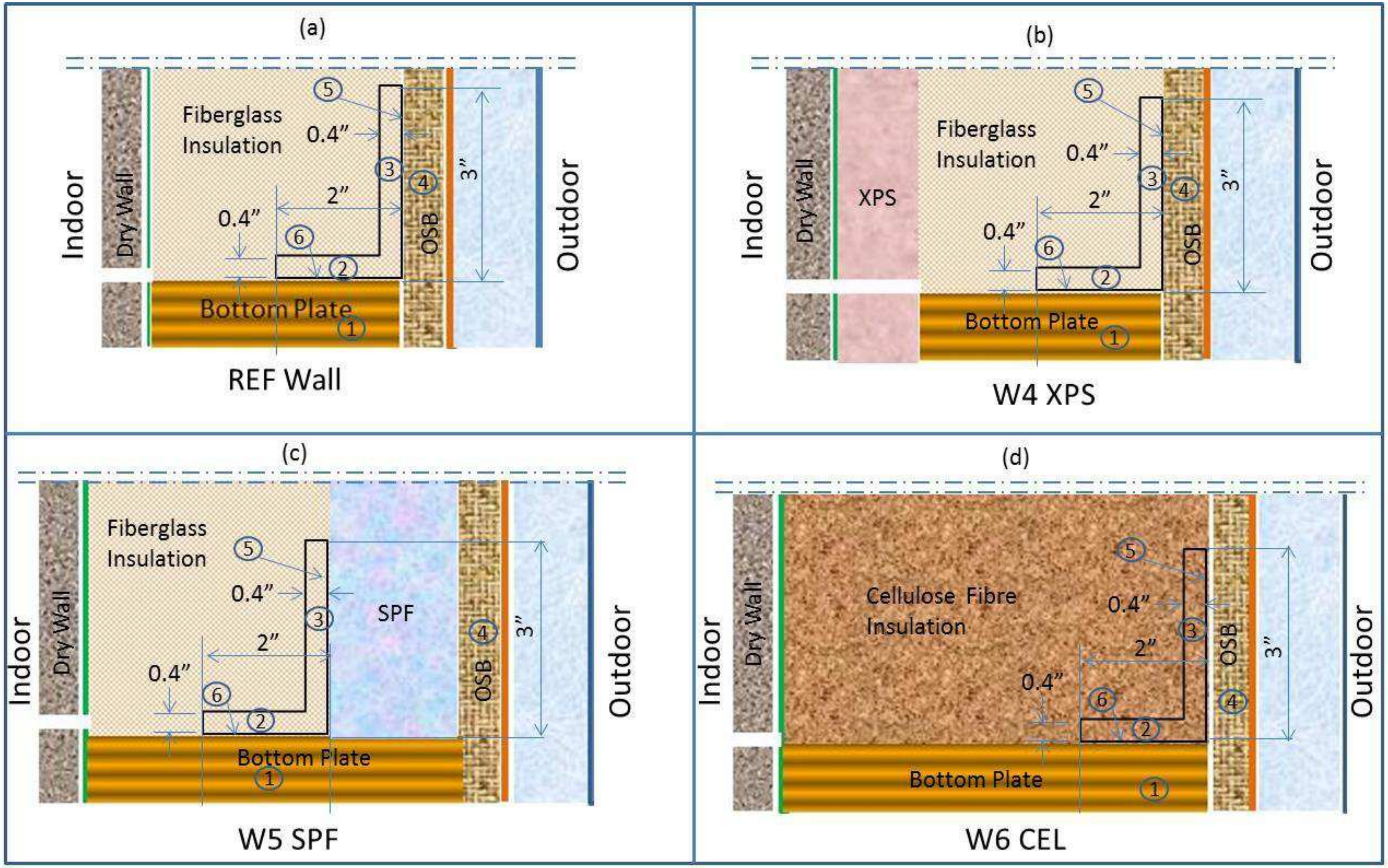


Figure 14. Locations in the bottom of wall assembly at risk of condensation and mould growth: "L" shape of cavity insulation of 2" long, 3" high and 0.4" thick, exterior portion of bottom plate of 2" long, OSB of 3" high, exterior surface of cavity insulation of 3" high, cavity insulation – bottom plate interface of 2" long (see Table 10)

Since there is a risk of condensation in the bottom portion of the XPS Wall of Phase 2 (see Figure 15 through Figure 19) as indicated earlier, M_{AVG} and M_{MAX} were also determined based on all locations at risk of condensation and mould growth, which are listed Table 9 and Table 10 for all wall systems of Phase 2.

In this report, the values of M_{AVG} and M_{MAX} that were determined based on the locations listed Table 9 are referred as “Case-I”. While, the values of M_{AVG} and M_{MAX} that were determined based on the locations listed in Table 9 and Table 10 are referred as “Case-II”.

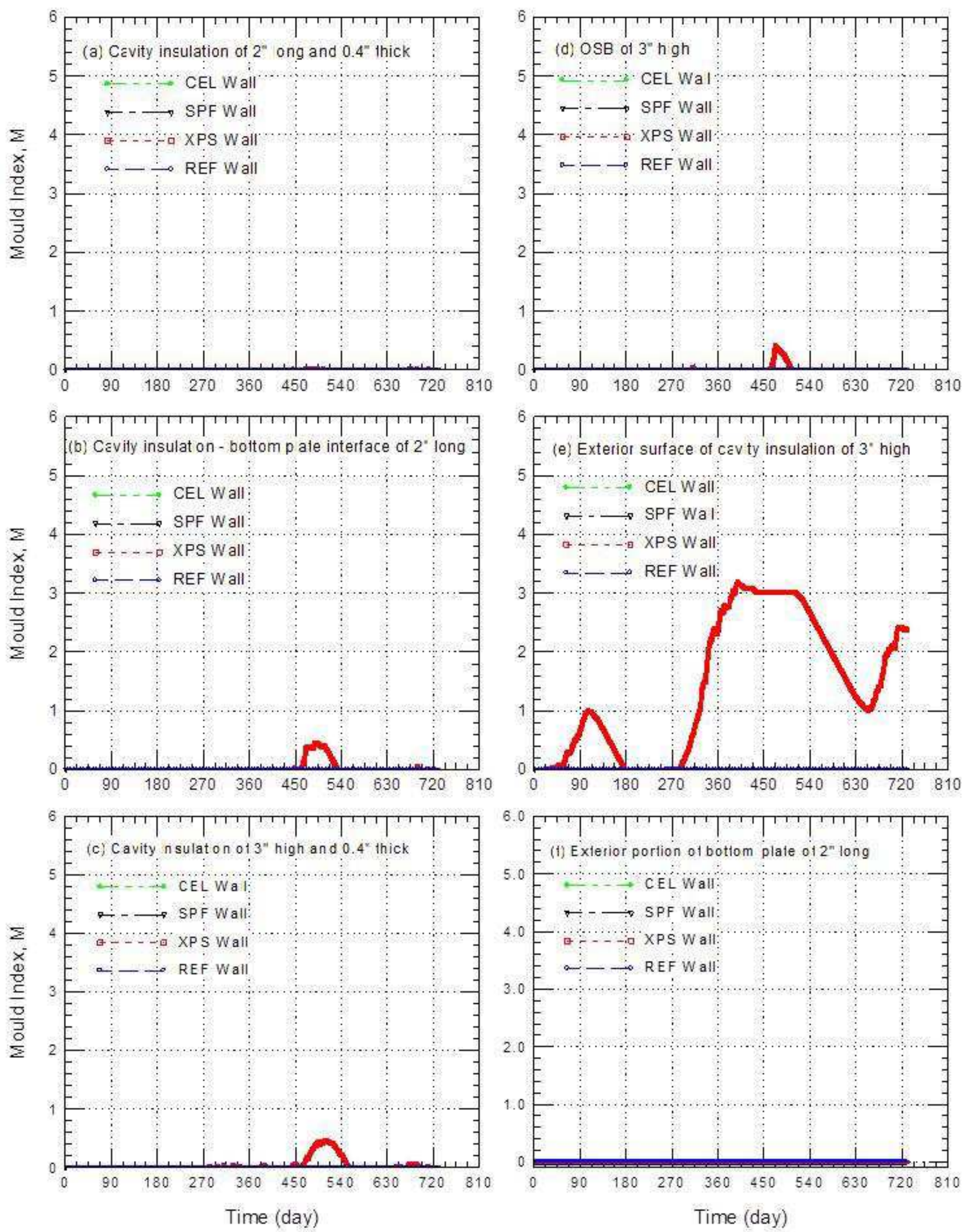


Figure 15. Comparison of the mould index at the locations of the bottom portion of the different wall assemblies shown in Figure 14 and listed in Table 10 (Ottawa weather)

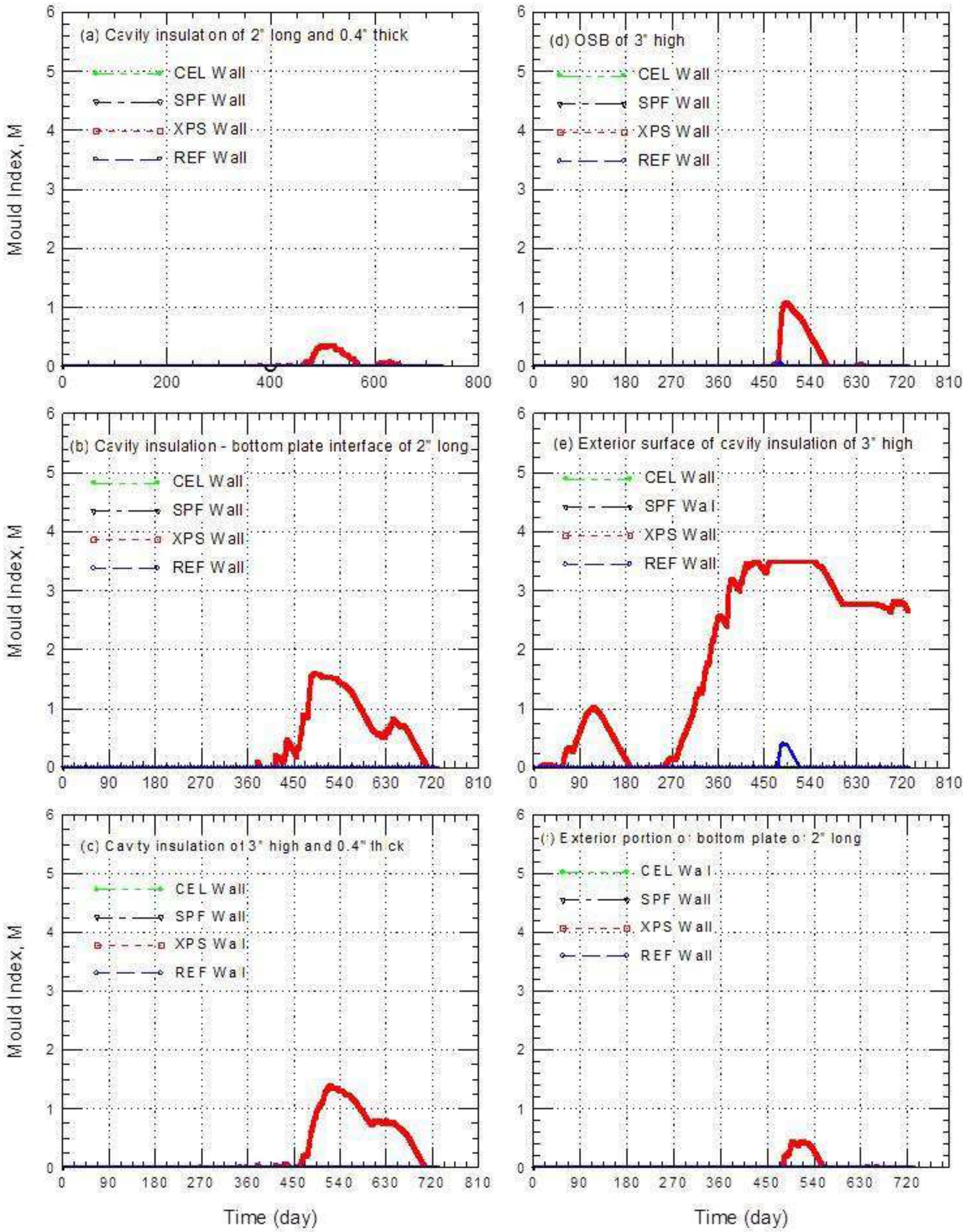


Figure 16. Comparison of the mould index at the locations of the bottom portion of the different wall assemblies shown in Figure 14 and listed in Table 10 (Edmonton weather)

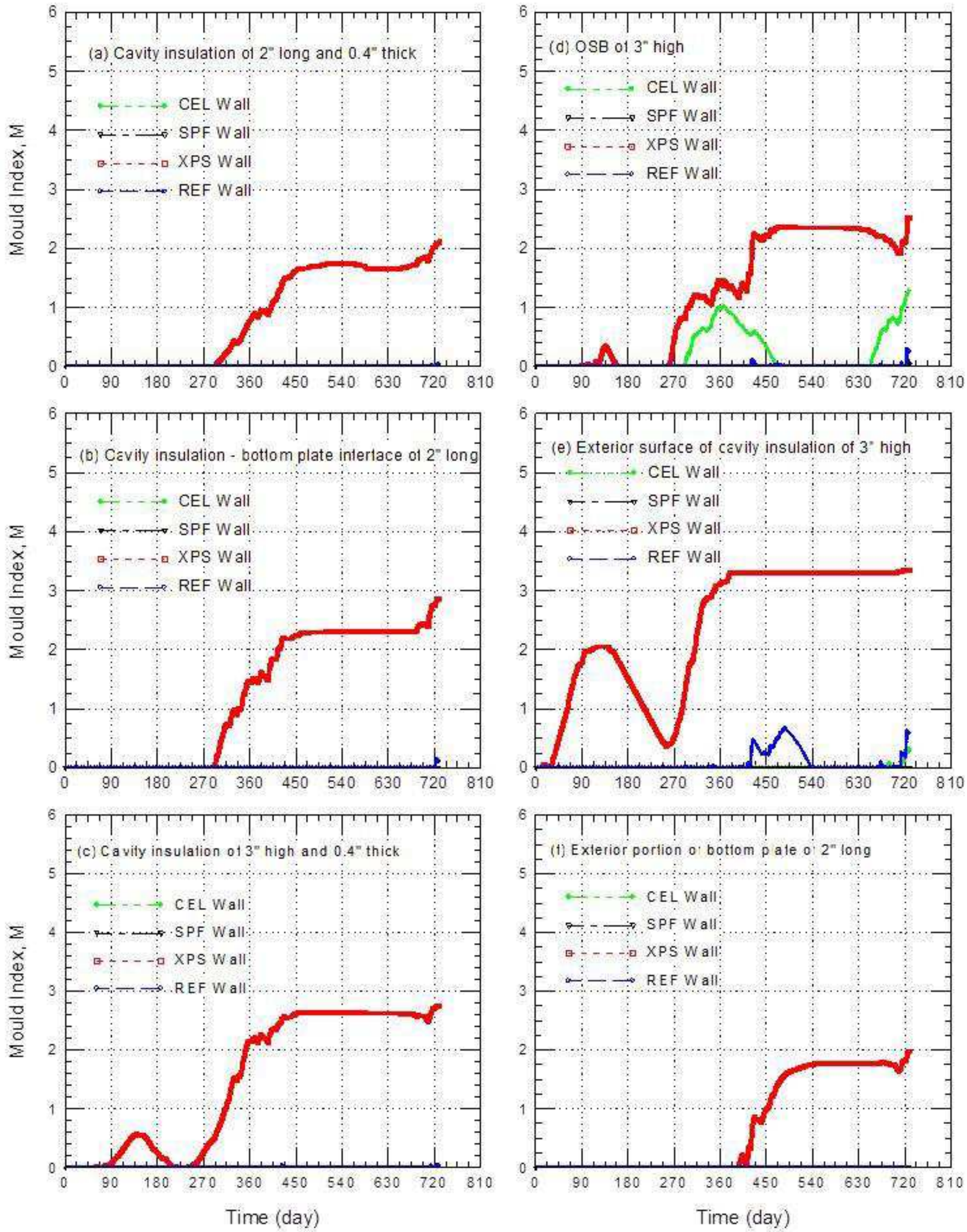


Figure 17. Comparison of the mould index at the locations of the bottom portion of the different wall assemblies shown in Figure 14 and listed in Table 10 (Vancouver weather)

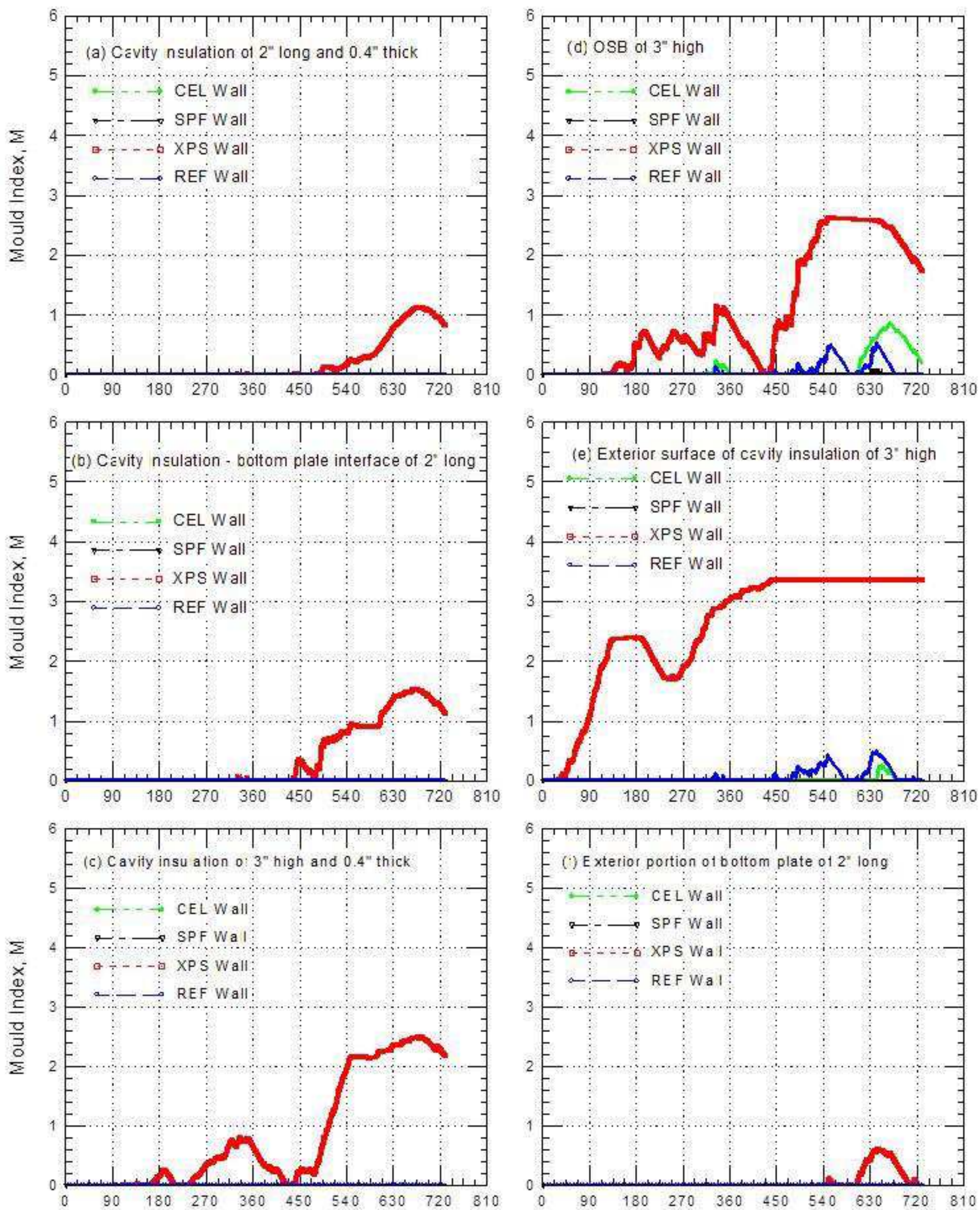


Figure 18. Comparison of the mould index at the locations of the bottom portion of the different wall assemblies shown in Figure 14 and listed in Table 10 (St. John's weather)

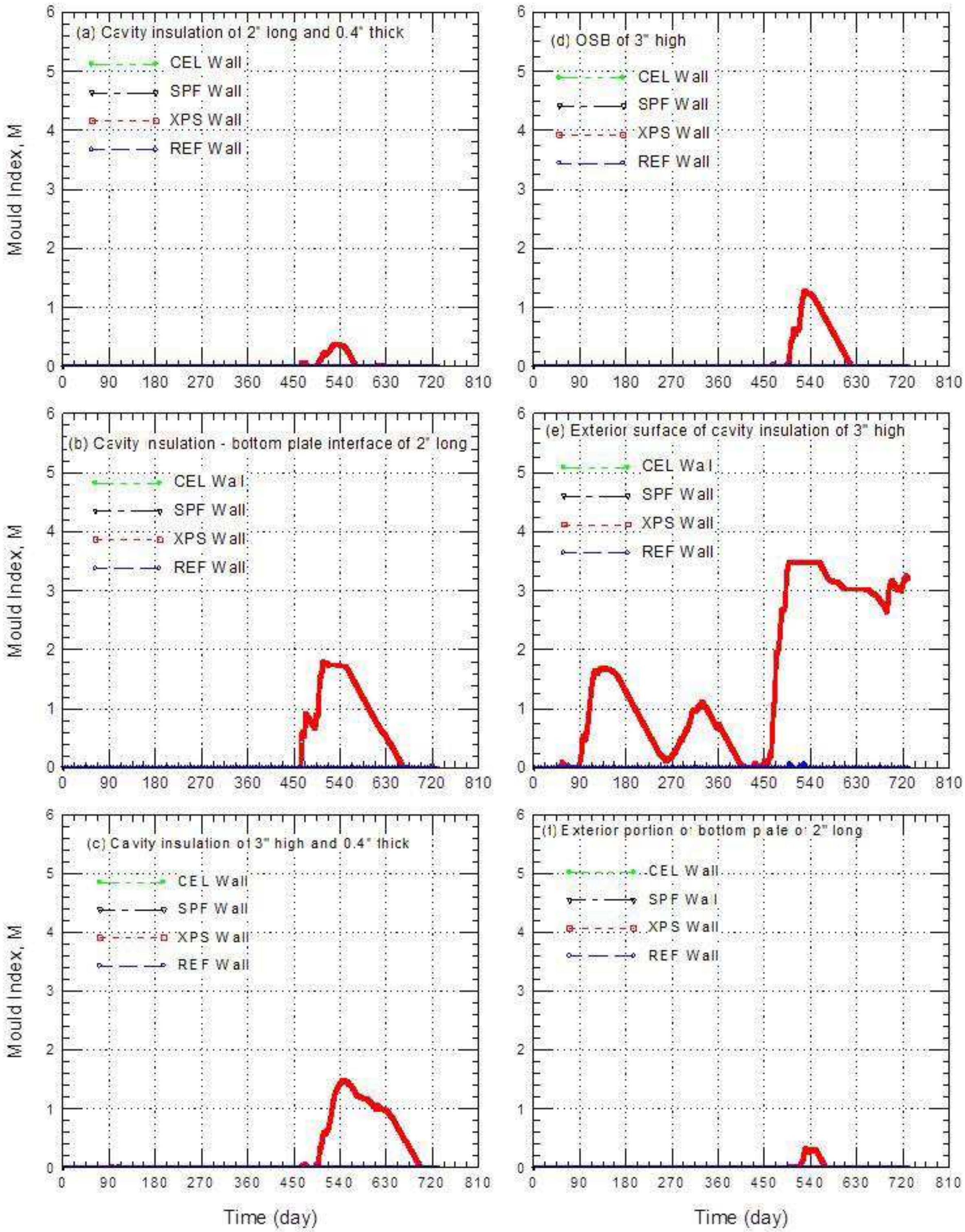


Figure 19. Comparison of the mould index at the locations of the bottom portion of the different wall assemblies shown in Figure 14 and listed in Table 10 (Yellowknife weather)

7. Results and Discussion

This section presents the results of the numerical simulations of the wall assemblies of Phase 2 using the simulation conditions listed in Table 5. The list of wall assemblies is provided in Table 1. The hygrothermal performance for different wall assemblies were obtained when these walls were subjected to the climates of five Canadian cities each differing in geographical location and that included: Ottawa (ON), Edmonton (AB), Vancouver (BC), St. John's (NL) and Yellowknife (NT). Note that the R-value of the stud-cavity insulation of the reference wall (REF Wall) is RSI-4.23 (R-24). The results derived for the REF Wall for different geographical locations except Yellowknife and that were provided in this report were obtained from a previously published NRC project entitled "Properties and Position of Materials in the Building Envelope for Housing and Small Buildings" (see [17] for more details).

7.1 Energy Performance

For both the average year and wet year, comparisons of the yearly heat losses in winter season and yearly heat gains in the summer season for the reference wall (REF Wall) and other walls of Phase 2 (XPS Wall, SPF Wall, CEL Wall) are shown in Figure 20, Figure 21, Figure 22, Figure 23, and Figure 24 for the climatic conditions of, Ottawa, Edmonton, Vancouver, St. John's and Yellowknife, respectively. It is important to point-out that the yearly heat losses and yearly heat gains shown in these figures are the heat losses/gains in the wall systems and are not necessarily the heat losses/gains one can expect in a house. Note that the summer season in this report was defined as when the outdoor temperature was greater than the indoor temperature, and vice versa for the winter season. The total nominal R-values of the wall systems are listed Table 3.

As expected, increasing the R-value of the wall system resulted in a decrease in both yearly heat loss and yearly heat gain. For example, the yearly heat losses of the wet year of Ottawa weather (see Figure 20) in the XPS Wall (RSI-5.97/R-33.9), the CEL Wall (RSI-6.95/R-39.5), and the SPF Wall (RSI-7.94/R-45.1) were 72%, 63%, and 57%, respectively, of that of the REF Wall (RSI-4.23/R-24). The corresponding results of the yearly heat losses of the wet year in the XPS Wall, the CEL Wall and the SPF Wall for other geographical locations, respectively, were for: Edmonton, 71%, 61% and 56% (Figure 21); for Vancouver ,72%, 62% and 56% (Figure 22); for St. John's, 71%, 61% and 55% (Figure 23): and for Yellowknife, 71%, 61% and 56% (Figure 24) of that of the REF Wall.

In summary, Figure 20 through Figure 24 show that whereas the REF Wall has the highest heat losses and heat gains. the SPF Wall has the lowest heat losses and heat gains, followed by the CEL Wall, and then the XPS Wall.

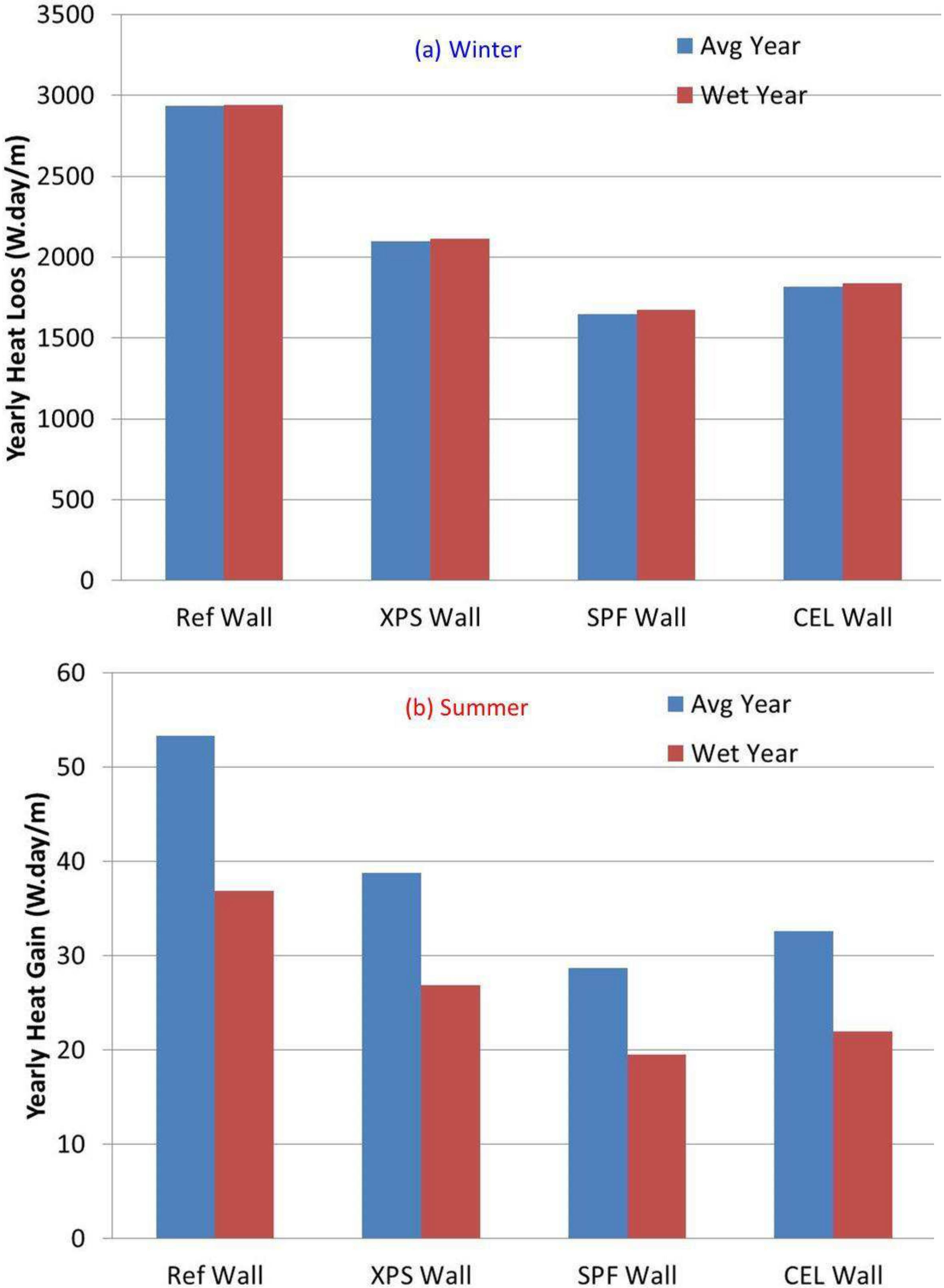


Figure 20. Comparison of yearly heat loss and heat gain of wall systems of different wall systems, subject to Ottawa weather

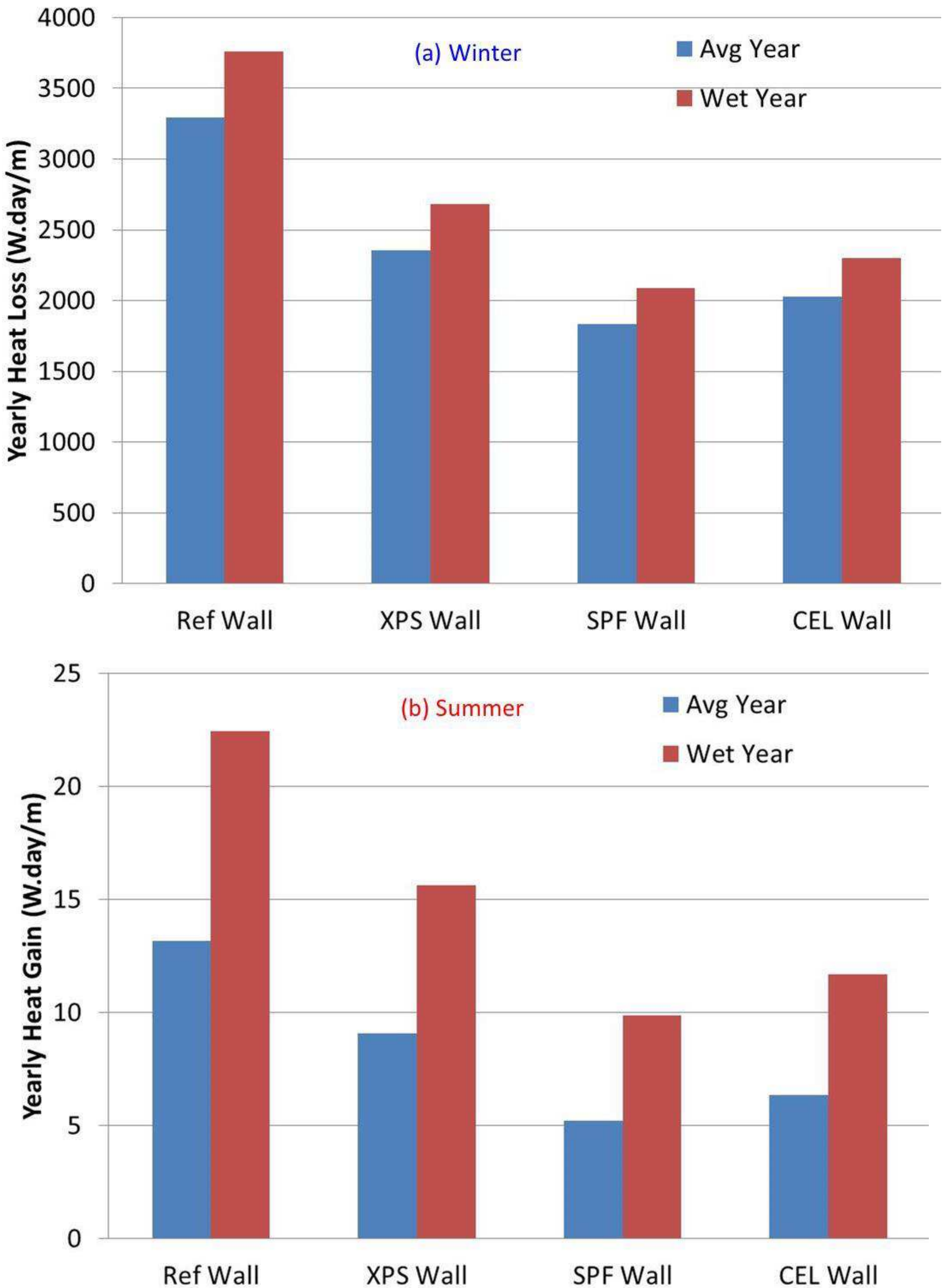


Figure 21. Comparison of yearly heat loss and heat gain of wall systems of different wall systems, subject to Edmonton weather

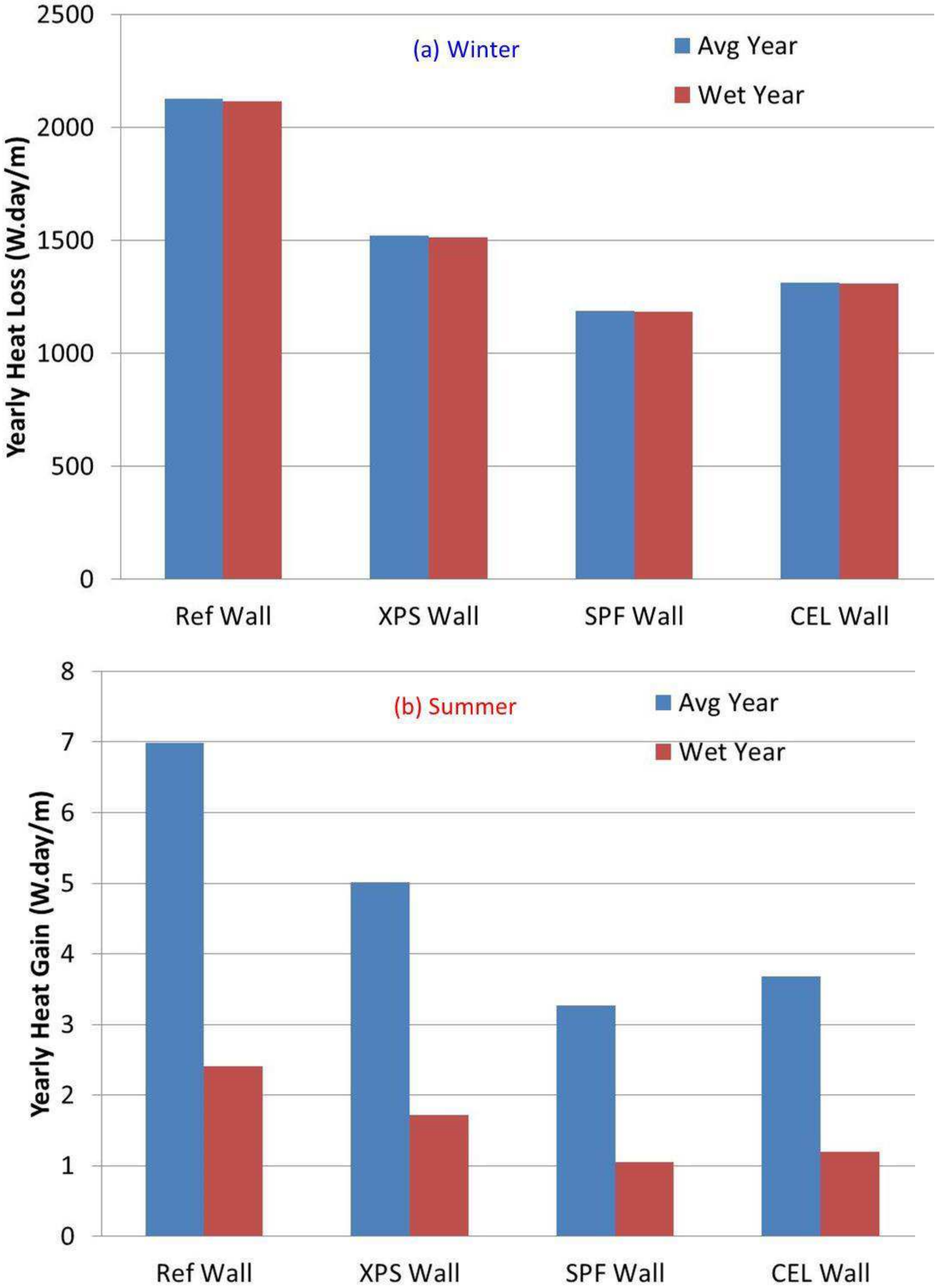


Figure 22. Comparison of yearly heat loss and heat gain of wall systems of different wall systems, subject to Vancouver weather

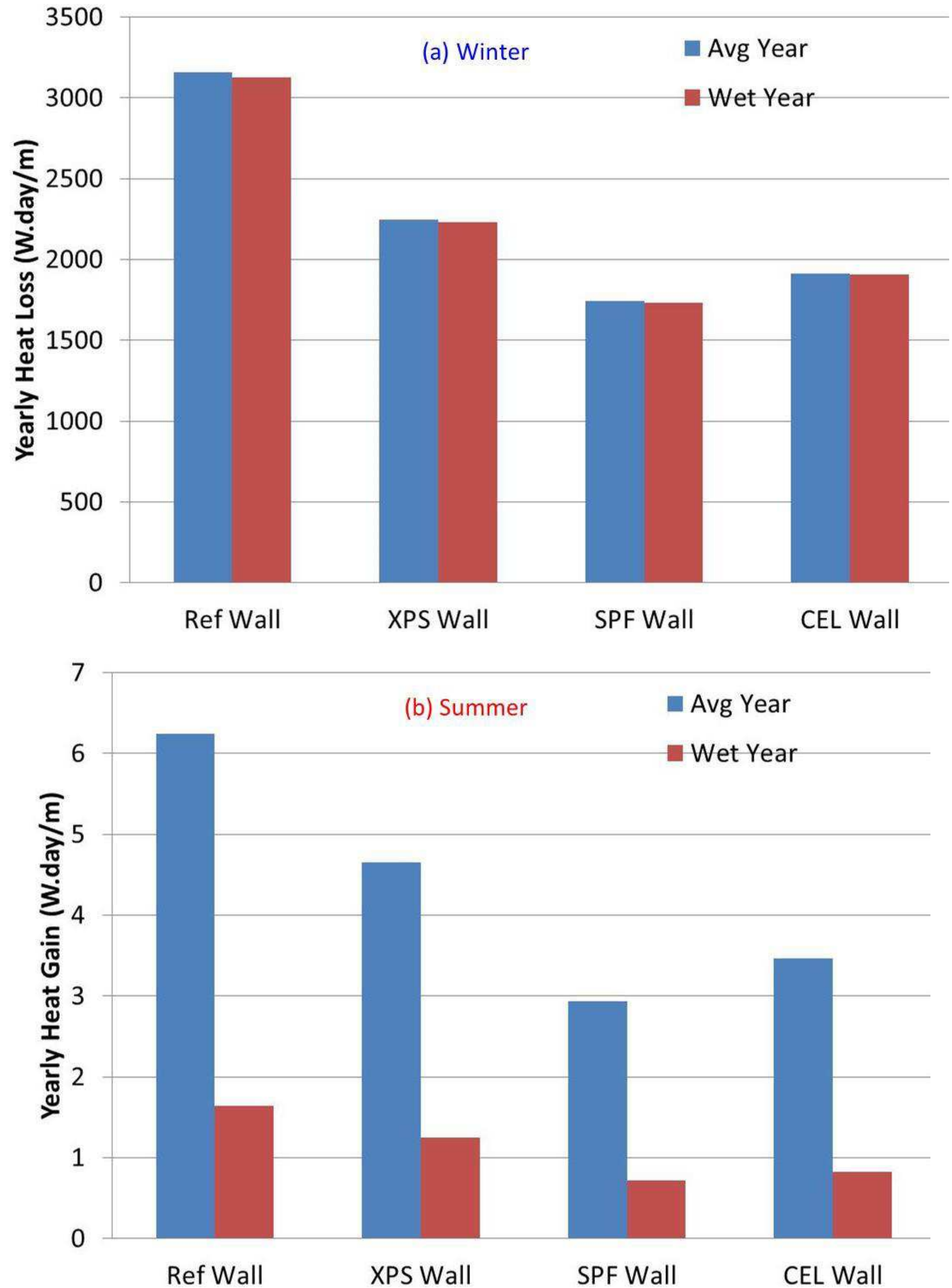


Figure 23. Comparison of yearly heat loss and heat gain of wall systems of different wall systems, subject to St. John's weather

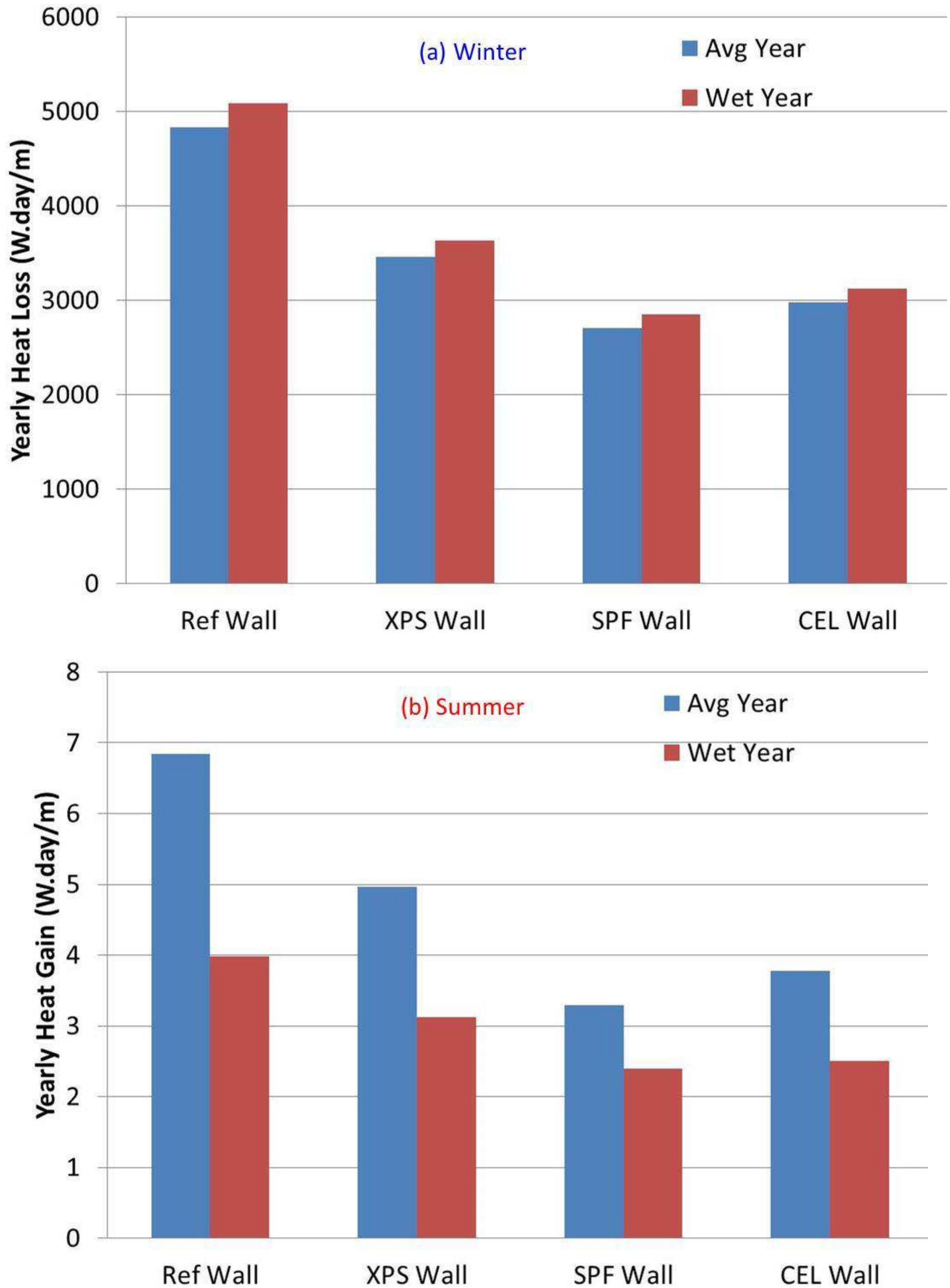


Figure 24. Comparison of yearly heat loss and heat gain of wall systems of different wall systems, subject to Yellowknife weather

7.2 Effect of Geographical Locations on the Hygrothermal Performance

The primary environmental parameters that greatly affected the hygrothermal performance as relates to the risk of condensation and mould growth are [13]:

- The outdoor temperature which can be represented by the Heating Degree Days (HDD). The greater the number of HDD the higher the risk for mould growth in a wall assembly. Amongst the geographical locations considered in this study, Yellowknife had the highest HDD (HDD = 8170), followed by Edmonton (HDD = 5120).
- The outdoor relative humidity which can be represented by the Moisture Index (MI). The higher the MI value, the smaller the drying potential of a wall assembly and hence, the higher the risk of mould growth. Amongst the geographical locations considered in this study, Vancouver had the highest value of MI (MI = 1.44), followed by St. John's (MI = 1.41).
- The wind speed. The higher the wind speed, the greater the air leakage rate across the wall assembly, and hence, the higher the risk for mould growth within the wall assembly.

Details for determining the air leakage rates of the different geographical locations are provided in reference [17]. Furthermore, the results of the air leakage rates of different geographical locations, provided in reference [13], show that amongst the geographical locations considered in this study, St. John's provided the highest air leakage rate across wall assemblies.

For Case-I in which the overall average value for mould index (M_{AVG}) and overall maximum value of mould index (M_{MAX}) were determined based on the locations listed in Table 9 for different wall assemblies (i.e. similar to the case of wall assemblies of Phase 1 [13]), Figure 25a and Figure 25b show a comparison of M_{AVG} and M_{MAX} for different wall assemblies of Phase 2 when subjected to different climatic conditions. As shown in these figures, the combined effects of the three environmental parameters, listed above, have brought about, in the case of walls subjected to the climatic condition of Ottawa the lowest values of mould index. For example, the overall average values for mould index for the REF Wall were 1.18, 1.98, 2.41, 3.05 and 1.06, respectively, for the climatic conditions of Ottawa, Edmonton, Vancouver, St. John's and Yellowknife (Figure 25a). Whereas the highest values of overall average mould index can be found for the REF Wall, XPS Wall, SPF Wall, and CEL Wall subjected to the climatic conditions of St. John's.

For Case-II in which the values of M_{AVG} and M_{MAX} were determined based on all locations at risk of condensation and mould growth and listed in Table 9 and Table 10 for different wall assemblies, Figure 26 also show that the lowest values of the overall average mould index can be found for the wall systems subjected to Ottawa climate, and the highest values of overall average mould index can be found for the wall systems subjected to St. John's climate.

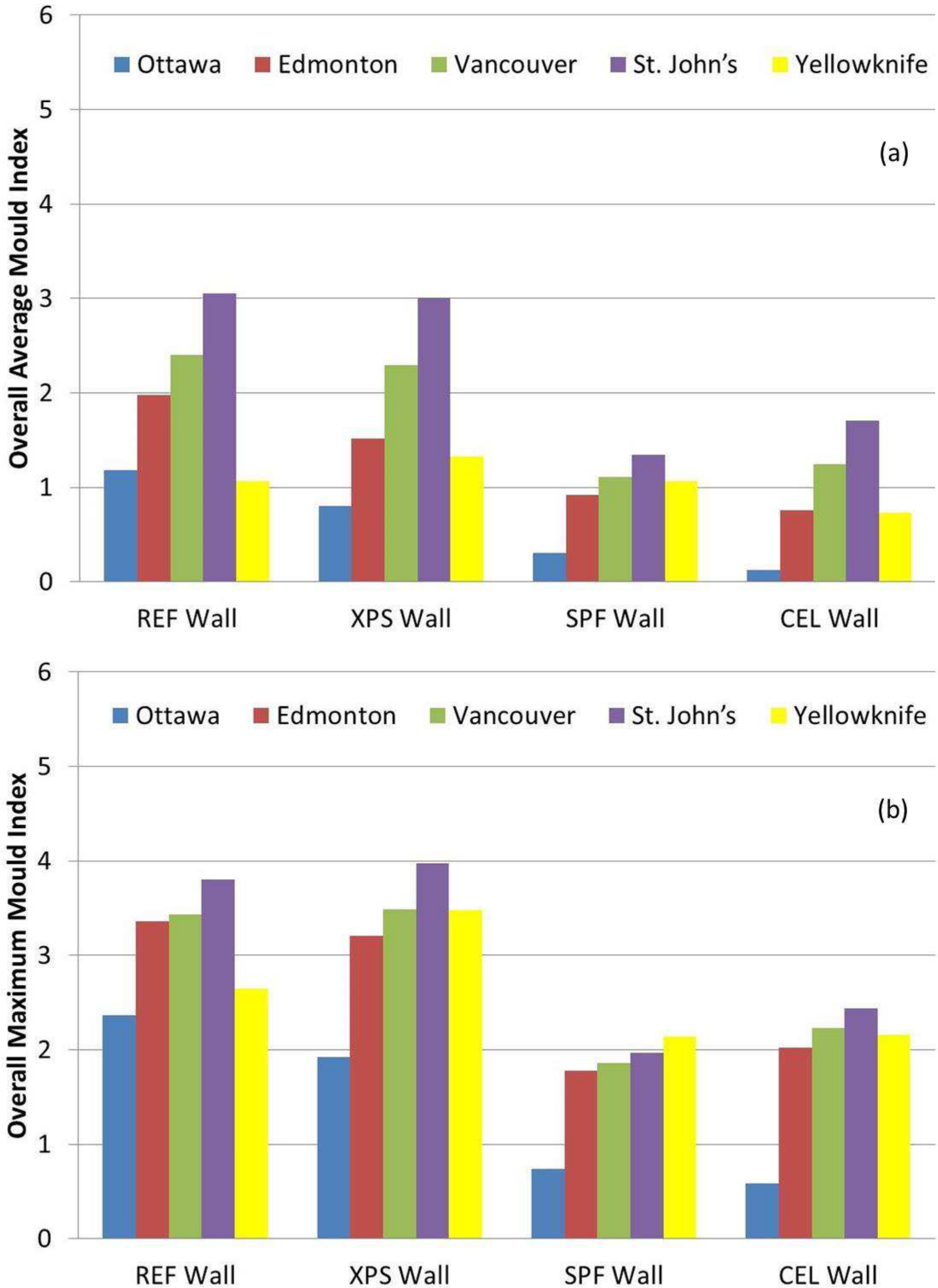
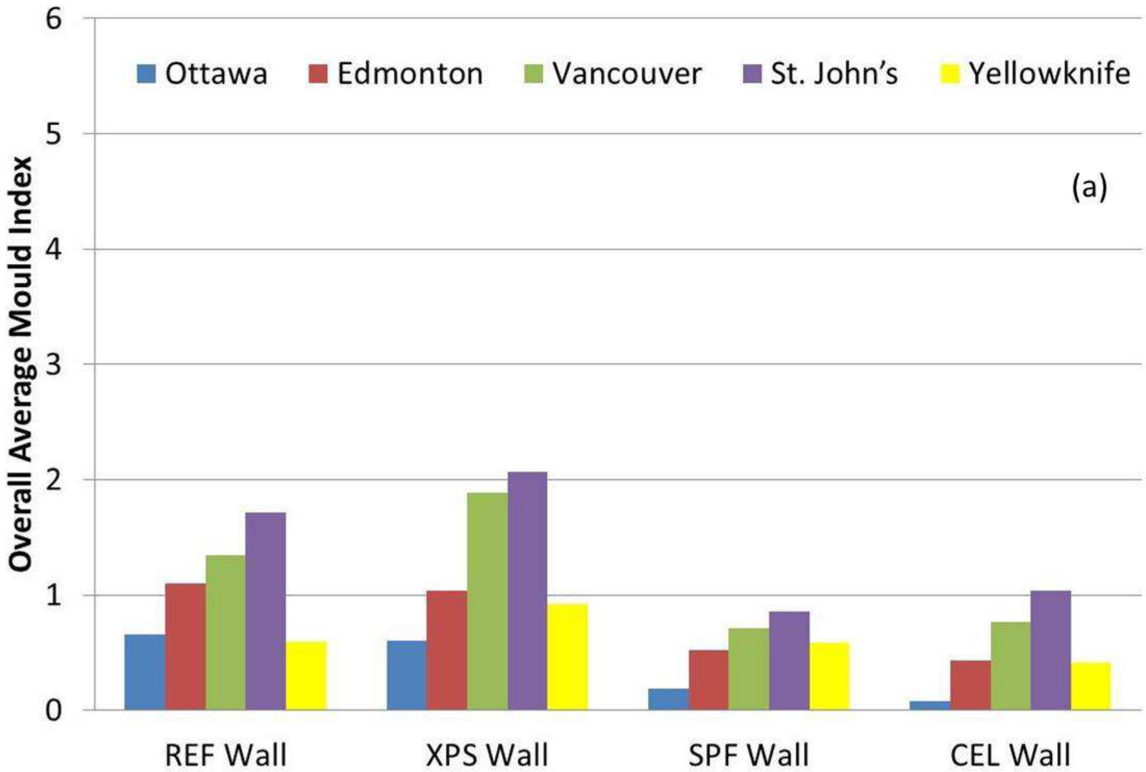


Figure 25. Effect of geographical locations on the overall maximum and average mould index (Case-I: results based on the locations listed in Table 9



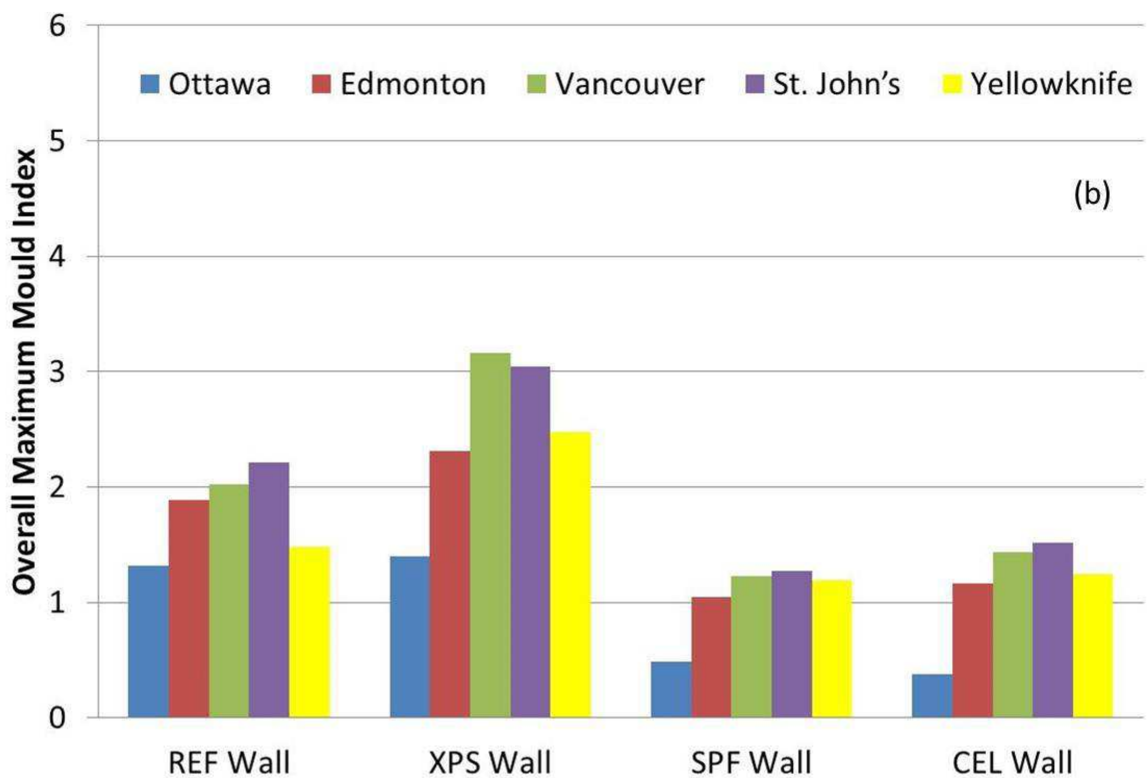


Figure 26. Effect of geographical locations on the overall maximum and average mould index (Case-II: results based on the locations listed in Table 9 and Table 10)

7.3 Hygrothermal Performance for different Walls

In this section, the results of the hygrothermal performance of all wall assemblies are compared for each climatic condition for both Case-I and Case-II described earlier. The results of the risk of condensation and mould growth are presented in Figure 27 through Figure 36 in the following order: Edmonton, Ottawa, Vancouver, Yellowknife and St. John's, and where:

- Figure 27 and Figure 28 for Edmonton, AB (cold, dry climate with HDD18 = 5120, MI = 0.48),
- Figure 29 and Figure 30 for Ottawa, ON (cold, dry climate with HDD18 = 4440 to 4500, MI = 0.84),
- Figure 31 and Figure 32 for Vancouver, BC (mild, wet climate with HDD18=2600 to 3100, MI = 1.44);
- Figure 33 and Figure 34 for Yellowknife, NT (cold, dry climate with HDD18 = 8170, MI = 0.58); and
- Figure 35 and Figure 36 for St. John's, NL (mild, wet climate with HDD18 = 4800, MI = 1.41).

7.3.1 Edmonton, AB

For Case-I (i.e., results based on the locations listed in Table 9) Figure 27a, b show comparisons of the values derived for both overall average mould index (M_{AVG}) and the overall maximum mould index (M_{MAX}), respectively, for the different wall assemblies. As shown in these figures, the values derived for both M_{AVG} and M_{MAX} of different wall assemblies are less than those for the code-compliant reference wall (REF Wall). However, as indicated earlier, there is a risk of condensation and mould growth in more locations, listed in Table 10, at the bottom portion of the XPS Wall only (see Figure 16 for walls subjected to the weather of Edmonton). As such, the results of Case-I are not fully representative for the "overall" hygrothermal performance of the wall assemblies. Note that the results of Case-I were included in this report for the purpose of comparing the hygrothermal performance of the wall systems of Phase 1 [13] with those of Phase 2. Furthermore, there is no risk of condensation in the locations listed in Table 10 for the wall assemblies of Phase 1.

By accounting for all locations in the wall assemblies of Phase 2 at risk of condensation and mould growth (i.e., Case-II in which the values of M_{AVG} and M_{MAX} were determined based on the locations listed in both Table 9 and Table 10), Figure 28a, b show comparisons of M_{AVG} and M_{MAX} for different wall assemblies. Figure 28a, b shows that the values of M_{AVG} and M_{MAX} of Case-II are lower than those of Case-I (Figure 27a, b).

Irrespective of whether the values of M_{AVG} and M_{MAX} of different wall assemblies of Case-II (Figure 28) are lower than those of Case-I (Figure 27), the results of Case-II are more representative for the "overall" performance of the wall assemblies in terms of comparing the values of M_{AVG} and M_{MAX} of the REF Wall against those of the other wall assemblies (i.e., XPS Wall, SPF Wall and CEL Wall). It is important to point out that the performance of wall assemblies having values of M_{AVG} and M_{MAX} lower than or equal those of the REF Wall is considered an acceptable solution. As such, all comparisons between the performances of the

REF Wall against the other walls of Phase 2 when subjected to different climatic conditions, are focused on the results of Case-II only; these results are presented below.

Figure 28a, b show that the derived values of M_{AVG} and M_{MAX}, respectively, for the SPF Wall (0.66 and 1.27) and the CEL Wall (0.54 and 1.44) are lower than those of the REF Wall (1.41 and 2.42). Conversely, the values of M_{AVG} and M_{MAX} for the XPS Wall (1.57 and 2.69) are higher than those for the REF Wall (1.41 and 2.42).

Note that the XPS Wall of Phase 1 [13] is similar to the XPS Wall of Phase 2 except that the XPS layer of 51 mm (2 in) thick in the former was located outboard of and installed onto the sheathing membrane, (see Figure 9 in the reference [13]) whereas the same XPS layer of 51 mm (2 in) thick in the latter (see Figure 9) was located inboard of the sheathing membrane (between the vapour barrier and the cavity insulations).

Although the total nominal R-values of Phase 1 and the XPS Wall of Phase 2 are the same (RSI-5.97/R-33.9), adding outboard insulation of 51 mm (2 in) of XPS as in the XPS Wall of Phase 1 [13] resulted in a warmer wall cavity temperature, and consequently, the formation of interstitial condensation occurring during the cold periods is less likely, and hence produces a lower mould index as compared to: (a) REF Wall (i.e. without outboard/inboard insulation), and (b) adding inboard insulation of XPS 51 mm (2 in) thick as in the XPS Wall of Phase 2.

Briefly, the performance of the XPS Wall of Phase 1 is “acceptable” due to the values of M_{AVG} and M_{MAX} of this wall are lower than those of the REF Wall [13]. On the other hand, the performance of the XPS Wall of Phase 2 is “not acceptable” due to the values of M_{AVG} and M_{MAX} of this wall being higher than those of the REF Wall as provided above.

7.3.2 Ottawa, ON

As was the case for Edmonton, in all instances, Figure 30a, b show that the values derived for the overall average mould index and overall maximum mould index for the SPF Wall (0.22 and 0.52) and the CEL Wall (0.09 and 0.42) are less than those for the REF Wall (0.84 and 1.69). Furthermore, the values of M_{AVG} and M_{MAX} for the XPS Wall (0.90 and 2.07) are higher than those for the REF Wall (0.84 and 1.69).

As compared to the results obtained for Edmonton, however, the values for M_{AVG} and M_{MAX} for these sets of walls are lower. For example, the values of M_{AVG} of the REF Wall, XPS Wall, SPF Wall and CEL Wall are, respectively, 0.84, 0.90, 0.22 and 0.09, for Ottawa (Figure 30a), whereas for Edmonton these respective values are: 1.41, 1.57, 0.66 and 0.54 (Figure 28a). The corresponding values of M_{MAX} for Ottawa, respectively, are 1.69, 2.07, 0.52 and 0.42, (Figure 30b), whereas for Edmonton these values, respectively, are: 2.42, 2.69, 1.27 and 1.44 (Figure 28b).

7.3.3 Vancouver, BC

Values of M_{AVG} and M_{MAX} for walls subjected to a Vancouver climate are greater than those of Ottawa and Edmonton. As for the cases for Ottawa and Edmonton, Figure 32a, b for Vancouver show that the values of M_{AVG} and M_{MAX} for the SPF Wall (0.81 and 1.38) and the CEL Wall (0.90 and 1.67) are less than those for the REF Wall (1.72 and 2.51). Also, the values of M_{AVG} and M_{MAX} for XPS Wall (2.01 and 3.23) are higher than those for the REF Wall (1.72 and 2.51).

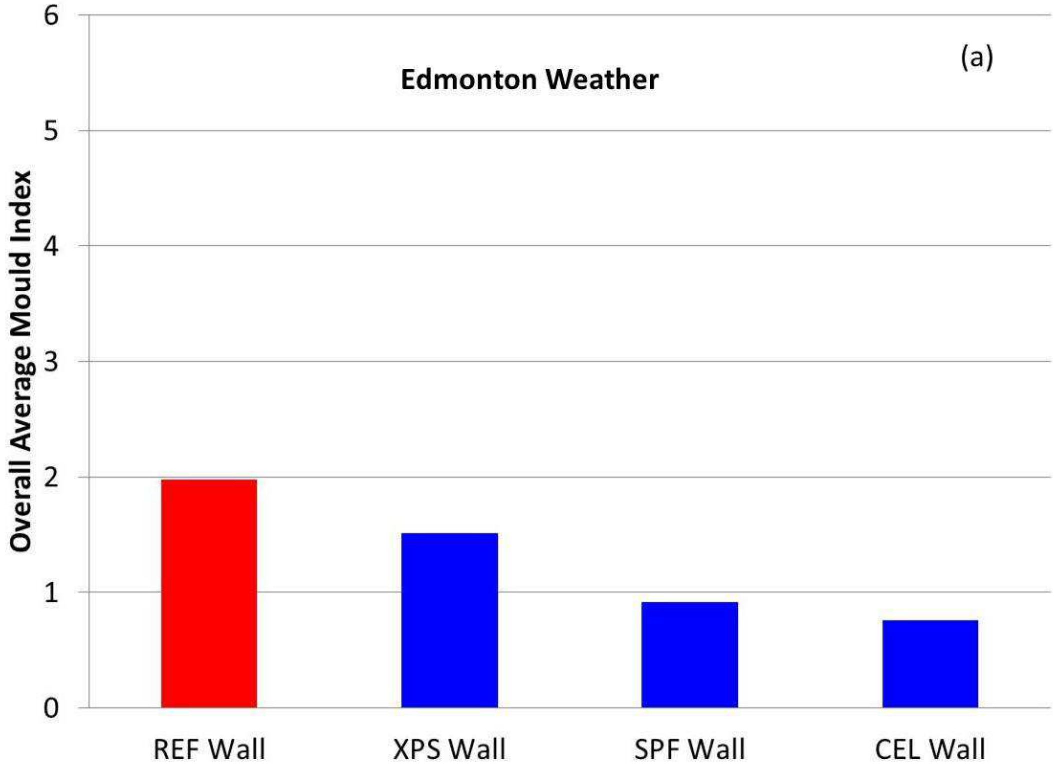
7.3.4 Yellowknife, NT

As for the cases of Ottawa, Edmonton and Vancouver, Figure 34a, b for Yellowknife show that the values of M_{AVG} and M_{MAX} for the SPF Wall (0.67 and 1.53) and the CEL Wall (0.52 and 1.54) are less than those for the REF Wall (0.76 and 1.90). As well, the values of M_{AVG} and M_{MAX} for the XPS Wall (1.05 and 2.90) are higher than those for the REF Wall (0.76 and 1.90).

7.3.5 St. John's, NL

As shown Figure 26a, the greatest values for M_{AVG} of the REF Wall, XPS Wall, SPF Wall and CEL Wall configurations occur in St. John's as compared to the other cities investigated. Note that the St. John's climate has the highest air leakage rate compared to the other geographical locations investigated (see the Appendix – A2 in reference [13]). Also, the St. John's climate is a wet climate with moisture index (MI = 1.41) slightly lower than that of Vancouver climate (MI = 1.44). For same climatic condition of St. John's, Figure 36a, b show that the values of M_{AVG} and M_{MAX} for the SPF Wall (0.97 and 1.46) and the CEL Wall (1.22 and 1.80) are less than those for the REF Wall (2.19 and 2.76). Furthermore, the values of M_{AVG} and M_{MAX} for the XPS Wall (2.39 and 3.40) are higher than those for the REF Wall (2.19 and 2.76).

In summary, the results presented in this section for different wall assemblies, subjected to different climatic conditions show that the hygrothermal performances of the SPF Wall and the CEL Wall are acceptable given that the values of M_{AVG} and M_{MAX} of these walls are lower than those of the REF Wall. Conversely, the hygrothermal performance of the XPS Wall is NOT acceptable due to the values of M_{AVG} and M_{MAX} of this wall are higher than those of the REF Wall.



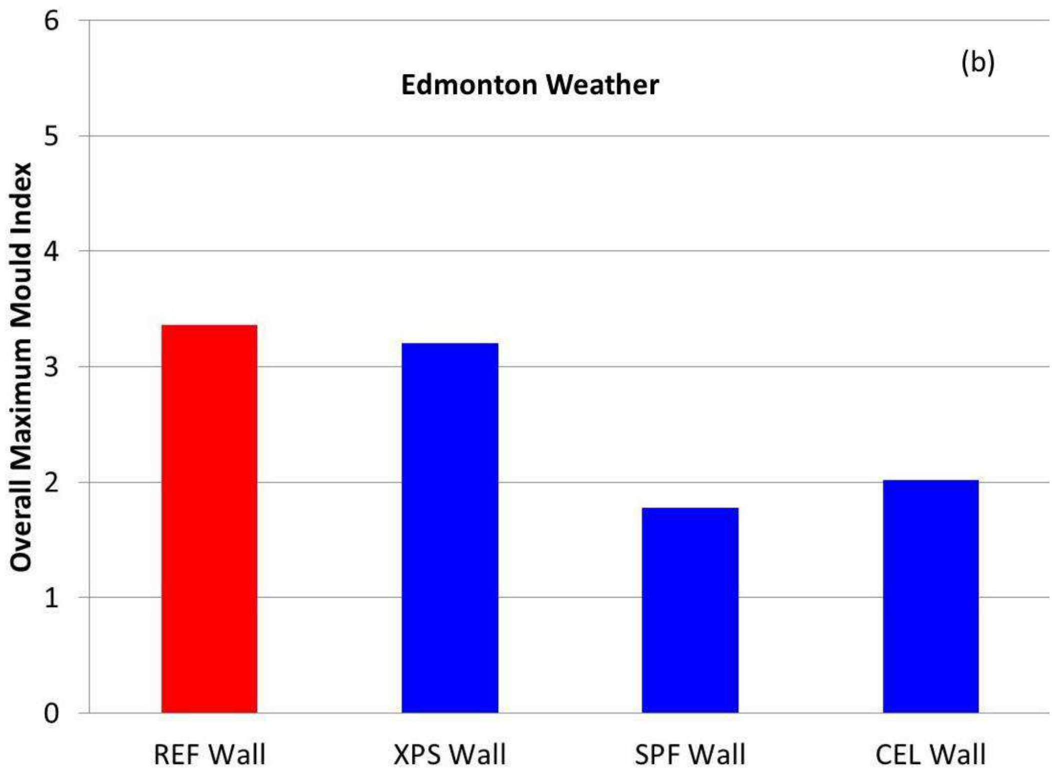


Figure 27. Comparison of overall maximum & average mould index of different wall systems, subjected to Edmonton weather (Case-I: results based on locations listed in Table 9

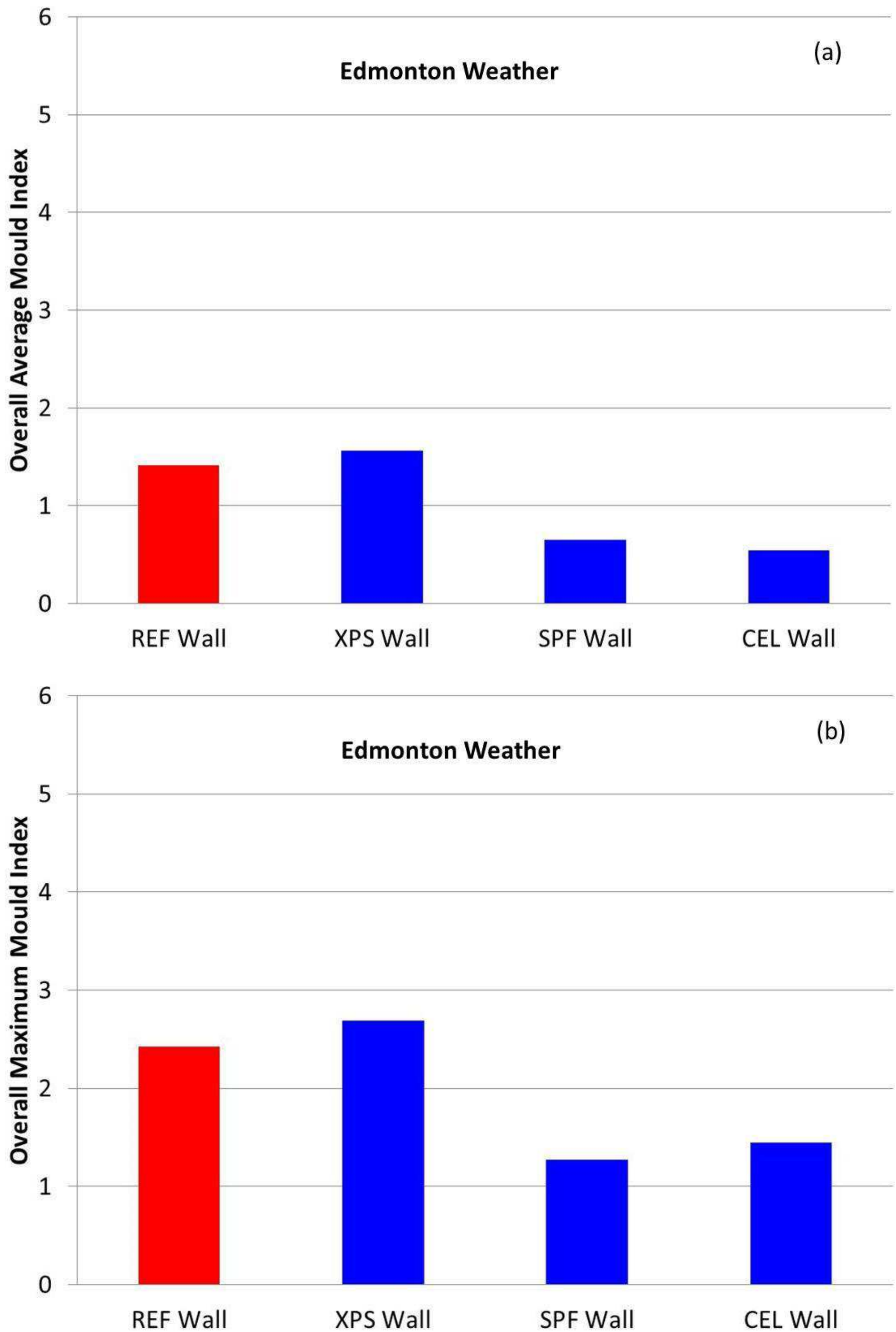


Figure 28. Comparison of overall maximum and average mould index of different wall systems, subjected to Edmonton weather (Case-II: results based on the locations listed in Table 9 and Table 10)

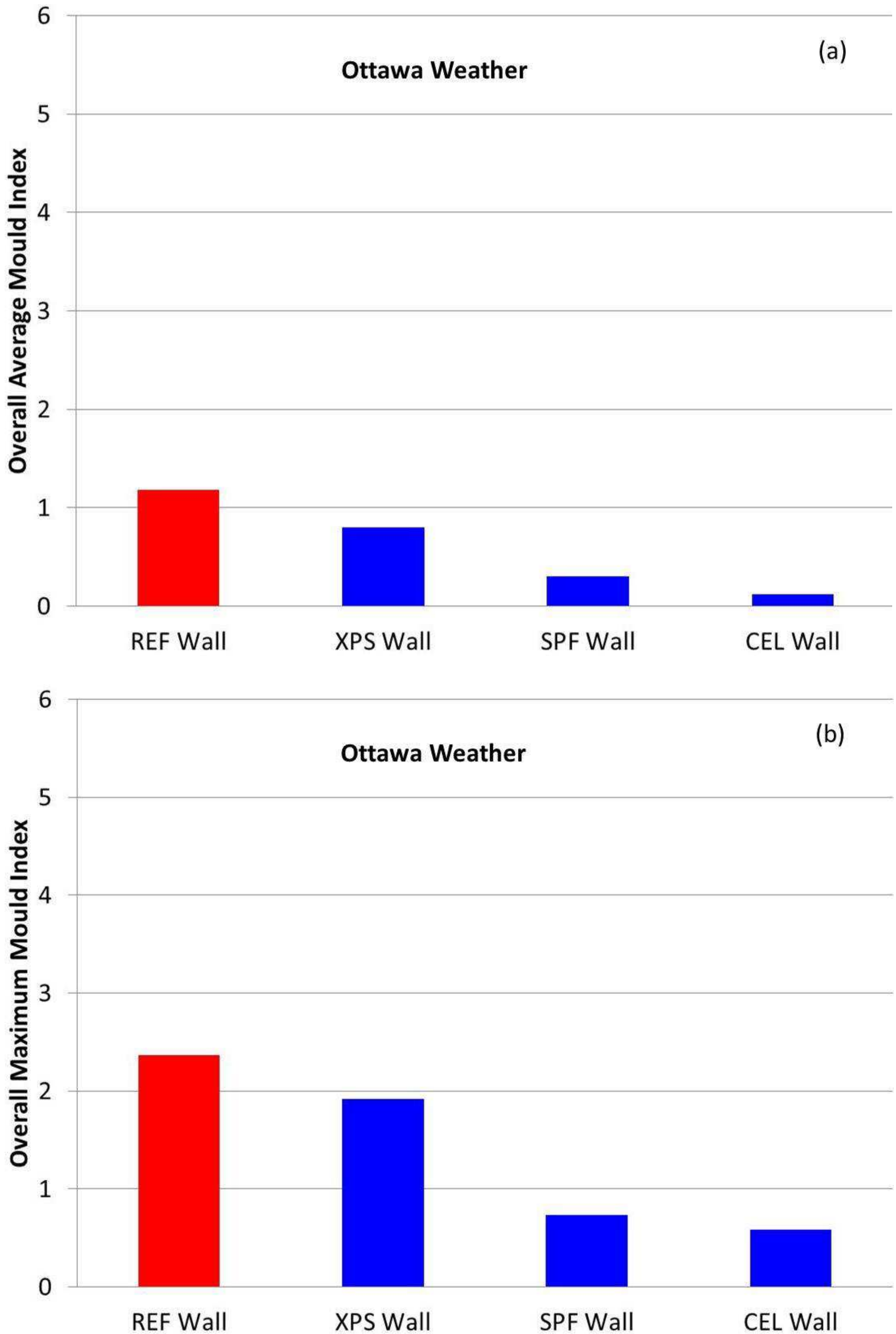


Figure 29. Comparison of overall maximum and average mould index of different wall systems, subjected to Ottawa weather (Case-I: results based on locations listed in Table 9)

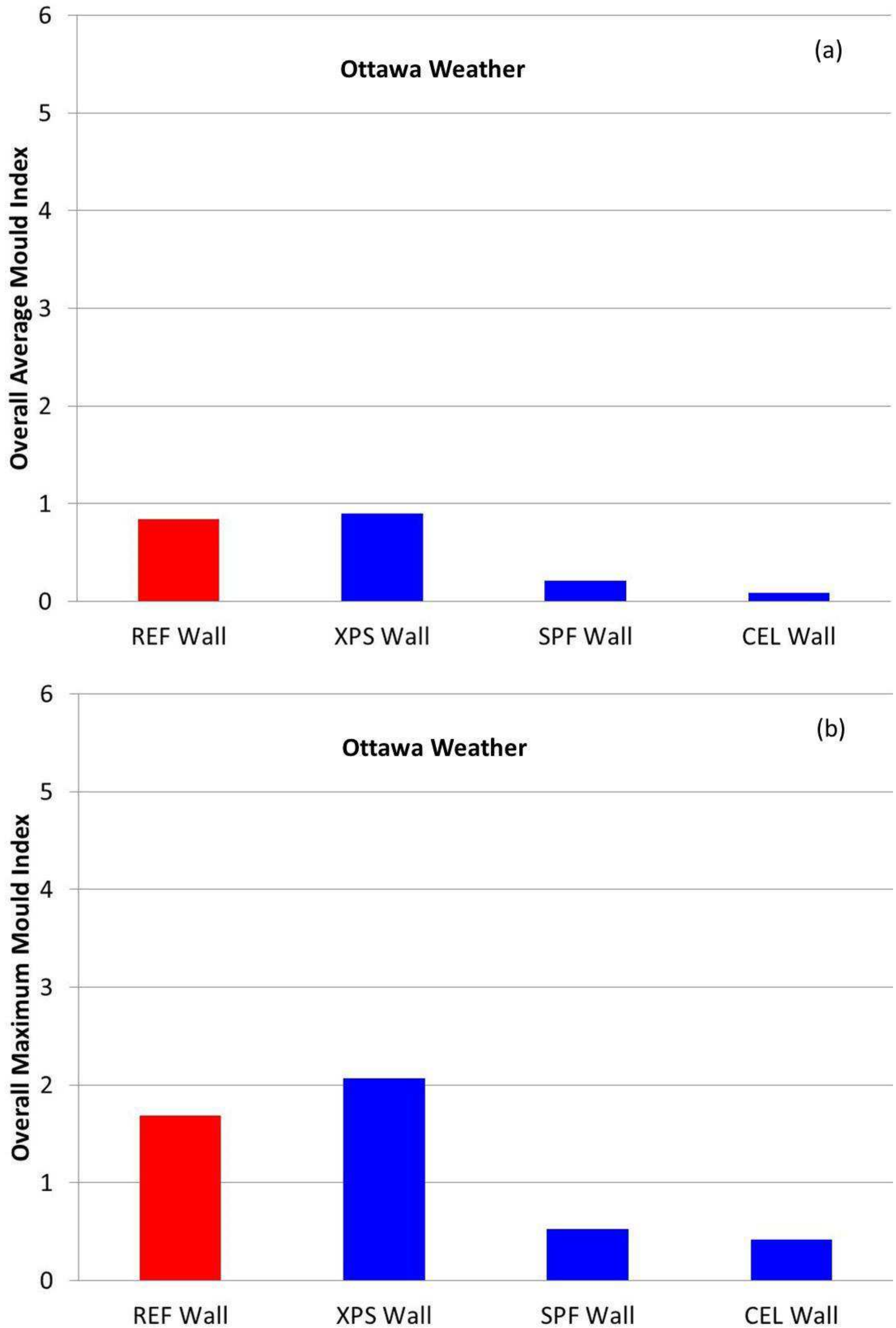


Figure 30. Comparison of overall maximum and average mould index of different wall systems, subjected to Ottawa weather (Case-II: results based on locations listed in Table 9 and Table 10)

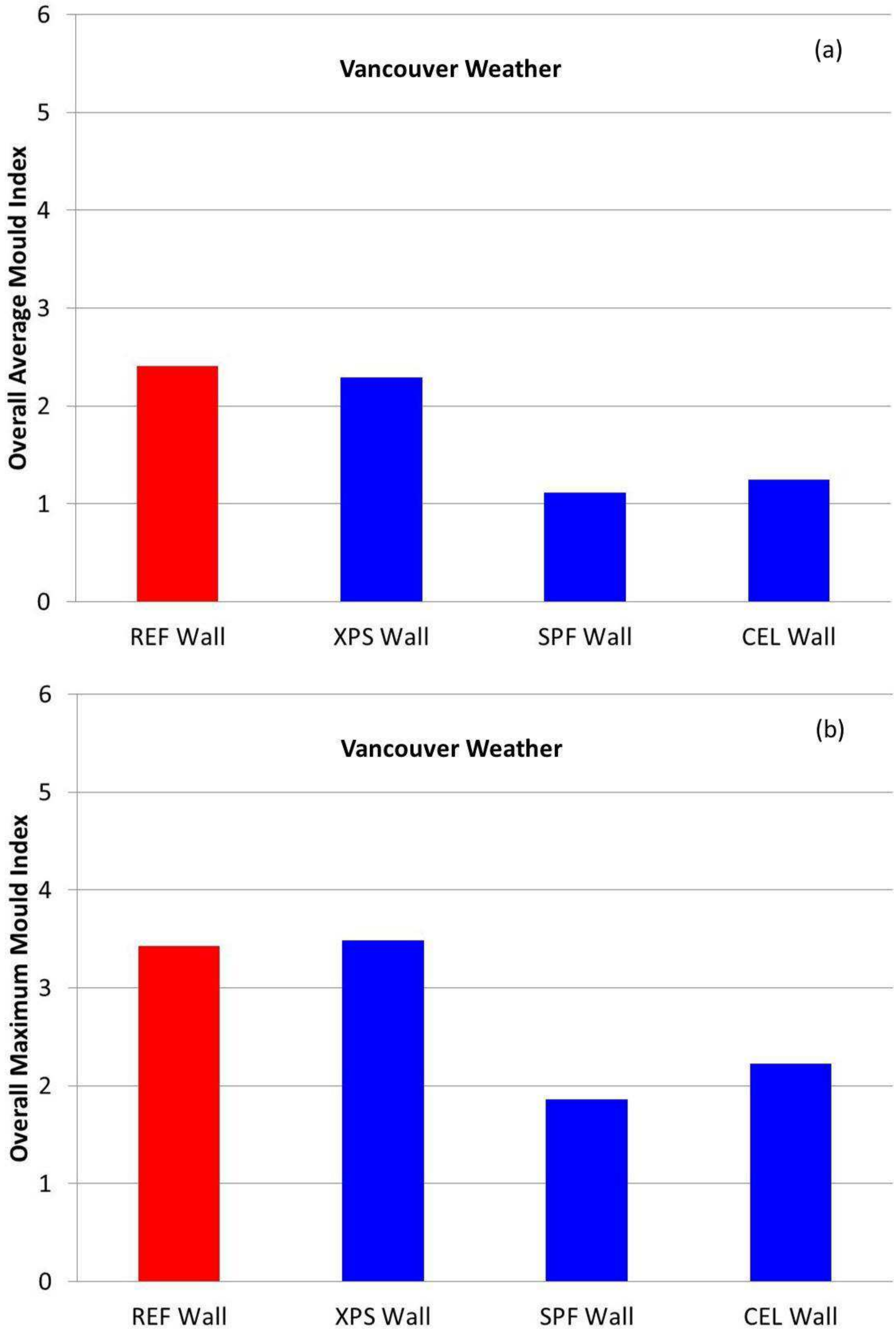


Figure 31. Comparison of overall maximum and average mould index of different wall systems, subjected to Vancouver weather (Case-I: results based on locations listed in Table 9)

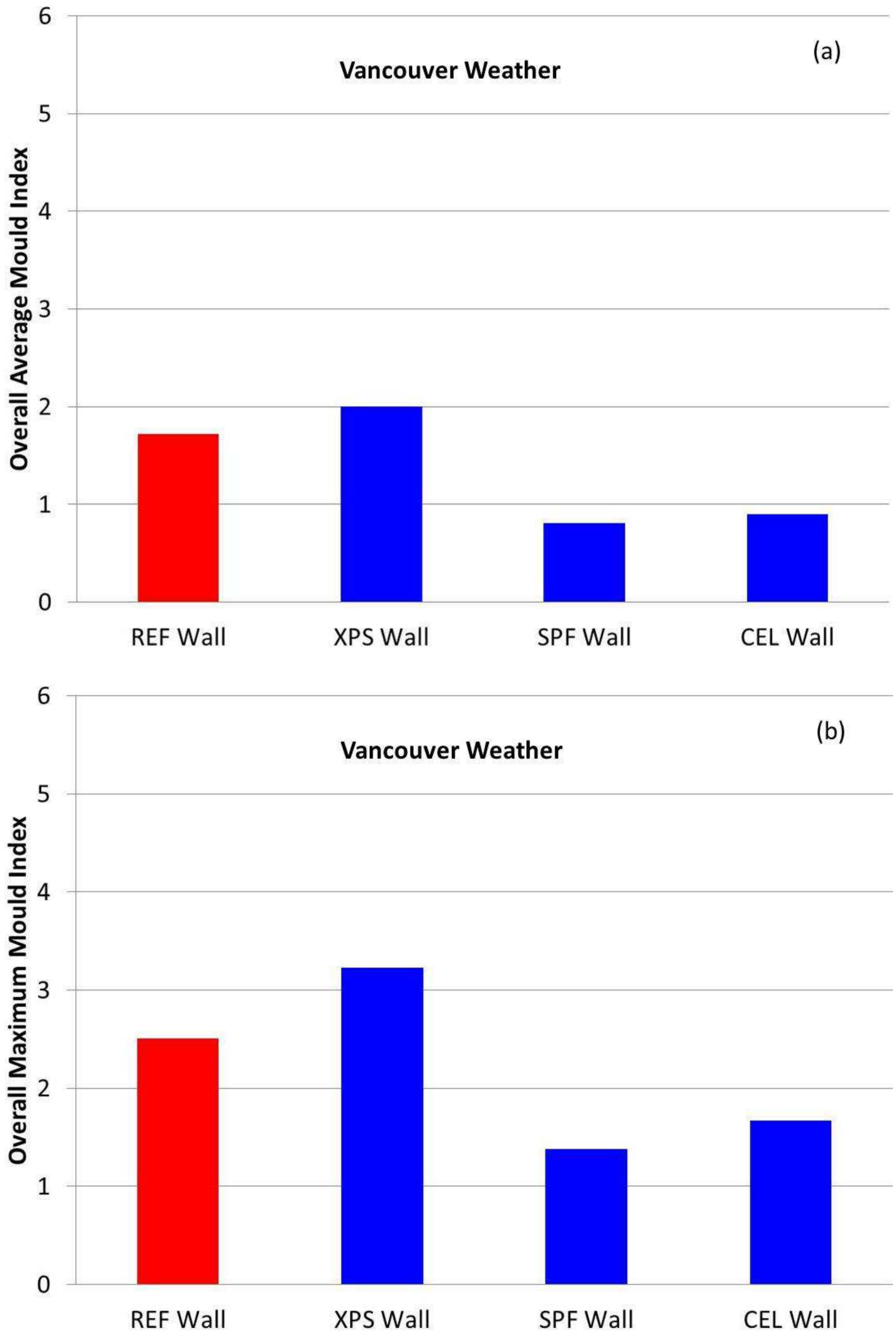


Figure 32. Comparison of overall maximum and average mould index of different wall systems, subjected to Vancouver weather (Case-II: results based on locations listed in Table 9 and Table 10)

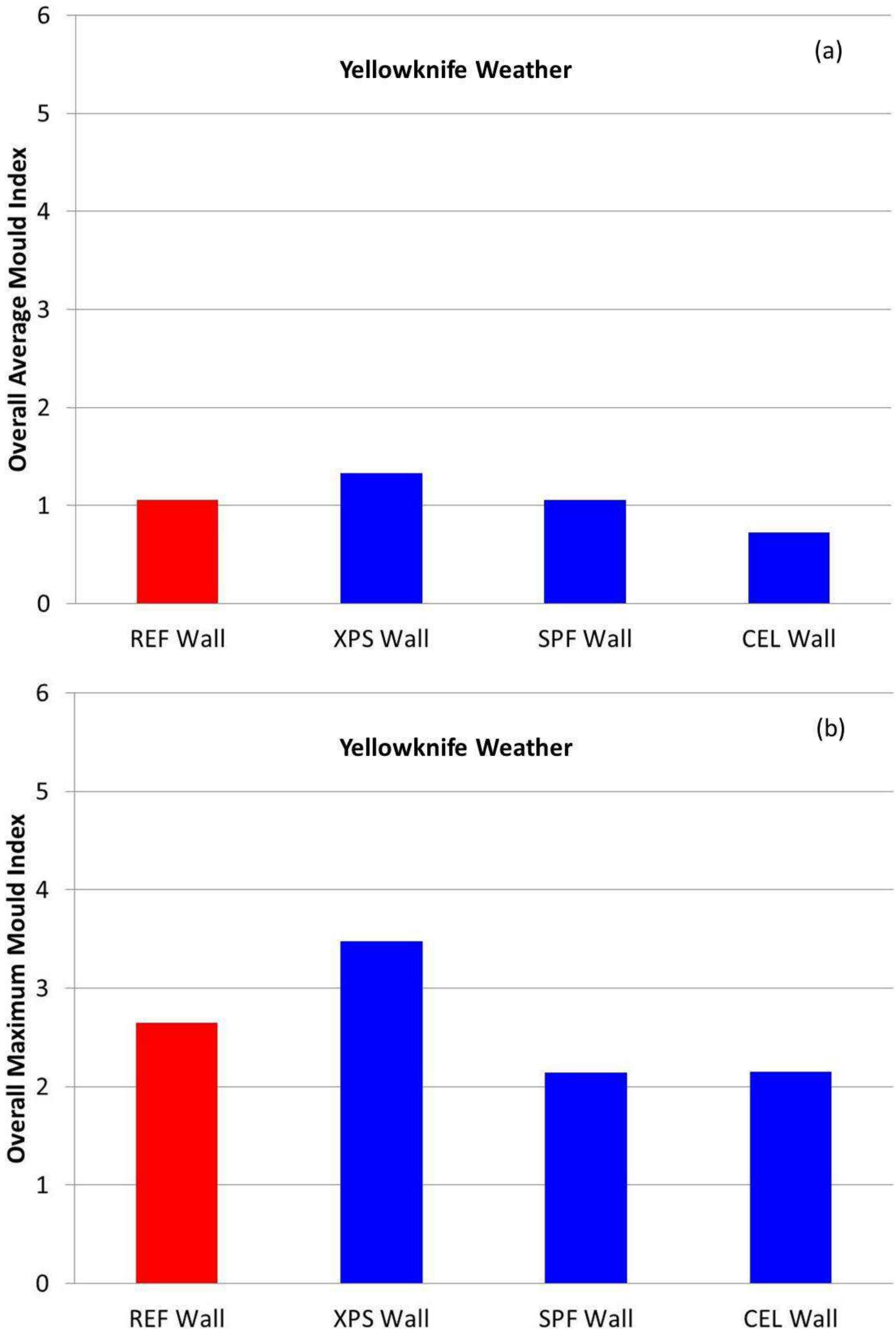


Figure 33. Comparison of overall maximum and average mould index of different wall systems, subjected to Yellowknife weather (Case-I: results based on locations listed in Table 9)

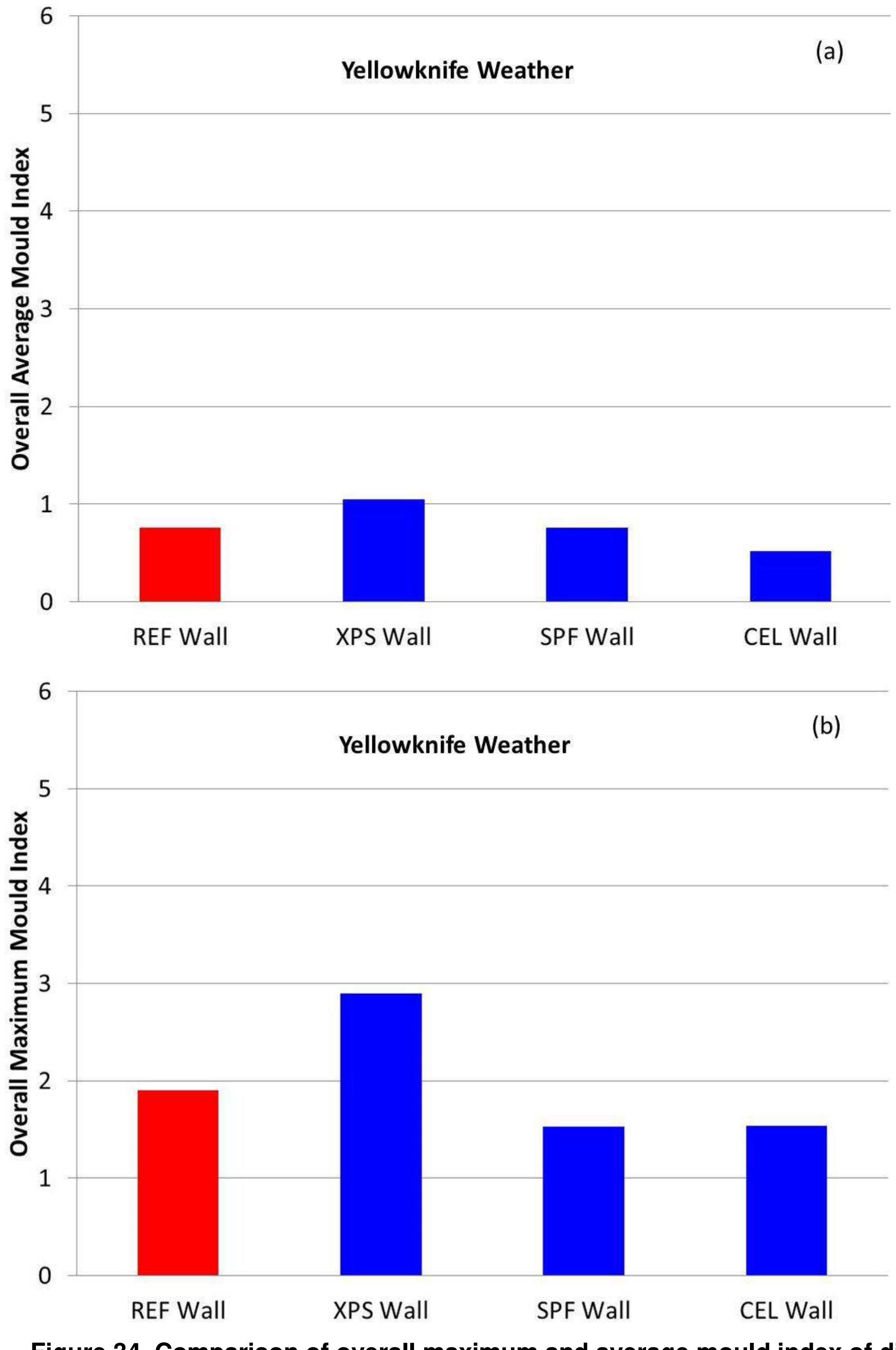


Figure 34. Comparison of overall maximum and average mould index of different wall systems, subjected to Yellowknife weather (Case-II: results based on locations listed in Table 9 and Table 10)

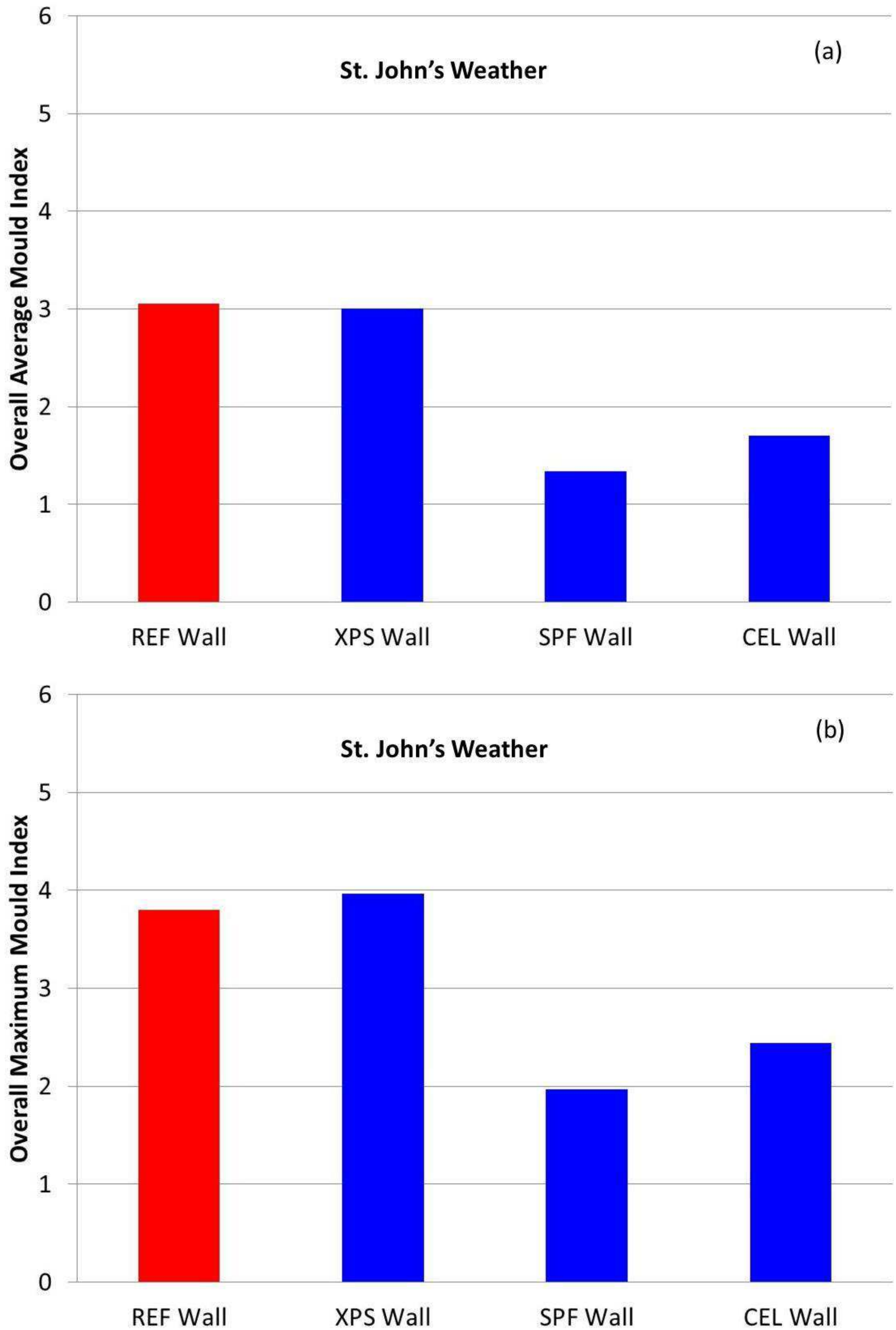
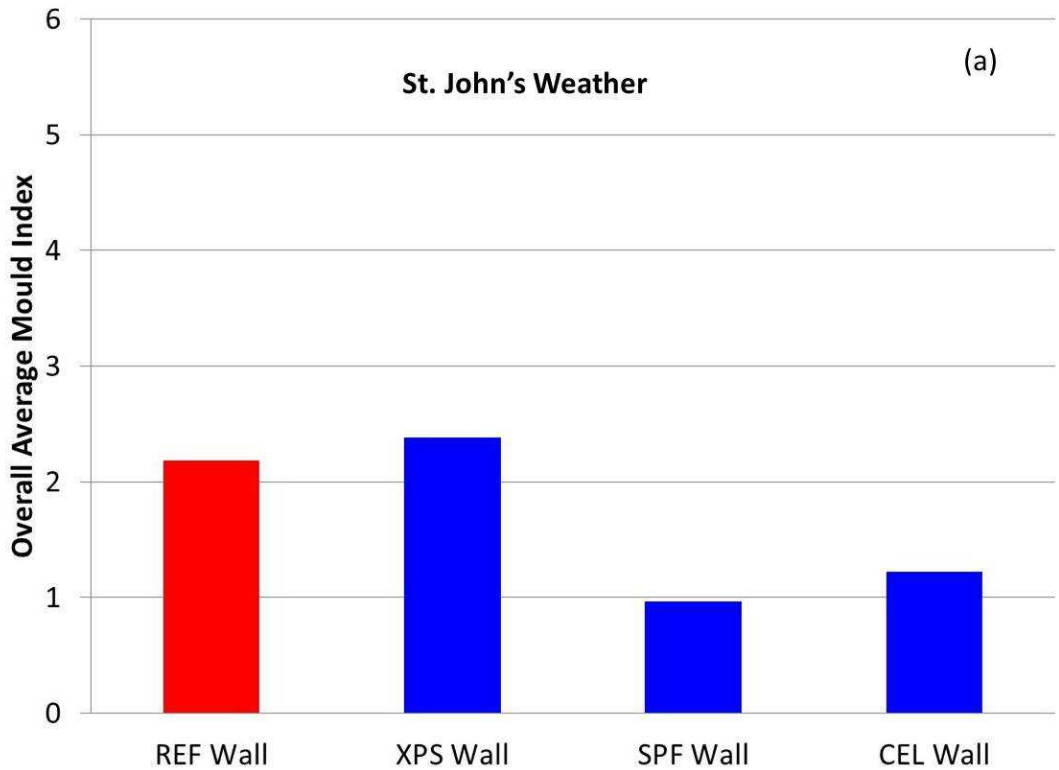


Figure 35. Comparison of overall maximum and average mould index of different wall systems, subjected to St. John's weather (Case-I: results based on locations listed in Table 9)



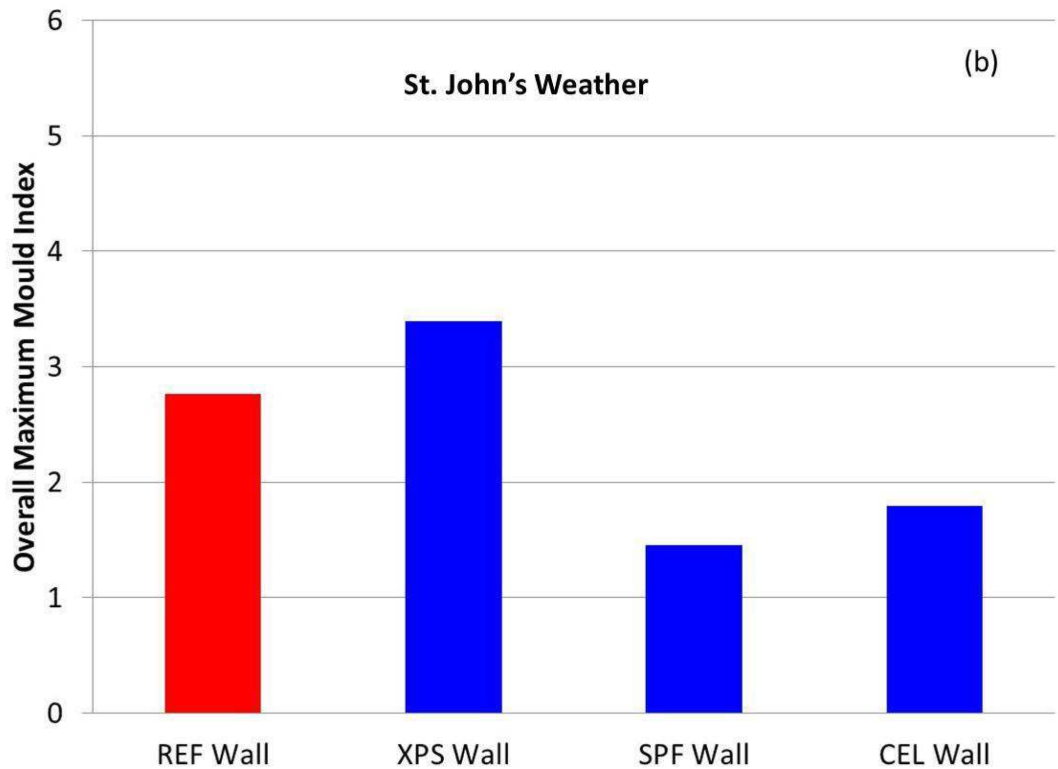


Figure 36. Comparison of overall maximum and average mould index of different wall systems, subjected to St. John's weather (Case-II: results based on locations listed in Table 9 and Table 10)

8. Concluding Remarks

The hygIRC-C model was first benchmarked against the experimental work carried out in the NRC-Construction's Field Exposure of Walls Facility (FEWF) for the three wall systems of Phase 2, namely the: XPS Wall, SPF Wall and CEL Wall. The benchmarking exercise consisted of completing transient numerical simulations, as was done in Phase 1 of this project [13]. The predicted measurements of the heat fluxes at different locations of the three wall systems were in good agreement with the experimental data.

Following the benchmarking of the hygIRC-C model, it was then used to conduct a parametric study to investigate the energy performance and the risk of condensation and mould growth in different wall assemblies when these assemblies were subjected to different climatic conditions in Canada, specifically, the climates of Vancouver (BC), Edmonton (AB), Ottawa (ON), St. John's (NL), and Yellowknife (NT). The modelling results for the different wall assemblies were expressed using the mould index criteria. The most recent mould growth model developed by Ojanen et al. [27] was used to determine the mould index of different materials within the respective wall assemblies.

Similar to a previous NRC study [17] and as provided in Phase 1 of this project [13], , the numerical results, based on the presumed air leakage path considered in this study, showed that the critical locations inside the wall assembly at risk of mould growth are the top and bottom portions of the wall assembly. These locations are listed in Table 9. The simulation results showed that there were additional locations in the bottom portion of the XPS Wall of at risk of condensation and mould growth, which were listed in Table 10.

The simulation results were presented on the basis of a simple form using the following two parameters:

- The overall average value of mould index (M_{AVG}) which is the average value of mould index at all locations within the assembly.
- The overall maximum value of mould index (M_{MAX}) which is the average value of the maximum mould index values at all locations within the assembly.

The two parameters were determined based on two cases, namely:

- Case-I, in which the values of M_{AVG} and M_{MAX} were determined based on the locations listed in Table 9 for different wall assemblies (i.e. similar to the case of wall assemblies of Phase 1 [13]).
- Case-II, in which M_{AVG} and M_{MAX} were determined based on all locations at risk of condensation and mould growth and listed in both Table 9 and Table 10 for different wall assemblies.

Irrespective of whether the values of M_{AVG} and M_{MAX} given for different wall assemblies of Case-II (Figure 28) are lower than those of Case-I (Figure 27), the results of Case-II are considered more representative of the "overall" performance of the wall assemblies.

For different climatic conditions, the results of Case-II showed that the values of M_{AVG} and M_{MAX} of the SPF Wall and the CEL Wall were lower than those of the code-compliant reference wall

(REF Wall). Conversely, the values of M_{AVG} and M_{MAX} of the XPS Wall were greater than those of the REF Wall.

For the REF Wall, XPS Wall, SPF Wall and CEL Wall, the climatic condition of St. John's (NL) appeared to have the most severe climate in comparison to the other four locations investigated (Vancouver (BC), Ottawa (ON), Edmonton (AB) and Yellowknife (NT)); the greatest values of the overall average mould index in the wall configurations amongst the five locations occurred in this location.

9. References

1. Ojanen, T., and Kumaran, M.K., "Air Exfiltration and Moisture Accumulation in Residential Wall Cavities", Thermal Performance of Exterior Envelopes of Buildings V, Clearwater, FL, 1992.
2. Karagiozis, A.N., and Kumaran, M. K., "Computer Model Calculations on the Performance of Vapor Barriers in Canadian Residential Buildings", ASHRAE Transactions, 99(2), pp. 991-1003, 1993.
3. Ojanen, T., and Kumaran, M.K., "Effect of Exfiltration on the Hygrothermal Behaviour of a Residential Wall Assembly", J. of Thermal Insulation and Building Envelopes, vol. 19, 1996.
4. Kumaran, M. K., and Haysom, J. C., "Low Permeance Materials in Building Envelopes", Institute for Research in Construction, National Research Council of Canada; Construction Technology Update #41, 2000.
5. Kumaran, M.K., and Haysom, J.C., "Avoiding Condensation with Low-Permeance Materials", Solplan Review (96), pp.18-19, 2001.
6. Chown, G. A., and Mukhopadhyaya, P., "NBC 9.25. 1.2.: The On-going Development of Building Code Requirements to Address Low Air and Vapour Permeance Materials", 10th Canadian Conference on Building Science and Technology: Building Science and integrated Design Process, Ottawa ON, May 12-13, 2005, v. 1, pp. 48-58.
7. Straube, J., "The influence of Low-Permeance Vapor Barriers on Roofs and Wall Performance", Buildings VIII Conference proceedings, paper # 184, 2001.
8. Brown, W.C., Roppel, P., and Lawton, M., "Developing a Design Protocol for Low Air and Vapour Permeance Insulating Sheathing in Cold Climates", Buildings X Proceedings, paper # 242, 2007.
9. Roppel, P., Brown, W.C., and Lawton, M., "Modeling of uncontrolled Indoor Humidity for HAM Simulations of Residential Buildings", Buildings X Proceedings, paper #212, 2007.
10. Maref, W., Rousseau, M.Z., Armstrong, M.M., Lee, W., Leroux, M., and Nicholls, M., Evaluating the Effects of Two Energy Retrofit Strategies for Housing on the Wetting and Drying Potential of Wall Assemblies: Summary Report for Year 2007-08 Phase of the Study, Report RR-315, pp. 1-118, NRC Institute for Research in Construction, 2011.
11. Maref, W., Armstrong, M.M., Rousseau, M.Z., Nicholls, M., and Lei, W., "Effect of Wall Energy Retrofit on Drying Capability", Solplan Review, (150), pp. 1-2, 2010.
12. Maref, W., Armstrong, M. M., Rousseau, M.Z., Thivierge, C., Nicholls, M., Ganapathy, G. and Lei, W., "Field Hygrothermal Performance of retrofitted Wood-Frame Wall Assemblies in Cold Climate", 13th Canadian Conference on Building Science and Technology - Winnipeg, Canada, 2011.
13. Saber, H. H. and Ganapathy, G., "Evaluation of Thermal and Moisture Response of Highly Insulated Wood-Frame Wall Assemblies — Phase 1; Part II: Numerical Modelling"; Report No. A1-000444.4; NRC-Construction, National Research Council of Canada, Ottawa, Canada; 12 January, 2016; 83 p.

14. Lacasse, M.A., Saber, H.H., Maref, W., Ganapathy, G., and Nicholls, M., 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 – Phase 1 and Phase 2, Report A1-000444.5, NRC-Construction, National Research Council of Canada, Ottawa, Canada; 8 January, 2016, 59 p.

15. ASTM Designation: C 1130-07, "Standard Practice for Calibrating Thin Heat Flux Transducers", Annual Book of ASTM Standards, sec 4, Construction, vol. 04.06, Thermal Insulation; Building & Environment Acoustic, pp. 577-584, 2009.

16. ASHRAE. 2009. 2009 ASHRAE Handbook –Fundamentals (SI), Chapter 26, Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc.

17. Saber, H.H., Maref, W. and Abdulghani, K., Properties and Position of Materials in the Building Envelope for Housing and Small Buildings, Report No. A1-004615.1, NRC-Construction, National Research Council of Canada, Ottawa, Canada, Dec., 31, 2014.

18. Saber, H.H., and Maref, W., "Risk of Condensation and Mould Growth in Wood-Frame Wall Systems with Different Exterior Insulations", BEST Building Enclosure Science & Technology Conference (BEST4), held in April 12-15, 2015, Kansas City, Missouri, USA, 19 p.

19. National Building Code of Canada (Section 9.25), Canadian Commission on Building and Fire Codes National Research Council of Canada, 2010.

20. Ojanen, T. and Kumaran, M.K., "Effect of exfiltration on the hygrothermal behaviour of a residential wall assembly: results from calculations and computer simulations", International Symposium On Moisture Problems In Building Walls, Porto - Portugal, 11 - 13 September, pp. 157, 1995.

21. ASHRAE 160-2009 Standard - Criteria for Moisture-Control Design Analysis in Buildings (ANSI/ASHRAE Approved), ASHRAE 2009, Atlanta, GA, 16 p.).

22. Glass, S.V., Hygrothermal Analysis of Wood-Frame Wall Assemblies in a Mixed-Humid Climate, United States Department of Agriculture, Forest Service, Forest Products Laboratory, Research Paper FPL–RP–675, pp. 1-25, April 2013.

23. Mukhopadhyaya, P., Kumaran, M.K., Lackey, J., Normandin, N., van Reenen, D., Tariku, F., "Hygrothermal Properties of Exterior Claddings, Sheathing Boards, Membranes and Insulation Materials for Building Envelope, Proceedings of Thermal Performance of the Exterior Envelopes of Whole Buildings X; 16 pgs., Clearwater, FL, December 2-7, 2007.

24. Kumaran, M.K., Lackey, J., Normandin, N., Tariku, F., van Reenen, D., A Thermal and Moisture Transport Property Database for Common Building and Insulating Materials; Final Report from ASHRAE Research Project 1018-RP, 229 pgs., 2004.

25. Hukka, A., and Viitanen, H.A., "A mathematical model of mould growth on wooden material, Wood Science and Technology", vol. 33 (6), pp 475-485, 1999.

26. Viitanen, H.A., and Ojanen, T., "Improved model to predict mould growth in building materials" Proceedings of Thermal Performance of the Exterior Envelopes of Whole Buildings X, 8 p., 2007.

27. Ojanen, T., Viitanen, H.A., Peuhkuri, R, Lähdesmäki, K., Vinha, J., and Salminen, K., "Mold Growth Modeling of Building Structures Using Sensitivity Classes of Materials", 11th International Conference on Thermal Performance of the Exterior Envelopes of Whole Buildings XI (Clearwater, (FL), USA, December-05-10), 10 p., 2010.