RISK ASSESSMENT OF WATER ACCUMULATION IN WALLS WITH EXTERIOR CONTINUOUS INSULATION

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ABSTRACT

Two critical aspects of sustainable construction are energy efficiency and durability. Energy efficiency of the building enclosure is achieved through minimizing thermal loads, thereby reducing building's energy consumption. Building enclosure durability is dependent on its ability to manage moisture which requires minimizing wetting sources and maximizing drying potential. Energy efficiency and durability are intertwined and interdependent. Recent changes in building energy codes include higher insulation R-values, continuous insulation, and continuous air barriers. The use of continuous exterior insulation changes traditional wall design and could impact the moisture management capabilities if incidental water intrusion occurs. Higher moisture sensitivity is due to lower drying rates, which are inherent to energy efficient assemblies, but could be further impacted by the type of exterior insulation material and the way it is added to the wall assemblies.

This paper investigates the relative risks of incidental water intrusion on the moisture management performance of wall assemblies with vapor impermeable and vapor permeable continuous insulation. Simulations were conducted for wood frame assemblies typical of new and retrofit residential construction across Canadian climate zones. The moisture intrusion was simulated by assuming a "driving rain defect", in which a fixed portion of the rain hitting the wall penetrates within the wall assembly. The performance of the wall systems was assessed by estimating the total moisture content of the wall, the moisture content of the OSB exterior sheathing and the relative humidity at the OSB/stud cavity insulation interface. Significant differences were found between wall assemblies with vapor permeable and vapor impermeable exterior insulation, as well as between different climates. The walls with vapor permeable continuous insulation have lower moisture risks when compared to the walls with vapor impermeable continuous insulation, for all climates investigated. All wall assemblies investigated dry significantly slower in marine climates than in humid cold climates.

INTRODUCTION

The most common measure for increasing the building envelope thermal performance is increasing the insulation R-value. For framed wall construction, this is achieved through both increasing the R-value of insulation within the stud cavity, and adding continuous insulation outboard of stud cavity. Continuous insulation is increasingly being required by energy codes. Such energy efficiency measures lead to changes in frame wall design, from the "traditional" wall with insulation within the stud cavity to the "hybrid" wall with insulation within the stud cavity as well as continuous exterior insulation. Hybrid wall design (with R_1 insulation within the stud cavity and R_2 exterior insulation) is becoming the most common design for

frame wall construction which meets energy code requirements, Figure 1. However, the type of exterior insulation and the way it is added to the wall could have unintended consequences on moisture performance.

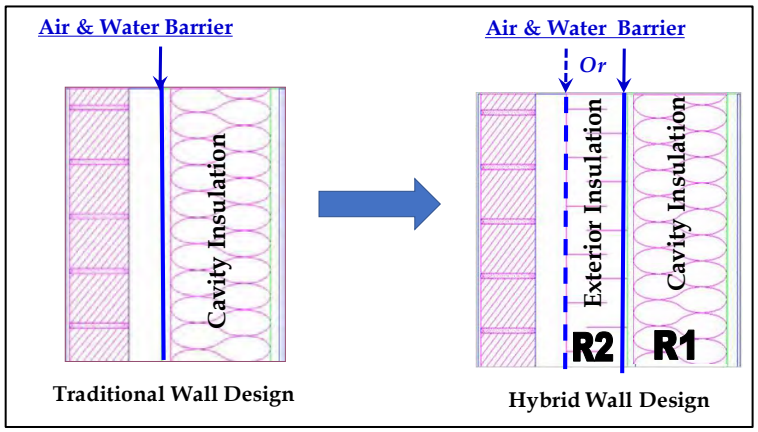

Figure 1: Changes from traditional to hybrid wall design driven by energy code requirements

The term "moisture performance" is defined as the ability of the wall system to balance moisture loads: minimize wetting sources (rain penetration, air transported moisture and vapor diffusion) and maximize drying rates (drainage, ventilation and vapor diffusion). A comprehensive building envelope quality assurance program could assist with minimizing the wetting sources by ensuring that critical cavity wall elements are effectively installed and free of defects. The other side of the moisture management balance, the wall assembly's drying ability is essential for dealing with incidental water intrusion. The drying ability is largely controlled by the design options and materials choices. Walls with continuous exterior insulation represent a special challenge for moisture management, for two reasons.

Firstly, the type of continuous insulation could significantly affect *diffusion drying* which can only take place through vapor permeable materials. As a reminder, based on vapor permeability the International Building Code (IBC) classifies the building materials into vapor permeable and vapor retarders [ICC, 2015]:

1) Vapor Permeable materials have a vapor permeance >5 perms: the higher the perms, the higher the vapor permeance for given conditions
2) Vapor Retarders have a vapor permeance < 10 Perms and are further classified into 3 classes:

    a. Class I: 0.1 Perm or less

    b. Class II: 0.1 < Perm ≤ 1.0 perm

    c. Class III: 1.0 < Perm ≤10 perm

When choosing an exterior insulation material, the main selection criteria is the R-value such as to meet the energy codes. The vapor permeance of exterior insulation materials, while critically important, is rarely considered even though a vapor impermeable exterior insulation is an unintended vapor retarder which could interfere with diffusion drying. Table 1 lists the insulation R-value and vapor permeance for

common exterior insulation materials and it shows that except for mineral wool, most common exterior insulation materials are vapor retarders: Spray Polyurethane Foam, Closed Cell (SPF, 1.9 Perm-inch) and Expanded Polystyrene (EPS, 2.7 Perm-inch) are vapor retarders Class III; Polyisocyanurate (0.75 Perm-inch) and Extruded Polystyrene (XPS, 0.8 Perm-inch) are vapor retarders Class II. The type of exterior insulation material is especially important for cold climates (climate zones 5 and above) where an interior vapor retarder is also required by code. The use of a vapor impermeable exterior insulation in such climates will place a second vapor retarder at the exterior side of the wall preventing moisture to escape to either inside or outside and potentially trapping it within the wall cavity.

Table 1: Common Continuous Insulation Materials

Insulation Product	**R-value/inch**	**Water Vapor Permeance, Perm-inch**
Mineral Wool Fiber Board	4	54
Spray Polyurethane Foam (SPF), Closed Cell	6	1.9
Polyisocyanurate	6	0.75
EPS (Expanded Polystyrene)	4	2.7
XPS (Extruded Polystyrene)	5	0.8

The risks of condensation in walls with exterior vapor retarders have been recognized by the design community: with insufficient continuous insulation outboard of exterior sheathing, the dew point temperature can occur inside the stud cavity leading to condensation and risk of materials degradation, mold growth and potential indoor air quality issues. The common way of addressing this concern is through design measures to keep the dew point temperature outboard of exterior sheathing. The National Building Code of Canada provides guideline on the minimum R_2/R_1 ratio *e.g.,* Outboard Thermal Resistance (R_2) to Inboard Thermal Resistance (R_1), as shown in Table 2, to prevent dew point occurrence within the stud cavity.

Table 2: R_2/R_1 Ratio in wall assemblies - 2015 NBC (National Building Code of Canada)

Heating Degree-Days (Celsius degree-days)	**Minimum R2/R1 Ratio: Total Thermal Resistance Outboard of Material's Inner Surface to Total Thermal Resistance Inboard of Material's Inner Surface**
up to 4,999	**0.20**
5,000 to 5,999	**0.30**
6,000 to 6,999	**0.35**
7,000 to 7,999	**0.40**
8,000 to 8,999	**0.50**
9,000 to 9,999	**0.55**
10,000 to 10,999	**0.60**
11,000 to 11,999	**0.65**
12,000 or higher	**0.75**

Source: Table 9.25.5.2., Ratio of Outboard to Inboard Thermal Resistance

However, dew point criteria provide an incomplete picture of the moisture management abilities of a wall assembly and could lead to a false sense of security. Dew point analysis only addresses the risk of condensation due to water vapor diffusion but provides no information on the wall's drying ability or the ability of managing incidental water intrusion (*e.g.* rain penetration, air transported moisture).

The *second* reason that exterior insulation could impact the moisture management abilities of the wall assembly is because depending on the insulation material and the way the continuous insulation is added to the wall it could interfere with drying mechanisms available. In order to dry out the moisture must diffuse from the interior cavity into adjacent spaces and then escape to the outside (since in cold climates drying to the inside is not possible due to interior vapor retarder required by code). Moisture can diffuse out from the wall cavity through vapor permeable WRB, but further diffusion is prevented by the vapor impermeable exterior insulation. In order to assist with drying in these systems, *drainage* and *venting* are essential. When exterior insulation is pressed against the WRB layer, neither drainage nor venting are available. Research shows that wall cavity ventilation is beneficial for wall structures, allowing them to dry out from incidental moisture intrusion into the wall cavity [Straube and Finch, 2009, Salonvaara et. al., 2007, Arena et. al., 2013]. However, ventilation behind cladding is ineffective in assisting diffusion drying in wall assemblies with vapor impermeable exterior insulation: even if the moisture diffuses out through the vapor permeable WRB, it cannot diffuse further through vapor impermeable insulation to reach the vented cavity behind cladding. Under these conditions the moisture can accumulate at the WRB/ci interface and suppress the driving force for diffusion drying of the wall cavity (Figure 2A). This would not be a problem in systems with vapor permeable exterior insulation where drying could continue through the insulation layer.

When exterior insulation is vapor impermeable, design details for drainage and venting behind the insulation board are essential for managing incidental water intrusion. Ventilation (bottom and top vents) was found to be more effective than venting (bottom vents only). The effective ventilation rate behind the cladding depends on both the wall system and the exterior climate. High winds and high temperature gradients result in higher flow rates. Design details for walls with vapor impermeable exterior insulation should include an airspace with venting/ventilation behind the continuous insulation board (Figure 2B). Drying of an air space involves the evaporation or desorption of moisture from materials adjacent to the airspace (e.g. diffusion of cavity moisture through exterior sheathing and vapor permeable WRB) followed by convective transport of moisture to the exterior environment. Ventilation within a wall system therefore has the potential to assist drying of incidental moisture intrusion in the wall cavity. The airspace behind continuous insulation can be created using WRBs with drainage channels, furring/ drainage lath spacer or preformed channels into the interior face of insulation board to provide water drainage and venting.

This paper provides examples of how advanced hygrothermal simulation models could estimate potential moisture risks of wall assemblies and assist in selecting the most robust design options to ensure that the improved energy efficiency does not come at the expense of durability of the building enclosure.

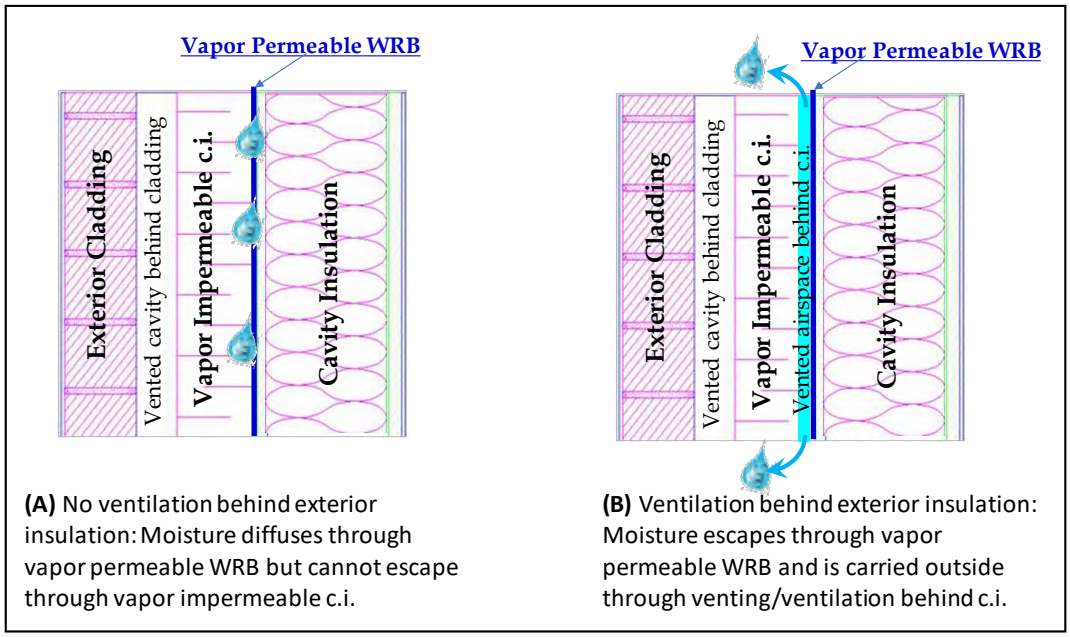

Figure 2: Schematic drying comparison for hybrid wall assemblies with and without venting behind vapor impermeable exterior insulation

SIMULATION PARAMETERS

WUFI simulations have been increasingly used to assess the moisture management abilities of wall assemblies, following changes in building energy codes [Straube and Smegal, 2009, Arena and Mantha, 2013, Straube and Schumacher, 2006, Weston, 2014]. The goal of current analysis was to assess the relative resilience to incidental water intrusion of different wall assemblies. WUFI® simulations (Wärme und Feuchte Instationär, or Transient Heat and Moisture Analysis) were performed for code compliant wall assemblies with different design features. The effect of two design parameters on the drying rates were investigated: (1) the vapor permeance of the exterior insulation (vapor permeable *vs.* vapor impermeable continuous insulation); (2) Venting behind vapor impermeable exterior insulation (vented *vs.* not vented).

1) Wall assemblies with two different types of exterior insulation were compared: a low vapor permeance XPS insulation (0.8 Perm-inch, Class II Vapor Retarder) and a high vapor permeance fibrous exterior insulation relatively new to the market (TWR-5, >50 Perm-inch) [Smegal, et.al, 2016].
2) To simulate venting behind vapor non-permeable XPS insulation in WUFI, a constant air change source of 10 air changes per hour (ACH) was assumed in a 5mm air cavity created by a WRB with drainable channels (DWCA). The value of 10ACH was assumed and it was chosen based on results from ASHRAE research report 1091 [ASHRAE], which states that the equivalent permeance of the wall assembly is drastically increased once the minimum threshold of 10 ACH is reached. This value is also seen as a conservative estimate based on research conducted by Straube and Finch (2009) which concluded that ventilation rates in a 0.75-in. vented cavity can range from 12 ACH to 100 ACH depending on vent size and location, solar exposure, wind direction and speed, and temperature gradients.

Three climate zones (5C, 6A and 7A) and six locations in Canada were investigated:

1) Calgary, Alberta - CZ 7A;
2) Montreal, Quebec - CZ 6A;
3) Saint John, New Brunswick - CZ 6A;
4) Toronto, Ontario - CZ 6A;
5) Vancouver, British Colombia - CZ 5C;
6) Winnipeg, Manitoba - CZ 7A.

For each city, a new construction (NC) and a reside construction (RC) were simulated. Three-year simulation period was used for all cases in order to identify the trends in moisture accumulation and drying rates of different wall assemblies. The typical wall assembly design, for all 3 climates investigated is shown in Figures 3-6.

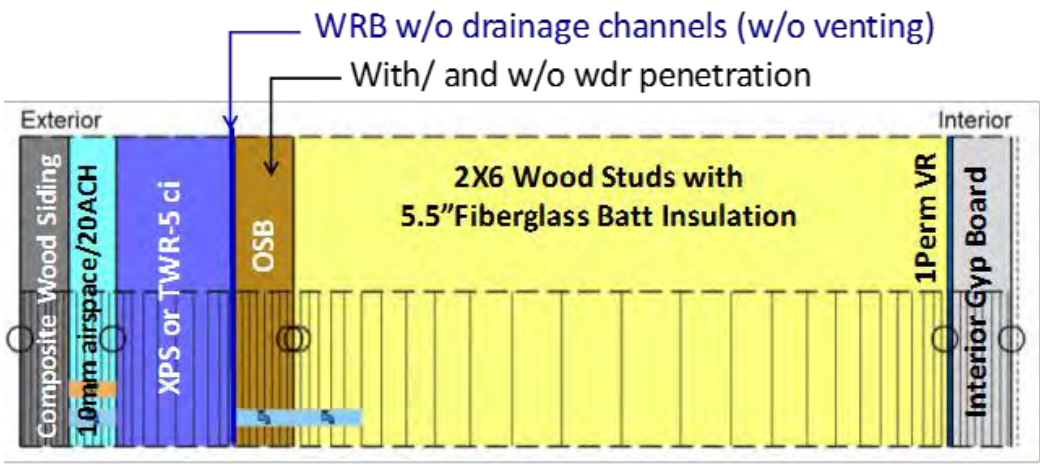

Figure 3: New Construction (NC) wall design without air space behind exterior insulation/No venting

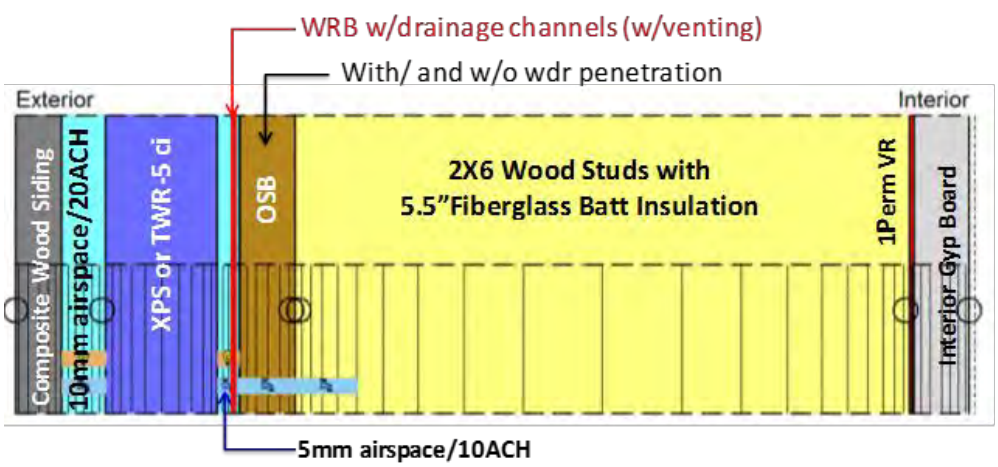

Figure 4: New Construction (NC) wall design, with airspace (5mm) and venting (10ACH) behind XPS exterior insulation

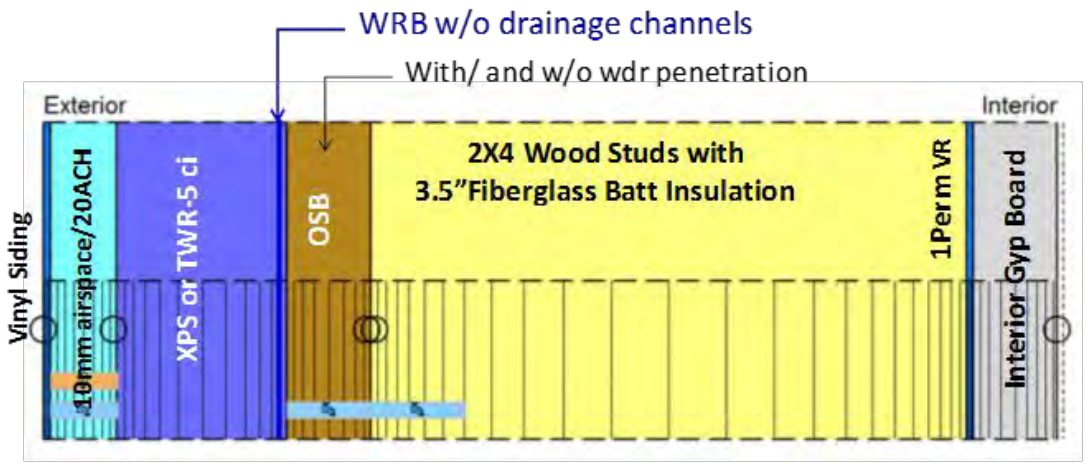

Figure 5: Re-side Construction (RC) wall design without air space behind exterior insulation

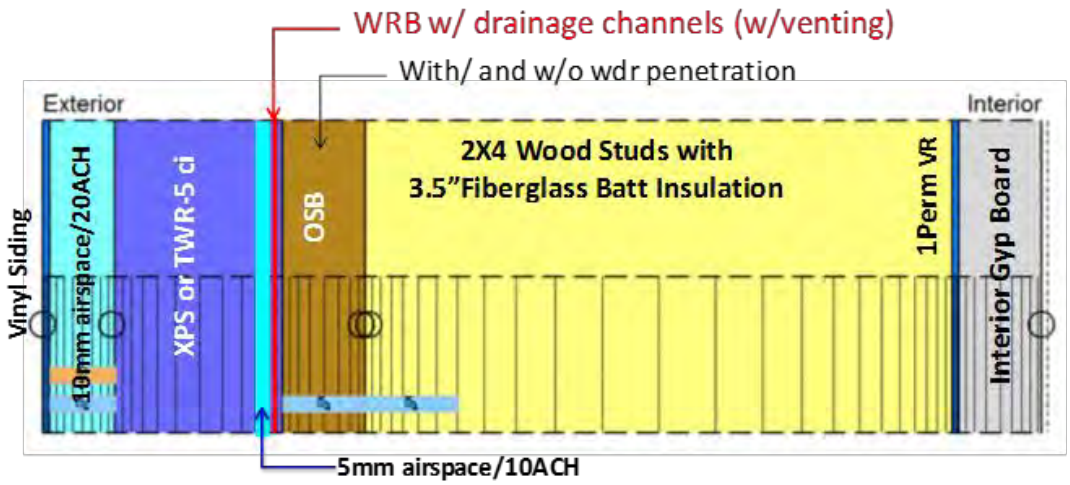

Figure 6: Re-side Construction (RC) wall design with air space (5mm) and venting (10ACH) behind XPS exterior insulation

For each city / construction combination five cases were simulated[1]:

1. Vapor permeable exterior insulation (TWR-5), NO water source (labeled ND = NO DEFECT)
2. Vapor permeable exterior insulation (TWR-5), 0.5% wdr penetration
3. Vapor impermeable exterior insulation (XPS), NO water penetration (labeled ND = NO DEFECT)
4. Vapor impermeable exterior insulation (XPS), 0.5% wdr penetration, No Venting (WRB w/o drainage channels)
5. Vapor impermeable exterior insulation (XPS), 0.5 % wdr penetration, Venting (WRB with

[1] 0.5 % wdr (wind driven rain) penetration assumes 0.5 % of wind driven rain hitting the wall as water source; Water Resistive Barrier (WRB) w/drainage channels assumes a 5mm airspace behind XPS board insulation which when coupled with design details could provide venting assisted drying following wdr penetration. The WRB with drainage channels were considered only for XPS walls because of the low vapor permeance of XPS insulation which significantly limits the diffusion drying capabilities of this assembly.

drainage channels)

WUFI SIMULATIONS RESULTS AND DISCUSSION

Three simulation output parameters were analyzed for all assemblies: Total moisture content in the wall assembly, OSB moisture content and %Relative Humidity at the OSB /cavity insulation interface. The impact of vapor permeability of exterior insulation (XPS *vs.* TWR-5) as well as venting behind XPS insulation (vented *vs*. not vented) was estimated for all climates/locations. Climate zones 6A and 7A show similar trends in water accumulation and drying rates so only the results for climate zone 7A are presented. The graphs for marine climate zone 5C show similar trends as climates 6A/7A but the drying rates are significantly different.

Total Moisture Content in the Wall Assembly

The total moisture content in the XPS and TWR-5 new construction (NC) walls, with and without wind driven rain penetration is shown in Figures 7 and 8, for climate zone 7A and 5C, respectively.

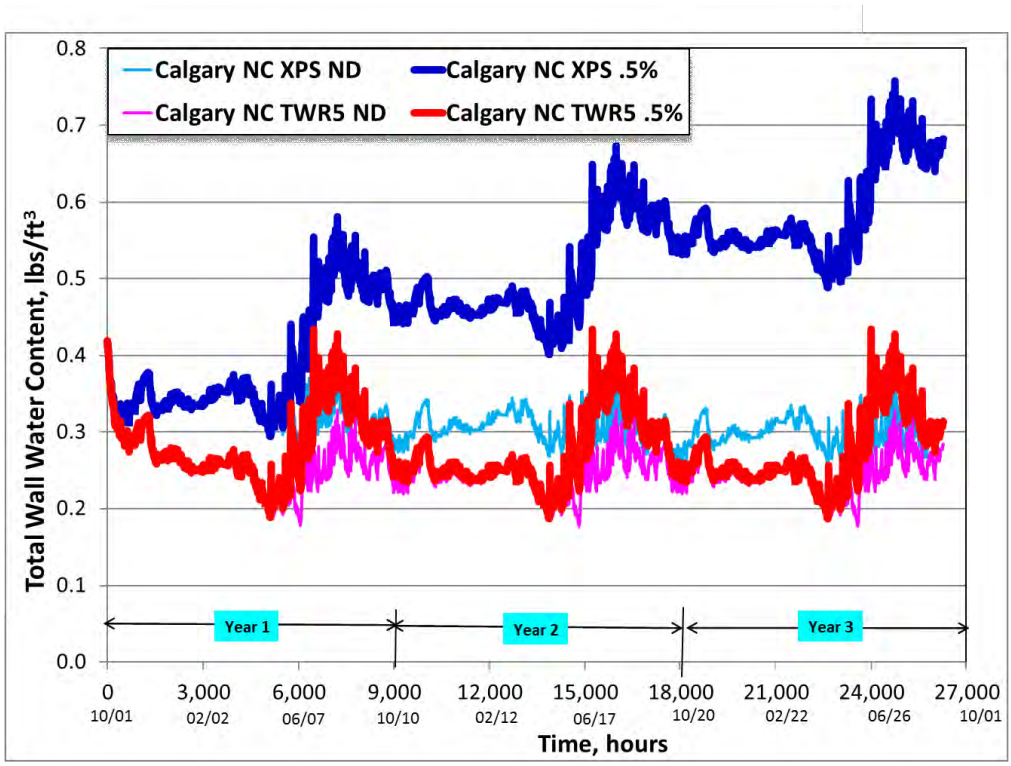

Figure 7: Total moisture content in NC wall assemblies in climate zone 7A (Calgary, Alberta)

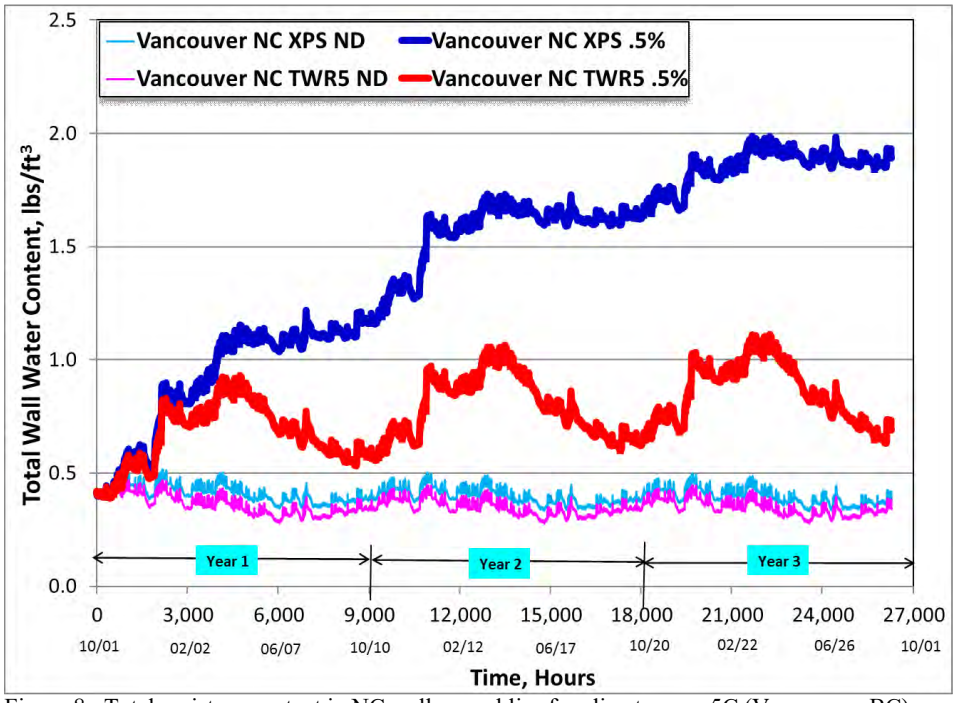

Figure 8: Total moisture content in NC wall assemblies for climate zone 5C (Vancouver, BC)

In the absence of water penetration (ND, NO Defects) when the only moisture transport is through water vapor diffusion, the total water content of both XPS and TWR-5 walls are very low (light lines) for both climate zones (7A and 5C). When wdr (wind driven rain) penetrations occur, the total amount of water is higher for both insulation types and both climates. However, the XPS walls show much higher water content than the TWR-5 walls throughout the simulation period, for both climates: the vapor permeable TWR-5 insulation allows faster drying when compared to the XPS walls. In addition, the water content of XPS walls shows an upward trend, increasing year over year, indicating potential for significant water accumulation and risk of moisture damage.

There is a significant difference between the two climates. The total moisture content for both NC wall assemblies for the climate zone 5C is higher than for the similar wall in climate zone 7A (note that the two charts are plotted on a different y-scale): the walls in climate zone 5C dry much slower following incidental rain penetration making the wall assembly much more vulnerable to moisture damage. The main reason for slow drying rates in marine climates is the low vapor pressure difference across the building envelope in these climates, as explained later.

OSB Moisture Content

The moisture content in the OSB exterior sheathing of XPS and TWR-5 NC walls is shown in Figures 9 and 10 for climate zone 7A and 5C, respectively. The potential impact of venting behind XPS insulation is also shown on these graphs (indicated as XPS/Vent).

In the absence of wdr penetration (ND), when the only moisture source in the OSB sheathing is from water vapor diffusion, the moisture content of both XPS and TWR-5 walls is very low (close to the OSB equilibrium moisture content), for both climates and throughout the 3-year simulation period.

When wdr penetrations occur, the NC wall assemblies with vapor permeable insulation (TWR-5) dry much faster than the XPS walls, in both climates. In addition, the wall assemblies with XPS vapor impermeable insulation show an upward trend with increasing moisture content year over year, for both climates, indicating potential for significant water accumulation and risk of moisture damage. The OSB moisture content increases year over year because the wall assemblies are unable to dry fast enough through low vapor permeance XPS, following wdr penetration events. However, if airspace with venting option behind XPS insulation is available, the OSB can dry in both climates, though at different rates. For both climates, the drying rates are fastest for the TWR-5 walls, followed by XPS-Vented walls, while the XPS- Unvented walls dry the slowest.

TWR-5 > XPS/Vented >> XPS/Not Vented

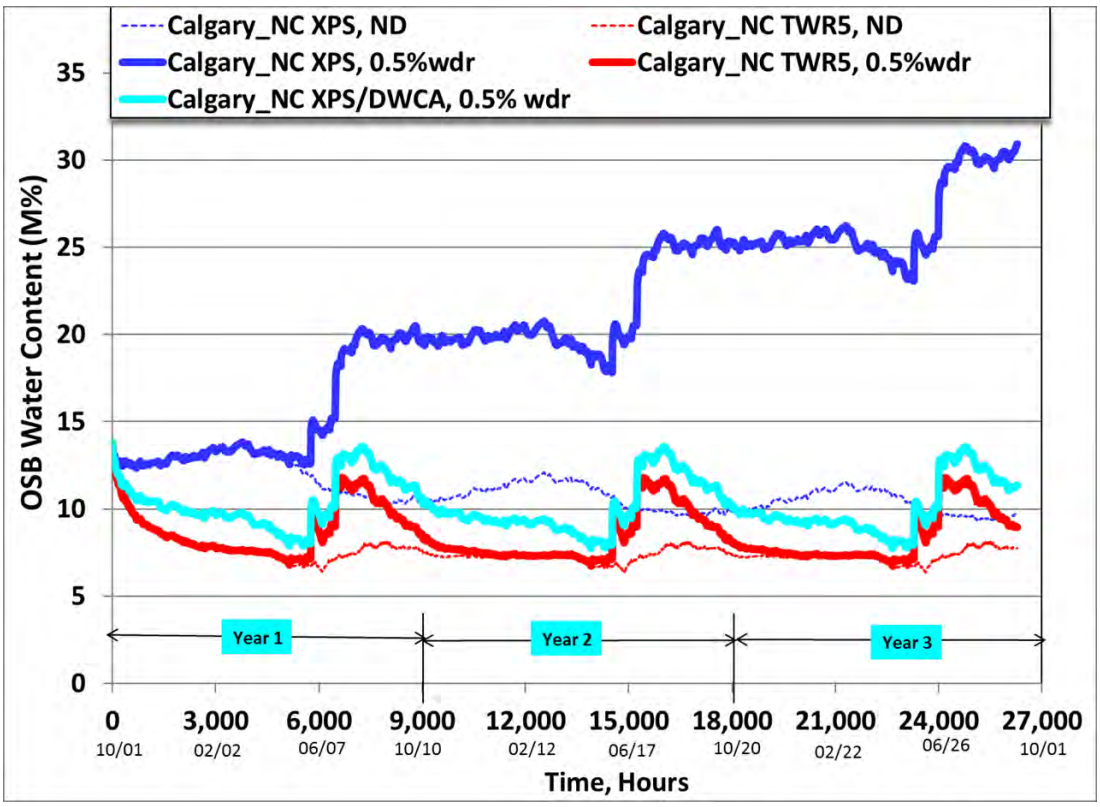

Figure 9: OSB moisture contend in the NC wall assemblies, climate zone 7A (Calgary, Alberta).

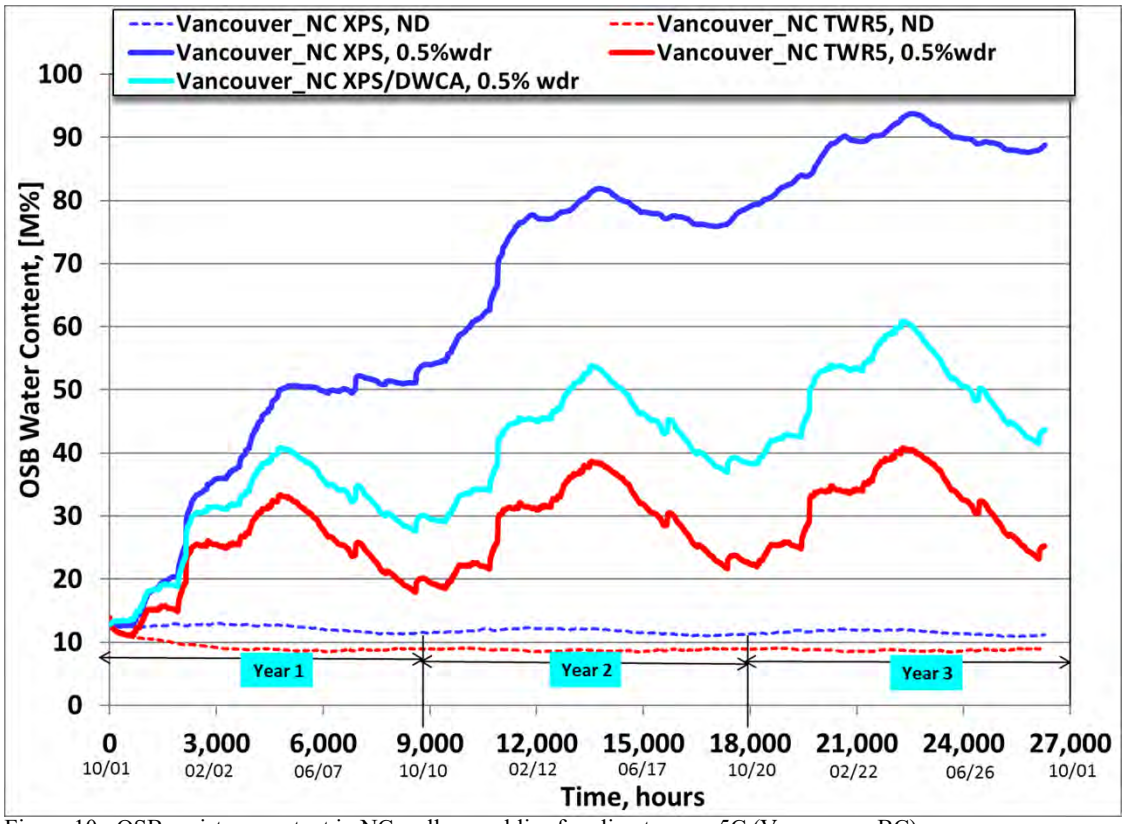

Figure 10: OSB moisture content in NC wall assemblies for climate zone 5C (Vancouver, BC)

The vapor permeance of WRB is very critical for drying – it allows moisture to escape from the wet OSB sheathing, but without venting the moisture cannot diffuse further through the vapor impermeable XPS. Both features, vapor permeable WRB and venting behind the XPS insulation are critical to allow drying of these wall assemblies. The airspace behind XPS insulation can be achieved through different means, *e.g.* WRB with drainage channels, furring, spacers, XPS with corrugated channels on the back.

There is a significant difference between the drying rates in the 2 climates: the OSB moisture content for every wall in marine climate 5C (Vancouver) is significantly higher when compared to the same wall under the same conditions in climate zone 7A (Calgary). Note the different y-axis scale in Figures 9 and 10 for climate zone 7A and 5C, respectively. The difference in the drying rates between the 2 climates is more evident in Figure 11 where the moisture content for both climates are plotted on the same chart: the thinner 3 lines at the bottom are for Calgary; the thicker 3 lines on top are for Vancouver.

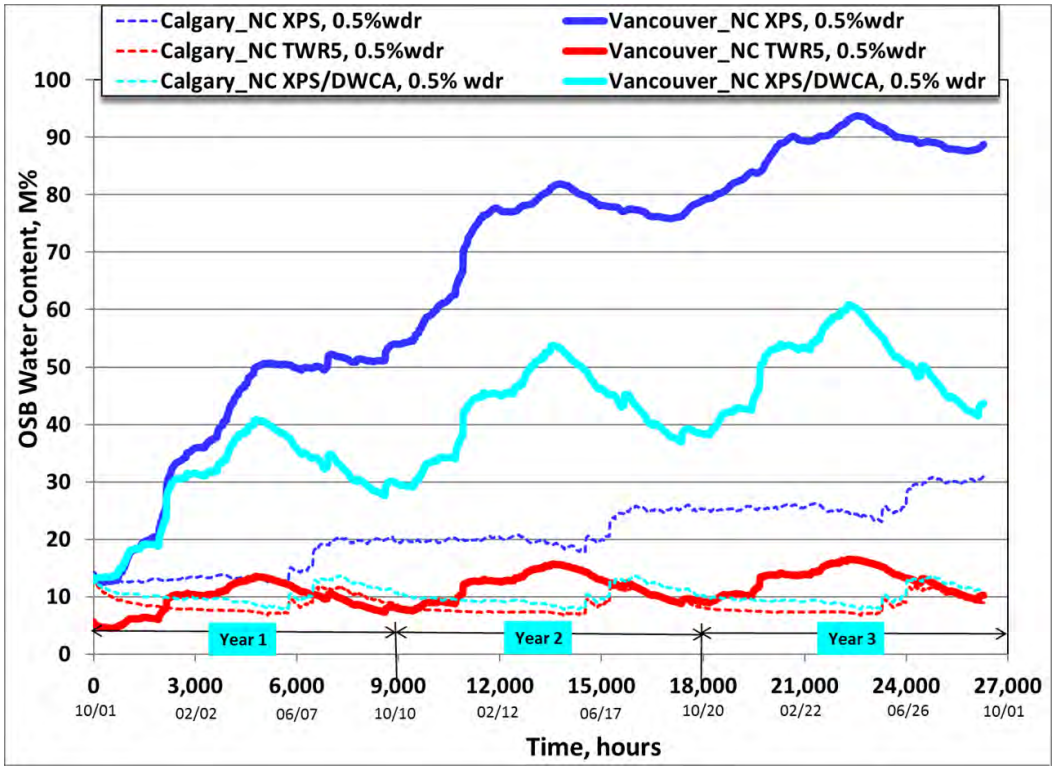

Figure 11: Drying rates comparison between 2 climates: OSB moisture content in NC wall assemblies for climate zone 5C (Vancouver, BC) and 7A (Calgary, Alberta)

Similar graphs for OSB moisture content for the reside construction walls (RC) are plotted in Figures 12 and 13 for climate zones 7A and 5C, respectively. The trends in the OSB drying rates for the reside construction (RC) are similar to those in the new construction walls, and are in the following order:

TWR-5 > XPS/Vented >> XPS/Not Vented

There is also a significant difference in the drying rates of the RC walls between the 2 climates: the OSB moisture content for every RC wall in marine climate 5C is significantly higher when compared to the same wall in climate zone 7A. The difference between the 2 climates is more evident in Figure 14 where the moisture content of RC walls for both climates are plotted on the same chart: the 3 thinner lines at the bottom are for Calgary; the 3 thicker lines on top are for Vancouver.

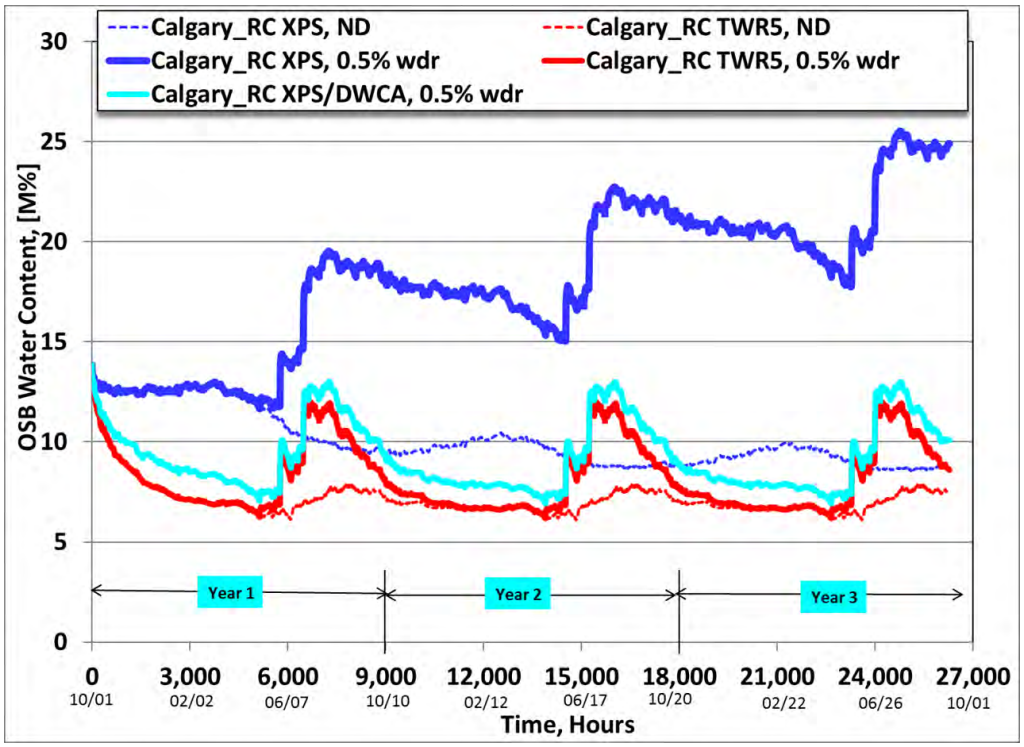

Figure 12: OSB moisture content in the RC wall assemblies for climate zone 7A (Calgary, Alberta)

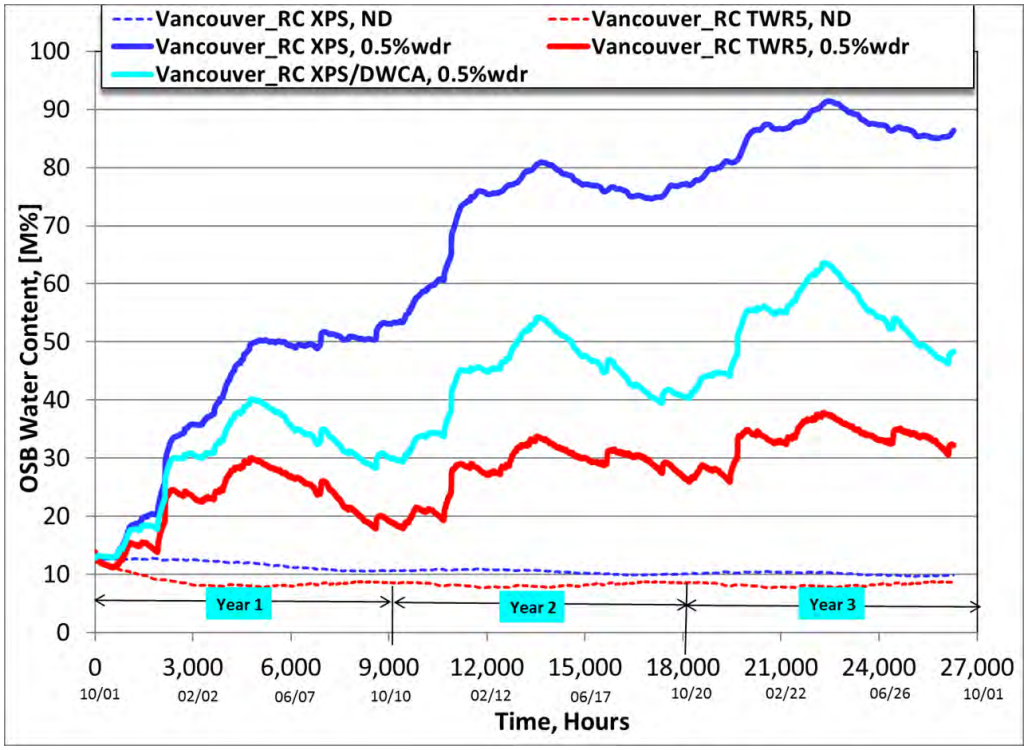

Figure 13: OSB moisture content in the RC wall assemblies for climate zone 5C (Vancouver, BC)

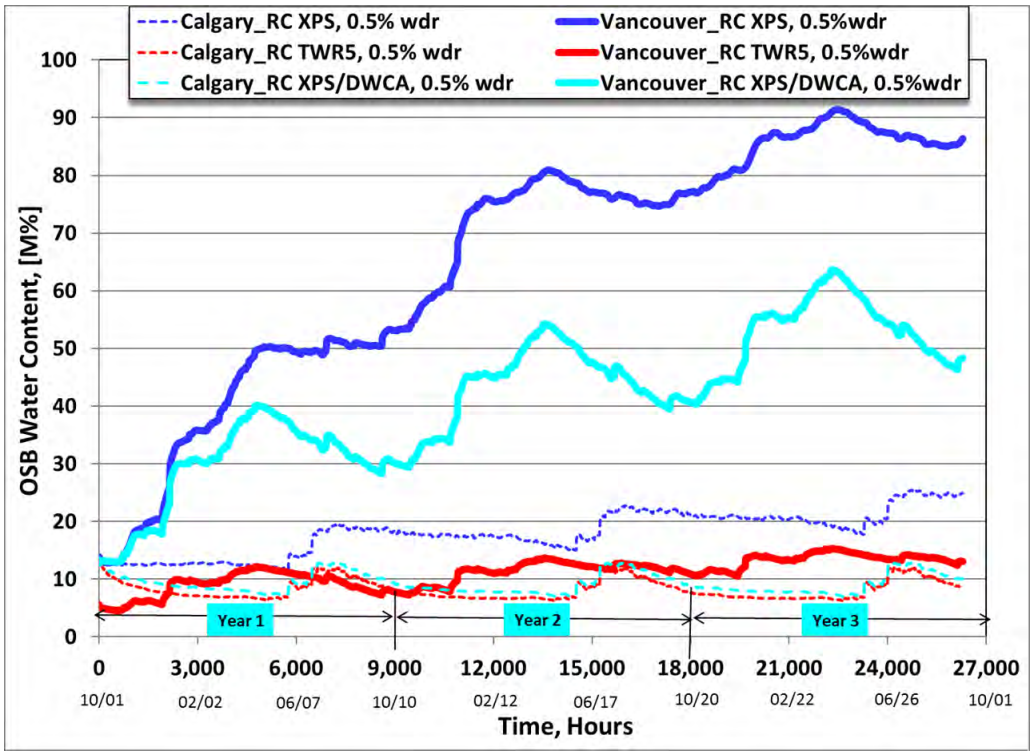

Figure 14: Drying rates comparison between 2 climates for the RC wall assemblies: OSB moisture content for climate zone 5C (Vancouver, BC) and 7A (Calgary, Alberta)

The marine climates have inherently low drying rates which makes the walls less tolerant to condensation and moisture intrusion. Vapor diffusion and venting are the main drying mechanisms for moisture to escape from the wall cavity. Vapor diffusion (g_v) is a linear function of vapor pressure difference (Δp) and the vapor permeance of building enclosure layers (δ_p):

$$g_v = -\delta_p \nabla p$$

Vapor permeance, a material property is a design choice: the more permeable the materials, the higher the diffusion drying rates for given climate conditions. However, the vapor pressure difference, which is the difference between the interior vapor pressure (design parameter/use conditions) and the exterior vapor pressure (climate dependent) cannot be controlled. The vapor pressure difference is inherently low in marine climates, which is the main reason for the inherently low drying rates in these climates. Figure 15 compares the hourly vapor pressure difference in climate zone 5C versus climate zone 7A: the vapor pressure difference in climate zone 7A is almost twice that of marine climate 5C at any given time of the year.

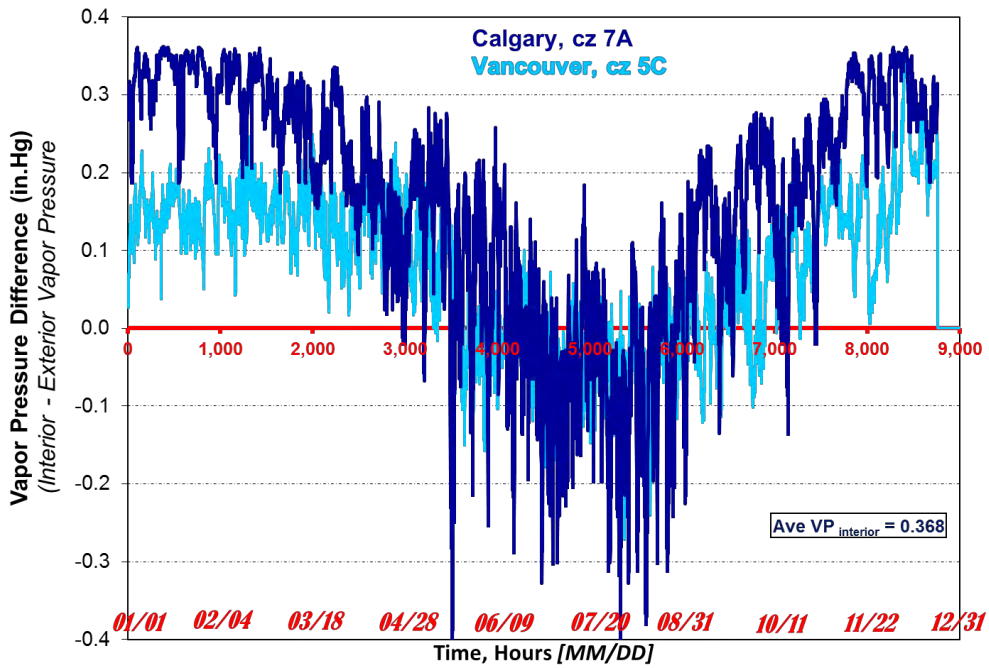

Figure 15: Average Vapor Pressure difference comparison between climate zones 7A and 5C

% Relative Humidity at the OSB /Cavity Insulation Interface

The % Relative Humidity at the OSB-cavity insulation interface for Calgary (cz 7A) and Vancouver (cz 5C) are shown in Figures 16 and 17, respectively.

In the absence of rain penetration (ND cases – No Defects), the RH is at or below 80% throughout the year, for both XPS and TWR-5 walls and for both climates. The RH is always lower for the TWR-5 walls (approx.70%) than for XPS walls (approx. 80%).

When repeated rain penetrations occur the RH at this interface increases for both walls and both climates. However, the RH is always lower for the TWR-5 wall than for the XPS wall for both climates. There is a significant difference between the 2 climates. In climate zone 7A, RH is above 90% for the XPS wall and about 80% for the TWR-5 wall for most of the 3-year simulation period. In climate zone 5C the RH is higher than for climate zone 7A, for both walls. The XPS wall reaches saturation and stays at 100% RH for most of the 3-year simulation period. The TWR-5 wall does not reach saturation, but the RH stays above 90% for most of the 3-year simulation period, when repeated rain penetrations occur. As discussed above, climate zone 5C (marine climate) is much less forgiving and the walls are more susceptible to moisture accumulation, even for walls with vapor permeable exterior insulation. The reason for increased susceptibility is the low drying rates for this climate. Because of lower drying rates in marine climates it is even more critical to avoid installation defects (to limit rain penetration) as well as provide design features which could assist with drying – such as vapor permeable materials in both directions, draining and ventilation behind exterior insulation.

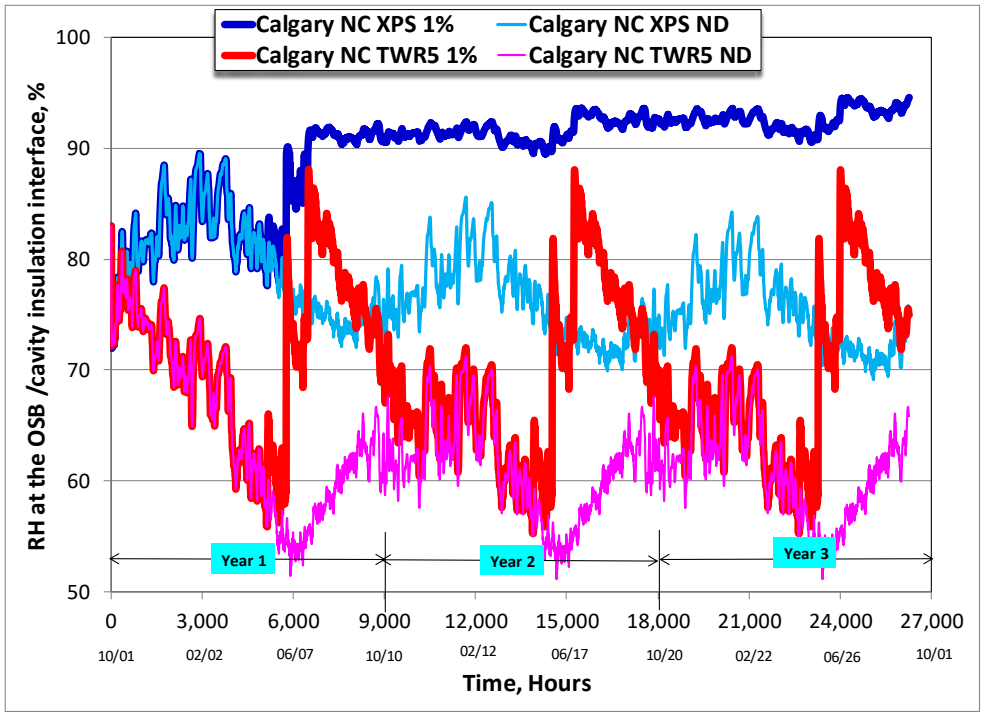

Figure 17: %RH at the OSB/cavity insulation interface for NC wall assemblies in climate zone 7A (Calgary, Alberta)

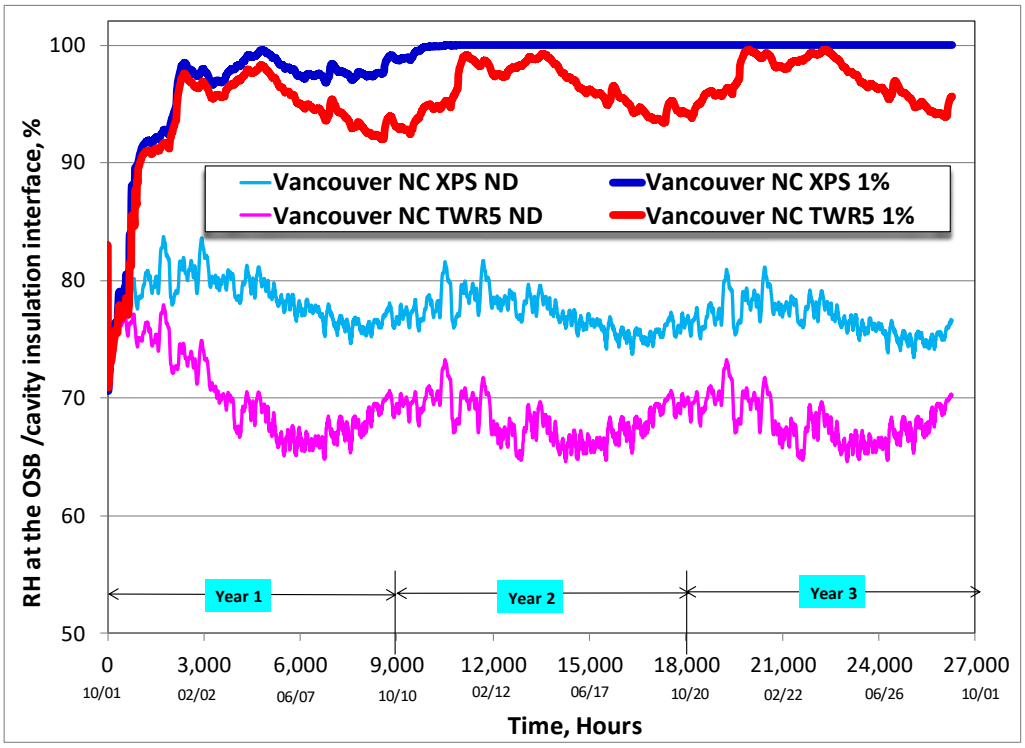

Figure 16: %RH at the OSB/cavity insulation interface for NC wall assemblies in climate zone 5C (Vancouver, BC)

CONCLUSIONS

The demand for energy efficient building envelopes has increased as a result of global need for reduced

energy use and lower carbon emissions. The use of continuous exterior insulation in frame construction is a key strategy to improving thermal performance and achieving an energy efficient building envelope. However, the type of exterior insulation and the way it is added to the wall assembly could often result in reduced moisture management capabilities if incidental water intrusion occurs. Many designers are often unaware of moisture and durability implications of the wall assemblies with exterior insulation. Materials choices and design detailing could prevent or minimize potential moisture problems so that energy efficiency does not come at the expense of durability. Advanced moisture analysis simulations such as WUFI® could be used to compare different design options and materials choices and to assist with design decisions.

The examples discussed in these paper show that wall assemblies with TW-R5 vapor permeable exterior insulation consistently show a higher ability to manage incidental water intrusion when compared to wall assemblies with vapor impermeable XPS exterior insulation: less water accumulation and faster drying rates are consistently observed for TWR5 walls when compared to equivalent XPS walls, for both climates, both new or reside construction. The walls with XPS exterior insulation dry significantly slower because the vapor impermeable insulation does not allow diffusion drying to the outside. An air cavity and venting behind the vapor impermeable XPS exterior insulation board are essential for drying.

A significant difference is observed between the two climates being compared in this analysis: the drying rates in marine climate 5C are significantly lower than those in climate zone 7A, for all walls. For this reason, climate zone 5C (marine climate) is much less forgiving and the walls are more susceptible to moisture accumulation, even if vapor permeable exterior insulation is used. The main reason for the slow drying rates in marine climates is the low diffusion driving force (low vapor pressure difference across the building enclosure which is inherent for marine climates). Because of higher moisture susceptibility in marine climates it is even more critical to avoid installation defects (avoid moisture intrusion) as well as provide every design feature which could assist with drying, such as vapor permeable materials in both directions, draining and ventilation behind vapor impermeable exterior insulation.

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