A Hygrothermal Comparative Analysis of Split-Insulated, High-RSI Wall Assemblies in Three Canadian Climates

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Abstract

As consciousness grows regarding the negative impacts most buildings have on the Earth's environment, techniques to mitigate this impact must emerge in mainstream design practices. A calibrated hygrothermal simulation was conducted using WUFI® Pro to assess predicted hygrothermal performance of a variety of wall assemblies that are likely to enter into mainstream design practices. The results of these simulations reveal the importance of designing assemblies that are resilient to field conditions that introduce more severe hygrothermal loads than standard vapour diffusion. It is clear that in order for a wall assembly to perform adequately under moisture ingress conditions, it must be able to dry freely to at least one side of the building enclosure. High-RSI assemblies with exterior XPS exhibited far diminished resiliency to driving rain penetration as compared to those without exterior insulation and those with exterior mineral wool.

Acknowledgements

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1.0 Introduction

In recent years, understanding of the significant contribution of buildings in greenhouse gas emissions has grown in Canada. In response, building codes have progressed greatly, and advanced performance standards have entered the mainstream. At the scale of the single-family home, designers have gravitated towards more highly insulated, thicker wall assemblies than those that have traditionally been constructed, in efforts to reduce the energy required for mechanical heating and cooling.

Attention to *effective* RSI, which describes the actual thermal resistance of the wall assembly as opposed to simply the resistance of the installed insulation, and reduction of thermal bridging has been shown to reduce energy use intensity substantially in a typical Canadian home (Stiffman and Fung, 2014; Suresh et al, 2011). This a very promising design strategy for designers in challenging climates, especially where space is limited and wall thickness becomes a critical factor. But while high RSI wall assemblies are known to be extremely effective at reducing heating and cooling energy consumption, variations on building envelope designs (i.e. component choice and placement) affect moisture management in both positive and negative ways. At the single-family residential scale particularly, some high RSI assemblies have an observed tendency to experience interstitial condensation, which can lead to mould and other failure mechanisms. As Canadian building codes shift towards legislating higher effective RSI values, new envelope strategies will inevitably surface in order to fulfill these requirements. It is important to understand the hygrothermal performance of assemblies designed to increase overall thermal performance of the building envelope.

This research used calibrated simulation to examine the hygrothermal implications of high RSI design strategies that are being used with increased frequently in order to meet more stringent thermal performance requirements published in Canadian building codes. In order to test the abilities of the hygrothermal analysis procedure, attention will be paid to three different climates, using Vancouver, Toronto and Edmonton as case studies in order to develop a climate-sensitive risk assessment matrix with relevance in three of Canada's most important economic sectors.

1.1 Objectives

This objectives of this research are:

- Use hygrothermal simulation to assess durability risks associated with high RSI wall assemblies employing different insulation-split allocations (% exterior vs % interior of sheathing plane) and insulating materials, in two different Canadian climates.
- Develop climate-sensitive design recommendations that reflect the relative moisture risks of selected high-RSI assemblies that are useful to designers, builders, and legislators across Canada.

1.2 Research Questions

To achieve the objectives, the following research questions will be answered:

1. What is the impact of split insulation on the hygrothermal performance of high RSI, wood framed wall assemblies in Toronto, Vancouver, and Edmonton?
2. What are the effects of air leakage and driving rain penetration on the hygrothermal performance of each of the investigated assemblies?
3. How sensitive is this performance to the configuration (% exterior RSI vs % interior RSI) and material properties of different insulating materials?

1.3 Background

The debate around hygrothermal performance of high RSI assemblies is complicated by building codes that do not always support or address hygrothermal best practices different enclosure design strategies. For instance, despite expert suggestions (Hutcheon and Handegord, 1995) that 38mm x 89 mm (2x4) walls with insulating sheathing (or 'split' insulated walls) tend to be hygrothermally superior to 38mm x 140mm (2x6) walls without exterior insulation (or 'interior' insulated walls), and better still are walls with entirely exterior insulation (or 'exterior' insulated walls), a continuous layer of rigid foam insulation outboard of the building's sheathing often requires an architectural or engineer's approval in order to gain acceptance by local municipal building departments (Lstiburek et al, 2014). This requirement is created by building code guidelines for the amount of insulation that is required to be outboard of the building sheathing, as a function of heating degree days (OBC, 2012). However, many experts have vigorously challenged the legitimacy of this legislation, and have called for closer consideration of the issue (Karagiozis et al, 2014).

While the analyses necessary to optimize the effective thermal performance of high RSI wall assemblies are well understood, accurate assessment of hygrothermal performance is more complex, and has not yet entered into the mainstream design process, especially at the single-family scale (Karagiozis, 2001). It is therefore important to assess the hygrothermal behaviour of high RSI wall assemblies in order to ensure that designing for high thermal resistance does not create inadvertent durability concerns. Because field testing and experimental investigation is expensive and limited in relevance to the specific location and assembly being scrutinized, heat, air and moisture simulation is a promising technique for assessing the hygrothermal performance of a variety of assemblies in different climates (Karagiozis, 2001). Using hygrothermal simulation, we can begin to develop design guidelines for climate-specific wall assemblies that are resilient to common stressors and moisture loadings, as well as the effects of construction deficiencies.

2.0 Literature Review

This Chapter focuses on the mechanisms governing the interaction of moisture and relevant elements in wood framed buildings leading to potential assembly failure, as well as best practices in hygrothermal analysis, especially with regards to the selection and verification of appropriate simulation boundary conditions.

2.1 Enclosure Design and Control Layers

The building envelope will be defined throughout this research as the system of components that separates the exterior environment from controlled, indoor space. It therefore must perform certain critical functions in order to effectively maintain indoor environmental conditions that are suitable for human occupancy. Contemporary building envelopes are designed to perform the following four functions, listed in order of importance (Lstiburek, 2007):

1. Control the penetration of bulk water from weather events, such as driving rain or snow
2. Control the infiltration and exfiltration of air
3. Control the transfer of heat both into and out of the building
4. Control the diffusion of water vapour, both from the interior and exterior

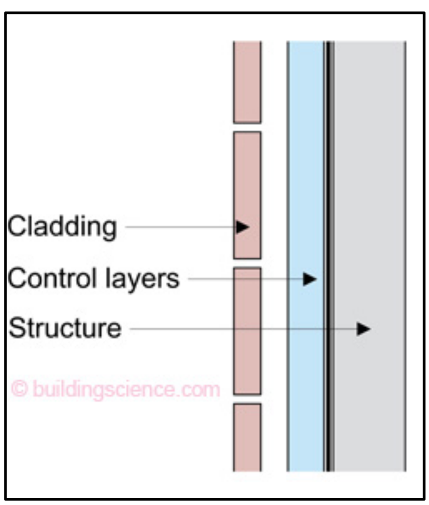


Figure 2.1.1: "The Perfect Wall Enclosure", conceptual diagram. In

this assembly, all control layers are continuous and outboard of the building structure, forming a ‘perfect’ separation. (Building Science Corporation, 2008)

Figure 2.1.1 depicts an enclosure concept commonly referred to as the “Perfect Wall.” In this approach, all control layers are located outboard of the building structure and are continuous, allowing the envelope to most effectively separate the structure from the elements that it is designed to control (Straube and Burnett 2005).

In the “Perfect Wall,” the cladding serves to protect the control layers from wind and ultraviolet exposure, as well as deflecting the vast majority of water from driving rain. Behind the cladding is an air cavity, designed to be free flowing so that the pressure is moderated with regards to the exterior air pressure. Behind the air cavity is the weather resistive barrier (WRB), which exists based on the assumption that some water will inevitably penetrate the cavity. Any penetrating liquid water is able to drain down the WRB and exit the assembly via the bottom of the air cavity. When sealed, the WRB will also form the air barrier, controlling the unwanted infiltration and exfiltration of air (Lstiburek, 2007). Behind the WRB is the thermal insulation layer, which regulates the rate at which heat may enter and leave the building. Finally, the vapour control layer is present outboard of the structure, ensuring that humid air does not penetrate the assembly and cause moisture accumulation on cold surfaces. Typically, a contemporary, timber building will utilize a single layer of oriented strand board (OSB) or plywood as structural sheathing, which is mechanically fastened to a wood-framed, stud wall inboard of the sheathing.

Critically, the ‘Perfect Wall’ design may not always be feasible to achieve in practice; for example, zoning issues such as minimum setbacks frequently exert pressure on designers to relocate some or all thermal insulation to be in plane with the building structure, in an effort to achieve a thinner wall assembly. This results in high RSI wall assemblies with ‘split’ insulation designs (Refer to Figure 2.1.2), which have demonstrated decreased resiliency to hygrothermal stressors when compared to exterior insulated walls, and even interior insulated walls in certain instances (Finch and Ricketts, 2012).

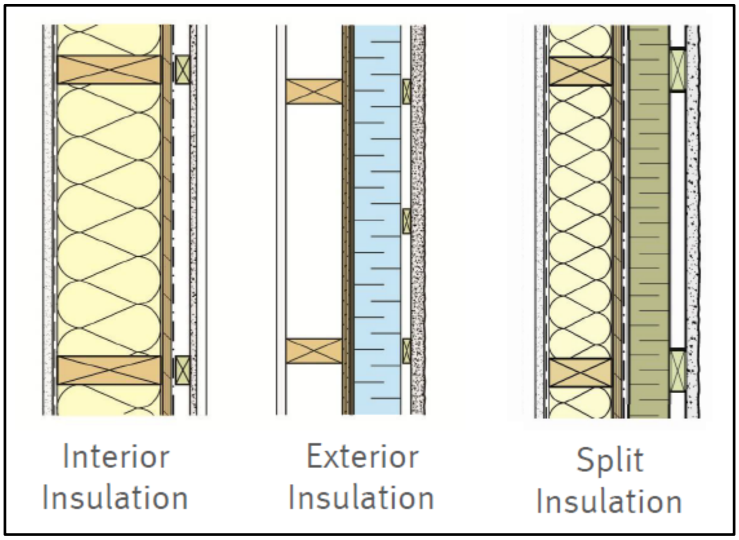


Figure 2.1.2: Insulation allocation techniques. Note that the Split-insulation strategy permits the greatest effective thermal resistance over the lowest required thickness (exterior is right; interior is left) (RDH 2012).

Split insulation assemblies result in unique temperature and moisture profiles across the wall assembly that are different that are different than the traditional assemblies (i.e. interior and exterior insulated assemblies). The long term hygrothermal performance of split insulation assemblies is not well understood or documented (Arena, 2013). As such, a detailed understanding of the physics governing the split-assembly's hygrothermal performance is required as building codes' prescriptive requirements push designers into the realm of split-insulation assemblies. The occurrence of interstitial moisture accumulation and the associated failure mechanisms have been observed with increased frequency (Arena, 2013). The reasons for this observed deterioration are complex and interrelated, but perhaps are driven in part by design practices that do not permit the rapid drying of wetted components that are susceptible to water-induced deterioration mechanisms.

Canadian building codes do make mention of these effects, prescribing minimum thermal resistance ratios (outboard vs inboard) based on heating degree days as shown in Table 2.1.1 (Canadian Commission of Building and Fire Codes, 2010). However, these ratios do not account for the various hygrothermal regimes that split-insulation wall assemblies frequently have, and may result in requirements for wall assemblies without any diffusive drying pathway for wetted components (OBC, 2012; Karagiozis et al, 2014).

Table 2.1.1: Minimum split insulation allocation ratio as a function of heating degree days under the Canadian National Building Code (CCBFC, 2010).

Heating Degree Days o Building Location, Celsius Degree Days	Minimum Ratio, Total Thermal Resistance Outboard of Material's Inn Surface to Total Thermal Resistance Inboard of Material's Inner Surface
Up to 4,999	0.2
5,000 to 5,999	0.3
6,000 to 6,999	0.35
7,000 to 7,999	0.4
8,000 to 8,999	0.5
9,000 to 9,999	0.55
10,000 to 10,999	0.6
11,000 to 11,999	0.65
12,000 or higher	0.75

2.2 Moisture Accumulation, Storage and Transport within Porous Media

Most building enclosures of single family homes in Canada are constructed with wood based and other hygroscopic materials. As such, it is important to understand the mechanisms by which water interacts with porous, hygroscopic materials, as the attributes of this interaction determine whether or not a building enclosure will experience moisture-induced deterioration. The four major sources of moisture in building envelope assemblies are (Schumacher and Straube, 2007): 1) Bulk water from precipitation, 2) Water vapour stored in air, either interior or exterior, 3) Built-in or stored moisture, either from manufacturing and/or construction processes, and 4) liquid or bound water from soil. In a typical enclosure, bulk water penetration (e.g. rain) accounts for over 95% of the water available to a building enclosure (Straube and Burnett, 2005).

Generally speaking, timber materials such as plywood and oriented strand board (OSB) are composed of particles of irregular shapes and sizes, creating complex, porous cross-sectional matrices (Morris, 1999). This porosity and associated pore connectivity directly affects the quantity of water, either bound, free, or vapour that may be transported through the medium of interest; for the purposes of analysis, this complex structure is simplified under the assumption that an overall, effective porosity may be determined from standardized test methodology (ASTM, 2010). From this understanding of the material composition of wood, intrinsic material properties have been developed in order to assist in the calculation and prediction of moisture transport through wood (ASTM, 2010).

The gaseous form of moisture present in an air mixture, water vapour, is transported through wood through the combined processes of convection and diffusion, together called 'advection.' It is important to note that in practice vapour diffusion is rarely a large contributor to net vapour transport through an assembly; rather, the ability of air to hold and transport large amounts of water vapour frequently results in convective moisture accumulation causing serious concern in the hygrothermal design process (Straube and Burnett, 2005). In order to calculate the mass-flow rate at which water vapour shall pass through a sample media of a fixed area, a derivation of Fick's law can be used as shown in Equation 1 (Hutcheon and Handegord, 1995):

$$dw_x / d\boldsymbol{\theta} = - \mu * A * dP_w / dx \qquad [1]$$

Where: $dw_x / d\boldsymbol{\theta}$ = the quantity of water vapour per unit time (ng/s),

μ= average vapour permeability of the sample (ng/m•Pa•s),

A = the sample's cross-sectional area (m^2), and

dP_w = the vapour pressure gradient (Pa/m) (Straube and Burnett, 2005).

Standard test methodology, ASTM E96, is widely used to accurately capture the average vapour permeability of most materials under typical conditions (ASTM, 2010). Karagiozis and Salonvaara (2001) note that at very high relative humidities, hysteresis effects may alter the average vapour permeability as compared to dry conditions; quantitative hygrothermal analysis is challenging under very high RH conditions for this reason (Peuhkuri, 2003).

Particularly relevant to the case of split insulation, designing with materials that have low vapour permeance present an interesting balancing act of positive and negative durability effects; in the case of exterior insulation with a low vapour permeance (e.g. commonly extruded polystyrene (XPS) in Canada), an assembly that has accumulated moisture inboard of this layer will be inhibited in its ability to dry to the exterior through vapour diffusion or convective drying. However; this same wall will, conceptually, be more resilient to moisture accumulation in the first place, because the temperature of the sheathing will be elevated and thus further from the sheathing's dew point temperature.

Perhaps more important than vapour diffusion, water vapour can also be transported to susceptible layers through the bulk transport of unmanaged air leakage into an assembly. This air can originate either from indoors or outdoors, and has the potential to deliver dangerously high amounts of water in a short period of time, orders of magnitude more than through vapour diffusion alone (Hutcheon and Handegord, 1995). Straube and Burnett (2005) have quantified the amount of water than can be transported from the interior of a building to a given layer in the assembly, layer j, by the convective flow of air as shown in Equation 2:

$$Q_{condensation} = \Delta V * (P_{w,in} - P_{ws,j}) / R_v * T \qquad [2]$$

Where: ΔV = the volume flow rate of air (m^3/s),

$P_{w,in}$ = the interior vapour pressure,

$P_{ws,j}$ = saturation vapour pressure at the temperature of layer j,

R_v is the gas constant for water vapour (461.5 J/kg*K) and

T = air temperature (K).

Note that this one-dimensional equation assumes that air leakage has no effect on temperature of the layer upon which moisture is accumulating, which is reasonable only for low air leakage rates due to air's relatively low heat capacity (Glass, 2013). It also assumes that the entirety of the moisture content of air that comes in contact with the condensing surface will accumulate on this surface; in laboratory testing, a maximum of 70% of this moisture has been found to accumulate on the condensing surface, therefore this equation will by definition overestimate the magnitude of convective accumulation of water vapour (Ojanen et al, 1994).

The transportation of water within a porous material becomes quite complex when examined in depth; the distinction between the driving forces influencing free water, bound water, and water vapour transport are critical to accurate numerical representation.

However for the purposes of this research, Darcy's equation (refer to Equation 3) will be used to represent the flow of free water through wood, under the reasonable assumption that its flow is free and laminar (McClung, 2013):

$$Q = K*A*\Delta P \qquad [3]$$

Where, Q = the air flow rate (kg/s),

K = air permeance (measured by ASTM E2178-13, expressed in μm/Pa*s,

A = cross sectional area (m^2), and

ΔP = driving air pressure difference (Pa) (Straube and Burnett, 2005).

2.3 Drying Mechanisms of High RSI Wall Assemblies

After any wetting event, moisture may be transported within (i.e. re-distributed) and/or removed by an assembly by a combination of four mechanisms. These are: 1) evaporation of water transported by capillary action to the surface of the wet material, 2) vapour transport by diffusion and/or air leakage, 3) drainage due to gravity, or 4) ventilation drying as represented in Figure 2.3.1 (Straube and Burnett, 2005).

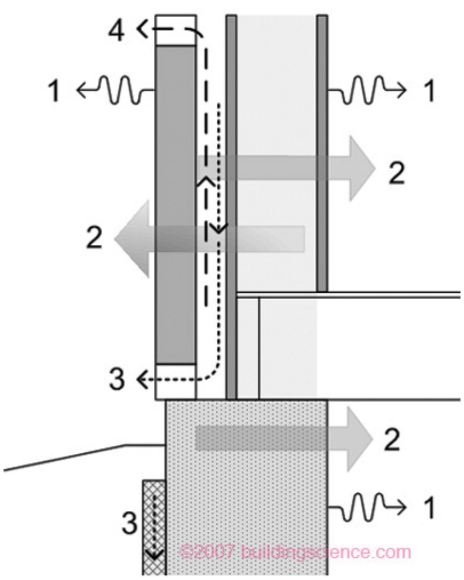


Figure 2.3.1: Conceptual illustration of drying mechanisms, including vapour diffusion, convection drying, and gravity-driven drainage drying. (Straube, 2007)

The efficacy of each of these drying mechanism depends on a combination of design factors such as: ambient climate conditions and material properties of relevant control layers in the wall assembly (e.g. permeance and hygroscopy) (Arena, 2013). Generally, drainage of bulk water due to gravity is expected to remove water at the greatest volumetric rate; however, a significant amount of moisture will typically remain absorbed into materials by capillary and surface tension forces (Straube and Burnett, 2005).This interstitial moisture will not be substantially dried by gravity-driven drainage, therefore provisions for other drying mechanisms (such as diffusion and cavity airflow drying) must be engaged (Ge and Ye, 2006).

The efficacy of diffusive drying depends on the configuration of vapour resistance within control layers of the assembly, as well as the magnitude and direction of the vapour drive (Straube and Burnett, 2005). If a layer of sheathing has accumulated moisture, and control layers outboard of the sheathing have a low vapour permeance, the ability of that sheathing to dry to the exterior will be low, implying that for an assembly with this characteristic to avoid deterioration and potential failure, the sheathing must either remain dry, or have an effective inward drying pathway. However, research has suggested that vapour diffusion rarely accounts for a large volume of water vapour transport; therefore neither drying nor wetting via diffusion is of critical concern in most circumstances, though extremely cold climates may require closer consideration of the psychrometric factors governing this risk, such as the dewpoint of indoor air and surface temperature of envelope components exposed directly to this air (Saber et al, 2010).

Most modern assemblies employ a vented airspace/drainage cavity between 10-50mm in thickness, separating the cladding from the control layers, commonly known as a 'vented rainscreen' approach (Straube and Schumacher, 2007). The intention of this design feature is to promote the convective transport of moisture from wetted elements away from the enclosure using the ventilation air's capacity to hold additional moisture. This airspace will also provide for a capillary break, and when properly detailed with a supported, continuous WRB inboard, a drainage plane for bulk water penetrating the cladding plane to dry due to gravity drainage (Ge and Ye, 2006). However, recent research has shown that merely providing for a free flowing airspace may not guarantee that substantial flow of air will occur, and thus convective drying of water will not necessarily occur at a consistently adequate rate (Falk and Sandin, 2012). The flow of this air is largely dependent upon the detail design of the cavity (e.g. whether horizontal or vertical battens are used), the force of friction acting on the ventilation air, and the pressure gradient between the intake and exhaust orifices, which is governed by the stack pressure acting on the wall (Falk and Sandin, 2012). Straube and VanStraaten (2010) measured a mean air flow rate of 89 ACH for a 20mm, vertically furred cavity; however, a range of 3 ACH to 468 ACH was observed during the measurement period and correlated closely to wind speed and direction (Straube and VanStraaten, 2010). Ge and Ye (2006) have created a validated numerical model demonstrating that an average ACH of 93 may appropriately describe most residential, vented rainscreens with 'lap' siding as the water shedding surface. The approximate rate of 100 ACH has been corroborated by RDH (2012), which enables users to iteratively calculate cavity airflow based on cavity design and environmental conditions such as hourly solar radiation incident on a vertical plane.

The potential variability of airflow could potentially be addressed during a modelling-based analysis, and correlated to the relative windiness of each of the three cities; however, the close correlation of measured drying to simulations using constant airflow rates suggest that idiosyncratic fluctuations may be empirically insignificant to the aggregated rate of drying in an assembly (Ge and Ye, 2006).

Furthermore, when convection occurs at design rates within the cavity, the drying capacity of cavity ventilation depends on the psychrometric conditions of intake air, and it has been shown that outdoor air in with a high humidity load (such as the marine climate of Vancouver) may even contribute to additional wetting of susceptible enclosure elements, even under the assumption that the OSB or plywood sheathing is saturated, thereby maximizing the vapour pressure at the layer to be dried (Ge and Ye, 2006). Furthermore, the idealized drying situation assumes that the saturated sheathing is exposed directly to the ventilation airstream; in reality, a WRB membrane such as spun bonded polyolefin will typically be applied to the exterior face of the sheathing. Further, in exterior or split insulated assemblies, some thickness of insulation that also has a vapour resistance may further inhibit the drying potential of wetted sheathing (Saber et al, 2010). Therefore, the effective vapour resistance of the layers outboard of the sheathing directly govern the efficacy of drying into the ventilation airstream, and in practice, airflow within the cavity has been measured to be significantly less able to extract moisture from the sheathing than under the idealized assumptions of the drying potential equation (Ge and Ye, 2006). Most validated hygrothermal analysis software have developed appropriate factors based on relevant material properties in order to account for this needed correction.

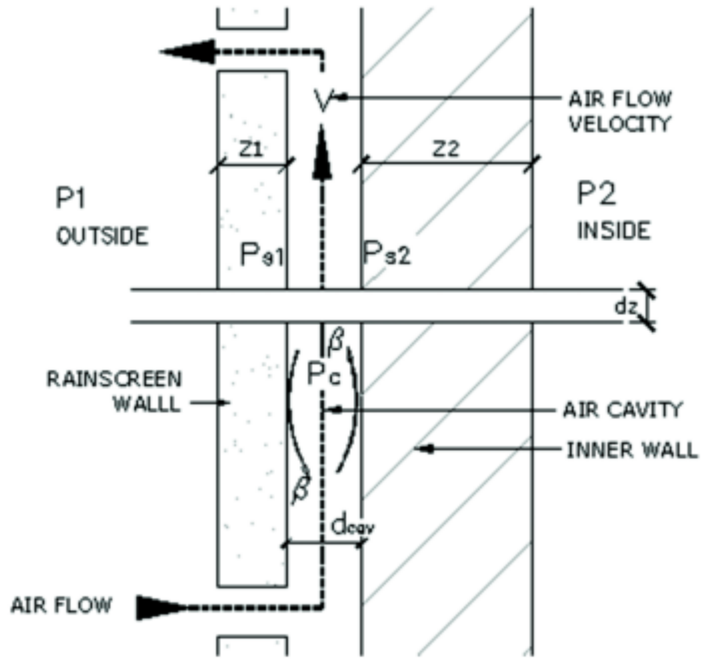


Figure 2.3.2: Moisture balance in a typical vented-rainscreen wall cavity. Note that the velocity of air flow, *v*, directly influences the rate of moisture removal from the wall assembly. In humid climates, P1 Outdoor conditions can greatly compromise the efficacy of drying through this mechanism, sometimes even comprising the source of moisture for a wetting event (Ge and Ye 2007).

2.4 Moisture Related Damage to the Building Envelope

There are five criteria that must be satisfied in order for a building envelope to experience moisture-related deterioration: 1) a moisture source must be available, 2) a route must be available for that moisture to travel into the envelope, 3) a force must be present to drive this moisture into the envelope, 4) the moisture must come into contact with a material that is susceptible to moisture damage, and 5) the moisture content must remain in excess of the susceptible material's 'safe-storage capacity' for a sufficient length of time (Straube, 2007). If any of these five criteria can be eliminated, there is no risk of moisture-related damage. In practice, the elimination of a moisture source is particularly infeasible in practice, due to the hyper-abundance of various forms of water in the environment, and the other constraints are also difficult to manage through design.

Building materials may experience moisture-related damage due to physical, chemical or biological phenomena (Viitanen, 2010). In the case of wood-framed structures, biological deterioration in the formation of mould is of particular concern (Viitanen, 2010). This is largely because the criteria necessary to avoid surface mould growth are more stringent than the performance criteria for other failure and deterioration mechanisms (TenWolde, 2008). In order for mould deterioration to occur, certain psychrometric thresholds must be exceeded for a sufficient period of time.

After a thorough review of extant standards and publication, the parameters derived in ASHRAE Standard 160P (1996), as well as those developed in Viitanen's Mould Growth Index (2010) are well regarded as criteria which must be avoided in order to eliminate the possibility of mould growth and further structural decay.

ASHRAE (1996) has identified the following failure criteria for framed assemblies: 1) 30-day running average surface RH > 80% when the average surface temperature during this time is between 5C and 40C, 2) 7-day running average surface RH>98% when the average surface temperature during this time is between 5C and 40C, or 3) 1-day running average surface RH = 100% when the average surface temperature is between 5C and 40C. Reaching any of these upper limits represents a failure as defined by ASHRAE (1996).

Viitanen's Index (VTT) is somewhat less conservative, and seems to be more widely accepted by design experts who are able to draw upon collected field data and professional experience. The VTT's failure criteria are highly complex mathematically, and take into account everything from climate factors, to building material, to duration and timing of hygrothermal exposure (Krus et al, 2010). VTT also has the ability to predict the growth rate and severity of mould, which is useful especially for projects wherein some mould growth might be unavoidable, such as wine cellars or retrofits of older homes in humid climates. The calculation algorithm is able to assign a rating of 0-6 to the selected input boundary conditions, with 0 indicating an instance predicted to experience no mold growth, and 6 representing 'dense coverage 100%' for a wood-based material. Note that the scale of this index changes slightly with changing substrate class; for instance, a stone substrate only ranges from 0-5, with 5 indicating 100% coverage (Viitanen and Ritschkoff, 1991).

Sedlbauer (2001) has also developed a biohygrothermal model with the goal of predicting mould growth in susceptible assemblies under non-static boundary conditions (Krus et al, 2010). His methodology, similar to Viitanen's, also uses a complex algorithm in order to predict the onset of sporulation, as well as the rate and extent of growth likely to occur. Sedlbauer's model has been integrated into a post-processor for WUFI, called WufiBio, which has been validated against field data as well as Viitanen's index to show universally close agreement (Krus at al, 2010). That said, it is important to note that these are all 'surface' based indexes; because of the challenge in quantifying interstitial oxygen levels, the accurate prediction of mould within the building material based on relative humidity at its boundary conditions is challenging (Karagiozis, 2001).

Also useful to performance evaluation of moisture-accumulation conditions is the study of the equilibrium moisture content (EMC) for wood, with water content expressed as a percentage of density. This is because critical engineering properties of wood, such as shrinkage and swelling, strength, and thermal conductivity all depend on the wood's EMC (Glass, 2013). The literature frequently references what is known as "safe storage capacity of wood," and seems to agree that EMC less than 20% - 28%, depending on the source consulted, by mass should be strived for during the hygrothermal design process (Glass, 2013; Straube and Burnett, 2005; Arena, 2013).

Based on the mechanics of moisture transport through wood media, a relationship between the surface relative humidity of a sample and its EMC at a given temperature has been derived numerically and widely verified experimentally (Straube and Burnett, 2005); this relationship is known as a 'sorption isotherm,' and has been rigorously calculated for wood at different temperatures. In field conditions of less than 50C, it has been found that temperature dependence of sorption is insignificant, and analyses may occur under the assumption of temperature independence (Straube and Burnett, 2005). At high relative humidifies, on the other hand, the sorption profile of wood has been found to vary significantly; this will be discussed at length in Section 2.5.

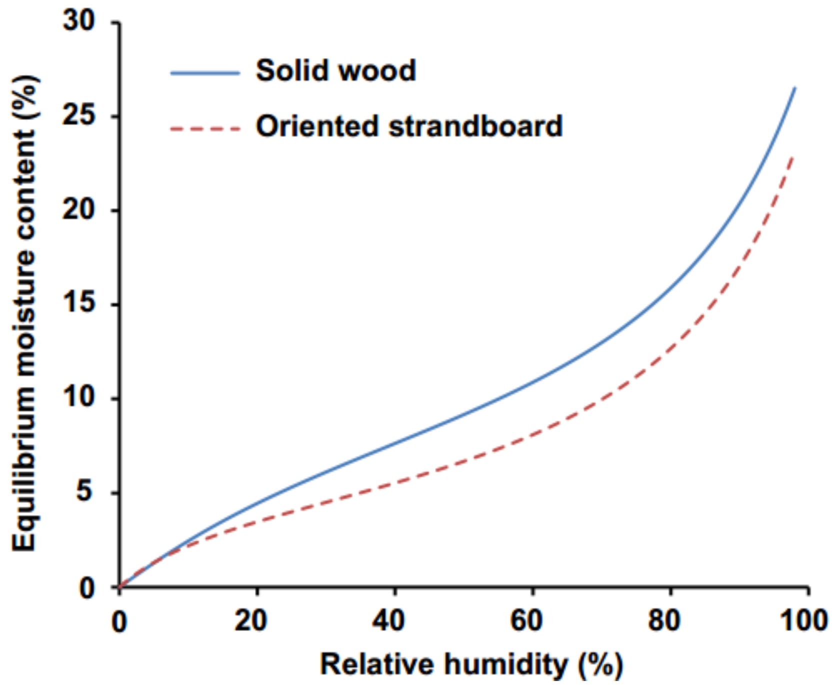


Figure 2.4.1: Sorption isotherm of solid wood and OSB at room temperature. Note the point of inflection occurring at approximately 80% RH, wherein the rate of moisture content accumulation increases rapidly due to the local saturation of wood-cells and the transition to abundant liquid water in the specimen's cross-sectional matrix (Glass, 2013).

In practice, wall assemblies typically experience periods of time wherein moisture accumulates on the sheathing by one or all of the wetting mechanisms described above, as well as periods of time during which the assembly is drying, by one or all of the mechanisms described above. The magnitude and rate of these processes determines what is referred to as the wall's 'moisture balance,' and is a critical factor in comparing hygrothermal performance over time, under different environmental stressors and in different climates (McClung, 2013).

Critical performance issues, such as mould sporulation, rapid mould growth, and likely decay of plywood and OSB sheathing each have been the subject of a great amount of scientific research and debate (Treschel, 2001; TenWolde, 2008). It is therefore difficult to conceive of establishing metrics for assessing the likelihood of occurrence for specific deterioration phenomena that are universally accepted within the scientific community. That said, for practical applications, threshold values for potential for mould onset (slow growth), as well as structural decay may be established relative to hours above specific moisture content thresholds. Those established by P.I. Morris (1998) represent well the various failure criteria found throughout the literature:

Table 2.4.1: Guide to moisture conditions for various development criteria for mould and fungi in wood. (Morris, 1999)

Moisture content	Colonisation	Growth	Spore production	Strength loss
0 - 14%	None	None	None	None
15 - 19%	Mould spores (few species)	Very slow	Neligible	None
20 - 24%	Mould spores Brown rot, mycelial cords[2]	Slow Slow	Minimal Slow	None Very slow
25 - 29%	Mould spores Brown rot, mycelial cords[2] Brown rot, mycelium[2] White rot, mycelium[2]	Moderate Moderate Slow Very slow	Moderate None None None	None Slow Slow Very slow
30 - 49%	Mould spores Brown rot, mycelial cords Brown rot, mycelium White rot, mycelium Brown rot, spores White rot, spores	Fast Fast Fast Slow Fast Slow	Prolific Limited[3] Limited[3] Limited[3]	None Fast Fast Slow
50 - 89%	Mould spores Brown rot, mycelial cords Brown rot, mycelium White rot, mycelium Brown rot, spores White rot, spores	Fast Fast Fast Fast Fast Fast	Prolific Limited[3] Limited[3] Limited[3]	None Fast Fast Fast
90 - 160%	Mould spores Brown rot, mycelial cords Brown rot, mycelium White rot, mycelium Brown rot, spores White rot, spores	Fast Slow Slow Fast Slow Fast	Prolific Limited[3] Limited[3] Limited[3]	None Slow Slow Fast
> 160%	not possible	None	Minimal	

2.5 Assessment of Hygrothermal Performance

After reviewing the published literature regarding the complex heat, air and moisture regimes associated with high-RSI wall assemblies it is clear that there exists a significant gap in terms of rigorous studies seeking to systematically assess hygrothermal performance of wood based structures. In practice, this assessment could take the generic form either of physically testing specific wall assemblies under prescribed environmental regimes, or simulating these effects using computer models (Straube and Schumacher, 2006). In order to analyze most effectively the extent to which hygrothermal boundary conditions improve or worsen the moisture balance of wall assemblies, hygrothermal simulation presents the opportunity for researchers and design practitioners to perform heat and moisture quantification that is accurate, but also cost and time effective, and able to be applied efficiently to unique designs in different climates (Karagiozis, 2001). When simulations are validated against measured field data, researchers may use simulation to calculate with a high degree of confidence the anticipated result of manipulating variables that would be challenging to test in the field. This approach is useful in order to make recommendations regarding the relative risk of various exposure regimes and envelope designs; however, caution must be exercised and care taken not to place undue confidence in the precision of these results. Because of the assumptions and limitations of the simulation software, issues such as gravity driven drainage can potentially be overlooked by the model. In instances where components reach critical points of saturation, drainage of liquid water becomes a critical factor in the moisture management of the assembly. In these instances, engineering judgement must be exercised to gain an accurate understanding of the impact of this drainage on the performance of the whole assembly, and to understand likely sources of model error.

A variety of hygrothermal simulation software packages are available to the building science community; broadly, these may be classified into three categories: simplified numerical models, hygrothermal design tools, and advanced hygrothermal models. With a recent improvement of user-friendliness of hygrothermal design tools, the usefulness of simplified models (such as the Glaser method popular in the 1990's) is relatively low, and their prevalence has decreased (Karagiozis, 2001). The critical distinction between hygrothermal design tools and advanced models is in their ability to directly predict durability based on the strength, frequency, magnitude, and duration of heat, air and moisture stressors; for example, advanced models are written with the intention of predicting phenomena such as the occurrence of corrosion on a steel member under air-leakage condensation conditions (Karagiozis, 2001).In comparison, specific failure criteria (such as ASHRAE 160P or Viitanen Mould Growth Index) must be determined by the researcher for hygrothermal design tools, and the simulated moisture content/relative humidity data given by the design tool reconciled with these criteria.

Of the hygrothermal design software available, WUFI® Pro is most widely-used in both the research community as well as the design industry for its user-friendly interface and range of custom material properties, and has been validated through field measurements to ensure accurate results given appropriate inputs (Kunzel, 1995). WUFI® Pro is a hygrothermal model for the analysis of building envelope constructions; it is a transient, one dimensional model that has been validated for a wide variety of materials and climatic conditions, and is designed to lend itself both to design verification and development, as well as detailed, hygrothermal research (Karagiozis, 2001). Its usage has also been described in depth in ASTM MNL 40, Moisture Analysis for Buildings, which aides in the selection of appropriate input boundary conditions (Treschel, 2001).

WUFI does have specific, well-documented limitations; for instance, at high relative humidities (>95%), the behaviour of OSB and plywood becomes somewhat eccentric (non-Fick's law compliant) due to hysteresis effects explained above in this Chapter. WUFI assumes a single moisture storage function (i.e. sorption isotherm) for each material, and does not allow for the user to modify the time required for EMC to be reached. It rather assumes instantaneous equilibration of local relative humidity with RH in the pore structure of the material (Peuhkuri, 2003). However, it is important to note that based on most published failure criteria, RH levels elevated to this extent will by definition qualify as a failing assembly; it is just the specific mechanisms of deterioration that may be challenging to comment on accurately. By and large, the literature (Kunzel, 1995) seems to suggest that WUFI's limitations are restricted to instances of exceedingly high relative humidity, and tend to cause overestimation of wetting under high moisture loads, which in theory trends towards conservative recommendations for design practitioners. For this research, WUFI® Pro was utilized to simulate the hygrothermal performance of the chosen wall assemblies due to its proven accuracy and acceptance.

2.6 Quantification of Hygrothermal Risk

A critical challenge inherent in hygrothermal simulation involves the establishing of failure criteria/damage models for the assembly in question. Deleterious effects such as efflorescence of brick, corrosion of steel elements, and freeze-thaw damage to concrete/masonry all are influenced differently by hygrothermal loadings, and therefore each must be examined closely wherever applicable. For the purposes of wood-framed construction, the relative risk of moisture damage to plywood/OSB sheathing is generally regarded as the strongest indicator of assembly performance. This is because experience has shown this element to be most prone to accumulate moisture due to vapour diffusion, air leakage as well as bulk water penetration, and is generally highly susceptible to biological deterioration (Finch and Ricketts, 2012). While OSB and plywood do have slightly different hygrothermal properties, they behave similarly enough that conclusions from this research of one are commonly accepted to apply to the other, and are classified by Viitanen in the same Substrate Class, indicating similar hygrothermal risk (Viitanen, 2010). For detailed research investigations focussing on specific material properties, however, it is advisable to focus on each material separately.

After a review of similar studies (Straube and Schumacher, 2012; Fox, 2013; Finch and Ricketts, 2012), the literature contains specific metrics and simulation test procedures that are used as proxies to quantify the risk of wood sheathing that is accumulating moisture at an unsafe rate as well as to understand an assembly's ability to dry. One of the more widely used metrics for comparing the risk of condensation between assemblies under different hygrothermal boundary conditions is referred to as 'hours of potential condensation' (Straube and Schumacher, 2010; Fox, 2013). Simply stated, hours of potential condensation is equal to the number of hours per year during which the sheathing is at a temperature lower than the psychrometric dewpoint temperature of air that it is in contact with, thereby being at 100% relative humidity.

It should be noted that this allows us to compare the frequency of potential condensation, however it does not provide insight on the magnitude or timing of moisture accumulation. In order to understand the magnitude of wetting, examination of moisture content within the sheathing is necessary. From a modeling-practice perspective, measures must be taken to reflect the different exposure regimes at different depths in the sheathing. That is, when exposed to driving rain, the exterior half of the sheathing will wet more drastically than the interior half, increasing the likelihood that deterioration begins in the exterior of the sheathing. Quartering a sheet of 12.5mm (½") plywood sheathing into four, 3.125mm (0.125") plywood components within the simulation model can be an effective analytical method for measuring moisture content across the sheathing. The researcher must use judgement to understand instances wherein the exterior sheet will likely be most critical, such as when evaluating driving-rain performance, but evaluating the interior sheet will be most conservative when evaluating air-leakage based condensation, for instance.

In summary, it is apparent that the long-term hygrothermal performance of split insulation is not fully understood or documented within the building science community. The mechanisms of drying and wetting that are most commonly experienced by a wall assembly are likely to cause previously unseen durability effects for split insulated assemblies because of their different water management mechanisms as compared to an interior-insulated assembly. While few studies have explicitly addressed these issues, the tools to accurately assess durability performance are certainly available, and a process using field testing to calibrate hygrothermal simulation can represent a cost-effective manner of accurately comparing hygrothermal performance of assemblies in different climates, under different moisture loadings. Because hygrothermal simulation software does not have the ability to predict biodeterioration under different hygrothermal conditions, commonly accepted failure parameters were accepted in this research in order to identify assemblies that are more likely to experience problems during their service life.

3.0 Methodology

In this Section, a technique for using a validated WUFI simulation to assess high-RSI wall assemblies in different climate zones, under different hygrothermal loadings, will be developed. An analytical procedure for evaluating the effects of specific loadings on interstitial condensation, envelope deterioration and potential mould growth will be explored and a method for concisely interpreting these results will be presented. Throughout this paper, the term high RSI was used broadly to describe the advanced assemblies that are currently being designed and constructed in order to achieve contemporary performance requirements, particularly EnerGuide 80, in continuation of previous research by others (Finch and Ricketts, 2012).

3.1 Selection of Test Assemblies

In continuation of research conducted by Finch and Ricketts (2012) "Hygrothermal Assessment of Acceptable Assemblies for EnerGuide 80 in Part 9 Construction, 2012 BCBC," the following assemblies were selected for assessment in this research[1]:

Table 3.1.1: Guide to test assemblies used within this paper.

#	Assembly
1	38mm x 140mm (2x6) with 140mm batt insulation
2	38mm x 140mm (2x6) with 140mm batt insulation and 51mm (2") exterior r
3	38mm x 140mm (2x6) with 140mm batt insulation and 102mm (4") exterior
4	38mm x 140mm (2x6) with 140mm batt insulation and 51mm (2") exterior X
5	38mm x 140mm (2x6) with 140mm batt insulation and 102mm (4") exterior
6	38mm x 89 mm (2x4) with 89mm batt insulation and 102mm (4") exterior m
7	38mm x 89 mm (2x4) with 89mm batt insulation and 153mm (6") exterior m
8	38mm x 89 mm (2x4) with 89mm batt insulation and 76mm (3") exterior XP
9	38mm x 89 mm (2x4) with 89mm batt insulation and 127mm (5") exterior X
10	38mm x 140mm (2x6) with 140mm batt insulation and 12.7mm (0.5") exteri
11	38mm x 140mm (2x6) with 140mm batt insulation and 25.4mm (1") exterio
12	38mm x 140mm (2x6) with 140mm batt insulation and 12.7mm (0.5")exteri
13	38mm x 140mm (2x6) with 140mm batt insulation and 25.4mm (1") exterio

[1] Insulation thicknesses in assemblies 1-9 were chosen to ensure that each assembly had a minimum R22 effective thermal resistance (RSI 3.88), as required for EnerGuide80 and this paper's definition of high-RSI. Assemblies 10-13 were selected as part of a sensitivity analysis for air leakage condensation.

Assessment of the above thirteen walls will enable analysis of a representative sample of assemblies that depict design concepts likely to enter mainstream relevance as building codes shift towards *effective* RSI requirements as explained in Chapter 1. Thicknesses of exterior insulation were selected based on the minimum, commonly available thickness that would meet RSI 3.88 (R22), and increased incrementally based on commonly manufactured and distributed construction materials. Furthermore, rigid mineral wool and XPS were selected to represent commonly used exterior insulation materials with very different vapour permeance; XPS representing the lower end of the permeance spectrum, and mineral wool as a relatively vapour-permeable insulating material. The performance of the above split-insulated assemblies is well contextualized when compared to that of a 38mm x 140mm (2"x 6"), interior-insulated assemblies, which are currently the minimum performing assemblies as required under most Canadian building codes, and whose performance under various hygrothermal loadings is well documented.

3.2 Material Properties

A substantial barrier to accurate hygrothermal simulation is the complexity of material data needed to effectively predict moisture transport through porous media such as wood, especially at the elevated relative humidities observed at hygrothermal failure (Arena, 2013). WUFI's reliance on a single sorption isotherm for each material, rather than one describing free water, one describing water vapour, and one describing bound water, for instance, implies that effects such as gravity drainage may be underestimated, and overly conservative results generated (Treschel, 2001).

However, because the assemblies that this research project will be evaluating do not use nonstandard materials (rather, they use typical materials in nonstandard configurations), the included ASHRAE 1018-RP [REF] sorption curves will suffice, as these databases are likely the most validated, well-benchmarked profiles in the world for hygrothermal modeling (Karagiozis, Kunzel, and Holm, 2001). Furthermore, because the literature defines failure criteria that are well within the range in which WUFI's sorption curves are known to be most accurate, the eccentric phenomena occurring at extremely high RH will likely not affect whether or not an assembly is expected to fail (ASHRAE, 2006; Krus et al, 2010).

3.3 Definition of Baseline Boundary Conditions

In order to provide a basis for comparison, all of the above assemblies will be tested under standard, climate conditions for Vancouver, Edmonton, and Toronto. Additionally, simulations of both the Southern exposure (primary solar) and primary driving rain exposure (orientation varies by location and is determined as per ORNL climate analyzer) will be conducted as appropriate in order to explore differing extreme boundary conditions.

3.4 Air leakage Condensation

The rate and source of air leakage into an assembly can vary substantially between assemblies, and is largely a function of construction quality, indoor psychrometric conditions and air pressure differential. Due to its varied nature, this research does not attempt to describe one discrete occurrence of air leakage in various assemblies; rather, it compares the overall resilience of split-insulated, high-RSI strategies with that of a baseline, 38mm x 140mm interior insulated assembly that has been proven to generally be successful in field conditions.

In order to analyze the resilience of a split-insulated assemblies to air leakage, a reasonable test-rate of air leakage was developed using the baseline 38mm x 140mm assemblythat is generally accepted not to fail when properly constructed. To achieve this, parametric analysis was performed for all climate locations in order to identify an air leakage regime that elevates sheathing moisture content to above 30% for approximately three weeks during the winter season; this load therefore represents a tolerable leak for the baseline wall, as it elevates moisture conditions to meet ASHRAE 160P failure conditions in winter, but allows the wall to dry out during the summer months (ASHRAE, 2006). The flow and psychrometric conditions describing this air leak was then introduced to each of the twelve split-insulated assemblies, and the results compared to those of the baseline wall assembly in order to compare the resilience of newer strategies with that of the accepted baseline (Finch and Ricketts, 2012 and TenWolde 2008).

3.5 Driving rain penetration

A similar comparative procedure was used to analyze the resilience of split-insulated assemblies to moisture damage due to driving rain penetration. An additional parametric analysis was completed using the baseline, interior insulated 38mm x 140mm (2”x6”) framed wall at each location in order to determine the fraction of driving rain that must reach the exterior face of the plywood sheathing in order to achieve a moisture content of over 30% for approximately three weeks during the winter. This leak is then deemed to be the maximum tolerable by the baseline assembly based on field experience as well as the published literature, so the split-insulated walls of interest must theoretically outperform the baseline in order to be acceptable for each test location (Finch and Ricketts, 2012 and TenWolde 2008).

3.6 Validation of WUFI Boundary Conditions

In order to ensure accurate simulation of real-world situations, a WUFI model was constructed for comparison with measured field data collected by students in at BCIT, and provided for the purposes of advancing this research (BCIT, 2012). The BCIT study was conducted over a two month period in the spring of 2012, using an experimental setup in Vancouver (Higgins, 2012). The researchers tested two different split-insulated assemblies; one assembly used 75 mm of exterior rigid mineral wool, while the other used 89 mm of exterior XPS board. Both assemblies were vented rainscreen-type walls, using cedar siding and 19mm x 64mm (1x3) vertical furring strips. The WRB was achieved with a standard spunbonded polyolefin (SBPO) material, and 89mm (3.5”) of batt insulation was included between the 38mm x89mm (2x4) studs. Finally, a 6 mil, continuous, polyethylene vapour retarder was placed between the stud wall and the interior environment as per local building code requirements. The interior environment was a semi-detached, single family house in downtown Vancouver.

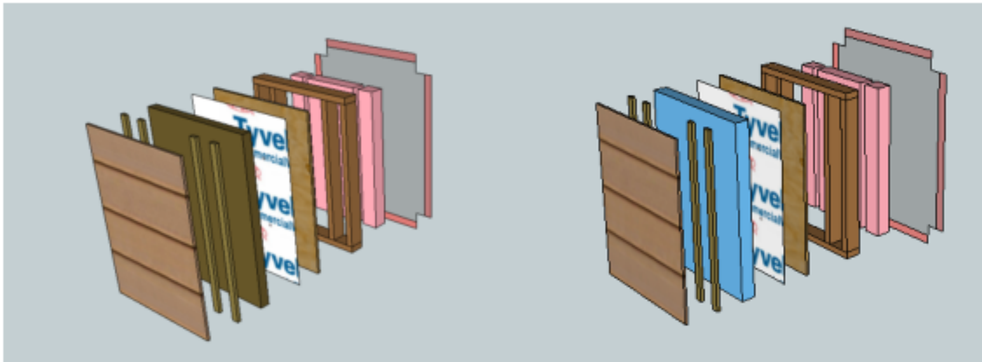


Figure 3.6.1: BCIT 2012 Test Assemblies (BCIT,

In order to quantify the ability of these assemblies to dry diffusively after a wetting event, the researchers strived to wet the plywood sheathing to 35% MC by mass, or 120 kg/m^3. This is reflective of the highest level of moisture that plywood may store as water vapour. Moisture pins were placed through the plywood sheathing of the wall, and hygrometers installed at the exterior interface of the sheathing and the stud cavity in order to record the relative humidity within the vented rainscreen. This process was repeated on both the North and South elevations of the building in order to capture the effects of maximum rain exposure, as well as maximum radiation exposure, respectively.

As shown on the below charts, actual wetting achieved was closer to 30%. However, in an attempt to construct WUFI models as objectively as possible, this study simulated the precise conditions that were described to us, prior to analyzing field data of any kind. Only after constructing these simulations were results compared with measured field data, which was generously shared by the BCIT research team and RDH Building Engineering for our usage.

Figure 3.6.2: Photograph of BCIT experimental set-up. (BCIT, 2012)

As part of this research, a WUFI model was created using matching boundary conditions of the four constructed cases; mineral wool (south), mineral wool (north), XPS (south), and XPS (north). Initial simulations were run using ASHRAE standard material properties, with the moisture content of the plywood sheathing increased to 120 kg/m^3 (i.e. 30% of 400 kg/m^3; the density of plywood) to reflect the wetted sheathing in the field test. Building rain load calculation was also performed to ASHRAE 160-P, using the FE and FD values of 1.0 and 0.25, respectively (Higgins, 2012). Surface transfer coefficients were chosen based on values for the silver-gray spruce cladding that made up the water shedding layer of the assembly, and the ORNL Vancouver "cold year" climate data was used. Indoor climate data was generated as dependent on outdoor conditions, as per EN 15026 (Fraunhofer, 2012).

Simulations were conducted with a constant cavity air flow rate of 50 ACH; this value is approximately 50% of the 93 ACH calculated by Ge and Ye's (2006) discussed in Section 2. The lower airflow is a function of the 122cm (4') cavity length constructed as part of the experiment. Each 1.2m (4') test assembly was separated with respect to airflow contamination from the one adjacent to it. Based on Equation 4 for calculating the pressure difference due to stack effect, a smaller cavity length causes a smaller pressure differential between the intake and exhaust openings in the cavity, which thereby reduces the volume-flow rate of air through the cavity (Hutcheon and Handegord, 1995).

$$\Delta P = C * a * h\ (1/T_0 - 1/T_i) \qquad [4]$$

Where: ΔP = potential stack pressure difference, Pa;

C = 0.0342;

a = atmospheric pressure, Pa;

h = stack height, m; T_o = outside temperature, K; and

T_i = inside temperature, K.

The measured field data was then compared to the results of the WUFI simulation files, as shown in Figures 3.6.3 through 3.6.6 below:

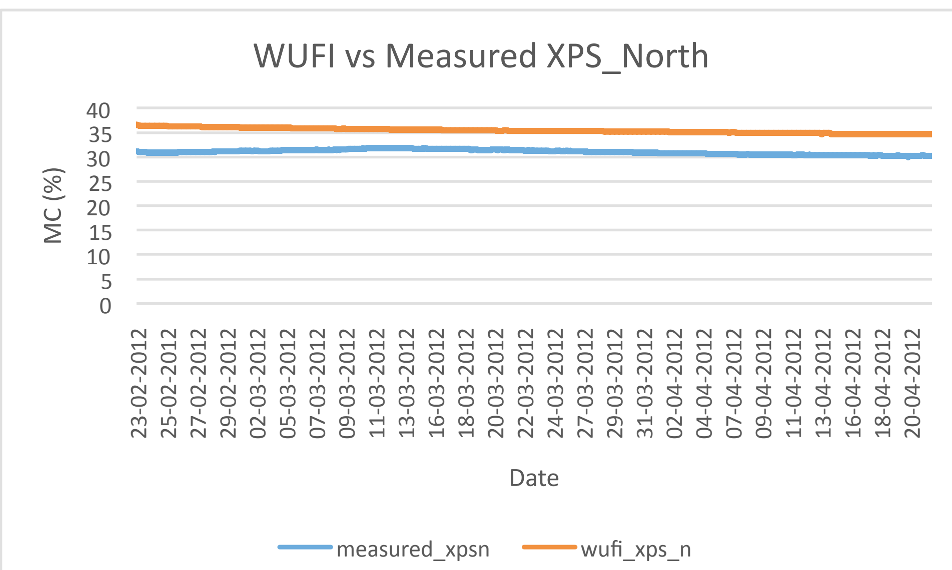


Figure 3.6.3: WUFI vs Measured MC of sheathing with exterior XPS on North elevation

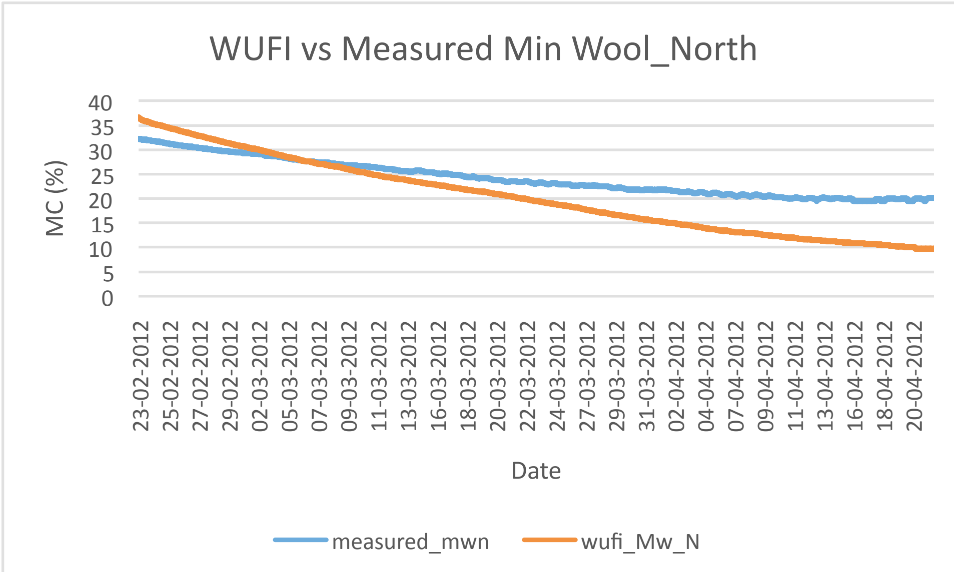


Figure 3.6.4: WUFI vs Measured MC of sheathing with exterior mineral wool on North elevation

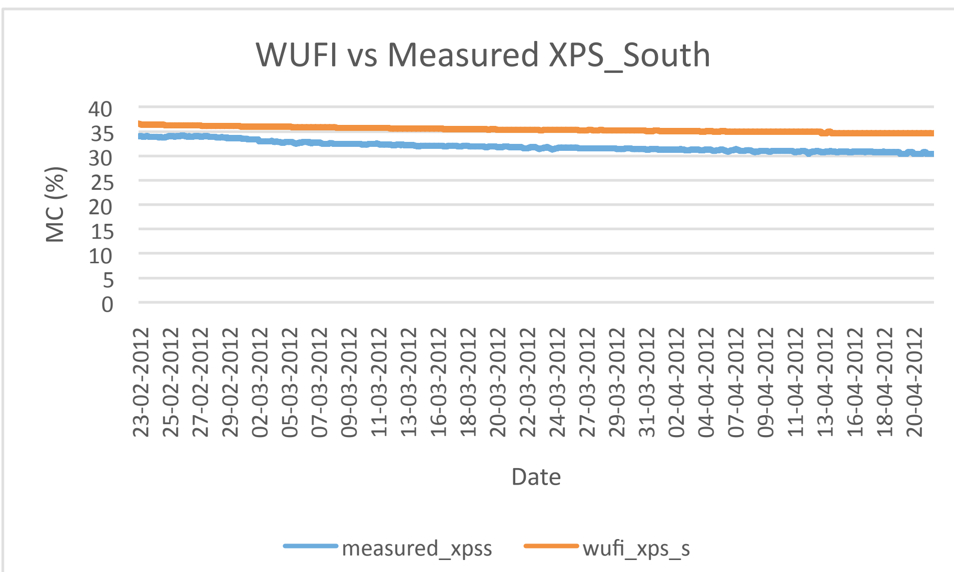


Figure 3.6.5: WUFI vs Measured MC of sheathing with exterior XPS on South elevation

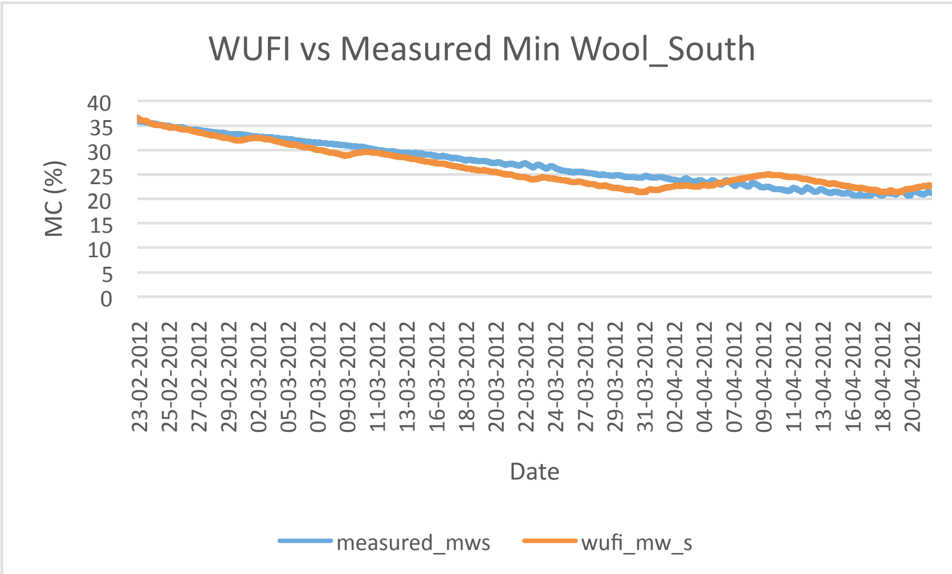


Figure 3.6.6: WUFI vs Measured MC of sheathing with exterior mineral wool on South elevation

The close agreement between this measured data with the results of the WUFI analysis indicate that the boundary conditions provided to WUFI can be used on other simulations of wall assemblies with one or more design/exposure variables being manipulated, while the remaining are held constant. Interestingly, note that WUFI seems to over anticipate drying for the mineral wool, northern exposure wall assembly, despite being simulated with identical boundary conditions as the other, well-correlated simulations. This could reflect different weather occurring during the experiment than predicted by the ORNL weather file for Vancouver, and will be kept in mind when analyzing the simulations to come.

Furthermore, it appears that during the experimental set-up, an average margin of error of 14% was experienced when attempting to wet the sheathing to 35% MC by mass, based on the data obtained from moisture sensors implanted in the sheathing. These results remain acceptable for the purposes of this calibration, because of the close correlation of drying trends. Finally, the lack of drying of the XPS in both orientations, in field data and simulation data, should be taken into consideration when critically evaluating the results of simulations that do not have corresponding field data.

4.0 Results

After completing the calibrated models described in Section 3, modified models were created to analyze each assembly in terms of the described failure metrics: (i) hours of potential condensation, (ii) hours of potential mould onset, and (iii) hours of potential decay and deterioration. All 13 assemblies were analyzed in Edmonton, Vancouver, and Toronto climates for south and wind-driven dominant elevations. Results are presented below.

4.1 Vancouver

Vancouver, British Colombia, as the third most populous metropolitan area in Canada, represents an important economic zone and a challenging climate in which to construct durable buildings. Categorized by the International Energy Conservation Code (IECC) (IECC, 2009) as a marine, mixed climate, Vancouver falls into IECC Zone 4 and is therefore representative of the largest temperate, humid climate zone found in Canada. After performing sensitivity analyses for both driving rain and air leakage, rates of 0.1% penetration and 1ACH were selected; the results of the analyses leading to selection of these values are presented in the Appendices. The primary orientation of driving rain exposure was determined to be the Western elevation. For baseline and air leakage tests, the Southern face was analyzed.

Figures 4.1.1 to 4.1.6 show present moisture content under baseline, air leakage, and driving rain penetration regimes and are plotted below in order to gain a qualitative understanding of the various assemblies' comparative hygrothermal performances:

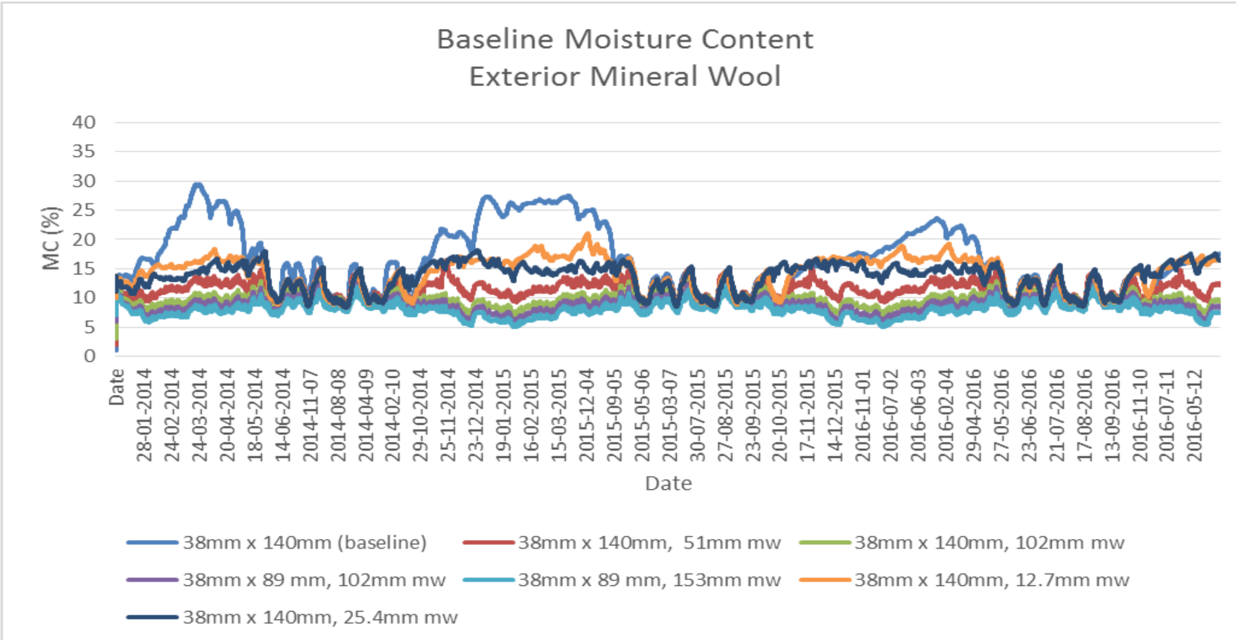


Figure 4.1.1: Baseline MC with exterior mineral wool.

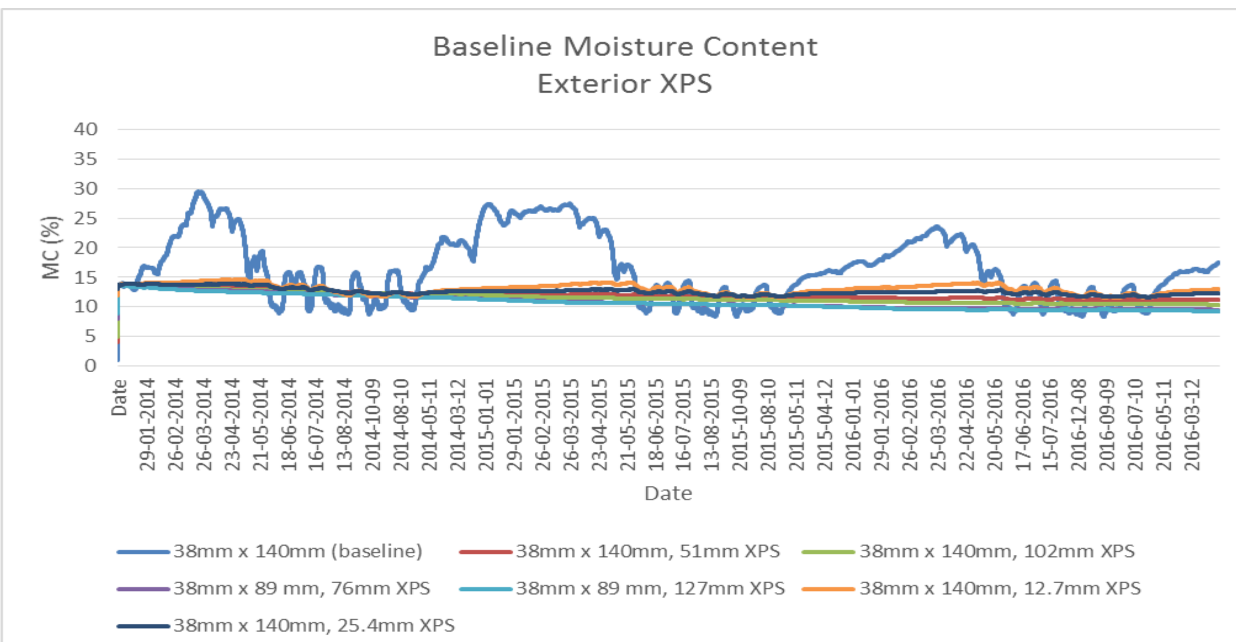


Figure 4.1.2: Baseline MC with exterior XPS

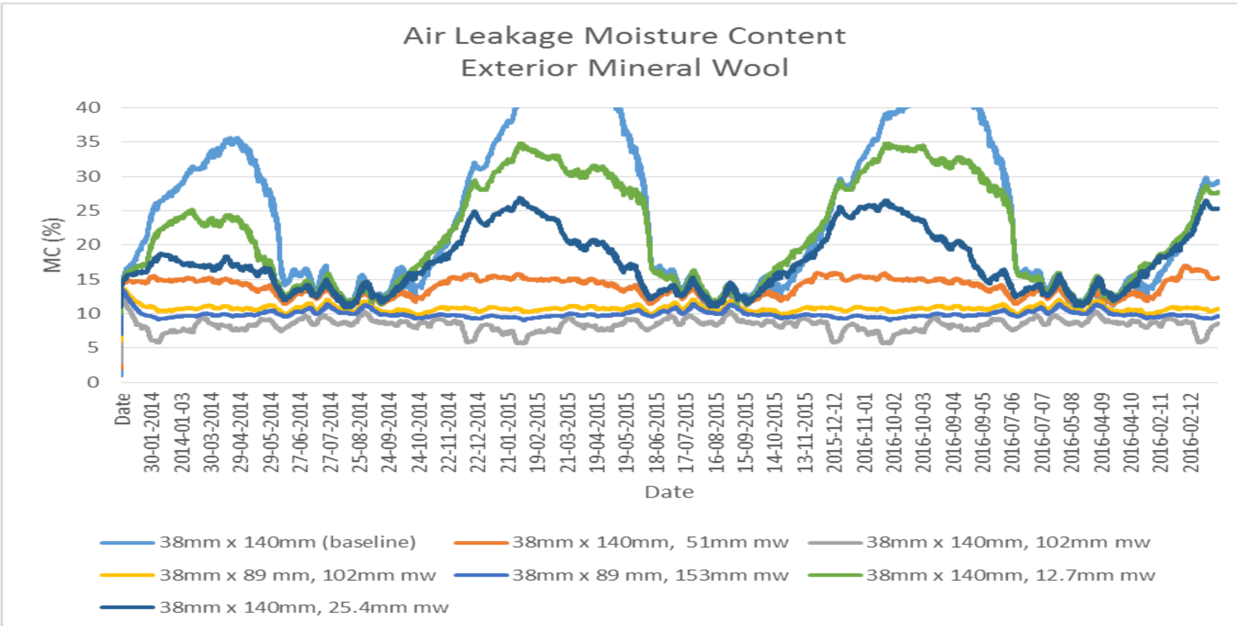


Figure 4.1.3: Air Leakage MC with exterior mineral wool

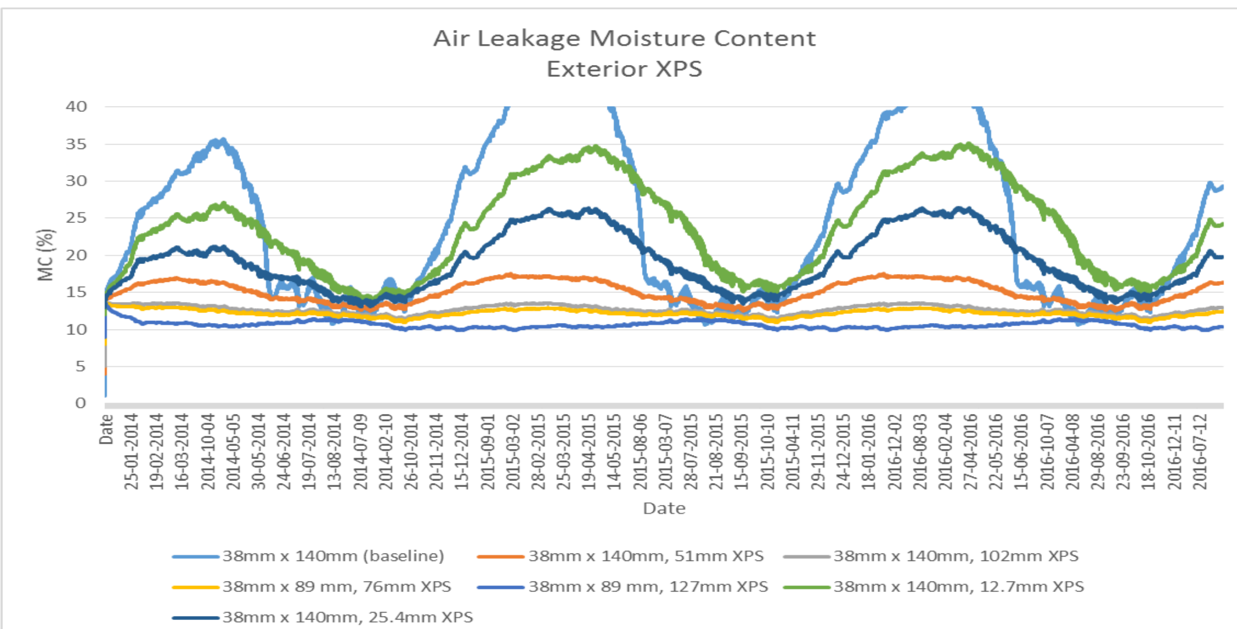


Figure 4.1.4: Air leakage MC with exterior XPS

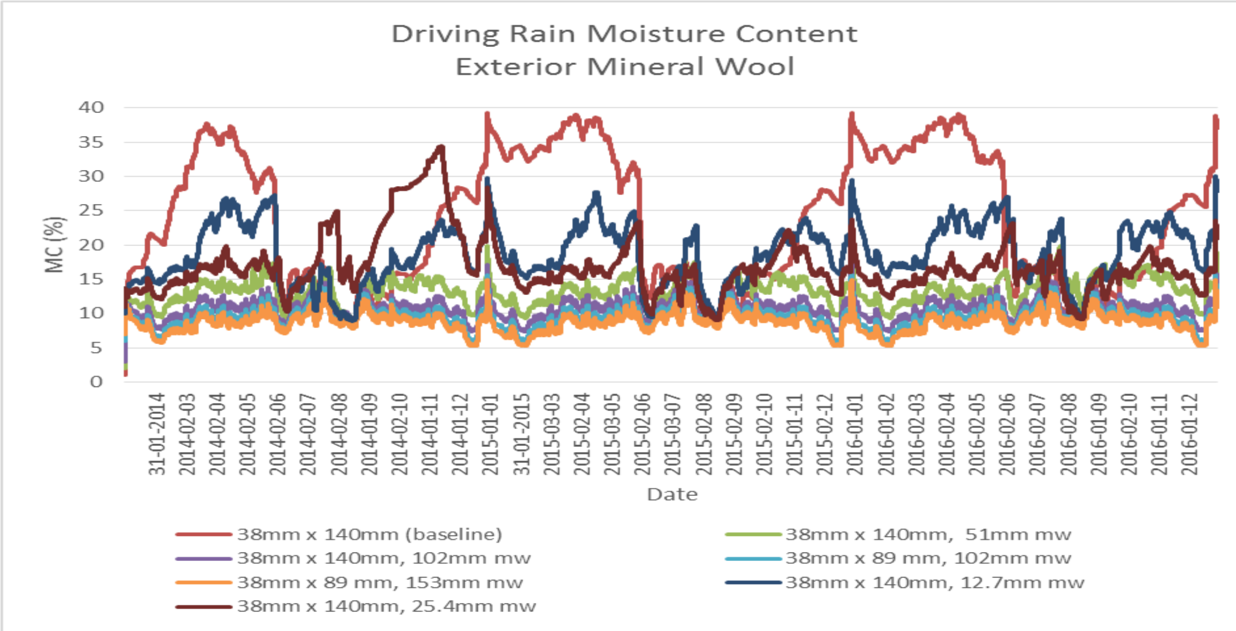


Figure 4.1.5: Driving rain MC with exterior mineral wool

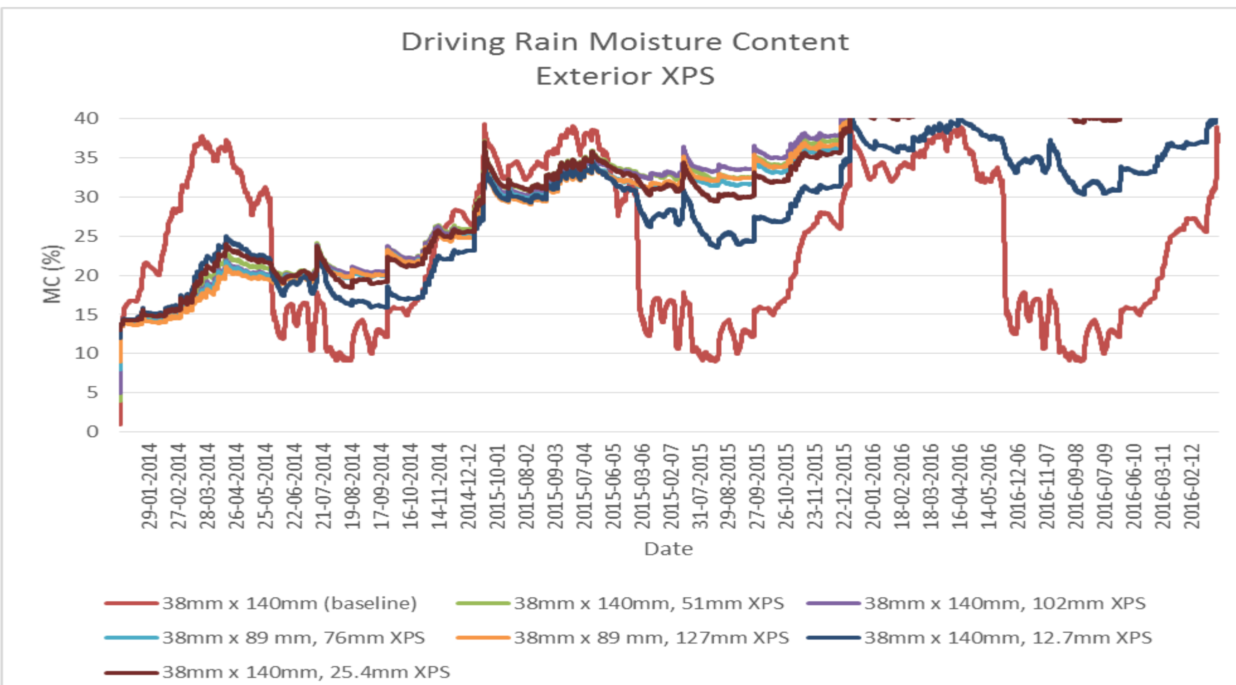


Figure 4.1.6: Driving rain MC with exterior XPS

It is evident from these charts that certain trends can be observed; to start, it is clear that moisture conditions for every assembly remain below 20% MC in the absence of hygrothermal loading by air leakage or driving rain penetration, indicating that none of the test assemblies will experience any potential mould onset under baseline conditions. Under air leakage into the assembly, the baseline assembly experiences MC of well over 30% for what appears to be a few weeks during the winter; that said, only the experimental, non high-RSI assemblies appear to experience elevated MC under this regime. Finally, driving rain penetration is clearly the most severe hygrothermal loading experienced by any of the assemblies with respect to moisture content elevation; virtually every XPS assembly experiences MC that appears to meet all failure criteria, and seems to worsen as time goes on, as opposed to mineral wool assemblies that appear to indicate adequate drying ability.

4.1.1 Condensation Risk Assessment

The relative humidity at both the interior and exterior faces of plywood sheathing was monitored hourly in WUFI, and all hours during which the sheathing experienced RH at or above 95% were considered to have the potential for condensation. A threshold of 95% was chosen in order to conservatively provide a margin for simulation error. Rather than quantifying hours at or over 100% RH, the 5% margin of error is intended to serve as a conservative strategy grounded in WUFI's well-documented lack of precision at elevated relative humidities (Kunzel, 1995).

After compiling all relative humidity data, analysis did not reveal any relative humidity values over 85% for any assembly tested, under baseline, air leakage, or even driving rain conditions. This was a highly unanticipated result, especially given the intuitive MC performance that will be demonstrated throughout the results sections to follow. Plausible explanations for this will be provided in the Discussion section, as well as recommendations for further research to understand more concretely the specific limitations of WUFI in analyzing this variable.

4.1.2 Potential for Mould Growth Onset

Based on criteria found in the literature, the threshold for the onset of mould in plywood was a moisture content above 20% occurring at temperatures above 5 C. Because mould spores may form in localized areas of the wall assembly and spread biologically, both the interior and exterior quartiles of the plywood sheathing were analyzed. Results are presented below in Figure 4.1.2 in the form of annual risk hours for each of the thirteen assemblies, under baseline, air-leakage, and driving-rain penetration conditions.

It is noteworthy that, under the baseline, ORNL-defined climate conditions, every split-insulated wall tested outperformed the 38mm x 140mm (2x6), interior insulated, base-case assembly. This indicates the resilience associated with increasing the temperature of plywood sheathing in Vancouver's wet climate.

Looking closely at the results of the air-leakage testing, it is important to note that, with the exception of experimental assemblies 10-13, only Wall 4, which is a 38mm x 140mm (2x6) split-insulated wall with 51mm (2") of exterior XPS, experienced any potential for mould growth. This indicates that the temperature regime in the assembly was such that the plywood sheathing experienced hours below its dewpoint temperature, and condensation occurred at the sheathing. Because of the low vapour transmission of XPS, this condensation was unable to dry to the exterior, which is the direction that the vapour drive exists for most of the year in Vancouver. This is supported by the higher risk hours measured at the exterior of the sheathing as compared to the interior, indicating that the vapour was being driven outwards but was unable to exit the assembly into the ventilation airstream. It is evident that the experimental walls 10-13 experienced a similar inhibition of drying potential into the airstream by the vapour transmission resistance factor associated with even the relatively thin exterior insulation.

Also of note is that the mineral wool assemblies experienced relatively superior hygrothermal performance as compared to interior insulated and XPS split-insulated assemblies under all loading regimes. Even with a rate of driving rain penetration that resulted in potential mould onset for nearly 35% of the year in the baseline assembly, the split-mineral wool assemblies (2,3,6 and 7) experienced virtually no potential for mould onset. This is likely because any adhering bulk water was driven outwards into the ventilation airstream by the large, vapour pressure gradient occurring at the sheathing, and was not inhibited by layers with high resistance to vapour transmission.

Note that throughout these charts, as well as all similar analyses, the generic nomenclature “Assembly_int” and “Assembly_ext” will be used to distinguish results obtained from moisture sensors placed in the inner and outer quartiles of plywood, respectively.

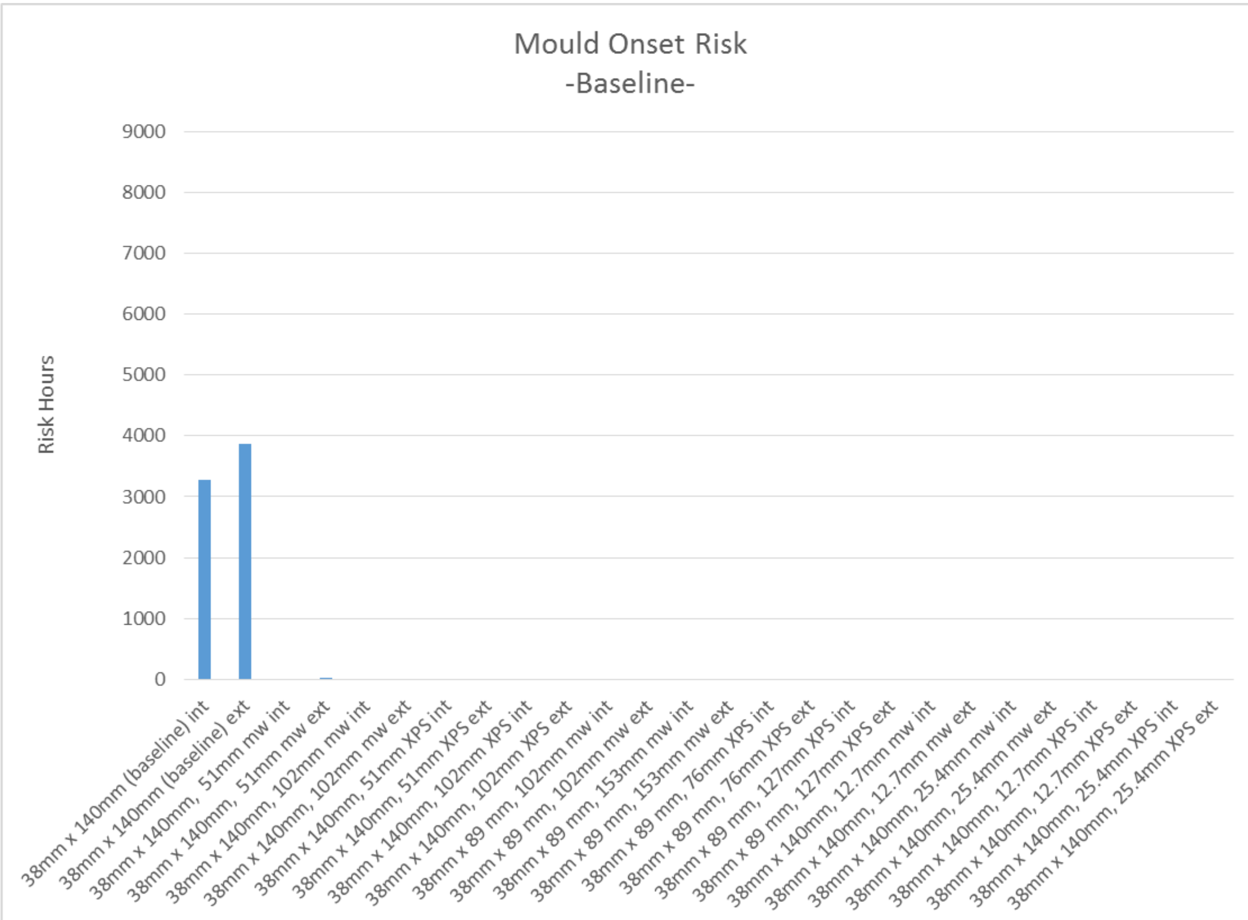


Figure 4.1.7: Potential for mould onset under baseline hygrothermal conditions

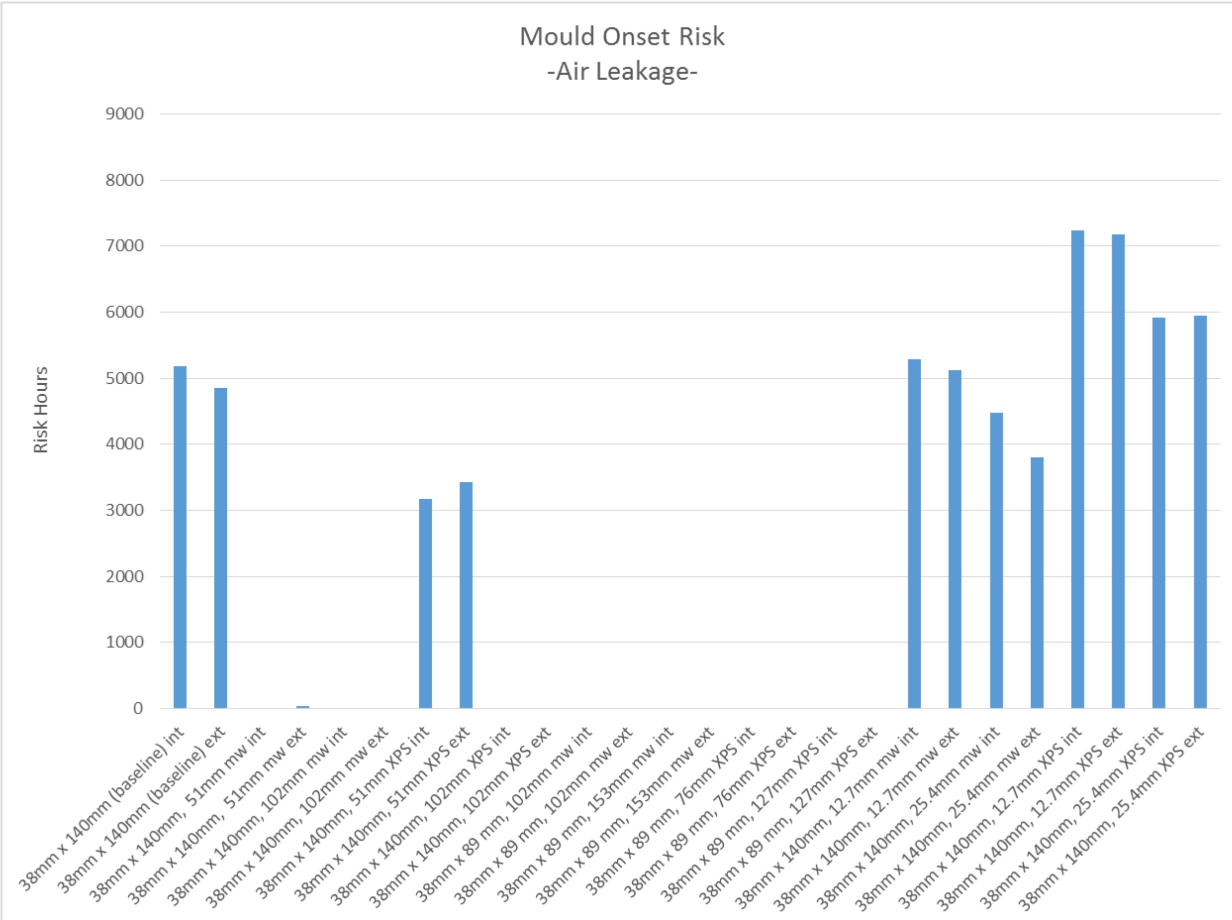


Figure 4.1.8: Potential for mould onset under air leakage regime

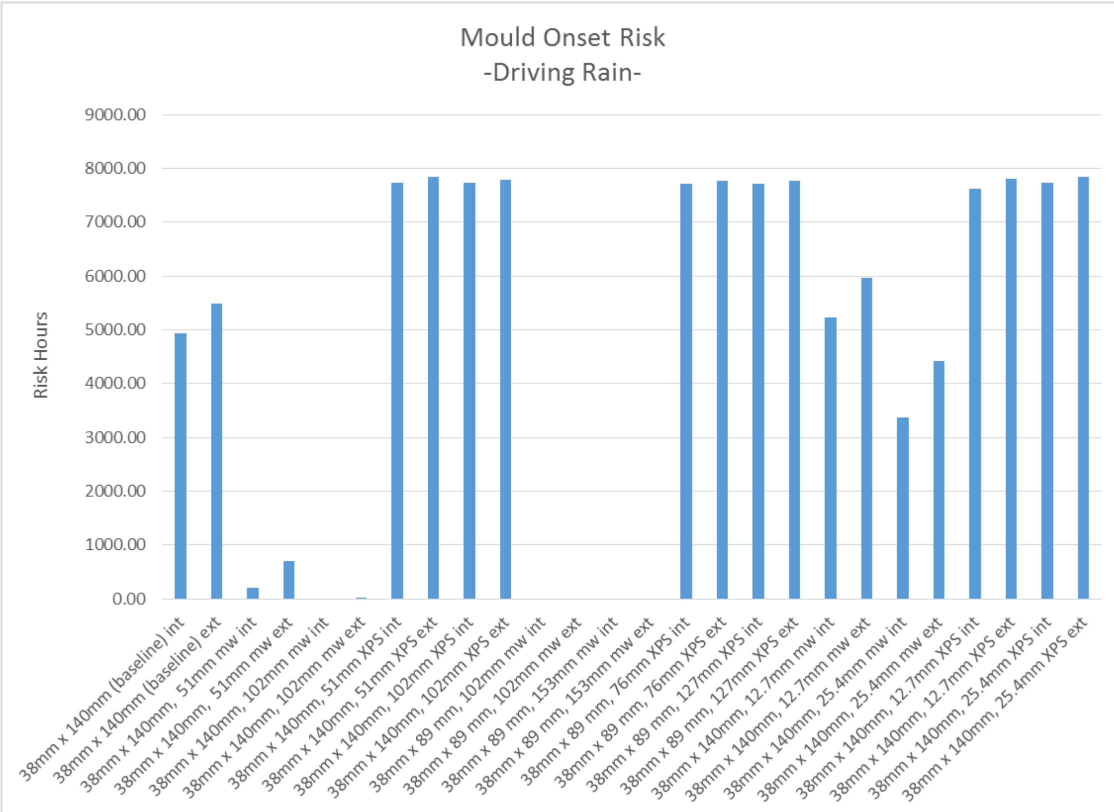


Figure 4.1.9: Mould onset risk under driving rain penetration.

4.1.3 Potential for Decay

The notion of precise criteria necessary for the decay of plywood sheathing is heavily debated in the literature; in order to provide a conservative basis for comparison, decay has been defined to potentially occur in any hour during which the moisture content is at or above 30% by mass, and to continue lasting until its MC has fallen below 20%(Fox, 2013). Additionally, for any period to meet the standards of 'decay,' temperature must be at or above 5 degrees Celsius, as mould growth is highly unlikely at lower temperatures (Sedlbauer, 2010).

The results of the potential decay analysis are presented for Vancouver in Figures 4.1.10 through 4.1.12 below:

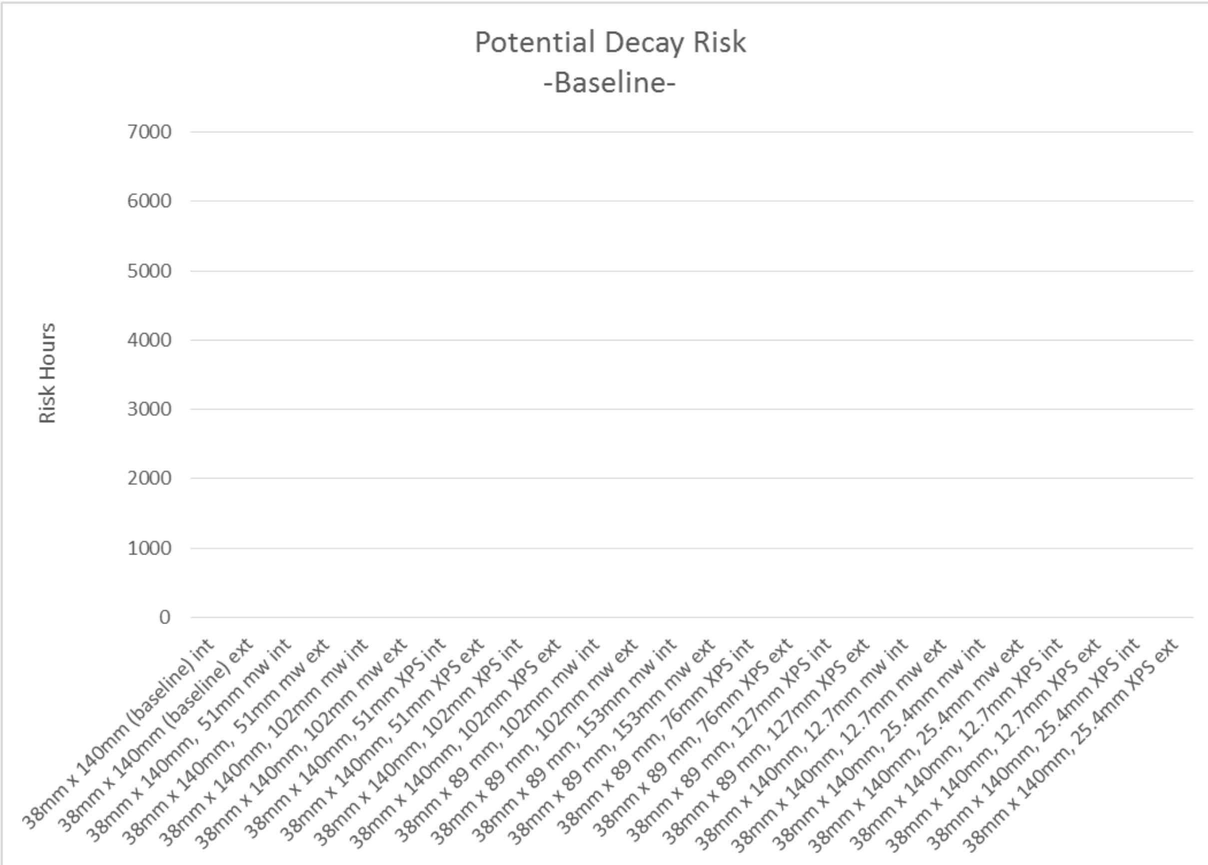


Figure 4.1.10: Potential decay risk under baseline hygrothermal conditions

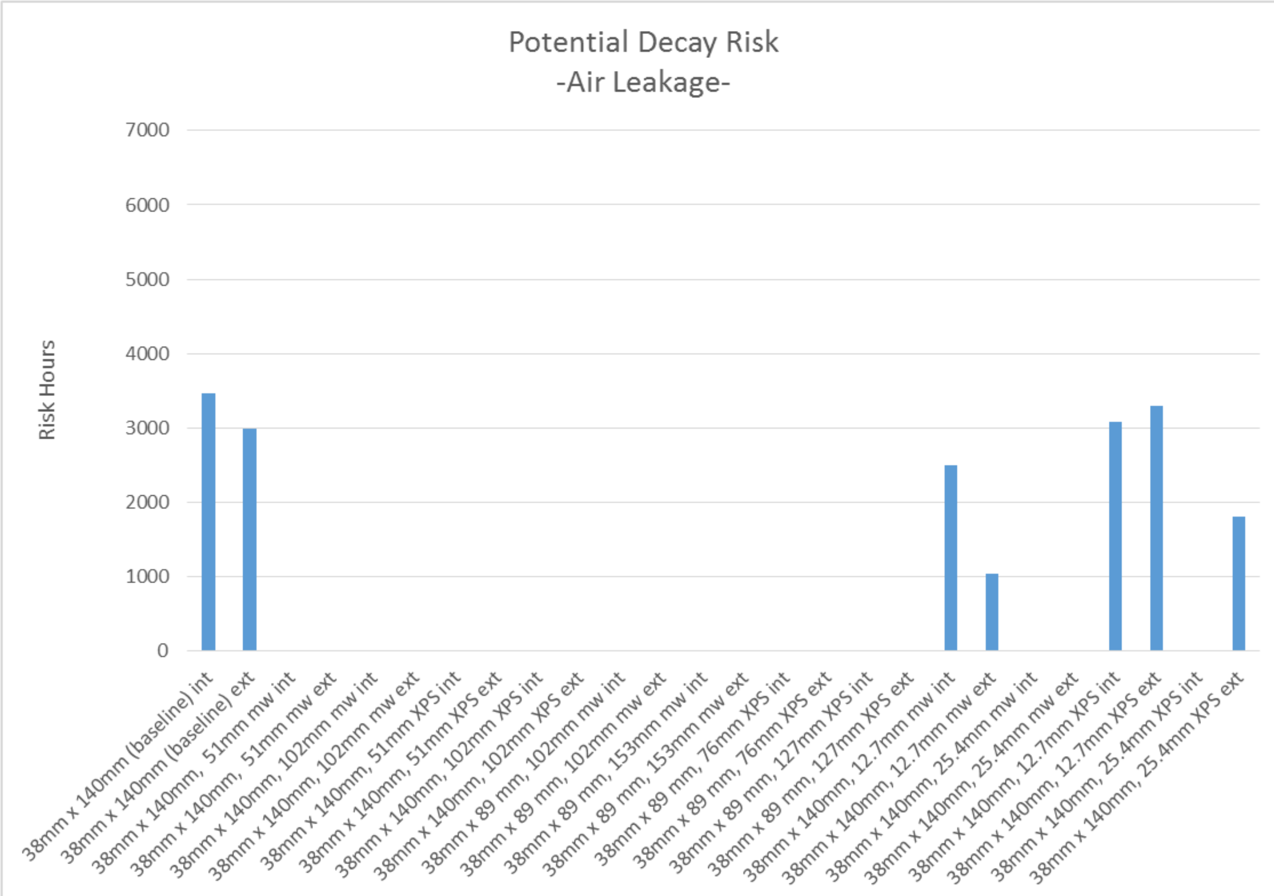


Figure 4.1.11: Potential decay risk under air leakage regime. Air leak is introduced to inner face of sheathing.

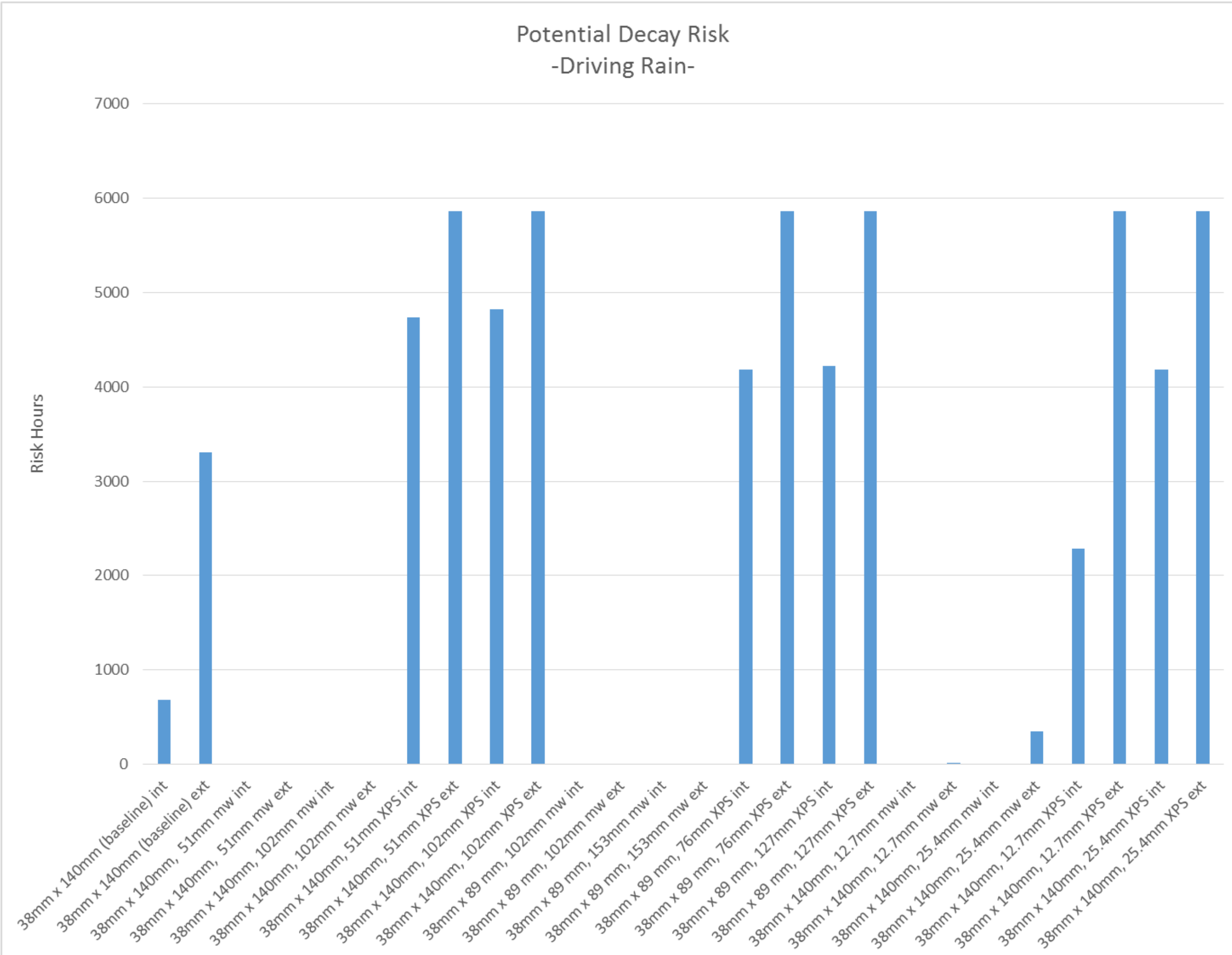


Figure 4.1.12: Potential decay risk under driving rain penetration. Leak is introduced to exterior face of sheathing.

Of immediate note is the lack of decay potential for any of the 13 assemblies under baseline conditions. This implies that, if moisture is not introduced to the sheathing from a source other than vapour diffusion (i.e either through air leakage or driving rain penetration), the assemblies are unlikely to experience any potential decay. However, eliminating moisture ingress is unlikely to occur in practice (Straube and Burnett, 2005). Under an air leakage regime resulting in potential decay for approximately 35% of hours in one year, all high-RSI assemblies perform well, exhibiting no potential decay hours. Only the experimental, split-insulated assemblies show potential for decay, which is intuitive for the same reasons described in section 4.1.2. Finally, under a rate of driving rain penetration that results in significant potential decay in the exterior quartile of the plywood and moderate hours of decay risk in the inner quartile, assemblies 4,5,8 and 9 all experience substantially elevated hours of potential decay as compared with the baseline assembly, while assemblies 2,3,6 and 7 experience no risk of decay. Of the experimental, non-high-RSI assemblies, numbers 10 and 11 (split-insulated with mineral wool exterior) perform significantly better than 12 and 13 (split-insulated with exterior XPS).

4.2 Toronto

Toronto, Ontario, which is Canada's largest metropolitan area, was also analyzed in order to provide data for a highly relevant geographical area of the Canadian economy. With a booming small-building construction sector in the areas surrounding the Downtown core, the economic impact of Toronto's housing market is enormous. Therefore, so too are the effects of improved durability in high-RSI assemblies. Toronto's climate is far more extreme than Vancouver's, both in heating and cooling seasons, and is typically categorized under IECC Zone 5 or 6, depending on the specific year of analysis. Note that the rates of air leakage and driving rain penetration were found to be 0.75 ACH and 0.1% penetration, respectively. The primary driving rain exposure was found to be the Northwest face, while air leakage and baseline simulations were conducted for the South façade. The results of all three hygrothermal loads are presented graphically below in figures 4.2.1 through 4.2.6 in order to facilitate a qualitative understanding of performance predicted for each assembly under various hygrothermal loadings:

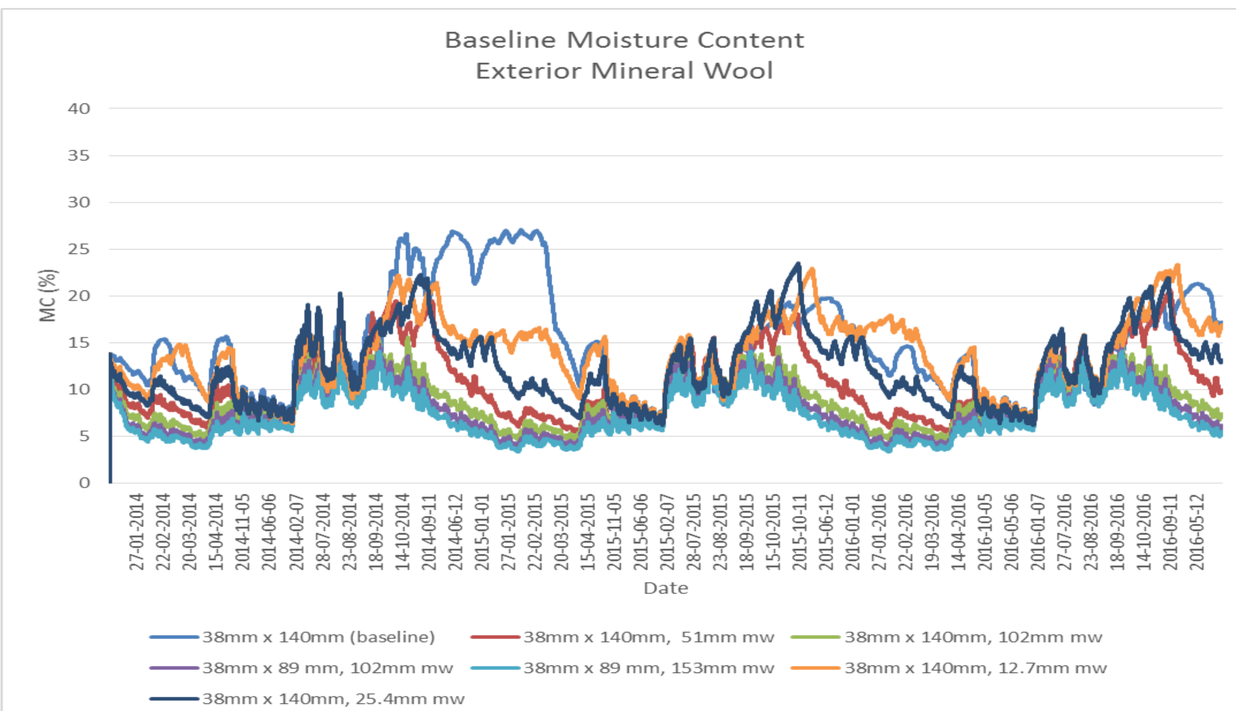


Figure 4.2.1: Baseline MC with exterior mineral wool

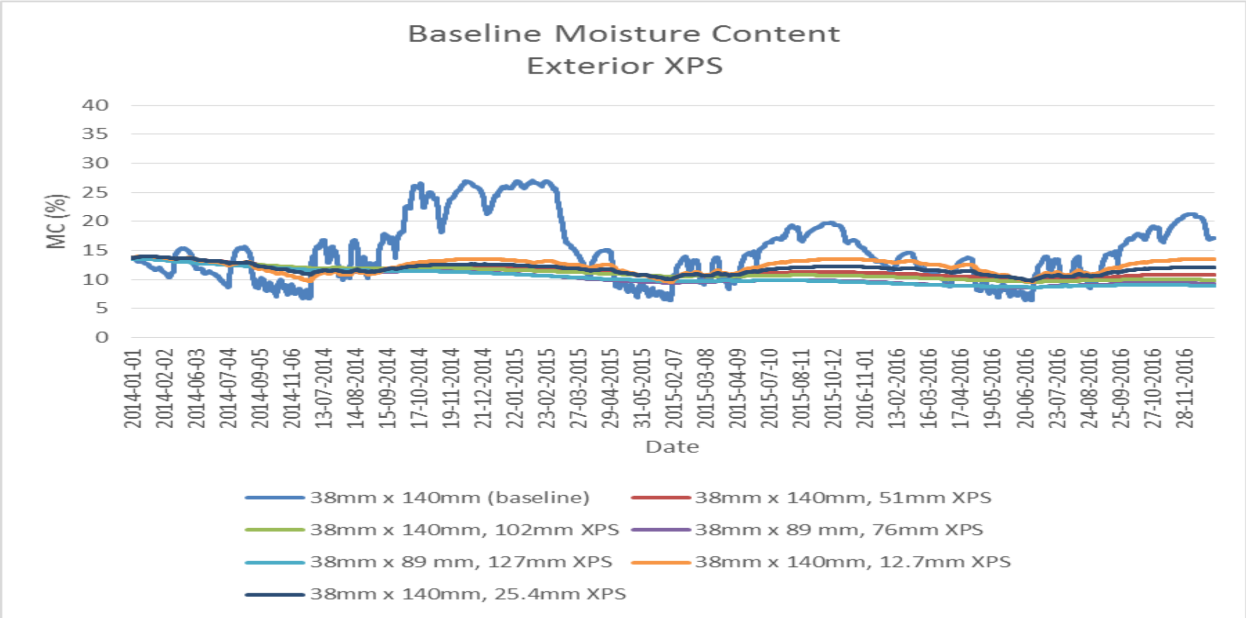


Figure 4.2.2: Baseline MC with exterior XPS

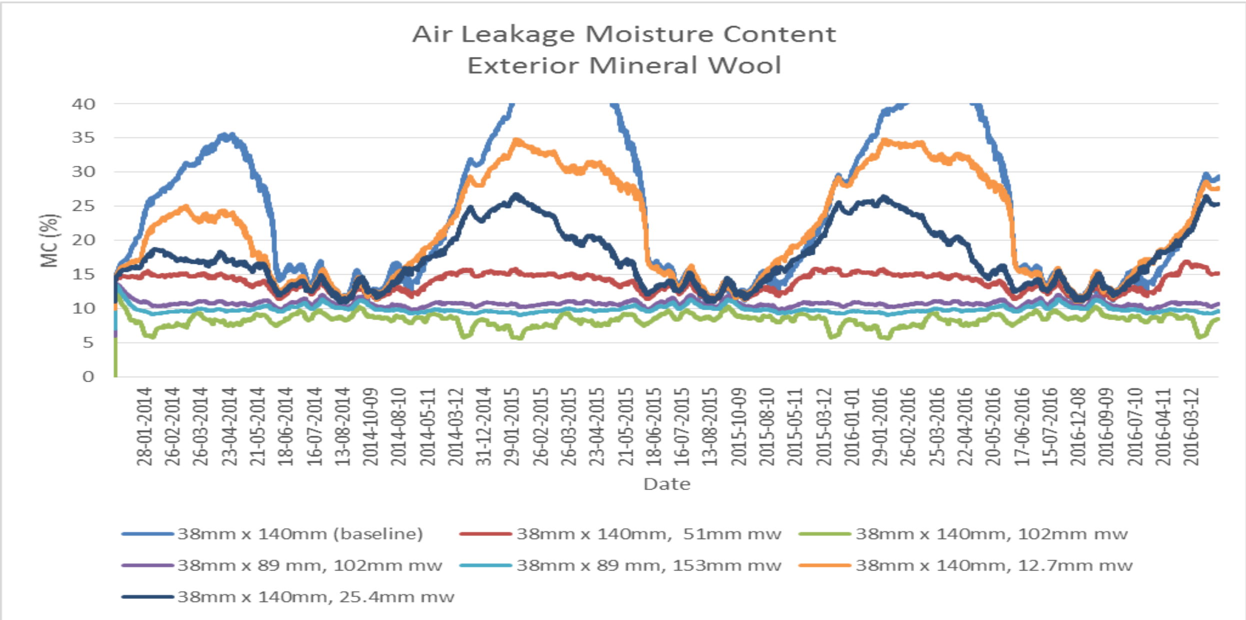


Figure 4.2.3: Air leakage MC with exterior mineral wool

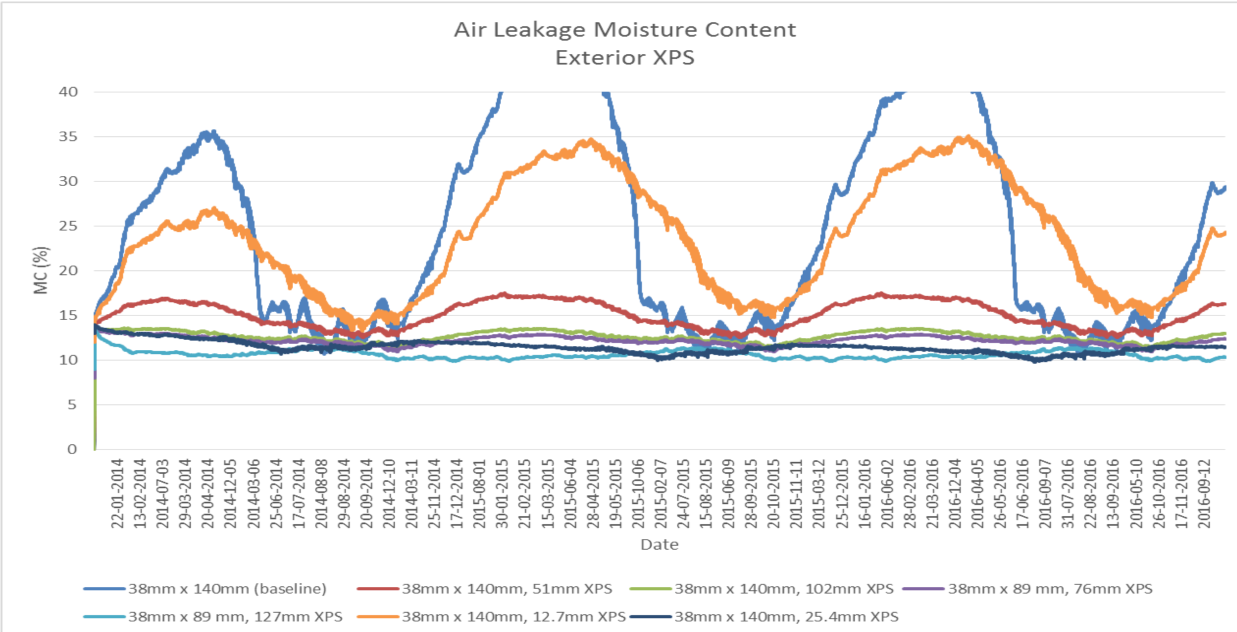


Figure 4.2.4: Air leakage MC with exterior XPS

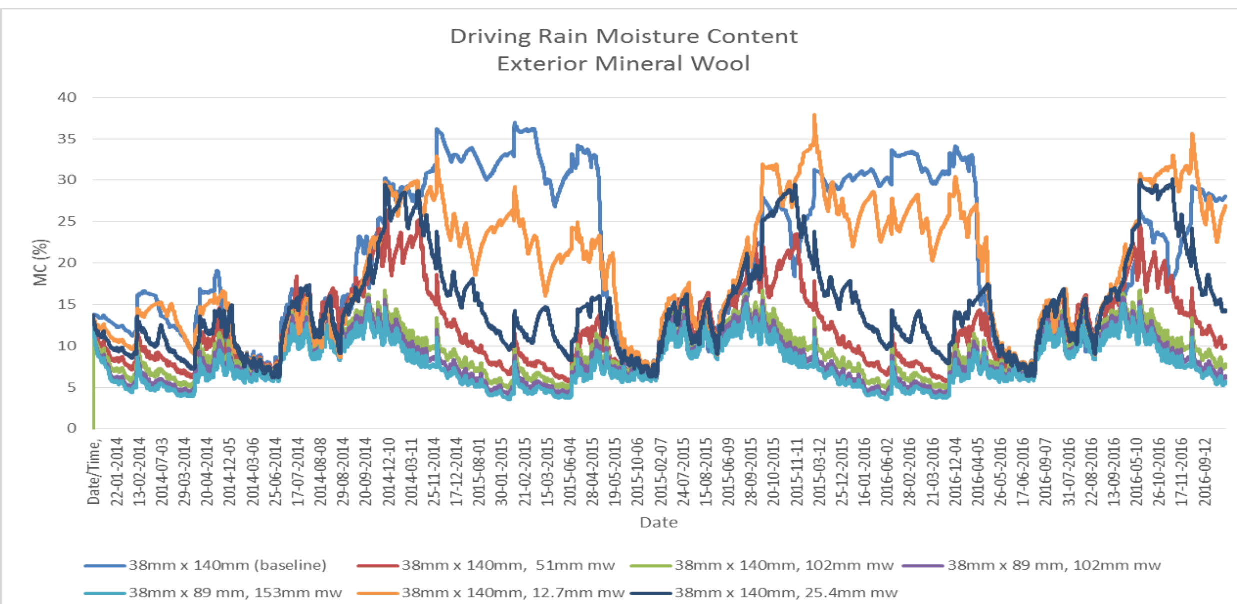


Figure 4.2.5: Driving rain MC with exterior mineral wool

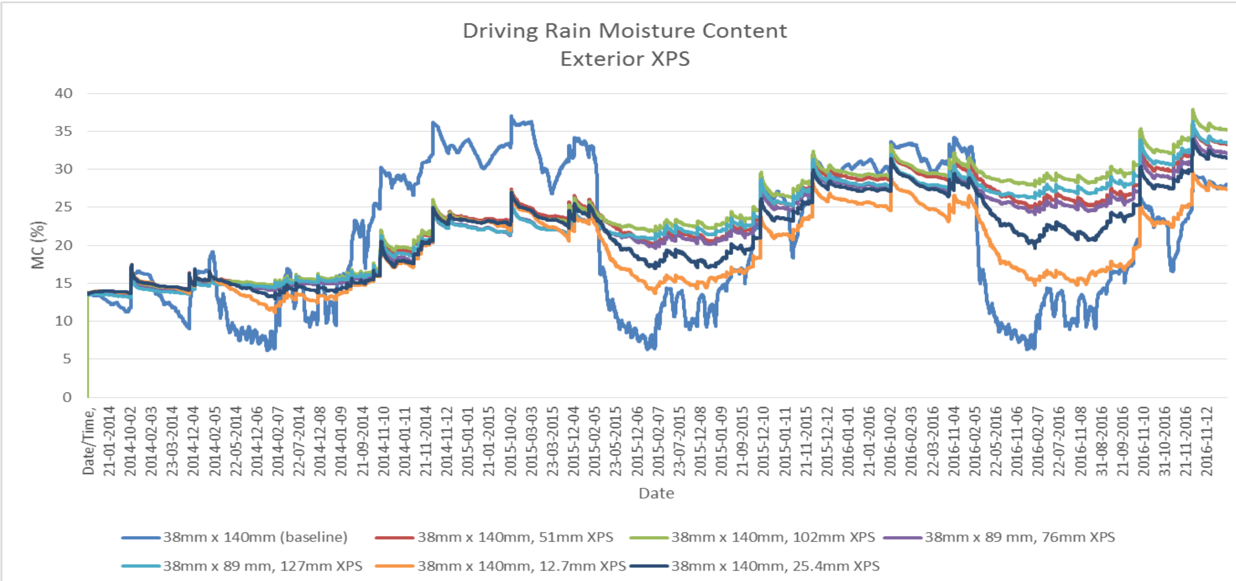


Figure 4.2.6: Driving rain MC with exterior XPS

Again, certain trends can be extrapolated from these charts; to start, it is clear that only the baseline and experimental, mineral wool assemblies exceed 20% MC in the absence of hygrothermal loading by air leakage or driving rain penetration, indicating that none of the high-RSI test assemblies will experience potential mould onset under baseline conditions. Under air leakage into the assembly, the baseline assembly again experiences MC of well over 30% for what appears to be a few weeks during the winter; once again, only the experimental, non-high-RSI assemblies appear to experience elevated MC under this regime. Finally, driving rain penetration represents the most dangerous hygrothermal loading experienced by any of the assemblies with respect to moisture content elevation; virtually every XPS assembly experiences MC that appears to exceed failure criteria, and seems to worsen as time goes on, as opposed to mineral wool assemblies that appear to indicate adequate drying ability. Interestingly, the high-RSI XPS assemblies do not appear to wet as substantially as they did in Vancouver, a result which will be examined in the Discussion section.

4.2.1 Condensation Risk Assessment

Using the same criteria as described in Vancouver, a condensation risk assessment was performed for each of the thirteen wall assemblies, under baseline, air-leakage, and driving rain penetration conditions in Toronto's climate. Once again, a surface relative humidity reading greater than 85% was not recorded at either the inner or outer plywood RH sensors for any period of time, therefore the results of condensation risk assessment were again null.

4.2.2 Potential for Mould Growth Onset

Again, the potential for mould growth onset was studied for the 13 different assemblies, under similar exposure regimes in Toronto. This has the ability to provide valuable, climate-sensitive data regarding the factors influencing the mould growth potential in split-insulated, high-RSI assemblies. Toronto's relatively more extreme temperatures, and lower wintertime moisture loads will provide an interesting basis for comparison to assembly performance in Vancouver's climate as in Section 4.1.2. These results were plotted in the form of annual risk hours based on Mould Growth Onset parameters of >20% MC and 5 degrees C. Again, both the inner and outer quartile of the sheathing were monitored.

Results describing the annual hours of potential mould onset can be found below in figures 4.2.7 through 4.2.9:

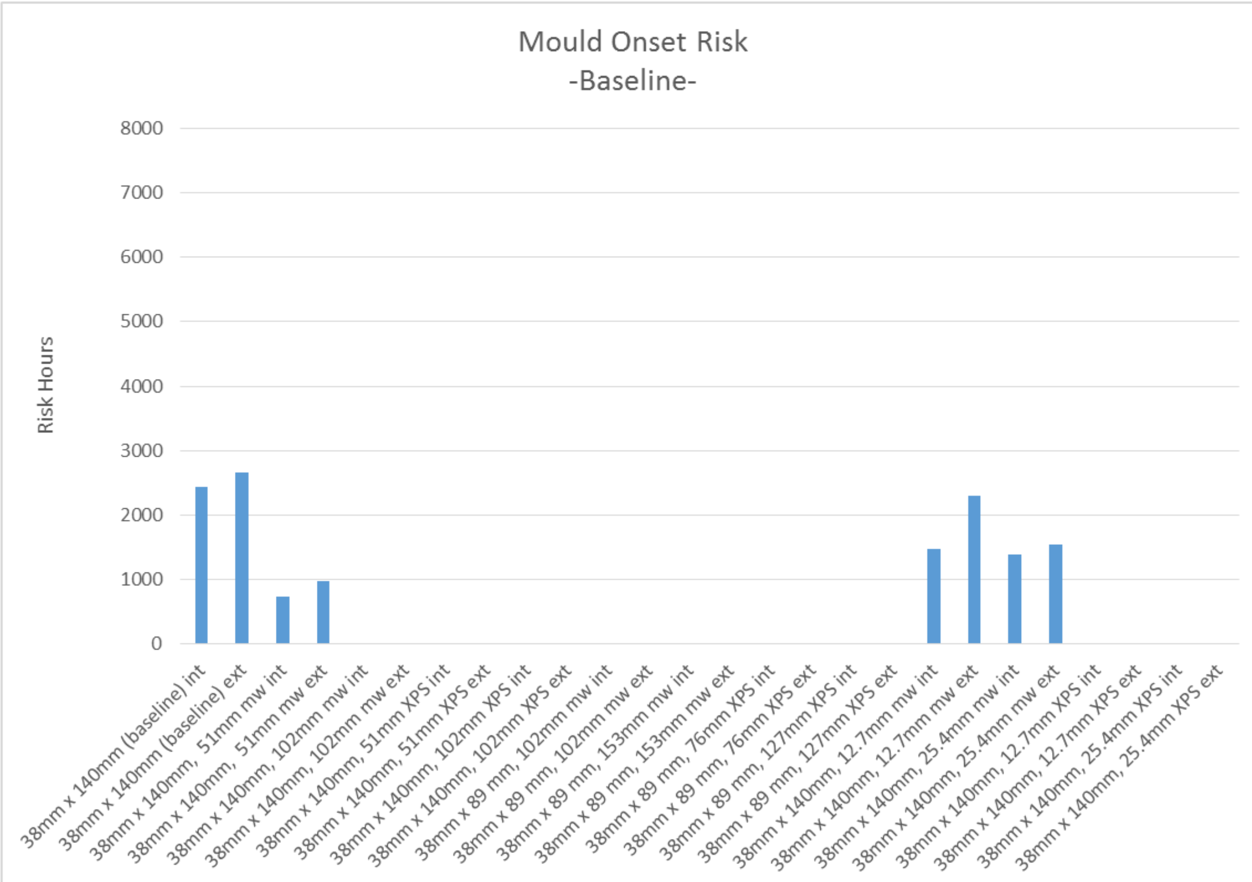


Figure 4.2.7: Mould onset risk under baseline hygrothermal conditions

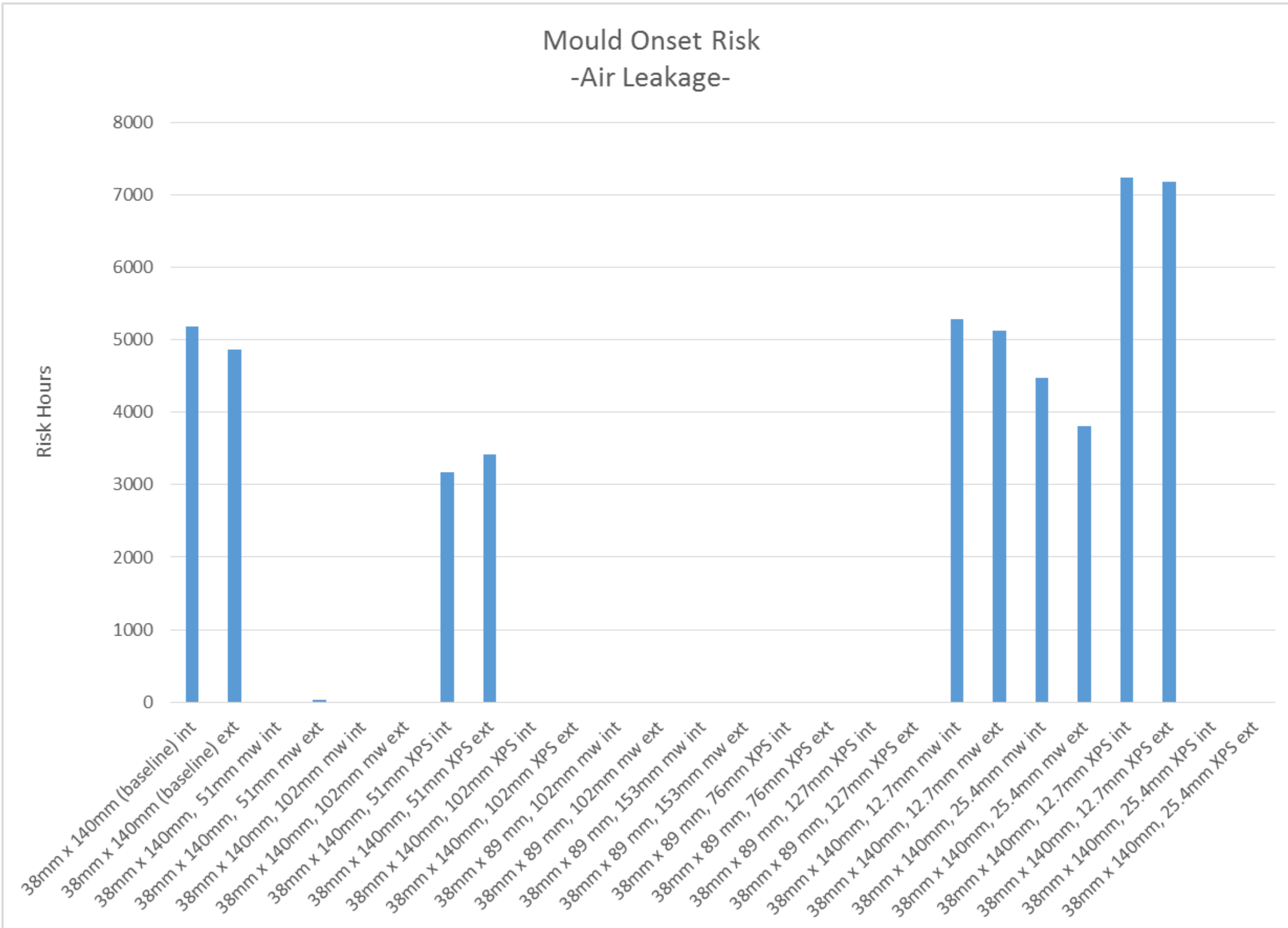


Figure 4.2.8: Mould onset risk hours under air leakage

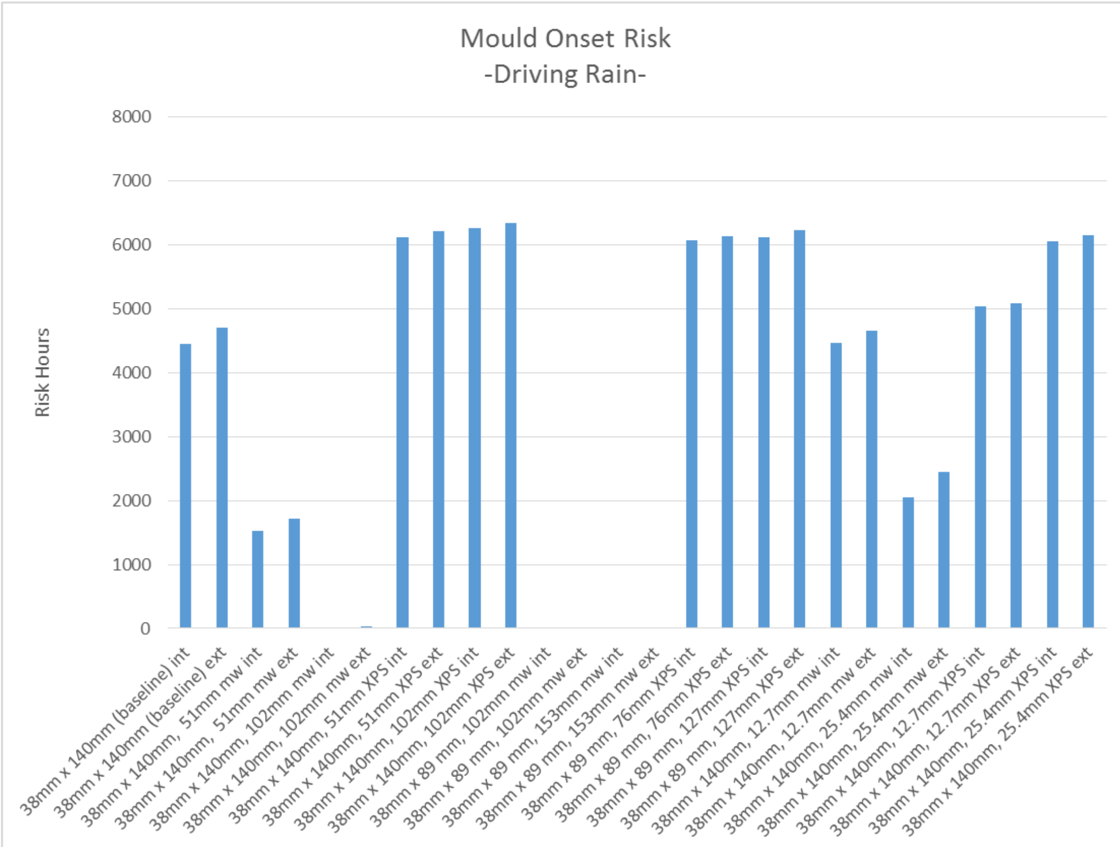


Figure 4.2.9: Mould growth risk house under driving rain regime.

It is noteworthy that, under baseline conditions, the only high-RSI, split-insulated assembly that experienced any periods wherein mould could potentially develop was Assembly 2, which is the baseline wall with 51mm (2") of exterior mineral wool. Likely, this captures the inward vapour drive of summer sun-driven moisture, either from the backside of the cladding, the SPBO, stored in the mineral wool itself, or even from the outdoor air itself as a moisture source. The relatively high vapour permeance of the mineral wool likely permits more inward transmission of water vapour, and because this phenomena is likely to occur in the summertime, surface temperatures will tend to be above 5 degrees C in this climate.

Under a rate of air-leakage that causes periods of dangerously elevated MC in the baseline assembly, the only high-RSI split-insulated assembly to experience potential for mould growth is Assembly 4, with a full 140mm (5.5") of batt insulation, and only 51mm (2") of exterior XPS. This indicates that the temperature regime in the assembly experiences periods of sheathing surface temperature below the relevant dewpoint conditions, and the exterior XPS restricts drying outwardly into the ventilation airstream.

Lastly, it is apparent that the mould-growth potential for driving rain is highly elevated in split-insulated assemblies with exterior XPS, but largely absent in those with equivalent RSI allocations using exterior mineral wool. As a relatively vapour-permeable material, mineral wool warms the sheathing (therein reducing its susceptibility to moisture accumulation) and permits substantial drying through outward vapour diffusion drying into the ventilation airstream, where it is convectively removed from the assembly. In practice, mineral wool's ability to drain freely due to gravity likely also facilitates substantial drying, provided the assembly is properly detailed; however, this effect cannot be simulated in WUFI. XPS on the other hand, likely creates upward capillary forces at the interface of the insulation and SBPO membrane, and does not permit a substantial amount of outward diffusion drying due to its low vapour permeance.

4.2.3 Potential for Decay

Consistent with observed performance, baseline walls (assembly 1) experience less than 100 hours annually of potential decay, without substantial hygrothermal loading. Again, decay has been defined as MC > 30%, counting hours until MC < 20%, T >5C. Interestingly, none of the high-RSI assemblies show signs of potential decay under a rate of air leakage that causes the baseline assemble to experience about 35% of the year as 'at-risk.' This can be explained by the surface temperature at the sheathing exceeding the dewpoint temperature for the entire sampling period. Again, driving rain is predicted to create an alarming portion of the year that can be categorized as 'potentially decaying' for XPS split-insulated assemblies, and no potential decay in mineral wool split-insulated assemblies; however, it is interesting to note that, as opposed to the results obtained in Vancouver, simulation of the high-RSI assemblies under driving rain penetration does not suggest that XPS performs substantially worse than the baseline assembly in Toronto's climate.

Results describing the annual risk of hygrothermal decay for all assemblies under baseline, air leakage and driving rain penetration are presented below in figures 4.2.10 through 4.2.12:

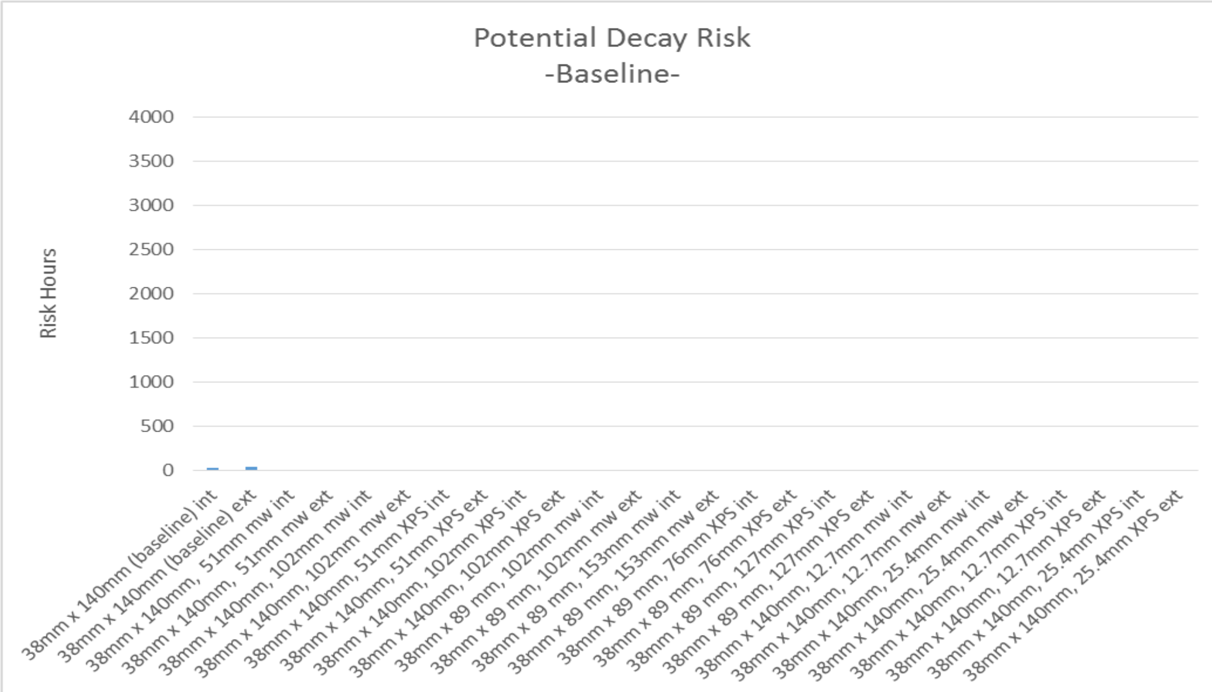


Figure 4.2.10: Potential decay risk under baseline hygrothermal conditions

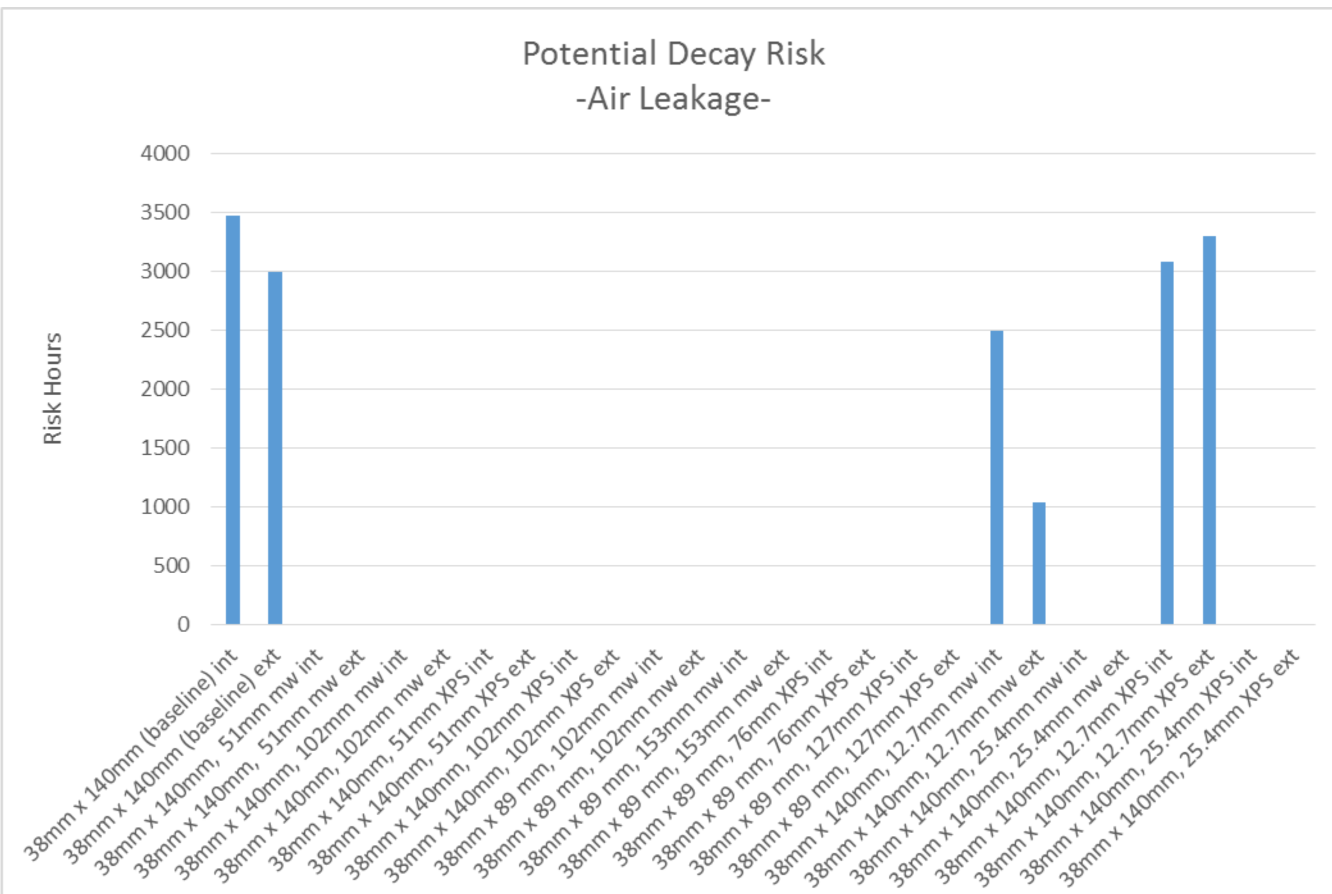


Figure 4.2.11: Potential decay risk under air leakage delivered to interior face of plywood

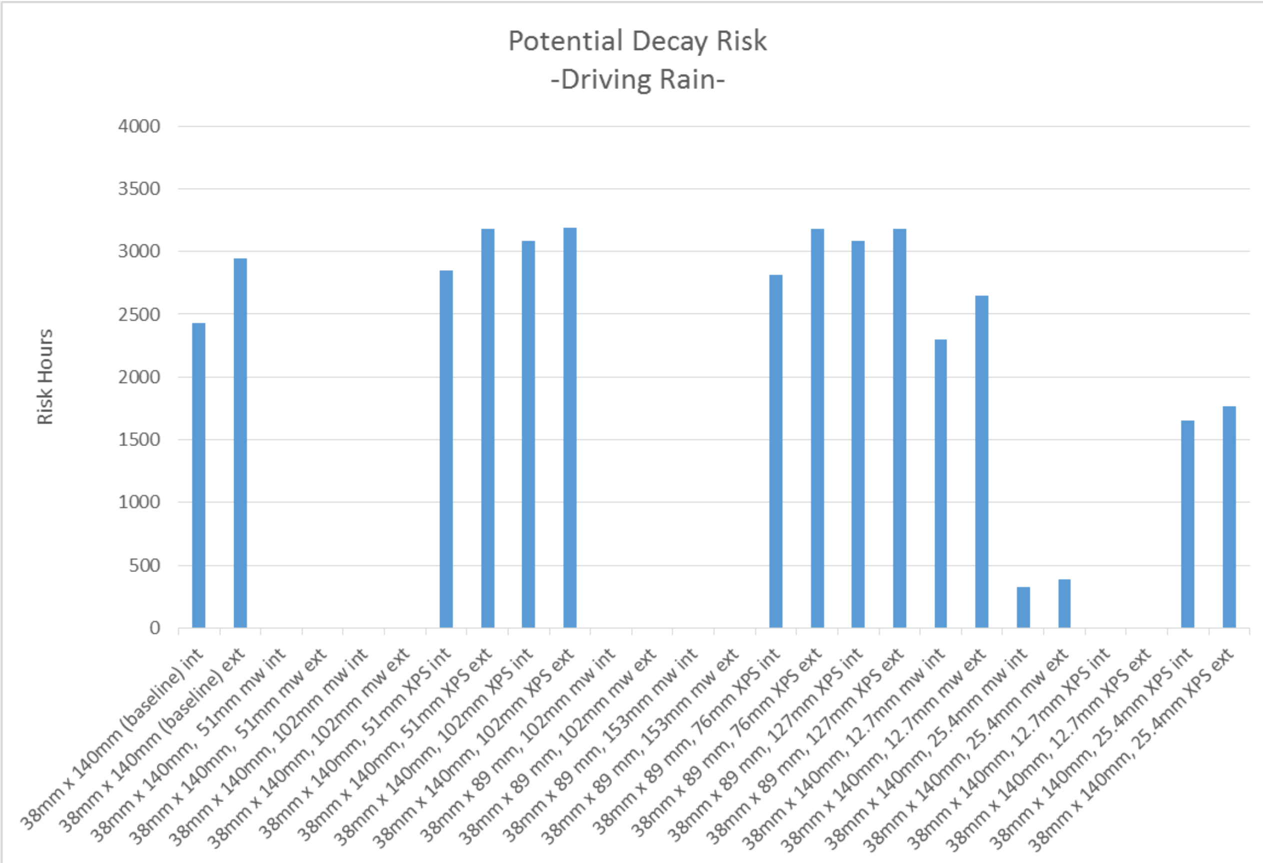


Figure 4.2.12: Potential for decay under driving rain penetration. Leak is delivered to exterior face of sheathing.

4.3 Edmonton

Edmonton, Alberta, as the fifth most populous municipality in Canada and hub of rapid economic growth and expansion, is an important economic zone and a challenging climate in which to construct durable buildings. Categorized by the International Energy Conservation Code (IECC) as climate zone 7B, Edmonton has over 10,500 heating degree days and is therefore representative of one of the coldest, population and construction centres in Canada (IECC, 2009). Figures 4.3.1 through 4.3.6 show present moisture content under baseline, air leakage, and driving rain penetration regimes and are again presented below to gain a qualitative understanding of the various assemblies' performances.

After performing sensitivity analyses for both driving rain penetration and air leakage, rates of 0.25% penetration and 0.2ACH were selected, respectively; the results of the analyses leading to selection of these values are presented in the Appendices. The primary orientation of driving rain exposure was determined from ORNL climate data to be the North-Western elevation. For baseline and air leakage tests, the Southern face was analyzed.

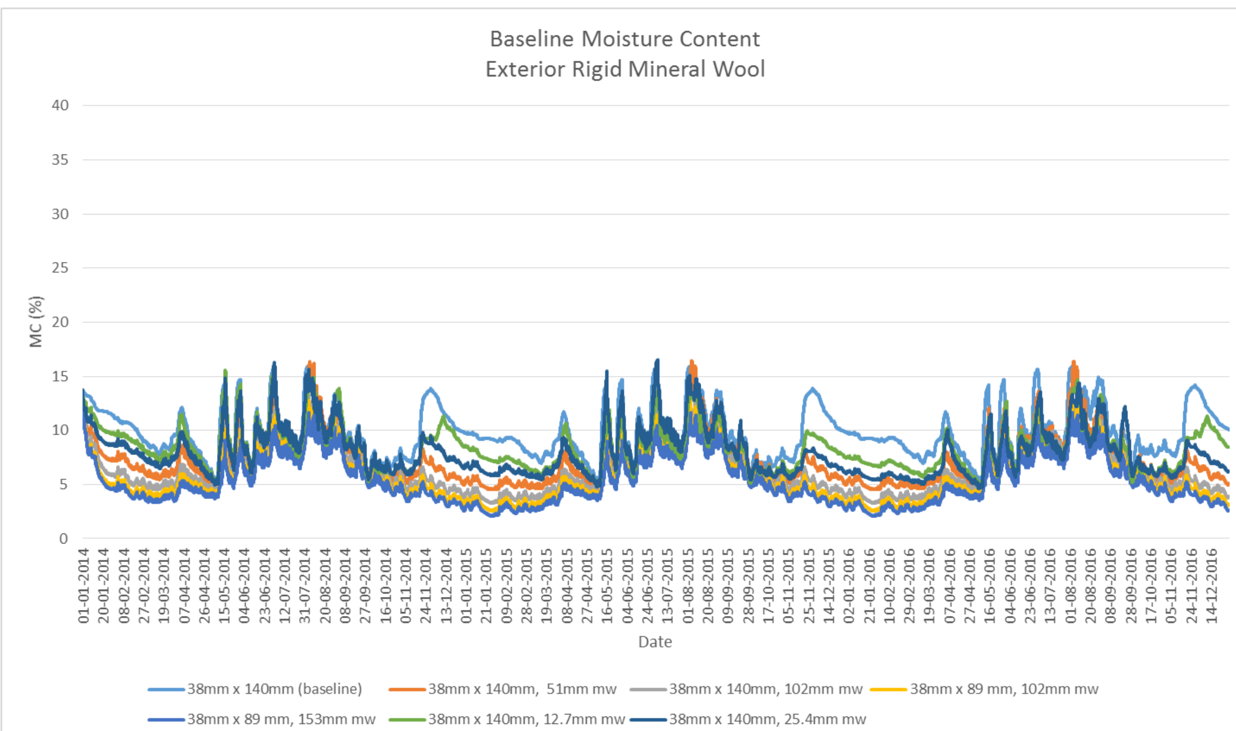


Figure 4.3.1 Baseline MC with exterior Mineral Wool

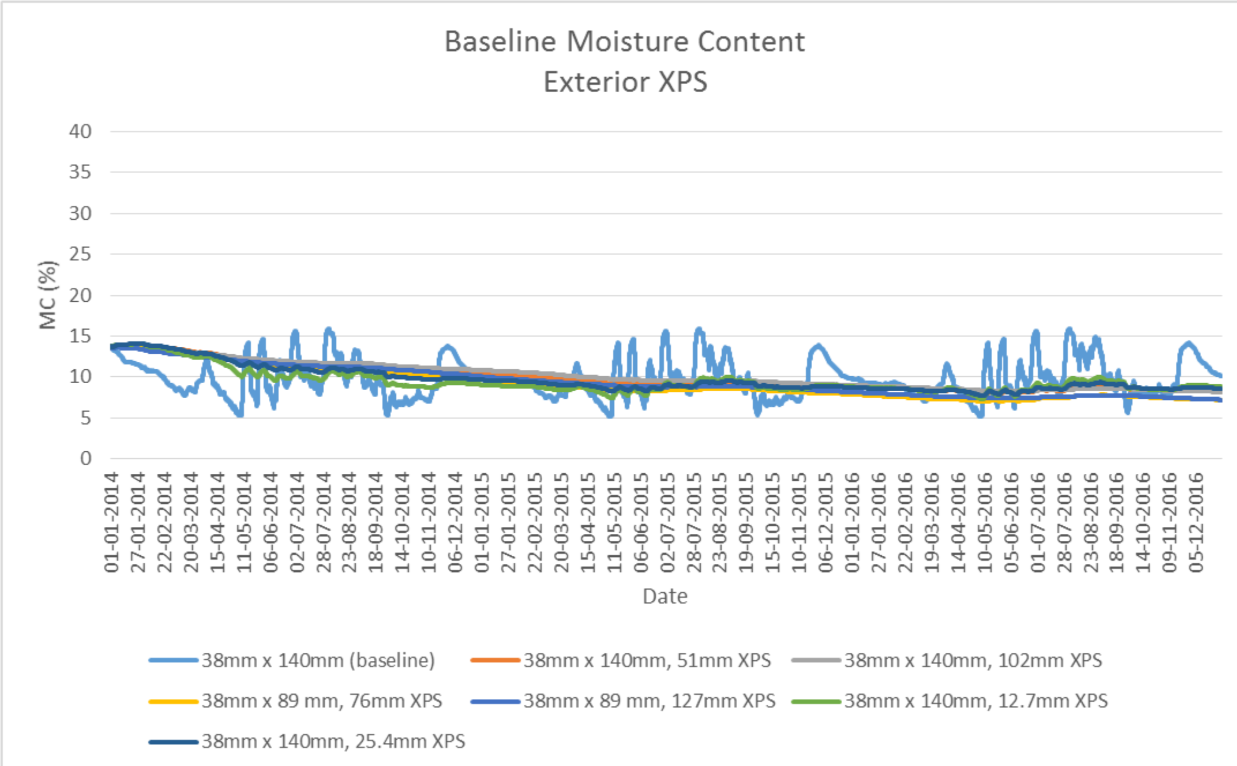


Figure 4.3.2: Baseline MC with exterior XPS

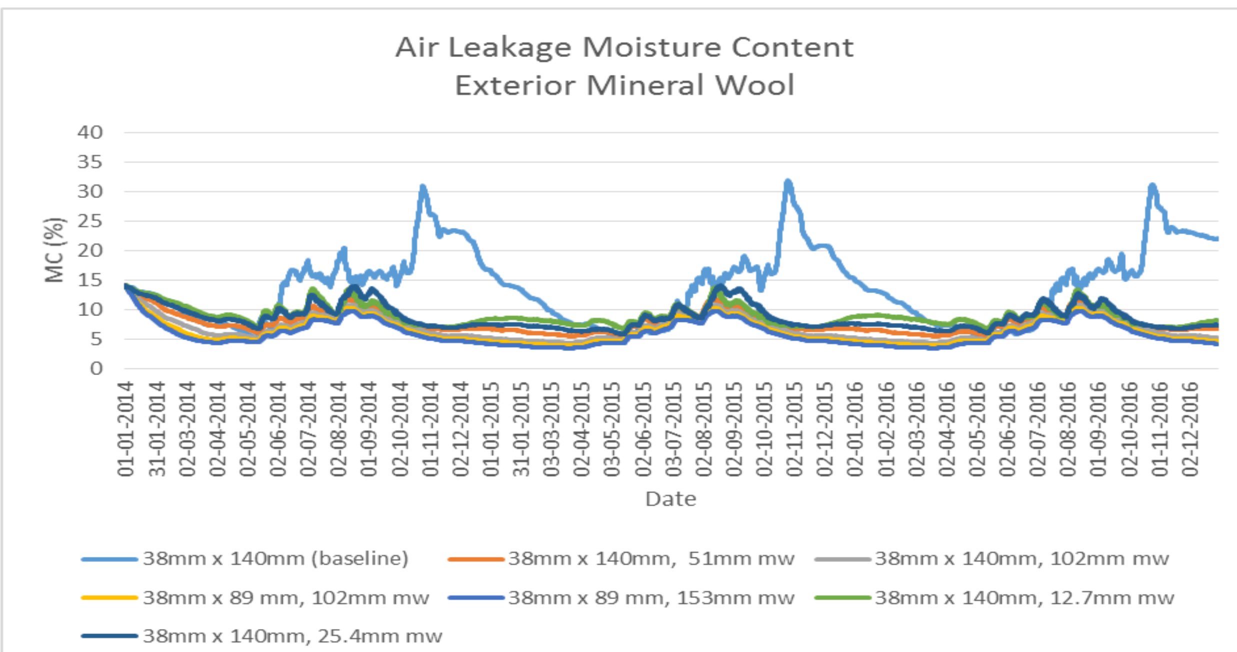


Figure 4.3.3: Air leakage MC with exterior mineral wool

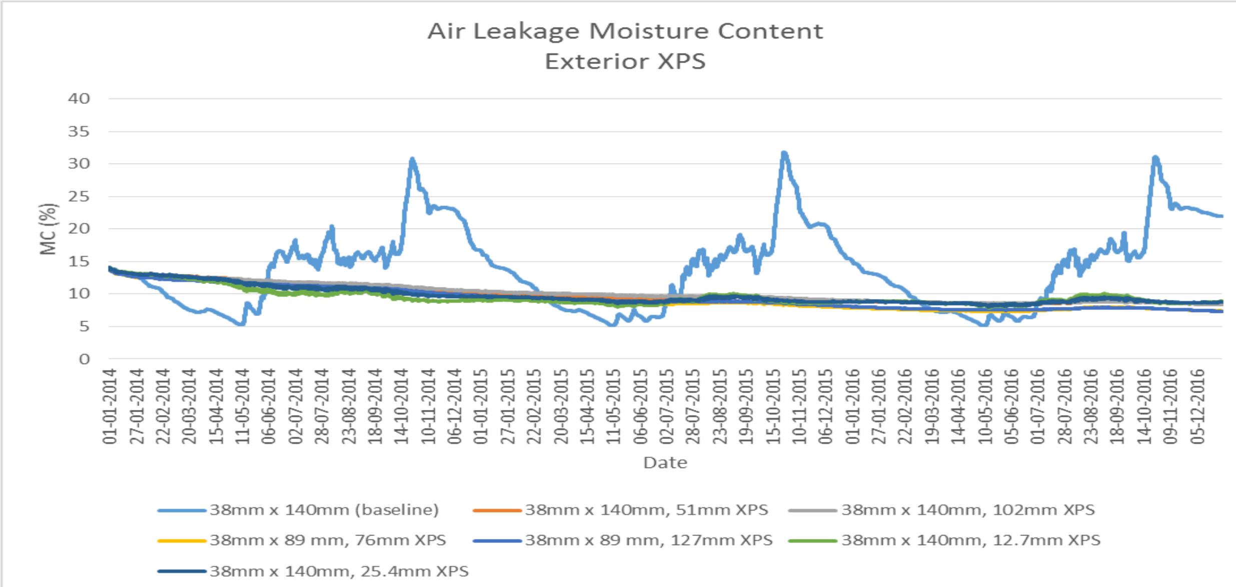


Figure 4.3.4: Air leakage MC with exterior XPS

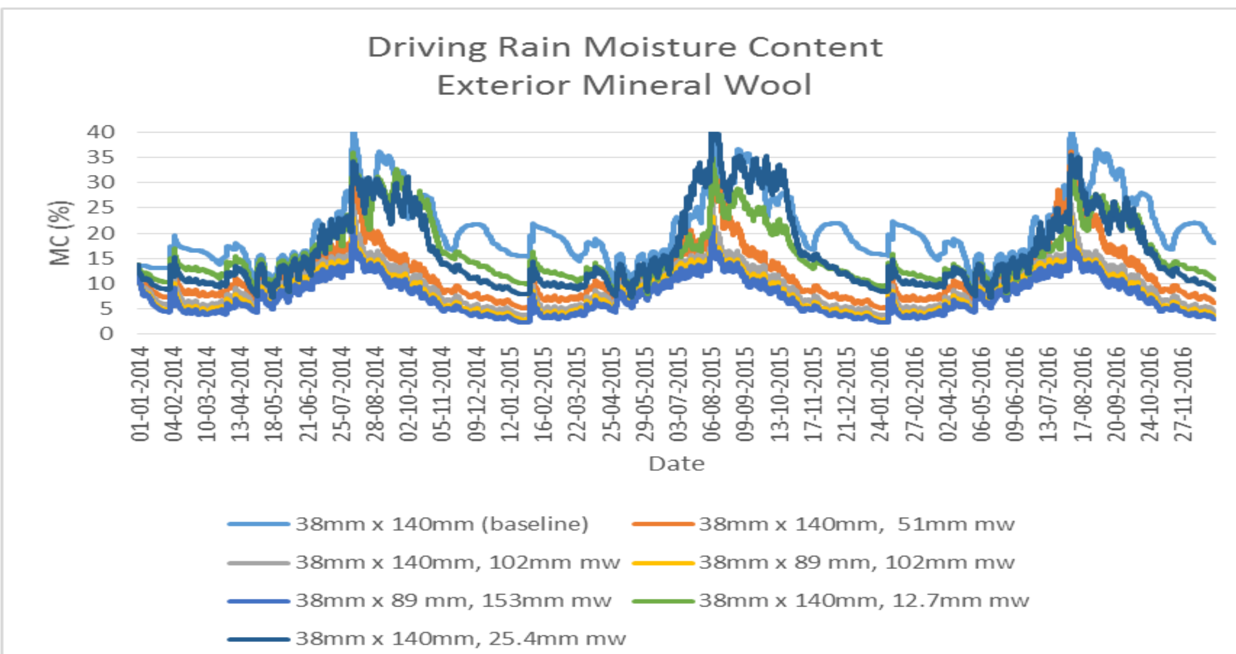


Figure 4.3.5: Driving rain MC with exterior mineral wool

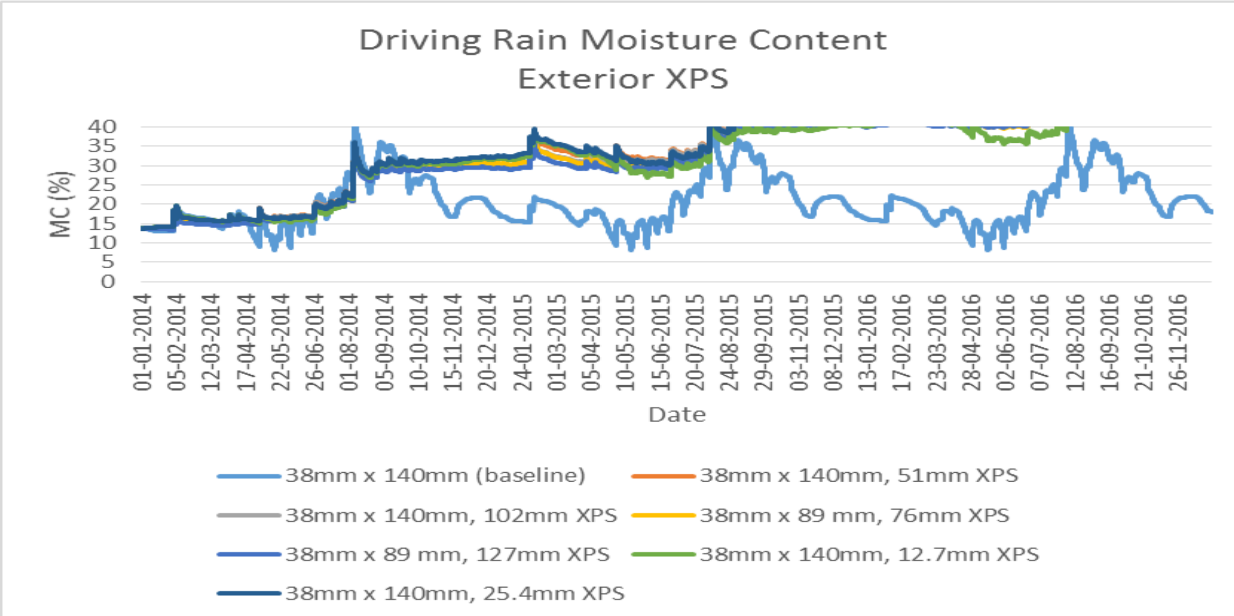


Figure 4.3.6: Driving rain MC with exterior XPS

4.3.1 Condensation Risk Assessment

Similar to the case studies in Vancouver and Toronto, none of the hygrothermal loadings yielded any surface RH result of over 85%, therefore each assembly once again did not experience any potential condensation. This result will be examined closely in the Discussion section, and possible explanations will be proposed. Edmonton represents perhaps the most reasonable case study wherein even air leakage would not result in elevated surface relative humidities, as the leaking air has a lower absolute moisture content than in the other cities based on the interior state point from which the air leak originates.

4.3.2 Potential for Mould Growth Onset

Using the same criteria as in the other two case studies (MC > 20%, T >5 C), potential for mould growth onset was quantified for each hygrothermal loading for all 13 test assemblies in Edmonton. Interestingly, under baseline conditions, only the interior insulated assembly experienced potential mould growth, with less than 100 hours annually. Additionally, air leakage introduced to the interior face of the sheathing failed to create any mould risk for all of the high-RSI assemblies, only yielding positive results for the interior-insulated and experimental 25.4mm mineral wool assembly. Driving rain penetration as described in Section 4.3 created dramatic instances of potential mould onset for every XPS assembly; however, as evinced in Figure 4.3.9, only assembly 2 (with 51mm of exterior mineral wool) experienced significant hours of potential mould onset out of the high-RSI, mineral wool assemblies.

Charts describing the mould onset risk for each assembly under all three loadings are presented below in figures 4.3.7 through 4.3.9:

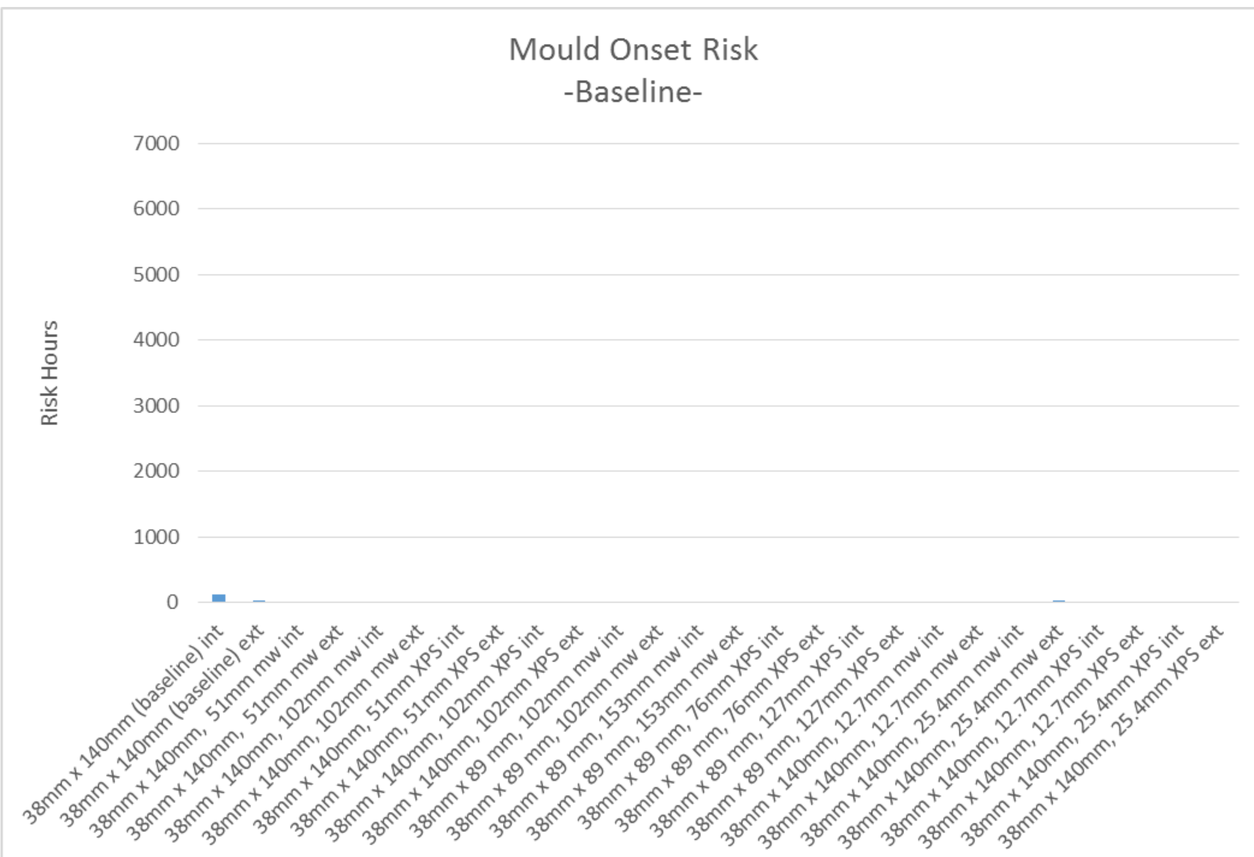


Figure 4.3.7: Mould onset risk under baseline hygrothermal conditions

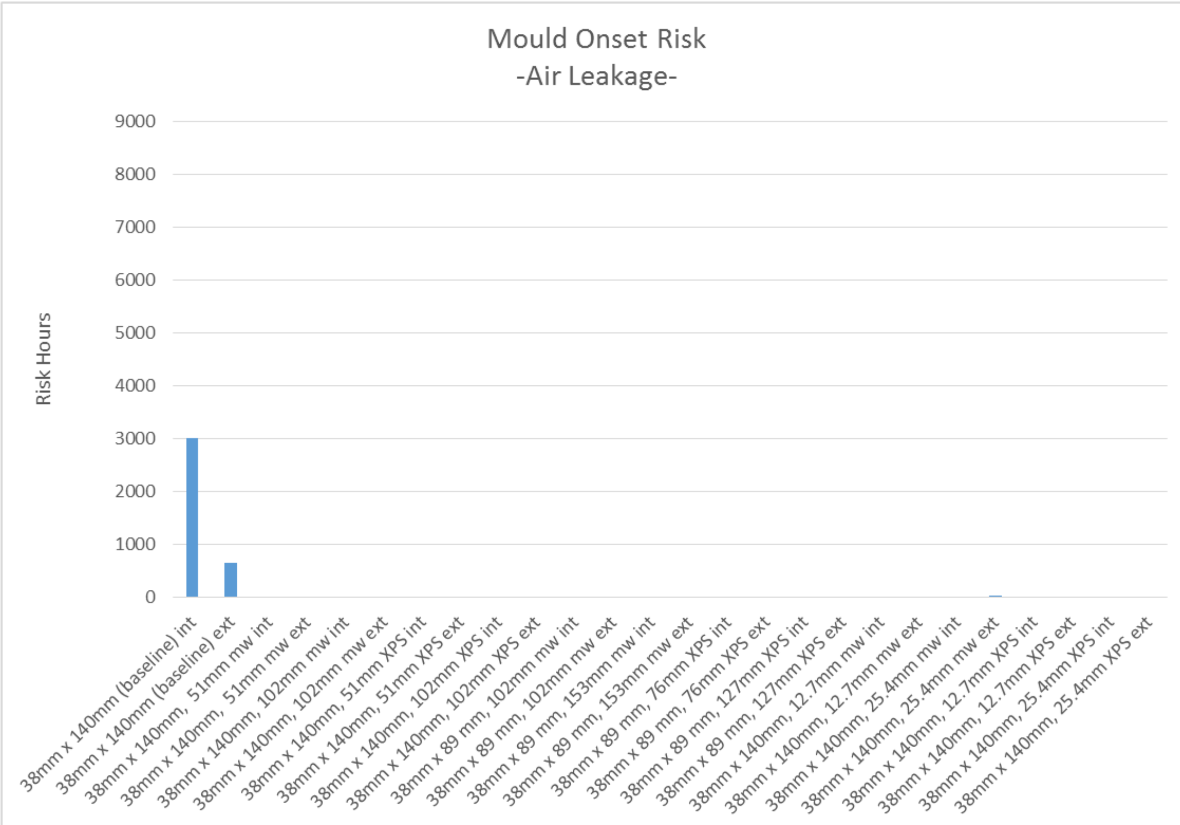


Figure 4.3.8: Potential for mould growth onset under air leakage regime

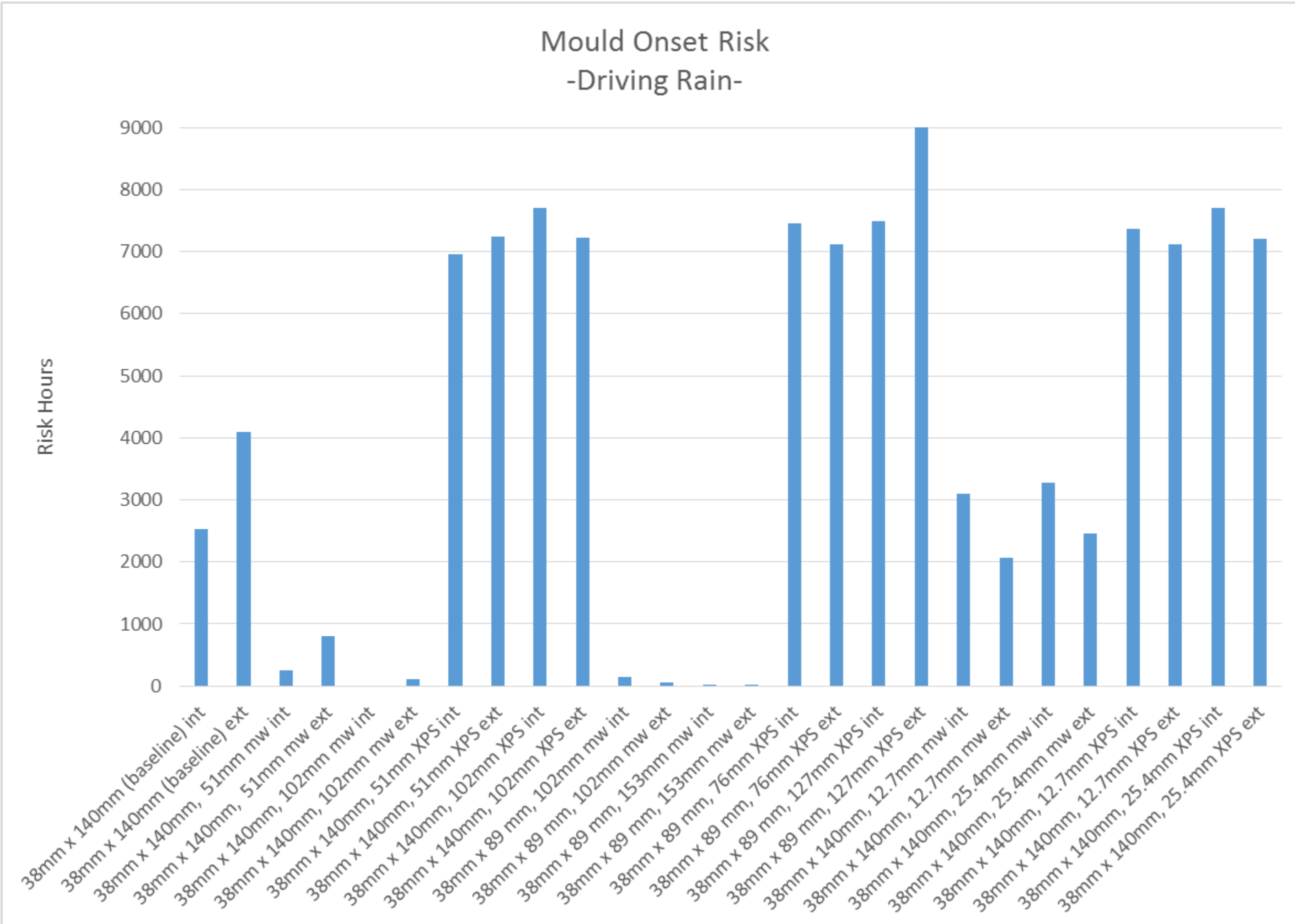


Figure 4.3.9: Potential for mould growth onset under driving rain penetration

4.3.3 Potential Decay

As defined in previous sections (MC > 30%, counting until MC < 20% is reached, T > 5C) potential decay hours were quantified on an annual basis for all assemblies under baseline, air leakage, and driving rain penetration loadings. Similarly to the other case-study cities, it is driving rain penetration that creates the greatest potential for decay and the associated bio-hygrothermal failure mechanisms. Interestingly, as compared to Toronto and Vancouver, Edmonton appears to show the greatest resilience to air-leakage induced decay, despite much lower wintertime temperatures and an overall colder climate. One potential explanation for this phenomenon is that Edmonton has much lower interior moisture loads as defined by EN 1025, both in absolute and relative terms.

The results of all analyses of potential decay for the thirteen test assemblies are presented below in figures 4.3.10 through 4.3.12:

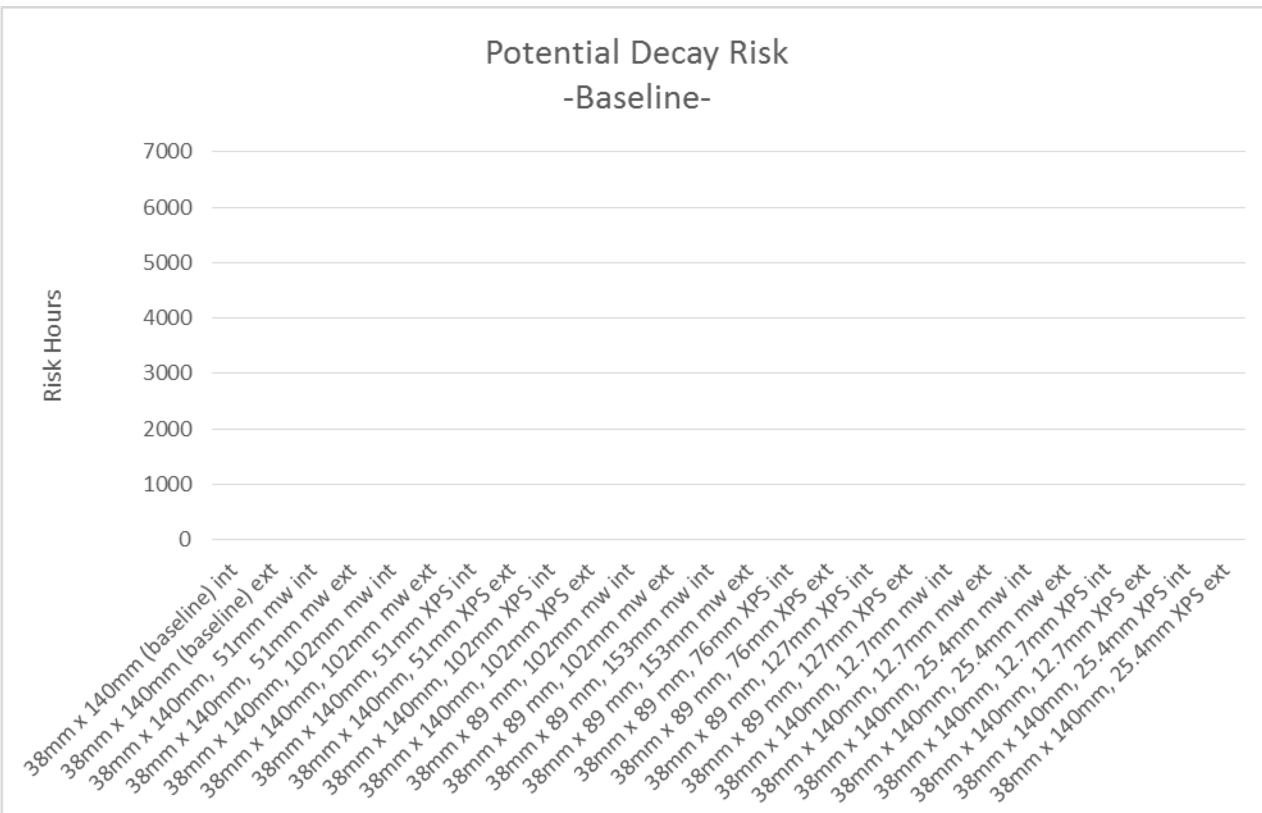


Figure 4.3.10: Potential decay risk under baseline hygrothermal conditions.

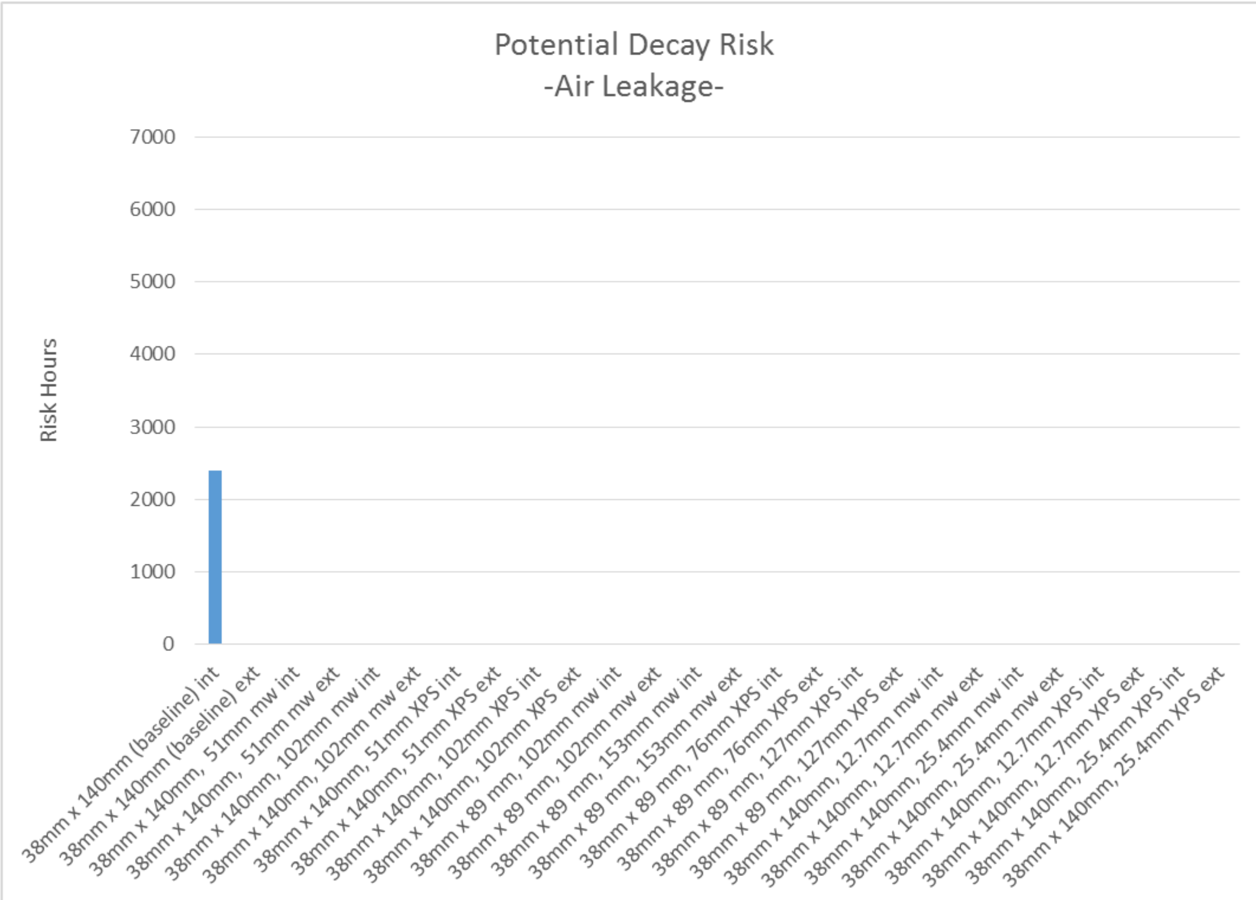


Figure 4.3.11: Potential for decay under air leakage regime. Leak is introduced to interior surface of sheathing.

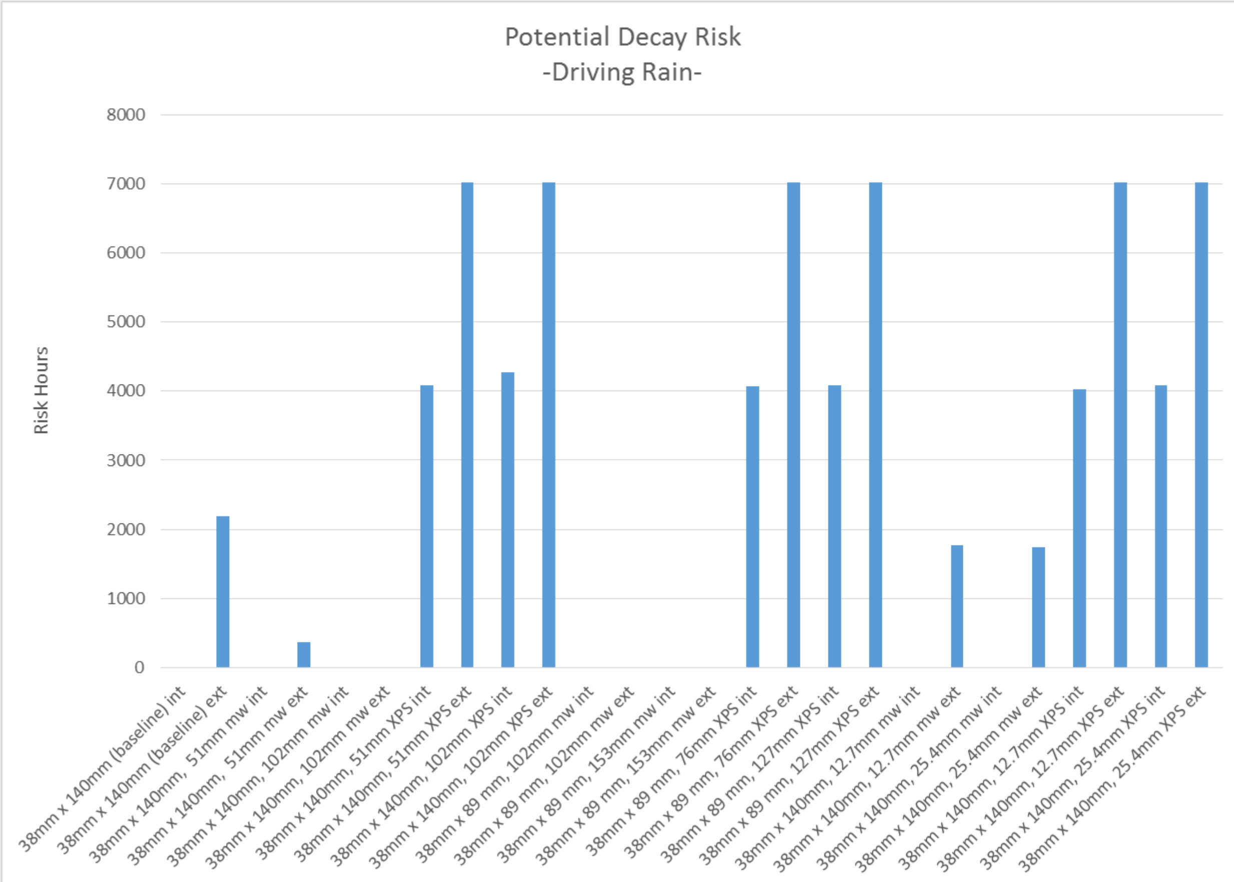


Figure 4.3.12: Potential for decay under driving rain penetration. Leak is introduced to exterior surface of sheathing.

5.0 Discussion

After assessing the hygrothermal performance of a sample of thirteen split-insulated assemblies, nine of which are highly likely to enter into mainstream, residential envelope design, several critical points of interest have been elucidated. This Section will capture these concepts as well as propose potential ways in which resiliency may be improved in certain assemblies without compromising thermal performance.

The most obvious trend found through this research is that virtually every high-RSI, split-insulated assembly substantially outperforms the baseline, interior-insulated wall under baseline exposure conditions that is typically constructed today. This points to the importance of designing to keep hygrothermally susceptible elements at a warm temperature, thereby reducing the relative humidity that experience in practice. That said, because the quantity of moisture that can be transported by vapour diffusion (assumed to be the primary mechanism of transport under baseline conditions) is quite low, these results are not surprising and must be viewed in concert with the performance effects of air leakage and driving rain penetration if design recommendations are to be made.

As explained in the Section 3, air leakage was simulated by identifying a constant flow regime of air leakage that causes sheathing MC to elevate to over 30% for approximately three weeks in the winter, and then return to safer conditions for the rest of the year. Applied to the eight high-RSI, split-insulated assemblies, this rate of leakage did not cause any hours of potential decay, and only created potential mould growth onset in Assembly 4 in Edmonton, Toronto and Vancouver, which is the assembly with the least advantageous allocation of exterior insulation and outward drying potential, with 51mm (2”) of XPS outboard of a 38mm x 140mm (2x6), batt-filled wall. The experimental assemblies 10-13 were selected to identify the minimum thickness of insulation required to avoid sheathing condensation under a reasonable air leakage regime. While all four assemblies did experience a significant amount of hours wherein mould growth onset is possible, only assemblies 10 and 12 experience any potential decay (in both cities) under the air-leakage regime selected. These assemblies each had only 13mm (0.5”) of mineral wool and XPS exterior insulation, respectively, which is thinner than any insulation board available commercially and represents a theoretical minimum split insulated assembly.

These results indicate that under extreme cold such as Edmonton experiences during winter, the sheathing can easily be kept above dewpoint temperatures for indoor air at relative humidities of up to 60%, and should be kept in mind when designing any enclosure in cold climates. That said, in wood-framed buildings with higher than average moisture loads (such as cafes, multi-generational homes, buildings with mechanical humidification, etc.) the risk of air leakage condensation problems can be significantly elevated, especially when split-insulated assemblies use exterior insulation that is not sufficiently vapour permeable to permit outward drying (such as XPS has shown to be under sufficient moisture loadings).

Perhaps more saliently, the results must be viewed in the context of WUFI's ability to model air leakage. Because air leakage in WUFI is defined by an air-change rate, it is likely that the software assumes an equal volumetric flowrate of air exiting the destination to which it is flowing into. That is, if a rate of leakage of 1 ACH is introduced into the plywood sheathing, a rate of 1ACH will also be exhausted back into the indoor space. Therefore, when the temperature of the inner face of plywood is above the dewpoint temperature of that plywood, the airstream will not deposit any significant quantity of moisture and the plywood will show a safe level of moisture performance. In reality, however, the leaking air is likely to remain in contact with the sheathing for a longer period of time, and could even pressurize the areas abounding the void through which it leaked, therefore depositing more moisture into the sheathing than WUFI is able to account for.

It is possible that this phenomenon plays a factor in the abnormal RH readings at the interior and exterior faces of the plywood. With a constant exchange of air that is defined by indoor psychrometric conditions, the sensor could be partially inundated with infiltrating and exhausting air, which would simply be at whatever statepoint the indoor air mixture is assumed to be at, which is RH of 70% as a summertime maximum.

Driving rain penetration was observed to cause the most hours of potential mould growth in every assembly in both climates by a significant margin; this is unsurprising given that the quantity of water that is introduced by rain is orders of magnitude greater than through diffusion or even air leakage. It is the XPS, split-insulated assemblies that exhibit by far the most severe potential for failure; while this trend is intuitive, the factors influencing the enormous separation by which hours of mould potential under driving rain penetration with split-insulated, XPS assemblies exceed all other loading scenarios is important to understand. It is clear that in both Canadian climates, given the design of a split-insulated wall with all mechanisms for drying situated outboard of the sheathing (reflecting the ubiquitous, large, outward vapour drive in Winter as compared to the smaller, inward vapour drive in Summer), the only place for bulk water that has penetrated the critical control layers to drain/dry, is to the exterior of the sheathing, into the ventilation cavity. This cavity becomes the drainage plane for free water in the case that moisture accumulation/ingress is severe, such as with driving rain penetration.

In the case of walls with exterior XPS, its ability to resist liquid water, as well as its low vapour permeance of XPS (43 $s^{-1} * m^{-2} * Pa^{-1}$ or 0.755 PERM/Inch as per ASTM E-96) greatly inhibits the potential for any of the mechanisms for drying mentioned in the literature review to occur outwardly into the vented cavity. Because it is assumed to be in direct contact with the sheathing membrane, capillary forces are likely to prevent even gravity-driven drainage down the sheathing membrane. It is, however, important to understand the critical mechanisms of drying, and WUFI's ability to model these mechanisms accurately.

Generally, WUFI simulates drying by means of water vapour diffusion through the assembly, but does have the ability to describe the effects of convective drying using tools such as the introduction of an air change rate as completed in this research. While the combination of vapour diffusion drying as well as convective drying can account for a high portion of the total drying experienced in an assembly, designers should take care to understand the potential for pathways of bulk, gravity-driven drainage (such as gaps and voids in materials) if model-based assessments are to accurately describe real-world data.

Interestingly, many exterior-insulated XPS assemblies have shown resilience to hygrothermal deterioration that is not explained by the modeling/testing results and assumptions typically accepted by researchers. One notion that has recently been informally discussed in the building science community is that during the construction process, XPS is installed with a relatively large amount of void area between panels, and may not sit entirely flush on to the WRB membrane immediately outboard of the sheathing.

That is, there could be an effective ~1mm gap between the inner face of the XPS and the exterior face of the WRB membrane, that would vent with outdoor air and remove some quantity of moisture from the wetted sheathing via convective drying into the airstream. Of course, this void would also be a significant drainage pathway for liquid water, but as noted above, this type of drying is difficult to model with WUFI. To test this theory, four 'drained XPS' assemblies were modeled in WUFI:

1) 38mm x 140 mm (2x6) with 51mm (2") of drained XPS,
2) 38mm x 140mm (2x6) with 102mm (4") of drained XPS,
3) 38mm x 89mm (2x4) with 76mm (3") of drained XPS, and
4) 38mm x 89mm (2x4) with 127mm (5") of drained XPS.

Each 'drained assembly' had a 1mm airstream between the XPS and the WRB, venting at 1ACH to the outdoor air, as shown in the below figure:

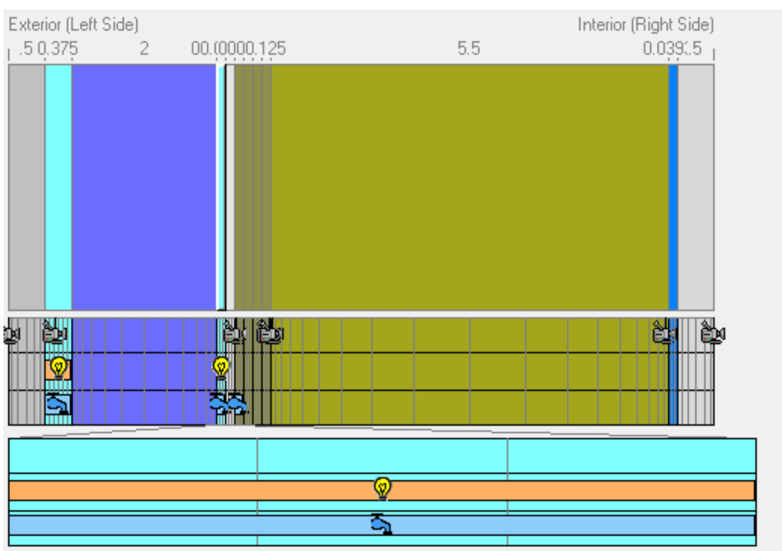
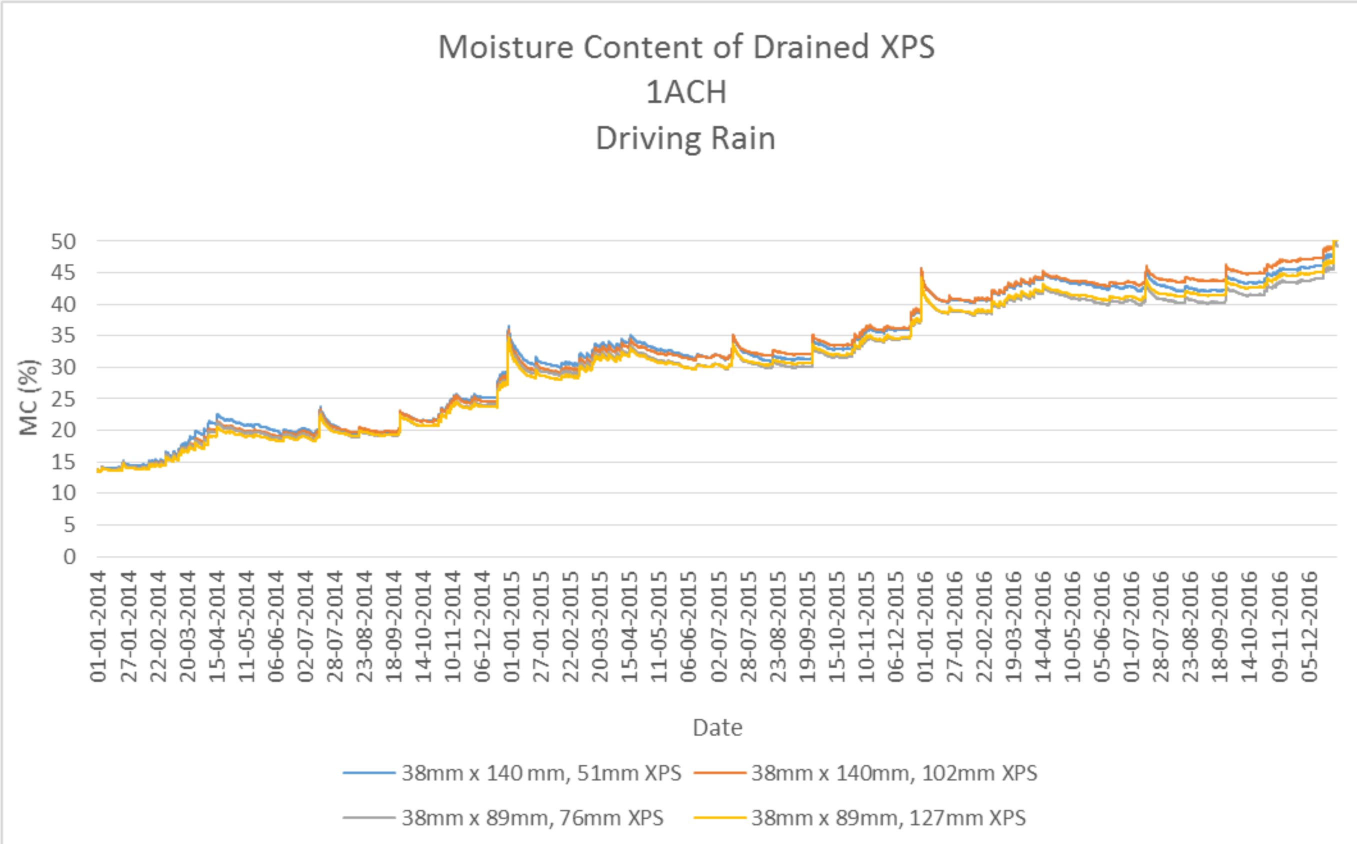


Figure 5.1.1: Illustrated depiction of 'drained XPS' assembly as modeled in WUFI

The results of this analysis are presented below in Figure 5.1.2, both in the form of each assembly's moisture content over time, as well as annual hours of potential mould growth onset (defined as MC >20% and temperature >5 degrees C)



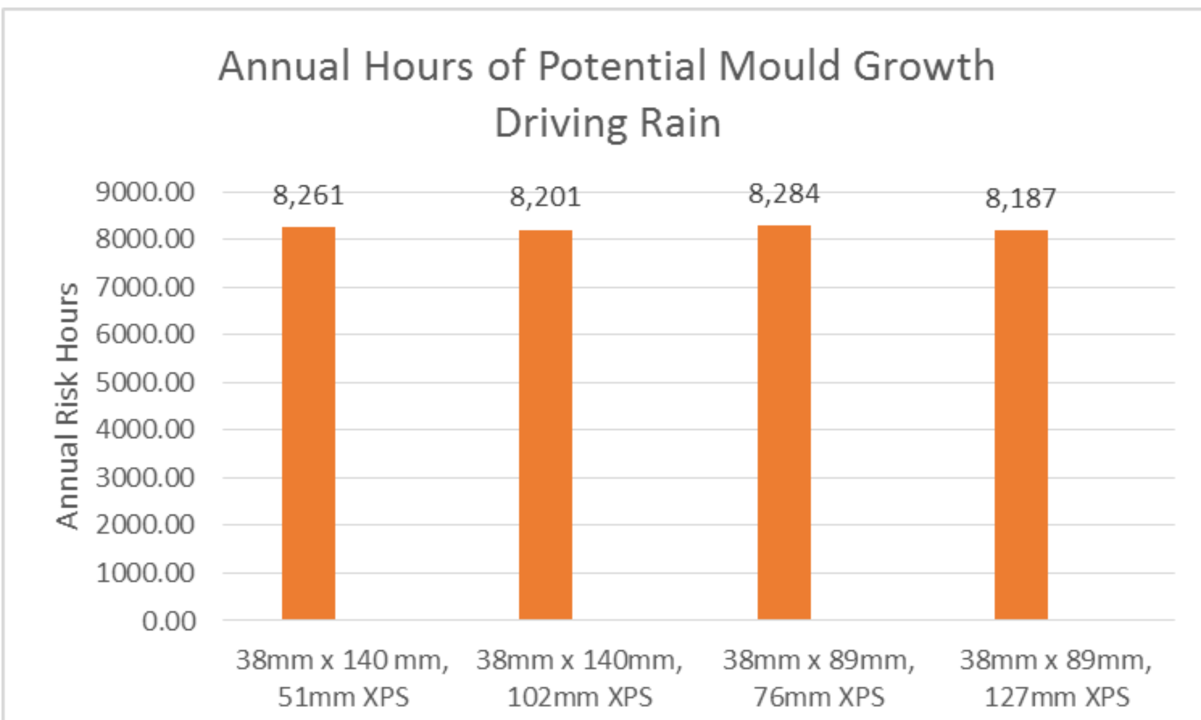


Figure 5.1.2:Moisture content and potential mould growth of drained XPS when exposed to driving rain in Vancouver

The results of this analysis clearly indicate that this small airstream venting at 1ACH does not have sufficient drying capacity to prevent the plywood from dangerously accumulating moisture (nearly 90% of the year experiences potential for mould growth onset). Therefore, increased rates of venting were tested for the split-insulated assembly with 51mm (2”) of exterior XPS, results presented in the chart below. It can be noted that, when the airstream was modeled to vent at a rate greater than 10ACH, which may be unreasonably high given the configuration of this assembly, the drained XPS assembly experiences adequate drying, and moisture accumulation does not substantially enter into the range of failure criteria presented throughout this paper. Combined with the gravity-driven drainage potential of this void, it seems important that future research validate the rate of airflow behind the XPS insulation, in order to gain a more accurate understanding of the psychrometric interactions governing this situation.

Charts of the drying trends predicted at various airflow rates (all using a split-insulated, 2” exterior XPS assembly exposed to driving rain), as well as an analysis of potential hours of mould onset (defined again as MC >20% and Temperature > 5 degrees C) are presented in figures 5.1.3 and 5.1.4 below:

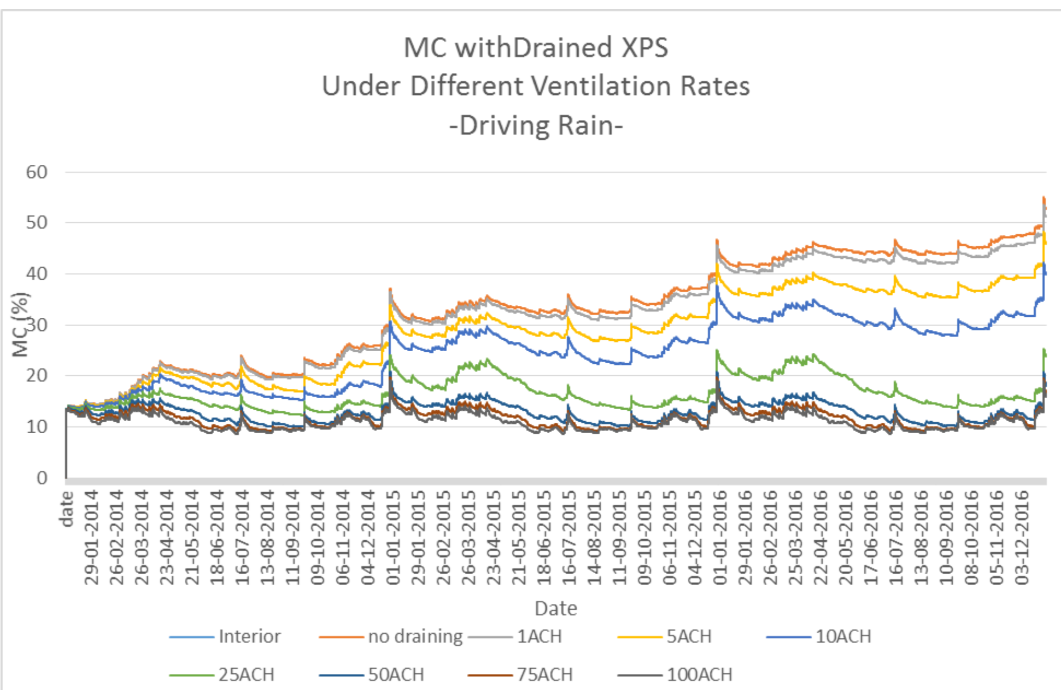


Figure 5.1.3 Moisture content with drained XPS under different 1mm cavity ventilation rates and driving rain penetration delivered to exterior face of sheathing

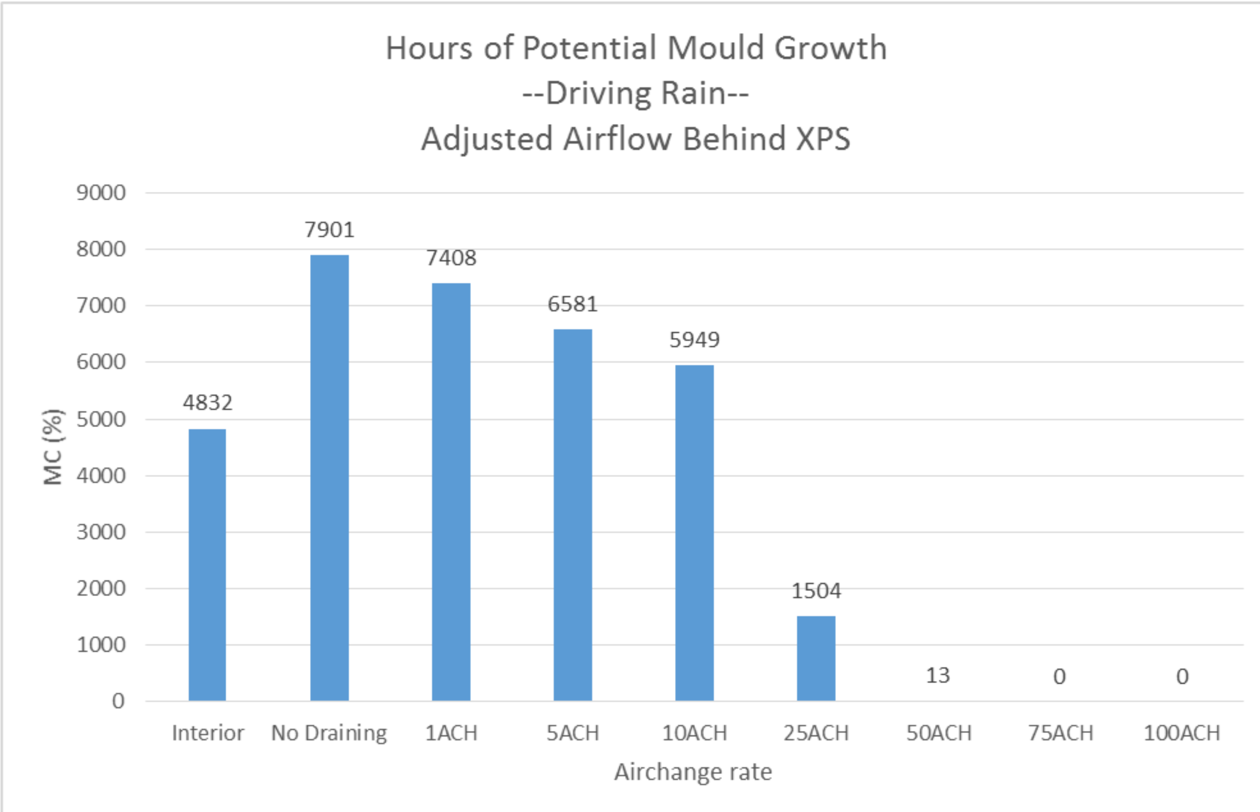


Figure 5.1.4: Potential for mould growth onset of drained XPS under different air exchange flowrates in the 1mm cavity

While sufficient airflow rates in the drained XPS assemblies are simulated to dry the assembly, it is unlikely that this procedure fully captures the phenomenon discussed above, wherein exterior XPS, split insulated assemblies are able to dry out after significant wetting in the field. Airflow of 50 ACH in a cavity that shouldn't experience a large degree of thermal stratification is quite unlikely. A more likely explanation for the enhanced drying of XPS insulated assemblies is that gravity-driven drainage down the 1mm cavity is able to remove a sufficient mass of liquid water to avoid hygrothermal issues. However, because WUFI is unable to account for bulk drainage of liquid water due to gravity, this phenomenon would go unnoticed. In future studies, field testing of bulk water drainage could be conducted in order to enhance the accuracy of hygrothermal simulation.

Additionally, because mineral wool, which has a rated vapour permeance of approximately 5721 $s^{-1} * m^{-2} * Pa^{-1}$ (100 PERM Inch) with slight variations based on density requirements of product, has shown superior hygrothermal performance under virtually every loading scenario, a sensitivity analysis was undertaken in order to determine the optimal permeance of foam insulation for exterior application in split-insulated assemblies with different thicknesses of exterior insulation, when exposed to driving rain penetration as described in Section 3. A list of the various insulation combinations can be found in Table 5.1.1 below:

Table 5.1.1: Guide to assembly number and corresponding thickness and permeance values tested

Assembly ('Series')	Thickness (mm)	Thickness (in)	Permeance (s-1 * m-2 * Pa-1)	Permeance (PERM* in)
1	25.4	1	43	0.755
2	25.4	1	286	5
3	25.4	1	1430	25
4	25.4	1	2861	50
5	25.4	1	4291	75
6	25.4	1	5721	100
7	51	2	43	0.755
8	51	2	286	5
9	51	2	1430	25
10	51	2	2861	50
11	51	2	4291	75
12	51	2	5721	100
13	76	3	43	0.755
14	76	3	286	5
15	76	3	1430	25
16	76	3	2861	50
17	76	3	4291	75
18	76	3	5721	100
19	102	4	43	0.755
20	102	4	286	5
21	102	4	1430	25
22	102	4	2861	50
23	102	4	4291	75
24	102	4	5721	100

Due to the ease of comparison and universal importance, hours of potential mould onset were again tracked using the same criteria as in the Edmonton, Vancouver, and Toronto analyses (i.e. >20 % MC and >5 degrees C). Results have been plotted nominally and logarithmically for ease of understanding, and a plot of changing moisture content over time has been included. For ease of qualitative interpretation, results have been separated graphically into two charts, one containing exterior thicknesses of 25.4mm and 51mm as well as one containing thicknesses of 76mm and 102mm.

The results of this analysis are quite interesting, and have been presented in Figures 5.1.4 through 5.1.7 below:

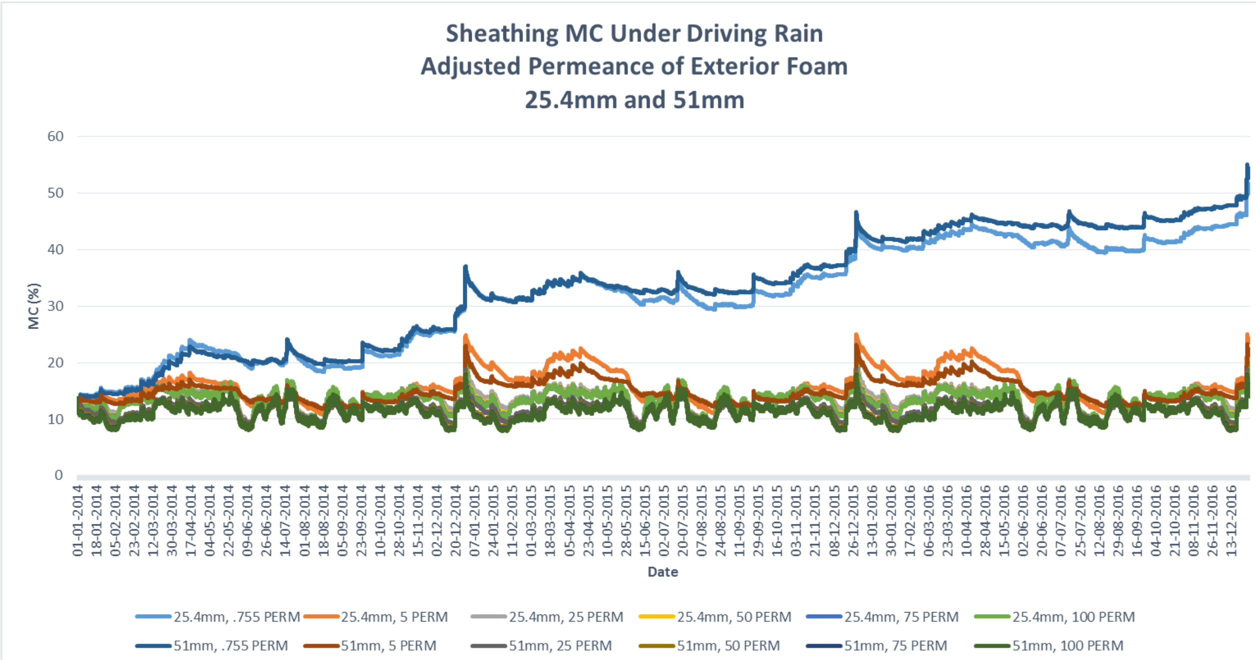


Figure 5.1.5: Sheathing MC under driving rain penetration with varied permeance of exterior insulation, 25.4 and 51mm thicknesses

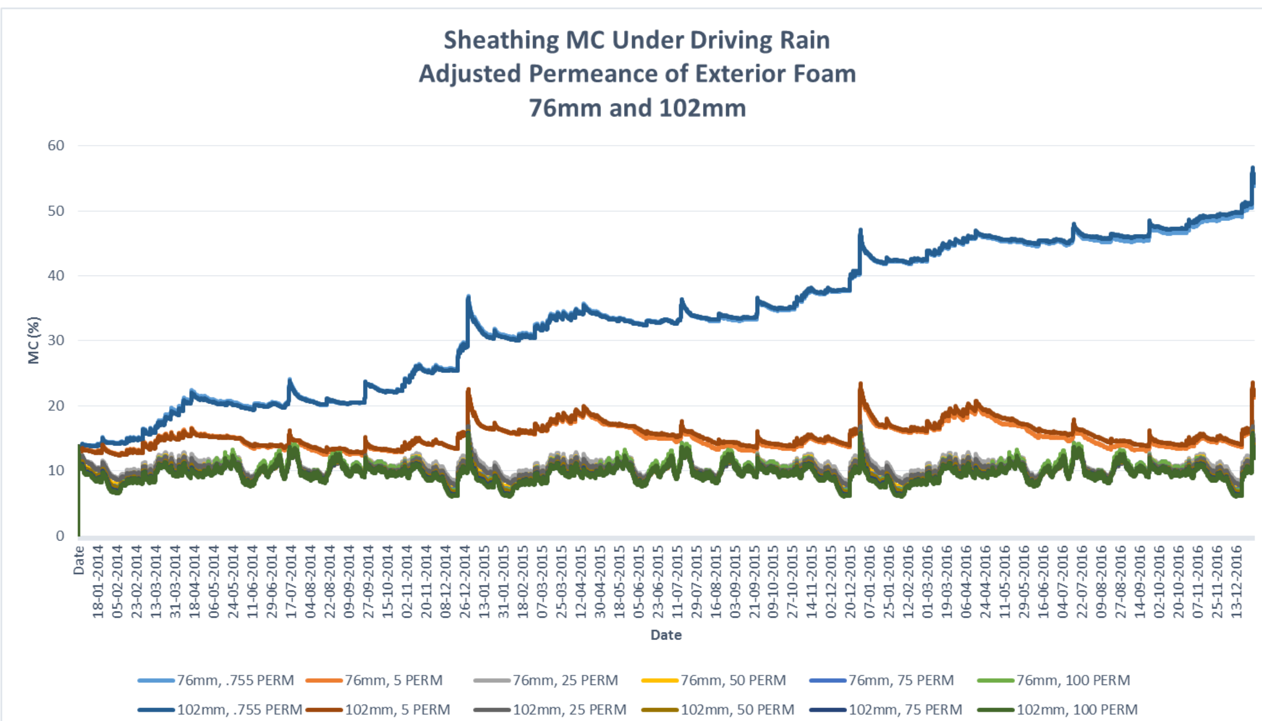


Figure 5.1.6: Sheathing MC under driving rain penetration with varied permeance of exterior insulation, 76 and 102mm thicknesses

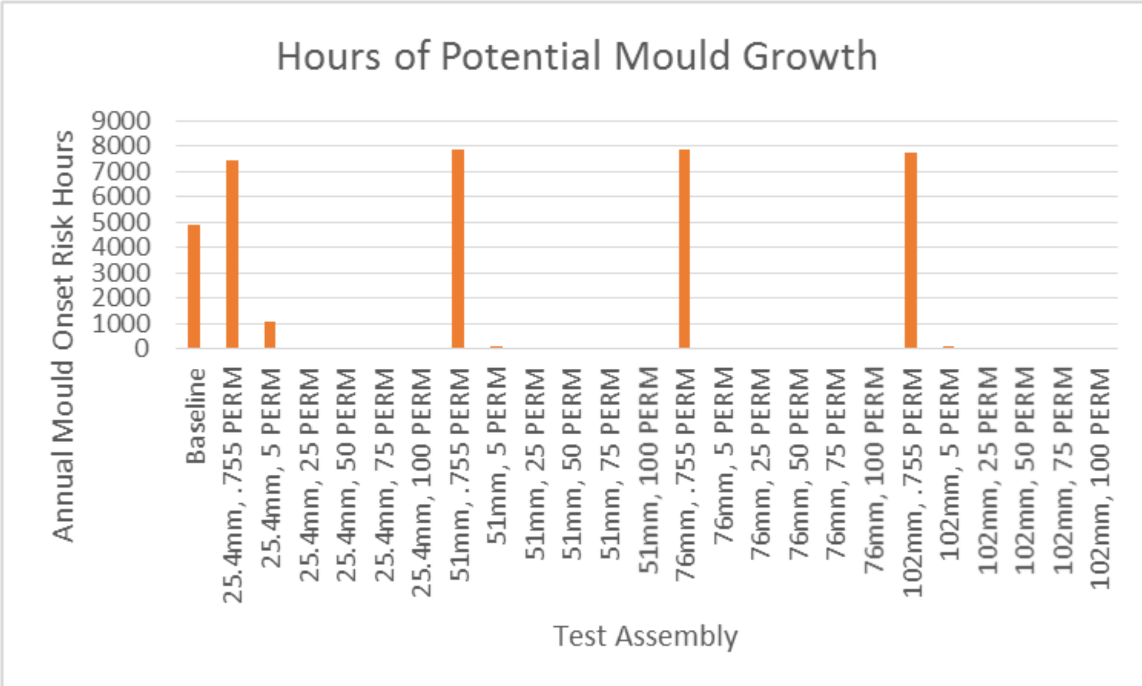


Figure 5.1.7: Potential for mould growth under driving rain penetration with varied permeance of exterior insulation

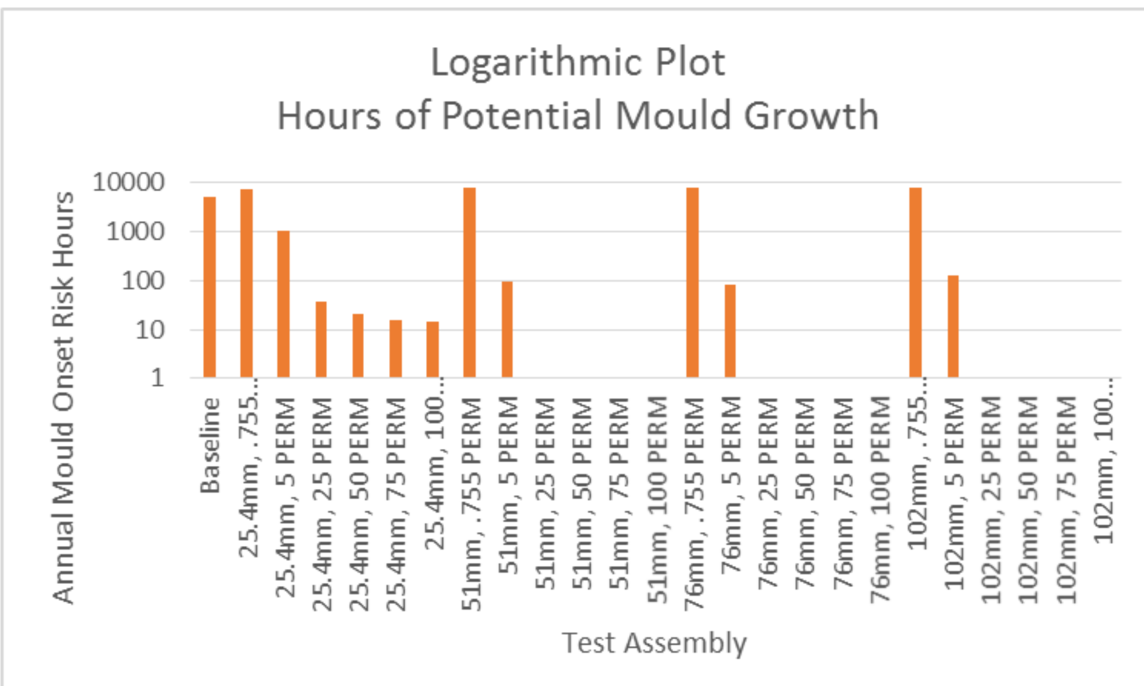


Figure 5.1.7: Potential for mould growth (plotted logarithmically) as modeled for each assembly of different thickness and vapour permeance

As shown in the above charts, for exterior insulation thicknesses ranging between 25mm (1”) and 102mm (4”) XPS at its current vapour permeance of 43 s^{-1} * m^{-2} * Pa^{-1} (0.755 PERM * Inch) performs worse than the baseline assembly, with more annual hours of potential mould growth. At a permeance of 285 s^{-1} * m^{-2} * Pa^{-1} (5 PERM Inch,) all thicknesses of insulation experience fewer hours of potential mould onset as compared to the baseline assembly; however, the greatest drop, again consistent for every thickness of insulation, occurs at 1425 s^{-1} * m^{-2} * Pa^{-1} (25 PERM Inch.) This result is most clearly elucidated in the logarithmically expressed results. Also of note, while it seems the ‘critical tipping point’ of 1425 s^{-1} * m^{-2} * Pa^{-1} (25 PERM Inch) results in the greatest marginal performance gain, walls appear to perform better with greater, exterior insulation thicknesses, which is intuitive based on the higher average sheathing temperature that this creates.

After analyzing both the instance of a 1mm vented space behind the exterior XPS, as well as adjusting the permeance of the exterior foam insulation, it is clear that opportunities exist (in concept) to reduce the risk potential of hygrothermal damage arising from exterior foam insulation. As noted, further analysis is necessary before considering either of these analyses to be proofs of concept, particularly verification of the airflow rate possible in the 1mm cavity behind the exterior XPS, and more likely, the ability of the 1mm plane to support gravity driven drainage. That said, if such a plane is situated behind foam insulation with greater permeance than is typical of XPS or expanded polystyrene (EPS), it is conceivable that assemblies with higher RSI per inch as well as increased tolerance to hygrothermal loadings may be designed. Naturally, advances in insulating materials must occur in order for these products to become available, but this information ought to be valued by the manufacturing industry as an opportunity to create higher performing, more resilient split-insulated assemblies.

Finally, the question as to whether a three year simulation period is sufficient time in order to analyze the drying potential of these assemblies. In order to assess, 10 year WUFI simulations were conducted for both 50mm by 150 mm (2x6) with 50mm (2”) XPS and 50mm by 100mm (2x4) with 75mm (3”) XPS assemblies under driving rain in Vancouver. As shown in the below graphs of moisture content (%), it is clear that these assemblies continue to accumulate moisture until reaching an EMC of just below 60%.

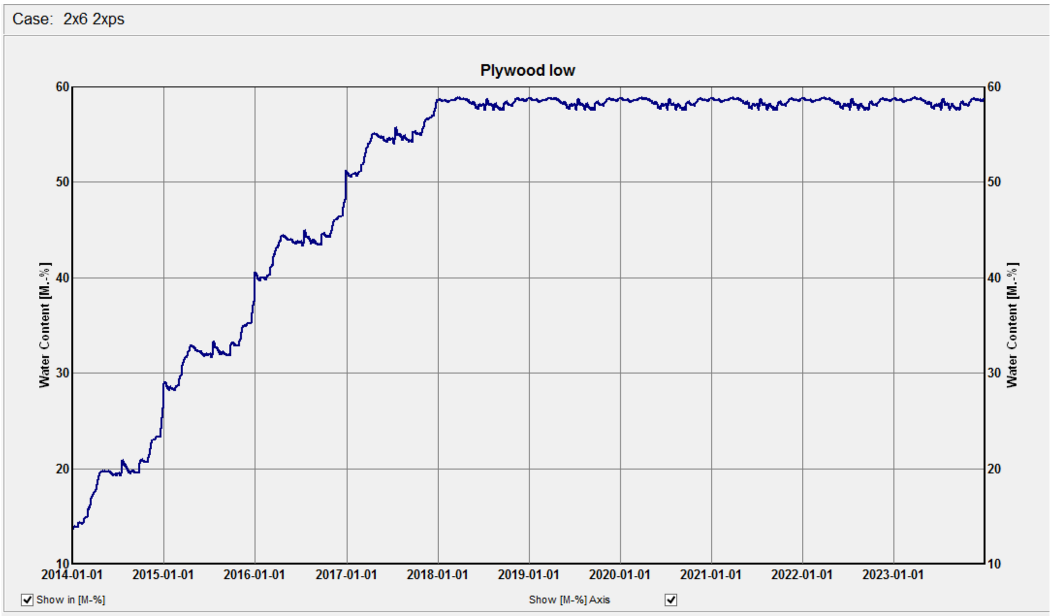


Figure 5.1.8: Moisture content at plywood sheathing of a 50mm x 150mm (2x6) assembly with 50mm (2") of exterior XPS under driving rain conditions in Vancouver.

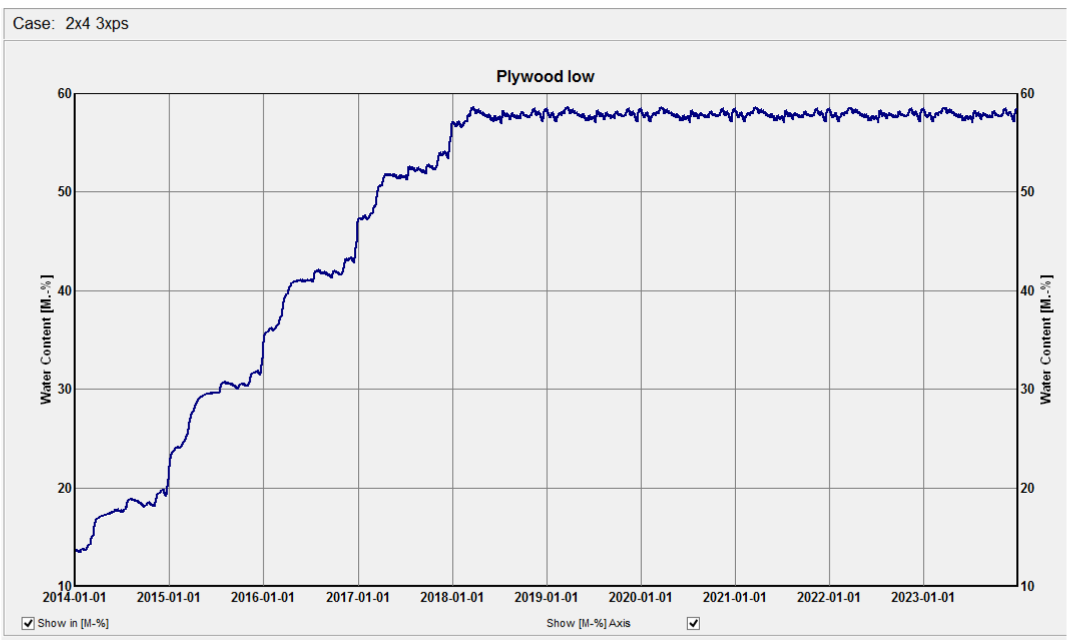


Figure 5.1.9: Moisture content at plywood sheathing of a 50mm x 100mm (2x4) assembly with 75 mm (3") of exterior XPS under driving rain conditions in Vancouver.

6.0 Recommendations for Future Research

It should be noted that due to feasibility constraints, the Toronto simulations were not able to be calibrated to measured field data in order to validate boundary conditions and surface transfer coefficients; rather, surface transfer coefficients and other relevant boundary conditions were taken from ASHRAE (ASHRAE, 2006). These results should therefore be valued for their comparative accuracy, rather than their likelihood to be accurate predictions of performance. That is, it is reasonable to put confidence in the result that an XPS, split-insulated assembly in Toronto has a much higher risk of decay than a mineral wool, split-insulated assembly in Toronto when exposed to a reasonable rate of driving rain. The precise, moisture content and surface RH of the plywood at a given date and time, however, must be field-monitored if to be predicted with confidence. It is therefore recommended for future researchers to validate the WUFI models produced herein to Toronto's climate through simple field experimentation as was conducted in Vancouver.

Additionally, it is important to understand the limitations of the calibrated loading process, particularly with respect to driving rain ingress. The calibrated loading process essentially exposes a constant rate of bulk water ingress or air leakage to the sheathing for the duration of the simulation time period. This rate varies by climate, based on the procedure outlined in the methodology section. In a field exposure setting, it is unlikely that all wall assemblies in Vancouver will experience a constant rate of 0.1% of all incident driving rain penetrating the control layers and reaching the sheathing. More likely is that certain homes will experience periodic driving rain penetration that is much higher, while others will experience no bulk water loading, or an extremely low amount, due to site exposure conditions that vary dramatically between buildings.

In reality, the constant rate of loading describes an idealized situation, unlikely to occur in field conditions, that allows us to make comparative statements between the relative resiliency of different assemblies to driving rain penetration and air leakage. Further research should be conducted in order to expose wall assemblies to the more variable driving rain penetration and air leakage regimes that are likely to be experienced in field exposure situations.

Findings presented in the Discussion section of this paper also have important implications in terms of assembly design and insulation manufacturing. Suggestions that vapour permeance of approximately 1425 $s^{-1} * m^{-2} * Pa^{-1}$ (25 PERM inch) is sufficient to allow outward drying under even a high driving rain penetration load could be capitalized on by manufacturers to develop a new product that is more vapour permeable than XPS, but has a higher RSI value than mineral wool. This product would ostensibly yield valuable energy savings, as well as increased resiliency for split-insulated envelopes. A critical step in achieving this idea would be to gain a more astute understanding of the manufacturing parameters

Another important parameter that had a major effect on model behavior is the rate of airflow in the vented rainscreen cavity. Assumed for feasibility reasons to average a constant rate of 93 ACH, based on Ge and Ye (2006), the major driver of this flow is the stack pressure differential within the cavity. This differential is influenced heavily by the amount of solar radiation experienced by a building façade, thereby affecting the temperature stratification regime, and in the dense cities of Toronto, Edmonton, and Vancouver, one home may experience vastly different UV exposure regimes on different faces, in different seasons. While there have been a multitude of high quality studies investigating this rate, no open-source files describing more realistic flow-rates over time were found. This could have a beneficial impact on simulation accuracy especially in longer-term studies, as the effects of seasonal drying and wetting become more pronounced.

Finally, the hygrothermal effects of different interior vapour control strategies could be explored in greater detail. Innovative vapour-retarder paints and membranes such as the “smart” vapour retarder, which experiences changing permeance based on surface relative humidity, have recently gained popularity as alternatives to the 6mil polyethylene sheet that is typically incorporated at the interior face of the structural stud wall in North American, cold-mixed climate assemblies. The literature does not currently contain peer-reviewed studies isolating the effects of these products, leaving an opportunity to verify that homes incorporating alternative vapour-control strategies are not increasing their likelihood of hygrothermal failure.

7.0 Conclusions

The following conclusions are based on the author's interpretation of outcomes generated throughout the course of this original research project. Recommendations generated herein should be considered when evaluating potential design options and legislature governing wood-frame enclosures in a variety of Canadian climates.

In general, it is clear that regardless of the allocation configuration of split insulation (% exterior RSI vs % interior RSI) provision for an effective pathway for diffusive and convective drying to the exterior of the structure is a prudent strategy for Canadian designers to always keep in mind. This largely depends on the permeance of the exterior insulation material, as supported by mineral wool assemblies outperforming XPS assemblies under both air leakage and driving rain penetration conditions. While XPS slightly outperformed the mineral wool assemblies under baseline conditions, perhaps due to its resistance to moisture transport from a summer inward vapour drive, none of the split insulated high-RSI assemblies experienced potential failure in any climate under baseline conditions.

Thus, it can be said that in general, splitting insulation can have beneficial hygrothermal impacts when compared to an interior insulated assembly, provided the insulating material has sufficient vapour permeance to permit drying after a reasonable wetting event. With XPS assemblies containing far more thermal resistance outboard of the sheathing than inboard of it, a modest rate of driving rain penetration that was well-managed by the baseline assembly showed definitive failure in comparison to the baseline and mineral wool assemblies. While draining this XPS at a high air change rate did show very good hygrothermal performance, factors necessary to naturally create this flow must be studied further to determine whether the required air exchange rate is even feasible.

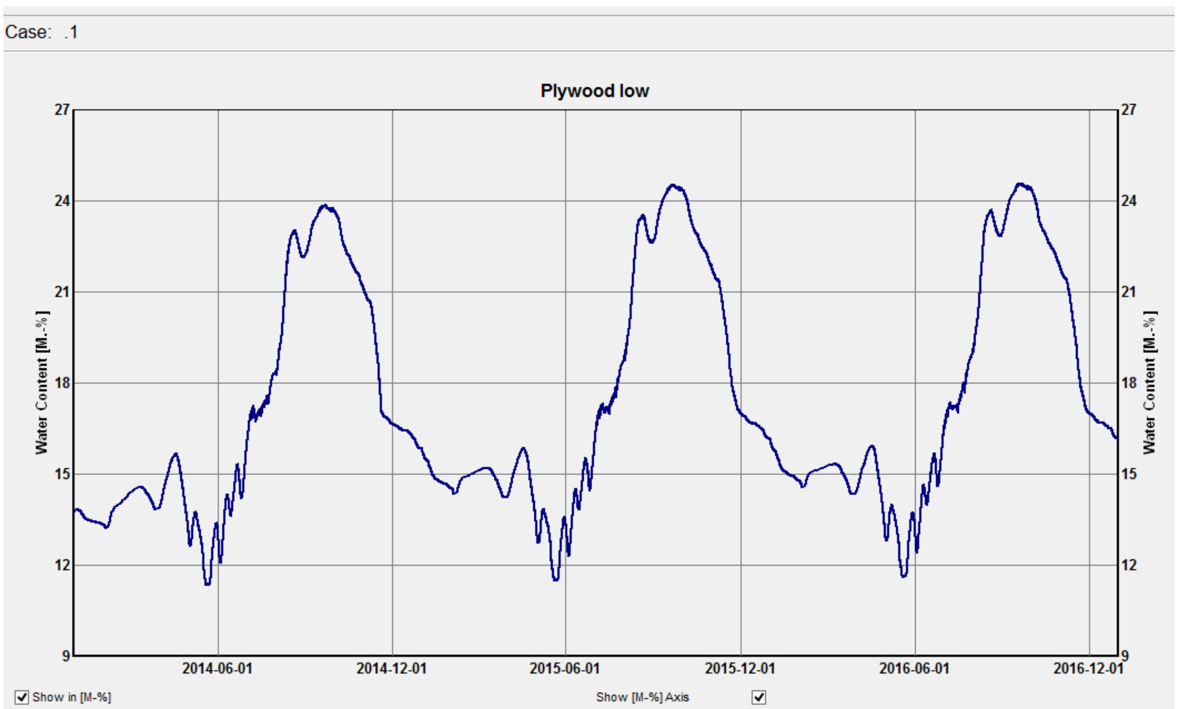
As supported by virtually every potential vapour drive/moisture ingress scenario, rock wool has shown hygrothermally superior performance to XPS when used as an exterior insulation product. It is clear that the marginal losses in summer-inward vapour drive performance are far outweighed in the Canadian climate, with its massive outward vapour drive in winter, by its ability to permit plywood drying to the exterior when wet.

That said, it is also possible that the ultra-high permeance of 5721 $s^{-1} * m^{-2} * Pa^{-1}$ (100 PERM * Inch) of common rock wool products is excessive from a hygrothermal management perspective; reducing permeance up to 1425 $s^{-1} * m^{-2} * Pa^{-1}$ (25 PERM * Inch) could be explored by manufacturers if it were able to improve the RSI / inch of rock wool to a level closer to that of XPS.

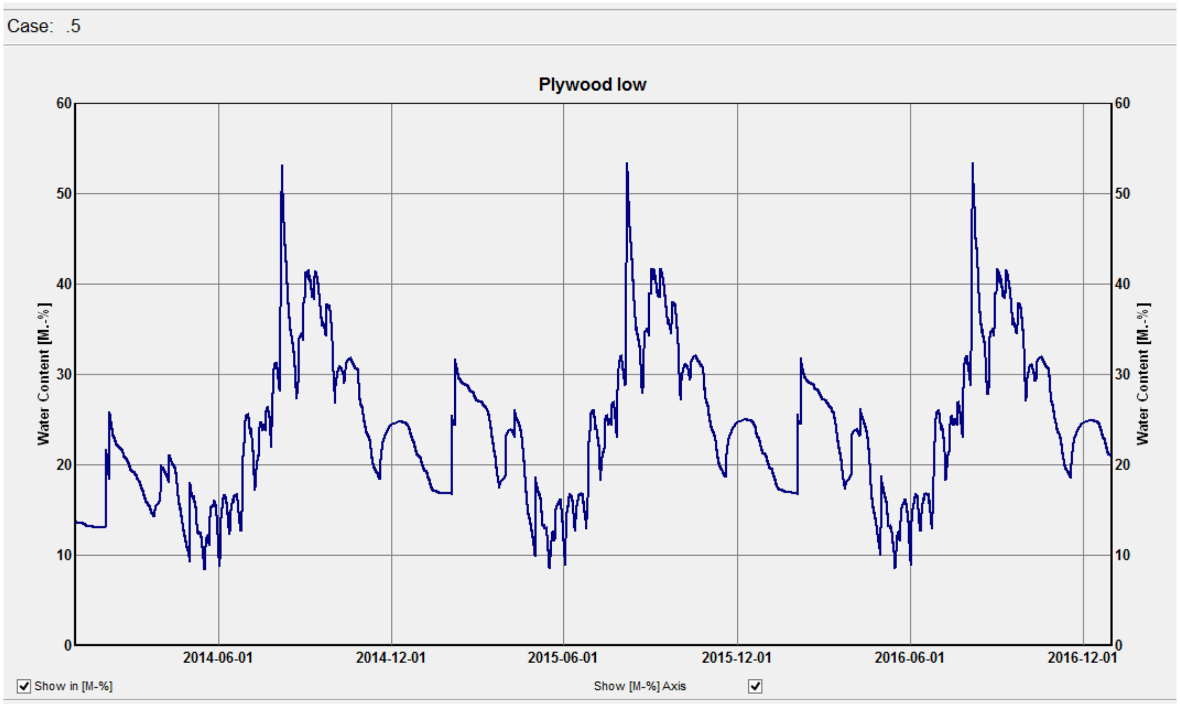
Finally, this research suggests that requirements for minimum RSI outboard vs inboard of the building sheathing may be misguided; the results of this study clearly indicate that split-insulated envelopes with undrained, vapour-impermeable exterior insulation will tend to fail when exposed to driving rain penetration regardless of the insulation allocation strategy.

Appendix: Calibrated Loading Analysis; Edmonton; Driving Rain

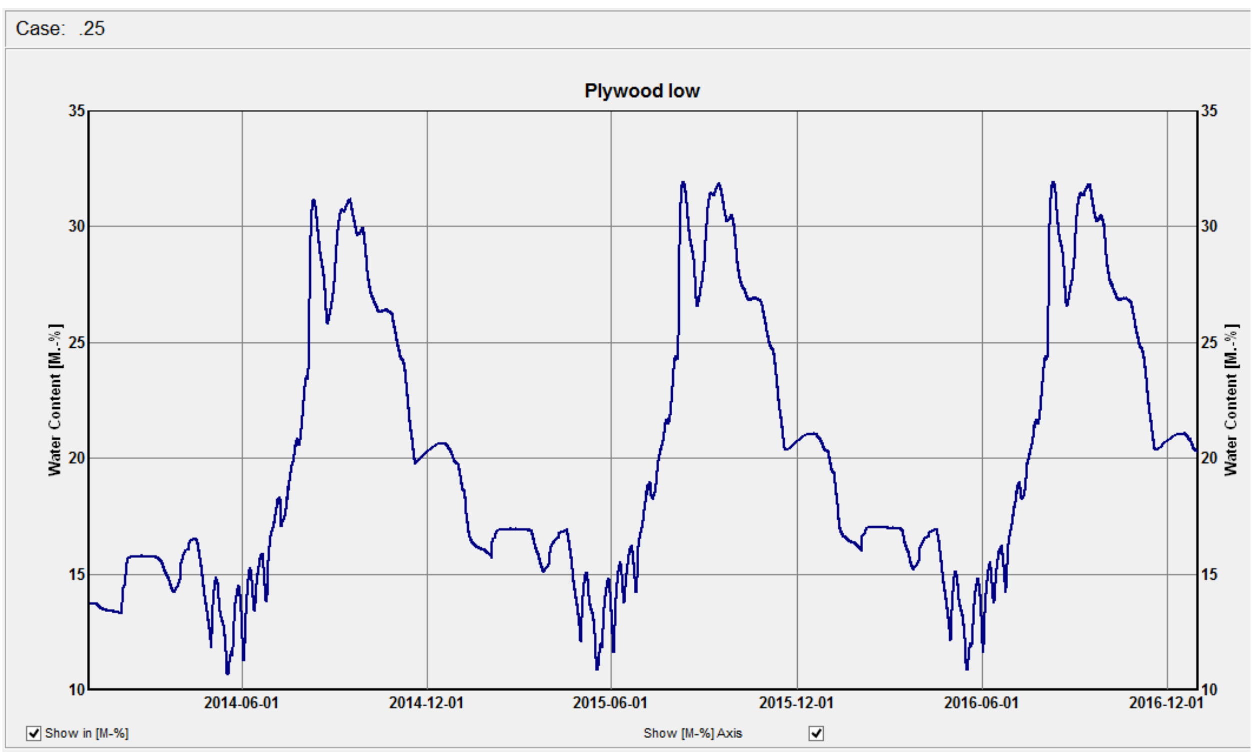
Below are results from the calibrated loading analysis performed in order to identify the upper limit of driving rain penetration tolerance of the interior insulated, baseline assembly in Edmonton. Note that 0.25% penetration was selected as the maximum acceptable load of water-ingress, and was therefore exposed to all assemblies in Edmonton.



0.1% Plywood MC (%) under 0.1% Driving Rain Penetration in Edmonton



Plywood MC (%) under 0.5% driving rain penetration in Edmonton



Plywood MC (%) under 0.25% driving rain penetration in Edmonton.

Works Cited

Arena, Lois. (2013) *Actual vs Predicted Moisture Performance of a Highly Insulated Wall.*

Energy Design Update. 33.9: 1-15.

ASHRAE 160P. (2009) *Criteria for Moisture-Control Design Analysis in Buildings.* American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

ASTM E96 - (2010). *Standard Test Methods for Water Vapor Transmission of Materials*. American Society for Testing and Materials.

Brun, C. (2013). *Vapour Diffusion Open Arctic Wall : A Comparison of Moisture Accumulation Potential Versus Other Cellulose Superinsulation Strategies.* Ryerson University.

Canadian commission on building and fire codes, & National research council of Canada. (2005). *National building code of Canada 2005*. National research council of Canada.

Falk, J., & Sandin, K. (2013). *Ventilated rainscreen cladding : Measurements of cavity air velocities, estimation of air change rates and evaluation of driving forces*, 59, 164–176.

Finch, G. & Ricketts, D. (2012) *Hygrothermal Assessment of Acceptable Assemblies for Energuide 80 in Part 9 Construction, 2012 BCBC.* RDH Building Engineering for British Columbia Ministry of Energy and Mines.

Fox, M. J. (2013). *HYGROTHERMAL PERFORMANCE OF HIGHLY INSULATED WOOD FRAME WALLS WITH AIR LEAKAGE*. Ryerson University.

Ge, H., & Ye, Y. (2006*). Investigation of Ventilation Drying of Rainscreen Walls in the Coastal Climate.* Thermal Performance of Exterior Envelopes of Whole Buildings ASHRAE International Conference.

Glass, S. V. (2013). *Hygrothermal Analysis of Wood-Frame Wall Assemblies in a Mixed-Humid Climate*. US Department of Agriculture, Forest Service, Forest Products Laboratory.

Haughton, L., & Murphy, C. (2003). *Moisture Exchange - Performance of OSB and Plywood Structural Panels.* (June), 6–13.

Higgins, J. (2012) *Exterior Insulation Retrofits: Drying of Sheathing with Rigid Stone Wool Versus Extruded Polystyrene.* British Colombia Institute of Technology.

Hutcheon, N. B., & Handegord, G. O. (1995). *Building science for a cold climate*. Wiley.

Karagiozis, A. N. (2001). Advanced Hygrothermal Models and Design Models Oak Ridge National Laboratory Building Technology Center BACKGROUND : WUFI-ORNL / IBP.

Karagiozis, A., Ph, D., & Holm, A. (2001*). WUFI-ORNL / IBP — A North American Hygrothermal Model.* Performance of Exterior Envelopes of Whole Buildings VIII : 2-7.

Karagiozis, A., & Salonvaara, M. (2001). *Hygrothermal system-performance of a whole building*. Building and Environment, 36(6), 779-787.

Karagiozis, Achilles, John Straube, and Joe Lstiburek. *Vapor Barriers — Building Science Conversations*. Building Science Corporation, 10 Jan. 2014. Web. 1 Feb. 2014.

Kesik, T., Rose, D. De, & Melnichuk, S. (2006). *HYGROTHERMAL PERFORMANCE CLASSIFICATION METHODOLOGY FOR WOOD-FRAME WALL ASSEMBLIES*. University of Toronto Halsall Associates Limited , Toronto , Ontario , Canada Department of Civil Engineering , University , 73–80.

Krus, M., Michael, S., & Sedlbauer, K. (2010). *Comparative Evaluation of the Predictions of Two Established Mold Growth Models*. Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference.

Künzel, H. M. (1995). *Simultaneous heat and moisture transport in building components*. IRB-Verlag.

Lstiburek, Joseph W. (2004) *Understanding vapor barriers.* ASHRAE journal 46: 40-51.

Lstiburek, J. W. (2007). *Standing Columns-Building Sciences-The Perfect Wall*. ASHRAE Journal, *49*(5), 74-79.

Mcclung, V. R. (2013). *Field Study of Hygrothermal Performance of Cross – Laminated Timber Wall Assemblies with Built – In Moisture by moisture removal mechanisms.* Ryerson University. Print.

Morris, P.I. (1999) *Understanding Biodeterioration of Wood in Structures.* British Columbia Building Envelope Council (BCBEC) and Forintek Canada Corp. Print.

Ontario Building Code. (2012). Ontario Buildings Branch, Ministry of Housing. Print.

Pavlik, Z., Pavlik, J., Jirickova, M., & Cerny, R. (2002). *System for Testing the Hygrothermal Performance of Multi-Layered Building Envelopes*. Journal of Building Physics, 25(3), 239–249.

Peuhkuri, R. (2003). *Moisture dynamics in building envelopes.* Technical University of Denmark (Danmarks Tekniske Universitet). ISSN 1601-2917.

Ojanen, T., Kohonen, R., & Kumaran, M. K. (1994). *Modeling heat, air and moisture transport through building materials and components*. Moisture control in buildings, 18-34.

Saber, H. H., Lacasse, M. A., Swinton, M. C., & Kumaran, M. K. (2010). *Benchmarking of hygrothermal model against measurements of drying of full-scale wall assemblies.* NRCAN NRCC-53573. 1-14.

Sedlbauer, K. (2001). *Prediction of mould fungus formation on the surface of and inside building components*. Holzkirchen: Fraunhofer Institute for Building Physics.

Smegal, J., & Straube, J. (2011). *Hygrothermal Analysis of Exterior Rockwool Insulation.* Building Science Press.

Stiffman, A. & Fung, A. (2014) *The Case for External Insulation in Low-Rise Buildings; A Toronto Case-Study.* Canadian Society for Mechanical Engineering (CSME) International Congress.

Straube, J. F., & Burnett, E. F. (2005). *Building science for building enclosures*. Building Science Press.

Straube, J., & Schumacher, C. (2006). *Assessing the Durability Impacts of Energy Efficient Enclosure Upgrades using Hygrothermal Modeling.* Building Science Press. 197-222.

Straube, J., & Schumacher, C. (2007). *Interior insulation retrofits of load-bearing masonry walls in cold climates*. Journal of Green Building, 2(2), 42-50.

Suresh B. Sadineni, Srikanth Madala, Robert F. Boehm. (2011) *Passive building energy savings: A review of building envelope components.* Renewable and Sustainable Energy Reviews. Volume 15, Issue 8.

Tenwolde, A. (2008). *ASHRAE Standard 160P; Criteria for Moisture Control Design Analysis in Buildings*, 167–172.

Trechsel, H.R. (2001).*Moisture Analysis for Buildings.* Manual, American Society for Testing and Materials.

Van Straaten, R. A., Kopp, G. A., & Straube, J. F. (2010). *Testing Water Penetration Resistance of Window Systems Exposed to "Realistic" Dynamic Air Pressures*". In International Conference on Building Envelope Systems and Technologies (ICBEST 2010), Vancouver, Canada.

Viitanen, H., Vinha, J., Salminen, K., Ojanen, T., Peuhkuri, R., Paajanen, L., & Lahdesmaki, K. (2010). *Moisture and Bio-deterioration Risk of Building Materials and Structures*. Journal of Building Physics, 33(3), 201–224.

Viitanen, H., & Ritschkoff, A. C. (1991). *Brown rot decay in wooden constructions. Effect of temperature, humidity and moisture.* Rapport-Sveriges Lantbruksuniversitet, Institutionen foer Virkeslaera (Sweden).