Building envelope summary: hygrothermal assessment of systems for mid-rise wood buildings (Report to Research Consortium for wood and wood-hybrid mid-rise buildings)

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REPORT TO RESEARCH CONSORTIUM FOR WOOD AND WOOD-HYBRID MID-RISE BUILDINGS

Building Envelope Summary – Hygrothermal Assessment of Systems for Mid-rise Wood Buildings

CLIENT REPORT: A1-004377.3

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Canada

REPORT TO RESEARCH CONSORTIUM FOR WOOD AND WOOD-HYBRID MID-RISE BUILDINGS

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The following staff members of project partner/collaborator organizations have contributed to the working groups and this progress report:

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NOMENCLATURE

Cladding system – the assembly of cladding materials and accessories that create the first line of defence within the field of the wall and at its continuity to wall components and penetrations.

Rainscreen cladding – cladding system founded on the premise that multiple-element protection is necessary to achieve effective control of rainwater penetration within the fabric of the wall (i.e., the structure, insulation) by means of a first line of defence and a second line of defence to reduce the risk of adverse effects on health (e.g., mold) and structural safety (e.g., wood decay, corrosion).

Rainwater penetration control assembly – the assembly of the first line of defence (i.e., cladding system) and the second line of defense, which effectively control rainwater from penetrating into the fabric of the wall. Manufacturers of rainscreen cladding need to define this assembly and its continuity to wall components and wall penetrations.

EXECUTIVE SUMMARY

Objective

The role of the building envelope research team in this project was to assess whether mid-rise wood-frame (LWF) and cross-laminated timber (CLT) building envelope solutions developed by the fire research team to meet the fire provisions of the National Building Code (NBC) 2010 Part 3 Fire Protection, would also meet the NBC Part 5 Environmental Separation requirements relating to the protection of the building envelope from excessive moisture and water accumulation. As well, these wood-based mid-rise envelope solutions were to be assessed for their ability to meet Part 3 Building Envelope of the National Energy Code for Buildings (NECB) 2011. Requirements relating to heat, air, moisture, and precipitation (HAMP) control by the building envelope are included in Part 5 Environmental Separation of the NBC 2010. Part 5 addresses all building types and occupancies referred to in Part 3, but unlike requirements for fire protection, this section of the code was written more recently and is generic, including requirements that are more objective-oriented rather than prescriptive requirements pegged to specific constructions systems. The investigated methodologies developed and adapted for this study took those code characteristics into account.

Approach

The approach consisted of applying two new methodologies developed in the last decade by NRC to meet the NBC's objective-based requirements: the first methodology was developed to analyse the new objective-based NBC requirements in Divisions A, and related 'deemed to comply' solutions in Division B of NBC Part 5. The second involves a step-by-step assessment methodology to determine acceptable moisture performance to NBC 2010 and energy performance to NECB 2011.

Two wall specimens were specified to incorporate all elements of fire protection and HAMP control elements. Specifications recorded the detail and rationale for the selections made. Water entry testing of the specified cladding system was performed to developed relationships between wind-driven rain weather data and water entry behind the cladding system – in this case, a generic fibre-cement panel cladding installed on a rainscreen system; these relationships were extended from traditional wind-pressure ranges used for low-rise construction to higher wind pressures applicable for mid-rise buildings.

The issue of interdependencies between the engineering solutions in each discipline is one that constantly confounds designers. Competing design solutions can occur between engineering disciplines, including fire engineering and HAMP control, and to a lesser extend between sound engineering of envelopes to control flanking, and HAMP control. These interactions were assessed and potential conflicting requirements were taken into consideration. In some cases, apparent compromises taken during the specification development phase were resolved through fire testing to investigate a specific issue. Three examples of investigations of such interdependencies include 1) a CAN/ULC-S134 test to investigate the fire spread characteristics given the presence of an air gap in the rainscreen design; 2) additional material property characterization and HAMP hygrothermal simulation to assess the moisture performance of fire-retardant treated sheathing strategies; and, 3) investigation by the acoustic research team of the mid-rise LWF envelope for flanking that featured a configuration that met both fire and environmental separation requirements.

NRC's hygrothermal performance assessment methodology is implemented for specific climate locations, with simulations involving multiple years of hourly weather data. There are approximately 680 locations in Table C-2 of the NBC 2010, with several representative locations for which long-term historical weather data exists. Information from these locations was used to determine the exterior boundary conditions for input files for hygrothermal simulation programs and hygrothermal testing in the laboratory. Through a methodology described in this report, eight representative climate locations were selected for hygrothermal assessment, based on three geographic considerations: moisture index of the climate specified in the NBC 2010, heating degree-day climate zone specified in the NECB 2011, and population. The analysis resulted in the following cities being recommended for detailed hygrothermal performance assessment: Vancouver, Prince Rupert, Yellowknife, Winnipeg, Toronto, Montreal, Quebec, and Halifax. A matrix of moisture indices and energy climate zones was produced to show how each of these selections cover the range of climates to be considered when addressing both the NBC 2010 and the NECB 2011.

For these locations, weather data sets were analyzed and selected to represent the wettest and average years out of available hourly climate records, typically 30 years of data for each location. These datasets were transferred to the modelling team.

A key parameter required as input to the numerical simulations is the percentage of water entry behind the cladding systems and through deficiencies as a function of wind pressure and wind-driven rain (WDR). In an effort to extend the applicability of the current National Building Code (NBC) requirements with respect to low-rise wood-frame structures to structures comprising mid-rise wood construction, the building envelope research team was tasked by the Mid-Rise Wood Buildings consortium to investigate the moisture management and water penetration performance of cladding systems and related deficiencies relevant to mid-rise buildings. Resulting functional relationships between impinging wind-driven rain and measured water entry behind the cladding into the rainscreen air space were passed on to the modelling team for use in the hygrothermal model.

Another key set of inputs to the hygrothermal simulation process is the hygrothermal properties of materials dataset. These properties are associated with each material selected for investigation. A full range of hygrothermal properties were developed for four materials that make up the fire protection strategy for mid-rise wood walls, and material properties of CLT were developed in collaborations with FPInnovations. For example, hygrothermal properties were developed for plywood pressure-impregnated with two different fire retardant chemicals. Regular gypsum sheathing, spray-applied polyurethane foam and cross-laminated timber were also tested for the range of properties needed for performance assessment. Finally, a sorption isotherm curve (the 'backbone' of hygrothermal simulation models) was developed for Red Pine, in collaboration with FPInnovations. The remainder of material properties needed to complete the full set of hygrothermal properties were obtained from the NRC material properties database, previously developed and published. Results of the hygrothermal property determinations were passed onto the modelling team.

The task of validating simulation models is often the most challenging and critical part of hygrothermal performance investigation. Credibility of the simulation tool is enhanced by its ability to simulate the key moisture transfer mechanisms of a wall that has the key characteristics of the walls contemplated for parametric study. The experiment designed for this study involved a specialized climatic chamber adapted for this project - NRC's Envelope Environmental Exposure Facility (EEEF). The facility simulates realistic winter conditions by controlling indoor and outdoor temperatures and produces realistic indoor and outdoor relatively humidity trends. The benchmark wall specimen separates the two chambers and is mounted on a custom weighing system based on the use of highly sensitive load cells and advanced micro processing technology to control and analyze the results. The weighing system tracks the total weigh change in a specimen over a test period – the weight change corresponding to the amount of moisture entering (wetting) or leaving (drying) the benchmark wall specimen over the course of an experiment. This experimental approach produces a reliable drying rate curve of the mid-rise LWF specimen that was compared to curves developed by the hygrothermal model of the experimental wall with the controlled boundary conditions. The comparisons lead to a refinement in the model to account for foam detachment from the wet studs (a phenomenon associated with the benchmark conditions only), and lead to our understanding that the model tended to be conservative in predicting the drying rate of studs under such wet conditions. These steps improved the modelling team's confidence that the model could be implemented in a parametric study involving stud drying. As well, because the relative impermeability of the spray-applied foam insulation results in quasi-one-dimensional drying through the stud, the modelling team expect that one-dimensional drying simulation through the CLT, which had comparable properties to the studs, would be equally well served by the one-dimensional hygrothermal simulation model, hygIRC 1-D.

The benchmarked hygrothermal model was then implemented for the specified LWF and CLT mid-rise walls in the climate locations selected, to determine whether the components of the envelope added to typical wood-frame construction for the purposes of mid-rise construction affect the moisture management capabilities of such walls. Key parameters included in this assessment were:

- Elements of fire protection added to the wall,
    - Encapsulation features inboard of the wall structure.
    - Cladding and rainscreen system shown by the fire research team to meet fire criteria through CAN/ULC-S134 testing.
    - The effect of different pressure-impregnated fire-retardant treatments for wood-based sheathing materials.
- Other key parameters associated with mid-rise construction, including:

- Potentially high initial wood moisture contents due to prolonged exposure to the elements during construction.
- Higher wind-driven rain loads associated with higher height the exposed walls.
- Spray-applied foam insulation in stud cavities that may be used to meet the NECB 2011 in colder NECB 2011 zones. (The same foam insulation product was also investigated in envelope assemblies by the fire research team.)

Simulations were executed and data analyzed and presented for assessment.

A pass-fail performance guideline was proposed for this assessment that is deemed by NRC to capture the intent of the NBC Part 5 for control of air moisture and precipitation. It involves an assessment of the moisture performance of the LWF and CLT mid-rise walls in a range of climates across Canada, and comparison of that performance to that of a previously defined code compliant benchmark. A wall moisture risk index termed RHT(92) had been developed under other projects. A risk index limit of RHT(92) ≤ 13 had been found to be consistent with a preponderance of moisture contents of wood elements below 19% moisture content, over a predominant portion of time in a two-year simulation featuring regionally-determined extreme weather patterns. That risk index was used in this project to develop an opinion based on the results of simulated performance of the mid-rise walls in the selected locations. Finally the same walls were assessed for their ability to meet maximum overall thermal transmittance prescribed in Part 3 of the NECB 2011 for each location.

Opinion

The results of the hygrothermal performance evaluation procedure documented in this report identify the climate locations in Canada for which the LWF and CLT walls described in this study were deemed to meet the intent of NBC 2010 Part 5, and NECB 2011 Part 3.

The results suggest that the additional fire protection measures incorporated to the specified LWF & CLT mid-rise wall specimens met the moisture risk index criteria proposed in this study for the following mid-rise building envelopes and location.

The LWF & CLT simulations results passed the moisture risk index assessment for all of the climate location investigated:

Prince Rupert, Halifax, Vancouver, Quebec City, Toronto, Ottawa, Yellowknife, and Winnipeg.

It should be noted, however, that the modelling did show that in locations with wetter climates (NBC Moisture Index substantially greater than 1), including Prince Rupert, Halifax and Vancouver, strapping alternatives for cladding support that are not susceptible to moisture deterioration should be incorporated in the LWF design, as was originally specified in this study.

The LWF and CLT specimens were also assessed against the maximum thermal transmittance requirements of NECB 2011 Part 3 Envelopes and passed for the following locations:

- Prince Rupert (Zone 5), Halifax (Zone 6), Vancouver (Zone 4), Quebec City (Zone 7A), Toronto (Zone 5), Ottawa (Zone 6), and Winnipeg (Zone7A).

To meet the NECB wall requirements for Yellowknife (NECB 2011 Zone 8), the LWF would need additional semi-rigid fibrous insulation outboard of the studs, and the CLT would require high R-value batts between the studs on the exterior of the CLT, instead of regular batts.

In addition, it was found that fire-retardant treatment that was applied to plywood through pressure-impregnation had negligible effect on the hygrothermal performance with respect to the moisture risk index obtained for Vancouver. As a result, our opinion is that this result applies to all locations considered for the reference LWF.

As an overall conclusion, the fire control measures proposed for mid-rise walls as solutions to NBC 2010 Part 3 for fire performance should also be considered to be solutions for NBC 2010 Part 5 and NECB 2011 Part 3, with the additional insulation identified for Yellowknife (Zone 8) to meet NECB 2011.

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1. INTRODUCTION

The role of the building envelope research team in this project was to assess whether wood-based building envelope solutions, as developed by the fire research team to meet the fire provisions of the National Building Code of Canada (NBC) 2010, would also meet the NBC Part 5 requirements relating to the protection of the building envelope. Accordingly, there was a need to determine whether the proposed solutions, as developed by the fire research team, were also able to adequately control heat, air, moisture and precipitation (HAMP) ingress into the building envelope. As well, those wood-frame mid-rise envelope solutions needed to meet the performance requirements given in the National Energy Code for Buildings (NECB) 2011.

Initially, the fire research team identified three types of exterior wall assemblies that would form part of their investigation:

a) Noncombustible exterior wall systems (the 'benchmark').

b) 'Protected' envelope assemblies featuring combustible structural elements (lightweight wood-frame approaches (LWF) and mass timber (cross-laminated timber - CLT) using noncombustible finishes and sheathing such as gypsum board.

c) 'Protected' envelope assemblies featuring combustible structural elements (LWF and mass timber) using pressure-impregnated fire-retardant-treated wood panels as exterior sheathing.

Approaches (b) & (c) were to be evaluated for their performance relating to their ability to control heat, air, moisture, and precipitation for a range of climate conditions across Canada. This was undertaken to ensure that recommendations developed in this study to address fire performance requirements of the NBC were also compatible with envelope HAMP performance requirements of Part 5 of the NBC 2010 and the NECB 2011. A review of HAMP-related objectives, functional statements and provisions associated with Part 5 are summarized in Section 2 of this summary report.

To perform the hygrothermal assessments of the proposed alternate solutions for combustible building envelopes meeting the requirements of the NBC 2010 Part 5, those code requirements were analysed and the following tasks were executed to address those requirements:

- Task 1 – Specifications of Envelope Details
- Task 2 – Selection of Climate Location & Climate Loads
- Task 3 – Water Penetration Lab Experiments
- Task 4 – Development of Hygrothermal Properties
- Task 5 – Benchmarking Experiments for Hygrothermal Modelling
- Task 6 – Hygrothermal Modelling and Analysis
- Task 7 – Development of an Opinion on 'Deemed to Comply'

This report summarizes the results of the code analysis and of all 7 Tasks.

2. NBC 2010 ANALYSIS – PART 5 HEAT, AIR, MOISTURE AND PRECIPITATION CONTROL

Requirements relating to heat, air, moisture, and precipitation (HAMP) control by the building envelope are included in Part 5 of the NBC 2010 - Environmental Separation. Part 5 addresses all building types and occupancies referred to in Part 3, but unlike requirements for fire protection, this section of the code was written more recently and is generic, including requirements that are more objective-oriented rather than prescriptive requirements pegged to specific constructions systems.

From the point of view of introducing innovative wood products to the market place that are intended to meet the heat, air, moisture and precipitation requirements of this section of the code, there are few built-in biases towards one system or another in Part 5. Nevertheless, for innovative envelope systems and when attempting to satisfy performance requirements set out in Part 5, this presents more of a challenge since there are no prescriptive requirements nor performance benchmarks against which building envelope professionals could demonstrate 'equal or better performance' than Code. The proposed strategy was to develop a method, based on previously-developed assessment procedures for HAM&P control that would assist the building professional in demonstrating compliance to Part 5 using innovative mid-rise wood-based envelope strategies.

2.1 Objectives, Functional Statements and Provisions in NBC 2010

Building envelope requirements for control of heat, air, moisture and precipitation in Part 5 relate to two root objectives in Division A of the NBC 2010: OS – Safety, and OH – Health. Specifically, the following objectives are addressed.

OS2 Structural Safety

An objective of this code is to limit the probability that, as a result of design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to structural failure. The risks of injury due to structural failure addressed in the NBC 2010 that are applicable in the particular instance of building envelope design are those caused by:

OS2.3 – Damage to or deterioration of building elements

Addressing OS2.3 through proper HAMP control is key to addressing structural safety and should contribute to a more 'durable' building envelope, although it should be noted that 'durability' per se is not a root object of the NBC 2010. As well, proper HAMP control is not the only factor to consider for structural safety, since the envelope components' resistance to chemical and biological degradation in the presence of moisture or water also needs to be considered. NRC's envelope system performance assessment relating to HAMP control takes into account all of these factors, for the particular components involved in the system.

OH1 – Indoor Conditions

An objective of this code is to limit the probability that, as a result of design or construction of the building, a person in the building will be exposed to an unacceptable risk of illness due to indoor conditions. The risks of illness due to indoor conditions addressed in this Code are those caused by:

OH 1.1 – inadequate indoor air quality

OH 1.2 – inadequate thermal comfort

OH 1.3 – contact with moisture

The building envelope strategies used to control HAMP and thereby minimize the risk of structural deterioration of wood elements in the envelope are largely believed to also address the health objective 'Indoor Conditions', although they may involve different degrees of stringency in the design. For example, the presence and growth of mould (which can lead to OH1.1 – inadequate indoor air quality) can occur on some envelope components at lower relative humidity levels in the envelope than say wood rot fungi, the presence of which can lead to OS2.3 – damage to or deterioration of building elements.

The NRC methodology that has been developed to quantify the risk of these conditions to occur takes both the safety objective and the health objective into account when assessing the moisture management performance of the envelope.

The functional statements in the objective-based NBC are attributes of the existing requirements – they describe in generic terms what function of the building or its components is expected to be performed to addresses the relevant root objectives of the code. As such, they define a clear path between the existing code requirement and the objective they are intended to address. The functional statements that apply to heat, air, moisture and precipitation control in the NBC 2010 Part 5 are listed below:

F51 – To maintain appropriate air and surface temperatures

F54 – To limit drafts

F55 – To resist the transfer of air through environmental separators

F61 – To resist the ingress of precipitation, water or moisture from the exterior or from the ground

F62 – To facilitate the dissipation of water and moisture from the building

F63 – To limit moisture condensation

F80 – To resist deterioration resulting from expected service conditions

Adequate control of HAMP involves the proper balance between minimizing wetting of the envelope (F51, F54, F55, F61, F63), and maximizing envelope drying (F62) such that the occurrence of conditions that set up deterioration mechanisms (F80) are avoided. The assessment methodology that was used for this project addresses all of these mechanisms in the context of a particular envelope system, the material properties of its constituent parts, and the outdoor climate and indoor conditions.

Example provisions in Division B are analyzed in the context of the objectives and functional statements which they address in Table 2.5.1 of the NBC 2010; this same table is given in Table 1.

Table 1 ─ Building Envelope – Resistance to Deterioration and Vapour Diffusion

Building Envelope – Environmental Separation 5.1.4.2.(1) Resistance to Deterioration							
Provision	FS-O Pair		Functional Statement		Link	Objective	
	FS	O	To <function>	What/from	So that	People/building	Not <harmed> due to
5.1.4.2.(1)	F80	OH1.1	To resist deterioration resulting from expected service conditions		So that	A person is not exposed to an unacceptable risk of illness due to inadequate indoor air quality	
	F80	OS2.3	To resist deterioration resulting from expected service conditions		So that	A person is not exposed to an unacceptable risk of injury due to damage or deterioration of the building elements	

Building Envelope – Environmental Separation 5.5.1.1.(1) Resistance to Vapour Diffusion							
Provision	FS-O Pair		Functional Statement		Link	Objective	
	FS	O	To <function>	What/from	So that	People/building	Not <harmed> due to
5.5.1.1.(1)	F63	OH1.1	To limit moisture condensation		So that	A person is not exposed to an unacceptable risk of illness due to inadequate indoor air quality	
	F63	OH1.2	To limit moisture condensation		So that	A person is not exposed to an unacceptable risk of illness due to inadequate thermal comfort	
	F63	OS2.3	To limit moisture condensation		So that	A person is not exposed to an unacceptable risk of injury due to damage or deterioration of the building elements	

Part 5 and other parts of the NBC also contain other objectives, functional statements and provisions relating to structural sufficiency, fire protection, and noise protection that were addressed by other teams and collaborators in the overall mid-rise wood project, and are therefore not addressed here directly, but taken into account as described in the next section.

Finally, requirements relating to HAMP control at grade and below grade were not addressed in this study as they are not specific to, nor different for 5- and 6-storey wood construction.

2.2 Interdependencies Among Various Requirements

The issue of interdependencies between the engineering solutions in each discipline is one that constantly confounds designers. A structural design for a seismic area involves extensive connectivity between shear walls and floor diaphragms, whereas to meet acoustical performance targets regarding sound transmission, it would be preferable to decouple some of the structural elements. Competing design solutions also occur between fire protection and HAMP - both need to be addressed in the design of exterior walls by incorporating elements that limit fire propagation up the exterior wall and also limit ingress of precipitation into the assembly. For example, air spaces behind the cladding are generally used to enhance precipitation ingress control, but may inadvertently introduce a fire propagation path, depending on the design. This issue was investigated by both the fire research team and the building envelope research team, resulting in the mid-rise LWF specifications in this document. Addressing the interaction between the technical disciplines plays a critical role in achieving acceptable whole building performance according to code.

The results of our selection of mid-rise lightweight wood-frame walls (LWF) and cross-laminated timber (CLT) walls, and associated analysis of interactions between disciplines, are presented in the next section.

3. SPECIFICATIONS OF ENVELOPE DETAILS (Task 1)

In a process of consultations with stakeholders, including the Canadian Wood Council (CWC), FPInnovations, and consultations with NRC's fire and acoustic research teams, specifications were developed for 2.44 m x 2.44 m wall specimens that were investigated for hygrothermal performance.

3.1. Main Elements of the LWF Envelope

The key elements of the mid-rise lightweight wood-frame envelope (LWF) are similar in many respects to conventional low-rise envelopes since the exterior walls planned for midrise buildings are not typically load-bearing for the main structure. Nevertheless, there may be an intensification of studs in mid-rise walls due to the prevalence of large window areas in, for example, mid-rise buildings built to date. As a result, what is left of the actual opaque wall features a greater proportion of studs per unit area. As well, the envelope walls investigated by the fire research team in this project featured perhaps less conventional selections of materials and numbers of layers involved to achieve both the maximization of fire load within the envelope to anticipate worst-case fire load conditions on the one hand, and on the other hand, the fire research team included elements that provide additional protection of the envelope from the fire safety standpoint, as part of the strategies of encapsulation and exterior flame propagation control investigated by the fire research team for mid-rise construction.

The elements that were specified are:

- Interior finish, including finishing boards and paint
- Air and vapour barrier control membranes, if any
- Wood framing
- Insulation in the stud cavities
- Sheathing membranes or Weather Resistant Barriers (WRBs)
- Cladding system, including rainscreen cavity as applicable and the cladding itself.

The rationale for the selection of each of these elements, as presented Table 2, is provided in the next several sections along with the options that resulted from discussions with the fire and acoustic research teams.

Table 2 ─ Summary of Specifications for Mid-rise Lightweight Frame Exterior Walls

Element	Baseline: Non-combustible LF (code minimum) - Envelope	Mid-rise Lightweight Wood-frame –Envelope	Comments
Interior Finish	Gypsum board – Type X	Gypsum board – Type X, 2 layers	Add resilient channels between gypsum board layers and framing to limit sound flanking?
Air Barrier System & Vapour Barrier	0.15 mm polyethylene lapped & caulked	Provided by SPF bonded to studs	Is polyethylene redundant with SPF and proper detailing?
Framing	Non-combustible light frame assembly – engineer's drawings to meet minimum code. Staggered stud.	38x140 mm wood studs @ 300 mm o.c. <u>Optional</u>: 38x140 mm wood studs @ 150 mm o.c. stagger.	Conventional, but narrower spacing. Intensified use of wood studs.
Insulation	140 mm batts; additional exterior furred batts to meet NECB 2011	Medium Density Spray-applied Polyurethane Foam (SPF) – 140 mm thickness	SPF chosen by fire research team meets CAN/ULC-S705.1 & NECB 2011 req's by Zone
Sheathing	12.7 mm exterior gypsum sheathing (generic)	12.7 mm exterior gypsum sheathing (generic). <u>Alternate</u>: 15.9 mm FRT plywood	Regular exterior gypsum sheathing use now rare; minimum code for buildings required to be of noncombustible construction.
Furring, WRB & flashing	1 or 2 layers asphalt-impregnated building paper.	2 layers asphalt-impregnated building paper. Furring: pressure treated, resistance to bio degradation	Details dependent on cladding & location to meet NBC 2010 5.6.1.1 & 5.6.2.2.(3)
Cladding	Fibre-cement panels	Fibre-cement panels	Generic materials affording minimum protection

3.2. Meeting Minimum Code with Generic Products

Most readers will be more familiar with proprietary manufactured products commonly specified for mid- and high-rise construction projects. For example several building product suppliers have their own brand of exterior gypsum sheathing commonly used in commercial building construction, which feature water and mould-resistant gypsum cores encased in a glass-mat facer on both sides. Nevertheless, since the research in this project was in support of generating information for potential code changes, it was important that the materials selected for the investigation were generic products that met minimum standards referenced in the code, while being representative of a code minimum solution in terms of performance – not representative of best practice[1]. For example, the sheathing specified in this project is simply exterior gypsum sheathing – a product that is still available but has been reported by local suppliers to be less in demand than proprietary products with enhanced moisture and fire properties. Such enhanced properties are currently not needed to make the case for the proposed 'encapsulation strategy' for fire performance, nor for the resulting moisture performance.

A similar rationale applies to the selection of Type X gypsum board that forms part of the encapsulation strategy for fire performance, and for the selection of a generic fibre-cement panel applied over a rainscreen design for the cladding system performance tests and hygrothermal simulations. This approach was used to populate most of the specification entries in Table 2.

3.3. Summary of Interrelated Factors from Fire and Acoustic Research Teams

As highlighted in Table 2, a number of factors that both relate to moisture control and fire protection, and vice versa, were flagged by the fire and acoustic research teams for consideration and review. These are summarised in Table 3.

[1] Selection of best practice proprietary materials at this stage of our investigation would limit the recommendations resulting from the research to only using the particular products specified, which would not be consistent with the way NBC requirements are generally developed.

Table 3─ Summary of Issues Interrelated to Moisture Management considering issues of Moisture, Energy, Fire and Acoustics

Envelope component	Interrelated Issues with Fire and Acoustics	Hygrothermal Issues
Cavity Insulation	Exploration of 'encapsulation strategy' in combination with combustible insulation in cavity.	High R-value, combustible insulation products could be used to meet NECB 2011 in some locations. Will such products limit the ability of mid-rise wood studs to dry?
Sheathing materials	Fire-retardant-treated wood-based sheathing materials investigated as potential means to limit exterior fire propagation.	Does the fire treatment of plywood alter the hygrothermal properties of the sheathing? If so, does this create a moisture performance issue for the envelope?
Cladding system	Minimum code, non-combustible cladding system: fibre-cement panels mounted on preservative-treated plywood strips. The fire research team investigated the role of the air space on exterior wall propagation of fire. Airspace is flashed at each floor.	Does the cladding system selected by the fire research team impact moisture management? The cladding system's resistance to water entry as a function of weather parameters was established in water entry tests undertaken in Task 4. Flashing at each floor defines the height of rainscreen airspace for modelling.
Sheathing paper	Two layers of code compliant sheathing paper may add to the fire load and possible flame spread inside the rainscreen cavity - investigated by fire research team.	Two layers of code compliant sheathing paper recommended for claddings that absorb water and moisture. Do the additional materials delay the outward drying in some climates? To be assessed in modelling.
Interior finishing assembly	Are resilient channels needed behind interior finishes to reduce flanking of sound through the envelope between adjacent suites?	Does the additional interior air space in the envelope assembly, formed by the resilient channels, affect the hygrothermal performance of the envelope? Current answer: unlikely. Parametric investigation is optional.

3.4 Recommendations for Hygrothermal Assessment of LWF and CLT Wall

3.4.1 Specification of the LWF Wall

The following exterior wall configuration shown in Figure 1 was the subject of the hygrothermal modelling assessment. It incorporates elements of enhanced fire protection for mid-rise construction at the interior face as part of the encapsulation strategy, and at the cladding assembly to limit exterior flame propagation. It also features a combustible insulation product to permit investigating whether the fire control mechanisms placed on either side of the insulation provided effective protection of the combined structural-thermal elements inside the assembly. Additional interior finish detailing (not shown) could be further investigated for enhanced acoustic performance to reduce flanking between floors through the envelope structure; e.g., resilient channels separating the two inner layers of Type X gypsum board.

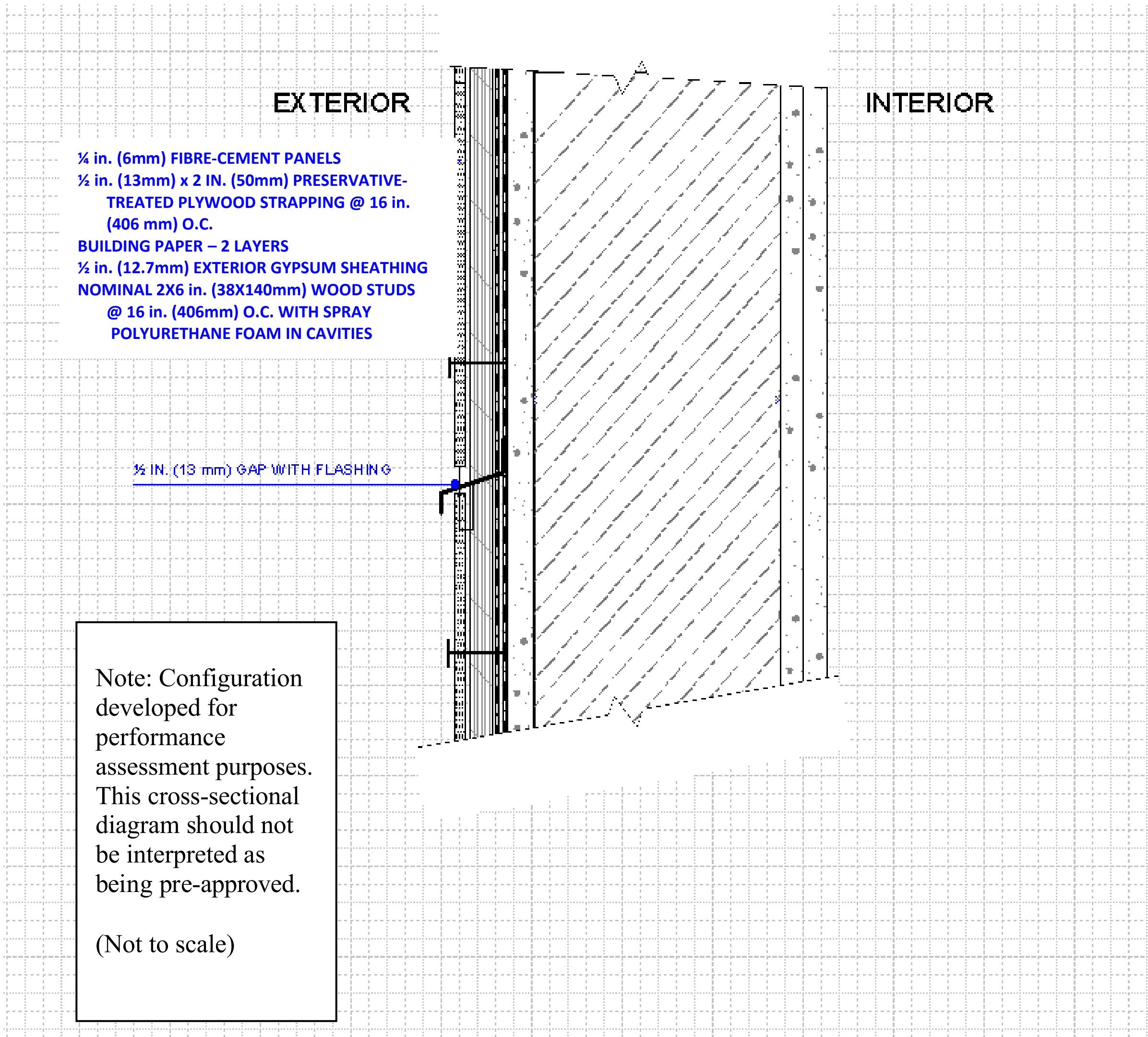

Figure 1 ─ Cross-sectional Diagram of the Mid-rise Lightweight Wood-frame Assembly to be assessed for Heat and Moisture Performance (not to scale)

3.4.2 Specification of the Cross-laminated Timber Wall

Both the fire research team and the acoustic research team have performed tests on cross-laminated timber (CLT) load-bearing party walls and shear wall assemblies. CLT construction can also be used for the exterior envelope, and accordingly, a CLT envelope specification was developed. Our recommendation is based on a configuration proposed by FPInnovations[2]

[2] CLT Handbook: Cross-Laminated Timber; edited by Sylvain Gagnon and Ciprian Pirvu. (c) FPInnovations, 2011. Chapter 10 (Enclosure), Figure 6.

combined with the encapsulation strategy specified above to meet the recommendations of the fire research team for LWF, with the same rationale. A 5-ply CLT system was chosen that was consistent with one concept design by FPInnovations[1]. Also note that the CLT thicknesses used in buildings are mostly governed by structural requirements as well as available products, panel lay-up, and other factors. Mid-rise buildings typically need thicker CLT wall panels than shorter buildings. The insulated assembly consists of nominal 2x6 (38x140 mm) stud framing with 140 mm mineral fibre insulation. The resulting cross sectional diagram is shown in Figure 2.

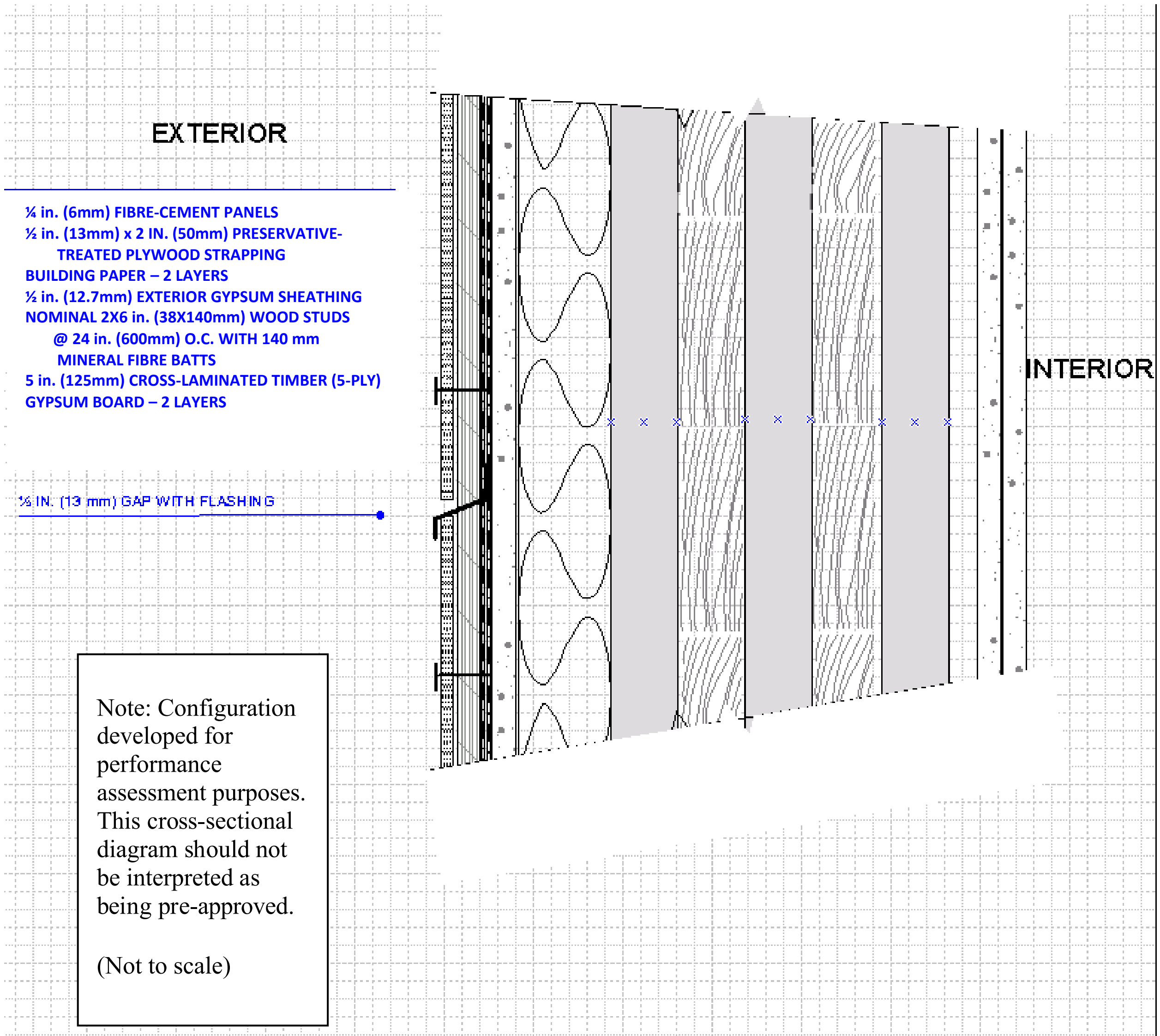

Figure 2 ─ Cross-sectional Diagram of the Cross-laminated Timber Assembly to be Assessed for Heat and Moisture Performance (not to scale)[3]

[3] Note: to accommodate electrical wiring and to achieve superior flanking sound control, the two layers of interior finishes could be mounted on resilient channels.

The specifications for the Mid-rise Light Wood Frame Walls and CLT walls are provided and discussed in more detail in report A1-100035-03. These specifications were used by the hygrothermal performance assessment team to construct specimens to be tested in the lab for water entry and to guide numerical representation of the walls for hygrothermal modelling.

4. SELECTION OF CLIMATE LOCATION AND CLIMATE LOADS (TASK 2)

The objective of the task is to select, from the 679 locations in Table C-2 of the National Building Code of Canada (NBC) 2010, several representative locations for which long-term historical weather data exists. This information from these locations can subsequently be used to determine the exterior boundary conditions for input to hygrothermal simulation programs and hygrothermal testing in the laboratory.

The design of the exterior walls of proposed mid-rise wood buildings is covered by Part 5, Environmental Separation, of the NBC 2010. Such exterior claddings should be designed by an engineer or architect. Although not specifically mandated, in general, the exterior walls are designed as pressure-moderated rainscreen walls, i.e. the walls have a drainage cavity.[4]

The exterior walls considered in this report are all assumed to conform to the National Energy Code for Buildings (NECB) 2011, specifically Sentence 3.2.2.2.(1) and Table 3.2.2.2. The NECB 2011 defines six different climatic regions for Canada. Examination of Table 3.2.2.2 shows that there are 5 different insulation requirements for the 6 climate zones; zones 7a and 7b have the same insulation requirements. There are potentially at least 5 different wall systems to evaluate assuming that 5 different insulation levels are proposed. Whereas the climate zones defined in the NECB 2011 are strictly thermal zones, those described in the IECC[5] and ANSI/ASHRAE Standard 169[6] are further refined into marine, dry, and humid moisture zones. Although originally defined for HVAC and humidification and dehumidification purposes, the sub-classification of thermal zones into moisture zones can be useful for the purpose of cladding evaluation. For the purposes of this project, the marine and humid zones have been combined into one zone classified as wet. For each thermal zone a dry and wet representative location was selected where possible.[7] Experimenters and modellers should be able to investigate the performance of the proposed exterior wall systems under higher or lower moisture loadings in a given thermal zone if required. A minimum of 9 locations was envisaged, one for each thermal/moisture zone combination.

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[4] Rousseau, M. Z.; Poirier, G. F.; Brown, W. C., *Pressure Equalization in Rainscreen Wall Systems,* Construction Technology Update, 17, 1998-07, Institute for Research in Construction, National Research Council of Canada p. 6

[5] ICC (International Code Council). 2012 International Energy Conservation Code (IECC). Falls Church, VA: International code congress.

[6] ANSI/ASHRAE 169-2006 "Weather Data for Building Design Standards (ANSI Approved)", American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2006, 70 pages.

[7] Zones 7 and 8 are very cold zones that for HVAC purposes are not divided into *dry* and *humid* classes. For moisture-related purposes neither are they are generally classified as *humid* or *dry*; these climates tend to be dry given that the climates are very cold, and thus much of the precipitation is delivered in solid rather than liquid form.

4.1. Classification Criteria: Thermal and Moisture

The first criterion with respect to the selection of climate loads is thermal performance. In Figure 3 the distribution of the thermal zones in Canada is illustrated. Zones are delineated by degree-days below 18°C, hereafter known as HDD18[8]. This requirement is obtained from the NECB 2011. . The zones are given in Table 4 along with the prescribed overall thermal transmittance requirements for above-grade opaque walls.

The second criterion is moisture-related. A practical definition of what constitutes wet and dry can be gleaned from the NBC 2010. A moisture index, MI, is defined in the NBC 2010 [Volume 2, Appendix C, Division B, C-6] (see Figure 4). The exterior cladding design criteria for Part 9 buildings are specified by the Clauses 9.27.2.2.5(a) and (b). The mandate provided in these clauses is that exterior walls should include a drainage cavity if MI > 1. For MI ≤ 1 a drainage cavity is not required. Note that in Part 9 of the code, and for climates with MI > 0.9 and HDD18 < 3400, a drainage cavity is required; i.e. the "Victoria exception". Thus the definition for wet and dry can be taken as MI >1 and M ≤ 1, respectively. This also admits the possibility of establishing boundary conditions and input files for cases where a proposed exterior wall is not a rainscreen wall. Such walls would be permitted under Part 5 of the NBC 2010. Note that for Zones 7a, 7b, and 8 (Arctic/Subarctic) there are no wet locations, and similarly for Zone 4 (Mixed) there are no dry Canadian locations as per the NBC 2010.

A third criterion is population. For each thermal and moisture division the largest population center would be selected as the representative location.

[8] http://www.climate.weatheroffice.gc.ca/Glossary-popup_e.html

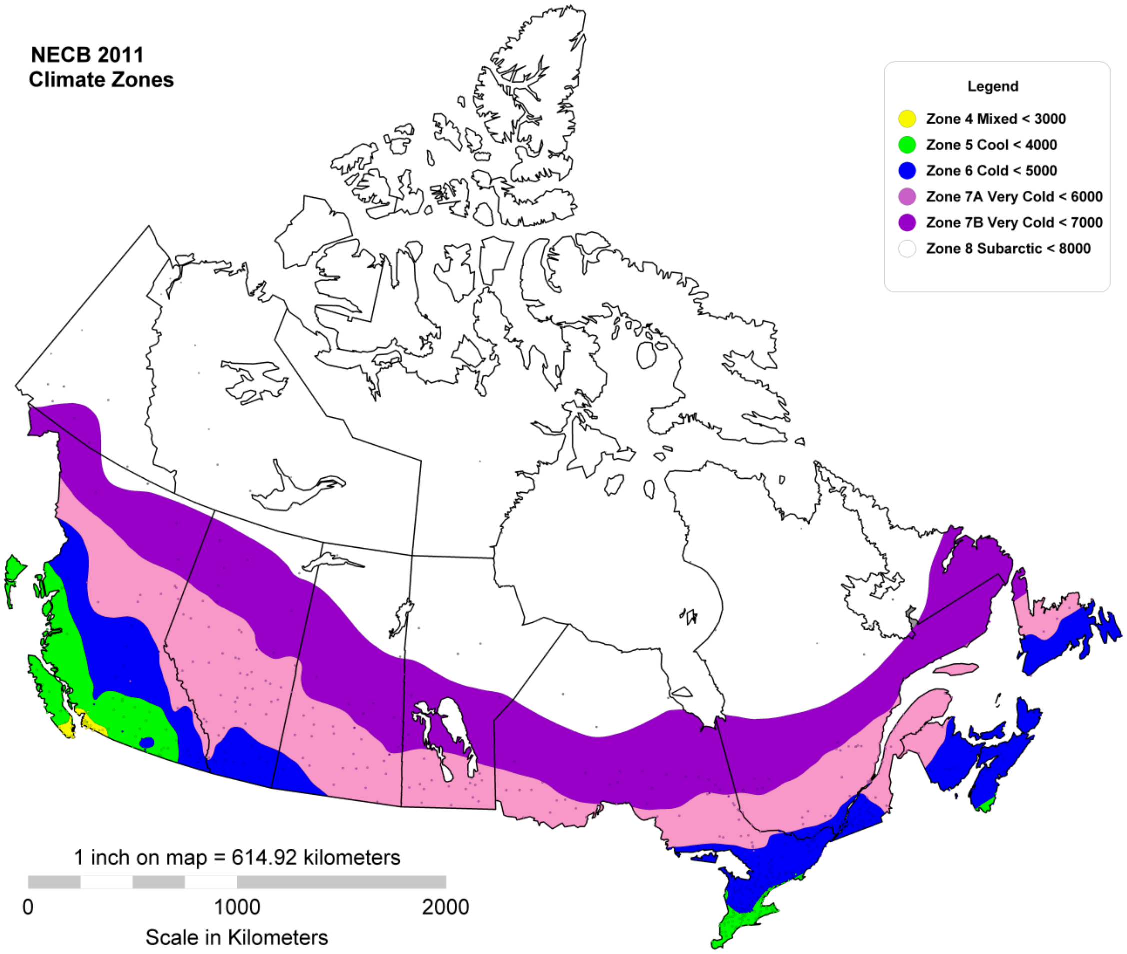


Figure 3 ─ Extended climate zone map of Canada. Zones defined by HDD18.

Table 4— Thermal Zones and Overall Thermal Transmittance Requirements
(source: Table 3.2.2.2. NECB 2011)

Description	Zone	HDD18	U-overall W/(m^2•K)*
Subarctic/Arctic	8	>=7000	0.183
Very Cold	7b	<7000	0.210
Very Cold	7a	<6000	0.210
Cold	6	<5000	0.247
Cool	5	<4000	0.278
Mixed	4	<3000	0.315

* - as required by the NECB 2011

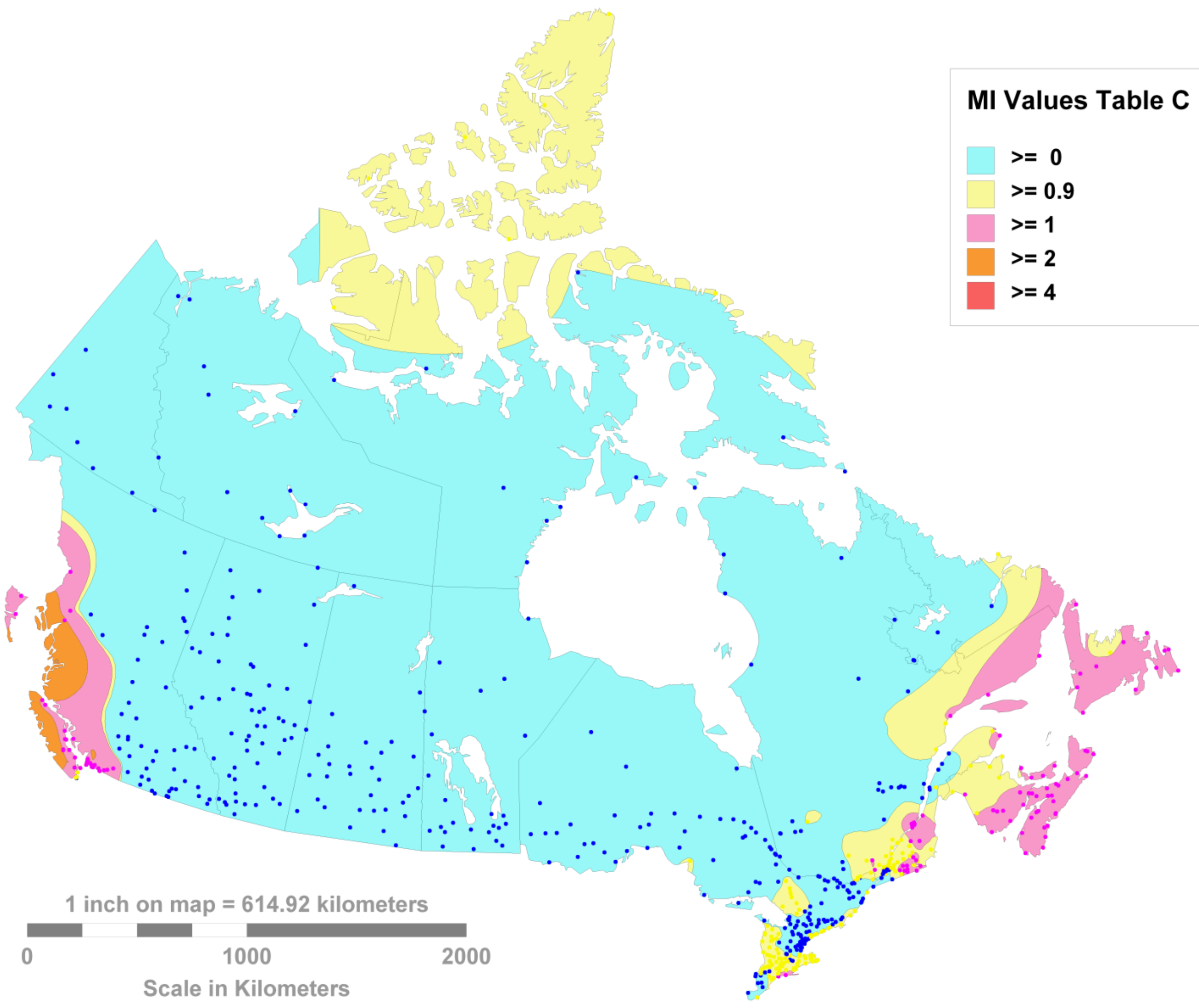


Figure 4 — MI values for Table C-2 locations and MI contours for Canada based on NBC 2010

4.2. Selecting Locations

Three selection criteria are possible: (1) the largest population center in a NECB 2011 zone or moisture class; (2) a thermal criterion, i.e., most degree-days below 18°C, and; (3) a moisture-based criterion, i.e., the MI. An example of the logic used for proposing a representative location for each climate zone is presented below for Zone 8. A more detailed analysis and a list of locations having long-term climate data are provided in report A1-100035-03.2.

Zone 8: There are 61 locations in Zone 8, 29 of which have long-term data readily available. The coldest location in the dataset is Alert NU (82°30′05″N ; 62°20′20″W) at 13,030 HDD18. The largest, coldest community is Cambridge Bay NU; with a population of 1,477 and having 11,670 HDD18. There are three large communities grouped around 10,000 HDDs, Iqaluit NU being the largest, with a population of 6,699. There is no climatological reason preventing the selection of the coldest location, so if a building envelope solution is sought that works for all locations then Alert NU could be selected. The most likely places in Zone 8 where a mid-rise building might be considered would be Iqaluit, and Yellowknife NT, the latter being the largest population center in this category.

4.3. Recommendations

It is recommended that the locations listed in Table 5 identified geographically in Figure 5, and selected using the population based criteria, be used for this project. These locations represent large markets within the specified climate zones, where mid-rise wood buildings are most likely to be built.

Table 5─ Recommended locations primarily based on population

Zone Description	Zone	Wet (MI > 1)	Dry (MI ≤1)
Subarctic/Arctic	8/9	n/a	Yellowknife (8170/0.58)*
Very Cold	7	Quebec City (5080/1.04)	Winnipeg (5670/0.58)
Cold	6	Halifax (4000/1.49)	Ottawa (Int'l) (4500/0.84)
Cool	5	Prince Rupert (3900/2.84)	Toronto (Pearson)(3980/0.86)
Mixed	4	Vancouver (Int'l) (2925/1.44)	n/a

* - bracketed terms are HDD18 and MI, respectively

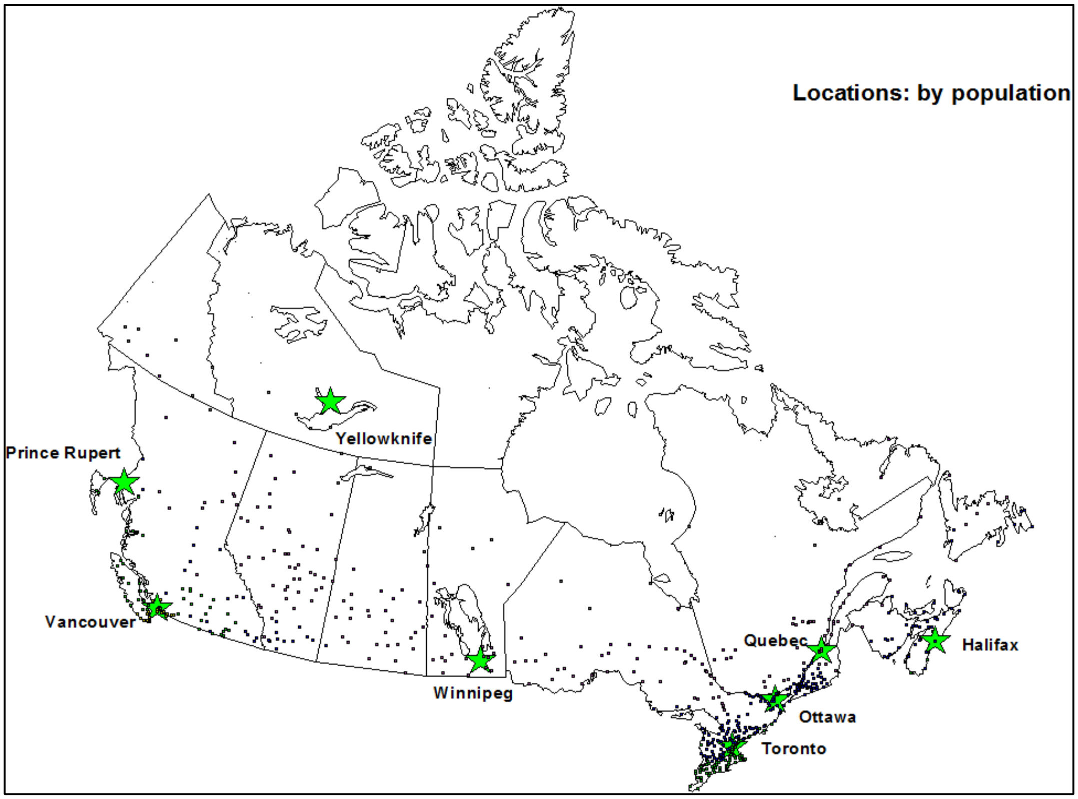


Figure 5 ─ Recommended locations selected on the basis of population, NECB 2011 climate zone and NBC 2010 Moisture Index, MI.

5. INVESTIGATION OF WATER PENETRATION THROUGH CLADDING AND DEFICIENCIES (Task 3)

5.1. Overview of Water Entry Testing

A key parameter required as input to the numerical simulations is the percentage of water entry behind the cladding systems and through deficiencies as a function of wind pressure and wind-driven rain (WDR). In an effort to extend the applicability of solutions to the current National Building Code (NBC) requirements with respect to low-rise wood-frame structures to structures comprising mid-rise wood construction, the building envelope research team was tasked by the Mid-Rise Wood Buildings consortium to investigate the moisture management and water penetration performance of cladding systems and related deficiencies relevant to mid-rise buildings.

Based on the specifications of mid-rise walls described in Section 3 of this summary report, a fibre-cement cladding system was selected for detailed investigation for water entry characteristics under the degree of wind-driven rain conditions associated with mid-rise buildings. As well, a stucco cladding system was also investigated, based on previous testing at NRC, to allow the investigation of cement-based porous cladding systems that could potentially be used for sections of mid-rise wall assemblies.

Water entry was evaluated in two ways. Correlations of water entry through the cladding system were developed for: (1) water entry rates around deficiencies based on tests conducted in this study, and (2) water entry rates through absorptive claddings based on previous test results of a stucco-clad wall specimen built to NBC requirements. In both cases, the correlations have been extended to cover wind pressures that could occur in mid-rise and taller buildings in some of Canada's windiest locations.

With respect to the previous study in which the water entry rates for an NBC-compliant stucco-clad wall specimen were assessed, this work permitted the development of practical correlations to determine the percentage of water entry rate per unit wall area due to wind-driven rain (WDR) and wind pressure differentials. However, these correlations were only applicable to low-rise residential buildings where the wind pressure is < 150 Pa. For mid-rise construction and taller buildings, however, the wind pressure can attain levels greater than 150 Pa. Therefore, there was a need to develop additional correlations that relate the percentage of water entry rate due to WDR that are applicable to situations where higher wind pressure loads exist. In this project, the water entry results were combined with those derived from water entry tests through deficiencies in a cladding system suitable for mid-rise buildings and subsequently used to assess the hygrothermal performance of mid-rise buildings under worst-case water entry conditions.

The following steps were undertaken and completed for establishing correlations to predict the rates of water entry behind cladding of mid-rise buildings during wind-driven rain events:

- Conduct a series of water entry tests over a wide range of simulated wind pressure and WDR loads to measure the water entry rate passing the cladding through deficiencies located in a fibre-cement cladding system.

- Use the test results to develop correlations for determining the percentage of water entry rate through deficiencies as a function of pressure difference across the assembly and water spray rate onto the cladding surface. The correlations are needed by the hygrothermal model to generate realistic water entry rates to the backside of the cladding, for wind and precipitation conditions recorded in the weather data for each location.
- Analyze the water entry data for the NBC-compliant stucco cladding for high wind pressures obtained in a previous NRC study and applicable for mid-rise and taller buildings and thereafter develop a correlation to determine the percentage of water entry rate as a function of wind pressure and WDR for absorptive claddings.

The water entry evaluation of fibre-cement cladding was conducted using the mid-scale Dynamic Wall Test Facility (DWTF). The mid-scale DWTF accommodates samples of up to 1.22 m by 1.83 m (4ft x 6ft) in size. The test set consisted of three 1.22 m by 0.61 m (4ft x 2ft) test specimens mounted into a single aluminum test frame having dimensions of 1.22 m by 1.83 m (4ft x 6ft).

Each specimen, in which was incorporated a deficiency consisting of three 2.5 mm diameter holes located directly above a ventilation pipe (which in this case consisted of a 114 mm (4.5 in) diameter PVC pipe), was tested for water entry. The three 2.5 mm diameter holes where intended to be representative of a sealant failure of the sealed gap located between the ventilation pipe and cladding. Each specimen was subjected to three water deposition rates for which water was sprayed directly above the deficiencies. To cover the range of driving rain wind pressures as might occur in different climatic regions of Canada, each water deposition rate was tested across several pressure steps that ranged between 0 Pa to 1150 Pa; this test range was determined by Cornick [Report A1-100035-03.2, Part 2] on the basis of a review of driving rain wind pressures and rainfall data for selected Canadian locations. Based on an 1150 Pa peak test pressure, the water entry test conditions were representative of conditions at all Canadian locations excluding the northeastern tip of Newfoundland (St. Anthony's) and the western side of the Queen Charlotte Islands. For each pressure step, a water entry test was conducted at each of the three water deposition rates for a 10-minute period.

A more in-depth description of the test protocol and apparatus used for this investigation is included in report A1-100035-03.3.

5.2. Water Entry Test Results

A number of water entry tests were performed and following an analysis of results, the following test results were selected to be included in the hygrothermal analysis. Result details and analysis are presented in report A1-100035-03.3.

5.2.1 The water entry test results: Test 2 of Specimen 1

The water entry test results for Test 2 of Specimen 1 are presented in Figure 6 and Table 6

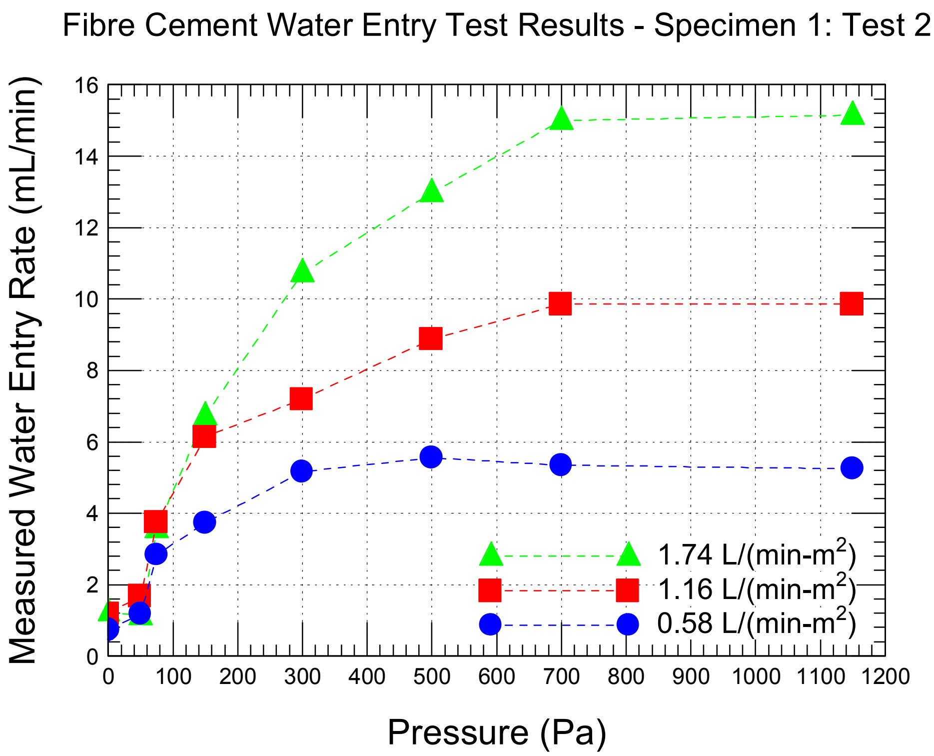


Figure 6 ─ Water Entry Rate test results for Specimen 1; Test 2

Table 6─ Water entry rates (mL/min) at different spray rates (L/min-m^2) for Specimen 1; Test 2

Applied Pressure (Pa)	Spray rate 0.58 L/min-m^2	Spray rate 1.16 L/min-m^2	Spray rate 1.74 L/min-m^2
0	0.73	1.19	1.23
50	1.17	1.68	1.12
75	2.83	3.76	3.56
150	3.73	6.14	6.72
300	5.16	7.19	10.73
500	5.56	8.88	12.98
700	5.34	9.86	15.00
1150	5.25	9.86	15.15

5.3 Correlations for Water Entry Through Deficiencies

In order to apply the water entry results, as provided in the previous section, to the hygrothermal simulations, the results were normalized to a value that can be implemented with ease by the model. In this case the water entry results were normalized to a standard 2.44 m x 2.44 m (8 ft x 8 ft) wall system. Due to the nature of the type of deficiency through which water penetrated (three 2.5 mm diameter holes located above a ventilation pipe), further consideration was required to estimate the number of ventilation pipes, or other penetrations, that might be encountered in an 8 ft x 8 ft wall section of a typical mid-rise building.

Considering a potential worst-case scenario, the following situation was proposed, focusing on the expected number of pipes that might penetrate the walls of a small dwelling unit (e.g. bachelor apartment) of a mid-rise building. If it is supposed that the dwelling unit has dimensions of 7.3 m by 7.3 m, or approximately 54 m^2 in size (24 ft x 24 ft), and has only one exterior wall in which are located three ventilation pipes (e.g. ventilation for kitchen stove, bathroom and dryer), then this provides for three ventilation pipes along a 7.3 m (24 ft) wall. Assuming the ventilation pipes are equally distributed along the wall, this suggests that there is ventilation pipe every 2.4 m (8 ft); such a scenario is depicted in

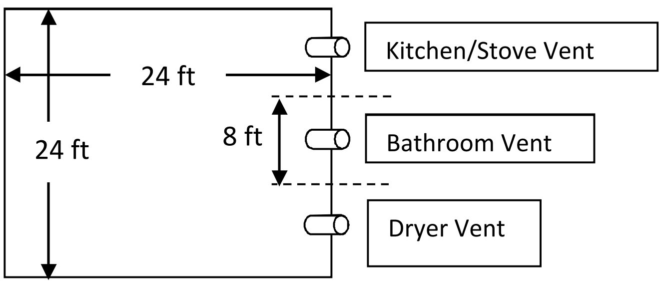


Figure **7**.

Using the previous designation of one vent per 2.44 m x 2.44 m (8 ft x 8 ft) of wall section allows the water entry rate results to be converted to a percentage water entry between the water passing the cladding and the total amount deposited onto the cladding in relation to the applied pressure differential across the wall and normalized to a 2.44 m by 2.44 m (8 ft by 8 ft) section of wall; the results derived from Test 2 of Specimen 1 are presented in Figure 8 and Table 7.

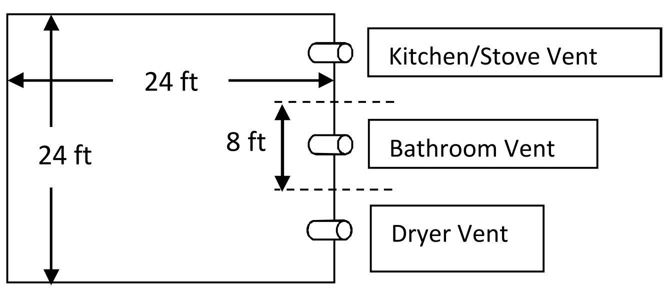


Figure 7 ─ Representation of the location of ventilation pipes along a 7.3 m section of wall for a small dwelling unit of a mid-rise building

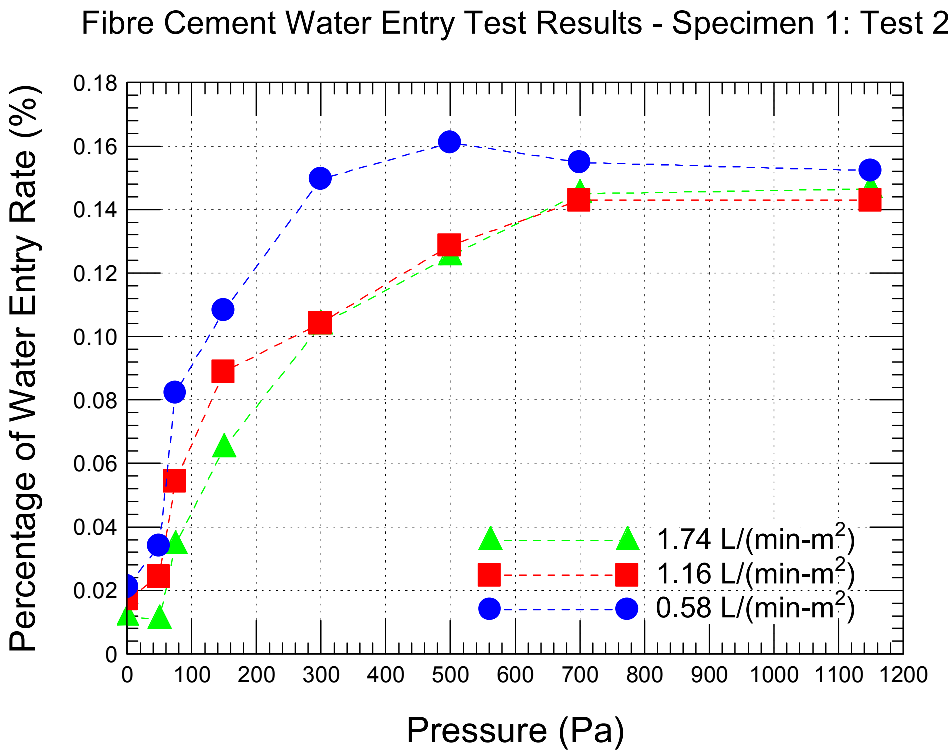


Figure 8 — Water Entry Percentage normalized to 2.44 m by 2.44 m (8 ft by 8 ft) wall

Table 7 — Water Entry Percentage normalized to 2.44 m by 2.44 m (8 ft by 8 ft) wall

Pressure Applied (Pa)	Spry rate 0.58 L/min-m^2	Spry rate 1.16 L/min-m^2	Spry rate 1.74 L/min-m^2
0	0.02%	0.02%	0.01%
50	0.03%	0.02%	0.01%
75	0.08%	0.05%	0.03%
150	0.11%	0.09%	0.06%
300	0.15%	0.10%	0.10%
500	0.16%	0.13%	0.13%
700	0.15%	0.14%	0.14%
1150	0.15%	0.14%	0.15%

The measurements of water entry rates through deficiencies at different water deposition rates were used to develop a correlation that covers a wide range of wind pressures and wind-driven rain loads; the data used to develop the correlation were those given in Figure 8. Water entry rates obtained in the tests were then expressed as a percentage of wind-driven rain (WDR) impinging on the surface of the test specimen wall. A comparison between the measured percentage of water entry rate and that calculated using the correlation are shown in Figure 9. As shown in this figure the calculated percentages of water entry rate are in reasonable agreement with the measured results. The correlations were incorporated in the hygrothermal model used in the simulations to determine water entry rates through deficiencies as a function of the wind pressure and wind-driven rain loads as might occur in the different climatic regions of Canada.

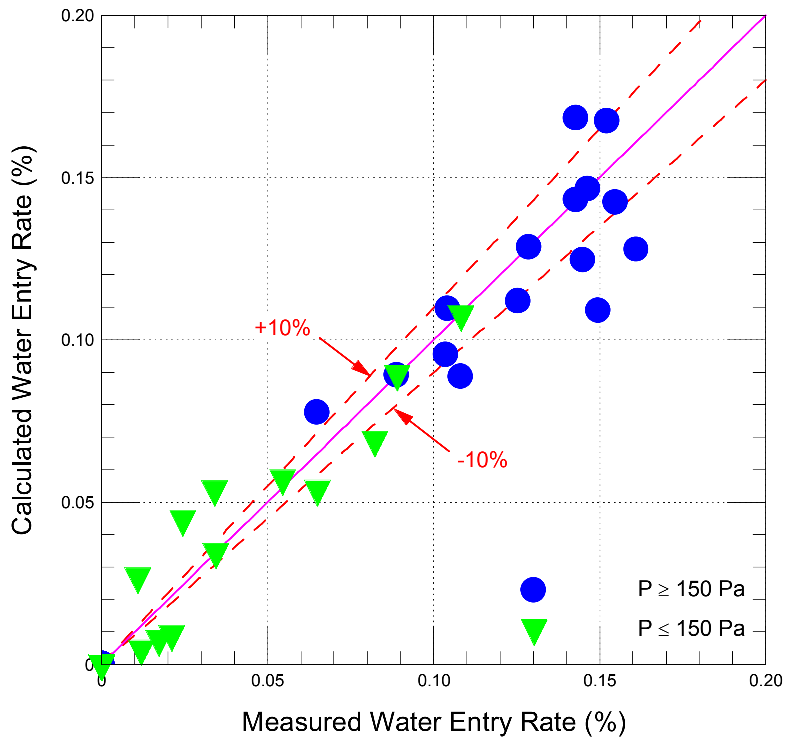


Figure 9 ─ Comparison between measured water entry rate and the correlation, expressed as percent of wind-driven rain.

6. CHARACTERIZATION OF HYGROTHERMAL PROPERTIES (Task 4)

To evaluate the hygrothermal performance of the generic exterior wall assemblies developed for use in mid-rise wood buildings, hygrothermal properties of materials used in the assemblies were needed as input data for hygrothermal modelling. Hygrothermal properties were developed for pressure-impregnated fire-retardant-treated plywood, regular gypsum sheathing, spray-applied polyurethane foam and cross-laminated timber. Results of the hygrothermal property determinations are documented is this section of the report.

6.1 Hygrothermal Properties of Selected Materials

The objective of this part of the research project was to generate a set of reliable and representative data on hygrothermal properties of a number of building materials selected by the fire research team including:

- Plywood with Fire-retardant Treatment A
- Plywood with Fire-retardant Treatment B

- Exterior Gypsum Sheathing
- Closed Cell Spray-applied Polyurethane Foam Insulation (SPF)
- Cross-laminated Timber (CLT – properties developed with FPInnovations)

The results of the testing, along with the methods used, are documented in report A1-100035-03.4

Lab-measured properties for conditions indicated are summarized in Table 8. Results in the report are provided for a range of conditions where, for example, the property varies significantly according to equilibrium RH or temperature conditions or in instances where both RH and temperature vary.

Table 8─ Summary of Measured and Referenced Hygrothermal Properties of Products Investigated[9]

Property @ Conditions	Plywood with Treatment A	Plywood with Treatment B	Exterior Grade Gypsum Board Sheathing	SPF meeting CAN/ULC-S705.1	CLT
Density (kg/m^3)	525.4	556.8	625.9	40.3	420
Heat Capacity[10] (J /(K·kg))	1880	1880	870	1470	1880
Thermal Conductivity @24 °C nominal (W/(m·K))	0.103	0.0936	0.159	0.0212	0.1114
Water Vapour Permeability[11] @ 50% RH (kg/ (m·s·Pa))	1.97×10^{-12}	2.23×10^{-12}	3.78×10^{-11}	1.87×10^{-12}	$1.80\text{x}10^{-12}$
Water Absorption Coefficient (kg/m^2 s^{½})	0.0034	0.0041	0.0015	0.00010	0.00195
Air Permeability (kg/(Pa·m·s))	$(5.12 \pm 6.57)\times10^{-12}$	$(3.77 \pm 4.18)\times10^{-12}$	$(4.44 \pm 1.43)\times10^{-12}$	$(2.64 \pm3.77)\times10^{-14}$	nil

As well, measurements were made to develop a moisture sorption isotherm curve for each material given in Table 8. This is a characteristic of hygroscopic materials that relates

[9] Partial list – see report A1-100035-03.4 for all properties and explanations.
[10] Kumaran, Mavinkal K, John K Lackey, Nicole Normandin, Fitsum Tariku, and David van Reenen. "A Thermal and Moisture Transport Property Database for Common Building and Insulating Materials: Final Report from ASHRAE Research Project 1018-RP." 2002
[11] Water vapour permeability measured for a range of RH – value reported in this table is for 50% RH.

equilibrium moisture content of the material to RH of the surrounding air for RH ranging from 50% to 95%.

6.2 Moisture Sorption Isotherm for Red Pine

In collaboration with FPInnovations, NRC developed moisture sorption isotherm curves[12] for specimens of Red Pine provide by FPInnovations. These sorption curves were used in the hygrothermal model for the parametric assessments.

6.3 Generic Material Properties

Hygrothermal simulation requires a complete set of material properties to execute simulations of walls specimens under investigation. NRC has a default data base of complete hygrothermal properties generated from a number of previous projects, with the information previously published and therefore in the public domain. To complement the properties generated and described in the previous section for this project, the properties of all other materials in the specified assemblies (LWF & CLT) that were required for simulation were selected from generic construction materials in NRC's existing database.

[12] Critical Assessment of Equilibrium Moisture Content of Wood and Wood-based Materials at High Relative Humidity. NRC Construction Report B-1463.1, June 15, 2011.

7. BENCHMARKING EXPERIMENT (Task 5)

The task of validating simulation models is often the most challenging and critical part of hygrothermal performance investigations. Credibility of the simulation tool is enhanced by its ability to simulate the key moisture transfer mechanisms of a wall similar to the one contemplated for parametric study. The experiment designed for this study involved the use of a specialized climatic chamber – namely, NRC's Envelope Environmental Exposure Facility (EEEF) – that was coupled with a custom weighing system based on the use of highly sensitive load cells and advanced micro processing technology to control and analyze the weighing results. The weighing system tracks the total weight change in a specimen over a test period – the weight change corresponding to the amount of moisture entering (wetting) or leaving (drying) the benchmark wall specimen over the course of an experiment. It was reasoned that this would provide quantitative data from which average moisture contents in key components of the experimental wall specimen could be obtained and reconciled with simulations results.

The following sections summarize the research approach and experimental results of the benchmark experiment. Details are provided in report # A1-100035-03.5 (see section 10).

7.1. Objective

The benchmark experiment had three objectives; to:

1. Determine the hygrothermal behaviour of full-scale (2.43-m x 2.43-m) wood-frame assemblies when subjected to steady and transient state hygrothermal conditions in a controlled laboratory environment, where both the indoor and outdoor environments were simulated in climatic chambers.

2. Assess the drying effect of the wood-stud frame with high initial moisture content.

3. Assess the degree to which the hygrothermal model, hygIRC, predicts key hygrothermal effects of this controlled experiment.

7.2 Scope of the Benchmark Experiment

The experimental work consisted of determining the hygrothermal behaviours of wood-frame wall components and assemblies under controlled laboratory conditions. Measurable hygrothermal effects were recorded and compared to that derived from using hygIRC.

The full-scale experiment was conducted on wall assemblies nominally having dimensions of 2.43 x 2.43 m. The wall components were specified to reproduce key components of the LWF wall described in Section 3 of this report (Figure 1). The wall specimen was composed of initially wet wood studs, dry OSB, and near-full cavity of SPF insulation applied on the wet studs. Foaming on wet studs is definitely not recommended practice but we specified this for the experiment because the study focussed on drying rates of wet studs. The interior finish featured gypsum board but no polyethylene. Cladding elements were forgone in this experiment to limit the initial weight of the specimen and increase the drying rate.

The hygrothermal properties were those established by material property testing (Section 5), complemented with hygrothermal properties from NRC's materials database.

Steady-state or transient laboratory conditions to which the components and assemblies were subjected were selected to simulate indoor and outdoor winter conditions with a temperature gradient across the wall, thereby developing interactive heat and mass (moisture) transfer effects that the model simulates.

Measurable hygrothermal effects include changes in moisture content of materials and changes in weight of wall components or assemblies over time. The experimental results were compared to those obtained from simulations using hygIRC.

7.3 Experimental Apparatus and Implementation

To achieve the objectives of this task, NRC's Envelope Environmental Exposure Facility (EEEF) was deployed and a custom weighing system based on the use of highly sensitive load cells and advanced micro processing technology provide weighing results (see Figure 100). The weighing system is capable of weighing 2.5-m x 2.5-m walls having nominal weights of up to 250 kg roughly to the nearest gram continuously over a test period. The weight data was used to determine weight loss over time of the wall assembly when exposed to controlled interior conditions (room side) and cold exterior conditions, simulating winter conditions. A full-scale test was carried out in controlled laboratory conditions over a period of time sufficiently long (about three months) as to permit quantifying gravimetrically the change and rate of change in moisture content of critical wall assembly components; e.g., wood studs.

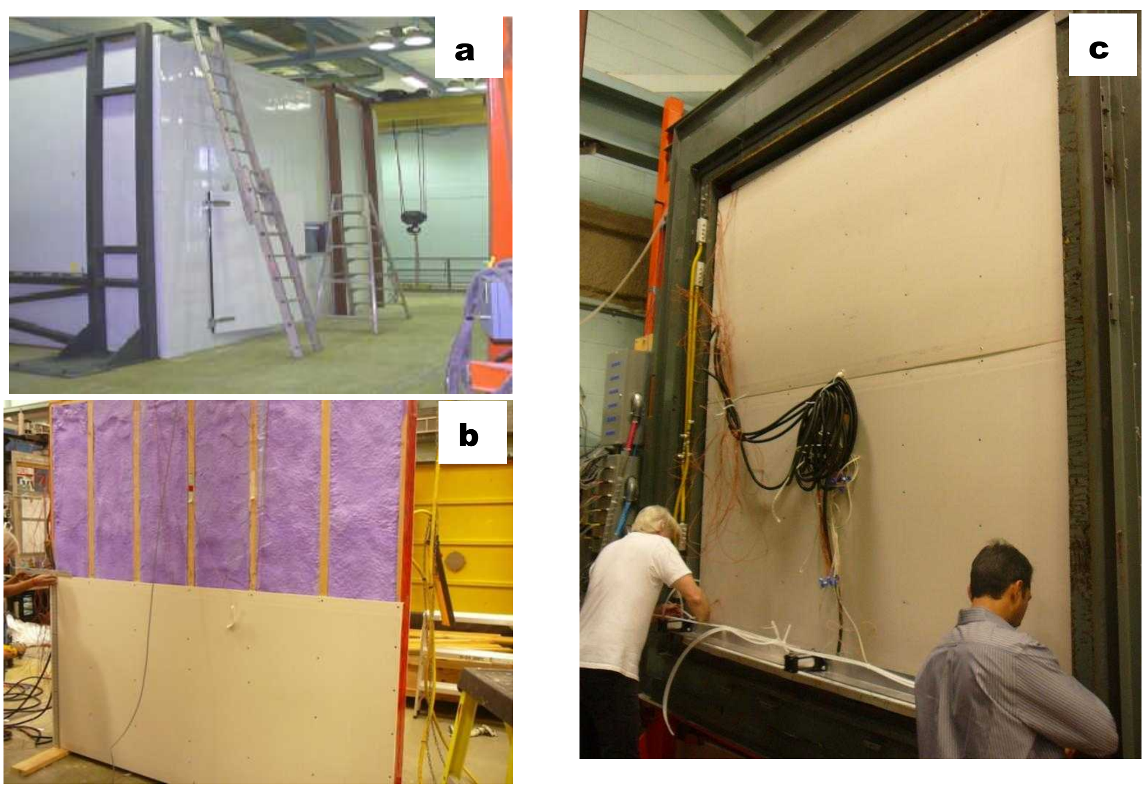


Figure 10 ─ Envelope Environmental Exposure Facility (a), LWF Mid-rise benchmark wall being assembled (b); and (c) Installation into EEEF with instrumentation.

7.4 Experimental results

Key inputs for model comparison with the hygrothermal performance of the benchmark wall are the initial moisture contents of the wood elements of the wall, and the time history of the drying curve of the wall specimen.

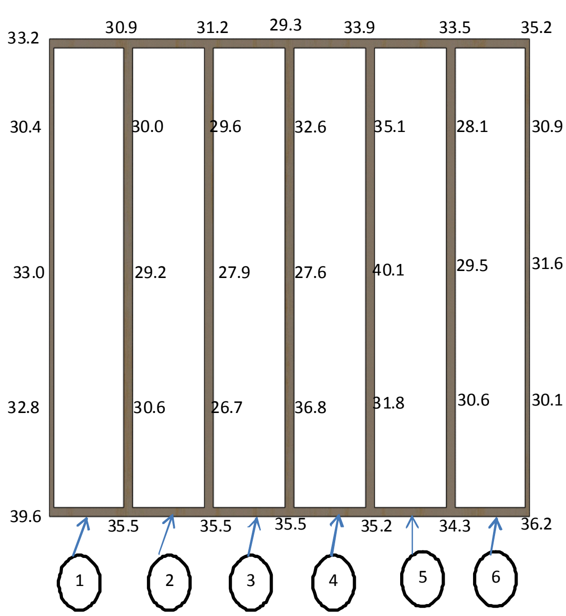
As a point of reference, the moisture content (MC) of the interior side of the studs where they come in contact with the gypsum board was measured with a Delmhorst hand-held moisture meter before installation of insulation and completion of the assembly. See readings shown in Figure 11.

7.4.1 Initial moisture condition – weight of the benchmark wall

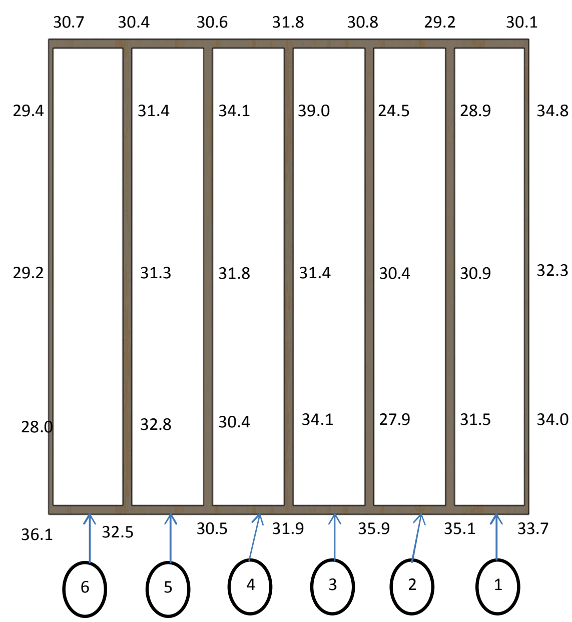
Table 9 shows the measured initial weight of the of the benchmark specimen with fully saturated studs. These were used to calculate the apparent moisture content of the studs by subtracting all dry elements of the wall specimen, including gypsum board, fasteners and instrumentation.

Table 9 ─ Weight of the wall at different stage of construction

	Weight at Dry condition (g)	Weight at wet condition (g)	Apparent Average Moisture Content (%)
Stud frame	51119	74717	46.2%
Complete wall	163379	191425	14.1%



Mid- stud cavity



Stud frame/Drywall - Interface

Figure 11 ─ Moisture content data on exterior and interior side of the frame measured with hand-held mete before installation of insulation and completion of the assembly.

The measured weight of the wall is the quantity used for hygrothermal benchmarking.

7.4.2 Total Weight of the Wall and Moisture Content

The raw data developed by the weighing system during the benchmark experiment is the drying curve recorded in Figure 12.

For any segment of a specified duration in this curve, the rate of drying over the time interval in the x-axis is the drop in weight of the wall in kilograms divided by the time interval of that specified duration. The curve can thus be analyzed in individual segments or continuously from the start of an identified period to the final condition. The latter approach was used to provide the comparison between experimental results and those derived from simulation. The measured loss in weight over a selected time interval of steady drying was directly compared to a predicted drying rate over the same interval using the simulation results of the hygrothermal model.

This data was passed on to the modelling team for comparison to results derived using the hygrothermal model.

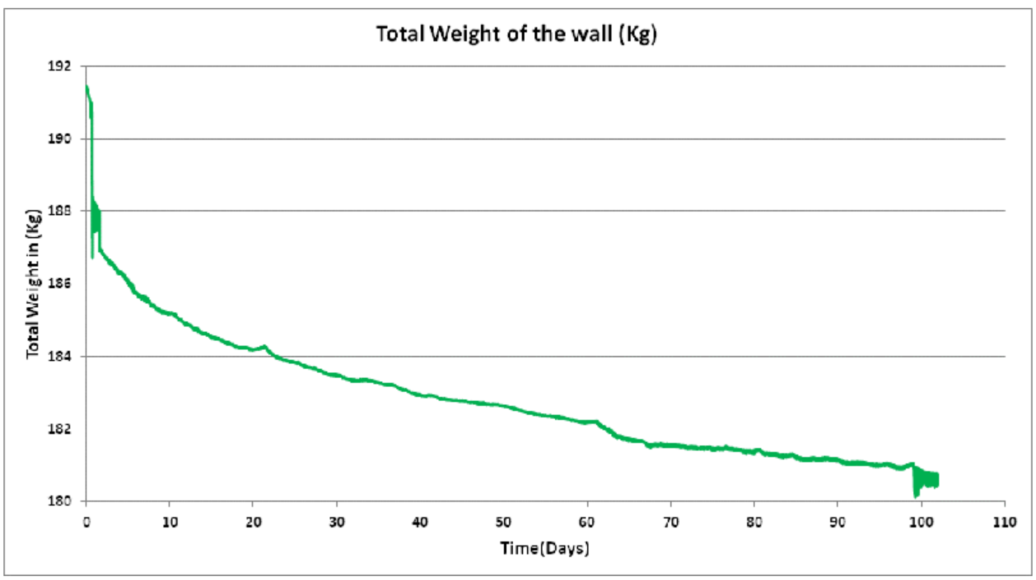


Figure 12 ─ Measured weight (kg) of the benchmark wall for over 100 days of drying

7.5 Comparison of Simulated and Experimental Results

The modelling team selected a period of 96 days from the experiment which featured steady drying results. This period of the data collection is shown as the red line in Figure 13, for which the start of the simulation is given as time of zero, and the average moisture content of the studs was established by the benchmark team to be 37%.

The hygIRC 2-D hygrothermal model was implemented to simulate drying of the benchmark wall over the full 96 days and comparisons between experimental results and simulated results are also shown in Figure 13. The experimental drying rate was measured to be 5.6 kg of moisture lost in 96 days of drying, whereas simulated drying rate obtained by the model under predicted the experimental results by about 43% or roughly 3/5 of the drying rate obtained through the experiment in 96 days.

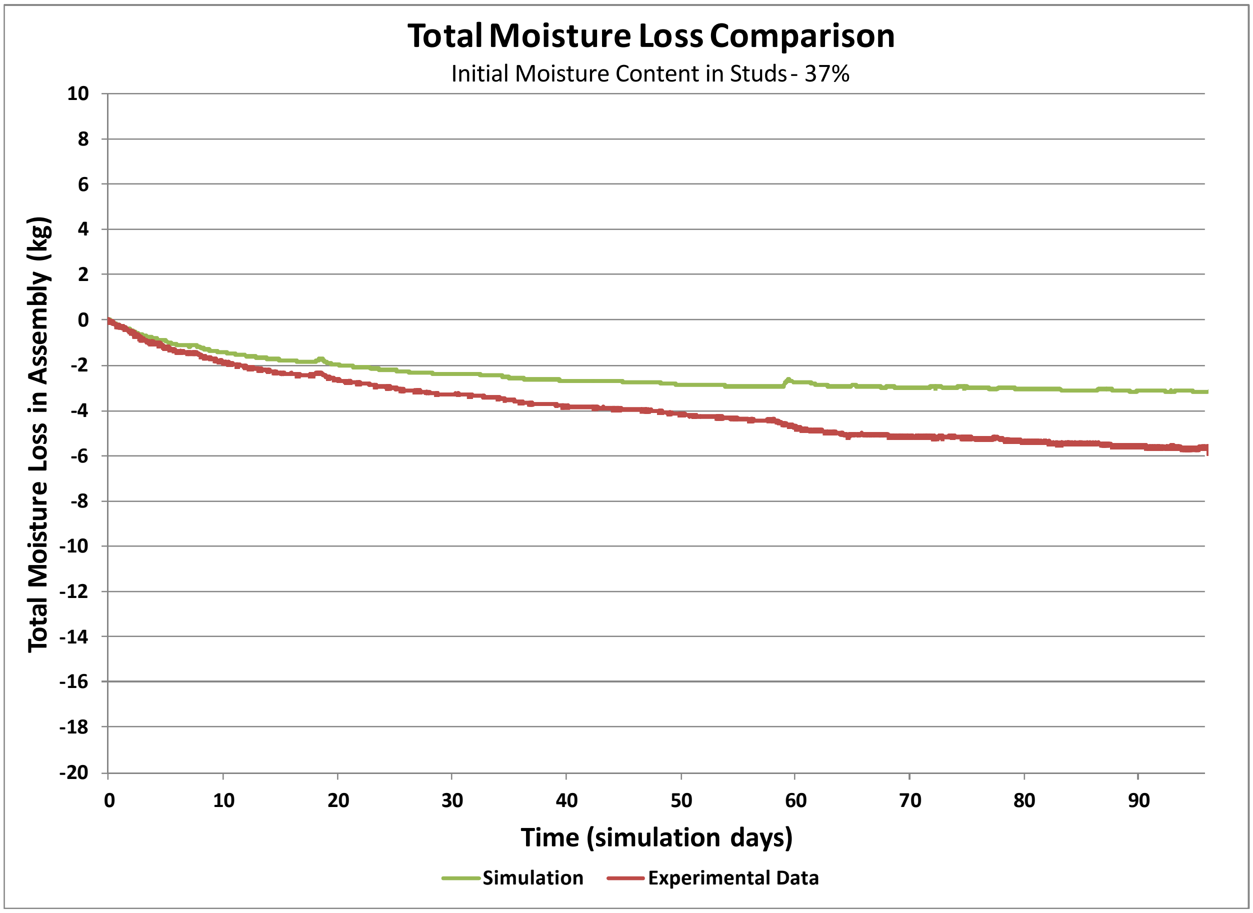


Figure 13 — Comparison of simulated and measured weight loss (kg) of the benchmark wall for 96 days of drying

The results obtained from the simulation incorporated a gap between the SPF and the studs as this was observed in the test specimen as shown in Figure 14. Further analysis of the simulation results suggested that differences to actual results could also be due to variations in property values of studs, sheathing and gypsum board finish, as well as normal construction tolerances in the fit between elements of the wall which could lead to additional paths of moisture movement in the actual benchmark wall. Such paths could not easily be represented in the model.

As a result, the modelling team chose to retain material properties used in the simulation with the understanding that the model would tend to be conservative in predicting the drying rate of studs under such wet conditions. These steps improved the modelling team's confidence that the model could be implemented in a parametric study involving stud drying, and yield credible results that are nevertheless believed to be conservative as relates to prediction of overall drying time.

As well, given that the relative impermeability of the SPF insulation results in quasi-one-dimensional drying through the stud, the modelling team expected that one-dimensional drying simulation through the studs (and later, through the CLT wall), would result in indicative, yet conservative, drying rates. Hence, if the wall assemblies could be shown to perform adequately on the basis of these conservative assumptions, it would be expected that actual walls, which inherently include construction tolerances, would dry at faster rates. It is based on this reasoning that the modelling team proceeded with the parametric study.

Figure 14 ─ Photo of foam delamination, presumed to be due to foaming on wet studs

8. HYGROTHERMAL ANALYSIS AND MODELLING (Task 6)

8.1. Objective Hygrothermal Modeling

Hygrothermal modelling of the LWF and CLT mid-rise walls was performed to determine whether the additional components of the envelope, which were added to typical wood-frame construction for the purposes of achieving a specific level of fire protection for mid-rise construction, would negatively affect the moisture management capabilities of such walls in select climates across the country. Key parameters included in this assessment were:

- Elements of fire protection added to the wall,
    - Encapsulation features inboard of the wall structure.
    - Cladding and rainscreen system shown by the fire research team to meet fire criteria through CAN/ULC-S134 testing.
    - The effect of different pressure-impregnated fire-retardant treatments for wood-based sheathing materials.
- Other key parameters associated with mid-rise construction, including:
    - Potentially high initial wood moisture contents due to prolonged exposure to the elements during construction.
    - Higher wind-driven rain loads associated with higher height the exposed walls.
    - Spray-applied foam insulation in stud cavities that may be used to meet the NECB 2011 in colder NECB 2011 zones. (The same foam insulation product was also investigated in envelope assemblies by the fire research team.)
    - Two layers of sheathing paper that could further protect the wood structure from water entry from the exterior but could also represent an additional combustible material and hence potentially greater fire load in the rainscreen assembly.

8.2. Overview of the Hygrothermal Modelling

A schematic of the analytical process is shown in Figure 15, in which the response of a wall assembly when subjected to simulated climate loads. The response of a wall assembly is determined on the basis of results derived from hygrothermal numerical simulation. Hygrothermal effects relate to changes in the temperature and moisture content (relative humidity) of individual components of the wall assembly. These effects are brought about by the transport and storage of moisture with air flow, transport of water vapour and liquid water across successive layers of different components of the assembly and the transfer and storage of heat through each component of the wall assembly. Numerical simulation takes into account the configuration of components within a wall assembly, the hygrothermal properties of individual components, and the degree of water entry through elements of the cladding on the basis of water penetration tests. Water penetration tests were conducted on wall assemblies to capture all water penetration phenomena that occur in the field of the wall as well as at the interfaces between the cladding and cladding penetrations such as venting air ducts.

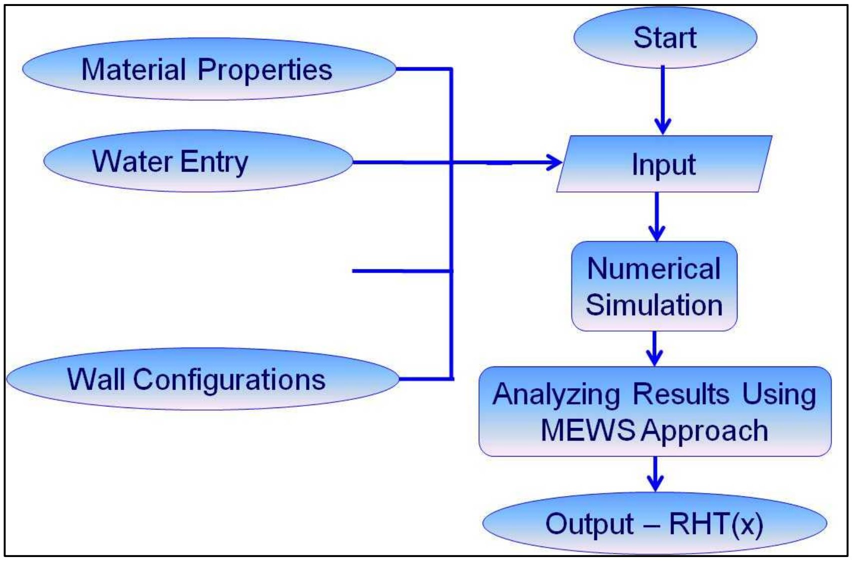


Figure 15 ─ Schematic of the analytical process followed in the derivation of the moisture risk index RHT using hygrothermal modelling

In order to obtain useful results from the simulations, the hygrothermal properties of components (materials properties) were determined (see Section 6; Task 4), and the configuration of the wall assembly was represented in a numerical format.

Apart from defining the component hygrothermal properties and numerical representations the wall assemblies, the simulated climate loads also required definition. In this respect, information derived from Task 2 (climate loads) provided the basis for input to the model.

Additionally, for the selected locations, simulations were carried out over a two-year period in which the first year is a "wet" year, and the next is an "average" year for the selected location. A "wet" year represents the wettest year in terms of annual rainfall over the entire record of 30 years for a particular location. The "average" year would be that year for which the average annual rainfall comes closest to the average over the recorded period. Finally, the direction of most severe wind-driven rain is established for each location, and the simulated wall is subjected to wind-driven rain from that direction, based on the weather data for the selected years. Analysis of the information presented in Figure 16 suggests that the wall direction for analysis in this example would be northeast – the direction of predominant wind-driven rain.

The output from simulations carried out to determine the response of the wall assembly to climate loads is provided in terms of the relative-humidity-temperature (RHT) index. The RHT index is a measure of the severity of the response in moisture sensitive components of the wall assembly when subjected to climate loads over the simulation period. It represents the cumulative time over which components are above minimum values of temperature and relative humidity. The greater the value of the RHT index, the greater the risk to deterioration of moisture-sensitive components in the wall.

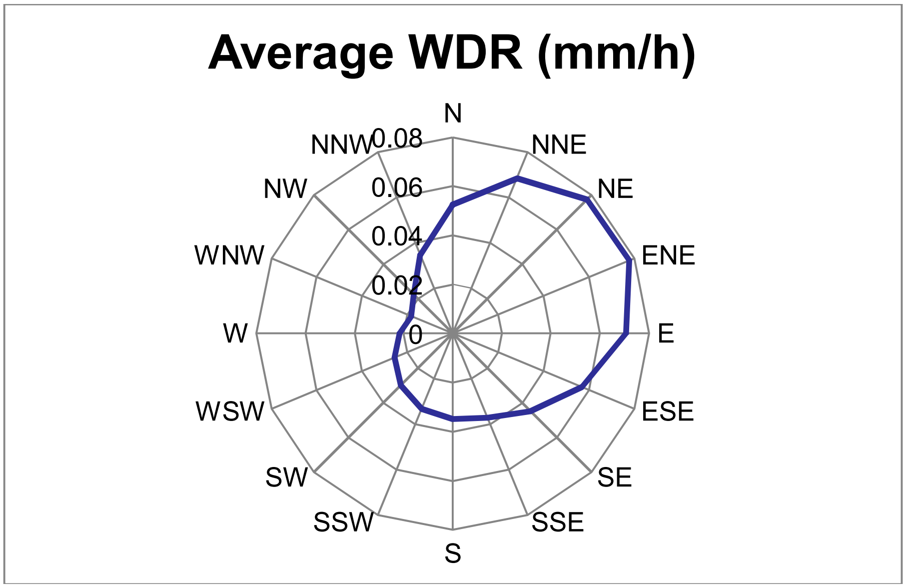


Figure 16 ─ Example average directional wind-driven rain (mm/h)

The RHT index is calculated at specific values of relative humidity that relate to humidity levels in moisture-sensitive components at which the onset of deterioration may occur. For example, the RHT index results provided below have been expressed as RHT(92), indicating that the index was calculated for a humidity level in components of 92% RH or higher.

The benchmarked hygrothermal model was implemented in a one-dimensional analysis as discussed above, for the specified LWF and CLT mid-rise walls in the climate locations selected.

Simulations were executed and data analyzed and presented for assessment.

8.3. LWF Mid-rise Wall Results

The first set of simulations involved the lightweight wood-frame midrise construction (LWF) described in Section 3 (Task 1). The results of the first simulation are reported in Figure 17 for the LWF in Vancouver. The initial condition of 19% is the starting point for the stud in this simulation as previously explained. The outer part of the stud layer nearest the sheathing is the topmost drying curve. In the scenario whereby the wall is closed-in in the winter, it is expected to dry out more slowly than the rest of the stud, because the outer wall is exposed to weak drying conditions in the winter. This is what the methodology refers to as the 'location of interest' to which the wall is subject to the RHT risk index analysis. The total stud dries out gradually and continuously (Stud Total) and the inside layer of the stud which is close to the interior of the wall in contact with the gypsum board dries the fastest (bottom line in Figure 17.)

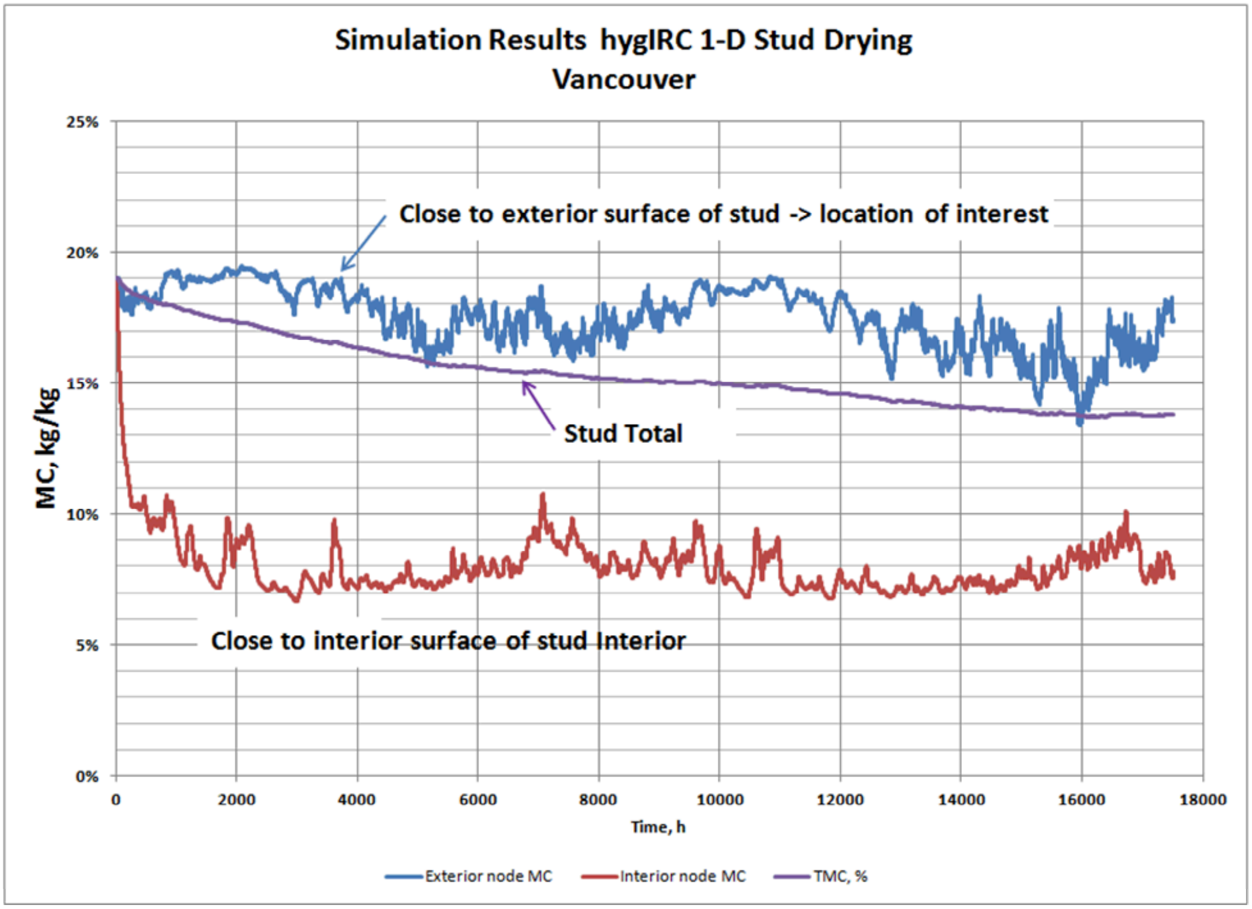


Figure 17 — Simulation results for Vancouver LWF.

Comparative examples of the drying of the outer stud layer are shown in Figure 18 for Vancouver, Toronto and Quebec City. During these 'wettest and average years' in these cities, the response of the outer stud in the LWF is similar – slow but relatively steady drying.

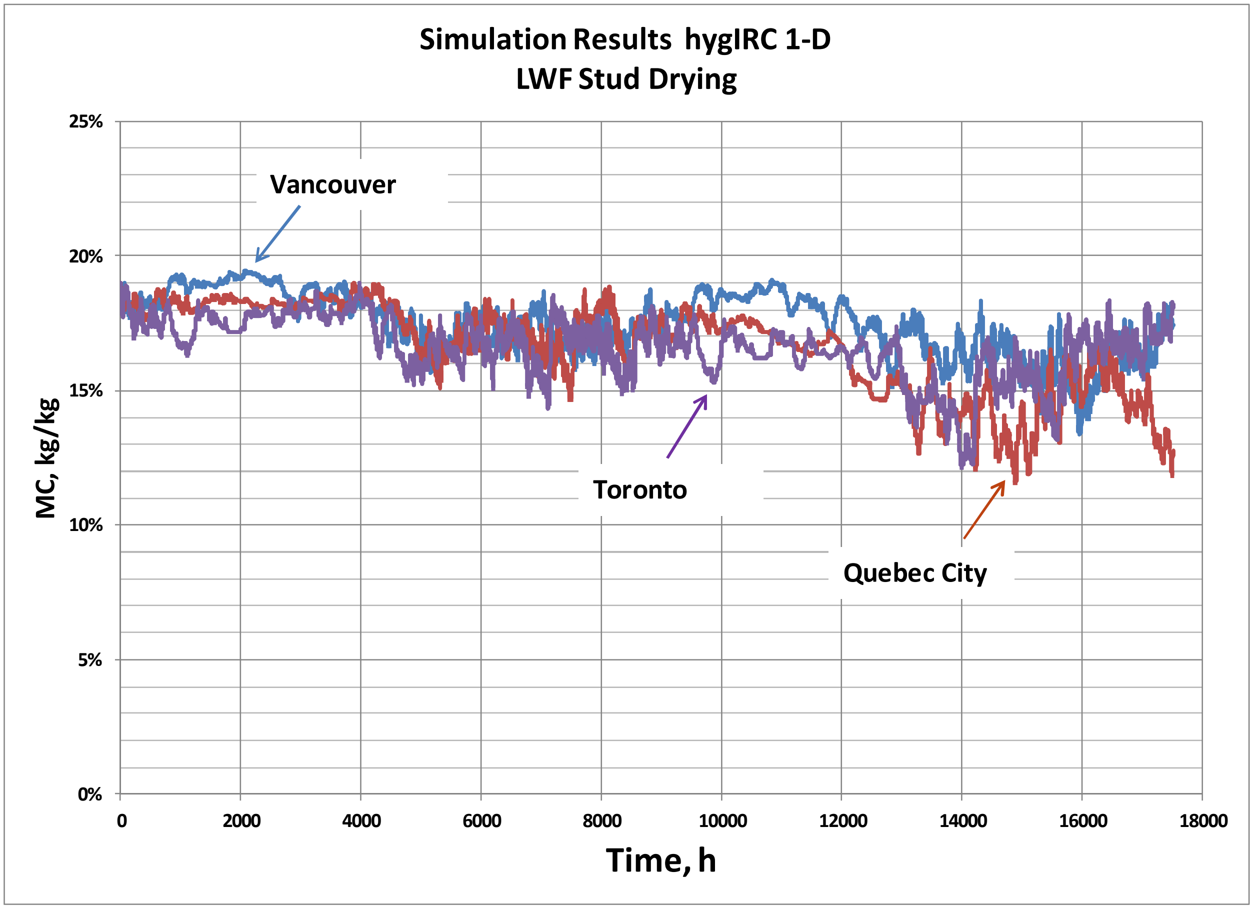


Figure 18 — Simulation results LWF in Vancouver, Toronto, and Quebec City.

[Only conditions for the exterior surface of the stud (location of interest) are shown]

The simulations were executed for all 8 cities selected in this study and the resulting moisture content curves of the outer stud layer were further analysed to develop associated moisture risk indices RHT(92) described in Section 8.2. The results of that analysis is shown in Table 10 below.

The gradual but relatively steady drying of the outer stud layer below 19% moisture content resulted in no RHT accumulation for 6 locations and virtually none for Halifax and Prince Rupert – the locations with the highest Moisture Risk Index (MI) as show in Table 10.

Note that the Moisture Index as recorded for each Canadian location in the NBC 2010 only characterizes the climate, whereas the RHT risk index is a measure of the resultant hygrothermal performance of the wall under study in a given climate. The higher the MI of a climate, the more difficult it is for poorly designed walls to maintain a zero risk.

Evidently the LWF provides a robust performance in these challenging climates.

Table 10─ Results of Simulations Mid-rise LWF

Location (City)	NECB 2011 Zones	Moisture Index (MI)	Simulated RHT(92)
Prince Rupert	Zone 5	2.84	~0
Halifax	Zone 6	1.49	~0
Vancouver	Zone 4	1.44	0
Quebec City	Zone 7A	1.04	0
Toronto	Zone 5	0.86	0
Ottawa	Zone 6	0.84	0
Yellowknife	Zone 8	0.58	0
Winnipeg	Zone 7A	0.59	0

Note. RHT(92) results for Prince Rupert and Halifax did show a few hours of moisture content above 19%, but these were not sufficient to increase the RHT index to 1.

8.4 Impact of Fire-retardant Treatment of Sheathing

Variations in LWF assembly configurations were investigated in the Vancouver ‘wet-year’/‘average-year’ combination using the hygrothermal model. The base case performance of exterior gypsum sheathing was compared to that of two fire-retardant-treated plywood sheathings as shown in Table 11.

Table 11 ─ Effect of Pressure-impregnated Fire-retardant Treatment,
Vancouver, Zone 4, MI=1.44

Exterior Sheathing	Simulated RHT(92)
Exterior Grade Gypsum Sheathing	0
Plywood with Treatment A	0
Plywood with Treatment B	0

The pressure-impregnated fire-retardant treatment of the plywood was seen not to increase the moisture risk of the studs behind the plywood in this challenging weather location.

8.5 CLT Mid-rise Wall Result

The evaluation procedure used for the LWF wall was repeated for all locations for the CLT wall described in Section 3 (Task 1) (Figure 2).

Figure 19 shows the simulated drying pattern of the CLT wall for Vancouver using the 1-D model. The exceptional drying of both the inner and outer layers of the CLT and steady drying of the interior elements which resulted in a steady drying of the whole CLT (labelled CLT Total). The inner core of the postulated saturated CLT dries steadily in both directions for this CLT configuration. The CLT configuration was inspired by the recommendations contained in the Envelope Section of the CLT Handbook by FPInnovations, and the additional fire protection measures specified here did not adversely affect the good performance expected by FPInnovations for that configuration.

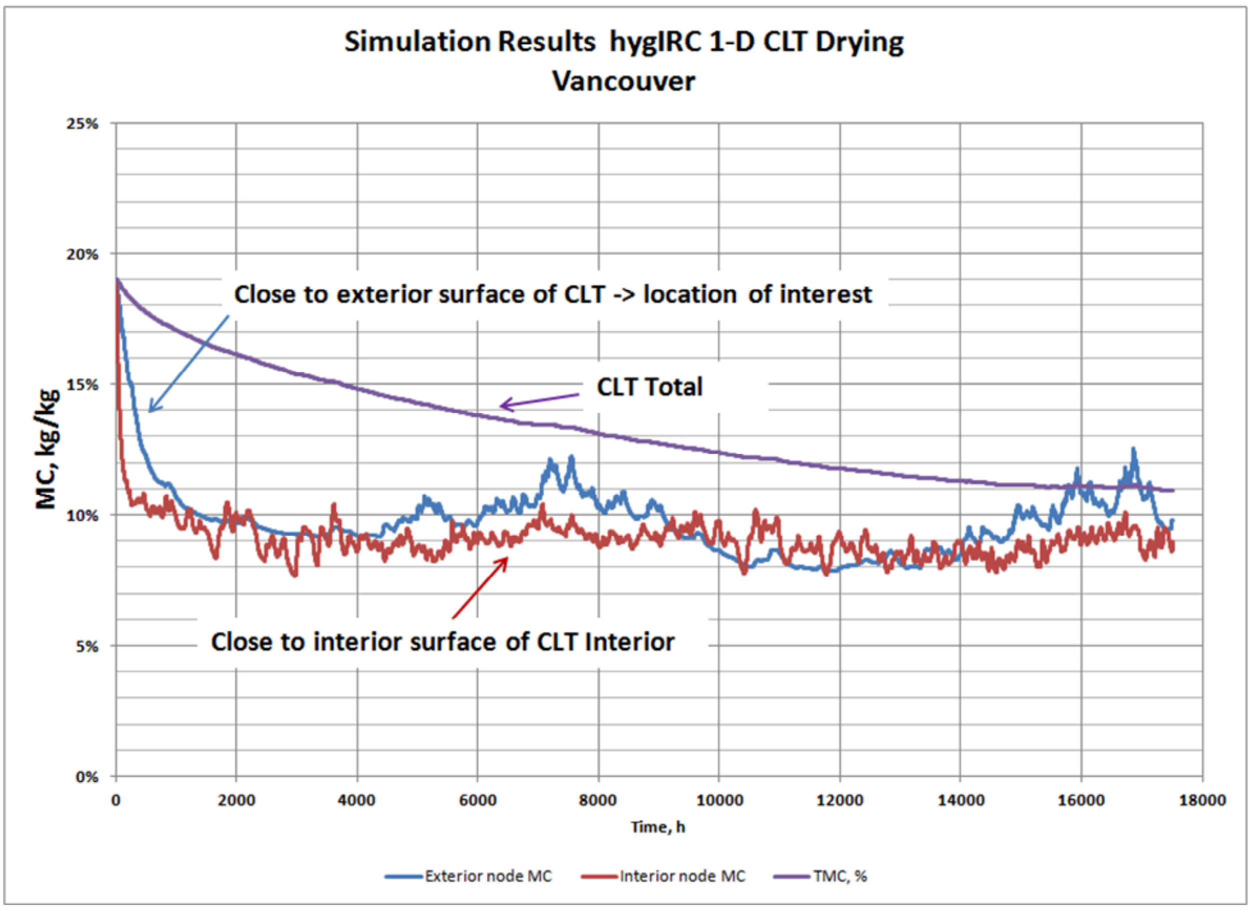


Figure 19 ─ Simulation results for Vancouver – CLT

Finally, the hygrothermal performance of a number of CLT walls was assessed for the 8 locations using the same assessment methodology as previously described. The results of the risk index RHT(92) assessment are presented in Table 12.

Table 12 ─ Results of Simulations Mid-rise CLT

Location (City)	NECB 2011 Zones	Moisture Index (MI)	Simulated RHT(92)
Prince Rupert	Zone 5	2.84	0
Halifax	Zone 6	1.49	0
Vancouver	Zone 4	1.44	0
Quebec City	Zone 7A	1.04	0
Toronto	Zone 5	0.86	0
Ottawa	Zone 6	0.84	0
Yellowknife	Zone 8	0.58	0
Winnipeg	Zone 7A	0.59	0

These RHT(92) results were used as a basis to develop an opinion on whether the various walls assessed and their alternatives were deemed to comply with the NBC 2010 Part 5, and the NECB 2011 Part 9; this is provided in Section 9 of the report.

9. OPINION ON 'DEEMED TO COMPLY WITH NBC 2010 & NECB 2011' (Task 7)

9.1 Pass/Fail Performance Benchmark

A pass-fail performance guideline was proposed for this assessment that is deemed by NRC HAMP researchers to capture the intent of the NBC Part 5 for control of air moisture and precipitation. It involves an assessment of the moisture performance of the LWF and CLT mid-rise walls in a range of climates across Canada, and comparison of that performance to that of a previously defined code-compliant benchmark wall assembly.

The point-form summary below highlights the key elements involved in defining the proposed moisture performance benchmark for this project.

- The approach is based on the results of a major consortium research project conducted at NRC on Moisture Management of Exterior Walls (MEWS) project. That methodology was applied and refined over the years to assess a number of wood-frame wall systems and claddings.[13]
- A benchmark stucco-clad wall was specified in a follow-up NRC consortium project of cladding manufacturers. The moisture performance of that benchmark wall was documented and used to define the minimum moisture management performance for a wood-based wall[14] and illustrates the proposed minimum performance over time.
- The moisture performance of the mid-rise wall configurations assessed in this project were compared to the developed performance benchmark of previous studies.
- Our opinion on 'deemed to comply' is assessed in one of three ways, summarized from simplest to more complex as the following:
    1. 19% Moisture Content Benchmark. Part 9 [NBC 2010, 9.3.2.5] requires that the moisture content of lumber be less than or equal to 19% at time of installation. This can serve as the initial (and simplest) benchmark of comparison. It is generally accepted that lumber will not deteriorate at moisture contents of 19% or less.[15] If the simulated dry-out of the wood elements in the wall is continually downward from an initial moisture content of 19% for the weather conditions selected and over the assessment period, then the wall under investigation is deemed to comply to the NBC 2010 for moisture control requirements.

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[13] Beaulieu, P., Cornick, S.M., Dalgleish, W.A., Djebbar, R., Kumaran, M.K., Lacasse, M.A., Lackey, J.C., Maref, W., Mukhopadhyaya, P., Nofal, M., Normandin, N., Nicholls, M., O'Connor, T., Quirt, J.D., Rousseau, M.Z., Said, M.N., Swinton, M.C., Tariku, F., van Reenen, D., MEWS methodology for developing moisture management strategies : application to stucco-clad wood-frame walls in North America, pp. 21, September 01, 2001. (NRCC-45213)

[14] Swinton, M.C., Lacasse, M.A., Armstrong, M.M., Saber, H.H., Mukhopadhyaya, P., Maref, W., Lohmann, F., Kumaran, M.K., Ganapathy, G., Nicholls, M., Abdulghani, K., Moisture Management Assessment of the Adhered Stone Cladding System - Final Summary Report, Internal Report. NRC Institute for Research in Construction, March-23-12 (IRC-IR-909)

[15] Wang, J., Clark, J., Symons, P., Morris, P. Time to Initiation of Decay in Plywood, OSB and Solid Wood under Critical Moisture Conditions. Proceedings of the International Conference on Building Envelope Systems and Technologies, Ottawa, Canada, 2010, Vol. 2, pp. 159-166.

2. If a wall exhibits moisture contents above 19% over the short term (i.e. less than 10 consecutive days of excursion above 19% moisture content) and the simulated moisture contents over the two-year period of simulation are predominantly below those shown in Figure 20, then the assembly is deemed to comply with the NBC 2010.

3. In instances where more marginal moisture management performance is observed as might occur when the wall assembly is subjected extreme weather conditions, and that involves periodic excursions of wood moisture content above 19%, NRC developed a Moisture Risk Index to assess the integrated risk of such excursions in a single number. Associated with the MEWS effort, FPInnovations collaborated with NRC to establish a relationship between the Moisture Risk Index and measured deterioration of the structural properties of wood for prolonged exposure to high RH environments within the envelope. That work constituted a key benchmark of the risk index approach[15]. Based on that work, and subsequent work involving an NRC consortium with the cladding industry, a conservative risk index limit was proposed by NRC of: RHT(92) ≤ 13. This value is consistent with the moisture content histories shown in Figure 20. This moisture risk index is deemed to incorporate a considerable margin of safety. For example, the research by Wang and Morris[15] demonstrated through systematic long-term testing of the deterioration of wood strength due to biological agents that loss of strength is associate with a Moisture Risk Index of RHT(95) of 1125 or greater, with wood moisture contents ranging between of 38% and 45%. As described in their report, even under the extreme conditions to which these assemblies were subjected, the dimensional lumber (hemlock heartwood) and aspen-based OSB took approximately 21 weeks for the onset of decay at 20°C, and plywood took 74 weeks.

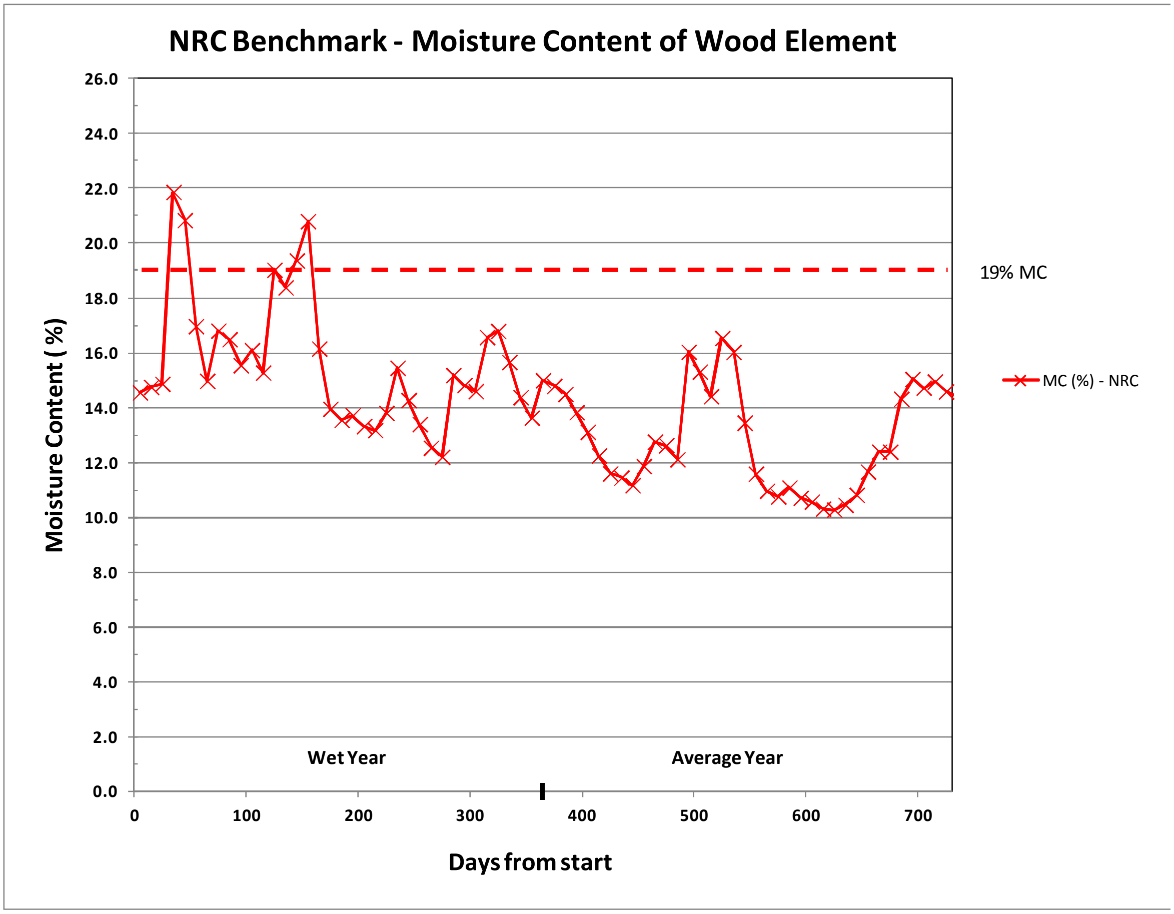

Figure 20 ─ Wood moisture content profile that is proposed by NRC to just meet the moisture management requirements of NBC 2010.

9.2 Simulated Performance of the LWF Wall in Selected Locations

As an example of how this procedure works, in Figure 21 is illustrated the processing of the results of the outer layer of the stud in the LWF in Vancouver, compared to NRC's proposed benchmark. It can be seen that unlike the benchmark results that accumulate RHT(92) with a result of 13, the LWF does not accumulate RHT and is therefore considered to provide superior moisture management to the benchmark. Relative performance below RHT(92) is unimportant in this comparison, as additional risk is not accumulated by either result.

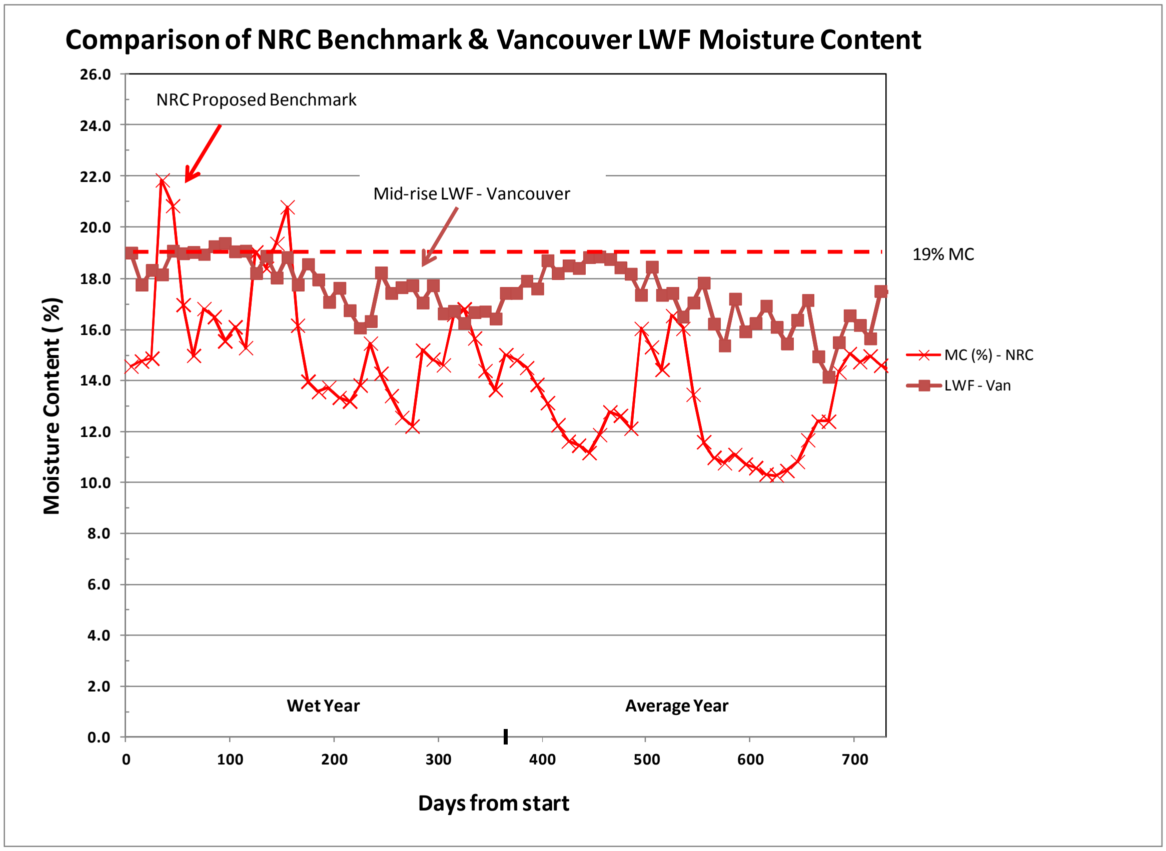

Figure 21 ─ Simulation results for Vancouver LWF. (Exterior surface layer of wood of Wood Stud reported every 10 days)

When this methodology is applied to the LWF results for all cities, the LWF is shown (Table 13; right-most column) to compare favorably to the benchmark in all locations, leading to NRC's opinion that the LWF is 'deemed to comply' to the moisture management provisions of Part 5 of the NBC for all locations investigated.

In Table 13, the Effective Thermal Transmittance of the LWF, as calculated with a code-compliant method, is compared to the requirement given in Part 3 of the NECB 2011 for each zone. It was noted that the LWF had sufficient insulation to pass requirements given in the NECB 2011 for all zones with the exception of Zone 8, where Yellowknife is the location that in this case represents Zone 8. In Yellowknife, an additional 38 mm of exterior rigid or semi-rigid insulation could be specified to meet the NECB 2011 requirement for that zone.

Table 13 ─Assessments for the LWF specimen in each of the 8 locations selected

Location (City)	NECB 2011 Zones	NECB 2011 Maximum Effective Thermal Transmittance ($W/m^2 \cdot K$)	LWF Effective Thermal Transmittance ($W/m^2 \cdot K$)	Pass for this NECB 2011 Zone?	Moisture Index (MI)	Simulated RHT(92)	Less than RHT(92)=13?
Prince Rupert	Zone 5	0.278	0.196	y	2.84	~0	Y
Halifax	Zone 6	0.247	0.196	y	1.49	~0	Y
Vancouver	Zone 4	0.315	0.196	y	1.44	0	Y
Quebec City	Zone 7A	0.210	0.196	y	1.04	0	Y
Toronto	Zone 5	0.278	0.196	y	0.86	0	Y
Ottawa	Zone 6	0.247	0.196	y	0.84	0	Y
Yellowknife	Zone 8	0.183	0.174*	Y*	0.58	0	Y
Winnipeg	Zone 7A	0.210	0.196	y	0.59	0	Y

* To meet NECB 2011 in Yellowknife, this wall requires an additional 38 mm exterior insulation (e.g. high density fibrous insulation). The location of placement of the insulation relative to the sheathing may have implications for fire performance.

9.2.1 Effect of various Fire-retardant-treated Sheathings

A similar RHT analysis was performed for the pressure-impregnated fire-retardant-treated wood sheathing options with the results shown in Table 14.

Table 14─ Flame Retardant Strategies in Exterior Sheathing Products Assessed for Vancouver Climate

Exterior Sheathing	NECB 2011 Zones	NECB 2011 Maximum Effective Thermal Transmittance ($W/m^2 \cdot K$)	LWF Effective Thermal Transmittance ($W/m^2 \cdot K$)	Pass for this NECB 2011 Zone?	Moisture Index (MI)	Simulated RHT(92)	Less than RHT(92)=13?
Exterior Gypsum Sheathing	Zone 4	0.315	0.196	Y	1.44	0	Y
Plywood with Treatment A	Zone 4	0.315	0.192	Y	1.44	0	Y
Plywood with Treatment B	Zone 4	0.315	0.191	Y	1.44	0	Y

9.3 Simulated performance of the CLT Wall in key locations

The same RHT analysis was also applied to the CLT. Due to the excellent drying capability of this configuration discussed above, and through the performance comparison to the proposed NRC Benchmark given in Figure 22, the CLT results, tabulated in Table 15, were all ‘deemed to comply’ with requirements set out in the NBC 2010 Part 5.

Similar to the LWF, the CLT configuration met the requirements of 7 Zones specified in the NECB 2011, but would need to use additional insulation in Zone 8 (Yellowknife in this example), to achieve the NECB requirements. This could be attained by substituting commercially available high R-value batts for the conventional batts in the 2x6 cavities on the exterior of the CLT structure.

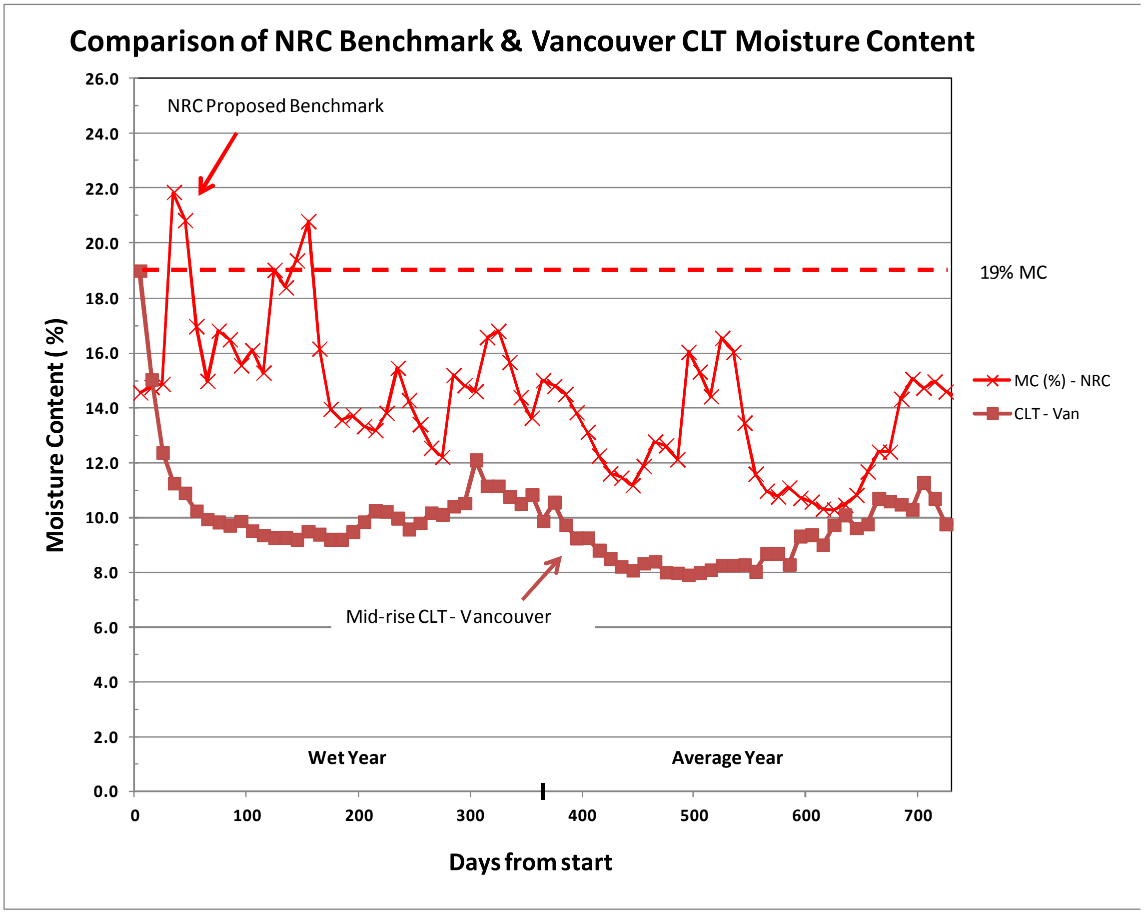

Figure 22 — Simulation results for Vancouver – CLT (Exterior surface layer of wood of CLT, reported every 10 days)

Table 15 ─ Assessments for the CLT specimen in each of the 8 locations selected

Location (City)	NECB 2011 Zones	NECB 2011 Maximum Effective Thermal Transmittance ($W/m^2 \cdot K$)	5 Ply-CLT Effective Thermal Transmittance ($W/m^2 \cdot K$)	Pass for this NECB 2011 Zone?	Moisture Index (MI)	Simulated RHT(92)	Less than RHT(92)=13?
Prince Rupert	Zone 5	0.278	.191	Y	2.84	0	Y
Halifax	Zone 6	0.247	.191	Y	1.49	0	Y
Vancouver	Zone 4	0.315	.191	Y	1.44	0	Y
Quebec City	Zone 7A	0.210	.191	Y	1.04	0	Y
Toronto	Zone 5	0.278	.191	Y	0.86	0	Y
Ottawa	Zone 6	0.247	.191	Y	0.84	0	Y
Yellowknife	Zone 8	0.183	.191	N*	0.58	0	Y
Winnipeg	Zone 7A	0.210	.191	Y	0.59	0	Y

* To meet NECB 2011 in Yellowknife, this wall requires high density fibrous insulation between the studs.

9.4 Opinion

The results of the hygrothermal performance evaluation procedure documented in this report identify the climate locations in Canada for which the LWF and CLT walls described in this study were deemed to meet the intent of NBC 2010 Part 5, and NECB 2011 Part 3.

The results suggests that the additional fire protection measures incorporated to the specified LWF & CLT mid-rise wall specimens met the moisture risk index criteria proposed in this study for the following mid-rise building envelopes and location.

The LWF & CLT simulations results passed the moisture risk index assessment for all of the climate location investigated:

Prince Rupert, Halifax, Vancouver, Quebec City, Toronto, Ottawa, Yellowknife, and Winnipeg.

The LWF and CLT specimens were also assessed against the maximum thermal transmittance requirements of NECB 2011 Part 3 Envelopes and passed for the following locations:

- Prince Rupert (Zone 5), Halifax (Zone 6), Vancouver (Zone 4), Quebec City (Zone 7A), Toronto (Zone 5), Ottawa (Zone 6), and Winnipeg (Zone7A).

It should be noted however that the modelling did show that in locations with wetter climates (NBC Moisture Index substantially greater than 1), including Prince Rupert, Halifax and Vancouver, strapping alternatives for cladding support that are not susceptible to moisture deterioration should be incorporated in the LWF design, as was originally specified in this study.

To meet the NECB wall requirements for Yellowknife (NECB 2011 Zone 8), the LWF would need additional semi-rigid fibrous insulation outboard of the studs, and the CLT would require high R-value batts between the studs on the exterior of the CLT, instead of regular batts.

In addition, it was found that fire-retardant treatment that was applied to plywood through pressure-impregnation had negligible effect on the hygrothermal performance with respect to the moisture risk index obtained for Vancouver. As a result, our opinion is that this result applies to all locations considered for the reference LWF.

As an overall conclusion, the fire control measures proposed for mid-rise walls as solutions to NBC 2010 Part 3 for fire performance should also be considered to be solutions for NBC 2010 Part 5 and NECB 2011 Part 3, with the additional insulation identified for Yellowknife (Zone 8) to meet NECB 2011.

10 REFERENCE LIST OF DETAILED NRC REPORTS FOR THIS PROJECT

A1-100035-03.1	MID-RISE WOOD CONSTRUCTIONS – Specifications of Mid-Rise Envelopes for Hygrothermal Assessment
A1-100035-03.2	MID-RISE WOOD CONSTRUCTIONS – Climatological Analysis for Hygrothermal Performance Evaluation
A1-100035-03.3	MID-RISE WOOD CONSTRUCTIONS – Investigation of Water Penetration through Cladding and Deficiencies
A1-100035-03.4	MID-RISE WOOD CONSTRUCTIONS – Characterization of Hygrothermal Properties.
A1-100035-03.5	MID-RISE WOOD CONSTRUCTIONS – Benchmarking of the Advanced Hygrothermal Model hygIRC – Large Scale Drying Experiment of the Mid-rise Wood Frame Assembly
A1-100035-03.6	MID-RISE WOOD CONSTRUCTIONS – Hygrothermal Modelling Benchmark: Comparison of hygIRC Simulation Results with Full Scale Experiment Results
A1-100035-03.7	MID-RISE WOOD CONSTRUCTIONS – Hygrothermal Modelling and Analysis

11 KEY RESEARCH REFERENCES

Beaulieu, P., Cornick, S.M., Dalgleish, W.A., Djebbar, R., Kumaran, M.K., Lacasse, M.A., Lackey, J.C., Maref, W., Mukhopadhyaya, P., Nofal, M., Normandin, N., Nicholls, M., O'Connor, T., Quirt, J.D., Rousseau, M.Z., Said, M.N., Swinton, M.C., Tariku, F., van Reenen, D., MEWS methodology for developing moisture management strategies : application to stucco-clad wood-frame walls in North America, pp. 21, September 01, 2001. (NRCC-45213)

Swinton, M.C., Lacasse, M.A., Armstrong, M.M., Saber, H.H., Mukhopadhyaya, P., Maref, W., Lohmann, F., Kumaran, M.K., Ganapathy, G., Nicholls, M., Abdulghani, K., Moisture Management Assessment of the Adhered Stone Cladding System - Final Summary Report, Internal Report. NRC Institute for Research in Construction, March-23-12 (IRC-IR-909)

Wang, J., Clark, J., Symons, P., Morris, P. Time to Initiation of Decay in Plywood, OSB and Solid Wood under Critical Moisture Conditions. Proceedings of the International Conference on Building Envelope Systems and Technologies, Ottawa, Canada, 2010, Vol. 2, pp. 159-166.