Hygrothermal Performance of Super-Insulated Double-Stud Wood Frame Wall Assemblies:

An Experimental Study

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ABSTRACT

Hygrothermal Performance of Super-Insulated Double-Stud Wood Frame Wall Assemblies: An Experimental Study

By Nima Khalkhali-Shijini

In cold climates, much of wood-frame building enclosure durability failures and indoor air quality issues stem mainly from excessive moisture within enclosure components and these issues are more pronounced in buildings with higher levels of thermal insulation, with frequent mold and fungal growth complications. Nevertheless, buildings have been increasing their insulation levels (and this trend is expected to continue) due to climate change, depleting natural resources, ever-rising energy prices and growing expectation for occupants' comfort and health.

Incorporation of insulation materials with higher moisture storage and buffering capacities and also employing vapour retarders that can let walls dry out to both interior and exterior spaces are potential solutions. While the hygrothermal behaviour of these insulation materials have been extensively tested in material labs and computer modeling projects, their actual performance in different climatic zones demands more field experimental studies.

In this study, a field experiment was designed to assess hygrothermal behaviors of five highly insulated test wall panels under Marine climatic zone of, Burnaby, British Columbia. Full size wall panel specimens of 'double-stud' wood-frame were instrumented with moisture and temperature sensors and filled with *Dense Cellulose Insulation* (*DCI)* and *Low-Density Spray Polyurethane Foam Insulation (LD SPFI)* under different vapour control layer scenarios of 4-mil Polyethylene film, Smart Vapour Retarder (SVR), and none. All test panels were exposed to the

controlled indoor and the actual outdoor climates and their hygrothermal response was recorded and analysed from 01 Sept 2016 to 31 May 2017.

The experimental results suggested DCI is a proper insulation material provided that it is equipped with a dedicated interior vapour barrier. The results also suggested while both DCI had LD SPF had acceptable moisture behaviour; DCI had slightly better performance than LD SPF. As for vapour control strategies, Smart Vapour Retarder (SVR) did not show an obvious advantage over 4-mil Polyethylene film and in some cases was slightly outperformed by polyethylene hygrothermally. As a general comment, the exterior sheathing board, plywood had the highest moisture activity and all other components, mainly the exterior and interior studs and plates remained in safe moisture ranges throughout the test period.

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I would like to dedicate this thesis to David Suzuki for his consistent fight for the Environment, you inspire me.

Contents

1.1 Table of Figures

1.2 List of Tables

1. INTRODUCTION

There are multiple drivers to lower energy consumption in buildings such as financial, environmental, strategic and political motives; however, the urgency of climate change demands immediate action in global scale. Climate Change has become a major concern in the past couple of decades.

The main foreseeable consequences of Climate Change are melting sea ice and glaciers, rising sea levels and more intense weather events (floods, droughts, and hurricanes), and due to ocean currents and other complex climate mechanisms, some places will become colder, crop and property losses, large masses of climate change refugees, flora and fauna extinctions will become more frequent (Stern, 2007).

In 1992, 2,400 representatives from NGO's and 17,000 people attended Rio, for The Earth Summit to seek pathways to reduce the destruction of irreplaceable natural resources and pollution of the planet with toxins, air pollution included (United Nations, 1992). Several final messages and recommendations were issued at the end of that conference and reducing fossil fuels consumption was one of the key final verdicts. After the Rio Summit, the Kyoto Protocol was signed in 1997 as an agreement between 160 countries, including Canada, to lower their collective greenhouse gasses by 5.2 percent compared to their 1990 levels by 2012.

The awareness and concerns about climate change further increased after Sterns Review on the Economics of Climate Change, a comprehensive scientific study (Stern, 2007) about economy of climate change. According to this review "*climate change is the greatest and widest-ranging market failure ever seen, presenting a unique challenge for economics*". The report highlights physical, ecological, social and critical impacts of climate change that requires immediate action and financial investment before reaching '*the point of no return*'. At this moment, there is little disagreement among scientists around the world about the correlation between human activity and climate change and it can impact all the nations in the world, some already happening or soon to come. People in northern Canada are already seeing retreating glaciers, experiencing shorter winter seasons and rivers that used to freeze and act as roads for their transportation now melt sooner in the season. In northern territories of Canada caribou and fish migration patterns is changing (Government Canada/Yukon, Retrieved 2018). Moreover, scientific models suggest increased frequency in extreme weather events such as violent storms and major floods across the world.

"In 1998, more than 450 experts from industry, academia, non-government organizations, municipalities, and federal, provincial and territorial governments joined in a two-year consultation process to develop solutions needed to address climate change." (BC Lays, retrieved 2018). Although Canada withdrew from this agreement in 2012, but later joined the Paris Agreement in 2015 that was an agreement among 196 countries committing members to contribute in different levels to a target of reducing their greenhouse gas emissions to a level that caps the global warming to a maximum of 2°C and with the possibility of furthering that target to maximum of 1.5°C increase of temperature to pre-industrial levels.

Canada Climate Change Action Plan 2000 (BC Lays, retrieved 2018) sets targets for different energy users sectors for reducing their GHG's (Greenhouse Gases) levels (UN, 2015).

CCCAP2000 reports, the major sectors contributing to GHG emissions are (Figure 1) transportation (25%), electricity (17%), oil and gas (18%), industry (15%), agriculture and forestry (10%), and buildings (10%), so each sector have to contribute to meeting the GHG emission reduction targets, including the building sector.

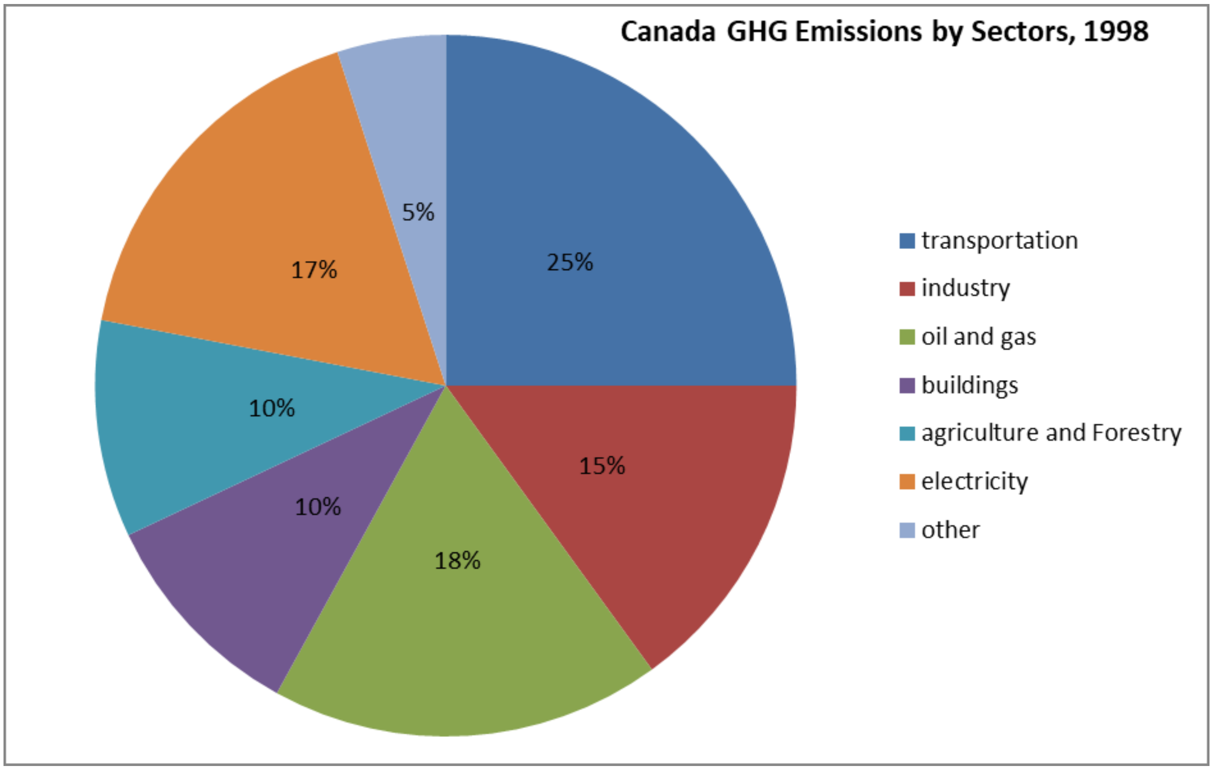


Figure 1- Canada GHG Emissions by Sectors, 1998

As for Canada CCAP2000, allocated shares to different sectors to contribute to a total of 65 megatonnes of GHG emissions reduction per year, and for building sector this percentage was 10% of total GHG reduction, 6.5 megatonnes reduction per year (Figure 1).

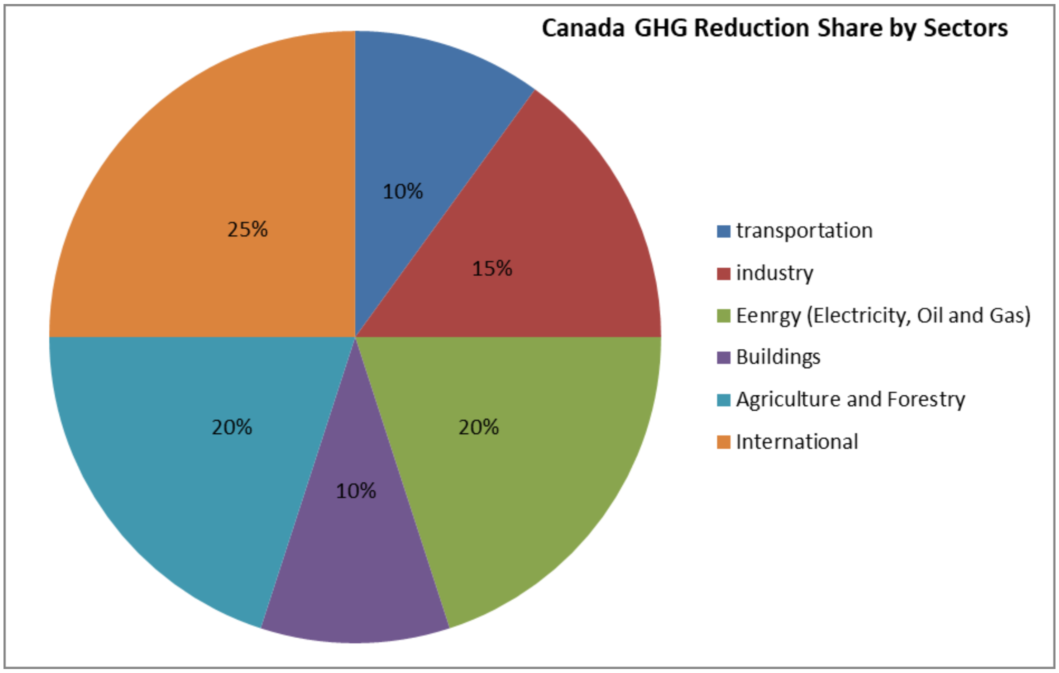


Figure 2- GHG Reduction Share by Sectors

As for British Columbia, one of the pioneers in sustainability and green practices, the provincial government has enacted significant pieces of climate action legislation pursuing reduction of emissions and transitioning to a low-carbon economy. These targets were set not just based on GHG for each sector, but also the financial and technical practicality of them. According to a study, the existing buildings use around two-thirds of the total consumed energy in the province which contributes to 41% of its total annual greenhouse gas emission (Light House Sustainable Building Centre, 2014).

One of the latest legislated plans, (GGRTA 2008, retrieved 2018), sets aggressive targets of reducing B.C.' GHG emissions 33% below its 2007 levels by year 2020 and a further reduction of 80% by year 2050.

Prior to GGRTA, the BC Building Code (BCBC) had already released its first Energy Efficient Buildings Strategy (EEBS) in 2005 to perform 25% better than the Model National Energy Code for Buildings (MNECB) which was the first Canadian energy code from 1997. The building sector includes residential, commercial and industrial that generate substantial amount of GHG emission by burning fossil fuels for space heating so by improving existing buildings a great potential for reducing fossil fuel consumption takes place, however building the new buildings more energy efficient was also deemed crucial to meeting saving targets.

Since early 1990's, BC Building Codes (BCBB) has been continually increasing its energy efficiency requirements for the province and city of Vancouver and this growing trend is expected to continue (Frappe-Seneclauze; MacNab, 2015).

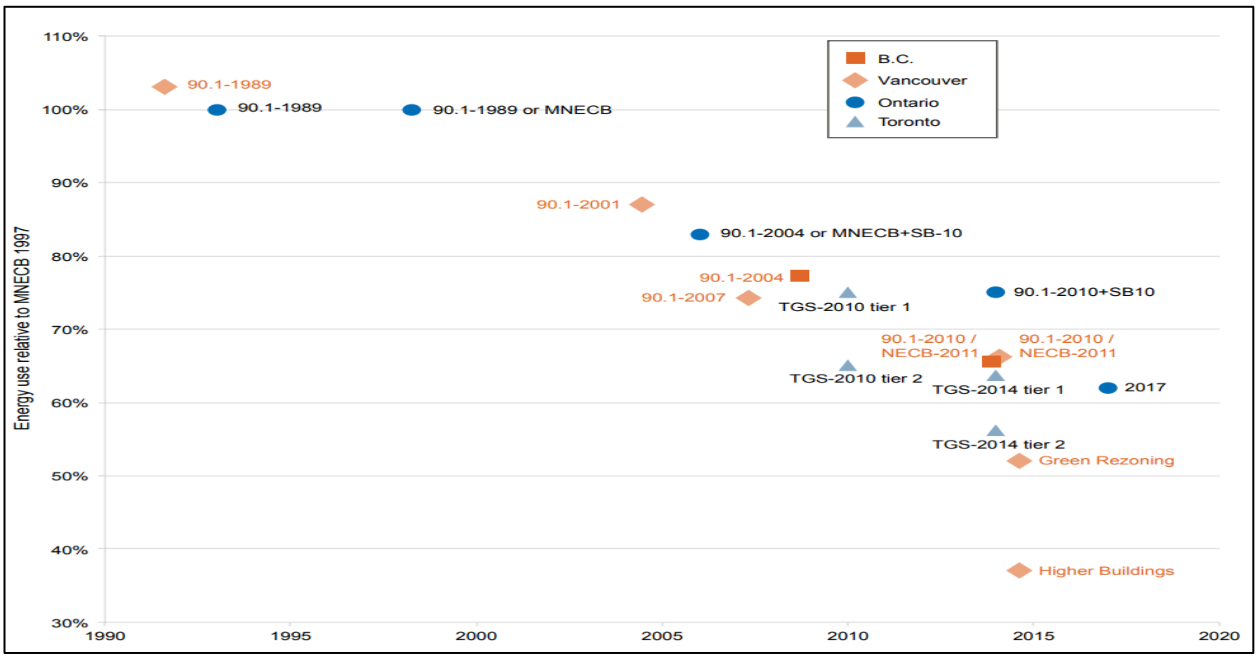


Figure 3- Evolution of Energy Performance Requirements in British Columbia and Ontario (Frappe-Seneclauze; MacNab, 2015)

Moreover, Carbon Tax Act (Carbon Act BC, retrieved 2018) has been in place since May 2008 in B.C. that adds additional tax to fossil fuels burned for transportation, home heating, and electricity and reduces personal income taxes and corporate taxes by a similar amount. In other words, this act puts a price on greenhouse gas emissions providing an incentive for buildings that lower their emissions.

All these examples (laws) demonstrate there is a big-scale unstoppable willingness to reduce energy consumption in the building sector. Energy end-use in buildings breaks down into a few categories mainly Space Heating, Hot Water, Plug Loads, Lighting, Air Conditioning, and Refrigeration, which the percentage of each depends highly on usage type of buildings (e.g. residential, office, or industrial). Regardless, space heating is one of the highest end user consumers of energy for most building applications. As an example (Figure 4) around 63% of the entire energy used in an average Canadian home is for space heating (NRCan, retrieved 2018).

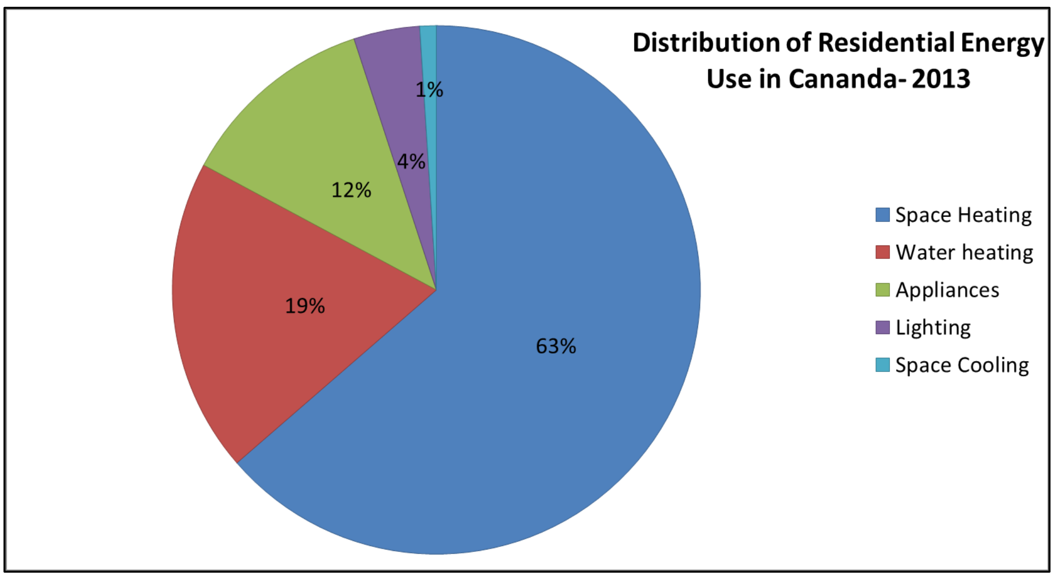


Figure 4- Distribution of Residential Energy Use in Canada- 2013

Henceforth there is a significant energy saving potential in residential buildings by reducing their space heating needs. On the subject of energy saving more is presented in appendix (9.1.2).

2 LITERATURE REVIEW

2.1 High Performance Wall Systems

As discussed earlier, energy codes and standards have been constantly raising the bar for energy efficiency codes and minimum requirements. The minimum thermal insulation resistance for BCBC, Part3 (Large Residential, Industrial, Commercial and Institutional Buildings) in City of Vancouver has been continually increasing and for wood frame walls above grade, is now R-19.6, (19.6 h.ft^2. °F/Btu), which is referenced to ASHRAE 90.1-2007, excerpt Table 5.5-5 (ASHRAE 90.1, 2007).

Europe has been leading the way in setting and following aggressive energy efficiency targets in building sector with Directive 2010/31/EU (European Parliament, 2010), committing members to achieve *Nearly Zero-Energy* buildings by 31 December 2020 for all new buildings and from after that date all new buildings occupied and owned by public authorities need to be *Zero-Energy* buildings. This directive commits members to "draw up national plans for increasing the number of nearly zero-energy buildings." Moreover, members are committed to come up with policies and measures and report the Commission of their national plans to achieve those targets. Based on Directive 2010/31/EU, heating, hot water, air-conditioning and large ventilation systems or a combination of them are calculated as part of the total energy consumption.

In North America, Canada also launched a new program, *R-2000 Net Zero Energy Pilot*, to recognize and give credit to buildings that have reached to zero energy performance in the country. *Zero-Energy (ZE), Zero Net-Energy (ZNE)*, or *Nearly Net-Zero Energy Buildings (nZEB)* refer to buildings that their total amount of energy used by building is almost the same as the amount of energy generated at the site.

To be able to achieve *Net-Zero* targets, setting integrated and aggressive standards to lower the total energy consumption of buildings seems inevitable. In that line, several energy standards were and are being created, namely Passive House (PassiveHouse, retrieved 2018), Energy Star (Energy Star, 2018).

Passive House (PassivHaus) started in Europe in early 90's which is a prominent standard that incorporates high-performance building enclosure members to contribute in achieving aggressive energy saving targets. In that line, stringent requirements for effective thermal resistance of the building enclosure components that can minimize thermal loss of building through thermal bridging and air leakage envelope are pursued.

Unlike ASHREA 90.1 with *prescriptive approach* that prescribes minimum R-values for wall assemblies located in different climatic zones, Passive House standard takes a *performance based* approach which looks at building energy performance as a whole and sets maximum energy consumption per unit area per year and to achieve the aggressive targets, all building envelope sections, including wall assemblies need substantially higher than normal thermal insulation levels and air-tightness compared to most other energy codes, including ASHRAE 90.1. The level of R-value needed depends on yearly average temperatures. For example in Sweden which is located in very cold climate, a typical PH wall assembly has insulation with 335 mm depth with thermal conductance of about 0.10 $W/m^2.K$ (PassiveHouse, retrieved 2018) that translates into R-56.8. In other words, an R-18 wall could be classed as a high R-value wall in a warm climatic zone, whereas an R-40 may be the minimum needed for somewhere in colder climate to achieve PH standard.

A computer modelling study was carried out (Straube, Smegal, & Jonathan, 2011) on industry-common high R-Value wall assemblies in North America. In this study twelve different wall configurations were analyzed and discussed on a variety of criteria; thermal and moisture control, constructability, cost, durability, and material use. The steady-state heat flow and moisture flow modeling was conducted in a climatic location of Zone 6 with rather cold winters and warm and humid summers of Minneapolis, US (similar climate to Toronto, Canada).

A criteria matrix was developed and different wall assembly types which were EIFS (Exterior Insulated Finish Systems), Advanced Framing wall, and SPF insulation walls were ranked based on several performance criteria. A general issue was discovered with wood frame walls without exterior insulation being susceptible to wintertime air leakage condensation. This was highly dependent on the quality of workmanship and good details (design and construction). A general conclusion was excluding wall designs from human construction factors by incorporating safety factors and redundancies for possible deficiencies.

In another similar study (Aldrich, Arena, & Zoeller, 2010), practicality of residential wood frame wall systems with R-30 and above was investigated. The number of high performance wall systems was reduced to three; Double-Walls, Exterior Foam Sheathing, and SIPs (Structurally Insulated Panels) as some of the most practical and common types in construction industry. Similar criteria to the previous study were discussed. SIPs, despite the common construction impression, if designed properly can be the least expensive, the most energy saving, and the least moisture associated problematic option. The other types were also represented as good options, depending on application and climate.

The multiple super-insulated wall systems reviewed can be classed into three main categories; exterior insulated, non-exterior insulated and wall assemblies insulated with new insulation materials. Below a brief is presented about each type.

2.1.1 Exterior Insulated Sheathing Walls

A variety of super insulated wall assemblies are used in construction industry that mainly differ in their exterior insulation, configurations of stud cavity, stud cavity insulation and wood framing. Four main types of exterior insulation are *extruded polystyrene (XPS), expanded polystyrene (EPS), high density sprayfoam, semi-rigid mineral wool insulation* with advantages and disadvantages over each other. While high density sprayfoam has excellent air-tightening qualities, it can curb the outward drying capability of wall system. On the contrary, although mineral wool has better outward drying, it has less resistance against inward solar driven vapour diffusion and doesn't offer the bonus of air tightening function of sprayfoam. Like sprayfoam, while foam boards such as XPS and EPS resist inward solar driven vapour diffusion, but they may not ensure as good air tightening quality of sprayfoam insulation (TIAC, 2018).

EIFS (Exterior Insulation and Finish System) is very common in almost every climate zone and has been evolving since its introduction in North America. This type of exterior insulated walls are non-load bearing building cladding systems that can provide exterior walls with thermal insulation, water resistance, and final finish in a preassembled composite material system. There is a stigma attached to EIFS for the past moisture related field failures (Aldrich, Arena, & Zoeller, 2010) which many of the failures were due to trapped water behind the EIFS because of poor water management detailing caused rot and corrosion. A continuous drainage plane is essential to avoid similar problems from happening. Fortunately, these days EIFS companies provide good documentation and design details with their product and this has lowered proportion of failed cases significantly. Fibreglass-Faced gypsum board could be a good option for the exterior sheathing as it has relatively good moisture tolerance. Depending on the targeted insulation level, EIFS walls come in various exterior thicknesses working in tandem with the stud space insulation. Since EIFS come with exterior insulation, the exterior sheathing board is kept warm and wintertime condensation is lowered, however, considering low vapour permeability of exterior foam insulation, there is less exterior drying potential.

Among other types of exterior insulated wall systems, *XPS Insulation without Extra Sheathing Board* is also an option. Since XPS has high level of moisture tolerance, air and vapour flow resistance, it has the potential to act as the water shedding surface, air and vapour barrier (should be meticulously taped in joints and interfaces) and can obviated the need for sheathing board saving on material use and cost (Straube et al., 2011). One important consideration is XPS should be protected against excessive water exposure and UV, so a ventilated rainscreen wall is a fitting application for it. Another concern could be its lower level of security with just cladding protecting probable break-ins. One important consideration is since the exterior foam is the air and vapour barrier, its joints should be meticulously sealed with tape. One specific consideration for Vancouver being located in a high seismic risk zone, the elimination of exterior sheathing may not be allowed, and this should be checked with the local structural code. This could be the same for other areas with high wind-load risks. Therefore, in some cases insulated sheathing and wood sheathing are used together. According to International Residential Code (IRC), an interior vapour barrier of class I, or II is still required if the total R-value of the exterior sheathing is less than 33% of total thermal insulation value of the wall assembly. Otherwise, a class III vapour retarder, such as latex paint suffices, IRC-Section N1102.5 (IRC, 2018). The main advantage of this system, in moisture engineering point of view, is higher surface temperature of the exterior sheathing which lowers both vapour diffusion and air leakage condensation risks. Another benefit of this assembly is reduction of inward vapour drive due to its low vapour permeability.

As discussed, the exterior XPS can impede outward drying of wall system, so a good alternative could be a similar wall system that semi rigid mineral wool replaces XPS insulation. From moisture engineering standpoint, it can have the advantage of not restricting the outward vapour flow as much as XPS insulation does (Salonvaara, T.Ojanen, Erkki, & Karagiozis, 1998). This translates into causing very low resistance on the way of outward diffusive drying. Furthermore, mineral wool is not susceptible to fire and doesn't degrade as much as foam insulation over time due to losing its blowing agent by weathering. Another advantage of semi-rigid mineral wools insulation is higher rigidity helps with a higher structural loading capacity compared to XPS and EPS insulation types.

Another type of an exterior insulated wall assembly is *Offset Framing with HD SPF (High Density Spray Polyurethane Foam)* (Straube et al., 2011). Offset framing is a suitable application for the increasing needs for energy retrofit solutions. It increases moisture related durability, is fast to build, and doesn't use the interior space (unlike double-stud walls). From constructability point of view, the cladding can be directly attached to the interior lumbers, independent of an exterior sheathing board. The exterior high density sprayfoam is not only the thermal control layer, but it can also work as air barrier, vapour control, and drainage plane. One main difference for these wall types is if the high level of insulation control is required, the offset framing has to become thick and large fasteners will be necessary to support the framing lumber for cladding installation which may be cost-prohibitive due to extra material use and installation labor time. In terms of moisture behavior, this is one of the best wall types as it keeps the wood sheathing warm, prevents air leakage, and eliminates thermal bridging. Thermal bridging is not only an energy consumption issue, but also can lead to condensation problem on the cold surfaces caused by thermal bridging elements. Because of the high level of vapour control in the exterior HD SPF insulation, if designed and installed properly, can eliminate the risk of wintertime air leakage condensation on the interior of exterior sheathing.

The last type of exterior insulated sheathing noticed in the literature reviewed is a rather new system that was first introduced Europe called *I-beam Timber Frames* (Yeat & Bath, retrieved 2013). This type of wall system changes the traditional rectangular wood studs to I-beams with thin web that cold (or thermal) bridging is significantly lowered. Moreover, the exterior sheathing almost eliminates thermal bridging effect. Proposed modifications are exterior continuous MW insulation, addition of a solid thin protective layer on interior vapour barrier (polyethylene) and leaving an empty space for services. The main reason for proposing the exterior MW insulation is maintaining the exterior sheathing warmer to lower its condensation risks of the vapour received from the intruding interior/exterior air directly or by vapour diffusion mechanism.

2.1.2 Non-Exterior Insulated Sheathing Walls

Among various types of non-exterior insulated wall systems, a rather common high-performance type in multifamily construction is double-stud wall assemblies (Straube et al., 2011). It is basically a regular exterior structural stud-wall system complemented with an interior non-structural stud wall with a gap between to be filled with insulation material. The interior wall supports services and interior finishing drywall and may save in wood lumber by being constructed with studs further apart, as it is usually non-load bearing. The vapour barrier may be installed either right behind the gypsum board, or behind the interior wall studs. This helps with less penetrations made for service installation. However, if the vapour barrier is installed behind the gypsum board, one big gap could be filled with blown-in cellulose insulation in one single stage, preferred by construction contractors. The vapour barrier is mostly a polyethylene film layer which can handle both air leakage and vapour diffusion. A common type of insulation material is cellulose that is blown in and has a good moisture buffering property, however since the exterior sheathing is exposed to exterior weather, if the installation is not carried out properly and gaps and holes are remained within, it can be susceptible to interior air leakage, and/or outward vapour diffusion through construction defects, winter condensation risk is possible.

Double-Stud wall systems with sprayfoam on interior surface of exterior sheathing board, is another option of for super insulated wall systems. This wall assembly is identical to double stud walls (previously discussed wall), with the difference of having high density (2.0 pcf) sprayfoam insulation applied to the interior surface of its exterior sheathing board (instead of blown-in cellulose filling the entire stud cavity). Commonly two inches of sprayfoam is applied because it's the most practically achievable thickness in one single pass (Straube et al., 2011). The sprayfoam insulation, if applied properly, addresses the air leakage concern through any missed defects in sheathing board and wood framing. Moreover, it covers the entire sheathing board which is a moisture sensitive material and becoming the condensation plane, if any condensation does happen. Another advantage of this wall assembly is it reaches slightly higher R-value due to its higher R-value/inch of high density sprayfoam compared to cellulose insulation (R-5.7/inch vs. R-3.5/inch). Therefore, by increasing the thickness of the SPFI for colder climates (e.g. Zone 6, 7, 8), air leakage condensation potential can be further curbed. Another variation of SPFI walls is Open Cell SPFI, with lower density (0.5pcf compared to 2.0 pcf of High density), lower thermal value/inch (R-3.5/inch vs. R-5.7/inch), and significantly lower vapour resistance. This will be further discussed (Table 2).

Another type of wall system that is commonly seen in high performance buildings, such as Passive Houses, is SIPs abbreviated for Structurally Insulated Panels which are basically a foam insulation sandwiched between two sheathing boards. The two sheathing boards are held and glued together by the foam within and the whole system can bear structural load, both gravitationally (dead and live loads) and laterally (seismic and wind loads). EIFs are typically constructed with a thickness of EPS that matches of standard framing lumber (e.g. 3.5", 5.5", and 7.5"), however, there are other variations of foam insulations, such as extruded polystyrene (XPS) and polyisocyanurate (PIC) to increase the R-Value/inch (Aldrich, Arena, & Zoeller, 2010). Although SIP panels are known for their continuous plane of insulation, but they are susceptible to loss of their effective R-value caused by thermal bridging effect of stiffeners, connection splines, as well as bottom and top plates. One of the prominent features of these walls is their continuous air and vapour barrier characteristic which helps lowering poor workmanship on construction sites.

Air leakage through the joints between panels has been a historical problem with these wall systems which can factor to condensation inside the sheathing boards. Fortunately, better standards and practice guides are available now which has lowered moisture related issues.

Table 1- Super-insulated Wall types

	Wall Type	Ext. Insulation	Stud Cavity Inslation	Ventilated Rainscreen?
None Ext. Insulated	Doube Stud	N/A	Blown-in-Cellulose	Yes
	Double Stud with Int. HD SPF	N/A	Hi Density Spray Polyurethane Foam	Yes
	SIPs	N/A	EPS	Yes
Ext. Insulated	EIFs	EPS	Blown-in-Cellulose	No
	XPS Ext.	XPS	Blown-in-Fiberglass	Yes
	S.R. MW Ext. Insulation	Semi Rigid Mineral Wool	Blown-in-Cellulose	Yes
	Offset Framing with HD SPF	High Density SPF	Fibreglass Batt	Yes
	I-Beam with S.R. MW	Semi Rigid Mineral Wool	Blown-in-Mineral Wool	Yes
New Insulation Material	VIP	Vacuum Insulated Panel	Blown-in-Cellulose	No
	Aerogel	Aerogel	Fibreglass Batt	Yes

2.1.3 Thermal Insulation and Vapour Control Strategies

In line with more environmentally friendly construction methods, the materials that use less natural resources and lower embodied energy are preferred and thermal insulation material has much room for efficiency in not only energy consumption, but also using more environmentally friendly construction materials and also insulation materials that have better performance hygrothermally. Insulation material not only affects heat flow in a wall assembly but also the air and moisture within.

Overall, the main idea for incorporation of thermal insulation in wall assemblies is reducing conductive heat loss through building envelope, however convective heat loss can be significant through leakage paths like holes and gaps. This can be addressed by incorporation of air barriers and reducing air leakage points such as gaps and holes on the exterior surfaces of walls. Henceforth, insulation types that fill the gaps within wall assembly can be very helpful. SPF and blown-in glassfibre and cellulose insulations are claimed to help with reducing air leakage in wall assemblies.

To reduce conductive heat loss, thermal conductivity is measured in material laboratory. Thermal conductivity is usually symbolled with λ and is measured in W/m.K (Watts per meter-Kelvin) which is the gauge for insulation material effectiveness. Traditionally insulation materials are mineral based such as glass fibre, stone wood, expanded polystyrene, and polyurethane foam which all have acceptable performances; however, they are made of non-renewable natural recourse and have relatively high *embodied energy* (Hurtado, Rouilly, Vandenbossche, & Raynaud, 2016). *Embodied energy* is the total amount of all the energy consumed to produce any goods or services. For this reason, construction industry is looking for greener organic insulation materials that are not only from renewable resources, but also have lower embodied energy levels. Jute, flax, and hemp have shown relatively good thermal insulating properties in studies (Madurwar, Releganokar, & Manadavgane, 2013). Another organic and renewable insulation material is Cellulose Fibre Insulation (CFI), not only is comprised of renewable material with one of the lowest embodied energy numbers among all other types but also has relatively good thermal insulating properties (Hammond & Jones, 2008). Moreover, CFI is claimed to have good acoustical and moisture buffering properties too. A high moisture buffering capacity can help with regulating interior peak moisture levels (Morensen, Rode, & Peuhkuri, 2005).

Table 2- Insulation Types, applications and specification

Insulation Type	Typical Use	R-value per inch (RSI)	Vapour Permeability	Air Permeability
Fibreglass (Batts)	Stud cavities, between attic trusses	R-3.0 to 4.2 (0.53 to 0.75)	High	High
Fibreglass (Blown fibres)	Blown into stud cavities, attic loose-fill	R-2.5 to 3.7 (0.44 to 0.65)	High	High
Fibreglass (Dense Pack)	Sprayed into stud cavities	R-3.5 to 4.0 (0.62 to 0.70)	High	High
Fibreglass (Semi-rigid board)	Exterior cavities exposed to dampness, window spandrel panels	R-3.5 to 4.2 (0.62 to0.75)	High	High
Mineral or Rock wool (Batts)	Stud cavities	R-3.0 to 4.2 (0.53 to 0.75)	High	High
Mineral or rock wool (Rigid and Semi-rigid board)	Exterior cavities exposed to dampness, window spandrel panels, fire-stopping	R-3.5 to 4.3 (0.62 to0.76)	High	High
Cellulose (Blown fibres)	Stud cavities, attic loose-fill	R-3.0 to 3.8 (0.53 to 0.67)	High	High
Cellulose (Dense Pack)	Sprayed into stud cavities	R-3.5 to R-3.8 (0.62 to 0.67)	High	Medium
Extruded Polystyrene (XPS) Rigid Board	Sheathing, roofing (where exposed to water), below-grade, below slab, Cavities exposed to dampness	R-4.0 to 5.6 - R-5.0 typical (0.70 to 1.0)	Low	Low
Expanded Polystyrene (EPS) Rigid Board	Sheathing, roofing (where protected from water), below-grade, cavities, EIFS, ICFs	R-3.7 to 4.3 (0.65 to 0.76)	Low	Low
Polyisocyanurate Rigid Board, foil or fibreglass faced	Roofing (where protected from water), sheathing, cavities	R-6.0 aged (1.06)	Low	Low
½ pound low-density open-cell spray polyurethane foam	Stud cavities, attics below sheathing	R-3.6 to 3.8 (0.63 to 0.67)	High	Low
2 pound high-density closed-cell spray polyurethane foam	Exterior of sheathing, attics below sheathing, below-grade	R-5.0 to 6.0 aged (0.88 to 1.06)	Low	Low

More comprehensive of each type of thermal insulation is presented in Table 2.

2.1.3.1 Insulation Material Types

As for thermal resistance value of the different types of insulation, a normalised number of thermal resistances (R-Value), over average prices researched at the time of writing this are presented in the two bar charts below. As we can see, although, Vacuum Insulated Panels (VIP), are relatively expensive and may appear cost prohibitive at the first look but considering the R-Value per unit thickness that they provide, they are fairly efficient whereas Aerogel that has is less costly per unit thickness, is in fact more expensive for the insulation value it provides.

2.1.3.1.1 VIPs (Vacuum Insulated Panels)

VIPs (Vacuum Insulated Panels) have been recently introduced to construction industry. This insulation type boasts thermal insulating properties that are five to eight times better than other conventional insulation material types. This translates into possibility of achieving high thermal resistance with minimum use of wall thickness (R-39/inch). One moisture control consideration associated with them thermal bridging in the perimeter of the panels that can contribute to condensation of the vapour in the air. Moreover, if seams are not carefully sealed, air borne vapour can get though by air pressure (e.g. wind pressure), or diffusion.

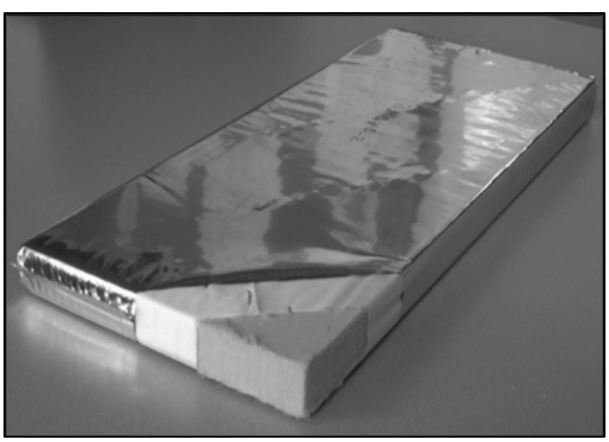


Figure 5- Vacuum Insulated Panels (VIP's)

Another concern associated with VIP's is the long-term performance in a wall assembly which is not proven yet.

Considering these facts, it is advisable to use VIP's combined with a conventional insulation layer as a redundancy measure. DOW Corning claims that their VIP proprietorial panels can maintain 80% of its initial R-value properties for 30 years (DowCorning, 2013).

2.1.3.1.2 Aerogel

Another innovative insulation material is aerogel insulation. The Space-loft aerogel panels is a product of Aspen company with R-value 10.3/inch (Aerogels, Aspen, retrieved 2013) which is the highest number after VIP insulation. The panels are installed with fasteners to the existing interior and exterior walls.

Figure 6- Aerogel Insulation, Installation

Figure 7- Aerogel Insulation panels

The foam-like panels is sandwiched between framing and internal and/or external sheathing and work in combination with a typical conventional

Table 3- Insulation Type R-Values and Cost

Insulation Type	R-value/inch	$/ft2/R-Value
VIP	40	0.15
Aerogel	10	1.25
HD SPF	6.5	0.025
PIC	6.5	0.1
XPS	5	0.1
EPS	4.1	0.07
S.R. MW	4	0.16
Cork Insulation	4	0.20
LD SPF	3.6	0.17
FG Batt	3.1	0.025
Loos Fill	3	0.03

2x6 wood stud wall with FG batt insulation batts. They cost around $1.25/ft2/R-vale which makes them by far the most expensive option, sixty times more expensive than fibreglass insulation.

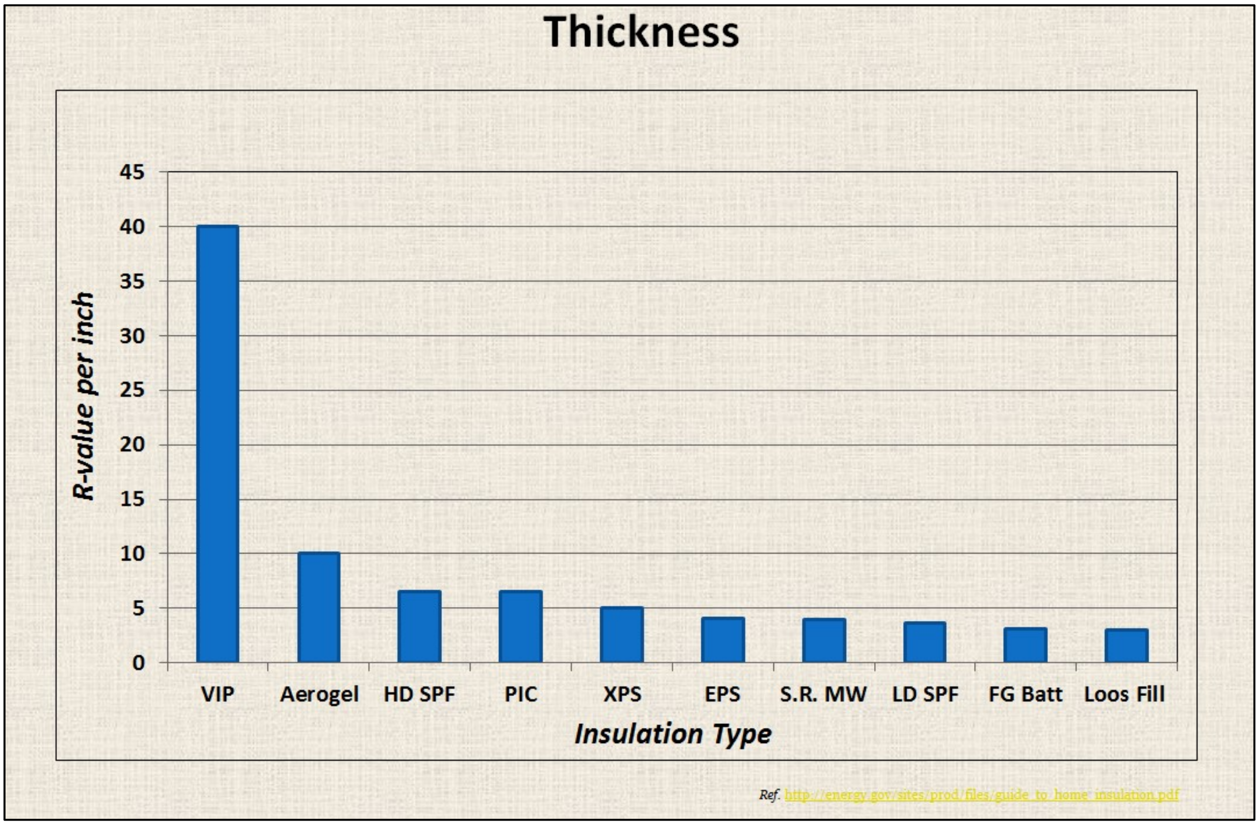


Figure 8- Insulation R-Value per Thickness (Guide to Home Insulation, 2018)

Thus, a better financial analysis metric will be thermal resistance of a unit thickness per cost. Figure 9 shows the commonly used Glass Fibre Batt Insulation (GFBI) is the most cost effective thermal insulation types. Low Density Spray Polyurethane Foam Insulation (LD SPFI), costs higher than fibre glass and cellulose, however it is still less costly than VIP and High-Density Spray Polyurethane Foam Insulation (HD SPFI).

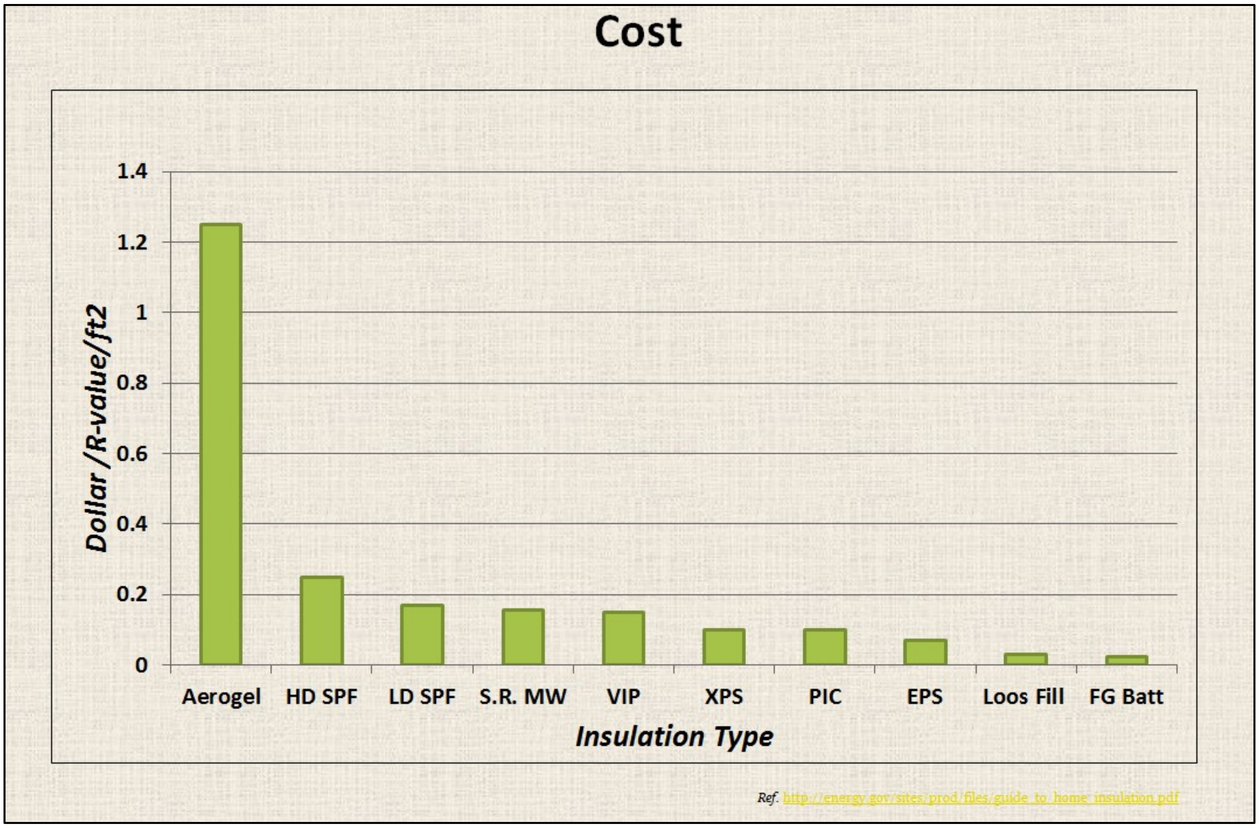


Figure 9- Insulation Cost per R-Value (Guide to Home Insulation, 2018)

2.1.3.1.3 Cellulose Insulation

Cellulose comprises of two French words, *cellule*, for living cell and *glucose* for sugar. Cellulose Fibre Insulation (CFI) is one of the oldest types of insulation material which has been used in different forms such as straw, cotton, sawdust, hemp, corncob, cardboard and newspapers. Monticello, the house of third president of United States built in 1772, was insulated with cellulose (Wiki, retrieved 2018). Modern cellulose insulation which comes mainly from recycled newsprint is ground and treated with fire and mold resistant additives have been used since 1950s and became more popular in building construction industry from 1970s. Cellulose insulation application in buildings gained much momentum around 1973-4 after Arab oil embargo due to the general financial interest for conserving on energy bills and since cellulose was relatively inexpensive and accessible, in a few years many cellulose manufacturers entered this industry and the market continued to grow in the US as a tax credit incentivised further home owners to build more energy efficiently. Following some major concerns and incidents about fire hazards, government of the US started introducing and enforcing standards for cellulose insulation manufacturers. A safety standard was passed by *the Federal Consumer Products Safety Commission passing 16 CFR Part 1209,* which essentially regulated four attributes of cellulose insulation; settled density, corrosiveness, critical radiant flux and smoldering combustion. Moreover, manufacturers were held reliable for minimal claimed R-Values per thickness of their products. The new regulations imposed higher costs on manufacturers that increased the prices leading to less demand. A recent study suggests blown-in cellulose can reduce fire hazard as it inhibits oxygen movement in insulation in case of a fire incidents (NRCan, 2000).

Among different types of building thermal insulation materials, cellulose stands out with one of

Insulation material	Embodied energy (MJ/kg)
General Insulation	45
Cellular Glass	27
Cellulose	0.94–3.3
Cork	4
Fibreglass (Glasswool)	28
Flax (Insulation)	39.5
Mineral wool	16.6
Paper wool	20.17
Rockwool	16.8
Woodwool (loose)	10.8
Woodwool (Board)	20
Wool (Recycled)	20.9

Table 4- Embodied Energy of some Insulation Materials (Rouilly, Vandenbossche, & Raynaud, 2015)

the least environmental footprints among all other types of insulations as it has the lowest embodied energy among all (Hannond; Jones, 2011).

This insulation type is usually available either in prefabricated panels or in bulk packages to be applied loose or in some cases wet. Typically, a mix of borax and boric acid, with a dose of around 15%-20% of the mass of cellulose fibres is added for fire and mold resistance. (Hurtado, Rouilly, Vandenbossche, & Raynaud, 2016). In one laboratory experiment (Herrera, 2005) half-scale wall units insulated with cellulose insulation with a concentration ranges of sodium polyborate were exposed to the ambient weather of a whole summer and random samples of insulation were examined closely. It was found that sodium polyborate precludes five most mold fungi from growing, sodium polyborate plays an essential role in structural durability.

Other advantages of cellulose are its good thermal and acoustical resistance and can accommodate relatively high amounts of moisture (Mortensen, Rode, & Peuhkuri, 2005) and prevent noise transmittance from the building envelope. Moisture storage capability can be very helpful with buffering moisture peaks especially during night and daytime moisture drive variations in shoulder seasons and lowering the amount of air-borne moisture being condensed by reaching the cold components of wall assembly.

The buffering capacity of cellulose has been a controversial subject though. In one study (Rode, 2000) the role of moisture several insulation materials in moderating vapour diffusion wetting effect was studied. The insulation materials were cellulose, representing organic products, and mineral wood (rock wool), representing almost none hygroscopic materials. A one-dimensional hygrothermal tool was used to simulate different walls and boundary conditions. The analysis suggested, unless there is no vapor retarder or other material between the insulation layers of the walls and their adjacent spaces, the hygroscopic capacity of the insulation material cannot act as a buffer for the indoor relative humidity level. On the other hand, if there was low vapor diffusion resistance between the insulation layer of a wall and the indoor space, the diffusive drying can desiccate the room but insignificantly, nevertheless, it may cause high humidity levels in the exterior construction parts, with higher risks of fungal attacks. This study concludes a vapour barrier with low vapour permeability as a safe measure in constructing cellulose walls.

Moisture buffering capacity of several construction materials, including cellulose insulation was tested in another laboratory experiment which was performed in an air and moisture tight test room consisting of a highly insulated steel box (Mortensen, Rode, & Puhkuri, 2005). The materials tested were mineral wool, cellulose insulation, plasterboard, cellular concrete and paint. Some hygroscopic materials can buffer moisture peaks and help with moderating relative humidity peak periods and moisture content of walls or even building materials. In that test the full-scale test specimens were exposed to cyclic humidity variation like an inhabited indoor environment. The results suggested that finishes of walls have a big impact on peak MC and RH levels of underlying materials. It was also found that hygroscopic materials such as cellulose insulation, that is essentially the quality of some materials to attract and hold water have good moisture buffering capacity when compared to non-hygroscopic materials. In another field experimental study (Peuhkuri, Rode, & Hansen, 2003), cellulose insulation's moisture performance was compared to several other organic insulating materials such as rock wool, sheep wool, flax, glass fiber and aerated concreted and expanded perlite. The results showed the capability of cellulose insulation and some other fibrous materials such as flax to moderate the oscillations of indoor relative humidity and reducing slightly the peak relative humidity levels.

There are two general methods of installing cellulose fibre insulation, *loose-fill* and *wet-spray*. In loose-fill method cellulose is blown into walls by air pressure into the stud cavity and in wet spray method, water is added to cellulose fibres during installation via a pump to add specific amounts of water ratio to it. More detail is presented below (9.1.4.1, 9.1.4.2).

2.1.3.1.4 Spray Polyurethane Foam (SPF)

Spray Polyurethane Foam (SPF) is made by mixing and reacting two liquid components that create foam. Polyurethane was invented in 1937 with basic idea of mixing two inert substances of small volumes to trigger a chemical reaction and expand its volume substantially it into a kind of foam like material with exceptional thermal, air and vapour flow resistances (Bayer Global, retrieved 2016). Following that invention, polyurethane was adopted in a variety of industries such as shoe making, car upholstery, refrigeration, aviation, etc., but it wasn't until 1979 that polyurethane entered construction industry as an insulation material (Polyurethanes, retrieved 2018).

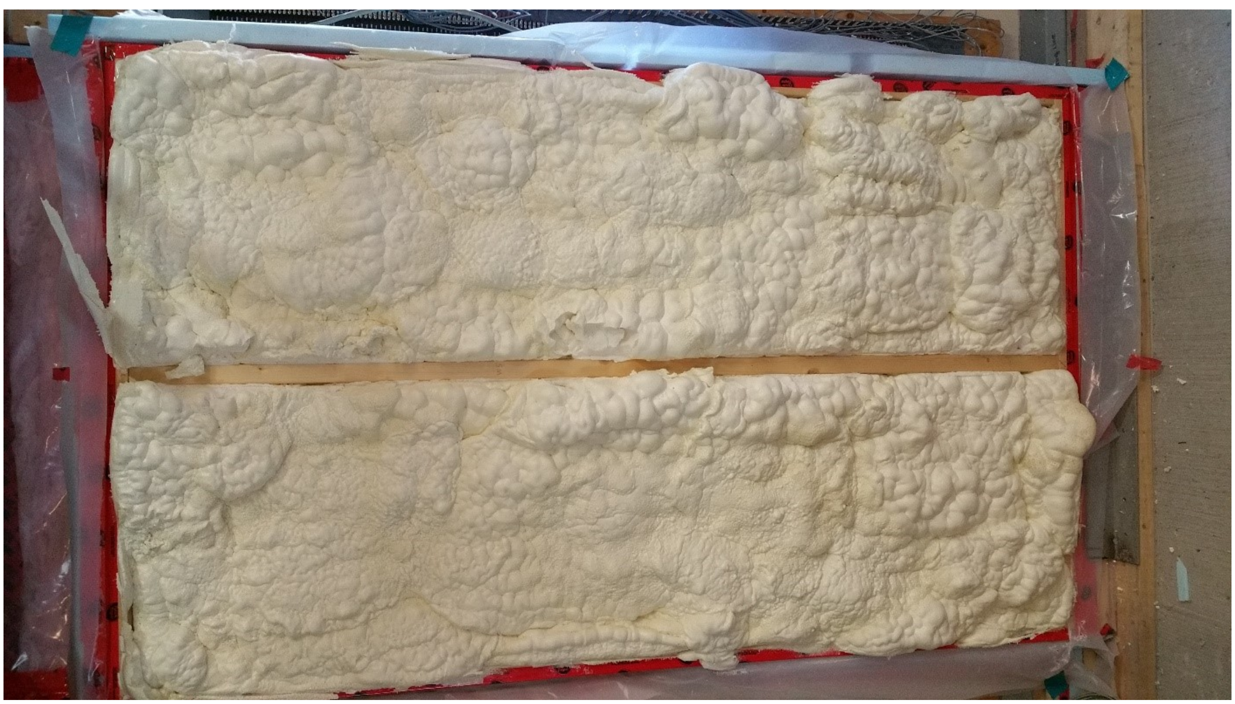


Figure 10- Polyurethane Spray Foam Application (photo by author)

Spray Polyurethane Foam (SPF) comes in a variety of structure and densities, *Open Cell* to *Closed Cell* and Low to *High Density*, ranging from 0.5-3.0 pcf. One of the most important considerations about sprayfoam is proper application and to do so the applicators must be trained and highly skilled. The Canadian National Building Code references CAN/LUC S705.2 from (ULC, 2015) the application standard to be followed during all installations of 2lb medium density closed cell polyurethane foam; “Every installer must be licensed to spray foam and hold valid photo ID issued by their Quality Assurance Program (QAP) provider showing their license is in good standing”. Before applying SPF, a rigid substrate must be cleaned of any residue, dust, or oil and dry. It is essential that the two components be mixed in the correct proportion and also in the right temperature for proper chemical reaction to cure well, otherwise the mixture can be prone to shrinkage or exothermic reaction of the foam caused by cold substrate and improper curing (Smith, 2009) that will fail to reach the expected R-values. To address this problem in cold seasons, the substrate can be heated before application starts. A properly trained SPF is usually aware of all these issues and prepares everything necessary before installation.

In Canada medium density SPF should meet CAN/LUC S705.2 in (ULC, 2015). Installation Standard and must be under the supervision of a licensed contractor whereas in the US this is not the case. By higher densities of SPF, the air leakage rate decreases, however it usually contributes to more conductive heat loss, so the overall RSI value of the insulation may not necessarily go higher with density. As for material properties of Open and Closed Cell SPF (Table 5), HD SPF with compressive strength of around 185 kPa is around forty times stronger than LD SPF which has nominal compressive strength of 4.8kPa. Thermal resistance of HD SPF stands among one of the highest of the typical insulations R-values, second only to polyisocyanurate with R-6.0, while LD SPF stands at the bottom of R-value per thickness of around R-3.4, like conventional glassfibre batt insulation.

Open Cell or Low-Density SPF like closed-cell is applied by spraying that can provide a continuous insulation. Similar to Closed Cell SPF, the Open Cell type has two components which should be applied by skilled applicators. Common applications of this type of insulation in construction industry is filling gaps and cracks around windows and doorframes, closing gaps around gas lines and water faucets or dryer vent hoses, and covering electrical cables and boxes seams and HVAC vent penetrations left gaps in building envelope. Two-component sprayfoam is generally applied in two methods of low and high pressure, 250 and 1,000 psi respectively with several safety considerations to consider. The applicators need to wear protective hear, full eye protection, respirators, and gloves during the job (Sprayfoam, retrieved 2016).

Table 5- Material Property of HD vs. LD SPF Insulation (Smith, 2009)

Property	Compressive Strength	Thermal Resistance	Air Permeance	Vapour Permeance
Open Cell SPF	4.8 kPa (0.7 psi)	RSI = 0.6 m2.K/W (R-value=3.4 hr.ft2.°F/Btu)	0.002 L/s.m2 @ 75 Pa	1,200 ng/Pa.s.m2
Closed Cell SPF	185 kPa (27 psi)	RSI = 1.05 m2.K/W (R-value=6 hr.ft2.°F/Btu)	0.0001 L/s.m2 @ 75 Pa	90ng/Pa.s.m2

Low Density spray foam is commonly used for walls, unvented attics, to ducts and ceilings, and in vented attics and crawl spaces. It can act as an air barrier and has some vapour resistance, but with its common thickness it does not reach the 1 Perm prescribed by NBCC, Part 9. Another advantage of this type of insulation is its relatively soft and flexible texture after curing which helps it to accommodate the likely settlement of buildings over time, not affected cracks or breakage in the insulation over time. Moreover, open cell SPF is claimed to have better acoustical properties due to its softer texture.

As for vapour permeance of this type of sprayfoam, it depends vastly on type of application and chemical components and mixing ratios, but for one-inch thickness of Open-Cell SPF could be around 1,200 $ng/Pa.s.m^2$ as opposed to 90 $ng/Pa.s.m^2$ for the same thickness of closed cell.

2.1.3.2 Vapour Control Strategies

A vapour barrier is any material that can prevent excessive vapour in the air from reaching to moisture sensitive materials. In construction industry a vapour barrier is commonly used in walls, ceilings and floor assemblies primarily to prevent interstitial condensation issues that is caused by excessive moisture in the air going below its dew-point temperature and deposited as liquid water.

Vapour control layers are commonly classified based on their moisture vapour transmission rate, or vapour permeability that can be reported as US perm or SI perm. (1.0 US perm = 57 SI perm = 57 ng/s. m^2. Pa). In American standards, vapour permeance of a given material that is tested under ASTM E96 Desiccant test is classed as a vapour barrier if it is below 0.1 perm and is classed as vapour retarder if its permeance is between 0.1-1.0 US perm.

One big controversy over application of vapour barriers is while it may prevent or retard moisture from entering the wall assembly, but on the other hand it may slow down the drying process of walls when they get wet. In other words, a vapour barrier can cause reduction in 'drying capacity' of building enclosure wall assembly. This is a more common challenge in 'mixed climates' that vapour gradient may alternate from inward to outward in warm and cold season respectively. According to National Building Code of Canada (NBCC) 2006, Part 5, a vapour barrier is necessary "where a building component or assembly will be subjected to a temperature differential and a differential in water vapour pressure except for the cases it can be shown that uncontrolled vapour diffusion will not adversely affect any of '(a) health or safety of building users, (b) the intended use of the building, or the operation of the building services.' So, a vapour barrier is not necessary if conditions 'a' and 'b' can be met and verified.

Various alternatives for vapour barriers or vapour retarders are already commonly in use in construction industry such as incorporation of insulation materials that can either accommodate or buffer higher amounts of moisture. Another alternative recently introduced to construction industry by some manufacturers is using vapour control layers that can change its vapor resistance with variation in relative humidity in the ambient air and within the insulation cavity. One commercial product commonly named as Smart Vapour Retarders (SVR) which its manufacturers claim it can enhance wetting and drying behaviour of walls by changing its vapour resistance in different relative humidity and temperature conditions. SVR is essentially a plastic film like layer usually applied behind the interior sheathing board, e.g. gypsum board, aiming to block or retard the interior high-pressure vapour from diffusing outwardly into walls assemblies, while letting it dry back to the interior if the vapour gradient changes into inwardly in warmer exterior periods. This translates into lower vapour permeance in heating season (winter), and higher vapour permeance in cooling season (summer). SVR (A.K.A variable permeance vapour barrier) may come in two kinds of film or paper. The plastic film types are essentially a transparent layer looking very similar to the conventional polyethylene film. This product has been researched since early 2000s in Europe by CertainTeed’s parent company Saint-Gobain in France named MemBrain. According to manufacturers of MemBrain its vapour

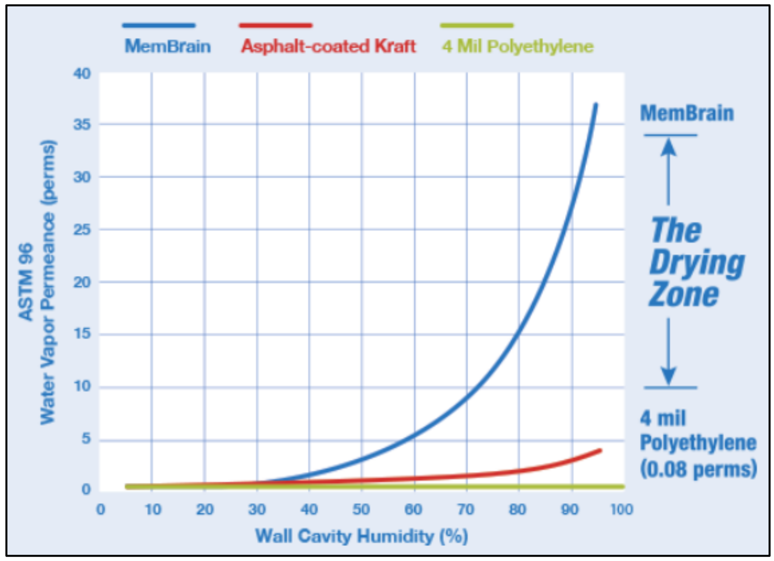


Figure 11- Vapour Permeance of MemBrain Vs. 4-mil Polyethylene and Asphalt-coated Kraft (MemBrain, retrieved 2018)

permeability can change from 1 to 35 US perm changing with wall cavity humidity levels (MemBrain, retrieved 2018). Two other types of SVR products are *Intello* & *Intello-Plus* by Pro Clima, and *DB+* produced by 475 High Performance Building Supply companies. *Intello-Plus* is produced from Polypropylene as its fleece with polyethylene copolymer as its membrane reinforced with polypropylene non-woven fabric. According to its data sheet, its vapour permeability can change from *0.13-13 US perms*, tested in accordance to EV IS 1252 standard, equal to *7.46-746* $ng/s.m^2.\ Pa$ (Pro Clima, Retrieved 2018). DB+ as a less expensive vapour permeance variable option is made from recycled paper and reinforced with a bi-directional reinforcement layer which could be applied in roofs, walls and floors. According to the manufacture datasheets, its vapour permeance ranges from 0.8-8 perms depending on humidity levels of the boundary conditions on its vapour-open side (475 High Performance Buildings Supply, Retrived 2018).

2.2 Hygrothermal Performance Assessment

There are three major types of studies in building science, field experiment, laboratory testing and computer modelling. These three types of studies often complement each other in an iterative process. Moreover, hygrothermal performance of walls assemblies depends on many factors such as the configuration of walls, interior and exterior boundary conditions as well as existence of additional moisture loads such as incidental penetration of rainwater. This makes each study unique and not easily extendable.

Henceforth, in this literature review, studies are categorised into field, laboratory and computer modelling and a combination of the three types as a fourth case scenario. Each of these four types of studies are broken down further into with or without liquid water penetration existence within the studied walls, so overall eight categories of studies are discussed here.

An area leading to moisture mismanagement in design is related to materials hygrothermal properties. In the process of moisture engineering, the hygrothermal properties of materials are either taken from previously available test results, or from laboratory tests. Firstly, the actual used materials used in each study may vary noticeably from the ones used from other similar studies found in literature. Secondly, the properties estimated can change over time significantly skewing the envisioned performance of the walls over time. Thermal insulation is a very common example that degrades depending on various parameters such as sun, temperature fluctuation, and moisture levels in the ambient air.

Simulation Modeling is predicting the performance of the real world digital prototype of a physical model. This could be useful in helping designers and engineers gaining a faster and less expensive understanding of the system performance under expectable real conditions, so it can reduce the number of required prototypes which can save cost and time in the design stage. In hygrothermal simulation, building envelope assemblies like enclosure walls are defined by the hygrothermal properties of their components under predictable boundary conditions. The boundary conditions are usually directly dependent on the indoor and outdoor ambient environments. Multiple studies have been carried out aided with computer simulation modelling programs, such as WUFI (Kunzel, 1995), hygIRC (Mukhopadhyaya, et al., 2003), (Maref, Booth, Lacasse, & Nicholls, 2002), MOIST (Zarr, Burch, & Fanney, 1995) and HAMFit (Tariku et al., 2010). Regardless of which program is a more fitting tool, at the very first step they all require accurate input data to produce reliable information and the hygrothermal properties of test specimen's components under varying conditions such as temperature and relative humidity should be readily available. As an example, the vapour permeability of plywood sheathing under different relative humidity levels and temperatures is needed. Material properties are usually tested in building material laboratories. Outdoor air condition is one of the major uncertainties of a field experiment. Proper statistical analysis of previous recorded weather data can help with acceptable approximated numbers to be used in computer modeling. The important condition here is availability of weather data for the subject study.

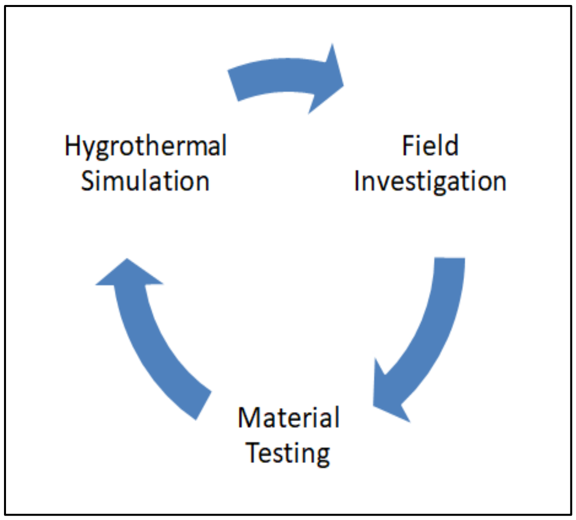


Figure 12- Building Science Study Types

Once reliable material properties are available and computer modeling is created if a few iterations of field testing are carried out it can help with verification and fine tuning of the simulation model. In building science studies, a field research translates into collecting data outside a laboratory and in an actual environment with direct observation or measurements followed by self-analysis which usually involves recording of specific data. This data is usually indoor temperature and relative humidity, outdoor ambient temperature, ambient relative humidity, receiving solar radiation, wind speed and direction, horizontal precipitation and receiving wind driven rain over specific time intervals, usually one minute. The results are later analysed through different methods depending on the studied subject. For example, in moisture behaviour study of walls in a field experiment, the moisture gain of wood components over time is measured directly (A.K.A Direct Measurement).

For instance, a field experiments can shed light on the amount and frequency of intruding water into wall assemblies as well as clarification on the water entry path and its accumulation patterns.

For the scope of this study, moisture behaviour of wall assemblies, many studies have been done in the building science field, including all three methods of computer modelling, laboratory experiment and filed experiment on implications of wetting on wood frame walls. Wetting studies include liquid and vapour water intrusion in different mechanisms, such as air-borne vapour diffusion and liquid water intrusion (simulated and actual). Some of the relevant studies are presented below.

2.2.1 Field Experiments

2.2.1.1 With liquid water Penetration

Liquid water can penetrate a wall assembly either from behind their WRB (Weather Resistive Barrier) leaking to the exterior surface of exterior sheathing board or it can leak into the wall assembly's insulation cavity through the construction defects of building envelope interfaces, such as window to wall, wall to wall, wall to balcony interfaces. In one study, (Mukhopadhyaya, et al., 2003) it was found out that lower water absorption capacity of the cladding can enhance moisture responses of wall assemblies. This reemphasizes the importance of controlling water intrusion by shedding or drainage as the first line of defense.

In another field experimental study (Mao, Fazio, & Rao, 2009) 31 full scale wall specimens in a two-storey test hut were put into test. The variables were cladding types, rainscreen air gap, WRB (Weather Resistive Barrier) type, exterior sheathing type and vapour retarder. The interior and exterior climates were similar for all walls. Same amount and pattern of liquid water was introduced to all walls by incorporation of a water tray at the bottom of the insulation cavity simulating the leaked rainwater penetration through construction defects. One of the main ideas of this test was developing a moisture response evaluation methodology that can be used as a baseline for comparing walls drying capacity, also known as Moisture Indicator. Similar to structural engineering that there is load and response, moisture was considered as the load that came from the evaporated liquid water from water trays and moisture response was accumulation of moisture in wall components (wetting) and evacuation of moisture from the assembly (drying). The concept of 'In-Cavity Evaporation Allowance' abbreviated as ICEA was developed which translated into 'maximum loading under which acceptable functions of the particular envelope can still be maintained'. This studied found good agreement between ICEA numbers and the wet stains on the sheathing board observed and the gravimetric samples. Some findings from ICEA numbers suggested walls with stucco cladding, with or without rainscreen air gap, had a general poor drying capacity. Also, while a vapour barrier on the warm side of wall can retard outward moisture diffusion, it may cause lower inward drying capability of walls too.

In another study (Teasdale-St-Hilaire, Derome, & Fazio, 2004), moisture response of several full-scale wood-frame wall specimens under introduced liquid water were studied in an environmental chamber that could simulate both indoor and outdoor climates. Six wall specimens 840mm in height and 1,075mm in width, simulating the height of a wall section below an installed window, were built with various vapour retarder types (polyethylene, paint) and different types of exterior sheathing boards (OSB, plywood, asphalt-coated fiberboard) and subsequently their bottom plates were partially immersed in 13 mm of water for 31 days and then placed on top of each of the bottom plates of the walls. The results of this study suggested the influence of a vapour retarder on overall drying performance of a wall is closely tied to the type of sheathing board in use. For example, OSB with lower vapour permeance relies more on the interior drying and if the interior vapour membrane is more vapour permeable it can benefit more from inward drying. On the other hand, the wall with fiberboard as its exterior sheathing board is mainly drying to the exterior and a more vapour open interior vapour retarder may not help as much and can make walls more exposed to the interior vapour diffusion. This study concludes when an exterior sheathing board has low vapour permeance, the effect of vapour retarder becomes critical.

Another comprehensive study was conducted on various wall assemblies with different wall configuration (Salonvaara, T.Ojanen, Erkki, & Karagiozis, 1998) in Finland. Twelve wall assemblies were built with and without air cavity and air leakage gap, different types of interior vapour control levels and two different types of stud cavity insulation and no liquid water wetting was conducted. As a general conclusion a wall assembly with highly breathable exterior sheathing board like fibreboard with rainscreen air cavity had the least amount of moisture accumulation in both top and bottom of sheathing board. This suggests a general strategy of preventing walls to get wet from inside and letting them dry out to the exterior in cold climates. Prevention of air leakage and incorporation of mineral wool into stud cavity as insulation which lets moisture migrate out easily were some other measures that contributed to better moisture performance of walls. Moreover, in order to get the most advantage of a ventilated cladding the exterior sheathing should have high enough vapour permeability to keep up with the amount of moisture the ventilated air cavity can expel. In other words, if the exterior sheathing has low vapour permeability, like OSB sheathing, the ventilated rainscreen does not take full advantage of drying capability of the ventilated rainscreen. Another interesting study was related to the role of an air cavity behind the cladding; the need for cavity ventilation was not substantiated entirely as it remains dependent on wall configuration and climate (Tariku & Ge, 2010). However, it was observed that wall cavity has the potential to help wall assemblies dry if foreseen in design such as incorporation of highly vapour breathable exterior sheathing.

2.2.1.2 Without liquid water Penetration

Multiple field experimental studies have been carried out on hygrothermal performance of wood-frame walls without extra (direct) liquid water introduction. In one study (Tariku, Simpson, & Iffa, 2015), conducted in Burnaby BC with marine climate, four full-scale test panels were installed in a test facility and introduced to the actual exterior climate and controlled interior air conditions. Several walls were installed on various orientations of the test facility with different exposures to wind-driven rainwater (WDR) and their wetting and drying behaviours were investigated and compared. Walls' construction was a common 2x6 SPF wood framing filled with glassfibre batt insulation adding to R-20 of overall thermal resistance and came with plywood as their exterior sheathing board. Walls incorporated different interior vapour retarder types. The results suggested that vapour diffusion is a critical moisture load even for mild climates such as south western part of British Columbia. In this study the role of vapour retarder was found significant as the wall without an interior vapour retarder experienced significantly higher MC levels on its plywood sheathing board. On the other hand, drying rate of a wall without an interior vapour retarder was 38% higher than the one with polyethylene as its interior vapour control layer.

2.2.2 Laboratory Experiments

Several studies have been carried out in laboratories on hygrothermal properties of building materials in isolation and as part of a whole wall assembly. While in some studies, vapour diffusion and/or air-borne vapour were the only sources of wetting, in some other experiments liquid water was also added to simulate and study the effect of possible rainwater leakage into wall assemblies.

2.2.2.1 *With liquid water Penetration*

In one laboratory study (Alturkistani, Fazio, & Rao, 2008), water was introduced to six wall assemblies of various configurations of sheathing boards and cladding and controlled amounts of liquid water were added by a hose to a water tray placed at the bottom of stud cavity to simulate penetrated and accumulated rainwater. The exterior climate was maintained at 8°C and 76% RH while the interior climate was held at 21°C and 35% RH levels. In this method moisture load and evacuation could be determined and make a moisture load and response correlation for each wall as a comparative mean of drying capacity of walls. This method takes into account the nonlinear profile with height of the absorbed vapor mass as well as the vapor pressure profile and yields a nonlinear evacuation moisture flow profile with maximum values. The results suggested that fiberboard as exterior sheathing board offers the best outward drying compared to OSB and plywood and stucco inhibit drying of walls compared to other types of cladding, such as wood siding.

In another study conducted by (Teasdale-St-Hilaire, Derome, & Fazio, 2004), drying rates of 19 large-scale wall assemblies were experimented in the field. The walls came with 2x6 wood frames with 6-mil polyethylene as their vapour barrier and were filled with glassfibre batt insulation. There were three different types of exterior sheathing board, OSB (Oriented Strand Board), Plywood and asphalt-coated fibreboard. The objective of this study was assessing moisture impact of small amounts of water penetrating into a wall assembly, so the test walls were introduced with liquid water. Water was introduced to walls in two different methods, immersion of bottom plates into liquid water and direct introduction of 0.5 litre of liquid water through a peristaltic pump. Subsequently walls were all exposed to simulated indoor and outdoor ambient environments. The exterior ambient environment conditions were extracted from Montreal historic weather data. The moisture behaviour of test walls was monitored and compared. The final report concluded that while immersion of bottom plate was easier to conduct, introducing water from the top is closer to the natural incident of water penetration. As for wetting and drying, temperature showed a significant role in drying of the walls. Another interesting observation was wood sheathing can change the rate of drying in walls as walls that had the most permeable sheathing board showed the highest drying. So, fiberboard had the highest drying followed by plywood and OSB had the lowest drying among all.

2.2.2.2 Without liquid water Penetration

Some laboratory studies have been done on sole vapour wetting impacts on walls. In one study, the drying capacity of wall panels based on their type of the exterior sheathing board was experimented in a controlled laboratory environment (Mao, Fazio, & Rao, 2009). Six wall panels with different types of sheathing boards (OSB, Fiberboard and Plywood) and two different scenarios of vapour retarder (Polyethylene or None), were put into test. Temperature, RH and MC of various locations across the wall assemblies were monitored. The findings suggested that the gravimetric samples closer to the bottom had higher levels of moisture content in general and decreases when moving higher up from the bottom of the walls. This study concludes a drainage possibility at the bottom of stud cavity could be a good strategy to evacuate any incidental water leakage in wall assemblies. Also, it was suggested a more vapour permeable vapour retarder or smart vapour retarders can help with drying capability of walls as a general measure.

2.2.3 Computer Modelling Experiments

2.2.3.1 Without liquid water Penetration

In a computer modelling experiment (Hagentoft & Harderup, 1996), moisture conditions of a north facing wall located in a climate similar to North of Sweden were assessed. The modelled wall from outside was brick veneer, 25 air gaps, a 50mm Mineral Board, 200mm of cellulose insulation, 0.2 mm polyethylene film (or none), another 45mm air-space and 13mm of interior gypsum board. So cellulose insulation remained constant but different scenarios of with and without vapour retarder and air leakage were modelled. This experiment concluded that for the walls modelled in cold climates similar to North of Sweden an interior vapour retarder is necessary since when it was eliminated the moisture levels went over acceptable values. This study also highlights the role of interior moisture supply and air leakage as determining factors in moisture response of walls.

2.2.4 Computer Modelling and Field/Laboratory Experiments

Computer modelling is often combined with a field and/or laboratory study so that its results can be refined. A good example of this is a study (Maref, Booth, Lacasse, & Nichollos, 2002) that was a comprehensive project comprising of computer modelling, hygRIC. The laboratory could accommodate multiple and different types of full-scale and mid-scale wood-frame wall specimens to determine the hygrothermal responses of test specimens under steady and transient state conditions. The laboratory was also equipped with a full-scale weighing system that could determine minor changes in walls weight in precision of grams which would account for variation in wetting or drying as the only entering or exiting mass within the test wall panels. This study had several objectives such as "developing test protocols for calibrating various types of moisture sensors, setting-up of data acquisition protocols, determining wetting protocols for wood components, assessing the significance and limitations of gravimetric analysis". Once a hygrothermal modelling tool goes through a few iterations of validation and fine-tuning like the project study above, it can be used with higher reliability.

2.2.4.1 With liquid water Penetration

In 2003, the U.S. Department of Energy in pursuit of science backed changes in Building Codes. Oak Ridge National Laboratory (ORNL) in collaboration with Building Science Corporation worked on developing a plan to perform a series of hygrothermal computer simulations to assess the role of vapour retarders for different climatic zones (Karagiozis, Lstiburek, & Desjarlais, 2007).

Two different wall systems of brick veneer and vinyl siding were selected since they represent wall cladding hygrothermal performance extremes.

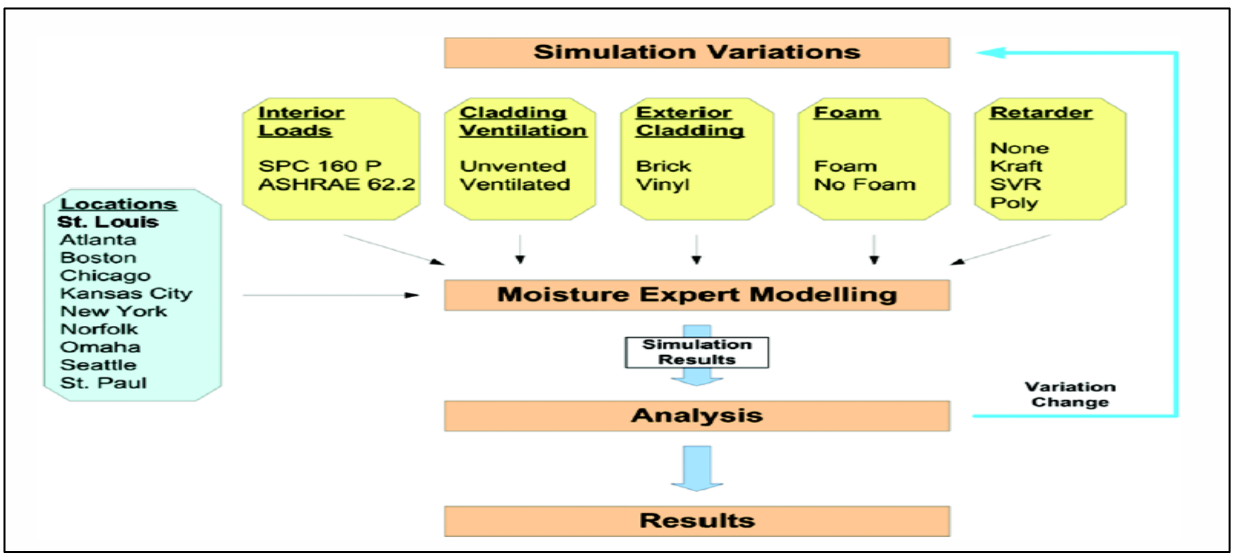


Figure 13- Summary of Parametric Analysis (Karagiozis, Lstiburek, & Desjarlais, 2007)

While brick system represents a sorptive "reservoir" cladding that can absorb and store high amounts of rainwater, vinyl siding system allows almost no liquid water absorption and is very air permeable. The objective was to come up with some guidelines for the type and configuration of vapour retarders in various climatic zones within the U.S. In the model one percent of the

WDR reaching the cladding was loaded behind the sheathing membrane as well as the impact of air conditioning (Figure 13).

The final report, divided the entire U.S. map into several climatic zones based on their annual temperature and wetting indices and north western part of Washington state with Marine climate, was placed in zone 4C. The climate of this region of the U.S. is like the Lower Mainland, British Columbia, so the recommendations for this zone could be considered for Vancouver as well. For this climatic category, the final findings suggested the common vented vinyl cladding could work with a variety of vapour retarder strategies over any type of sheathing board including OSB, plywood, fiberboard and even gypsum had satisfactory moisture performance.

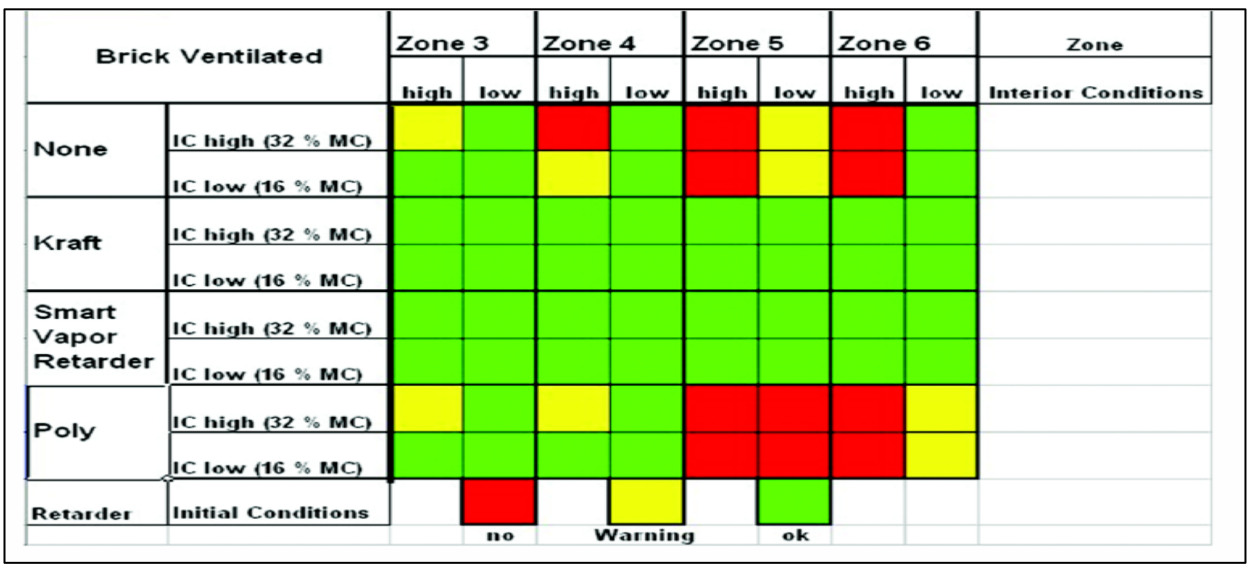


Figure 14- Results for Ventilated Brick Cladding Systems (Karagiozis, Lstiburek, & Desjarlais, 2007)

The suggested interior vapour retarder included 4-mil polyethylene, asphalt coated paper, smart vapour retarder and a paint coating of 8 perms (Figure 15). On the other hand, brick veneer was not a proper option with interior polyethylene but good for all other vapour retarder strategies. One limitation of this research was excluding air infiltration and exfiltration (Figure 14).

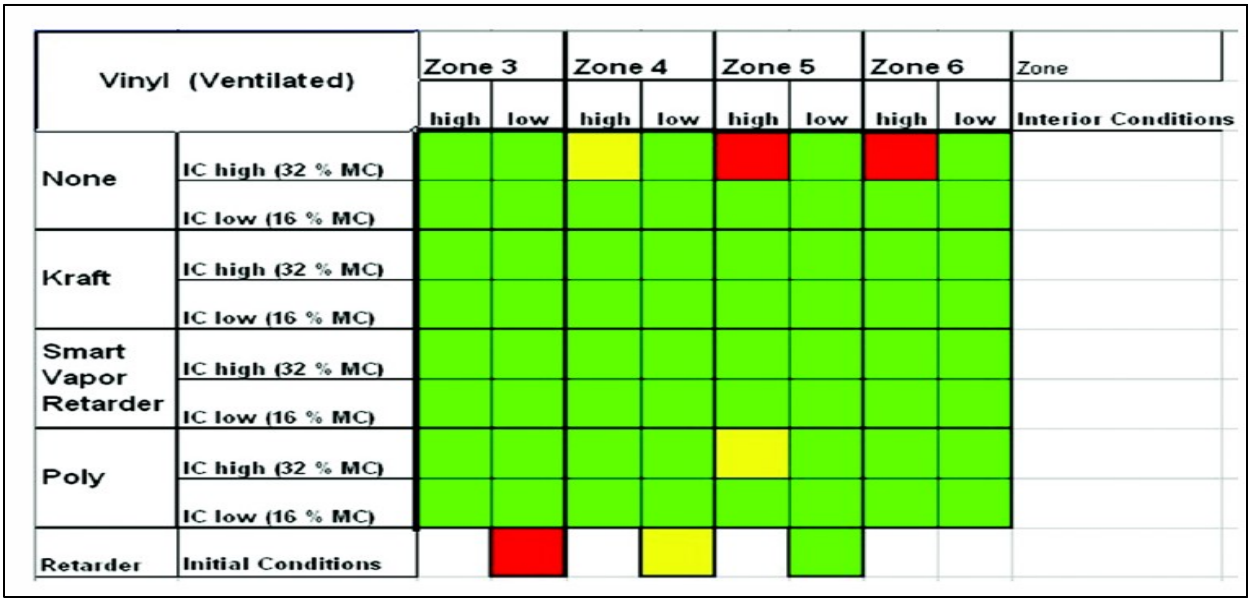


Figure 15- Results for non- absorptive vinyl cladding systems (Karagiozis, Lstiburek, & Desjarlais, 2007)

In another field experimental study (Finch & Straube, 2007) role of ventilated rain-screen in drying capacity of walls was investigated. The wall assemblies that field data was collected were from four buildings in total, three of them located in Lower Mainland, BC and one in Waterloo, ON. The walls had different claddings, ventilation air space gaps and insulation types. The collected field data was compared to hygrothermal modelling tool, WUFI 4.0, 1D. Moreover, water leakage behind WRB and also in insulation cavity was modelled. The results suggested higher ventilation rates helps with faster drying rates of wood sheathings. The impact of water leakage led to elevated moisture content even in ventilated rainscreen wall assemblies. It was also found out that if rainwater leaks into the stud cavity its impact on wetting is going to be higher.

2.2.4.2 Without liquid water Penetration

Several other field or laboratory hygrothermal studies complemented with computer modelling without liquid water intrusion have been conducted to investigated wetting and drying trends. In one study (Straube J. , 2009) the effect of vapour retarders in moisture behaviour of several wall assemblies installed in the basement of a building located in cold climate was investigated. The actual measured boundary conditions were input in the one-dimensional hygrothermal model, WUFI. The field measurements showed in summertime inward vapour drive is noticeable in the above-grade portions of the walls, while an interior vapour control layer reduces the interior vapour diffusion penetrating into walls, however, for either case of with or without polyethylene vapour layer, wood moisture content stayed below critical levels.

In another study (Arena, Owens, & Mantha, 2013), performance of dense-packed cellulose insulation in double-stud wall assemblies, with overall R-40 was both measured and then compared to WUFI 5.2 hygrothermal modelling tool in a variety of climatic zones, 4A, 5A, 6A, and 7. The field experiment was a test facility located in climate zone 5A and two test bays on the south and north façade accommodated the test walls. WUFI results suggested this wall assembly dries entirely in about one year and its moisture peak decreases for the following years. Overall, the wall assembly is predicted to perform safely for the south façade but for the north face the modelling prediction was marginal to fair.

In another study, role of spray polyurethane foam on above grade wall systems was investigated in a combination of full-scale natural exposure field tests, climate chamber measurements, and hygrothermal computer modeling (Straube, Smith, & Finch, 2009). The objective of the study was to determine if sprayfoam can obviate the need for an extra layer of interior vapour retarder or not. Walls of 2x6 wooden frames with around R-20 overall thermal resistance with different types of insulations and vapour control strategies were modelled for seven different climatic zones. The climates were from Heating Degree Days (HDD's) of 3,000 to 10,000 and also for different level of indoor relative humidity levels, from low, medium and high. Some walls had two inches of HD SPF applied to the interior side of the exterior OSB sheathing board with and addition of fiberglass batt insulation, some others were filled totally with LD SPF applied on the interior surface of OSB filling the entire insulation cavity. The modelled results indicated that for a 2x6 wall filled with LD SPF there is no need for an extra layer of vapour barrier, however for colder climates such as Calgary or Winnipeg, this thickness of LD SPF may not be sufficient and safe replacement for a vapour retarder layer depending on the interior RH levels. On the other hand, the 2” of HD SPF applied on interior surface of OSB was found sufficient and safe to be replaced with the conventional polyethylene for all climates, as extreme as Yellowknife in the north of Canada.

2.3 Hygrothermal Performance Indicators

As discussed earlier to evaluate and compare the moisture responses of high-performance walls in various climatic zones a moisture yardstick is required, nevertheless there is no consensus on one single yardstick in building science study field as various researchers have developed or adopted different moisture indicators. The essence of any moisture indicator should be incorporation of both time and wetness in regions of focus of a test specimen. As discussed earlier, a super insulated wall system, the high level of thermal insulation can cause the exterior sheathing staying cold in heating season and vulnerable to condensation. So, the exterior sheathing board is a potential risky area and can be considered as the region of focus and a moisture indicator should focus on the recorded moisture levels on the exterior sheathing board. There are a few different moisture indicator yardsticks in building science field, such as RHT (Relative Humidity and Temperature), Drying Capacity, DEI (Drying by Evaporation Index), ICEA (In Cavity Evaporation Allowance), Wetting and Drying Trend, and MI (Mold Index). A brief about each is presented below.

2.3.1 Relative Humidity and Temperature Index (RHT Index)

In a study by NRCan (National Resources Canada) a novel moisture indicator termed as RHT was introduced (Mukhopadhyaya et al., 2003). The study was part of the MEWS (Moisture Management for Exterior Wall Systems) project, a research consortium project comprising of various partners such as EIFS (Exterior Insulation and Finish Systems) industry and Canadian Wood Council to develop guidelines for moisture management strategies for low-rise wood – frame exterior wall systems in North America. The moisture responses of four different wall assemblies were investigated in various North American cities with different climatic conditions. The approach was utilization of RHT (Relative Humidity & Temperature) moisture indicator along with a modeling tool, hygIRC, developed by NRCan/IRC to assess and compare how different walls perform in different climatic zones in respect to moisture. The modeling tool benefits from RHT index to get refined in an iterative and cyclic loop and vice versa. The accumulative results of moisture and temperature over a total of three years was incorporated. The amount of this water, that was aimed to simulate the intrusion of water through a typical defect in window-to-wall interface, was determined from either full-scale or small-scale MEWS lab tests, or from statistical weather data. The wetness index for climate is termed as MI (Moisture Index) that is independent of construction of wall assemblies and considers wetting and drying indices (WI and DI). WI is based on annual rain fall and DI on annual potential evaporation (Cornick, et al., 2002). The results indicated that long-term moisture response of the wall assemblies have a good correlation between the RHT indicator and climatic conditions represented by moisture index (MI); the wetter locations with higher MI experienced higher levels of RHT indicator.

2.3.2 Drying by Evaporation Index (DEI)

An alternative moisture indicator called DEI (Drying by Evaporation Index) was developed and introduced in a field experimental study (Fazio; Rao; Alturkistani; Ge, 2006). Wall configuration and climatic variation, mainly temperature, relative humidity, pressure gradient across wall, and initial moisture content of wall components are the determining factors to work out DEI number. Moreover, air leakage induced by defects in construction, material properties and all other hygrothermal pre-existing conditions affect DEI rates. DEI number is built upon the rate of movement of the moisture out of stud cavity; a higher number implies greater capacity to evacuate the moisture in the stud cavity translating into a better drying capacity. In this experiment walls were introduced to simulated intruding water source through water trays at the bottom of the stud cavity. Moisture levels was monitored and recorded by gravimetric samples and moisture content pins and temperature of the regions of interest were recorded by thermocouples. The trays were fed by water tubes and water level (volume) was controlled by sensors and kept constant while water evaporating from the surface. The total amount of water evaporated from the trays equals the amount of water added to the tray. This added water can be worked out by adding the amount of the moisture absorbed by wall assembly components surrounding the stud cavity to the amount of water that is evacuated from the assembly. Once wall assembly components reach steady-state MC condition, the amount of water added to the tray equals the amount of water evaporating from the system, otherwise called the DEI index. DEI is measured and expressed in gram of water moisture evacuated out of the wall assembly and can be calculated by subtracting the total added moisture content of all the wall assembly components from the water added to the tray. From the test recorded data, it was learned that vapour pressure rises when approaching to the bottom of the stud cavity (from top). This suggested more concentration number of moisture sensors closer to the bottom plate for future similar tests. Another finding from that experiment was more water vapour permeability of the exterior sheathing can enhance drying (more DEI index). Surprisingly, in stucco applied directly on fiberboard sheathing this was opposite.

2.3.3 In Cavity Evaporation Allowance (ICEA)

In continuation of the previously discussed DEI study, in another study (Mao, Fazio, & Rao, 2009) a more inclusive indicator, In Cavity Evaporation Allowance (ICEA) was introduced. Through plotting MC levels against time and combining the resulting graph with the evaporation rate against time graph, MC of wall assembly is achieved versus evaporation rate (Figure 16). This experiment concluded ICEA moisture indicator has a good correspondence with the wet stains on various parts of the wall assembly mainly close to the bottom of the stud cavity. Moreover, walls cladded with stucco showed lower ICEA translating into lower drying capability. It was also learned that vapour barrier behind the interior gypsum board sheathing while restricts interior induced wetting of the stud cavity, could also limit wall drying process once their moisture levels rose.

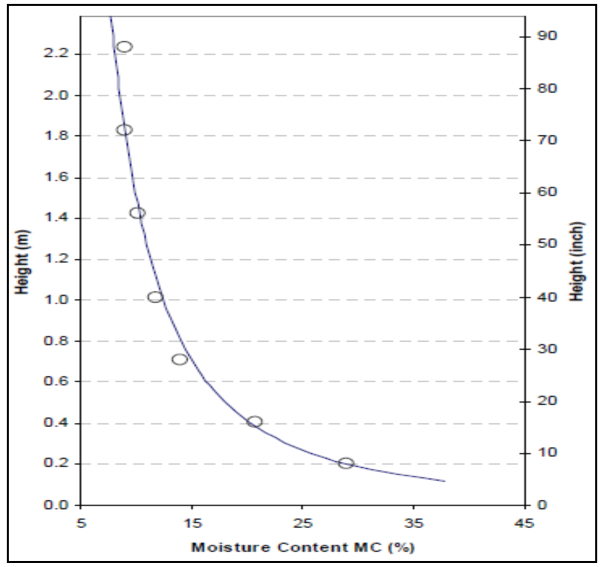


Figure 16- Moisture Content Vs. Sensors Height (Alturkistani, Fazio, & Rao, 2008)

2.3.4 Mold Index (MI)

Mould or mildew is a fungal growth that can lead to production of toxins with adverse human health and building durability consequences. To avoid mold consequences the best approach is preventing it from being born (germination) and to do so the first step is learning more about its viability. A comprehensive laboratory study was done on mold behaviour (Hukka & Viitanen, 1999), essentially a mathematical model that simulates mould fungi growth on wooden material, based on a regression models for mould on pine and spruce wood species.

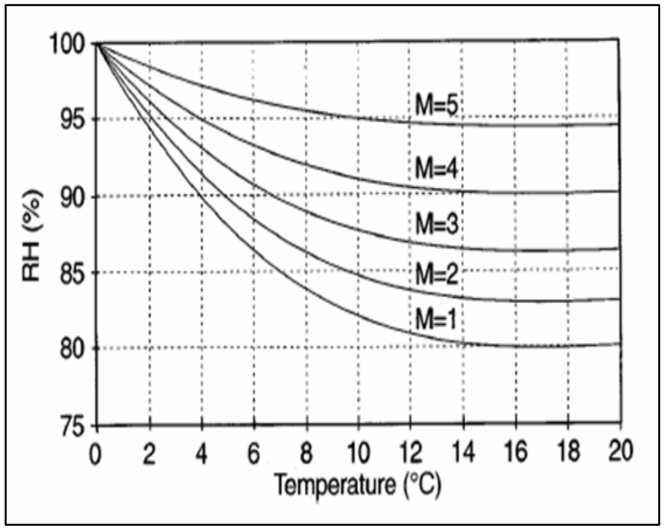


Figure 17- Mold Index Variation with RH and Temperature (Hukka & Viitanen, 1999)

The main advantage of this model is assessing directly the main wood-moisture related issue, mould growth. This model consists of a differential equation that describes mold growth rate in different conditions, mainly exposure time, temperature and relative humidity. In this equation mold has a maximum level that varies based on temperature and RH rates. The calculation of mold index is based on prior studies' observations of mould growth on surface of multitude wood samples exposed to arbitrary fluctuating temperature and relative humidity scenarios.

Table 6- Description of Mold Growth Rates (Hukka & Viitanen, 1999)

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

The calculation of mold index is based on prior studies' observations of mould growth on surface of multitude wood samples exposed to arbitrary fluctuating temperature and relative humidity scenarios. This methodology was further developed a few years after in another study (Ojanen, et al., 2010) by expanding from just wood to several other materials. Moreover, the new model could work with other HAM (heat, air and moisture) models or even used as a post-processing tool. Also, this model had improved in accuracy by including effects of seasonal long dry or cold periods that not only do not allow growth but also can kill mold or having mold index declined. In this new model, materials are presented into different sensitivity classes from resistant to very sensitive. It has to be noted that this model does not guarantee exact prediction of mold in different cases and conditions, but it is just an estimation tool as there are many uncertainties in nature of this methodology such as actual temperature, relative humidity and especially material type in materials layers.

Table 7- Mold Sensitivity Classes (Hukka & Viitanen, 1999)

Mold Sensitivity Class	Materials
Very Sensitive	Untreated wood; includes lots of nutrients for biological growth
Sensitive	Planed wood, paper-coated products, wood-based boards
Medium Resistant	Cement or plastic based materials, mineral fibers
Resistant	Glass and metal products, materials with efficient protective compound treatments

2.3.5 Wetting & Drying

Observation of wetting and drying trends over periods of time is probably the most common way of assessing moisture behaviour of wood-framed wall assemblies in building science research. Although it is not as detailed as some other methods such as mold index, but it is less subjective. Wetting and drying assessment is assessment of recorded MC or RH levels over at least one year and ideally three years. Some key metrics are MC maximums, duration above critical levels and the duration and distance of those critical periods. Many studies have been conducted using this method.

In a study (Teasdale-St-Hilaire, Derome, & Fazio, 2004), that was discussed earlier in more details, the "*rate of drying*" of nine wall specimens were compared based on relative humidity levels in stud cavity and moisture contents of sheathing boards

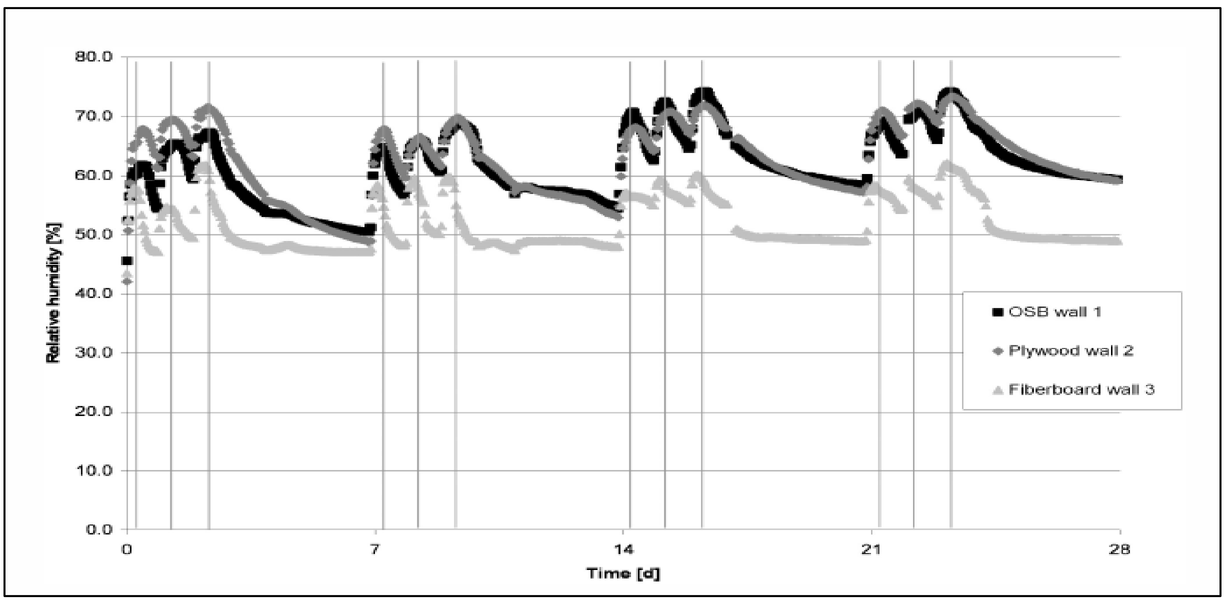


Figure 18- Relative Humidity in the stud cavity (Teasdale-St-Hilaire, Derome, & Fazio, 2004)

Although MC response of wood depends on a wide variety of factors such as moisture sensitivity of substrate surface material, solar radiation, existence of food (dust, etc.), but in building science field there are some generally accepted threshold levels for relative humidity and moisture content. For example, relative humidity of below 80% and moisture content of lower than 19% is generally considered safe zones but depending on some other factors 28% MC levels may also be considered safe. In this experiment, RH stayed well below 80% for the entire test period (Figure 18), so this can be counted as safe moisture behaviour for the test period.

However, except for the wall with fiberboard, all other walls reached or passed the risky MC levels of 24% and above (Figure 19).

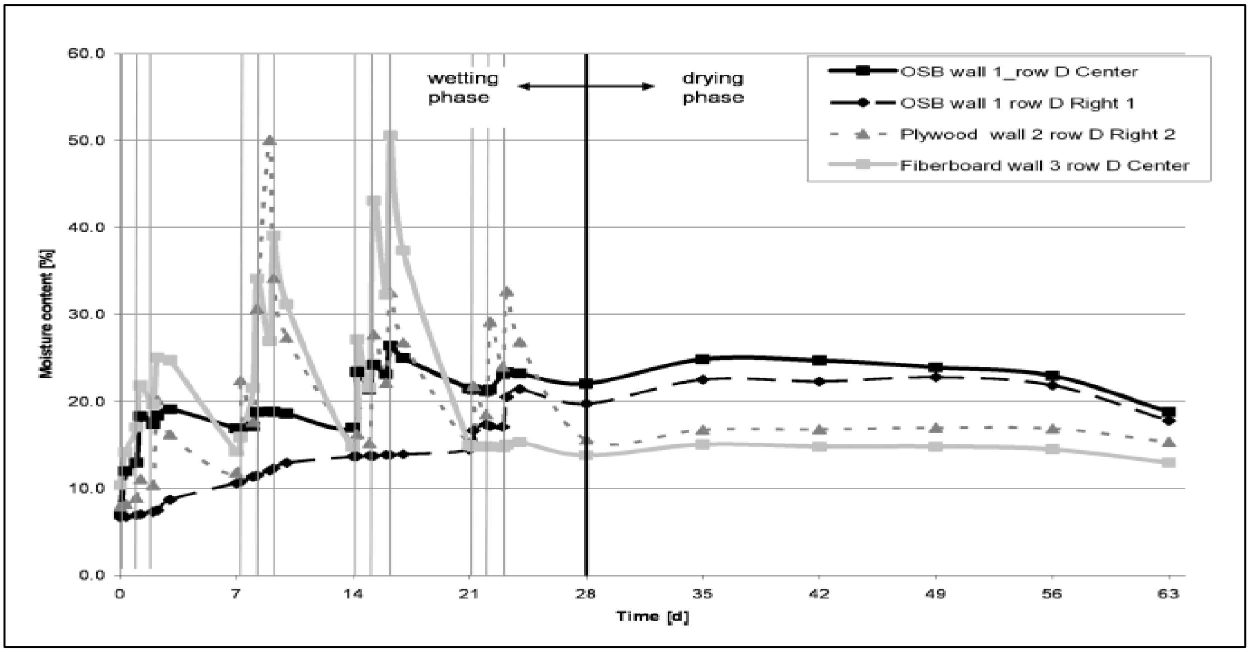


Figure 19- MC of OSB vs. Plywood vs. Fiberboard (Teasdale-St-Hilaire, Derome, & Fazio, 2004)

Wetting and drying of exterior sheathing board of two enclosure walls was analyzed in another field experimental study (Tariku & Ge, Moisture Response of Sheathing Board in Conventional and Rain-Screen Wall Systems with Shiplap Cladding, 2010). The boundary conditions were outdoor coastal climate of Lower Mainland, BC, and the indoor temperature and humidity levels were controlled by mechanical system. The walls were conventional construction of 2x6 wood framing filled with glassfibre batt insulation and polyethylene was incorporate as their vapour barriers. The objective was to assess and compare the effects of vented or ventilation on drying rates of walls.

Based on the wetting and drying graphs (Figure 20), it was verified that there is generally noticeable moisture accumulation on the exterior of sheathing board in winter time compared to summer time. Moreover, during the nine months of monitoring period, from March to December 2009, the plywood sheathing went under a period of wetting and drying,

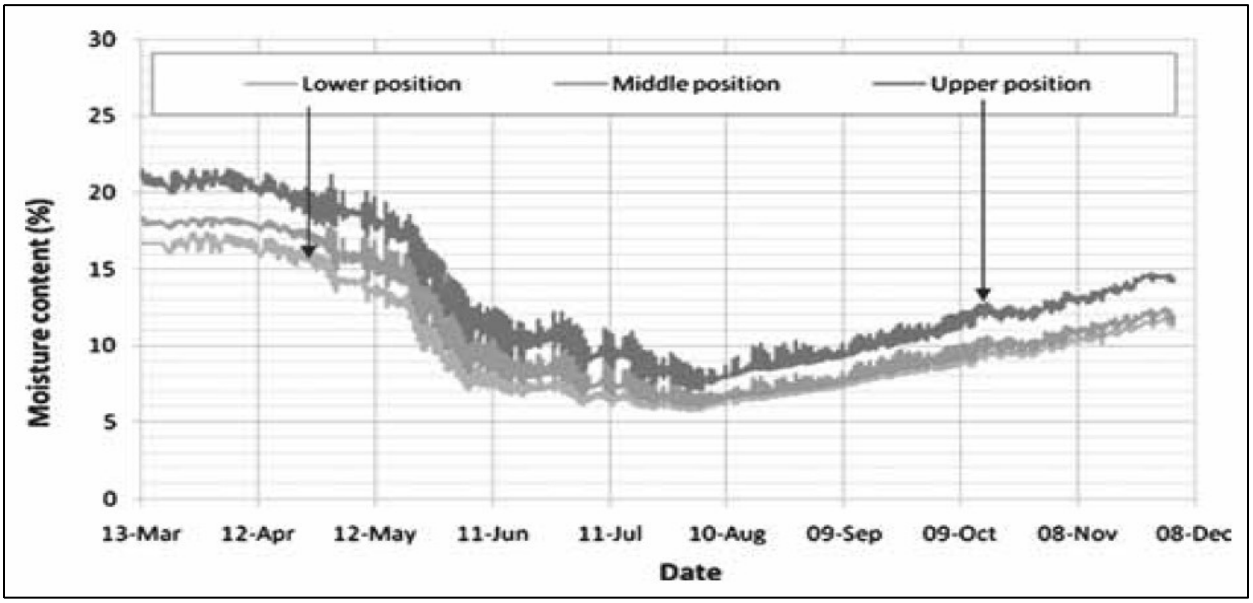


Figure 20- MC in Lower, Middle and Upper Sections ((Tariku & Ge, 2010)

In another experimental study in the same test facility (Tariku & Sympson, 2013), impact of airflow through rainscreen cavity on hygrothermal performance of wall systems was investigated. Three similar 2x6 wall panels (with glassfibre batt insulation and polyethylene as their interior vapour barrier), but with no air gap, vented and ventilated were exposed to outdoor climate and controlled indoor air conditions, with no liquid water injection. The recorded moisture content amounts were plotted and compared for the lower, middle and upper section of the walls (Figure 21).

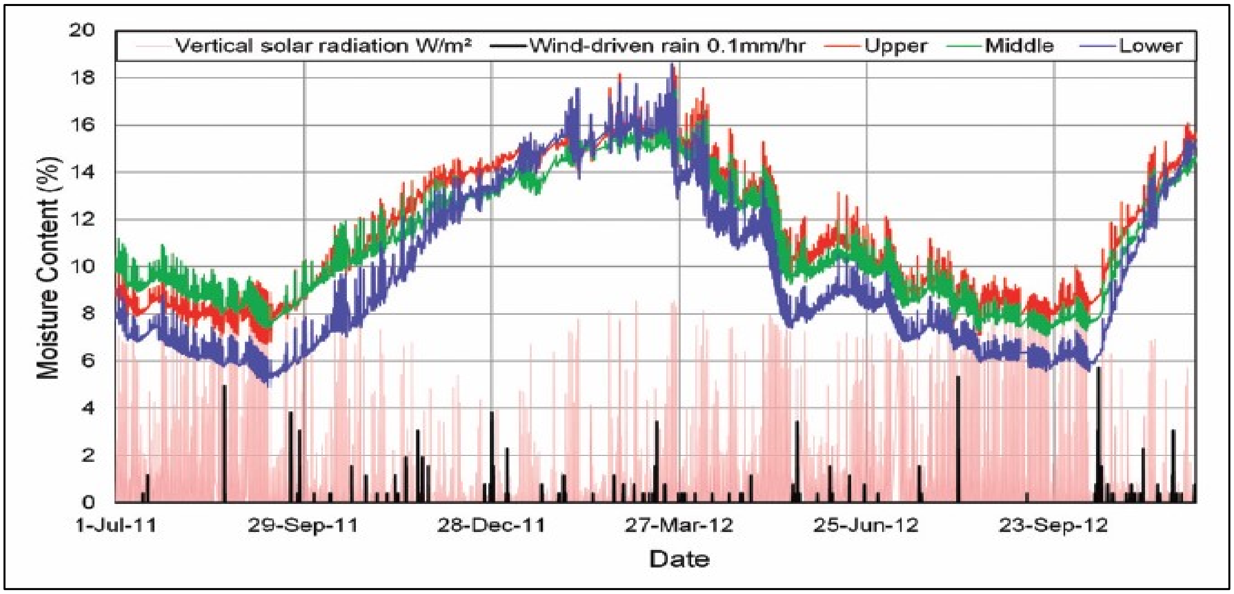


Figure 21- Hourly Avg. MC in Plywood Sheathing- No-Air-Gap Wall ((Tariku & Sympson, 2013)

The results compare the wetting and drying patterns (duration, lows and highs). As an example, both vented and ventilated wall systems had their MC under 14% for the entire monitoring period while unvented wall experienced up to 4.5% higher levels (Figure 22).

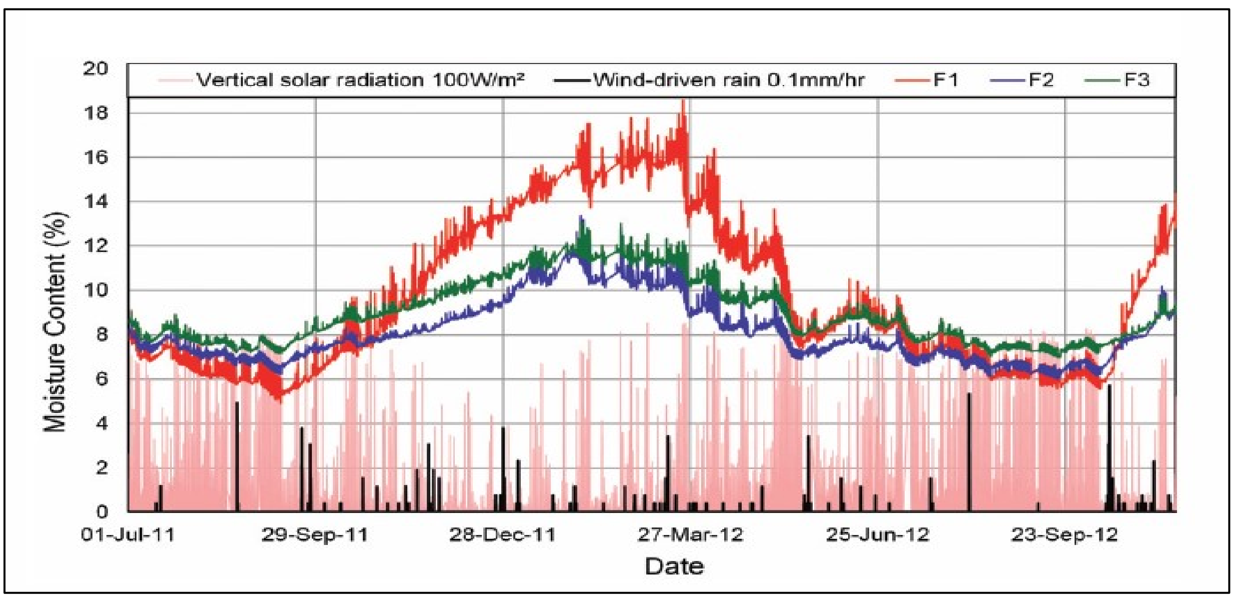


Figure 22- MC of Walls with No-Air-Gap, Vs. Vented, Vs. Ventilated ((Tariku & Simpson, 2015)

Another study (Tariku, Simpson, & Iffa, 2015), four full-scale wall panels similar in glassfibre insulation and plywood sheathing but different in vapour control and rainscreen choices were installed in different orientation of the same facility in Burnaby, BC. One orientation (SE) had significantly more exposure to sunlight but also wind-driven rain, while the other orientation had less sunlight but less wind-driven rain as well.

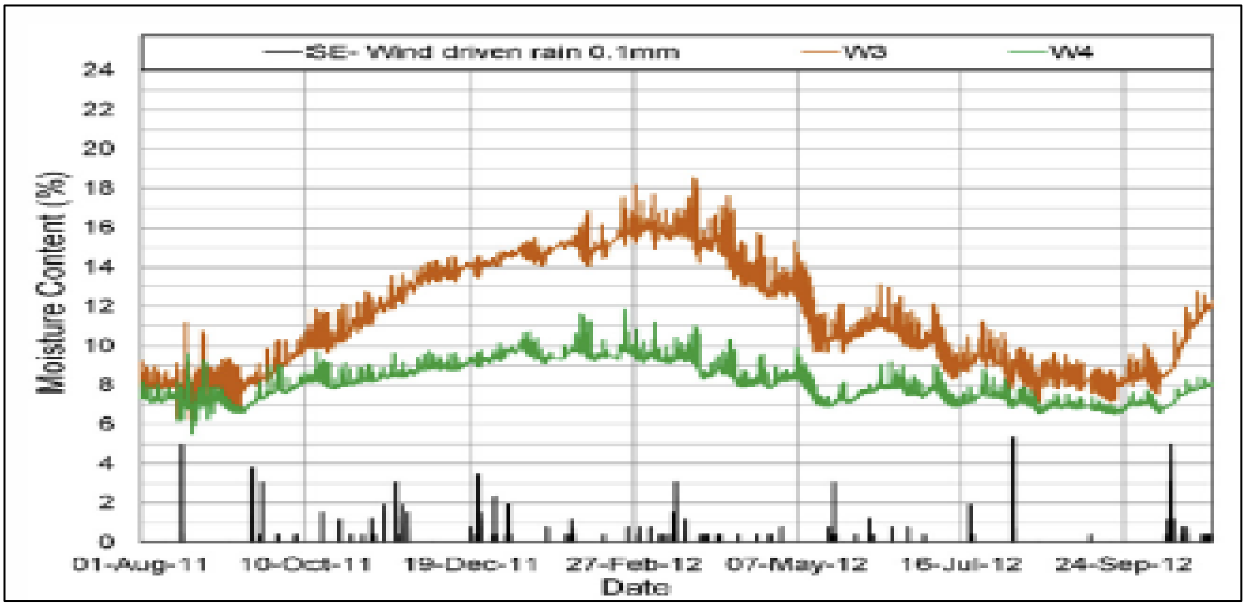


Figure 23- Comparison of two walls, same position (upper part of sheathing board) (Tariku, Simpson, & Iffa, 2015)

The wetting and drying potentials of the test panels under predominantly vapour diffusion and wind-driven rain was studied over a course of fifteen moths recorded data. Based on MC graphs (Figure 23), the results suggested that capillary break could decrease maximum MC levels up to 50%. As for vapour control strategies, the walls without vapour barrier had 38% better drying. This study concluded that even in mild climates vapour diffusion is a critical load.

3 PROBLEM STATEMENT

At this stage the building industry is still learning to address moisture related complexities, construction industry is on the verge of making another drastic shift towards more aggressive energy conservation targets. ASHRAE 90.1, the adopted energy standard by city of Vancouver, is constantly elevating its energy saving target that demands higher levels of enclosure thermal resistance and airtightness levels of building enclosure (Figure 24).

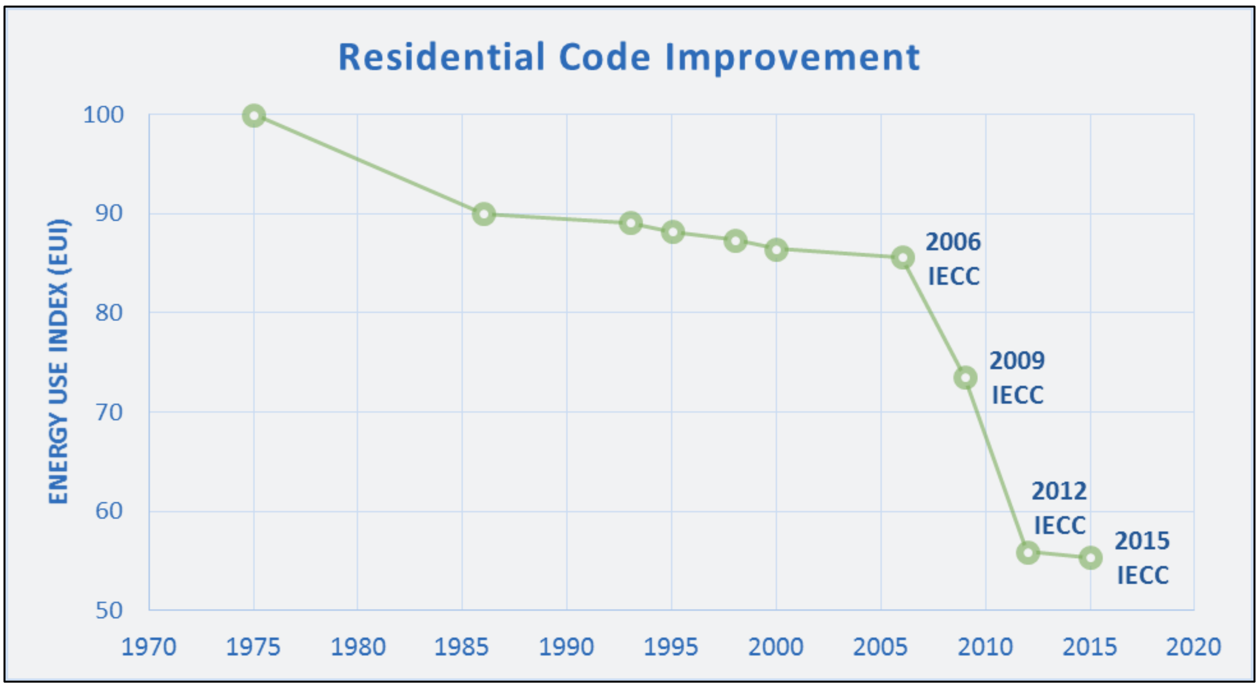


Figure 24- Residential Code Improvement in BC, Canada (The Building Codes Assistance Project, retrieved 2018)

As mentioned earlier, all the previously discussed moisture related issues with new construction system, if not addressed properly, will be more pronounced in a building that is built under stringent energy requirements. In the event of a wetting incident, vapour diffusion, or airborne vapour leakage into a super insulated wall assembly vapour may condense on the cold surfaces and making sensitive wall assembly components (e.g. exterior sheathing board, wood framing, and insulation) wet. In this situation, if the moisture cannot be evacuated from the wall system in a timely manner, it may incur severe consequences on building durability and occupants' health.

Figure 25- Mold on Plywood Sheathing ((Green Building Advisor, retrieved 2018)

As for Low Density Sprayfoam, if it is not vapour resistant enough, and if applied without a primary vapour barrier to block the interior vapour diffusion, it may lead to excessive vapour diffusing into walls and condense on the cold surfaces, exterior plywood and framing and lead to mold, fungi and corrosion problems.

Although several studies have been done on moisture performance of LD SPF and Wet Applied Cellulose Insulation, little has been done in actual field for super insulated walls, with insulation levels of up R-40 that is typical for high energy performance buildings that qualify for aggressive standards such as “Net Zero” and “Passive House”.

One of the main objectives of this study is investigating how a combination of Wet Applied Cellulose Insulation with different vapour control strategies responds hygrothermally over an extended period of raining and cold season.

The common practice in wood-frame buildings is preventing the interior vapour diffusion into walls by a vapour control layer, usually a thin polyethylene sheet, and letting the moisture within dry out to the exterior (Lstiburek, 2002). This strategy has proven effective with the typical single-stud walls filled with fiberglass batt insulation. However, for other types and levels of insulation like cellulose and high R-value walls, the efficacy of this method has not been proven in the field of wet and mild marine climatic zone of lower mainland, BC, Canada. One possible solution is vapour retarder polyethylene film being replaced with a more breathable vapour retarder layer such as Smart Vapour Retarders (SVR) that its vapour permeability increases with relative humidity levels. Another solution may be eliminating the interior vapour control layer altogether and relying on vapour storage and buffering capacity of insulation materials such as cellulose with the theory of facilitating walls drying to both interior and exterior. Nevertheless, this situation can in turn expose the assembly to higher level of interior vapour diffusion in heating season that vapour diffusion drive is outward.

A major concern for the case of “super insulated” wall assemblies, with insulation levels of higher than R-30 which further lowers the amount of leaving the building enclosure, is walls drying capability may not be sufficient and timely if they get wet with the various wetting mechanisms mentioned earlier. Super-insulated walls inhibit the interior heat that could expel the moisture within walls.

Figure 26- Super Insulated Wall Assemblies (Golden Eagle Homes, retrieved 2018)

4 RESEARCH APPROACH

4.1 Research Objectives

This research project aims to investigate drying capability of highly insulated double-stud walls with DCI and OC FPFI under different vapour control and liquid water penetration scenarios. Also, the effectiveness of DCI in eliminating the need for an extra interior vapour retarder is studied.

4.2 Research Scope

This study investigated the wetting/drying patterns and likelihood of mold growth of wood-frame walls installed in the SE orientation of the perimeter of a test facility located in a test facility located in Burnaby, BC. The test facility is in a Marine Climate and test period was from 1 Sep 2016 to 31 May 2017. SE orientation of this test facility is associated with more wind-driven rain amounts and higher solar radiation rates. The Interior and exterior Boundary Conditions were typical average residential and actual exterior outdoor weather conditions respectively. This research study did not include air infiltration/exfiltration within the test walls.

4.3 Research Hypotheses

Based on the literature review conducted, the following hypotheses are made:

- More moisture gain in vicinity of water injection source on plywood sheathing is expected
- More wetting on exterior studs and plates is expected compared to the interior studs and plates
- More wetting is expected during the colder and more wet months of the test period (Nov-Mar) compared to the shoulder season periods of Sep, Oct, Apr, and May

4.4 Research Methodology

To achieve the experimental objective, a field experiment was chosen to see the actual hygrothermal performance of test specimens in the local climate. Five wall assemblies with R-40 (effective) double-stud type filled with two different insulation types and incorporated three different vapour control strategies are considered for the study. The test panels are exposed to similar outdoor climate and indoor climate and their relative performance in response to identical boundary conditions are assessed.

Wall Construction Type		***Stud Cavity***			Gap (mm)	***Vapor Control***	***Water Leakage***
	Wall#	Insul. Type	R-Value per Inch	Stud to Stud (mm)			
A	1	DCI	3.8	281	**128**	***Poly***	***None***
	2					***None***	***Yes***
	3					***Poly***	***Yes***
	4					***SVR***	***Yes***
B	5	LD SPF	3.2	333	**181**	***Poly***	***Yes***

Insulation types and vapour control strategies were the variables of this experiment. As for insulation types, wall#1-4 incorporated Wet Applied Cellulose Insulation whereas wall#5 had Open Cell Polyurethane Spray Foam filled its stud cavity. As for vapour control strategies, while walls number one and three incorporated 4-mil polyethylene and wall number four had Smart Vapour Retarder as its interior vapour retarder, wall number two did not include an extra interior vapour control layer. Moisture loads was limited to indoor and outdoor vapour diffusion plus a specific amount of simulated rainwater penetration behind the WRB (Weather Resistive Barrier) of walls. Also except for wall number one, all other walls were introduced to the same amount and location of simulated rainwater penetration between the WRB and exterior surface of plywood sheathing board.

Wetting and Drying trends were recorded and graphed and moisture content of sensitive area of wall assemblies mainly plywood sheathing and exterior wood frame was studied. To do so, maximum moisture content levels, wetting and drying durations and also the duration and frequency of the numbers above threshold levels were investigated. Other than moisture content, the likelihood of mold development was calculated from moisture content recorded data, material properties and temperature data) and subsequently the graphed mold indices were studied individually and comparatively.

In this study walls were similar in total effective R-value (R-40), similar in exterior cladding of hardy-board fiber cement cladding, 18mm of ventilated rainscreen, experimental variables in this study Vapour Retarders, WRB (Tyvek) and interior sheathing board (13mm gypsum board panels). Moreover, the interior and exterior weather conditions were similar for all walls.

5 EXPERIMENTAL SETUP

Five wall panel specimens were built, instrumented and installed in a test facility located in Burnaby near Vancouver, BC. The wall panels were double-stud wood framed which had a gap in middle to increase the thermal insulation level while eliminating the effect of thermal bridging. All wall panels were instrumented with temperature and various types of moisture sensors (Relative Humidity, Moisture Content, and Moisture Detection Sensors) located in regions of interest with more moisture related anticipated problems, mainly the exterior plywood sheathing and wood framing. Subsequently the stud cavity of the walls was filled with Wet Applied Cellulose Insulation and Low-Density Spray Polyurethane Foam (LD SPF). After letting the cellulose insulation walls dry out for about one month, walls incorporated three different interior vapour control strategies, 4-mil polyethylene, Smart Vapour Retarder (SVR), or No Vapour Retarder. Subsequently they were exposed to an HVAC controlled indoor air and actual outdoor weather conditions. The walls sensors' results and boundary conditions data were transferred and recorded to a Data Acquisition System (DAQ), in 5-minute and one-minute intervals respectively and later used to analyze the results. More detail is presented in the following sections.

5.1 Overview of the Test Facility

Five double-stud wall assemblies were constructed, instrumented and erected in the South-East (SE) orientation of the Building Envelope Test Facility (BETF) at British Columbia Institute of technology, BCIT, Burnaby campus. The test facility is in an open turfed area surrounded by a low-rise developed facility in the south, forested area in around 50m distance in the west and an open parking lot and forested area at the east and north sides, overall exposed to wind driven rain on its all facades. BETF can accommodate up to 5m of height, so there is enough space for installation of two full-scale (1.2m (width) x 2.4m (height)) wall panels. The interior condition of the test facility was controlled by HVAC system throughout the test period. The exterior enclosure of the test facility building is exposed to the actual outdoor weather conditions throughout the test periods which is recorded by a weather station on the roof and facades recording solar radiation, wind speed and direction, horizontal precipitation and wind driven rain, temperature and relative humidity on one-minute intervals and all the data is sent to the DAQ system for further analysis.

In this study, specific amounts of water were injected to the interior side of exterior plywood sheathing, simulating accidental WDR water intrusion from a typical window and wall interface. As for framing and stud cavity space, the regions of interest were instrumented with moisture content (MC), Relative Humidity (RH), Thermistors (Ts), Moisture Detection Tapes (Md), and Heat flow sensors. The recorded data were transferred to a Data Acquisition (DAQ) system and the results were used to analyse and compare drying and wetting trends of walls in the regions of interest.

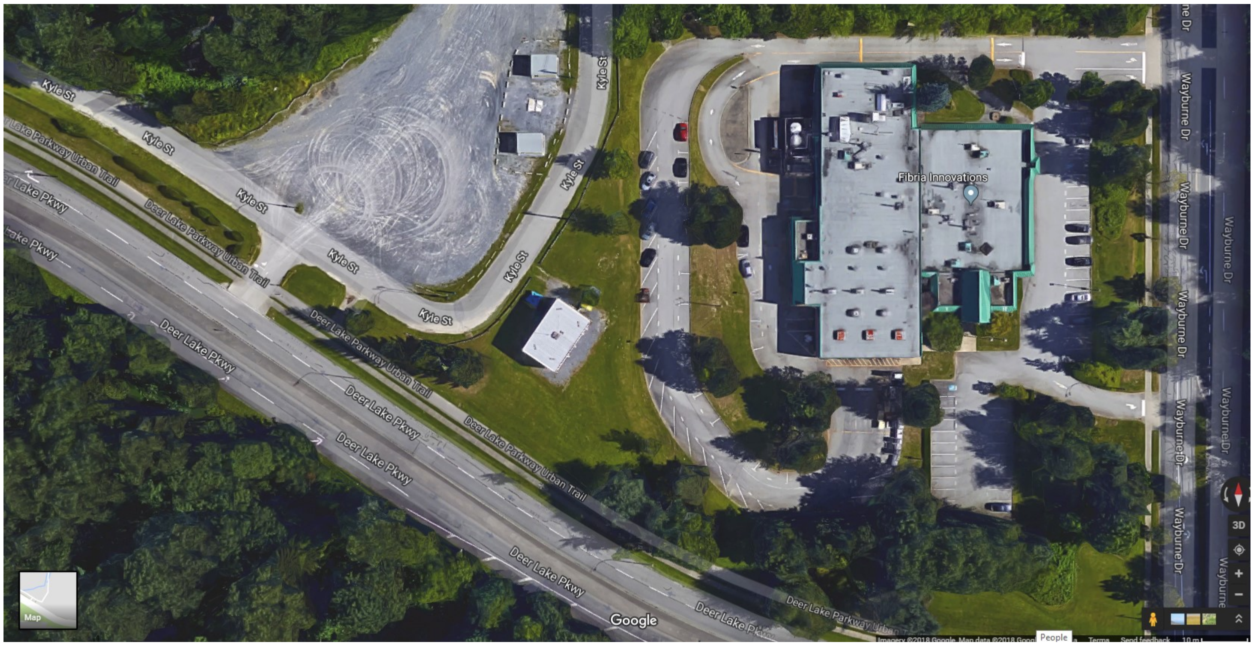


Figure 27- Overview of the Test Facility (Google Map)

Figure 28- Building Envelope Test Facility (BETF) in BCIT (by author)

5.2 Experimental Design

Experimental designed was targeting to measure, record and analyze the metrics which are representation of hygrothermal response of test walls. Those metrics were mainly *Moisture Content (MC)*, *Temperature* and *Relative Humidity (RH)* which are widely accepted, researched and used in hygrothermal studies. Moisture Content (MC) is the ratio of total weight of present moisture in a solid material divided by total weight of solid dry material. This metric is the most common moisture index for assessing the amount of moisture in wood material in both academic and industrial languages. Moisture Content sensors in this experiment were electric resistive pins that estimate the amount of moisture content based on measured electric resistance between the tips of electric probes. Electric resistance gives out the MC estimated numbers by the correlation curves that are created from laboratory tests (correlation between MC and electric resistance for each type of wood material).

The number of MC sensors in each location of test walls (or MC sensor concentration) was decided based on how much moisture sensitive and moisture exposed different locations of wall components were expected to be. Wood components are moisture sensitive in nature and for that reason MC sensors were designed and allocated for plywood sheathing as well as the vertical studs and plates. The result was a matrix of MC sensors on plywood and framing which will be discussed in more detail in upcoming sections.

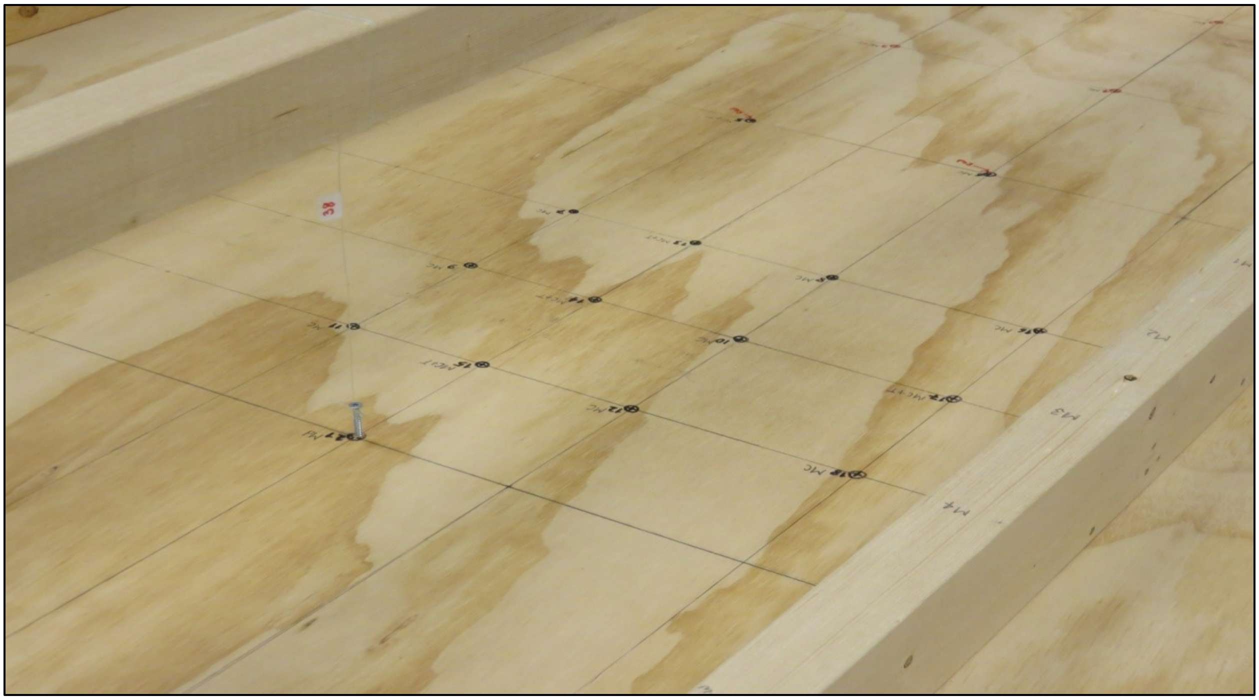


Figure 29- Plywood Sensors Layout (photo by author)

RH is the ratio of vapour by pressure to the vapour pressure of vapour saturation point at a given temperature). RH sensors were used to measure and represent the amount of humidity in the ambient environments of interest (air and porous insulation materials).

As for Temperature sensor or Thermistor (Ts), not only it is essential to come with MC and RH sensor for correction and vapour pressure calculations, but also it is an essential metric to investigate for understanding hygrothermal behaviour of test walls.

Forty five sensors in total were connected to a Data Acquisition System (DAQ) with data recorded in one-minute intervals. The principle behind a DAQ system is translation of electric voltage/resistance into metrics of interest through computer programs specifically calibrated for each specific sensor. More detail about DAQ system is presented in the appendix section 9.3.1.

5.3 Test Wall Panels

Five wall panels with different insulation and vapour control strategies, but similar in all other wall components were constructed, instrumented and installed in the perimeter of the Building Envelope Test Facility (BETF). Three of the walls had their insulation cavity filled with 280mm depth of Dense Cellulose Insulation (DCI, or Wet Applied Cellulose) and another wall used Low Density (or Open Cell) Sprayed Polyurethane Foam (LD SPFI) Insulation to fill in the same cavity insulation depth as the Wet Applied Cellulose walls approximating to R-40 (40 °F-ft^2-h/Btu) for all walls.

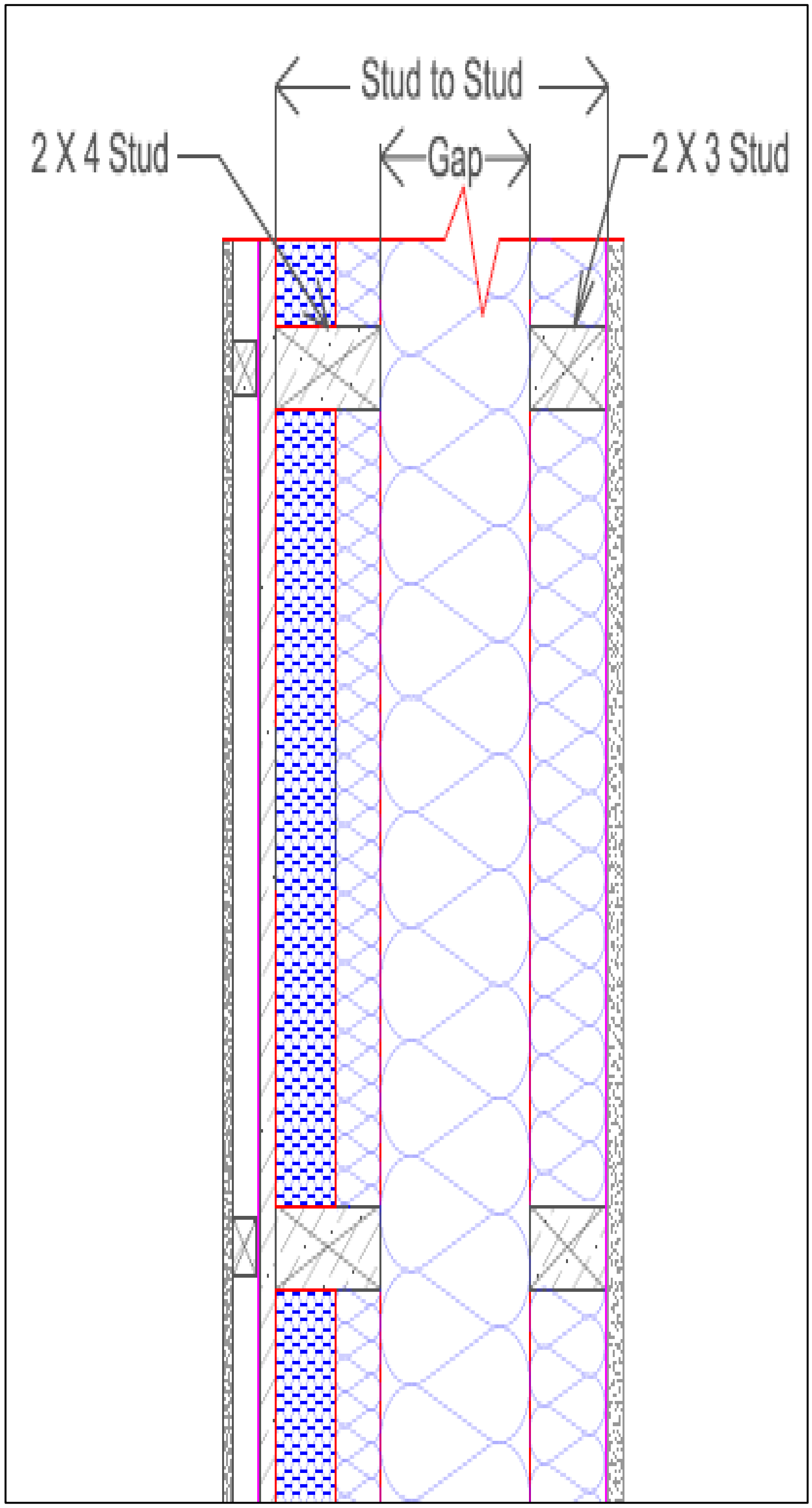
The R-value per thickness of insulation types were 3.8 and 3.2 °F-ft^2-h/(Btu.in) for LD SPF and DCI respectively. A 5% drop in nominal R-value was considered accounting for thermal bridging.

Table 8- Wall Panels Construction and Variables

Wall Construction Type		***Stud Cavity***			Gap (mm)	***Vapor Control***	***Water Leakage***
	Wall#	Insul. Type	R-Value per Inch	Stud to Stud (mm)			
A	1	DCI	3.8	281	128	***Yes***	***None***
	2					***None***	***Yes***
	3					***SVR***	***Yes***
	4					***Poly***	***Yes***
B	5	LD SPF	3.2	333	181	***Poly***	***Yes***

This is to investigate the effect of incorporation of different types of insulation types on the wetting and drying (or moisture) behavior of the walls with the given configuration.

Five Wall Panels (4’ x 7’) common in, Interior Gypsum Board, Rainscreen Ventilated Cavity, Advanced Framing System (24” o.c.), R-40 (effective), Double Stud and SPF Wood Framing, Plywood Sheathing. The wall panels are insulated with DCI or OC SPFI and different in Vapour Control strategies of Poly (4-Mil Polyethylene Film), SVR (Smart Vapour Retarder) and none.



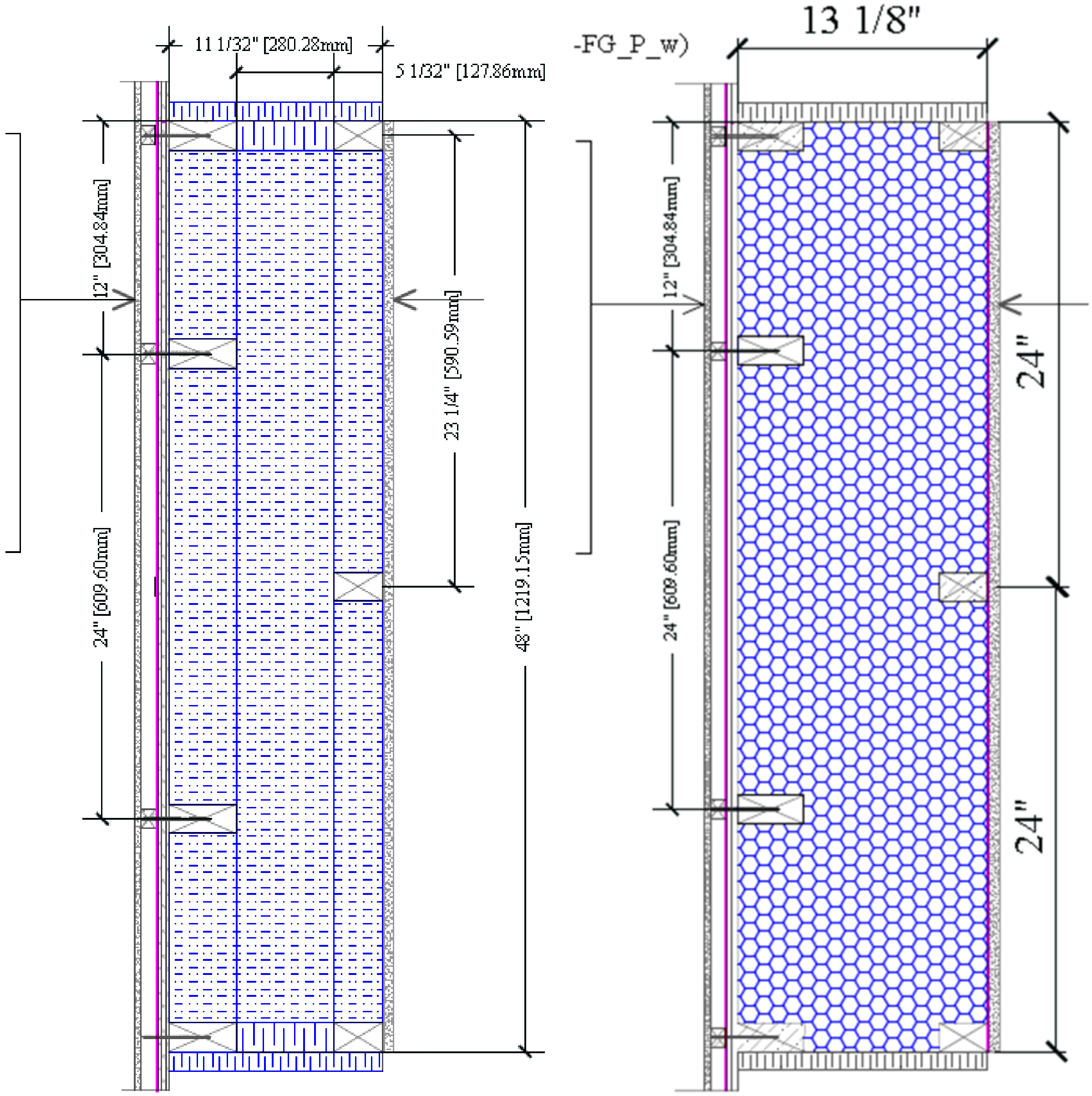


Figure 31- Wet Applied Cellulose and OC SPF Insulation Walls

As for vapour control strategies, one wall with Wet Applied Cellulose had no vapour control layer behind its interior sheathing board (Gypsum Board), another Wet Applied Cellulose wall and the wall with LD SPFI had a 4mm polyethylene as their vapour barrier, and the third wall with Wet Applied Cellulose employed Smart Vapour Retarder (SVR) acting as its vapour barrier/retarder.

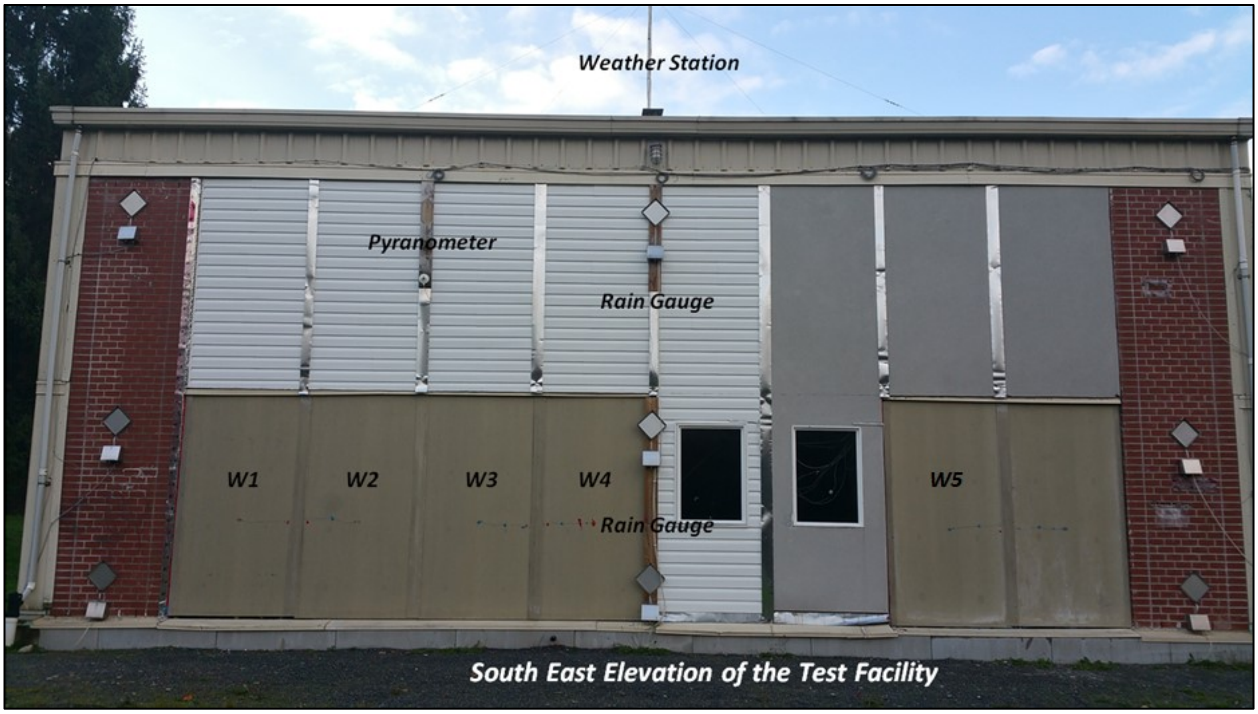


Figure 32- Building Envelope Test Facility (BETF), SE Elevation (photo by author)

Their exterior face of plywood sheathing was layered with a Water Resistive Barrier (WRB) which is a single layer of polyolefin fabric (Tyvek) and cladded with fiber cement panels (hardyboard siding) separated with 19mm of air gap with the same 19 mm opening at the top and bottom to act as a ventilating rainscreen cavity. The last layer of the wall assembly is a typical gypsum board panel facing the interior of the test hut which was installed on a 4-mil polyethylene sheet as the vapour barrier.

To prevent any lateral interference of heat, air or moisture between walls, all wall panels were encased with a polyethylene sheet and Tyvek as well as a minimal of 2" extruded polystyrene foam (XPS) all around the perimeter. Any remaining gaps for passage of wires was filled and sealed with canned foam. More detail of walls construction, instrumentation and installation is presented below.

Figure 33- Wall Panels- Encased in Vapour, Air and thermal barrier in the perimeter (photo by author)

5.4 Instrumentation

5.4.1 Sensors layouts

To record hygrothermal response of region of interest, multiple sensor types were employed. This included Moisture Content (MC), Thermistor (Th), Relative Humidity (Rh), Heat Flow (Hf), and Moisture Detection Tape (Md) sensors.

As for the concentration of MC sensors, the middle height section of plywood sheathing was the location of water injection and also closest the exterior environment with the coldest temperature so was predicted to be the most moisture accepting location, so the highest concentration of sensors was for that section, nine MC sensors altogether, (Figure 34 and Figure 35Figure 34). After middle height section of plywood, the upper and lower part of plywood were also expecting to be fairly moisture susceptible as these locations also are affected by colder exterior ambient environments and can go up in MC by diffusing moisture condensate there. Three MC sensors were allocated for the lower section of plywood in the centre line and two MC sensors for the upper sensors centre line. One more sensor was allocated for the lower section to assess probable liquid water flow on plywood by gravity.

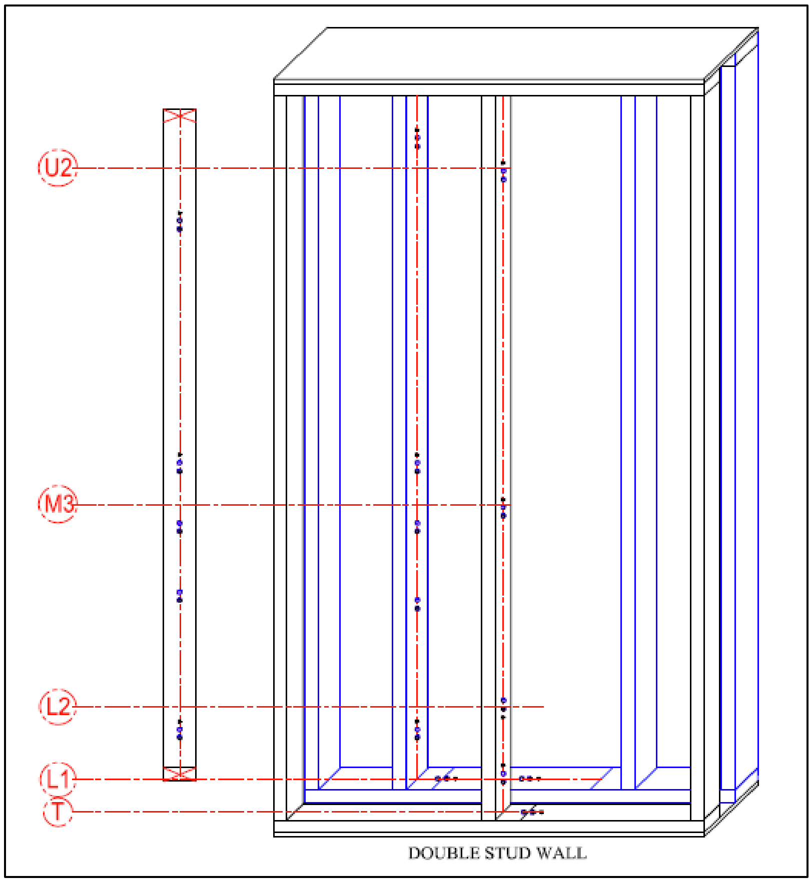


Figure 34- Interior and Exterior Framing MC+Ts Sensors

Other than plywood, two MC sensors were allocated for the interior vertical studs and one more MC (three) sensors for the exterior vertical stud, as it is also fairly close to the exterior environment and more likely to be higher in MC levels. For the plates, one MC sensor was designed and installed for each top and bottom plates (four sensors in total) to assess MC levels of those locations.

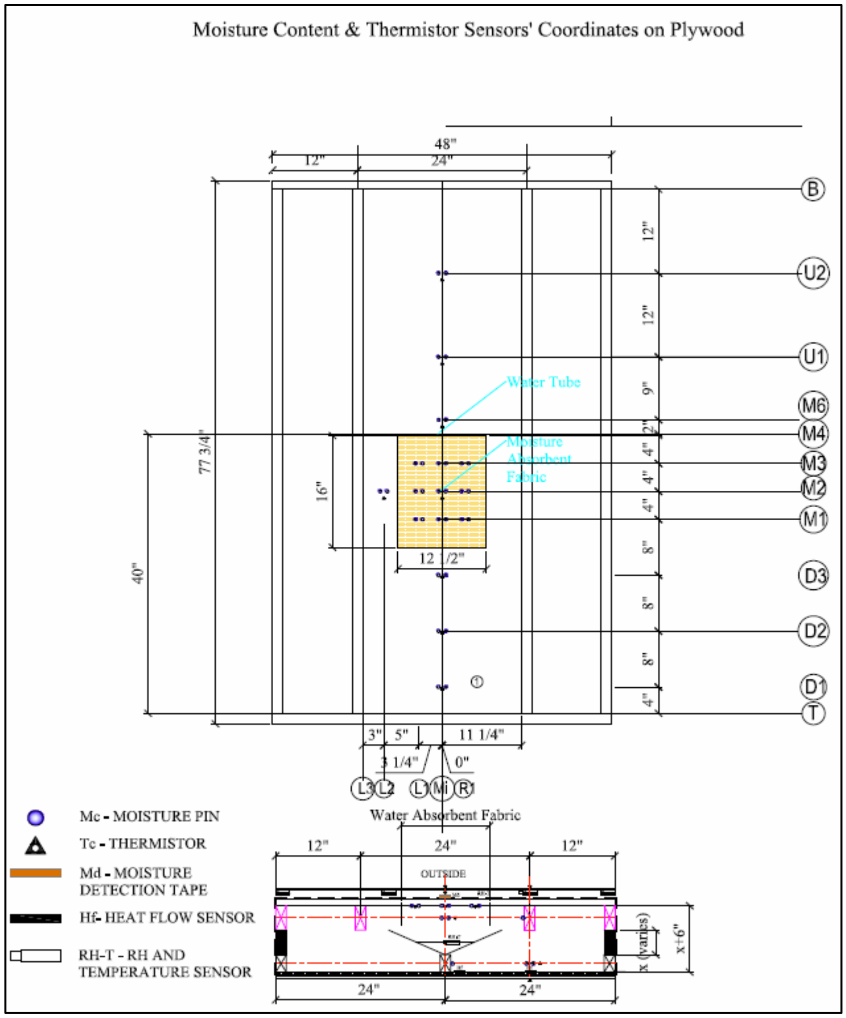


Figure 35- Plywood Sheathing MC+Ts sensors

As for Relative Humidity measurement, three RH sensors were installed in lower, middle and upper section of insulation in centre of lateral as well of thickness of each stud space.

As for temperature measurements, in total, fifteen thermistor sensors were installed on plywood sheathing, vertical studs and plates, three with each RH sensor within the insulation, and two more thermistor sensors were allocated on gypsum board and hardyboard panel siding.

5.4.1.1 *Thermistors (Ts)*

Temperature measurement is required to assess hygrothermal behavior of points of interest on wood surfaces as well as the interior and exterior boundary conditions. Moreover, to work out MC and RH temperature of the points of measurement is needed, so MC and RH sensors have to be accompanied by a temperature sensor. In this research two-prong wired NTC thermistors with insulated wires were used. The operating temperature was -40°C to +125°C with tolerance level of +/- 1%. The product information can be found at (DM Technology Corporation Limited, retrieved 2018). Only the end tips of wires were uninsulated to be soldered to the connecting wires. To avoid short circuit between the wires, all the uninsulated ends were covered by Shrink Wraps that were affixed after soldering by aid of a heat gun (Figure 36).

5.4.1.2 *Moisture Content (MC) pins*

Moisture Content sensors correlate electrical resistances between the tips of its two moisture pins and the moisture content of the measuring materials; plywood and SPFI wood in this case). The outer surfaces of all pins were factory-insulated all around except for 2 mm of their tips and also their end had no insulation as it is meant to be soldered to the wires connecting them to the Data Acquisition System (DAQ) to record the data. The MC pins were home-made from cutting in half and treating Delmhorst 26-ES. Insulated Pins (Delmhorst, retrieved 2018). The reliable MC measurement with this system is from 6-28%. The two moisture pins were placed inside two predrilled holes 25 mm apart which were hammered gently inside a bit wider in diameter than pins' diameter to avoid damaging the insulation around them. Pins were entered half thickness of the wood, 8mm and 13mm deep for plywood and wood framing (studs and plates) respectively. After installing the moisture pins, two more steps were taken. First, to avoid moisture capillary movement, the interface of pins and plywood surface was sealed with a two-component epoxy which also stabilized moisture pins in place. Secondly, as the cavity was going to be filled with damp cellulose insulation, to avoid electrical short circuit between pins, they were covered with a liquid electrical insulation on the uninsulated pins' ends and the soldered wires (Figure 36).

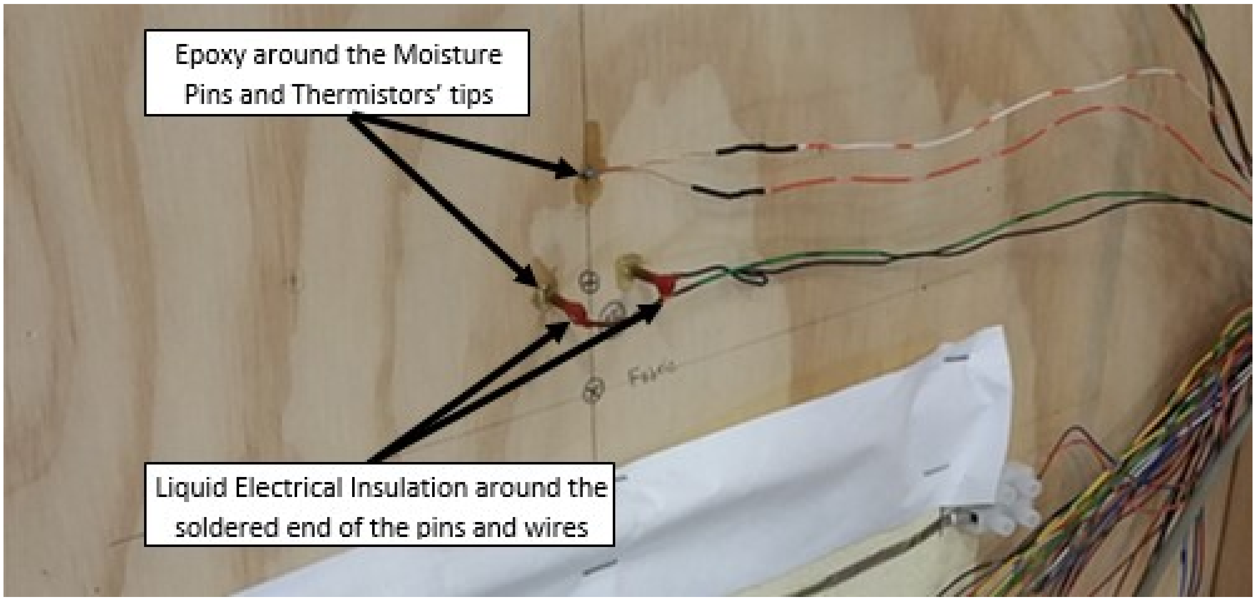


Figure 36- Sealing Moisture Pins' interface with Plywood with Epoxy

5.4.1.3 Relative Humidity (RH) Sensors

In order to assess the moisture condition within cellulose insulation, RH sensors were Honeywell HIH-4000 series with operating temperature of -40°C to +85°C with reliable RH levels of up to 90%. More information can be found at (Honeywell Company, retrieved 2018). The sensors were newly-used and had all calibration coefficients provided by the manufacturer. The RH sensors were coupled with thermistors were placed at three different heights in the centre depth of walls, 12", 32" and 63" from top of the bottom plate (Figure 35) and were secured in mid-thickness of stud space by gluing a hand-made small truss with plastic tube. RH sensors came with individual calibration coefficients to make corrections for the reading data. To avoid displacement of the sensors during insulation placement, they were taped to a bracing which were epoxied to the designated locations.

5.4.1.4 Moisture Detection Tape (Md) Sensors

Moisture detection tapes were used in two locations, one under the soaker hose to sense if the water injection is working properly. The product had an operating range of -40° to 50 °C. Data sheet if the manufacturer can be found at (SMR, retrieved 2018). The second location was in the centre and middle depth of exterior bottom plate as an extra measurement for the possibility of injected and/or condensed water runs down on plywood and accumulates on the bottom plate. This provided a redundancy measurement parallel to the MC sensors.

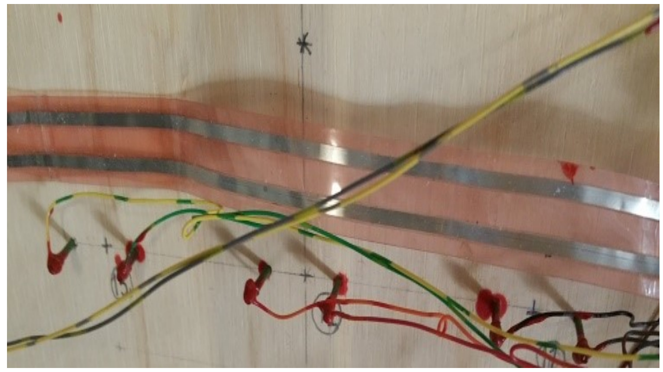


Figure 37- Moisture Detection Tape (photo by author)

5.4.1.5 Heat Flow Sensors

Heat flow sensors used were 1.25"x1.25" product, F Series. They were provided with calibration numbers by the manufacturer (Concept Engineering, retrieved 2018). They were all glued by a conductive plate to the exterior surface of gypsum boards (Figure 38). These were used to evaluate the heat flow patterns for future experiments in correlation with the boundary conditions and moisture content variation in insulation.

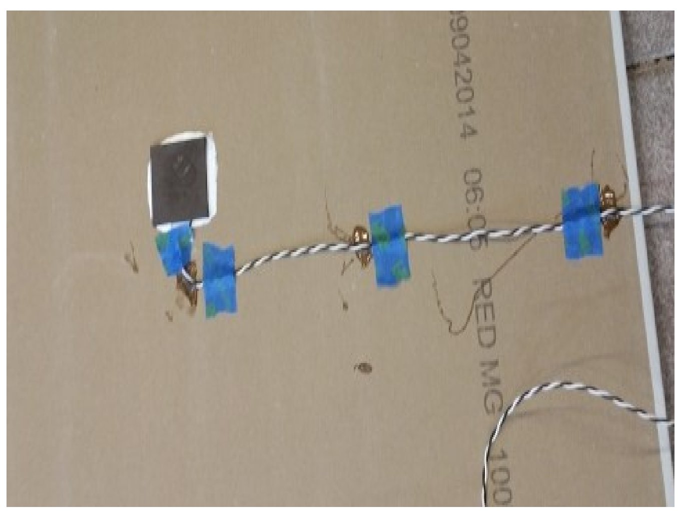


Figure 38- Heat Flow Sensor (photo by author)

5.4.2 Wiring and DAQ System

Double-string cables were incorporated for connecting the various types of sensors mentioned earlier. The colors were used to label each double-wire to specific sensors within walls. In this study a total of nine 4-pair and one 25-pair wire were used for each wall adding up to around 60 sensors for each and 300 for four walls altogether.

Figure 39- Moisture Pins- Insulated at the ends and sealed by epoxy on wood (photo by author)

Figure 41- Wall Panels and Primary Terminal Strip (photo by author)

Figure 40- Terminal Strips for Sensors Wiring before DAQ (photo by author)

The wires representing each sensor, were collected in a primary terminal strip mounted outside each wall and then sorted in a secondary terminal strip station based on sensor types to be sent and connected to the data acquisition (DAQ) system that records the electrical voltages on 1-min regular intervals. Application of the secondary terminal strip panel was very helpful in troubleshooting stage as MC, RH and Ts sensors were all sorted and easy tracked and found where there was an anomaly.

5.4.3 Water Injection System

The idea of injecting water into walls was simulating the likely water intrusion behind the WRB which was Tyvek for this test. The amount of this water as discussed earlier was 150mL injected in three days (50mLeach day, three days in a row) which was introduced to a water absorbing fabric installed between the exterior surface of plywood sheathing and Tyvek.

Figure 42- Soaker Hose and Bras Connection

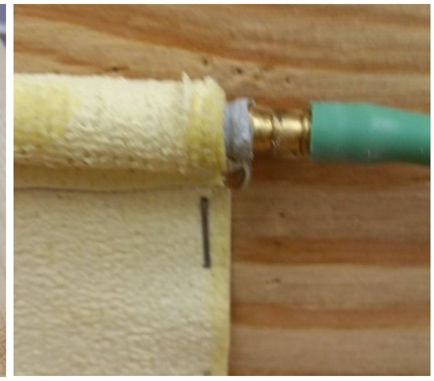


Figure 43- Connecting Soaker Hose to Wetting Tube

Fabric selection was the result of comprehensive laboratory experiments conducted before walls were built which several types of fabric available in market were chosen and tested with water injection. The selection criteria were water retention, uniformity and maximum capacity. Several tests were conducted to choose the most appropriate fabric (Figure 44).

Figure 44- Water Absorbent Fabric Laboratory Tests

This was done after wall panels were already installed, so a rectangular cut was made by to tuck in the absorbing fabric with the perforated tube on its top, soaker hose (Figure 43), which was put together with a brass connection to the flexible tube (Figure 42).

The tube was guided moving on the surface of WRB to be entered into the building through the gap between wall panels. Once tube entered the test facility, it could be hooked up to a peristaltic pump that is capable of injecting low amounts of water to very slow rates. The pump model in this study was “Cole-Parmer Masterflex L/S model 77800-60” and water was injected in rate of 2.5mL/min.

5.5 Test Panels Preparation and Installation

Figure 45- Wood Frame Wall Construction

Wall panels were built by framing together SPF (a commercial term for woods mix of Spruce, Pine and Fir) 2x3 and 2x4 nominal sizes of wood lumbers which are in more exact numbers (38mm x 64mm) and (38mm x 89mm) respectively. The wood lumbers were cut and put together by glue and screws into two separate frames of 1975mm (height) x 1219mm (width) measured from their outside perimeter. Once frames' glue was cured, the exterior 2x4 frame was laid over and fastened to a 1975mm x 1219 mm pre-cut plywood sheathing. The interior face of plywood sheathing was divided in three sections by putting two more 2x4 studs (vertical stud) 24 inches from each other and 12 inches apart from the studs in the perimeter (Figure 34, Figure 35).

The second 2x3 framing (interior), was separated from the framing attached to the plywood sheathing (exterior framing), by XPS (Extruded Polystyrene) and glue. Interior frame had another middle vertical stud in its centre line.

Once framing was ready, MC sensors' locations were all marked (Figure 45), then holes were drilled appropriately to hammer moisture content probe pins into them and let the pin tips stop at the half thickness of plywood (8mm penetration) and wood frames (19mm penetration). The next stage was installing all the sensors (that were already soldered to wires) and pass them through the premade holes that were big enough to let the wires and sensors enter the walls from the sides of the exterior studs (Figure 46).

After this stage, the holes on the side of vertical studs were filled and air-sealed by spraying a one-component canned sprayfoam.

Afterwards moisture pins were hammered into predrilled holes and fixed and sealed by a two-component epoxy that was not only stabilizing the pins, but also sealing the gap in the perimeter of holes made by hammering. It needs to be noted that the holes were drilled wide enough to let the moisture pins get inside without damaging the insulating coating of pins and tight enough to have the pins stable.

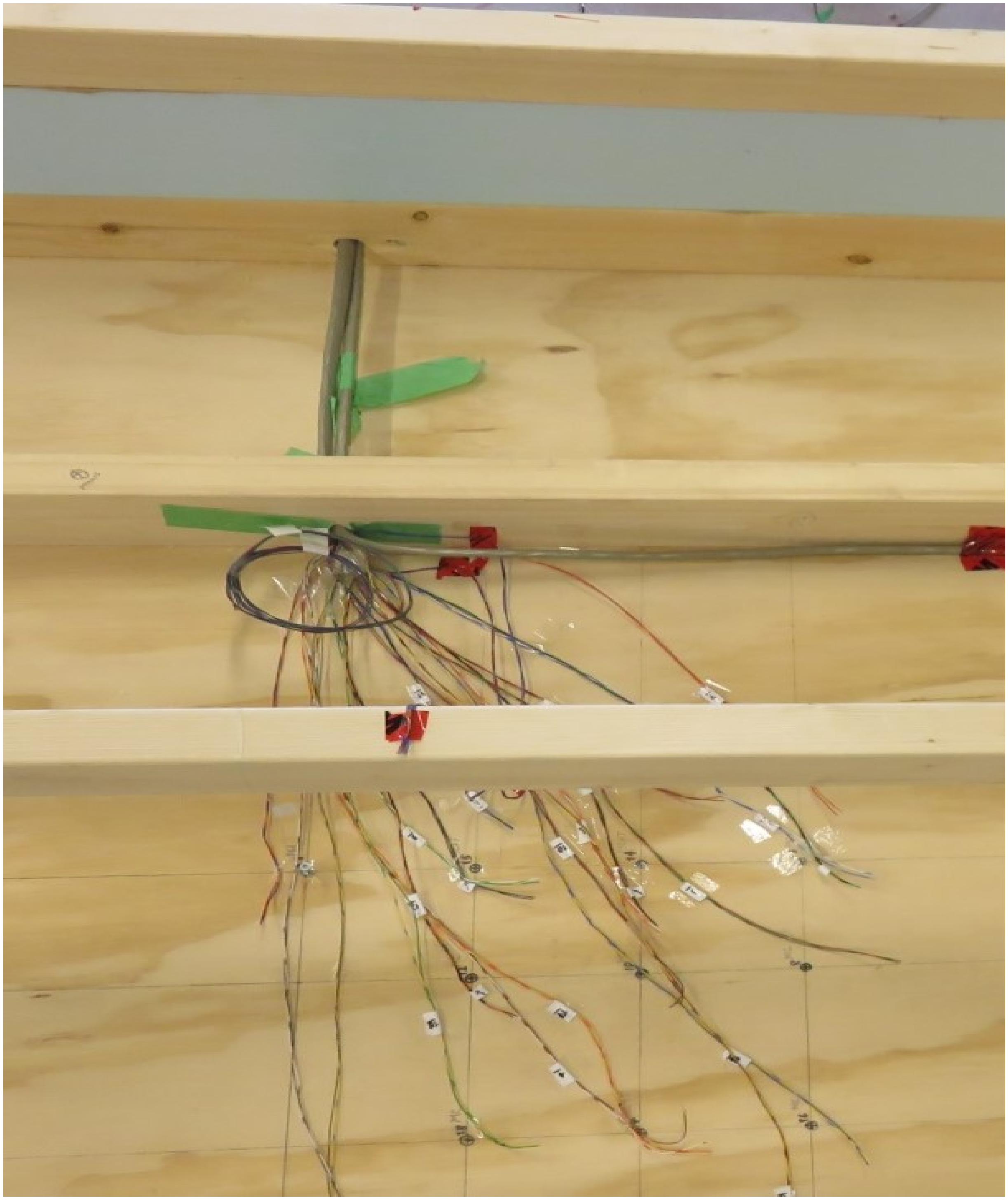


Figure 46- Sensors Wires Entering Walls

Then pre-soldered thermistors were fixed into place momentarily by a piece of tape and then secured to the surface of wood by application of the same type of epoxy. Moreover, an insulating paint (red color) was applied to the soldered end of pins to prevent short-cut electric currents later after filled with insulation (Figure 47).

Figure 48- RH and Thermistor (RH+T) Sensors-Installed

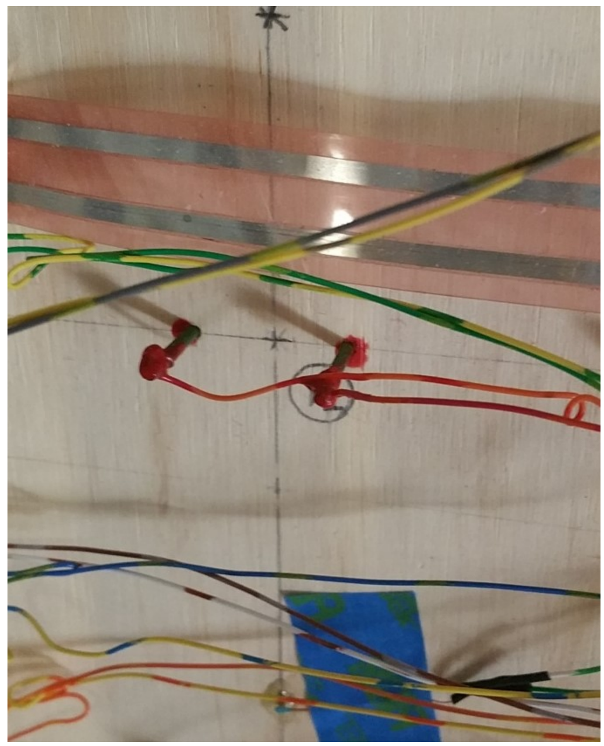


Figure 47- Insulating Paint on Soldering Pin Ends and Wires Ends

At this stage, RH sensors accompanied by a thermistor sensor were tucked into a pre-cut Tyvek layer to protect them from any excessive condensation (resulting oxidation and damage) and then were erected and stabilised in place by a custom-made truss made from a rigid plastic tube (Figure 48).

Figure 49- Walls ready for WRB and Polyethylene

Figure 50- Water Tube through Exterior Stud

Subsequently, a transparent tube was entered the wall by drilling another hole through the vertical exterior studs to feed the soaker hose and wetting fabric (for future studies that interior plywood sheathing is going to be wetted). This hole was also filled with single-component sprayfoam (Figure 50).

Figure 51- Wall Panels Ready for Installation

After this stage, the entire exterior perimeter of each wall panel was encased with Tyvek to act as WRB (Weather Resistive Barrier), and then another layer of polyethylene was overlapped on the perimeter side of the walls and around 20 inches of extra waiting width was left in order to later be taped and sealed with the interior vapour barrier (Figure 33), except for wall#2 that had no vapour barrier.

Once walls were all instrumented and wrapped in Tyvek and plastic film, they were all ready to make the SE building enclosure ready for installation (Figure 51Figure 52).

The next stage was dismantling the previous enclosure walls and preparing the installation opening for erecting and installing the new wall panels. In installation stage an extra piece of 2-inch thick XPS was added to the bottom of each wall to reduce thermal exchange with ground especially in colder periods of the test (Figure 52).

Another important installation consideration was making sure all the walls maintained their air-tightness continuous, so the WRB and polyethylene that was already in place was carefully overlapped and taped with an extra pre-cut layer of polyethylene (Figure 53).

Figure 52- XPS Thermal Insulation on the bottom of walls

Figure 53- Maintaining Air-Tightness Continuity for Building Envelope and Wall Panels

Figure 55- Flashing and Waiting WRB Overlap for Water Shedding of Siding

Figure 54- Walls Erecting in Building Enclosure

Subsequently walls were all erected and installed next to each other but separated with a 2” wide pre-cut piece of XPS insulation to prevent lateral thermal exchange between the test walls. Another important factor in installation was incorporating water flashing that was sealed to the upper WRB layer and also wide enough to accommodate walls and the extra space for 19mm of ventilated rainscreen space (Figure 55).

After WRB was properly sealed with duct tape, wood strappings with 19mm thickness (3/4”) were fastened to walls studs to securely attach the hardyboard panels as the final exterior finishing for walls (Figure 56).

Figure 56- Walls Installed with 2" XPS Insulation between Panels

Figure 57- Attaching Wood Strapping

After finishing the exterior installation, the final touches of the walls instrumentation were completed from the interior space and after final sensor troubleshooting, walls were ready for thermal insulation installation (Figure 57).

Figure 58- Wet Cellulose Application Process- First Layer

Two types of insulation were applied in this experiment, Dense Cellulose (DCI) and Open Cell Polyurethane Sprayfoam (OC SPF). Dense Cellulose Insulation was applied by mixing the dry ingredients with proper amount of water and spraying the mixture. This type of cellulose insulation has chemical treatments to prevent mold growth, so the application was done in a covered chamber to prevent the chemicals spread around and the applicators had proper breathing masks, goggles and clothing. The application of cellulose had to be done in a couple of rounds of thickness so that cellulose is stable in place. After installation was done, walls were left exposed with blowing fans turned on facing them for a couple of weeks until they all dried out. The complete dryness of walls could be checked by MC and RH sensor already running.

Figure 59- Application of Wet Cellulose in Isolated Chamber

As for Open Cell (or High Density) Sprayfoam Polyurethane (OC (or HD) SPF) insulation, they were also applied by professional licensed and highly skilled applicators, with mixing two components in a mixer and applying them through a nozzle. This process was also carried out in a covered chamber and the applicators were also properly clothed to avoid the toxic fumes. Once the application was done, the projecting bubbles were trimmed flush with the exterior surface of interior framing to allow for the vapour barrier and interior gypsum board be installed.

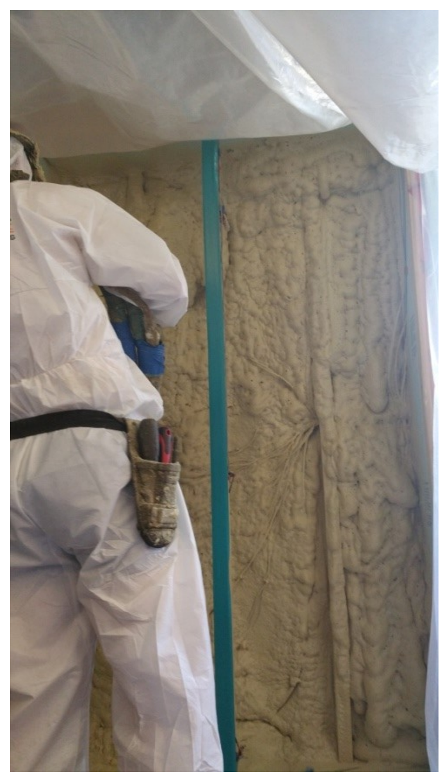


Figure 60- - Application of OC SPF

After insulation was cured and dried enough, the final vapour barrier layers, Polyethylene, SVR (except for wall#2), where added and taped to the waiting precut layers from the walls construction stage discussed earlier followed by installing the interior S sheathing, 5/8” gypsum board panels.

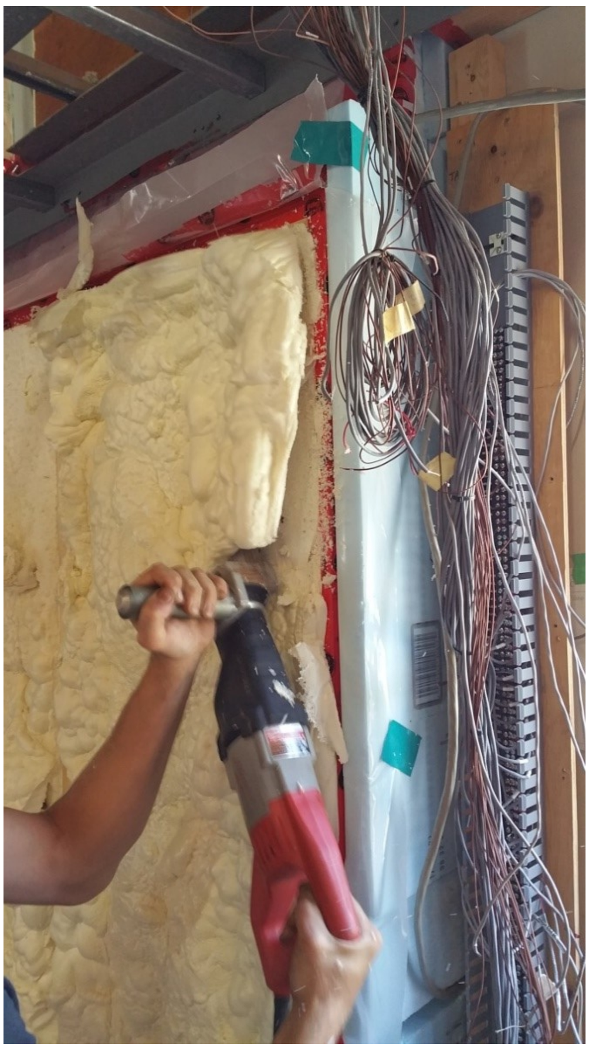


Figure 62- Sprayfoam Trimming

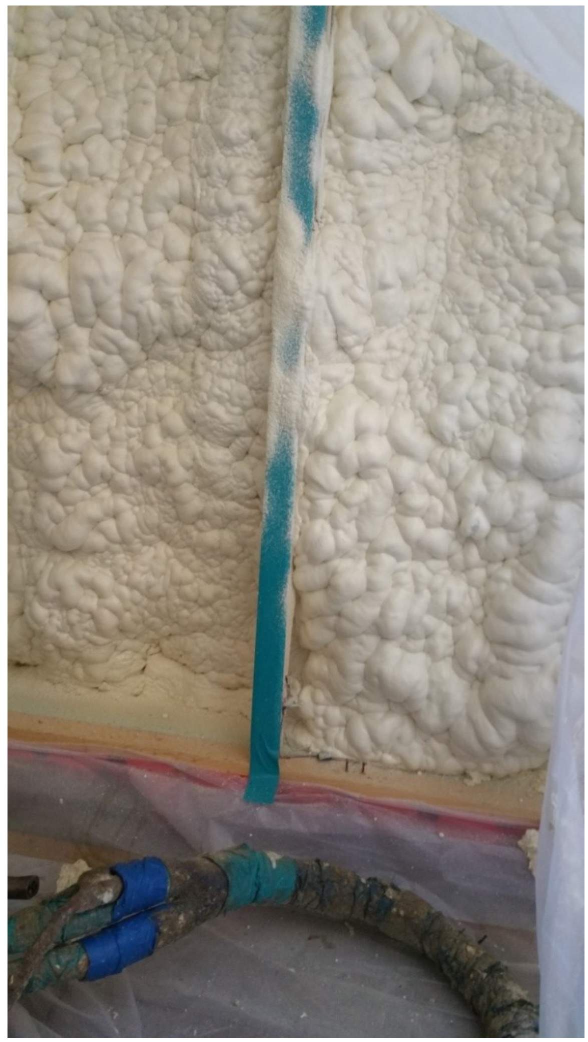


Figure 61- Applied Sprayfoam (First Layer)

Figure 63- Vapour Barrier Incorporation in Cellulose Test Walls

5.6 Weather Station Specification and Details

The weather station is located on top of the roof of the test hut and consists of “RM Young 05103-10 Wind Monitor”. Wind speed and direction is measured by “RM Young 81000” wind sensor model that is capable of 2D as well as 3D wind speed measurements.

Figure 64- Weather Station Gauges on SE Elevation (photo by author)

To measure and record the ambient outdoor temperature and relative humidity “Sonic Temp (Vaisala HMP45A RHT Sensor)” is used in the station. Solar radiation sensor was measured by Kipp & Zonen CMP3 and SP Lite pyranometers one on the roof (horizontal), and two other ones on the centre of SE and NW Façades at about 12’ in elevation (Figure 64).

A total of 24 vertical rain gauges located on the 4 elevations of the test facility. These rain gauges consist of a custom-made diamond shaped stainless steel rain catchment that feeds a RM Young tipping buckets, #52234, housed in a custom made stainless steel box. The catchment area is approximately 515 cm^2 and the tipping bucket is calibrated to tip every 2ml of water. Therefore, a tip count of 25.76 indicates an average depth of 1mm of water has fallen over the entire catchment area, or 0.0388 mm per tip. The horizontal rain gauge is a Texas Electronics TR-525 Rainfall sensor. The whole unit is factory made and has a catchment area of 473 cm2 and a tipping bucket that tips when it contains 4.73 ml of rain. Henceforth, it takes 10 tips to equate to 1mm of rain fall or each tip indicates 0.1 mm of rain fall.

Figure 65- Rain Catchment Diamond

6 RESULTS AND DISCUSSION

6.1 Data Analysis Methodology and Procedure

Walls' construction was completed by end of June 2015 and their insulation space was filled with wet dense cellulose insulation so that the data collection could start at beginning of Sep 2015, however walls moisture content for walls did not dry out or not even did not reach to similar levels in two months. Since the relative performance assessment of the walls can be done only if they start with moisture content levels so data of 01 Sep 2016-31 May 2017 are used in this study.

Due to large number of MC sensors (and the accompanying thermistor sensors for each wall), the general moisture behavior of each wall is first compared as an overall glance to all the sensors together, but then for practicality and simplification purposes, five categories of sensors were selected, grouped and averaged into a single value and weighed against each other. In total, three group categories of sensors were defined on plywood, lower, middle and upper sections, plus two more group categories of framing, consisting of the interior framing (adjacent to the interior gypsum sheathing board), and the exterior framing (adjacent to the exterior plywood sheathing board).

6.2 Hygrothermal Indices

In this study, two general moisture performance indices were adopted in parallel. The first index, which is the more common one in hygrothermal studies, looks into the wetting and drying behaviours of walls over the test period. In this approach the MC increase (wetting) and decrease (drying) over time is investigated, within various locations in a single wall assembly or compared to the other wall assemblies (similar sensors locations for each wall). This approach, while simple, is rather subject to various interpretations.

The second moisture performance index used in this study, was Mold Index (ASHRAE, 2016), and while it is primarily a computer modelling moisture performance index, but was adopted in this project for two reasons; firstly, mold as discussed comprehensively in previous chapters, is one of the major moisture related performance concerns in wood frame buildings so by comparing mold formation rates, wood frame walls components can be gauged against each other in a more direct way. Secondly, unlike other methods, Mold Index combines all different factors of moisture content amount, duration, fluctuation, temperature, and substrate material sensitivity lumped into one single accumulative final number. This number while somewhat oversimplified, but overall can help with a unified and less subjective comparison. In that line, several limitations and modifications for simplification and practicality reasons were accepted and carried out.

Firstly, the recorded data in this project for various wood frame locations were all from Moisture Content (MC) sensors, while Mold Index (MI) is designed based on Relative Humidity (RH) rates, not from Moisture Content. To get around this obstacle, a regression analysis was conducted from the sorption isotherm database results of a previous study (unpublished yet) with similar wood material (in BCIT Building Science department material lab) and MC was converted to RH numbers to calculate Mold Index for the locations of MC sensors.

Secondly, mold index is essentially an index created based on mold development on the *surface* of materials, whereas the moisture content data in this research are from the mid thickness of plywood sheathing and framing as the location of tip of moisture probe pins.

Despite these limitations and assumptions, mold index was adopted as a comparative moisture performance criterion for its mentioned advantages.

6.3 Ambient Climates

Figure 66 presents the daily averages of recorded exterior ambient climate from the sensors located on the same orientation of the installed wall panels. It shows relative humidity fluctuations starting of around 80% at the beginning of the study and going up to 90% by end of the year, and then starting to decrease on average, from March 2017 with extended periods of averages as low as below 60% by end of May 2017. In this graph we can see there are periods of sharp spikes of drop or increase, which could be the effect of temperature or rain events. Temperature daily average variation start with around 15-17°C in early September 2016, going down overall to around -8°C by middle of December, with some weekly fluctuations. From middle of December temperature daily average starts rising again to periods of above 20°C by end of the test period in late May 2017. Relative humidity and temperature values combined can be translated into the more workable parameter of vapour pressure that is presented in proceeding sections.

6.3.1 Exterior RH & Temperature (24 hr Avg.)

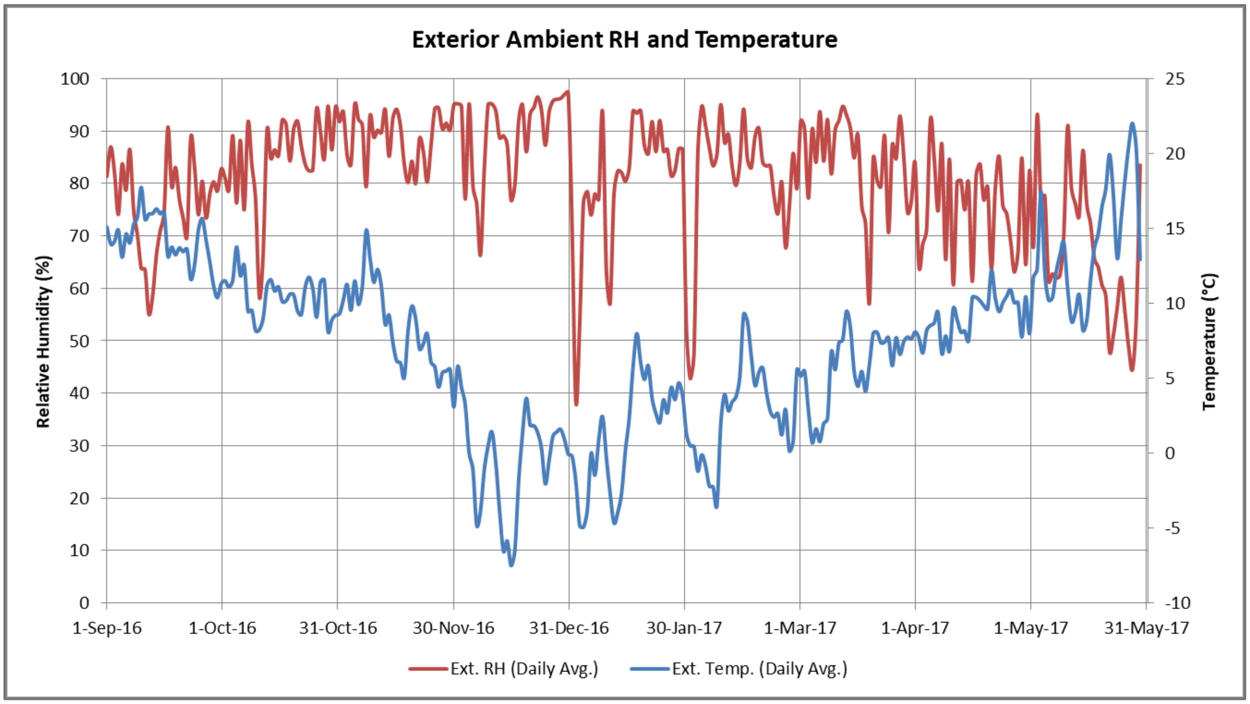


Figure 66- Exterior RH and Temperature

6.3.2 Interior RH & Temperature (24 hr Avg.)

Unlike the exterior ambient climate with daily RH and Temperature fluctuations, the conditioned interior environment had a controlled temperature of around 20°C for almost the entire test period, and different seasonal RH controlled levels, 60% until 01 Dec, 52% from 01 Dec 2016 to 01 Feb 2017, 56% from 01 Feb-02 Apr 2017 and 55% from 02 Apr-25May 2017.

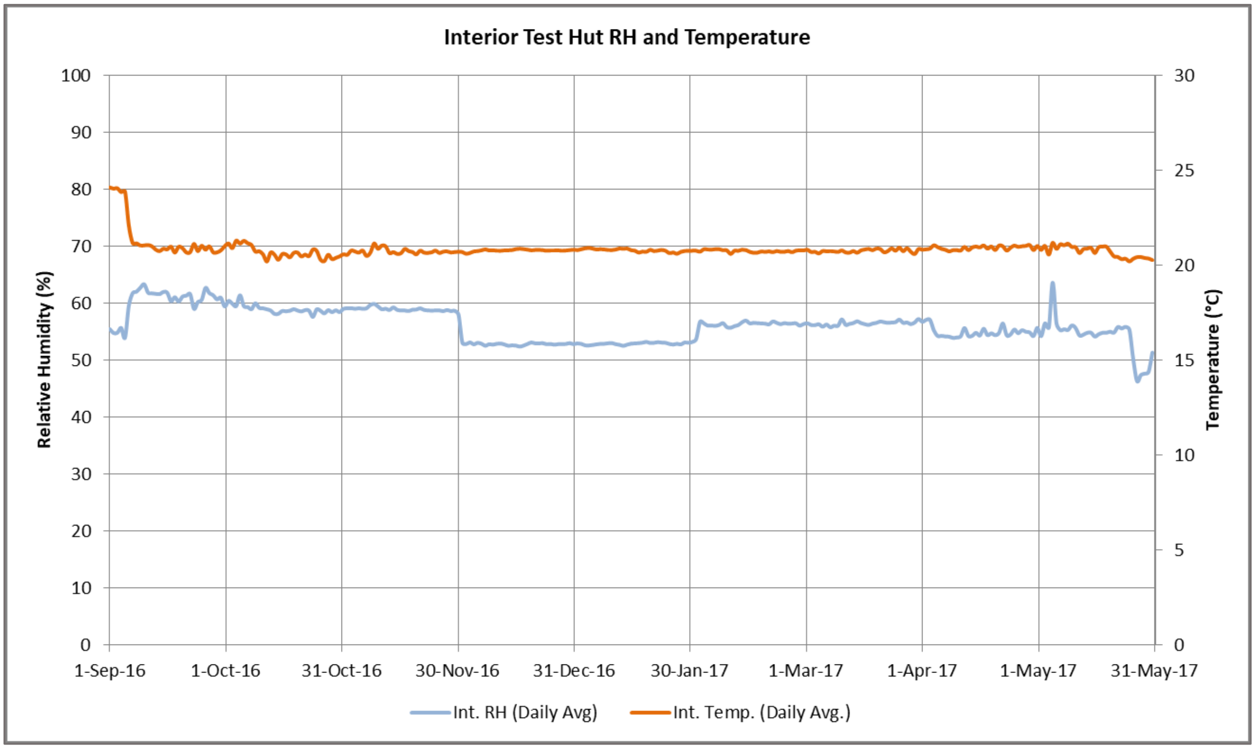


Figure 67- Interior (Test Hut) RH and Temperature

6.3.3 Exterior & Interior Vapour Pressure (24 hr Avg.)

The below graph combines, the RH and Temperature data results of the interior and exterior ambient environments, into a single vapour pressure value to compare. For this graph, 'The Ideal Gas Law' is used to derive vapour pressure from temperature and relative humidity. There are many empirical formulas to do this conversion, for this study this formula was used:

$$P_v = P_{sat} * RH = (1000*EXP(52.58-6790.5/(273+t)-5.028*LN(273+t))) * RH/100,$$

t: temperature in degrees Celsius

Pv: Vapour Pressure

Psat: Saturated Vapour Pressure (at the given temperature)

RH: Relative Humidity

As we can see in the graph below, for the entire test period the vapour pressure of the interior environment remained higher than the exterior environment. This means the overall vapour gradient for this study remained from the interior to the exterior. For the interior air, vapour pressure started with around 1,600Pa and then was lowered to and maintained at1,400Pa by middle of October, that was lowered to 1,300Pa till end of January of 2017 that was raised again to 1,400Pa till end of the test period. But for the exterior weather, the vapour pressure was at its highest of 1,400Pa at the start of the test in Sept, and with seasonal fluctuations, went to almost 200Pa, by mid-winter with the highest vapour pressure gradient to the interior vapour pressure, up to 1,100Pa in January of 2017, then with many spikes and drops reached back to around 1,000Pa by end of May 2017, but still lower than interior vapour pressure. This means vapour flow is almost always from the interior to the exterior, excluding solar radiation effects on the exterior plywood sheathing board that is discussed in proceeding sections.

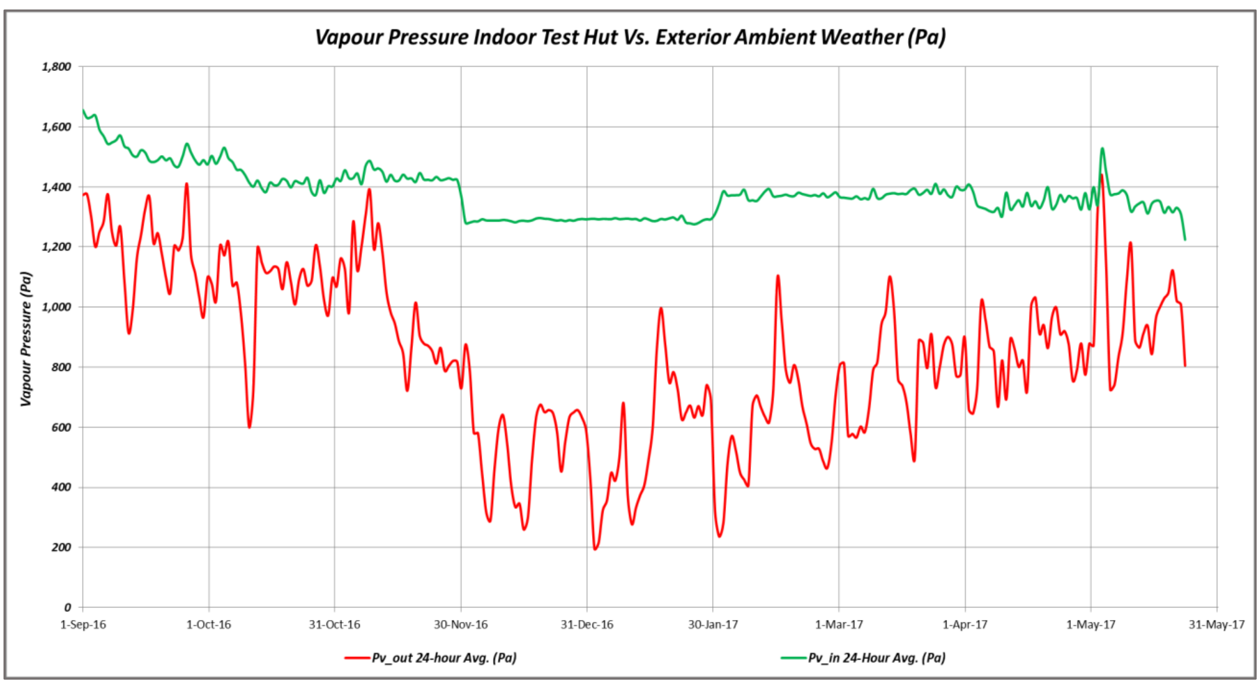


Figure 68- Vapour Pressure- Indoor Vs. Exterior

6.3.4 Solar Radiation

This is to show the effect of various daily and seasonal solar radiation received that in turn can affect drying of the walls (other than just RH and temperature numbers). When sun heats the exterior siding, it heats it up and affects the dynamics of ventilated rainscreen and temperature of plywood sheathing behind it. The effect of solar radiation on changing ventilation rate of rainscreen and also affecting vapour pressure of it and plywood sheathing is a rather complicated dynamism, but the results are presented here for an overall observation.

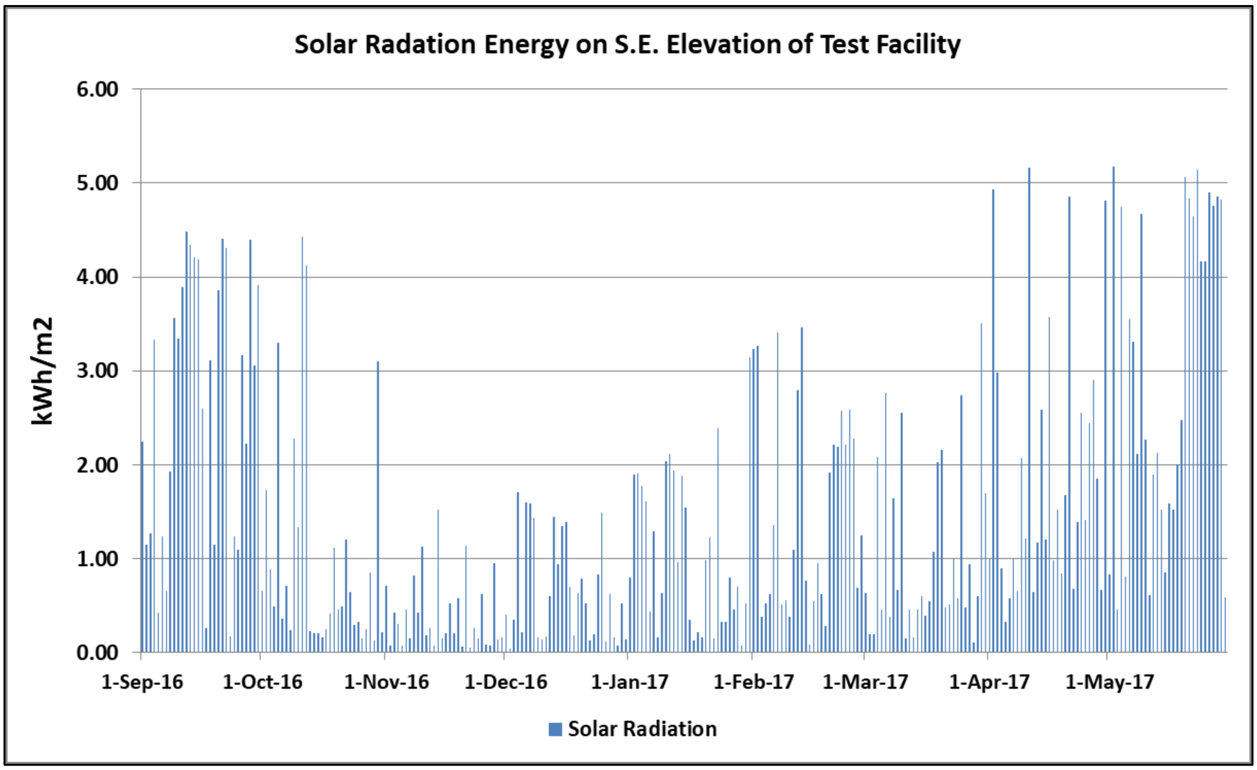


Figure 69- Recorded Solar Radiation on SE Facade

Figure 69 presents overall daily solar radiation energy recorded through the pyranometer installed on the SE orientation in KWh/m2. As expected, there is more solar radiation in September and October, then the least amount in Nov-Jan, then increasingly higher solar radiation gain from February-May 2017, peaking up at 5 kWh/m2 (from below 0.3 kJ/m2 in winter season).

6.3.5 Wind Driven Rain (WDR)

Figure 70 shows wind driven rain (WDR) caught on the rain gauge located on the top centre of southeast elevation of the test facility (isolated rain events). As we can see, significant rain events start from around October and continue through the end of April. As we can see there is less recorded WDR in January and February that must account for precipitation in form of snow rather than liquid rain.

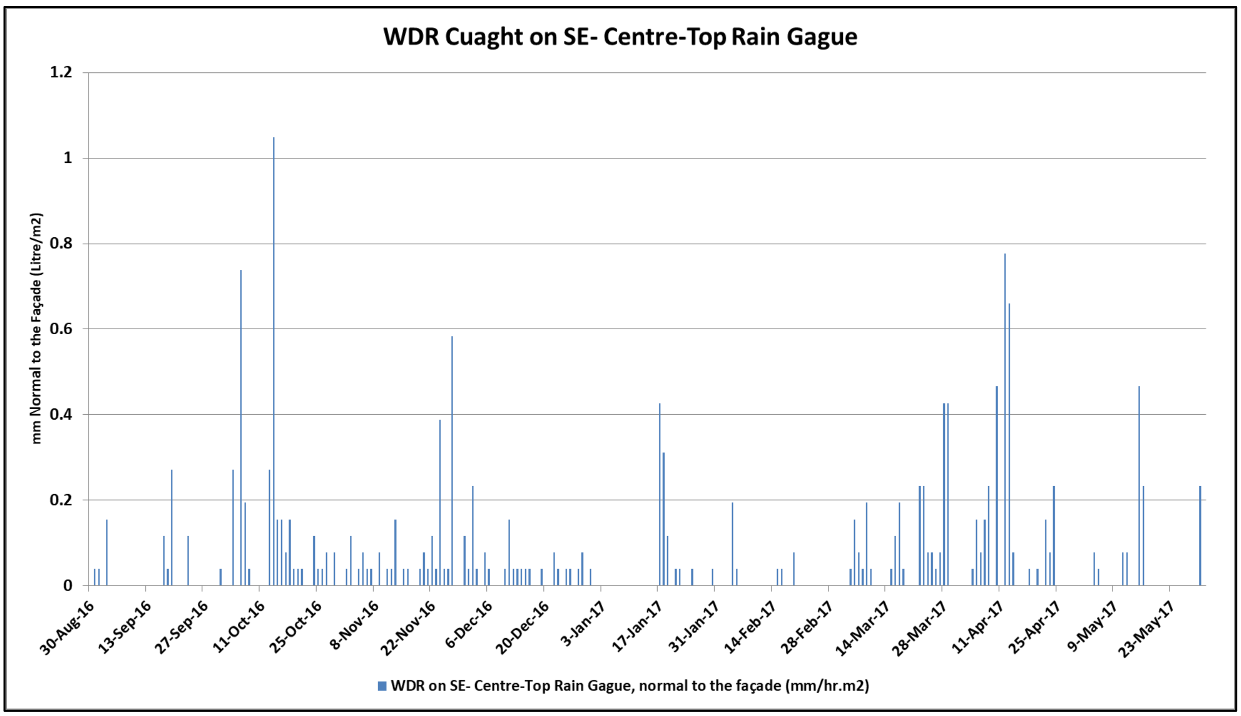


Figure 70- Wind Driven Rain (WDR) on Top Centre Gauge

One interesting observation is significant amounts of WDR in March and April of 2017 even more than November and December 2016 that rains more in this climate. This could be a seasonal exception for more rain at that time of the year or the effect of more wind carrying rain to be deposited or even pressured into wall sidings, albeit there is more solar radiation from

March Figure 69. This situation can account for reversing the drying trend and starting a secondary wetting development for walls around March 2017. As an example Figure 71 shows a secondary wetting from around 27 April-07 March.

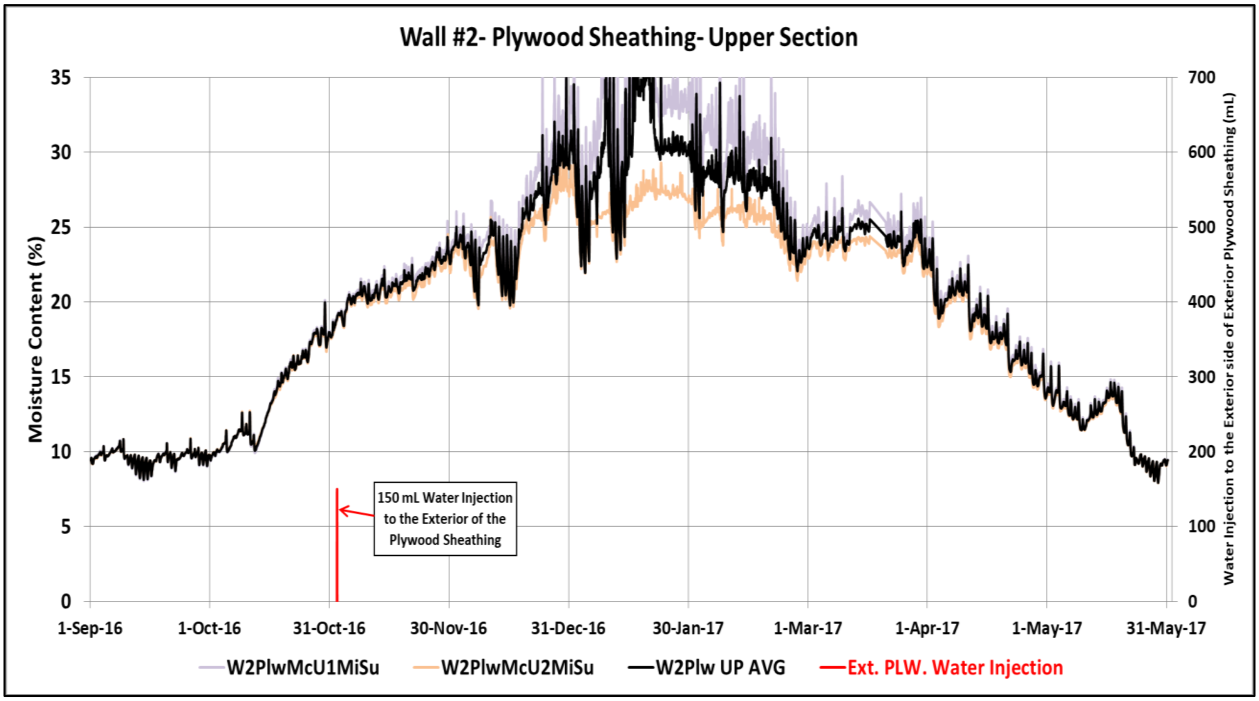


Figure 71- Effect of WDR on wetting and drying of Wall#2 (as an example)

6.4 Walls individual moisture performance

In this section, individual moisture performance of the five panels is looked into in detail. Firstly, an overall view of each wall is presented through their recorded moisture content and temperature sensors. Then the interior and exterior wood studs, top and bottom plates, and plywood sheathing in different heights are discussed with help of their moisture content and temperature graphed recorded data.

Then moisture response of stud space for each wall is looked into with help of the relative humidity (RH) and temperature recorded data and the mid-thickness of insulation gap. In the

Discussion section, moisture content rates for different locations of walls are compared against each other with help of vapour pressure graphs.

Also, Mold Index (MI) for three different elevations of plywood sheathing (low, middle, up) is presented and discussed as a concluding number. At the end, Summary section presents the main moisture drying and wetting trends and risks in an overall table.

6.5 Wall#1

6.5.1 All Sensors

Wall number one as explained earlier is double-stud frame filled with Dense Cellulose Insulation, with polyethylene as its vapour barrier, behind the interior gypsum board sheathing, with no extra water injection. First, we look at all the hourly average data to get an overall view of its hygrothermal performance, then for a clearer view, daily and group averages are investigated.

6.5.1.1 Temperature (Ts)

Figure 72, shows all the thermistor sensors recordings and as we can see at a glance, sensors closer to the interior environment experience less fluctuation in temperature. Moreover, the exterior sensors, experience sharp daily and nightly variations with low and high spikes. These sensors since were closer to the exterior environment were more affected by the temperature variations of the local ambient climate. This made a comparative analysis of the sensors a challenging task as most sensors results were overlapped on the graphs, 24-hour average graphs were created and used instead of the hourly average because neither mold index nor moisture content changes are affected in an hourly basis. Moreover, results were classified into three groups of interior and exterior framing and plywood thermistor sensors and presented in this section for wall number one, however, in later sections for other walls, thermistor results are presented only for sensor locations that there is considerable moisture or mold activity which is mostly on plywood sheathing for further investigation.

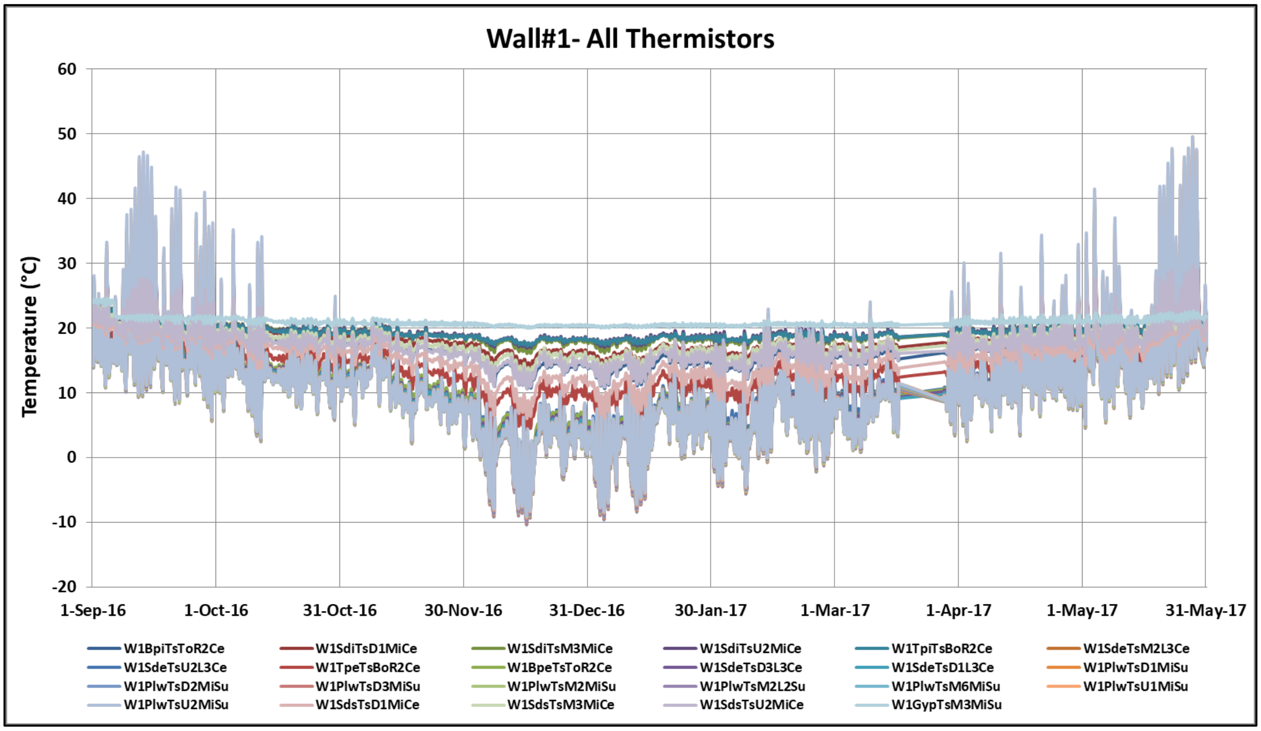


Figure 72- Wall#1- All Thermistors

6.5.1.2 Moisture Content (MC)

The graph below (Figure 73) presents the moisture content changes of all the sensors for Wall#1. In this wall, no water was introduced with the peristaltic pumps and the overall performance of all the sensors looks totally acceptable as no sensor recorded higher than 18% moisture content levels even in the peak of wetting season, for December 2016

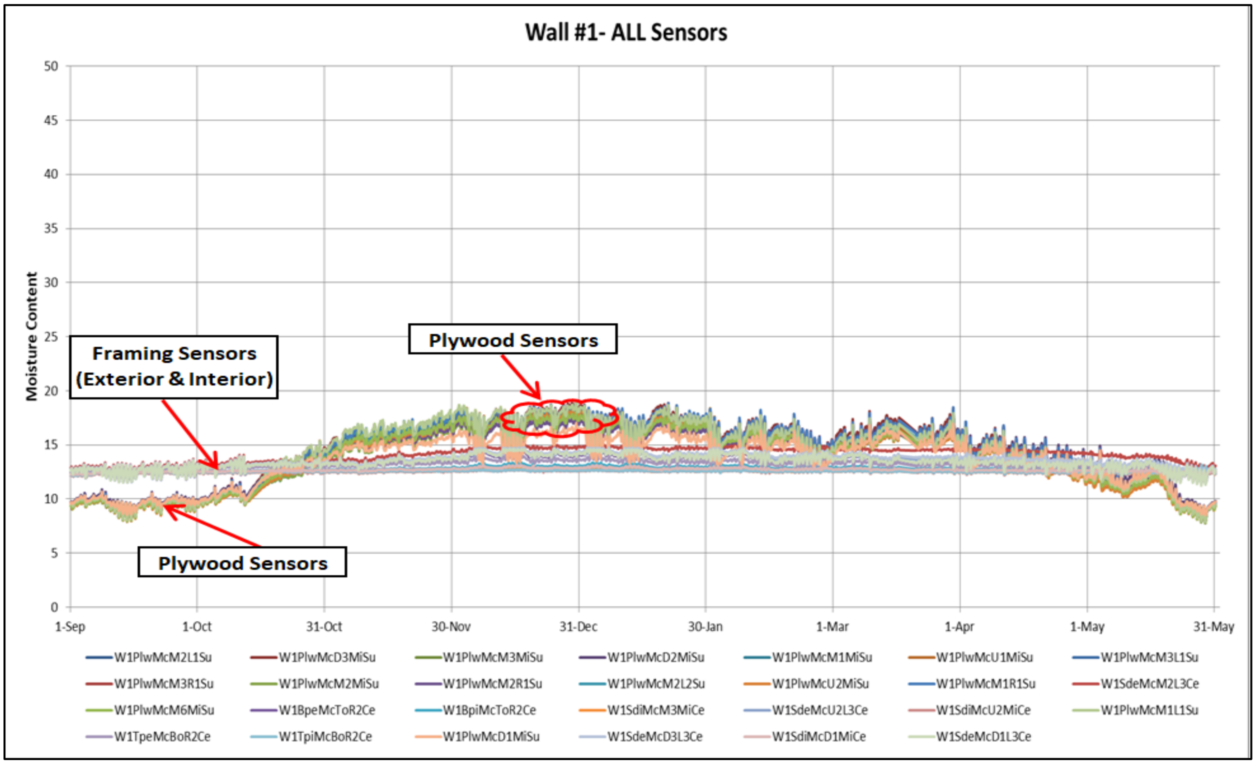


Figure 73- Wall#1- MC for All Sensors- Hourly Avg.

and January 2017. At a glance, we can see there is much less moisture gain and loss in framing compared to plywood, as all the framing sensors remained almost dry for the entire monitored test period with moisture gains of 2-3% in the peak wetting season. On the other hand, the plywood sensors recorded higher moisture gains of up to 9%. And the sharp drying of plywood sheathing that starts around beginning of April 2017 coinciding with solar radiation induced vapour pressure higher numbers (Figure 85).

The sensors results are also presented in interior and exterior of framing (vertical studs and top and bottom plates), in addition to the lower, middle (fabric area) and upper sections of plywood categories in proceeding sections.

6.5.2 Interior & Exterior Framing

Moisture content and temperature of interior and exterior framing (vertical studs and top & bottom plates) are discussed in more detail in this section.

6.5.2.1 Moisture Content (MC)

Figure 74 demonstrates moisture content of the interior and exterior studs and plates and also their calculated averages (in red and black colors respectively). At the first glance, it is obvious that the interior framing barely experiences any moisture increase throughout the entire test period and can be safely left out of any further moisture analysis for this wall.

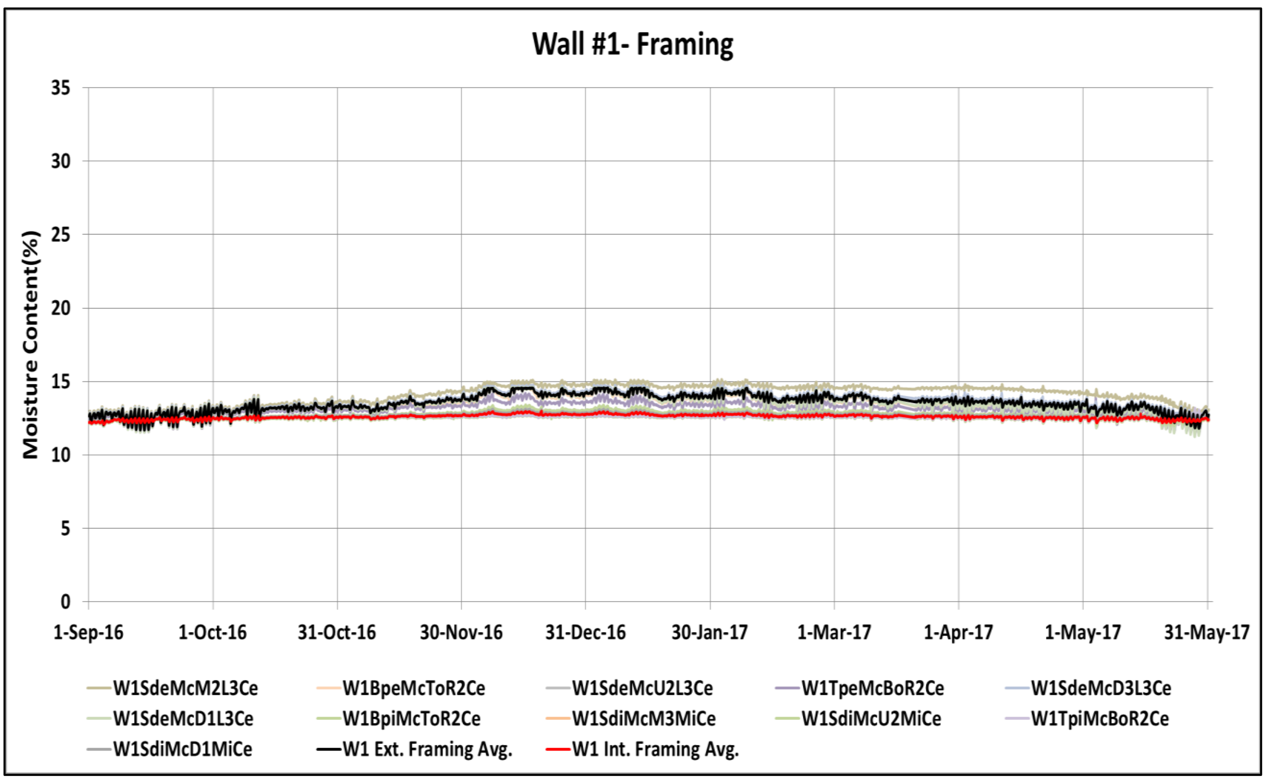


Figure 74- Wall#1- MC for All Framing Sensors- Hourly Avg.

As for the exterior framing, there is a moisture gain of just 2-3%, reaching to a maximum MC level of 15%. Henceforth, there is no real moisture related problem for this case.

6.5.2.2 Temperature (Ts)

6.5.2.2.1 Interior Framing

Figure 75 shows temperatures of various locations on the interior framing of Wall#1. The first things that stands out in this graph, is considerably lower temperature results for the bottom plate sensor, *W1BpiTsToMiCe,* compared to all other sensors which can be due to heat loss to the colder ground temperatures. After bottom plate, the thermistor on the vertical stud that is just four inches above the bottom plate, *W1SdiTsD1MiCe*, experienced the lowest temperature throughout the test period, while the other higher two sensors remained almost the same, being far enough from the colder ground effects. This situation could also be attributed to heat stratification phenomenon, that warmer air rises to higher levels.

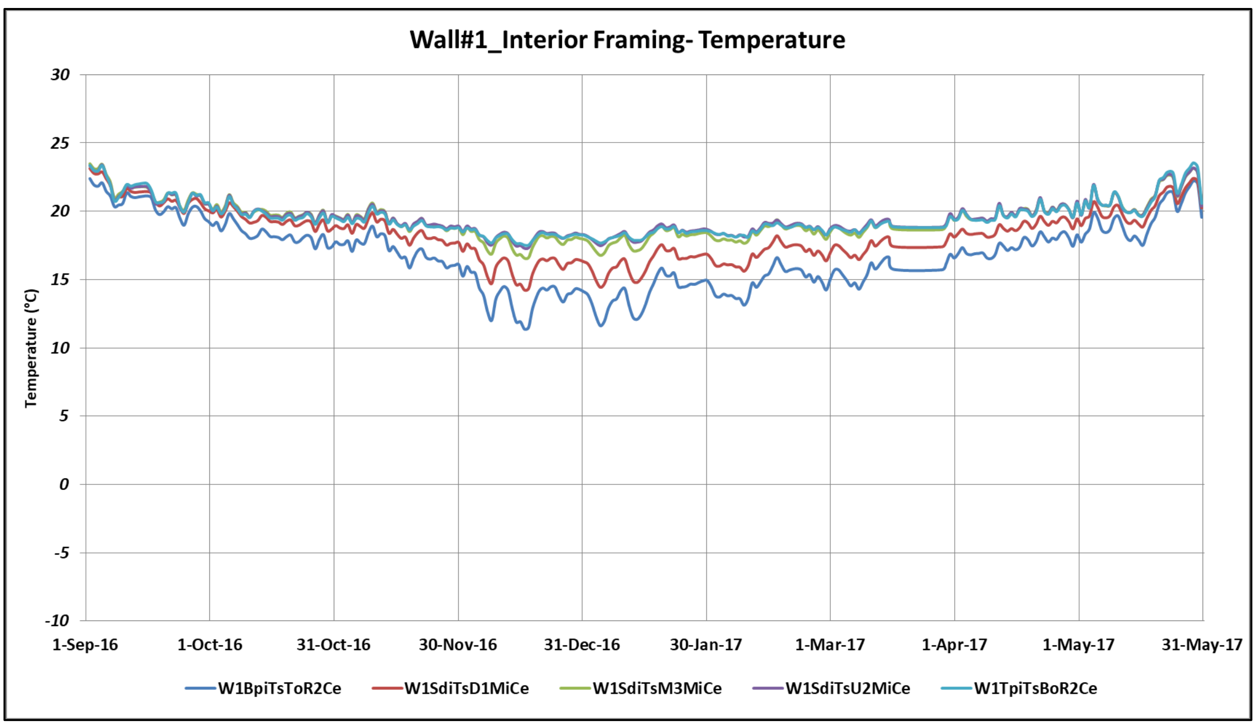


Figure 75- Wall#1- Temperature for Int. Framing Sensors- Daily Avg.

Overall, the temperature of all sensors stayed above 10 °C during the entire test period which is between the interior and exterior temperature variations.

6.5.2.2.2 Exterior Framing

As for the exterior framing, much wider range of temperature was recorded, affected by the changes of the exterior ambient climate. The coldest days of the test period happened in December and January that thermistors recorded temperatures of below freezing. On the other hand, a few days in shoulder months of October and May, had the warmest temperatures, reaching to 27°C.

Another interesting observation was except the top plate that stayed up to 5°C warmer, all other sensors had very similar temperature along the test period.

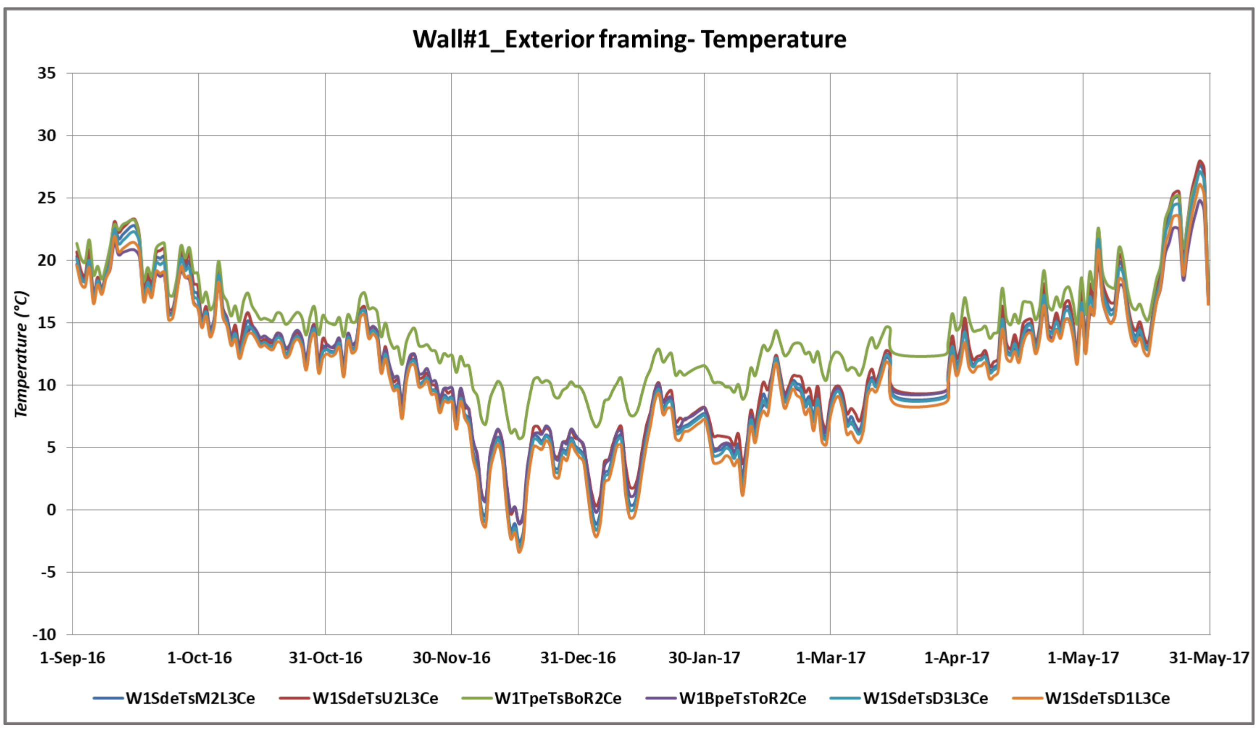


Figure 76- Wall#1- Temperature for Exterior Framing Sensors- Daily Avg.

The higher temperature of the top plate could be attributed to the heat stratification phenomenon that warmer and lighter air tend to rise to higher elevations and might have been trapped in the wooden chamber on top of the walls that were filled with glassfibre insulation material (Figure 77).

Figure 77- The Top Chamber for All Walls

6.5.3 Plywood Sheathing

Temperature and moisture content of plywood sheathing are presented in this section in average numbers. The average numbers are calculated from the three different height locations of plywood, lower, middle and upper heights discussed earlier.

6.5.3.1 Temperature

Figure 78 shows averaged temperature of plywood sheathing for lower, middle and upper section of plywood sheathing. At the very first glance, all the three vertical locations experienced almost exactly the same temperatures, throughout the entire test period. The variations were in close response with the outdoor seasonal changes, colder in winter and warmer in summer. Obviously solar radiation had a big role in heating walls, especially the closer to outside components. While exterior sheathing experienced as cold as -5°C in colder days (or nights) of December and January, it was as high as 30°C in late May 2017.

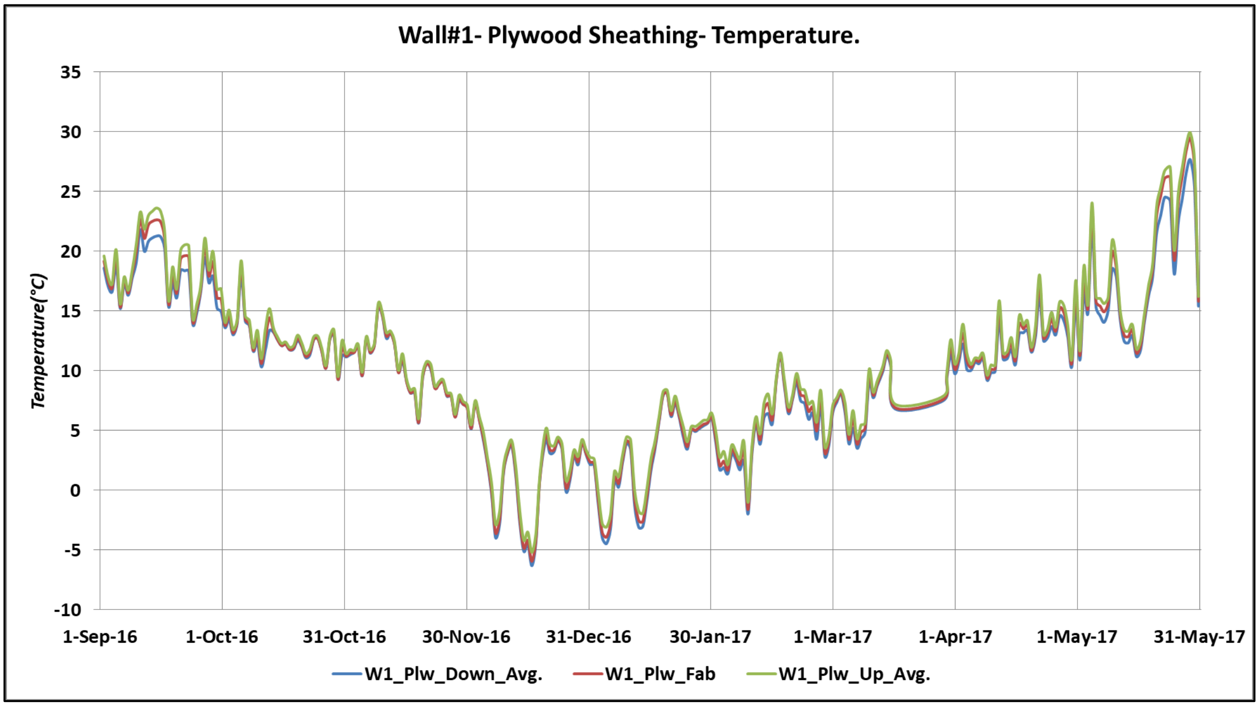


Figure 78- Wall#1- Plywood Sheathing Temperature

6.5.3.2 Moisture Content (MC)

Moisture Content behavior of plywood in the three different vertical levels, lower, middle and upper is discussed deeper in this section.

6.5.3.2.1 Lower Section Sensors

As we can see in Figure 79, the lowest height sensor, *W1PlwMcD1MiSu*, on plywood had up to 3% lower moisture rate compared to the highest elevation sensor *W1PlwMcD3MiSu* which is 16” higher than *W1PlwMcD1MiSu*. This could be due to moisture buoyancy phenomenon.

All sensors start from moisture equilibrium rate of around 9%, reaching to maximum levels of 17-19% by end of 2016 and drop back down to 9% by 31 May 2017. The averaged values are graphed with black color.

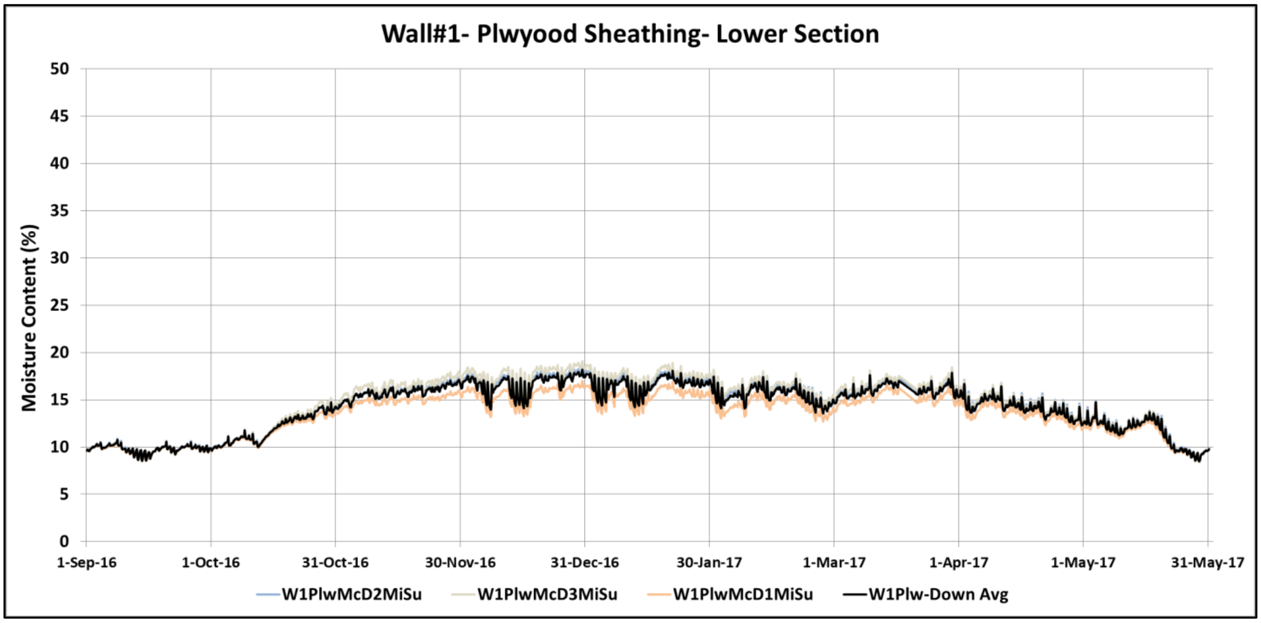


Figure 79- Wall#1- MC for Plywood, Lower Section Sensors- Hourly Avg.

6.5.3.2.2 Middle Height Sensors

Demonstrated in Figure 80 the nine recorded moisture content values are very similar with maximum variation of 2% between the sensors with the highest and lowest values. The black line represents the average value of all the nine sensors, starting from around MC of 9% at the beginning of the test period reaching to a maximum of 18% at the end of the year, and then drying back to the initial dry value of around 9% by end of the test on 31 May 2017.

Evidently there are some smaller and bigger fluctuations throughout the test period, accounting for daytime or nighttime, sunny or cloudy days and warmer or colder spells in the season; nevertheless, an obvious general and overall trend of wetting and drying is noticed. The 'no-wetting' season starts with MC of 10% at the beginning of the test period and continues until around mid-October that MC starts increasing and reaching to its 18% peak. And until around middle of January 2017, an overall drying starts and continues until the end of the test period to its initial moisture content at the beginning of the test period, below 10%. Interestingly, in the drying season, fluctuating wetting and drying periods is seen. This is not surprising in the shoulder season, Feb-Apr.

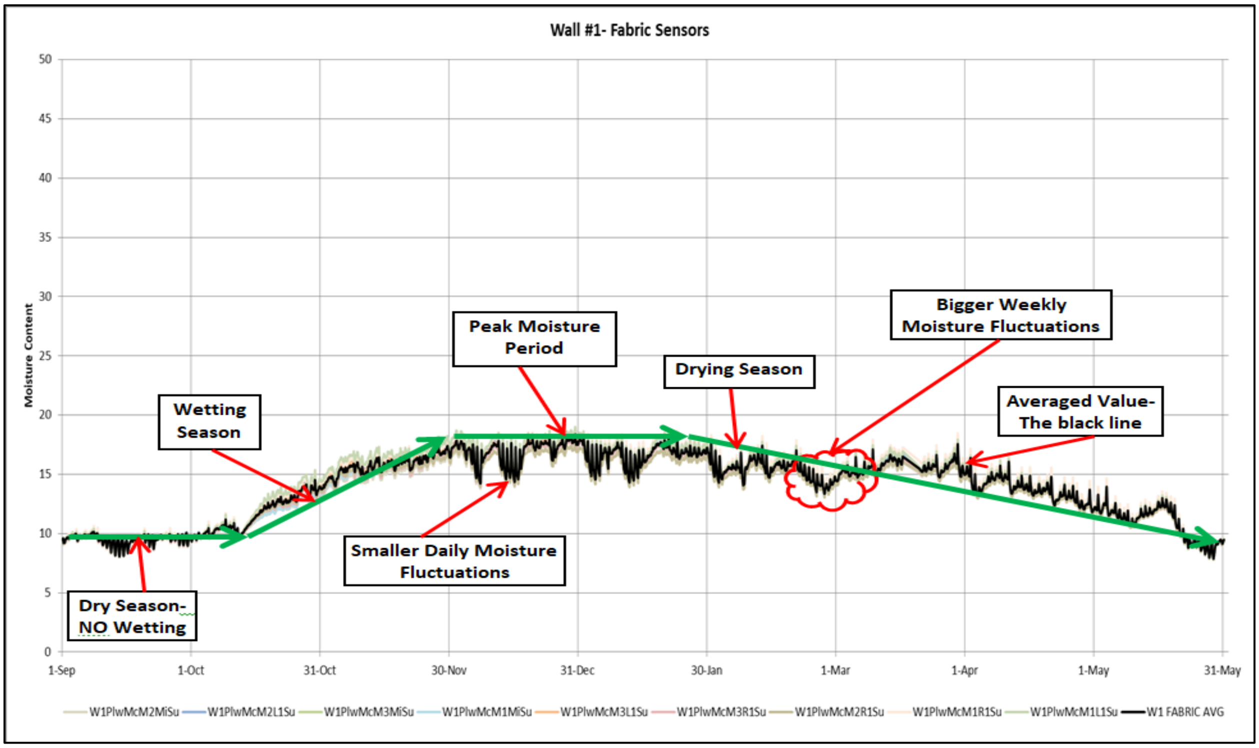


Figure 80- Wall#1- MC for Plywood, Middle Section- Hourly Avg.

6.5.3.2.3 Upper Section Sensors

The sensors at the upper level are 12" apart in height, but there is barely any difference in their moisture content levels throughout the entire test period Figure 81). The two sensors start both from 9% MC level, peak at 18% and drop back down to the starting value of 9% by the end of the test period. The two upper and lower sensors are averaged and graphed with black color that is almost entirely overlapping the other initial graphs as they are both very similar.

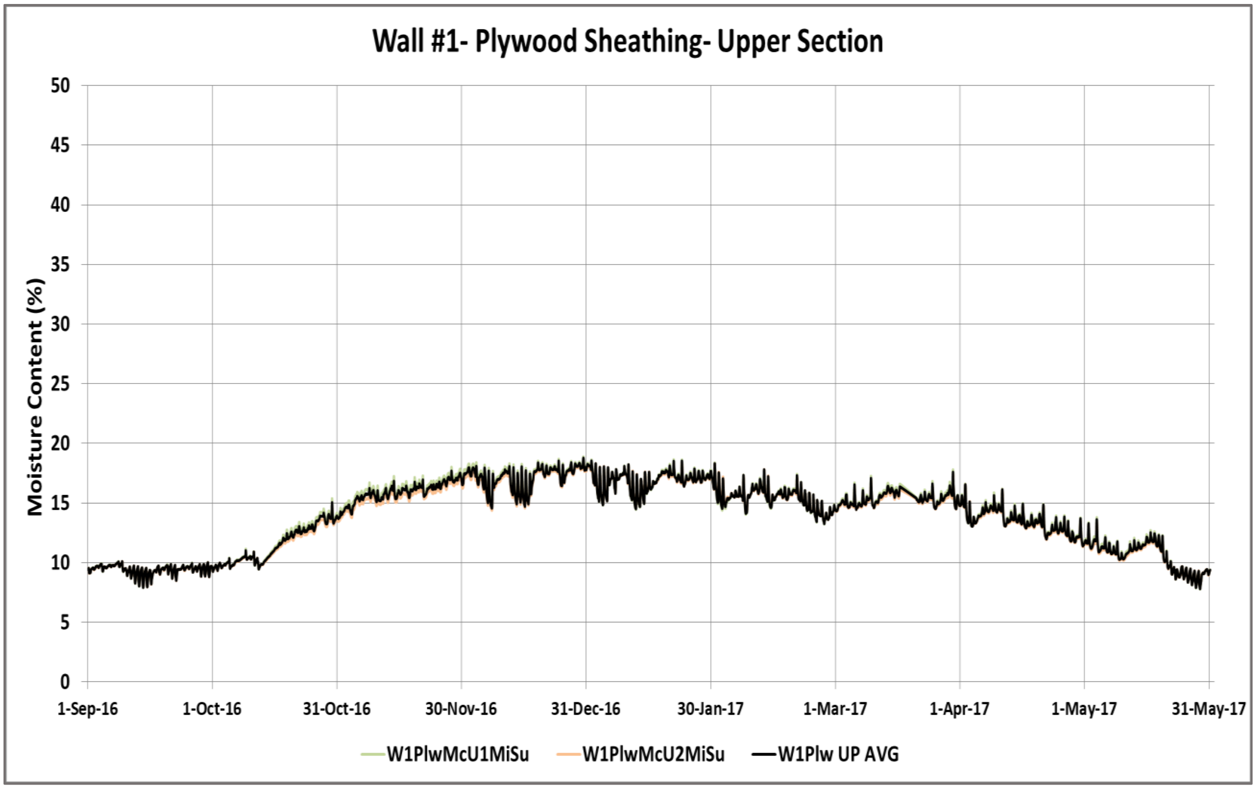


Figure 81- Wall#1- MC for Plywood, Upper Section Sensors- Hourly Avg.

6.5.4 Stud Space

6.5.4.1 Cellulose Relative Humidity (RH)

RH changes in insulation can be helpful in understanding wetting and drying of wood components and their moisture exchange with the ambient environments in the wall assembly.

Results of the three Relative Humidity (RH) sensors are presented here (Figure 82, Figure 83).

Figure 82 shows wide range of daily RH fluctuations interacting with daily changes of solar radiation, outdoor temperature and moisture levels of exterior layers (cladding and sheathing). These daily RH fluctuations often overlap so daily RH graphs (for all walls) were created for easier overall comparison (Figure 83). This will be the case for walls#2,3,4,5.

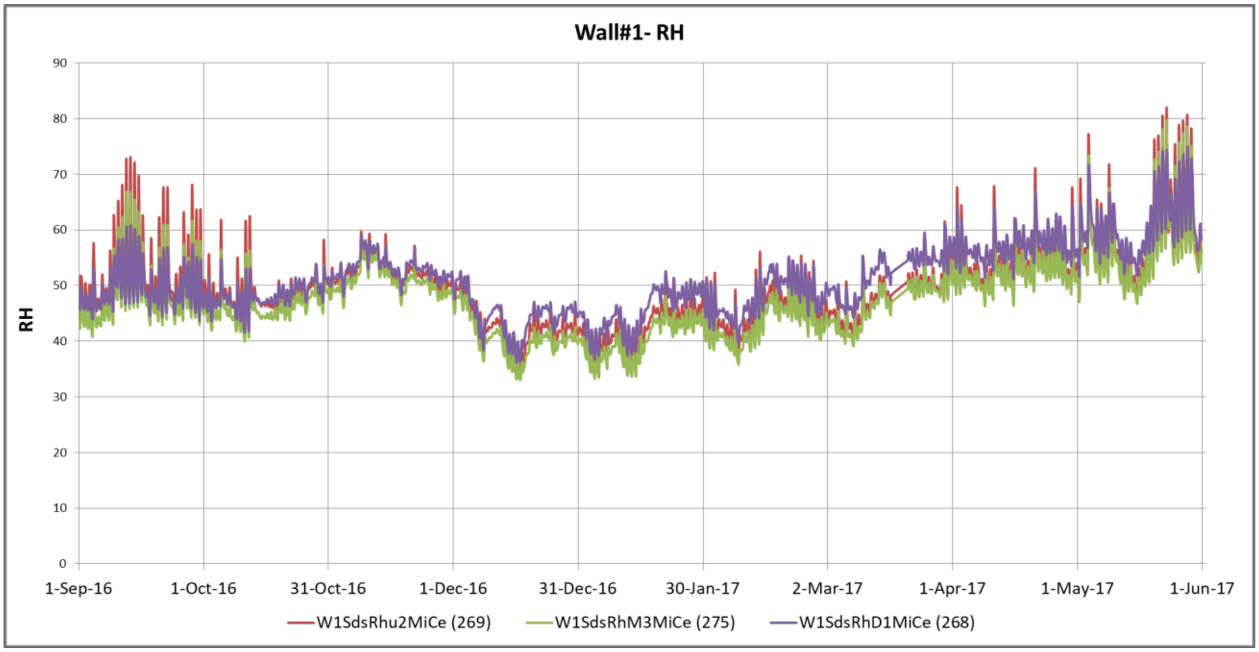


Figure 82- Wall#1- RH for Mid-Thickness of Insulation, Group-Averaged- Hourly

While relative humidity (RH) levels of this wall stayed within safe levels of below 70%, interestingly it had a different, and at some periods, almost reverse trend compared to the exterior framing and plywood sheathing. RH numbers reach to their peak level of around 55% by around middle of October 2016 and from then numbers start decreasing until middle of December 2016 to below 40%. From then RH levels has a fluctuating and yet steady overall rise until the end of the test period reaching its peak of just below 70%. This is almost totally the opposite behaviour compared to the MC levels discussed earlier which could be explained by moisture storage and buffering capabilities of cellulose insulation; by the end of December exterior framing and plywood sheathing are experiencing the coldest average temperatures of the test period, so vapour pressure is the lowest and consequently flows from the interior towards the exterior. This means the moisture within insulation starts to migrate towards plywood sheathing but this behaviour reverses as we go towards warmer season. At the warmer days of September, April and May, the exterior temperature and vapour pressure rises and consequently the vapour pressure gradient within the wall assembly reversed to inward causing rise of RH levels for insulation in the mid-thickness of the wall (Figure 83).

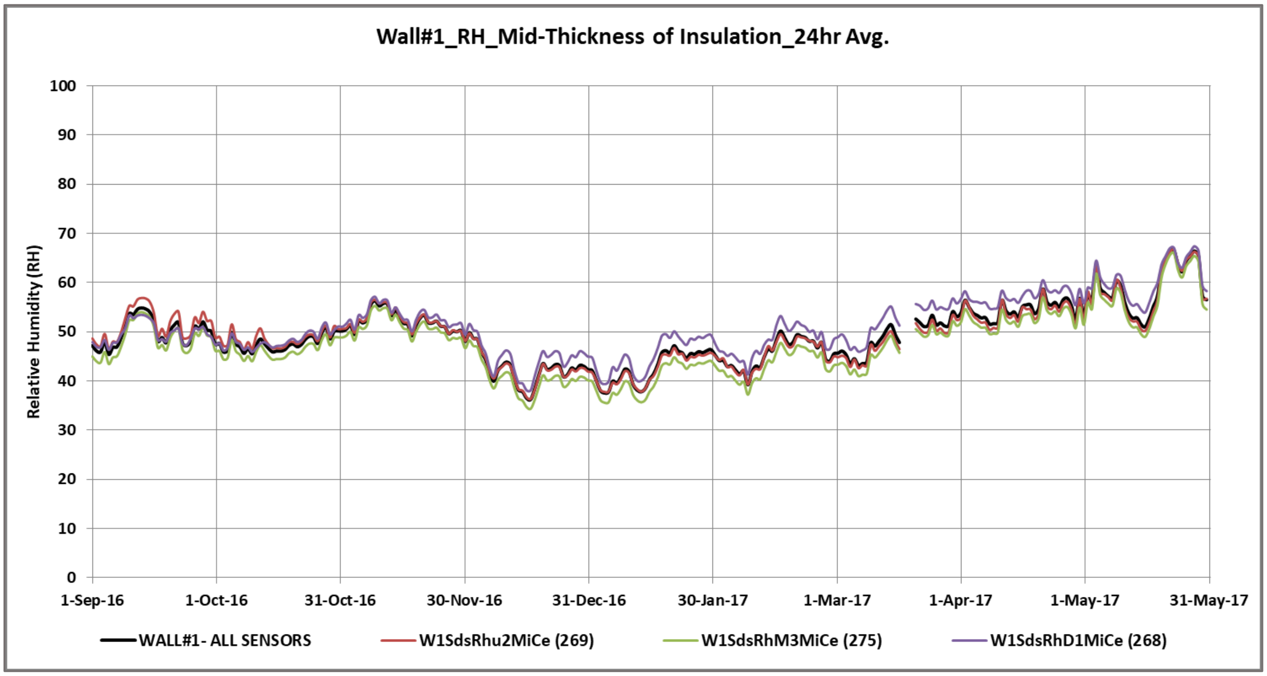


Figure 83- Wall#1- RH for Mid-Thickness of Insulation, Group-Averaged- Daily

6.5.4.2 Cellulose Temperature (Ts)

In Figure 84, there is up to 5°C difference in temperature between the lowest and upper sensors evident in the graph below. This trend is similar in the proceeding walls and will be discussed there too.

Heat stratification can be seen in Figure 84 accounting for the higher RH levels of lower elevation sensor, *W1SdsRhD1MiCe*, in the previous section.

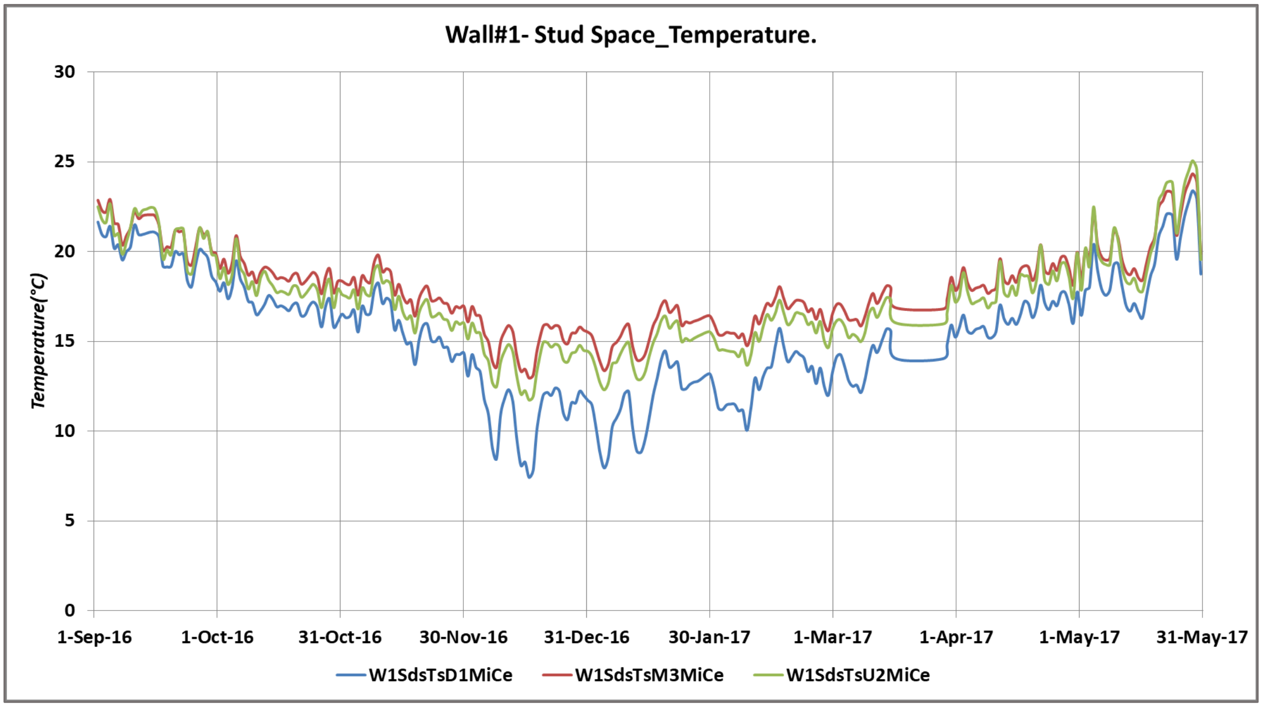


Figure 84- Wall#1- Temperature for Mid-Thickness of Insulation, Group-Averaged- Daily

6.5.5 Discussion

Figure 85, graphs the daily vapour pressure averages of indoor and outdoor ambient climate (Burnaby, BC, SE elevation of BETF) along with the calculated vapour pressure for the lower, middle and upper sections of the plywood sheathing to showing vapour gradient and its seasonal flow patterns for wall#1. The orange line shows the interior air vapour pressure and that is why it looks steady and flat, while the black line shows the vapour pressure in the exterior ambient air which changes daily and seasonally. There are several interesting observations from this graph; for the coldest and cloudiest periods, a duration of around six months, from 01 Oct 2016- 01 Apr2017, vapour pressure of plywood sheathing in all the three vertical positions remained below the vapour pressure of indoor air. This means there was no vapour pressure gradient or diffusive drying from outdoor to the interior environment. On the contrary, it was a consistent vapour pressure gradient from the interior towards plywood sheathing with a potential of elevating plywood's moisture content. Moreover, vapour pressure of plywood sheathing changed very similar to the exterior air vapour pressure, but it is also greatly affected with receiving solar radiation. A big portion of the test period, vapour pressure of plywood remained higher than outdoor. This means, vapour could dry from the plywood sheathing to the exterior environment. Overall, vapour pressure increased from bottom to top of plywood sheathing. This could be the effect of heat stratification that temperature rises and falls with elevation.

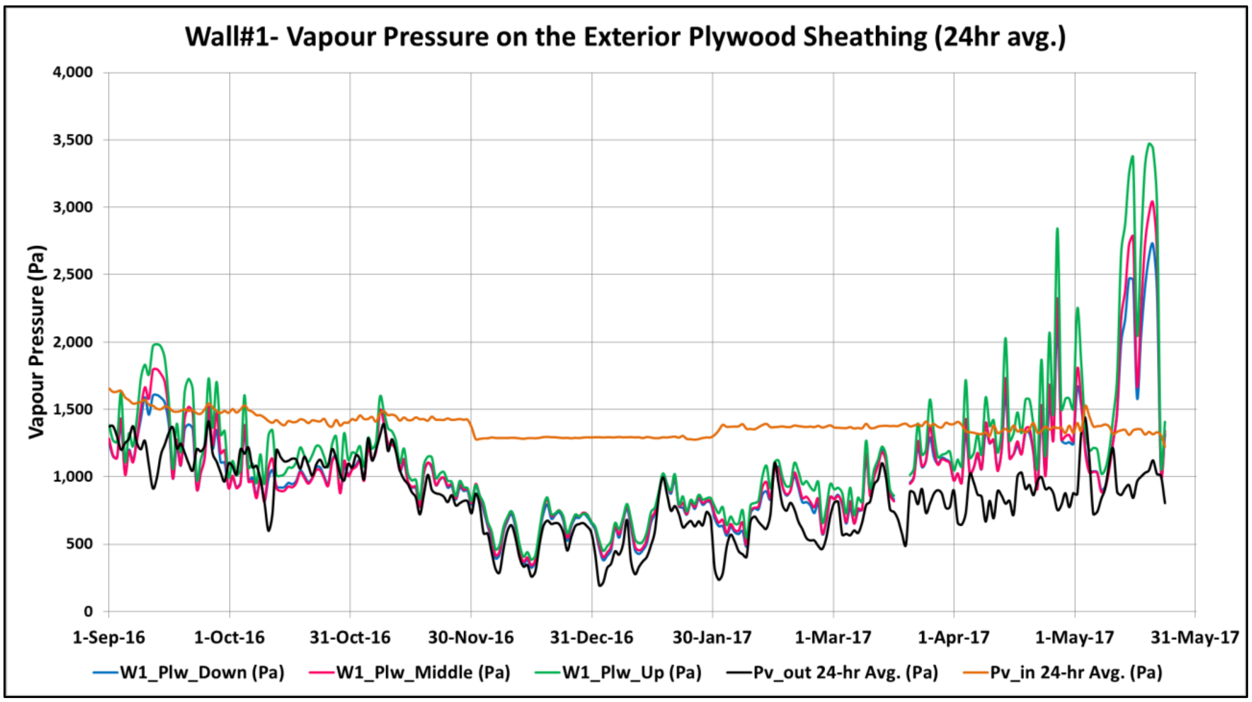


Figure 85- Wall#1- Plywood Vapour Pressure

For 01-31 Sept 2016 and 01Apr-31May 2017, total of three months that is associated with shoulder season, vapour pressure on plywood sheathing was not consistently changing with the exterior ambient environment, but in many periods significantly higher. The most extreme example occurred in around middle of April 2017 that vapour pressure of plywood rose to up 3,500 Pa, higher than both the interior vapour pressure (of 1,400 Pa) as well as the exterior vapour pressure (hovering around 1,000 Pa). This could mean two things; this vapour pressure hikes seen on the plywood sheathing should have been the effect of more solar radiation raising the temperature of HBP siding and plywood sheathing (indirectly, reflecting from HBP siding or from heated ventilated air in the rainscreen ventilated cavity (Figure 69). Secondly, on days that the vapour pressure on plywood sheathing goes above interior and exterior ambient environments, plywood could dry to both interior and exterior air environments and therefore the fastest drying occurs in those days (evident on the MC graphs).

As for moisture content (MC) changes, Figure 86 shows all the hourly average values of lower, middle (fabric) and upper section of the plywood sheathing and also framing, interior and exterior in wall#1.

As we can see (Figure 86), the three different vertical locations on plywood sheathing are almost identical in their MC changes and this further demonstrates evenness of MC levels in this type of wall if there is no intruding liquid water. It needs to be noted that in all MC graphs, there are some missing data (not recorded properly by DAQ), around three days from 18-21 May that the graph is disconnected. This does not affect the overall trend of MC and other data as we have enough data to look into moisture performance of walls.

Plywood sheathing starts gaining moisture around middle of October 2016, which is the time that precipitation rates increase, and temperature drops in Lower Mainland, BC (also visible on the weather data section). The lower exterior ambient temperature lowers the temperature of exterior plywood sheathing, leaving it more vulnerable to possible cases of air leakage or vapour diffusion condensation, so curbing possibility of air leakage is a very important consideration in hygrothermal design.

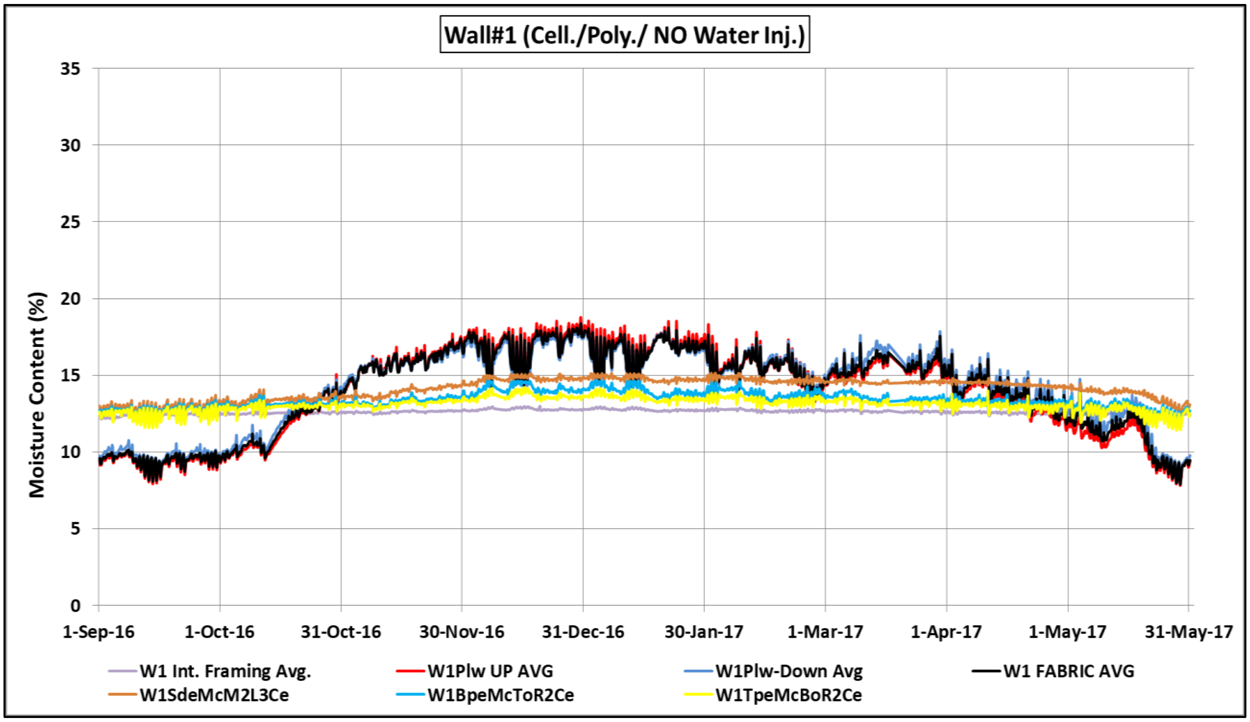


Figure 86- Wall#1- MC for Plywood and Framing- Group-Averaged- Hourly

There is very similar moisture level behaviour between the averages of the three main elevation areas. This can translate into effectiveness of cellulose insulation in lowering air gaps that can lead to higher moisture buoyancy and heat stratification within the stud space filled with insulation. In simple words, air and moisture cannot move around within the wall easily helped by cellulose insulation reducing air infiltration and/or exfiltration.

6.5.6 Mold Index (MI)

As a general comment for all walls, Mold Index (MI) sums up the moisture responses of plywood sheathing because this index not only includes moisture content rates, but also considers the temperature and substrate types with different moisture sensitivities.

As discussed earlier, MI is calculated from RH levels and as a general point, when RH levels go above 80% mold activity is a possibility if the temperature is favourable. Figure 87 shows that plywood sheathing was declining in MI rates in the coldest months of the winter season in December of 2016 and January of 2017. From February of 2017 that temperature averages start to rise again, mold activity also starts growing and gets to its peak by around end of April of 2017. From end of April, MI starts falling again (expect exterior framing) which should be due to effect of lower MC and RH levels of plywood sheathing at this time of the test period (although temperature is more favorable for mold growth). The final MI numbers are all below one which is classed as “no mold growth” or “Small amounts of mold on surface (microscope), initial stages of local growth” (Ojanen, et al., 2010).

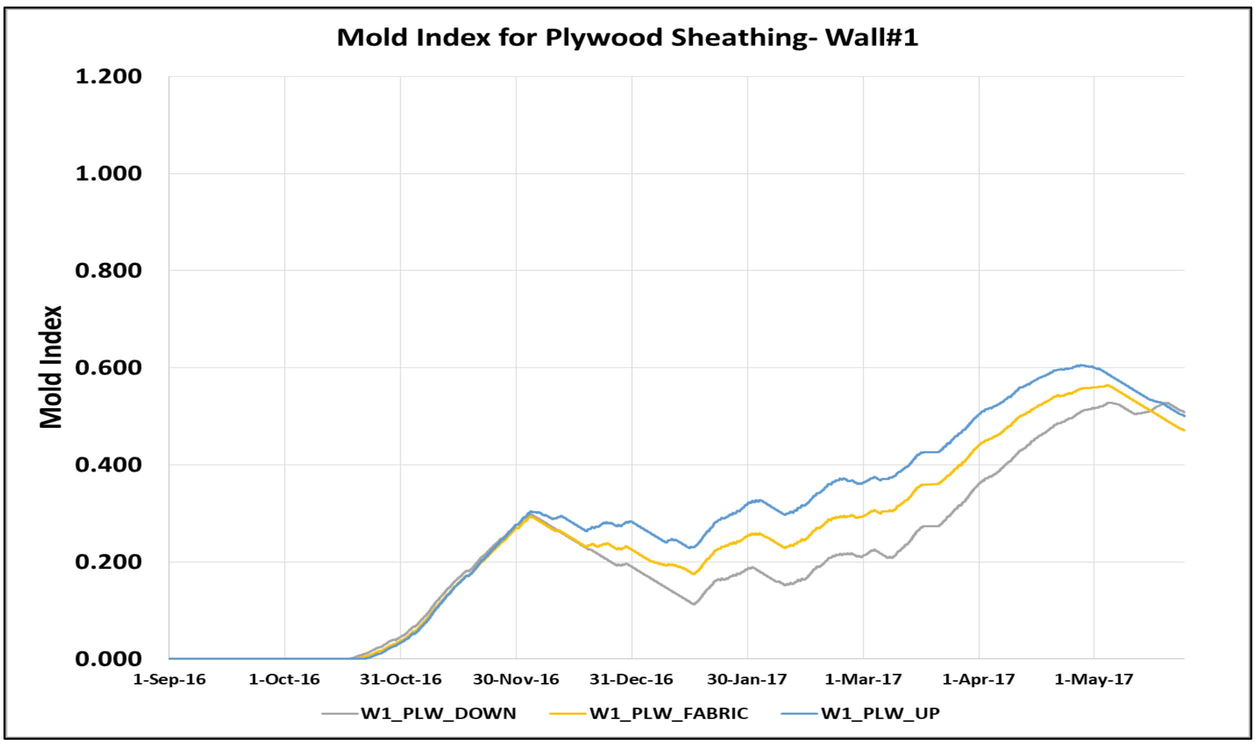


Figure 87- Wall#1-Mold Index for Plywood and Framing- Group-Averaged

6.5.7 Summary

- Plywood sensors recorded the highest moisture gain and subsequent loss, followed by exterior framing and the interior framing.

- None of the sensors in this wall recorded moisture contents close to risky moisture related rates (19-28%).
- Plywood sheathing had a relatively steady moisture content behaviour in various locations, starting from 9%, reaching its maximum of 18% by end of December and a bit of more fluctuating behaviour from end of December that drying starts until to its initial moisture content of 9% by 31 May 2017
- Exterior framing experienced a minimal moisture gain of up to 3% from 12% to 15% at its peak around at the end of 2016.
- Interior framing was barely affect by seasonal changes and stayed dry throughout the entire monitored nine months of the test period, from 01Sep 2016 to 31 May 2017, but had the highest final MI number due to its more favorable temperature levels for mold growth.
- Table 9 summarizes MC variation for plywood and exterior framing that are already discussed in this section.
- Mold Index remained below one (MI<1.0) for the entire test period.
- Relative Humidity had a different behaviour compared to MC levels of the exterior wood framing and plywood sheathing for the seasonal vapour pressure gradient changes from outward to inward.

Table 9-- Wall#1- Moisture Performance Summary

Wall#1	initial MC (%)	max MC (%)	MC gain (%)	Reached 28%?	days above 19%	# of wetting days	# of drying days	Final Mold Index	Overal Moisture Performance
lower Plw	9	18	9	No	0	90	150	0.51	Safe
Fabric	9	18	9	No	0	90	150	0.47	Safe
Upper Plw	9	18	9	No	0	90	150	0.5	Safe
Bottom Plate	13	14.5	1.5	No	0	120	150	-	Safe
Middle Stud	13	14	1	No	0	120	150	-	Safe
Top Plate	13	15	2	No	0	120	150	-	Safe
Int. Frame	12	12.5	0.5	No	0	120	150	-	Safe

6.6 Wall#2

6.6.1 All Sensors

Wall number two is double-stud frame filled with Dense Cellulose Insulation, with NO vapour barrier behind its interior gypsum board sheathing and has extra water injection behind its Weather Resistive Barrier (WRB), which is Tyvek in this case. The hourly average data of this wall are presented and discussed for an overall view of its hygrothermal performance, followed by daily and group averages for more investigation of its moisture performance.

6.6.1.1 Temperature (Ts)

As presented in Figure 88, similar to the previous wall, sensors closer to the interior environment remain steadier while the exterior sensors, experience sharp daily and nightly variations with intensive spikes affected by the temperature variations of the outdoor climate. Temperature of exterior sheathing along with the exterior framing (but to a lesser extent), had temperatures varying from almost -10°C in high winter to almost 50°C towards the end of the test period, late May 2017, induced partly by more receiving direct solar radiation. In fact, these extreme high and low temperatures can help with declination of mold index (MI) as higher than 25-30°C can inhibit mold activity (Figure 103).

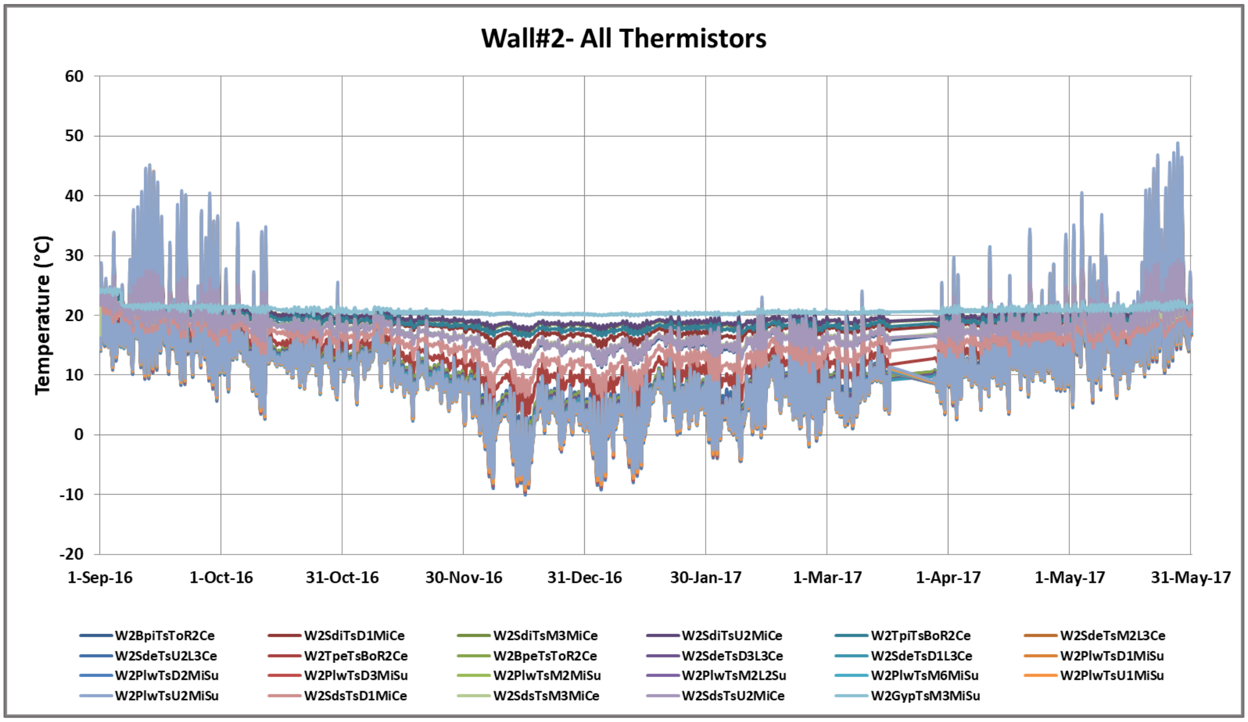


Figure 88- Wall#2- All Thermistors

6.6.1.2 Moisture Content (MC)

Figure 89 shows the moisture content results for the duration of investigated period of 01 Sep 2016- 31 May 2017 for Wall#2 for all MC sensors. Not surprisingly compared to wall#1, in this wall there is much more moisture gain (and the subsequent drying) and this should be the accumulative effect of removing the interior polyethylene vapour control and the injected liquid water.

As a general observation and at a glance, the plywood sensors experienced significantly higher levels of moisture content than exterior wood framing consisting of vertical wood studs plus top and bottom plates. Although the exterior framing had more moisture gain than the interior, but it still had steady but below risky levels of MC throughout the entire test period with no sharp moisture hikes after the water injection. The moisture content sensors on plywood recorded the highest levels of moisture gain compared to all other walls and obvious moisture content hikes closely after the exterior water injection occurred at the area that the water injection took place (close to the wetting fabric, in mid height of the plywood).

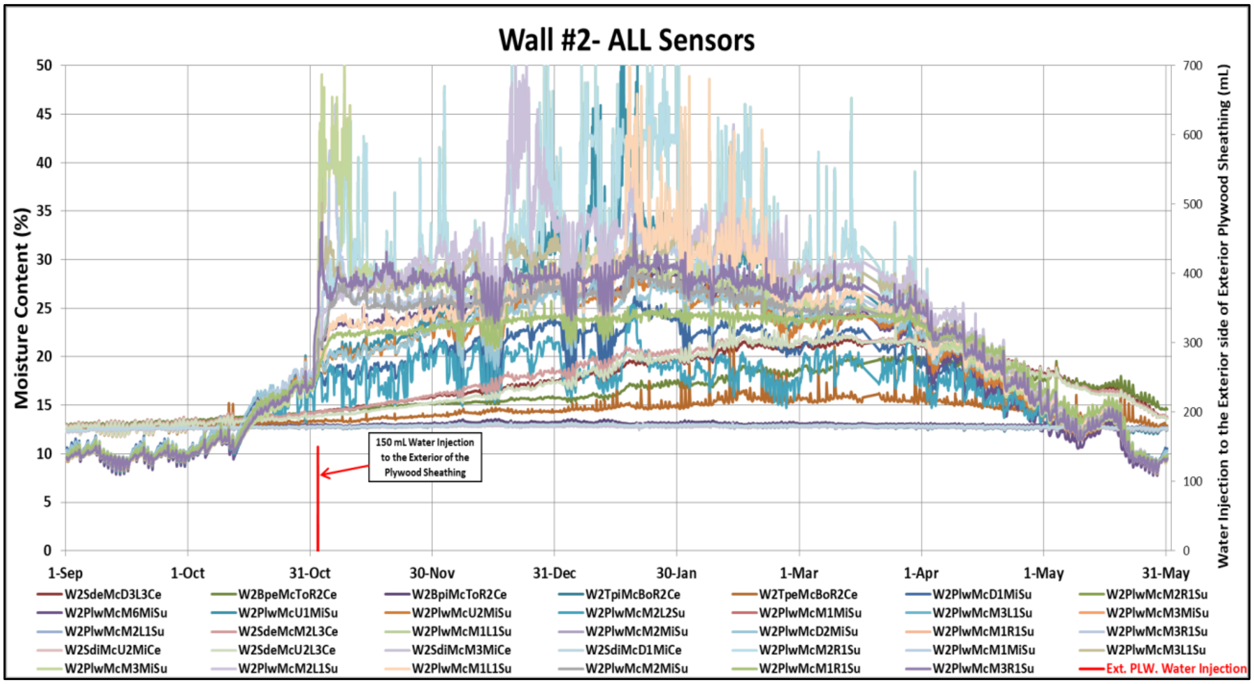


Figure 89- Wall#2- MC for All Sensors- Hourly Avg.

The interior studs and plates, which are closer to the interior environment, had negligible moisture content gain and remained dry throughout the entire test period similar to wall#1. One interesting observation on this graph is around the last ten days of May 2017 that we earlier saw the vapour pressure of plywood rose up to 3,300 Pa, there is a rapid and significant drying of plywood sheathing obvious on the MC graph presented above. This can prove the significant role of solar radiation on drying of plywood sheathing.

For a clearer discussion, as mentioned earlier, sensors were grouped into five different classes like wall#1 and are discussed further in this section.

6.6.2 Interior & Exterior Framing

The recorded data of Moisture Content (MC) and Temperature of Interior and Exterior Framing (vertical studs as well as top and bottom plates), are presented and discussed in this section.

6.6.2.1 Moisture Content (MC)

As shown Figure 90, the interior framing has barely any moisture gain throughout the entire test period and remained dry for all the six sensors planted along the vertical studs in addition to the top and bottom plates. These results were not surprising as the framing adjacent to the conditioned space stays within similar levels of RH and temperature (due to lack of vapour and thermal barriers) resulting in the interior framing staying within its initial MC rates. Moreover, the interior framing is not in the proximity of the water introduction, so not affected with it. This is translated into no moisture related concerns on interior wood framing.

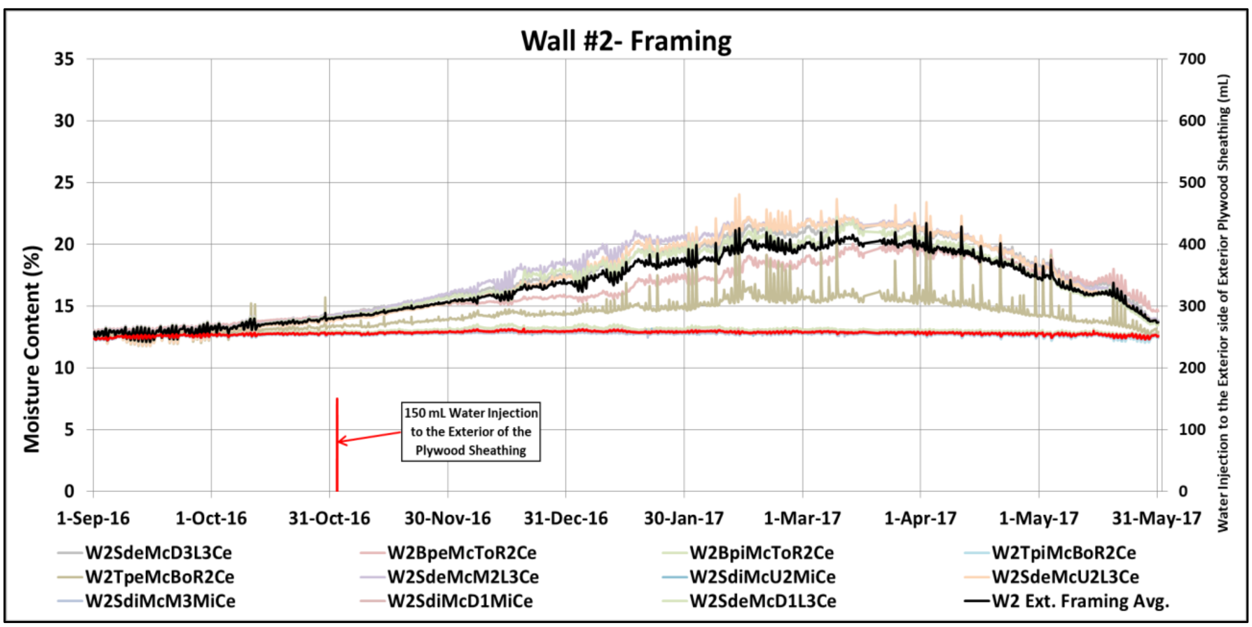


Figure 90- Wall#2- MC for All Framing Sensors- Hourly Avg.

On the other hand, for the exterior framing, there was an obvious moisture gain trend for all the sensors from the beginning of the test period, rising from around 13% to a maximum of around 22% over a period of more than six months by mid-April 2017. Another interesting observation is, unlike all the other sensors that had similar wetting and drying path, the top plate, *W2TpeMcBoR2Ce,* experiences around 5% lower maximum moisture gain and remained significantly drier throughout the entire monitoring period.

To investigate this further, temperature variation between different sensors is looked into.

6.6.2.2 Temperature (Ts)

6.6.2.2.1 Exterior Framing

Similarly to wall#1, temperature of the top plate remained distinguishably higher (up to 5°C) than all the other exterior framing sensors. This higher temperature can lower RH levels which in turn mean lower corresponding equilibrium moisture content. The general trend of temperature was similar to wall#1, affected by outdoor temperature and receiving solar radiation.

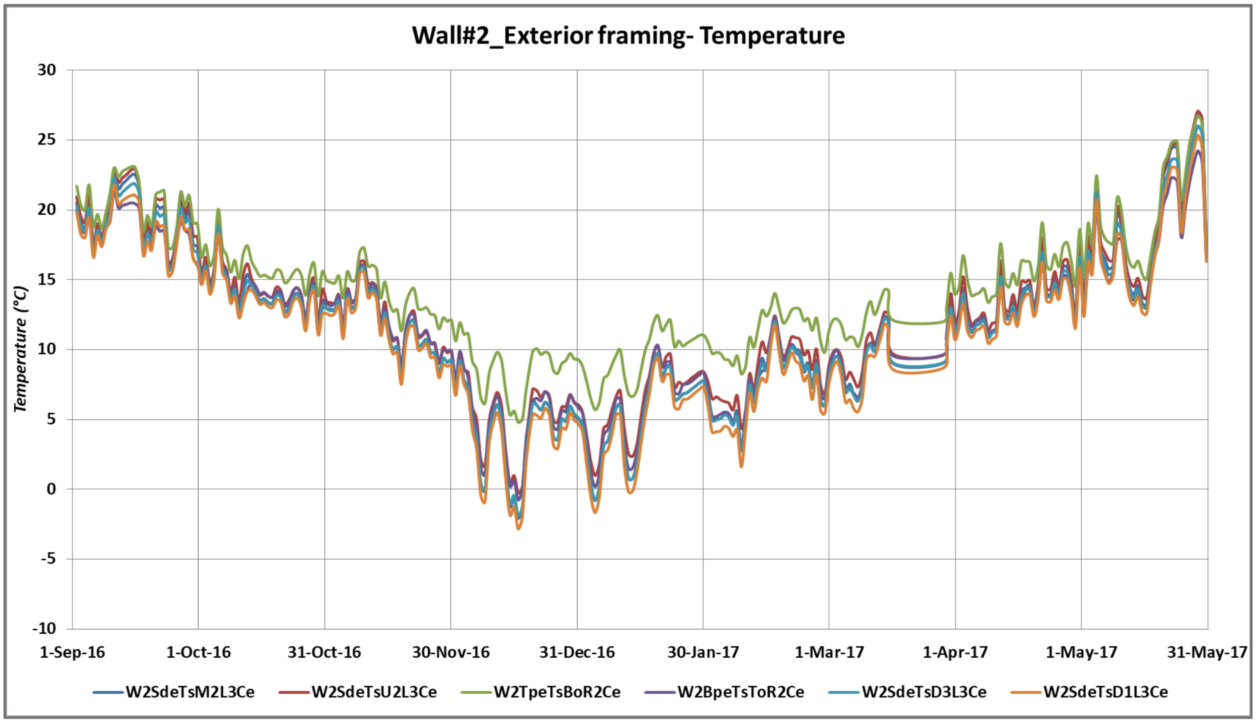


Figure 91- Wall#2- Temperature for Exterior Framing Sensors- Daily Avg.

6.6.3 Plywood Sheathing

As discussed earlier in this section, plywood sheathing of wall#2 experienced high levels of moisture gain and loss. More discussion is presented here.

6.6.3.1 Temperature

Similar to Wall#1, Temperature of plywood sheathing is the average numbers calculated from the lower, middle and upper heights. Since the temperature results are almost identical to the previous wall, the discussion presented in 6.5.3.1 also applies here.

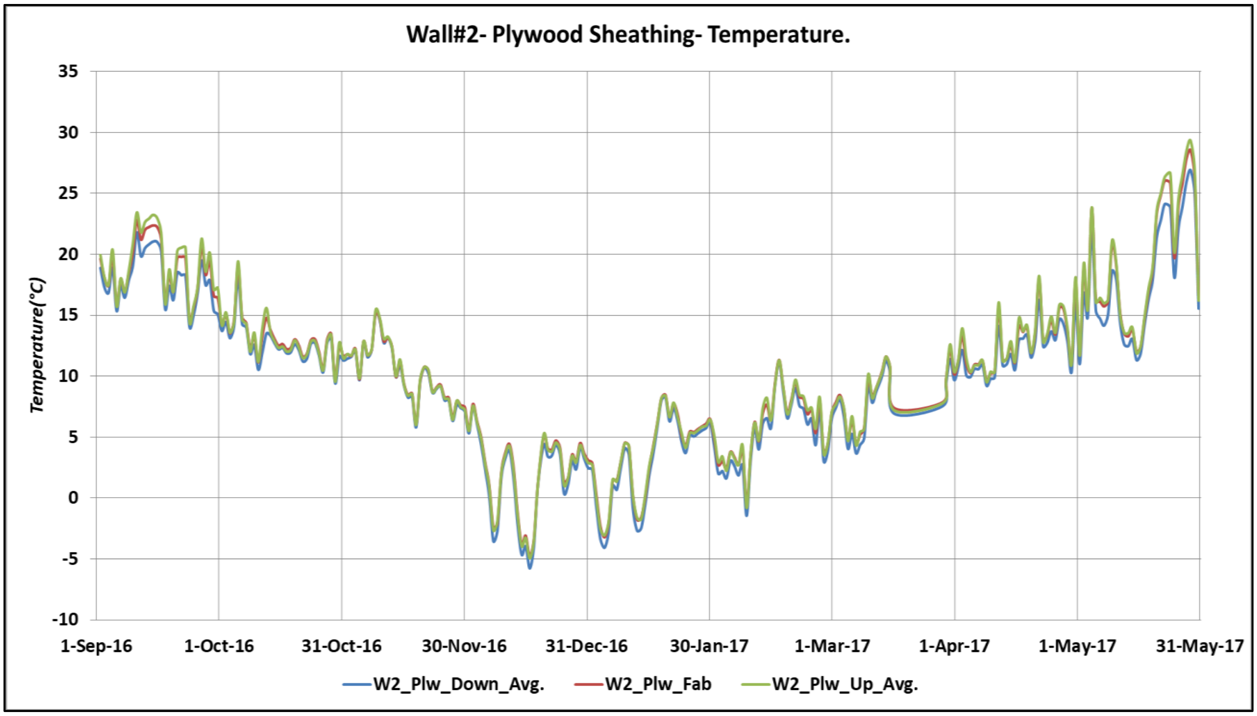


Figure 92- Wall#2- Plywood Sheathing Temperature

6.6.3.2 Moisture Content (MC)

Moisture Content behavior of plywood sheathing in the three different vertical levels, lower, middle and upper is discussed deeper in this section.

6.6.3.2.1 Lower Section

Evident in Figure 93, the moisture behavior of three different sensors on the plywood sheathing in three different height levels are presented. The three sensors are at 4”, 12”, and 20” from the top of the bottom plate, W2PlwMcD1MiSu, W2PlwMcD2MiSu, W2PlwMcD3MiSu respectively. The graphed data shows a clear pattern of more moisture gain at the higher vertical position in comparison with lower positions. This must be mainly attributed to the proximity of higher level sensors to middle section of the wall that liquid water is injected. The injected water can be trapped inside the cellulose insulation and passed to the lower sections over longer period of time.

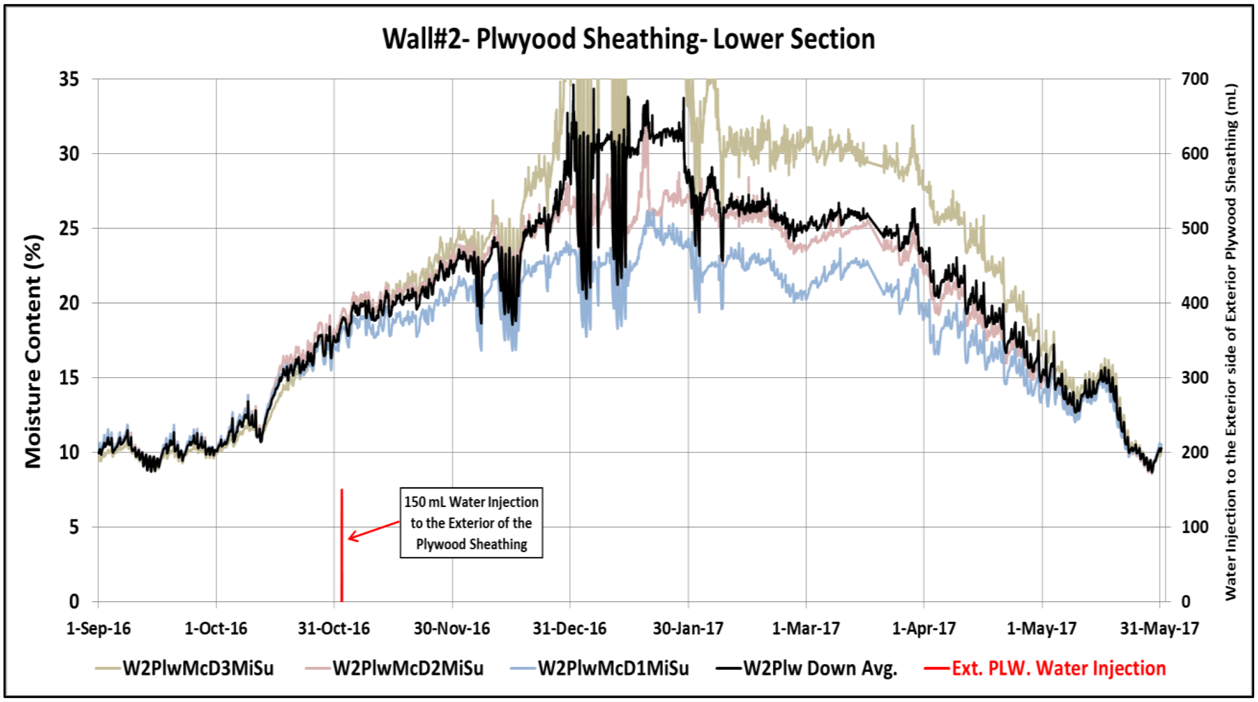


Figure 93- Wall#2- Moisture Content- Lower Plywood Sheathing

A general limitation noticed in this graph, is for *W2PlwMcD3MiSu* and at the peak periods of moisture gain, starting around end of December of 2016, there is a very sharp hike in moisture content, leaving it higher than reliable MC numbers detectable by the current system of electric MC probes. Nevertheless, it is still demonstrating there is higher wetting associated with more proximity to the water intrusion, which is quite expectable. In this case, *W2PlwMcD3MiSu* was the only sensor that went and stayed more than continuous two months above the general moisture content risky limit of 28%. This could cause moisture performance failure of that section of wall#2 and consequently the entire wall, leading to mold germination concerns. On the other hand, the other two lower sensors stayed below the threshold moisture content of 28% for the entire monitoring period, but this wall can be considered failed in moisture performance as mold starts from the weakest link in a wall assembly.

Similar to wall#2, an averaged MC was calculated here (in black color), to compare the general behaviour of lower plywood section with other wall test panels, showing the highest MC levels in December 2016 which stayed above 30%, a very concerning level!

6.6.3.2.2 Middle Section

The middle height of this wall was predictably the wettest area of all other walls, since it is not only affected by interior vapour diffusion but also the injected water on the fabric. Interestingly, vapour pressure of stud space in this section of wall is even higher than the interior air vapour pressure during September and October of 2016, meaning insulation could dry not only to the interior but also to the exterior and plywood. From December 2016 this pattern changes and vapour pressure of insulation drops below interior vapour pressure, most probably because of its decreasing temperature affected by the colder exterior weather, so vapour should flow from interior towards insulation at periods with this condition.

After March 2017 that the outdoor climate starts getting warmer, this trend is resumed and vapour pressure of both interior and exterior goes above interior air, so inward drying (on top of outward drying) is expected.

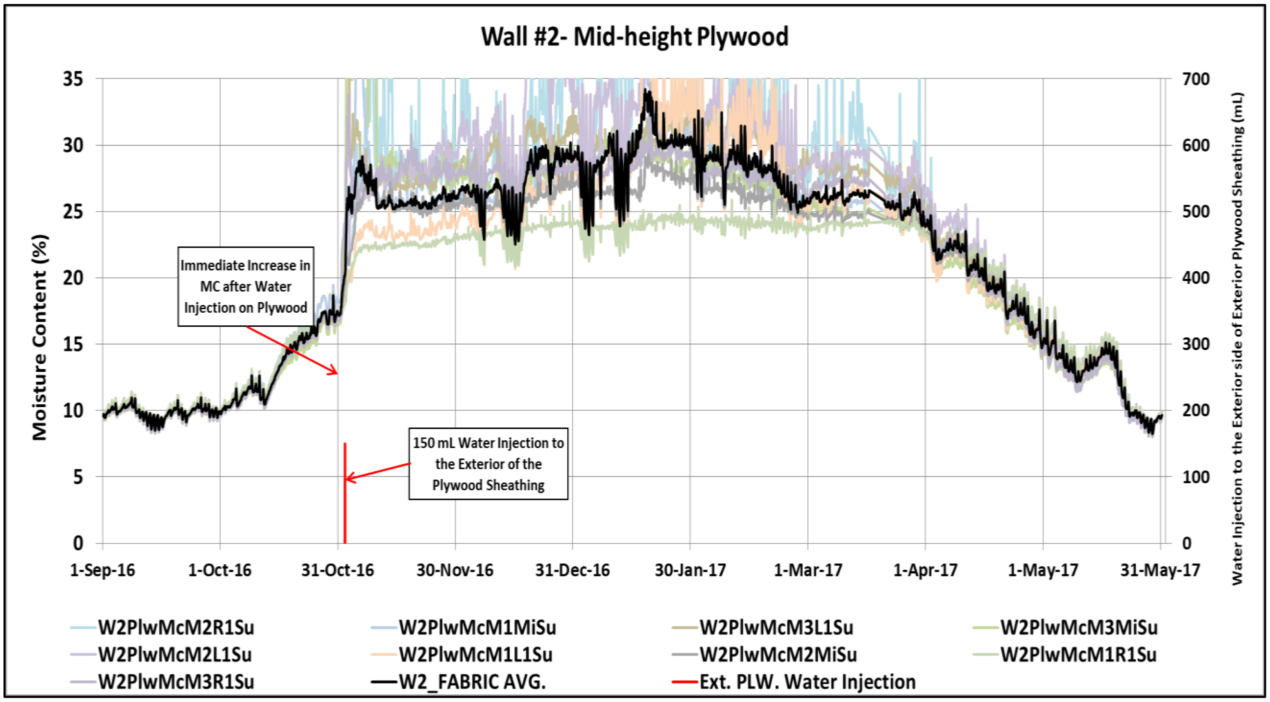


Figure 94- Wall#2- MC for Plywood, Middle Section- Hourly Avg.

Predictably, the sensors that are closer to the water injecting tube should have received more share of the injected water; however, this also depends on the pattern of wetting occurrence. As we can see in the pictures of wetting tests Figure 95 (conducted on the same type of fabric prior to installation), the wetting pattern could vary vastly depending on the pores of injecting tube (soaker hose), water pressure, temperature, sediments clogging up some pores randomly, etc. And this is a major reason of incorporation of nine sensors and averaging

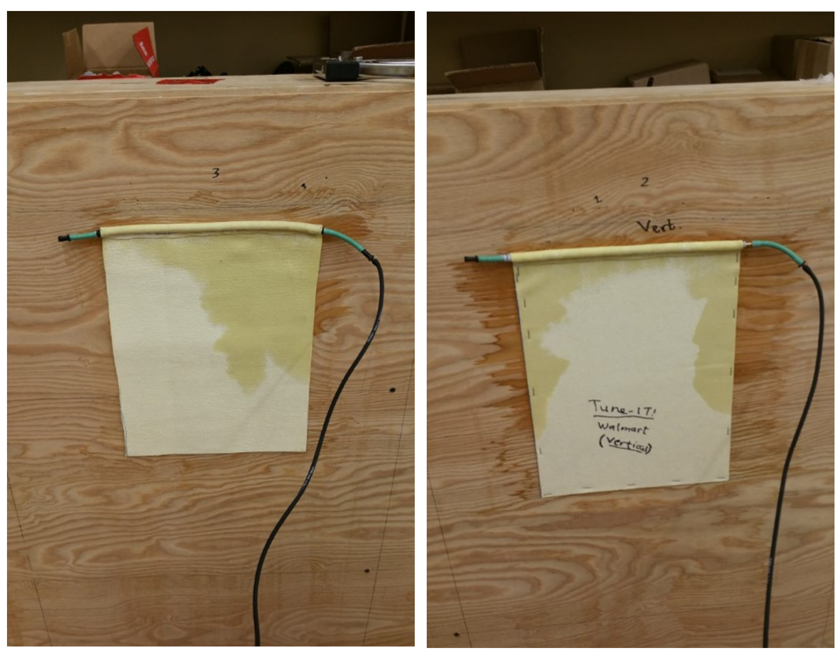


Figure 95- Wetting Experiment on Fabrics

the results into a single number in the graph below to address the randomness nature of recorded data.

Another interesting observation from this graph is such a small amount of water intrusion,150 mL (less than a small glass of water), could elevate MC level of plywood sheathing in that area by around 10% within a couple of days which did not dry out back to safe levels for around five months from the injection date. The moisture content for this case is hovering over risky areas of 28% from around mid-December and does not dry out to lower than 19% for about four months. This is a very risky moisture behaviour.

6.6.3.2.3 Upper Section

This section of plywood sheathing behaved very similar Figure 96 to the other vertical locations of middle and lower sections as discussed earlier, but predictably more comparable to the lower section with no water injection.

In this section of the wall, the lower sensor, demonstrated a significantly higher level of MC compared to the other sensor at its peak, reaching to higher than 40% MC by middle of January 2017. Although there is no noticeable moisture increase after the water injection in early November of 2017, but with the high moisture capacity and buffering properties of cellulose insulation, it could have absorbed the moisture from the middle section of the plywood and transferred it the other sections. In that situation and as expected, the closer the other receiving components of the wall were to the injected water location, the higher the amounts of moisture were received. This may explain why the lower MC sensor, *W2PlwMcU1MiSu*, which is just 11” higher than the wetting tube, rises to significantly higher levels (up to 15% higher) of MC compared to the other MC sensor, *W2PlwMcU1MiSu*, which is located at 12” higher.

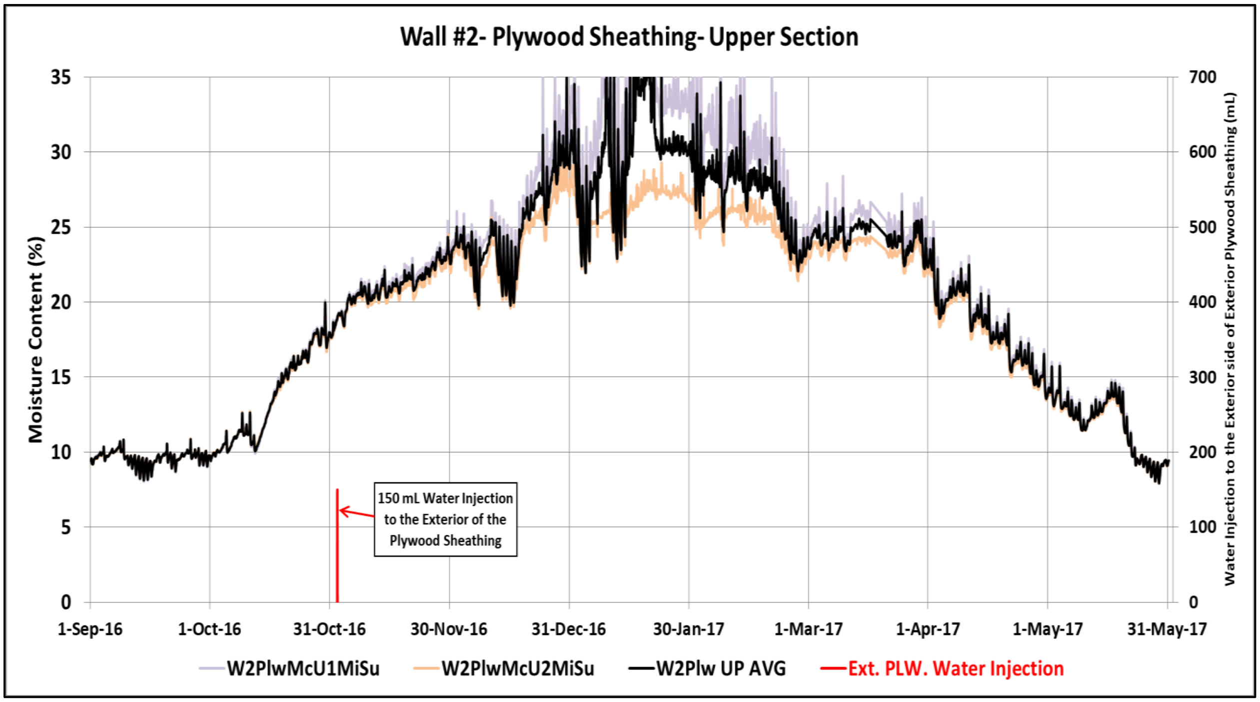


Figure 96- Wall#2- MC for Plywood, Upper Section Sensors- Hourly Avg.

Although the higher-level sensor also approached the threshold of 28% of MC, it was just for a very short time period and did not go over 28%, whereas the MC recorded by the lower sensor, went well over 28% (up to 40%) and stayed in the "red zone" for around *two month*, from around 20 Dec 2016 to 20 Feb 2017.

Again, for comparison reason with other walls, the averaged MC for the higher section of plywood was calculated and graphed (in black color) which overall, shows risky moisture behaviour for two months. This will be further discussed in next sections.

6.6.4 Stud Space

In this section the relative humidity (RH) and temperature of mid-thickness of insulation gap (filled with DCI) is discussed.

6.6.4.1 Cellulose Relative Humidity (RH)

For this wall, four different wetting and drying periods are noticeable. The first wetting period was a rising period from 01 Sept, 2016 to 10 Nov, 2017, for around 10 weeks in total. This RH increase should have been mainly due to vapour diffusing from the interior space because this wall lacks an interior vapour control barrier layer to block interior vapour intrusion.

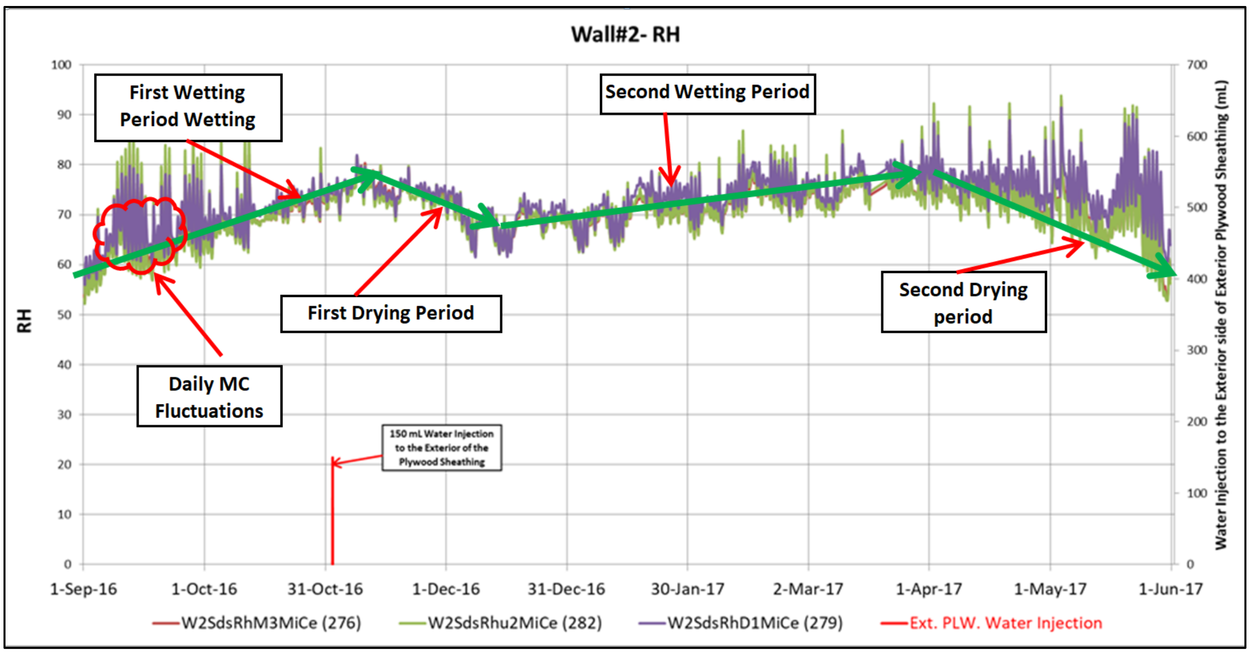


Figure 97- Wall#2- RH for Mid-Thickness of Insulation, Group-Averaged- Hourly

During this period, RH levels increased from around 57-59% (like the interior RH level then), to close to a maximum of 80% by around end of first week of November same year. After then a first period of drying started and continued for around five weeks till mid-December, drying to 65%. The latter period could be explained by moisture transferring from the insulation to the wood components of the wall. At the end of this period in mid-December, another fluctuating yet overall gradual increase starts, as the wooden components could have reached to their maximum moisture equilibrium capacity levels with the coldest and wettest time of the year; as a result, the insulation starts accepting moisture from both the interior environments and wood framing and plywood and reaching again to its highest level of above 80% by end of March 2017. A more distinguishable daily average graph made from the hourly average graph is presented in Figure 98.

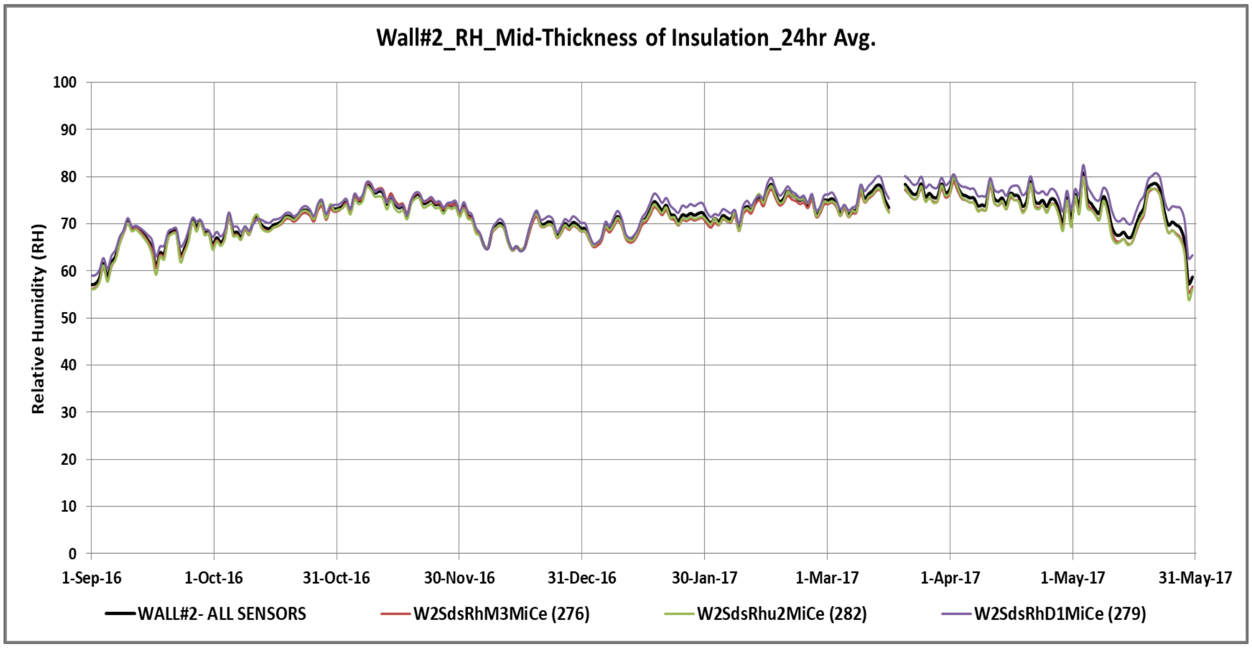


Figure 98- Wall#2- RH for Mid-Thickness of Insulation, Group-Averaged- Daily

From end of March, the second and period of drying starts, moisture is also drying to the interior environment helped by warmer exterior sheathing raising the vapour pressure of its moisture and thus driving its moisture out of wood components inwardly. Moreover, since there is a constant moisture exchange between insulation and wood components of the wall, the dryer the wood components become, the more moisture they can accept from the insulation material within the gap space of the wall, so this can further accelerate the drying of wood components.

As evident on the graph, by the end of the monitoring period, RH was dried out back in a short period of just a few days (from around 20 May to 31 May 2017) to its initial level of 55%.

6.6.4.2 Cellulose Temperature (Ts)

Heat stratification phenomenon in this wall is seen in Figure 99 as the lowest thermistor in the stud space records considerably lowers (3 to 5°C) temperatures.

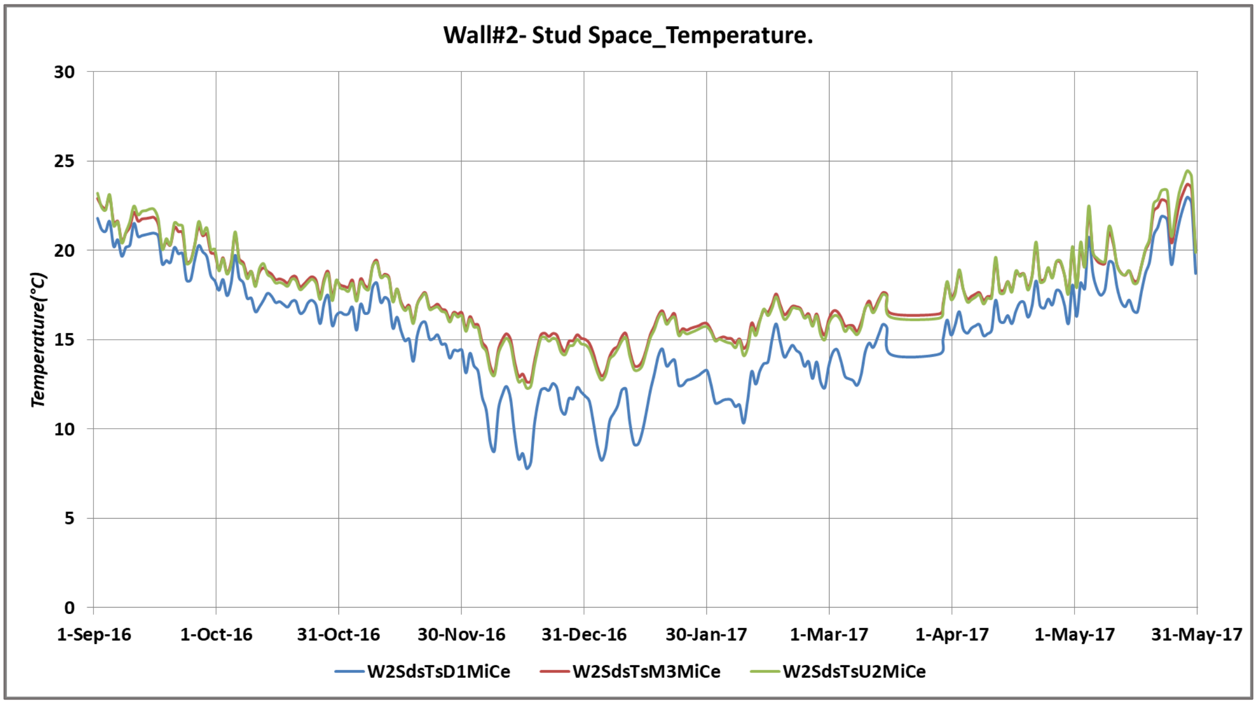


Figure 99- Wall#2- Temperature for Mid-Thickness of Insulation, Group-Averaged- Daily

Mid thickness insulation temperature is affected obviously with the outdoor seasonal and daily temperature changes, however moderated with the interior conditioned air temperature. So, unlike plywood sheathing, the minimum temperature in the coldest season, drops not any lower than 8°C (compared to -10°C of plywood sheathing), but it is lower than 20°C of the indoor climate. Similar to the previous wall, there is an obvious temperature variation between the lower and the other two middle and upper parts of wall, with maximum of 5°C temperature on lower section of insulation. This should be the effect of colder ground temperature and heat stratification as discussed earlier.

6.6.5 Discussion

In this section vapour pressure and moisture content results of wall#3 are discussed in higher and concluding levels.

Like the previous wall vapour pressure of exterior air remains lower than the interior air, so the overall vapour gradient is from interior to the exterior (Figure 100). The vapour pressure of plywood sheathing for all three different elevations (low, middle and up), is like the exterior vapour pressure, but it rises in more sunny periods of September, April and May. One interesting observation is vapour pressure of plywood is higher with higher elevation on plywood which could be the effect of moisture buoyancy and heat stratification. The highest vapour pressure reached in this wall is for the last week of May 2017 that the upper location of plywood sheathing reaches around 3,300 Pa, which is more than twice as the interior vapour pressure and triple of the exterior vapour pressure. This means there is a very high potential of drying for the plywood in both inward and outward directions which since it was not intercepted by a vapour barrier like polyethylene film in this wall should have had relatively rapid drying effects for the plywood sheathing.

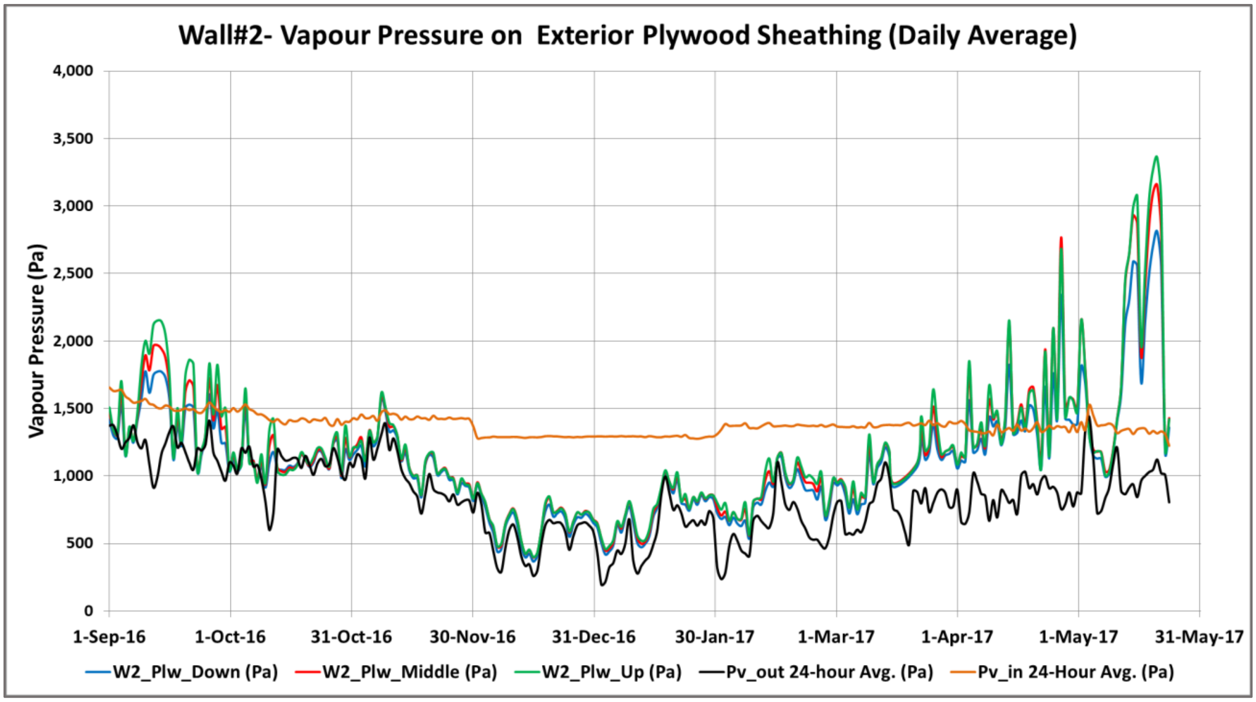


Figure 100- Wall#2- Plywood Vapour Pressure

The averaged vapour pressure of all the different vertical heights for this wall shows (Figure 101) vapour pressure of outdoor as the lowest followed by plywood sheathing, mid-thickness of insulation space and interior air, except for the warmer and sunnier days of shoulder season that insulation space and/or plywood sheathing go beyond indoor vapour pressure, so had inward drying potential.

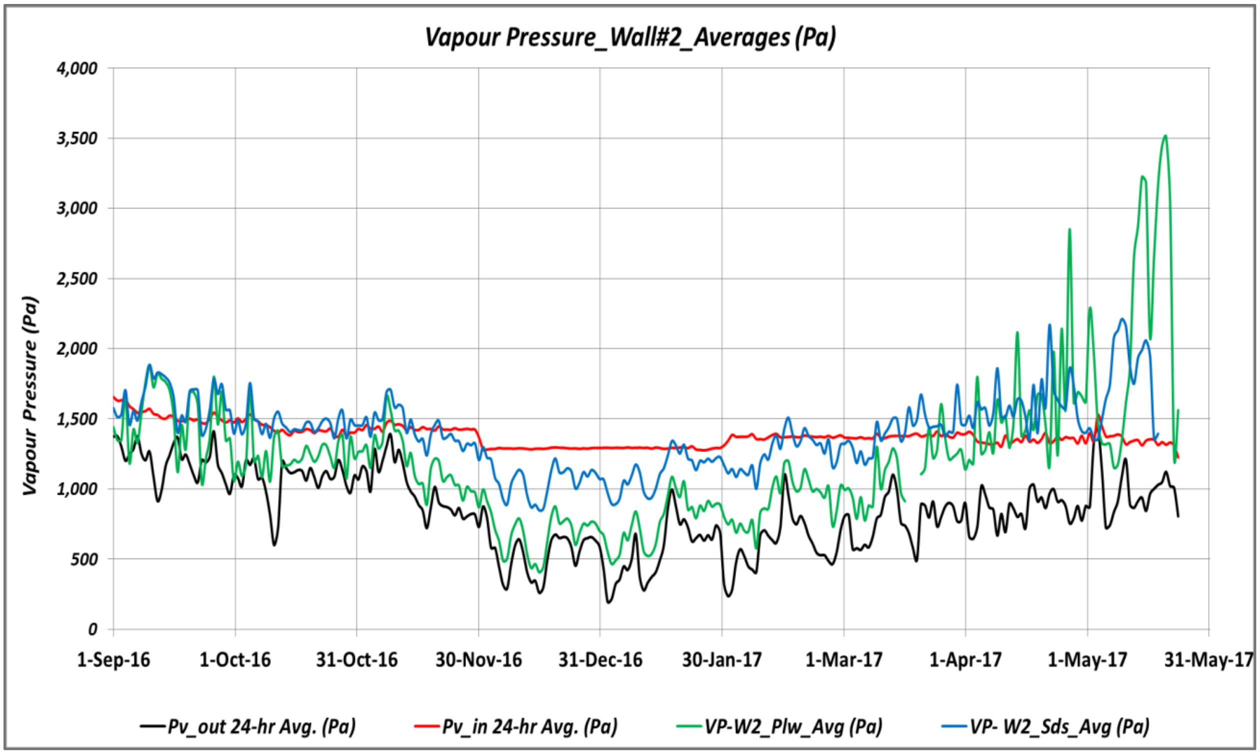


Figure 101- Wall#2- Vapour Pressure- Total Averages- Daily

Figure 102 summarizes MC rates of exterior framing as well as the average rates of plywood sheathing sensors and interior framing sensors in wall#2. Similar to previous wall, interior framing sensors were barely affected by neither water injection nor change of the season and remained dry for the entire test period. After the interior framing, top plate sensor had the least moisture gain among other sections, not exceeding the safe MC rates of around 16-17% (ignoring the spiky anomalies). Bottom plate had higher moisture levels than top plate, reaching to its maximum of 20% by middle of March 2017 and staying on that rate for another three weeks. The exterior vertical stud experience noticeably higher MC levels than the previous locations so far, reaching to 22% by early February 2017 and remaining that wet for another six weeks.

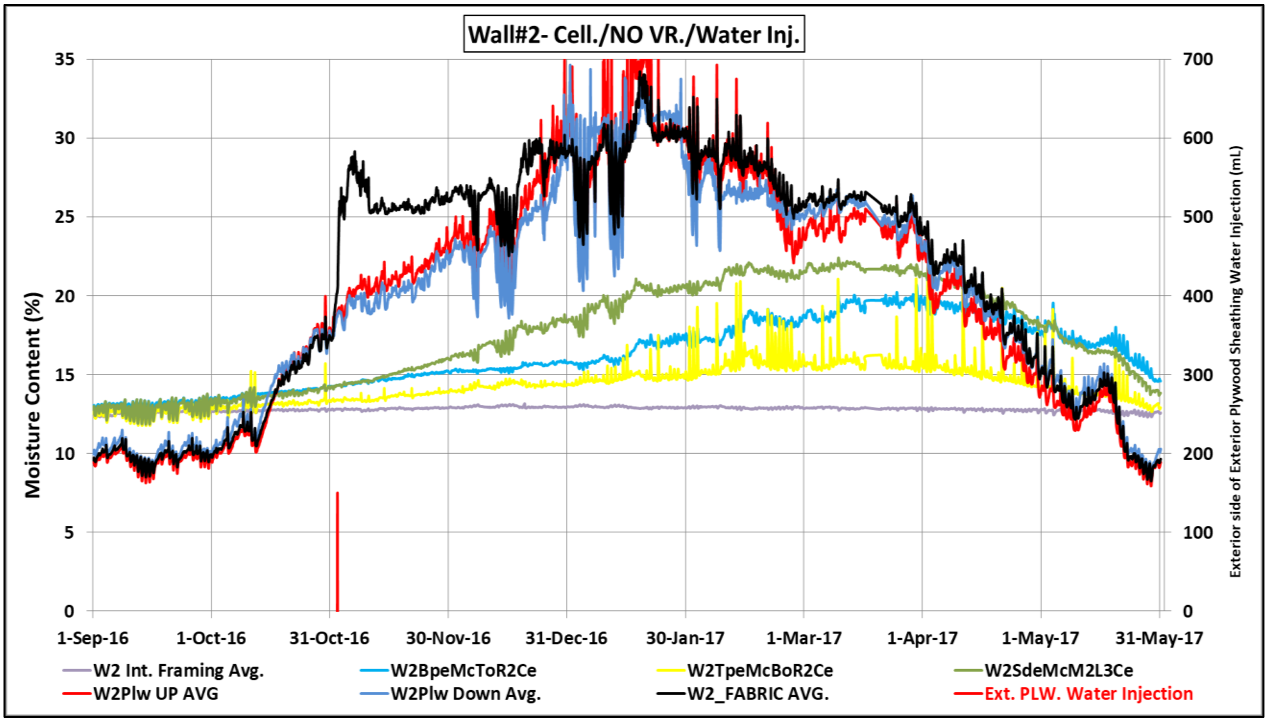


Figure 102- Wall#2- MC for Plywood and Framing- Group-Averaged- Hourly

Although the moisture gain of exterior framing sensors (plates and stud) was significantly higher than the interior framing, yet it stayed below 22. On the other hand, the averaged MC on plywood sheathing surpassed the 28% threshold for all the three locations of lower, middle, and higher locations.

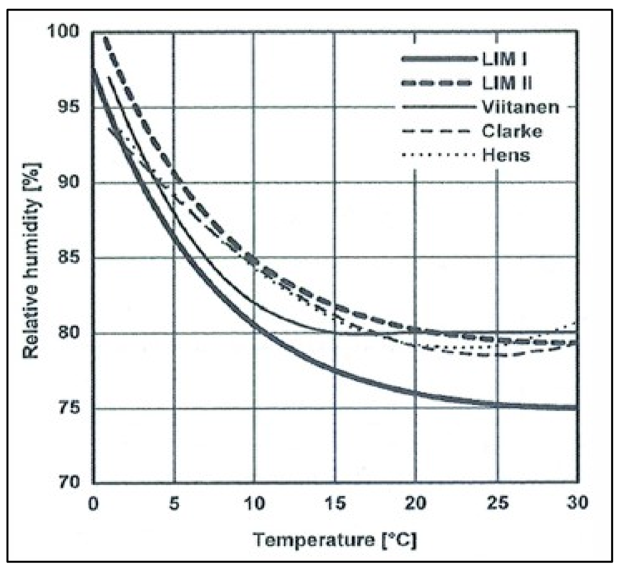


Figure 103- Mold Activity changes with RH and Temperature

The MC levels on the lower and upper sections of the plywood are very similar with no immediate effect from the injected water, whereas the middle section demonstrates a very sharp MC increase of around 15%, followed by a small drop of around 5%, then plateauing by middle of November that intersects with the lower and upper MC location graphs. This can suggest that a rather slow process of moisture exchange between the middle section (with excessive injected moisture) to/from indoor and outdoor environments as well as all other wall components (wood and cellulose insulation) happens until they reach to a moisture balancing point in around middle of November. From that date, all the sensors continue another wetting period of around one month, with 10-15% more moisture gain. This moisture must be from the out-of-wall sources, predominantly the indoor airborne vapour. All the plywood sensors start their drying process from the middle of January 2017, beginning at 33-35%, drying to around 10% MC by the end of the testing period.

One interesting observation is that there are periods of fluctuation between drying and wetting behaviour in this continuum, the most obvious one occurring 10-17 March 2017 that weather got colder and wetter (Figure 70, Figure 69, Figure 66) so the drying trend was reversed and plywood starting gaining moisture again for a round one week.

6.6.6 Mold Index (MI)

As for Mold Index changes for wall#2 Figure 104), unlike wall number one, the averaged plywood demonstrated mold activities starting around middle of October of 2016 and increasing in slope especially after the water injection incident at 02 November, reaching its first peak by around end of November. One very interesting observation on this graph is although the MC on plywood sheathing keeps rising from end of November (Figure 93, Figure 94, Figure 96), the slope decreases slightly. This should be the effect of colder temperature on plywood sheathing which reduces mold activity.

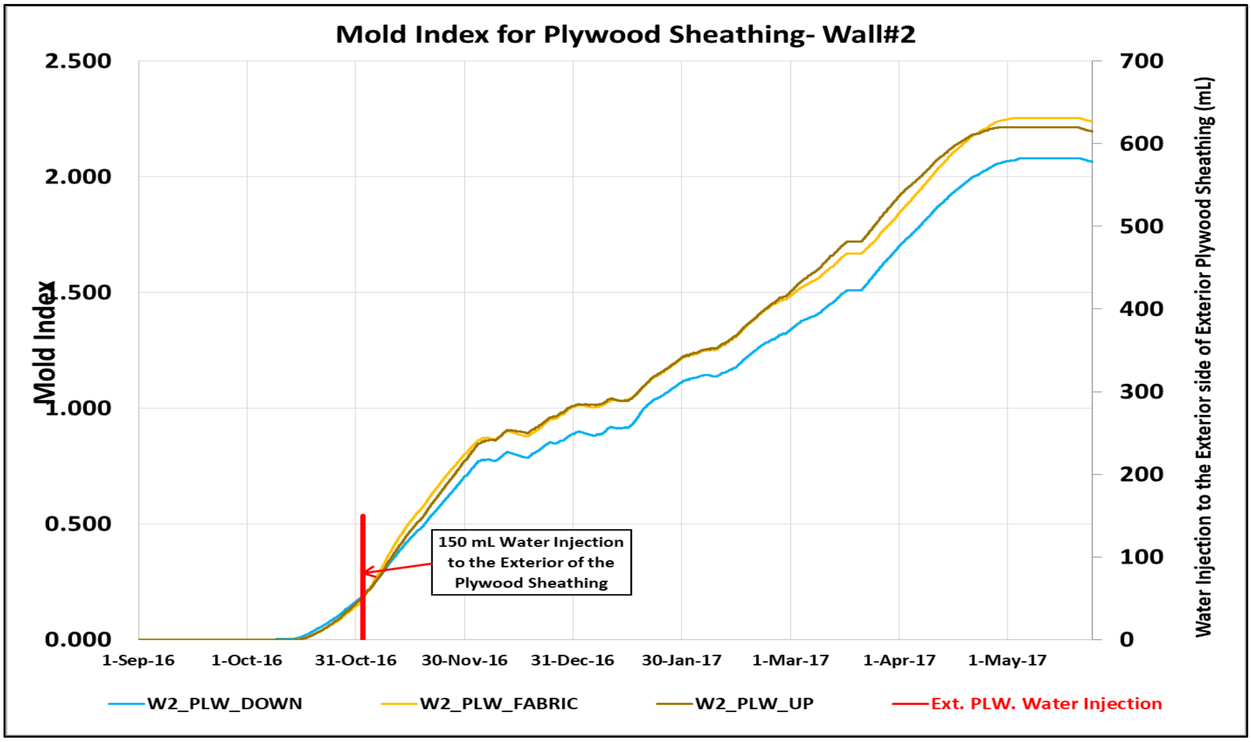


Figure 104- Wall#2-Mold Index for Plywood and Framing- Group-Averaged

For the same reason when from around middle of January the average temperatures started rising again, mold growth activity increased again and continued by around end of April 2017.

Overall, although mold activity did occur, it did not approach critical levels of MI= 3-5 (Figure 105), so for the duration of this test, mold index numbers suggested safe levels, however if this trend continues, the cumulative mold rate may go beyond safe levels in a couple of more years. Understanding longer terms of mold activity for this wall demands longer research period.

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

Figure 105- Mold Index Levels Description (Ojanen, et al., 2010)

6.6.7 Summary

Table 10 summarizes the discussed MC and MI behaviours. All sections of plywood sheathing reached and exceeded MC levels of 33%, with Mold Index reaching 2.2, while, the exterior framing did not go beyond MC of 22%.

Table 10- Wall#2- Moisture Performance Summary

Wall#2	initial MC (%)	max MC (%)	MC gain (%)	Reached 28%?	days above 19%	# of wetting days	# of drying days	Final Mold Index	Overal Moisture Performance
lower Plw	10	33	23	yes	165	110	130	2.07	Fail
Fabric	10	33	23	yes	170	110	130	2.24	Fail
Upper Plw	10	35	25	yes	165	110	130	2.20	Fail
Bottom Plate	12	20	8	No	30	195	75	-	Risky
Middle Stud	12	22	10	No	90	195	75	-	Risky
Top Plate	12	17	5	No	0	195	75	-	Safe
Int. Frame	12	13	1	No	0	120	150	-	Safe

As a conclusion, plywood sheathing failed in moisture response followed by the exterior bottom plate and exterior vertical stud that could be classed as risky moisture behaviour. The safest response was the interior frame (not surprising). Overall, this wall failed in response to the moisture load and boundary conditions of this test.

6.7 Wall#3

6.7.1 All Sensors

Wall#3 is double-stud frame filled with Dense Cellulose Insulation, with conventional 4-mil polyethylene as its vapour barrier behind the interior gypsum board sheathing which is like wall number one but with additional water injection behind its WRB. As an overall view of its hygrothermal performance the hourly temperature and moisture content is investigated in high levels in this section.

6.7.1.1 Temperature (Ts)

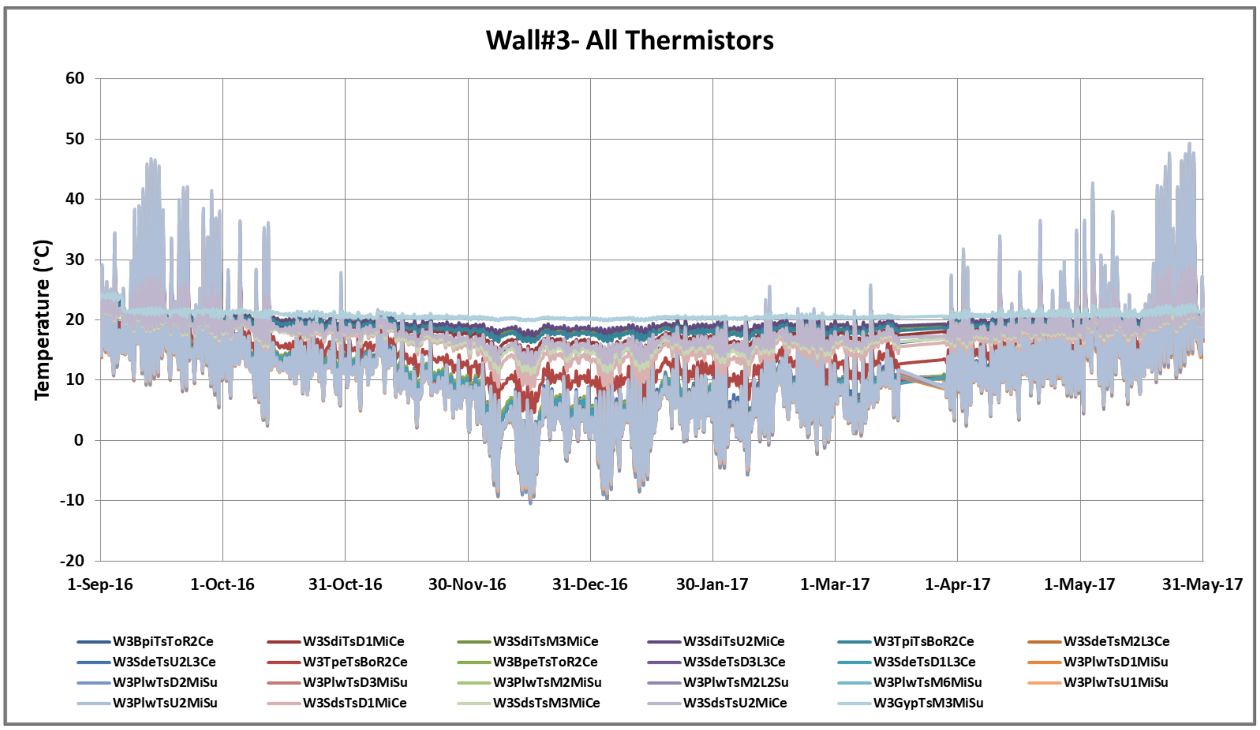


Figure 106- Wall#3- All Thermistors

Like the previous walls, interior thermistors recorded very similar to the interior conditioned environment hovering around 20°C but the exterior framing and more so plywood sheathing were affected by the exterior temperature and solar radiation changes, varying from -10°C to 50°C in winter and summer respectively (Figure 106).

6.7.1.2 Moisture Content (MC)

Moisture Content levels of Wall#3 are presented in Figure 107. With a glance, several MC trends are noticed; firstly, the effect of water injection on the exterior plywood sheathing is obvious on most plywood sensors. Secondly, there is a clear difference between moisture levels of framing, compared to plywood sheathing, while interior framing looks almost entirely unaffected by seasonal changes, the exterior framing does go through the seasonal wetting and drying behaviour nevertheless its moisture peak is lower than plywood sheathing, like the previous walls so far (Wall#1-2).

Another observation is almost all sensors start peaking up in MC around middle of October 2016 and are back to their initial MC by the end of the monitored test period, so wetting and drying is from Middle of October to end of May of the year after.

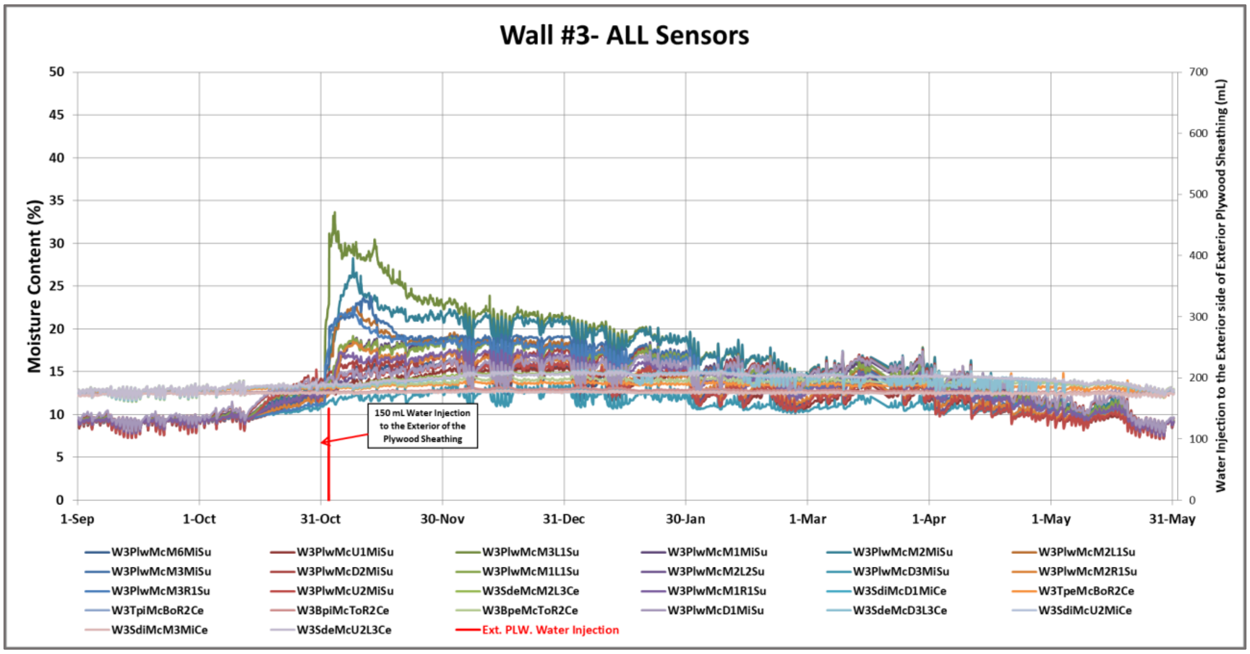


Figure 107- Wall#3- MC for All Sensors- Hourly Avg.

6.7.2 Interior & Exterior Framing

Moisture Content and temperature results for the interior and exterior framing are presented in this section.

6.7.2.1 Moisture Content (MC)

For the framing MC results of Wall#3 (Figure 108), while interior studs and plates remained unaffected by seasonal change, the exterior framing did have a moisture gain of maximum 2%, peaking at 15% of MC, which is negligible. Even the water injection did not affect the moisture gain of the framing in this case which can suggest the role of cellulose insulation's moisture capacity. Overall, no moisture related concern for framing appears for this case.

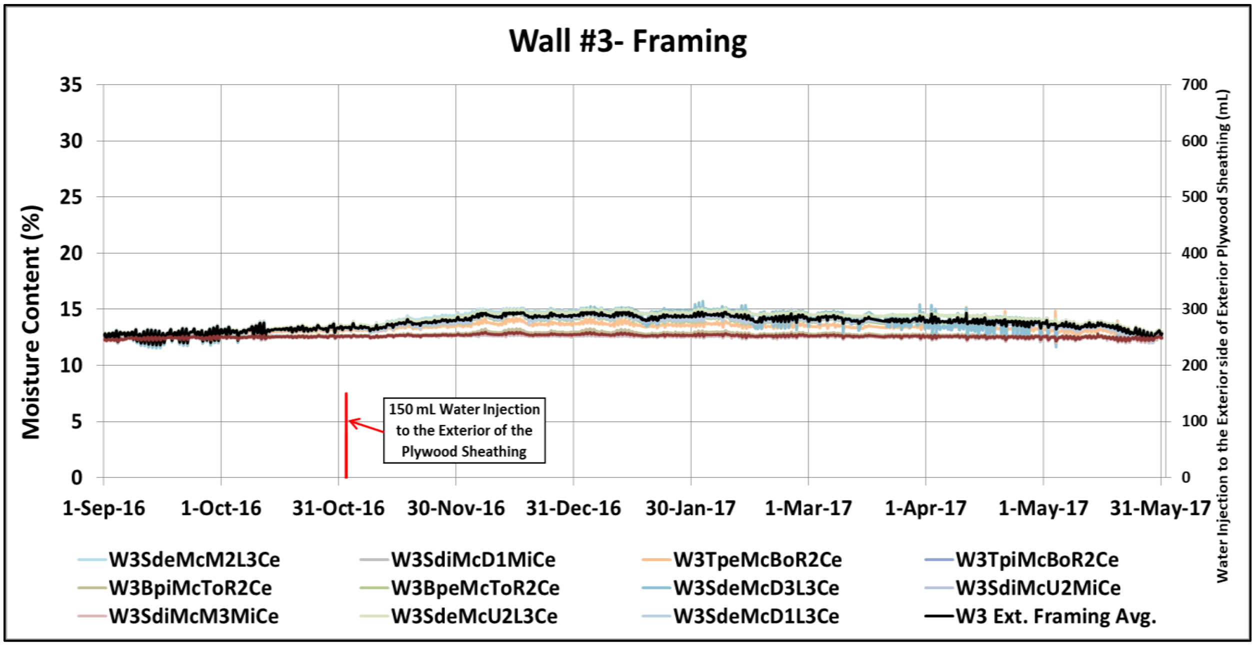


Figure 108- Wall#2- MC for All Framing Sensors- Hourly Avg.

6.7.2.2 Temperature (Ts)

6.7.2.2.1 Exterior Framing

The exterior framing temperature results for this wall (Figure 109), like the previous ones, was closely affected by the exterior seasonal and daily temperature variations. Also, its top plate experienced visibly higher temperature than all other sensors (that had very similar temperatures). As an example, in around middle of December 2016 that top plate experienced a minimum temperature of around 6°C, all other sensors had dropped to around -2°C, which translates into 8°C of difference. This condition as discussed earlier is likely to be the effect of heat stratification and also the possibility of trapped heat in the upper insulated chamber Figure 77).

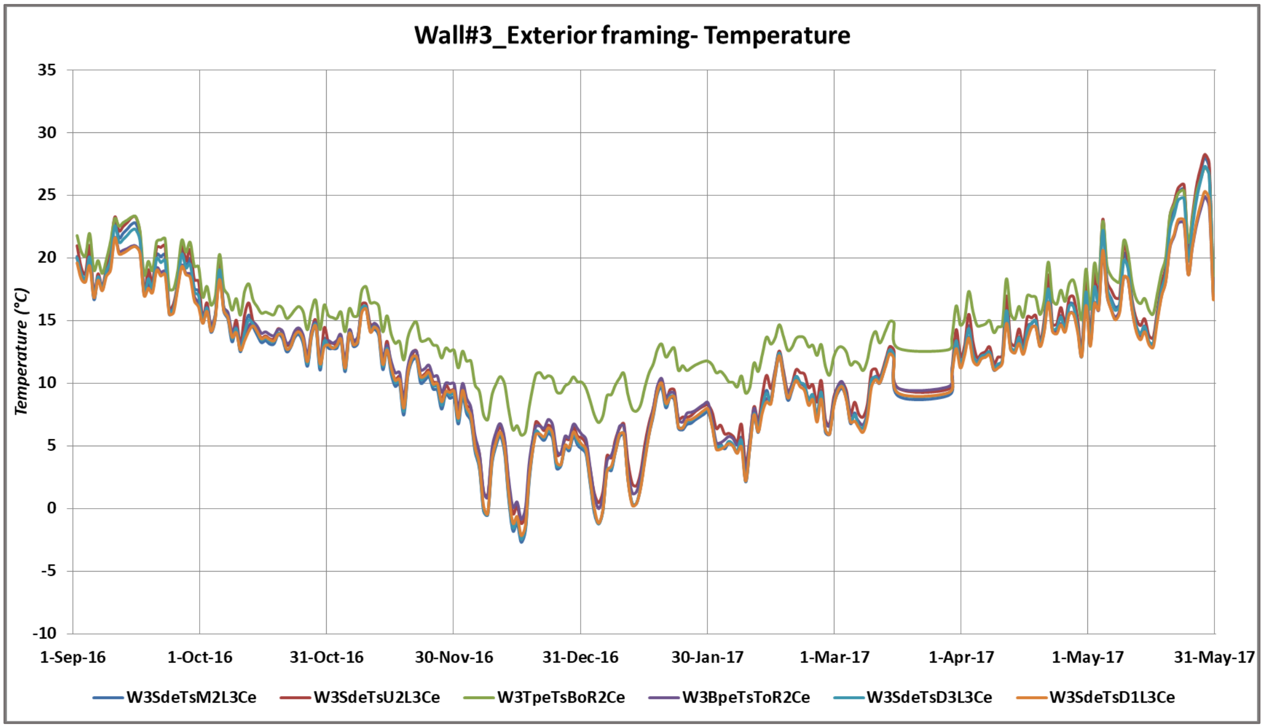


Figure 109- Wall#3- Temperature for Exterior Framing Sensors- Daily Avg.

6.7.3 Plywood Sheathing

As closer look into moisture content and temperature of these sensors is presented in this section.

6.7.3.1 Temperature

Figure 110 shows temperature of plywood sheathing that are average numbers calculated from the lower, middle and upper heights and are almost identical to the results presented for walls #1&2, already discussed in 6.5.3.1.

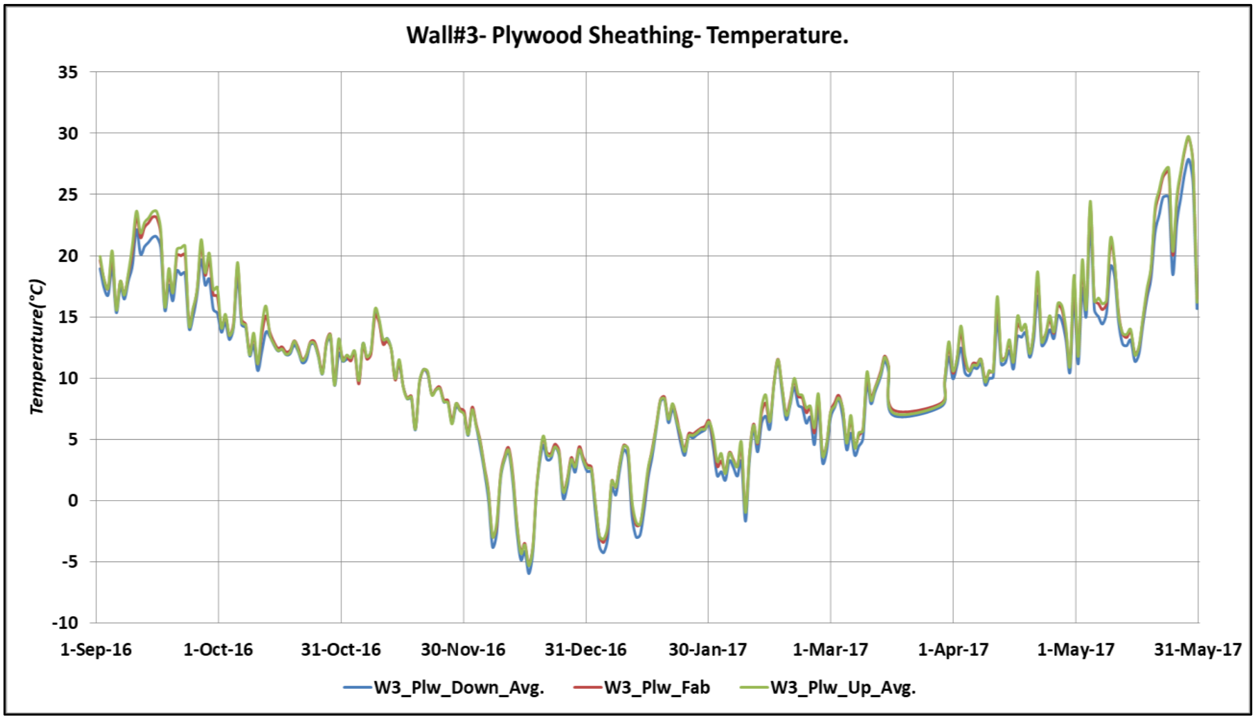


Figure 110- Wall#3- Plywood Sheathing Temperature

6.7.3.2 Moisture content (MC)

6.7.3.2.1 Lower Section Sensors

Moisture content results (Figure 111) are further discussed in the lower section of plywood sheathing for this wall.

The bottom section of plywood sheathing was not noticeably affected with the water injection incident. The MC in this section experienced a similar wetting and drying trend as the previous walls, especially wall number one, starting with moisture gain around middle of October continued until middle of January 2017 that drying starts and continues by the end of the test period. Surprisingly the sensor closest to the wetting fabric recorded a noticeable lower MC trend compared to the ones below which is counter intuitive.

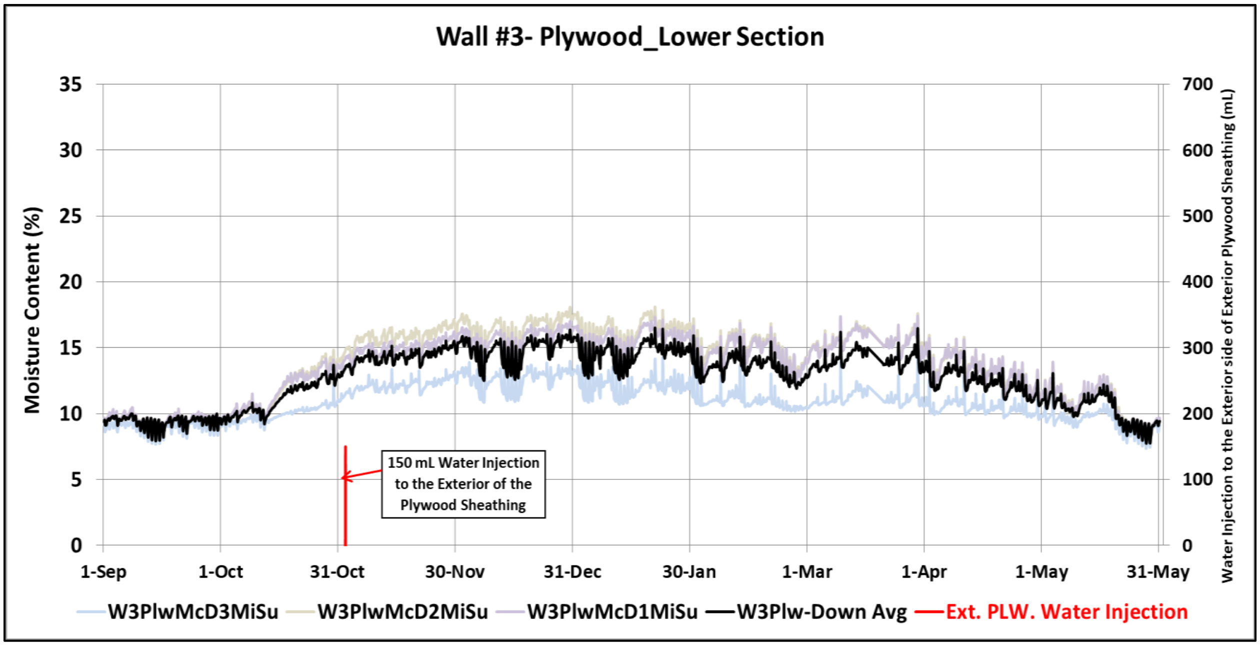


Figure 111- Wall#3- MC for Plywood, Lower Section Sensors- Hourly Avg.

A possible explanation for this behaviour could be the higher effect of thermal bridging between plywood and bottom plate closer to the lowest section of the plywood sheathing, which can increase RH levels of that area resulting in more MC gain from the colder surfaces (equilibrium sorption and desorption phenomena), or in cold enough spells, more condensation occurrence or hours in the duration of recorded data on the surface of plywood sheathing.

6.7.3.2.2 Middle Section

Contrary to the lower section of the plywood, there is an almost instantaneous MC rise in its middle section (Figure 112), after the water injection occurrence at the beginning of November, but the amount of this moisture rise varies significantly depending on the position of the sensor on the fabric. This could be mainly attributed to the ununiformed nature of liquid water distribution on the fabric as discussed earlier. Henceforth we mainly look into the averaged MC which is in black color.

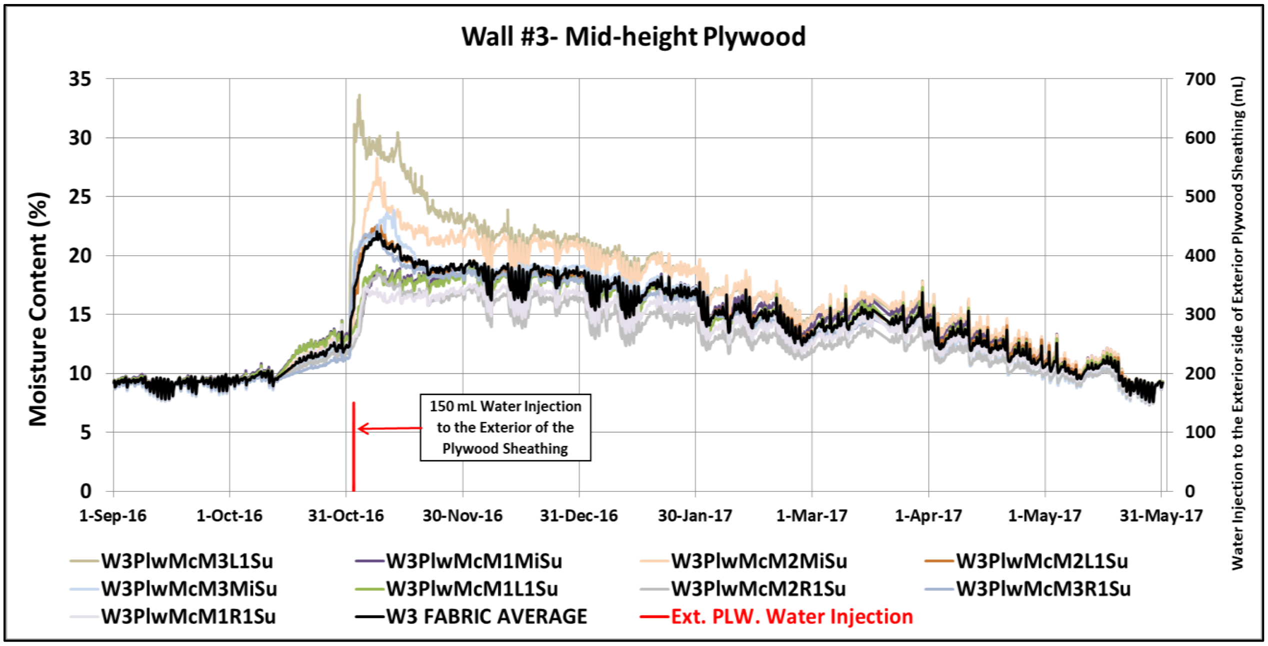


Figure 112- Wall#3- MC for Plywood, Middle Section- Hourly Avg.

The wetting season starts in around middle of October 2016, with a steady and gradual slope, until the beginning of November 2017 that water injection to the exterior surface of plywood sheathing comes into play. At this point there is a very sharp increase in MC rising from 12% all the way to 22% in less than a week. From around 10 November 2016 there is a low and steady slope, drying all the way to the end of the test period on 31 May 2017. Although this test does not show alarming moisture related concerns for this case, however it shows the fairly long time for an intruding liquid water to dry out.

6.7.3.2.3 Upper Section

As for the upper section of the plywood, unlike the fabric area, no direct effect of water injection is noticed (Figure 113). In fact, this section of plywood remained fairly dry for the entire test period, with a maximum of just above 16% MC by end of December 2016 and lowering back down to 9% MC of initial rate by the end of the test period.

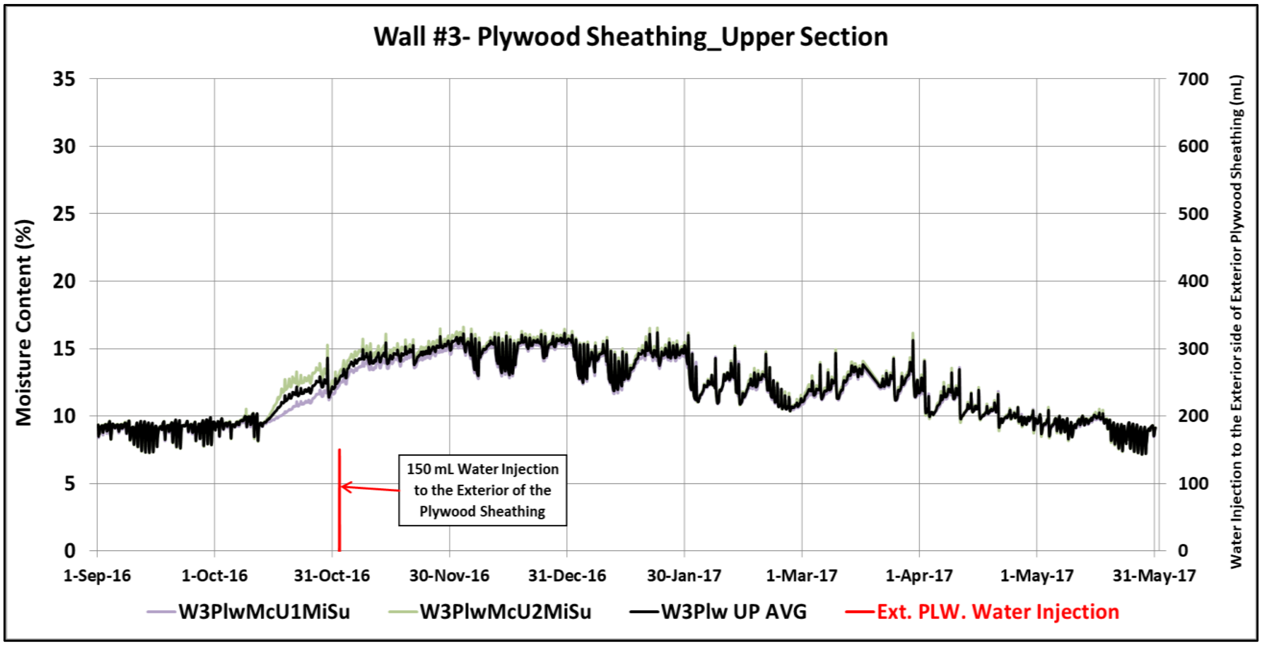


Figure 113- Wall#3- MC for Plywood, Upper Section Sensors- Hourly Avg.

So, the sensors for this section of wall#3 did not raise any hygrothermal concern. Also, the two sensors had initially a slight moisture gain difference from mid-October but merged by mid-November 2016 and remained the same by the end of the experiment.

6.7.4 Stud Space

Relative Humidity (RH) and Temperature results of stud space are presented and discussed in this section.

6.7.4.1 Cellulose Relative Humidity (RH)

Figure 114 depicts the hourly recorded RH levels of mid-thickness of cellulose insulation, and like the other walls, has intensive daily spiky levels that makes it hard to distinguish overlapping lines of the three sensors. So, a 24-hour average is created instead to be able to see the RH changes of different sensors better Figure 115).

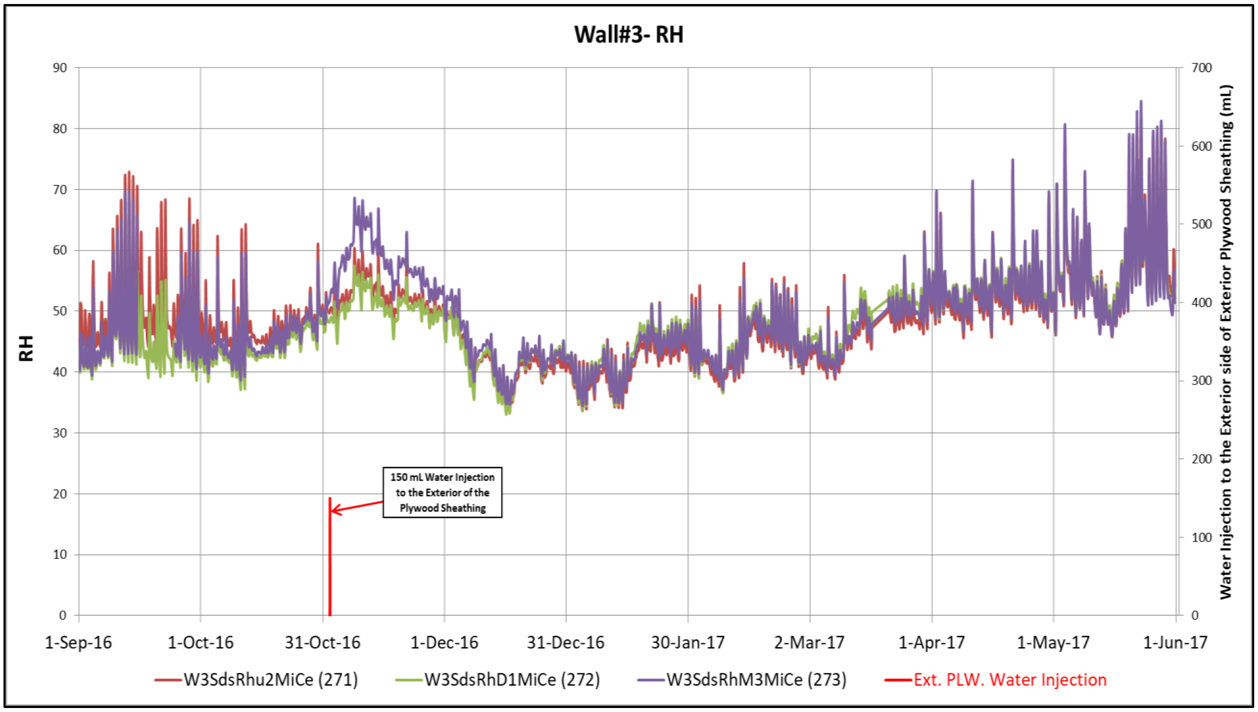


Figure 114- Wall#3- RH for Mid-Thickness of Insulation, Group-Averaged- Hourly

The RH levels of this wall started with RH levels of around 60%, and (except for the daily or short day-to-day fluctuations) hovered around the same level by the middle of October. After October a steady rise started and continued by middle November, peaking at around 55% for the bottom and upper sensors, but around 65% for the middle sensor. This 10% difference can be attributed to the effect of injected water since the middle sensor starts diverging from the other two at the beginning of November that is exactly after the water injection date. This divergence took around one month to converge back to the same levels of the other two sensors, by end of November.

From around 10 November, insulation starts drying most likely due to giving off its moisture to the wood components of the wall assembly (plywood and framing). Insulation gets to its lowest level of around 35% by middle of December. From this point, insulation starts picking up moisture again, gradually but with short daily fluctuations, until it reaches its peak of around

60% RH by end of April. From first of May, a sharp slope of drying starts again, but with almost the same slope RH goes back up again in a couple of days. In last couple of days of May another abrupt drying is evident which lands on around 55% of RH. These recurrent switching between drying and wetting in month of May should be the effect of concurrent rainy and sunny as well as warm and cold days of spring season.

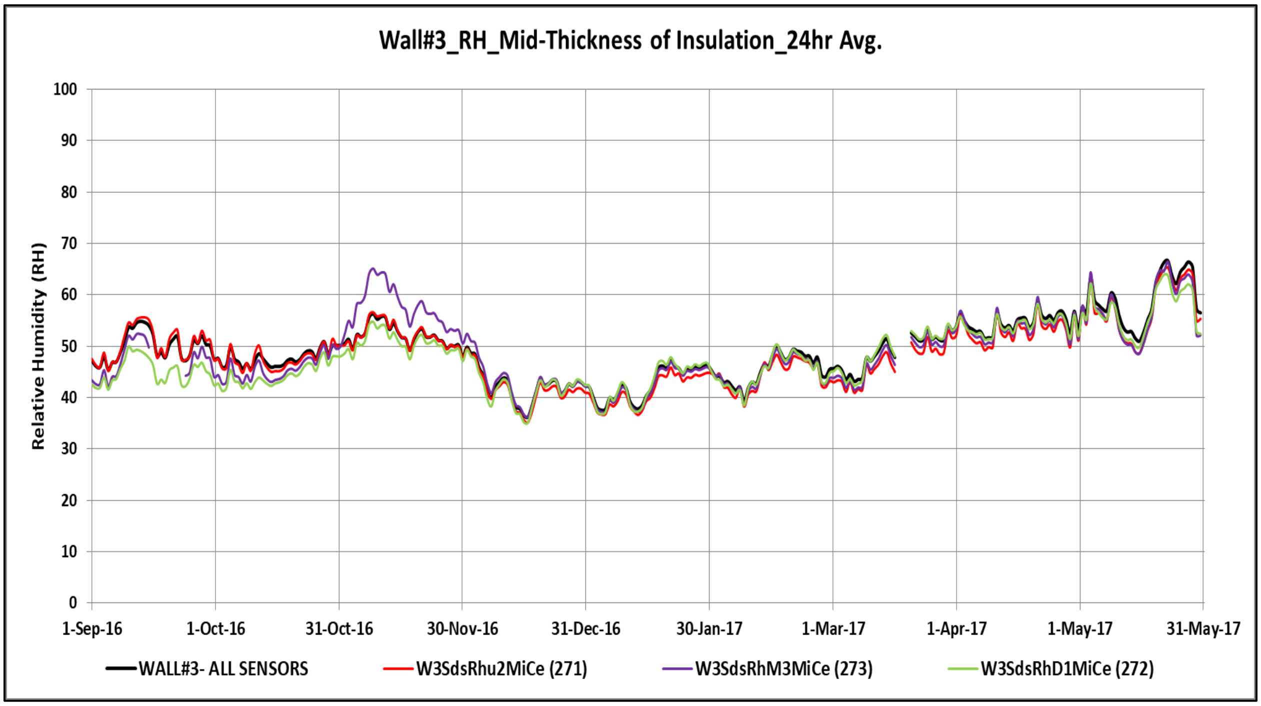


Figure 115- Wall#3- RH for Mid-Thickness of Insulation, Group-Averaged- Daily

6.7.4.2 Cellulose Temperature (Ts)

Figure 116 presents the 24-hour average temperature of mid-thickness of cellulose insulation in wall number three. Similar to the previous walls, temperature is the lowest for the lowest sensor, *W3SdsTsD1MiCe*, and highest*, W3SdsTsU2MiCe* for the highest thermistor sensor.

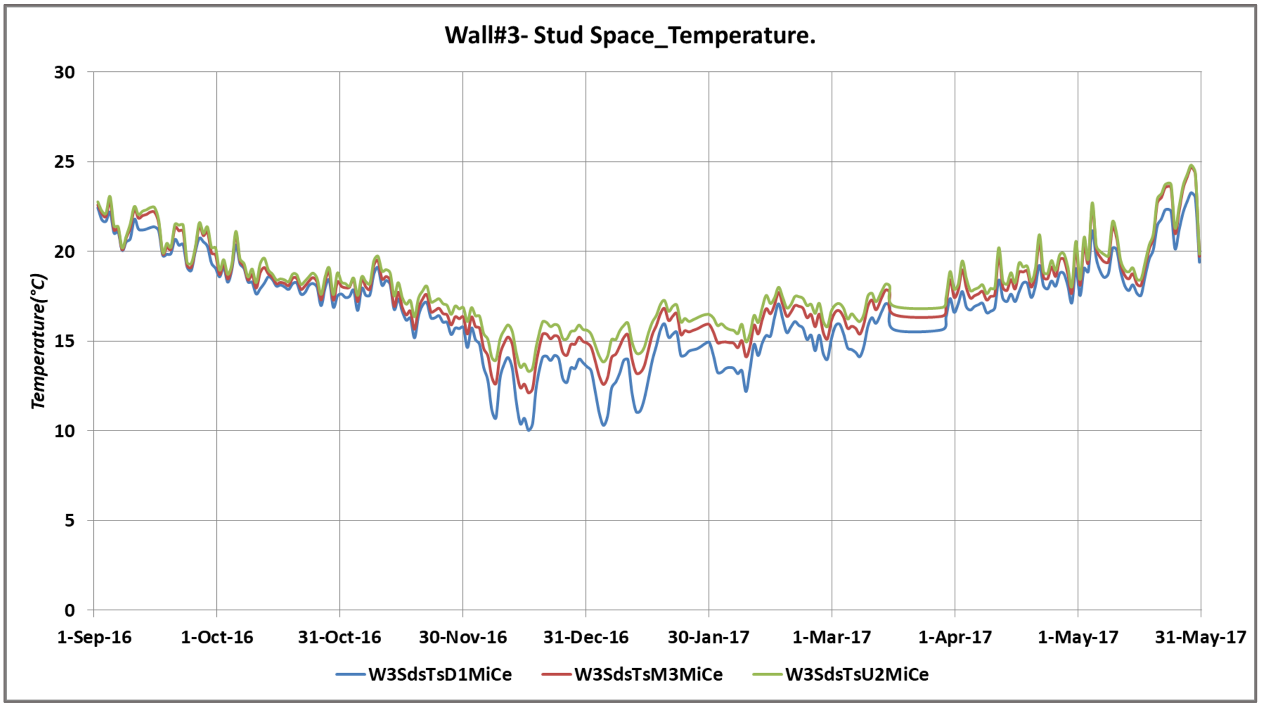


Figure 116- Wall #3- Stud Space Temperature

Temperature starts at around 22-23°C in early September, and gradually and affected by outdoor seasonal variation decreases to its lowest by middle of December, 10°C for the lowest thermistor and around 13°C for the highest. Then with more frequent and bigger fluctuations, rises back by the end of the season to maximums of almost 25°C.

6.7.5 Discussion

In this section vapour pressure and moisture content results of wall# are discussed and concluding remarks are suggested.

As for vapour pressure, Figure 117 shows that the exterior air experiences lower vapour pressure than the interior air, making the vapour gradient outward. The vapour pressure of plywood sheathing for all three different elevations (low, middle and up), is closely affected with the exterior ambient vapour pressure, with escalated rates whenever receiving more solar radiation. Vapour pressure of plywood sheathing goes slightly higher from bottom to top. The maximum vapour pressure reached 3,000 Pa by end of the testing period which is around 10% lower than wall#2 which this is likely to be for the generally lower level of humidity present in this wall, nevertheless still significantly higher than the interior and exterior vapour pressure levels at that time of the test period helping with accelerated drying for the plywood in both direction.

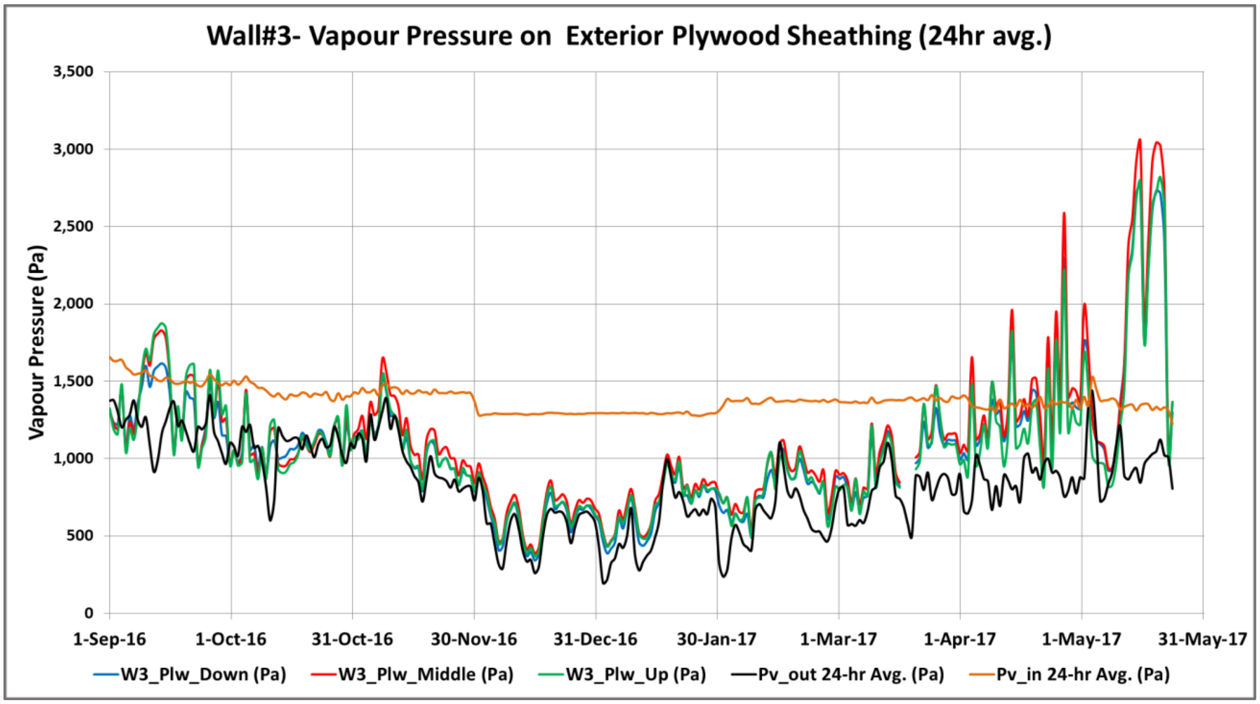


Figure 117- Wall#3- Plywood Vapour Pressure

Figure 118 compares the average vapour pressure of plywood sheathing in interaction with indoor and outdoor environments as well as the stud space. The vapour pressure of plywood sheathing remained below indoor vapour pressure from middle of September 2016 to end of March 2017 but exceeded indoor vapour pressure for a few days until before September 2016 (From April and March 2017 vapour pressure was affected by outdoor solar radiation receiving on the walls). Vapour pressure at mid-thickness of cellulose insulation remained slightly (or in some sunny days cases more than slightly) below the vapour pressure of plywood sheathing and above outdoor vapour pressure for almost the entire test period, suggesting the vapour flow should have been mostly outward from indoor to insulation, then to plywood sheathing and finally from plywood sheathing to outdoor.

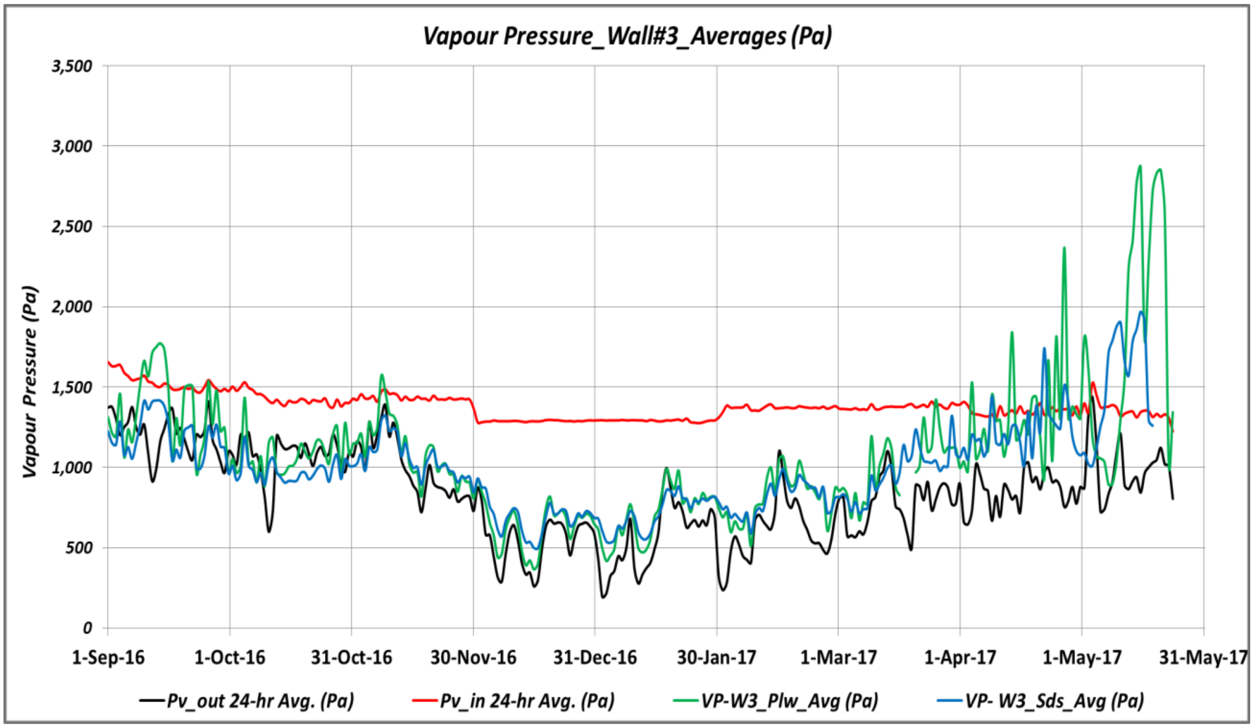


Figure 118- Wall#3- Vapour Pressure- Total Averages- Daily

Interestingly in a few days in September and October 2016, vapour pressure of insulation and also plywood sheathing, dropped even lower than outdoor vapour pressure. This means in those days, there was a potential for walls to accept diffusing moisture from both indoor and outdoor. Like the previous walls, in more wet and cloudy season of November 2016 to end of March 2017, plywood and insulation are closely following outdoor vapour pressure trends and in warmer periods of end of fall and spring, solar radiation raises their vapour pressure to higher levels than outdoor and even indoor environments.

Figure 119 summarizes averaged MC of plywood and framing. The results show the lowest level of MC starts with interior framing remaining almost totally dry, its MC hovering over 12-13%, for the entire test period, followed by the exterior framing with fairly low moisture gain and drying, remaining on 12-15% MC range. For the plywood sheathing region, the lower and upper sections raised to a similar maximum level of just 16% MC by the end of wetting season in 31 December 2016, and both dried out to the initial MC level of 9% but the upper sensor dried faster. This could be the effect of heat stratification phenomenon, albeit maybe very slow due to limiting effect of dense cellulose filling up the stud space and limiting air movement.

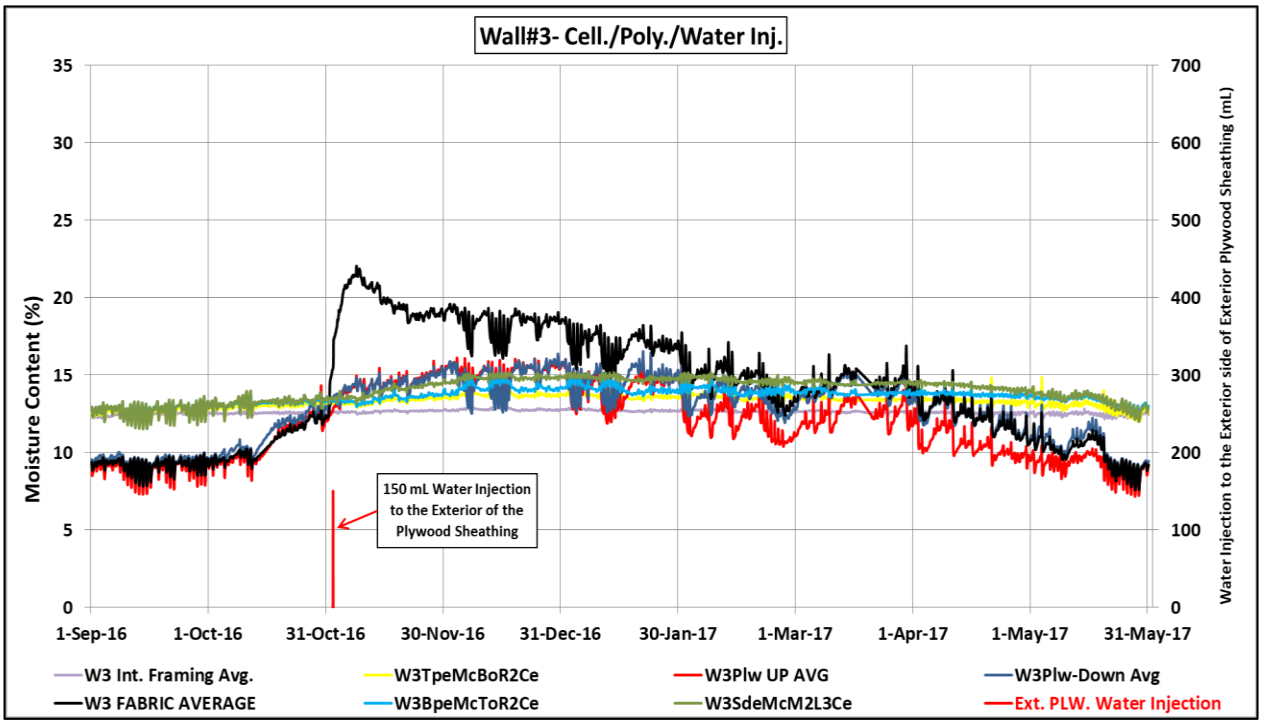


Figure 119- Wall#3- MC for Plywood and Framing- Group-Averaged- Hourly

The middle plywood area had the highest MC levels, reaching to a 22% within a few days after water injection, 5% higher than the lower and upper sections of plywood, and took around six months (almost until the end of the experiment) to get back to lower and upper sections of plywood. This situation suggests small amounts of water as little as 150mL leaks into this kind of walls with conventional polyethylene film vapour barrier, it takes almost an entire drying season to dry or balance out with other moisture absorbing components within the wall assembly. Overall, this wall had acceptable hygrothermal behaviour with the test conditions of this experiment.

6.7.6 Mold Index (MI)

Figure 120 presents Mold Index results of plywood sheathing for wall#3. The overall mold activity was low remaining below mold index of one (MI<1.0). The fabric area had the highest mold activity among other vertical locations rising sharply right after the water injection, until early December followed by a less steep slope reaching its maximum level of around MI = 0.7 at around 20 April 2017. Afterwards, MI started declining to below 0.6, mainly due to lower MC levels of plywood sheathing at this period of the test. The two other locations of plywood sheathing lower and upper levels, that were further from the water injection source, had very minimal mold activity and ended up with zero mold index. This can suggest no mold concern if there is no liquid water penetration for this wall.

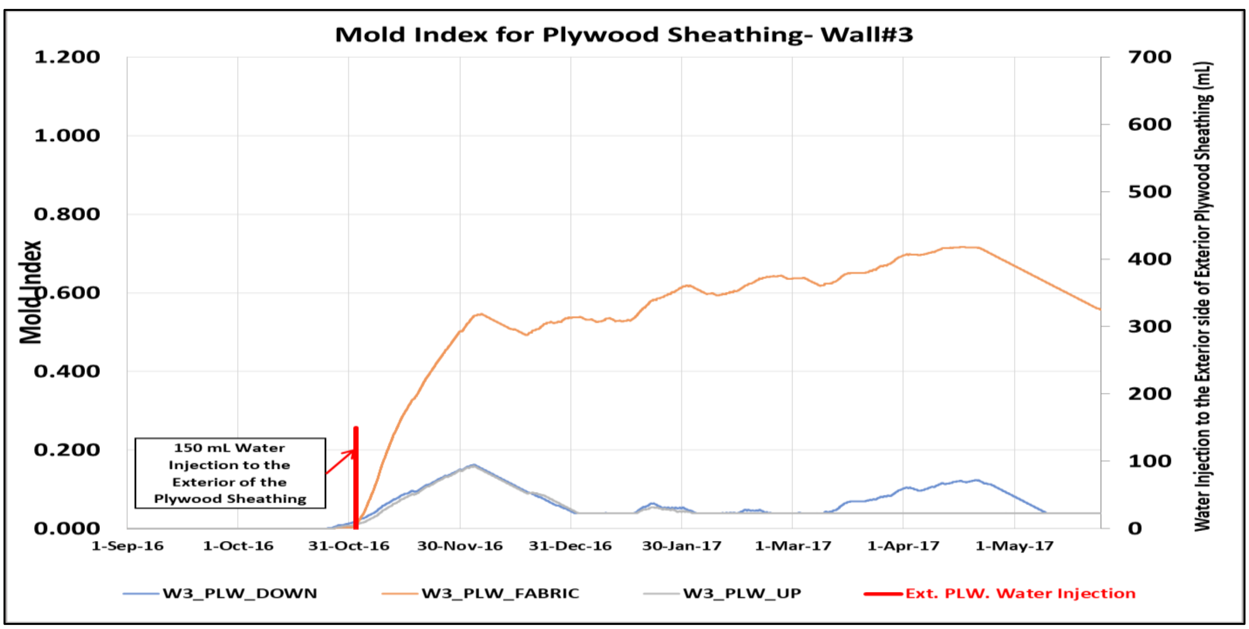


Figure 120- Wall#3-Mold Index for Plywood and Framing- Group-Averaged

6.7.7 Summary

Table 11 summarizes all the MC and MI rates and their rising and falling periods that are discussed above. Overall, except middle section of plywood sheathing, all other locations of this wall had totally safe moisture response. Mold index for all locations, even at the liquid water injection area of plywood sheathing (middle height), was low. Lowe and upper parts of plywood sheathing had similar moisture levels of maximum 16%, and the exterior framing did not go beyond 15%, all very safe levels. Overall, this wall had a safe moisture response.

Table 11- Wall#3- Moisture Performance Summary

Wall#3	initial MC (%)	max MC (%)	MC gain (%)	Reached 28%?	days above 19%	# of wetting days	# of drying days	Final Mold Index	Overal Moisture Performance
lower Plw	9	16	7	No	0	120	150	0.04	Safe
Fabric	9	22	13	No	14	70	200	0.56	Risky
Upper Plw	9	16	7	No	0	120	150	0.04	Safe
Bottom Plate	12.5	14	1.5	No	0	150	120	-	Safe
Middle Stud	12.5	15	2.5	No	0	150	120	-	Safe
Top Plate	12.5	13.5	1	No	0	150	120	-	Safe
Int. Frame	12	13	1	No	0	120	150	-	Safe

6.8 Wall#4

6.8.1 All Sensors

Wall#4 is a double-stud frame filled with Dense Cellulose Insulation, with smart vapour retarder (SVR) used as its major vapour control layer behind the interior gypsum board sheathing which like walls number two and three, had extra water injection behind its Weather Resistive Barrier (WRB). For an overall view of its hygrothermal performance, the hourly average temperature and moisture content data results are presented and discussed in this section.

6.8.1.1 Temperature (Ts)

All thermistors of wall number four sensors are presented below (Figure 121) for an overview. While the interior sheathing, gypsum board has the least variation, as it is conditioned with the interior air, the exterior siding and plywood sheathing have the most daily and seasonal temperature variations affected by the outdoor weather changes, ranging from -10°C to 50°C.

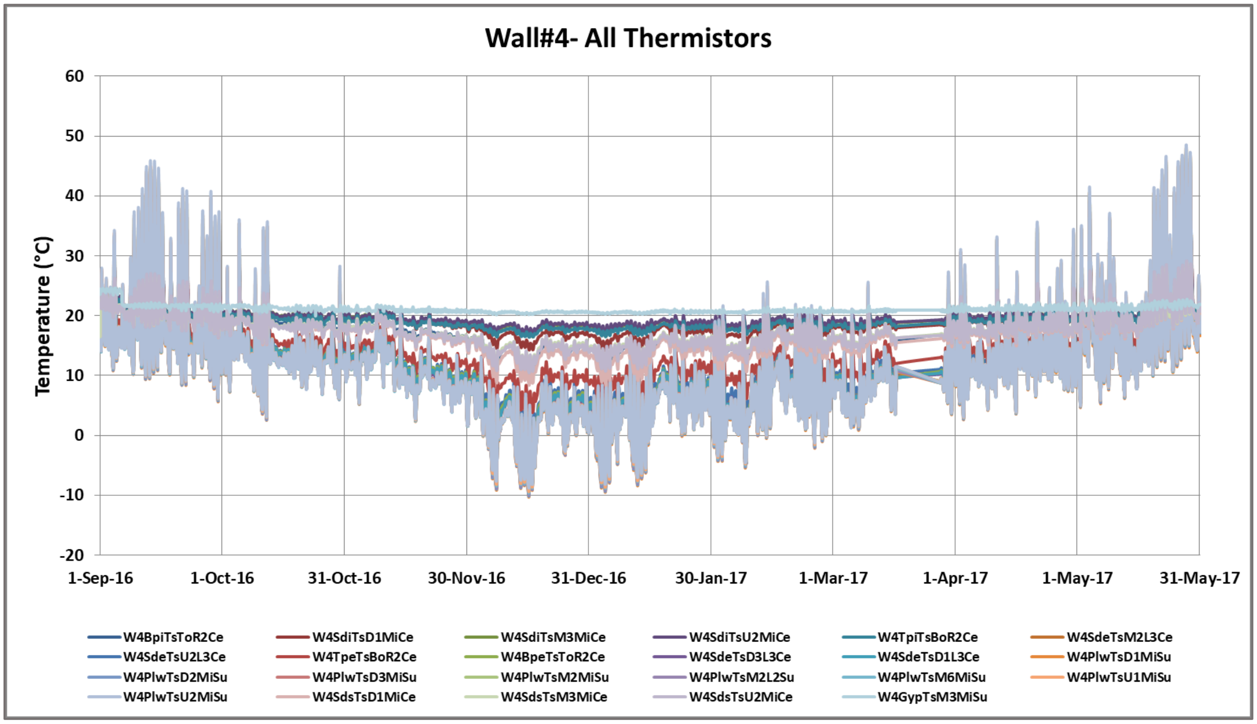


Figure 121- Wall#4- All Thermistors

6.8.1.2 Moisture Content (MC)

This wall is identical to wall#3, with just the difference of having Smart Vapour Retarder (SVR) as its vapour control layer behind gypsum board sheathing.

Similar to wall#3, water injection raised MC of plywood sheathing seen on a sharp slope in Figure 122. Also, for the exterior framing while remains in the safe zones, had higher MC rates than the interior framing sensors (that stayed almost dry for the entire test period), but experienced less MC peaks compared to the plywood sheathing sensors.

The MC levels of plywood sheathing especially for the sensors located in the middle section that is affected by the injected water also summits around middle of October 2016 and returns to their initial MC until the end of the experiment.

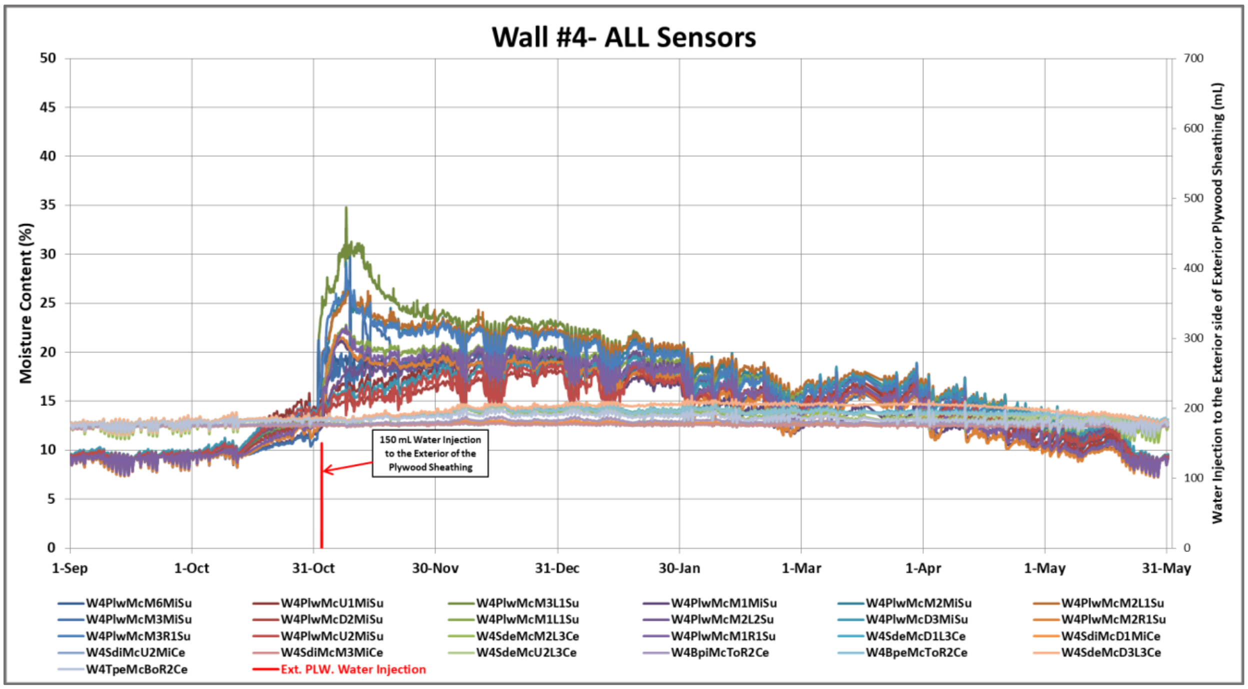


Figure 122- Wall#4- MC for All Sensors- Hourly Avg.

6.8.2 Interior & Exterior Framing

Moisture Content and temperature results for the interior and exterior framing are presented in this section.

6.8.2.1 Moisture Content (MC)

Moisture Content results of framing are presented in Figure 123. As for the interior and exterior framing, like wall#3, there is no hygrothermal behaviour concern with the sensors on those locations and even for the worst case of exterior framing, the MC level even did not reach to higher than 15%, with a marginal 2-3%. Another observation is the sensor in the relative vicinity of the injected water source, *W4SdeMcD3L3Ce*, had the highest, albeit still low, amount of moisture gain compared to all other sensors.

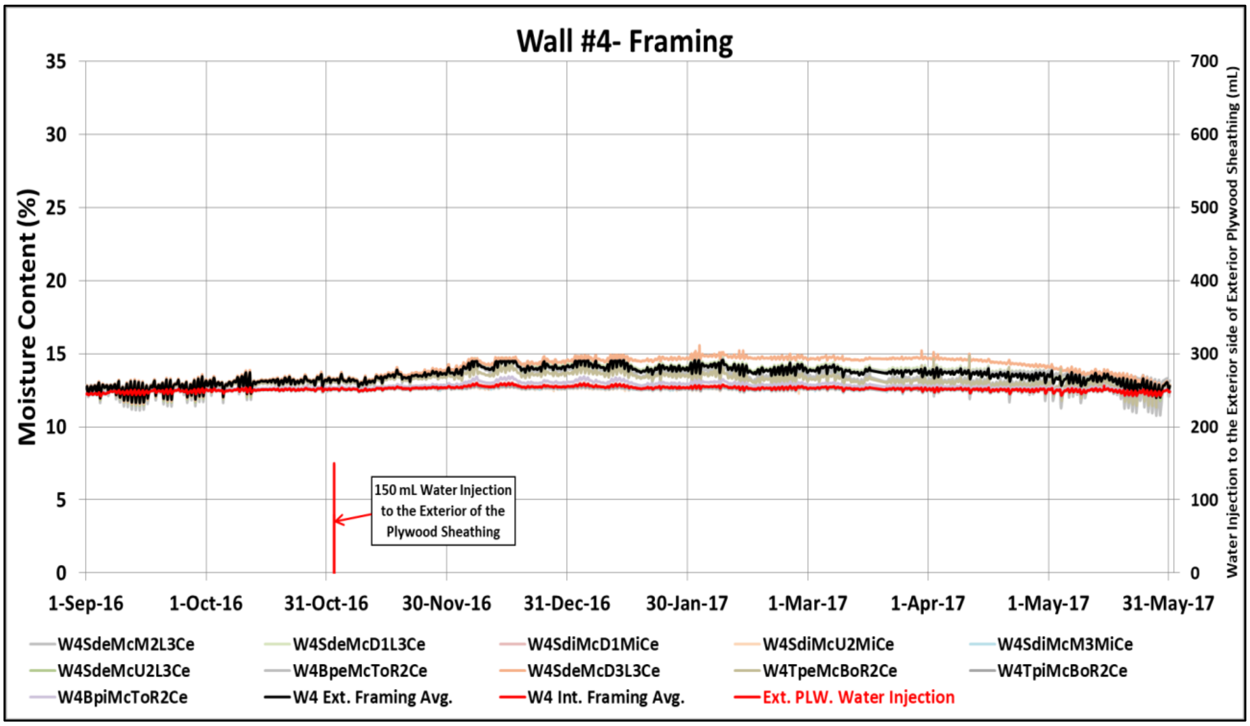


Figure 123- Wall#4- MC for All Framing Sensors- Hourly Avg.

6.8.2.2 Temperature (Ts)

6.8.2.2.1 Exterior Framing

Figure 124 shows similar temperature seasonal trend as outdoor temperature happens on the exterior framing, but a bit moderated by the indoor temperature as the thermistors are a couple of inches towards the interior compared to plywood sheathing. As an example, while the minimum temperature of mid-December on exterior framing is around -3°C plywood sheathing that is closer to outdoor recorded -10°C for the same time. Like previous walls, top plate remains noticeably warmer than all other exterior framing sensors, up to 5°C difference in December.

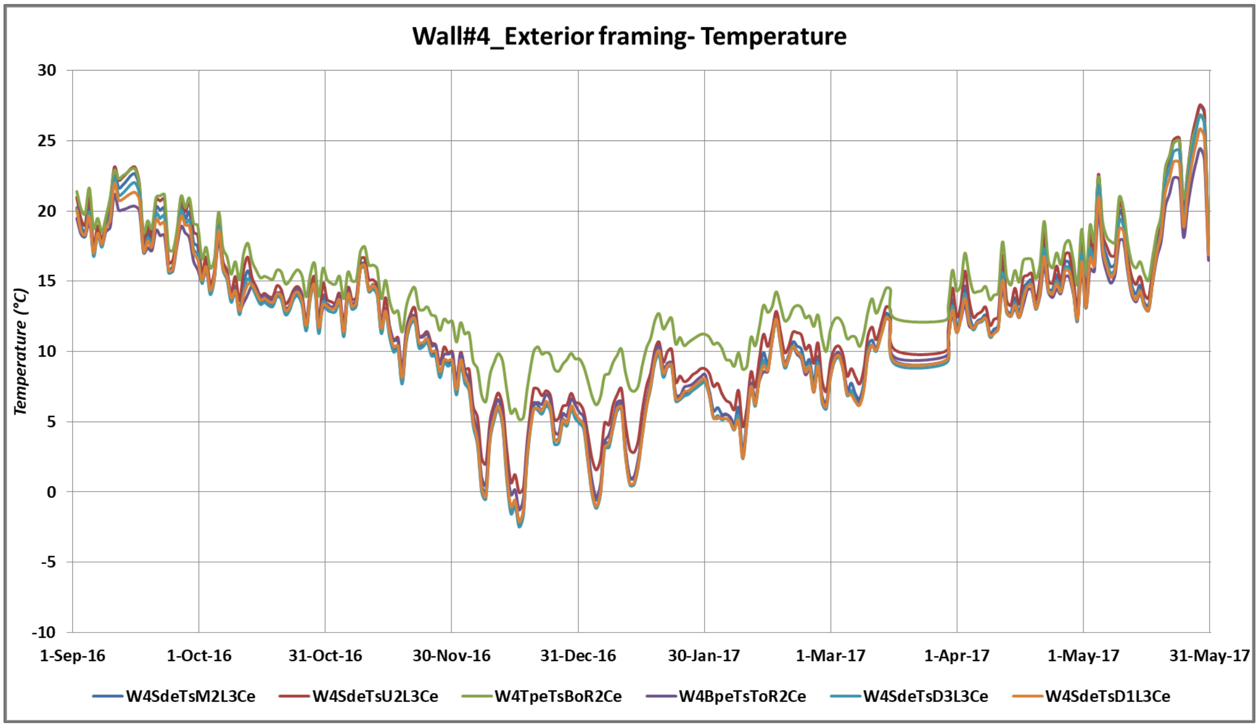


Figure 124- Wall#4- Temperature for Exterior Framing Sensors- Daily Avg.

6.8.3 Plywood Sheathing

6.8.3.1 Temperature

Similar to Wall#1-3, temperature of plywood sheathing is presented in this section (Figure 125) in average numbers calculated from the lower, middle and upper heights of plywood and are identical to the discussion presented in 6.5.3.1.

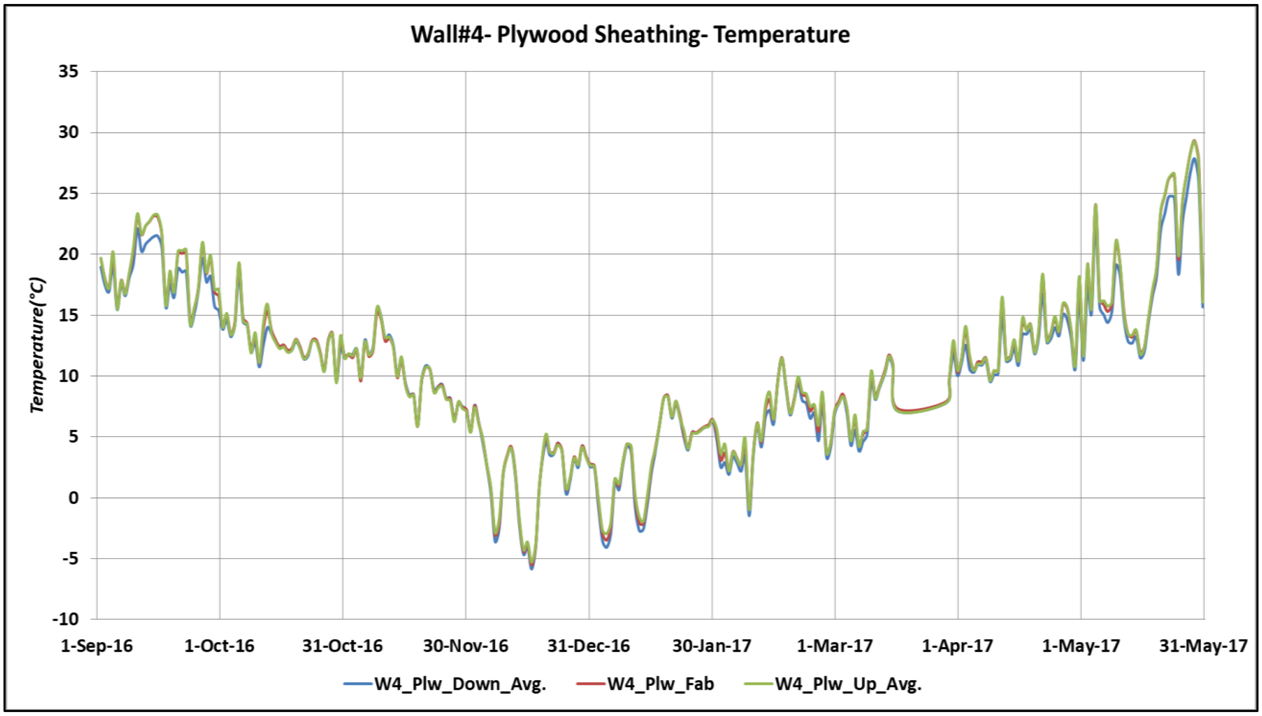


Figure 125- Wall#4- Plywood Sheathing Temperature

6.8.3.2 *Moisture Content (MC)*

Moisture Content behavior of plywood sheathing in the three different vertical levels, lower, middle and upper is discussed deeper in this section.

6.8.3.2.1 Lower Section Sensors

The recorded MC graph (Figure 126) demonstrates a noticeable increase in MC levels for the three sensors in differential elevation positions, *W4PlwMcD1MiSu*, *W4PlwMcD2MiSu, and W4PlwMcD3MiSu,* from bottom to top, each 8” (20cm) apart in vertical coordinates. Although the closer MC sensors to the source of water injection (*W4PlwMcD3MiSu)*, experienced the highest amount of moisture gain, however this trend had already started in middle of October, more than two weeks prior to the water injection date. Furthermore, the water injection did not even have a visible impact on MC increase immediately after the injection date. This should be due to moisture capacity of cellulose insulation and wetting fabric that can absorb the flowing water. Nevertheless, at the peak of MC, around end of December 2016, the MC sensor at the highest level of this section, *W4PlwMcD3MiSu*, stayed below 20%, while the lowest sensor did not go above 15%. This translates into a safe moisture behaviour response for that area of the wall with the test conditions.

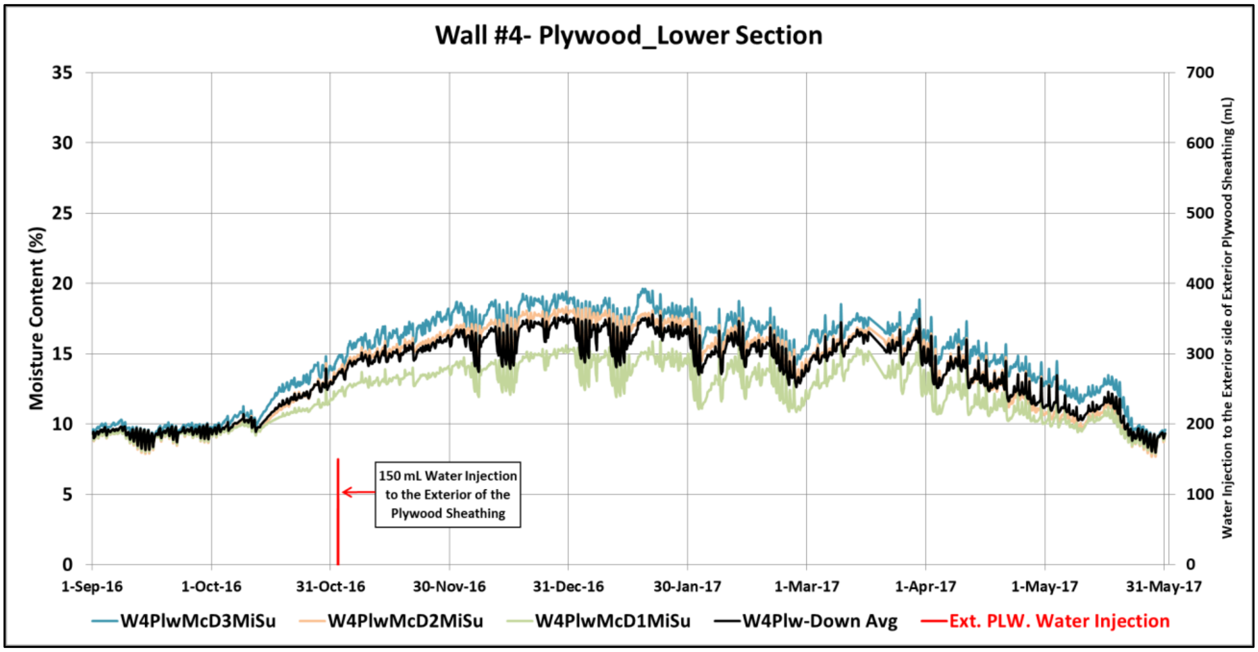


Figure 126- Wall#4- MC for Plywood, Lower Section Sensors- Hourly Avg.

6.8.3.2.2 Middle Height Sensors

Unlike the lower section of plywood sheathing, the fabric area is obviously and significantly impacted by the water injection amount in early November (Figure 127). There is a rapid increase in moisture content that varies considerably for the nine different sensors on plywood sheathing. The highest increase was in *W4PlwMcM3L1Su*, which is the sensor right below left side of the soaker hose, the water injection source, followed by *W4PlwMcM3R1Su*, the sensor at the same vertical level, but on the right side of the soaker hose. This can translate into an ununiformed wetting, starting from the left side and then the right side of the fabric. A rather slow and gradual wetting seasons start from around 10 Oct (like the previous walls) followed by a conspicuous slope of moisture gain at beginning of November that the 150mL injected water accelerates plywood's MC gain significantly. Within one week, all the sensors reach to their maximum levels, obviously induced by injected water. The averaged graph (with black color) reaches a maximum of 24% by around 10 Nov 2017. This day is when a constant overall drying started, albeit with daily fluctuations (especially in the shoulder season months of April and March), until returning to its initial MC of around 9% by the end of test period. A general conclusion for this wall is wetting had a significant impact on middle of plywood. More discussion is presented in Mold Index (MI), 6.8.6 section.

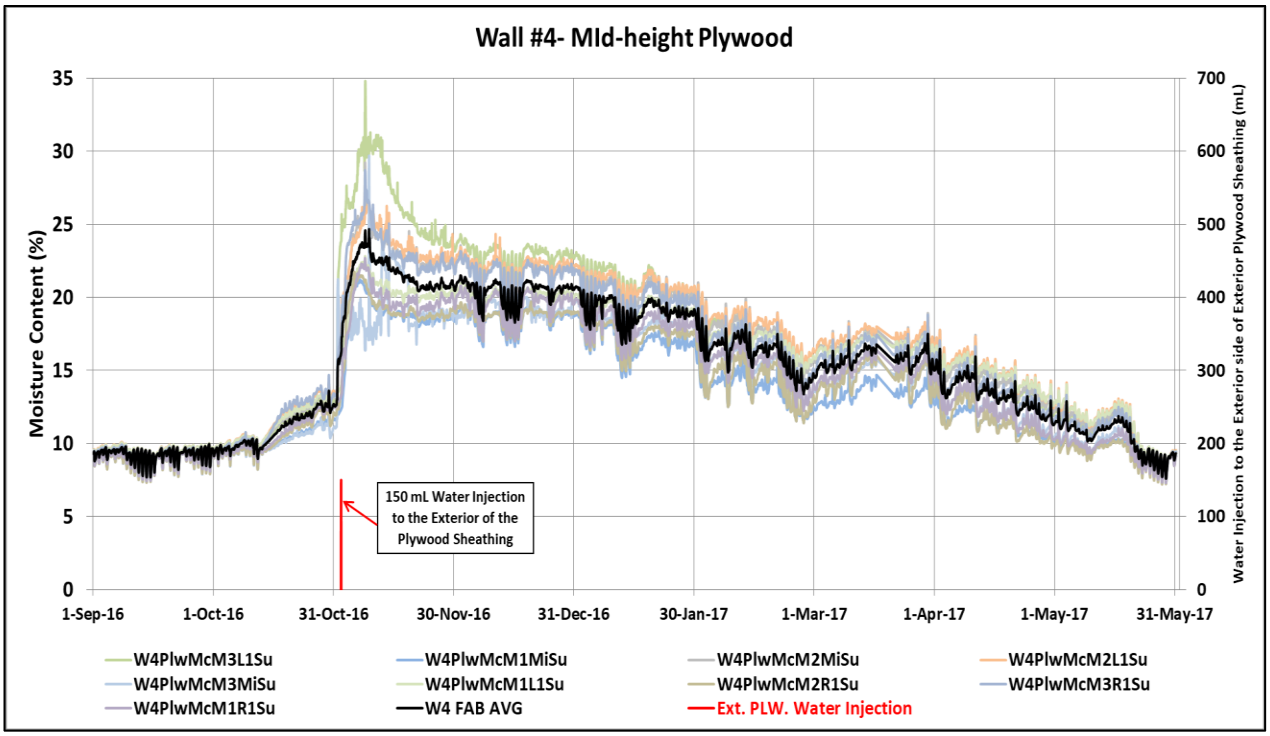


Figure 127- Wall#4- MC for Plywood, Middle Section- Hourly Avg.

6.8.3.2.3 Upper Section

On Figure 128, the two sensors at the top section of plywood sheathing, *W4PlwMcU1MiSu* and *W4PlwMcU2MiSu,* had strikingly similar behaviour, almost overlapped for the most part of the test period. There are three general wetting and drying trends associated with those two sensors; a stable and dry initial period, followed by a wetting and drying period. The stable period started from the beginning of the test on 01 September and continued till around 10th of October, when the wetting started and peaked by the end of the year at around 18%. This is when the drying starts and continues for around five consecutive months till end of May 2017 that plywood is dried back to its initial levels of around 9%. These two sensors had very similar behaviour to the sensors at the bottom section of plywood sheathing. The maximum MC was peaked at around 18%, which is within safe hygrothermal zones for this type of plywood with no risk of mold formation (further discussion on mold in 6.8.6).

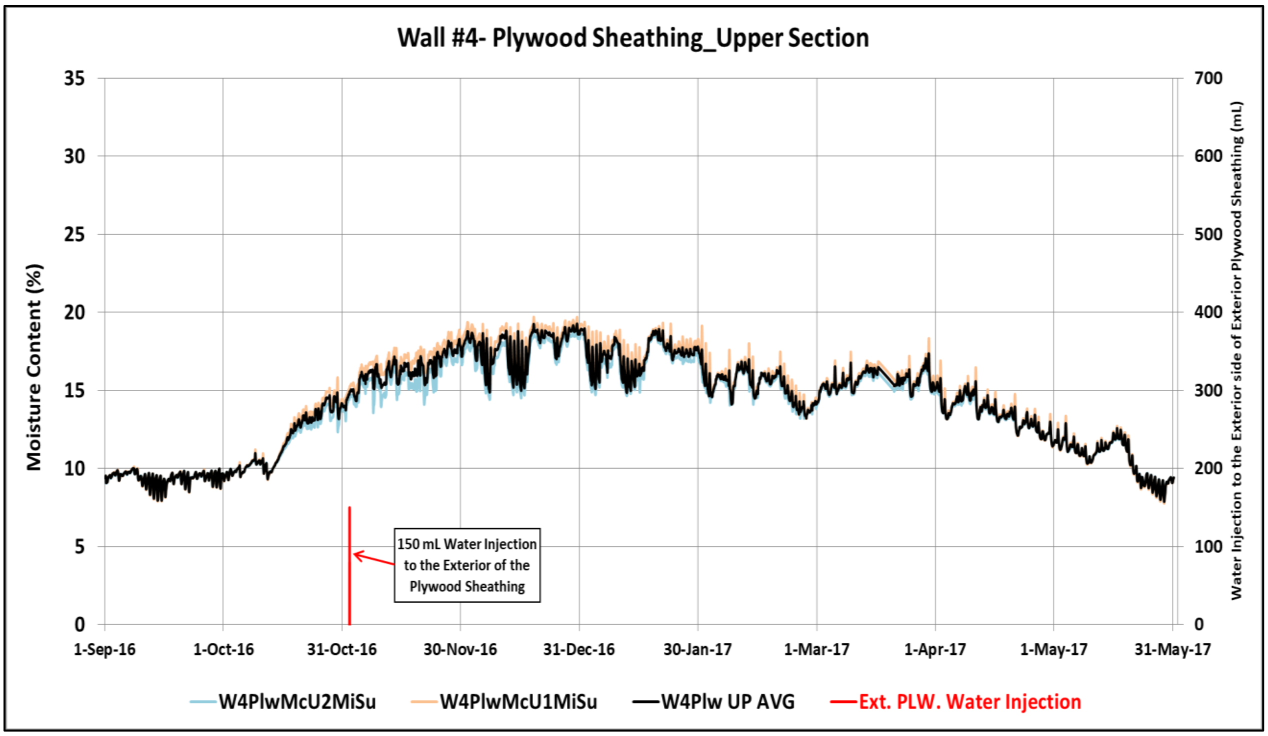


Figure 128- Wall#4- MC for Plywood, Upper Section Sensors- Hourly Avg.

6.8.4 Stud Space

6.8.4.1 Cellulose Relative Humidity (RH)

Figure 129 presents the hourly averages of Relative Humidity for all the three RH sensors in mid-thickness of cellulose insulation.

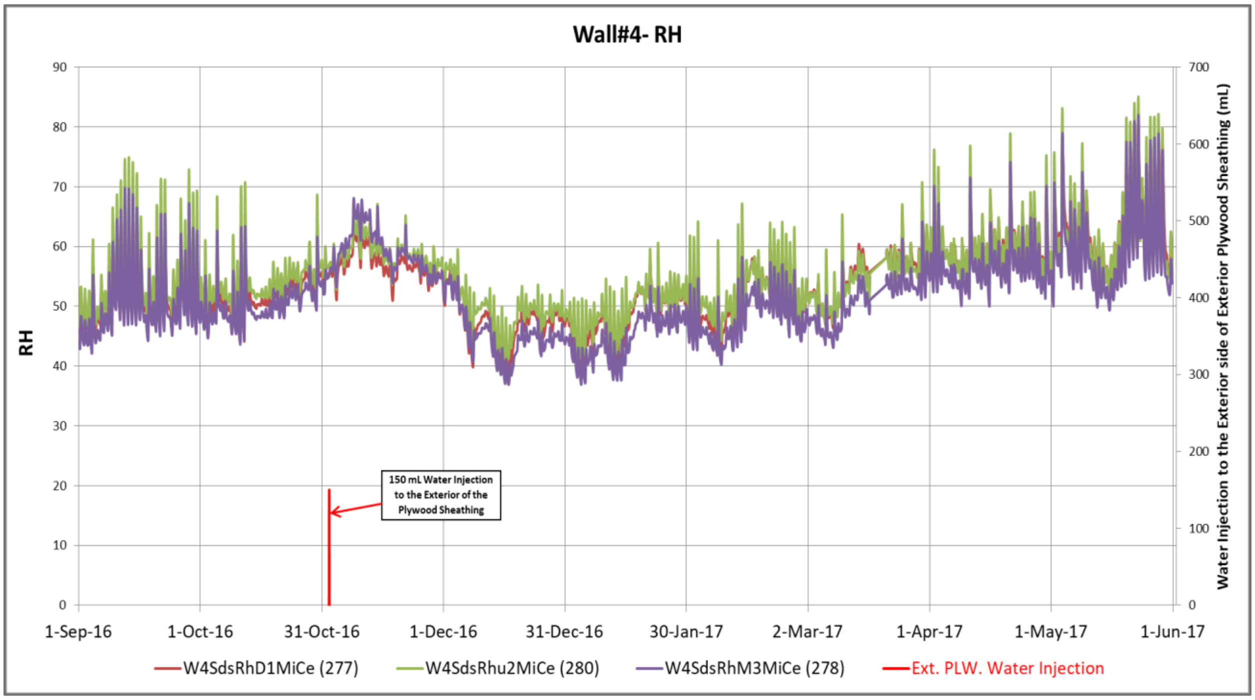


Figure 129- Wall#4- RH for Mid-Thickness of Insulation, Group-Averaged- Hourly

As a general observation, RH levels for wall number four that has SVR as its vapour control layer is very similar to wall#3 with 4-mil polyethylene, but slightly (around 3-5%) higher. RH level of this wall stayed within 45-48% RH by mid-October, then a four-week elevation of up to 65% that was followed by around one month of decline to below 40%. The last period was a fluctuating 4-5 month of slight overall increase (wetting) to the final value of 55%. An interesting observation for this graph is the sharp daily fluctuations of September and also April and May 2017 with their relatively warm days and cold nights bounce around the moisture in plywood to and out of insulation on a continual basis.

6.8.4.2 Cellulose Temperature (Ts)

Figure 130 shows the temperature of middle thickness of stud space for wall#4. Temperature of middle thickness of insulation space follows a similar seasonal pattern of outdoor temperature and plywood but moderated with the conditioned indoor climate.

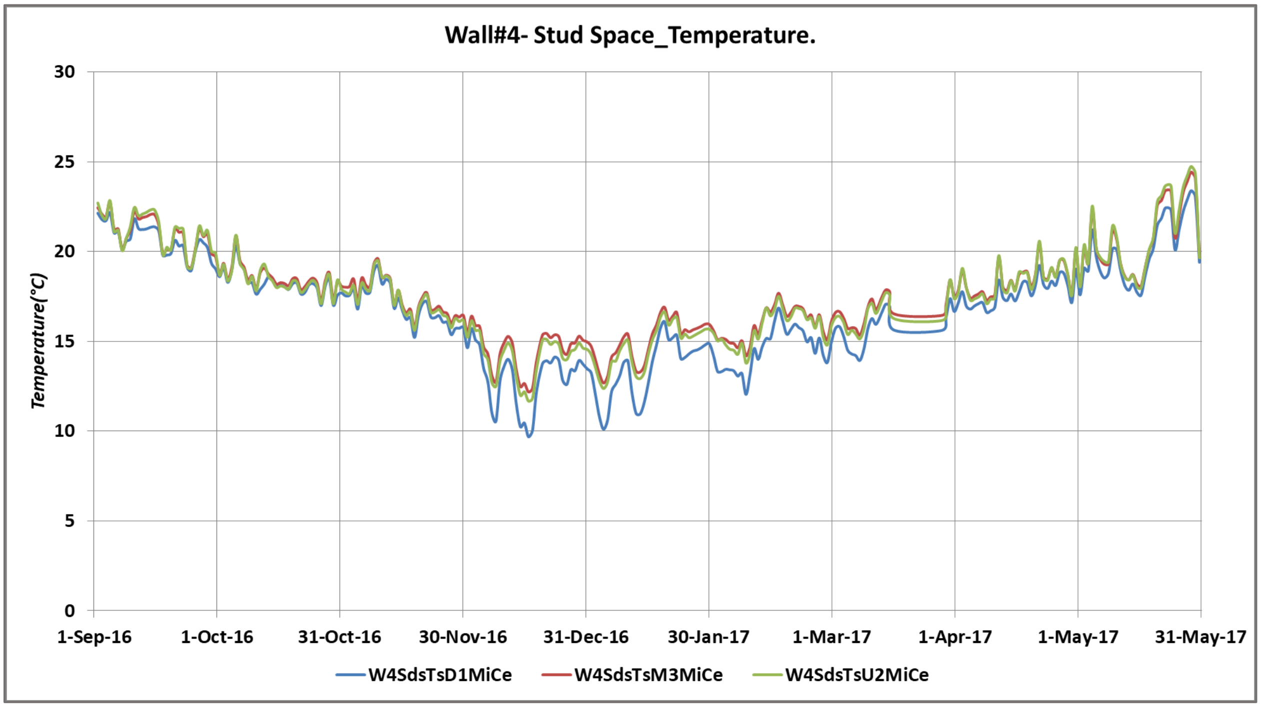


Figure 130- Wall #4- Stud Space Temperature

Temperature started from around 22-23°C in early Sep 2016 and follows a declining trend (with daily or few-daily fluctuations) down to minimums of around 10°C by middle of Dec 2016. The coldest sensor like the previous walls is the lowest sensor which is 20 inches from top of the bottom plate and recorded around up to 3°C colder than the results for the middle and upper sections of plywood sheathing.

6.8.5 Discussion

The calculated 24-hr average vapour pressure results of indoor, outdoor and overall averaged of three sensors located at the lower, middle and upper section of plywood sheathing as well as mid-thickness of cellulose insulation are presented here in Figure 131. The graph shows the vapour pressure of plywood sheathing is directly changing with outdoor ambient temperatures, but in cloudy days with low solar radiation, it is very similar to outdoor ambient vapour pressure, otherwise plywood sheathing absorbs the solar radiation and may become warmer than the exterior environment which can cause its vapour pressure also to increase excessively. This increase in some more sunny periods goes even higher than the interior vapour pressure mostly occurring in shoulder seasons of fall and spring.

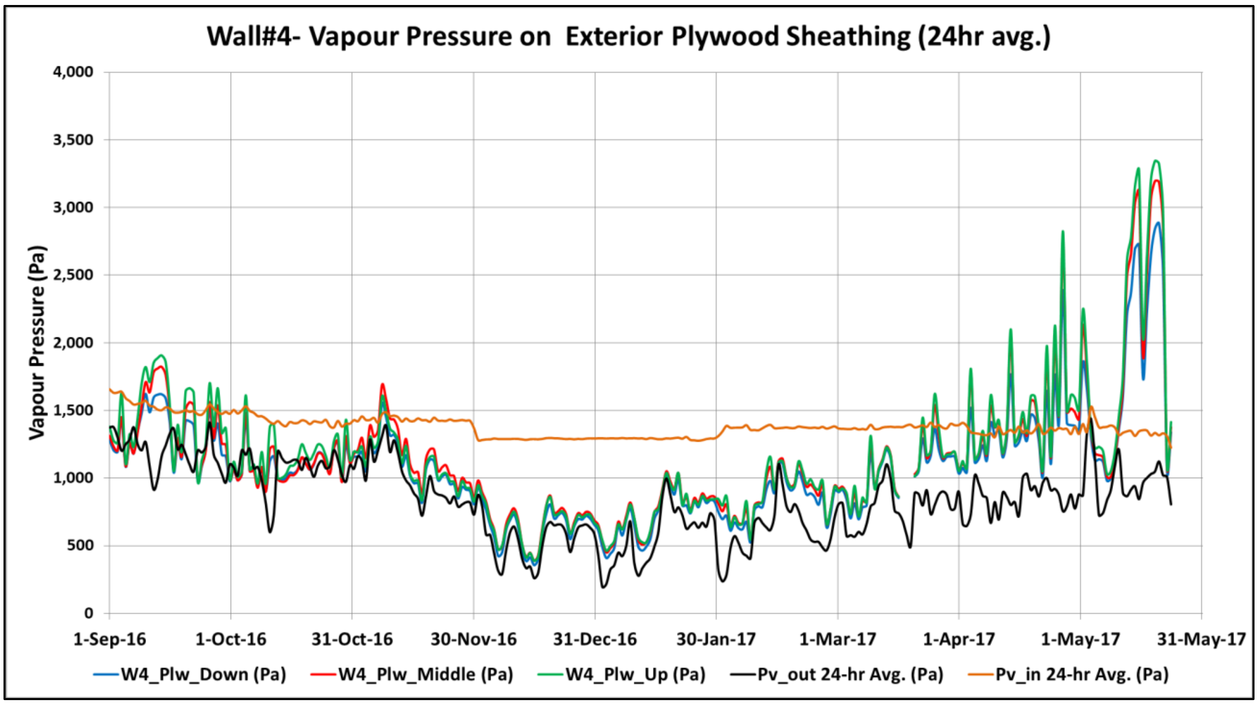


Figure 131- Wall#4- Plywood Vapour Pressure

Figure 132 compares vapour pressure of indoor, outdoor with the averages of plywood sheathing and stud space. The vapour gradient is from interior to exterior in colder and wetter days of the test and fluctuating on days of shoulder season.

For almost 80-90% of the entire test period vapour pressure of indoor air remained higher than plywood sheathing, stud space and outdoor climate, meaning vapour flow tendency is outward. In Sep, Apr, and May there are days that plywood sheathing experiences higher vapour pressure rates than cellulose insulation and both interior and exterior climates, so there were potentials of vapour diffusion from plywood to both interior and exterior which should have accelerated drying process.

Another interesting observation is in Oct-Feb, unlike the previous wall, mid-thickness of cellulose insulation has slightly higher vapour pressure than plywood sheathing. This can translate into a bit of higher vapour permeability of SVR compared to the 4-mil polyethylene film applied in wall#3.

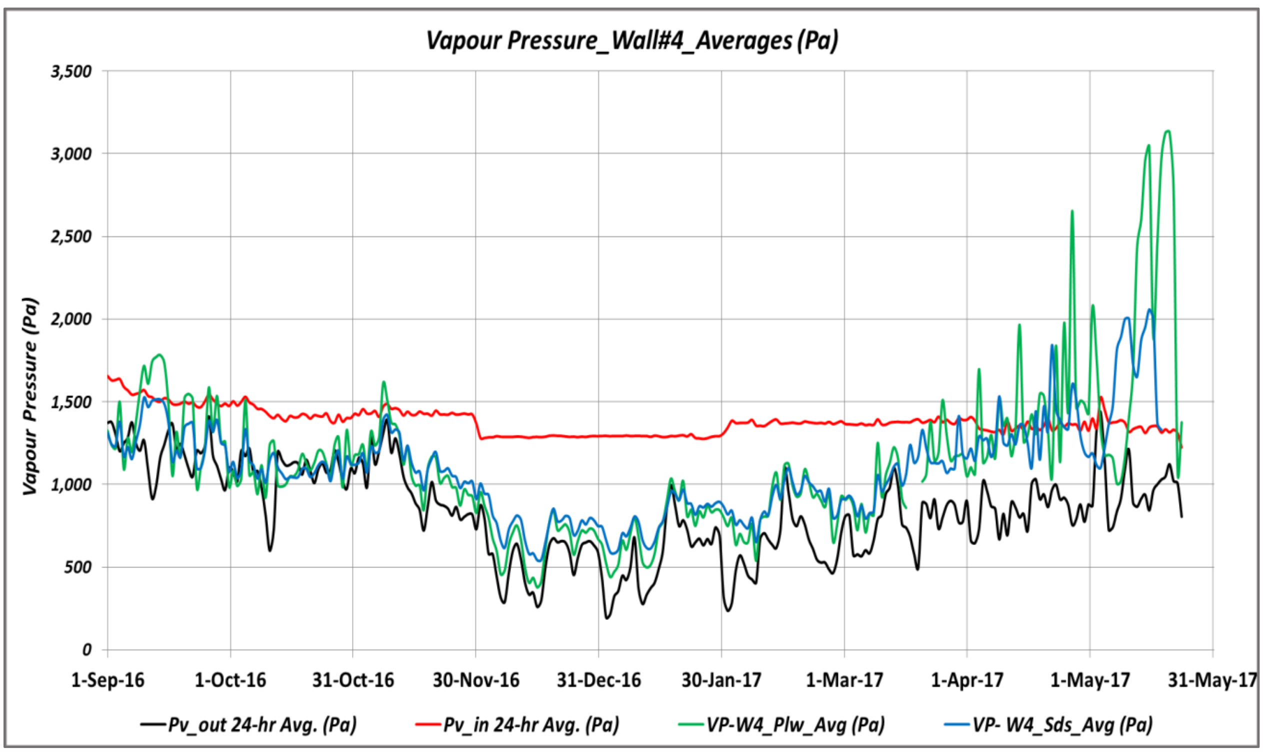


Figure 132- Wall#4- Vapour Pressure- Total Averages- Daily

Figure 133 summarizes and compares the averaged MC levels of wall#4. This is very similar to the previous wall, as interior framing remained fairly dry throughout the entire test; the exterior framing had negligible MC increase of 2-3%, upping at around a maximum of 14% which is just around 1% lower than the previous wall with polyethylene as its vapour retarder.

As for plywood sheathing MC again, the only section that was impacted by water injection was the fabric middle section area located next and right below the water source, wetted by gravitational flow of the liquid water and wicking of plywood sheathing and cellulose insulation. Comparing the lower and upper sections of plywood sheathing, the upper section started gaining more moisture of up to 2% by the end of the wetting season, around 31 December. This situation is rather difficult to explain, but a possible explanation could be variation in density of installed cellulose insulation. As a general observation, if there is no incidental water leakage into this type of wall, with the test condition of this experiment, this wall should have a safe hygrothermal performance.

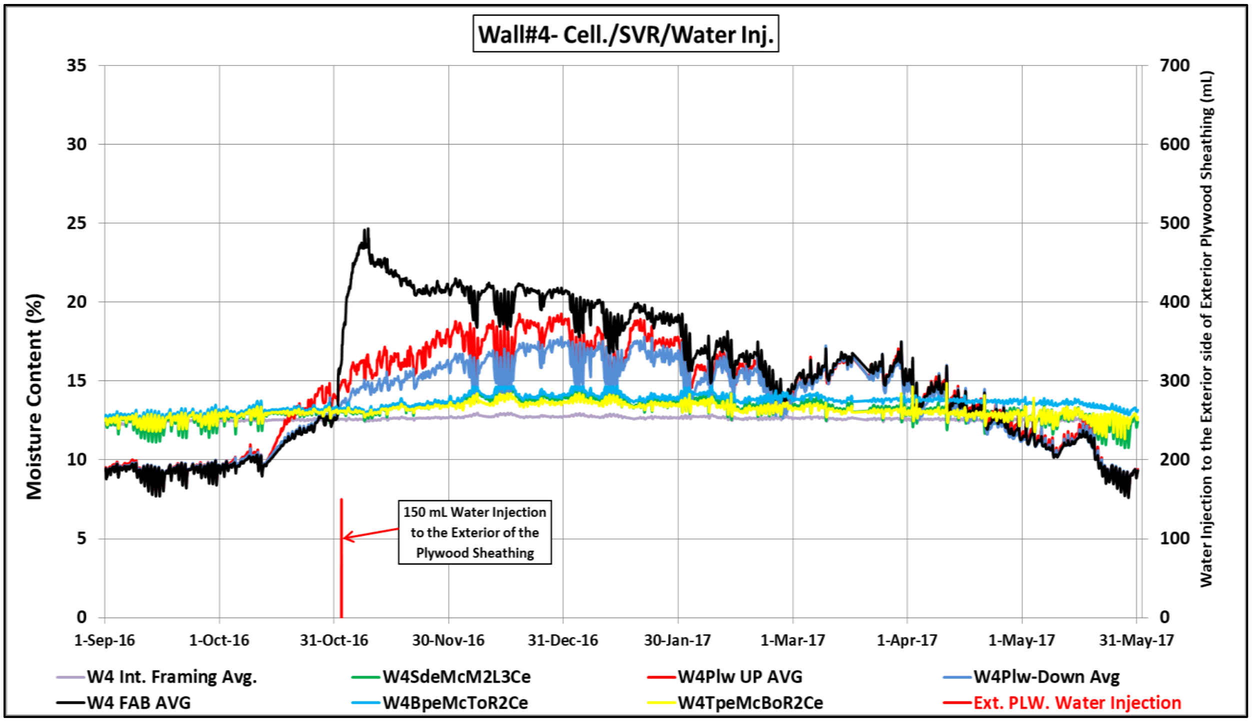


Figure 133- Wall#4- MC for Plywood and Framing- Group-Averaged- Hourly

6.8.6 Mold Index (MI)

As for mold growth Figure 134, mold growth for the fabric area of plywood sheathing started right after the water injection date at the beginning of November 2016 with a rather steep slope until end of November and then slowed down a bit affected by the colder temperatures of the season, but still growing until end of April that reached its maximum level of MI_{max} = 1.15 and final number of just above 1.0.

The lower and upper sections of plywood had a very similar profile, except numbers were lower considerably lower; for the upper plywood mold index reached MI_{max} was 0.75 and final number of MI= 0.65. As for the lower section, MI_{max} was 0.40 and final number landed on MI=0.30.

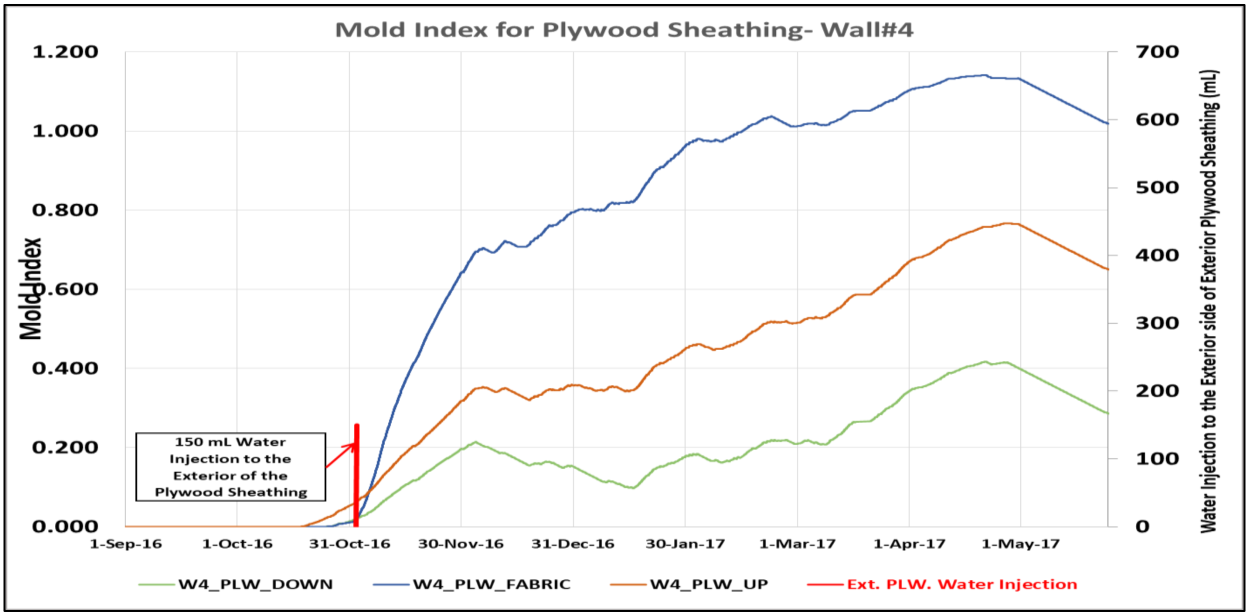


Figure 134- Wall#4-Mold Index for Plywood and Framing- Group-Averaged

6.8.7 Summary

Table 12 summarizes the moisture content and mold index values and periods below. For framing, both interior and exterior, moisture gain was very low, with maximum of 1.5% for all top and bottom plates as well as the vertical stud. While predictably, the middle section of plywood sheathing had the highest moisture gain of 15%, reaching to alarming rates of 24%, the upper and lower sections of plywood did not go beyond 19%.

Table 12- Wall#4- Moisture Performance Summary

Wall#4	initial MC (%)	max MC (%)	MC gain (%)	Reached 28%?	days above 19%	# of wetting days	# of drying days	Final Mold Index	Overal Moisture Performance
lower Plw	9	18	9	No	0	120	150	0.29	Safe
Fabric	9	24	15	No	65	70	200	1.02	Risky
Upper Plw	9	19	10	No	0	120	150	0.65	Safe
Bottom Plate	12.5	14	1.5	No	0	135	135	-	Safe
Middle Stud	12.5	13.5	1	No	0	135	135	-	Safe
Top Plate	12.5	13.5	1	No	0	135	135	-	Safe
Int. Frame	12	13	1	No	0	120	150	-	Safe

As for the mold index, just the middle height of plywood had the final Mold Index of 1.02, and the rest stayed below that level. Overall, this wall had a rather risky moisture response because of middle of plywood having relatively high moisture rates.

6.9 Wall#5

This wall, unlike the other walls, incorporated low density polyurethane sprayfoam, but similar to wall#1&3, had 4-mil polyethylene acting as vapour barrier behind its interior gypsum boards sheathing and had 150mL of water injection on its exterior side of plywood sheathing board, behind WRB.

6.9.1 All Sensors

For an overall view of its hygrothermal performance, the hourly average temperature and moisture content data results are presented and discussed in this section.

6.9.1.1 Temperature (Ts)

Temperature trend of wall#5 is very similar to the previous walls, ranging anywhere from 45-50°C in sunny days of September and May, to -10°C in December and January on its HBP siding. Gypsum board and interior framing like the interior conditioned temperature recorded around 20°C, while plywood sheathing and exterior framing were affected by the exterior weather. More detailed discussion is presented later in this section.

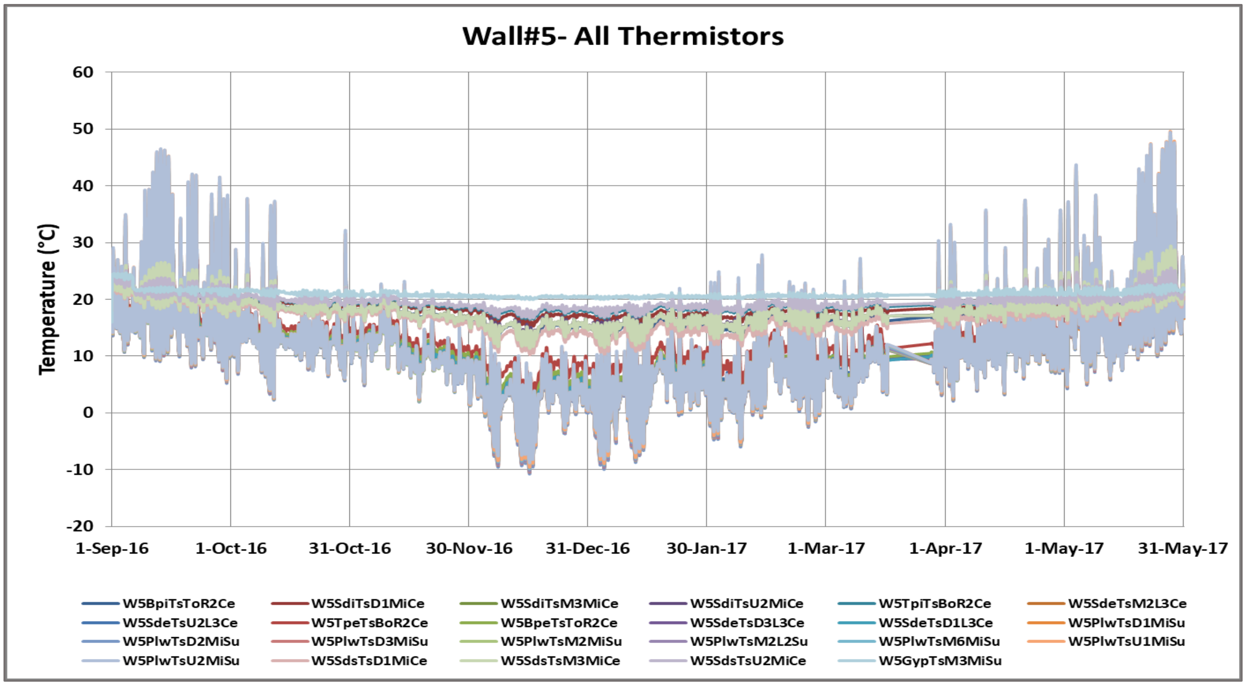


Figure 135- Wall#5- All Thermistors

6.9.1.2 Moisture Content

Figure 136 shows the results of all the MC sensors for wall#5. At an overview, wood framing (studs and plates) showed a rather different moisture content behaviour compared to plywood sheathing. Moreover, some plywood sheathing sensors were obviously affected immediately after water injection date on early November. For a clearer comparison more detailed graphs were created and are presented in this section.

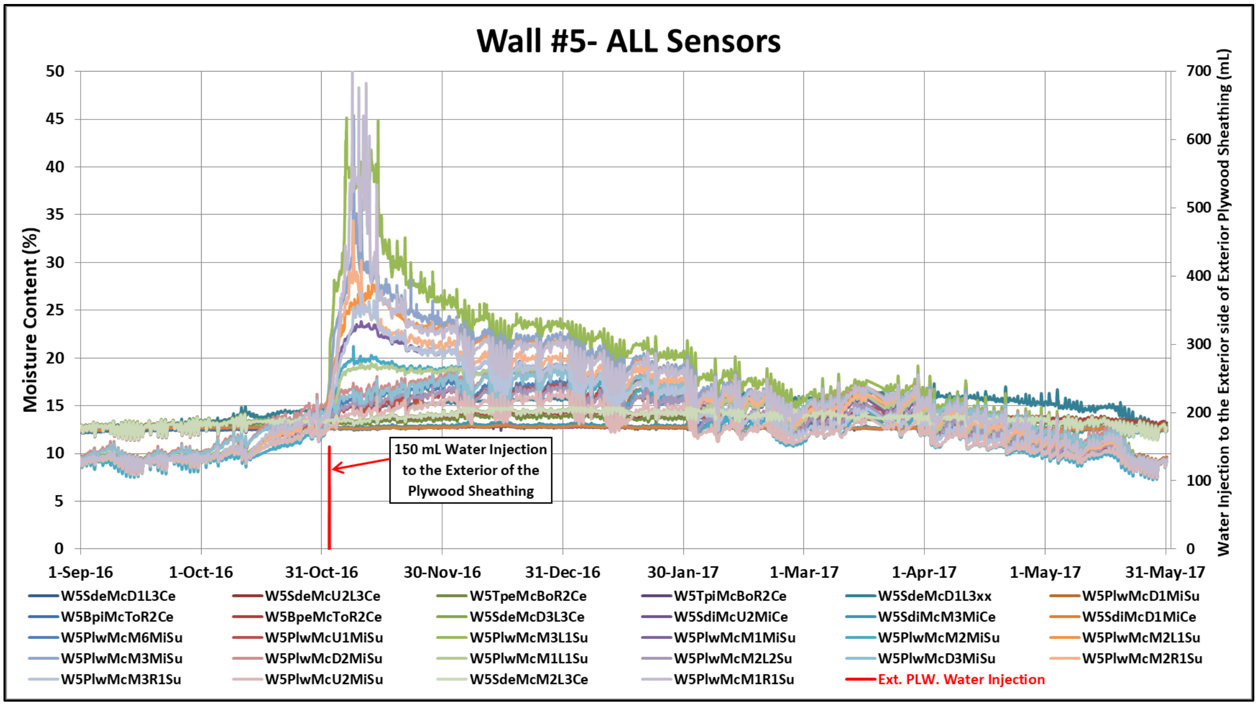


Figure 136- Wall#5- MC for All Sensors- Hourly Avg.

6.9.2 Interior & Exterior Framing

Hourly Moisture Content (MC) for the interior and exterior framing and daily temperature results for exterior framing (vertical stud an also top and bottom plates) of wall#5 are presented in this section.

6.9.2.1 Moisture Content (MC)

As evident in Figure 137, the interior and exterior framing did not have much of moisture gain throughout the entire test period. The interior framing barely gained any extra moisture at all, staying around the initial MC of around 12-13% and the exterior framing while did experience some wetting and drying, but it was rather negligible, 2-3%, from the beginning of the test period to its peak at the end of December 2016. From the peak of MC at the end of December drying started and continued declining up to its initial MC of around 12% by 31 May 2017 which ended of the test period. Like the previous walls, neither of interior or exterior framing had a noticeable impact from the water injection at beginning of November.

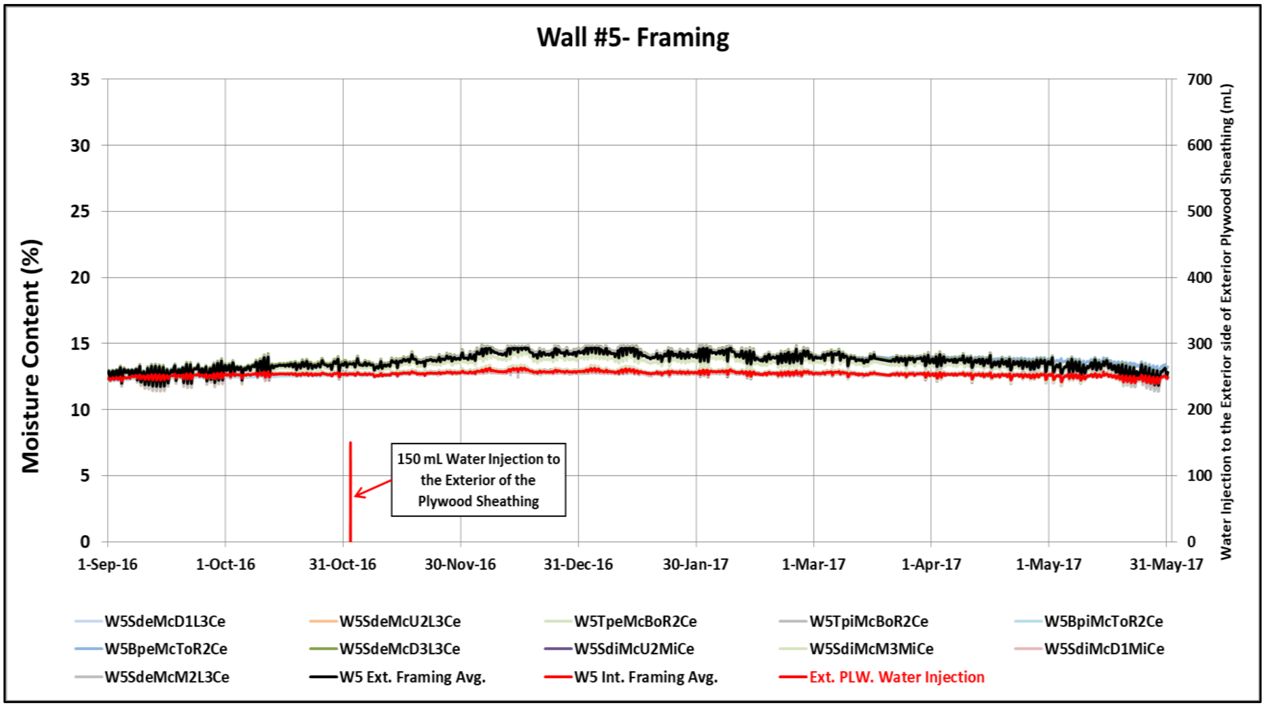


Figure 137- Wall#5- MC for All Framing Sensors- Hourly Avg.

6.9.2.2 Temperature (Ts)

Since the interior framing is almost identical to the interior conditioned environment, just the temperature of exterior framing of wall#5 is discussed in this section.

6.9.2.2.1 Exterior Framing

Figure 138 presents the 24-hour averaged temperature of the exterior framing, including top and bottom palates of wall#5. Temperature of exterior framing is directly affected by the exterior weather seasonal variation but moderated by the conditioned indoor air, ranging from -3°C in mid-December to 27°C at end of May. Like the previous walls, top plate experienced relatively higher numbers compared to all other framing sensors, up to around 5°C in cold periods of winter. All other sensors had very similar temperatures.

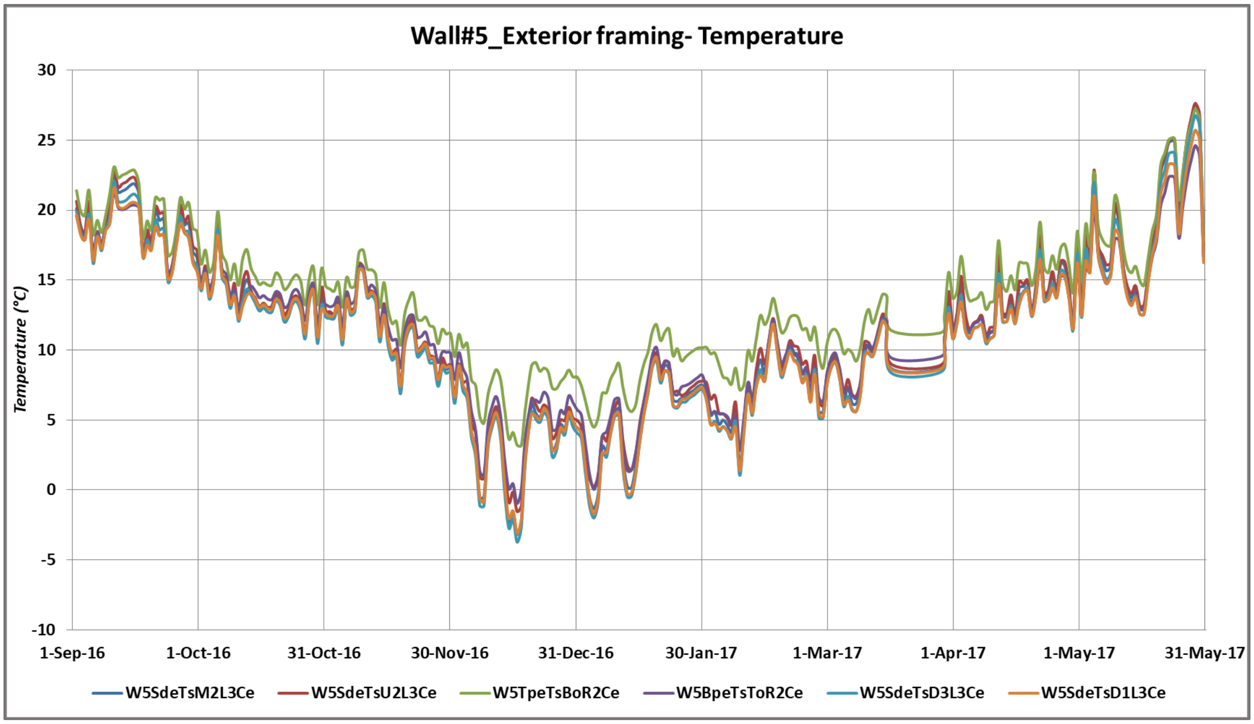


Figure 138- Wall#5- Temperature for Exterior Framing Sensors- Daily Avg.

6.9.3 Plywood Sheathing

Temperature and moisture content averages of recorded data of plywood sheathing on wall#5 (lower, middle and upper sections) are presented in this section.

6.9.3.1 Temperature

Similar to the previous walls, all three vertical levels of plywood sheathing had almost identical temperatures throughout the entire test period. The temperature rates were directly influenced by the exterior ambient temperature and the amount of solar radiation received on those walls. While plywood had below freezing temperatures of up to -5°C in mid-December 2016, it had maximums of close to 30°C at end of May 2017.

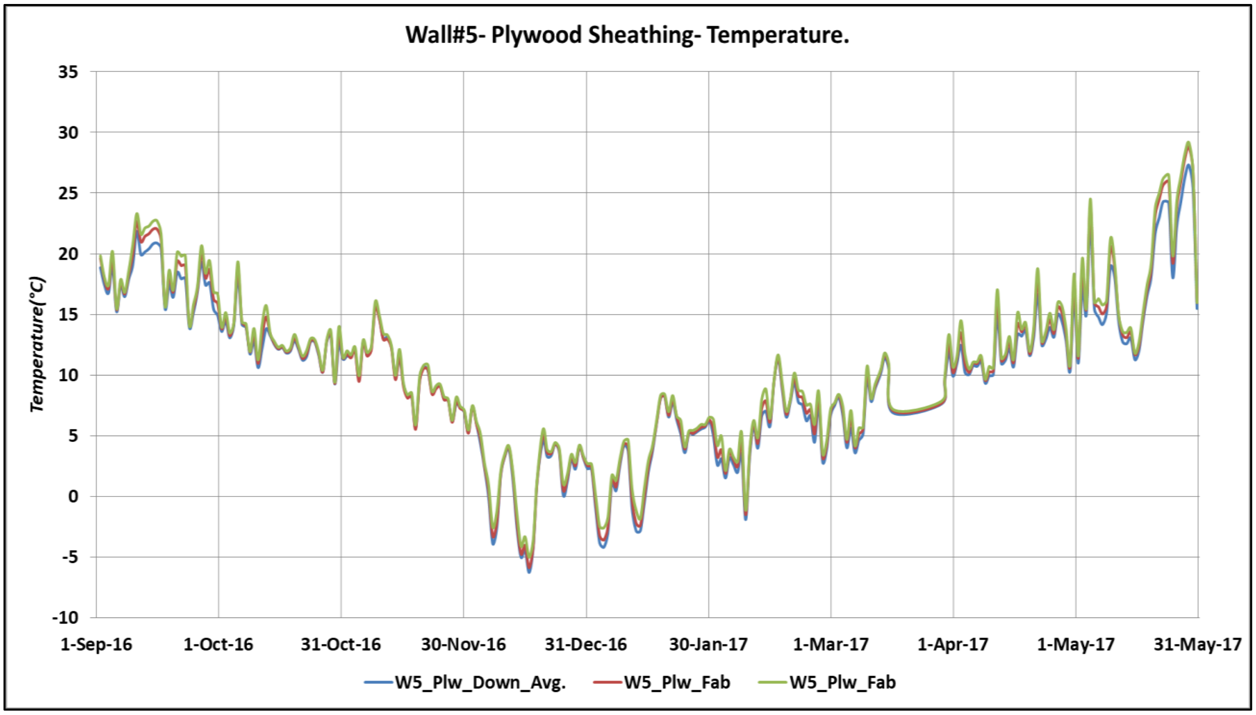


Figure 139- Wall#5- Plywood Sheathing Temperature

6.9.3.2 Moisture Content (MC)

Hourly average moisture content results of three different vertical locations of plywood sheathing for wall#5 are presented and discussed in this section.

6.9.3.2.1 Lower Section Sensors

Figure 140 presents hourly averages of the lower section of plywood sheathing for wall#5. The wetting period started from around beginning of October with the initial moisture content of around 10% and peaked at around 18% by end of December. From around early January 2017, no higher MC was recorded and instead an overall trend of drying, albeit fluctuating, started and continued until the end of the testing period on 31 May 2017. Like the previous walls, shoulder season temporary colder and wetter weather spells did affect MC rates of these sensors noticeably more than the previous walls with cellulose insulation. This difference is an indication of moisture storage capacity and buffering differences between cellulose and polyurethane sprayfoam insulation materials. This will be further analyzed in the upcoming chapters.

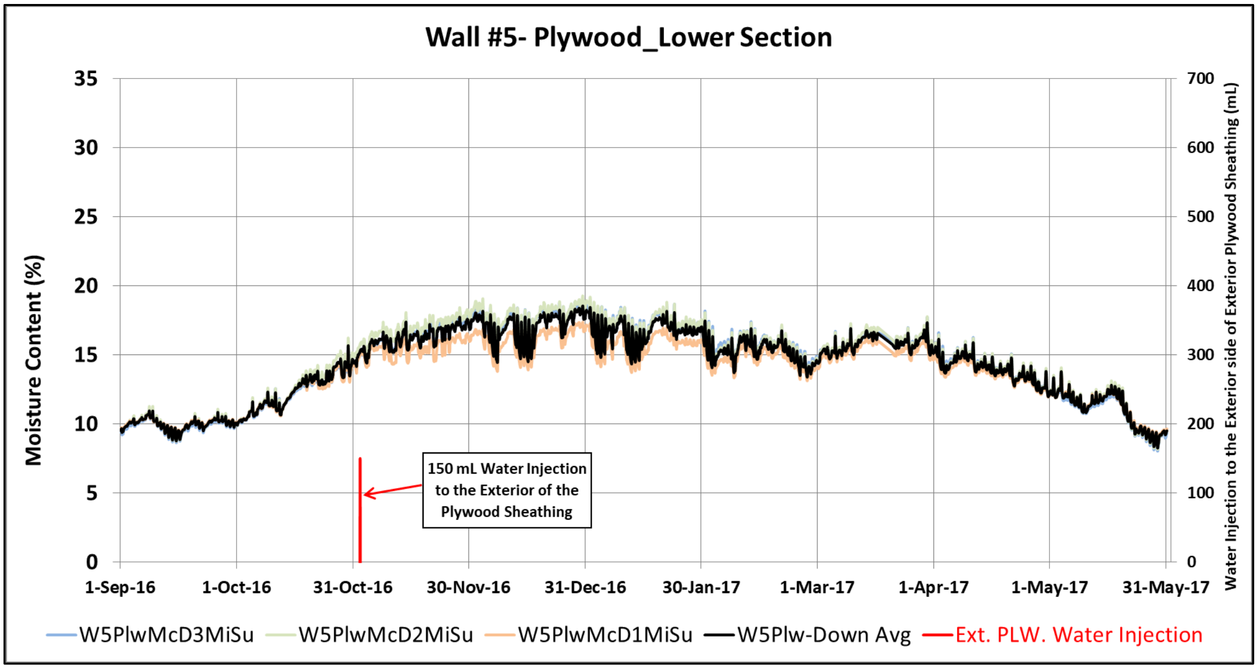


Figure 140- Wall#5- MC for Plywood, Lower Section Sensors- Hourly Avg.

Another interesting observation for this wall, like other previous walls, was the lower section of plywood was not visibly affected by the 150mL injected water at the beginning of November 2016. This could suggest the amount of water was not significant enough to reach to the lower levels, and/or sprayfoam could divert and maintain the water within, preventing it from reaching to the lower levels of the plywood sheathing.

6.9.3.2.2 Middle Height Sensors

Figure 141 presents MC hourly averages for the middle section of plywood sheathing for wall#5. Unlike the lower level of plywood sheathing, the fabric area was visibly affected by the 150mL water injection at the beginning of November; however, some sensors were affected quite more. We can see in the graph below, that the left side sensor W5PlwMcM1L1Su, although locating at the top row and the closest to the source of injected water, had the lowest moisture gain after the injection date. On the other hand, the top right-side MC sensor recorded 20/30% higher levels of MC gain. Like the previous cases, this could be due to the asymmetrical nature of water flow on the fabric suggesting most of the injected water should have flowed mostly from the right side of the soaker hose rather than the left side. To make a more practical analysis of the moisture content behaviour of the wall, an average was calculated and graphed in black color (like the previous walls) to be used for comparing with the sensors of other sections of the wall.

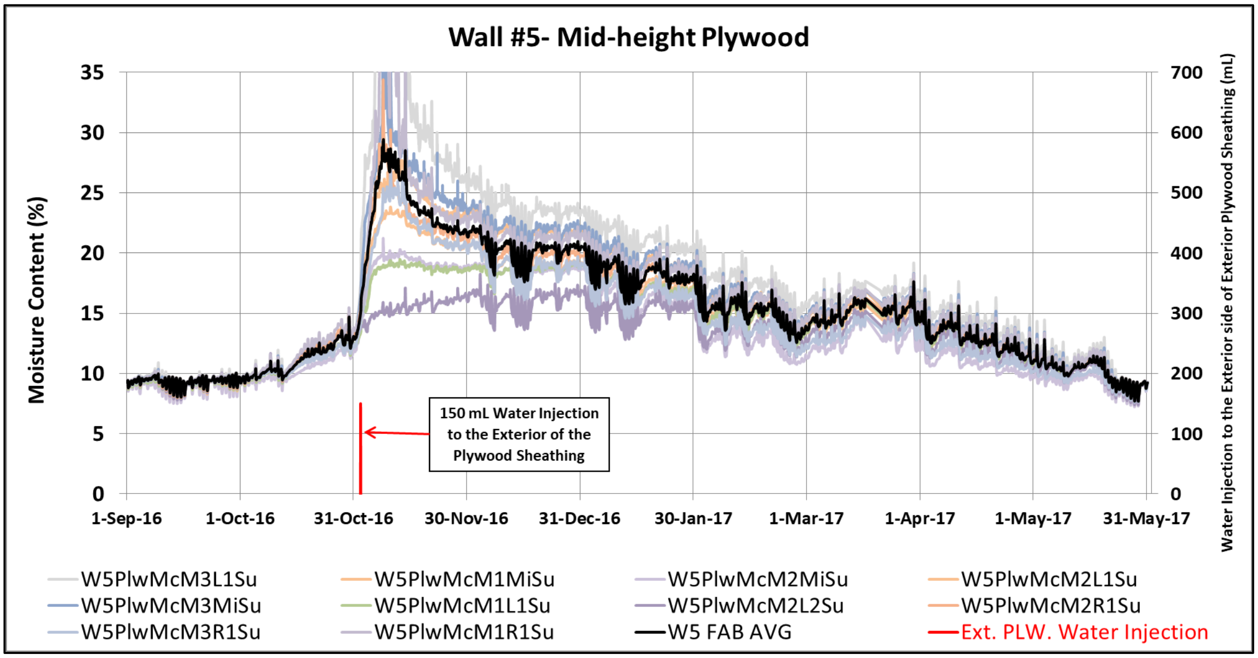


Figure 141- Wall#5- MC for Plywood, Middle Section- Hourly Avg.

As we can see in Figure 141, the main wetting season, started around middle of October and continued on with a relatively moderate slope until the beginning of November that the injection of 150mL water boosted moisture gain dramatically, raising the average MC level of the area from around 13%, to around 29% within just around one week. While this level of MC is above the moisture risky threshold of 28%, however, it was just a short spike, so further assessment of mold risk is deferred to the Mold Index analysis that is presented further in this chapter. After the water injection induced peak MC around 10 November, all the sensors recorded an overall drying trend until the very end of the experiment by 31 May 2017.

6.9.3.2.3 Upper Section Sensors

Similar to the lower section, the upper section of plywood sheathing was barely affected with water injection penetration. Moreover, the other general moisture behaviour of the wall was also very similar to the lower section, but the maximum moisture content was slightly lower than.

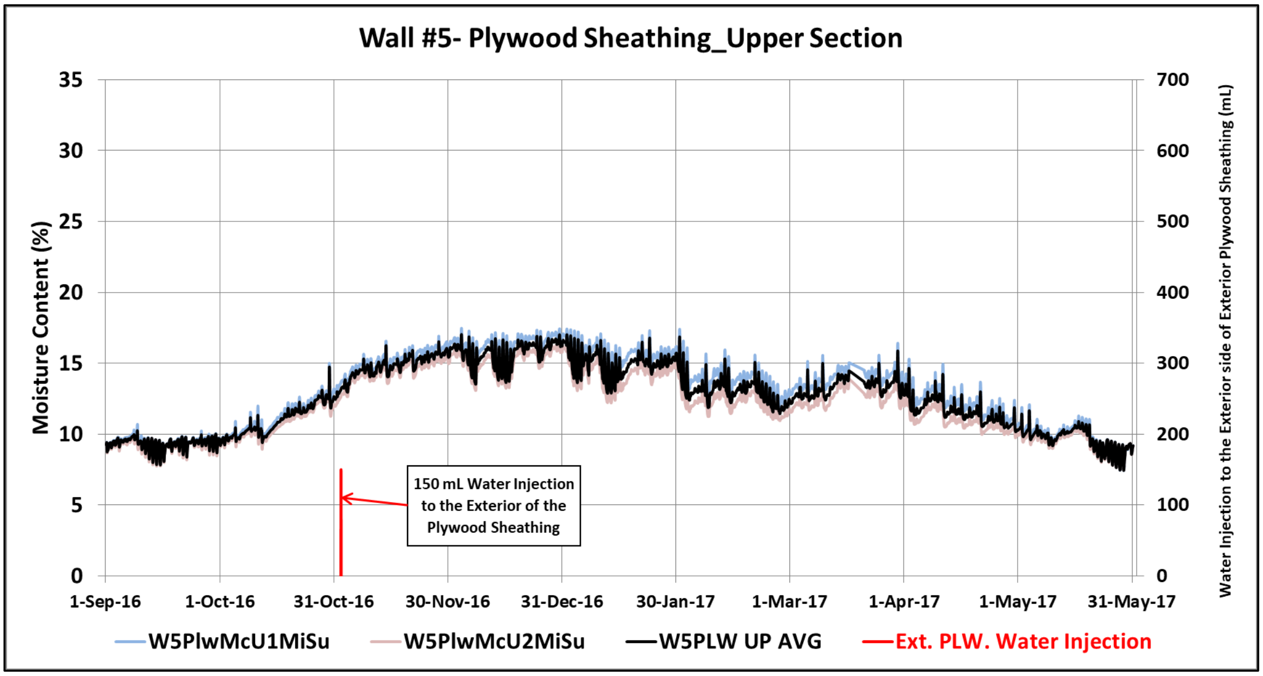


Figure 142- Wall#5- MC for Plywood, Upper Section Sensors- Hourly Avg.

While the lower section experienced up to 19% of MC at its peak, this wall did not go beyond 17% by 31 December 2017 that sensors recorded the maximum rate of MC of the entire rest period. This might be the effect of more of the injected water reaching down to lower sections of plywood by gravity. More comparative analysis is further discussed in later chapters.

6.9.4 Stud Space

6.9.4.1 Cellulose Relative Humidity (RH)

Figure 143 shows the graphed hourly average data of RH of wall#5 at the mid-thickness insulation in three different vertical levels, lower, middle and upper.

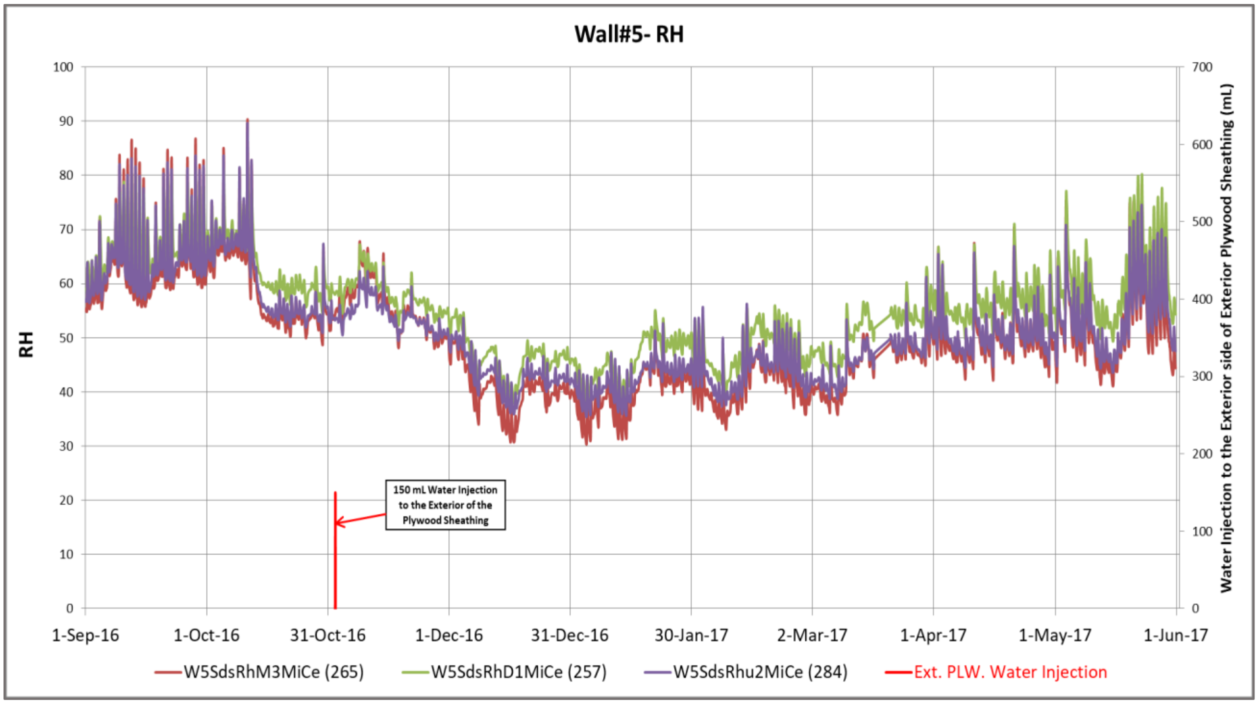


Figure 143- Wall#5- RH for Mid-Thickness of Insulation, Group-Averaged- Hourly

Except for the first six weeks of the test RH levels, the rest of the recorded RH numbers were very similar to walls number one, three and four that were filled with cellulose insulation instead of low density sprayfoam with had a vapour control layer similar to this wall.

On the other hand, RH level of this wall was lower than wall#2 with no vapour barrier layer.

As for the temperature of stud space (Figure 144) this wall, the most obvious heat stratification among all other walls was seen at the upper sensor recorded and remained up to 6°C higher than the lower sensors. This condition had a determining effect on having higher RH levels for the lower sensor as that RH sensor was colder and consequently the RH levels increased by around 5% as visible in the RH graph (Figure 143).

6.9.4.2 LD SPF Temperature (Ts)

Temperature of mid-thickness Low Density Polyurethane Spray Foam (LD SPF) is presented in Figure 144. Interestingly there is an obvious temperature variation pattern of higher temperature at the higher elevations; temperature of the top thermistor in insulation is up to around 6°C warmer than the lower position. This is noticeably higher than the previous cellulose filled walls and it could be due to the more porous nature of LD SPF compared to DCI (Dense Cellulose Insulation), so air can more easily move around and rise by buoyancy. This temperature pattern is useful to explain moisture behavior variation of this wall in different vertical positions.

Overall for temperature trend of stud space, there is a fluctuating yet steady trend with obvious effect from the outdoor seasonal temperature variations.

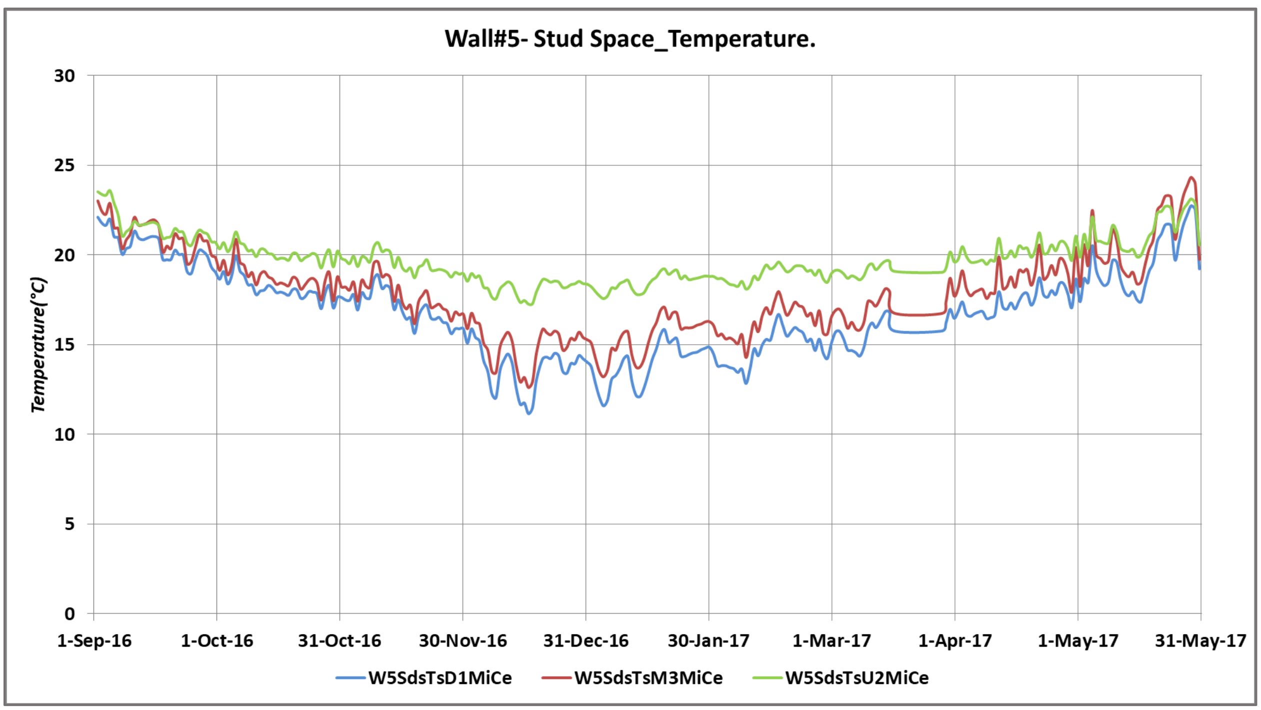


Figure 144- Wall#5- Temperature for Mid-Thickness of Insulation, Group-Averaged- Daily

6.9.5 Discussion

In this section vapour pressure and moisture content results of wall#5 are presented and discussed in concluding views.

As for vapour pressure, the calculated 24-hr average results of indoor, outdoor and overall averaged of three sensors located at the lower, middle and upper section of plywood sheathing as well as mid-thickness of cellulose insulation are presented in Figure 131.

Vapour pressure of plywood sheathing fluctuates under indoor and over outdoor vapour pressures for a good majority of test period from October to April, so its gradient is from indoor to outdoor so walls get wet from interior vapour and dries to the exterior environment by diffusion mechanism.

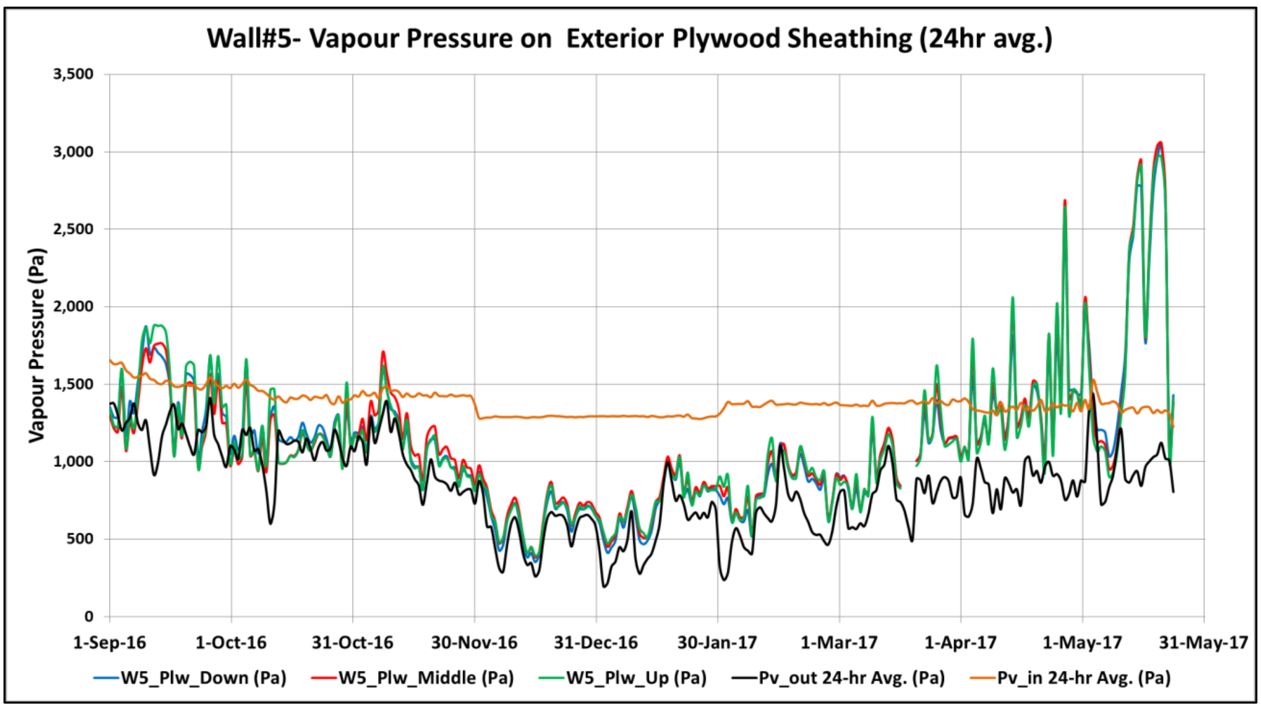


Figure 145- - Wall#5- Plywood Vapour Pressure

Figure 146 presents vapour pressure averages of all plywood sensors, stud space and compares them to the indoor and outdoor conditions. In summary of what previously discussed, vapour pressure of indoor is always higher than outdoor. Also, for a good majority of the whole testing period, vapour pressure of both plywood and insulation is lower than indoor. Therefore, there is a potential of diffusion from indoor to outdoor, however since there is a vapour barrier installed for this wall, the main determining factors are vapour pressure differences of stud space, plywood and outdoor environments. As seen in this graph, for a good majority of the year, vapour pressure of stud space and plywood is higher than outdoor, so outward drying has been a major drying mechanism.

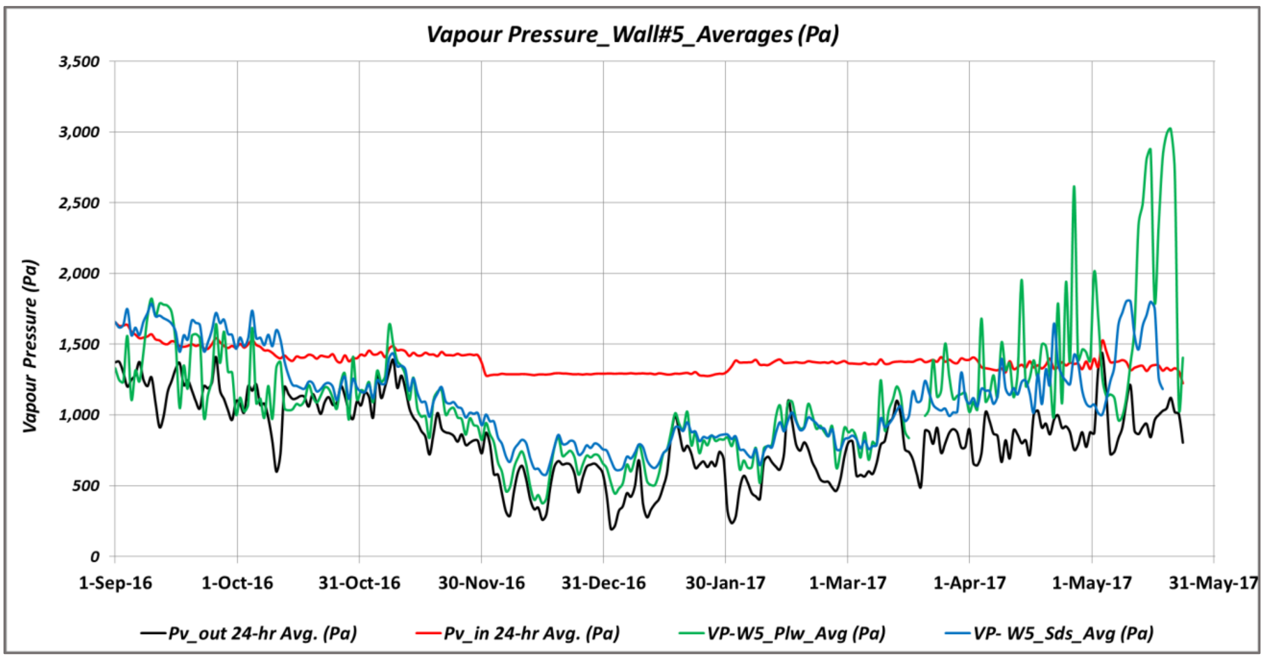


Figure 146- Wall#5- Vapour Pressure- Total Averages- Daily

As for moisture content trends, as a summary and an overall comparison between different locations of the wall, like the previous walls, the interior and exterior framing remained almost dry for the entire test period with minimal moisture gain. As for the plywood sheathing, it was not surprising that the only area noticeably affected by the water injection was the fabric area, with a very sharp hike of around 15%, reaching to alarming rates of 28% within around just one week.

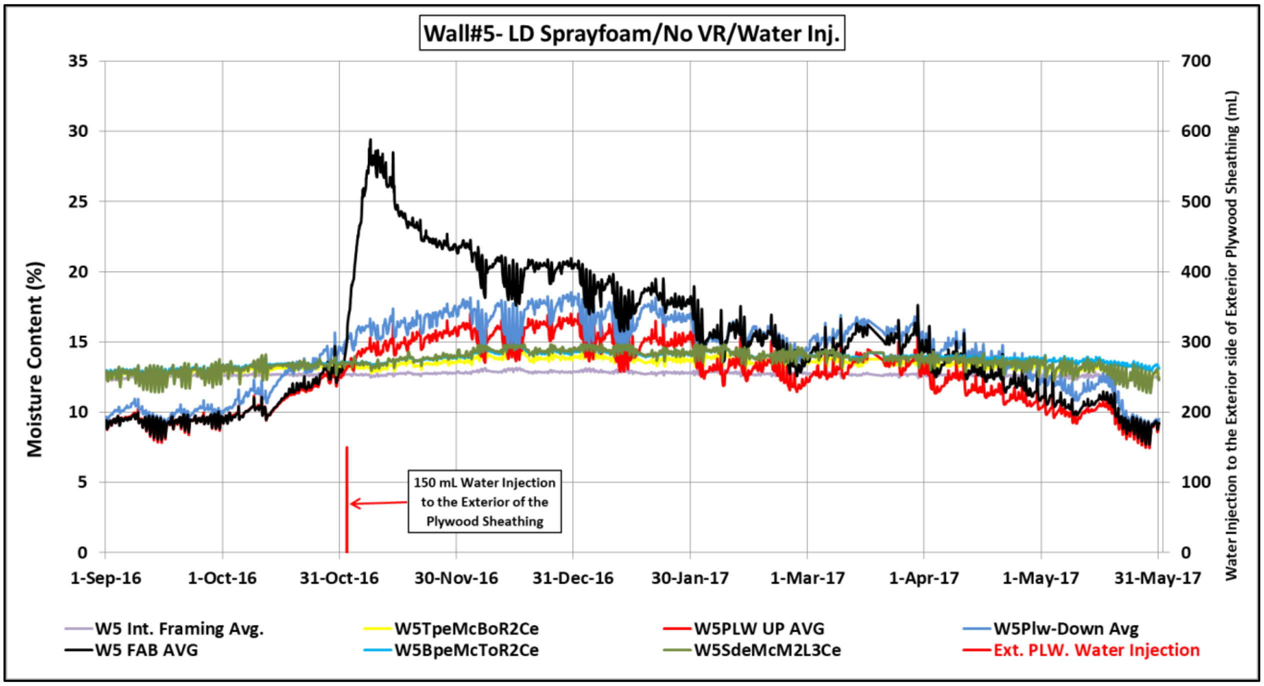


Figure 147- Wall#5- MC for Plywood and Framing- Group-Averaged- Hourly

The lower and upper sections of the plywood sheathing were not noticeably affected by water injection and while they both started from dry status of 9%, the lower plywood started peaking up moisture with visible higher rates of around 2-3%. These higher MC levels for lower sensors compared to higher sensors of plywood sheathing could be attributed to heat stratification, moisture buoyancy, and possibility of some of the injected water flowing down to lower levels by gravity. Overall, except for the middle section of plywood sheathing that passed risky levels of moisture content, all other sensors behaved hygrothermally safe.

6.9.6 Mold Index (MI)

As presented in Figure 148, mold activity on plywood sheathing of wall#5 started around middle of October for the lower section with a smooth slope, however after the water injection at the beginning of November mold index growth for the fabric increased significantly and around one month reached to MI = 0.8.

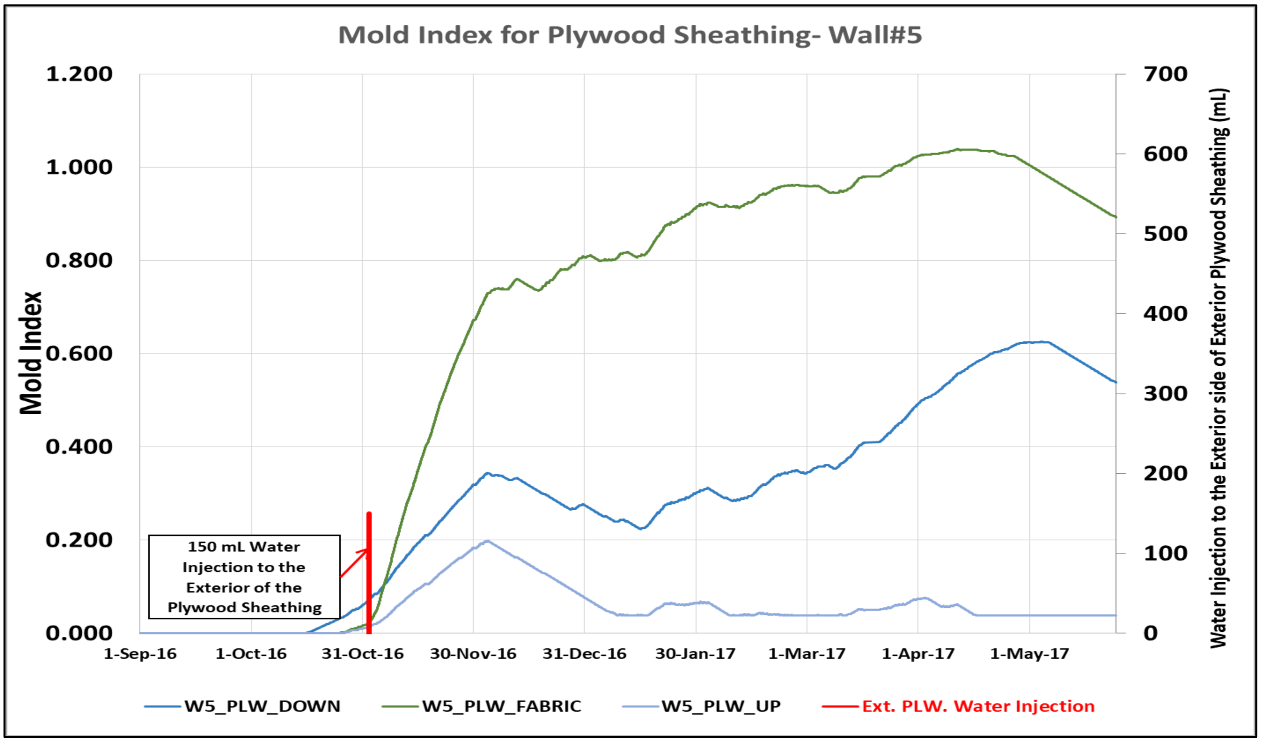


Figure 148- Wall#5-Mold Index for Plywood and Framing- Group-Averaged

Then it continued growing but with a slower pace until it reached its maximum level of around MI_{max} = 1.05 by around middle of May 2017, and then started declining to around MI_{Final} = 0.9 by end of May 2017. The other two locations of plywood sheathing, lower and upper, ended up with MI final of 0.55 and 0.05 respectively. So, around half of mold activity for the lower level compared to the middle level (that is close to the injected water), and almost zero mold activity for the higher level of plywood.

6.9.7 Summary

Table 13 summarizes hygrothermal behaviour of wall#5. The MC results suggest although the fabric area reaches a maximum of 27% MC, the final Mold Index of that area lands on 0.89 which classes as low mold presence (for the one-year duration of this test). The other locations had no concerning moisture content levels or mold index levels, so could be considered having acceptable hygrothermal response.

Table 13- Wall#5- Moisture Performance Summary

Wall#5	initial MC (%)	max MC (%)	MC gain (%)	Reached 28%?	days above 19%	# of wetting days	# of drying days	Final Mold Index	Overal Moisture Performance
lower Plw	9	18	9	No	0	120	150	0.54	Safe
Fabric	9	27	19	No	60	70	200	0.89	Risky
Upper Plw	9	17	8	No	0	120	150	0.04	Safe
Bottom Plate	12.5	14.5	2	No	0	130	140	-	Safe
Middle Stud	12.5	15	2.5	No	0	130	140	-	Safe
Top Plate	12.5	14	1.5	No	0	130	140	-	Safe
Int. Frame	12	13	1	No	0	120	150	-	Safe

6.10 Comparing all Walls

So far hygrothermal performance of the testing walls has been looked into individually and independently. In this section walls are being compared all together for similar sensor locations. For this comparison averaged metrics of Moisture Content (MC), Relative Humidity (RH), Mold Index (MI) were weighed against each other.

6.10.1 Interior Framing

Moisture Content of the Interior Framing sensors is presented in Figure 149. The graph shows interior framing had lower than 2% moisture gain for all five walls that is practically in total safe zone, so there is no need to do further mold analyses for the interior framing.

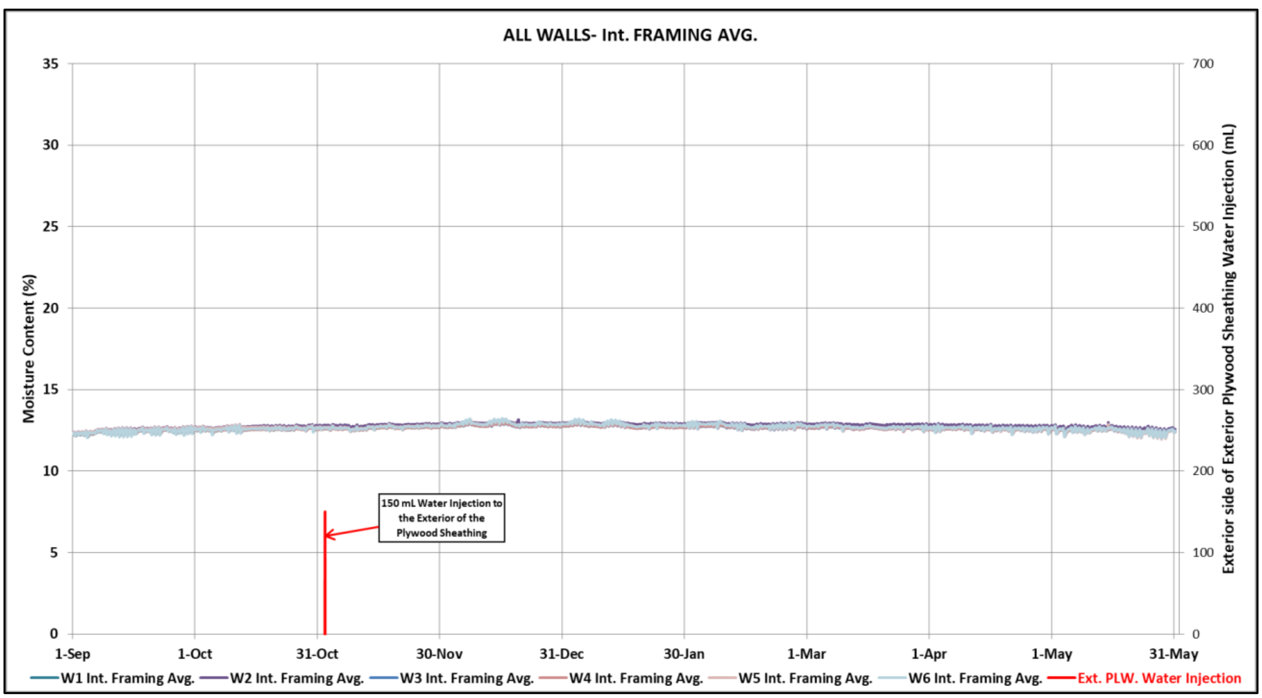


Figure 149- All Walls Moisture Content- Interior Framing Averages

Table 14 summarizes the main hygrothermal metrics for the interior framing of wall#5. As we can see, there is barely any moisture gain (of maximum 1%) for all five walls, no exception. So, as a conclusion, the vertical studs, top and bottom plates for all these double-stud wall assemblies, behaved very safely for the cases of this experiment and is also expected to behave very safely for other super insulated walls with more severe vapour and liquid moisture loading.

Table 14- -Comparing All Walls- Moisture Content Average- Interior Framing

Interior Framing	initial MC (%)	max MC (%)	max MC gain (%)	Reached 28%?	days above 19%	# of wetting days	# of drying days	Overal Moisture Performance
WALL #1	13	14	1	No	0	120	150	Safe
WALL #2	13	14	1	No	0	120	150	Safe
WALL #3	13	14	1	No	0	120	150	Safe
WALL #4	13	14	1	No	0	120	150	Safe
WALL #5	13	14	1	No	0	120	150	Safe

6.10.2 Exterior Framing

Moisture Content results of five sensors are presented in this section as MC is the most common and understood moisture performance in index academic research.

The reported sensors are the lower, middle and upper section of the vertical exterior framing (stud) as well as the top and bottom plates. More details about exact location of sensors can be found in 5.4.1.

6.10.2.1 *Bottom Plates*

Moisture Content results of five walls for bottom plates are presented in Figure 150. Except for wall#2, with no vapour barrier, all other walls had minimal moisture gain and remained dry throughout the entire test period. Only the bottom plate of wall#2 reached alarming rates of 19%, however it died out in a few days and can be considered moisture safe.

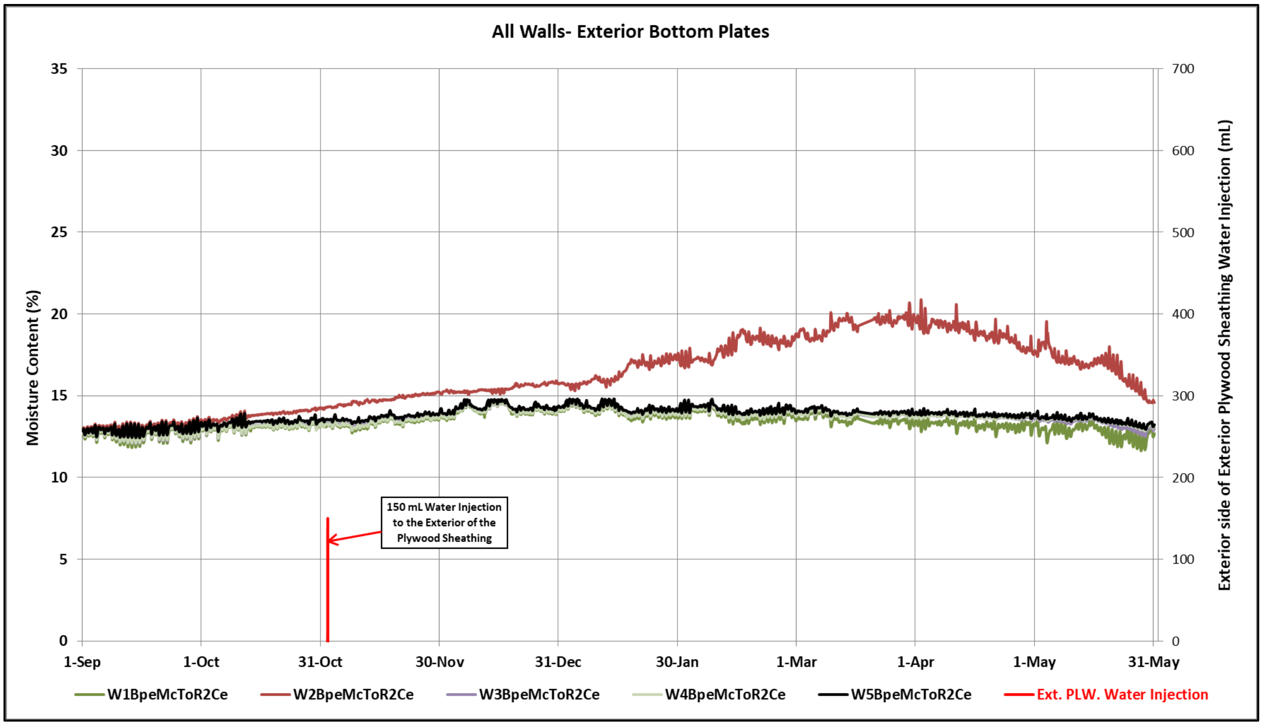


Figure 150- All Walls Moisture Content- Exterior Bottom Plates

Table 15 summarizes all the moisture gains and losses of bottom plates for all five walls, with maximum 1.5% moisture gain for walls with 4-mil vapour barrier as opposed to 7% for the only wall without a vapor barrier. All walls had a quite safe moisture behaviour on top plate whereas moisture response of wall#2 was not as safe, yet acceptable.

Table 15- Comparing All Walls- Moisture Content- Exterior Bottom Plates

Ext. Bottom Plates	initial MC (%)	max MC (%)	max MC gain (%)	Reached 28%?	days above 19%	# of wetting days	# of drying days	Overal Moisture Performance
WALL #1	13	14.5	1.5	No	0	135	135	Safe
WALL #2	13	20	7	No	0	210	60	Acceptable
WALL #3	13	14.5	1.5	No	0	135	135	Safe
WALL #4	13	14.5	1.5	No	0	135	135	Safe
WALL #5	13	14.5	1.5	No	0	135	135	Safe

6.10.2.2 Top Plates

Like the bottom plate, top plate for all the walls with 4-mil polyethylene vapour barrier, remained dry for the entire test period, with 1-2% moisture gain (Figure 151). Unlike bottom plate, although wall#2 without a dedicated vapour barrier had noticeably higher moisture gain compared to all the other four walls while not approaching alarming rates and stayed below 17% MC. The spiky increases in moisture content are mostly the effects of solar radiation that can be ignored.

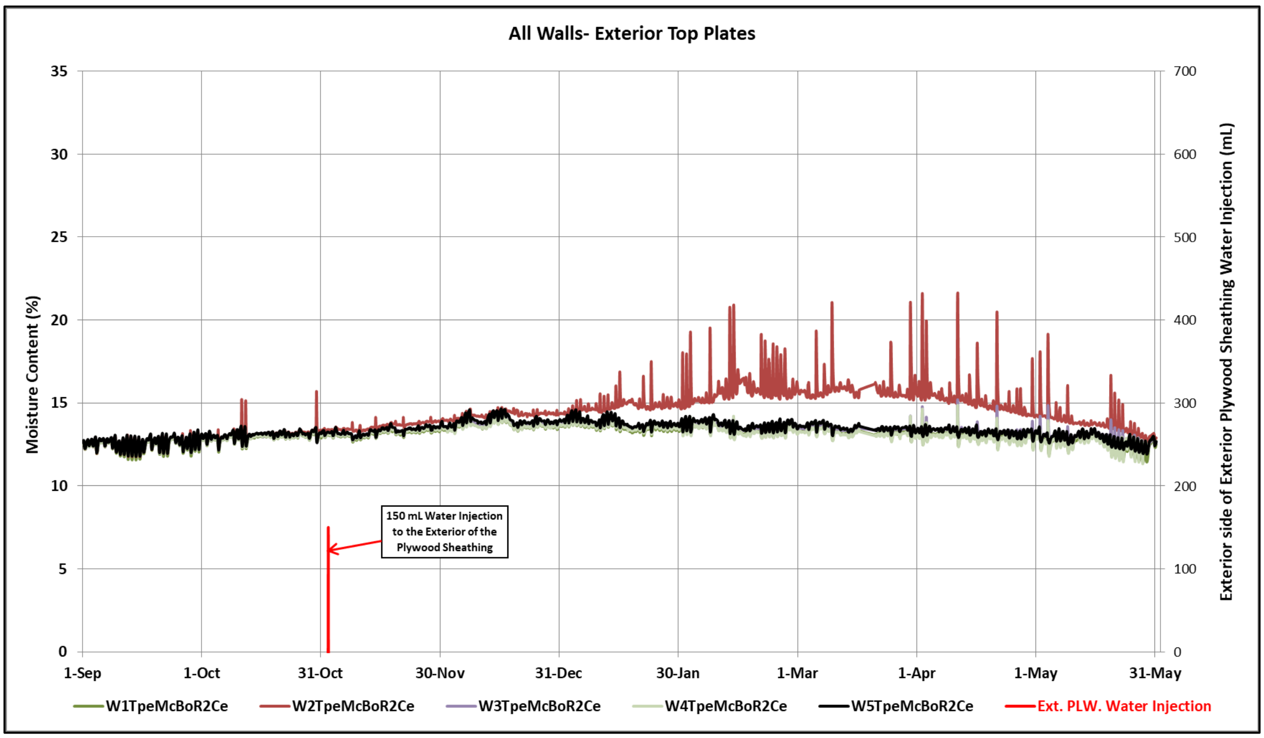


Figure 151- All Walls Moisture Content- Exterior Top Plates

Table 17 summarizes the initial, maximum and duration of moisture gains and losses for all the top plates. While wall#2, experienced 4% moisture increase it is still not a concerning amount, so top plates were all considered safe. The safer moisture response of top plates compared to bottom plates can be attributed to heat stratification phenomenon.

Table 16- Comparing All Walls- Moisture Content- Exterior Top Plates

Ext. Top Plates	initial MC (%)	max MC (%)	max MC gain (%)	Reached 28%?	days above 19%	# of wetting days	# of drying days	Overal Moisture Performance
WALL #1	13	14.5	1.5	No	0	120	150	Safe
WALL #2	13	17	4	No	0	165	115	Safe
WALL #3	13	14.5	1.5	No	0	120	150	Safe
WALL #4	13	14.5	1.5	No	0	120	150	Safe
WALL #5	13	14.5	1.5	No	0	120	150	Safe

Table 17-Comparing All Walls- Moisture Content- Exterior Top Plates

6.10.2.3 Lower Height Stud

The moisture content of lower section of exterior vertical stud is presented on Figure 152. Similar to top and bottom plates, wall#2, with no dedicated vapour barrier, had by far the most moisture gain among all and went above 19% of moisture content. On the other hand, all other walls remained dry on bottom of the lower section of their exterior vertical stud. One interesting observation is none of the vertical studs on their lower section were noticeably affected by the water injection on the exterior plywood.

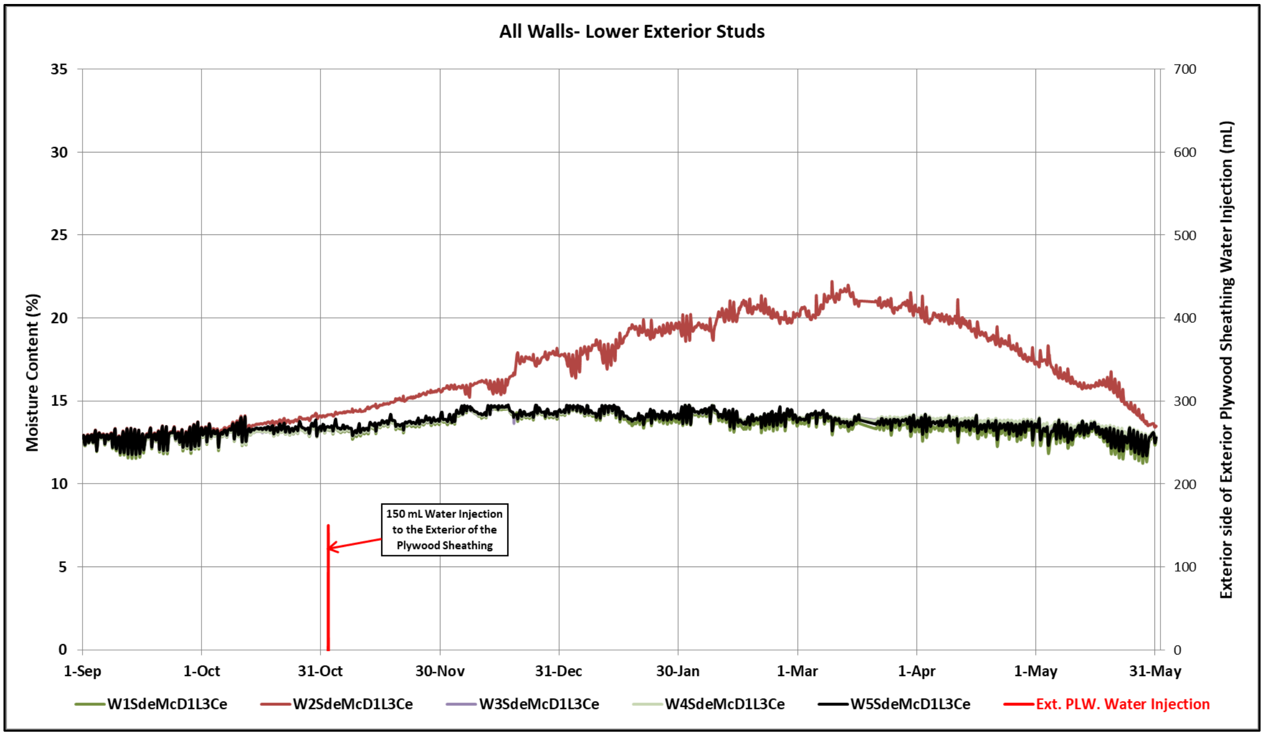


Figure 152- All Walls Moisture Content- Exterior Studs- Lower Height

As we can see on Table 18, wall#2 had an alarming amount of 9% moisture gain reaching up to 22% in its maximum around middle of March 2017. The MC of this location remained above 19% (which is a rather risky area) for around three months. This can be considered unsafe moisture behaviour.

Table 18- Comparing All Walls- Moisture Content- Exterior Studs- Lower Height

Ext. Studs Lower Section	initial MC (%)	max MC (%)	max MC gain (%)	Reached 28%?	days above 19%	# of wetting days	# of drying days	Overal Moisture Performance
WALL #1	13	14.5	1.5	No	0	135	135	Safe
WALL #2	13	22	9	No	90	195	75	Risky
WALL #3	13	14.5	1.5	No	0	135	135	Safe
WALL #4	13	14.5	1.5	No	0	135	135	Safe
WALL #5	13	14.5	1.5	No	0	135	135	Safe

6.10.2.4 Middle Height Stud

The moisture content of mid elevation of the exterior stud, for all five walls is presented in Figure 153. The moisture increases and decreases of this case, look very similar to the lower segment of the exterior vertical studs, with maximums of 22% for wall#2, and around 15% for all other walls. Moisture content of wall#2 remained above 19% for around 100 days, so slightly longer than the bottom section of studs.

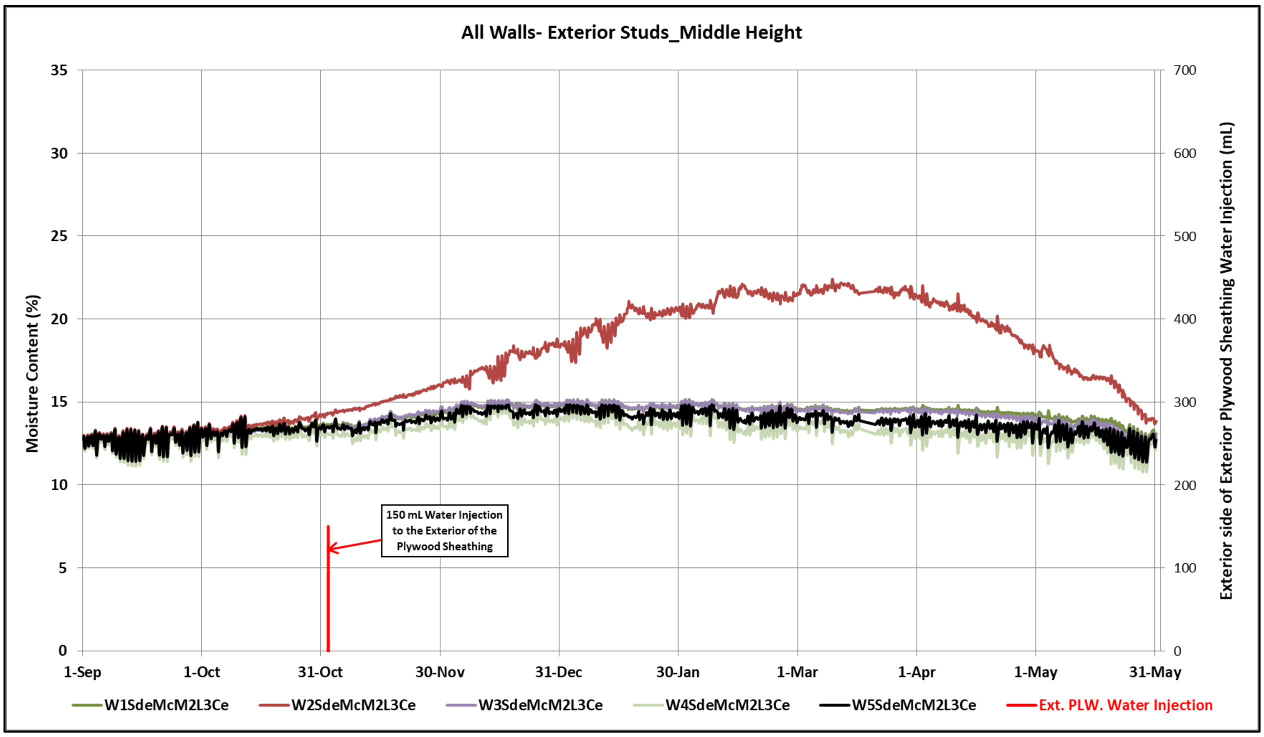


Figure 153- All Walls Moisture Content- Exterior Studs- Middle Height

Table 19 summarizes the numbers for this case. As reflected, similar to the previous case, none of the sensors exceeded 15%, but wall#2, so the vapour barrier was quite effective in keeping excessive moisture out of exterior framing at middle height section as well with the test boundary conditions in this experiment.

Table 19- Comparing All Walls- Moisture Content- Exterior Studs- Middle Height Upper Section

Ext. Studs Mid Height	initial MC (%)	max MC (%)	max MC gain (%)	Reached 28%?	days above 19%	# of wetting days	# of drying days	Overal Moisture Performance
WALL #1	13	15	2	No	0	135	135	Safe
WALL #2	13	22	9	No	100	195	75	Risky
WALL #3	13	15	2	No	0	135	135	Safe
WALL #4	13	15	2	No	0	135	135	Safe
WALL #5	13	15	2	No	0	135	135	Safe

6.10.2.5 Upper Height Stud

Figure 154 shows the comparative moisture content of the upper sections of vertical studs and very similar to the middle and lower section, the only significant moisture gain belongs to wall#2, without a dedicated vapour barrier. All other walls remained relatively dry on this section of wood framing.

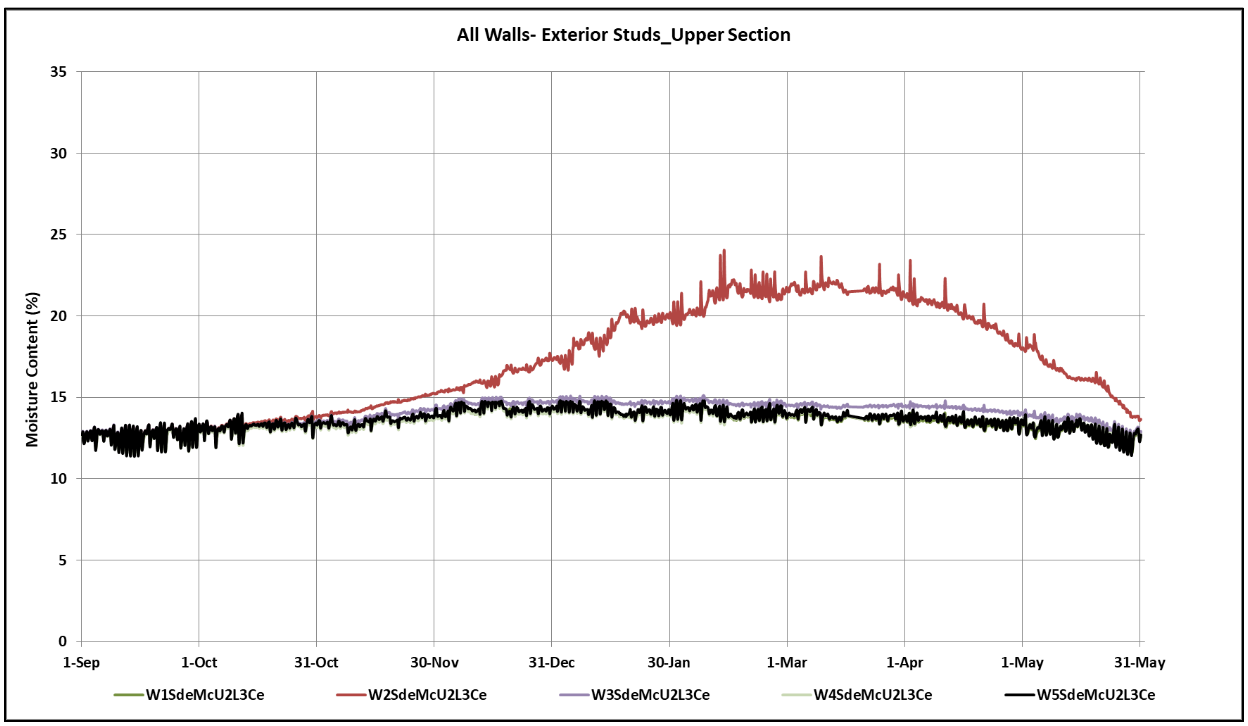


Figure 154- All Walls Moisture Content- Exterior Studs- Upper Section

Summarized in Table 20, wall#2 was the only wall that experienced above 19% moisture content levels which lasted for duration of around 100 days, similar to the middle height section.

Table 20- Comparing All Walls- Moisture Content- Exterior Studs- Upper Section

Ext. Studs Upper Section	initial MC (%)	max MC (%)	max MC gain (%)	Reached 28%?	days above 19%	# of wetting days	# of drying days	Overal Moisture Performance
WALL #1	13	15	2	No	0	135	135	Safe
WALL #2	13	22	9	No	100	195	75	Risky
WALL #3	13	15	2	No	0	135	135	Safe
WALL #4	13	15	2	No	0	135	135	Safe
WALL #5	13	15	2	No	0	135	135	Safe

6.10.3 Lower Plywood

The averaged results of three MC+T sensors located on plywood sheathing's centre line that represents the lower section of the wall as well as the RH sensors located at the lower section of mid-thickness of insulation gap, 12" higher from the bottom plate are presented and compared for all five walls tested for the duration of this experiment.

6.10.3.1 Moisture Content (MC)

For the moisture content of lower plywood sheathing, wall number two is the only one that goes beyond moisture risky rates and all other walls behaved very safely, never going above 18% of moisture content. One rather surprising result on this graph is that wall#1 which is expected to have lower MC rates compared to wall#3 (both are identical in construction but wall#1 had no water injection) had slightly higher recorded moisture content which should have been the opposite. This could be for several reasons, including different density for the cellulose insulation and probability of slightly different solar radiation reception because of their positions on the south east orientation. This needs further investigation after end of the test period, including more pyranometers as well as taking samples of the installed cellulose insulation to test and compare their hygrothermal properties.

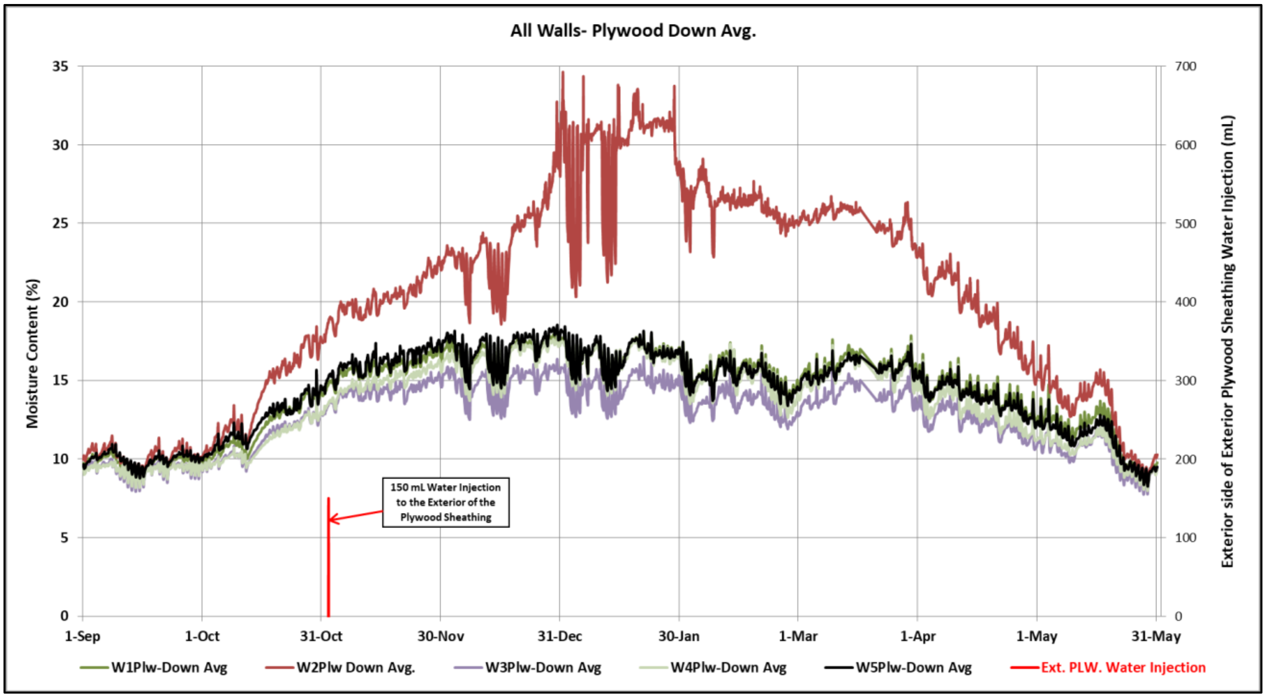


Figure 155- MC for All Walls- Lower Section of Plywood- Hourly Avg.

Overall for the bottom section of plywood sheathing, the lowest MC levels belonged to wall#3 with cellulose and 4-mil polyethylene, followed closely by wall#4, wall#1, and wall#5. The highest MC levels was again for wall#2 for.

6.10.3.2 Stud Space

6.10.3.2.1 Relative Humidity (RH)

The graphs in Figure 156 present the hourly average of relative humidity levels for the lower section of insulation space in its middle thickness for all five walls. Overall, insulation stayed the wettest for wall#2 throughout the entire test period. For wall#5, except for the first six weeks, its RH levels was very similarly to all other walls that had an extra vapour control layer, wall#1, wall#3 and wall#4.

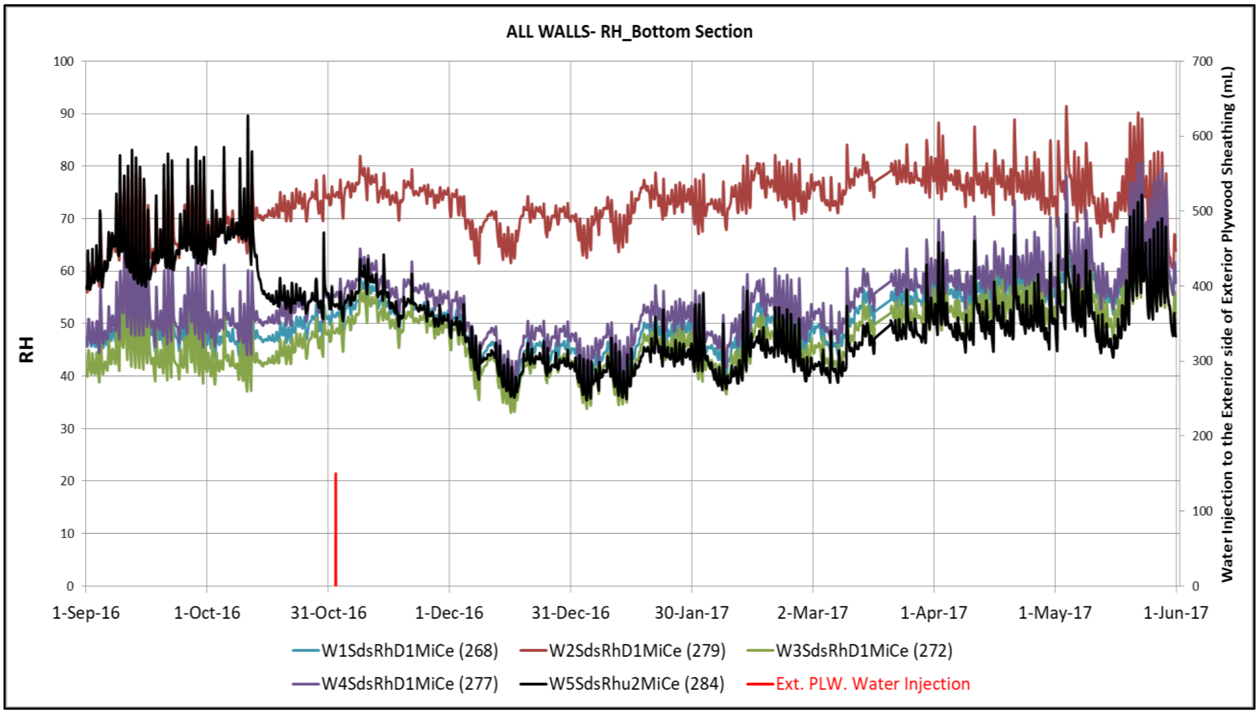


Figure 156- All Walls, RH for the Bottom-Mid-Thickness of Insulation, Group-Averaged- Hourly Avg.

Moreover, wall number three with conventional polyethylene was drier than wall number four with SVR throughout the entire test period.

6.10.3.3 Mold Index (MI)

As for mold index for the lower section of plywood sheathing, all walls performed well except wall#2 that had significantly higher mold index growth. Similar to the previous moisture content rankings, the safest wall was wall#3, followed by wall#4, wall#1, wall#4, and wall#5, but all within close proximity.

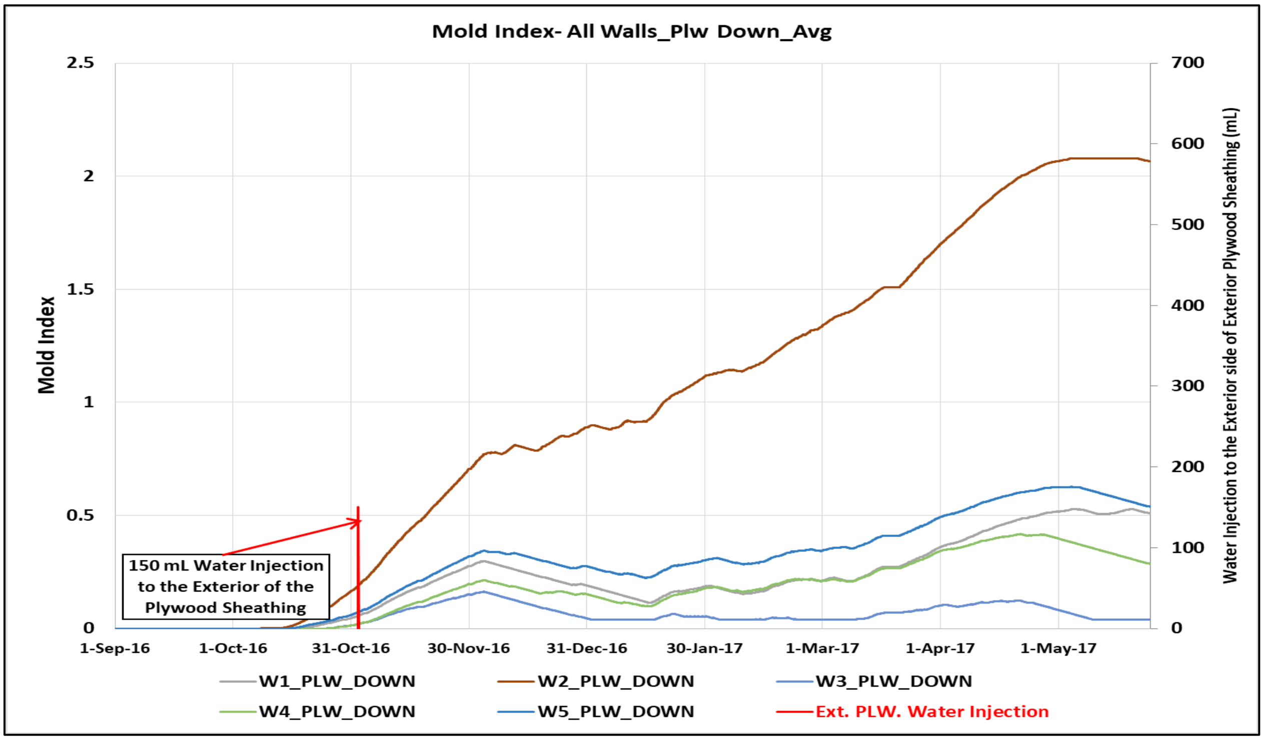


Figure 157- MI for All Walls, Lower Section of Plywood

Mold Index of wall#2, reached to alarming rates of MI=2. This is considered as “several mold growth colonies in microscopic scales (Figure 105) which can translate into the onset of moisture growth (germination) which is hard to reverse it.

6.10.3.4 Summary

Table 21 summarizes all the moisture content and mold index numbers discussed above for the lower section of plywood sheathing. Except wall#2, all other walls had a rather safe moisture response for the duration and conditions of the experiment. MC for wall#2 reached maximum rate of 35% which is in a risky area and there is no surprise why Mold Index was predicted to go beyond 2.0 within just one single year of this experiment.

Table 21- All Walls, Moisture Performance Summary of Lower Section of Plywood

Plywood- The Upper Section	initial MC (%)	max MC (%)	max MC gain (%)	Reached 28%?	days above 19%	# of wetting days	# of drying days	Mold Index	Overal Moisture Performance
WALL #1	9	18	9	No	0	90	150	0.50	Safe
WALL #2	9	35	24	**Yes**	150	110	130	2.20	**Risky**
WALL #3	9	16	7	No	0	90	150	0.04	Safe
WALL #4	9	19	10	No	0	90	150	0.65	Safe
WALL #5	9	17	8	No	0	90	150	0.04	Safe

6.10.4 Middle Height Plywood

In this section as explained earlier nine MC sensors were installed on plywood sheathing in a matrix of 3x3, in three rows and three columns, first row 28 inches above top of bottom plate, and the other two rows located 4” and 8” from the bottom row. The centre column is located on the centre line lateral dimension of the wall panel and the two other columns are each 3 $^{1/4}$” apart from the centre line. There was also one thermistor installed in the centre of the matrix and all the nine MC sensors were coupled with that sensor assuming the MC sensors were all in close enough proximity to have very close temperatures. Temperature results were necessary to make corrections for MC calculations and also to calculate relative humidity from moisture content as well as mold index. Moreover, having temperature variation per se was a useful metric for understanding the hygrothermal behaviours of the walls.

This area was chosen to represent the middle height section of a wall that is associated with water penetration from window sill. Moreover, RH results are from the sensor located at the middle section of mid-thickness of insulation gap, 32 inches higher from top of bottom plate.

6.10.4.1 Moisture Content (MC)

The average moisture content of middle section of plywood sheathing in hourly averages are presented below for all walls. All walls (except wall#1 that had no water introduction) were affected visibly by the injected water, but in different rates. Interestingly the moisture content levels of wall#2 and wall#5 were raised more than the other walls. This could be the effect of higher vapour vapor pressure in those walls and less drying possibility of the introduced liquid water.

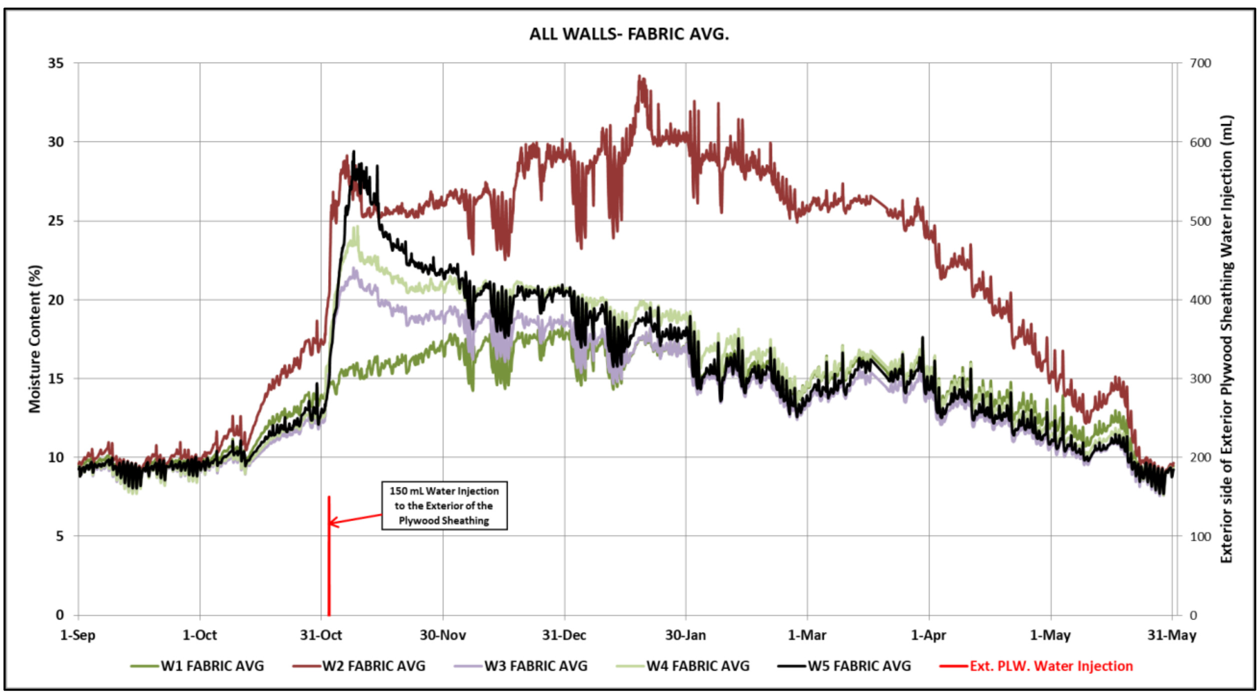


Figure 158- MC for All Walls- Mid-height Section of Plywood- Hourly Avg.

After the water injection, while wall#3, wall#4 and wall#5 started decreasing in moisture content in very similar patterns, wall#2 not only did not start to dry but rose in its moisture content to even higher levels reaching its maximum of around 33% by middle of December.

On the other hand, wall#5 continued drying and was down to 18% of MC by middle of December, in similar levels as wall#1, wall#3 and wall#4 with extra vapour control layers. Moreover, from around end of January, wall#5 was the driest wall among all.

Overall, wall#5 demonstrated excellent drying capabilities for a probable liquid water leakage intrusion occurrence.

6.10.4.2 Stud Space

6.10.4.2.1 Relative Humidity (RH)

The relative humidity levels of mid-thickness of insulation located at the middle height of the walls are presented below. At the very first glance the trend between walls is very similar to the lower section, as wall number#2 and wall#5 start with similar RH levels and continue together until around 10 October that wall#5 loses around 10% of RH within just a couple of days and joins the other cellulose insulated walls that have incorporated a vapour control layer of either polyethylene or smart vapour retarder behind their interior gypsum board sheathing.

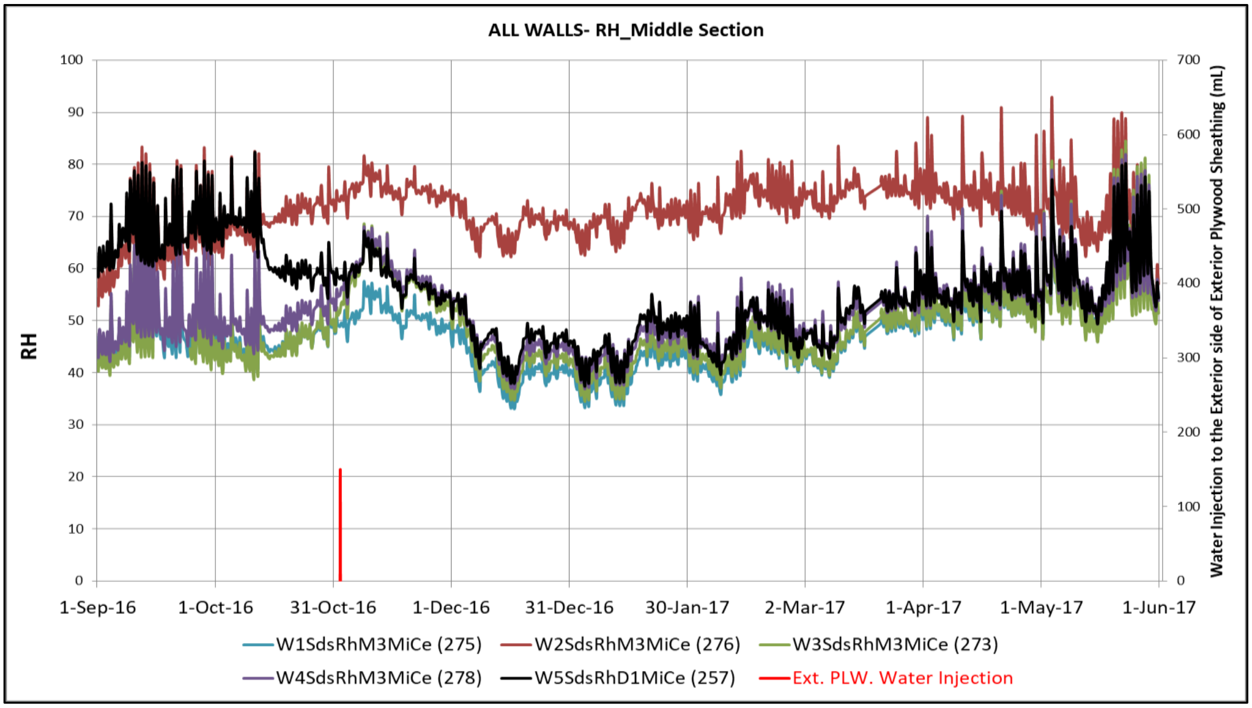


Figure 159- All Walls, RH for the Mid-Height of Mid-Thickness of Insulation, Group-Averaged- Hourly Avg.

Interestingly wall#5 with LD SPF with an extra polyethylene vapour control layer, while very similar to the other walls, from around early December is the driest insulation until end of the test.

6.10.4.3 Mold Index (MI)

Mold Index sums up the overall performance all walls in the middle section of their plywood sheathing which is the main region of focus for this study. As expected wall#2 had the highest calculated mold activity, more than twice than all other walls. Interestingly, wall#5 had slightly lower mold activity than wall#3 with SVR as its vapour barrier, but wall#4 performed better than wall#5 and better than the wall with SVR, so conventional polyethylene was more effective than SVR for this study. And finally, and expectedly wall#1, with no water introduction, performed better than all other walls and slightly better than wall#3 with water introduction, for the middle height section of plywood sheathing.

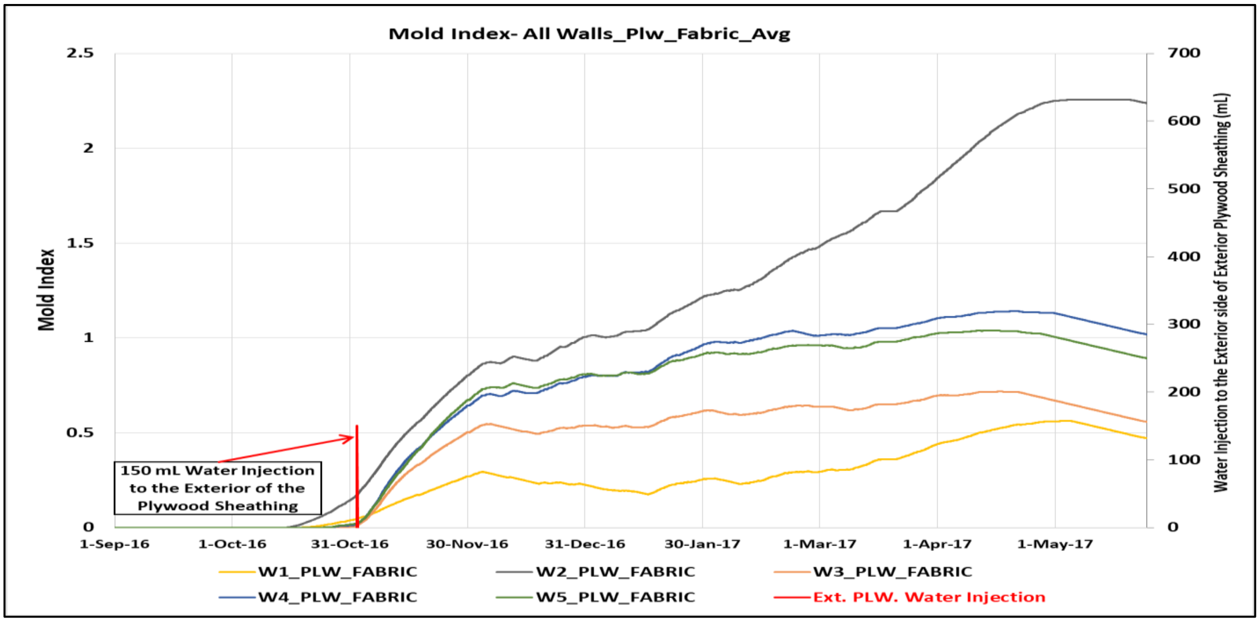


Figure 160- MI for All Walls, Mid-height Section of Plywood

6.10.4.4 Summary

The safest wall was wall#1 with 18% of maximum moisture content, followed by wall#3, with 22% of moisture content, then wall#4that reached 24% of moisture content. Wall#5 with sprayfoam reached alarming rates of 28%, only lower than wall#2 with no vapour barrier that reached 33% of moisture content.

Table 22- All Walls, Moisture Performance Summary of Middle-height Section of Plywood

Plywood- The Fabric Section	initial MC (%)	max MC (%)	max MC gain (%)	Reached 28%?	days above 19%	# of wetting days	# of drying days	Mold Index	Overal Moisture Performance
WALL #1	9	18	9	No	0	90	150	0.47	Safe
WALL #2	9	33	24	**Yes**	165	110	130	2.24	**Risky**
WALL #3	9	22	13	No	15	40	200	0.56	Safe
WALL #4	9	24	15	No	75	40	200	1.02	Safe
WALL #5	9	28	19	**Yes**	60	40	200	0.89	Safe

Similar trend was seen for mold index, except that wall#5 had slightly lower mold index. In conclusion, wall#2 was failed in moisture performance and wall#5 had the most risky moisture response.

6.10.5 Upper Plywood

The moisture content and mold index results of upper section of plywood sheathing (the average of two sensors, located 12 and 24 inches from the bottom surface of the top plate), as a representation of the upper section of exterior sheathing of our walls are compared for all the five walls in this section. Also, RH results for the mid-thickness of insulation space, twelve inches lower from the bottom of top plate are presented here.

6.10.5.1 Moisture Content (MC)

As presented in Figure 161, like the lower and middle sections of these walls, wall#2 had by far the highest moisture content levels among the five walls tested in this experiment, going to alarming rates of 30% of moisture content.

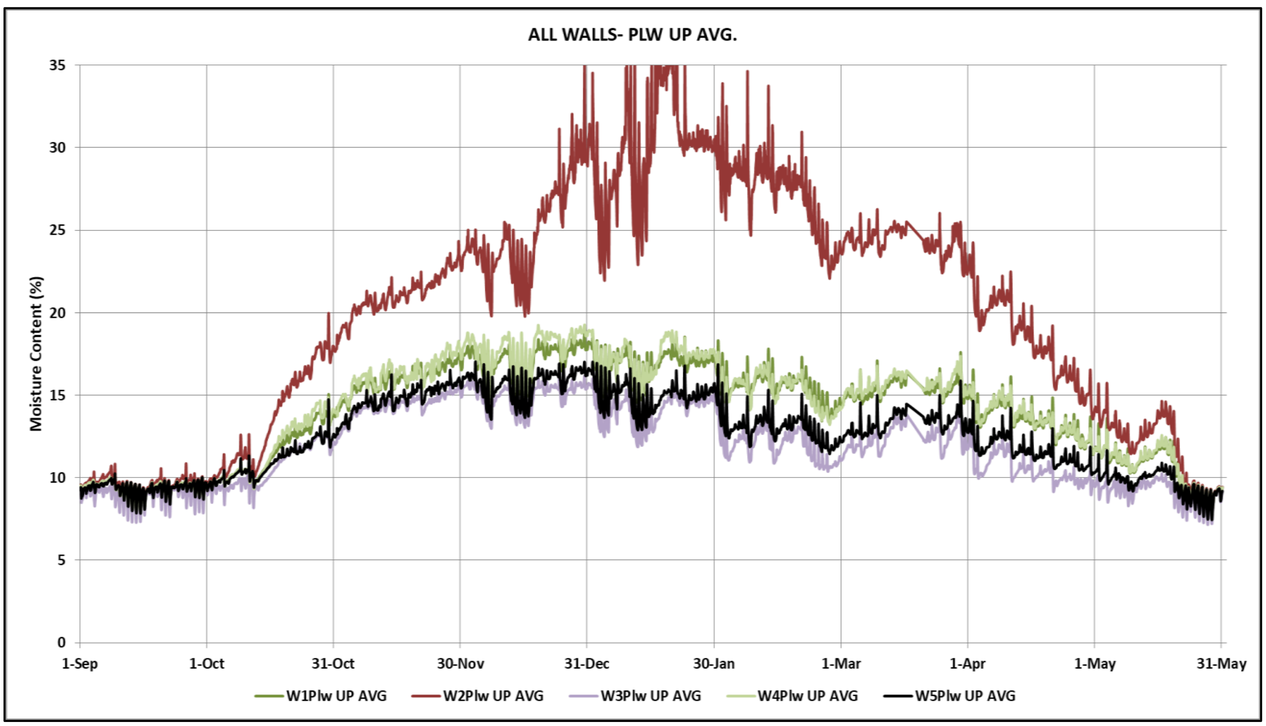


Figure 161- MC for All Walls- Upper Section of Plywood- Hourly Avg.

On the other hand, all other walls stayed below 18% throughout the entire test period. Wall#5 performed better than all other walls except wall#3with SVR. Contrary to all other walls, smart vapour retarder (SVR) demonstrated a better performance for the upper section of the plywood, compared to wall#1 and wall#3 with 4-mil polyethylene with or even without water injection and also slightly better than wall#5 with LD SPF.

6.10.5.2 Stud Space

6.10.5.2.1 Relative Humidity (RH)

Relative Humidity (RH) results for the upper section of the walls have similar overall trend as the previous sections, lower and middle sections.

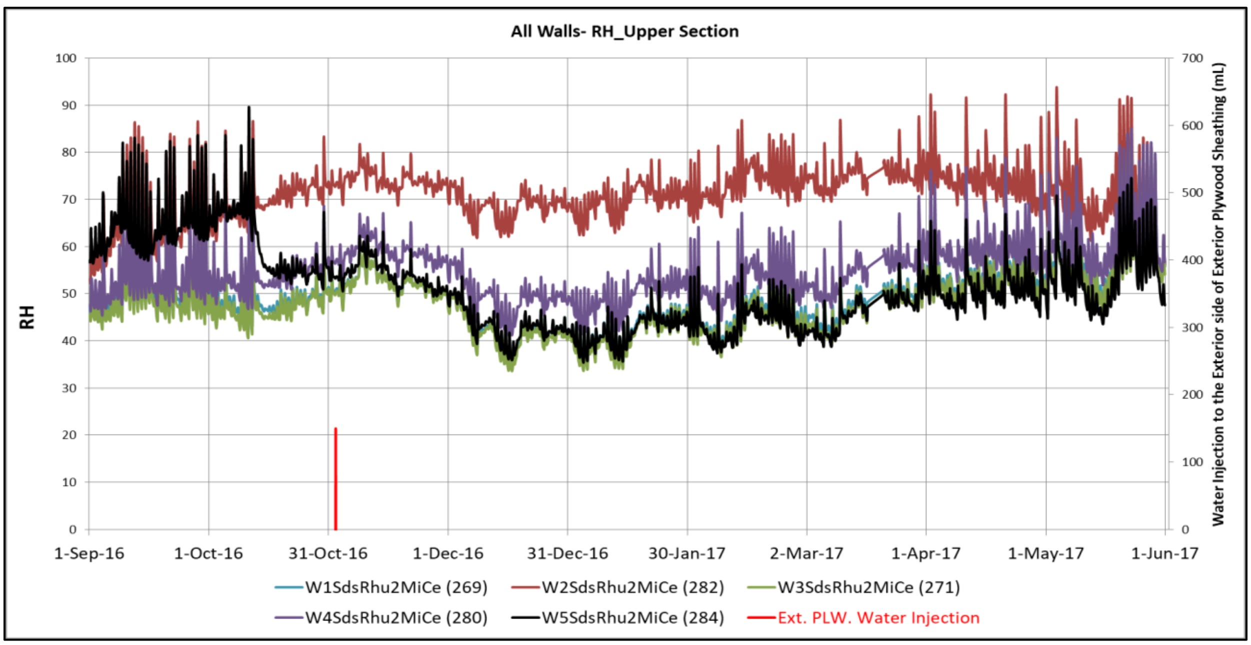


Figure 162- All Walls, RH for the Upper Section of Mid-Thickness of Insulation, Group-Averaged- Hourly Avg.

Like the previous sections of insulation, for the upper section wall#2 and wall#5 started with similar levels at the beginning of the test in whole September and half of October, but as soon as outdoor temperature drops, the vapour pressure gradients changes and humidity within the upper section of insulation of wall#5 starts drying out to the interior wood components or drying to the exterior environment passing across through the plywood sheathing. This should explain partly why from this point plywood sheathing starts rising as part of this extra moisture should have come from the insulation.

On the other hand, RH levels of upper section of dense cellulose insulation do not go down in wall#2. By around middle of November, RH levels of wall#5 reaches to almost identical rates of wall#3, wall#1 that both have 4-mil polyethylene as their internal vapour barrier while wall#4 with smart vapour retarder (SVR), shows around 5-10% of higher RH levels. Overall, wall#2 was significantly moister than all other walls within its insulation for the vast majority of the entire test period, around 15-25% of RH which is substantial.

6.10.5.3 Mold Index (MI)

Not surprisingly, wall#2 again had the highest calculated mold index numbers, ending up with numbers above 2.20, while all other walls stayed well below 0.65 to almost zero mold index numbers. For this section of the wall, wall#3 and wall#5 finished with almost zero mold index numbers by end of the test period, and wall#1 and wall#4 had slightly higher predicted mold activity and final mold index in comparison, 0.50 and 0.65 mold indices, but both well below concerning levels.

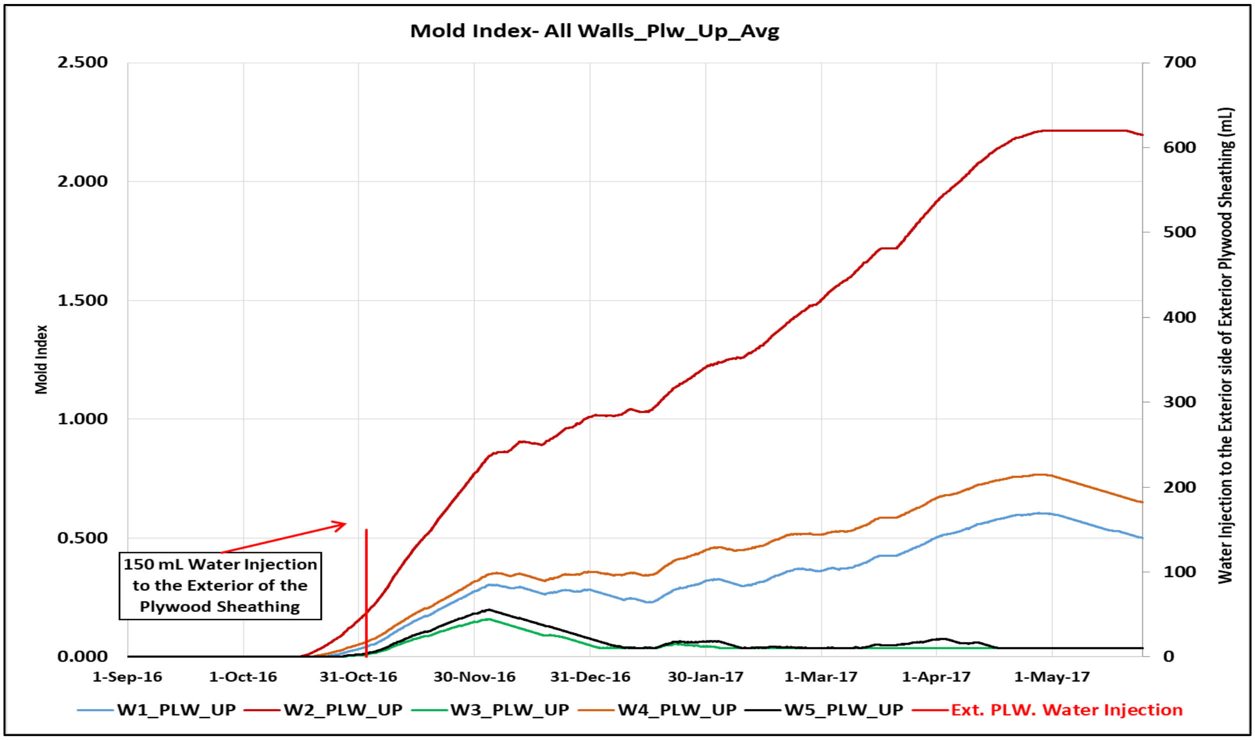


Figure 163- MI for All Walls, Upper Section of Plywood

6.10.5.4 Summary

Table 23 summarizes results of mold index and moisture content discussed in this section.

The highest moisture content belongs to wall#2, the lowest for wall#3. Wall#2 had the highest mold index reaching to 2.20, while the lowest mold index was for wall#3 and wall#5 of almost zero (0.04). Overall, wall#2 hygrothermally is unsafe and did not perform well hygrothermally.

Table 23- All Walls, Moisture Performance Summary of Upper Section of Plywood

Plywood- The Upper Section	initial MC (%)	max MC (%)	max MC gain (%)	Reached 28%?	days above 19%	# of wetting days	# of drying days	Mold Index	Overal Moisture Performance
WALL #1	9	18	9	No	0	90	150	0.50	Safe
WALL #2	9	35	24	**Yes**	150	110	130	2.20	**Risky**
WALL #3	9	16	7	No	0	90	150	0.04	Safe
WALL #4	9	19	10	No	0	90	150	0.65	Safe
WALL #5	9	17	8	No	0	90	150	0.04	Safe

6.11 Grand Summary

As shown in Table 24, while MC levels of all wall#1 was all below 19% throughout the entire test period, for walls #3, 4, and 5 except for the middle section of plywood, it remained in the safe area. Wall#2 with no dedicated interior vapour barrier went well above alarming numbers of 28% on its plywood and slightly above risky threshold of 19" for its exterior studs and exterior bottom plate.

Table 24- Grand Summary for MC

	Maximum Moisture content								
	Plywood Low	Plywood Middle	Plywood Up	Ext. Stud Lower	Ext. Stud Middle	Ext. Stud Up	Ext. Bottom Plate	Ext. Top Plate	Int. Framing
Wall#1	18	18	18	14.5	15	15	14.5	14.5	14
Wall#2	32	33	35	22	22	22	20	17	14
Wall#3	16	22	16	14.5	15	15	14.5	14.5	14
Wall#4	17	24	19	14.5	15	15	14.5	14.5	14
Wall#5	18	28	17	14.5	15	15	14.5	14.5	14

As for Mold Index on plywood sheathing, wall#2 had the highest numbers of above 2 which mold formations are supposed to be visible with aided tools which is a bit too early for the life length of plywood, so it can be considered unsafe mold response.

Table 25- Grand Summary for Mold Index

	Final Mold Index		
	Plywood Low	Plywood Middle	Plywood Up
Wall#1	0.51	0.47	0.50
Wall#2	2.07	2.24	2.20
Wall#3	0.04	0.56	0.04
Wall#4	0.29	1.02	0.65
Wall#5	0.54	0.89	0.04

7 CONCLUSION

In this study, moisture management of different test walls with two types of insulation, dense cellulose insulation (DCI) and open-cell spray polyurethane foam (OC SPF) with different vapour control strategies and under a small amount of water penetration being injected behind their WRB was pursued. The results emphasized the critical role of a vapour barrier for walls with DCI as the only wall that was lacking a vapour retarder (poly or SVR) reached critical MC levels on its plywood sheathing. As for different vapour control strategies, both SVR and polyethylene were found effective in better moisture management of walls with cellulose DCI, but no significant advantage for SVR was noticed over conventional polyethylene film. As for insulation types, DCI had slightly better moisture management compared to LD SPF.

Another general observation was while the interior studs and plates (top and bottom) remained almost totally dry throughout the entire test period the exterior studs and plates had some minor moisture gain, but all within safe moisture zones.

As a general conclusion Dense Cellulose Insulation (DCI) can be used as a suitable insulation choice for a super insulated double-stud wall if an extra layer of vapour barrier is incorporated behind its interior sheathing board, even if exposed to small amounts of rainwater penetration behind its WRB. On the other hand, Open Cell Spray Polyurethane Foam (OC SFP) did not handle the small amount of liquid water as safely as walls with cellulose.

8 FUTURE RESEARCH

As mentioned earlier, in this research relatively a one-time small amount of water, 150mL was injected behind the WRB on the sheathing board to assess hygrothermal response of test walls. While this is a rather common building envelope failure, it is not the most critical loading. The amount and frequency of penetrated rainwater behind WRB can be higher linked with the exterior rain events. Moreover, in the likely cases of building envelope interface defects, rainwater may penetrate into stud cavity and be trapped inside. Henceforth further research in higher amounts and frequency as well as location of penetrated water is a good area for future research.

In the subject of vapour control strategies, while the necessity of either a polyethylene or SVR was ascertained as opposed to no vapour control, the gypsum board sheathings had no vapour resistive paint (oil-based, neither latex paint, etc.). Therefore, further research on capability of a mere paint coating on gypsum board sheathing to handle moisture properly is deemed.

Another possible area is incorporation of different vapour permeability for exterior sheathing boards such as OSB (Oriented Strand Board) to seek potentials for better moisture response of test walls. It is assumed that fibreboard with higher and OSB with lower vapour permeability compared to plywood should enhance and inhibit drying capacity of walls. This needs to be tested and verified.

Another important area for future research is incorporation of air leakage (interior or exterior) into walls stud space to assess the claimed prominence of cellulose insulation in hygrothermal response to the introduced air leakage. To do so application of more RH+T sensors within insulation space for more in-depth analysis of moisture distribution will be instrumental.

And finally, as discussed earlier, the results of a field test can be cross-checked with a hygrothermal simulation model, for verification of field experiment results and enhancement of the computer modelling. To do so, disassembly of walls and comparing the visually observed mold status with computer modelling prediction is suggested.

9 Appendix

9.1.1 Moisture Damage History

Buildings had been constantly evolving from thousands of years ago for more comfort, health and operation cost, mostly by trial and error to serve those purposes in a rather slow process, however with acceleration of technology progression in construction methods in the past few decades, some changes did not have sufficient time to prove their adaptability for different applications and climates. One of the biggest changes that buildings have taken on is higher insulation and air-tightness levels of building envelopes and in order to do so building envelopes started incorporating insulating materials and air barriers to lower the amount of energy loss through the building enclosure. This transition was many drivers such as seeking more comfort, healthier environment, security, environmental urgencies, etc. that some were undertaken voluntarily, but some were pushed forward by other drivers.

One of these major shifts was in early 1980's after the sudden hikes in oil prices following the Arab Oil Embargo. At that point then energy bills started to become more of owner's decision-making factor whereas for the governments, political uncertainties became more highlighted. This was when energy conservation became an urgent task and many buildings started adopting more energy efficient construction methods through incorporation of various types of thermal insulations and air barriers in building envelope.

Walls started to turn into complex assemblies incorporating drywall, air/vapour barriers, still/wood frames with cavities in between filled with thermal insulation. This relatively new construction trend grew rapidly also because it was faster and cheaper to build. In the U.S., government offered tax cuts and incentives (USCongress, 1975) which encouraged adoption of the new energy efficient construction systems. Moreover, this new trend coincided with free global trade, an influx of new construction materials from all over the world which further increased the pace of this roller coaster. At this stage a big confusion existed for the right way to assemble construction materials into a whole system that could perform well in response to different interior and exterior climatic loads. Henceforth the knowledge gap contributed to random adoption of wall assemblies from all over the world without accounting for different climates and applications. The main criteria for selection of a wall assembly became common construction practices, cost and aesthetics and this coincided with a trend towards more insulated and air tight building envelopes. Different climates had different environmental loads, for example in a hot and dry environment UV ray could be a big concern, in an open land, wind load could be of concern, but for a wet climate, moisture could be a concerning environmental load. This moisture could also come from the interior and vary for different applications.

In the past and with relatively low insulation levels and air leaky enclosure walls, the interior moisture stemmed from occupants, cooking, showering, etc. would leave buildings from the leakage paths and should any rainwater penetrate building enclosure, in most cases it was able to escape the assembly helped by the indoor heat being wasted to the exterior environment. On the contrary, the new generation of building enclosures, with minimal air leakage and heat loss across their enclosure may not benefit as much from those natural moisture handlings.

Leaky Condo Crisis is a notorious example of moisture mishandling occurred in Lower Mainland of British Columbia and New Zealand. Auckland, NZ was severely impacted by a moisture caused crisis. In a document by (Royal Society, 2002), it was reported that around 90% of low rise buildings built around 1985-2000 were impacted by water ingress and building envelope failures.

As for Vancouver area, many wood-frame buildings were impacted severely by moisture in a variety of ways, mainly water leakage, condensation and low construction defects (Hershfield, 1996). From around mid-1980s to early 2000s, in response to very high demands for new residence and schools a construction boom took place mostly in Greater Vancouver and Lower Mainland. The rushed construction boom resulted in importing construction material and adopting construction methods from other parts of the world with different climates and jurisdictions (Weslowski, 2016), but sadly these methods did not turn out well for wet climate of this climate. It was estimated that around 45% of the 160,000 condominiums and 57% of the schools built in British Columbia from 1985 to 2000 had water ingress issues (Stueck, 2008). Another consequence of highly air-tight building envelope is occupants' health that could be seriously compromised if there is not enough fresh air causing health complications such as Sick Building Syndrome (SBS) (Hedge et al., 1997) and mold spores heath implications on building occupants (Davis, 2001) are two prominent examples.

With the passage of time this ignorance took its toll and many building started to perform poorly hygrothermally in many locations. Wet climates like Lower Mainland, British Columbian (LMBC), were impacted by moisture implications. In mid-1980's many building in Vancouver were found rotten and moldy a majority of which had to be demolished prematurely (bcdex.com, 2013). This problem imposed billions of dollars financial loss on building owners, insurance companies and other stakeholders. Based on a research (bcdex.com, 2013), it was estimated that over $3 billion financial loss was imposed on condo owners by 1985 in LMBC excluding the health implications of the inhabitants as a very important public concern. According to National Building Code of Canada (NBCC), "changes that do not lead to unacceptable consequences may be tolerated" and unacceptable consequences are damages leading to loss of structural strength, or to health symptoms of the occupants". Failures from moisture could have physical, chemical, or biological causes. However, in wood-framed buildings, molds and fungi are often stated as the most common moisture caused issue (Mao, Fazio, & Rao, 2009).

This situation forced stakeholders to take drastic actions and the first step was to find the main cause of the problem. The magnitude of rot, mold and fungi inflicted by excessive moisture was unprecedented and the situation was puzzling as moisture had always coexisted with buildings without as much problems as then. Soon it was revealed that there was no quick and easy answer to this problem and a big knowledge gap in building Science surfaced. Prior to the new insulation generation buildings if the main water sources (rain and ground water) were controlled, buildings would perform acceptably, so the question was what elements exactly had changed in buildings could have contributed to buildings being impacted by moisture on that scale.

Consequently, to find an answer to this conundrum all the recent changes in construction system were reviewed and many forensic studies were conducted. Some initial findings suggested a few explanations. Firstly, prior to incorporation of highly insulated enclosure walls, buildings used to lose (or waste) more heat through their enclosure. Heat would expel the moisture in the enclosure walls, whereas in the new cases with highly insulated enclosure walls much less heat could pass through envelope with lower levels of drying potential. Secondly, high level of insulation in cold seasons would help interior side of walls stay warmer, while leaving the components towards exterior surfaces colder. The cold surfaces, if exposed to the diffusing outward interior vapour or infiltration of air containing airborne vapour, may get wet by condensing the receiving vapour. The problem may be even more complicated if other exterior liquid water sources (e.g. driven rain, initial construction moisture, or flooding incident) find their ways into the wall assembly through gaps, seams and cracks. It was also revealed that moisture vulnerable materials, if stay wet "long enough" can foster mold followed by fungi and rot (Lstiburek, 2002). Many of the discussed buildings failed either structurally by fungi or due to health-related issues of their occupants, induced mainly by mold spores. A survey conducted in mid-90's (Hershfield, 1996) revealed some of the construction deficiencies contributing to moisture response failures in the Lower Mainland of Vancouver, BC. The research was steered by BERC (Building Envelope Research Consortium) and its objective was to "help identify key aspects of the design, construction and operations and maintenance processes leading to the problems and provide a focus for the efforts to resolve these." The forensics of this research revealed that the main causes of the enclosure failures were stemmed from shortage of knowledge in both design team and trades' personnel which was reflected in underdeveloped building Science codes and practice guides that had its roots in lack of prior research in the field. The final report pointed at excessive water intrusion from exterior into building enclosure was the main source of problematic moisture and had caused most of the problems.

At this point the question was how much moisture is "too much", and how long is "too long". Moreover, "which construction materials were more sensitive to moisture and susceptible to moisture related damages?"

To find an answer to those essential questions first it needs to understood that moisture sensitivity of different materials vary significantly and moisture damage is usually a matter of time that how long it takes before different rates of moisture cause rot, decay, mold or corrosion in different building materials (Lstiburek, 2002).

While other factors such as heat and UV radiation can compromise building envelope functionality as well, but moisture remains the major risk amongst all as it directly or indirectly contributes to many other durability issues such as erosion, corrosion, mold and fungi formation and more damage functions (Mao, Fazio, & Rao, 2009). While any building envelope component is likely to be exposed to each or a combination of different wetting sources in their service life, however the magnitude of these wetting sources is not the same for different climates and applications.

Unlike structural engineering that design-based approach is not a new concept, building envelope engineering was still in its infancy. Structural codes were developed since the turn of 20th century that to withstand structural loads appropriate codes and standards started to develop helping structural designers with safe design criteria. Now we know while there is no argument on the importance of buildings structural safety, it is not the only one; buildings must be durable, sustainable, energy efficient, and environmentally friendly. Furthermore, health and comfort of the occupants that are all what building Science is pursuing are not dispensable factors. The design process shall incorporate simultaneous analysis of the building performance in terms of energy efficiency, building envelope's durability and indoor environmental conditions using tools such as HAMFitPlus (Tariku, Kumaran, & Fazio, 2010).

9.1.2 HAM (Heat, Air, Moisture)

As building envelope is essentially a separator between indoor and outdoor environments any building envelope is expected to control heat, air and water vapour flow and leave out rain penetration, noise, fire, solar, etc. Among all the control functions, regulating Heat, Air and Moisture (HAM) is at utmost essence as the transaction between heat, air and moisture (liquid and vapour) within and across wall assemblies can affect not only durability of building components, but also influences the energy consumption, the environment and occupants' comfort and health. While there is no doubt that limiting air flow and heat transfer across building envelope conserves energy, various studies have revealed that without a suitable moisture management strategy, durability of walls can be compromised which can reverse the initial target of lowering the cost and environmental footprints of buildings on the long run.

To investigate the overall effect of each element in a wall assembly, it should be noted that there is a whole multifactorial dynamism between Heat, Air, and Moisture (HAM) between the interior and exterior climates as well as within a wall assembly.

In common practices of construction industry HAM are controlled by thermal insulation, air barriers (or limiting air infiltration/exfiltration across building envelope), and vapour barriers respectively. With a closer building Science look, there are a few suspects after walls became more thermally insulated, air tight and vapour tight.

The three elements of HAM are not independent from each other as they are constantly changing in a contained environment and affecting one another. *Heat* is internal (thermal) energy, associated with the movement of molecules. At a given state any system contains certain amount of energy that is the sum of Internal, Potential, and Kinetic Energy. *Air*, while contains certain amount of heat and *Moisture*, can move and carry its heat and moisture with it while moving. On the other hand, *Moisture Displacement* could also be a heat transfer mechanism moving its heat content with it while travelling. Also, for building enclosure applications, liquid water from precipitation can flow from leakage passages and flow by gravity or capillary action and change heat content of building envelope. Moreover, temperature variation of air causes density difference that will cause air flow and temperature variation changes vapour pressure in the air that can change diffusion rate for it out of a contained environment.

So, as we can see there is a dynamic multifactorial correlation between Heat, Air and Moisture within a space which makes hygrothermal analysis of building envelopes a rather comprehensive task.

For a better understanding of HAM and their correlations a brief is presented below about the Science of Heat, Air, and Moisture entities and the correlations between them.

9.1.2.1 Heat Transfer

Heat transfer matters because it affects thermal comfort, condensation, energy consumption and moreover ties into vapour barrier and air barrier requirements. Heat energy can flow from one body to another due to temperature difference and this heat energy movement rate is usually measured in Watts (W) or Joules per second. Another common metric in heat transfer is Heat Flux which is the heat flow per unit area usually in Watts per square meter (W/m^2).

Heat transfers through three major mechanisms conduction, convection and radiation; below is a brief about each mechanism.

9.1.2.1.1 Heat Transfer through Conduction

Conductive Heat Exchange can happen when there is temperature difference between two points of a non-hollow material through direct molecular contact. Molecular movement is correlated to their temperature and when there is a heat difference between two points the heat energy is transferred from warmer to colder temperature by direct molecular vibration. Conductive heat transfer is related to thermal properties of the medium material. Examples of conductive heat transfer for a building enclosure application are window frames, concrete balcony and wall steel or wood studs.

Thermal Conductivity (usually termed as k), is the measurement of the steady-state heat flux through a unit thickness of homogeneous material induced by a unit temperature difference which in metric system it is measured in *W/(m.°C)* (in metric system). Thermal Resistivity is the inverse of Thermal conductivity measured in *(m.°C)/W* , so the higher number translates into more resistance against heat flow which is associated with more insular material. Thermal Conductance measures heat flux through a component of thickness "L" induced by a unit temperature difference and its unit in metric system is W/(m2.°C). On the other hand, *Thermal Resistance* which is the inverse of thermal conductance is essentially the resistance of a certain material of a certain thickness in a certain temperature range (m2.°C)/W.

Specific Heat Capacity is another important thermal property of a given material which is the amount of heat energy change in a unit mas of material with a unit change in temperature in Joules per mass per temperature in Kelvin, J/(kg.K). Thermal properties could be found from various sources, mainly ASHRAE Handbook of Fundamentals, and from manufacturers' index properties for specific materials.

Conductive Heat Transfer is essentially a three-dimensional phenomenon and according to Fourier's Equation;

$$q = - k.\ grad\ (t) = - [k_x \,.\, d_t/d_x + k_y.d_t/d_y + k_z.d_t/d_z],$$

q= heat flux (W/m2), t = temperature (°C), k (apparent thermal conductivity).

While the nature of conduction is three dimensional, but for the nature of building envelop heat transfer and simplification reasons, a one-dimensional introduction is presented here (a three dimensional is more accurate, but out of scope of this thesis).

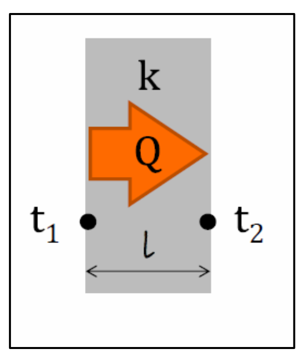


Figure 164- 1D Heat Transfer

The simplified one-dimensional Fourier Law for conductive heat transfer;

$$Q = -k. A. dt/dx = -A. k/l (t_2 - t_1) = A. k/l (t_1 - t_2)$$

Q= Heat Transfer Rate, A= C ross-sectional Area normal to heat flow, (t1 – t2) = temperature gradient producing heat flow

9.1.2.1.2 Heat Transfer through Convection

Convection is another heat transfer mechanism but happens through displacement of fluid material. For a building envelope, Convection of air can happen in various means, it can be *Natural* (or *Free*) when there is a density variation in the air (usually induced by temperature difference), or be *Forced* (by mechanical system), or also be induced by *Wind*. Examples of convective heat transfer are air circulation within loose-fill insulation material of a wall assembly, gaps around a poorly installed window frame, or unintentional exchange of air between the interior and exterior environments through building enclosures.

Convective heat transfer depends on type of fluid and nature of the flow. A simplified equation expressing heat transfer rate through ***Air*** is;

$$Q = h_c . A_s (t_s - t_f)$$

Q = rate of heat transfer between fluid & surface (W), hc = convection heat transfer coefficient (W/m^2. K), ts = surface temperature (°C), t_f= temperature of the fluid (°C)

From the formula above is it evident that Air flow is not independent from temperature or Heat. In buildings for both HVAC (Heating, Ventilation and Air Conditioning) design and building envelope performance, air leakage is a very important matter. As mentioned earlier heat can be displaced by air movement, so a simplified formula to calculate the amount of heat transferred by air movement is presented below.

From the Ideal Gas Law, there are two components associated with heat transfer through fluids, Net Latent Heat Transfer and Net Sensible Heat Transfer. Net sensible heat transfer is more related to the nature of air, and net Latent Heat Transfer is more related to the vapour in the air.

Net Sensible Heat Transfer of air is associated with heat capacity of air termed usually as Q_s:

$$Q_s = \dot{V} . \rho . c_p (T_{int} - T_{ext})$$

$\dot{m}_a$ = mas flow rate (kg_a/s) = Q.ρ, $\dot{V}$ = air volume flow (exchange) rate (m^3/s), ρ = air density (kg/m3), C_p = specific heat capacity of air (J/kg.K), T = temperature of air (°C)

Any material contains an internal energy associated with molecules vibration and when the internal energy is added with the product of its pressure and volume it is called enthalpy. Therefor if a matter is displaced so does its energy which is the total of heat and work. So, by entering and exiting moisture to an environment in form of vapor, gas, fluid or even solid (ice) the thermal energy of moisture is transferred between those environments.

Net Latent Heat Transfer of air is associated with heat capacity of the moisture/vapour in the air termed usually as Q_a:

$$Q_l = \dot{V} . P.c_p .(W_{int} - W_{ext}) (h_{fg} + 1.86*t)$$

Q_l = latent heat transfer (kW), W_{int} = humidity ration of air leaving, W_{ext} = humidity ration of air entering, $h_{fg} \approx 2501$ kJ/kg_v, t = average of indoor and outdoor temperatures (°C)

The formula above demonstrates on of the interconnections of Heat, Air Flow, and Moisture (HAM).

9.1.2.1.3 Heat Transfer through Radiation

Radiation transfers thermal energy through electromagnetic waves through a transparent medium, such as air or glass, so unlike conduction and convection does not rely on a solid or fluid to transport its energy from a higher to lower temperature body. Any matter transfers heat at its surface when its temperature is above absolute zero and the rate of this heat transfer is related to its absolute temperature and surface characteristics. Heat energy can radiate from a warmer to a colder surface is they *see each other*, so it occurs through open spaces but can also happen in more micro levels such as porous materials.

Radiative heat transfer is proportional to absolute temperature powered by four.

$$P_{net} = A.\ \sigma.\ \varepsilon.\ (T^4 - T_0^4)$$

A = Emitting Surface (m^2), σ = 5.678 10-8, $W/m^2.K^4$ (Stefan Boltzman Constant, ε = the Surface Emissivity

Examples of radiation are solar radiation, radiative heat loss to cold surfaces of building envelope by occupants that can cause thermal discomfort, and night sky radiation.

From the formula above and for a building enclosure application, radiative heat transfer can be controlled by lowering surface emissivity of materials such as low-e coating on window glass panes, or application of low emissivity films within a wall assembly. Usually sunlight is short-wave, that could be direct, diffused, or reflected and the emitting heat from surfaces such as indoor material, exterior building envelope surface and heat emitting from the earth surface are long-wave.

9.1.2.2 Air Transfer

The first part of Air Transfer was already explained in the Convection section above. As a basic rule, air moves from higher to lower air pressure, or $Q = f(\Delta P)$ with Q is volumetric flow rate and P is pressure, meaning flow rate is a function of differential air pressure for point A to point B. In simple words for each unit volume of air leaving a control volume, another volume must enter it, which this is called conversation of mass. Air flow driving forces are either through free convection that is related to gravitational or thermal variations which results in stack effect and buoyancy respectively. On the other hand, air flow can be by forced convection, either wind or from mechanical systems in buildings. Both mechanical system and wind can create driving forces on wall assemblies moving moisture in or out of it. While mechanical systems can be adjusted to specific levels, wind is highly variable and uncertain in occurrence time and frequency, direction and speed.

9.1.2.3 Vapour Flow

"Water vapor, water vapour is the gaseous phase of water. Water vapor can be produced from the evaporation or boiling of liquid water or from the sublimation of ice. Unlike other forms of water, water vapor is invisible. Water vapor is continuously generated by evaporation and removed by condensation. It is lighter than air and triggers convection." (Wikipedia, 2018).

Vapour exists in the air in different rates and comes from different sources, from *outside*, *inside* or *built-in* moisture. Vapour movement is generally from more vapour to less seeking equilibrium in any control volume as a basic law of physics. Vapour can flow by diffusion or travel airborne.

9.1.2.3.1 Water Vapour Diffusion

The vapour existing in indoor and outdoor airs has always a certain pressure, termed as vapour pressure or P_v and the differential vapour pressure between two different environments, ΔPv creates a driving force driving the vapour from the lower to the higher vapour pressure passing through a medium material. In general, vapour diffuses from more to less concentration trying to reach equilibrium which is usually a rather slow process. The pace of this process depends directly on the type of material vapour diffuses through, for example concrete, brick stone and wood highly slow down (or retard) vapour diffusion process while some others may totally block vapour diffusion like metal, glass, and plastics (polyethylene). The rate of vapour diffusion depending on type of material is measured and termed as vapour permeability and vapour permeance for specific thicknesses.

Diffusion could also be a problematic issue for building envelope assemblies with imposing condensation when reaching lower than dew-point temperatures and being deposited as liquid water or condensation.

To address this issue in construction industry vapour retarders are commonly applied within wall assemblies to slow down vapour diffusion so that walls can have enough time to dry out the entering moisture before reaching critical levels. To correct placement of a vapour retarder is key in this matter otherwise moisture can get trapped within a wall assembly and create mold, corrosion or fungi. As a rule of thumb, vapour retarders are placed in the relatively higher vapour pressure side or mostly the warmer side of a wall assembly with the permeance of the warmer side being less than the colder side. This rule works for most cases.

Vapour flow in Fick's Law depends on vapour pressure gradient and the vapour permeability of the medium material;

$$m_v = -\mu \cdot grad\,(P_v),$$

mv = moisture flux (ng/s.m^2),

μ= Water vapour permeability (ng/(Pa.s.m))

P_v = Vapour Pressure (Pa)

In three-dimensional moisture flux the formula above is as below;

$$m_v = -[\mu_x . dP_v/dx + \mu_y . dP_v/dy + \mu_z . dP_v/dz]$$

m_v = moisture flux, ng/s.m2

P_v = vapour pressure, Pa

μ_x, μ_y, μ_z = water vapour permeability in x, y, z directions, perm= ng/(Pa. s.m)

For simplification reasons it can be assumed that vapour pressure drive in wall assemblies is one dimensional perpendicular to surfaces parallel to walls' plane.

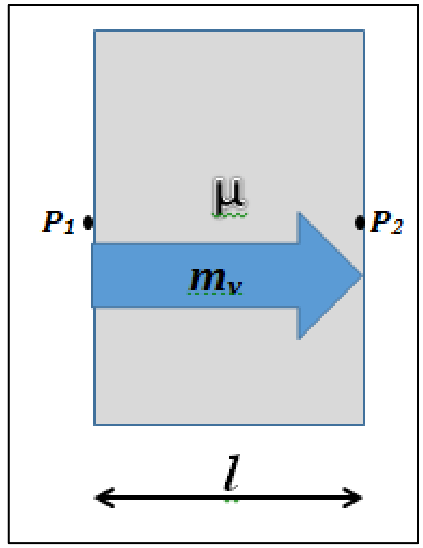


Figure 165- Vapour Diffusion

So, the simplified 1D Fick's Law Equation becomes;

$$M_v = -\mu . A . dP_v/dx, \; m_v = -\mu . dP_v/dx$$

$M_v = m_v . A$

M_v =water vapour transmission rate (ng/s)

m_v = water vapour transmission flux (ng/s.m^2)

dP_v = pressure difference which produces flow (Pa)

dx = distance through the flow path (m)

A = cross-sectional area normal to heat flow

Assumptions: constant permeability & are over a length "l", & vapour flux (i.e. steady-state) so the 1D Fick's equation can be integrated:

$$Mv = A . (\mu/l) . (Pv1 - Pv2); \; Mv = A . M . (Pv1 - Pv2); \; Mv = A (Pv1 - Pv2)/Rv$$

M = Permeance (PERM = ng/(Pa.s.m2)),

Rv = water vapour resistance ((Pa.s.m2)/ng)

Vapour permeability of materials is commonly measured in Perm, which is equal to 57.4 ng/Pa.s.m^2 and usually changes for different relative humidity and temperature conditions.

Table below summarizes Heat, Air and Moisture (HAM) transfer discussed above (Finch, 2013).

	Heat Transmission	**Air** Heat Convection	**Air** Water Vapor Flow	**Moisture** Water Vapor Diffusion	**Moisture** Liquid Water Flow
Concern	Comfort & Energy	Comfort & Energy	Durability	Durability	Durability
Potential Force	ΔT (°C)	ΔP_a (Pa)	ΔP_a (Pa)	ΔP_v (Pa)	Various
Direction of Drive: *Heating*	OUT *****	IN / OUT ***	IN / OUT *****	OUT ***	IN *****
Cooling	IN ****	IN / OUT **	IN / OUT **	IN ***	IN *****
Swing Seasons	IN / OUT **	IN / OUT *	IN / OUT *	IN / OUT *	IN ***
Control Intent	SLOW / **RETARDER** << 100%	STOP / **BARRIER** 100%	STOP / **BARRIER** 100%	SLOW / **RETARDER** <<100%	STOP / **BARRIER** 100%
Preferred Location	**Outside Super-structure**	**Anywhere (Warm Side)**	**Anywhere (Warm Side)**	**Warm Side**	**Close to outside**

Figure 166- Heat, Air, and Moisture (HAM) Dynamism (Finch, 2013)

9.1.2.4 Building Science Role

Building Science amalgamates material Science, meteorology, architecture, thermodynamics, and more in a multi-disciplinary approach to shed light on the complexities. In the aftermath of the recent moisture related building crises it was revealed that much room existed for improvement in building Science as the underdeveloped codes and standards in moisture engineering was the manifestation of this chasm. This was and still is an obstacle on the way of moisture engineering field. Henceforth, the main effort should be concentrated on developing building Science standards and codes which can specify thresholds, related examples of which, how long is too long for walls to stay wet, what temperature and humidity ranges are to be avoided, what type of substrate and light contribute to mold growth and so forth.

Due to the wetting sources and mechanisms, moisture cannot be handled properly unless the wetting sources and mechanisms are seen and addressed in the design and construction stages. Moreover, any moisture management strategy should also consider incorporating less moisture sensitive materials with more capacity for expected or incidental moisture intrusion for the design lifetime of the construction assembly (Lstiburek, 2002). While preventing moisture intrusion into walls could be the easiest and least expensive measure, some amount of moisture intrusion is inevitable or otherwise not practical. On the bright side, walls have some moisture tolerance capacity and may well handle different amounts of moisture if it doesn't go beyond their tolerance level. The tolerance level of walls depends on various factors mainly wall components' moisture tolerance levels in both volume and duration. If more moisture tolerant construction materials are employed and the entered moisture is evacuated from walls timely, the moisture tolerance of walls improves.

One of the factors that can help with better drying of walls is moisture breathability or permeability of the assembly which allows moisture to leave the assembly by vapour diffusion mechanism. For moisture to dry, interior and/or exterior air are the available drying paths, so using interior and exterior vapour breathable sheathing boards that are not blocked by a vapour barrier so that they allow the intruded moisture to diffuse out of walls is an option. On the other hand, less vapour diffusion resistance could also let the moisture in the interior or exterior ambient environments diffuse into walls. Likewise, if cladding get wet by rainwater, solar radiation can elevate push it into walls if there is not a vapour barrier in place. Other than vapour barrier, insulation type is also a determinant in drying capability of walls (this will be discussed more in detail later).

Henceforth, there is a whole dynamism of moisture getting in and out of wall assemblies and the key is finding a balancing point that limits moisture entry while letting it out timely. However, as there are many variables involved for each application; indoor relative humidity and temperature variation depending on type of use (residential, office, etc.), outdoor micro and macro climate variations, and most importantly numerous configurations finding that balancing point does not have an easy answer and varies based on all the variables involved.

As a result, a multipronged strategy that limits wetting in the first place and balances out the moisture accumulation based on all the factors affecting the hygrothermal behaviour of walls should be pursued. Once the probable wetness and its duration is estimated, a design that allows walls to evacuate the excessive moisture in time is the way to go and this is where building Science comes into play again with the concept of "wetting and drying behavior (or cycle)" (Tariku & Ge, 2010).

As mentioned there are many variables that affect moisture performance of a wall assembly and each may have an overall helpful or harmful effect on walls hygrothermal behaviour. A smart design enhances the role of the variables that are under our control such as wall assembly's build. To do so in a scientific way, the effect of each wall component on the overall moisture performance should be singled out by excluding all other variables. For example, if the objective is to see what type of insulation is conducive to the long-term moisture performance of walls, insulation should be the only component that is different between the tested samples so that any variation could be attributed to it and a meaningful comparison could be reached. This is applicable for all different methods of research in Science.

There are three general methods of research in building Science, *Simulation*, *Field Experiment*, and *Laboratory Testing*. These three methods work hand in hand and complement each other in an iterative process.

Since this research project is a field investigation on proposed novel wall assembly system, a comprehensive literature review was conducted on a variety of subject areas. The subjects reviewed can be categorized under 4 main categories of Moisture Loads, Moisture Indicators, Hygrothermal Performance Assessment, and High-Performance Wall Systems which follows.

9.1.2.4.1 One Concern about Thermal Insulation

Thermal insulation in enclosure walls can have two main responses in cold season; *reduction in heat transmission* and causing the phenomenon of *cold surfaces*. As for heat transmission reduction, while higher thermal insulation helps with lowering the amount of conductive heat transmission to the exterior (Straube J. , 2007), but it doesn't help with better drying of walls when they get wet through various mechanisms, namely rainwater intrusion, air leakage and diffusive condensation. The common practice of application of thermal insulation within the stud space in wood-frame studded walls leaves the exterior sheathing and framing colder compared to no or less insulated walls. If this insulation causes some of the wall assembly components closer to the exterior colder environment drop below the dew-point temperature of the interior penetrated vapour stemmed from air leakage or vapour diffusion, it can lead to condensation of that vapour and consequently having wall components get wet (Straube, Smegal, & Jonathan, 2011). This is further discussed in later chapters.

9.1.3 Moisture Management

As discussed in previous chapters while more thermally insulated enclosure wall assembly reduce the immediate conductive heat loss across the enclosure, it may not be very conducive to the durability of buildings located in wet and cold climates. To understand moisture behaviour in building applications, a brief is presented below.

9.1.3.1 Moisture Loads and Different Climates

Understanding the main wetting mechanisms is the very first step to control moisture entry. There are generally three main categories of moisture sources, liquid water, vapour in the air, and initial moisture content in construction materials transferred in various mechanisms, mainly vapour flow, liquid flow and capillary. The two most understood wetting mechanisms are liquid flow and capillary suction. The sources of these two mechanisms, precipitation (rain, or snow), or groundwater are not unknown for the construction industry as they have been mastered over centuries and the strategies to manage them have evolved over time, in many cases by trial and error. These strategies are somewhat similar in different locations, for example the way rain penetration is managed in Vancouver through shingled roofs is very similar to Toronto and Florida. In addition to precipitation and groundwater, construction material may start off initially wet such as moist wood framing/plywood or wet concrete during curing stage which is termed commonly as *initial moisture content*. Brick, wood, and other water absorbing construction materials can get wet from precipitation if not stored and covered properly before or during construction or not dried out before building is closed from the exterior.

On the other hand, there are two wetting mechanisms that come from the *vapour* in the air that are not as easily noticed and managed. The vapour in the air penetrates building enclosures from the ambient air movement or vapour diffusion. Since the amount of air-borne vapour in different climates may significantly vary in different locations, vapour loads of a building located in

Vancouver should be taken differently in moisture design from the one built in Toronto, Tallahassee, or Phoenix. Historically moisture management approach pursues preventing building assemblies getting wet from the interior and the exterior climates while letting it dry out to either the interior, or the exterior, or both (Lstiburek, 2002). This seems easy in theory but since moisture transfer is driven by vapour gradient and thermal gradients and these factors are both transient, vapour wetting is not a predictable phenomenon.

9.1.3.2 Moisture Sources

As discussed earlier, moisture sources on building envelope comes either from the exterior, interior or construction materials. The exterior moisture sources are very much dependent on the local climate and terrain that are not under our control. On the other hand, the interior moisture sources are mainly the indoor airborne moisture that may find its way through air leakage and diffusion. Controlling indoor relative humidity levels and reducing air leakage paths are measures that our more controllable in which can lower wetting load. Lastly the construction moisture is another factor that can be controlled with preventing construction materials getting wet in transportation, storage, construction and post-construction stages. More is discussed about each of mentioned moisture sources below.

9.1.3.2.1 Exterior Moisture Sources

From the exterior sources, precipitation (rain and snow), groundwater, and in-borne humidity in the air are the major players. Groundwater could be avoided with creating a capillary break, so not a complicated task. Rain and snow reach building envelope walls by wind (Wind Driven Rain), from leaky gutters, or by splashback from the ground. Again, leaky gutters are not complicated to be addressed and splashback could be avoided in design stage. The remaining sources that cannot be avoided and are not straightforward to quantify and addressed in design are *wind driven rain* and *airborne moisture (vapour)*.

Knowing the main wetting mechanisms is the very first step to control moisture entry. There are generally three main categories of moisture sources, liquid, vapour, and initial moisture content in construction materials.

The two most common wetting mechanisms are liquid flow and capillary suction. The sources of these mechanisms, precipitation (rain, or snow), or groundwater are not new in construction industry and have been known for a quite a while and strategies to manage them have been developed over time, in many cases by trial and error. These strategies are somewhat similar in different locations. For example, the way rain penetration is managed in Vancouver through shingled roofs is very similar to Toronto and Florida.

Precipitation is the liquid water from rain, ice, snow, hail, and ice. Precipitation load on the enclosure walls depends on several factors, not only the precipitation amount, intensity and pattern, but also how much of that rain reaches the enclosure walls and how much of which is shed, runoff, splashed back, absorbed and found its way into wall components.

In moisture management there is no control over precipitation, however there are a few factors manageable in design stage such as building orientation, overhangs, deflectors, sills, etc. that can reduce the amount of moisture that can contact enclosure walls in the first place. Moreover, part of the rainwater that reaches enclosure walls can be removed by water runoff and drainage. The last line of defense will be better drying capacity of walls and less moisture sensitive materials which is explained later in this chapter.

From the mentioned sources, Wind Driven Rain (WDR) can be the largest moisture source of enclosure load which can be predicted from annual rainfall, wind speed/direction data and also building envelope exposure factors. Among several empirical equations to predict WDR, ASHRAE 160 standard and Straube and Burnett's methods (Straube & Burnett, 2005) are most simplified ones that demonstrate the role of micro and macro environmental and geometrical specifications. Straube and Burnett (Straube & Burnett, 2005) present a formula that includes rain intensity and direction factors as well as topography and building envelope geometry and overhang factors:

$$Rwdr = RAF \times (\ ) \times \cos(\theta) \times U(h) \times Rh$$

Rwdr = WDR intensity on to a vertical surface [mm/hr.m2]

RAF = Rain Admittance Factor

(Vt) = Driving Rain Factor

θ = angle of the wind to the wall's normal

U(h) = wind speed at the height of interest [m/s]

Rh = horizontal rainfall intensity [mm/hr.m2]

Traditionally building enclosures were pursuing to keep rainwater out of interior of buildings; however, the new enclosure systems are designed for higher levels of controls to avoid biological growth, corrosion, freeze-thaw problems and so forth (Straube & Burnett, 2005). If water was falling just vertically it was a relatively uncomplicated task to prevent it from reaching a wall assembly, but water can reach walls by even a light breeze. Amount of the water deposited on a wall depends on a variety of factors, such as wind speed and direction, height of the wall, angle of the wall with wind direction, and average rainfall on horizontal plane. Several studies have revealed that in an average low-rise building about 10 to 20% of the rain is deposited on walls (Straube & Burnett, 2005). With some design strategies such as incorporation of overhangs in on walls the amount of wind driven rain could be significantly reduced. In one study (Hershfield, 1996) conducted in the aftermath of leaky condo crisis in Vancouver, it was revealed that the houses with good overhangs experienced much less moisture related damages compared with the ones without overhangs. As discussed earlier preventing wind driven rain from entering wall assembly is the most effective moisture management strategy. If some amount of water reaches the surface of a wall, various scenarios could happen. As soon as rainwater finds its way to the surface of the wall a film begins to flow downward under the gravity force (if not affected by wind). Existence of a hole or gap can drive this flowing water right into the wall with driving forces of wind, capillary and gravity itself. These all depend on the material properties of the wall too. One of the important material features is liquid diffusivity of the cladding material. This means if water wets a surface how fast material sucks the water into itself (Mukhopadhyaya et al., 2007). In a cladding material such as brick with high liquid diffusivity properties, water will be absorbed mainly through capillary suction and surface tension and stored in brick veneer. This stored water can be dry out or transferred to the other sections by solar driven rain, or wind pressure and stack effects to other sections of the wall. If a cladding surface has low water storage and liquid diffusivity it tends to shed majority of the wall if there is not gap, or hole in the wall. The problem becomes more noticed when there is a gap, or capillary break in the wall and a source of pressure such as blowing wind drives the water inward to the wall assembly (Straube & Schumacher, 2005).

On the other hand, there are two wetting mechanisms that come from the vapour in the air. The vapour in the air penetrates building enclosures from the ambient air movement or vapour diffusion. Since the amount of air-borne vapour in different climates may significantly vary in different locations, vapour loads of a building located in Vancouver should be taken differently in moisture design from the one built in Toronto, Tallahassee, or Phoenix. Historically moisture management approach pursues preventing building assemblies getting wet from the interior and the exterior climates while letting it dry out to either the interior, or the exterior, or both (Lstiburek, 2002). This seems easy in theory, but since moisture transfer is driven by vapour and thermal gradients and these factors are both transient, it is not a steady state and predictable phenomenon.

As for the exterior vapour load, in cold climates the dominant vapour transition happens from interior to exterior and the opposite for hot and humid climates is the case. This will suggest an interior vapour barrier for a building located in cold climate such as Alaska and on the exterior side of building enclosure for a warm and humid climate like Florida. However, not all climates experience year-round cold, or warm weather and could have mixed climates. This is the case for many locations in Canada, Vancouver included. These all are more reasons of the importance of a design-oriented approach when it comes to choosing a wall system that is new such as super-insulated wall systems.

In addition to interior and exterior wetting sources, construction material could have been initially wet such as moist wood framing or plywood and wet concrete during curing. This moisture is also termed as Initial Moisture Content. Brick, wood, and other water absorbing construction materials could get wet from precipitation if not covered. This could happen before or during construction and not dry out timely.

As for the interior wetting sources the vapour in the indoor air, as one of the major wetting sources, comes from both occupants' activities and any material or furniture that bears moisture. Examples for occupants' activities are cooking, showering, breathing, and sweating and for the moisture bearing materials, firewood and wet clothes are two examples.

In building envelope to deal with moisture if the source of liquid is controlled the wetting and drying through the vapour in the air is the main factor to investigate. These factors are mere climatic parameters and not in our control, so we need to account for them when designing buildings in different climates. Obviously, a building built in Vancouver has more moisture related complications compared to a building built in Phoenix. To do so a variety of moisture references to gauge wetting and drying possibilities in different climates against each other such as *The Scheffer Index*, *ANK-ONRL Method*, *Annual Driving Rain Index (aDRI)* and *Moisture Index Reference Years.*

Scheffer proposed a 'Climate Index Value' to make an estimation of decay risks based on geographic locations in the United States, for wood components that is exposed to the above ground exterior conditions. This index is meant to be just a comparison between different climatic locations, not to predict decay development in specific types of wood.

$$\textbf{Scheffer Index} = \Sigma\ (\text{Jan-Dec})\ [(T-2)\ (D-3)]/16.7;$$

where T is mean monthly average temperature (°C), D is mean number of days per month with 0.25 mm or more of precipitation, and (T – 2) = 0 if T<2.

Based on Scheffer Index (Scheffer, 1971) the Moisture Reference year (MRY) was introduced by Cornick and Dalgliesh expended to Canadian geographical locations (Cornick & Dalgliesh, 2004), which both wetting and drying capacities of the exterior air is taken into account, termed as wetting and drying indices. It is basically analysis of the historic weather data such as annual rainfall, humidity ratio and temperature.

MI = f (Wetting Index, Drying Index) = f (WI, DI)

$$MI = [(WI_{normalized})^2 + (1 - DI_{normailized})^2]\ \text{^}0.5$$

Where "I" is the index of interest

WI: average annual rainfall on the ground, kg/m2-yr

DI: capacity of air to take up water vapour

$\Delta w = W_{sat}(T) - W_{ambient}(T) = W_{sat}(1-\mu)$; *kg-water/kg-air*

; μ *: degree of saturation* – $w_{ambient}/w_{sat}$; w_{sat}: *humidity ratio at saturation*

$DI = \boldsymbol{\Sigma}^{k}_{h=1}\Delta w$; *kg-water/kg-air.year*

k= number of hours in a year, i.e. 8760 or 8784

The graph below is an example of Moisture Index (MI) for some different climatic locations, Seattle, Winnipeg, Ottawa, Wilson, and Phoenix. On the graph below the distance from the zero X and Y axes represents the final MRY so the further away from the centre, the more overall moist ambient air in that specific year that data are studied. In the example below, Wilson has the highest MRY, followed by Seattle, Winnipeg and Phoenix ranks as the least moist city, not surprising.

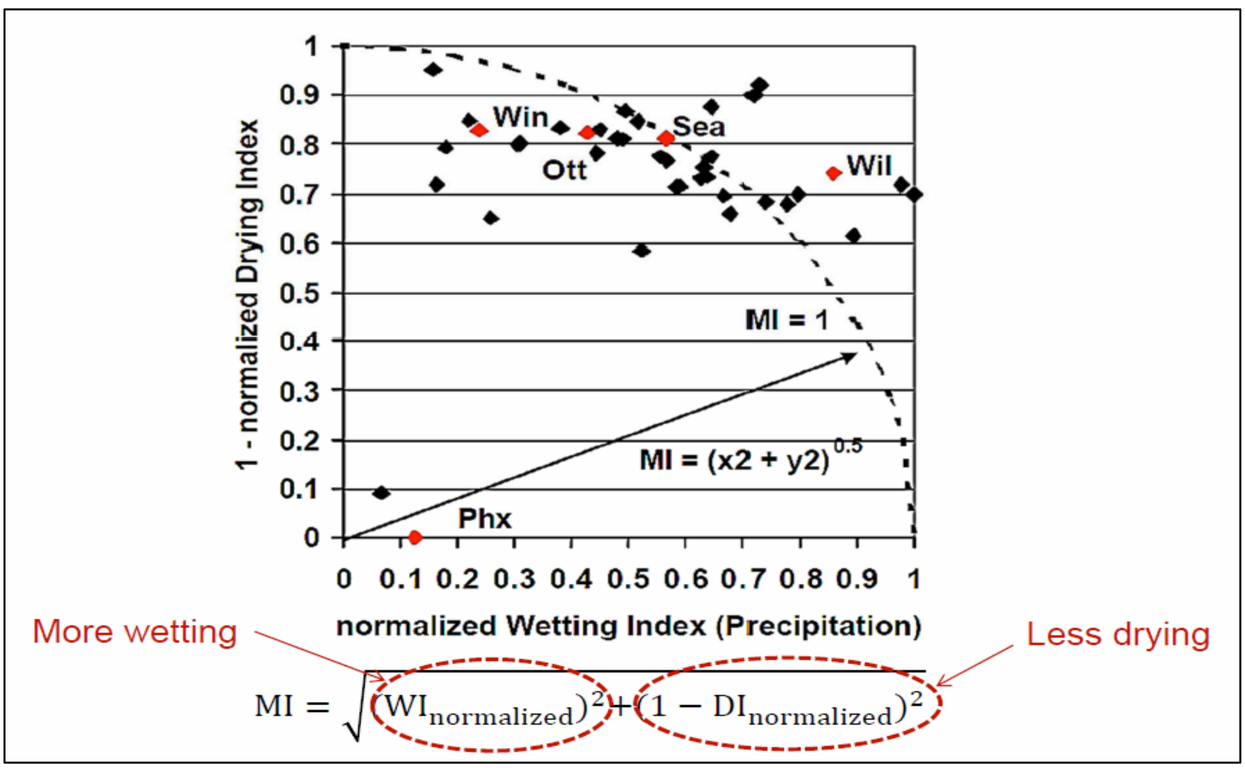


Figure 167- Moisture Index (MI) for Seattle, Winnipeg, Ottawa, Wilson, and Phoenix

Hygric Load includes the vapour moisture in the air and the liquid moisture from the wind driven rain (Karagiozis A. , 2003). In this method, the exterior moisture load of a wall enclosure not only depends on the deposited wind driven rain, but also infiltration and exfiltration and the amount of moisture the exterior air contains with in turn is related to the climate.

$$\Sigma_{E,\,W,\,N,\,S}\,\textit{Hygric Load} = \Sigma_{t=0,8760}\, w + \Sigma_{t=0,8760}\,(m_{air}\rho_{air}) + \Sigma_{t=0,8760}\, Q_{WDR}$$

Hygric load = yearly moisture load potential, kg water
w= moisture content in the air
$m_{air}.\rho_{air}$ *= moisture load due to infiltration/exfiltration*
Q_{WDR} *= moisture due to wind-driven rain*

9.1.3.2.2 Interior Moisture Sources

Interior moisture sources come from people, activities, abnormal loads and construction stage moisture. Buildings occupants add to the interior moisture either directly by perspiration and breathing or indirectly by activities such like cooking, cleaning, showers, drying clothes, using fireplace and materials such as moist fire wood. Abnormal loads in buildings can come from swimming pool or gyms. Initial moisture remained in materials from the construction stage could also contribute to the internal moisture loads.

As a result, the higher levels of air-tightness of building envelopes, if not equipped with proper ventilation strategies, can increase the interior relative humidity and in turn acting as a wetting source and curtailing the drying capacity of enclosure walls (higher interior relative humidity means less diffusive drying to the interior environment). This has become mostly a problem in the wintertime as in the past, with leaky building envelops the moist interior air would have been mixed with the cold and dry exterior air resulting in lower overall interior relative humidity levels. On the other hand, in building with higher air-tightness, if there is no proper ventilation strategy in place, interior relative humidity can go beyond safe levels. This higher moisture rate in the air, as mentioned earlier, could either exceed the dew point of cold surfaces within the building envelope components causing condensation, or increase the interior vapour pressure and thus vapour gradient force to penetrate into building envelope sensitive parts as a potential moisture damage risk (Straube & Burnett, Building Science for Building Enclosures, 2005).

9.1.3.2.2.1 Air Leakage Condensation

Interior Relative Humidity (RH) affects directly the phenomenon of wintertime air leakage condensation within wall assembly. The interior finish of interior walls is usually gypsum board drywall. In a high R-value wall that gypsum wall and the air barrier behind it (if the case) could be (if there is the insulation doesn't inhibit air movement, like fibre glass batt insulation) the only line of defense against air leakage, extreme caution should be exerted by construction team to avoid any defect in the drywall. However, poor workmanship is a fact that often contributes to post-occupancy performance defects. A non-sealed electrical outlet, lighting fixtures holes, or leaving gap in the air barrier system are examples of that *[Ref.]*. Moreover, post occupancy behavior induced defects (as simple as hammering a nail into a wall) are common and with not much control on them. Leaked air can reach to the "too cold" surfaces of wall component through the stud cavity. The leaked air will be pushed in wall through stack effect and/or wind washing. Once air finds its way into the wall, it recirculates in the stud cavity by various mechanisms such as, "re-entrant loop", looping around air permeable insulation, and looping through gaps around insulation (Straube, Smegal, & Jonathan, 2011). This phenomenon pushes the interior warm and "moist enough" air to reach "cold enough" surfaces leading to condensation issues.

Henceforth, the best strategy is having a contingency plan for possibility of air leakage. The be able to work out what is actually "too cold" surface and "too moist" interior air, dew point temperature corresponding to the surface temperature can be extracted from psychrometric chart. With two correlated variables in hand, a two-prong approach has to be followed; controlling both interior relative humidity by proper air ventilation and component's surfaces temperature in design stage ideally by incorporation of insulation at the exterior side of sheathing board (a.k.a Exterior Insulation). This translates into keeping the dew-point temperature of interior air above surface temperature of wall assembly surfaces to avoid air leakage condensation [Fig1].

While this will be an iterative process, but the interior relative humidity in different seasons is not a totally unknown area and has been studied earlier with some recommended rates available (Lstiburek, 2002). For a "mixed-climate" which has cold winters and warm and humid summers, a maximum and minimum of 13°C and 4°C surface temperature is the limitation suggested for potential condensing surfaces, for cooling and heating seasons respectively

The coldest place potential of condensation for the cooling season (summer) is the interior sheathing board (mostly gypsum board) and for the heating season (winter) is usually the exterior sheathing (plywood, oriented strand board or OSB, fibreboard, etc.). Using RH limits, the surface temperature of the coldest region within the wall assembly can be designed to stay below dew-point temperature as the first step of the iterative approach. This will be done through extra exterior insulation, as much as needed. The boundary conditions are assumed to be 21°C for the interior and the coldest extreme 30-year temperature recorded in Vancouver, -18°C for the exterior.

By doing so we design a wall assembly that minimizes air leakage induced condensation, even if air leakage does happen. However, this is not necessarily the best strategy, as it is likely to be an expensive design. Another way to tackle air leakage condensation is covering the entire interior surface of the exterior sheathing panel with high density (2.0 psf) sprayfoam (SPFI) insulation.

Sprayfoam, if applied properly, can act as the condensation plane replacing sheathing board surface (if some level of condensation tolerance is seen in design). If the applied sprayfoam is thick enough, its interior plane will become warmer, minimizing the overall condensation incidents and duration per year. However, this strategy can limit inward drying potential of the exterior sheathing (Straube et al., 2011).

Another design approach for air leakage condensation potential is determining the tolerance level of sensitive construction materials in response to wetting incidents. This level will be to the extent which no undesirable moisture behavior of the wall assembly ensues. This strategy is a practical and realistic design approach that can reduce the construction cost significantly. To do so a hygrothermal transient modeling (e.g. WUFI), or an actual field, or lab measurement will be needed.

9.1.3.2.2.2 Vapour Diffusion

In cold season, the components closer to the exterior side of the wall, if not insulated enough from outside will be left cold. If interior vapour reaches this cold surface water vapour may condensate on the sheathing board or any other component that is below dew point temperature causing fiber saturation of the substrate which can trigger mold formation.

The fact that wetting source comes is the interior airborne vapour and interior temperature is usually controlled and within a rather narrow span, relative humidity can is mainly the main gauge which in turn translates into interior vapour pressure and dew point temperature. The two latter are the major driving factors for vapour diffusion and air leakage condensation respectively so relative humidity ranges and fluctuation ranges should be understood well for any moisture design. However, determining interior relative humidity levels is in correlation with various other factors which makes it not a straightforward task for a moisture management design that hinges on outward interior moisture transitions that in turn is correlated to interior relative humidity.

To gain a better understanding of interior relative humidity its major sources has to be considered. Outdoor vapour pressure, indoor parameters, and wall assembly characteristics and moisture content are the major contributors to interior RH levels and it is essential to understand them all well to comprehend relative humidity transient behaviors. Exterior vapour pressure interacts closely with interior vapour pressure and as in summer that there is more moisture in the outdoor ambient air, more moisture finds its way to the interior environment leading to higher levels of indoor relative humidity. Number of occupancy and activities and air-leakage and ventilation strategies also affect the indoor relative humidity. To add to this complexity of this already complicated equation, in-built moisture content in the wall assembly is involved too.

There are many methodologies for estimating interior RH level, such as ASHRAE160, Sine Curves, EN13788 and EN15026. Most of these methods suggest fluctuating interior RH levels over time and that is what happens in practice. Nonetheless, for a comparative study on relative performance of the testing walls, the maximum constant levels for interior RH are workable. The only variation will be considered for seasonal change, that interior RH_{in} ranging at 20-30% (Straube, Smegal, & Jonathan, High-R Walls Case Study Analysis, 2011) and around 60% for summer. As a conservative approach, 40% and 65% RH are proposed for winter and summer respectively and this is what proposed to be created in test huts for the experiment.

9.1.3.3 Moisture Management

As a general approach, any moisture management strategy for a building envelope should consider four main steps;

A- Control of moisture entry (air, water shedding and vapour control layers), B- Limiting moisture accumulation (drainage),

C- Removal of the excessive moisture (vapour diffusion).

D- Selection of less moisture sensitive construction materials

Any practical and achievable strategy should consider using these four steps in concert. In other words, the moisture entered should be balanced out with the moisture evacuated from the wall assembly before it is ‘too late’ for the moisture tolerance level of the construction material that the moisture was deposited on. From all the wetting sources, vapour diffusion, although not the most detrimental of all, is usually one of the most puzzling sources as it is not visible and alters with boundary condition variables such as exterior and interior climates. Since in building envelope, enclosure walls usually comprise the biggest surface areas of building enclosure and usually have the least solar exposure depending on their orientation, compared to roofs, so in this study walls are the main area of focus.

For proper moisture behavior of wall assemblies, in a nutshell, a balance between entry and removal of moisture is the objective. As discussed above, the main moisture sources need to be predicted and addressed in design stage;

a. *Liquid Water* and *Capillary* (Rain, Groundwater, Plumbing failure, etc.)

b. *Vapour* in the Air (Diffusion and Air-borne, from indoor and outdoor)

These sources are either exterior or interior. As for the exterior moisture sources, assuming plumbing is not within enclosure walls (as not allowed in many North American building codes), rainwater is usually the main source which usually is blown to the surface of enclosure walls by the help of wind, or *Wind Driven Rain (WDR)*. This deposited liquid water may partly be deflected, shed off the cladding, or evaporate back to the exterior environment. From the amount of moisture remaining on the cladding, some of it may penetrate walls through wind pressure and capillary phenomenon and some other may find its way directly into wall assemblies through building enclosure interface defects, examples of which, window-to-wall or balcony-to-wall interfaces' seams, cracks, or unintended openings.

For the interior wetting sources, the vapour in the indoor air, one of the major wetting sources, comes from both occupants' activities and any material or furniture that bears moisture. Examples for occupants' activities are cooking, showering, breathing, and sweating and for the moisture bearing materials, firewood and wet clothes are two examples. The interior vapour moisture source in the air can either diffuse into enclosure wall assemblies or alternatively find its way through air leakage gaps or holes in the interior sheathing board such as electrical outlets.

9.1.3.4 Climate Enigma

Vapour diffusion can be a rather puzzling mechanism as it is not visible and changes with temperature and relative humidity levels of interior and exterior climates. In cold climates and in heating season the vapour pressure gradient is from the interior to the exterior and a common practice is incorporation of a vapour barrier (or retarder) behind the interior sheathing board (mostly gypsum board), whereas in hot and humid climates, the vapour barrier commonly is applied on the exterior side of the exterior sheathing board (Plywood, OSB, etc.) to intercept vapour flow from outside into the wall assemblies. While this may seem an easy solution, not all climates experience year-round cold, or warm and humid weather. The climates which vapour flow gradient alternates from inward to outward are termed as Mixed Humid climates, and Vancouver in Lower Mainland of British Columbia (LMBC), Canada falls in that category. A Mixed Humid climate is defined as a region that receives more than 20 inches of annual precipitation and has approximately 4,500 heating degree days or less and where the monthly average outdoor temperature drops below 45°F during the winter months (Lstiburek, 2002) and

Vancouver and most of British Columbia falls within that definition, so this complexity has to be dealt with in this region. Apart from the seasonal and daily variability of vapour pressure gradient, Vancouver is in one of the wettest climatic zones in North America that building envelope elements are exposed to significant amounts of moisture from precipitation and vapour in the outdoor ambient air with lower chances of drying.

Another potential moisture related issue is the lower vapour permeance of some of the new common construction materials such as polyethylene film, or Oriented Strand Board (OSB) that can retard vapour diffusive drying of wood frame wall assemblies to the lower vapour pressure environment which is the exterior in cold climates and in the heating season. The application of higher levels of insulation can also add to this problem by reducing the temperature variation across the exterior sheathing board causing lower vapour pressure gradient further reducing the amount of vapour diffusing out of the wood-frame walls to the lower vapour pressure climate (Straube, Smith, & Finch, 2009).

Even if we accept the argument that the local common construction practice of a polyethylene film layer behind the interior drywall has proven more or less effective with the typical wood frame walls filled with fiberglass batt insulation, however, for other types and levels of insulation (like cellulose and high R-value walls), the effectiveness of this method has not been proven in the field of wet and mild marine climatic zone of lower mainland, BC, Canada.

9.1.3.5 Drying

Excessive moisture can impact building envelope the highest among all other loads in variety of ways such as discoloration, mold and mildew, fungi, deterioration, corrosion, etc. and *drying* translates into removal of the excessive moisture from building envelope components timely, is crucial for enclosure walls performance and durability. Excessive moisture can leave enclosure walls with a variety of mechanisms mainly evaporation, diffusion, drainage and ventilation.

9.1.3.5.1 Drainage/Vented/Ventilated/Evaporation

Excessive moisture if in form of liquid could be drained from building envelope as the second line of defense (after deflection).

A rule of thumb by ASHRAE 160 prescribes, "*In the absence of specific full-scale test methods & data for the as-built exterior wall system being considered, the default value for water penetration through the exterior surface shall be 1% of the water reaching that exterior surface. The deposit site for the water shall be the exterior surface of the water-resistive barrier. If a water-resistive barrier is not provided, then the deposit sites shall be described & a technical rationale for its selection shall be provided.*"

This translates into possibility of water penetration, so drainage would be necessary to address this possibility. Drainage is essentially removal of larger drops of water by gravitational force as the smaller drops of water may not be drained due to larger surface tension and capillary force. There are several drainage systems common in building envelope engineering, such as sole *Vented*, *Ventilated*, and *Ventilated & Pressure Moderated* which all incorporate a gap between siding and WRB/exterior sheathing which is termed as *rainscreen* cladding system. While in Vented systems, a gap is incorporated at the bottom of the rainscreen to shed any liquid moisture that reaches the surface of WRB, the Ventilated systems add another gap at the top to increase air movement and its drying capacity to evacuate liquid moisture from rainscreen. Ventilation is air replacement in a space by another air that is drier, cooler and fresher through natural buoyancy, wind, and mechanical systems. The moisture within building envelope components can reach the surface and then evaporate to the outside environment from higher to lower vapour pressure and if this moisture is removed faster the rate of evaporation can increase too as the replaced air if less humid can accommodate more evaporating moisture.

The third system, *Ventilated & Pressure Moderated,* compartmentalizes rainscreen to moderate high wind pressure that can factor into pushing liquid water into WRB and exterior sheathing board. Compartmentalization also can help with structural stability of rainscreen cladding especially for highrise applications.

9.1.3.5.1.1 Vapour Diffusion Condensation

Vapour diffusion is a function of differential vapour pressure levels between interior and exterior climates. While there is a rich source of recorded exterior weather conditions for many climates, the interior weather conditions for moisture load is widely affected by many other variables such as the exterior climate, building envelope characteristics and building occupants behaviours and ventilation strategies. Henceforth, there is a high level of uncertainty and variability associated with choosing a fitting interior moisture load in the air (in form of vapour). In the heating season for cold climates, interior temperature is significantly warmer than mean outdoor temperature. Based on thermodynamic basic laws we know warmer air can hold more moisture inducing higher vapour pressure. If the interior vapour pressure is higher than exterior vapour pressure, indoor-to-outdoor vapour pressure gradient acts as the driving force for the interior water vapour diffusing it from the interior space towards the exterior. In a building that no dehumidification is in place, moisture diffusion could only be intercepted if vapour is stopped by a vapour barrier. Controlling the relative humidity (RH) levels by limiting the interior moisture sources can definitely help but is not a safe strategy design.

Vapour diffusion is driven by vapour pressure gradient across the perimeter walls which can significantly differ from location to location based on climatic zones. As extreme example of confusion in design is a wall assembly with interior vapour barrier in a predominantly warm and humid climate such as Florida. Another common moisture management mistake is having multiple extra vapour barriers within a wall assembly. This is based on the notion that a wall should be prevented to get wet from both interior and exterior at any cost, however in the likely event of moisture getting into wall assembly, insufficient drying capacity can lead to undesirable moisture response.

For all the concerns discussed above in walls with significantly higher thermal insulation namely "high-performance wall assemblies", moisture management can turn into an even more complicated task. The current code requirement for R-value of exterior walls in Vancouver is around R-20, whereas high performance walls call for R-30 and higher for Vancouver and similar Heating Degree Days (HDD) climatic locations. As the shift towards higher R-value seems inevitable and the main concern is if they are adopted with no proper moisture engineering design, many of these walls are in risk of moisture performance related failures again. This project focuses on developing a more scientific and practical knowledge of the hygrothermal performances of high performance wall systems and the potential risks associated with them.

Since a typical residential house in Vancouver keeps the interior temperature constant by thermostats, with no moisture control, interior vapour pressure calculation is not as easy as outdoor, even if the interior temperature remains constant. The interior moisture is affected by occupancy, activities and other interior moisture generation sources. ASHRAE160 suggests three methods to calculate residential indoor vapour pressure in residential buildings that don't have HVAC system in place as a function of a few variables such as exterior hourly vapour pressure, number of rooms in a house, and minimum design ventilation rate. For example, a three-bedroom house with 4 occupants translates into 14 lit/day of moisture generation. Since super-insulated building envelopes are usually incorporated in aggressive energy standards like Net-Zero and Passive House and those standards have significantly higher airtightness levels and ventilation level requirements compared to ASHRAE160, the interior relative humidity is not necessarily similar to what ASHRAE160 calculates. The best source of information is the actual measured data for specific applications. A study (Tariku & Simpson, 2015) was conducted on four apartment units in Vancouver, BC with different humidity levels within 17 months. The results suggested that highly occupied unit can have interior relative humidity of 7-23% higher than lower occupied units. While lower occupancy units varied from 43% in winter to 51% in summer, the highly occupied units experienced 65% RH, which 58% was recommended by the authors as a rate for computer modelling. So, a high occupancy unit could be adopted as a conservative approach for both winter and summer seasons in Vancouver to come up with a safe

9.1.3.6 Moisture Damage

Rain, temperature, humidity and interior climate are environmental loads and some of the main moisture responses or impacts are corrosion, decay, rot, and mold. Among all the limiting conditions, mold has such an importance that is the main criterion for many moisture engineering designs. In one study (Lstiburek, 2002), similar to structural engineering that load, and load responses are correlated, moisture and its responses are represented as hygrothermal loads on wood frame walls similar to structural loads.

Mold only grows if there is enough moisture content in the air. This moisture amount in the air is commonly represented by level of relative humidity (RH). In regular indoor temperatures, mold germinates at the range of 80-95% RH (Ojanen, et al., 2010). If moisture sensitive construction materials such as wood framing and sheathing boards like plywood, Oriented Strand Board (OSB), etc. get wet, they may develop mold given the right temperature and enough time is in place. For mold to live, although it relies on a variety of factors such as food, oxygen, favourable temperature and moisture, however other than moisture, all other factors are not quite within our control as mold already uses wood as its food, oxygen is omnipresent, and temperature is affected by the exterior climate, so controlling moisture is the most practical strategy to control mold growth. Based on various studies, if moisture content of wood-based materials goes beyond a certain threshold depending on type of substrate and environmental conditions (Ojanen, et al., 2010) for a long enough period mold can germinate and may not leave the wall assembly as easy. Once germinated, mold doesn't die out under normal circumstances and becomes dormant if other factors like temperature and oxygen are not favorable for them anymore (Nielsen, 2002). While more complicated than just a single number, but Moisture Content of 28% is a commonly agreed threshold in industry (We will get more into details of moisture content and relative humidity in this study).

Once mold is born within walls, it can have two dire consequences; firstly, if there is a leakage path, mold spores can dissipate to the indoor air which is a health hazard for the occupants, especially for people with breathing disorders (like asthma) and babies (Davis, 2001) (Hedge et al., 1997). Secondly, mold can develop into destructive fungi over time that undermines the structural integrity of wood leading to structural failure.

If moisture sensitive construction materials such as wood framing and sheathing boards like plywood, Oriented Strand Board (OSB), etc. get wet, they may develop mold given the right temperature and enough time is in place. Based on various studies, if moisture content of wood-based materials goes beyond 28% for long enough, mold can germinate, and it will not leave walls easily. While mold needs mild temperature to germinate, once born, it will stay dormant and wait for favourable temperatures to grow and nourish. Mold relies on food, oxygen, favourable temperature and moisture to live and other than moisture, all other factors are not within our control as it already uses wood as its food and oxygen is omnipresent and temperature changes with the exterior climate. The only real factor that is under our control is moisture. Once mold is germinated within walls, it can have two consequences; firstly, if there is an air leakage path, once there is an air pressure gradient, mold spores can dissipate from inside the wall to the indoor air and cause health hazard for occupants, especially with the ones with breathing disorders (like asthma) and babies [Ref.]. Secondly, mold can develop into destructive fungi over time that undermine the structural integrity of wood leading to structural failure.

Despite all the risks associated with mold, fortunately if there is a suitable moisture management strategy is in place, it can be avoided or controlled, but for the mild temperature and excessively wet climates such as Pacific Northwest Marine climate, moisture management needs more diligent effort in design, construction, and even post occupancy behaviour. As for Vancouver that is in a rather wet climatic zone with year-round high relative humidity levels. This climate is notorious for mold infested wood frame buildings which have led to many cases of indoor air quality issues and premature demolition cases *[Ref.].*

9.1.3.7 Super Insulated Walls

For all the reasons discussed above the higher levels of insulation and air tightness, the more moisture related issues are to be expected. For instance, in PassivHause standard which is a stringent energy efficiency building standard typical enclosure walls have around twice thermal insulation, or otherwise called super-insulated walls, and six times higher air tightness levels compared to Canadian complied code requirements (R-40 vs. R-20 and ACH of 0.6 vs. 3.5 ACH) for cold climates. The major concern for these walls is while allowing the least amount of heat be wasted out of building enclosure could help with short-term energy conservation, it may not help the drying capability of walls if they get wet with the various wetting mechanisms.

Super-insulated walls further inhibit the outward flow of the interior heat, which can be the most effective and helping mechanism to expel the moisture within walls to the outdoor environment. Moreover, and as discussed earlier, with higher insulation levels, the exterior sheathing can become even colder with more number of yearly hours having the sensitive wood components drop below dew-point temperature causing the regular or incidental diffused and air-borne interior moisture condense on the cold surfaces.

Despite all the moisture risks associated highly insulated wood frame walls, however considering the urgency of climate change and the Green House Gas (GHG) emissions associated with building's heating energy coming from fossil fuels, building codes have been and will be continuing raising the bar for energy performance requirements to minimize building sector's environmental footprint during and after construction stage. As super-insulated walls are going to be more moisture risky, extra caution in design and construction is needed so that they can limit, remove and withstand typical moisture loads for each application and climatic zone. In other words, while preventing moisture intrusion, and removing the entered moisture should be considered in the first place, selecting more moisture tolerant construction materials for the wall assembly components' areas with higher levels and duration of moisture accumulation is a safe and wise design strategy. The removal of already entered moisture, translates into better "drying capacity" with incorporation of building Science principles.

9.1.4 Cellulose Insulation

9.1.4.1 Dry Cellulose (Loose Fill)

Loose-Fill cellulose insulation is among the first types of cellulose insulations used in buildings for energy retrofitting of old homes attics floors and walls. The R-value of loose fill cellulose is R-3.2-3.8/inch, measured in ASTM C518 standard test method. For the new construction walls, one way of installing it blowing dry fluffy cellulose on the ground horizontally into walls cavity, then erecting walls and installing them in place.

Another more common technique is pumping loose cellulose into walls cavity from the top through some cut holes at top of interior sheathing board, mostly gypsum board. For new wall constructions, it is blown behind some retainers or net.

One major issue with this type of insulation is its settlement of up to 20%. In (Bomber & Shirtliffe, 2003) study blown density was measured as 34.8 kg/m3 for horizontal applications whereas in a design density of 44.4 kg/m3. So, settlement of loose-fill cellulose is a major concern. It needs to be noted that there is a difference between *blown density* that is the *declared density after installation* compared to *design density* of the fibres which is *measured after impact and/or cyclic humidity testing*.

Figure 168- Retaining Net for installation of blown-in Cellulose (Uphillhouse, retrieved 2018)

One of the measures taken to mitigate this issue is compartmentalization of cavity by retainers mostly vertically for better filling, but this technique is not always adequate for settlement problem as it is still prone to leaving behind gaps in the corners and tight spaces. In a study it was determined that on average loose-fill cellulose insulation settles around 21.5% after installation, partly from drop impact and partly from cyclic humidity variations (Bomber & Shirtliffe, 2003). Gaps and empty spaces in insulation cavity can lead to convective heat loss and air leakage induced condensation on cold spots.

9.1.4.2 Wet-Spray Applied Cellulose

One of the solutions introduced to cellulose insulation industry to address the settlement issue was spray-applied or wet-applied technique. The main reason for adding water is increasing the integrity of the insulation texture by elevating its density which will help with preventing settlement. To prevent settlement, a minimum of 57 kg/m3 is suggested (Pablo Lopez Hurado, 2016) which is not easily achievable in *loose fill* common insulation methods, but *wet spray* can reach that target if applied properly. Furthermore, since wet cellulose is sprayed with pressure, it can fill in all the corners and gaps in walls preventing undesired air circulation in the insulation cavity which can drop the effective R-value of walls to up to 30% (Straube J. , 2007). Compared to wet-applied cellulose, the conventional glassfibre batt insulation has relatively low moisture capacity and usually after installation, corners and gaps cannot be covered well leading to air circulation undermining their thermal performance. A laboratory study (Bomber & Brown, 1993) tested a few insulation types with different densities, under a few temperature and air leakage defect gaps. The results revealed that convective heat loss through defects goes higher if the insulation type is less dense and the gaps at corners and framing stemmed from poor workmanship in the field are more present. This reduction in effective R-value measured in a test wall assembly reached up to surprisingly high 25-33% compared to the initial R-value without convective heat loss within the insulation (Figure 169).

	Product 1			Product 2			Product 3		
T_{cold}	0%	3%	6%	0%	3%	6%	0%	3%	6%
−5°C	3.15	3.08	2.87	3.29	3.22	3.10	2.95	2.80	2.53
−20°C	–	3.07	2.62	3.37	3.23	2.97	–	2.76	2.24
−35°C	3.38	2.96	2.35	3.43	3.12	2.75	3.14	2.68	2.00

Figure 169- R-value variation with temperature and defect gaps (Bomber & Brown, 1993)

Depending of the season, climate, and thickness of applied cellulose it takes anywhere from 24 hours to a few weeks to dry out after application. Another advantage of wet-applied cellulose is it does not require a retainer or net for installation which reduces construction cost and time.

9.1.4.3 Moisture Issue of wet-applied Cellulose Insulation

Despite the installation advantages of sprayed cellulose Insulation, since it is applied wet, it may increase the initial moisture content of wall components to critical levels that cannot dry out timely. This depends widely to the climate and season of application as wet wood framing may not easily expel the extra moisture especially if the application is done in cold and wet season. In a study (CMHC, 2013), wet cellulose was applied in south facing walls and rim joists in a detached wood-frame house in Alberta. The walls included four different scenarios; one standard construction with polyethylene as vapour barrier, second and third walls were constructed standard method, but both without polyethylene vapour barrier, one with 25mm vent holes through the exterior wall (to increase ventilation in walls), and the other was with a tightly sealed cavity (no ventilation through the wall). It was revealed that it took six months for the walls to dry out entirely from the added water from wet insulation and after a year with signs of deterioration in one of the walls. This study also concluded that cellulose cannot be relied on as a sole effective air barrier.

In one field experimental study (Salonvaara, T.Ojanen, Erkki, & Karagiozis, 1998), it was shown that even professional and licensed wet-applied cellulose insulation applicators often go over the maximum installation suggest amount of 40% moisture content (MC) for insulation material (at application time) often reaching to as high as 70% of MC. This study concludes if cellulose is applied wet in winter of cold climates there will be high risks of insufficient and untimely drying.

Another potential issue with wet-applied cellulose insulation is degradation of its thermal resistance with higher levels of moisture content. In one laboratory study (Veljelis, Gnipas, & Kersulis, 2006), moisture behaviour of several walls with loose-fill cellulose insulation sandwiched between two layers of brick walls were studied. This study was partly aimed at investigating thermal conductivity of cellulose under varying moisture content, so samples of cellulose insulation were collected and put into test. The specimens were collected from the buildings enclosures in October month (before moisture accumulation period) and in April month (after moisture accumulation period) to determine the moisture content of loose fill cellulose insulation. The specimens were collected from both continuous walls as well as the sections under and over windows. The results showed moisture content of cellulose changed in the range of 8.9% to 15.3% but moisture content had a significant difference of around 13% from closer to the exterior side to the interior.

9.2 Sorption Isotherm Regression Analysis (Reverse)

As discussed earlier, for interpretation of recorded data, Mold Index (MI) was also adopted, however, the moisture levels of walls were recorded by MC sensors whereas MI uses Relative Humidity (RH) numbers, so MC numbers had to be converted to RH numbers to be used in MI calculations. To do so, the results of a previous study Building Science Laboratory for sorption isotherm graphs of similar plywood and lumbers were used. While the plywood and lumber material of the previous and present study were not the same, but they were of similar wood species and were adequately useful for the comparative purposes. To be able to obtain RH from MC, the original sorption isotherm axes were converted so that the regression results would yield

RH on the Y or vertical axis based on MC located on the X or horizontal axis. The recorded data were broken down into smaller segments so that the highest level of accuracy in regression was achieved, $R^2>0.99$. More detail is found in the upcoming section and the appendix chapter.

9.2.1 Spruce (for Wood Framing)

The sorption isotherm test data for spruce wood from the previous study, its graph, and the converted sorption isotherm graph are presented in this section. The regression formula for spruce wood that was used for converting MC numbers into RH numbers is presented too.

Table 26- Spruce Wood Sorption Isotherm Data

Spruce- Sorption Isotherm Data	
RH	MC (%)
0.0000	0.0545
0.1000	0.3931
0.2000	0.8911
0.3000	1.6697
0.4000	2.8351
0.5000	4.5199
0.5500	6.4347
0.6000	7.0117
0.6500	7.7284
0.7000	8.6472
0.7500	9.8754
0.8000	11.6173
0.8500	14.3213
0.9030	19.6531
0.9080	20.4215
0.9130	21.2652
0.9180	22.1962
0.9230	23.2300
0.9280	24.3854
0.9330	25.6868
0.9380	27.1655

Spruce- Sorption Isotherm Data	
RH	MC (%)
0.9430	28.8627
0.9480	30.8341
0.9530	33.1566
0.9580	35.9397
0.9630	39.3455
0.9680	43.6250
0.9730	49.1900
0.9780	56.7688
0.9800	60.6432
0.9830	67.7856
0.9880	85.4462
0.9930	118.4893
0.9940	128.7431
0.9950	140.9083
0.9960	155.3330
0.9970	172.1609
0.9980	190.7900
0.9985	200.1284
0.9990	208.7905
0.9991	210.3780
0.9992	211.9020

As the table above presents, MC levels hovering around 12-20% are corresponding to RH levels of 80-90%, which are closer to our test numbers.

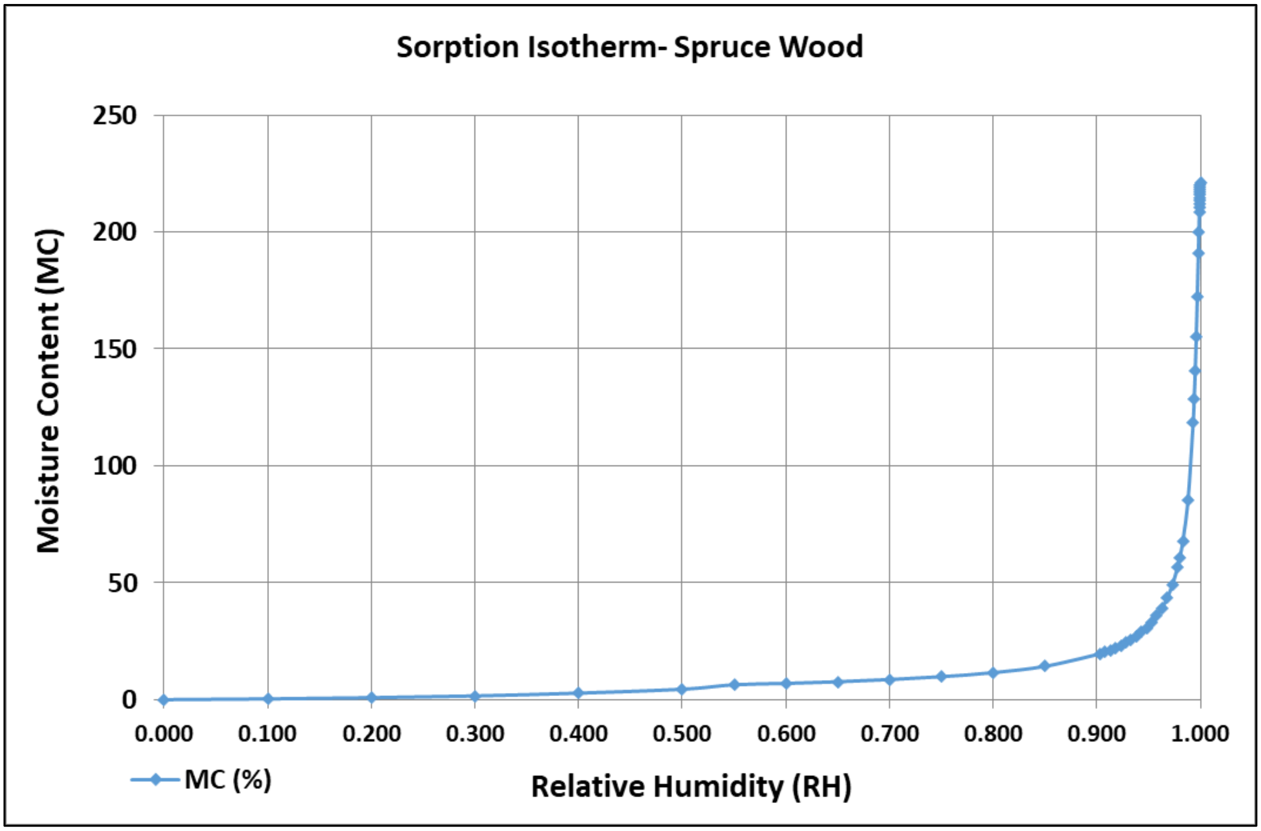


Figure 170- Spruce Sorption Isotherm Graph

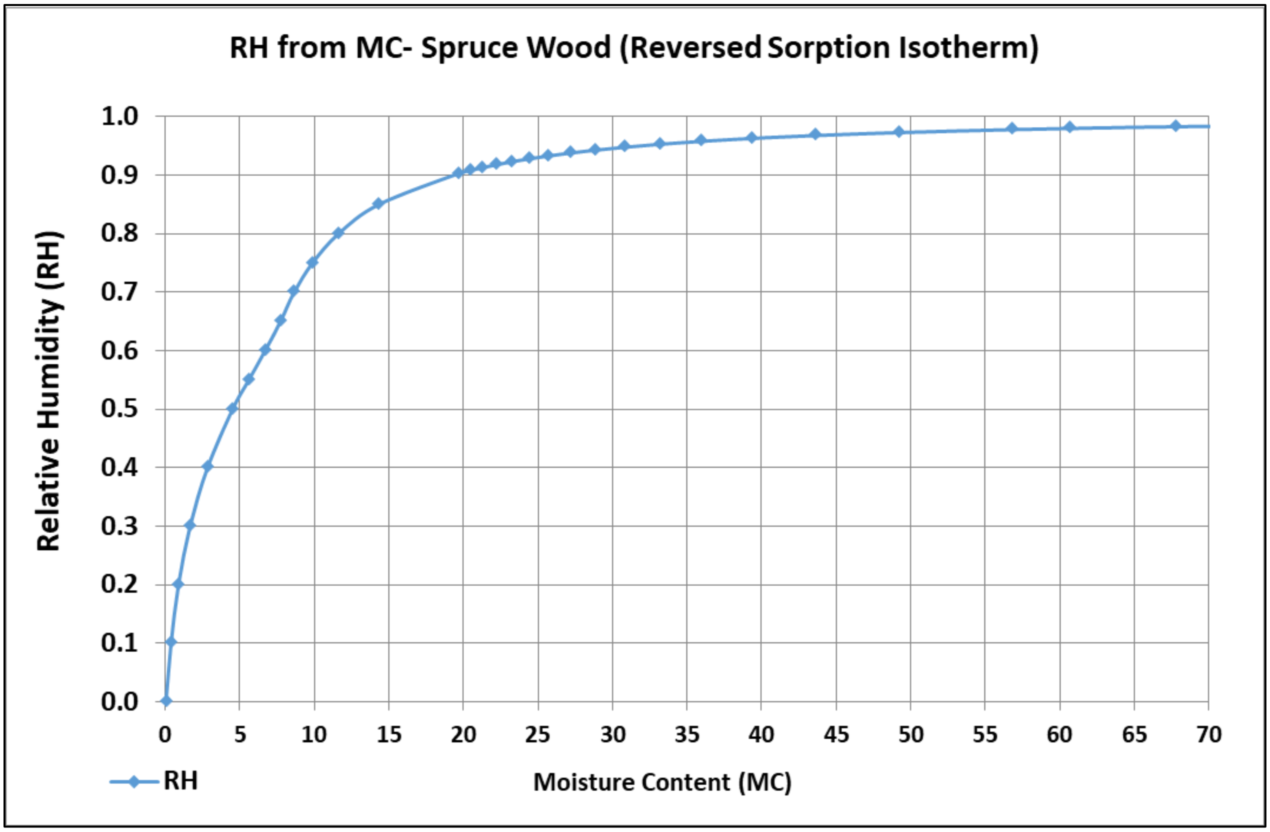


Figure 171- Reversed Sorption Isotherm for Spruce

Table 27- Spruce Sorption Isotherm Regression Analysis

MC range	MC to RH Conversion Formula- Plywood	R^2
0.05-4.52	RH = -0.0225 * MC^2 + 0.2085 * MC + 0.0107	0.991
4.52-6.43	RH = 0.0261* MC + 0.382	1
6.43-14.32	RH = -0.0044 * MC^2 + 0.1273 * MC - 0.0799	0.996
14.32-30.83	RH = -0.0003 * MC^2 + 0.0199 *MC + 0.6312	0.997
30.83-67.79	RH = -2E-05 * MC^2 + 0.0031* MC + 0.8741	0.997

9.2.2 Plywood (For Exterior Sheathing)

The regression results for plywood sheathing board that was used for converting MC numbers into RH numbers which are followed below. The corresponding RH levels of the recorded MC levels of 8-40% are 50-97% of RH as presented in the table and sorption isotherm graph below.

Table 28- Plywood Sheathing Sorption Isotherm Data

Plywood- Sorption Isotherm Data		Plywood- Sorption Isotherm Data	
RH	MC (%)	RH	MC (%)
0.0000	0.0375	0.9630	32.3615
0.1000	1.8578	0.9680	35.1956
0.2000	3.4130	0.9730	38.7115
0.3000	4.9246	0.9780	43.1899
0.4000	6.4136	0.9800	45.3447
0.5000	7.8882	0.9830	49.0913
0.5500	9.0190	0.9880	57.2338
0.6000	9.3470	0.9930	69.2618
0.6500	9.7740	0.9940	72.4147
0.7000	10.3463	0.9950	75.9308
0.7500	11.1452	0.9960	79.9027
0.8000	12.3278	0.9970	84.4919
0.8500	14.2426	0.9980	90.0714
0.9030	18.1644	0.9985	93.5626
0.9080	18.7366	0.9990	98.1521
0.9130	19.3652	0.9991	99.3311
0.9180	20.0590	0.9992	100.6619
0.9230	20.8287	0.9993	102.2011
0.9280	21.6874	0.9994	104.0386
0.9330	22.6515	0.9995	106.3275
0.9380	23.7415	0.9996	109.3508
0.9430	24.9838	0.9997	113.6959
0.9480	26.4128	0.9998	120.8172
0.9530	28.0737	0.9999	135.5676
0.9580	30.0282	1.0000	190.0000

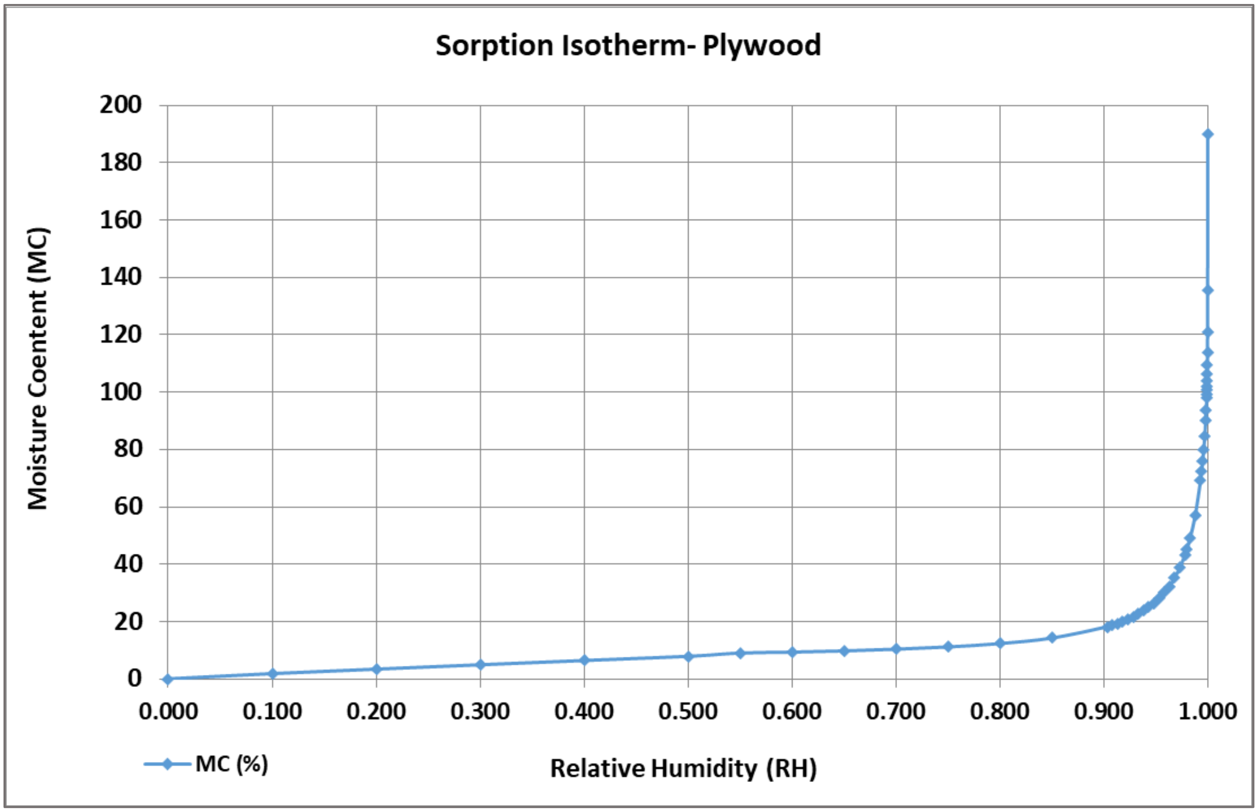


Figure 172- Sorption Isotherm of Plywood Sheathing

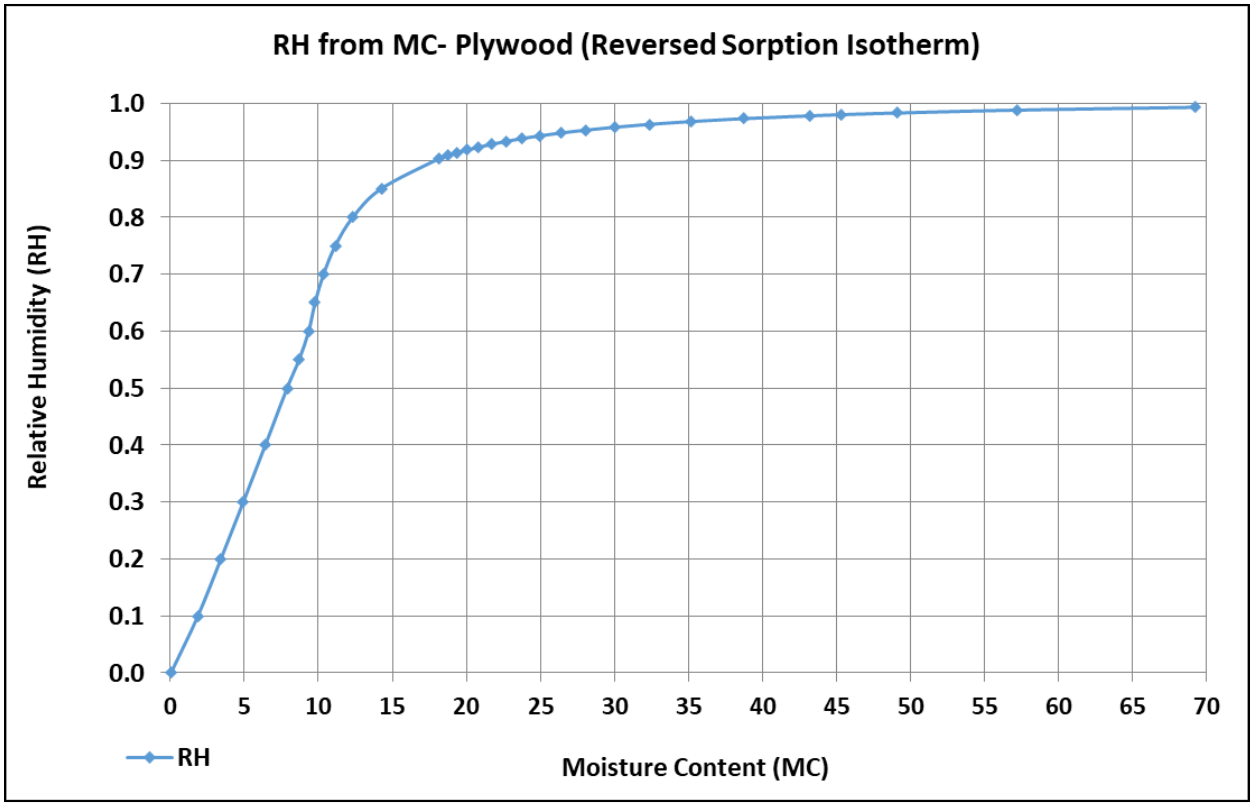


Figure 173- Reversed Sorption Isotherm for Plywood Sheathing

MC range	MC to RH Conversion Formula- Plywood	R^2
0.04-7.89	RH = 0.0642 * MC - 0.0126	0.998
7.89-9.02	RH = 0.0442 * MC - 0.1512	1
9.02-14.24	RH = -0.0111 8 MC+ 0.3123* MC - 1.3527	0.993
14.24-24.98	RH = -0.0006 * MC^2 + 0.0336* MC + 0.5022	0.998
24.98-57.23	RH = -4E-05 * MC^2 + 0.0046 * MC + 0.8552	0.995

Table 29 Table 30- Plywood Sorption Isotherm Regression Analysis

9.3 Experimental Setup

9.3.1 DAQ Specifications and Programming

Agilent 34980A with 8 of the 34922A modules.

Moisture Content Conversion – This is the logic and formulas in the Vee program used to calculate the moisture content at the moisture pins.

Step 1: DAQ reads the voltage drop across the sensing resistor and the power supply.

Step 2: Calculate MC resistance. From the voltage drops we can calculate the resistance across the moisture pins with the following formula:

MC = (5000000/VDsr) *(VDps-VDsr)

(The resistance (in ohms)= 5,000,000 **Ω** of the sensing resistor.

VDsr = the voltage drop across the sensing resistor.

VDps = the voltage drop across the power supply.

Step 3: Calculate MC1 = (67.579-0.1224*(LOG10(MC/1000)^3)+2.6038*LOG10(MC/1000)^2-20.752*LOG10(MC/1000))

MC is the calculated resistance from above

Step 4: Calculate Y2 = (0.85*(MC1)+0.779)

MC1 is the calculated value from above

Step 4 Calculate MC% = (((Y2+0.567-0.026*Tmp+0.000051*(Tmp^2))/(0.881*(1.0056^Tmp))-SCFb])/SCFa)

Y2 is the calculated value from above

Tmp is the temperature from the thermistor that is closest to the moisture pins

SCFa and SCFb are the species correction factors for the wood type the moisture pins are in, i.e. SPFI, plywood, OSB

RH Conversion

For the RH sensors the voltage is read across the output pins and converted the reading to RH using the following formula:

RH% = (VDrh – Rhof)/Rhsl

- VDrh is the voltage output from the sensor
- Rhof is the offset that is specific for the sensor
- Rhsl is the slope that is specific for the sensor
- Rhof, Rhsl are specific for each sensor as they were calibrated in the factory.

Temperature

Temperature is converted from a resistance to a temperature by the DAQ.

DAQ is fed with what type of thermistor is on a channel and it outputs a temperature.

9.3.2 Test Hut HVAC System

The main test hut HVAC system consists of two air handling units (AHU) that condition the air to the desired set point, control the ventilation rate and the ratio of recirculated and fresh air. Both systems are located at the ceiling level, with one in the north area of the building the other in the south. Each system has a DX coil and corresponding exterior condenser for cooling, and an electric resistance heater for heating.

For the Heat Pumps, one is in the North side of the test facility (HP1), another in the South (HP2).

The HVAC system inside the test facility also consists of 4 humidifiers that control the interior RH. They are located in the upper and lower areas of both the north south interior side of the building.

Humidifiers: Nortec NHMC Steam Humidifiers, 208 Volt, Cylinder Model #421, max output 30 lbs/hr, HU1A – North Lower, HU1B – North Upper, HU2A – South Lower, HU2B – South Upper

All the systems are controlled through a Delta Controls DSC 1616.

Test Hut Interior Set Points

The test hut interior conditions should be kept at the following levels for the prescribed dates.

- Jun 1 - 24° Celsius & 55% RH
- Sept 1 - 21° Celsius & 60% RH
- Dec 1 - 21° Celsius & 55% RH

Heating & cooling is controlled through a program running on the DDC system that looks at the delta between the set point and the thermostat temperature. There is one thermostat located on the northern interior column, east side, that controls the north AHU (HP1) and a second thermostat located on the southern interior column, east side, that controls the southern AHU (HP2).

Heating will engage when thermostat temperature is 0.7° C below set point and turn off when 0.2° C or less below set point. The cooling will engage when thermostat temperature is 0.7° C above set point and turn off when 0.4° C or less above set point.

Humidification is also controlled through the DDC system by engaging the respective humidifiers when the thermostat(s) indicate the actual RH levels are below the programed set point. The DDC variable for the humidifiers has the proportional band set to 3% so the humidifiers will only engage or disengage when outside of that range.

Even though the humidifiers output is maxed at 25% (approx. 7.5lbs/hr), set from control panel of humidifier, it was found that the output from the humidifiers raised the humidity levels so that there was a large RH range in the test hut. Three of the four humidifiers have been turned off, north lower is the only one left running, and it was found that this reduced the fluctuation in the interior RH of the test hut. The test hut interior conditions should be checked every month by following the 'Test Hut Interior Conditions Analysis' and making appropriate adjustments to the HVAC system if required.

The sizing of the dampers for determining how much outdoor air is mixed with the return air is based upon respective pressure sensors measuring the pressure delta between the test hut interior and exterior. The DDC setup is to allow enough outdoor air to come in as to not pressurize the building, i.e. a 0 Pa pressure delta, to a maximum of 50% fresh air.

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