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# Vapour Diffusion Open Arctic Wall: A Comparison of Moisture Accumulation Potential Versus Other Cellulose Superinsulation Strategies

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# A COMPARISON OF MOISTURE ACCUMULATION POTENTIAL VERSUS OTHER CELLULOSE SUPERINSULATION STRATEGIES


By

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**VAPOUR DIFFUSION OPEN ARCTIC WALL:**
**A COMPARISON OF MOISTURE ACCUMULATION POTENTIAL VERSUS OTHER CELLULOSE SUPERINSULATION STRATEGIES**

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## Abstract

Superinsulation is becoming increasingly attractive in the construction of energy efficient new homes or energy retrofit projects. By increasing the thermal insulation inside walls, new possible unforeseen building durability issues arise that were otherwise not present during standard 2"x6" construction, as there is less potential for drying. The reduced drying is often attributed to using low permeance materials in the building enclosure. One method to combat the reduced drying potential is to use the highest permeable vapour diffusion open materials for all building enclosure components such as the "Arctic Wall". The purpose of this study is to determine how the Arctic Wall performs in Fairbanks, Alaska in addition to other climates, and how it also compares with other common vapour diffusion open methods.

The results of experimental simulation using WUFI 5.2 hygrothermal software have shown that all vapour diffusion open walls have a potential for condensation that is most dominated by the heating load across the climates that were tested. The Arctic Wall was found to be safe to use in all climates using the tested methods, but still poses a potential risk due to potential condensation due to air leakage. The results of this study have shown that the Arctic Wall performed on par with other vapour diffusion open strategies.

## Acknowledgements

I would first and foremost like to thank my supervisor, Dr. Russell Richman for introducing me to the Arctic Wall concept. His guidance, expertise and advice throughout this project has influenced my academic path and helped me shape this project to its eventual conclusion.

I would also like to thank Vera Straka, my second reader for the additional input and insight as an advisor.

I would like to express my gratitude to Thorsten Chlupp for attempting to build an Arctic Wall in a very cold climate to prove it can be done and volunteering his knowledge and experience through correspondence.

Thanks also go to Bruno Grunau and the team at CCRHC for being generous in sharing their data and findings about the Arctic Wall.

I would finally like to thank my wife Shira, for the love, support and patience she has provided throughout my studies.

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# 1. Introduction

Superinsulation methods in conjunction with high levels of air-tightness are currently being examined as a method to contribute to the goal of reducing energy use in buildings. With the increase in insulation values, more effort and examination is needed to keep the moisture balance of the building enclosure in check as an increased risk of moisture damage in the building envelope material layers can occur. Traditionally, the vapour retarder was exclusively situated the interior side of the thermal control plane as an almost impermeable vapour control layer using a polyethylene sheet as described by the CMHC "the vapour retarder should be at or near the inside surface of the insulation and would most commonly be 0.15mm [6 mil] polyethylene sheeting at the inside face of the studs or vapour-retardant paint on the finished drywall" (Canada Mortgage and Housing Corporation, 2013). Using vapour diffusion open materials in conjunction with variable permeance vapour retarders are one method to attempt to influence how moisture behaves in walls with high thermal resistance. Although the behaviour of a building enclosure with standard insulation methods is well known, no attempt has been made to determine how well different vapour diffusion open wall profiles compare to each other such as the Arctic Wall in terms of dynamic moisture behavior. Not much is known about which material properties and aspects climate contribute to moisture accumulation in walls that could potentially develop mould in a superinsulated scenario.

## 1.1 What is an Arctic Wall

The Arctic Wall [Figure 1], a new superinsulated wall designed by Thorsten Chlupp can be defined as a platform/balloon frame hybrid system with an interior platform and an exterior balloon gusset system to support the insulation and cladding (Chlupp 2011, Grunau 2007). A superinsulated wall can be defined as a wall whose requirements for thermal insulation is designed above and beyond the local Building Code requirements and one that reduces thermal bridging when it can be avoided. In addition, the total dense pack cellulose thermal insulation has a slightly higher thermal resistance than other superinsulation methods. The Arctic Wall uses CDX plywood and sheathing adhesive tape as a component of the air barrier system and vapour retarding system, which is more vapour open than OSB at higher vapour partial pressures while having a hygronic buffer capacity due to the use of cellulose insulation. With the addition of stud cavity insulation, the location of the vapour retarder is located inside the insulation layer, but closer to the interior side. The exterior sheathing substrate and spun bonded polyolefin [SBPO] is removed in favour of a more vapour diffusion open sag resistant weather resistant barrier made by either SIGA called Majcoat© or a Thermoplastic Elastomer-Ether-Ester [TEEE] Solotex Mento Plus©.

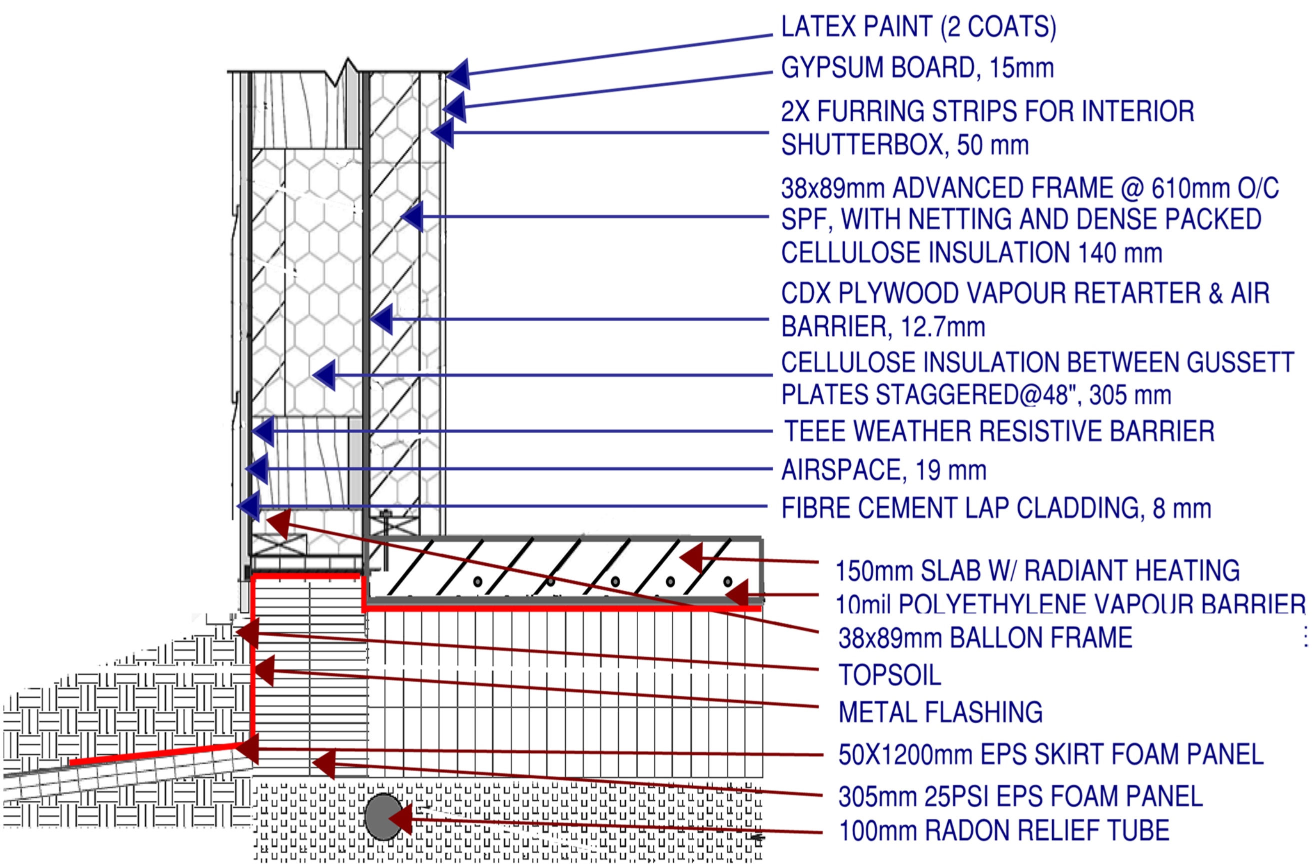


**Figure 1: The Arctic Wall inside an enclosure, which has CDX plywood for a vapour retarder, no exterior sheathing with 550mm of insulation (Grunau 2012, Chlupp 2013)**

## 1.2 Objectives

The purpose of this project is to determine if the as-built Arctic wall in Fairbanks Alaska is suitable for various Canadian climates by examining the hygrothermal properties of that wall using WUFI 5.2 (Fraunhofer Institut Bauphysik, 2011) in comparison to other superinsulated wall systems

By comparing the Arctic Wall to other superinsulated wall design methods that utilize plywood, OSB and SBPO/polypropylene hybrid co-polymer vapour retarders in different configurations, this paper will try to determine if the Arctic Wall performs better for those climates and if maximum vapour openness is truly the best option for these climates.

By examining the hygrothermal behaviour of these wall systems in various climates, this paper will determine what climate characteristics and/or material selection govern a superinsulated wall.

The final objective would be to determine if the requirements for low permeance sheathing by the National Building Code need can be ignored as all of these superinsulation methods do not utilize this strategy, or if a new set of rules is required.

## 1.3 Scope, Purpose and Research Questions

The current trend to make a building enclosure more energy efficient involves high levels of thermal and air leakage in conjunction with energy efficient heating and cooling systems. Different “superinsulation” methods need to be examined to determine which strategies are appropriate for specific climates. Thicker insulated wall methods present an inherent difficulty to dry out to a safe level in comparison to traditional construction methods. The research questions for this study are:

1. How will vapour diffusion open walls designs as-built in Fairbanks, Alaska perform in other Canadian cities in terms of moisture management?
2. How does the Arctic Wall compare with superinsulated walls using similar moisture management strategies?
3. Are modifications necessary for vapour diffusion open walls for various Canadian climates and what recommendations can be made when using these walls in different cold climates?

# 2. Literature Review

Many factors that affect hygrothermal performance of walls have been examined from different perspectives by researchers. This section will review the current literature dealing with the different factors affecting performance including the current state of knowledge about these topics. The major factors include the prediction of mould growth risk, the moisture balance of [how water enters or leaves the wall system through different means], the principles of vapour diffusion transport, the difference between OSB and plywood for use as a vapour retarder, how low-permeance insulated sheathing is used in 2”x6” construction, the affect of moisture on building durability and finally, how the building enclosure selection is affected by climate.

## 2.1 Mould appearance and growth prediction

To help identify which moisture conditions inside the wall could possibly lead to a building enclosure failure, it would be beneficial to determine the parameters of mould growth. Once the findings of previous mathematical models have been tallied, the most appropriate set of rules can be organized and used to determine safe levels of temperature and relative humidity inside a material layer.

A building material failure can be defined if an irreversible deformation occurs to that material caused by physical, biological, or chemical processes (Trechsel H. R., 2001). Mould growth on any material surface or inside a bulk material can pose a danger to the inhabitants of a building by releasing mould spores into the air, which deteriorate materials and cause indoor environmental quality problems for its inhabitants, thus satisfying the biological process requirement for a failure.

To understand how mould begins to multiply, we must first understand the four stages of a mould life cycle: The first being (i) spores, followed by(ii) germination, (iii) matured mycelium, and (iv) Sporangiophores which is new spore development (Trechsel H. R., 2001). Mould spores are everywhere in the environment, so their presence is uncontrollable. The growth of mould in any condition is undesirable. Germination is the stage at which the mould first begins to reproduce: for the purpose of this study, germination is the moment that will be used as the point of mould failure. This effect can be prevented by the design of the wall if it can stay below a certain temperature and relative humidity over a period of time [Figure 2] (Hukka & Viitanen, 1999). Decay fungi, also known as brown-rot or soft-rot fungi, does not begin its germination until about 95% relative humidity, making for the familiar blue-stain mould fungi the governing design conditions as its relative humidity requirement for germination is much lower (Trechsel & Bomberg, 2009).

One of the more commonly used mathematical models formulated to predict mould growth on a wood substrate's surface has used 80% relative humidity which translates to about 16% moisture content in wood as the lower limit of mould growth (Hukka & Viitanen, 1999). The Seldbauer mathematical model for mould prediction was used for WUFI-BIO 3.0 programming, and predicted the amount of time to mould germination accurately but could not accurately predict mould growth after germination (Black, 2006). If that model cannot predict mould growth, then it cannot predict how drying potential effects the growth. The Seldbauer model predicting germination at 75%-80% relative humidity as the onset of germination and can be considered more conservative than other models such as Hukka & Viitanen that predict 80% relative humidity as the minimum threshold measured in-situ conditions (Black, 2006).

For mould spores to grow on a surface, there is a requirement of the presence of oxygen, a food source, and optimal temperature and relative humidity conditions [Figure 3] (Ontario Association of Architects, 2003). The optimum growth conditions for each of these factors in addition to exposure time per day in [Figure 4] are illustrated (Sedlbauer, 2002). Although the starch and sugar food source of cellulose insulation is similar to wood products, the composition of bulk materials is not the same as surface materials of which these models are based upon. The bulk cellulose has more surface area to possibly provide more food, but if there is little air movement, then the supply of oxygen is diminished, possibly altering the model.

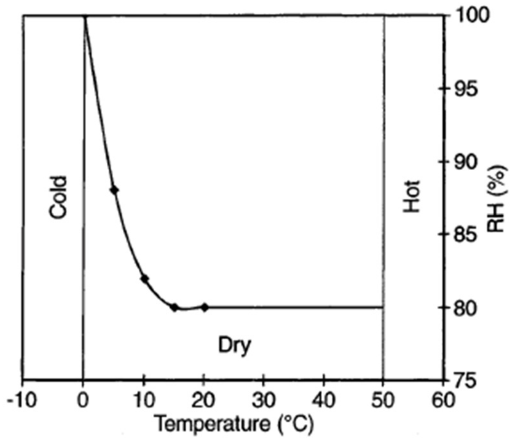


**Figure 2: The line of germination shows the conditions for the emergence of mould growth on a wooden substrate in the mathematical model (Hukka & Viitanen, 1999)**

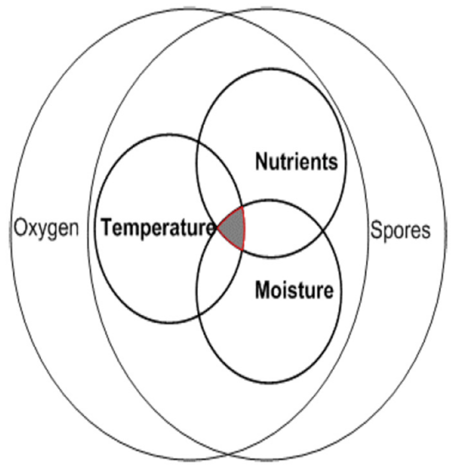


**Figure 3: The five conditions required for mould growth or germination (Ontario Association of Architects, 2003)**

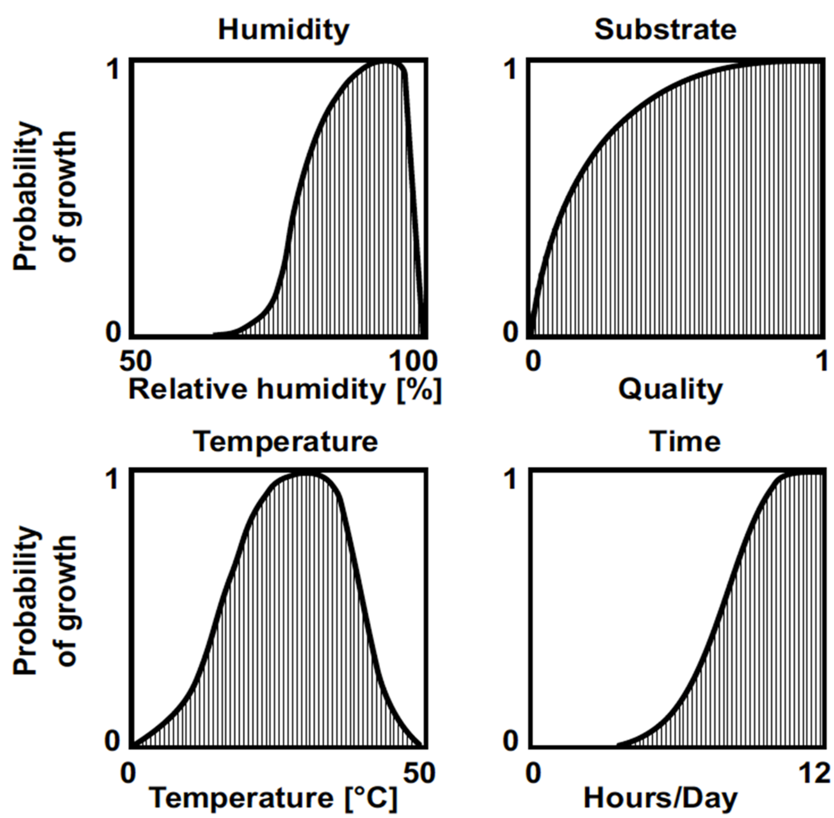


**Figure 4: The optimal conditions for the possibility of mould growth (Sedlbauer, 2002)**

Since no studies exist that investigate the mould growth in cellulose bulk matter due to the difficulty of observation, these mathematical models cannot be used effectively as they are for surface mould growth.  It is unknown how much of an effect the reduced amount of oxygen will have on that growth as shown in [figure 3].  In addition, reliable correction factors for cellulose products do not exist and may be not possible to predict (Black, 2006).  During a simulated heavy rain load, the boric acid component of cellulose insulation can lose its fungal resistance properties as it leaches out of the paper (Klamer, Morsing, & Husemoen, 2004).  This effectiveness of the boric acid adds another unexpected level of uncertainty to the prediction of mould.

Due to this information not being available, a different set of criteria will be used to measure the possibility of mould growth.  This can be accomplished by tallying the number of hours past a predetermined failure threshold.  A value of 30 consecutive days will above 80%RH conditions can be used.  This value was selected because ASHRAE 160P rules indicate that 30 consecutive days as the minimum possible amount of time for mould growth at 80% relative humidity (American Society of Heating, Refrigeration and Air-Conditioning Engineers, 2009).  This value should be conservative, as it does not take into account the drying per day that could affect mould growth [Figure 4].

## 2.2 Moisture

### 2.2.1: Moisture balance

Influence of evaporation of water by vapour diffusion is a goal of this paper to show where drying can be most controlled as material layers and composition can be changed. For a wall section to have excess moisture that can lead to mould failure, the rate at which new moisture is added to the wall must exceed the ability for that wall to dry out. Each wall has a varying amount of moisture storage capacity before it can no longer store the excess moisture safely [Figure 5]. When the wall system reaches this threshold the possibility of mould growth can occur. Those walls can be dried by the following mechanisms: [Figure 6] (Straube & Burnett, Building Science for Building Enclosures, 2005).

1. Evaporation by capillary suction
2. Evaporation by water vapour diffusion or air leakage
3. Drainage of free water
4. Cladding ventilation air changes

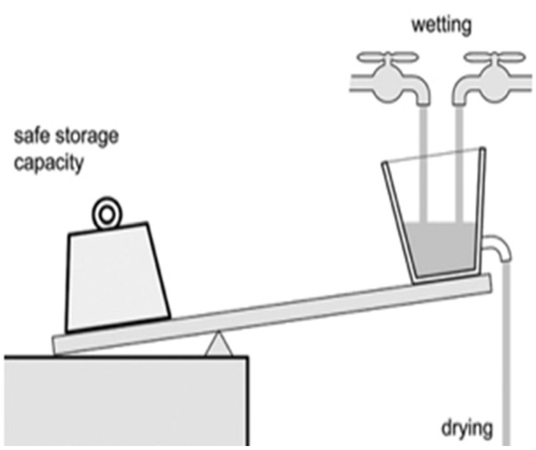

Figure 5: A wall's moisture balance system analogy (Straube & Burnett, Building Science for Building Enclosures, 2005)

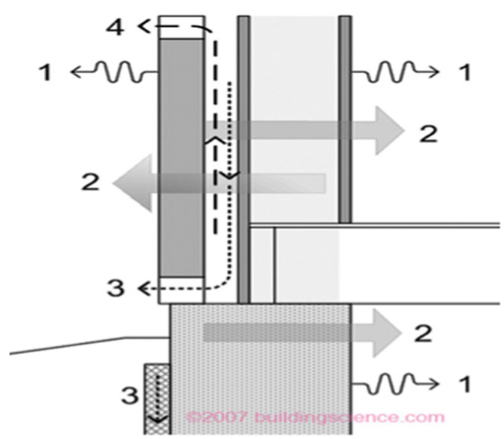

Figure 6: Drying mechanisms (Straube & Burnett, Building Science for Building Enclosures, 2005)

The ability to utilize all four of these drying methods will be crucial to prevent the onset of mould growth. Unfortunately the biggest shortcoming of WUFI hygrothermal software is the lack of an air leakage prediction factor. It must be acknowledged that air leakage can be more influential than water vapour diffusion on bulk moisture deposits in walls. In a common exaggerated example, air leakage was more influential by up to two orders of magnitude for a one inch square hole in drywall versus a single 1200mm x 2400mm drywall sheet [Figure 7] (Lstiburek, 2004). With many new superinsulated homes that are designed with the goal to achieve ACH @ 50 Pa values of less than 0.6, this ratio will undoubtedly be significantly reduced as air leakage is designed to be minimized, making diffusion more dominant than this previous value used in [figure 7]. Although air leakage is a more dominant factor, the water vapour diffusion effects are not well understood for Arctic Wall type of building enclosure. Drainage of free water is controlled in this simulation by the SIGA Majcoat water resistive barrier, and cladding ventilation air changes can be adjusted by cladding type.

The wall system can also be wetted by the failure to control or deflect the effects of each one of these four mechanisms with some being more dominant than others.

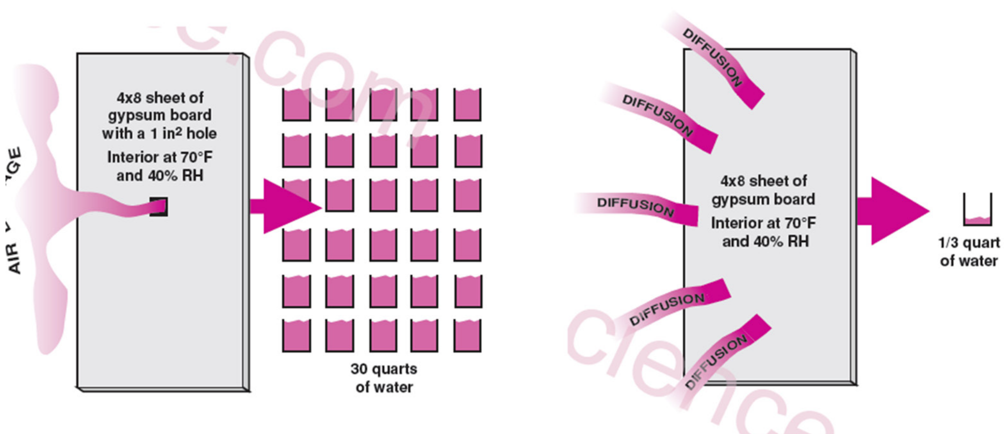


**Figure 7: Air leakage can be far more influential than diffusion. A newly designed superinsulated enclosure will by design have less air leakage than older cavity only insulation homes. This example could become obsolete with a new more accurate air leakage rate. (Lstiburek, 2004)**

### 2.2.2: Cladding air changes

The rate at which a wall section dries can be increased by encouraging air changes in the air cavity behind the cladding by choosing appropriate cladding. Straube & VanStratten argued that cavity ventilation rates do not change by a significant margin between 20mm and 50mm cavity depths, meaning that the thickness of the strapping is not critical assuming no blockage of airflow inside the cavity (as cited in Simpson, 2010). The air change rate behind ventilated fibre-cement siding varies considerably depending on wind speed and orientation. A mean of 89 ACH with a minimum of 3 ACH and up to 468 ACH during some wind gusting for ventilated fibre-cement siding was measured by Straube & VanStraaten (as cited in Simpson, 2010). Cavity air changes are an effective mechanism for drying out a wall. The real cavity air change conditions are affected by wind induced pressure difference and thermal buoyancy (Straube & Finch, 2009). Accurate measurement of the amount of drying that cladding air changes provide requires a data file that has the climactic measured wind pattern over time that can be inputted into WUFI. Since this data is not available, cavity air change rates are assumed to be constant at 89 ACH behind the fibre cement siding. The location of the wind measurement on the elevation can change the reading. These effects cannot accurately be measured without a two-dimensional hygrothermal simulation.

### 2.2.3 Vapour open principles

With the goal of maximizing drying potential, the diffusion open principle allows unwanted moisture to pass clear through to the other side of the enclosure without low permeance material layer barriers hindering that flow. A vapour control layer can be defined as the building component(s) or materials that are used to hinder the flow of vapour diffusion. The vapour diffusion open wall in heating season [Figure 8] allows more moisture laden air to pass thorough the vapour retarder more in comparison to the standard non-superinsulation practice. The amount of moisture that does pass through is a delicate balance. By allowing more moisture to travel through by using plywood instead of a polyethylene sheet as a vapour retarder, there is potential for elevated moisture levels at the sheathing [if it is a component of the wall system]. This negative effect is countered by the property of plywood of becoming even more vapour open in high vapour partial pressures [figure 10]. The advantage of this type of wall during cooling season, the moisture passes through quickly. The only slight hindrance in a diffusion open wall is latex paint layer on the interior, which can be classified as a type II vapour retarder, depending on the number of paint layers.

The issue with the standard practice is that the polyethylene provides a potential condensation plane as the inward driven moisture cannot pass through and dry to the interior. This causes a potential buildup of moisture inside the bulk of the cellulose insulation where it is backed up and can lead to mould, rot and possible failure. It has been suggested that polyethylene should be avoided in air-conditioning buildings if possible due to this issue (Lstiburek, 2006).

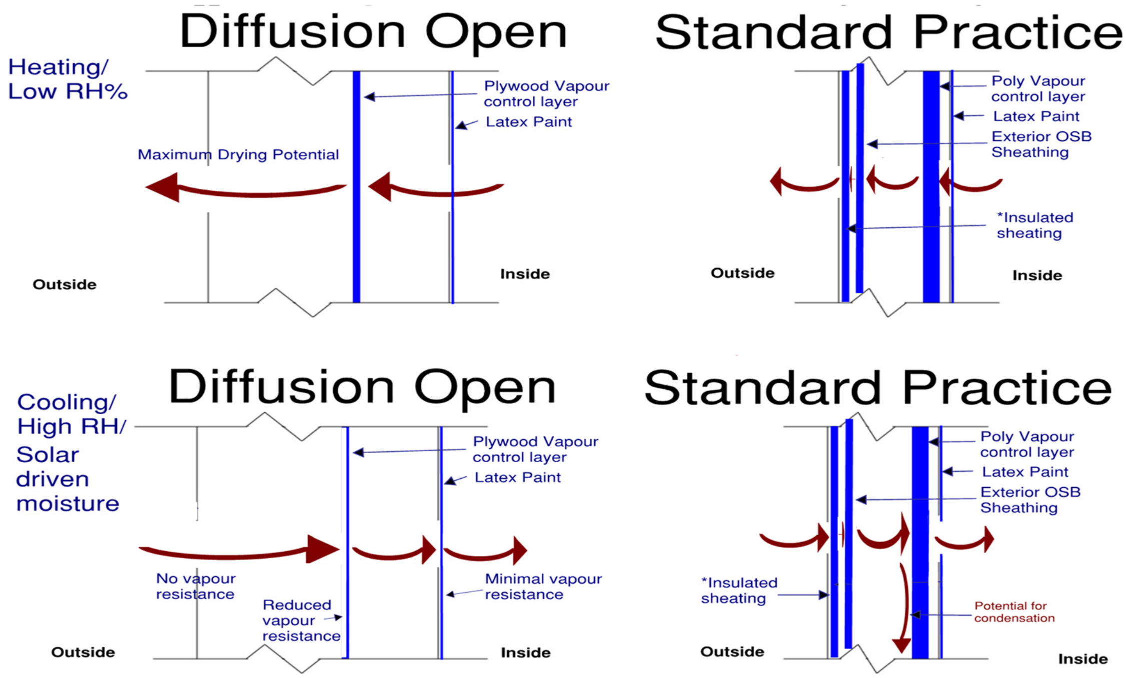


**Figure 8: The vapour diffusion open principle: In both vapour diffusion open walls [top and bottom left], there is only one intentional variable permeance vapour control plane, with the latex paint providing an unintentional vapour retarding layer. If water enters the wall system, it has few barriers to pass through to exit to the other side. The standard wall on the top right can slow down wintertime vapour diffusion well, but may create a condensation plane during high moisture events to the interior in cooling season, which the cellulose will absorb and accumulate over time.**

To further help encourage drying, the vapour diffusion open principle works by selecting building materials that have a primary focus of being vapour diffusion permeable, with other qualities being of lesser importance. Generally, the drying mechanisms in a wall work well for dissipating built-in moisture if there are no vapour diffusion barriers when using cellulose insulation (Carll, TenWolde, & Munson, 2007). This logic can be extended to other materials in order to promote drying. A "smart vapour retarder" can aid in this drying by its variable permeability properties depending on vapour partial pressure. Two smart vapour retarders made of nylon and a one made of synthetic fibres with strips of polyethylene were field tested and showed to perform well during the spring and summer as the material became more permeable under Central European conditions [Figure 9] (Künzel & Leimer, 2001). The polyethylene hybrid's smart retarder dried less, and carried a higher moisture content than the nylon vapour retarder.

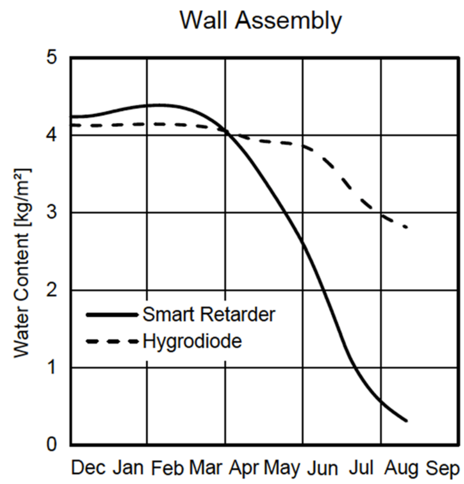


**Figure 9: Total wall system average water content using smart vapour retarders show that drying does occur during spring and summer using the smart vapour retarder. This is generally in contrast to as opposed to possible accumulation using pure polyethylene (Künzel & Leimer, 2001)**

The biggest downside for using a nylon-based retarder is its quality as a sheet membrane; it is less workable in comparison with rigid based products, which do not have a tendency to tear at fasteners under differential building pressures (Lstiburek, 2007). If a service cavity exists to the interior of a protected vapour retarder, close attention to proper installation of strapping needs to be paid when using this material. If the cellulose is densely packed at high pressures to prevent settling, the sheet material can sag, as there is no rigid substrate or netting behind it. The Arctic Wall uses 16mm gypsum board as a substrate to prevent sagging or tearing. Plywood or OSB can be considered as part of a vapour retarding system as they too have variable vapour diffusion properties.

### 2.2.4 OSB and Plywood as smart vapour retarders

Plywood or OSB can be used as the main component of a vapour retarding system with the one caveat of being hygroscopic materials that are susceptible to decay if exposed to high levels of moisture. A safe level of 16% moisture content was cited as the safe cutoff threshold for fungi on a wood surface and generally considered a conservative value (Trechsel & Bomberg, 2009). Generally, plywood was found to dry slightly faster than OSB in wall assemblies using different wetting strategies (Teasdale-St-Hilaire, Derome, & Fazio, 2004). Although plywood dries

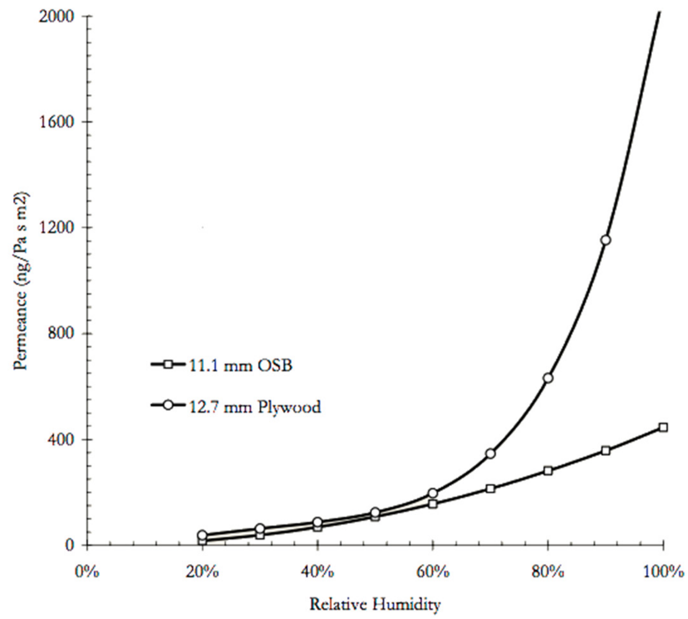


**Figure 10: The average OSB and Plywood permeance values. Research by (Kumaran et al. 2002) as cited in (Straube & Burnett, 2005).**

faster than OSB, it absorbs more moisture during wetting processes in laboratory conditions (Hazleden & Morris, 2009). The variable nature of the permeance of these materials can classify them as smart vapour retarders [Figure 10].

OSB is denser and therefore less permeable taking longer to reach equilibrium from built-in moisture or any wetting (Black, 2006). The outboard face of the plywood is slightly more vapour restive than the core, most likely due to the fact the surface receives a treatment against possible built-in moisture conditions and that the crushed OSB's cells are compressed, increasing the density (Black, 2006). This would mean that the values measured for OSB and plywood are homogenized as a whole. Ideally during a hygrothermal simulation, a separate material layer for the surface layer would be a better choice, but that data is not available. Reliable correction factors for different wood species may never be available due to variations in manufacturing processes (Black, 2006). In general, plywood is more vapour diffusion open than OSB, making it the more appropriate choice for the Arctic Wall. It is possible that the Arctic Wall could possibly be too vapour diffusion open for some constructions and climates.

## 2.3 Insulated sheathing

### 2.3.1 Existing requirements

If the goal of the Arctic Wall is to achieve maximum vapour openness, it should have to address the omission of insulated sheathing its design if it is to be used in other climates. Low permeance sheathing has been used in 2"x4" and 2"x6" construction to increase the temperature of the outboard insulation to combat condensation. While those low permeance materials can prevent the exfiltration air from reaching the dew point temperature by increasing the temperature of the outboard side of the cavity insulation, it also presents a barrier for moisture-laden air to escape through vapour diffusion. The National Building Council took this sensitive balance into account by developing a "Ratio of Outboard to Inboard Thermal Resistance" for low air and vapour permeance for insulated sheathing [Figure 11] (Canadian Commission of Building and Fire Codes, 2010). The guideline represents the minimum ratio required for the insulated sheathing to raise the cavity insulations outer edge to safe levels above the dew point. There is no mention of this ratio having a maximum value where vapour diffusion is slowed down too much. Brown, Roppel & Lawton also noted that NBC's rules applied to buildings with 35% relative humidity in the heating season and attempted to take that into account higher relative humidities of up to 60% with a maximum recommended value for 38x89mm and 38x140mm studding [Figure 12](Brown, Roppel & Lawton, 2007). The acceptable levels of what moisture content that were considered acceptable in both the National Building Code, and (Brown et al., 2007) used an arbitrary value "if the moisture content level in the wall cavity was comfortably lower than the base case wall assembly" (Chown & Mukhopadhyaya and Brown et al., 2007). This is suggesting that the

| Heating Degree-Days of Building Location, Celsius Degree-Days | Minimum Ratio, Total Thermal Resistance Outboard of Material's Inner Surface to Total Thermal Resistance Inboard of Material's Inner Surface |
|---|---|
| Up to 4 999 | 0.20 |
| 5 000 to 5 999 | 0.30 |
| 6 000 to 6 999 | 0.35 |
| 7 000 to 7 999 | 0.40 |
| 8 000 to 8 999 | 0.50 |
| 9 000 to 9 999 | 0.55 |
| 10 000 to 10 999 | 0.60 |
| 11 000 to 11 999 | 0.65 |
| 12 000 or higher | 0.75 |

**Figure 11: NBC's recommendations for ratio of outboard to inboard thermal insulation. It is only based on heating degree-days. (Canadian Commission of Building and Fire Codes, 2010)**

acceptable levels of moisture content from condensation are still unknown. With possible increased interior humidity levels in superinsulated homes due to air tightness, and insulated sheathing with high vapour permeance, these set of rules would be inadequate for a vapour diffusion open Arctic Wall.

By design the Arctic Wall and other dense-packed cellulose based superinsulation methods do not use a strategy to prevent the bulk cellulose from reaching the dew-point temperature by using non-moisture damaging insulating materials on the exterior. A high permeance material, rockwool can be used as a substitute for low permeance foam.

Rockwool insulation was found to be more effective at drying than XPS as an insulated sheathing in a January and July scenario in Portland, Oregon and can be useful as a possible low permeance sheathing alternative (Smegal & Straube, 2011).

According to American Society of Heating, Refrigerating, and Air-Conditioning Engineers ASHRAE 160P standard, it should be assumed that 1% of driving rain will penetrate the weather resistive barrier from construction errors or by design. The rainwater will be deposited into the exterior side of the cellulose insulation, further complicating the matter of contributing to wetting cellulose in that location (as cited in Fraunhofer Institut Bauphysik, 2011)

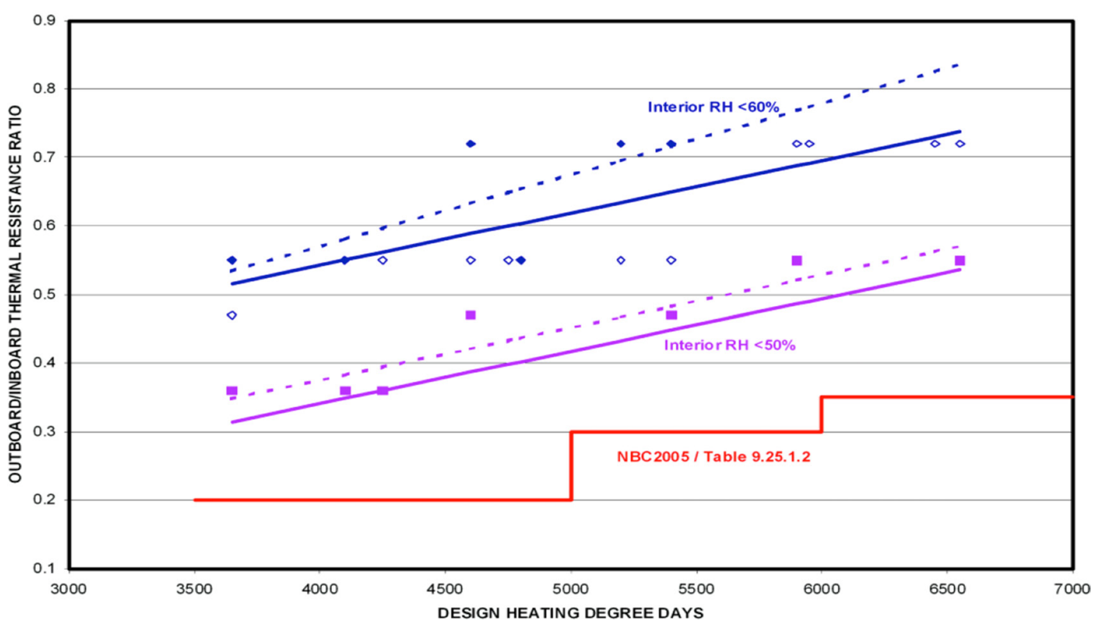


**Figure 12:The recommended insulated sheathing ratio in the heating season for different design relative humidities. The maximum recommended value [solid line] and a marginal pass [dotted line] are shown (Brown, Roppel, & Lawton, 2007)**

### 2.3.2 Insulated sheathing and condensation inside bulk materials

Without low-permeance insulated sheathing to protect the insulation, the location of where the condensation occurs is difficult to prediction and depends on many variables.

This can be illustrated using the following example of water flow in a sink [figure 13, left side]: The fast flowing water moves effortlessly as it hits the sink surface, but begins to slow down as it hits the termination shock. This is the location where the velocity of that water slows down enough so that capillary forces to the sink become stronger than the velocity. Now if we were to insert a bar of soap in the sink on the inside of the termination shock, then the flow will hit the soap and slow down prematurely [figure 13, right]. The location of that shock is known, as it is a stationary object. Just as in a superinsulated wall, the water vapour in the air hits the exterior sheathing. Even if the amount of water in the kitchen sink were increased if the tap is opened up slightly, the location of the soap [condensation plane] remains the same just as the location of exterior sheathing remains the same. As there is no exterior sheathing in the Arctic wall, the exfiltration does not have a plane to condense on, but it must hit the termination shock at some location as exfiltrating air will condense as it comes in contact with

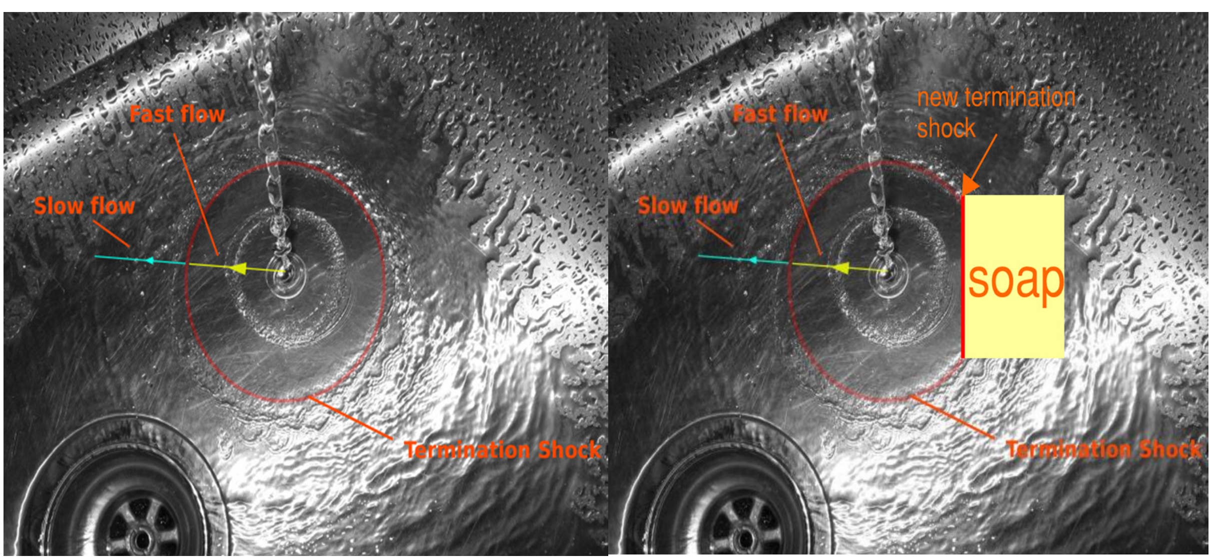

Figure 13: Termination shock without and with a barrier to block water flow (TiCPU, 2009)

the cold exterior air.  If vapour flow is not impeded by a diffusion open design, the depth that this occurs can vary depending on hourly time steps and due to other forces such as various climate conditions.

The question is put forth then, where does the condensation occur?  Any location to the interior of this termination shock should be considered safe, but that can be a very conservative estimate, as the cellulose has a moisture storage capacity that can dry to the exterior, and can reduce the required insulation ratio.

Current mould mathematical models do not measure the mould potential in bulk material due to the difficulty of measuring mould growth.  Experimental mould measurement validation is difficult because the process involves the researcher observing the mould and measuring the diameter of the sample in three-dimensional bulk which cannot be seen. This difficulty in observation is why current experiments focus on surface growth.  The sample could be oxygen depleted due to having only a small amount of air passing over the mould colony surface, which would decrease growth rate.

## 2.4 Superinsulation and building enclosure durability

There are several factors which make the superinsulated enclosure difficult to dry and therefore, making them susceptible to mould. This problem is relatively new as the methods have changed in the last half century. The durability of the building enclosure is put at risk by using slightly different construction practices that are more sensitive to deficiencies due to high levels of moisture. Lstiburek named four major factors that make modern enclosures more delicate (Lstiburek, 2007).

- Increased levels of thermal resistance in walls distribute heat over a larger volume. Drying potential is reduced, as less heat energy is available by volume to dry to the exterior.
- There is a reduced permeability of building enclosure components such as using polyethylene as a vapour retarder, which is more impermeable as the building code requires. Some other materials such as insulated sheathing and vinyl wallpaper are also impermeable.
- More use of materials that are sensitive to biological growth including paper-faced gypsum board, wood framed materials, fiberglass insulation and others.
- Reduced ability for materials to store and redistribute moisture to other locations. This is probably referring to fiberglass batt insulations, which is more sensitive to mould formation than cellulose. Many older walls also tended to use concrete block as part of the structure, which could carry a higher amount of moisture that is not a common a building practice today for single detached homes.

Since superinsulated walls are more difficult to dry out than non-superinsulated walls, being able to dry in both directions is essential for the wall section to dry out. With these four main reasons why walls are harder to dry out, there is less room for error in building enclosure design.

## 2.5 Climate factors

### 2.5.1: Exterior climate file data

Orientation of the cardinal positions of the building enclosure affects the hygrothermal results more than any other climate factor (Salonvaara, Sedlbauer, Holm, & Pazera, 2010). The ASHRAE RP-1325 standard compiles a metric to determine which years are most damaging to buildings. Sample wall and roof sections were included as part of the metrics. The criteria for the metrics include severity of weather, time of wetness, mould index, and seasonal temperature & relative humidity that were tested on a sample wall section. Three weather files were constructed for each city based on these criteria, which sampled various climate variables from different years to create an artificial climate file called as part of the TMY3 system [thermal model year] (Salonvaara et al., 2010). "Year one" represents the worst weather conditions based on a sample size of thirty years, with "year two" and "year three" representing the second and third worst. Year one is considered an extreme weather year that uses the highest values attained from the dataset [figure 14 and 15]. The chances of three consecutive years are unlikely, so the "year one" weather file should only be used for conservative simulations (Fraunhofer Institut Bauphysik, 2011). All other simulations can use year 3 since that year is still hygrothermally dangerous to wall sections as it is sustained for a long period of time of 5 years.

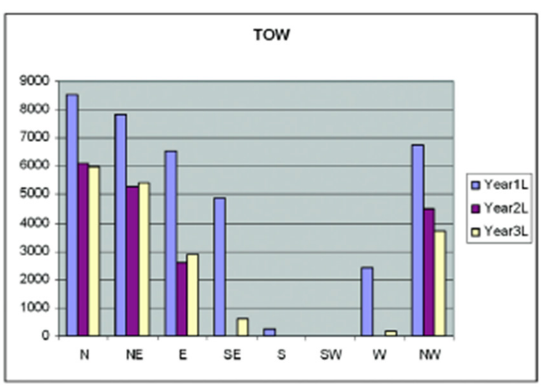


**Figure 14: In a sample wall section, the amount of time of wetness is increased significantly in the extreme year illustrating why the extreme "year 1" should be used in unusual circumstances (Salonvaara et al., 2010).**

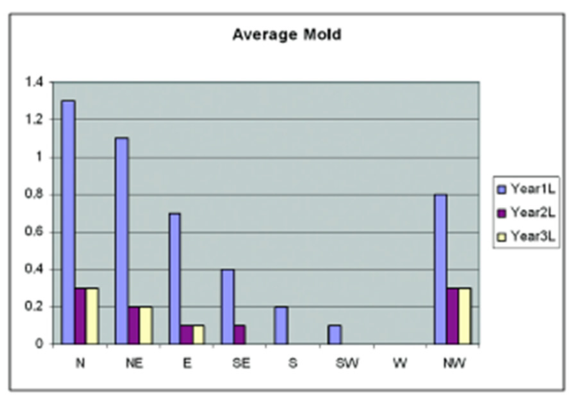


**Figure 15: In a sample wall section, the extra exposure increases the mould index significantly in the Vitannen model for year 1. Values over 1 indicate visual growth observed with a microscope (Salonvaara et al., 2010).**

### 2.5.2: General Climate Factors

Heating degree-days and relative humidity of a climate were used to determine a “climate zone” and from there make recommendations on the vapour retarder rules that are required for that region [Figure 16](Lstiburek, 2009). It is also possible to create a precipitation map for a region to determine minimum cladding ventilation method, which seems to be based on precipitation [Figure 17](Lstiburek, 2009). Both regional maps are beneficial tools in helping to choose the building enclosure moisture management strategies. When using superinsulation methods however, the fact that the enclosure can hold more moisture due to its large hygric buffer capacity, these recommendations do not take into account this excess moisture and the rules may have to be altered. The influence of each individual climate factor effect on the superinsulated wall is unknown.

Heating degree day factor can provide an adequate basis for recommendation of vapour retarder types and their permeance; however, it does not adequately take into account the cooling degree days for the climates which may also be a governing factor on vapour diffusion strategy choice.


**Figure 16: Hygrothermal regions based on heating degree days (Lstiburek, 2009)**

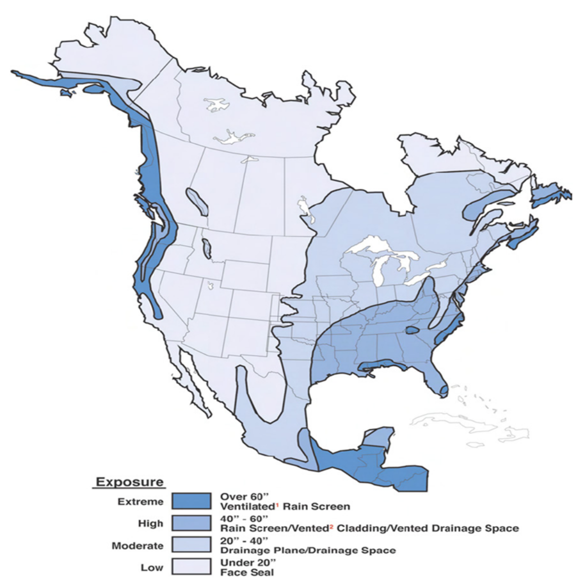


**Figure 17: Cladding venting recommendations based on precipitation (Lstiburek, 2009)**

One effective strategy for standard 2”x6” construction, as suggested by Lstiburek, is to use a vapour retarder that has the highest possible permeance while meeting local codes (Lstiburek, 2009). This allows the heating load requirements to be dominant while being as vapour diffusion open as possible. The cladding rules help supplement those climate choices, but it does not encompass all the climate variables. Different Canadian cities and Fairbanks, AK are compared to show that HDD, CDD and precipitation have no direct correlation to each other except for solar radiation, which appears to increase in milder climates [Table 1]. The issue with using these charts for the selection process for superinsulation is that the climate factors that are most influential in choosing the vapour retarding method is unknown.

To further complicate the matter, wind speed is the catalyst for driving rain and it varies depending on the wall orientation. Every other factor in this table, the direction, diurnal and time of year is critical for simulation of wetting events. Springtime and summertime wetting events and early morning wetting on the East Elevation can play a larger role on depositing bulk moisture in the system by any other driving mechanism.

**Table 1: Climate statistics for Canadian cities and Fairbanks. All variables in this chart are independent of one another. The value for heating degree-days is one of many factors to consider for wall design.[1] (Environment Canada, 2013)[2] (Alaska Climate Research Centre, n.d)[3] (Fraunhofer Institut Bauphysik, 2011).**

| Climate Comparison | Heating Degree Days[1,2] | Cooling Degree Days[1,2] | Precipitation (mm) [1,2] | Precipitation rain only (mm) [1,2] | Wind average (km/h)[1,2] | Solar radiation[3] (kWh/m2/a) |
|---|---|---|---|---|---|---|
| Vancouver, BC | 2926 | 44 | 1199 | 1155 | 11.8 | 2824 |
| Toronto, On | 4066 | 252 | 793 | 685 | 14.7 | 2645 |
| Montreal, QC | 4575 | 235 | 967 | 760 | 14.3 | 2635 |
| Ottawa, On | 4602 | 245 | 943 | 732 | 12.9 | 2617 |
| Calgary, AB | 5108 | 40 | 413 | 321 | 14.8 | 2451 |
| Edmonton, AB | 5190 | 76 | 477 | 366 | 12.2 | 2441 |
| Quebec City, QC | 5202 | 133 | 1230 | 924 | 13.6 | 2560 |
| Winnipeg, MB | 5778 | 186 | 513 | 416 | 16.9 | 2468 |
| Fairbanks, Alaska | 7592 | 34 | 1651 | 271 | 5.4 | 2304 |

# 3. Methodology

To determine whether a wall design is appropriate for each climate, it must be subjected to various simulated tests. Parametric analysis using WUFI© 5.2 hygrothermal software will be conducted on each wall section to determine all necessary hygrothermal functions with the output exported to a spreadsheet to extract needed information. The most common superinsulation methods will be compared to the Arctic Wall. Material properties were obtained from various manufacturers with most specific material data favoured. If manufacture data was not available, a value that could be obtained from literature for the material was used. If properties from both of those sources are not available, then WUFI database (that used many sources) information were all used. Due to different material samples having different properties, consistency was favoured over the other factors such as the selection for OSB and Plywood, whose properties can vary even within the same batch of data.

For the purposes of this study, in addition to Toronto and Fairbanks, two additional cities were chosen to house the superinsulated walls to attempt to illustrate which factors are most in each city or if any trends can be seen. Winnipeg was selected due to having a heating and cooling load requirement roughly in between Fairbanks and Toronto. Vancouver was also selected as a climate with a low heating and cooling load and high driving rain potential and lower seasonal drying potential.

## 3.1 Wall types and monitoring locations

Since the as-built Arctic Wall has a clear wall U-value of 0.075 $m^2k/W$ [R75 BTU/h $ft^2$ °f], all other cases will alter the exterior width of the thermal insulation to match the same U-value. This method of altering the thermal insulation was selected because the plywood gusset sizes can be easily altered to accommodate any thermal insulation thickness. This was done to attempt to give each wall the same drying potential in terms of heat energy per volumetric unit. The designation "A" was put at the end of each case number with a U-value of 0.075 $m^2k/W$. In addition, at the end of each case number, the value of "75" was inserted to represent the Imperial R-value of that wall.

An additional simulation for every wall type was also conducted by reducing the thermal insulation to achieve a wall U-value of 0.095 $m^2k/W$ [R60 BTU/h $ft^2$ °f]. This value was chosen as many superinsulated homes constructed today reflect slightly lower thermal insulation values. The value of "60" was inserted to represent the commonly designed to Imperial R-value design values and will be given the designation "B" at the end of each case number. The reduction of thermal insulation was accomplished by reducing the advanced framing from 38x140mm [2"x6"] to 38x89mm [2"x4"] @610mm [24"] O/C. In addition, the interior thermal shutters were removed as only some superinsulated homes have this item installed. With these items removed, the exterior portion of the insulation is adjusted to achieve close to R60 walls as the plywood gusset can easily be cut to size.

Although these superinsulated walls with R60 are not designed to the *Passive Haus* standard, its requirements for thermal insulation is close to R60 helped form the basis for choosing that value. The Passive House Planning Package's suggests a typical clear wall value of 0.1 $m^2k/W$ [R57 BTU/h $ft^2$ °f] (Feist 2007). A different approach recommended by Straube of a U-value of 0.14 to 0.095 $m^2k/W$ [R40-60 BTU/h $ft^2$ °f] for *Passiv Haus* designs (Straube, 2009).

The monitoring locations for each test are in different areas which is dependent on where mould issues are most likely to happen [figure 18]. It is expected that the highest vapour partial pressures will occur on the exterior side of the cellulose for mould and condensation tests. Inward drive is most likely to be slowed down just before it hits the vapour retarder. Drying measures the total water content of the wall, while the insulation ratio measures different points along the exterior side of the insulation.

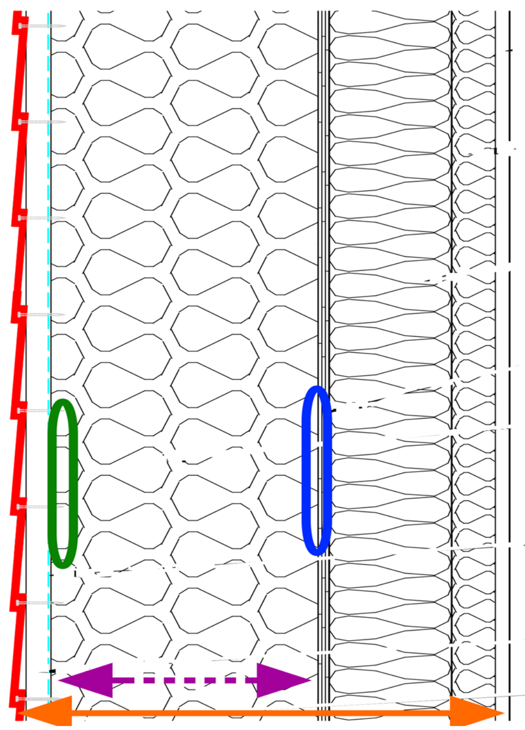

**Figure 18: The monitoring locations of each test. For Condensation and mould, the monitoring location is just to the interior of the WRB (green). For inward drive, the location is just to the exterior of the vapour retarder (blue). Drying potential measures the total water content of all components of the wall (orange). Insulation ratio measures individual points along the exterior side of the insulation (purple)**

### 3.1.1 Case 1A and 1B: Arctic Wall 75 and (Arctic Wall 60)

The Arctic Wall 75 uses latex painted 15.9mm gypsum board and a netting layer behind to prevent sagging from the extra high pressure of densely packed cellulose [Figure 19]. When using gypsum board, the paint is an extra unavoidable vapour control layer. The higher pressures required for installation are due to the width of the wall. In theory, the thicker the wall, the higher the density should be to prevent sagging. A layer of furring strips built to 50mm is below the gypsum to allow space to accommodate interior thermal shutters. For the Arctic Wall, 38mm x 140mm [2"x6"] advanced framing is used with imbedded 50-70kg/$m^3$ densely packed cellulose insulation. The only differences between the Arctic Wall 60 and the Arctic Wall 75 are that the Artic Wall 60 reduces the framing to 38x89mm [2"x4"] advanced framing and removes the accommodation for internal shutters. This is done not only to reduce the amount of amount thermal insulation, but also to remove the option for interior shutters, which many superinsulated homes do not have. It also reduces framing costs and allows for a larger usable floor plate if desired.

The vapour control layer for this wall is the 12.7mm exterior grade CDX plywood with vapour open sheathing tape. This type of system is used because it can also serve the purpose as the main component of the air barrier system. The biggest factor for the selection is that this material is more permeable than OSB, especially at high vapour partial pressures. It can also handle light exposure to rain during construction.

Vertical 38mm x 38mm heat-treated ledger board is fastened on top of the plywood air/vapour retarder every 610mm. The ledger allows the gussets to attach to the structure, as cutting through the plywood would make the constructability difficult in maintaining continuity in the air barrier. The heat-treated (or composite) lumber is used because 38x38mm dimension is only commonly offered in pressure-treated lumber that could possibly off-gas. Pressure-treated lumber is also not appropriate, as when it is delivered to building sites, it usually has a high moisture content and shrinks as it ages. This can loosen the gussets over time.

The 305mm gussets serve many purposes. First, it allows a lot of volume to accommodate the thermal insulation and is designed with minimal lumber which reduces thermal bridging. Second, the gussets also provide a substrate for the weather resistant barrier. Window bucks can serve in place of the gussets and heat-treated lumber as it provides the same function to house the insulation.

The weather resistive barrier is more vapour diffusion open than SBPO and rigid enough so that sheathing is not required. It requires strapping to hold it in place and prevent the WRB from tearing. The weather resistive barrier, originally specified for Siga Majcoat WRB was replaced with TEEE WRB in the simulations as more material data could be obtained for it. The air space that the strapping provides doubles as a vented air space for the cladding. Finally, fibre-cement cladding was the surface layer.

The purpose for examining this wall is to determine the condensation, mould, drying potential and sheathing ratio to determine if it can be safely built for each city. In comparison to the other examined walls, the plywood is the most vapour diffusion open vapour retarder of all cases. With the current WRB, the whole wall has the highest permeance of all cases, which will test the theory if maximum vapour permeance in all materials is the most hygrothermally safe practice in comparison to the OSB counterpart [case 3].

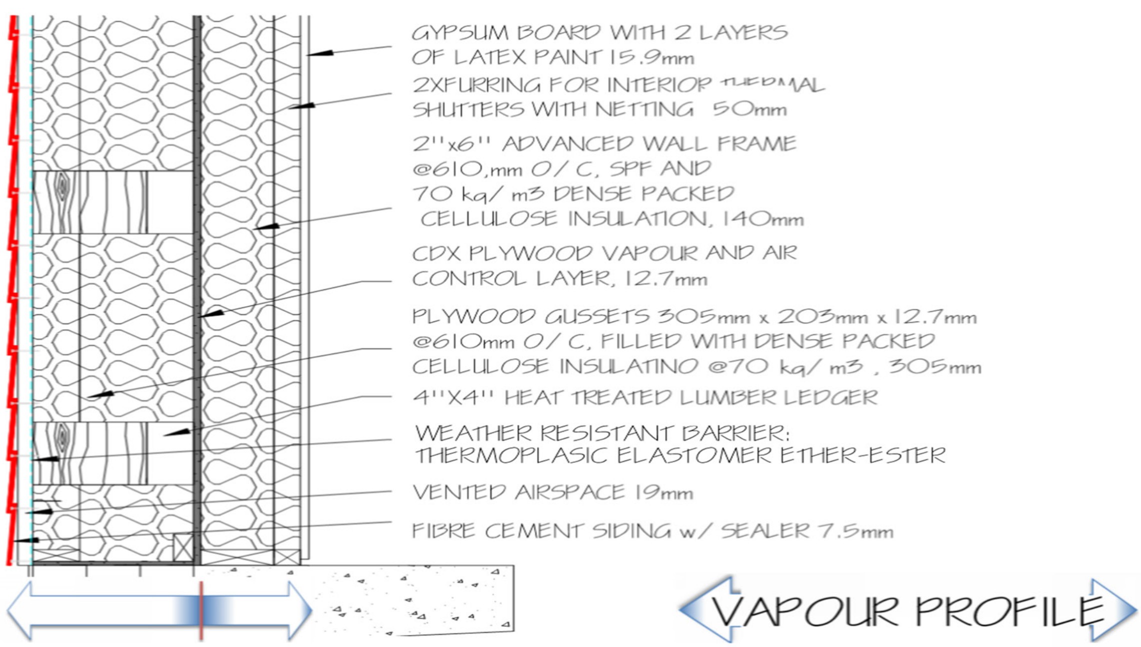


**Figure 19: Arctic Wall 75 with plywood air/vapour retarder. The Arctic Wall 60 has the same composition with the exception of using 38x89mm framing and without the accommodation for the thermal shutters.**

### 3.1.2 Case 2A & 2B Co-polymer 75 & (Co-polymer 60)

Co-polymer 75 and Co-polymer 60 also utilize painted gypsum on top of 38mm (2"x3") strapping. The strapping serves as a small service cavity, a substrate to the gypsum board, and gives dimensional stability for the SBPO/polypropylene hybrid sheet membrane it is on top of and slightly smaller thermal shutter space than the Arctic Wall service cavity [figure 20]. The strapping provides a small buffer between the gypsum wallboard and the vapour diffusion open air/vapour control layer, Solotex Intello Plus© [Co-polymer]. The method of application of the sheet membrane air vapour control layer can provide familiarity to installers who use polyethylene vapour retarders. This same familiarity has the caveat of being difficult to ensure good air sealing on interior sheet membrane vapour retarder applications.

Of all the cases, this vapour retarder is more than half as permeable than OSB between 20-90% RH. A 38x140mm (2"x6") structure helps support the plywood gussets which do not need a ledger board as there is no vapour retarder to pierce through as in the Arctic wall. The gussets themselves extended 330mm beyond the structure to give similar thermal resistance to the Arctic Wall. The WRB, airspace and cladding are the same as the Arctic Wall. In the Co-polymer 60 case, the framing is reduced to 38x89mm(2"x4") with the gussets extending 279mm beyond the framing.

The purpose of examining this case is to determine if the location of the vapour retarder on the front face of the thermal insulation coupled with no built-in moisture in the membrane and the lowest permeance can pose advantages in mould and drying potential over the wood based vapour control solutions.

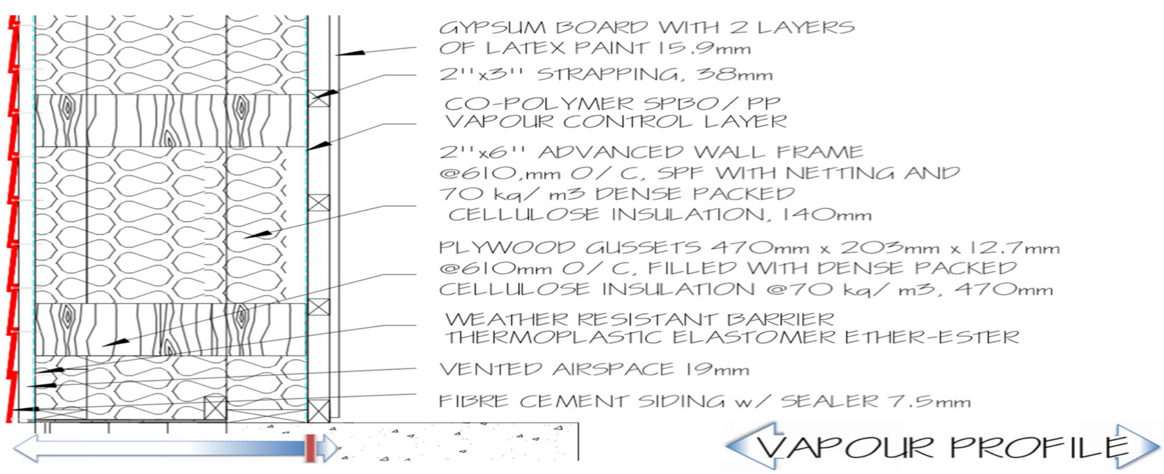


**Figure 20: The board based VR is removed in favour of a vapour diffusion open SBPO/polypropylene layer**

### 3.1.3 Case 3A & 3B: OSB 75 & (OSB 60)

Both OSB 75 and OSB 60 cases have the exact same composition as the Arctic Wall 75 and Arctic Wall 60 in case 1 with one alteration. The vapour retarder is comprised of 11.9mm OSB instead of 12.7mm plywood, which is a commonly used size for exterior sheathing in current building practices [Figure 21]. The OSB 60 wall uses 38x89 framing and removes thermal shutter accommodations just as the Arctic Wall 60. This wall has the same one-dimensional hygrothermal profile as a Larsen Truss or a double stud wall, which are common choices for superinsulated walls. Whereas OSB can be more susceptible to damage from moisture, it is less expensive than CDX plywood, which can make it more desirable for superinsulating. The familiarity of installers using OSB for sheathing purposes is countered by the difficulty in assuring good adhesion using technical tape in comparison to plywood.

OSB has the characteristic of being slightly less permeable than plywood at all vapour partial pressures. By examining this wall, it will be possible to determine whether maximum vapour openness poses any advantages or disadvantages when using wood-based vapour retarders from a hygrothermal perspective.

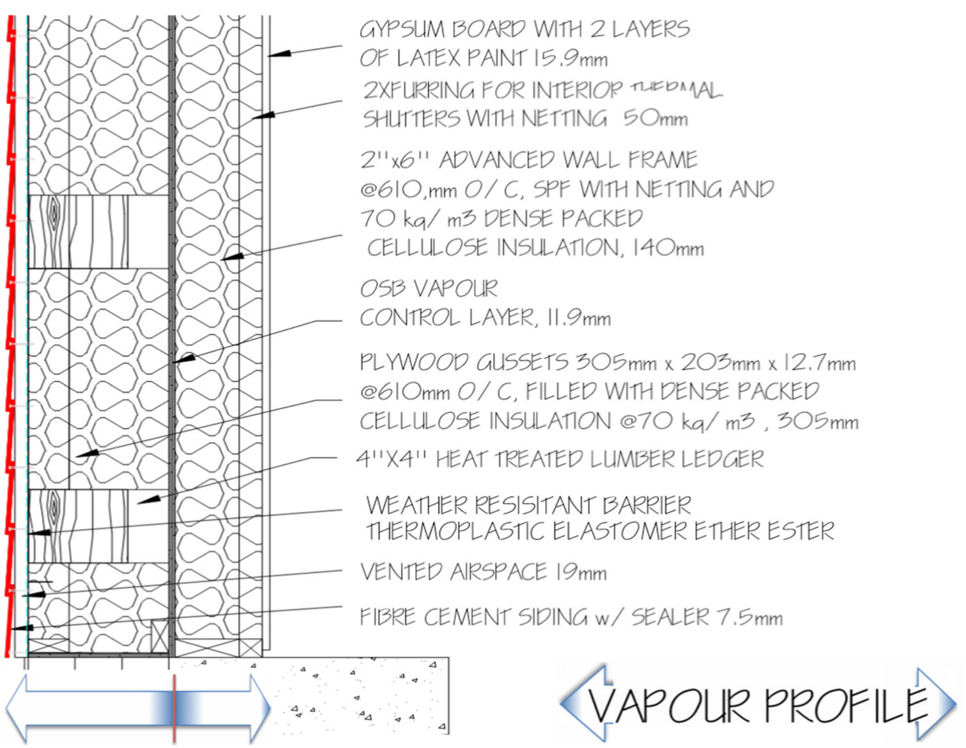


**Figure 21: OSB 75, a more vapour-closed wall in comparison to the plywood Arctic Wall. The OSB 60 wall uses 38x89mm (2"x4") advanced framing and does not include thermal shutters.**

### 3.1.4 Case 4A & 4B: Sheath 75 & (Sheath 60)

The compositions of Sheath 75 and Sheath 60 are almost identical to case 2 with one major difference which is that a layer of spun-bonded polyolefin on top of OSB sheathing replaces the vapour diffusion open weather resistive barrier present in case 2 [figure 22]. This technique can add an extra air barrier layer in addition to the interior layer. Installers are currently familiar with installing the air barrier system in this method. Although the SBPO weather resistive barrier has less than half of the permeance than the TEEE, it is the OSB substrate that adds a vapour control layer when it may not be desired. It is more vapour diffusion closed when it should be open (in the summer) and vice versa. In the Sheath 60 case, the gussets extend 279mm outside of the structure just as in Case 2B, co-poly 60.

This case will help to answer the question of whether it is advantageous to do away with the practice of installing OSB sheathing and SBPO air barrier in favour of a weather resistive barrier that requires no substrate.

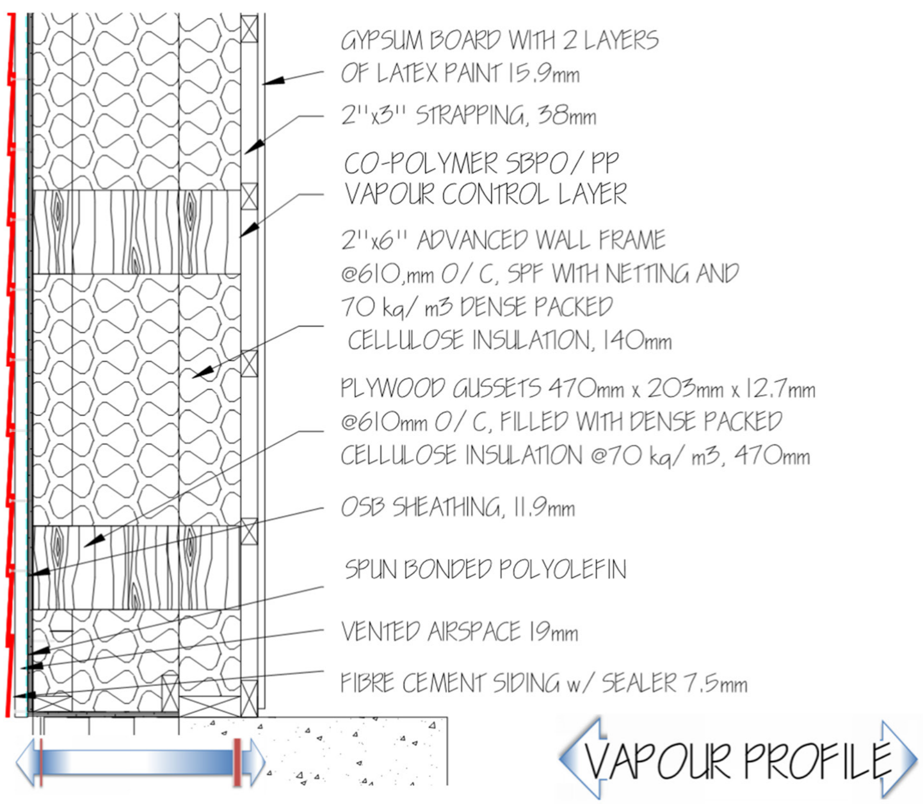


**Figure 22: This sheath 75 wall is covered with a traditional OSB sheathed and SBPO exterior. It is very similar to case 2, but uses a different weather resistive barrier system.**

### 3.1.5 Case 5A and 5B: Arctic Interior 75 and (Arctic Interior 60)

Case 5A and 5B represents a superinsulation choice where no insulation is desired in the frame cavity, which is to be used as a utility chase and can house internal thermal shutters if need be [figure 23]. This method can be beneficial for future renovations after the home is completed to use for future wiring, ducts or pipes.

Since there is no thermal insulation installed in the cavity, this wall is thicker than the Arctic Wall. It is called the "Arctic Interior" because the composition of the wall is identical to the Arctic Wall, but all of the thermal insulation is to the exterior of the vapour retarder at 457mm thick. The "Interior" name refers to the placement of the vapour retarder. The Arctic Interior 60 also uses 38x89mm studs but with 368mm of insulation. Like the Arctic Wall, a ledger is required to fasten the gussets to the structure.

Since only the placement of the vapour retarder is moved from within the wall to in front of it, it is possible to see whether there are advantages to keeping the vapour control plane on the interior of the wall.

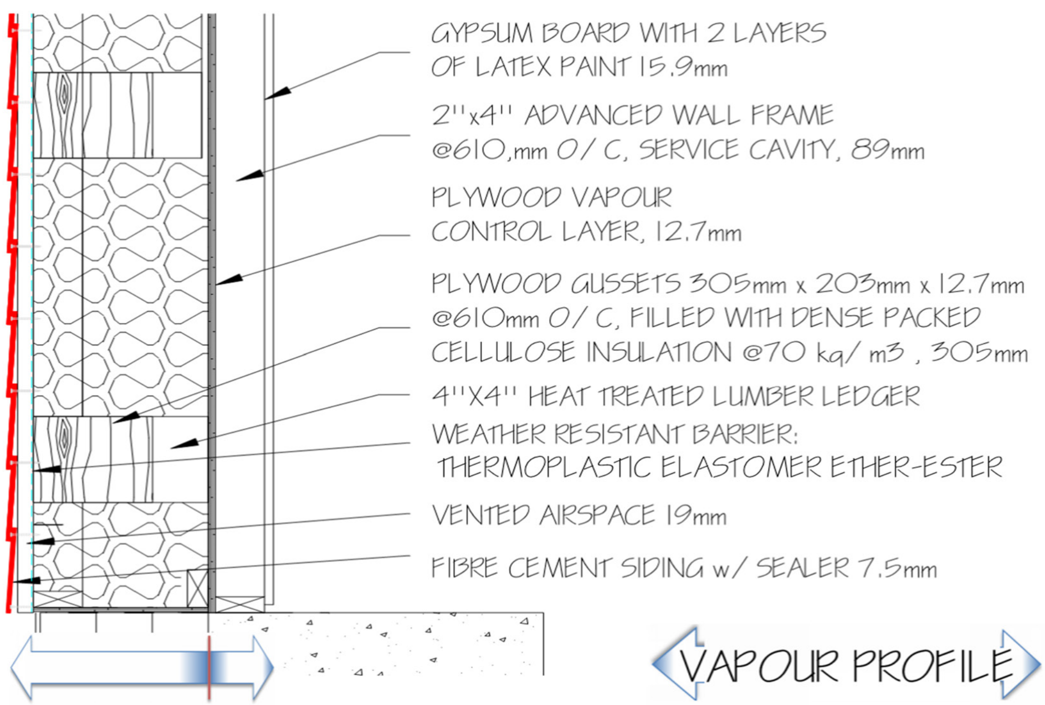


Figure 23: Arctic Interior 75 with no insulation on interior side of the vapour retarder

### 3.1.6 Case 6A and 6B: OSB Interior 75 (OSB Interior 60)

Case 6A and 6B have the exact same composition as the Arctic Interior, except for the fact that the vapour retarder is made of OSB rather than plywood [figure 24]. OSB was selected as an alternative to plywood for the same reasons that Case 3 uses OSB in the centre of the wall. Like the Arctic Interior, the OSB Interior 75 utilizes 457mm of thermal insulation and OSB Interior 60 has a gusset thickness of 368mm

using the same concept as an Arctic Interior, but the OSB Interior 75 can also show the differences of using a more vapour diffusion closed OSB material.

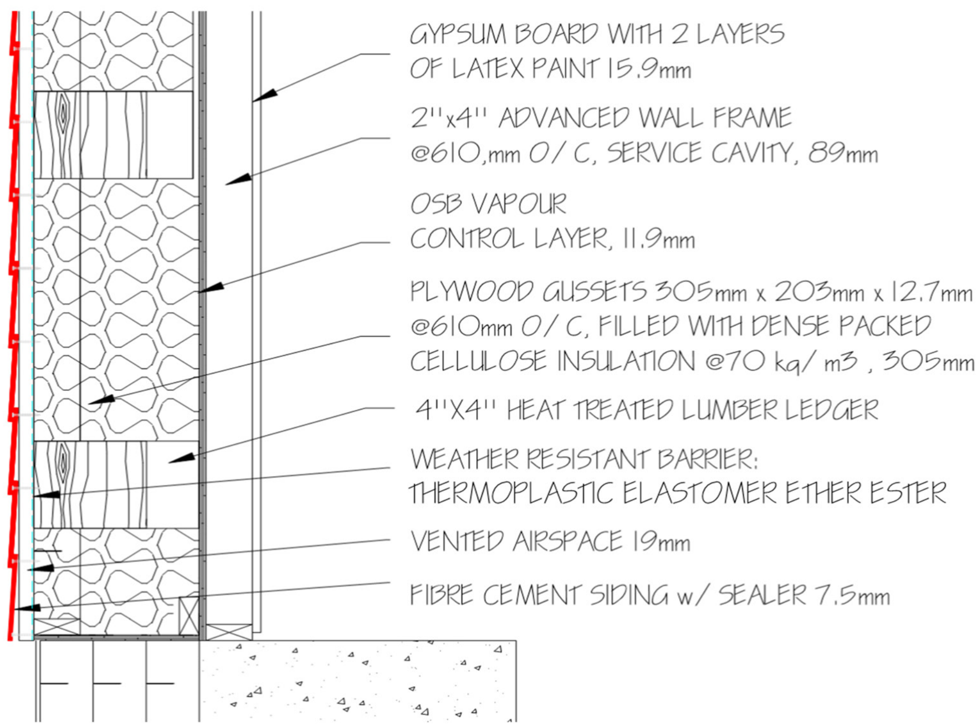


**Figure 24: OSB Interior 75, very similar to the Arctic Interior as the vapour retarder is made of OSB instead of plywood.**

**Table 2: Wall system case table**

| Cases | Clear Wall RSI m²K/W (BTU/h ft2 °F) | Total Insulation Thickness | Weather resistive barrier | Exterior Sheathing | Exterior Plywood gusset size | Vapour control layer | Structure |
|---|---|---|---|---|---|---|---|
| Case 1A (Arctic Wall 75) | 13.3(75.4) | 495mm (19.5") | Thermoplastic Elastomer-Ester-Ether | n/a | 305mm (12") | 12.7mm (1/2") CDX plywood | 140mm (2"x6") 610mm o.c. +50mm cavity |
| Case 1B (Arctic Wall 60) | 10.6 (60.2) | 394mm (15.5") | TEEE | n/a | 305mm (12") | 12.7mm (1/2") CDX plywood | 89mm (2"x4") 610mm o.c. |
| Case 2A (Co-polymer 75) | 13.3(75.4) | 470mm (18.5") | TEEE | n/a | 330mm (13") | Co-polymer 0.2mm | 140mm (2"x6") 610mm o.c. +38mm cavity |
| Case 2B (Co-polymer 60) | 10.5 (59.7) | 368mm (14.5") | TEEE | n/a | 279mm (11") | Co-polymer 0.2mm | 89mm (2"x4") 610mm o.c.+38mm cavity |
| Case 3A (OSB 75) | 13.3(75.3) | 495mm (19.5") | TEEE | n/a | 305mm (12") | 11.9mm (15/32") | 140mm (2"x6") 610mm o.c. +50mm cavity |
| Case 3B (OSB 60) | 10.6 (60.1) | 394mm (15.5") | TEEE | n/a | 305mm (12") | 11.9mm (15/32") | 89mm (2"x4") 610mm o.c. |
| Case 4A (Sheath 75) | 13.4(75.9) | 470mm (18.5") | Spun-bonded polyolefin | 11.9mm (15/32") OSB | 330mm (13") | Co-polymer 0.2mm | 140mm (2"x6") 610mm o.c. +38mm cavity |
| Case 4B (Sheath 60) | 10.6 (60.3) | 368mm (14.5") | Spun-bonded polyolefin | 11.9mm (15/32") OSB | 279mm (11") | Co-polymer 0.2mm | 89mm (2"x4") 610mm o.c. +38mm cavity |
| Case 5A (Arctic Interior 75) | 13.1(74.1) | 457mm (18") | TEEE | n/a | 457mm (18") | 12.7mm (1/2") CDX plywood | 89mm (2"x4") 610mm o.c. |
| Case 5B (Arctic Interior 60) | 10.64 (60.4) | 368mm (14.5") | TEEE | n/a | 368mm (14.5") | 12.7mm (1/2") CDX plywood | 89mm (2"x4") 610mm o.c. |
| Case 6A (OSB Interior 75) | 13.03 (74.0) | 457mm (18") | TEEE | n/a | 457mm (18") | 11.9mm (15/32") OSB | 89mm (2"x4") 610mm o.c. |
| Case 6B (OSB Interior 60) | 10.62 (60.3) | 368mm(14.5") | TEEE | n/a | 368mm (14.5") | 11.9mm (15/32") OSB | 89mm (2"x4") 610mm o.c. |

## 3.2 Hygrothermal simulation analysis strategy

For the purposes of this study, in addition to Toronto and Fairbanks, two additional cities were chosen to house the superinsulated walls to attempt to illustrate which factors are most in each city or if any trends can be seen. Winnipeg was selected due to having a heating and cooling load requirement roughly in between Fairbanks and Toronto. Vancouver was also selected as a climate with a low heating and cooling load and high driving rain potential and lower seasonal drying potential.

### 3.2.1 Cellulose material properties

Dense pack cellulose was selected to be the only insulation to be tested for several reasons. The original Arctic Wall utilized cellulose in the as-bulit home in Fairbanks. Cellulose also contains a low-embodied energy, and does not have the off-gas potential in comparison to foam products. Hygrothermally speaking, it has the potential to redistribute moisture if a heavy wetting event occurs and it can safely handle the passage of moisture in a vapour diffusion open setting without causing mould, which may occur in low-density fiberglass products. It is also an inexpensive material for a home that requires vast amounts of insulation to achieve the desired thermal control properties for that building. Although mineral wool shares many of the same advantageous properties as cellulose, the cost is significantly more.

Different cellulose properties of were compiled into many sample Arctic Wall simulations in Fairbanks using WUFI to determine the stability and accuracy of those available materials [Section 8.2]. It was apparent very early on that different cellulose material property sources produced very different hygrothermal results from sample simulations. Testing would begin with the cellulose materials in the WUFI database and outside sources were only considered if built-in WUFI materials were deemed inaccurate. The desirable cellulose material properties were selected based on density, k-value, permeability quality, suction/redistribution numerical quality, moisture storage, built-in moisture assumption by installation method. Stability of the simulation was tested by recording CPU time, which indicated stability, mesh convergence failures & required adaptive time steps, heat flux stability, moisture balance and total system water content.  One material property would be removed (suction)or altered (built-in moisture) to determine its effect on the system as a whole.

It also appeared that the built-in moisture values would have a large affect the eventual results as the hygrothermal analysis as shown in later sections which indicated that the first year results often proved to have the most potential for moisture problems.  If the cellulose was installed by the dense-pack method, no extra water is added to the system, the built-in moisture value should reflect the installed value as delivered by the manufacturer.  This choice will provide more liberal results than elevating the moisture content beyond the built-in moisture.

The ISOFLOC L© cellulose was chosen for a few reasons.  First of all, the ISOFLOC L© built-in moisture was disclosed as 4.5 kg/m$^3$ (59% m.c.) through correspondence with the manufacturer to Fraunhofer IBP.  (Fraunhofer IBP, 2011). A study was also conducted by Fraunhofer IBP to determine the moisture storage capacity, suction and redistribution values of that cellulose and was cited in IBP Investigation H942 (Fraunhofer IBP, 2007).  The thicker the wall, the more pressure must be exerted to prevent settling which increases the density.  The cellulose density was most likely based on common 38x89mm or 38x140mm construction. The required installed density of dense-packed cellulose  superinsulated wall was quoted as 64 kg/m$^3$ in a 300mm [12"] wall and 82 kg/m$^3$ in an ~ 675mm[27"] equivalent wall by one cellulose installer (Holladay, 2011). Although the Arctic Wall thickness falls in between these values, increasing the material density from 50kg/m$^3$ to a higher value reduces the moisture storage capacity as the volume for moisture to occupy is reduced.  Since moisture storage data was not available when installed at a higher density, the density material properties was left unchanged in the material property.   The water vapour diffusion resistance factor adopted the values from ASHRAE 1018-RP as cited in Fraunhofer IBP to reflect a variable value for cellulose (National Resources Council of Canada, 2002, Fraunhofer IBP 2011).

### 3.3.1 Condensation potential

During the heating season, as the exfiltration air and the diffused water move closer to the exterior side of the wall, the humidity ratio of the air decreases if condensation takes place as the moisture laden air moves towards colder material layers. The vapour that diffuses outwards is mixed with moisture from air leakage. Since the air leakage component cannot be measured using WUFI, only a comparative factor can be used to differentiate the wall performance in different cities. As the humidity of the interior boundary condition fluctuates seasonally and so does the dew point temperature of that interior air.

This following method allows the dew point of the interior condition to be measured by reading the temperature and humidity at every hourly time step. The vapour pressure at saturation can be estimated by the following equation (Straube & Burnett, 2005).

$$\mathrm{P}_{ws} = 611.2 \cdot e^{\left(\frac{17.67\,(T)}{T+243.5}\right)} \qquad [Pa]$$

Where;

$\mathrm{P}_{ws}$ is the saturation vapour pressure

T is the temperature in °C

As the relative humidity decreases, so does its condensation temperature. The relative humidity fluctuates from 30% in the winter to 60% in the summer. For the interior condition, the vapour partial pressure can be determined as its percentage of the saturation vapour pressure.

$$\mathrm{P}_{w} = \frac{RH}{100} \cdot \mathrm{P}_{ws} \qquad [Pa]$$

With the vapour partial pressure determined, the dew point temperature of the interior condition can be estimated by (Straube & Burnett, 2005).

$$t_d = \frac{4030}{18.689 - \ln(\frac{p_w}{133})} - 235 \qquad [°C]$$

Where $t_d$ is the dew point temperature of the interior air

With the dew point temperature determined for each hourly time step estimated, this value could represent the minimum safe temperature for any condensation potential through air leakage.

The colder material layers drive up the relative humidity of that air to high levels to the point where it is cold enough to possibly condense into free water. A location of concern for the Arctic Wall the outermost layer of thermal insulation. Using the above method for calculating dew-point temperature, the number of hourly time steps below the interior condition dew point temperature will be recorded for each wall section and compared to each other in the same climates. Various climates will also be compared to determine if a climate factor is more dominant than the wall material composition.

The monitoring location is just to the interior of the weather resistive barrier. Hygrothermal analysis is to be performed for five years starting in October using ASHRAE RP-1325 year 3. ASHRAE RP-1325 year 3 was used instead of the year 1 file, as it could lead to an accumulation where bulk water would not normally occur for five consecutive worst years. Since the bulk water can take a long time to leave the system, the year 3 file was a better choice for this test.

This method, used by Straube & Smeagal is similar to determining the dew point of inside air for every hour of the year by recording its vapour partial pressure (Straube & Smeagal, 2010). Fore every hour that the temperature was below that of the condensation temperature, it would be considered to have potential to condensate due to air leakage.

### 3.3.2 Mould potential

Since germination or the growth of mould is dependent on not just the relative humidity and temperature, but it also depends on the amount of time a material surface is exposed to those conditions. ASHRAE 160P criteria attempts to form the following set of rules of acceptable limits exposure for any material in a building enclosure before a deficiency can take place: (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2008)

1. *30-day running average surface RH <80% when the 30-day running average surface temperature is between 5°C and 40°C, and*
2. *7-day running average surface RH <98% when the 7-day running average surface temperature is between 5°C and 40°C, and*
3. *1-day running average surface RH <100% when the 1-day running average surface temperature is between 5°C and 40°C.*

The two biggest drawbacks of using this method are that it lacks an absolute time that of when the onset of germination does or does not occur and that it does not take drying into account on an hourly scale. This means that measuring consecutive hours above the predetermined threshold would not take into account brief drying periods or repetitive high moisture and drying occurrences that could disrupt the results. These set of rules help form the basis of the mould growth criteria of this paper with three alterations. Firstly, rule number #3 has been discarded for this study, as the condition of maintaining 100% relative humidity for one day is rare if not impossible due to sorption effects of material capillary pores (Fraunhofer Institut Bauphysik, 2012). Since the material is near saturation, capillary forces are most dominant in the pores and the excess moisture would diffuse to other locations in the wall due to high hygric buffer capacity of the cellulose [or other materials]. Essentially the wall would have to have unrealistic copious amounts of water in unusual circumstances to attain these values.

For the same reasons as rule #3, rule #2 to be maintained for seven days is also unlikely unless the building enclosure is designed as a vapour trap with two low permeance materials on both sides of the thermal insulation enclosure as found in case 5a in (Roos, 2011). Each superinsulated wall section was examined using this rule in this study, and not a single hourly failed condition occurred over the course of any of the simulations. Due to this result, this second rule was not considered a governing factor in superinsulation wall selections in any city for this paper and is also discarded.

The mould analysis will be determined by rule #3. Vapour partial pressures for the interior boundary condition were calculated to the nearest 0.01% for each time step. ASHRAE RP-1325 year 1 method by Salonvaara et al., will be used, as mould calculations should be more conservative as mould is more of a danger to human health than condensation potential for example (Salonvaara et al., 2010)

### 3.3.3 Inward vapour drive

During springtime rains, a small fraction water is deposited on the cladding and on the water resistive barrier due to driving rain. The cooling season drives the moisture inward, and bulk water in conjunction with solar driven moisture will send water to the outboard side of the vapour retarder. Since superinsulated walls hold more bulk moisture than standard walls due to its large volume and hygric buffer, the amount of water sent inward is larger. Since the bulk water will hit a surface, one monitoring position will be observed on the outboard side of the exterior insulation that touches the vapour retarder. Since the formation of mould is the primary concern of this method, ASHRAE RP-1325 year 1 method by Salonvaara et al., will also be used for monitoring and begins for five months from May to September (Salonvaara et al., 2010).

### 3.3.4 Drying potential

A wall that can dry quickly has better chance of avoiding deficiencies than one that is slow to dry out. Two methods will be used to simulate drying. The first method will illustrate the wall's ability to dry out in the springtime in a single season, which will be from an induced condition. The more aggressively the wall can dry, the more the drying potential can be revealed. In a hypothetical scenario, a wall may be exposed to a springtime condition that is normally dry, but if there is no induced condition, it would be difficult to illustrate the drying potential if no moisture is available inside the wall to dry. From an induced condition, every day during the springtime has the ability to dry out water. Of course these results will be highly affected by the choice of climate file. The second method measures the mean total system water density to illustrate how well the wall is able to shed water in the long term. The two methods will be given equal weight when calculating total drying potential.

#### *3.3.4.1 Induced condition*

This first method was utilized by Straube and Smeagal but is slightly altered and will involve elevating the exterior material layer's moisture content to an artificially elevated value of close to 100% relative humidity to simulate the ability of its maximum drying potential (Struabe & Smeagal, 2009). Rather than saturating and examining only the OSB sheathing as previously done by Straube and Smeagal, a material layer will be created that is just internal to the weather resistive barrier [figure 25](Straube & Smeagal, 2009). This is accomplished by loading an exterior 11.9mm

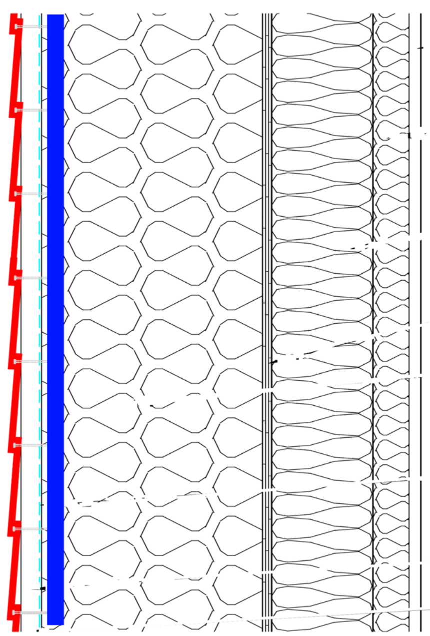

**Figure 25: The blue rectangle indicates the location of saturated cellulose for induced simulation.**

thick slice of cellulose [OSB for case 4A, 4B] loaded to 250 kg/m3 of water, which is near saturation, and allows the driving forces to distribute that water inwards. In theory, a more vapour open design should allow that water to pass through the vapour retarder easily.

The total system water content that is lost from the loaded condition provides more useful information using this method, rather than observing only the sheathing layer as previously done in Straube and Smeagal, as all material components contribute to the total system water content, for better or for worse (Straube & Smeagal, 2009). In the Arctic Wall and other non-exterior sheathing walls, the saturated layer is the most external cellulose plane as it has no sheathing. The climate year that helps to accelerate drying is more useful than one that has more rain events. ASHRAE RP-1325 year 3 by Salonvaara should be a drier year in comparison to year 1 and will be used from June 1 to mid August (Salonvaara et al., 2010). It should be noted that Fairbanks year 3 file has a much higher moisture loading value than the year 1. This may be due to the criteria for "worst year" not having weighted driving rain as a high priority according to the ASRHAE RP-1325 standards.

#### *3.3.4.2 Long Term Drying Potential*

A long-term ability for a wall to dry out is also beneficial as it is possible that some of the drying factors come into play at different times of the year depending on the construction as each has its own advantages in different seasons. A wall that is drier on a regular bases should be able to handle heavy rain events better than one that is already loaded to a higher level. To illustrate this, a long-term drying potential metric will be used. The simulation begins at 80% moisture content for all materials except cellulose at 59% for 5 years. The mean yearly values will be recorded using ASHRAE RP-1325 year 3.

### *3.3.4.3 Summary*

**Table 3: The four major hygrothermal analysis criteria's monitoring locations and measurement methods**

| mechanism | goal | m.c (RH%). initial conditions | climate file | years | monitor position | absolute value | start | weight |
|---|---|---|---|---|---|---|---|---|
| condensation | effects of no insulative sheathing | Cellulose 59%, (as delivered), rest 80% | year 3 ASHRAE 1325rp | 5, averaged out each year | Cellulose agaist WRB or sheathing (case 4A,4B) | yes | 01-Oct | 1 |
| mould | effects of no insulative sheathing | Cellulose 59%, (as delivered), rest 80% | year 1 ASHRAE 1325rp | 5, continuous | Cellulose agaist WRB or sheathing (case 4A,4B) | yes | 01-Oct | 1 |
| inward drive | vapour retarding material backup | Cellulose 59%, (as delivered), rest 80% | year 1 ASHRAE 1325rp | 5, continuous | outboard of vapour retarder | yes | 01-May | 1 |
| Drying | Maximum summer inward drying potential | exterior cellulose layer touching WRB, 11.9mm@250 kg/m3, rest 80% | year 3 ASHRAE 1325rp | 0.25, continuous | Bulk mositure loss from system water content | no (induced condition) | 01-Jun | 0.5 |
| | Long term drying potential | Cellulose (59%) as delivered, rest 80% | year 3 ASHRAE 1325rp | 5, averaged out each year | Mean stabilized system water content | yes | 01-Oct | 0.5 |
| Ratio | Location reqiured for protected insulation | Cellulose 59%, (as delivered), rest 80% | year 3 ASHRAE 1325rp | 5, averaged out each year | Starting at 30% from the exterior to 65% @ 5% increments | yes | 01-Oct | n/a, depends on worst value of either mould or condensation |

### 3.4 Insulated sheathing

The location of the condensation usually occurs on the exterior sheathing. In 5 out of 6 cases, there is no plane for the water to condense on, but rather a plane whose depth varies depending on exterior conditions in bulk matter.

Rather than developing a specific exterior insulated sheathing ratio using the method as proposed by Brown, a result based ratio using WUFI will be used based on minimum possible condensation risk (Brown et al., 2007). The disadvantage of this method is if condensation due to air exfiltration occurs it does not account for how much moisture condenses and can be safety stored inside the cellulose in addition to its steady state condition.

The cellulose with be analyzed various depths starting at a ratio of 0.3 from the exterior up to 0.65, and record the amount of times the temperature of the material is below the dew point of the interior moisture laden air. These two values were chosen because 0.3 was a lower value than any value recorded by Brown et al., and 0.65 represented the approximate location of the vapour retarder (Brown et al., 2007). If the ratio were higher than 0.65, then insulation to the interior of the vapour retarder would be included in that ratio. Increments of 0.05 between 0.3 and 0.65 will be used.

Determining the insulated sheathing ratio is based on condensation potential risk. It is more useful to determine the value for non-consecutive days than consecutive days due the amount of yearly exposure time being more useful whether it was consecutive or not. This section of the experiment does not compare the exposure to a known standard such as ASHRAE 160P, but rather to each other as the standard for determining acceptable insulated sheathing ratio conditions is still unknown.

A maximum value of 30 non-consecutive days per year will be considered the conservative safe limit borrowing the ASHRAE 160P rule for 30 consecutive days at 80%RH as the most conservative possible estimate. The deeper the monitoring location is inside the cellulose from the exterior (i.e. the ratio begins to increase), the air leakage condensation potential approaches zero as the insulation is closer to interior boundary conditions. At some ratio, there is no chance for condensation at that location. The value for maximum possible ratio for that location will most likely be a conservative estimate.

# 4. Results and Discussion

## 4.1 Condensation potential

In a Fairbanks climate, all walls varied between 235 to 242 days per year below the dew point of the interior air [Figure 26]. The differences between each case shows that in a vapour diffusion open design, the composition of the material layers has negligible effect on the influence of condensation in a very cold climate such as Fairbanks [Table 5]. Winnipeg follows Fairbanks with an average of 200 days per year, Toronto with 156 days and Vancouver with 63 days. As heating demand decreases, the less the heating demand and the more influential the OSB in case 4A, 4B benefit the exterior cellulose. The reason for the climate-dominated results has to do with the fact that the exterior cellulose is completely exposed to the exterior climate variables with only a weather resistive barrier to protect it. It would also explain why case 4A, 4B performed better than all other cases as the cellulose was insulated by the exterior OSB sheathing and weather resistive barrier. Of course that could mean that the OSB sheathing itself may have excessive moisture but it was not tested in this study.

The north elevation in every city and every case proved to be the worst performer, which would rule out the presence of driving rain as a stronger influence than the heating load and solar radiation that drives it inwards.

In all climates, the severity of the condensation values is unknown, as the influence of wall composition and climate may or may not potentially safely dry out the bulk moisture.

Condensation due to air leakage potential in the insulation is far more susceptible to the climate factors, specifically heating degree-days in all cities than the composition of the wall section. This is not surprising given that the most exterior part of the insulation has only a WRB to protect it from the outdoor climate.

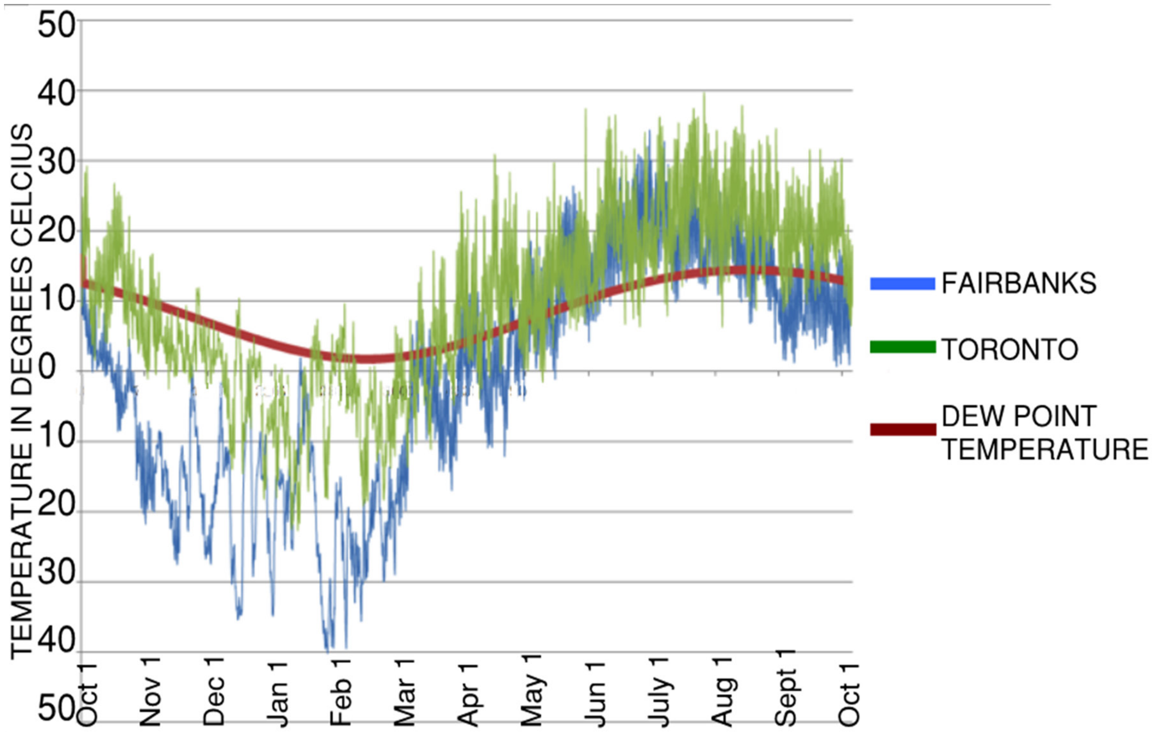


**Figure 26: Arctic Wall condensation potential in Fairbanks [blue] and Toronto [green] in the second simulated year starting in October. The entire heating season is below the dew point temperature of the interior air.**

| | Fairbanks | Winnipeg | Toronto | Vancouver |
|---|---|---|---|---|
| Case 1a Arctic 75 | 241.7 | 200.8 | 158.4 | 65.6 |
| Case 1B arctic 60 | 240.9 | 200.1 | 157.5 | 64.3 |
| Case 2a Co-poly 75 | 241.5 | 202.4 | 158.3 | 65.4 |
| Case 2b Co-poly 60 | 240.6 | 199.7 | 157.0 | 63.9 |
| Case 3A OSB 75 | 241.7 | 200.8 | 161.8 | 65.6 |
| Case 3B OSB 60 | 240.9 | 200.1 | 157.5 | 64.3 |
| Case 4A Sheath 75 | 236.6 | 194.4 | 148.8 | 54.2 |
| Case 4B Sheath 60 | 235.3 | 193.1 | 146.6 | 52.6 |
| Case 5A Arctic Int 75 | 241.5 | 200.6 | 158.3 | 65.2 |
| Case 5B Arctic Int 60 | 239.9 | 199.3 | 156.0 | 63.9 |
| Case 6a OSB int 75 | 241.5 | 209.4 | 158.3 | 65.2 |
| Case 6B OSB int 60 | 240.8 | 199.8 | 157.2 | 63.8 |
| Total days per year in 5 year weighed average | 240.2 | 200.0 | 156.3 | 62.8 |

**Table 4: Number of days per year exterior cellulose layer is below the dew-point**

## 4.2 Mould

### 4.2.1 Mould: ASHRAE 160P method results

No cases in any of the four cities produced levels that come close to failure [Figure 27]. In Fairbanks, Winnipeg and Toronto, only the exterior OSB sheathing walls cases produced any possible consecutive failure hours. However the value was very low between 2.5-4 consecutive days. In Vancouver on the other hand, 7 out of 12 results produced the exact same value for failure at 277 consecutive hours or 11.5 days, with the sheathing 75 wall at 11.6 days. This shows that Vancouver is more susceptible to possible mould growth than the other cities, but not enough for any germination to occur.

For the exact same results for 7 out of 15 cases to occur has less to do with the effect of the composition of walls influencing moisture balance, but more to do with a sudden drying period breaking the consecutive streak.

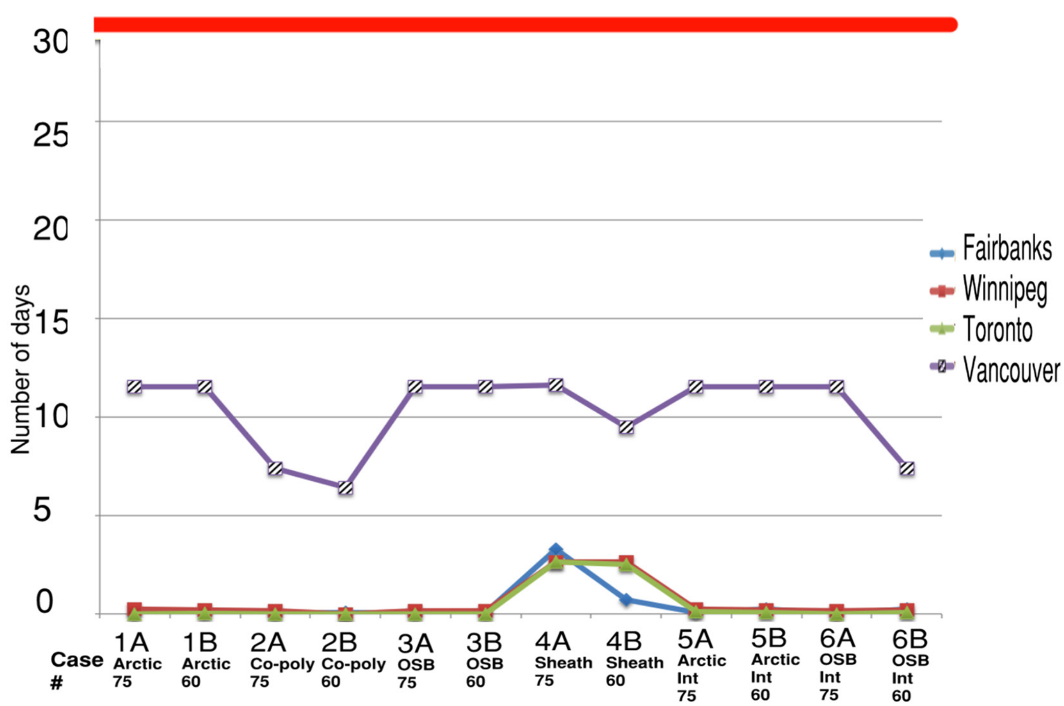


**Figure 27: The maximum amount of consecutive days for each tested year where each case failed to pass the requirements for ASHRAE 160P mould rule #1. The highest value of almost 12 days does not come close to the failure criteria of 30 days for these rules. Out of all tested cases, 8 out of the 12 results had the exact same results and show an inherent weakness of ASHRAE 160P rule set.**

If the method used in this section counted non-consecutive hours, the result for this simulation would have turned out differently. Non-consecutive days can be defined by summing all the non-consecutive hours from the start of the simulation year (8760 hours total) where there is a potential for mould growth without regards to whether those hours occurred consecutively or not. The advantage of counting non-consecutive hours is that brief drying periods to not interrupt the counting process that resets the counter to zero at every brief drying period.

This revised method to determine if mould growth potential occurs will be to count the number of hourly time steps up to 30 non-consecutive days with values above the relative humidity and temperature line in the Hukka and Vitannen model as shown in [Figure 2]on page 7 (Hukka & Vitannen, 2002). The reason for using that model instead of ASHRAE 160P rule #1, is, that at cold temperatures, the time to germination [m=1] slows down and can be taken into account. It is not possible to accurately incorporate the drying results into the mould growth model without using the Sedlbauer or other method (Sedlbauer, 2002). An advantage of using non-consecutive values is that brief drying periods of up to 10 or 11 hours per day over the course of the whole simulation should have no effect on germination, but would register a false negative when tallying up the amount of consecutive hours required by ASHRAE 160P when using the Hukka & Viitanen model in [figure 2].

The following example will illustrate how false negatives can occur when counting consecutive hours [table 5]. Although this example uses only a single day worth of time steps, but the principle can be applied to over a course of weeks or months. Another advantage of using this method, is that brief drying periods are better taken into account as most hourly mould potential events tend to be bunched together, and not spread evenly over the course of a whole year.

| Hour | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | Total Maximum consecutive | Total non-consecutive |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mould potential? 1=yes, 0=no | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 7 | 18 |

**Table 5: Consecutive versus non-consecutive days. 24 hours representing a single day are recorded for mould potential. A value of 1 indicates that mould potential is possible, while a value of 0 indicates no possible growth. A maximum of 7 hours (hours 0-6) ignores the mould potential occurring at all other hours with a value of 1. The tabulation of 7 hours could easily be counted as low mould potential, but 18 non-consecutive can be high. Counting non-consecutive days ignores the brief drying periods, which goes not affect germination, and more closely adheres to the Sedlbauer mould growth model in figure 4. (Sedlbaur, 2002).**

### 4.2.2 Mould: Non-consecutive days per year

All of the elevated moisture levels in every city occur on the north elevation with no concern in the south elevations and marginal on the east and west elevations. This is due to the fact that the cladding remained below freezing temperatures during heating season and does not have the opportunity to dry out as easily as on the other elevations in the vented cavity over a long period of time than a sun driven rain event escalation. In case 5A in Vancouver at the beginning of heating season moisture escalation, the water content of the cladding on the North Elevation measured 136kg/m$^3$, while the South remained at 64kg/m$^3$. The disparity is constant throughout the heating season.

The lack of days with mould in each case seems to be influenced by vapour diffusion open designs. All cases stabilize over the long term and produce no mould emergence threat in any city as no escalation occurs [Figure 28].

During the first year built-in moisture can play a much larger factor for mould potential than long-term analysis. For Fairbanks, Winnipeg and Toronto, only Case 4A and 4B show time steps with failures, but not enough to break the 30-non consecutive day threshold [Figure 29]. While several cases become problematic in Vancouver due to its wet climate, they do not become a concern for damage. The co-polymer [case 2A, 2B] performed better all cities than [Case 4A, 4B].

In Vancouver all cases are only marginally pass, except for case 2A, 2B and 4B, which fared much better. In those cases, the highest moisture levels occurred at the coldest period during the heating season for 24 non-consecutive days over a period of 65 days in total. It should be noted, that during the hours below this threshold were only marginally lower which suggests that with less stringent standards, the value could have easily been 65 days, and could be a failure. All of the cases with elevated moisture levels use a wood based vapour retarder, which demonstrates that its built-in moisture can play a factor in elevated moisture levels. For case 5A, the co-polymer vapour retarder also has a lower permeance rating than the wood based counterparts which implies that it is possible that OSB and plywood options may be too vapour open for heating season in a milder Vancouver climate. The better result could suggest that maximum vapour openness does not necessarily correlate to the best results in Vancouver's climate.

Many of the mathematical models for mould growth are based on the surface of wood, and not in the bulk of a wood based products such as cellulose. It is unknown whether this would have an effect on mould growth, as cellulose has different properties than wood.

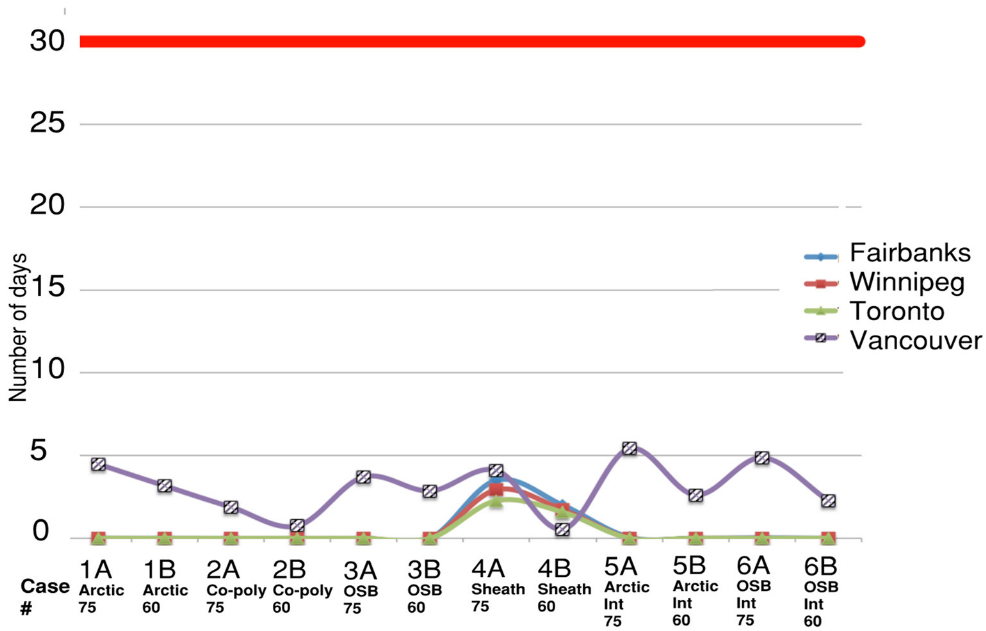


**Figure 28: Number of mould days per year averaged over five years. The red line represents the minimum possibility of mould growth.**

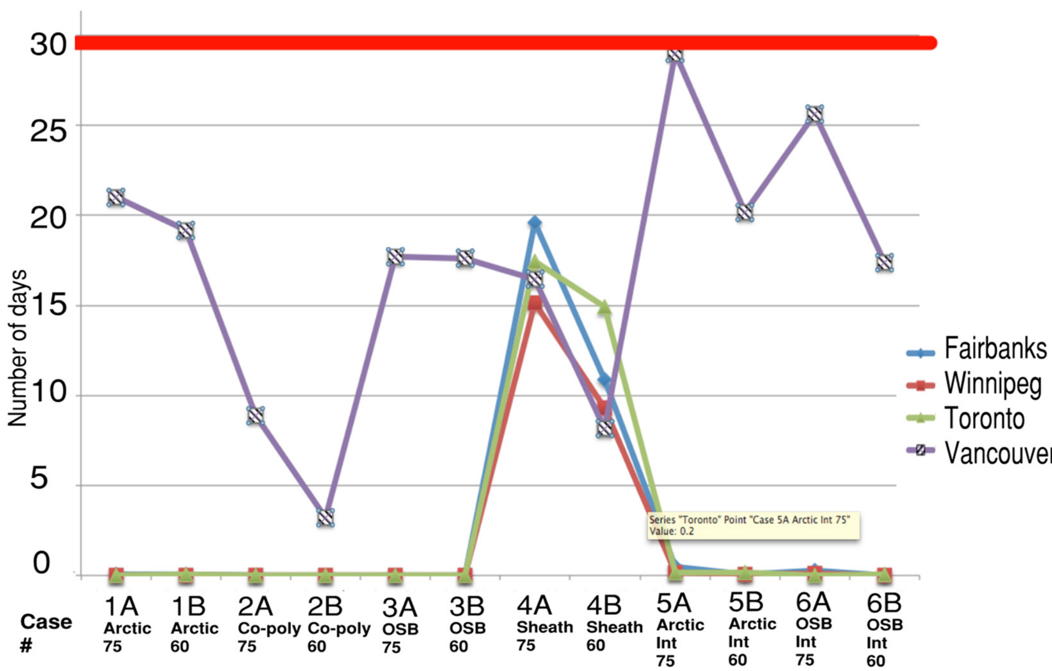


**Figure 29: Number of days in the first year where mould production is possible using a non-consecutive method**

## 4.3 Inward drive

When testing for first year and long-term problems, no accumulation occurred on the interior of the vapour retarder in any city. All of the variable permeance vapour retarders allowed more moisture to pass through than could be accumulated by its low permeability. Since all of the vapour retarding methods worked as intended, all can be considered equally as effective in this category and inward drive is not a concern for the tested cases. This implies that vapour diffusion open designs are effective at dissipating excess inward driven moisture.

## 4.4 Drying

### 4.4.1 Induced condition in summer

The order of each case from best to worst performing in terms of water content lost is the same for all cities although the spread is larger for the top performing cases in Toronto [Figure 30] and Vancouver [Figure 31]. All the cases that used either OSB or Plywood as a vapour retarder [1,3,5,6] performed the best and were most aggressive at drying out. The improvement over the co-polymer based case 2 is due to the fact that the wood based vapour retarders have a high built-in moisture, so a slight improvement of those cases is negated. Although the co-polymer membrane vapour retarder permeance values are higher than the wood based vapour retarders, the permeability of the material itself is orders of magnitude higher in comparison to wood products. This is due to the thickness of the wooden material at either 119 or 127mm, while the co-polymer is inserted at 1mm. Not only is the permeability lower, but the ability to hold moisture storage shows that the wood-based materials can pass the material quicker.
This improvement can be due to the fact that the wood-based products have a moisture carrying capacity, where sheet membranes do not. The advantages of the wood-based vapour retarders do not become apparent until one week after the induced rain [torrent] event.

Case 4A, 4B dries out at a very slow rate in comparison to the rest of the cases. At the end of the ten-week simulation, approximately 1.5kg/m3 still needs to be dried out in comparison to the other cases. When the simulation time was extended, it took approximately three years to dry out the same amount of moisture as the rest of the cases. This would suggest that this wall section is sensitive to high moisture related events.

The colder Fairbanks [Figure 32] and Winnipeg [Figure 33] climates aggressively dry out the induced condition within the first week and stabilize after six weeks. Toronto is slightly less aggressive and stabilizes after the full ten week simulation. Vancouver is only slightly worse than Toronto and also takes the full ten weeks term to dry out.

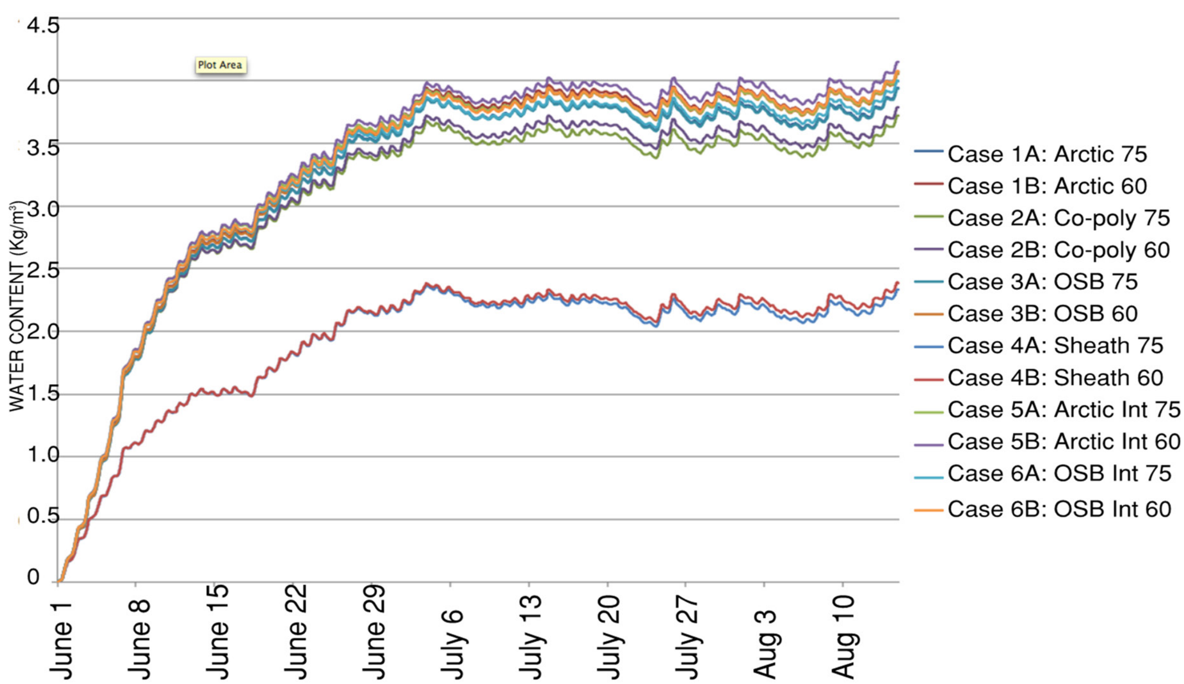


**Figure 30: Fairbanks total system water volume lost from an induced condition.**

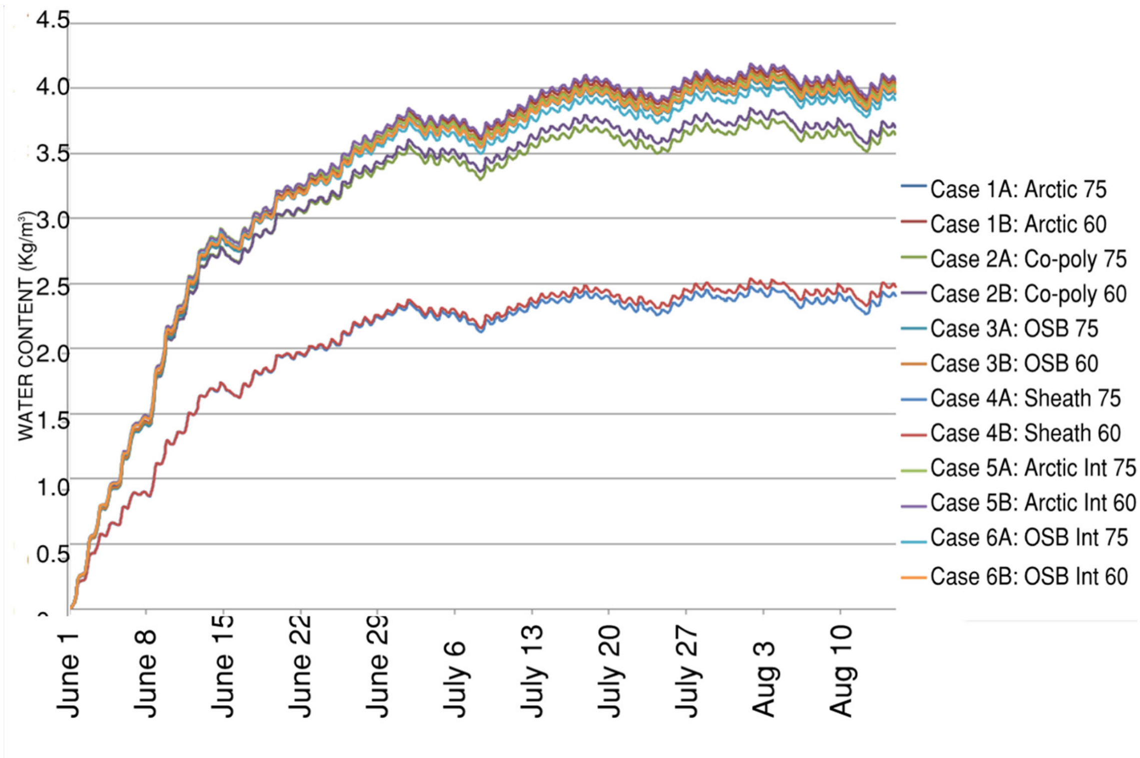


Figure 31: Winnipeg drying potential from induced condition

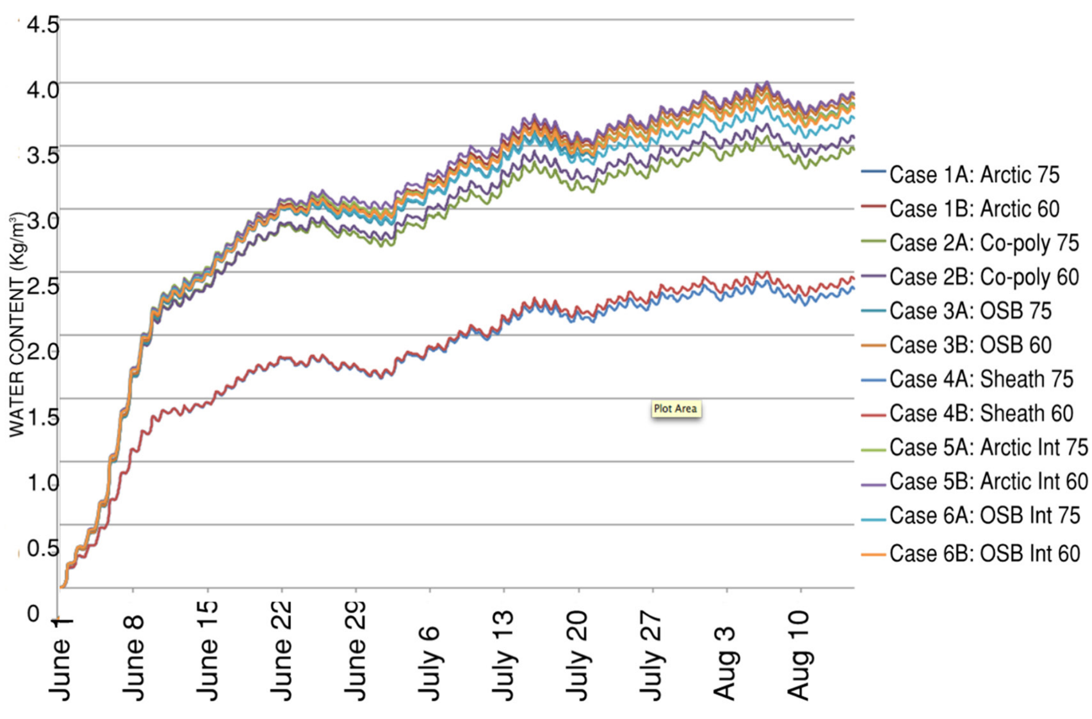


Figure 32: Toronto drying potential from induced condition

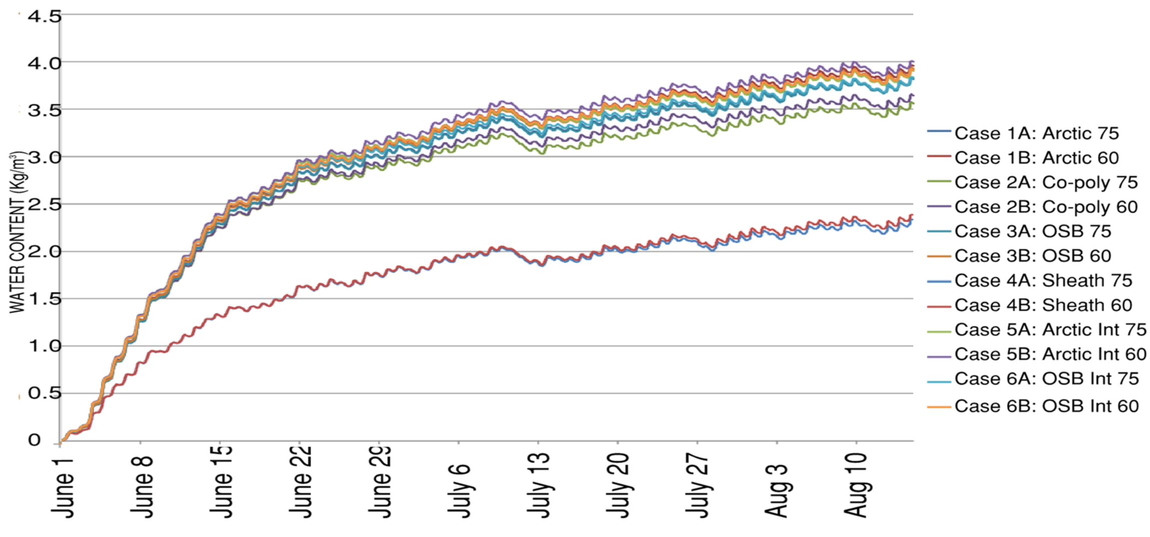


**Figure 33: Vancouver drying potential from induced condition**

### 4.4.2 Mean long term system water content

The mean system water content shows that choosing between an Arctic Wall or OSB based wall produces almost an identical long term moisture content [Figure 34]. The city location did not change the resulting order of best to worst performing in plywood and OSB based systems. The co-polymer systems were the best performing overall. The sheathed based walls held only slightly more water than an Arctic wall. Fairbanks and Winnipeg's climates produced very similar results, with Toronto being slightly more wet and Vancouver being the wettest of all.

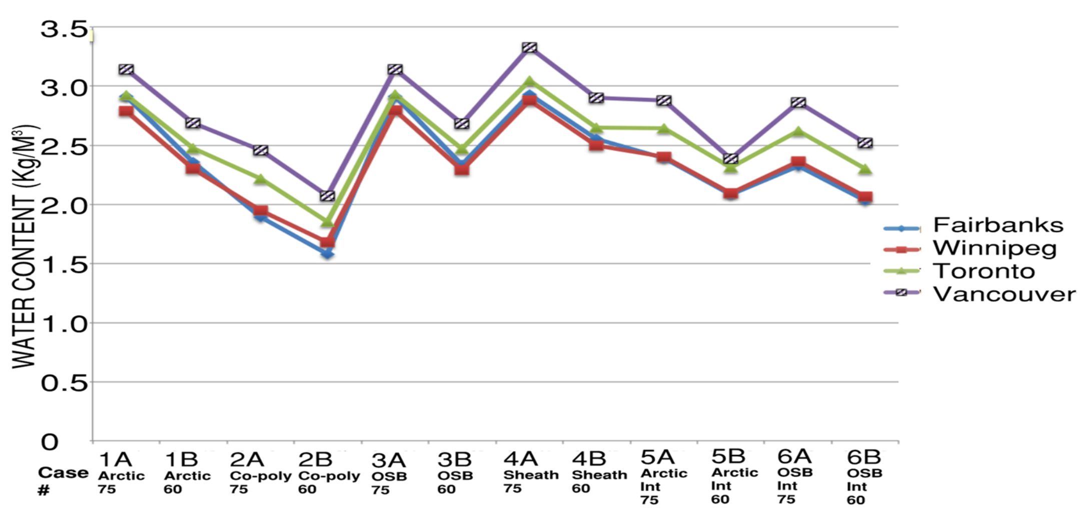


**Figure 34: Long term system water content over 5 years in kg/m3**

## 4.5 Insulated sheathing ratio

Since the tested cases have shown that mould risk is quite minimal for the exterior monitoring position, the exterior sheathing ratio is governed by the condensation potential results. The difficulty with determining the ratio is that moving the monitoring position towards the interior, the number of days of condensation potential is reduced, but as with the condensation analysis, the benchmark of safe condensation potential levels are still unknown.

In Fairbanks, the city with the highest condensation potential, only Arctic Wall 60 and OSB 60 have no chance for condensation at a ratio of 0.65 [Table 6]. The rest of the cases require an even higher value. Since the tested methodology only was measured up to 0.65, a trend line was used for the rest of the cases which indicate that the average value for all cases would fall somewhere around 0.7 and 0.75[Figure 35].

In Winnipeg, all cases were either 0.55 and 0.6 for with mixed results [Table 7]. It would seem that for both Fairbanks and Winnipeg, the change from RSI 13.2 to RSI 10.5 reduces the ratio by approximately 5%. Toronto faired better with cases between 0.35 and 0.45 and in this milder climate the choice of case seems to have a negligible impact on the ratio [Table 8]. Finally the ratio in Vancouver was less than 0.3. Wall selection type also had a negligible impact on the ratio [Table 9]. By examining the tables, it can plainly be seen that heating load is the dominant factor in choosing the proper ratio at any ratio value, but the effect of other climate values is unknown. The new vapour diffusion ratios have been overlaid on top of the graph by Brown et al., to show the average ratios for each city [Figure 33] (Brown et al., (2007). With the addition of air leakage introduced in the value in the Brown et al., method, the results from this study is very similar to their results with the relative humidities (Brown et al., (2007). Although the ratios are similar, it is very unlikely that in Fairbanks for example, over 70% of the thermal insulation value would need to be substituted for one that is not as sensitive to high levels of moisture. These models do not effectively take drying into account, which could account for the large ratios. These results have shown that if the model in this paper is conservative, the Brown et al., model is conservative as well and needs to be reexamined (Brown et al., (2007).

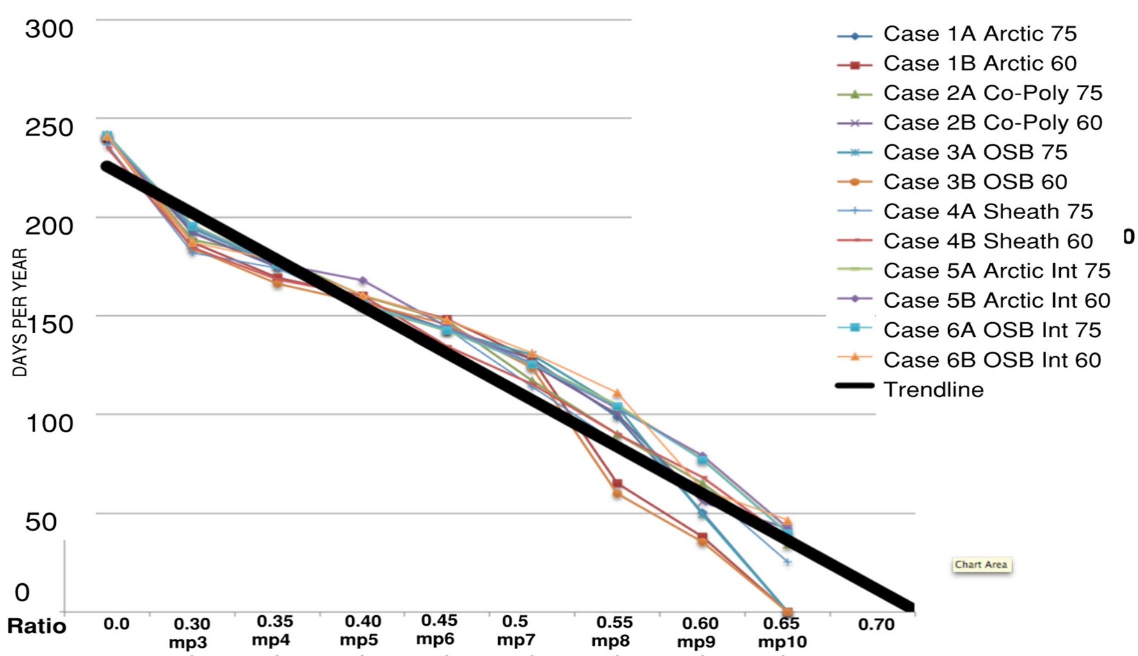


**Figure 35: The number of days of potential condensation for each case at different depths inside the material from the exterior in Fairbanks. The black trend line was added to show the approximate ratio for Fairbanks since the upper limit of the tests was 0.65. Only Arctic 60 and OSB 60 have a ratio of 0.65 or less. OSB 75 value is N/A at 0.65**

| Fairbanks | | Ratio 0.0 | Ratio 0.3 mp3 | Ratio 0.35 mp4 | Ratio 0.4 mp5 | Ratio 0.45 mp6 | Ratio 0.5 mp7 | Ratio 0.55 mp8 | Ratio 0.6 mp9 | Ratio 0.65 mp10 |
|---|---|---|---|---|---|---|---|---|---|---|
| year 3 | Case 1a Arctic 75 | 241.7 | 192.3 | 174.6 | 154.8 | 142.6 | 128.0 | 99.1 | 50.5 | n/a(inner side of VR) |
| | Case 1B arctic 60 | 240.9 | 187.1 | 169.4 | 160.1 | 148.5 | 128.2 | 65.1 | 38.0 | 0.0 |
| | Case 2a Co-poly 75 | 241.5 | 188.5 | 179.7 | 160.2 | 147.3 | 117.0 | 90.0 | 65.3 | 34.1 |
| | Case 2b Co-poly 60 | 240.6 | 192.1 | 174.8 | 157.5 | 143.0 | 125.5 | 100.1 | 55.8 | 42.3 |
| | Case 3A OSB 75 | 241.7 | 194.3 | 175.8 | 155.2 | 142.6 | 130.3 | 104.0 | 49.7 | n/a(inner side of VR) |
| | Case 3B OSB 60 | 240.9 | 184.3 | 166.3 | 156.7 | 145.8 | 123.8 | 59.9 | 35.6 | 0.0 |
| | Case 4A Sheath 75 | 236.6 | 182.1 | 174.1 | 154.8 | 143.5 | 114.3 | 85.9 | 62.5 | 25.5 |
| | Case 4B Sheath 60 | 235.3 | 184.5 | 168.4 | 159.9 | 134.6 | 115.7 | 90.3 | 68.2 | 36.9 |
| | Case 5A Arctic Int 75 | 241.5 | 195.9 | 176.3 | 155.7 | 142.1 | 125.8 | 104.9 | 77.4 | 40.2 |
| | Case 5B Arctic Int 60 | 239.9 | 195.1 | 176.3 | 168.0 | 144.3 | 125.8 | 103.3 | 79.4 | 42.7 |
| | Case 6a OSB int 75 | 241.5 | 195.5 | 176.4 | 155.7 | 142.5 | 125.6 | 104.2 | 76.9 | 39.9 |
| | Case 6B OSB int 60 | 240.8 | 187.4 | 178.0 | 160.5 | 147.7 | 131.1 | 111.0 | 62.2 | 46.6 |

**Table 6: In Fairbanks, the location with the highest condensation potential, only the Arctic Wall 60 and the OSB 60 have a maximum ratio of 0.65, while the other cases require a higher ratio for this location.**

| Winnipeg | | Ratio 0.0 | Ratio 0.3 mp3 | Ratio 0.35 mp4 | Ratio 0.4 mp5 | Ratio 0.45 mp6 | Ratio 0.5 mp7 | Ratio 0.55 mp8 | Ratio 0.6 mp9 | Ratio 0.65 mp10 |
|---|---|---|---|---|---|---|---|---|---|---|
| year 3 | Case 1a Arctic 75 | 200.8 | 144.5 | 123.4 | 97.7 | 84.3 | 59.4 | 27.1 | 0.1 | n/a(inner side of VR) |
| | Case 1B arctic 60 | 200.1 | 138.3 | 126.8 | 101.0 | 90.0 | 54.3 | 27.8 | 10.8 | 0.0 |
| | Case 2a Co-poly 75 | 202.4 | 138.3 | 126.8 | 101.0 | 90.0 | 54.3 | 27.8 | 10.8 | 0.0 |
| | Case 2b Co-poly 60 | 199.7 | 142.5 | 118.7 | 95.9 | 82.6 | 64.3 | 42.9 | 8.4 | 0.7 |
| | Case 3A OSB 75 | 200.8 | 145.8 | 125.2 | 98.3 | 84.6 | 63.9 | 29.4 | 0.0 | n/a(inner side of VR) |
| | Case 3B OSB 60 | 200.1 | 132.4 | 107.8 | 97.3 | 86.4 | 62.1 | 9.4 | 0.0 | 0.0 |
| | Case 4A Sheath 75 | 194.4 | 134.6 | 123.3 | 98.0 | 86.6 | 51.1 | 24.7 | 9.5 | 0.2 |
| | Case 4B Sheath 60 | 193.1 | 136.6 | 113.0 | 100.8 | 74.8 | 56.2 | 32.4 | 15.7 | 0.0 |
| | Case 5A Arctic Int 75 | 200.6 | 146.2 | 123.1 | 97.4 | 83.4 | 63.8 | 40.7 | 19.3 | 0.0 |
| | Case 5B Arctic Int 60 | 199.3 | 145.5 | 121.5 | 109.7 | 84.2 | 66.0 | 44.5 | 22.2 | 0.4 |
| | Case 6a OSB int 75 | 209.4 | 145.9 | 122.5 | 97.3 | 83.1 | 63.6 | 40.0 | 19.1 | 0.0 |
| | Case 6B OSB int 60 | 199.8 | 137.3 | 123.8 | 100.3 | 87.6 | 70.4 | 51.7 | 12.2 | 1.8 |
| | | 200.0 | | | | | | | | |

**Table 7: Winnipeg's ratio is slightly mixed, but averaged in at 58%. The yellow cells indicates a pass, but condensation readings did occur**

| Toronto | | Ratio 0.0 | Ratio 0.3 mp3 | Ratio 0.35 mp4 | Ratio 0.4 mp5 | Ratio 0.45 mp6 | Ratio 0.5 mp7 | Ratio 0.55 mp8 | Ratio 0.6 mp9 | Ratio 0.65 mp10 |
|---|---|---|---|---|---|---|---|---|---|---|
| year 3 | Case 1a Arctic 75 | 158.4 | 68.2 | 49.1 | 25.6 | 12.3 | 5.1 | 0.0 | 0.0 | n/a(inside of VR) |
| | Case 1B arctic 60 | 157.5 | 40.4 | 29.7 | 20.6 | 8.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Case 2a Co-poly 75 | 158.3 | 54.9 | 29.9 | 20.2 | 4.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Case 2b Co-poly 60 | 157.0 | 69.2 | 49.2 | 26.6 | 15.9 | 8.2 | 2.8 | 0.0 | 0.0 |
| | Case 3A OSB 75 | 161.8 | 70.0 | 50.8 | 26.1 | 12.4 | 6.9 | 0.0 | 0.0 | n/a(inside of VR) |
| | Case 3B OSB 60 | 157.5 | 61.4 | 36.6 | 26.9 | 17.6 | 7.5 | 0.0 | 0.0 | 0.0 |
| | Case 4A Sheath 75 | 148.8 | 59.6 | 48.8 | 26.6 | 16.0 | 2.7 | 0.0 | 0.0 | 0.0 |
| | Case 4B Sheath 60 | 146.6 | 63.5 | 40.2 | 30.0 | 11.2 | 5.4 | 0.8 | 0.0 | 0.0 |
| | Case 5A Arctic Int 75 | 158.3 | 71.5 | 50.8 | 26.6 | 14.6 | 7.5 | 1.6 | 0.0 | 0.0 |
| | Case 5B Arctic Int 60 | 156.0 | 71.3 | 51.3 | 38.8 | 16.8 | 8.4 | 2.9 | 0.0 | 0.0 |
| | Case 6a OSB int 75 | 158.3 | 71.4 | 50.6 | 26.5 | 14.4 | 7.5 | 1.5 | 0.0 | 0.0 |
| | Case 6B OSB int 60 | 157.2 | 64.6 | 54.0 | 30.1 | 18.9 | 10.0 | 3.9 | 0.0 | 0.0 |

**Table 8: Toronto insulation ratio average to 0.4 Yellow cells are considered a pass, but are highlighted to distinguish them from perfect scores**

| Vancouver | | Ratio 0.0 | Ratio 0.3 mp3 | Ratio 0.35 mp4 | Ratio 0.4 mp5 | Ratio 0.45 mp6 | Ratio 0.5 mp7 | Ratio 0.55 mp8 | Ratio 0.6 mp9 | Ratio 0.65 mp10 |
|---|---|---|---|---|---|---|---|---|---|---|
| year 3 | Case 1a Arctic 75 | 65.6 | 5.6 | 3.8 | 1.4 | 0.0 | 0.0 | 0.0 | 0.0 | n/a(inner side of VR) |
| | Case 1B arctic 60 | 64.3 | 5.4 | 3.7 | 2.6 | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Case 2a Co-poly 75 | 65.4 | 5.1 | 4.6 | 2.3 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Case 2b Co-poly 60 | 63.9 | 7.5 | 4.2 | 1.7 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Case 3A OSB 75 | 65.6 | 6.0 | 4.0 | 1.5 | 0.0 | 0.0 | 0.0 | 0.0 | n/a(inner side of VR) |
| | Case 3B OSB 60 | 64.3 | 5.0 | 3.3 | 2.1 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Case 4A Sheath 75 | 54.2 | 4.6 | 3.7 | 1.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Case 4B Sheath 60 | 52.6 | 4.8 | 3.5 | 2.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Case 5A Arctic Int 75 | 65.2 | 6.6 | 4.2 | 1.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Case 5B Arctic Int 60 | 63.9 | 7.9 | 4.3 | 3.3 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Case 6a OSB int 75 | 65.2 | 6.6 | 4.2 | 1.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Case 6B OSB int 60 | 63.8 | 5.6 | 4.5 | 2.6 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 |

**Table 9: Vancouver Insulation Ratio**

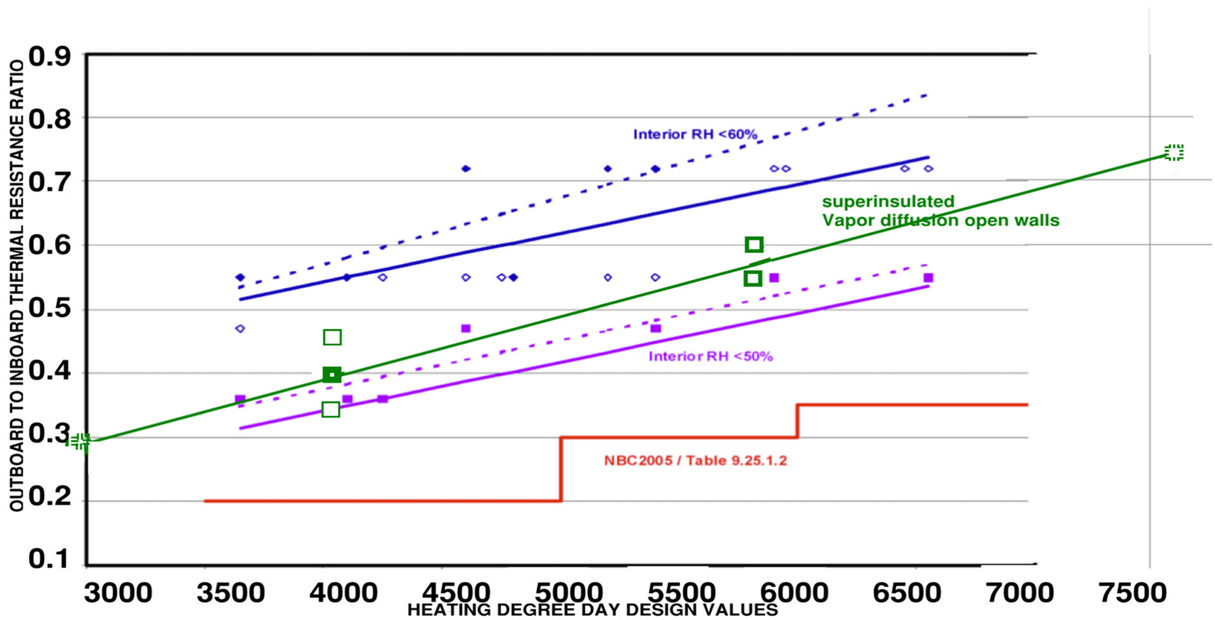


**Figure 36:From left to right on the green line, the exterior insulation ratios of superinsulated walls for Vancouver [approximated], Toronto, Winnipeg, and Fairbanks [approximated]. The graph was overlaid on (Brown, Roppel, & Lawton, 2007). The purple line is the interior recommended ratio by Brown et. al, (2007) for similar relative humidity boundary in the heating season.**

## 5. Conclusions

In general, the difference between using a plywood vapour retarder and an OSB vapour retarder has shown in every test that the results are negligible between the two. Maximum vapour openness by using a plywood vapour retarder as opposed to an OSB does not necessarily benefit the wall system in both interior and centre-of-wall vapour retarder locations. All cases with the higher thermal insulation option hold in more moisture content than the walls with less thermal insulation. This indicates that there is more risk with higher insulation levels.

Since all wood-based vapour open designs produced similar moisture content results, there is no benefit to using the Arctic Walls CDX plywood over OSB double studded or Larsen Truss wall choices based on this analysis. It is unknown whether this trend will hold up for climates milder or hotter than a Vancouver scenario or when air leakage is adequately simulated.

Wood product vapour retarders may be too vapour open for milder climates with heavy rain loading as shown in Vancouver. The better result could suggest that maximum vapour openness does not necessarily correlate to the best results in milder climates. In Fairbanks, Winnipeg and Vancouver, the plywood and OSB results were negligible in every category suggesting that hygrothermally speaking, it makes little difference which choice is used when maximum vapour openness is not necessarily desired.

The SBPO/PP co-polymer vapour retarder wall provided the best results in all categories, while the exterior OSB/SBPO sheathing wall performed the worst in most categories. This shows that using a TEEE WRB is better practice than OSB with SBPO. Although drying potential is severely reduced in cases using SBPO with OSB, the walls did not fail the mould test suggesting that even with reduced drying potential, this construction practice should be safe to use in all cities tested except Vancouver which should be considered risky.

Hypothetically, any moisture susceptible area due to condensation on the exterior can be replaced with Rockwool. It is unlikely that 75% of the exterior insulation in an Arctic Wall would have to be constructed with rockwool as it is not cost effective for large amounts of insulation. As a result, the real condensation ratio needs to be found.

## 5.1 Condensation potential

The different wall cases have little impact on the number of potential days of condensation potential per year. Heating degree-days is most dominant for condensation potential values with solar radiation possibly playing a role in the result and the amount driving rain having less of an impact than heating degree-days when the results are compared to table 1.

## 5.2 Mould

### 5.2.1. ASHRAE 160P method

Using this method, no case in any city failed; however, the SBPO/PP interior vapour retarder performed the best. This advantage was only negligible in Fairbanks, Winnipeg and Toronto, but more pronounced in Vancouver. The fact that many more hourly time steps have failed in Vancouver shows that the choice of superinsulation method should be given more attention in this city than others.

### 5.2.2. Non-consecutive days method

In terms of mould risk for colder climates such as Fairbanks, Winnipeg and Toronto, all vapour diffusion open designs should function as intended. The exterior OSB sheathing with SPBO based wall section did prove to accumulate more moisture in the heating season in comparison to all other sections, but still within marginally acceptable limits. This shows that substituting OSB exterior sheathing and SPBO in vapour of a sag resistant vapour open vapour retarder should always be a better choice for vapour diffusion open designs.

The Arctic Wall and Arctic Interior wall produced no measurable benefits over the OSB and OSB interior wall counterparts in this category. In a wetter, milder Vancouver climate, a more vapour diffusion closed co-polymer vapour retarder wall seemed to be the least prone to mould in the heating system which suggests that maximum vapour openness is not necessarily desired for that climate. The slower drying process suggests that wood-based vapour retarders may take too long to dry out from a lack of temperature difference and heavy rains. It may also be that the lower vapour diffusion properties of the SPBO could be more favourable in wetter climates.

The amount of thermal insulation for each case had a negligible outcome with both OSB and Arctic Wall, but there is a larger difference between all other cases using this method.

### 5.2.3 Mould: Non-consecutive versus consecutive method

When consecutive versus non-consecutive results are compared to each other in Fairbanks, Winnipeg and Toronto, similar patters are shown in the exterior OSB sheathing cases, but many more failure hours have occurred using the non-consecutive method [figure 37]. This shows that more hourly failures were missed using the consecutive method. The results for Vancouver show the differences between the cases in the same city a little more clearly as which of those cases performed the worst and by wide margins. With these results it is possible to see that the methods that utilized an interior SBPO/PP vapour retarder performed the best. The co-polymer case 2B is the only case with more days using the ASHRAE 160P method. This result can be explained as the non-consecutive method takes cold temperatures into account, and did not count days between the 5-15° Celsius at between 87.5-80% curve from [figure 2]. This shows that the SBPO/PP vapour retarder only marginally failed many of the hourly time steps that were counted as consecutive in the ASHRAE 160P method.

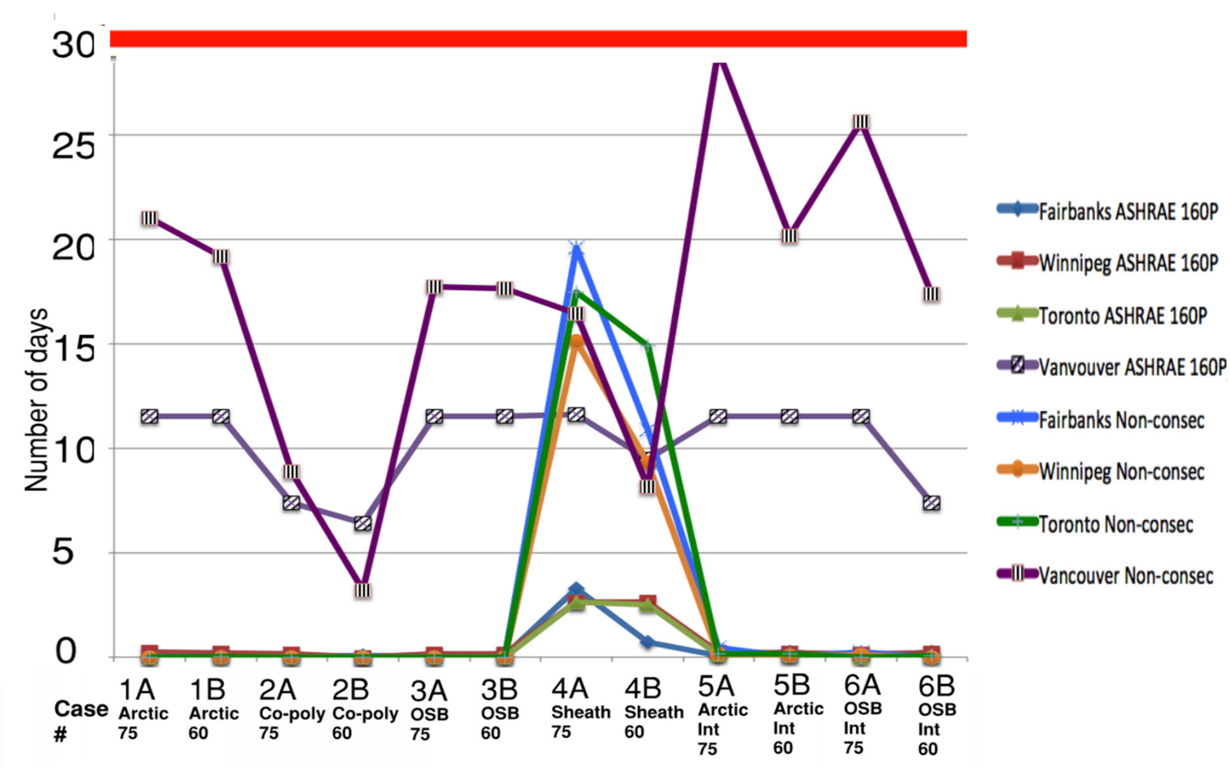


Figure 37: With the consecutive and non-consecutive results overlaid, it can be seen that in Vancouver and Case 4A,4B in the other cities have an elevated reading suggesting that the ASHRAE 160P consecutive result was restricting the actual mould potential

## 5.3 Inward drive

For all cases, there is no concern for mould growth in any climate, which suggests that the Arctic wall and other variable vapour diffusion retarders are successful at mitigating moisture to pass successfully into the interior and pose no danger. All types of superinsulated walls that were simulated can be used and no changes to the composition of those walls are needed. Maximum vapour diffusion openness is not required for this category.

## 5.4 Drying

### 5.4.1 Induced drying

In the Induced drying condition scenarios, the Arctic Wall produced approximately 1% less moisture in $kg/m^3$ in Fairbanks, Toronto, and Winnipeg, and 3% less $kg/m^3$ in Vancouver than its OSB counterpart. The advantage of using plywood over OSB in this case is negligible. Plywood and OSB vapour retarders perform better than the co-polymer or exterior OSB sheathing wall as their total water content was on average 0.25kg/m3 lower system wide after the middle of the heating season. The difference between all wood based vapour retarders showed negligible differences in results, which illustrates that these materials are better at dissipating heavy rain events in cooling mode than the co-polymer membrane.

### 5.4.2 Long term drying

In the first year is when all cases become problematic as its built-in moisture elevates total moisture levels. When substituting the TEEE weather resistive barrier with OSB sheathing and SBPO, the drying performance is worse as the sheathing acts as a vapour retarder slowing down outward drying. The OSB also has built-in moisture that the sheet membrane TEEE does not. These effects are more apparent in Toronto and Vancouver. The wall sections with exterior OSB sheathing produced comparable long-term results with the other wall sections, but showed slow drying potential for rain events. For drying, it may be possible that ASHRAE RP-1325 Year 1 simulations could show this weakness a little better as it would keep the wall wetter for a longer period of time.

The the SBPO/PP interior vapour retarder wall produced the lowest result indicating that it can handle more volume of water from sudden rain events. The Arcitc wall, OSB and OSB sheathing had the highest levels of long term moisture suggesting that wall composition plays a larger role than the vapour diffusion properties of the vapour retarder. In general walls with higher amounts of thermal insulation had higher amounts of long-term moisture content.

When looking at rain loading over the course of a year, the SBPO/PP co-polymer had lower moisture content than the other cases even though it did not dry the fastest after a heavy rain event (from induced conditions). This would suggest that long term drying has more of a lasting effect and than being able to dry after a rain event, which makes long term metric more important than the induced metric if no mould occurs soon after the wetting event.

## 5.5 Exterior insulation ratio

The results would seem to indicate that Arctic Wall and OSB would produce the lowest ratio for condensation potential in Fairbanks and Winnipeg. However the average was only negligible. The choice of superinsulation wall type has a larger impact on the ratio in the colder climates of Fairbanks and Winnipeg, but has little effect in Toronto and Vancouver. Current available models and this study have shown exterior insulated ratios are conservative as the safe level of condensation is unknown.

# 6. Recommendations

Without knowing the effects of condensation potential due to air infiltration, recommendations cannot be made based on that test. Without knowing the real requirement for the exterior sheathing ratio, it is difficult to make a recommendation of how thick a layer of mineral wool should be. At the very least, a rigid mineral wool layer should be used on the exterior portion of the cellulose [figure 38] to protect the outer layer.

The SBPO/PP co-polymer and wood based vapour retarder options simulated can be used in Fairbanks, Winnipeg and Toronto as no mould occurred. Exterior walls with OSB sheathing and SBPO can also be safely used, but due to the reduced drying ability after heavy rain events, other superinsulated options should be favoured over this wall type. All vapour diffusion open walls can also be used in Vancouver, but due to the milder, wetter climate, wood based diffusion open vapour retarders and exterior sheathing should be avoided in favour of the SBPO/PP co-polymer interior based vapour retarder.

The window buck and gussets that hold the exterior cladding substrate layer should still remain out of plywood in all climates that were tested.

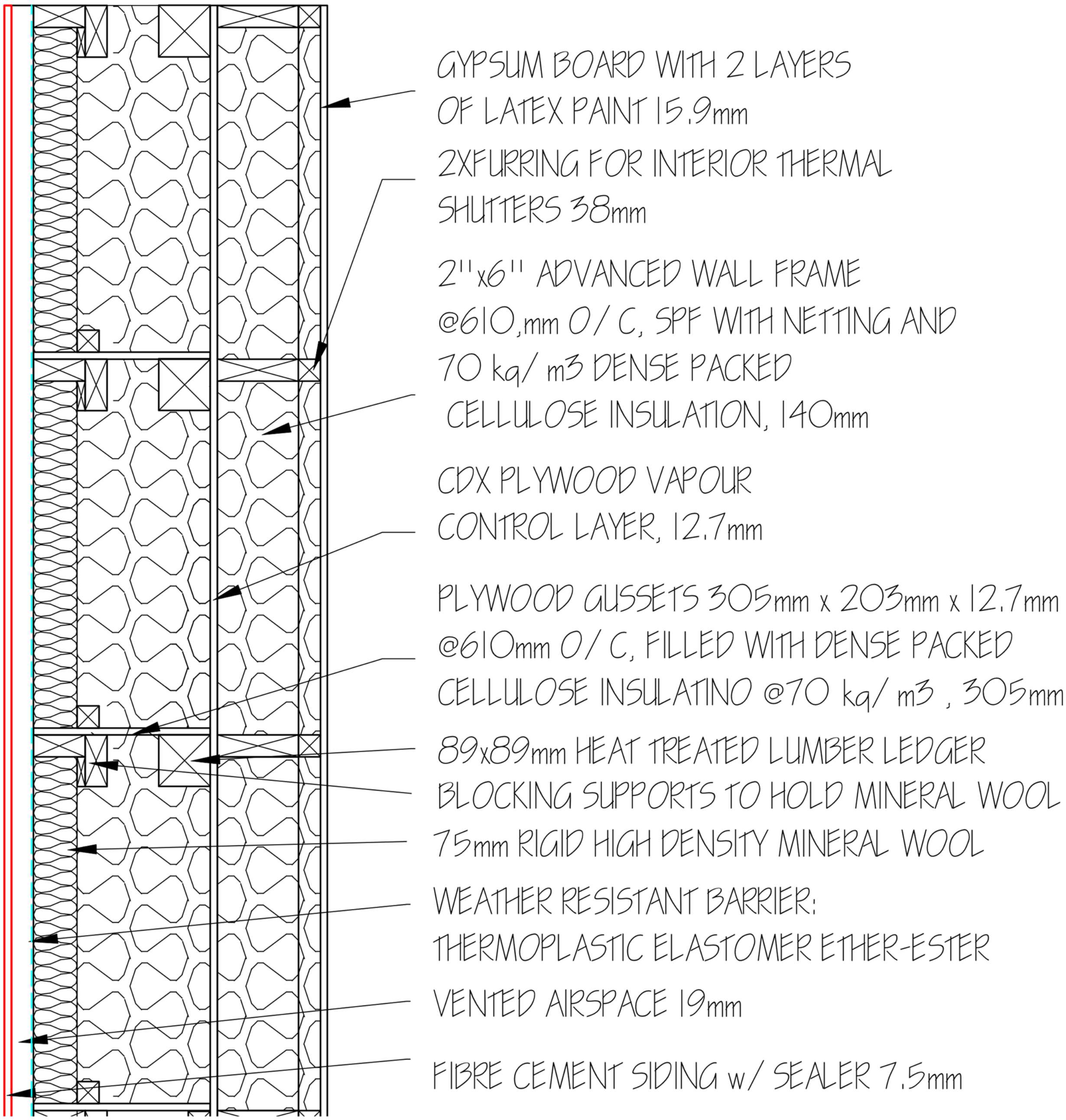


**Figure 38: Plan view drawing of a modified superinsulated Arctic Wall: How mineral wool can be used as a replacement for exterior insulated sheathing. The method of constructing the Arctic Wall is the same, but before the weather resistive barrier is installed, blocking can be screwed into the gussets at such an angle that 100mm high density rigid insulation can slide into position easily.**

# 7. Future work

It may be possible to consider the effects of condensation, mould, inward drive and drying potential together and be able to calculate the proper sheathing ratio for vapour diffusion open walls. This problem can be solved by using a HAM and climate model and combine the Hukka & Viitanen, (1999) mould growth calculation method while utilitlizing the drying portion of that equation to determine how much of the condensed moisture occurs and dries. By repeating the process while moving the monitoring position inwards the ratio can be determined.

The ratio jump between each point would suggest that a higher resolution than 0.05 for determining ratio would indicate more accurate results. The insulation ratio should address not only a minimum ratio, but a maximum if low permeance insulated sheathing is to be used.

It would be beneficial to know if, with reduced air leakage requirements of superinsulated homes, how severity of the condensation potential value would be reduced from an old house that leaks and therefore condenses more.

# Appendix A: Materials table

| | Density [kg/m3] | Porosity [m3/m3] | Heat Capacity J/[kgK] | Thermal Conductivity [W/mK] | Water Vapour Diffusion Resitance Factor [-] | [v] indicates values that vary |
|---|---|---|---|---|---|---|
| Factory applied Primer Sealer layer | n/a | n/a | n/a | n/a | 1040[1] | Fibre cement primer sealer info was not obtained, so the reapplication of in situ primer/searler value was used |
| Fibre cement board | 1424 [3][9] | 0.479 [2][9] | 841.5[2] | 0.24 [3] | 933.3 [3][9] | Mukhopadhyaya et al. (2009,)Fraunhofer Institut Bauphysik, (2011). Custom material turned off suction due to highly increased CPU time for convergence |
| Spun bonded polyolefin WRB (TYVEK©, Canadian) | 400 [4] | 0.001[2] | 1500 [2] | 2.4 [2] | 109.33 [4] | Fraunhofer values taken from SBPO in NA database |
| Solitex Mento Plus © WRB | 283.3 [5] | 0.001[2] | 1500 [2] | 0.17 [5] | 50 [5] | Porosity and Heat capacity based on SBPO which is comprised of similar materials, but manufactured differently |
| Air space (without additoinal moisture capacity, 20mm) | 1.3 [2] | 0.001[2] | 1000 [2] | 0.13 [2] | 0.56 [2] | Porosity in Air layers were changed in recent update to 0.001 This helped stabilize the simulation and reduce unrealisitc moisture storage potential in air |
| Air space (without additoinal moisture capacity, 5mm) | 1.3 [2] | 0.001[2] | 1000 [2] | 0.13 [2] | 0.79 [2] | |
| Air space (without additoinal moisture capacity, 40mm) | 1.3 [2] | 0.001[2] | 1000 [2] | 0.13 [2] | 0.38 [2] | |
| Air space (without additoinal moisture capacity, 90mm) | 1.3 [2] | 0.001[2] | 1000 [2] | 0.13 [2] | 0.17[2] | |
| Dense Pack cellulose | 50[6,7] | 0.95 [6] | 2150 [2] | 0.037 [2][9] | 1.86[2][9] | Density of materials based on average of Rasmussen, (2003) at centre point of wall. The values are a hybird of Fraunhofer IBP's ISOFLOC L and North American WVDRF in Fraunhofer Institut Bauphysik, (2011). Values chosen were based on a sensitivity analysis also considering moisture storage and suction/redis values |
| Plywood High | 600 [2] | 0.96 [2] | 1880 [2] | 0.101[2][9] | 383.2 [2][9] | High values used due to irregular values on other plywood materials in Fraunhofer Institut Bauphysik, (2011) |
| OSB High | 725 [2] | 0.95 [2] | 1880 [2] | 0.115[2][9] | 1015 [2][9] | OSB High used as it's values were attained from the same project as the plywood values in Kumaran et al. (2002) and used in by Fraunhofer Institut Bauphysik, (2011) |
| PP/SBPO vapour retarder, Solitex Intello © | 115[2] | 0.086 [2] | 2500 [2] | 2.4 [2] | 130000 [2][9] | All values in Fraunhofer database. These values are slightly different than manufacturer data. Proclima trade literature appears to "estimate" or round of values for data avaiable to public with the WVDRF being absent , Fraunhofer values have a higher confidece rating. Note that 130000 WVDRF is based on actual material thickness of 0.0002mm and not the minimum WUFI input thickness of 0.001mm, otherwise the value would be 26000. Intello and Intello Plus was quoted as having the same WVDRF in a private email to the distributor |
| Interior Gypsum Board | 625 [2] | 0.706 [2] | 870 [2] | 0.160 [2][9] | 7.03 [2][9] | Fraunhofer Institut Bauphysik, (2011) |
| Latex paint and primer, 2 coats | | | | | 600 [8] | |

Notes

1 (Hutcheon & Handegord, 1997)
2 (Fraunhofer IBP, 2011)
3 (Mukhopadhyaya, Kumaran, Lackey, Normandin, van Reenen, & Tariku, 2007)
4 (E.I. du Pont de Nemours and Company , 2007)
5 (Pro Clima, (n.d.)
6 (Fraunhofer IBP, 2007)
7 (Rasmussen, 2003)
8 (American Society of Heating Refrigerating and Air-conditioning Engineers, 2009)
9 Values that vary dependant on many several factors

## Appendix B: Cellulose sensitivity analysis

| | Cellulose versions | stability<br>Large ΔT,RH% arctic wall S ashrae yr 3 | Density kg/m3, superins 50-70 ideal, min 35 for 2x6 | k value | CPU time (minutes) | consistancy<br>total material wc start (kg/kg) | wc plateau (kg/kg) | wc stable (kg/kg) | *conv failures @ 100 mesh slices | moisture balance Δkg/m3 | heat flux stability | WVDRF quality | suction/ redistribution | moisture storage | built-in moisture (installation method?) | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Default | Fraunhofer | adaptive | 70 | 0.040 | 5 | 7 | 6 | 3.5 | 13 | 0 | stable | constant | missing | holds more | 12 | 1 |
| | North America | adaptive | 30 | 0.036 | 14 | 3.8 | 3 | 1.5 | 109 | 0.3 | | variable | missing | rough curve | 5.5 | 2 |
| | MASEA | adaptive | 55 | 0.036 | divergence | | | | | | | constant | not accurate | rough curve | 6.59 | 3 |
| | ISOFLOC L (after sens. analysis) | not adaptive | 50 | 0.037 | 5 | 5 | 4.2 | 2 | 25 | 0.03 | | constant | probably okay (v1) | holds less | 7.8 | 4 |
| old hybrids | hybrid NA MASEA frau - before sensitivity | adaptive | 70 | 0.036 | divergence | | | | 1000 | | unstable | | not accurate | not accurate | 5.5 | 5 |
| (before analysis) | hybrid no suction - before sensitivity | adaptive | 70 | 0.038 | 11 | 7 | 6.2 | 3.66 | 111 | 0.3 | | variable | n/a | holds more | 5.5 | 6 |
| New hybrids | ISOFLOC with NA WDVRF | not adaptive | 50 | 0.037 | 5 | 5 | 4.2 | 2 | 12 | 0.01 | | variable | probably okay (v1) | holds less | 7.8 | 7 |
| | ISOFLOC with mu & density adjust | not adaptive | 70 | 0.037 | 5 | 5 | 4.2 | 2 | 18 | 0.01 | | variable | probably okay (v1) | holds less | 7.8 | 8 |
| | ISOFLOC V5-2 verbatim -new suction and MS | not tested | 50 | 0.037 | 5 | 5 | 4.2 | 2 | 9 | 0.01 | | constant | tested, more data points | IBP tested | IBP tested | 9 |
| best | ISOFLOC V5-2 with [v] WVDRF from NA | not tested | 50 | 0.037 | 5 | 5 | 4.2 | 2 | 11 | 0.01 | | variable | tested, more data points | IBP tested | IBP tested | 10 |
| | ISOCELL Zellulosedammstoff | not tested | 50 | 0.037 | 5 | 5 | 4.2 | 2.6 | 13 | 0.02 | | constant | tested, less data points | IBP tested | IBP tested | 11 |
| low m. storage | ISOCELL Zellulosedammstoff [v]wvdrf NA | not tested | 50 | 0.037 | 5 | 5 | 4.2 | 2.6 | 13 | 0.02 | | variable | tested, less data points | IBP tested | IBP tested | 12 |

ISOFLOC vs. ISOCELL notes

Legend
- perfect/ideal
- will work,could be better or slight inaccuracy
- bad technique
- junk or very inaccurate data

Notes
1 better than NA,MASEA, high built-in moisture probably due to spray applied application assumption, no suction values
2 convergance failures probably due low MESH and suction, slight innacuracies. High cpu+
3 Suction and redistribution curve is not accurate at all - Never use this material
4 far better than the above 3, potential candidate
5 MASEA suction caused the instability
6 convergance failures probably due to moisture storage. values Values probably okay, but needs a denser grid
7 Version 1.
8 increasing the density without changing moisture storage values. Unknown if relashionship is linear. Data may or may not be in literature
9 affects MC of materials, but not RH%
10 perfect, increased mesh produces less conv failures. Values acceptable, the moisture storage for ISOFLOC requires a higher m.c to reach equivalent RH%. The result is that the ISOCELL will always have a higher RH%. MC of ISOCELL seems low, could be due to borates or other additives
11 Also a good candidate
12 various monitoring positions were up to 4%RH higher in cold temperatures @outbound ins. for the arctic wall, other locations less severe also has low moisture storage

# Appendix C: Hygrothermal boundary Conditions

WUFI® Pro 5.2 Fraunhofer IBP

## Boundary Conditions

**Exterior (Left Side)**

Location: Fairbanks; ASHRAE Year 1

Orientation / Inclination: South / 90 ° , E,N,W

**Interior (Right Side)**

Indoor Climate: WTA Guideline 6-2-01/E

User-Defined Sine Curve Parameters

Interior: 21.5 Celcius with 1.5 degree amplitude peaking on July 29, 45%RH amplitude of 15 peaking on aug 16

## Surface Transfer Coefficients

**Exterior (Left Side)**

| Name | Description | Unit | Value |
|---|---|---|---|
| Heat Resistance<br>- includes long-wave radiation | | [m²K/W] | 0.029<br>yes |
| Sd-Value | | [m] | 1.04 |
| Short-Wave Radiation Absorptivity | Stucco, dark (aged) | [ - ] | 0.6 |
| Long-Wave Radiation Emissivity | Stucco, dark (aged) | [ - ] | 0.9 |
| Adhering Fraction of Rain | According to inclination ar | [ - ] | 0,7 |
| Explicit Radiation Balance | | | no |

**Interior (Right Side)**

| Name | Description | Unit | Value |
|---|---|---|---|
| Heat Resistance | | [m²K/W] | 0.12 |
| Sd-Value | | [m] | 0.6 |

# Appendix D: Result graphs

## D.1: Condensation

| | Fairbanks | Winnipeg | Toronto | Vancouver |
|---|---|---|---|---|
| Case 1a Arctic 75 | 241.7 | 200.8 | 158.4 | 65.6 |
| Case 1B arctic 60 | 240.9 | 200.1 | 157.5 | 64.3 |
| Case 2a Co-poly 75 | 241.5 | 202.4 | 158.3 | 65.4 |
| Case 2b Co-poly 60 | 240.6 | 199.7 | 157.0 | 63.9 |
| Case 3A OSB 75 | 241.7 | 200.8 | 161.8 | 65.6 |
| Case 3B OSB 60 | 240.9 | 200.1 | 157.5 | 64.3 |
| Case 4A Sheath 75 | 236.6 | 194.4 | 148.8 | 54.2 |
| Case 4B Sheath 60 | 235.3 | 193.1 | 146.6 | 52.6 |
| Case 5A Arctic Int 75 | 241.5 | 200.6 | 158.3 | 65.2 |
| Case 5B Arctic Int 60 | 239.9 | 199.3 | 156.0 | 63.9 |
| Case 6a OSB int 75 | 241.5 | 209.4 | 158.3 | 65.2 |
| Case 6B OSB int 60 | 240.8 | 199.8 | 157.2 | 63.8 |

## D.2: Mould ASHRAE 160P method

| | Fairbanks | Winnipeg | Toronto | Vancouver |
|---|---|---|---|---|
| Case 1a Arctic 75 | 0.0 | 0.3 | 0.0 | 11.5 |
| Case 1B arctic 60 | 0.1 | 0.2 | 0.0 | 11.5 |
| Case 2a Co-poly 75 | 0.0 | 0.2 | 0.0 | 7.4 |
| Case 2b Co-poly 60 | 0.1 | 0.0 | 0.0 | 6.4 |
| Case 3A OSB 75 | 0.0 | 0.2 | 0.0 | 11.5 |
| Case 3B OSB 60 | 0.1 | 0.2 | 0.0 | 11.5 |
| Case 4A Sheath 75 | 3.3 | 2.6 | 2.6 | 11.6 |
| Case 4B Sheath 60 | 0.7 | 2.6 | 2.5 | 9.5 |
| Case 5A Arctic Int 75 | 0.1 | 0.3 | 0.1 | 11.5 |
| Case 5B Arctic Int 60 | 0.3 | 0.2 | 0.1 | 11.5 |
| Case 6a OSB int 75 | 0.0 | 0.2 | 0.0 | 11.5 |
| Case 6B OSB int 60 | 0.3 | 0.2 | 0.1 | 7.4 |

### D.3: Mould, Non-consecutive method

Average days/ 5 years

| | Fairbanks | Winnipeg | Toronto | Vancouver |
|---|---|---|---|---|
| Case 1a Arctic 75 | 0.0 | 0.0 | 0.0 | 4.5 |
| Case 1B arctic 60 | 0.0 | 0.0 | 0.0 | 3.2 |
| Case 2a Co-poly 75 | 0.0 | 0.0 | 0.0 | 1.9 |
| Case 2b Co-poly 60 | 0.0 | 0.0 | 0.0 | 0.8 |
| Case 3A OSB 75 | 0.0 | 0.0 | 0.0 | 3.7 |
| Case 3B OSB 60 | 0.0 | 0.0 | 0.0 | 2.9 |
| Case 4A Sheath 75 | 3.5 | 2.9 | 2.3 | 4.1 |
| Case 4B Sheath 60 | 2.0 | 1.7 | 1.6 | 0.5 |
| Case 5A Arctic Int 75 | 0.1 | 0.0 | 0.0 | 5.4 |
| Case 5B Arctic Int 60 | 0.0 | 0.0 | 0.0 | 2.6 |
| Case 6a OSB int 75 | 0.0 | 0.0 | 0.0 | 4.9 |
| Case 6B OSB int 60 | 0.0 | 0.0 | 0.0 | 2.3 |

Worst elevation in first year

| | Fairbanks | Winnipeg | Toronto | Vancouver |
|---|---|---|---|---|
| Case 1a Arctic 75 | 0.0 | 0.0 | 0.0 | 21.0 |
| Case 1B arctic 60 | 0.0 | 0.0 | 0.0 | 19.2 |
| Case 2a Co-poly 75 | 0.0 | 0.0 | 0.0 | 8.9 |
| Case 2b Co-poly 60 | 0.0 | 0.0 | 0.0 | 3.2 |
| Case 3A OSB 75 | 0.0 | 0.0 | 0.0 | 17.7 |
| Case 3B OSB 60 | 0.0 | 0.0 | 0.0 | 17.6 |
| Case 4A Sheath 75 | 19.6 | 15.1 | 17.5 | 16.5 |
| Case 4B Sheath 60 | 10.9 | 9.3 | 14.9 | 8.2 |
| Case 5A Arctic Int 75 | 0.5 | 0.2 | 0.2 | 29.0 |
| Case 5B Arctic Int 60 | 0.0 | 0.1 | 0.2 | 20.2 |
| Case 6a OSB int 75 | 0.3 | 0.1 | 0.0 | 25.6 |
| Case 6B OSB int 60 | 0.0 | 0.0 | 0.1 | 17.4 |

### D.4: Inward Drive

Average days/year

| | Fairbanks | Winnipeg | Toronto | Vancouver |
|---|---|---|---|---|
| Case 1a Arctic 75 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 1B arctic 60 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 2a Co-poly 75 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 2b Co-poly 60 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 3A OSB 75 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 3B OSB 60 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 4A Sheath 75 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 4B Sheath 60 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 5A Arctic Int 75 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 5B Arctic Int 60 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 6a OSB int 75 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 6B OSB int 60 | 0.0 | 0.0 | 0.0 | 0.0 |

Worst elevation in first year

| | Fairbanks | Winnipeg | Toronto | Vancouver |
|---|---|---|---|---|
| Case 1a Arctic 75 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 1B arctic 60 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 2a Co-poly 75 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 2b Co-poly 60 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 3A OSB 75 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 3B OSB 60 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 4A Sheath 75 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 4B Sheath 60 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 5A Arctic Int 75 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 5B Arctic Int 60 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 6a OSB int 75 | 0.0 | 0.0 | 0.0 | 0.0 |
| Case 6B OSB int 60 | 0.0 | 0.0 | 0.0 | 0.0 |

## D.5: Drying

Induced moisture loss in kg/m$^3$

| | Fairbanks | Winnipeg | Toronto | Vancouver |
|---|---|---|---|---|
| Case 1a Arctic 75 | 3.934 | 3.999 | 3.844 | 3.737 |
| Case 1B arctic 60 | 4.062 | 4.090 | 3.939 | 3.815 |
| Case 2a Co-poly 75 | 3.714 | 3.701 | 3.522 | 3.428 |
| Case 2b Co-poly 60 | 3.779 | 3.022 | 3.621 | 3.522 |
| Case 3A OSB 75 | 3.924 | 3.993 | 3.839 | 3.663 |
| Case 3B OSB 60 | 4.045 | 4.061 | 3.905 | 3.877 |
| Case 4A Sheath 75 | 2.326 | 2.405 | 2.380 | 2.212 |
| Case 4B Sheath 60 | 2.368 | 2.469 | 2.447 | 2.261 |
| Case 5A Arctic Int 75 | 4.059 | 3.989 | 3.858 | 3.789 |
| Case 5B Arctic Int 60 | 4.143 | 4.122 | 3.955 | 3.871 |
| Case 6a OSB int 75 | 3.991 | 3.950 | 3.760 | 3.693 |
| Case 6B OSB int 60 | 4.070 | 4.014 | 3.825 | 3.761 |

Mean value, Long term total system water content kg/m$^3$

| | Fairbanks | Winnipeg | Toronto | Vancouver |
|---|---|---|---|---|
| Case 1a Arctic 75 | 2.913 | 2.788 | 2.924 | 3.142 |
| Case 1B arctic 60 | 2.357 | 2.301 | 2.473 | 2.686 |
| Case 2a Co-poly 75 | 1.889 | 1.947 | 2.214 | 2.459 |
| Case 2b Co-poly 60 | 1.579 | 1.676 | 1.850 | 2.072 |
| Case 3A OSB 75 | 2.915 | 2.793 | 2.928 | 3.145 |
| Case 3B OSB 60 | 2.336 | 2.291 | 2.470 | 2.682 |
| Case 4A Sheath 75 | 2.931 | 2.880 | 3.050 | 3.330 |
| Case 4B Sheath 60 | 2.555 | 2.497 | 2.646 | 2.904 |
| Case 5A Arctic Int 75 | 2.388 | 2.399 | 2.642 | 2.880 |
| Case 5B Arctic Int 60 | 2.084 | 2.094 | 2.312 | 2.386 |
| Case 6a OSB int 75 | 2.325 | 2.361 | 2.623 | 2.865 |
| Case 6B OSB int 60 | 2.034 | 2.065 | 2.299 | 2.521 |

# Appendix E: Wall Results Summary

| City | Measure | Case 1A Arctic 75 | Case 1B Arctic 60 | Case 2A Co-poly 75 | Case 2B Co-poly 60 | Case 3A OSB 75 | Case 3B OSB 60 | Case 4A Sheath 75 | Case 4B Sheath 60 | Case 5A Arctic Int 75 | Case 5A Arctic Int 60 | Case 6B OSB Int 75 | Case 6B OSB Int 60 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fairbanks | Condensation [total days/year] | 242 | 241 | 242 | 241 | 242 | 241 | 237 | 235 | 242 | 240 | 242 | 241 | 240.0 |
| | *Mould long term [days per year] | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 2 | 0 | 0 | 0 | 0 | 0 |
| | *Mould, 1st year [days per year] | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 19.6 | 10.9 | 0.5 | 0.0 | 0.3 | 0.0 | 3 |
| | Mould ASHRAE 160P method | 0.0 | 0.1 | 0.0 | 0.1 | 0.0 | 0.1 | 3.3 | 0.7 | 0.1 | 0.3 | 0.0 | 0.3 | 0.4 |
| | Inward Drive [days per year] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Drying -induced event- w.c. lost [kg/m3 | 3.934 | 4.062 | 3.714 | 3.779 | 3.924 | 4.045 | 2.326 | 2.368 | 4.059 | 4.143 | 3.991 | 4.070 | |
| | Drying -long term [kg/m3] | 2.913 | 2.357 | 1.889 | 1.579 | 2.915 | 2.336 | 2.931 | 2.555 | 2.388 | 2.084 | 2.325 | 2.034 | |
| | Ratio | >0.65 | 0.65 | >0.65 | >0.65 | >0.65 | 0.65 | >0.65 | >0.65 | >0.65 | >0.65 | >0.65 | >0.65 | |
| Winnipeg | Condensation [total days/year] | 201 | 200 | 202 | 200 | 201 | 200 | 194 | 193 | 201 | 199 | 209 | 200 | 200.0 |
| | *Mould long term [days per year] | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 2 | 0 | 0 | 0 | 0 | 0 |
| | *Mould, 1st year [days per year] | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 15.1 | 9.3 | 0.2 | 0.1 | 0.1 | 0.0 | 2 |
| | Mould ASHRAE 160P method | 0.3 | 0.2 | 0.2 | 0.0 | 0.2 | 0.2 | 2.6 | 2.6 | 0.3 | 0.2 | 0.2 | 0.2 | 0.6 |
| | Inward Drive | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Drying -induced event- w.c. lost [kg/m3 | 3.999 | 4.090 | 3.701 | 3.022 | 3.993 | 4.061 | 2.405 | 2.469 | 3.989 | 4.122 | 3.950 | 4.014 | |
| | Drying -long term [kg/m3] | 2.788 | 2.301 | 1.947 | 1.676 | 2.793 | 2.291 | 2.880 | 2.497 | 2.399 | 2.094 | 2.361 | 2.065 | |
| | Ratio | 0.55 | 0.55 | 0.55 | 0.60 | 0.55 | 0.55 | 0.55 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | |
| Toronto | Condensation [total days/year] | 158 | 157 | 158 | 157 | 162 | 157 | 149 | 147 | 158 | 156 | 158 | 157 | 156.3 |
| | *Mould long term [days per year] | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 0 |
| | *Mould, 1st year [days per year] | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 17.5 | 14.9 | 0.2 | 0.2 | 0.0 | 0.1 | 3 |
| | Mould ASHRAE 160P method | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.6 | 2.5 | 0.1 | 0.1 | 0.0 | 0.1 | 0.5 |
| | Inward Drive [days per year] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Drying -induced event- w.c. lost [kg/m3 | 3.844 | 3.939 | 3.522 | 3.621 | 3.839 | 3.905 | 2.380 | 2.447 | 3.858 | 3.955 | 3.760 | 3.825 | |
| | Drying -long term [kg/m3] | 2.924 | 2.473 | 2.214 | 1.850 | 2.928 | 2.470 | 3.050 | 2.646 | 2.642 | 2.312 | 2.623 | 2.299 | |
| | Ratio | 0.40 | 0.35 | 0.35 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.45 | |
| Vancouver | Condensation [total days/year] | 66 | 64 | 65 | 64 | 66 | 64 | 54 | 53 | 65 | 64 | 65 | 64 | 62.3 |
| | *Mould long term [days per year] | 4 | 3 | 2 | 1 | 4 | 3 | 4 | 1 | 5 | 3 | 5 | 2 | 3 |
| | *Mould, 1st year [days per year] | 21.0 | 19.2 | 8.9 | 3.2 | 17.7 | 17.6 | 16.5 | 8.2 | 29.0 | 20.2 | 25.6 | 17.4 | 17 |
| | Mould ASHRAE 160P method | 11.5 | 11.5 | 7.4 | 6.4 | 11.5 | 11.5 | 11.6 | 9.5 | 11.5 | 11.5 | 11.5 | 7.4 | 10.3 |
| | Inward Drive [days per year] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Drying -induced event- w.c. lost [kg/m3 | 3.737 | 3.815 | 3.428 | 3.522 | 3.663 | 3.877 | 2.212 | 2.261 | 3.789 | 3.871 | 3.693 | 3.761 | |
| | Drying -long term [kg/m3] | 3.142 | 2.686 | 2.459 | 2.072 | 3.145 | 2.682 | 3.330 | 2.904 | 2.880 | 2.386 | 2.865 | 2.521 | |
| | Ratio | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | |

*indicates alternative method used

- Indicates that result is acceptable
- Indicates a marginal pass result
- Indicates a poor or failed result
- Indicates an unknown result

**Cells in Red indicate poor or unacceptable performance. Orange cells indicate unknown severity of the result. Yellow cells indicate a borderline pass result. Green cells indicate a pass result.**

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