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Field Monitoring of Hygrothermal Performance of a Wood-Frame House in the Lower Mainland of BC Built to the Passive House Standard

by

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Summary

A single-family wood-frame house in the Lower Mainland of British Columbia built to the German Passivhaus (Passive House) standard was monitored to investigate its thermal performance and durability in this mild climate. Two double-stud walls, south- and north-facing, were instrumented during construction to measure moisture and thermal performance. A limited amount of thermal modelling was conducted to compare with the field measurements.

Monitoring over the past 20 months showed that:

- The double-stud walls, south- and north-facing, were both performing well in terms of durability. The moisture content (MC) measured at the bottom of the studs was in general below 15% after the construction was completed. The MC of the south-facing wall dropped from an initial 20%, measured during construction, to about 11% after construction was completed. During the same period of time, the MC of the north-facing wall fell from about 19% to 15%; the slightly higher MC in this wall compared to that in the south-facing wall was a result of lower amounts of solar gain in this orientation.
- The relative humidity (RH) measured on the interior side of the medium-density fibreboard (MDF) exterior sheathing in the south-facing wall ranged from 70% to 80%, and occasionally up to 90% during the winter. Being typical of exterior sheathing conditions without exterior insulation in this mild climate, the corresponding RH ranged from 80% up to 100% in the north-facing wall in the winter, indicating potential vapour condensation at this critical location.
- Based on vapour pressure analysis, no steep vapour pressure gradients between any specific layers were found in these two walls, indicating the overall vapour permeable nature and good drying performance of the wall design. This could be partially attributed to the use of plywood as structural sheathing located between the double-stud walls as the air barrier and vapour retarding layer, and using MDF as the exterior sheathing.
- In the south-facing wall, the vapour pressure analysis showed a vapour drive in the summer from the exterior layers towards the interior layer, primarily due to high temperature outside. The exterior sheathing should have good drying potential if wetting occurred. On the other hand, the partial vapour pressures were largely consistent across the north-facing wall in the winter, not showing a strong vapour drive from interior to exterior in this mild climate. The exterior sheathing would have poor drying performance if wetting occurred in this location.
- The simulated temperature distributions based on THERM 6.3 simulations were generally in good agreement with the measured temperatures across the walls, indicating that the thermal simulation was reasonably accurate. The effective R-value of the double-stud walls of this passive house was calculated to be approximately R-50 ($hr \cdot ft^2 \cdot F/Btu$) or RSI-8.8 ($m^2 \cdot K)/W$) (i.e. with a thermal transmission coefficient of 0.114 $W/m^2 \cdot K$).

The use of heat flux sensors was not successful in this work, probably due to improper sensor calibration or in-situ installation. Its use needs further exploration to measure heat flow in building envelopes in order to validate calculated effective thermal insulation.

Acknowledgements

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FPInnovations would like to thank its industry members, Natural Resources Canada (Canadian Forest Service); the Provinces of British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, Nova Scotia, New Brunswick, as well as Newfoundland and Labrador, and the Government of Yukon for their guidance and financial support for this research.

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1 Objectives

- To collect field hygrothermal performance data from a single-family wood-frame house in the Lower Mainland of British Columbia (BC) built to the German Passivhaus (Passive House) standard;
- Help to validate design assumptions related to the use of plywood, a structural sheathing located between double-stud walls as an air barrier and a vapour retarding layer, and using medium-density fibreboard (MDF) as an exterior sheathing to make the assemblies “vapour permeable” compared with the traditional assembly designs.

2 Introduction

Buildings generally account for very large amounts of energy use, greenhouse gas emissions, and water use. For example, residential buildings in Canada consumed 17% of secondary energy use (i.e., form of energy generated by conversion of primary energies, e.g. electricity from gas, nuclear energy, coal, oil, fuel oil) and produced 15% of greenhouse gas emissions in 2009 (Office of Energy Efficiency, 2011). Over the last few decades, new houses in Canada have been in general getting larger but they have also been becoming more energy efficient. Thermal insulation and airtightness levels, two important thermal characteristics of building envelopes, have been increasing over the past few decades (Parekh *et al.* 2007). Related to this, Canadian building codes have been increasing the minimum energy-efficiency requirements, which typically mean increased thermal insulation of building envelopes. The latest changes at the national level include the publication of the National Energy Code for Buildings (NECB) in 2011 for Part 4 buildings (NRC, 2011) and the addition of Section 9.36–Energy Efficiency into the National Building Code of Canada (NBC) in 2013 for Part 9 housing (NRC, 2013). The Province of British Columbia (BC) has adopted the NECB, together with the ASHRAE 90.1 Standard (2010) for large buildings, effective December 2013. BC has also adopted the majority of the provisions under Section 9.36 of the NBC to replace the energy requirements in the current BC Building Code, effective December 2014.

Aside from these minimum requirements, more and more designers and builders have been building to above-code levels of energy efficiency through various “green” building programs and labelling systems, such as Energy Star, R-2000, Built Green, LEED, Net Zero Energy, and Passive House. The R-2000 Program was introduced in 1981 by Natural Resources Canada (NRCan) as a voluntary standard, covering all of the major aspects for reducing home energy consumption, in partnership with the Canadian Home Builders’ Association (NRCan 2005). Regarding airtightness, the requirement is less than 1.5 air changes per hour (ACH) at a pressure differential of 50 Pa. This program has been the leading energy-efficiency home program in the country since the 1980s and has also been guiding the building codes to increase energy-related requirements. As of 2012, the minimum energy-efficiency levels in building codes had almost caught up to R-2000, therefore NRCan revamped the R-2000 program such that it will once again be a leading edge program, aiming to reduce energy requirements by 50% compared to the code minima in 2013. The concept of Net Zero Energy home is certainly another step-up in terms of house energy conservation, targeting that the consumed energy will be less than the generated energy on an annual basis. The Net Zero Energy Building Certification, a program operated by the International Living Future Institute using the structure of the Living Building Challenge, requires that the building should have a net zero energy consumption for 12 consecutive months. On the other hand, Passive House, a labelling program originating in Germany as Passivhaus based on concepts originally developed in the 1970s in Canada for R-2000, is one of the most stringent among these programs and standards. For example, it has fixed-performance requirement targets including that the space-heating load must be less than 15 kWh/m^2 per year and that the air tightness must be less than 0.6 ACH @ 50 Pa. Correspondingly the building envelope must have superior insulation and airtightness, and minimal thermal bridging. The thermal transmission coefficients (called "U-value" in this report) of external walls, slabs, and roofs are usually required to be within 0.1 to 0.15 W/m²·K, equivalent to effective thermal resistance R-values (h·ft^2·F/Btu) from 38 to 57, or RSI-values (m^2·K/W) from 6.7 to 10. Such stringent thermal requirements often favour the use of wood materials for framing because wood has considerably lower thermal conductivity and thermal bridging compared to other structural materials (Morrison Hershfield 2014). Since its introduction in BC with the construction of the Austrian Passive House for the 2010 Winter Olympics, Passive House has become popular in the design community, and several houses have been built to this standard.

The main objective of this project was to investigate the durability performance of highly insulated building envelopes with reduced drying potential in the mild, wet climate area of BC. Based on a literature review on energy efficiency (Wang 2011), durability concerns regarding highly insulated building envelopes increase in heating-dominated climates, resulting from increased vapour condensation potential at exterior layers, particularly at exterior sheathing. This is partially a result of reduced heat transfer from the interior due to the high insulation levels and consequently the larger temperature differentials between the interior and exterior elements. This also typically results in reduced drying potential of the assembly. To address such concerns and to improve building envelope design, quite a few studies have been carried out in recent years to provide field test results (Fox 2014). The general consensus is to use exterior insulation to keep the exterior sheathing warm and thereby reduce the vapour condensation potential and improve drying performance (Finch *et al*. 2013; FPInnovations *et al*. 2014). Another important factor that is closely associated with thermal insulation is airtightness of building envelopes. In envelope assemblies with a very low level of thermal insulation (e.g. old houses with a minimal amount or no thermal insulation in walls and roofs), a high level of air leakage could be a powerful force to dissipate moisture and maintain durability performance, particularly when rain penetration occurs in service. But for highly insulated assemblies, air leakage accelerates interstitial vapour condensation; therefore airtightness must be controlled to reduce moisture risks.

Another important reason for monitoring this house was that a number of innovative ideas and products were employed in the design and construction of the building envelope. This included using the structural sheathing, a layer of plywood installed between double-stud walls, as the primary air barrier and vapour retarding layer, and using a type of "breathable" MDF as exterior sheathing. Collecting hygrothermal performance data on the envelope assemblies may therefore validate design assumptions, improve future designs, and further develop best practice guides (Finch *et al*. 2013; FPInnovations *et al*. 2014). Such work may also facilitate the adoption of locally manufactured wood products for use in passive houses and other highly energy efficient homes. Furthermore, the work may facilitate the manufacture of innovative wood products in Canada.

3 Staff

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4 Materials and Methods

The primary approach in this project was to collect of moisture and thermal performance data from two walls of the house, south- and north-facing, through installing instruments during construction. A limited amount of modelling, as a potential design tool, was conducted to compare with the field data.

4.1 House Design Features

This two-storey house is located in Langley, BC, in Climate Zone 4 based on Canadian building codes (NRC 2011; NRC 2013), with a square foot area of about 4800 ft^2. Its main living area, as shown as the black part in Figures1 and 2, was designed to meet the Passive House standard. The cross-hatched blue part, i.e. the garage and green house shown in the plan of the main floor (Figure 3) is not part of the Passive House design. The plan of the house has a rectangular shape as a means to maximize compactness and minimize the ratio between the thermal envelope area and the heated volume. This ratio is typically below 0.7 m^2/m^3 for a passive house to minimize thermal bridging and improve envelope thermal efficiency.

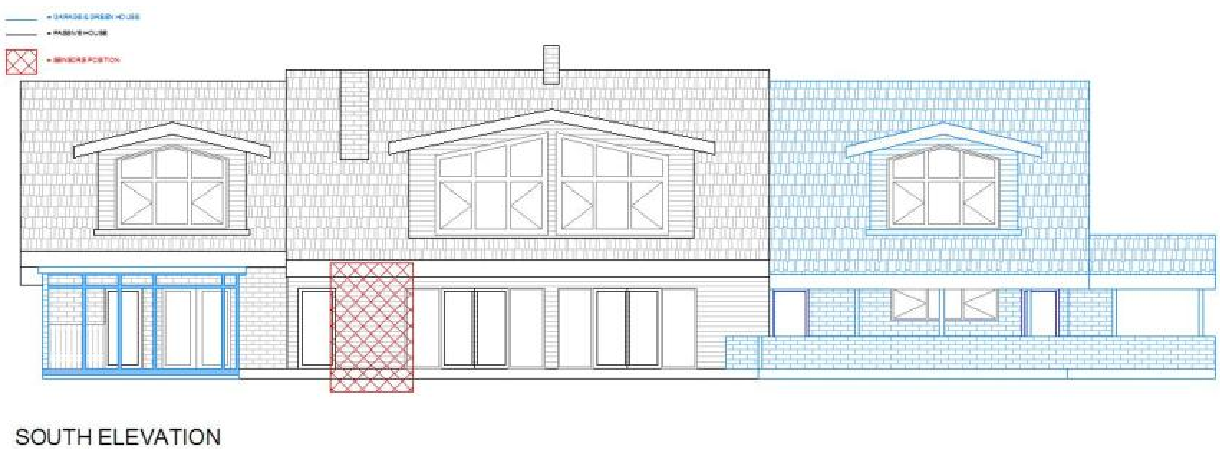


Figure 1 South elevation of the house (Instrumented stud cavity shown cross hatched in red)

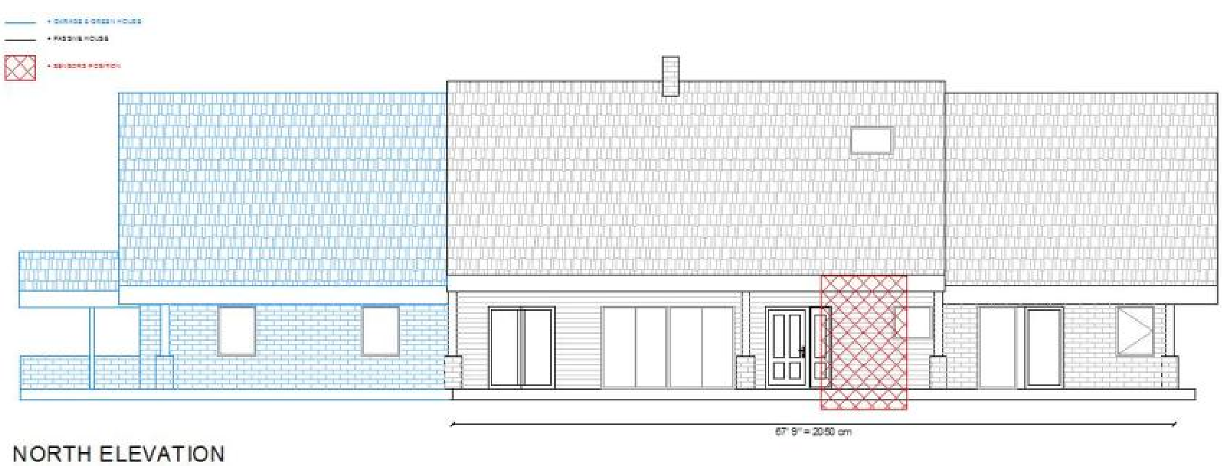


Figure 2 North elevation of the house (Instrumented stud cavity shown cross hatched in red)

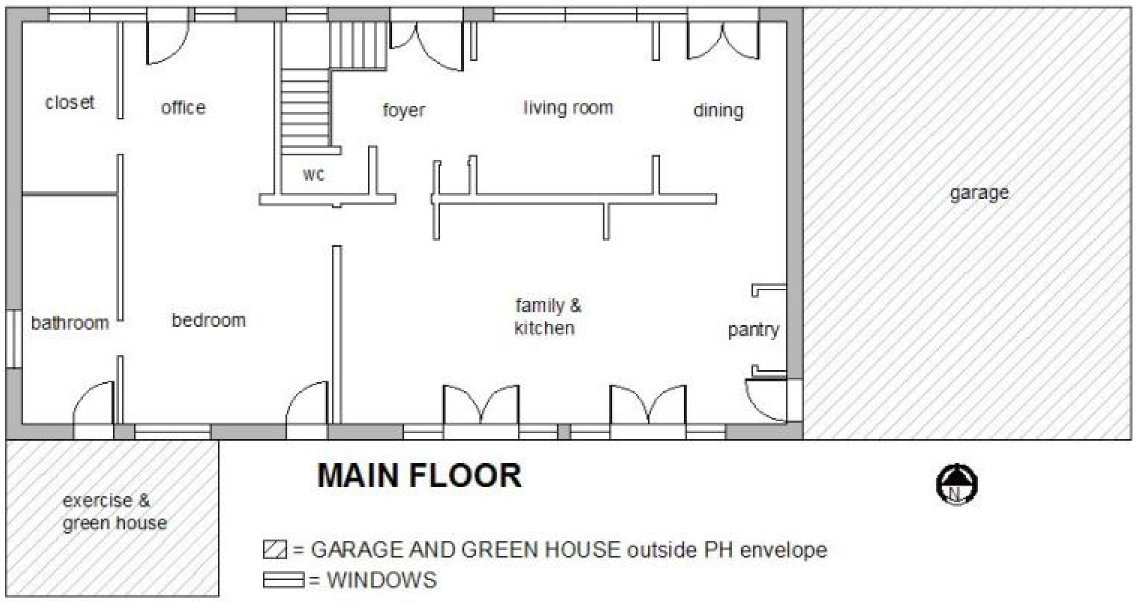


Figure 3 Plan of the main floor of the house

Due to budgetary constraints it was decided to monitor the performance of two main exterior walls only. As shown in Figures 4 and 5, the typical exterior walls of the passive house were built with double-stud walls including an exterior wall built with nominal 2 by 10 in. (with actual dimensions of 38 mm by 235 mm) Douglas-fir dimensional lumber, spaced at 24 in. (610mm), for bearing most structural loads. The interior wall was built with nominal 2 by 4 in. (with actual dimensions of 38 mm by 89 mm) "SPF" (Spruce-Pine-Fir) dimensional lumber, for accommodating services such as electrical and plumbing. Mineral wool batt insulation was installed in the stud cavities to achieve the desired thermal resistance. The walls were prefabricated together with the mineral wool insulation and an exterior MDF sheathing. This product, based on Methylene Diphenyl di-isocyanate (MDI) adhesive, was imported from Europe (AGEPAN®). Its use in this house had the special purpose of making the thick walls "breathable", i.e. high vapour permeance (see Appendix 1 for vapour permeance test results of a number of wood panel products) to allow moisture to dissipate towards the exterior. This product has been commonly used in Passive Houses built in Europe and recently in North America. There is interest from a Canadian company to manufacture such products. Outside this non-structural sheathing, it was a water-resistive but vapour permeable membrane. Nominal pressure-treated 1 by 2 in. lumber strapping, with an actual thickness of 19 mm, was used to create a drained and ventilated air space between the membrane and the fibre cement siding. The building code requires a clear air space (i.e. the so-called rainscreen cavity), not less than 10 mm deep, to improve drainage and drying in coastal climates (NRC 2010).

Another distinct feature of these walls was that a layer of plywood, 3/8" (9.5 mm) in thickness, was installed between the two walls as both a structural sheathing and an air barrier, with gaps between the boards sealed with a specialized tape, also imported from Europe. Furthermore, there was no added vapour barrier relying instead on the taped plywood to retard moisture diffusion. In the heating-dominated Canadian climates, an interior vapour barrier, often a 6 mil (0.15 mm) polyethylene sheet or sometimes a primer or paint on drywall has been traditionally used to minimize vapour diffusion from the interior living space into the building envelope assemblies. In a cold climate, heated interior living space typically has higher vapour pressures in the winter compared with the exterior environment. Based on the building code requirements in Canada (NRC 2010), the vapour permeance of a vapour barrier should not be greater than 60 ng/(Pa·s·m^2), measured in accordance with ASTM E 96 (2013) using the desiccant (dry cup) method. The use of polyethylene also often functions as the air barrier of the assembly. It was proven that such an air barrier, when properly sealed and protected, can achieve long-term airtightness performance based on inspection of energy efficient houses built in the Prairies since the 1970s (Proskiw and Parekh 2004; Orr *et al*. 2013). However, arguments against using a material with very low vapour permeance have been around for years. Polyethylene is not as commonly used in the cold climates in the U.S. as in Canada, although Class I (materials with vapour permeance below 0.1 perm, i.e. about 6 ng/(Pa•s•m^2)) or II (materials with vapour permeance ranging from 0.1 to 1 perm, i.e. about 60 ng/(Pa•s•m^2)) vapour retarders are required in the building codes for Climate Zones 5, 6, 7, 8 and Marine 4 (International Code Council 2012). Based on building science theories associated with Passive House, building envelopes perform when they are made "breathable"; strictly there is no need for a vapour barrier. On the other hand, wood-based panels can provide some level of vapour resistance by preventing excessive vapour diffusion from the living space, serving as a "vapour-retarding layer". Plywood and OSB, in thicknesses typically used for sheathing, often have vapour permeance slightly above 60 ng/(Pa·s·m^2) under typical service humidity conditions (Kumaran 2002; Appendix 1). Moreover, a great benefit of wood materials is that the vapour permeance typically increases with increasing humidity in the environment, i.e. functioning as "a smart vapour barrier" (Kumaran 2002; Alsayegh *et al*. 2013; FPInnovations and Binational Softwood Lumber Council 2013).

In the case of this house, having a rigid air barrier in the middle, protected with a wall on each side, has benefits including eliminating the need to penetrate this layer for services. Service penetrations in specified air barriers are often the major causes for air leakage in typical buildings. The airtightness of this house was reported to be 0.4 ACH @ 50 Pa based on a blower-door test conducted in early May, 2012, before the drywall was installed. This is a superb result and the envelope would have become even tighter after the drywall was installed. For comparison, typical houses in BC are among the leakiest houses in the country with average airtightness of close to 8.0 ACH @ 50 Pa before retrofit and over 6.0 after retrofit (Parekh *et al*. 2007). Although it is required by a few energy-related programs such as R-2000 and Passive House, achieving certain airtightness is not generally required by the Canadian building codes. However, the newly approved Energy Efficiency Bylaws of the City of Vancouver requires housing airtightness of 3.0 ACH @ 50 Pa, effective on March 20, 2014 (www.vancouver.ca).

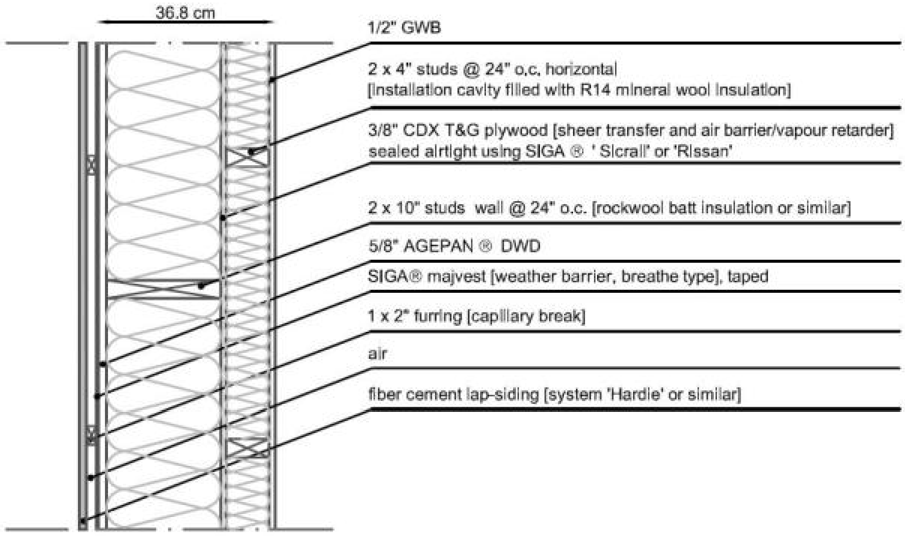


Figure 4 Section drawing of the double-stud wall assembly

Figure 5 A photo of the double-stud wall of the house

4.2 Instrumentation

In each of the two selected walls, a reasonably clear stud cavity that had minimal servicing was selected as a test bay for instrumentation (as shown as the red part in Figures 1 and 2, respectively). The test bay was adjacent to a window and patio doors. Four resistance-based moisture pins were installed to measure wood moisture content (MC) at the bottom of two studs (middle at the stud depth) and two locations at the adjacent MDF sheathing (on the interior side). The readings from the studs were calibrated for "Douglas-fir" based on the coefficients available in the literature (Garrahan 1988); the readings for the two MC pins on the MDF were simply based on calibration for average wood species because no calibration was conducted for the MDF product due to budget constraints. Wood-based composites in general have lower equilibrium moisture content (EMC) than solid wood of the same species due to the effects of the adhesive and heat applied during the manufacturing process. For uniform and consistent products, such as MDF in particular, the MC readings would have been lower if they had been calibrated properly. The pins on the studs also provide measurements of the local temperature, required for calibration of the MC readings. Three moisture detection sensors were installed both inside and outside of the MDF sheathing (i.e. between MDF and the membrane), as well as the interface between the sheathing and the bottom plate. These self-adhesive tape-like sensors were used to detect potential liquid water caused by rain penetration or vapour condensation. Such products have been primarily used in buildings to provide warnings of water leaks when the measured electrical resistance is under a threshold around 100K ohms, with a measurement principle different from commonly used moisture pins. Four pairs of RH/T sensors were installed at chest height, central in the stud cavity, to measure the relative humidity (RH) and temperature across the wall assembly, including the interior living space, outside the drywall, outside the plywood structural sheathing, and inside the MDF sheathing. In addition, two heat flux sensors (Omega “HFS-4”) were installed close to the RH/T sensors to measure heat flow. It was known that heat flux sensors are very sensitive and require careful calibration and precise installation to minimize influence from irrelevant factors; steady state conditions should also be achieved during the test (Armstrong *et al*. 2011). The use of this type of sensor in this house was partially to help us gain experience in using such sensors. However, the readings turned out not to make sense, probably due to improper calibration or in-situ installation. Therefore the heat flux readings were not included in this report.

In total, 13 sensors were installed in each wall. Each sensor was connected individually using cables to data acquisition units located in a cupboard on the ground floor. They were programmed to log data hourly and transmit data when a computer running special software was in proximity. The data collection started in early May, 2012 during construction. A computer was kept in the house for immediate data collection when the owner moved into the house in October, 2013. No weather station was set up at the site; climate data was acquired for the closest meteorological station (www.climate.weatheroffice.gc.ca, White Rock) when local weather data was needed for analysis.

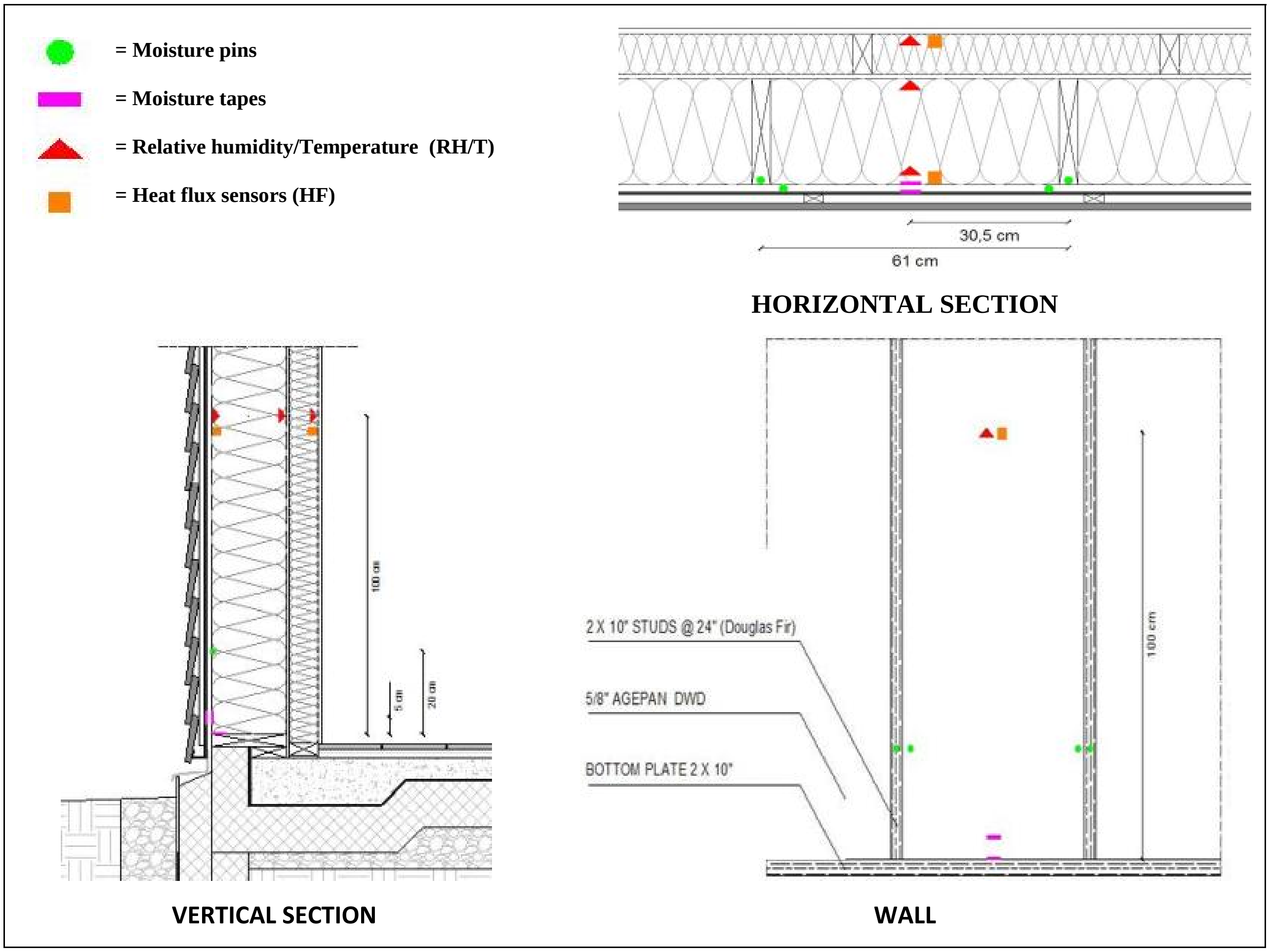


Figure 6 Locations of sensors in each wall

Figure 7 Photo of two installed MC pins and one moisture detection tape (left, on MDF sheathing and a stud) and an RH/T sensor and a heat flux sensor (right, interior of MDF sheathing)

4.3 Thermal Modelling

Use of computer software including THERM 6.3 and WUFI pro 5.0 was explored by the co-author to simulate thermal resistance and hygrothermal performance. It was found that the moisture-related results based on WUFI simulation were largely not comparable to the field measured data. One of the reasons was that we did not have appropriate material property data as input for a number of products used in the walls, such as the MDF and the sheathing membrane. Related to this software, quite a few studies have been conducted or are currently underway in Canada or the US to validate and improve hygrothermal simulation for wood-based building envelopes (Arena *et al*. 2013; McClung *et al*. 2014). On the other hand, it was found that the simulated temperature distributions based on THERM 6.3 were in general agreement with the measured temperatures across the wall. Therefore only the thermal resistance calculation was reported here. THERM was developed by the Lawrence Berkeley National Laboratory of the United States and is a well-known 2-D thermal modelling tool in the design community. In principle it simulates the heat flow through each element of the assembly and subsequently calculates the thermal transmittance in $W/m^2{\cdot}K$, as currently required by the NECB (NRC, 2011), or the thermal resistance, typically expressed as effective thermal resistance RSI-value, $m^2{\cdot}K/W$, as currently required by Section 9.36 of the NBC (NRC, 2013). R-values, in $h{\cdot}ft^2{\cdot}F/Btu$, are commonly used by practitioners in North America.

This thermal simulation exercise was conducted for a range of walls, from a typical wall built with nominal 2 by 4 in. studs, a wall built with nominal 2 by 6 in. studs, a wall built with nominal 2 by 10 in. (with actual dimensions 38 mm by 235 mm) studs, and various combinations for double-stud walls, as shown in Figure 8. They all had studs spacing of 24 in. (610 mm). Most walls simulated did not take into consideration the layers outside the exterior sheathing, but the simulation of the double-stud walls used in this passive house, labeled as PH WALL in Figure 8, considered the air space (as a layer of still air) and the cladding. The contribution of an air space to thermal resistance is certainly affected by ventilation (Tariku and Simpson 2013); but the impact was not assessed in-depth in this study. Table 1 lists the major parameters used for the thermal modelling.

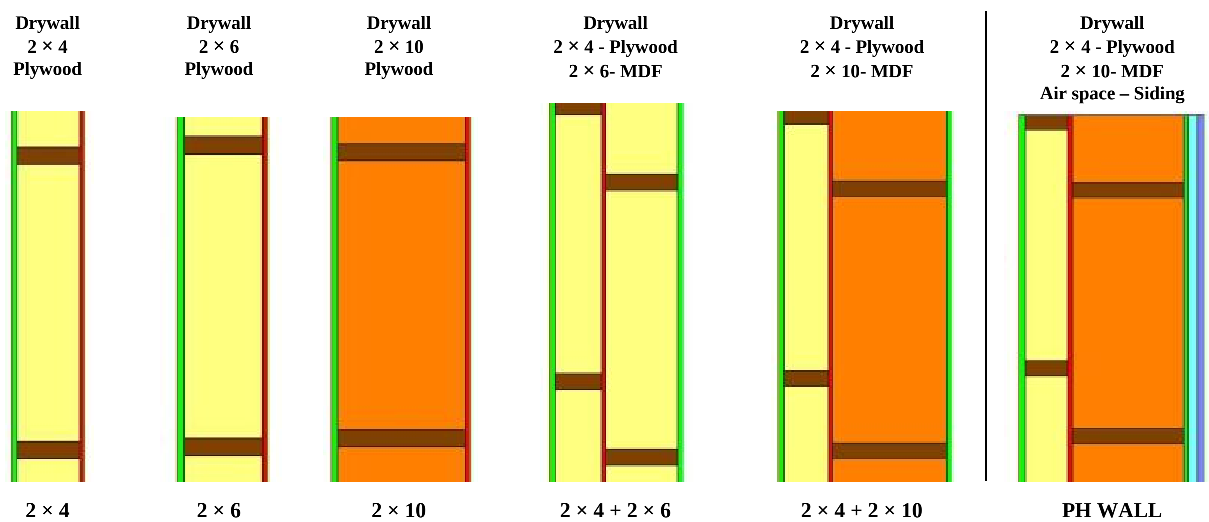


Figure 8 ***Models of a range of walls used for thermal modelling***

Table 1 Major material parameters used for thermal modelling

Materials	Thickness (mm)	Thermal conductivity	
		Btu/h·ft·F	W/m·K
Drywall (gypsum)	13	0.098	0.170
Douglas-fir studs	Not aligned between 2 × 4 and 2 × 10 walls	0.081	0.140
Insulation (mineral wool batt)	325 (for a total thickness of 2 × 4 + 2 × 10)	0.024	0.041
Plywood	10	0.058	0.101
MDF	16	0.052	0.090
Air layer	20	0.075	0.130
Fibre cement siding	13	0.147	0.255

5 Results and Discussions

5.1 Moisture Performance

Figures 9 and 10 show the moisture data collected by the moisture pins installed in the studs and the MDF sheathing of the two walls. The data collection started in early May, 2012, after the walls were covered with the roof. Unfortunately there was about four months' loss of data from most sensors starting in early June caused by construction damage. The MCs of the studs (measured close to the bottom plate at half depth) in the south-facing wall were around 20% in May when the monitoring was started. At that time there was excessive rain and it was believed that the prefabricated walls were exposed to wetting to a certain degree during construction. The MC readings dropped to about 13% when the data collection was restored in the fall and they gradually came to stabilization around 10-11%. By comparison, the MC measured from the studs in the north-facing wall started with a similar MC around 20% in May, it gradually reached around 15%, about 4-5% higher than that from the south-facing wall. The measured MC from the MDF of the south-facing wall was about 10% and that from the north-facing wall was about 12% during majority of the test period. As discussed above, the actual MC of the MDF would have been even lower if the sensors had been properly calibrated for the product used. The drier condition in the south-facing wall must have resulted from higher levels of solar gain in the south orientation. The lower limit of MC readings shown in Figures 9 and 10, around 8.8%, was caused by a known limitation of measuring wood MC based on electrical resistance. The resistance in wood becomes too high to measure accurately when the MC gets too low. The readings from the two moisture tapes (Figure 11,) showed a few spikes, probably resulting from local humidity changes, but were all far above the threshold of 100K ohms. Therefore no liquid water was detected. The other tape in the south-facing wall was dysfunctional and the data was not included.

The measured data in general indicates that these two walls both dried and had good durability performance for the locations monitored during this period of time. It was reported (Arena *et a*l. 2013)) that the double-stud wood-frame walls built with a traditional approach in North America (e.g. using OSB as the exterior sheathing and sprayed cellulose insulation in the walls) also showed good hygrothermal performance in a field study in Climate Zone 5A in the US. A survey conducted by FPInnovations for six older-generation energy efficient houses in Saskatoon, a very cold and dry climate (Zone 7 A based NECB 2011), found good durability performance for the double-stud walls used in those houses (Orr *et al*. 2013). But concerns certainly exist for such thick walls without exterior insulation due to increased vapour condensation potential and reduced drying ability at the exterior sheathing location (Fox 2014). Regarding durability criteria, research has shown (Wang *et al*. 2010) that at a temperature around 20°C, decay fungi cannot colonise kiln-dried wood products unless the MC rises to a threshold of 26% (which can be considered the low end of fiber saturation point) and stays above this for long enough time. On the other hand, building envelope assemblies, particularly with materials having low vapour permeance or high levels of insulation, may have much reduced drying performance once they get wet (Wang 2014). Appropriate on-site moisture management is therefore always good practice to prevent excessive wetting, particularly for prefabricated assemblies and composite wood products.

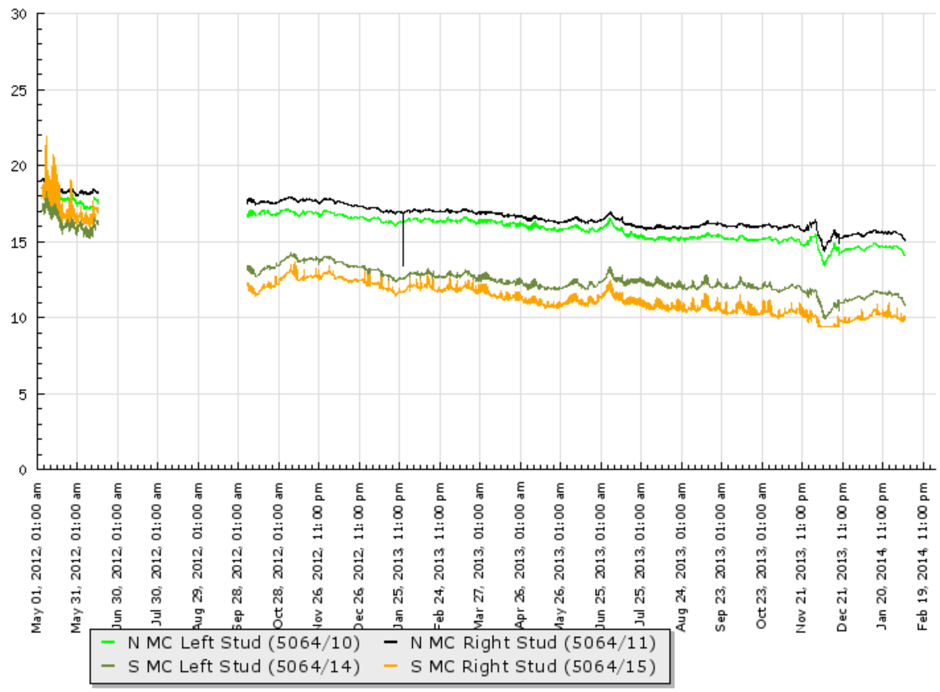


Figure 9 MC readings (in percentage) from moisture pins installed in the four studs of two walls (data loss from June to September, 2012)

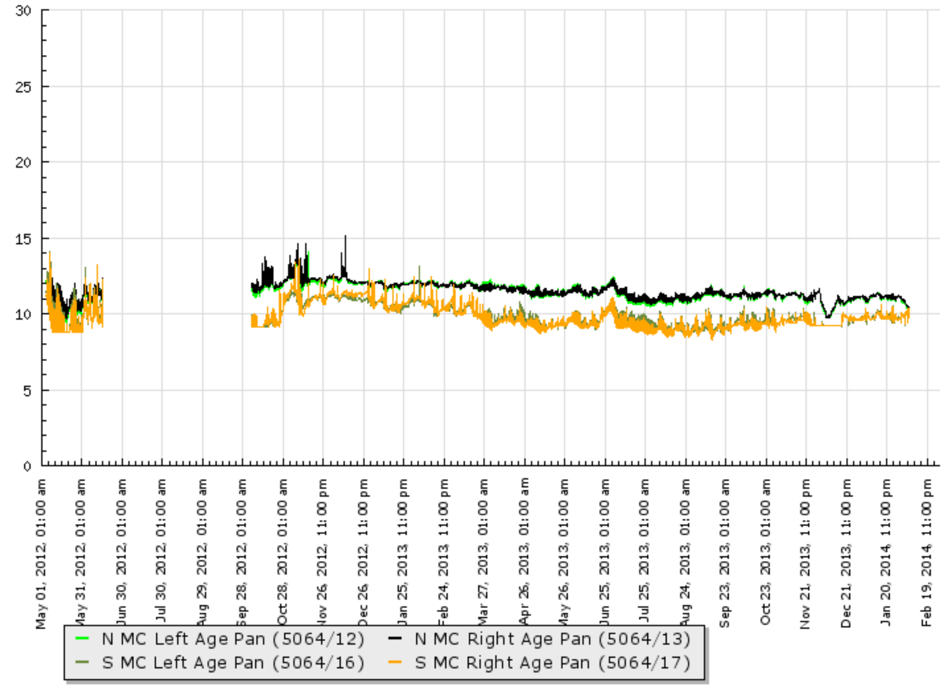


Figure 10 MC readings (in percentage) from moisture pins installed in MDF sheathing of two walls (data lost from June to September, 2012)

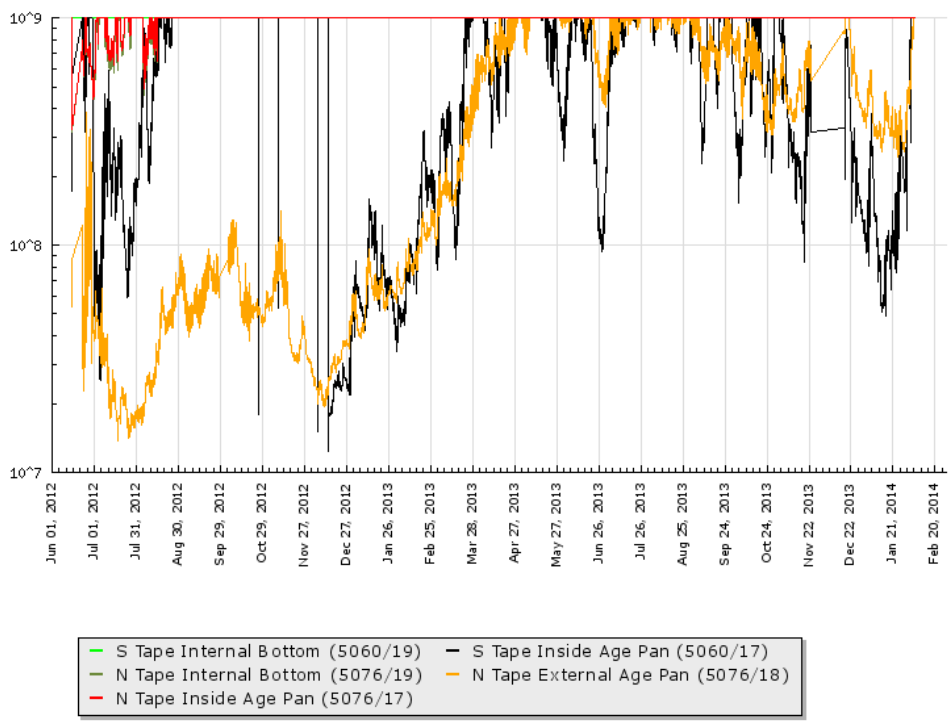


Figure 11 Measured electrical resistance (in ohms) from moisture tapes installed in two walls

5.2 Temperature and Vapour Pressure Differentials

5.2.1 Temperature and RH

Figures 12 and 13 show the readings of temperature and RH from the south-facing wall; Figures 14 and 15 are the corresponding readings from the north-facing wall, started when the house was occupied in November, 2012. Unfortunately there was about one month's loss of data due to a power shortage of the system in December, 2013. The interior temperature was maintained around 20°C. Except for the readings on the interior side of the MDF sheathing, the general trend of temperature reduction from the interior living space, through the exterior side of drywall, the exterior side of plywood, and into the stud cavity was obvious in both walls, in the winter season in particular. The large fluctuations measured from the interior side of the MDF exterior sheathing, which was very close to the air space of the rainscreen walls and then the exterior environment, were largely due to the variation in solar gain. This is most evident for the south-facing wall in the summer. Solar gain varies based on weather conditions and orientation, and is typically highest when sunlight is directly on the walls. For absorptive cladding types, such as stucco, this solar energy can drive moisture absorbed in the cladding towards the interior, i.e. the so-called "inward solar vapor drive". This can cause serious durability concerns in areas particularly with continental climates. But for this house, such inward vapour drive should not be a large concern due to the use of low-moisture absorption composite cement siding in a mild climate. Furthermore, the solar energy can turn into a good drying force for building envelopes.

The trend of RH changes in general followed the changes in temperature, naturally in reverse. The higher the local temperature, the lower the RH usually was. The RH in the living space appeared to fluctuate around 40% and often reached 30% in the winter. It is believed that such a humidity level is quite low compared to typical interior conditions in this climate (Finch *et al*. 2007). The owner of the house did complain about the indoor environment being uncomfortably dry. Low indoor humidity could be associated with airtight building envelope, over mechanical ventilation, and low interior moisture load.

The RH measured from both outside the drywall and outside the plywood structural sheathing remained generally below 60%, and occasionally above 60% for short periods of time. However, it is typically the interior of exterior sheathing that has the highest moisture risk in heating-dominated climates. This location is exposed to potential vapour condensation, caused by air exfiltration or outward vapour drive, especially for a highly insulated assembly under large temperature differentials (Wang 2011). The exterior sheathing is certainly also most susceptible to rain leaks when occurring. Focusing on the vapour condensation concern in the winter time, Figures 13 and 15 show that the RH on the interior side of the MDF sheathing ranged from 70% to 80%, and occasionally up to 90% in the south-facing wall, and from 80% up to 100% in the north-facing wall. Such results were typical of conditions in this mild climate and consistent with other measurements (Finch *et al*. 2007; Tariku and Ge 2011). The data indicates that the vapour condensation potential existed at this critical location, for the colder north-facing wall in particular. Such high RHs could allow mould to grow; fortunately the high RHs did not coincide with warm weather in this application. It is generally accepted that mould growth needs a minimum surface RH around 80% to grow on wood at a temperature of 20-25°C; although under such marginal conditions, it could take months or longer for mould to initiate even on non-resistant wood materials (Nielsen *et al*. 2004). Compared with decay, mould does not reduce wood strength but affects appearance and raises potential health concerns for susceptible individuals. Most incidents of mould growth in buildings are associated with wetting caused by liquid water sources, such as a rain leak and vapour condensation.

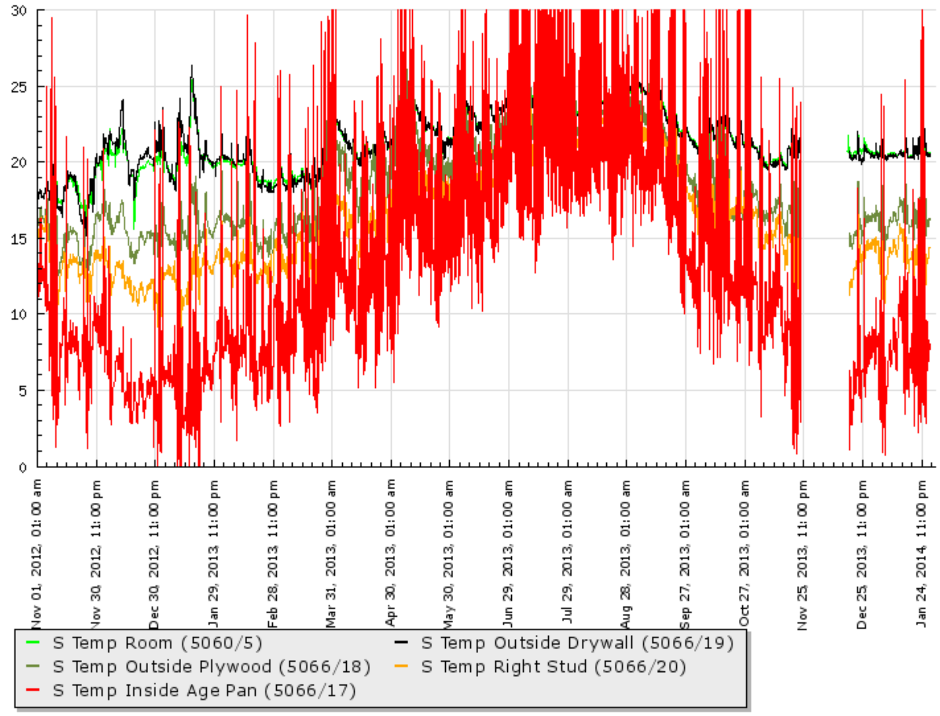


Figure 12 Readings of temperature from the south-facing wall

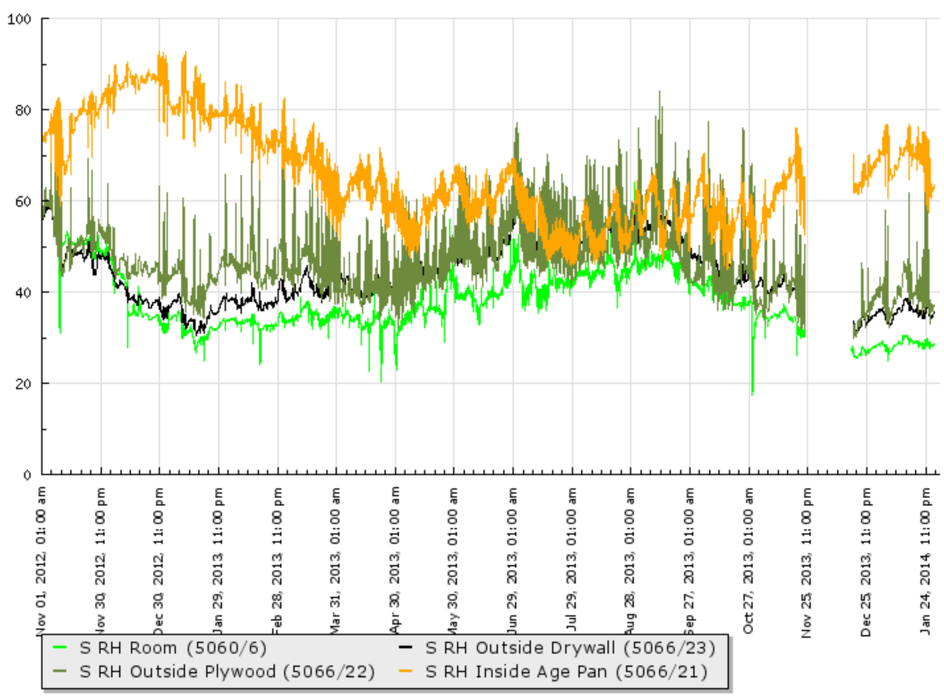


Figure 13 Readings of relative humidity from the south-facing wall

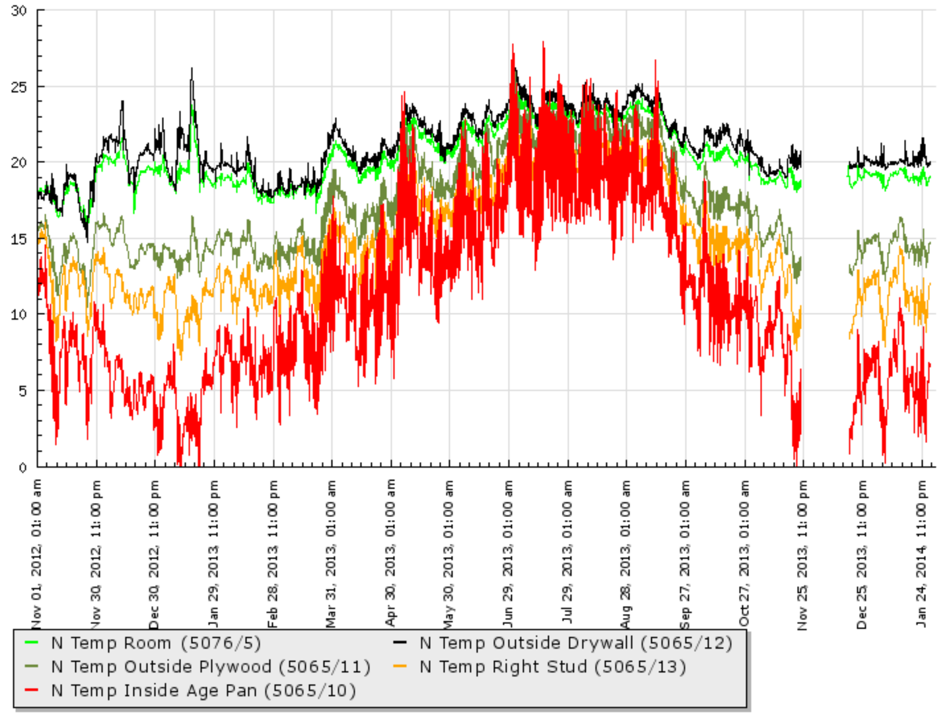


Figure 14 Readings of temperature from the north-facing wall

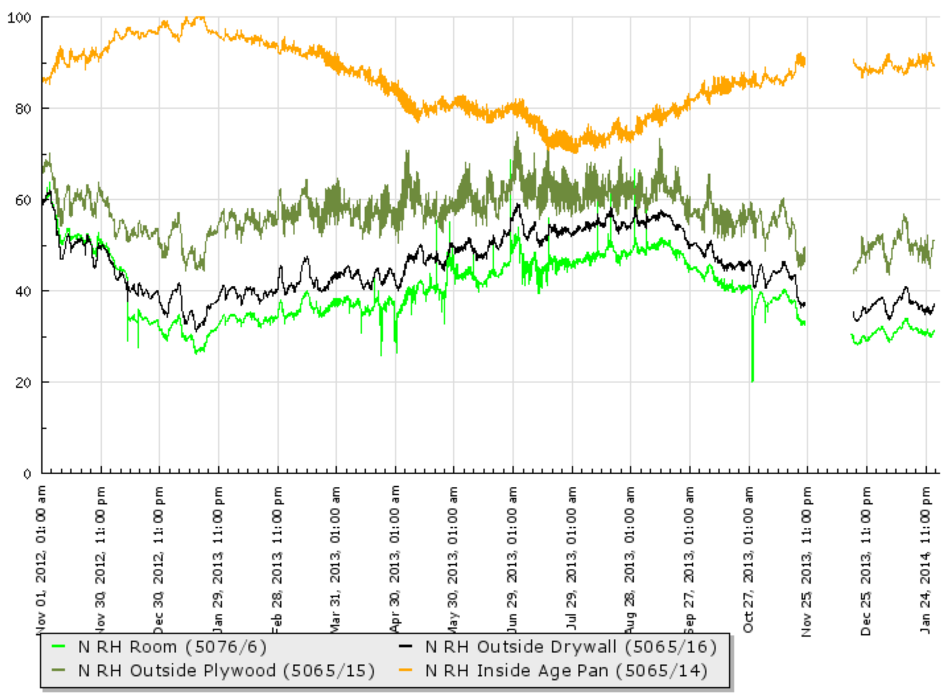


Figure 15 Readings of relative humidity from the north-facing wall

5.2.2 Comparison in Temperature between Measurements and Thermal Modelling

Comparisons were made between measured temperature from these two walls and the temperature results based on the thermal modelling using THERM 6.3. A time, November 9, 2012 at 8:00 am, was randomly chosen to represent the winter heating season when large temperature differentials occur between the interior and the exterior environment. The field measurement data was exported from the data logging system. The thermal simulation used the measured indoor temperature and the outdoor temperature data downloaded for the weather station close-by as realistic boundary conditions, and the simulation results were illustrated in Figure 16. These two sets of data were then put together in Figure 17 and also summarized in Table 2. The minor discrepancies between them indicated that the thermal simulation was reasonably accurate. It was reported that thermal simulation using models was more reliable than moisture simulation (Nofal *et al*. 2001). In general fewer variables are involved and reasonably accurate material property data are available for thermal modelling.

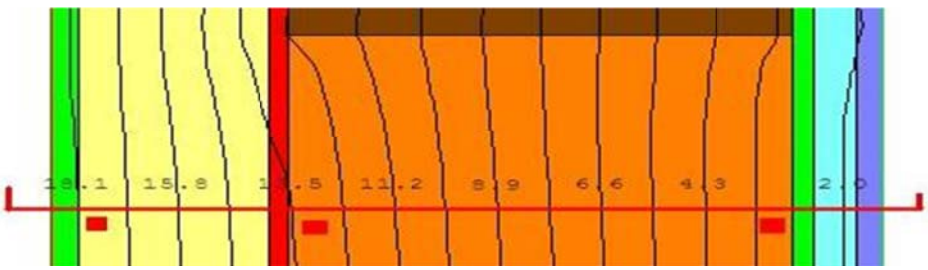


Figure 16 Temperature distribution across the wall based on thermal modelling

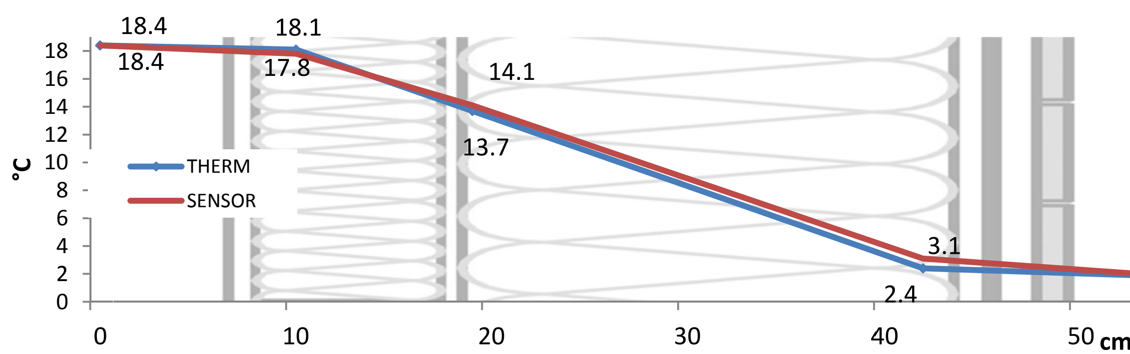


Figure 17 Temperature distribution across the wall based on thermal modelling and in-situ measurements

Table 2 Comparisons in temperature distribution across the wall based on thermal modelling and in-situ measurements

Layer/location (from left to right in Figure 15)	Simulation result (°C)	Sensor reading (°C)	Differences (°C)
Interior space	18.4	18.4	-
Outside drywall	18.1	17.8	0.7
Outside plywood	13.7	14.1	0.4
Inside MDF	2.4	3.1	0.3
Exterior environment	1.8	1.8	-

5.2.3 Vapour Pressure Differential across Wall

It was decided to calculate vapour pressure differentials based on the measured temperature and RH across the wall assemblies to assess the direction of vapour flow. This could help to shed further light on potential interstitial vapour condensation and drying performance of the assemblies. The outside weather data came from the same weather station close-by. First the saturated vapour pressure, Pws, was calculated using the Clausius-Clapeyron equation at a given temperature T_c (℃):

$$Pws\ (Pa) = 100 \times 6.112 \times \exp((17.67 \times T_c)/(T_c+243.5))$$

The partial vapour pressure, i.e. the actual local vapour pressure, Pw, was then calculated for a given RH (in percentage):

$$Pw\ (Pa) = RH \times Pws/100$$

Two times were chosen: one was August 12 at 16:00 for the south-facing wall to represent a summertime condition when there was no space conditioning, and the other was December 1, 2012 at midnight for the north-facing wall to represent a wintertime condition when there was space heating in the living space. Vapour flows are typically in reversed directions in summer and in winter mainly due to the very different outdoor environments. The calculated saturated vapour pressures and the partial vapour pressures as well as the differences between them for the south-facing wall were listed in Table 3 and illustrated in Figure 18. The vapour pressure on the interior side of the MDF sheathing was higher than those at greater depth in the wall, primarily resulting from the higher exterior temperature. Therefore vapour was being driven from the exterior layers to the interior layers. The vapour could also dissipate to the exterior environment since there was a similar vapour pressure differential to the exterior. There was a small vapour pressure gradient across the plywood structural sheathing, indicating some level of resistance to vapour flow. However, in general the partial vapour pressures were consistent across the wall assembly, suggesting that no considerable moisture amount could build up in this wall. The difference between the saturated vapour pressure and the partial vapour pressure for a specific location indicates the local drying potential. The data in Table 3 and Figure 18 suggested that the drying potential of the MDF sheathing was very high with a difference between the saturated and partial vapour pressure of 4403 Pa, if the sheathing was wet at the time.

Table 3 Vapor pressure and saturation pressure inside the south-facing wall on August 12, 2012

Layer (from left to right in Figure 17)	Measured temperature (°C)	Measured RH (%)	Calculated saturated vapour pressure (Pa)	Calculated partial vapour pressure (Pa)	Difference between saturated and partial vapour pressure (Pa)
Interior space	21.6	75.0	2598	1953	645
Outside drywall	22.3	76.0	2705	2051	654
Outside plywood	25.5	90.0	3271	2954	317
Inside MDF	41.4	45.0	7981	3578	4403
Exterior environment	25.4	59.0	3257	1921	1336

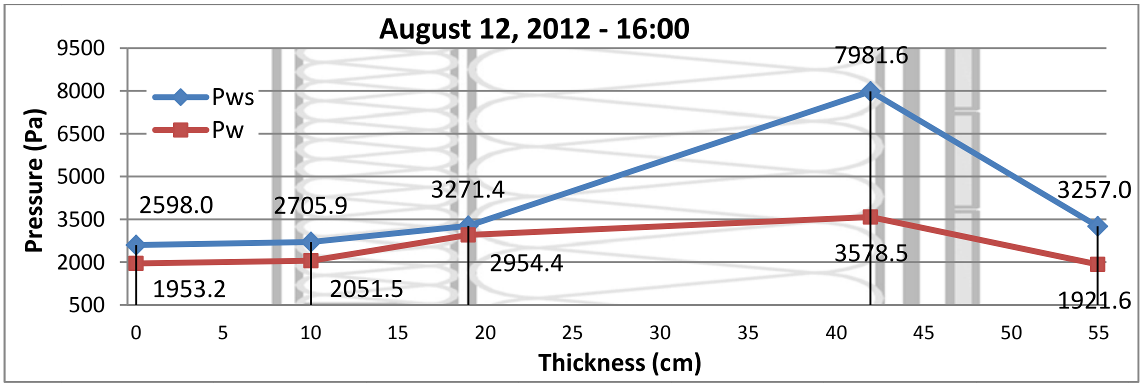


Figure 18 Calculated vapour pressure distributions across the south-facing wall based on in-situ measurements on August 12, 2012

At the selected winter time for the north-facing wall (with results shown in Table 4 and Figure 19), the partial vapour pressures were more consistent across the wall and there were no steep vapour pressure gradients, indicating no significant vapour flows occurring. The reasons included that there was a higher indoor temperature but the humidity levels in the exterior layers were also higher, being typical of the mild climate. Although it is commonly assumed that vapour flows from interior to exterior in a heating-dominated climate, there was no moisture accumulation in this wall, either. However, the small gap between the saturated and partial vapour pressure at the MDF sheathing, i.e. 219 Pa, indicated that the drying potential would be very low, if the panel got wet.

Table 4 Vapor pressure and saturation pressure inside the south-facing wall on December 1, 2012

Layer (from left to right in Figure 18)	Measured temperature (°C)	Measured RH (%)	Calculated saturated vapour pressure (Pa)	Calculated partial vapour pressure (Pa)	Difference between saturated and partial vapour pressure (Pa)
Interior	19.7	49.0	2303	1122	1181
Outside drywall	20.4	47.8	2405	1148	1257
Outside plywood	16.6	53.7	1897	1018	879
Inside MDF	9.4	81.5	1184	965	219
Exterior	8.9	85.0	1145	973	172

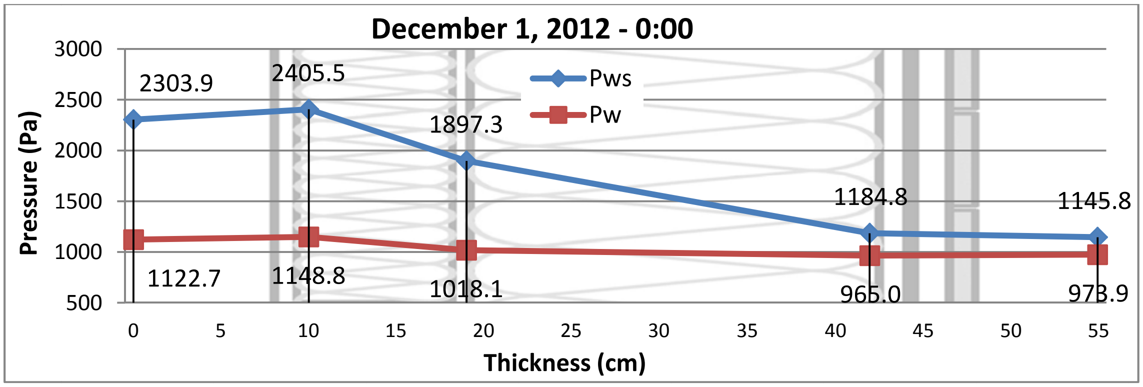
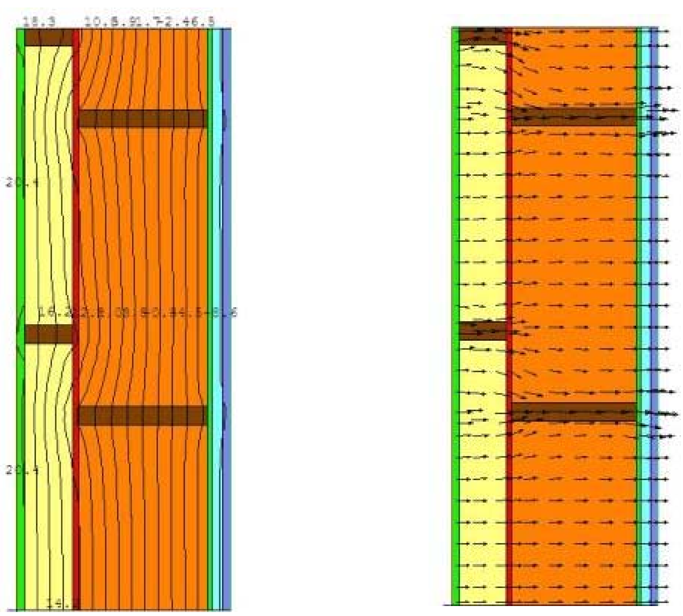


Figure 19 Calculated vapour pressure distribution across the north-facing wall based on in-situ measurements on December 1, 2012

5.3 Thermal Modelling

Thermal transmission (expressed as U-value in this report, $W/(m^2\cdot K)$) and its reciprocal, i.e. the thermal resistance (expressed as RSI-value, in $(m^2\cdot K)/W$), were calculated based on THERM 6.3. The heat flow was demonstrated in Figure 20 using isotherm planes and heat flux vectors. The graphs showed the relative weak areas in the assembly in terms of thermal insulation, i.e. thermal bridging areas. These primarily included the studs for such a wall. Compared with other structural materials, such as steel and concrete, wood has much better thermal resistance and less thermal bridging effect (Morrison Hershfield 2014). But insulation materials typically provide 2 to 4 times more thermal resistance than wood (NRC, 2013). The discontinuous and staggered studs between the double walls certainly improved the overall thermal efficiency.



ISOTHERM **FLUX VECTORS**

Figure 20 Demonstration of heat flow from inside side (left) to exterior side (right) of the PH WALL using isotherm planes or flux vectors

Table 5 Thermal modelling results based on THERM

Wall (shown in Figure 8)	U-factor $W/m^2 \cdot K$	RSI-value $m^2 \cdot K/W$	R-value $h \cdot ft^2 \cdot F/Btu$
2 × 4 wall	0.451	2.22	12.59
2 × 6 wall	0.303	3.30	18.76
2 × 10 wall	0.190	5.27	29.94
Double-stud wall (2 × 4 + 2 × 6)	0.185	5.42	30.77
Doube-stud wall (2 × 4 + 2 ×10)	0.138	7.25	41.15
PH WALL	**0.114**	**8.77**	**50.00**

The calculated thermal performance values are summarized in Table 5. Focusing on the R-value for discussion, it increased with increase in stud depth. Comparing the notional wall with nominal 2 by 10 in. lumber and the double-stud wall with nominal 2 by 4 in. and nominal 2 by 6 in. lumber, at the similar wall thickness, the double-stud wall had slightly higher R-value due to the thermal break provided by having two walls. The double-stud wall also created an interior service wall to minimize chances of having horizontal penetrations thereby protecting the specified air barrier. The actual walls used in this passive house, taking into consideration the air space and the siding, achieved a U-factor of 0.114 $W/m^2 \cdot K$, an effective R-value of 50 or RSI-value of 8.8, considerably better than the double-stud wall built with nominal 2 by 4 in. and nominal 2 by 10 in. lumber. In the thermal simulation, the air in the rainscreen wall cavity was considered to be a layer of still air, which could have slightly overestimated the thermal insulation effect. Nevertheless, this wall had a superior thermal insulation level. The utility fees of this house have been considerably lower than those of an adjacent house with only 10^{th} of the size, based on the feedback from the owner. For comparison, the required RSI-value in the NBC for above-grade opaque walls of Part 9 houses is RSI-2.78, with an R-value of 15.8 for this area (Climate Zone 4), with or without a heat-recovery ventilator, based on the newly added Section 9.36 (NRC-2013). This requirement can be achieved by a wall built with nominal 2 by 6 in. dimensional lumber, when the new energy requirements for houses take effect in December, 2014.

6 Conclusions

The performance monitoring of the two walls of this passive house, starting when the house was being built about 20 months ago, demonstrated that:

- The double-stud walls, south- and north-facing, were both performing well in terms of durability. The MC measured at the bottom of the studs remained below 15% after the construction was finished, for the locations monitored during this period of time. The MC of the south-facing wall dropped from about 20%, measured during construction, to about 11% after the construction was completed. During the same period of time, the MC of the north-facing wall fell from about 19% to 15%.
- The RH measured on the interior side of the MDF exterior sheathing in the south-facing wall ranged from 70% to 80%, and occasionally up to 90% in the winter. However, being typical of exterior sheathing without exterior insulation in this mild climate, the corresponding RH ranged from 80% up to 100% in the north-facing wall, indicating potential vapour condensation at this critical location.
- Based on vapour pressure analysis, no steep vapour pressure gradients were found in these two walls, indicating the overall vapour permeable nature and good drying performance of the wall

design. This could be partially attributed to the use of plywood, a structural sheathing located between the double-stud walls as the air barrier and vapour retarding layer, and using MDF as the exterior sheathing.

- The analysis showed a vapour drive from the exterior layers of the south-facing wall towards the interior layer, primarily due to the high temperature outside. The exterior sheathing had a good drying potential if wetting occurred. On the other hand, the partial vapour pressures were consistent across the north-facing wall in the wintertime, without showing a strong vapour drive from the interior in this mild climate. The exterior sheathing would have poor drying performance if wetting occurred in this location.
- The temperature distributions based on THERM 6.3 simulations were generally in good agreement with the measured temperatures across the walls, indicating that the thermal simulation was reasonably accurate. The effective R-value of the double-stud walls of this passive house was calculated to be approximately R-50 ($hr \cdot ft^2 \cdot F/Btu$) or RSI-8.8 (($m^2 \cdot K)/W$) (i.e. with a thermal transmission coefficient of 0.114 $W/m^2 \cdot K$).

7 Recommendations

The use of heat flux sensors needs to be further explored, particularly around sensor calibration and installation, in order to validate calculated effective thermal resistance of building envelopes.

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Appendix I: Vapour Permeance Testing of Wood Panels

Very preliminary vapour permeance testing based on ASTM E96: Standard Test Methods for Water Vapor Transmission of Materials, was conducted in the FPInnovations laboratory to compare several wood-based panels, including MDF (medium-density fibreboard based on MDI adhesive) from a Canadian manufacturer and a European manufacturer, and LDF (low-density fibreboard, used as non-structural sheathing or insulation) from a Canadian manufacturer and a European manufacturer, as well as OSB and plywood purchased from a local building supply store (as listed in Table 1). Three specimens were tested for each product, mostly from one small panel only.

The two LDF products had very similar vapour permeance results and were the most permeable among the six products tested. The European MDF was more permeable than the Canadian product, but both were highly permeable. The plywood and OSB specimens had much lower vapour permeance than the other four products tested, but were more vapour permeable than the vapour barriers defined by the Canadian building code. Based on the code (NRC, 2005), vapour barriers are materials with permeance not greater than 60 ng/(Pa·s·m^2), measured in accordance in ASTM E 96 (ASTM E 96, 2013) using the desiccant (dry cup) method. The permeance of most wood materials increases slightly with increase in humidity levels in the environment, which enables better drying when the humidity increases.

More testing is needed for wood materials to provide reasonably accurate property data for thermal and hygrothermal modelling of wood-based building envelopes. A few studies in the past included a limited number of wood products (Kumaran *et al*. 2002; Alsayegh *et al*. 201), more work is required to cover different products, wood species, different use conditions, and to account for the large variations typically associated with wood products.

Table 1 Vapour permeance testing results of six panel products based on the desiccant method*

Materials	Thickness	Density	Permeability (material property)	Permeance (for a given thickness)
	(mm)	(kg/m³)	(ng/Pa·s·m)	(ng/Pa·s·m²)
MDF No. 1 (Canadian, manufactured by Westfraser)	16.5	771.9	11.6	704.4
MDF No. 2 (European, “AGEPAN”)	16.4	569.5	20.8	1265.7
LDF No. 1 (Canadian, “DonaCona”)	10.8	234.6	33.2	3075.4
LDF No. 2 (European, “Steico”)	10.0	255.3	31.8	3182.0
OSB (Canadian, made with aspen)	12.5	649.0	2.3	184.3
Plywood (Canadian, made with “SPF”)	12.8	514.8	2.2	174.4

*All numbers in the table were an average of three replicates.