Spray Polyurethane Foam: The Need for Vapour Retarders in Above-Grade Residential Walls

Report for: Canadian Urethane Foam Contractors Association

Building Engineering Group, University of Waterloo

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Table of Contents

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Executive Summary

Spray polyurethane foam (SPF) is an airtight foam plastic insulating product installed in-situ by spray application. The product is used in the walls, floors, and roofs, of both commercial and residential construction. There are two broad classes of SPUF; low-density 8 kg/m^3 (0.5 pcf), open cell and quite flexible foam, and a high-density 32 kg/m^3 (2 pcf) closed cell rigid foam. Both product classes are studied here.

A common question encountered by SPF applicators, building designers, and code officials is the need for an additional vapour barrier or retarder. Experience by many contractors and some consultants suggest that special low permeance layers such as polyethylene are rarely needed in many types of walls. Theory indicates that closed cell foam is sufficiently vapour impermeable to control diffusion condensation and that low-density open-cell foam applications may require additional vapor diffusion control in some extreme environments. However, the need for, and type of additional vapour control layers remains unanswered to many.

A research project was initiated to help answer these questions. The objective of the project was to provide recommendations, based on sound scientific evidence, of the need for additional vapour control for both classes of SPF installed in framed walls of a wide range of building occupancy types and cold climates. A combination of full-scale natural exposure field tests, climate chamber measurements, and hygrothermal computer modeling was applied.

The National Building Code of Canada specifies that vapour barriers are not required when "it can be shown that uncontrolled vapour diffusion will not adversely affect any of, (a) health or safety of building users, (b) the intended use of the building, or (c) the operation of the building services. The research demonstrated the ability of typical framed walls using spray polyurethane foam insulation, with and without additional vapor barrier layers, to meet these requirements.

More specifically, the research concluded♠ that:

- Closed-cell (about 2 pounds per cubic foot density or more) spray foam applied in thicknesses of over 2" (50 mm) will control vapor diffusion to safe levels in all climates up to 10000 HDD and interior winter-time relative humidities of up to an over 50%RH. As thickness increases the level of diffusion control increases. The

♠ for walls with exterior layers of sheathing, membranes, cladding and other layers with a permeance of more than about 60 ng/Pa s m^2

diffusion control is equivalent to walls with the traditional fiberglass batt and polyethylene.

- Open cell (1/2 pound per cubic foot density) foam can control diffusion in climates that are not too cold (eg under 4500 HDD) and when the interior winter RH level is controlled by appropriate ventilation to below about 40%. Open cell foam does not have sufficient vapor control for use in very cold climates (4500 HDD to 5000 HDD) unless the interior winter-time RH is strictly controlled (to below about 30%RH).
- For either type of foam, the wood framing provides sufficient inherent vapor resistance to maintain the moisture content within the safe range even in very cold exterior climates
(10 000 HDD) and very humid interior conditions (50%RH in winter).

As for all walls made of all materials, a functional air barrier assembly must be provided, as well as rain control, fire control, structural sufficiency, etc.

The one-D WUFI Pro 3.3 hygrothermal modeling program was validated as an effective and accurate tool for predicting the moisture content of the sheathing in the field tests. It can be used to predict the performance of other wall assemblies in other climates if care is taken to define the material properties and boundary conditions.

Climate chamber vapor diffusion tests on a range of different products were conducted under a temperature gradient. These tests confirmed the performance noted in the field tests and demonstrated that different commercial products of the same class (closed cell or open cell) performed in a very similar manner.

An interesting observation noted in the materials sub-system climate chamber tests is that the HCFC-245 blown foam behaved essentially the same as the legacy HCFC-141b products. The vapour permeance of the new generation appears to be slightly less than the previous one.

Moisture Content (MC) in Wood Exterior Sheathing Subjected to Various Canadian Climates and Interior Relative Humidities

Chart values are %MC by dry mass of wood and represent a predicted maximum annual value

Legend: (green) = MC < 20%, no mold growth; (yellow) = MC is 20 to 28%, potential for mold growth; (red) = MC > 28%, moisture problems expected, this design is NOT recommended

Wall Construction			Vancouver HDD 3000			Toronto HDD 4000			Ottawa HDD 4500			Calgary HDD 5000			Winnipeg HDD 6000			Yellowknife HDD 8000			Inuvik HDD 10000		
Contents of Cavity	Depth of Cavity	Type of Vapour Control	Low RH 30/55%	Med. RH 40/60%	High RH 50%	Low RH 30/55%	Med. RH 40/60%	High RH 50%	Low RH 30/55%	Med. RH 40/60%	High RH 50%	Low RH 30/55%	Med. RH 40/60%	High RH 50%	Low RH 30/55%	Med. RH 40/60%	High RH 50%	Low RH 20/50%	Med. RH 30/55%	High RH 50%	Low RH 20/50%	Med. RH 30/55%	High RH 50%
Fiberglass (FG)	5.5"	Polyethylene sheet	12%	12%	12%	11%	11%	11%	10%	10%	10%	9%	9%	9%	10%	10%	10%	11%	11%	11%	10%	10%	10%
Fiberglass (FG)	5.5"	Latex paint+primer	14%	18%	21%	18%	25%	30%	21%	27%	33%	22%	28%	35%	28%	37%	43%	27%	37%	43%	35%	43%	46%
Spray Polyurethane Foam (SPF) – Open Cell	5.5"	Latex paint+primer	14%	15%	17%	14%	18%	21%	16%	20%	23%	16%	20%	22%	21%	26%	28%	20%	25%	27%	24%	28%	29%
Spray Polyurethane Foam (SPF) – Closed Cell[3]	2"SPF +3.5"FG[1]	Latex paint+primer	13%	14%	14%	12%	13%	13%	11%	12%	12%	10%	11%	11%	13%	13%	13%	13%	13%	14%	12%	12%	12%
Spray Polyurethane Foam (SPF) – Closed Cell[3]	2"SPF in 3.5/5.5"	Latex paint+primer	12%	13%	13%	11%	12%	13%	10%	12%	12%	10%	11%	12%	13%	14%	14%	12%	13%	14%	13%	14%	14%
Spray Polyurethane Foam (SPF) – Closed Cell[3]	3.5" SPF in 3.5/5.5"	Latex paint+primer	12%	13%	13%	12%	12%	12%	10%	11%	11%	9%	10%	10%	12%	12%	12%	12%	12%	12%	11%	12%	12%
Wood Stud[2]	3.5" or 5.5"	Latex paint + primer	7%	7%	7%	7%	7%	7%	5%	6%	6%	5%	5%	5%	6%	7%	7%	7%	7%	7%	5%	5%	6%
Other Applicable Locations (Heating Degree Days below 18°C) *From Environment Canada's Canadian Climate Normals 1971-2000*			Vancouver (2926), Abbotsford (2981), Victoria (3040)			Windsor (3524), Niagara Falls (3661), Kelowna (3869), Oshawa (3917), Hamilton (4012), Halifax (4030), London (4057), Toronto (4065)			Kitchener-Waterloo (4288), Kingston (4289), Montréal (4518), Moncton (4585), Ottawa (4602), Charlottetown (4715)			St. John's (4881), Trois-Rivières (4929), Calgary (5108), Prince George (5132), Sherbrooke (5151), Québec City (5202), Sudbury (5343)			Regina (5660), Edmonton (5708), Thunder Bay (5717), Winnipeg (5777), Saskatoon (5852), Whitehorse (6811)			Yellowknife (8256)			Inuvik (9767), Iqaluit (10117), Resolute (12526)		

General Notes:

a. Walls are residential wood frame with light-colored, thin cladding facing north: this is a worse-case scenario for cold-weather diffusion wetting

b. Results are for OSB sheathing. Plywood sheathing values will be equal or lower. OSB permeance is always over 60 ng/Pa·s·m^2 in exterior sheathing applications.

c. Sheathings of DensGlas, FiberBoard, and Gypsum Board are all very vapor permeable and hence will have lower moisture contents

d. Thicker foam will always result in lower wintertime sheathing moisture contents

e. Effective Air Barrier is assumed to be installed, as is proper rain control

Specific notes:

1. Apply SPF directly onto back of exterior sheathing
2. MC values are for outer 1/2" of wood stud
3. Closed Cell SPF should be applied in total thicknesses of more than 2" (50 mm), usually in lifts of no more than 2" (50 mm)

Summary Results of Vapor Barrier Requirements

1 Introduction

Spray polyurethane foam (SPF) is an airtight foam plastic insulating product installed in-situ by spray application. The product is used in the walls, floors, and roofs, of both commercial and residential construction. There are two broad classes of SPF; low-density 8 kg/m^3 (0.5 pcf), open cell and quite flexible foam, and a high-density 32 kg/m^3 (2 pcf) closed cell rigid foam. Both product classes are studied in the research reported here.

A common question encountered by SPF applicators, building designers, and code officials is the need for an additional vapour barrier or retarder. Experience by many contractors and some consultants suggest that special low permeance layers such as polyethylene are rarely needed in many types of walls. Theory indicates that closed cell foam is sufficiently vapour impermeable to control diffusion condensation and that low-density open-cell foam applications may require additional vapor diffusion control in some extreme environments. However, the need for, and type of additional vapour control layers remains unanswered to many builders, designers, and code officials.

The objective of this research project is to provide recommendations, based on sound scientific evidence, of the need for additional vapour control for both classes of SPF installed in framed walls of a wide range of building occupancy types and cold climates.

1.1 Background

It is well understood in the construction industry that increasing insulation is a cost-effective means to reducing energy consumption over the life of the structure and thereby reducing the environmental and economic impact of operating energy consumption. Not as well understood, however, is that the amount of energy savings depends on the choice of insulation, how is it installed and where it is located in the building enclosure assembly. Poor design and workmanship can reduce the effectiveness of the insulation and produce an enclosure that transfers much more heat than the theoretical value of the insulation would indicate. In addition, if enclosure weaknesses such as thermal bridging are not properly addressed, the heat transfer will short circuit around the insulation, making the heat control layer less effective overall.

The most commonly available insulating materials are fibreglass, rock wool, cellulose, and foam plastics. Each class of product has different characteristics, such as fire resistance, costs, vapor permeability, ease of installation, etc. One of the most often listed characteristic is that of the resistance of heat flow per unit thickness.

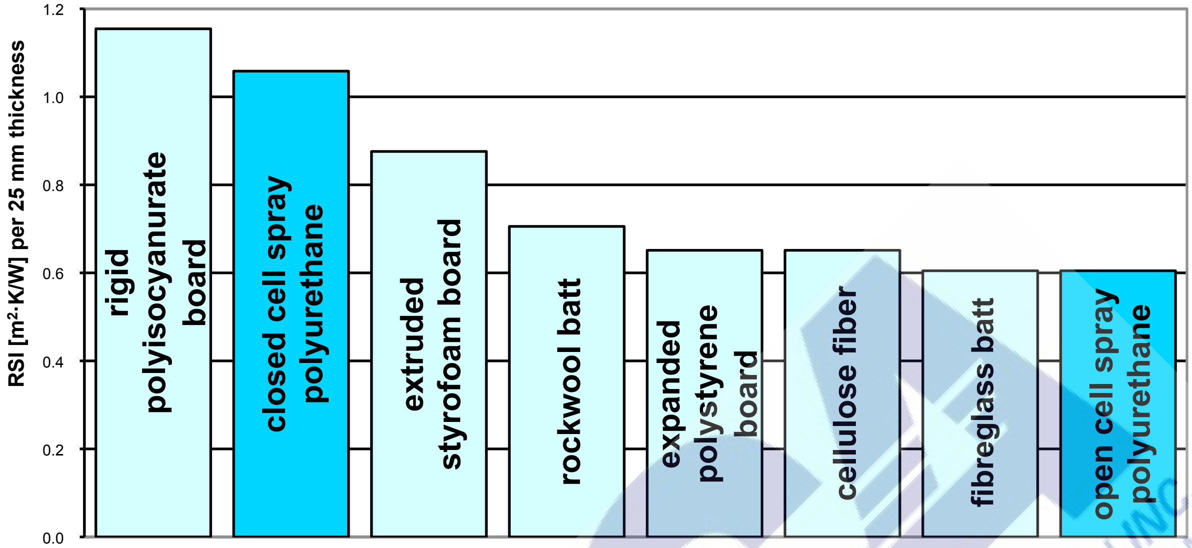

Figure 1.1: Average RSI values of Common Insulation Types (Straube & Burnett 2005)

Some insulation materials have the added benefit of providing significant resistance to air leakage or vapour diffusion or both. For example, some types of foam plastic have a high resistance to flow of heat, air and vapour and therefore have the potential to function as the heat, air and moisture control layers. At the other end of the spectrum, a material like fibreglass batt performs well as a heat control layer only. In an enclosure using fibreglass as the heat control layer, the air and moisture control layers must be designed and provided separately with other materials.

Spray polyurethane foam (SPF) is one type of foam plastic that is of great interest in building enclosure design because it can perform very well as multiple control layers. SPF provides one the highest heat resistances of any commonly available insulation products. The foam is created and applied on-site from a two-component liquid that mixes as it is being sprayed from a pressurized gun. The two liquids react chemically, bubbles form, the product expands, and the liquid is transformed into cellular plastic. The advantage of the on-site application process is that the liquid foam enters cracks, gaps and irregular cavities and fills them up as it expands. Once it cures, SPF creates a seamless, semi-rigid thermal and air barrier layer.

Medium and high density spray polyurethane foams also provide considerably more vapour resistance than traditional insulation materials. As a result, there will be applications in which medium and high density SPF can serve as the vapour control layer. Unfortunately, there is often confusion on the part of designers, builders and code enforcement officials about if and when these cases exist. If the cases could be identified and codified, the construction industry could benefit from eliminating a time consuming and costly step in construction.

1.2 Vapor Barriers and Air Barriers

Air has a limited capacity to hold water vapor: this maximum capacity drops significantly as the temperature drops. Condensation occurs when the air's capacity at a surface is exceeded and water vapor reverts to a liquid. Water vapor moves to potential condensation surfaces by two mechanisms:

1. vapor diffusion, the flow of vapor only from regions of high vapor content to regions of low vapor content and
2. convection (typically called air leakage), the flow air from regions of high pressure to regions of low pressure carrying water vapor along with it.

Vapor barriers or vapor diffusion retarders address the flow of vapor by diffusion only. Air barrier systems control the flow of vapor by air flow.

Airflow transports much more vapor than diffusion in most cases. Air barrier systems are always required in buildings (and required by Canadian building codes), and are often provided by sealed, continuous and supported 6 mil poly, sealed and continuous drywall, or sealed and continuous housewrap products, etc. Air barriers also ensure good thermal performance, reduce sound transmission, and help ensure good indoor air quality.

Spray polyurethane foam of both types can be part of an air barrier system. Continuity must be provided whenever the SPF is not fully adhered to an air impermeable substrate. Foam sprayed between studs provides an excellent air barrier. However, wood-to-wood joints between double studs, at sill plates to floor sheathing, and joints around windows require sealing to provide a continuous air barrier.

Vapor diffusion can transport sufficient quantities of vapor to result in condensation in some cases. To control the amount of vapor transported by diffusion, vapor barriers (e.g., 6 mil poly. The National Building Code of Canada specifies that vapour barriers are not required when:

> "it can be shown that uncontrolled vapour diffusion will not adversely affect any of, (a) health or safety of building users, (b) the intended use of the building, or (c) the operation of the building services."

The research reported here investigated the ability of typical framed walls using spray polyurethane foam insulation, with and without additional vapor barrier layers, to meet these requirements. In all cases, a functional air barrier system was provided (in the form of sealed drywall or a continuous chain of SPF and wood), as this is required in all buildings.

1.3 Experimental Program

The research consisted of there phases:

- Field measurements of performance of SPF and fiberglass batt insulated walls in a real wall exposed to the environment of South-western Ontario. The computer model was validated in this phase.
- Laboratory measurements of vapor diffusion wetting in a climate chamber under steady-state conditions. Different brands of SPF were investigated in this phase.
- Computer modeling of performance under a wide range of Canadian climate conditions, interior occupancies, and materials.

Each of the research phases is described in the separate chapters that follow.

2 Field Measurements

2.1 Introduction

This chapter presents the setup and results of a full-scale field investigation of the need for additional vapour retarding layers in both types of SPF in framed walls. Eight test walls were constructed and installed in the University of Waterloo's BEGHut test facility, maintained at a high (50%RH) interior humidity level. The moisture content of the exterior wood sheathing and wood studs were monitored for a period of over two years and the results used to assess performance.

Hygrothermal modeling was then performed and compared to the observed results to validate the model. Using the validated hygrothermal model, recommendations for the use of additional vapour control layers as a function of SPF type, wall assembly, and climate (interior and exterior) are discussed.

2.2 Experimental Setup

2.2.1 Test Facility Description

The University of Waterloo's BEGHut, located in Waterloo, Ontario is designed to investigate the performance of full-scale wall assemblies under natural exposure in this climate. This facility is maintained at a constant 20°C and 50% RH year-round. This is a high level for an office or residential building in cold climates, but is representative of museums, hospitals, and swimming pools. Interior relative humidity levels for houses in this climate zone typically range from 30-40% during the winter and 50-60% during the summer months.

2.2.2 Test Walls

The four assembly types (north and south duplicates; eight 2' wide test walls total) were installed November 2005 in the University of Waterloo's test hut (See Table 2.1).

Great care is taken using techniques developed over the last 20 yrs to isolate the performance of adjoining test panels from one another. Each test panel is surrounded by an insulated, airtight, waterproof, vapor impermeable frame (see Figure 2.3). Illustrations of the test hut and the layout of typical removable 4' x 8' panel slots are shown in Figure 2.2.

Assembly N6/S6	Assembly N7/S7	Assembly N8/S8	Assembly N9/S9
Brick	Brick	Brick	Brick
Ventilated Cavity (1½")	Ventilated Cavity (1½")	Ventilated Cavity (1½")	Ventilated Cavity (1½")
Water Resistive Barrier (Tyvek)	Water Resistive Barrier (Tyvek)	Water Resistive Barrier (Tyvek)	2" of 2 pcf closed cell spray polyurethane foam (light orange color)
½" OSB Sheathing	½" OSB Sheathing	½" OSB Sheathing	½" fiberglass faced exterior gypsum sheathing
2"x6" studs filled with 5 ½" of ½ pcf open cell spray polyurethane foam (beige color)	2"x6" studs filled with 4 ½" to 5 ½" of 2 pcf closed cell spray polyurethane foam (light green color)	2"x6" studs filled with 4 ½" to 5 ½" of 2 pcf closed cell spray polyurethane foam (light orange color)	2"x4" steel studs filled with R-12 fiberglass batt insulation
½" Gypsum Drywall	½" Gypsum Drywall	½" Gypsum Drywall	½" Gypsum Drywall
1 layer Primer and 2 layers Latex Paint	1 layer Primer and 2 layers Latex Paint	1 layer Primer and 2 layers Latex Paint	1 layer Primer and 2 layers Latex Paint

Table 2.1: Full-Scale Wall Assemblies (from Exterior to Interior)

For this project the typical BEGHut wall configuration was modified. Two 4' wide walls are used, four 2' wide walls were used in this project. As shown in Figure 2.1, the SPF test walls are located at panel slots 6 and 7 on the north side and 20 and 21 on the south. It is important to note that for this SPF project, the wall naming convention is North and South Walls 6, 7, 8, and 9. Walls 1 through 5 are used for other experiments but also include four datum walls which were used to compare the SPF walls to more traditional construction. The datum walls are of similar 2x6 wood frame construction, but are insulated with fiberglass batt insulation and vapour control is achieved with and without a polyethylene vapour barrier and painted gypsum drywall. The datum walls were installed on the north and south orientations at approximately the same time as the SPF walls. All framing and OSB was the same type from the same supplier.

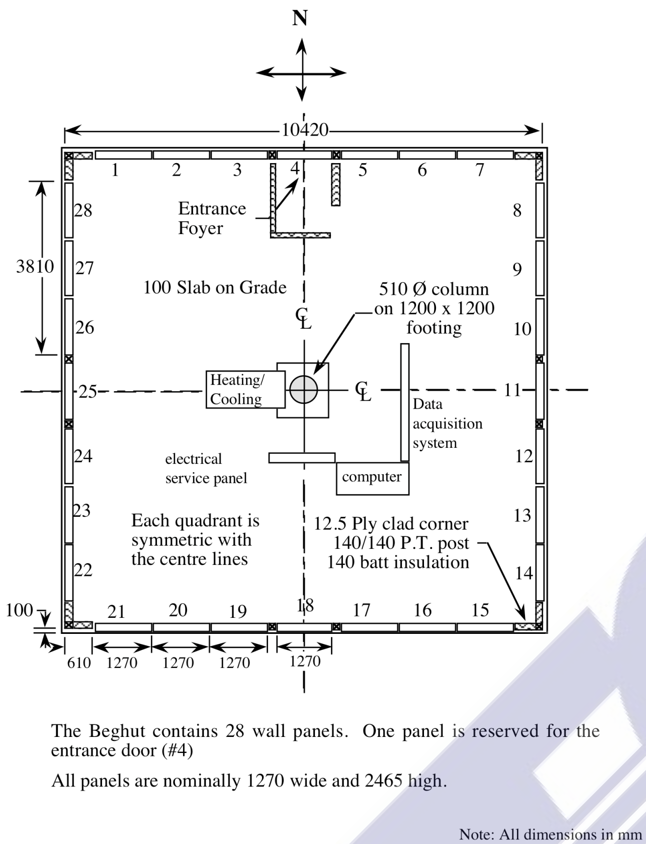

Figure 2.1: Plan view of BEGHut, showing orientation and panel locations

Figure 2.2: Opening perimeter details for removable test walls

The overall dimension of the four SPF walls is approximately 2400 mm wide by 2400 mm tall. Each test wall is approximately 600 mm wide with wood studs spaced at 400 mm on center. The brick veneer wall is ventilated with 10 x 80 mm open head joints at the bottom and top of the wall spaced every apart every two bricks (total of 5 vents bottom and 5 vents top). Air sealing techniques were used during construction to ensure accidental air leakage would not impact the results. Both types of SPF are resistant to airflow, and make up part of the air barrier system within these walls

Wall sensors measure temperature, relative humidity, and wood moisture content; in addition, interior and exterior conditions at the test hut are measured, including temperatures, relative humidities, wind speed & direction, solar radiation, and rainfall. The same sensor layout was used in all walls (as much as possible), in order to allow for direct comparisons between the walls. All sensors shown in the following diagrams are installed at the vertical centerline of the wall; a section at this plane is used to show sensor placement.

The sensor layout and wall construction details are shown in Figure 2.3 through Figure 2.9**Error! Reference source not found.**. Note that these figures do not include flashing or air sealing details: they are meant as a schematic representation of the wall assemblies.

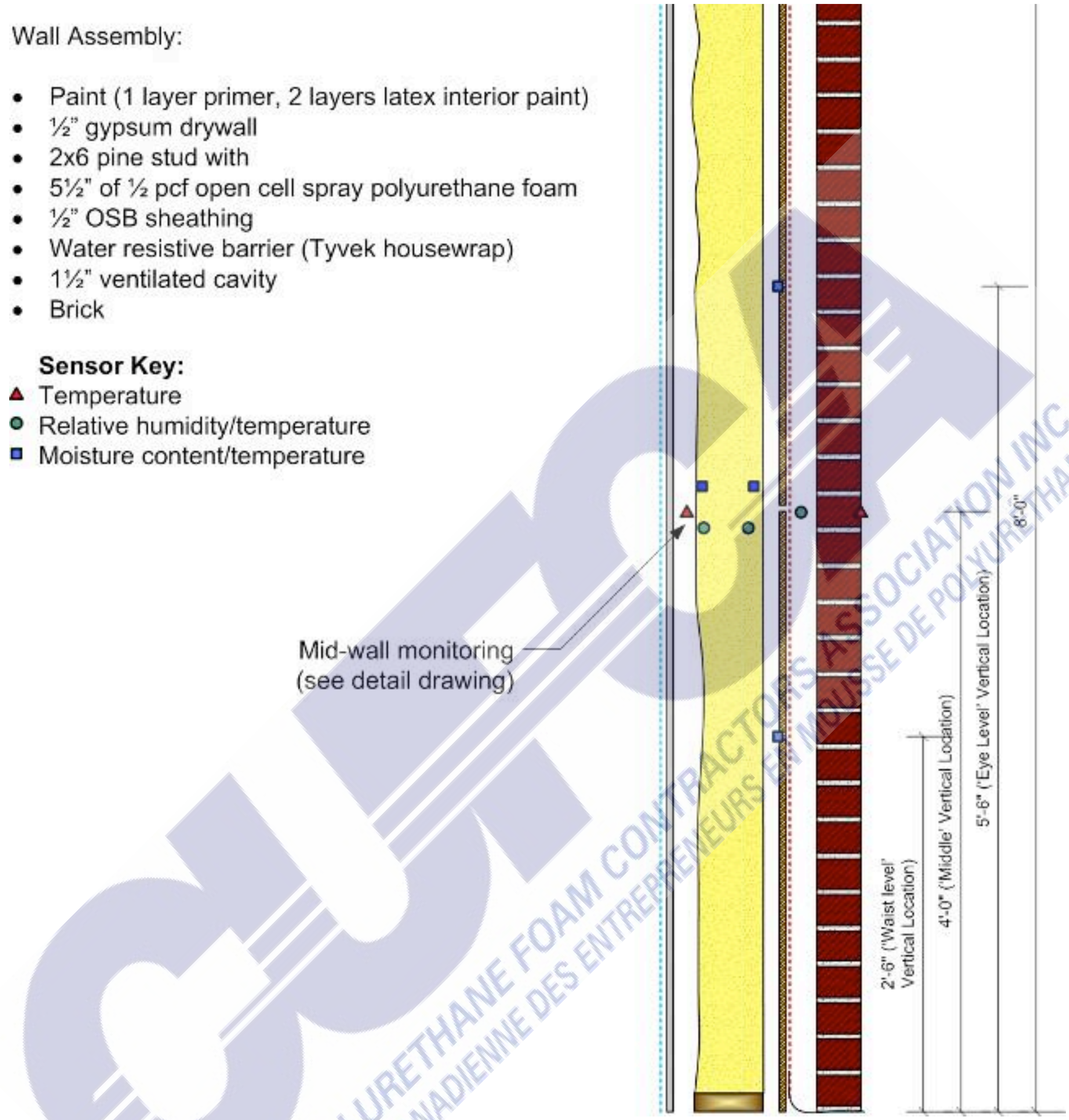

Figure 2.3: Wall Assembly 6 (1/2 pcf open cell SPF)

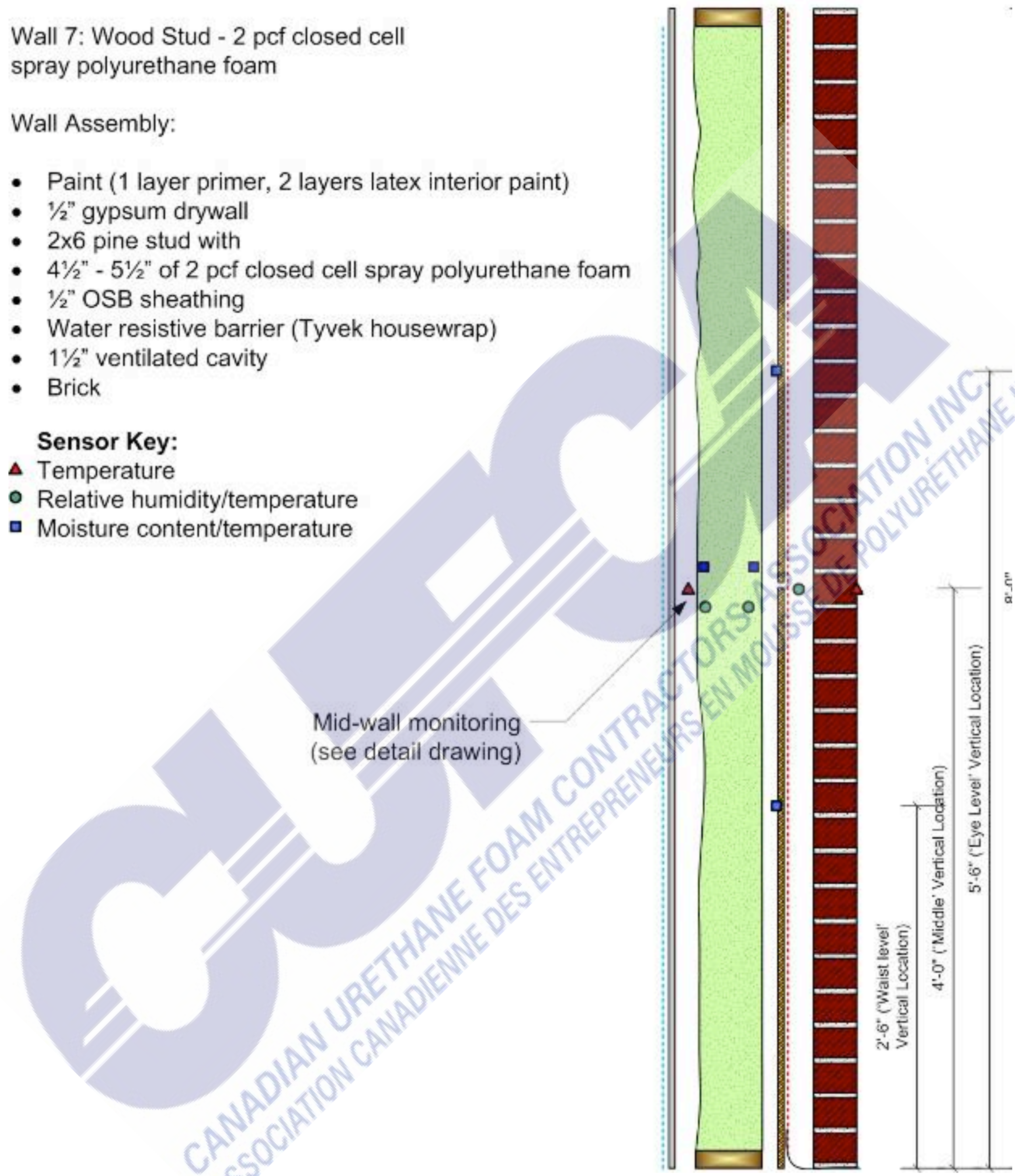

Figure 2.4: Wall Assembly 7 (2 pcf closed cell SPF – light green)

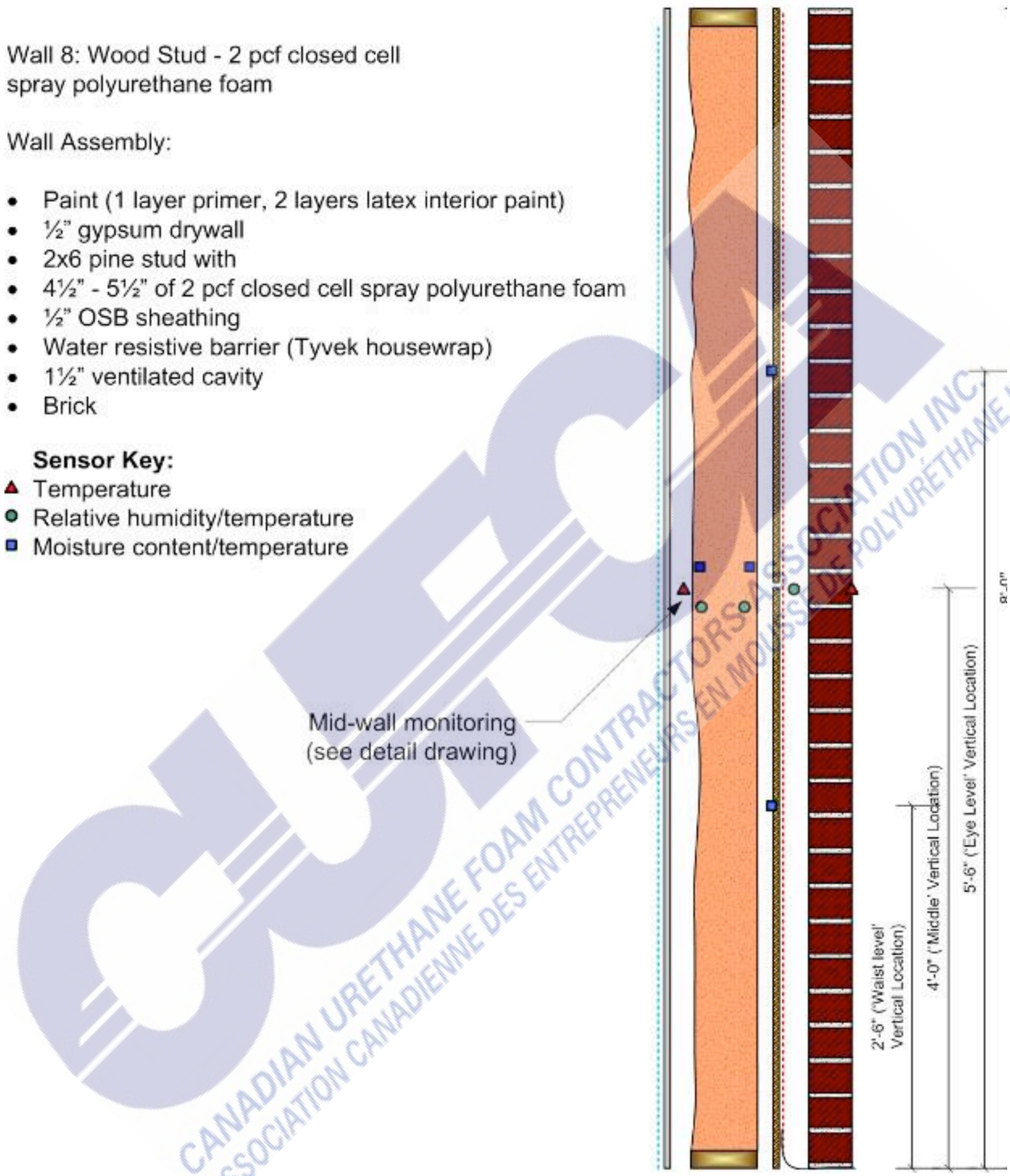

Figure 2.5: Wall Assembly 8 (2 pcf closed cell SPF – light red)

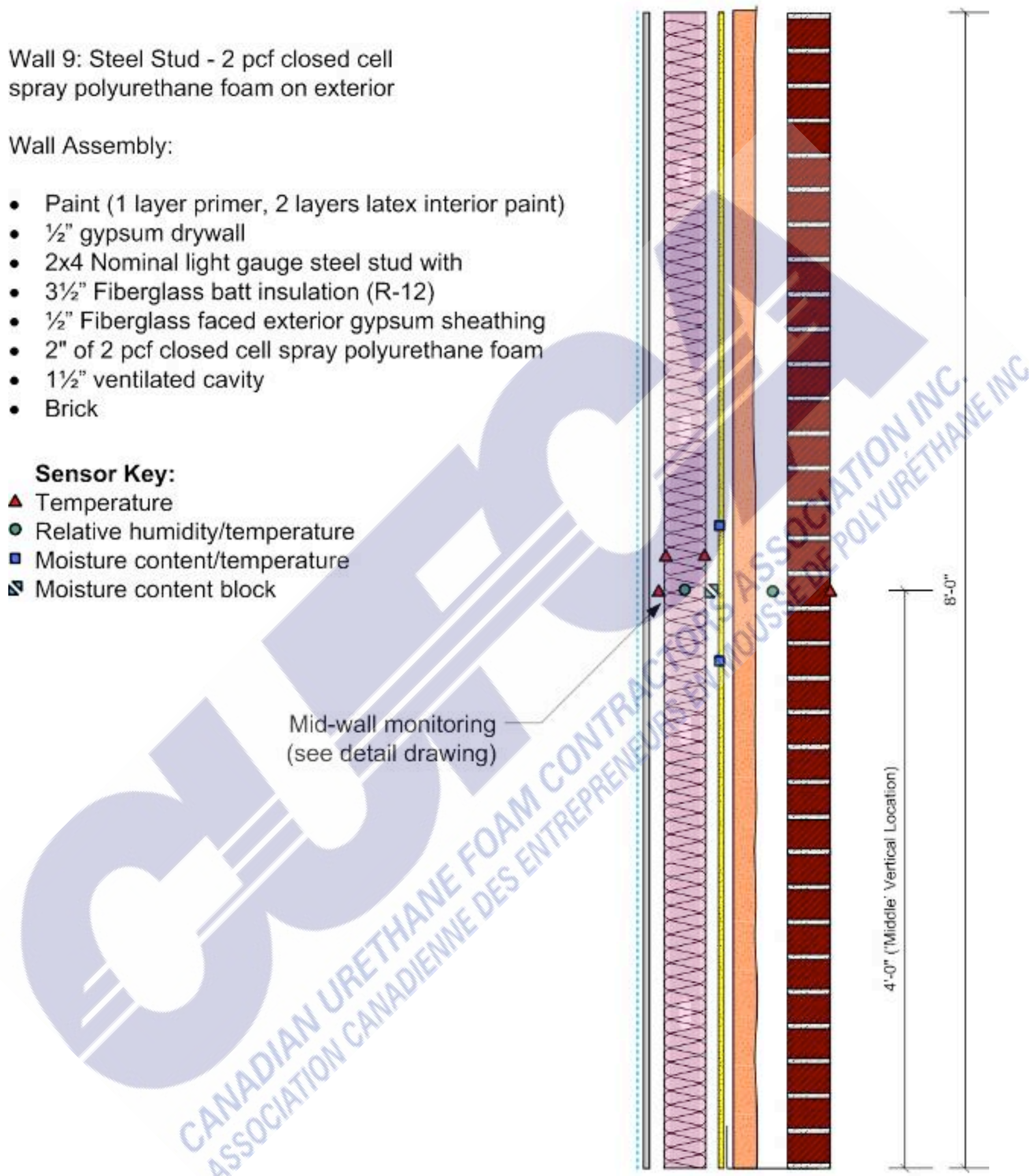

Figure 2.6: Wall Assembly 9 (Steel Stud/Batt Insulation, 2 pcf closed cell exterior – light red)

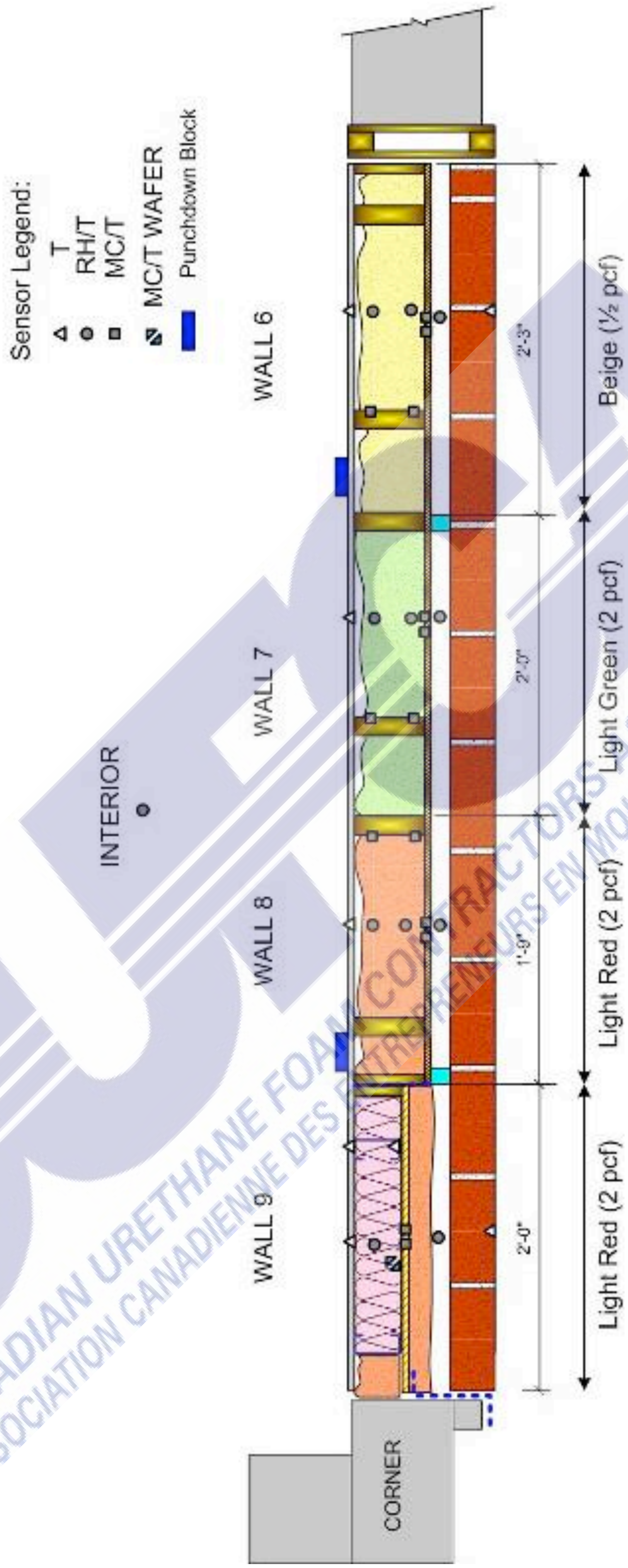

Figure 2.7: Wall Assemblies Installation in BEGhut (plan view)

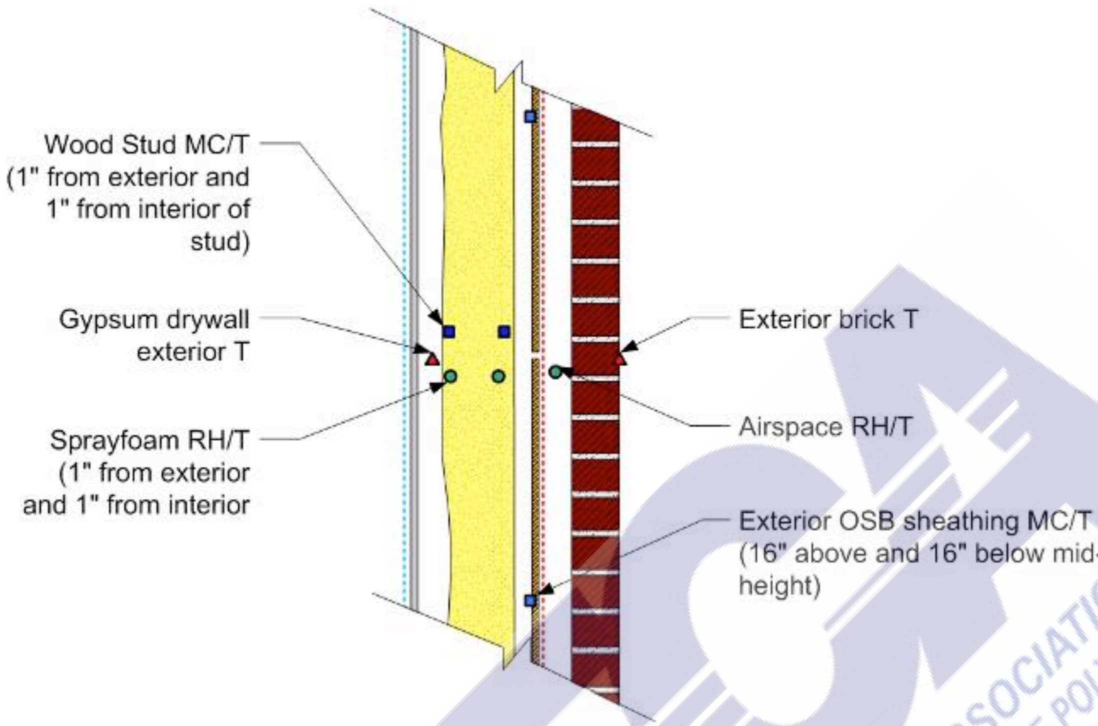

Figure 2.8: Wood Stud Wall Assembly (Walls 6, 7, 8) close-up of sensors

Exterior temperature, relative humidity, and environmental conditions including: rainfall, wind speed, wind direction, and solar radiation are measured at the roof of the BEGHut and are common measurements for all BEGHut projects.

Temperature, relative humidity, and wood moisture content sensors were installed in the test panels along the centerline of the stud bays Sensors were installed at mid-height of the walls approximately 1200 mm from ground level. The same sensor layout was used in all walls in order to allow for direct comparisons between the assemblies.

Brick temperatures are measured at the outboard face; the sensors are embedded in the brickwork mortar.

Airspace conditions are measured with both a temperature/relative humidity sensor; sensors hang in the open airspace of the cavity.

Stud space temperature and relative humidity are measured at two locations embedded within the SPF; located at 25 mm from the exterior sheathing and 25 mm from the interior drywall.

In the wood stud walls (6, 7, and 8) moisture content and temperatures are measured at the inboard and outboard sides of the wood studs (approximately 10 mm or 3/8" from the faces); these measurements can be used to reveal moisture drives towards the interior or exterior of the assembly and demonstrate that the wood studs are vapor resistant.

Wood Sheathing moisture content and temperature are measured in the OSB exterior sheathing (walls 6, 7, and 8). Sensors are located at 400 mm (16") above and 400 mm(16") below the mid-height, "eye-level" and "waist height" correspondingly. The construction gap between the sheets of OSB sheathing is located at wall mid-height, and it should be noted that while the OSB is from the same batch, the top and bottom OSB sheathing in the wall corresponds to a different sheet of wood. Sheathing moisture content reflects drives and gradients across the assembly; temperature is used to correct the moisture content measurement.

Interior temperature and relative humidity is measured with an interior sensor suspended in the interior space of the test hut.

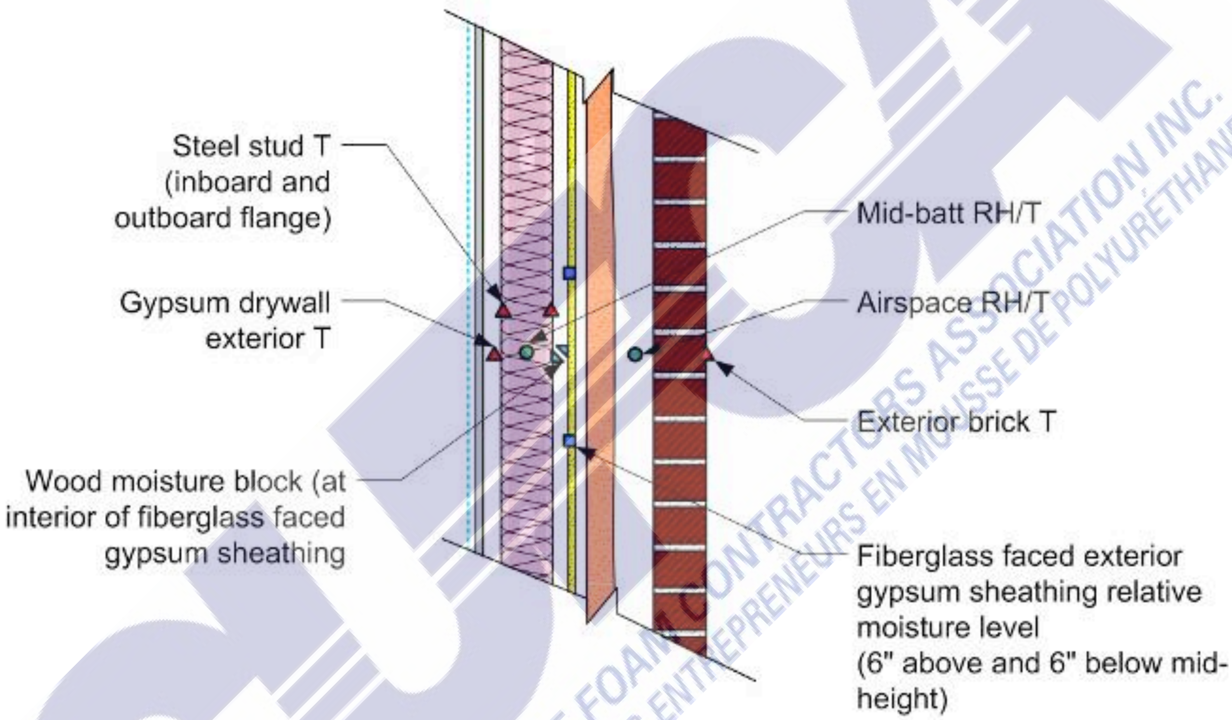

Figure 2.9: Steel Stud Wall Assembly (Wall 9) close-up of sensors

Gypsum relative moisture level and temperature are measured in the exterior fiberglass-faced gypsum (wall 9). Moisture pin sensors are located at 150 mm (6") above and 150 mm (6") below the mid-height. The gypsum sheathing is one continuous approximately 2' wide by 8' tall sheet. The same sheet was cut into two halves, one for each of the north and south walls. Gypsum sheathing relative moisture level reflects drives and gradients across the assembly; temperature is used to correct the moisture content measurement. In addition to moisture pins embedded into the gypsum sheathing, a wood moisture block was installed to the interior of the gypsum sheathing. The wood moisture content is used to correlate with the relative gypsum moisture level.

In the wood stud test walls stud space temperature and relative humidity are measured at two locations located at 1" from exterior sheathing and 1" from interior drywall. These sensors are used for these important measurements typically used to characterize walls against each other and assess performance.

In the steel stud wall (Wall 9) stud space temperature and relative humidity are measured at mid-thickness in the insulation batt. These sensors are used for these important measurements typically used to characterize walls against each other and assess performance.

In the steel stud wall two additional temperature sensors were installed at the inboard and outboard steel stud flanges. The sensors measure the temperature difference across the stud to assess the effect of thermal bridging of the steel studs across the batt insulation.

At the interface between the exterior side of the drywall and the stud bay cavity a temperature sensor is installed. The temperature sensor can be used, for instance, to compute the relative humidity at the drywall, given the dewpoint of the stud space (from the T/RH sensor). Tem

The moisture content, temperature and relative humidity sensors are measured automatically every five minutes and averaged over the hour by a Campbell Scientific CR1000 system. In addition average wind speed & direction, solar radiation, and net rainfall are recorded every hour. Typical instrumentation details and wood moisture-content correlations can be found in Straube & Schumacher (2002). Wood stud wood moisture content readings are corrected for temperature and for species whereas OSB has been corrected for temperature only. Species corrections for Canadian OSB are available from only a limited data set (Onysko 2006). All OSB MC data reported in this paper are uncorrected for species. The currently available data shows a true gravimetric moisture content of about 2% lower than the uncorrected MC presented here for the range of 15%MC to over 30%MC.

2.2.3 SPF Material Properties

Three different SPF products were selected for use in the study. Both distinct classes of SPF commonly used in construction, high-density (2 pcf) closed-cell or low-density (0.5 pcf) open-cell foams, were represented. The products chosen for this study were provided by one large manufacturer; however the material properties are representative of other products available in the industry that meet the CAN ULC 705.1 Standard. The climate chamber studies reported in Chapter 3 demonstrate that the products in each class perform in a very similar manner.

All spray foams were installed by a licensed applicator under normal interior conditions. Material properties taken from published material property data for the three types of SPF are and summarized in Table 2.2. The values are all for the cores of the product and exclude the surface film.

The open cell foam (Type C) was sprayed to a full stud cavity depth of 140 mm. Excess foam was removed to allow drywall installation. The surface skin was removed. Note that the surface skin provides little resistance for open cell foams (as is demonstrated in the climate chamber tests in Chapter 3). The closed cell foams (Types A and B) were sprayed to an average depth of 130 mm within the 140 mm stud bay to allow flush placement of the drywall over the uneven surface of the foam. This method maintained the surface skin integrity of the closed cell foam.

Table 2.2: SPF Material Properties (From manufacturers literature & CCMC evaluations)

Material Properties	Type A – red	Type B – green	Type C – yellow
Type	Closed cell	Closed cell	Open cell
Density	32 kg/m^3 (2 pcf)	32 kg/m^3 (2.0 pcf)	8 kg/m^3 (0.5 pcf)
Thermal Conductivity (Long Term Design Value)	0.024 W/m K	0.024 W/m K	0.042 W/m K
Insulating Value (Long Term Design Value)	RSI 1.06 per 25.4mm R 6.0 per inch	RSI 1.06 per 25.4mm R 6.0 per inch	RSI 0.6 per 25.4mm R 3.4 per inch
Vapour Permeability	1.8 ng/Pa·s·m	2.2 ng/Pa·s·m	33.0 ng/Pa·s·m
Vapour Permeance for Thickness Installed	14 ng/Pa·s·m^2 for 130 mm	17 ng/Pa·s·m^2 for 130 mm	236 ng/Pa·s·m^2 for 140 mm

2.3 Results

The analysis focuses on the results for the eight-month winter period from early November to July 2006. The interior and exterior boundary conditions for the experiment are presented followed by a discussion of the open cell and closed cell SPF wall results.

2.3.1 Boundary Conditions

Indoor and outdoor temperature and relative humidity conditions are shown in Figure 2.10 for the eight month monitoring period from November 10th, 2005 to July 10th, 2006.

2.3.1.1 Open Cell SPF (Wall 6)

Temperature, relative humidity, moisture content, vapour pressure, and dewpoint temperature plots were analyzed for the open cell SPF walls (N6 and S6). Performance relating to the durability of the materials, mainly the moisture content of the OSB sheathing and wood studs is discussed.

According to manufacturer and CCMC data sheet, open cell SPF has a vapour permeability of around 33.0 ng/Pa·s·m. Therefore, 140 mm of the material has a permeance of approximately 236 ng/Pa·s·m^2. The gypsum drywall and latex paint/primer have a vapour permeance in the order of 2000 and 300 ng/Pa·s·m^2 respectively. Summing the permeance in series, the total assembly permeance on the interior side of the sheathing is approximately 124 ng/Pa·s·m^2. A typical residential wall with a polyethylene vapour barrier would have a vapour permeance inboard of the sheathing of <5 ng/Pa·s·m^2, regardless of the type of insulation.

Typical wood framed walls constructed with a polyethylene vapour barrier do not usually experience problems in the winter as a result of vapour diffusion to the exterior, as the polyethylene is impermeable to the interior water vapour source. However experience has shown that these walls can experience problems when other moisture sources including outward cold-weather air leakage condensation and rain water leakage, or because sun-driven inward vapor flow cannot dry to the interior during warmer weather.

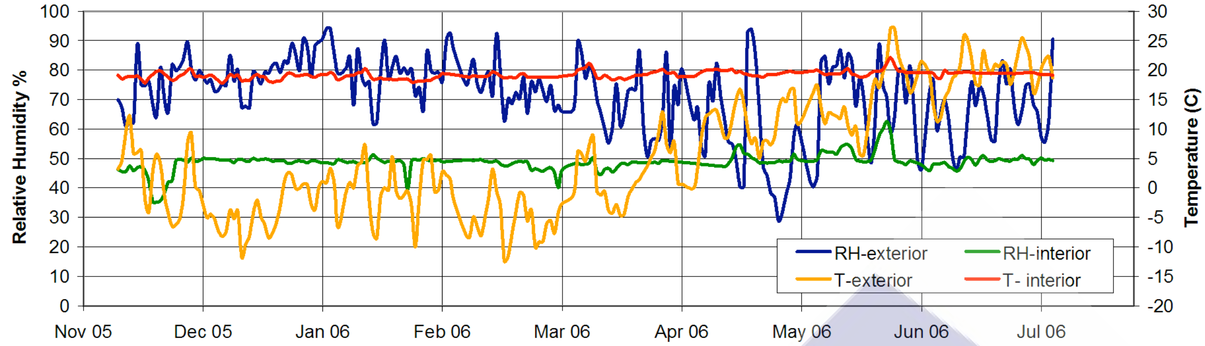

Figure 2.10: Exterior and Interior Air Temperature and Relative Humidity (November to July)

In order to experimentally determine if additional vapour resistance is required for the open cell SPF and how much is required, the open cell walls were instrumented to determine how much moisture would accumulate at the sheathing, driven by vapour diffusion in absence of a vapour barrier. Prior to the experiment it was predicted that the open cell SPF walls would experience some wintertime vapour diffusion condensation which would increase the sheathing moisture content. The results of the testing show that walls on both north and south orientations are experiencing wintertime vapour diffusion with peak moisture levels within the sheathing and studs at the end of winter. This increase in moisture content at the sheathing and studs is shown in Figure 2.11 for wall N6 and Figure 2.12 for wall S6.

The OSB sheathing in the north wall had moisture content exceeding 30% MC for approximately 2 months and 20% for almost 4 months continuously. This is a dangerous level of moisture. Sheathing moisture contents were much lower within south wall S6 and exceeded 20% MC for only a few weeks. Differences appear to be as a result of higher sheathing temperatures observed in the south walls from increased solar radiation, compared to the north, which would reduce the amount of vapour diffusion condensation. Warmer sheathing results in drier sheathing. The moisture content of the studs remained within safe levels for duration of the test, reaching a peak of 16% in wall N6 at the outboard edge.

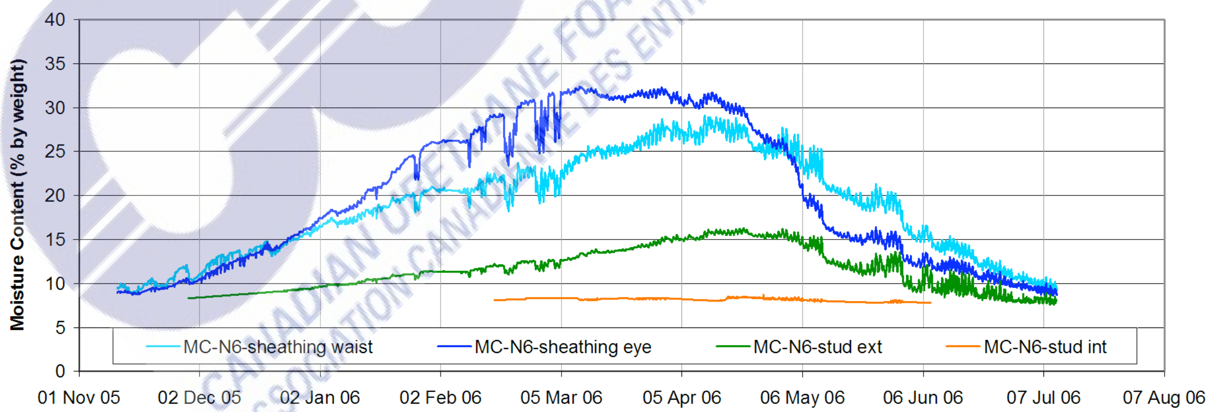

Figure 2.11: Wall N6 – Open Cell SPF Moisture Content of Sheathing and Studs

When the exterior temperature increased in April, both walls quickly dried down to levels below 10% by the beginning of July.

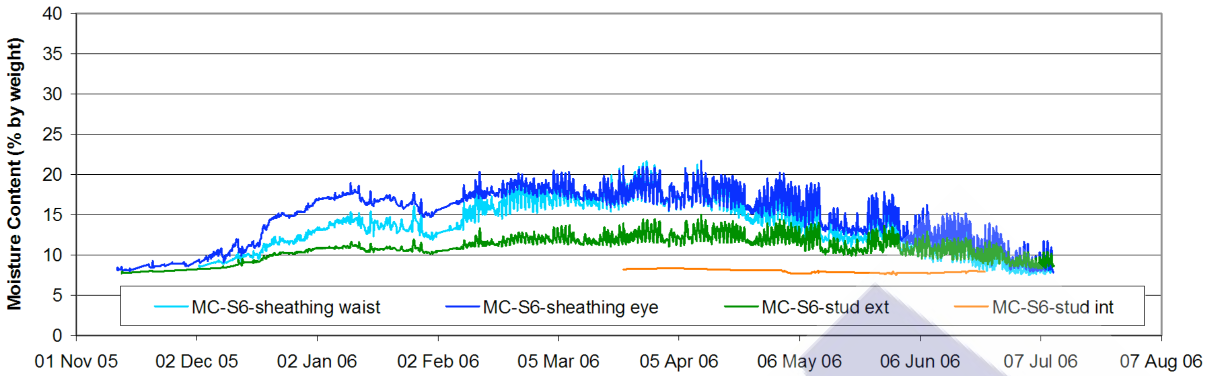

Figure 2.12: Wall S6 – Open Cell SPF Moisture Content of Sheathing and Studs

From these results, it can be concluded that the level of vapour control is insufficient for this wall assembly in a north orientation under these interior conditions (50%RH wintertime levels), but could also be representative of a wall at any orientation which was shaded from the sun during the winter. During the summer the walls appear to be performing well.

Wall N6 is further compared to wall N2 which has essentially identical construction except for the use fiberglass batt insulation instead of open cell SPF. Figure 2.13 compares the moisture content of the OSB sheathing for both of these walls.

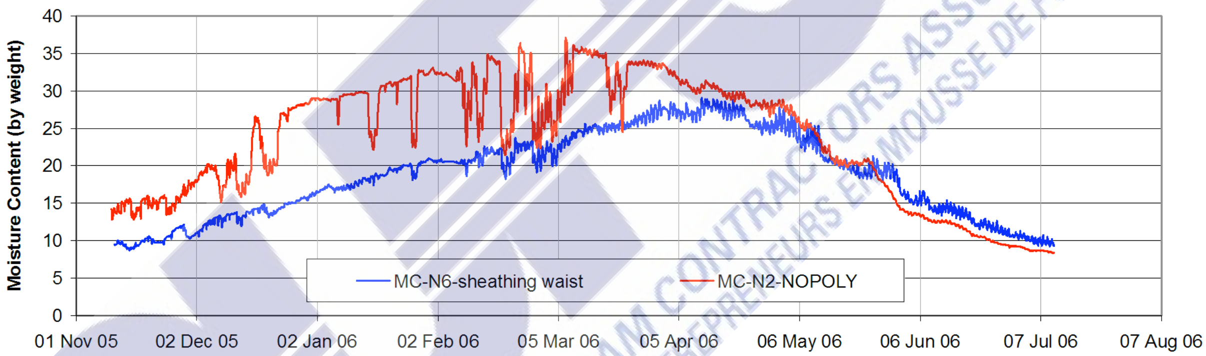

Figure 2.13: Moisture content of Sheathing Wall N6 (open cell) versus datum wall without poly

The moisture content of the OSB sheathing in the standard wall with no poly is higher than the SPF wall in the same orientation, with moisture contents above 30% for prolonged periods of time. This shows the relative damping effect of the SPF, and the impact of a difference in inboard vapor permeance of approximately 124 ng/Pa·s·m^2 for the SPF wall versus 215 ng/Pa·s·m^2 for the fiberglass batt datum wall with the same interior paint layer and gypsum drywall.

Moisture transport within the open cell SPF walls can be analyzed using vapour pressures (absolute moisture levels) within the wall assembly. Figure 2.14 plots the vapour pressures of the interior air, exterior air, cladding cavity air, and at the interior face of the OSB sheathing from November to July. A typical winter week from December 1st to 7th is shown in further detail in Figure 2.15 and a typical summer week from July 1st to 7th is shown in Figure 2.16 to show the difference in seasonal vapour pressure gradients.

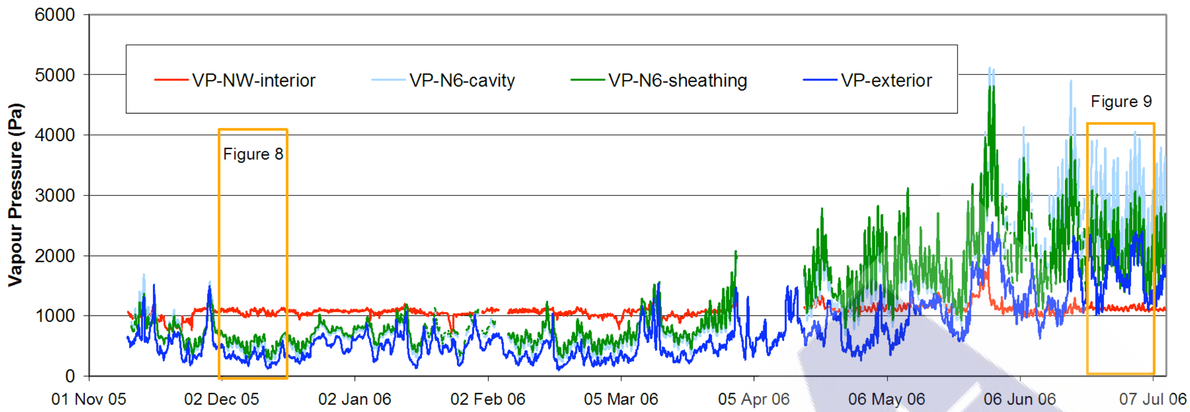

Figure 2.14: Wall N6 – Open Cell SPF Vapour Pressures within Wall Assembly (Nov to July)

During the winter months the interior test house vapour pressure is, on average, 300-500 Pa higher than the sheathing and exterior air, resulting in a small but consistent vapour drive towards the exterior (Figure 2.15). During the spring, with higher temperatures and increased solar radiation, the vapour pressure of the exterior air, sheathing, and cavity space increases significantly above the interior vapour pressure and vapour flow is reversed. Vapour differences in the spring and summer are in the order of 1000-2000 Pa, much higher than the winter. The much higher warm weather vapor pressures explain why drying occurs at a faster rate in warmer weather.

An analysis of the vapour pressures in the summer (Figure 2.16) indicates that vapour is flowing towards the interior resulting in increased relative humidity within the foam and at the foam-to-gypsum drywall interface. However as the paint layer is relatively permeable, the vapour is able to flow through to the interior. The relative humidity at the interface between the gypsum board and gypsum drywall ranges between 60 to 80% during the time in the summer when this drying occurs. If the interior RH were maintained at a higher level (a more typical 60%) during summer the vapor pressure difference would drop by about 10%, as would the vapor diffusion flow rate to the interior.

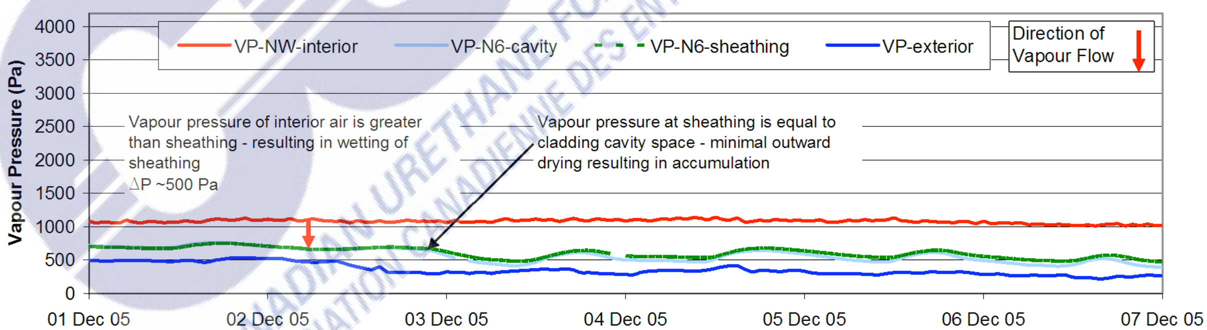

Figure 2.15: Wall N6 – Vapour Pressure Gradient during a typical winter week (Dec 1-7, 2005)

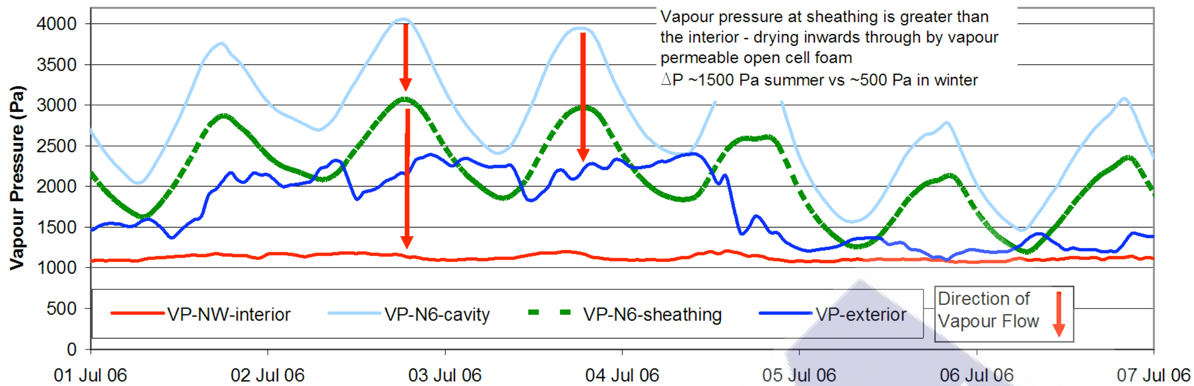

Figure 2.16: Wall N6 – Vapour Pressure Gradient during a typical summer week (July 1-7, 2006)

Interior conditions of 20°C and 50% RH result in a vapour pressure of approximately 1200 Pa, which results in a high wintertime vapour diffusion drive to the exterior. If the interior conditions were instead set at 20°C and 30%RH, more typical cold weather wintertime values, the vapour pressure would be significantly lower (approximately 700 Pa), which would result in significantly smaller vapour drives. This would result in a reduced moisture accumulation at the sheathing. This is further modeled and discussed in the following section on hygrothermal modeling.

2.3.2 Closed Cell SPF (Walls 7 & 8)

The performance and moisture content of the OSB sheathing and wood studs is discussed for the closed cell SPF walls 7 and 8. The two closed cell SPF products used in this experiment have a vapour permeability of approximately 2 ng/Pa·s·m, thus for 130 mm the permeance is approximately 15 ng/Pa·s·m^2. Summing the permeance of the drywall and paint in series the net permeance is approximately 14 ng/Pa·s·m^2 inboard of the sheathing, much lower than the open cell foam at 125 ng/Pa·s·m^2 and compares well to polyethylene at <5 ng/Pa·s·m^2. It should therefore be expected that the closed cell SPF walls should have lower wintertime sheathing moisture contents than the open cell SPF walls.

The results of the testing show that both walls 7 and 8 on both north and south orientations are experiencing peak moisture levels of up to 20% within the sheathing and <15% in the studs at the end of winter, lower than the open cell SPF walls. Figure 2.17 plots the moisture content of the sheathing and studs in wall N7. Walls N8, S7 and S8 show similar results.

Walls on the south tracked the same moisture levels as the north, with a peak moisture content of up to 20% and drying down during the summer (although not as low as the open cell walls). The south walls experienced more spikes in the moisture content, which correlated with solar drives. The SPF walls are compared to the datum wall N3 which is constructed with batt insulation instead of SPF and a polyethylene vapour barrier at the interior.

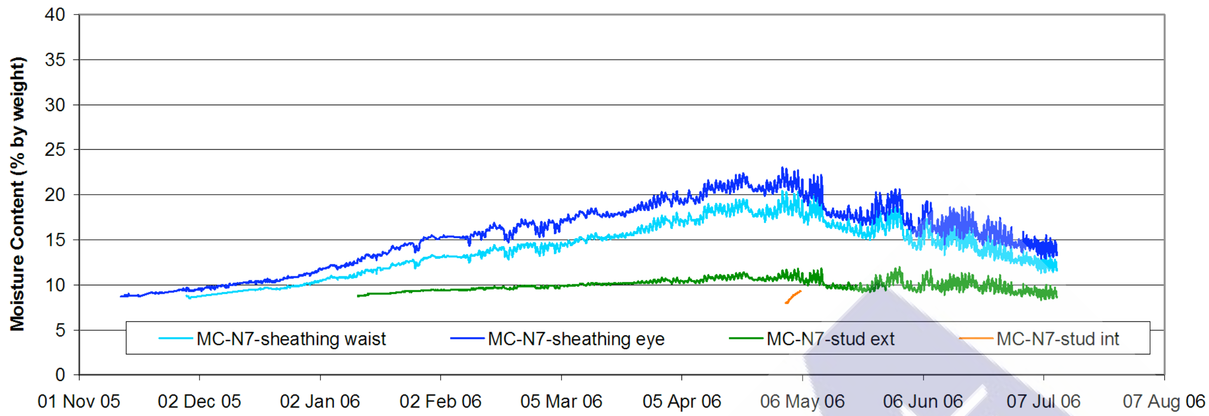

Figure 2.17: Wall N7 – Closed Cell SPF Moisture Content of Sheathing and Studs

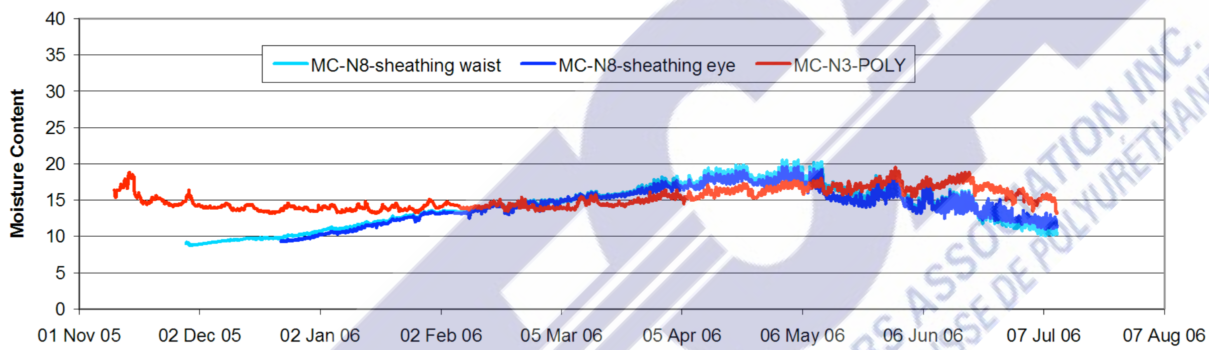

Figure 2.18: Moisture content of Sheathing Wall N8 (closed cell) versus datum wall with poly

The closed cell SPF wall performs with similar trends to the poly wall (Figure 2.18), however the poly wall started with higher initial moisture contents from the warm weather (the walls were built 2 months earlier). The SPF wall could also be experiencing a very small vapour drive from the interior, which would increase the wintertime moisture content, similar to the open cell SPF walls and hence the peak a few months earlier. Also the drying appears to be improved with the closed cell SPF as shown in June and July.

Upon closer examination the moisture source for the closed cell walls appears to be *largely from the exterior*, ie. from high relative humidity within the cavity space behind the brick. The sheathing moisture content is less affected by the interior conditions than the conditions behind the cladding. The relative humidity within the ventilated cladding cavity is a function of the exterior temperature, moisture storage in the cladding, and cladding ventilation rates. Brick has the capacity to store large amounts of moisture from rain and then release it as vapour. Ventilation is provided in these walls by top and bottom vents similar to previous BEGHut tests which have been shown to be sufficient to allow for significant sheathing drying rates (Straube et al. 2004). The BEGHut walls are typical of a single storey house construction with 600 mm overhangs, and past experiments have shown a driving rain factor (DRF) of approximately 0.2 can be used to predict the amount of driving rain (Straube et al. 2005).

From these results, it can be conclusively stated that the level of vapour control provided by the closed cell SPF is sufficient to prevent high moisture contents during the winter months.

2.3.3 Wood Stud Performance

Although closed cell SPF has sufficiently low vapor permeance (in thicknesses of about 2”) to act as a vapor retarder, contractors, designers and code officials sometimes believe that vapor will diffuse through the wood studs to the exterior, bypassing the vapor resistance of closed cell SPF.

The vapor permeability of solid wood is approximately 1.4 ng/Pa·s·m, which for an 89 mm stud is a permeance of 16 ng/Pa·s·m^2 or for a 140 mm stud a permeance of 10 ng/Pa·s·m^2. These permeances are very low and compare to the permeance of 140 mm of closed cell SPF, which is about 14-17 ng/Pa·s·m^2.

The measured moisture content of the studs in the field testing were lower than that of the OSB behind the foam. This result should not be surprising as the wood is predicted to have a similar permeance to that of closed cell SPF, but with much more storage capacity.

Needless to say, it can be concluded based on theory and measurements that wood studs require no additional vapor diffusion control layer.

2.4 Hygrothermal Model Validation

The WUFI 4.0 Pro computer program was used to model the test walls. WUFI is an advanced commercially available hygrothermal moisture program used by numerous practitioners. Its accuracy has been verified against numerous full-scale field studies of enclosure performance (roofs, walls, foundations, parking garage decks, etc.) over a number of years (Kuenzel 1995, Kuenzel & Krus 1997, Kuenzel 1998, Hens et al 1996). It is one of the few models that can properly account for rain absorption (Straube 2003). Given the appropriate material data, WUFI calculates heat and moisture flow every hour under the influence of sun, rain, temperature and humidity.

A WUFI computer model was built of each test wall system using materials available in the WUFI database. The open and closed cell SPF material properties were modified to match those provided by the manufacturers where they differed from the WUFI database. Real BEGHut interior and exterior environmental data (rain, solar radiation, wind, temperature, relative humidity) was input in the WUFI model as the model boundary conditions.

First run simulations with the real weather data provided excellent correlation with the measured results. Further simulations were performed and variables systematically adjusted to calibrate the results of model predictions to the measured data. Simulated temperature, dewpoint, and moisture content results were compared to measured data to ensure accuracy. This comparison provided a great amount of confidence in the ability of the model to interpolate and extrapolate to other situations. For comparison purposes the moisture content result in the sheathing for open cell wall N6 is shown in Figure 2.19.

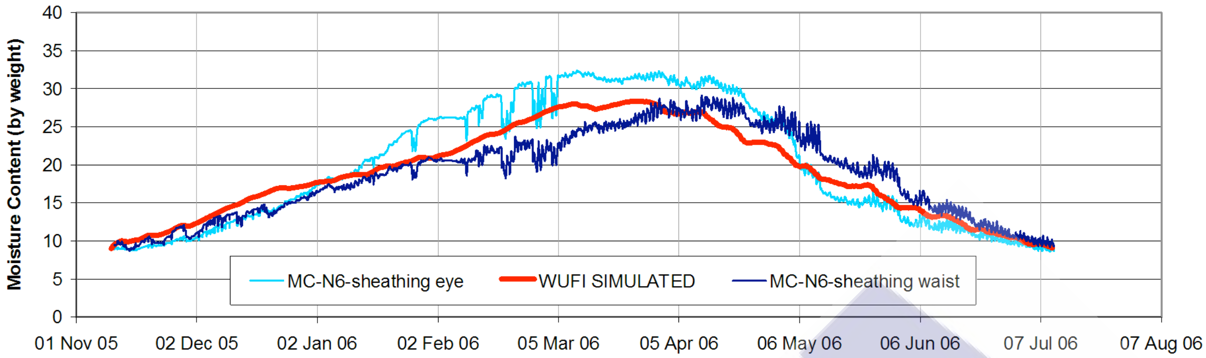

Figure 2.19: Wall N6 - Measured Moisture Content Compared to WUFI Simulated Results

A number of parametric simulations were performed and are presented here, using the eight months of the BEGHut data to determine the impact of interior relative humidity, orientation and vapour control layer. Further extrapolation to other climates is performed using climatic data within the WUFI database for longer than 8 months.

2.4.1.1 Indoor Relative Humidity

The interior conditions of the BEGHut are at a relatively constant 20°C and 50% year round. A wintertime relative humidity of 50% is high for typical residential and commercial buildings in this climate, but typical of a museum or hospital. A parametric analysis was performed using WUFI to show the impact of a 50% relative humidity has on the measured results for the open cell SPF walls. Figure 2.20 shows the impact of a 30%, 40%, 50%, and 60% interior relative humidity during the winter when the temperature is maintained at 21°C for a north oriented wall (using a 300 metric perm paint layer).

This plot shows the importance of a moderate indoor relative humidity and the impact it has on the performance of the OSB sheathing. An indoor relative humidity greater than 35-40% will result in cautionary moisture levels at the sheathing for this wall assembly under these exterior conditions. A relative humidity of 60% or higher would represent a indoor pool room or room with significant and constant moisture source, where a wall with open cell SPF and without vapour retarding layer would certainly perform poorly. Also as seen from the field results, walls exposed to greater solar radiation can be expected to have lower moisture contents. The north orientation is the worst case for cold weather diffusion. Multi-year simulations were also performed using weather data for Toronto with similar trends and results.

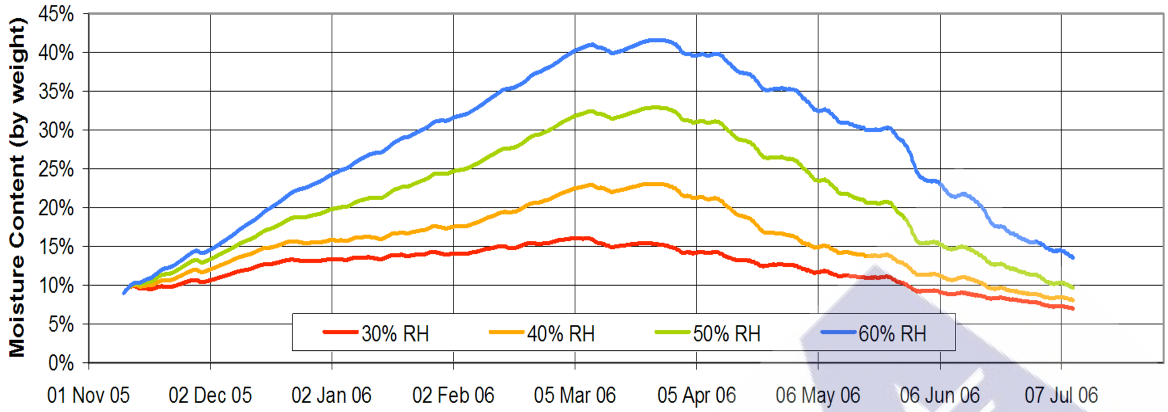

Figure 2.20: N6 Open Cell SPF - Impact of Interior RH on Moisture Content of OSB Sheathing (Toronto Climate)

The closed cell SPF results are not shown as the modeling confirmed it is sufficiently vapour resistant and hence the sheathing moisture content not significantly impacted by the indoor relative humidity. This is valid even when 50% interior humidity was considered for a standard year in Edmonton.

2.4.1.2 Vapour Control Strategy

The current vapour control strategy consists of commercially available latex paint on gypsum drywall in addition to the open or closed cell SPF. The paint has a vapour permeance of approximately 300 ng/Pa·s·m². Hygrothermal modeling was used to determine the effect of this paint layer, and whether and vapour retarding paint with a permeance of 30 ng/Pa·s·m² would be sufficient vapour control for the open cell SPF wall. This was compared to a wall with a polyethylene vapour barrier and to a wall with a more permeable 600 ng/Pa·s·m² paint. The results are compared in Figure 2.21 for a north-oriented wall with interior conditions of 21°C and 50% RH.

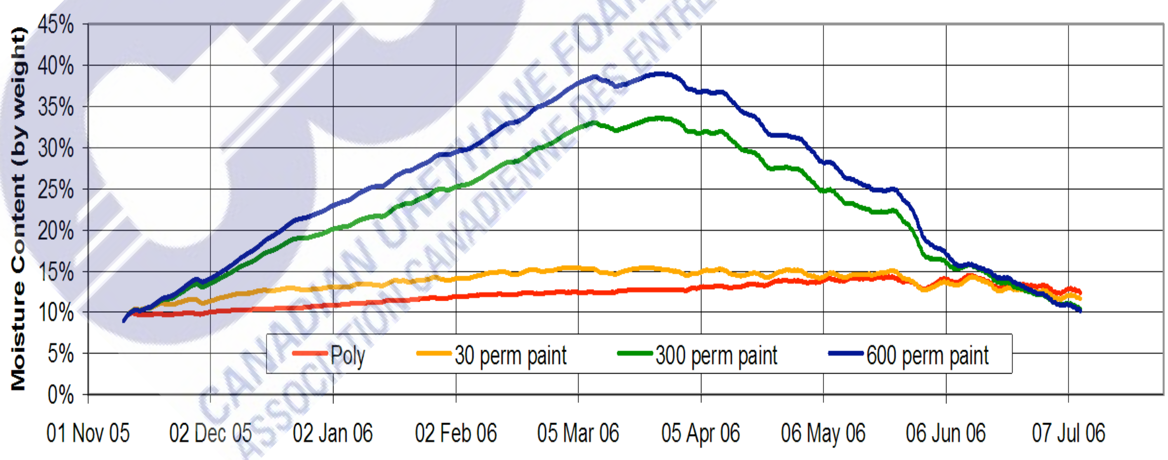

Figure 2.21: Wall N6 - Impact of Different Interior Vapour Control Layer on Moisture Content of OSB Sheathing (Toronto Climate)

This plot of moisture content (Figure 2.21) shows that with a vapour retarding paint or polyethylene vapour control can be achieved during the winter months with open cell SPF.

Even in the very high relative humidity cases, safe levels of wintertime sheathing moisture content can be achieved merely by using a vapour retarding paint. Multi year simulations were also performed using weather data for Toronto with similar trends and results.

As the closed cell SPF is sufficiently vapour resistant, the modeling showed that the OSB performance was not impacted by additional vapour control layers on the interior.

2.5 Conclusions & Recommendations

This chapter presented the setup and results of an experimental investigation of the need for additional vapour retarding layers in both open and closed cell SPF in wood framed walls used for residential and commercial occupancy. Results encompassing a full winter of testing and model validation were presented.

The open cell SPF walls had insufficient vapour resistance during the winter in Southern Ontario's climate at interior conditions of 20°C and 50% RH to keep sheathing moisture contents below 20%, particularly on the north orientation which had moisture contents above 30% for a few months. The closed cell SPF walls however did have sufficient vapour resistance to maintain sheathing moisture contents below 20% for the same challenging interior conditions.

Hygrothermal modeling was performed and compared to the observed results to validate the model. The WUFI 4 model was shown to be able of predicting the measured performance of a number of different walls. Using the validated hygrothermal model, preliminary recommendations for the use of additional vapour retarder layers as a function of SPF type, wall assembly, and climate can be developed.

The field measurements showed that the OSB and wood stud moisture contents of the open cell SPF walls during the winter were significantly impacted by the interior relative humidity and interior vapour control layer permeance. Using standard interior latex paint (in the order of 300 ng/Pa·s·m^2) and an interior relative humidity of greater than 40% during the winter in a cold climate (over about 4000 HDD ºC) can result in dangerously high moisture contents of the sheathing as a result of vapour diffusion. Maintaining an indoor winter relative humidity of less than 40% is recommended. However, because of the sensitivity of the wall to changes in interior relative humidity, additional vapour control is recommended with open cell SPF in climates of more than about 4000 HDD ºC. A vapour retarding paint (in the order of 30 ng/Pa·s·m^2), smart retarder, or polyethylene sheet are better choices for vapour control in such cold climates.

The measured and modeled moisture content of the OSB and studs in the closed cell SPF walls were little affected by changes to the interior relative humidity or vapour control layer permeance. Modeling showed that even in climates as cold as Edmonton (about 6500 HDD ºC), interior RH levels of 50% can be accommodated with no additional vapor control layer.

The wood studs have sufficient inherent vapor resistance that they do not require a supplemental vapor control layer. The wood studs remained dry both winter and summer without the need for a polyethylene sheet vapor diffusion retarder.

Field measurements showed, and modeling confirmed, that when SPF is installed inboard of hygroscopic sheathing, moisture accumulation can occur due to solar driven moisture from brick cladding especially if relatively vapour impermeable SPF is used. Basic building physics suggests that it if this moisture increase is excessive, it can be controlled by installing the closed cell foam on the exterior of the sheathing to both increase the sheathing temperature and provide resistance to vapour flow.

3 Climate Chamber Tests

3.1 Introduction

The field tests reported in Chapter 2 provided a demonstration of full-scale field performance in s specific application as well as some information to validity the of hygrothermal modeling. Much more detail is available in Smith (2009).

There are numerous brands of SPF available, and new types proposed for future use (i.e., HCFC-245 blowing agents). To provide side-by-side performance measurements of a range of different SPF products, a less expensive and more controlled laboratory experiment was undertaken.

3.2 Experimental Scope and Design

The objective of the lab experiment was to determine how much resistance to water vapour diffusion was offered by various spray polyurethane foam (SPF) insulation products installed in representative wall assemblies subjected to large-gradient temperature and humidity conditions.

The scope of the experiment was to test the most common types of open and closed cell spray polyurethane foam insulation used in Canadian residential and commercial construction. Fibreglass batt insulation was included in the test as a reference case.

3.3 Test Setup

An 8'x8' frame was sub-divided into compartments to allow for simultaneous testing of all of the samples. This frame was inserted into a climate chamber.

One side of the climate chamber was conditioned to simulate room temperature with a high humidity load and high temperature (25 C and 50%RH); the other side was conditioned to simulate cold outdoor conditions of about -10 C and 60%RH. The test boxes were subjected to large, steady gradients for temperature and relative humidity over a period of 57 days. These conditions are rather severe, and not representative of residential applications. The intention, as in the test house study, was to stress the samples and observe performance in demanding conditions to aid in understanding, not to replicate performance in the wall or roof of a house.

Water accumulation was observed through periodic mass gain measurements and moisture content readings in the exterior oriented strand board (OSB) sheathing of each test box.

Twenty different test wall systems samples, each 16" wide by 16" high, were tested in a climate chamber under steady-state cold weather conditions. Wall samples were primarily comprised of 2x6 wood framed assemblies with OSB sheathing.

Eight different foam type/thickness combinations were tested, with each combination having a test box with a polyethylene vapour barrier (the A-series) and a test box without a polyethylene vapour barrier (the B-series). A ninth combination of A and B test boxes included fibreglass batt insulation. The fibreglass acted as a reference case for standard wood frame wall construction. Two more test boxes were built, one to investigate the performance of high density foam and the other to investigate flame retardant treated foam on exterior gypsum and steel studs. Table 3.1 lists the details of each combination and its test purpose.

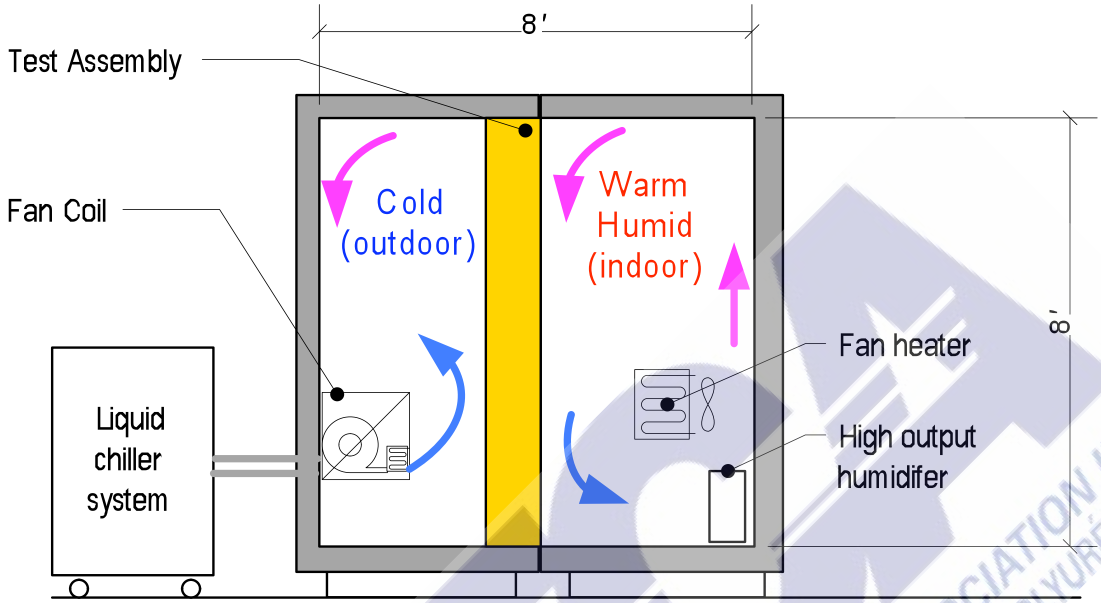

Figure 3.1: Climate Chamber Setup

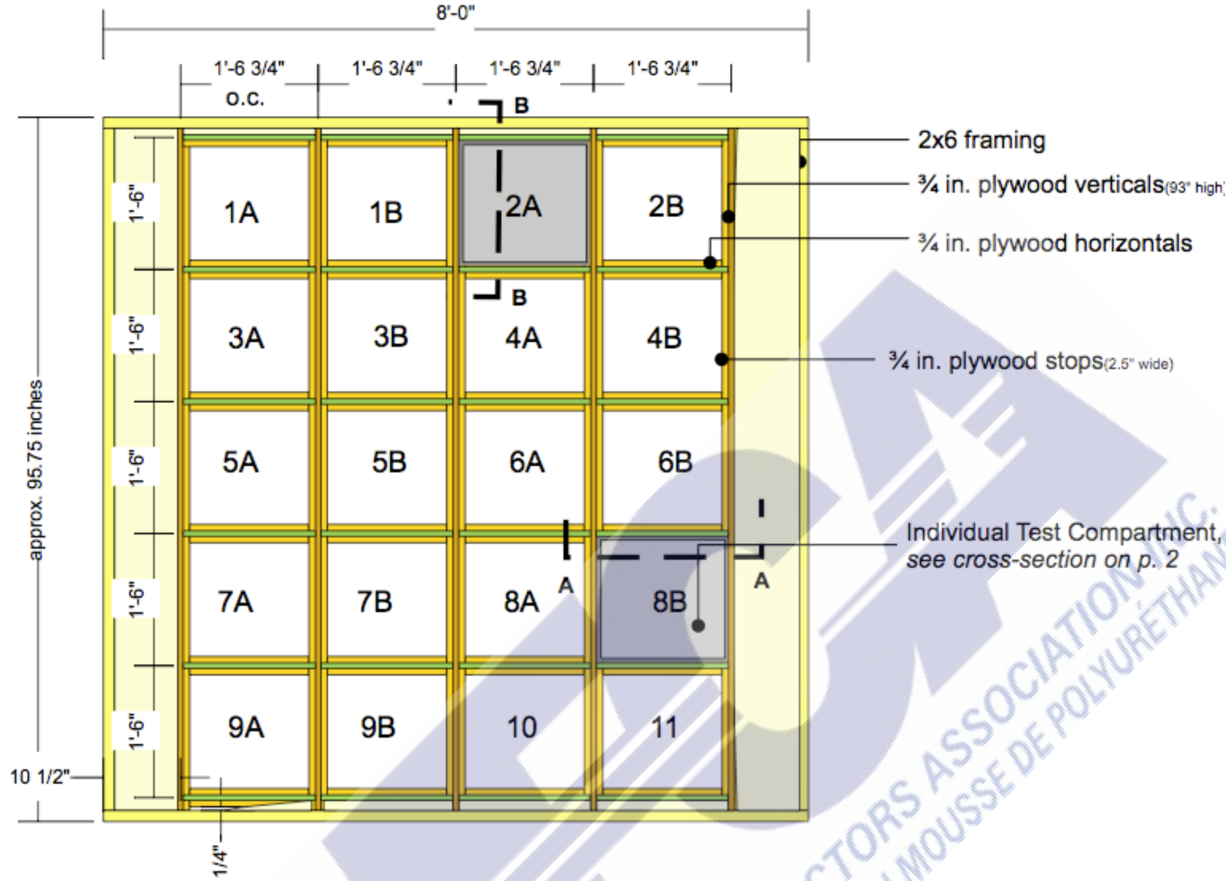

Figure 3.2: Elevation of Test Frame

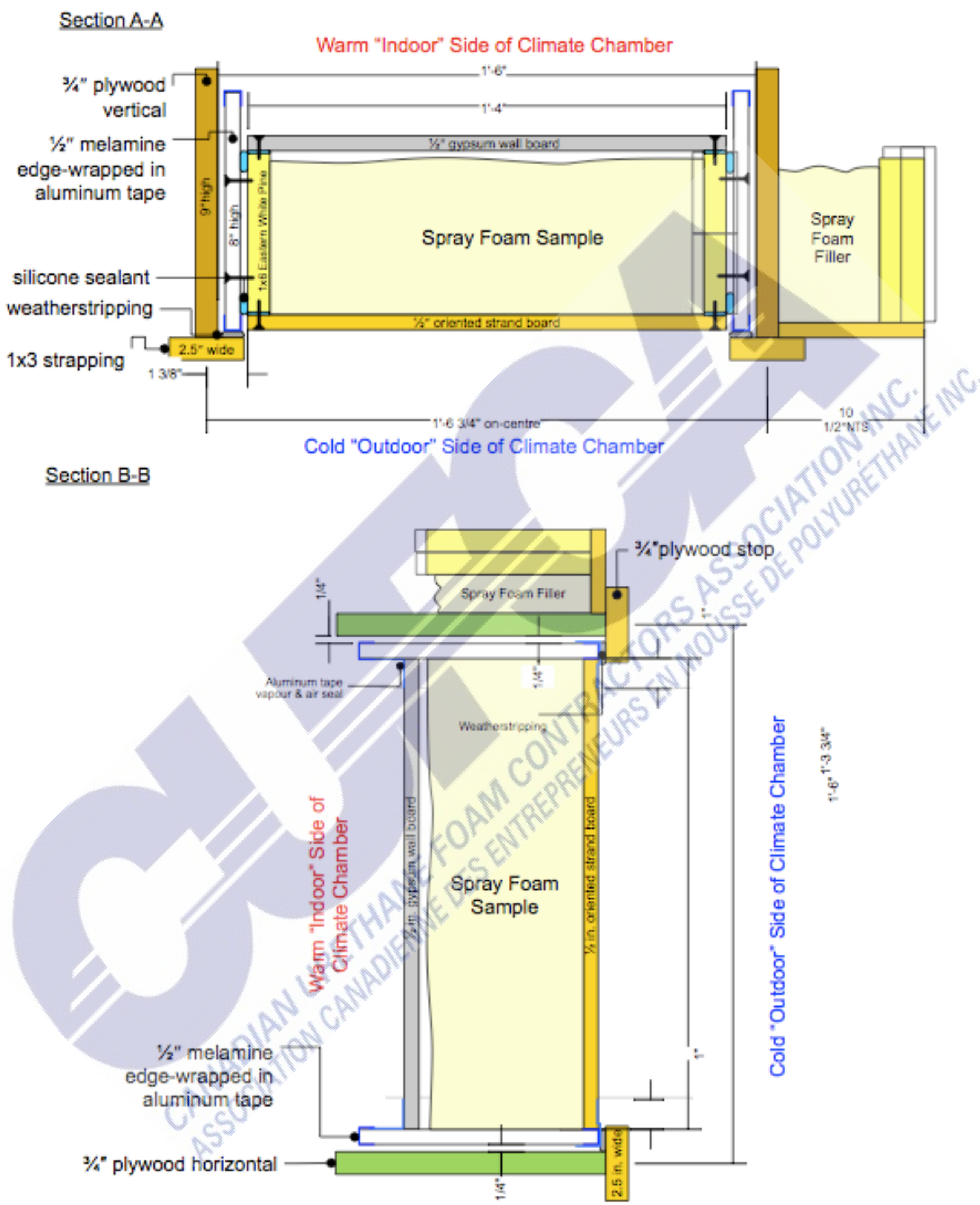

Figure 3.3: Sections Through Test Boxes

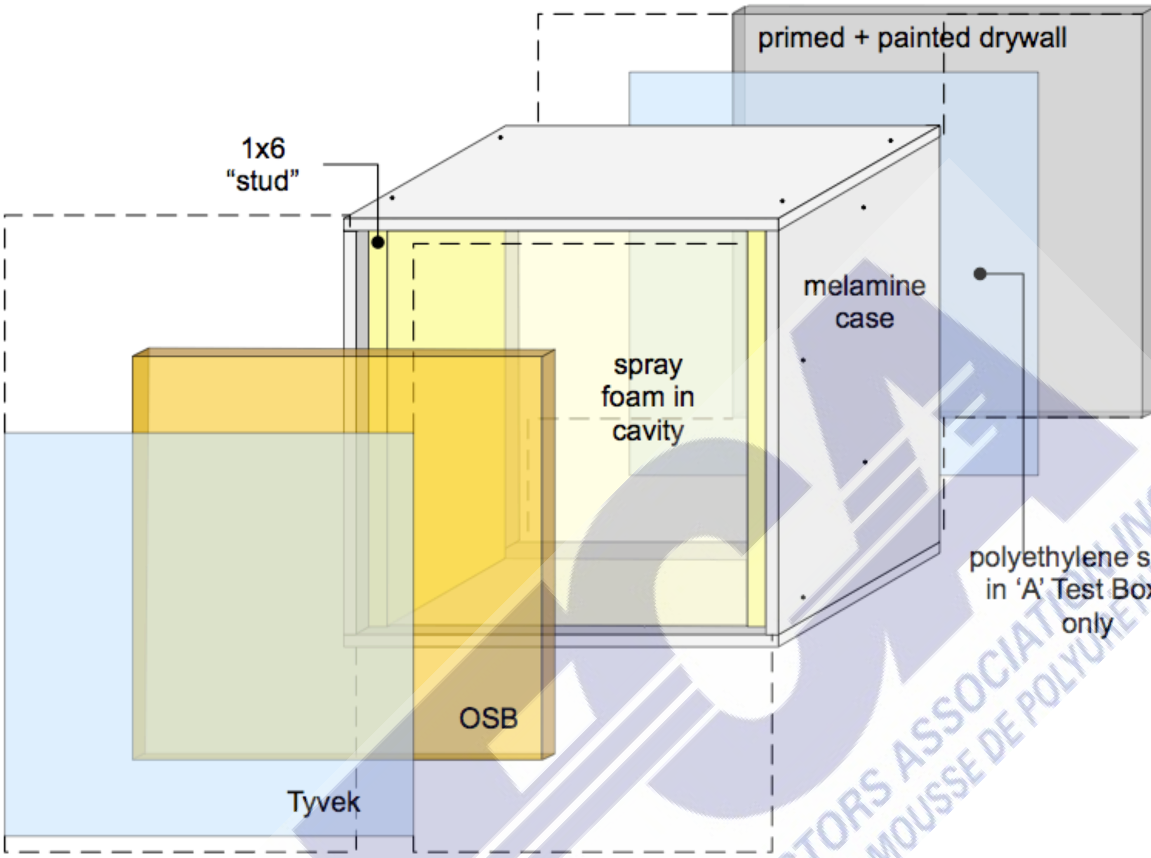

Figure 3.4: Exploded Isometric of the Test Boxes

Insulation	Test Boxes with Poly	Test Boxes with No Poly	Purpose of Test	
CLOSED CELL SPF				
BASF 3.5"	**1A**	**1B**	+/- poly	+/- mfgr
DOW 3.5"	**2A**	**2B**	+/- poly	
PF7300 3.5"	**3A**	**3B**	+/- poly	+/- depth
PF7300 4.5"	**4A**	**4B**	+/- poly	
Demilec Soya 3.5"	**5A**	**5B**	+/- poly	+/- depth
Demilec Soya 4.5"	**6A**	**6B**	+/- poly	
OPEN CELL SPF				
Demilec 5.5"	**7A**	**7B**	+/- poly	+/- mfgr
Icynene 5.5"	**8A**	**8B**	+/- poly	
OTHER				
Fibreglass	**9A**	**9B**	datum	
OTHER CLOSED CELL SPF				
Polar Foam Class One - 2" min.	-	**10**	commercial demo	
Polar Foam 3 pcf density - 2" +/-	-	**11**	role of density	

Table 3.1: Summary of Test Specimens

3.3.1 Moisture Content and Mass Measurements

Mass measurements of the entire test assembly were taken with a Sartorius Model FBC6CCE-H scale. The chambers had to provide a separation between the warm and cold side when the test boxes were removed otherwise, warm, humid air would flow into the cold side making it that much more difficult to maintain constant below-freezing conditions. The test boxes themselves could not be taken out of the cold chamber for weighing because ambient air conditions in the lab would immediately lead to condensation forming on all cold surfaces of the test box, affecting the accuracy of the mass measurements.

The solution to these constraints was to remove the samples from the test assembly. Before any box was pulled from the assembly, the whole face of the warm side of the assembly was covered with a curtain fashioned from a polyethylene sheet, over which a layer of foil-faced polyisocyanurate board was clamped. This measure served to minimize air and heat transfer from the warm side to the cold when a test box was removed from the assembly. The test box was weighed inside the cold chamber using a scale resting on the roof of the chamber (which maintained the scale at its desired operating temperature range). A small hole was drilled through the ceiling roof. A chain was attached to the under-scale hook of the scale. The chain extended directly down through the hole to about one meter below ceiling level. A hook at the end of the chain could support a test box by its wire handle . The chain was removed and the hole covered over whenever mass measurements were completed.

Once mass measurements were complete all test boxes were measured for moisture content. Each box had three pairs of moisture content pins installed on the face (Error! Reference source not found.). The pins were created from insulated brass nails that were driven from the outside so that the uninsulated tips were on the inside face of the OSB panel, the surface where moisture content was predicted to be highest (Figure 3.6). The pins were installed as pairs separated by 1 inch. A Delmhorst J-4 wood moisture meter was attached to the wire leads soldered to the exposed side of the pins to read the moisture content.

Figure 3.5: Three Moisture Content Pins Installed in Test Panel OSB through Tyvek

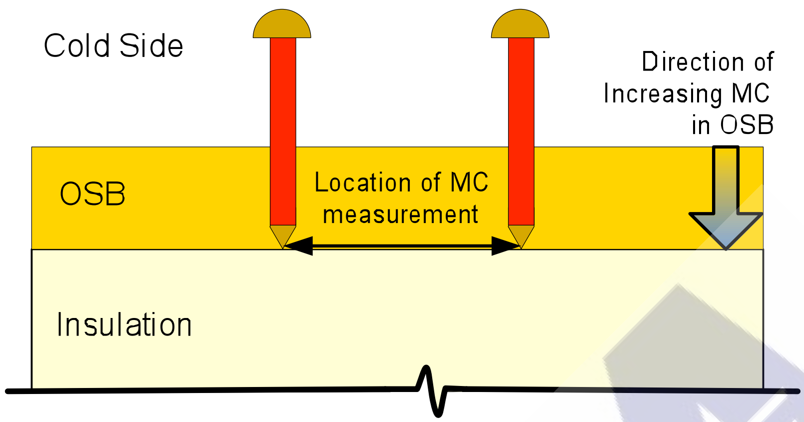

Figure 3.6: Schematic of Moisture Pins in OSB

3.4 Experimental Procedure

The moisture content and mass readings were measured and recorded approximately every ten days. The mass measurements were taken before the start of the test and at six other intervals up to and including the final day 57. Every test box was weighed at the start and on day 57, and on at least four of the six intervening measurement periods. Generally, the boxes predicted to have a relatively large mass change over time were weighed more often.

The temperature in the cold climate side was maintained with two liquid chillers. At day 47 one of the chillers failed and the temperature on the cold side rose to about 0 C.

3.5 Results

3.5.1 Gravimetric Measurements

Figure 3.7, shows the mass of water accumulation in the A-series of test boxes that contained a full polyethylene vapour barrier between the gypsum board and the insulation. Mass gains in the test boxes were in the 100 g range over the 57 day test period.

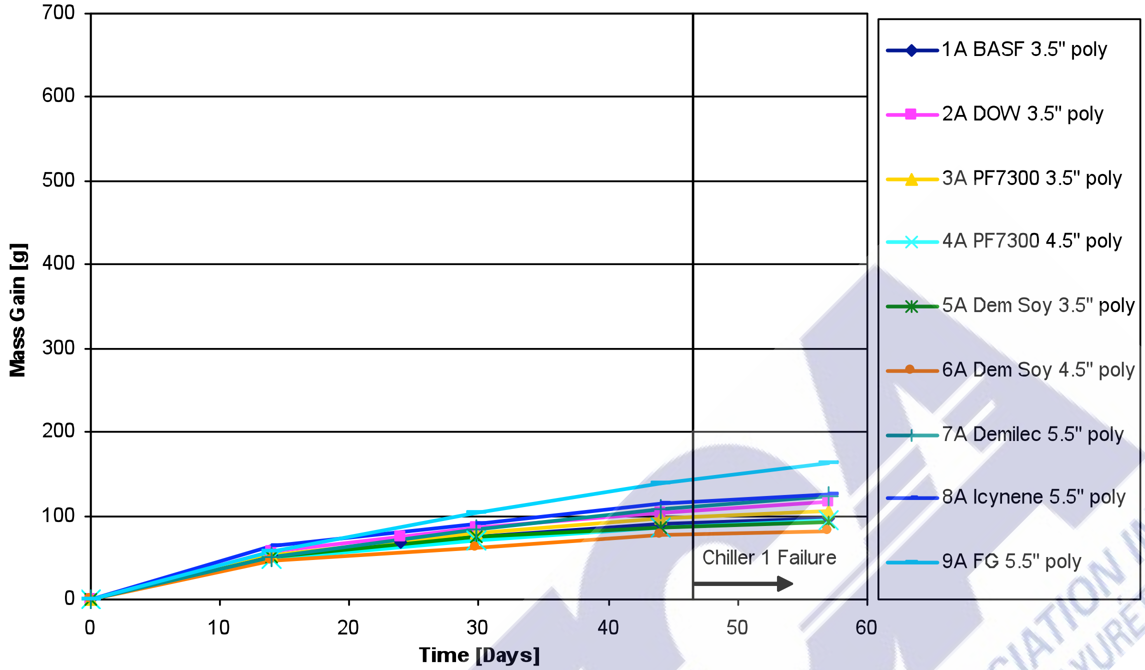

Figure 3.7: Mass Gain Rate of A-series Test Boxes with Polyethylene Vapour Barrier

The second chart, Figure 3.8, shows the results for the B-series test boxes which had no polyethylene vapour barrier. The fibreglass (9B) and open cell SPF (7B and 8B) samples have the highest vapour permeance values and the largest mass gains over the test period. Average mass gains for the lower permeance test boxes were in the 200 g range, almost twice the gains seen in the A-series boxes.

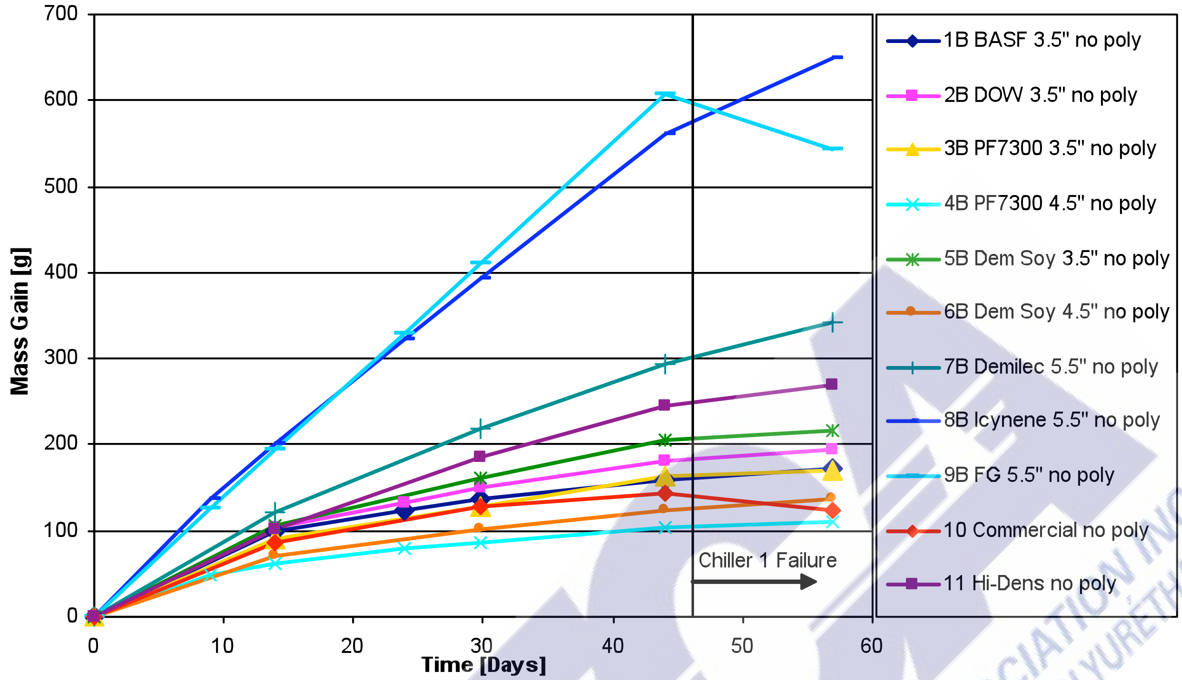

Figure 3.8: Mass Gain Rate of B-series Test Boxes with No Polyethylene Vapour Barrier

3.6 Moisture Content Measurements

The Delmhorst wood moisture meter passes a small electrical current through the wood and measures the electrical resistance of the wood between the two pins. Water has a lower resistance than dry wood and the electrical current follows the path of least resistance, therefore the measurement occurs at the wettest part of the OSB (Figure 3.6). In this case, the OSB is wettest at the interior face which happens to be the location that is of most interest in the experiment. The coating on the pins tends to further isolate the reading to the interior face in case there were any anomalies in the deposition of water or in the structure of the OSB.

The Delmhorst meter is calibrated to base all moisture content readings in terms of Douglas-fir at 70°F. Each MC reading was corrected for species and temperature given that the material was OSB and the temperature was typically -10°C when measurements were taken. Equation 3-1 from Garrahan (1988) calculates the corrected temperature from the uncorrected MC measurement, the temperature when the MC was taken, and two species-dependant regression factors. Engineered wood products such as plywood and OSB may be of no easily identifiable species, therefore generic coefficients for these products have been developed. Straube, Onysko and Schumacher (2002) published values for the regression coefficients as $a = 1.1114$ and $b = 0.366$ for OSB.

$$MC_c = \frac{\left(\dfrac{MC_u + 0.567 - 0.0260t + 0.000051t^2}{0.881(1.0056^t)}\right) - b}{a}$$

Equation 3-1

MC_c	[%]	Corrected moisture content
MC_u	[%]	Uncorrected moisture content reading
t	[°C]	Temperature of the wood
a, b	[-]	Species-dependent regression coefficients: $a = 1.1114$, $b = 0.366$

The corrected average MC measurements of the OSB in each test sample OSB are presented in Figure 3.9 and Figure 3.10.

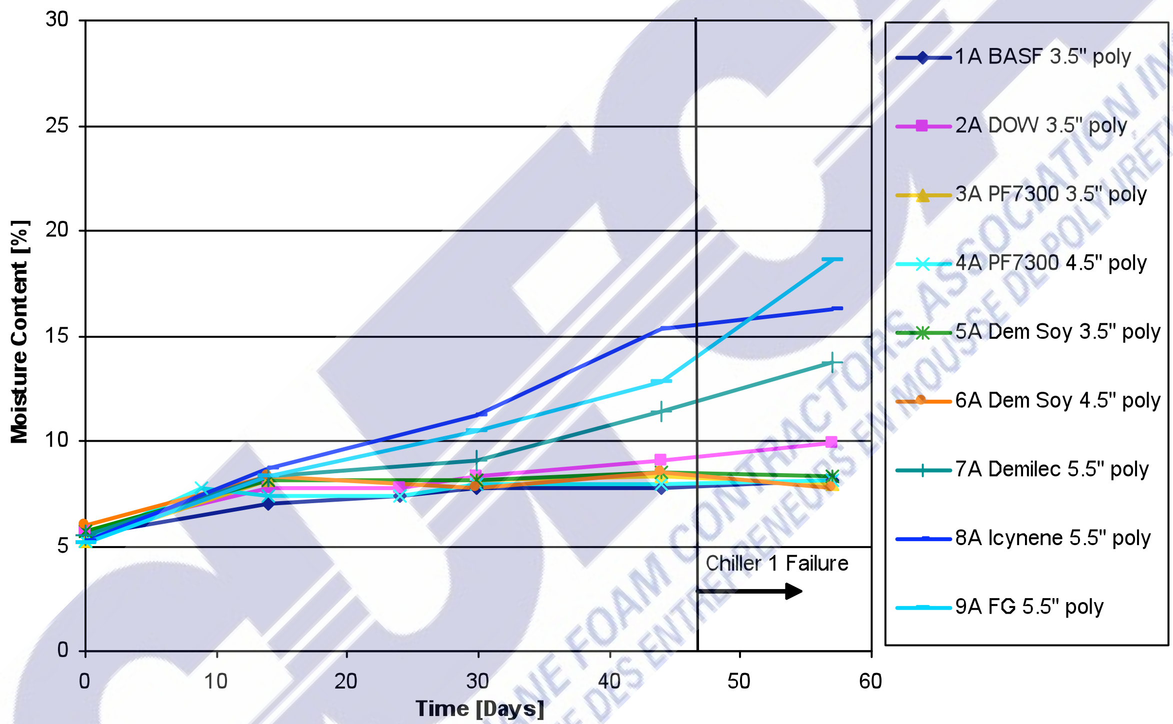

Figure 3.9: Corrected MC of OSB in A-series Test Boxes with Polyethylene Vapour Barrier

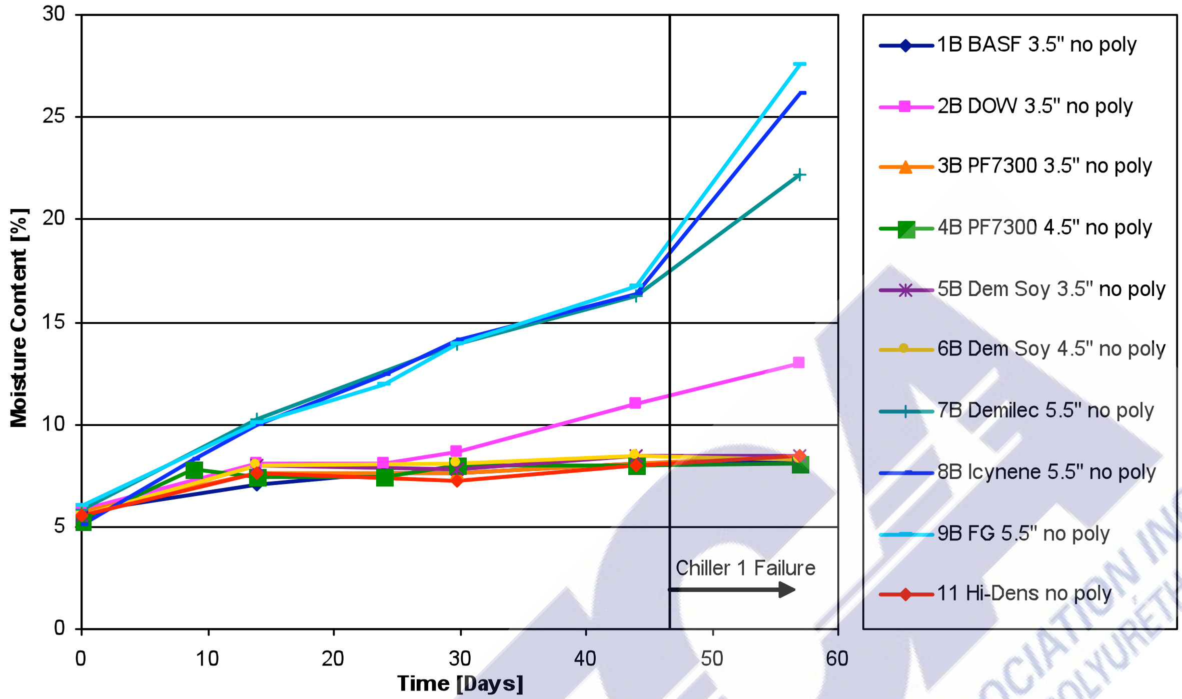

Figure 3.10: Corrected MC of OSB in B-series Test Boxes with No Polyethylene Vapour Barrier

3.7 Analysis

The first conclusion to note from these tests is the use of polyethylene sheet vapor barriers does not present the rise in moisture content of the sheathing or overall moisture gain in the test samples. This is due to adsorption of water vapor into the OSB from the cold side of the climate chamber to the OSB.

The moisture content of the OSB remained in the safe zone even after 50 days of extreme conditions for all of the closed cell SPF wall samples. The presence or absence of polyethylene had no discernible effect on the moisture content of the OSB sheathing.

The fiberglass wall showed very significant mass gain and OSB MC rise when no polyethylene vapor retarder was used. The two open cell SPF also showed significant moisture uptake, although slightly less than fiberglass. Although the fiberglass and open-cell walls performed between with poly than without, they gained significantly more moisture in the OSB even with polyethylene than the closed cell SPF.

An interesting observation noted in the materials sub-system climate chamber tests is that the HCFC-245 blown foam behaved essentially the same as the legacy HCFC-141b products. The vapour permeance of the new generation appears to be slightly less than the previous one.

4 Modeling

The field measurements presented in Chapter 2 demonstrated that careful application of the WUFI hygrothermal model allowed for the prediction of real wall performance. The climate chamber measurements supported the expectation that each of the example products of the two classes of spray polyurethane (2 pcf and ½ pcf) behaved similarly to other products in its class. This chapter of the report extends the results from the experimental program to a wide range of wall types and climates

4.1 Modeling Approach

Seven different wall assemblies (containing different types of SPF based on the results of the physical testing described earlier) were parametrically modeled in different Canadian climates. Based on initial modeling runs, and the results of the field studies, it was clear that the worst-case scenario for cold-weather diffusion wetting was always a north-facing orientation (because of the lack of solar radiation heating on this orientation). Similarly, light-weight and light-coloured claddings absorb the least solar radiation, have the coldest sheathing temperatures, and hence have the most winter wetting due to diffusion.

Seven wall types were considered. Wall 7 considers the performance of the wall through a solid framing element such as a stud, joist, plate, or lintel.

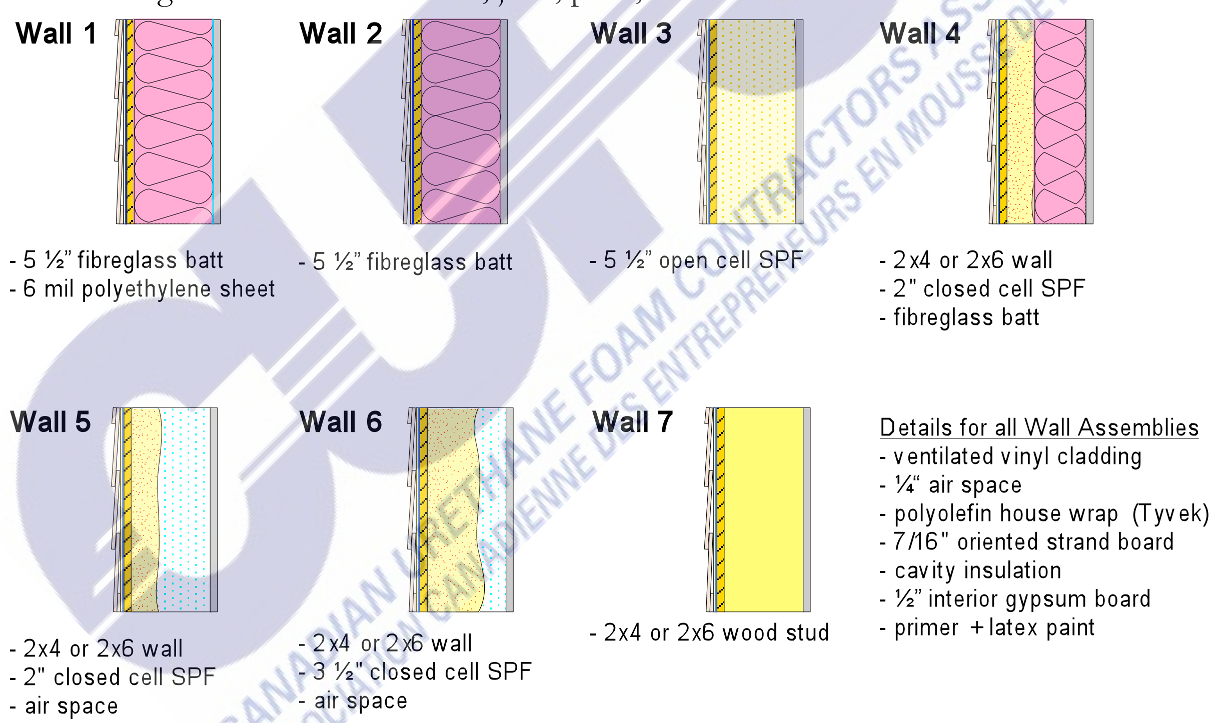

Figure 4.1: Cross-Sections of Wall Types Modelled

4.2 Exterior Climate

Every simulation case was run for seven different Canadian climates. The climates were categorized according to the number of heating degree days below 18°C. Heating degree days (HDD) are calculated by summing the number of degrees each average daily temperature is below 18°C for a full year of historical temperature data. The total number provides a measure of how much annual heating is required in a particular location (Figure 4.2).

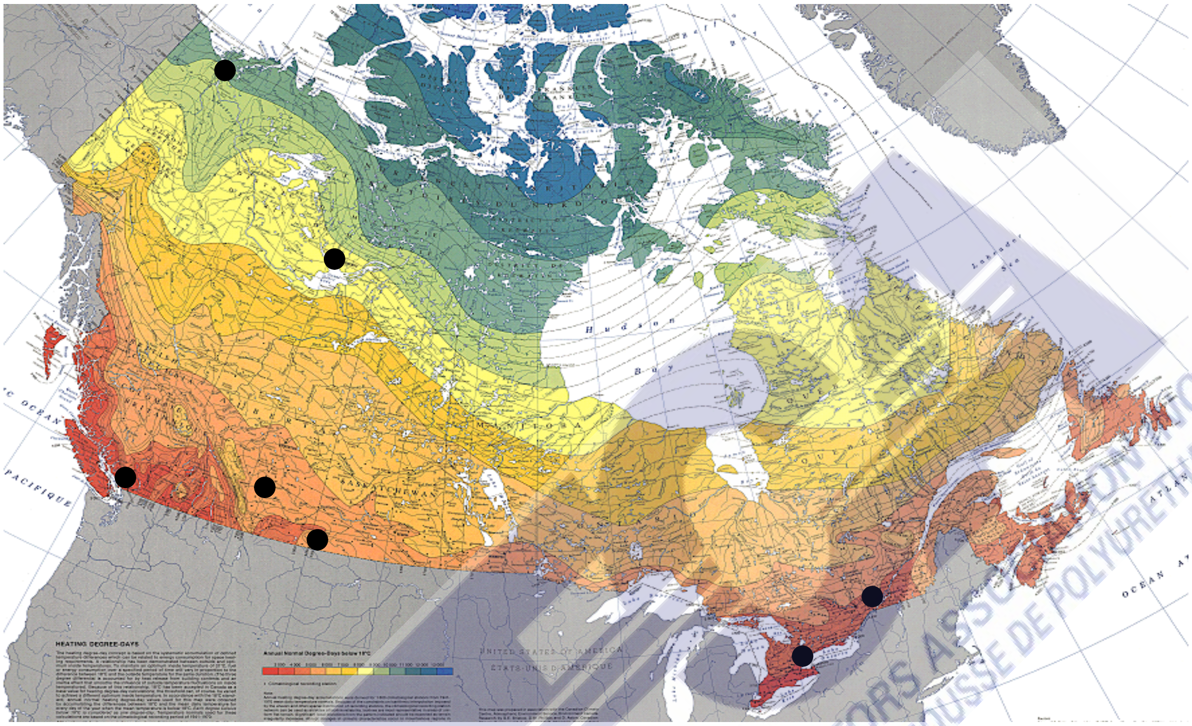

Figure 4.2: Canada Heating Degree Days and Simulation Cities (National Atlas of Canada, 5th ed.)

For Canada, most populated locations are in the range from 3000 to 6000 HDD, with most northern communities in the 6000 to 10,000 HDD range,Table 4.1. The heating degree data is derived from Environment Canada's online database for *Canadian Climate Normals 1971-2000* (Environment Canada, 2008). The city associated with each climate category is a representative location only (the black circles on the map in Figure 4.2). The results of the simulations in any given category apply to other geographic locations with HDD values in the same range. The urban core populations of the cities listed in Table 4.1 represent more than 60% of the Canadian population based 2006 Statistics Canada census data.

The seven climate locations used in these simulations are listed in Table 4.2 with a nominal HDD for the category and the actual HDD derived from the climate file used in the WUFI simulation for that particular location. Note the HDD values from the WUFI climate file and from Environment Canada's Climate Normals are not the same. The two values were derived from different data sets, however, they fall within the prescribed HDD range for the category. The table also lists general conditions for temperature, relative humidity and rainfall to give a sense of how the climates differ from one another.

Each WUFI climate file contains a one-year data set of hourly information for temperature, relative humidity, wind speed, wind direction, rain fall, air pressure, cloud cover, solar radiation, and long wave radiation.

Table 4.1: Canadian Cities by Climate Category

HDD Climate Category (with range)	Representative Location (with HDD)	Some Cities in this Range (with HDD)
HDD 3000 (Up to 3500)	Vancouver (2926)	White Rock (2782) Abbotsford (2981) Victoria (3040)
HDD 4000 (3501 to 4250)	Toronto (4065)	Windsor (3524) Niagara Falls (3661) Kelowna (3869) Oshawa (3917) Hamilton (4012) Halifax (4030) London (4057)
HDD 4500 (4251 to 4750)	Ottawa (4602)	Kitchener-Waterloo (4288) Kingston (4289) Montréal (4518) Moncton (4585) Charlottetown (4715)
HDD 5000 (4751 to 5500)	Calgary (5108)	St. John's (4881) Trois-Rivières (4929) Prince George (5132) Sherbrooke (5151) Québec City (5202) Sudbury (5343)
HDD 6000 (5501 to 7000)	Winnipeg (5777)	Regina (5660) Edmonton (5708) Thunder Bay (5717) Saskatoon (5852) Whitehorse (6811)
HDD 8000 (7001 to 9000)	Yellowknife (8256)	Dawson (8166)
HDD 10,000 (9001+)	Inuvik (9767)	Iqaluit (10117) Resolute (12526)

Table 4.2: Summary Climate Statistics for Cities in WUFI Simulations

Representative Locations	Vancouver	Toronto	Ottawa	Calgary	Winnipeg	Yellowknife	Inuvik
Nominal Heating Degree Days (<18°C)	3000	4000	4500	5000	6000	8000	10,000
HDD<18°C in WUFI Climate File	3056*	4022*	4874*	5384*	6377*	8243**	9935**
Mean Temperature, °C	9.1	6.7	5.2	2.5	1.2	-4.5	-9.2
Max. Temperature, °C	27.2	32.8	36.1	30.6	33.9	27.8	28
Min. Temperature, °C	-11.1	-23.3	-28.3	-36.7	-45.0	-42.8	-47.2
Mean Relative Humidity, %	78	76	67	63	73	66	67
Maximum Relative Humidity, %	100	100	100	100	100	100	100
Minimum Relative Humidity, %	14	21	18	14	19	17	24
Normal Rain Sum, mm/year	1169	606	586	304	309	161	114

*WUFI Climate Files derived from ASHRAE International Weather for Energy Calculations (IWEC). All files are "cold year" versions.
**WUFI Climate Files derived from typical meteorological year (TMY2) data sets from the 1961-1990 National Solar Radiation Data Base.

4.3 Indoor Climate

The temperature for interior conditions in all simulations was set at 22°C with an annual variation of 1°C, Figure 4.3. Each climate category was modeled with three interior climate conditions – low, medium and high indoor relative humidities (Table 4.3). The actual number used for the indoor climate settings depended on the climate category. For example, a low interior relative humidity (30%) in a warmer, rainier climate like Vancouver is higher than what would be considered a low interior relative humidity (20%) in a cold, northern climate like Yellowknife.

Table 4.3: Categories for Indoor Relative Humidities

Climate Categories	Low RH*	Medium RH*	High RH
HDD 3000 Vancouver HDD 4000 Toronto HDD 4500 Ottawa HDD 5000 Calgary HDD 6000 Winnipeg	30% to 55%	40% to 60%	50%
HDD 8000 Yellowknife HDD 10,000 Inuvik	20% to 50%	30% to 55%	50%
Description of possible conditions in this RH category	- older, air-leaky construction - newer buildings with mechanical ventilation - few occupant activities contributing to humidity load - condensation rarely forms on standard windows during cold snaps	- more air tight construction - operating a mechanical humidifier - high humidity loads from frequent cooking, washing, and firewood storage - condensation often forms on standard windows during cold snaps	- mechanically-generated RH levels are constantly high year round - examples are indoor pools, hospitals, museums - condensation constantly forms on standard windows during cold snaps

*Seasonal variation - low end of range in winter, high end of range in summer

The seasonal variations in the low and medium RH categories follow a sine wave formation which leads to the high end of range occurring on August 1, selected as the high point of the summer season. The low end of the range occurs six months later on February 1, the low point of the winter season. The indoor climate conditions for the Low RH category of 30 to 50% are shown in the screen capture of Figure 4.3.

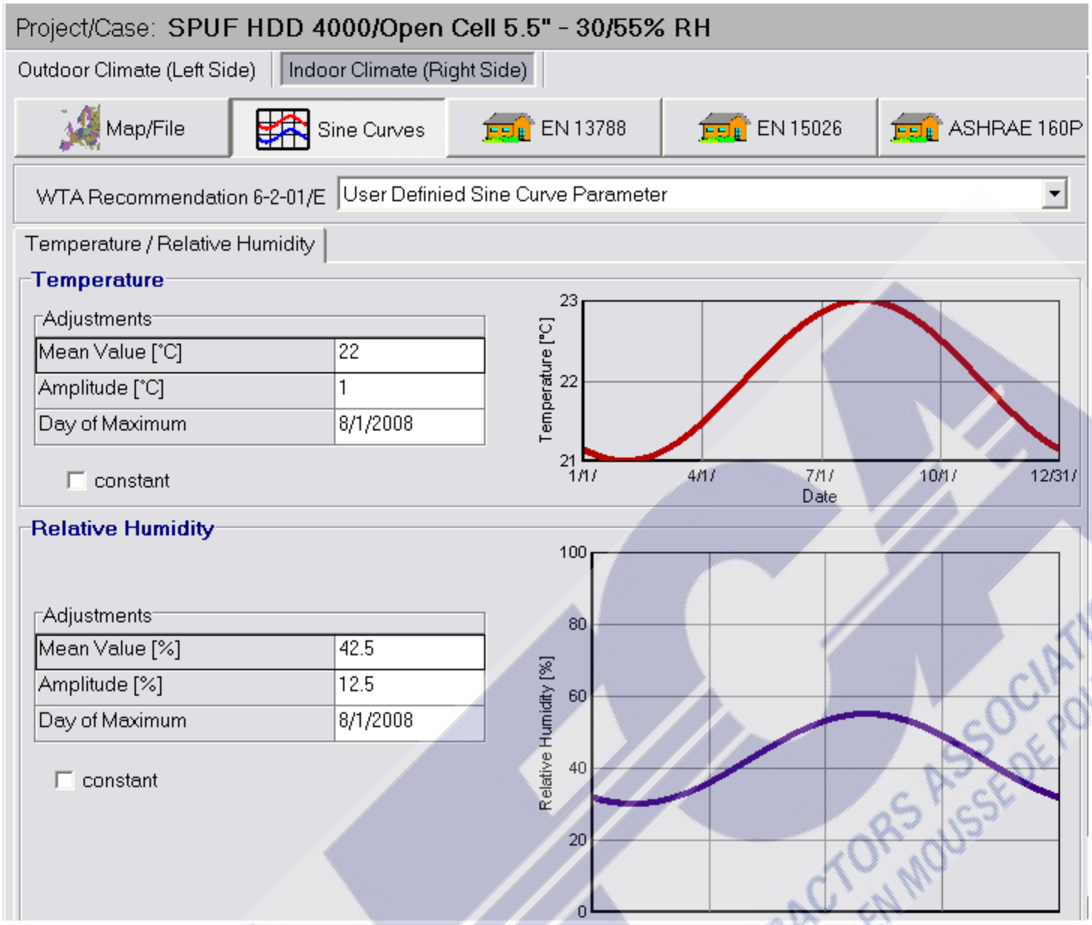

Figure 4.3: Screenshot of WUFI Plot of Low RH Category 30-50%

4.4 Simulation Procedures

All of the wall simulations began with a constant temperature of 22°C across all components. The only layers with any appreciable initial moisture content were the OSB layer (at 55 kg/m³ or 8.5% moisture content by dry mass) and the wood stud (at 30 kg/m³ or 6% moisture content by dry mass). These settings correspond to the typical range from 4% to 10% moisture content of wood products in post-construction conditions (Morris 1998).

The modeling period ran for one year from August 1, 2007 to August 1, 2008 in time steps of one hour. August was chosen as the starting month because it typically represents an annual trough in plots of exterior wood sheathing moisture content values. An August start date allows the annual winter moisture content peaks to plot in the center of the graph, which us useful since they are of most interest. The simulations were run until an equilibrium, or steady state, level was reached. This was defined as the moisture content in the sheathing being equal to the moisture content in the previous year.

			Materials Vary with Assembly Type						Materials in Every Modelled Assembly			
			Fibreglass Batt		Closed Cell SPF*		Open Cell SPF**	Poly Vapour Barrier	Gypsum Board	Oriented Strand Board (OSB)	Polyolefin Membrane (Housewrap)	Ventilated Vinyl Cladding†
	thickness, t [m]		0.14	0.09	0.09	0.05	0.14	0.001	0.013	0.011	0.0002	0.004
	thickness, t [in.]		5.5	3.5	3.5	2	5.5	6 mil	0.5	7/16	1/128	1/64
Thermal Properties	symbol	formula										
Thermal Conductivity, Dry W/m·K	k	-	0.035	0.035	0.024	0.024	0.042	2.3	0.2	0.092	2.4	0.5
Thermal Resistance - metric, m²·K/W	RSI	=t/k	4.00	2.57	3.75	2.08	3.33	0.00	0.06	0.12	0.00	0.01
Thermal Resistance - imperial, hr·ft²·°F/Btu	R-value	=RSI·5.678	22.7	14.6	21.3	11.8	18.9	0.0	0.4	0.7	0.0	0.0
Vapour Properties												
Water Vapor Diffusion Resistance Factor	VRDF	=185/μ	1.30	1.30	89	89	5.80	50000	8.3	812.8	328.4	0.05
Vapor Diffusion Thickness	Sd value	=185/M	0.2	0.1	8.0	4.4	0.8	50.0	0.1	9.0	0.1	0.0002
		=185·t/μ										
Permeability, ng/Pa·s·m	μ		142.3	142.3	2.1	2.1	31.9	0.004	22.3	0.2	0.6	3700
Permeance, ng/Pa·s·m²	M	=μ/t	1016	1581	23	42	228	4	1755	20	2817	925000
Other Properties												
Bulk Density, kg/m³	ρ	-	30	30	39	39	7.5	130	850	650	448	2400
Porosity, m³/m³	Ψ	-	0.99	0.99	0.99	0.99	0.99	0.001	0.6	0.95	0.001	0.01
Specific Heat Capacity, J/kg·K	c_o	-	840	840	1470	1470	1470	2300	850	1880	1500	1000

*average values for BASF, Demilec HeatLok and Heatlok Soya, DOW, & Polar Foam

**average values for Demilec Sealection and Icynene Gold Seal

† Assumes a light-coloured cladding

Figure 4.4: M

Moisture Content (MC) in Wood Exterior Sheathing Subjected to Various Canadian Climates and Interior Relative Humidities
Chart values are %MC by dry mass of wood and represent a predicted maximum annual value

(green) = MC < 20%, no mold growth; (yellow) = MC is 20 to 28%, potential for mold growth; (red) = MC > 28%, moisture problems expected, this design is NOT recommended

Wall Construction			Vancouver			Toronto			Ottawa			Calgary			Winnipeg			Yellowknife			Inuvik		
			HDD 3000			HDD 4000			HDD 4500			HDD 5000			HDD 6000			HDD 8000			HDD 10000		
Contents of Cavity	Depth of Cavity	Type of Vapour Control	Low RH 30/55%	Med. RH 40/60%	High RH 50%	Low RH 30/55%	Med. RH 40/60%	High RH 50%	Low RH 30/55%	Med. RH 40/60%	High RH 50%	Low RH 30/55%	Med. RH 40/60%	High RH 50%	Low RH 30/55%	Med. RH 40/60%	High RH 50%	Low RH 20/50%	Med. RH 30/55%	High RH 50%	Low RH 20/50%	Med. RH 30/55%	High RH 50%
Fiberglass (FG)	5.5"	Polyethylene sheet	12%	12%	12%	11%	11%	11%	10%	10%	10%	9%	9%	9%	10%	10%	10%	11%	11%	11%	10%	10%	10%
Fiberglass (FG)	5.5"	Latex paint+primer	14%	18%	21%	18%	25%	30%	21%	27%	33%	22%	28%	35%	28%	37%	43%	27%	37%	43%	35%	43%	46%
Spray Polyurethane Foam (SPF) – Open Cell	5.5"	Latex paint+primer	14%	15%	17%	14%	18%	21%	16%	20%	23%	16%	20%	22%	21%	26%	28%	20%	25%	27%	24%	28%	29%
Spray Polyurethane Foam (SPF) – Closed Cell[3]	2"SPF +3.5"FG[1]	Latex paint+primer	13%	14%	14%	12%	13%	13%	11%	12%	12%	10%	11%	11%	13%	13%	13%	13%	13%	14%	12%	12%	12%
Spray Polyurethane Foam (SPF) – Closed Cell[3]	2"SPF in 3.5/5.5"	Latex paint+primer	12%	13%	13%	11%	12%	13%	10%	12%	12%	10%	11%	12%	13%	14%	14%	12%	13%	14%	13%	14%	14%
Spray Polyurethane Foam (SPF) – Closed Cell[3]	3.5" SPF in 3.5/5.5"	Latex paint+primer	12%	13%	13%	12%	12%	12%	10%	11%	11%	9%	10%	10%	12%	12%	12%	12%	12%	12%	11%	12%	12%
Wood Stud[2]	3.5" or 5.5"	Latex paint + primer	7%	7%	7%	7%	7%	7%	5%	6%	6%	5%	5%	5%	6%	7%	7%	7%	7%	7%	5%	5%	6%
Other Applicable Locations (Heating Degree Days below 18°C) *From Environment Canada's Canadian Climate Normals 1971-2000*			White Rock (2782), Vancouver (2926), Abbotsford (2981), Victoria (3040)			Windsor (3524), Niagara Falls (3661), Kelowna (3869), Oshawa (3917), Hamilton (4012), Halifax (4030), London (4057), Toronto (4065)			Kitchener-Waterloo (4288), Kingston (4289), Montréal (4518), Moncton (4585), Ottawa (4602), Charlottetown (4715)			St. John's (4881), Trois-Rivières (4929), Calgary (5108), Prince George (5132), Sherbrooke (5151), Québec City (5202), Sudbury (5343)			Regina (5660), Edmonton (5708), Thunder Bay (5717), Winnipeg (5777), Saskatoon (5852), Whitehorse (6811)			Dawson (8166), Yellowknife (8256)			Inuvik (9767), Iqaluit (10117), Resolute (12526)		

General Notes:
a. Walls are residential wood frame with light-colored, thin cladding facing north: this is a worse-case scenario for cold-weather diffusion wetting
b. Results are for OSB sheathing. Plywood sheathing values will be equal or lower. OSB permeance is always over 60 ng/Pa·s·m^2 in exterior sheathing applications.
c. Sheathings of DensGlas, FiberBoard, and Gypsum Board are all very vapor permeable and hence will have lower moisture contents
d. Thicker foam will always result in lower wintertime sheathing moisture contents
e. Effective Air Barrier is assumed to be installed, as is proper rain control
Specific notes:

Figure 4.5: Model Summary Results

5 Conclusions and Recommendations

The objective of this research project was to provide recommendations, based on sound scientific evidence, of the need for additional vapour control for both open-cell low-density and closed-cell medium-density SPF installed in framed walls of a wide range of building occupancy types and cold climates.

The National Building Code of Canada specifies that vapour barriers are not required when:

"it can be shown that uncontrolled vapour diffusion will not adversely affect any of, (a) health or safety of building users, (b) the intended use of the building, or (c) the operation of the building services.

The research demonstrated the ability of typical framed walls using spray polyurethane foam insulation, with and without additional vapor barrier layers, to meet these requirements in at least some Canadian climates for walls with exterior layers of sheathing, membranes, cladding and other layers with a permeance of more than about 60 ng/Pa s m^2.

Closed-cell (about 2 pounds per cubic foot density or more) spray foam applied in thicknesses of over 2" (50 mm) will control vapor diffusion to safe levels in all climates up to 10000 HDD and interior winter-time relative humidities of up to and over 50%RH. As thickness increases the level of control increases. The diffusion control was equal or better than walls with the traditional fiberglass batt and polyethylene.

Open cell (1/2 pound per cubic foot density) foam can control diffusion in climates that are not too cold (eg less than 4500 HDD18) when the interior winter RH level is controlled by appropriate ventilation to below about 40%RH. Open cell foam does not have sufficient vapor control for use in very cold climates (4500 HDD and more) unless the interior winter-time RH is strictly controlled (to below about 30%RH).

For either type of foam, the wood framing provides sufficient inherent vapor resistance to maintain the moisture content within the safe range even in very cold exterior climates (10 000 HDD) and very humid interior conditions (50%RH in winter).

As for all walls made of all materials, a functional air barrier assembly must be provided, as well as rain control, fire control, structural sufficiency, etc.

The one-D WUFI hygrothermal modeling program was validated as an effective and accurate tool for predicting the moisture content of the sheathing in the field tests. It can be used to predict the performance of other wall assemblies in other climates if care is taken to define the material properties and boundary conditions.

Climate chamber vapor diffusion tests on a range of different products were conducted under a temperature gradient. These tests confirmed the performance noted in the field tests and demonstrated that different commercial products of the same class (closed cell or open cell) performed in a very similar manner.

An interesting observation noted in the materials sub-system climate chamber tests is that the HCFC-245 blown foam behaved essentially the same as the legacy HCFC-141b products. The vapour permeance of the new generation appears to be slightly less than the previous one although the variations may be statistically insignificant.

Although it can be postulated that the same conclusions would apply to the vapor control in sloped and flat roof assemblies, the different exposure (to sun and night-sky radiation) and the typically low vapour permeance of roof claddings (such as asphalt and steel) mean that modeling and testing should be undertaken for critical applications.

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