

# Field Performance of Spray Polyurethane Foam: The Role of Vapour Diffusion Control

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## **ABSTRACT**

A research project was implemented at the University of Waterloo to study the performance of both open and closed cell spray polyurethane foam insulation (SPUF) in frame wall applications typical of residential construction. The project involves the testing of full-scale wood frame walls exposed to natural climatic conditions for a period of two years. Results of the first year of study are presented, as well as results from hygrothermal simulation to show the impact of climate, materials, and interior operating conditions based on a validated model. Based on field testing and validated hygrothermal simulation recommendations on the need for supplemental vapour diffusion control layers for either open or closed cell SPUF are developed.

## **INTRODUCTION**

Spray polyurethane foam (SPUF) 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  $8 \text{ kg/m}^3$  (0.5 pcf), open cell and quite flexible foam, and a high-density  $32 \text{ kg/m}^3$  (2 pcf) closed cell rigid foam. Both product classes are studied in the research reported here.

A common question encountered by SPUF applicators 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. However, the need for, and type of additional vapour control layers remains unanswered to many builders, designers, and code officials.

This paper presents the setup and results of an experimental investigation of the need for additional vapour retarding layers in both types of SPUF in framed walls. Eight test walls were constructed and installed in the University of Waterloo's BEGHut test facility and will be monitored for a period of two years. Hygrothermal modeling was 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 SPUF type, wall assembly, and climate (interior and exterior) are discussed.

This 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 SPUF installed in the walls of a wide range of building occupancy types and climates.

## **EXPERIMENTAL SETUP**

### **TEST FACILITY DESCRIPTION**

The University of Waterloo's BEGHut, located in Waterloo, Ontario was used for this research to investigate the performance of full-scale wall assemblies under natural exposure in this climate. This facility is maintained at a constant  $20^\circ\text{C}$  and 50% RH year-round. This is a high level for an office or residential building in cold climates, but is representative of museums and hospitals.

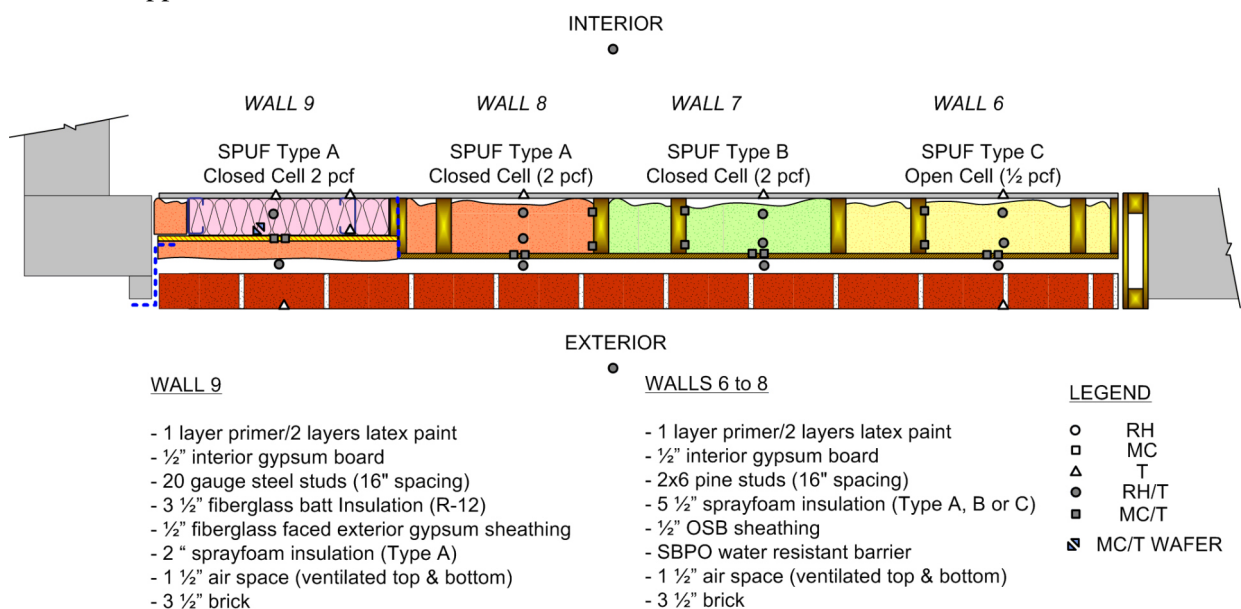
Interior relative humidity levels for this climate typically range from 30-40% during the winter and 50-60% during the summer months.

## TEST WALLS

Eight full-scale walls in total, four different wall assemblies, one of each on the North and South orientations were installed into the BEGHut in November 2005. The four wall assemblies consist of:

- Three 2x6 wood frame walls insulated with two different types of closed cell SPUF (Type A, B) and one open cell SPUF (type C) within the stud space and,
- One 2x4 steel stud/gypsum wall insulated with fiberglass batt insulation within the stud space and insulated with a closed cell SPUF (Type A) on the exterior of the gypsum sheathing.

The walls referred to in this report follow BEGHut naming convention and are labeled as north walls N6 through N9 and south walls S6 through S9. Walls 1 through 5 are used for other experiments but also include four datum walls which are referenced in this paper. 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 SPUF walls. Figure 1 shows the four different wall assemblies including sensor locations which are discussed in the following sections. All walls were allowed to equilibrate to exterior conditions. All framing and OSB was the same type from the same supplier.



**Figure 1: SPUF test wall assemblies including sensor location**

The overall dimension of the four SPUF 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 SPUF are resistant to airflow, and make up part of the air barrier system within these walls

This paper discusses the results from the wood frame test walls 6 through 8. Results from the steel stud/gypsum wall 9 are not discussed in this paper.

## SPUF MATERIAL PROPERTIES

Three different SPUF products were selected for use in the study. Two distinct classes of SPUF are commonly used in construction, high-density closed-cell or low-density open-cell foams. 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. All spray foams were installed by a licensed applicator under ideal interior conditions. Material properties taken from published material property data for the three types of SPUF are and summarized in Table 1.

**Table 1: SPUF Material Properties (From Manufacturers Literature & CCMC Evaluations)**

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

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 (but the surface skin provides little resistance for open cell foams). 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.

## MONITORING SYSTEM

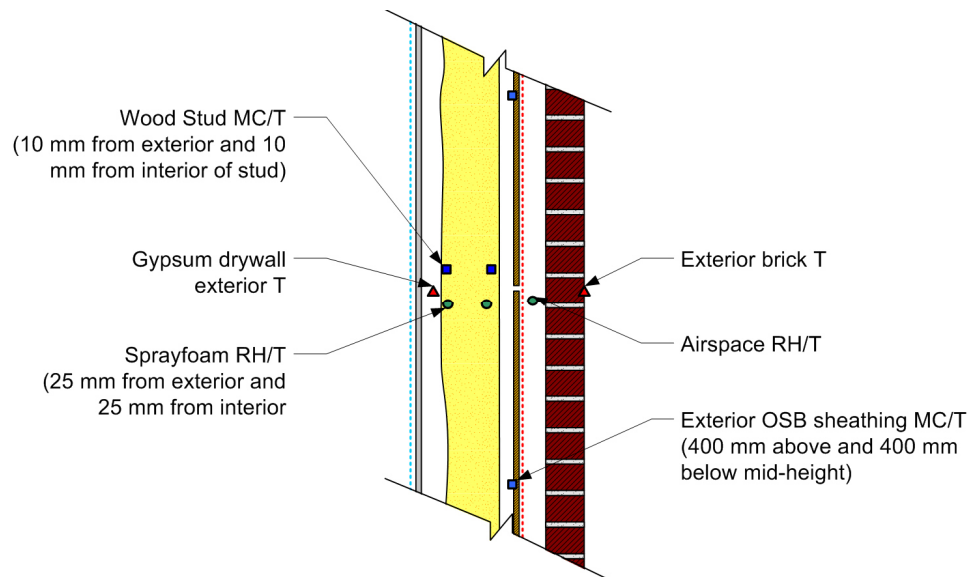
Temperature, relative humidity, and wood moisture content sensors were installed in the test panels along the centerline of the stud bays as shown in Figure 1 previously. Sensors were installed at mid-height of the walls approximately 1200 mm from ground level. Figure 2 shows the location of the sensors within the wall for the wood frame wall assemblies. The same sensor layout was used in all walls in order to allow for direct comparisons between the assemblies.

An explanation of the choice and placement of sensors is discussed by wall component, moving from the exterior of the wall to the interior.

- Exterior temperature, relative humidity, and environmental conditions including: rainfall, wind speed, wind direction, and solar radiation are measured at the roof of the BEGHut.
- Brick temperatures are measured at the outboard face; the sensors are embedded in the brickwork mortar.
- Airspace (cladding cavity) conditions are measured with both a temperature/relative humidity sensor; sensors hang in the open airspace of the cavity.
- Wood moisture content and temperature are measured in the OSB exterior sheathing. Sensors are located at 400 mm above and 400 mm below mid-height of the wall and referred to as “eye-level” and “waist height” correspondingly. A 5 mm construction gap between the sheets of OSB sheathing is located at wall mid-height (1200 mm from floor), and the while the OSB is from the same batch, the top and bottom OSB sheathing in the wall corresponds to a different sheet of wood.

- Wood moisture content and temperatures are measured at the inboard and outboard sides of the wood studs (approximately 10 mm from the inboard and outboard edges).
- Stud space temperature and relative humidity are measured at two locations embedded within the SPUF; located at 25 mm from the exterior sheathing and 25 mm from the interior drywall.
- Temperature is measured at the interface between the exterior side of the drywall and the stud bay cavity.
- Interior temperature and relative humidity is measured with a sensor hanging within the BEGHut.

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 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.



**Figure 2: Wood Frame Wall Sensor Location (vertical section through mid-height)**

## RESULTS

As of July 10<sup>th</sup>, 2006, eight months of data have been collected for the eight walls. This paper focuses on the results for these first eight months. While the entire study is planned for a total of two years, the preliminary data provides sufficient information to discuss the performance of these walls.

The interior and exterior boundary conditions for the experiment are presented followed by a discussion of the open cell and closed cell SPUF wall results.

## BOUNDARY CONDITIONS

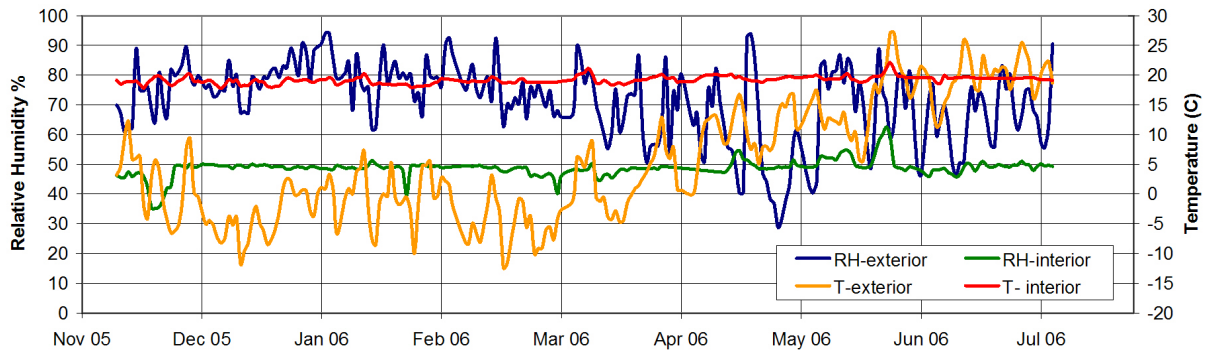
Indoor and outdoor temperature and relative humidity conditions are shown in Figure 3 for the eight month monitoring period from November 10<sup>th</sup>, 2005 to July 10<sup>th</sup>, 2006.

### OPEN CELL SPUF (WALL 6)

Temperature, relative humidity, moisture content, vapour pressure, and dewpoint temperature plots were analyzed for the open cell SPUF 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.

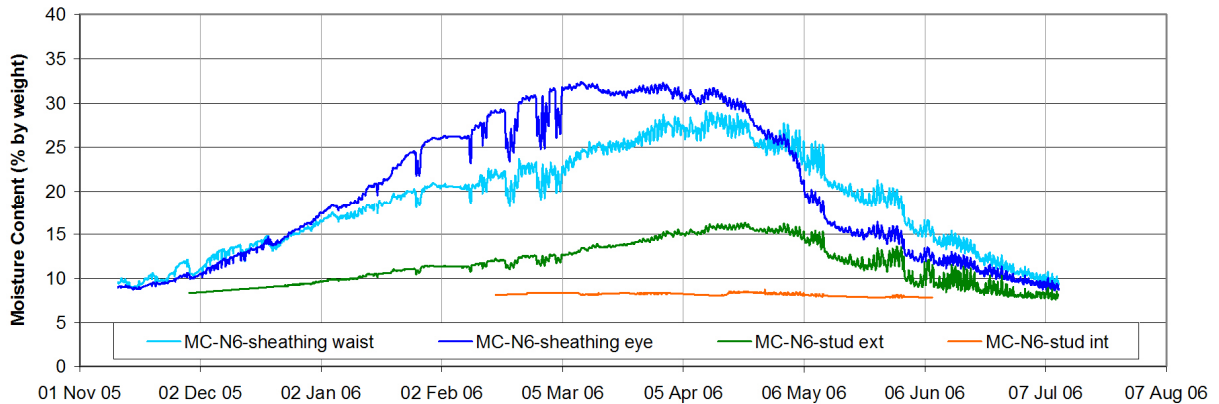
Open cell SPUF has a vapour permeability of  $33.0 \text{ ng/Pa}\cdot\text{s}\cdot\text{m}$ , thus 140 mm of the material permeance is approximately  $236 \text{ ng/Pa}\cdot\text{s}\cdot\text{m}^2$ . The gypsum drywall and latex paint/primer have a vapour permeance in the order of 2000 and  $300 \text{ ng/Pa}\cdot\text{s}\cdot\text{m}^2$  respectively. Summing the permeance in series, the net permeance is approximately  $124 \text{ ng/Pa}\cdot\text{s}\cdot\text{m}^2$  inboard of the sheathing. A typical residential wall with a polyethylene vapour barrier would have a net vapour permeance inboard of the sheathing of  $<5 \text{ ng/Pa}\cdot\text{s}\cdot\text{m}^2$ , 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 run into problems when other moisture sources including interior air leakage condensation, rain water leakage, or sun driven moisture cannot dry to the interior during warmer weather.

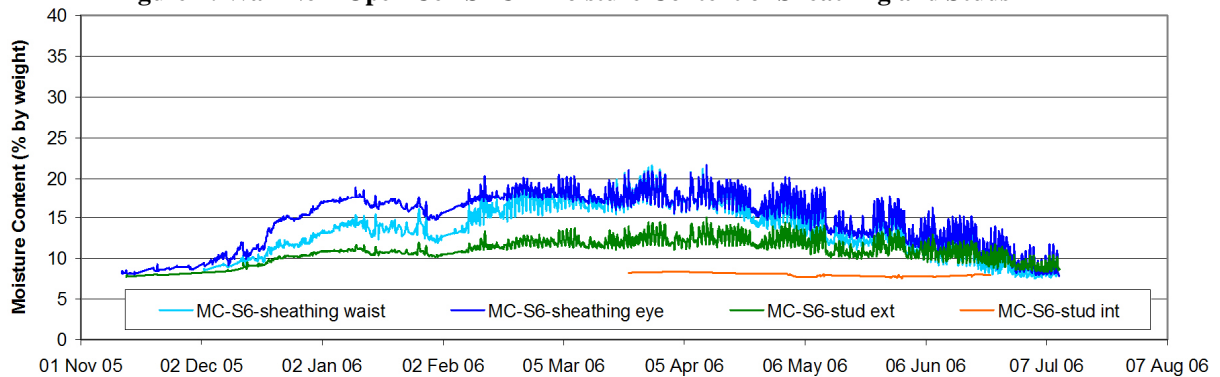


**Figure 3: Exterior and Interior Air Temperature and Relative Humidity (November to July)**

In order to experimentally determine if additional vapour resistance is required for the open cell SPUF and how much is required, the open cell walls were constructed 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 SPUF 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 4 for wall N6 and Figure 5 for wall S6.



**Figure 4: Wall N6 – Open Cell SPUF Moisture Content of Sheathing and Studs**

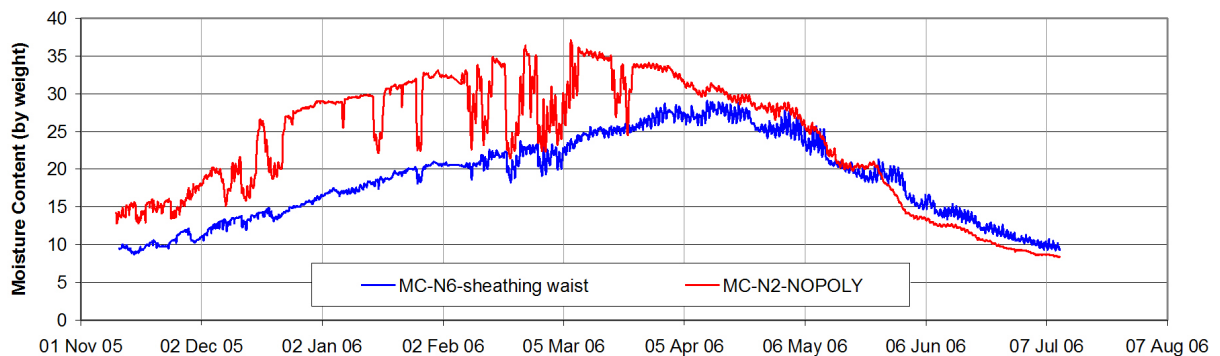


**Figure 5: Wall S6 – Open Cell SPUF Moisture Content of Sheathing and Studs**

The OSB sheathing in the north wall had moisture content exceeding 30% MC for approximately 2 months and 20% for almost 4 months continuously. 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 is 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. When the exterior temperature increased in April, both walls quickly dried down to levels below 10% by the beginning of July.

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, 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 reasonably well, however hygrothermal simulation will be used to determine the impact of different claddings, higher rain exposure etc.

Wall N6 is further compared to datum wall N2 which has similar construction but constructed with fiberglass batt insulation instead of SPUF. Figure 6 shows the difference in moisture content at the OSB sheathing for both of these walls.

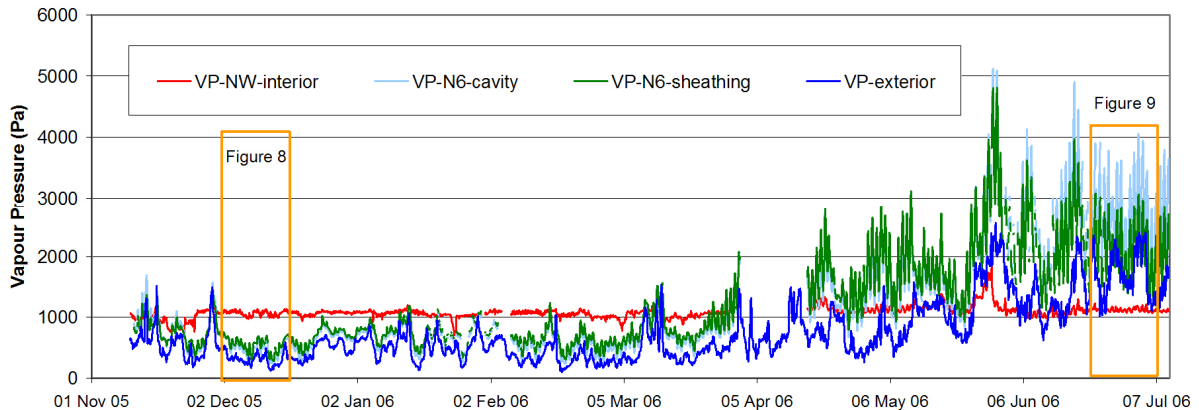


**Figure 6: Moisture content of Sheathing Wall N6 (open cell) versus datum wall without poly**

The moisture content of the OSB sheathing in the datum wall is higher than the SPUF wall in the same orientation, with moisture contents above 30% for prolonged periods of time in the datum wall. This shows the relative damping effect of the SPUF, and a difference in inboard permeance of approximately  $124 \text{ ng/Pa}\cdot\text{s}\cdot\text{m}^2$  for the SPUF wall and  $215 \text{ ng/Pa}\cdot\text{s}\cdot\text{m}^2$  for the fiberglass batt datum wall with the same interior paint layer and gypsum drywall.

Moisture transport within the open cell SPUF walls can be analyzed with vapour pressures (absolute moisture levels) within the wall assembly. Figure 7 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 1<sup>st</sup> to 7<sup>th</sup> is shown in further detail in

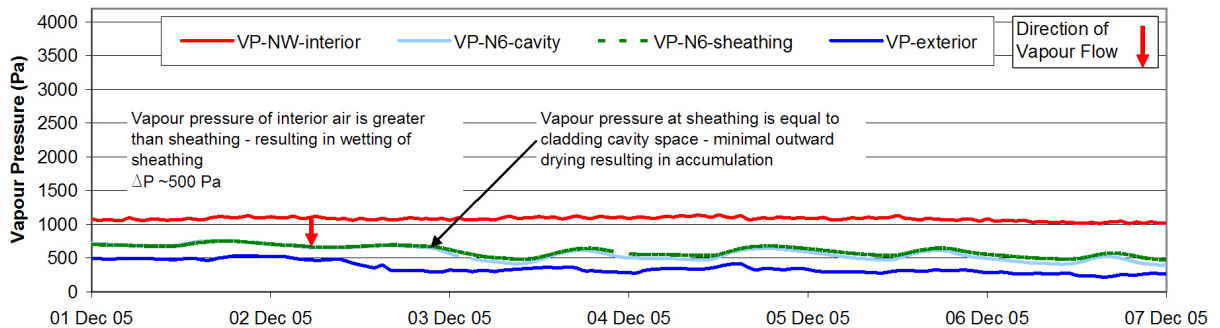
Figure 8 and a typical summer week from July 1<sup>st</sup> to 7<sup>th</sup> is shown in Figure 9 to show the difference in seasonal vapour pressure gradients.



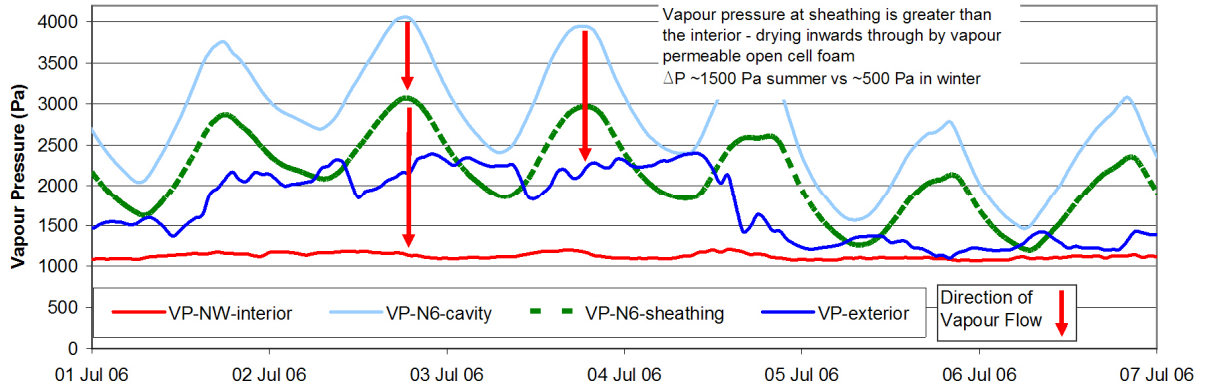
**Figure 7: Wall N6 – Open Cell SPUF Vapour Pressures within Wall Assembly (November to July)**

During the winter months the interior air vapour pressure on average is 300-500 Pa higher than the sheathing and exterior air, resulting in a small but consistent vapour drive towards the exterior. 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, hence why drying occurs at a faster rate.

An analysis of the vapour pressures in the summer indicate that vapour flow is occurring 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% while this drying occurs in the summer. If the interior RH were maintained at a higher level (say 60%) during summer the vapor pressure difference would drop by about 10%.



**Figure 8: Wall N6 – Vapour Pressure Gradient during a typical winter week (December 1-7, 2005)**



**Figure 9: Wall N6 – Vapour Pressure Gradient during a typical summer week (July 1-7, 2006)**

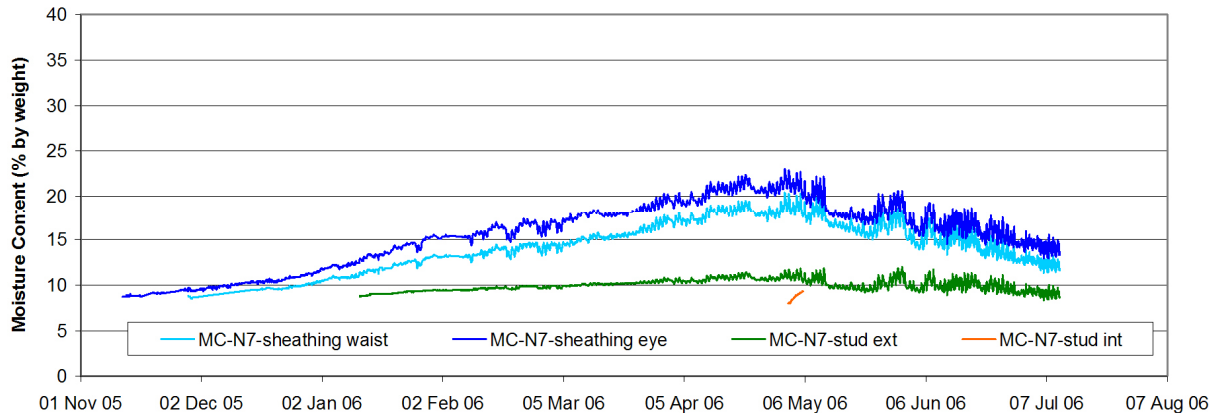
Interior conditions of 20°C and 50% RH result in a vapour pressure of approximately 1200 Pa, which results in a high wintertime vapour drive to the exterior. If the interior conditions were instead set at 20°C and 30% more typical wintertime values, the vapour pressure would be significantly lower at 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.

### CLOSED CELL SPUF (WALLS 7 & 8)

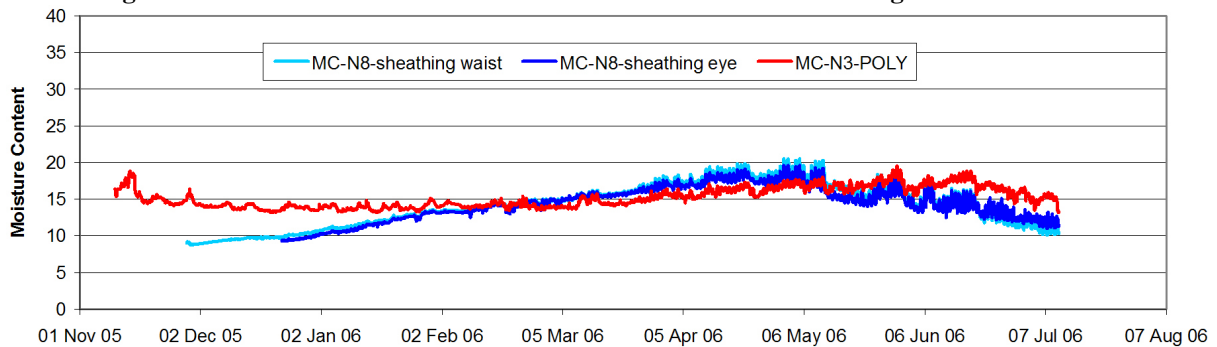
The performance and moisture content of the OSB sheathing and wood studs is discussed for the closed cell SPUF walls 7 and 8. The two closed cell SPUF products used in this experiment have a vapour permeability of approximately 2 ng/Pa·s·m, thus for 130 mm the permeance is approximately 15 ng/Pa·s·m<sup>2</sup>. Summing the permeance of the drywall and paint in series the net permeance is approximately 14 ng/Pa·s·m<sup>2</sup> inboard of the sheathing, much lower than the open cell foam at 125 ng/Pa·s·m<sup>2</sup> and compared to polyethylene at <5 ng/Pa·s·m<sup>2</sup>. It should therefore be expected that the closed cell SPUF walls should have lower wintertime sheathing moisture contents than the open cell SPUF 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 SPUF walls. Figure 10 shows a plot of the moisture content of the sheathing and studs in wall N7. Walls N8, S7 and S8 show similar results.

Walls on the south tracked at 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 SPUF walls are compared to the datum wall N3 which is constructed with batt insulation instead of SPUF and a polyethylene vapour barrier at the interior.



**Figure 10: Wall N7 – Closed Cell SPUF Moisture Content of Sheathing and Studs**



**Figure 11: Moisture content of Sheathing Wall N8 (closed cell) versus datum wall with poly**

The closed cell SPUF wall performs with similar trends to the poly wall, however the poly wall started with higher initial moisture contents (was running for 2 months prior). The SPUF 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 SPUF walls and hence the peak a few months earlier. Also the drying appears to be improved with the closed cell SPUF as shown in June and July.

Upon examining the data the moisture source for the closed cell walls appears to be largely from the exterior, i.e. from high relative humidity within the cavity space behind the brick and 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) equal to 0.2 to accurately predict the amount of driving rain (Straube et al. 2005).

From these results, it can be concluded that the level of vapour control provided by the closed cell SPUF is sufficient to prevent high moisture contents during the winter months; however continued monitoring and hygrothermal simulation will be used to determine the impact of rain and wetting events on these results, specifically in the summer months.

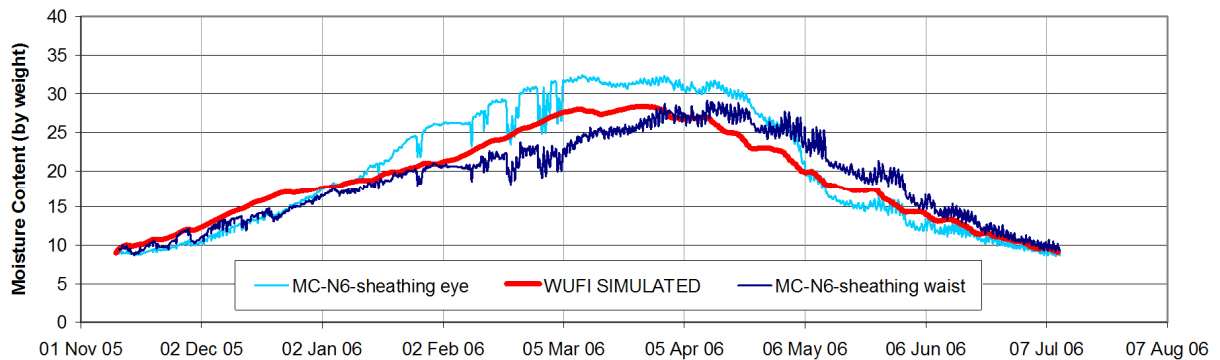
A question sometimes raised by contractors, designers and code officials is that the wood studs are more permeable than the foam and would now allow water vapour transport to the exterior. The measured moisture content of the studs in the field testing were lower than that of the OSB. The permeability of solid wood is approximately  $1.4 \text{ ng/Pa}\cdot\text{s}\cdot\text{m}$ , which for an 89 mm stud is a permeance of  $16 \text{ ng/Pa}\cdot\text{s}\cdot\text{m}^2$  or for a 140 mm stud a permeance of  $10 \text{ ng/Pa}\cdot\text{s}\cdot\text{m}^2$ , which is very low and compares to the permeance of 140 mm of closed cell SPUF, which is about  $14\text{-}17 \text{ ng/Pa}\cdot\text{s}\cdot\text{m}^2$  depending on application details.

## HYGROTHERMAL MODELING

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 SPUF 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 12.



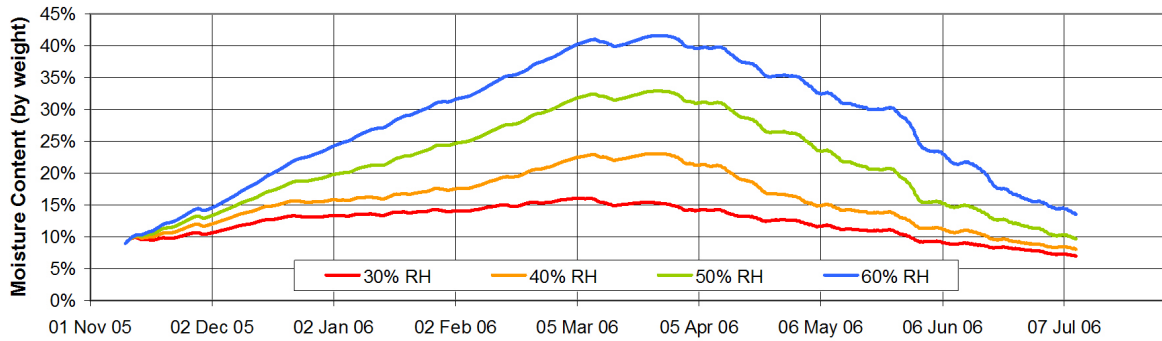
**Figure 12: Wall N6 - Measured Moisture Content Compared to WUFI Simulated Results**

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.

### 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 SPUF walls. Figure 13 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 SPUF 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.

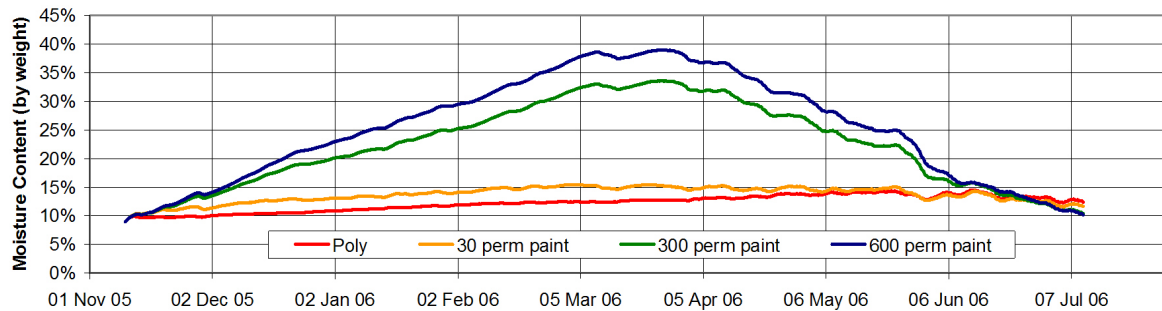


**Figure 13: N6 Open Cell SPUF - Impact of Interior RH on Moisture Content of OSB Sheathing**

The closed cell SPUF 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.

### 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 SPUF. The paint has a vapour permeance of approximately  $300 \text{ ng/Pa}\cdot\text{s}\cdot\text{m}^2$ . Hygrothermal modeling was used to determine the effect of this paint layer, and whether and vapour retarding paint with a permeance of  $30 \text{ ng/Pa}\cdot\text{s}\cdot\text{m}^2$  would be sufficient vapour control for the open cell SPUF wall. This was compared to a wall with a polyethylene vapour barrier and to a wall with a more permeable  $600 \text{ ng/Pa}\cdot\text{s}\cdot\text{m}^2$  paint. The results are compared in Figure 14 for a north oriented wall with interior conditions of  $21^\circ\text{C}$  and 50% RH.



**Figure 14: Wall N6 - Impact of Interior Vapour Control Layer on Moisture Content of OSB Sheathing**

This plot shows that with a vapour retarding paint or polyethylene vapour control can be achieved during the winter months with open cell SPUF. 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 SPUF is sufficiently vapour resistant, the modeling showed that the OSB performance was not impacted by additional vapour control layers on the interior.

### CONCLUSIONS & RECOMMENDATIONS

This paper presented the setup and results of an experimental investigation of the need for additional vapour retarding layers in both open and closed cell SPUF in wood framed walls used for residential and commercial occupancy. Results encompassing the first winter of testing and some preliminary modeling were presented.

The open cell SPUF 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 SPUF walls however did have sufficient vapour resistance to maintain sheathing moisture contents below 20% for the same interior conditions.

Hygrothermal modeling was performed and compared to the observed results to validate the model. Using the validated hygrothermal model, recommendations for the use of additional vapour retarder layers as a function of SPUF type, wall assembly, and climate can be developed.

The field measurements showed that the OSB and wood stud moisture contents of the open cell SPUF 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<sup>2</sup>) and an interior relative humidity of greater than 40% during the winter in a cold climate (over about 4000 HDD °C) 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 SPUF in climates of more than about 4000 HDD °C. A vapour retarding paint (in the order of 30 ng/Pa·s·m<sup>2</sup>), 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 SPUF 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 °C), interior RH levels of 50% can be accommodated.

Field measurements showed, and modeling confirmed, that when SPUF is installed inboard of hygroscopic sheathing, moisture accumulation can occur due to solar driven moisture from brick cladding especially if relatively vapour impermeable SPUF is used. Basic building physics suggests that 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.

The hygrothermal model can be applied to other climates and future work will provide recommendations of the need for additional vapour control for both classes of SPUF installed in the walls of a wider range of building occupancy types and climates.

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