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June 17, 2014

Andrew Cole, Executive Director
Canadian Urethane Foam Contractors Association Inc.
3200 Wharton Way
Mississauga, Ontario, L4X 2C1

P: 866-467-7729

Via email: acole@cufca.ca

Re: Building science consulting and data analysis services – University of Waterloo BEGHut Cathedral Ceiling Report

Mr. Cole:

This report presents an analysis of data from a full-scale field investigation that was conducted by the University of Waterloo, under the supervision of Dr. John Straube. As discussed in previous correspondence, the University's analysis of collected data was delayed by staffing issues. Subsequently, CUFCA and Building Science Consulting Inc. (BSCI) entered into an agreement to have BSCI complete the analysis and related hygrothermal modeling.

The objective of this report is to present a summary of the full scale vented and unvented cathedral ceiling monitoring research at the University of Waterloo, as well as summarize the results of a series of hygrothermal simulations for different cathedral ceiling assemblies over a range of Canadian climates.

Please feel free to contact me if you have any questions or would like to discuss this report once you have read it. I can be reached by phone at 519.505.0433 or by email at jsmegal@buildingsciencelabs.com.

Thank you,

Jonathan Smegal M.A.Sc (Eng)
Building Science Consulting Inc.
167 Lexington Court, Unit 5
Waterloo ON, N2J 4R9
Phone: 519.342.4731
Email: jsmegal@buildingsciencelabs.com

CANADIAN URETHANE FOAM CONTRACTORS ASSOCIATION INC.

Ventilation and Vapour Control for SPF-insulated Cathedral Ceilings

June 2014

Prepared by **Building Science Consulting Inc.**
167 Lexington Court, Unit 5
Waterloo, Ontario
Canada N2J 4R9

Jonathan Smegal, M.A.Sc.
John Straube, PhD, P.Eng

www.buildingscienceconsultinginc.com

Acknowledgements

This report was prepared by Building Science Consulting Inc. based on data collected at the University of Waterloo BEGHut. The BEGHut is a unique natural exposure test facility operated by the Building Engineering Group in the Department of Civil Engineering. The BEGHut allows for the monitoring of more than 600 channels of temperature, humidity, and moisture content data from 27 full-scale test panels exposed to weather representative of large parts of the populated regions of Eastern Canada and the North Eastern United States. It has been used since 1990 to field test a variety of full-scale clay brick veneer, vinyl, ICF, strawbale, and EIFS wall systems. More information can be found at http://www.civil.uwaterloo.ca/beg/BEG_hut.htm

Contents

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 buildings. There are two broad classes of SPF generally used in the construction industry: low-density 8 kg/m^3 (0.5 pcf) open-cell foam, which is quite flexible, and medium-density 32 kg/m^3 (2 pcf) closed-cell rigid foam. Both product classes are studied in the research reported here.

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

1.1 Background

There is a growing need for effective and reliable means of insulating cathedral ceilings in wood framed homes. Cathedral ceilings have become more popular over time, as consumers look to use more attic space as storage space or special purpose rooms, and demand higher and more interesting ceilings. However, cathedral ceilings have traditionally had poor performance in cold climates because they are sensitive to air leakage condensation.

Ventilation of wood-framed roofs has traditionally been used to allow water vapour that entered a roof or attic space to dry to the exterior. The ventilation is required because the amount of moisture introduced cannot dry through the vapour barrier provided by most roofing materials (asphalt shingles and metal roofing are very vapour impermeable). Small air leaks can be tolerated in well-ventilated cathedral ceilings. Ventilation of roof spaces has traditionally been provided by including a 2” air space between the underside of the roof sheathing and above the insulation together with appropriate intake vent areas and outlet vent areas at or near the ridge. It is not practical to achieve ventilation at inside corners, dormers, and roof hips without extensive cross strapping to ensure cross ventilation.

SPF is often used to provide insulation and air tightness in cathedral ceilings. If an effective air barrier is installed, the amount of air leakage moisture is significantly reduced, and the need for ventilation may be eliminated. However, despite years of successful application, the unvented airtight 2.0 pcf closed-cell SPF roof is still often met with resistance from designers, building owners, and code officials. The use of 0.5 pcf open-cell SPF in unvented roofs can also be successful, but open-cell may require additional vapour control in cold climates and/or when used in conjunction with high humidity indoor conditions.

1.2 Vapour Barriers and Air Barriers

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

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

Vapour barriers or vapour diffusion retarders address the flow of vapour by diffusion only. Air barrier systems control the flow of vapour by airflow. In a cathedral ceiling application, as noted above, it is airflow that primarily causes condensation issues and prompts the need for ventilation. Air barriers also help 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 effective 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.

Although airflow is the primary cause of condensation issues in cathedral ceilings, vapour diffusion can result in condensation in some cases. To control the amount of vapour transported by diffusion, the National Building Code of Canada [5.5.1.1(3)] 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.”

In the commentary for the National Building Code of Canada (A-9.25.5.2), it states an assumption that the interior relative humidity in cold climates should not exceed 35% based on the average monthly maximum vapor pressure differences between the interior and exterior of 750 Pa to avoid moisture accumulation levels that may lead to deterioration.

The research reported here investigated the ability of typical framed cathedral ceilings using spray polyurethane foam insulation, with and without additional vapour 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 two phases:

1. Full-scale residential vented and unvented cathedral roof systems were exposed to the climate of South-western Ontario with approximately 4288 HDD18 from Environment Canada’s Canadian Climate Normals, and the heat and moisture-related performance measured in detail for more than 1 year with an elevated interior relative humidity
    a. Controlled intentional wetting events were compared to the exterior of the roof sheathing for all of the roof assemblies.
2. Hygrothermal simulations were conducted to support the measured data of the full scale roof systems, and to predict the performance of identical roof systems under various interior relative humidities in various cold climates.

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

2 Field Measurements

This chapter presents the setup and results of a full-scale field investigation of the need for additional vapour control or ventilation in both types of SPF in cathedral roofs. Seven test roofs were constructed and installed in the University of Waterloo's BEGHut test facility, maintained at three levels of indoor humidity over two years. The moisture content of the exterior wood sheathing and wood studs as well as relative humidity and temperature were monitored for a period of over two years and the results used to assess performance.

2.1 Experimental Setup

2.1.1 Test Facility Description

The University of Waterloo's BEGHut, located in Waterloo, Ontario, is designed to investigate the performance of full-scale enclosure assemblies under natural exposure in this climate. This facility can be 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 has been measured in poorly ventilated and air tight residential construction. It is more representative of museums and hospitals. 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.

2.1.2 Test Roofs

The seven roof assemblies were installed on the East orientation of the hip roof in November of 2009 in the University of Waterloo's test hut (see Table 2.1). All of the assemblies were constructed with OSB roof sheathing, black asphalt shingles, and interior painted drywall so these were left out of the description table.

Table 2.1: Full-Scale Roof Assemblies

Test Assembly	Insulation	Ventilation	Vapor Control	Air Control
Unvented Closed Cell (NCC)	R30 (~5")	No	ccSPF	SPF
Vented Closed Cell (VCC)	R30 (~5")	Yes	ccSPF	SPF
Vented Fiberglass (VFG)	R30 (~9 ¼")	Yes	Latex paint on drywall	Drywall
Unvented Painted Open Cell (NOCP)	R30 (~8")	No	Paint on foam and drywall	SPF
Vented Open Cell (VCC)	R30 (~8")	Yes	Latex paint on drywall	SPF
Unvented Open Cell (NOC)	R30 (~8")	No	Latex paint on drywall	SPF

For this project the typical BEGHut vented attic configuration was modified. Rafter bays were extended from the existing framing. Seven rafter bays of varying lengths were constructed on the East orientation of the test hut in the hip roof (Figure 1). A schematic of the test bays is shown in Figure 2. All of the test roofs have black asphalt shingles installed over tar paper and OSB as the exterior finish, and interior gypsum with primer and paint as the interior finish.

Figure 1 : Photo shows East orientation of test hut including hip roof

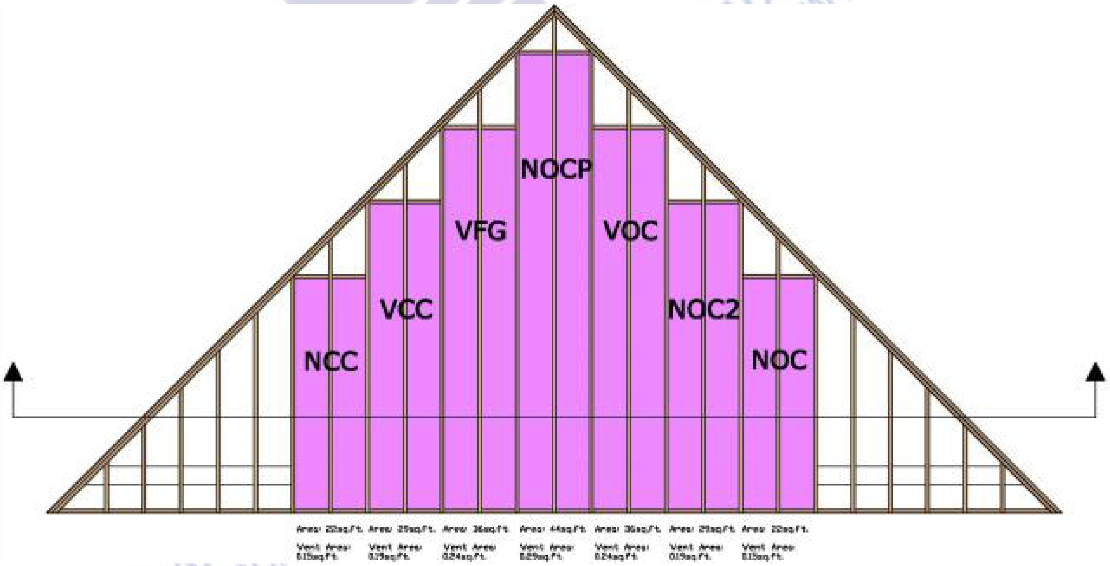

Figure 2 : Cathedral roof test areas

Venting in the three vented test roof assemblies was achieved with a soffit vent at the bottom of the roof connected to a continuous baffle installed the length of the test roof assembly connected to a roof vent at the top of the test roof section (see Figures 3 and 4).

Figure 3 : Continuous baffles from the bottom to the top of the test assemblies

Figure 4 : Vent holes drilled in the roof sheathing and covered with vents

The hygrothermal sensors measure temperature, relative humidity, and wood moisture content. Interior and exterior conditions at the test hut are also measured, including temperatures, relative humidities, wind speed & direction, solar radiation, and rainfall.

The same sensor layout was used in all roof assemblies (as much as possible), in order to allow for direct comparisons between the roofs. Moisture content, temperature and relative humidity sensors were measured automatically every five minutes and averaged over the hour by a Campbell Scientific data logger system. An example of an installed sensor package is shown in Figure 6. Figures 7 through 12 show plan and elevation sections of each test bay, and indicate the sensor layout and roof construction details for each. An unvented and a vented roof assembly are shown in Figure 8 and Figure 9 respectively. Key aspects of the installation include:

- In every test roof, there are two moisture content sensors, one in the sheathing, and one in the rafter.
- In both the vented and unvented roofs there are relative humidity sensors at two depths of the spray foam.
- Assemblies that included a void between the insulation and drywall also had an RH sensor in the void.
- Vented roof assemblies had an additional RH sensor in the ventilation cavity.
- All of the moisture content and relative humidity sensor locations were installed with a thermistor. In addition, there is a thermistor installed in every roof assembly between the shingles and the roof sheathing to measure the shingle temperature. In the vented roof assemblies, there are thermistors installed near the top and bottom vents of the ventilated cavity.

Note that Figures 7 to 12 do not include flashing or air sealing details: they are meant as a schematic representation of the roof assemblies to understand the systems and monitoring.

Wetting systems consisting of water storage media and a water injection tube were installed between the roof sheathing and building paper in each of the roof assemblies such that the moisture content measurement was directly below the wetting paper. Figure 5 shows the locations of the wetting systems as indicated by the tape on the building paper. The objective of the wetting systems is to inject a known volume of water to a controlled area of the sheathing at the same time for all of the roof assemblies to compare the wetting and drying results.

Figure 5 : Locations of wetting apparatus on the roof assemblies

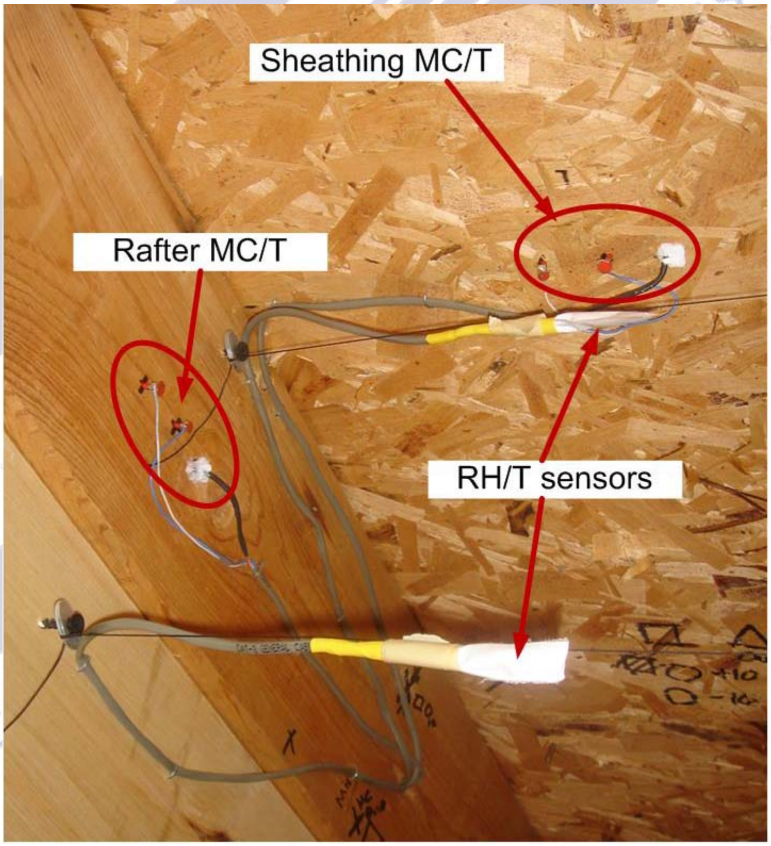

Figure 6 : Typical sensor configuration - unvented roof assemblies.

Figure 7 shows the Durovent baffle used during field testing. This is a polystyrene material that is water resistant with a net free vent area of 18.7 sq inches.

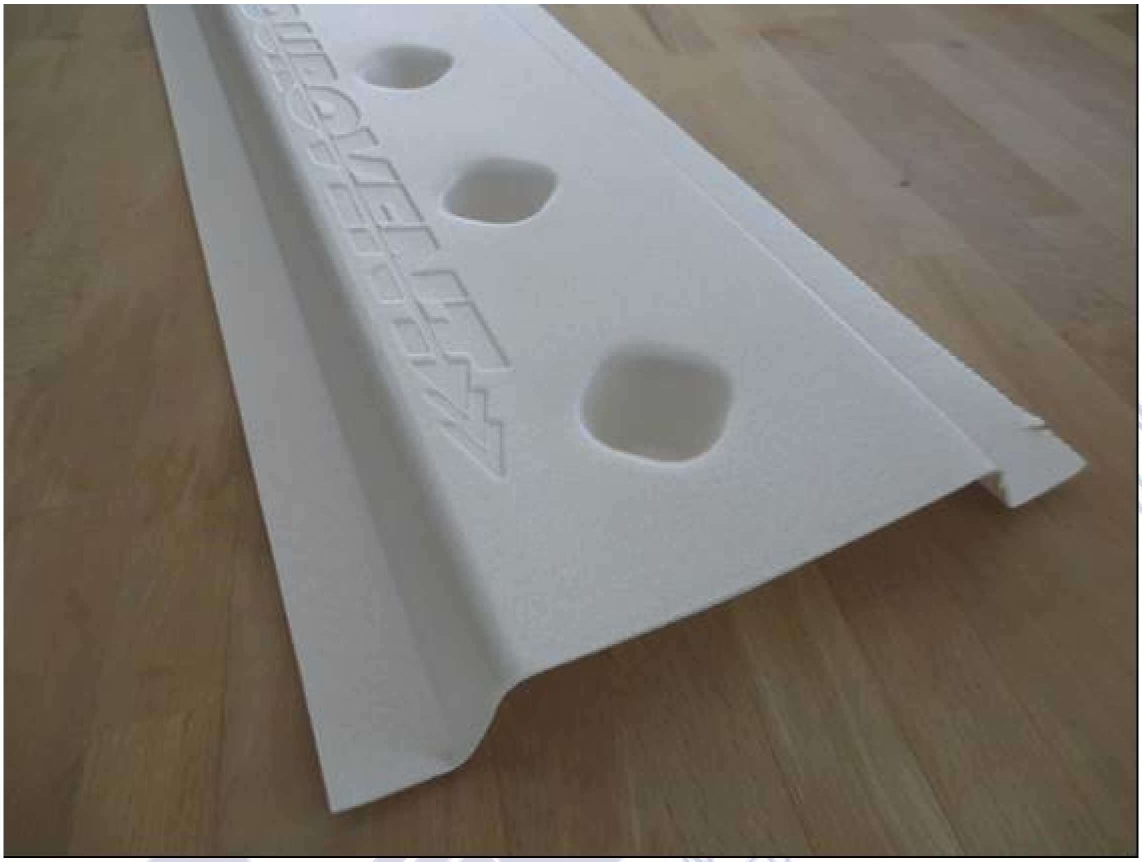

Figure 7 : Durovent baffle used in field testing

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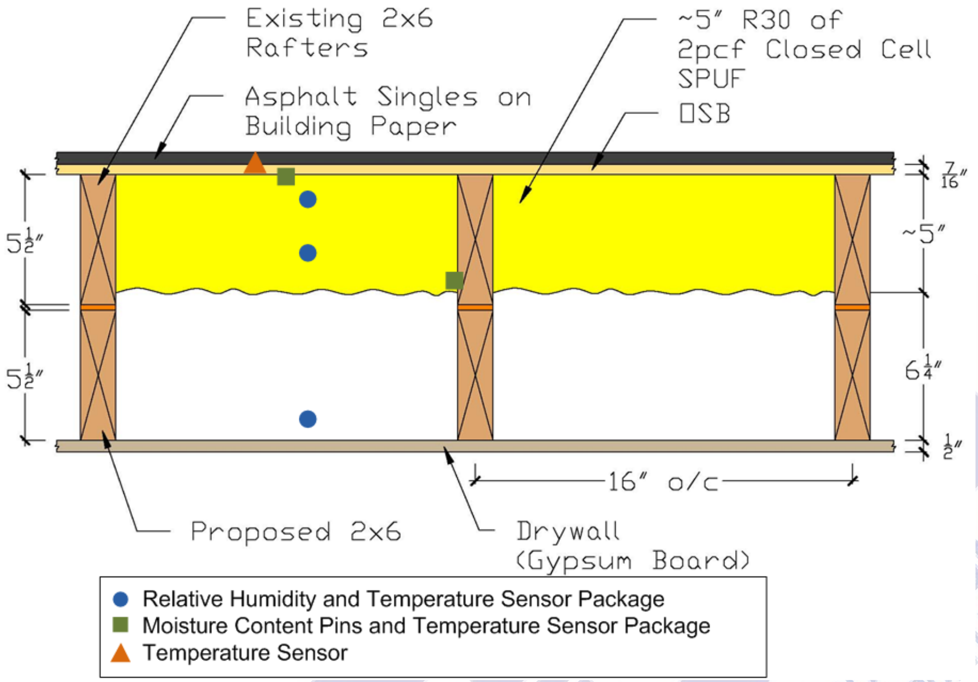

Figure 8 : Unvented ccSPF Instrumentation Plan

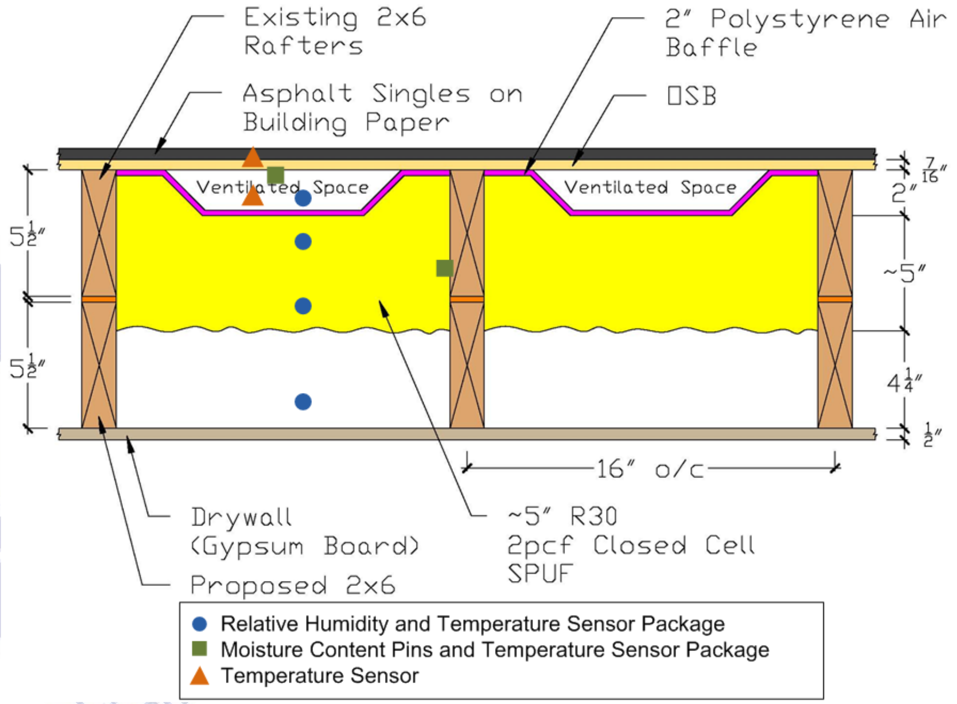

Figure 9 : Vented ccSPF Instrumentation Plan

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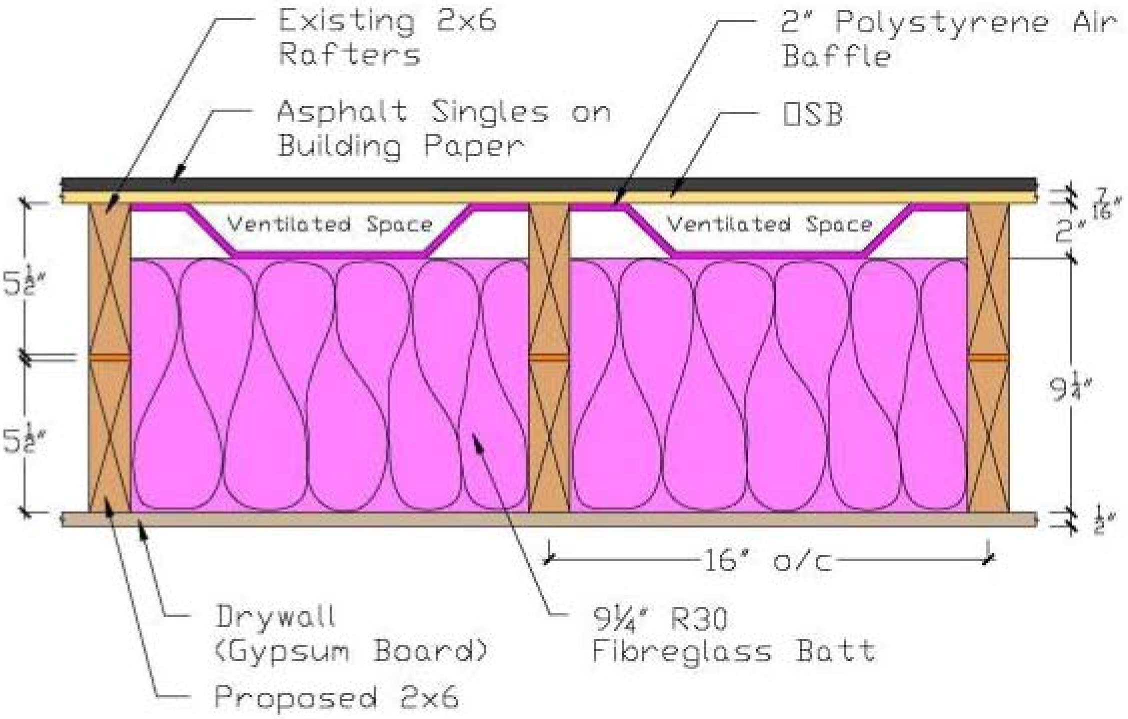

Figure 10 : Vented Fiberglass Batt Installation Plan

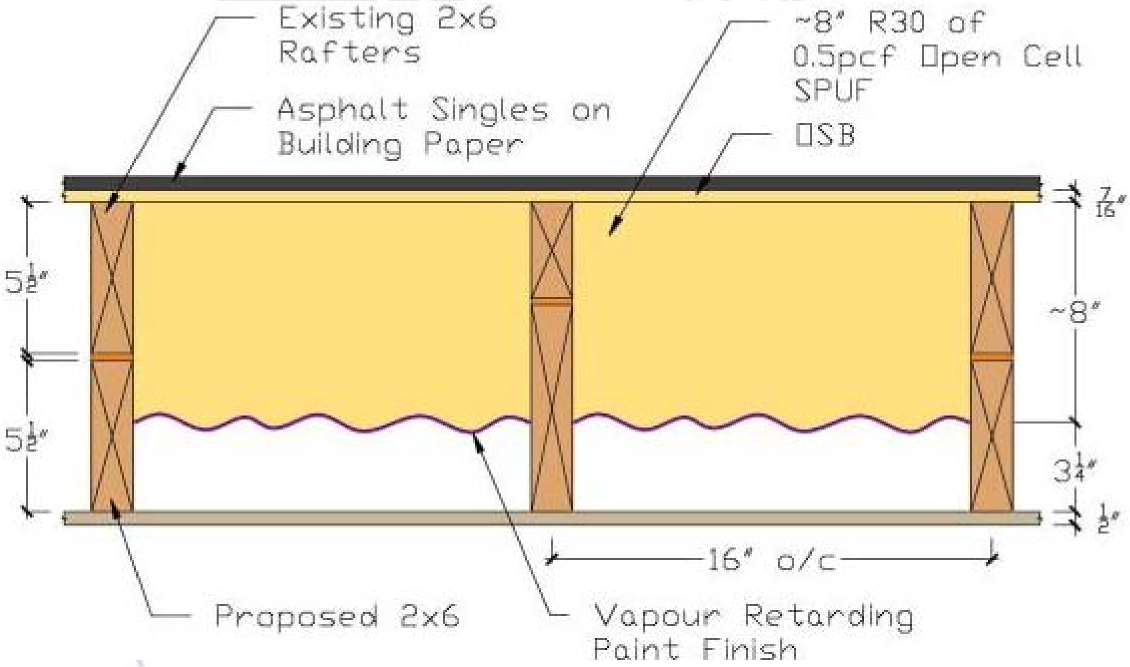

Figure 11 : Unvented Painted ocSPF Installation Plan

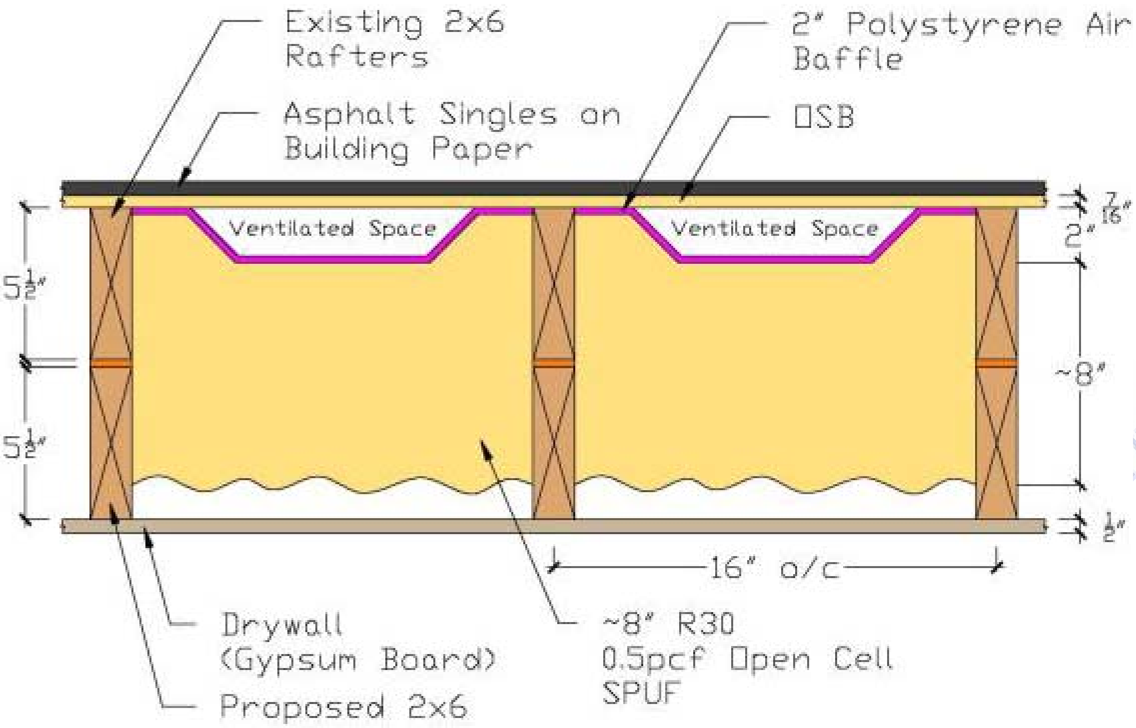

Figure 12 : Vented ocSPF Installation Plan

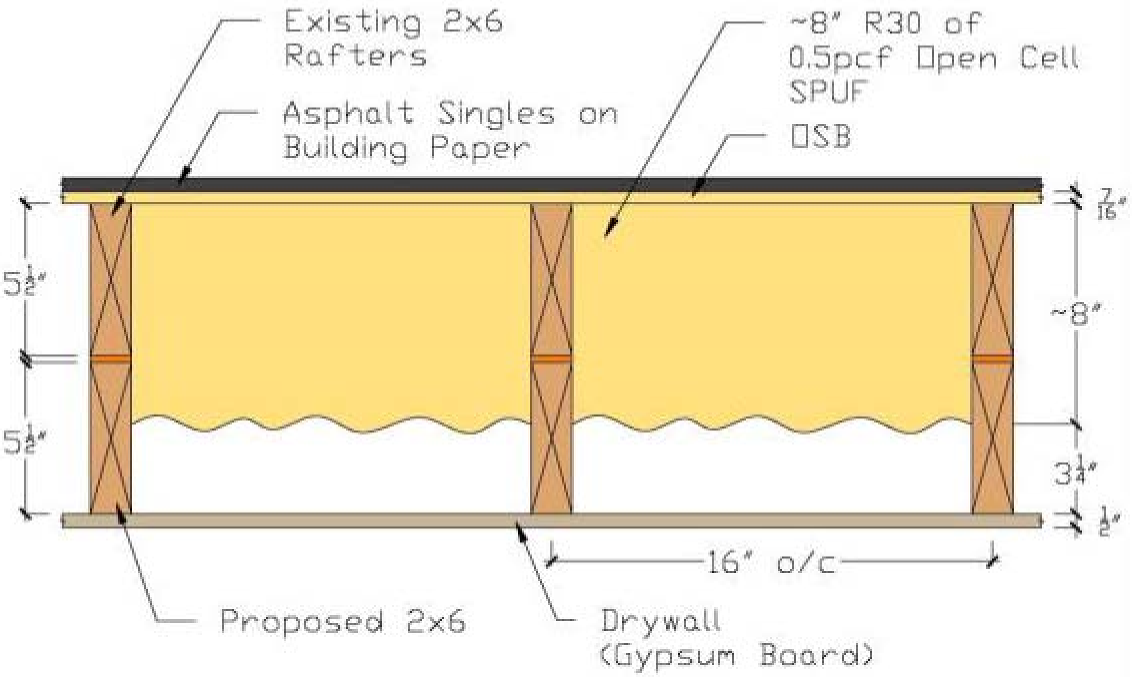

Figure 13 : Unvented ocSPF Installation Plan

2.1.3 SPF Material Properties

Two different SPF products were selected for use in the study. Both distinct classes of SPF commonly used in construction were represented, i.e. high-density (2 pcf) closed-cell and low-density (0.5 pcf) 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 normal interior conditions. Material properties taken from published material property data for the two types of SPF are summarized in Table 2.2. Both of the spray foams were installed to an R-value of approximately R-30. This requires approximately 8" (20cm) of 0.5pcf ocSPF, and approximately 5" (12.5cm) of 2.0 pcf ccSPF.

Table 2.2: SPF Material Properties Based on Manufacturers' Literature & CCMC Evaluations

Material Properties	Closed-cell	Open-cell
Density	39 kg/m^3 (2 pcf)	7.5 kg/m^3 (0.5 pcf)
Thermal Conductivity **(Long Term Design Value)**	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 0.6 per 25.4mm R 3.4 per inch
Vapour Permeability	2.1 ng/Pa·s·m	31.9 ng/Pa·s·m
Vapour Permeance for Thickness Installed	16 ng/Pa·s·m^2 for 127 mm	157 ng/Pa·s·m^2 for 203 mm

2.2 Results

The analysis focuses on the results for the period from February 2010 to October 2012. The interior and exterior boundary conditions for the experiment are presented, followed by a discussion of the open-cell and closed-cell SPF roof results.

2.2.1 Boundary Conditions

Indoor and outdoor temperature and relative humidity conditions are shown in Figures 13 and 14 respectively for the monitoring period from February 2010 to October 2012.

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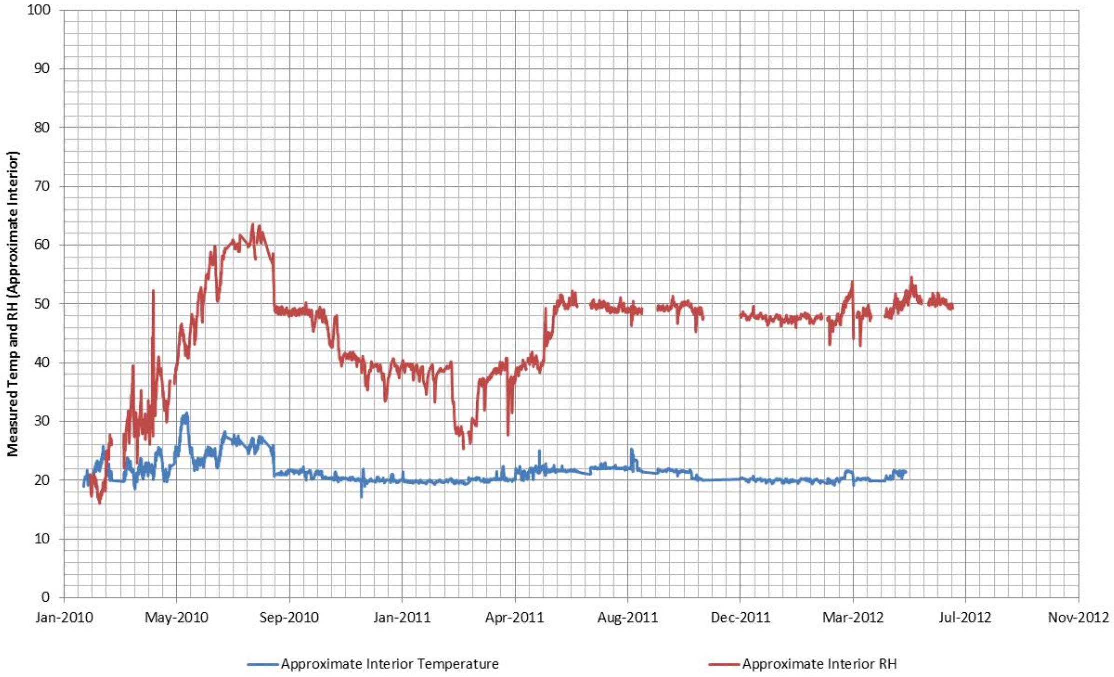

Figure 14 : Interior Boundary Conditions

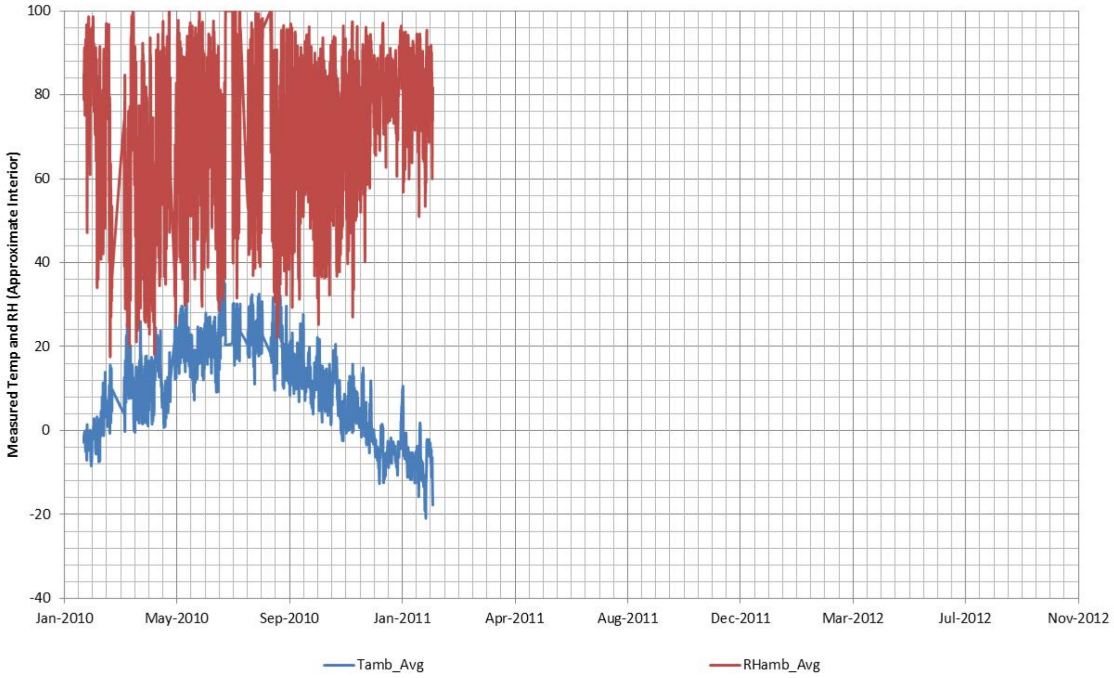

Figure 15 : Exterior Boundary Conditions

2.2.2 Analysis Criteria

Sheathing moisture content is used as the primary performance criteria because this location may experience moisture accumulation from the exterior in wet climates and, more importantly, is the first place where vapour diffusion condensation would occur in a cold climate during the heating season. In the case of these test roofs, the most significant moisture risks were at the locations of the wetting systems, which are used to compare the sheathing moisture performance under significant moisture stresses. Moisture contents of the sheathing will be used as a comparison rather than pass/fail criteria for the roof assembly. Generally, under normal conditions, the following criteria are used to assess the risk of various test assemblies:

Table 3 : Moisture Damage Risk Evaluation Criteria

No.	Criteria	Significance
1	Peak OSB sheathing moisture content less than 20%	No mold growth - very little risk
2	Peak plywood sheathing moisture content between 20% and 28%	Potential for mold growth eventually, depending on frequency and length of wetting, and temperatures during wetting. This design can be successful but conservative assessments usually require modifications to the assembly
3	Peak plywood sheathing moisture content >28%	Moisture-related problems are expected and this design is not recommended.

These moisture content thresholds are based on moisture physics and correlation of hygrothermal simulations with field investigations. These thresholds are not based on an existing standard, but on the extensive experience of BSCI with respect to moisture related issues, especially in cold climates.

The measured moisture content should be kept in context and good engineering judgment is required to determine the moisture risk to the sheathing. For example, elevated wood moisture contents in the cold winter months when the wood substrate is on the cold side of the assembly are much safer from a mold growth perspective than similar moisture contents in the summer, when the temperatures are in the correct range for optimal mold growth. Also, high moisture content for a short period followed by drying is not necessarily risky, as wood framed structures are able to manage high moisture contents for short periods without exceeding the safe storage capacity of the assembly.

The safe storage capacity is the amount of moisture an assembly is able to manage without suffering any moisture related issues. The baseline wood moisture content is a factor in the safe storage capacity since the lower the wood moisture content is during normal operation (without wetting events), the more moisture the wood can handle before reaching durability risk. If the measured wood moisture content is consistently higher, even if there are no moisture durability risks, there is less moisture buffering capacity in the wood before reaching moisture related durability risk levels.

Because OSB is an engineered wood product that varies between manufacturers, and varies over time, it is difficult to assign a safe moisture storage capacity. It has also been observed during long term testing that OSB may change its physical characteristics such as vapour permeance and adsorption after being subjected to high moisture environments such as elevated relative humidities, or moisture during construction.

2.2.3 Measured Moisture Content

The measured roof sheathing moisture content for all seven test roofs is shown in Figure 16. During the first winter, the interior relative humidity was approximately 40% and in the second winter, the interior relative humidity was approximately 50% (shown earlier in Figure 14). The measured moisture contents for Unvented ocSPF and Painted Unvented ocSPF exceeded 20% during the winter months with interior relative humidity of 40% and 50%. There was very little difference in the performance of the two unvented ocSPF roof assemblies. All of the other test roof assemblies had measured roof sheathing moisture contents that were quite safe (<15%) from a moisture durability perspective throughout the test period.

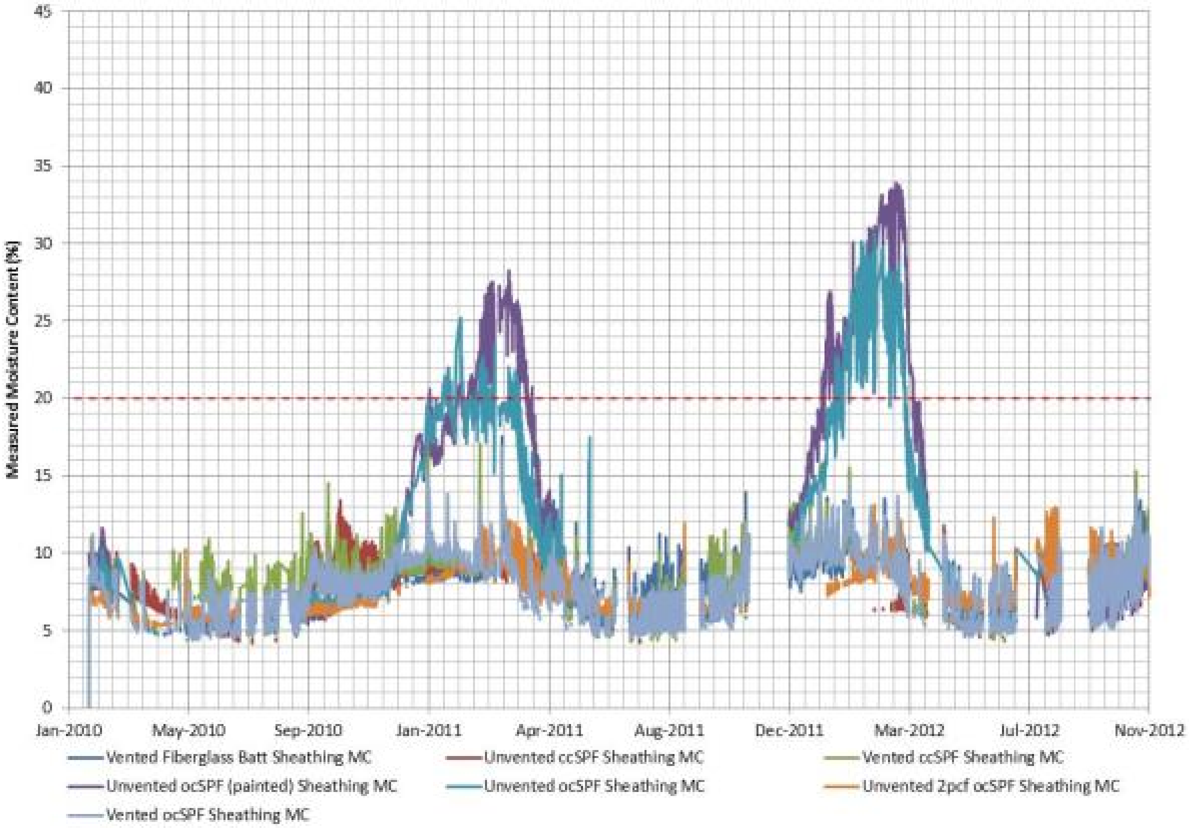

Figure 16 : Measured roof sheathing moisture contents for all seven test roofs

The measured rafter moisture content for all seven test roofs is shown in Figure 17. For every roof assembly, there are two rafter bays installed with each testing material. The rafter being measured is between the two rafter bays. The vented fiberglass assembly shows some increased moisture contents of the rafter even though the measured sheathing moisture content was quite low. Because of the air permeability of fiberglass, air and moisture can move freely throughout the roof system, and it is unclear what is causing the increased moisture content. A rafter moisture content measurement exceeding 40% generally indicates the presence of liquid water, potentially as a result of condensation. One hypothesis is that the continuous baffle is relatively vapour impermeable, and may not be removing moisture from the roof assembly, but instead protecting the roof sheathing from moisture in the roof assembly driven outward from the interior and acting like a cold-sided vapour retarder.

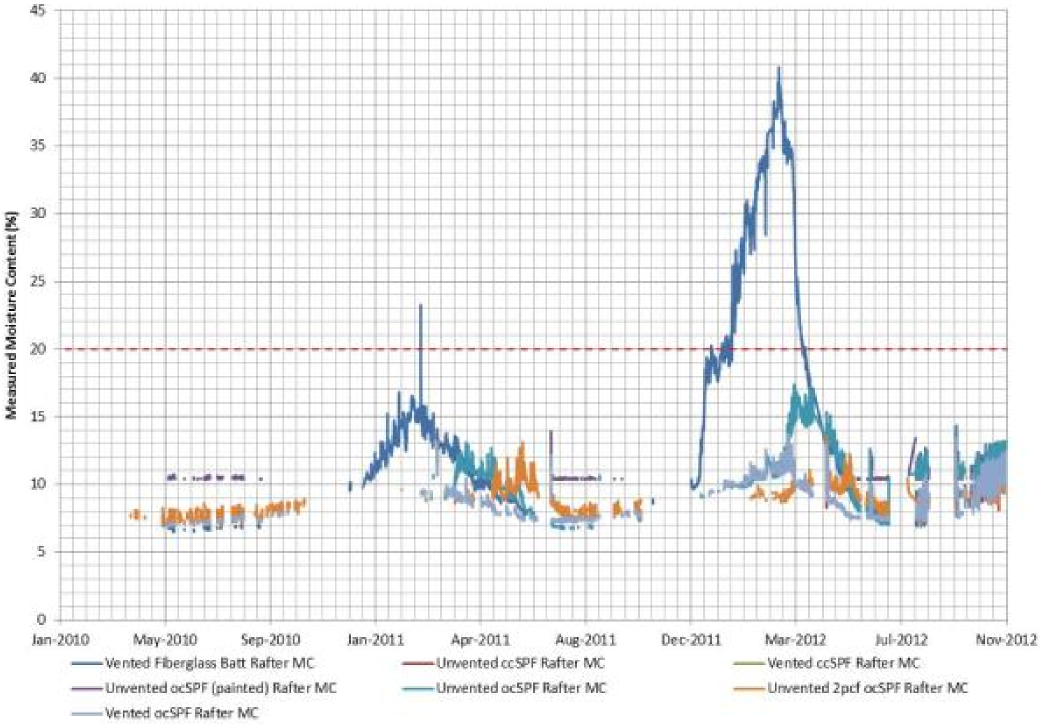

Figure 17 : Measured rafter moisture contents for all seven test roofs

Figure 18 shows how the increase in moisture content of the rafter in December 2011 correlates with the trend of decreasing falling temperatures. The red dashed line in Figure 18 indicates the 20% wood moisture content criteria as well 0°C (freezing).

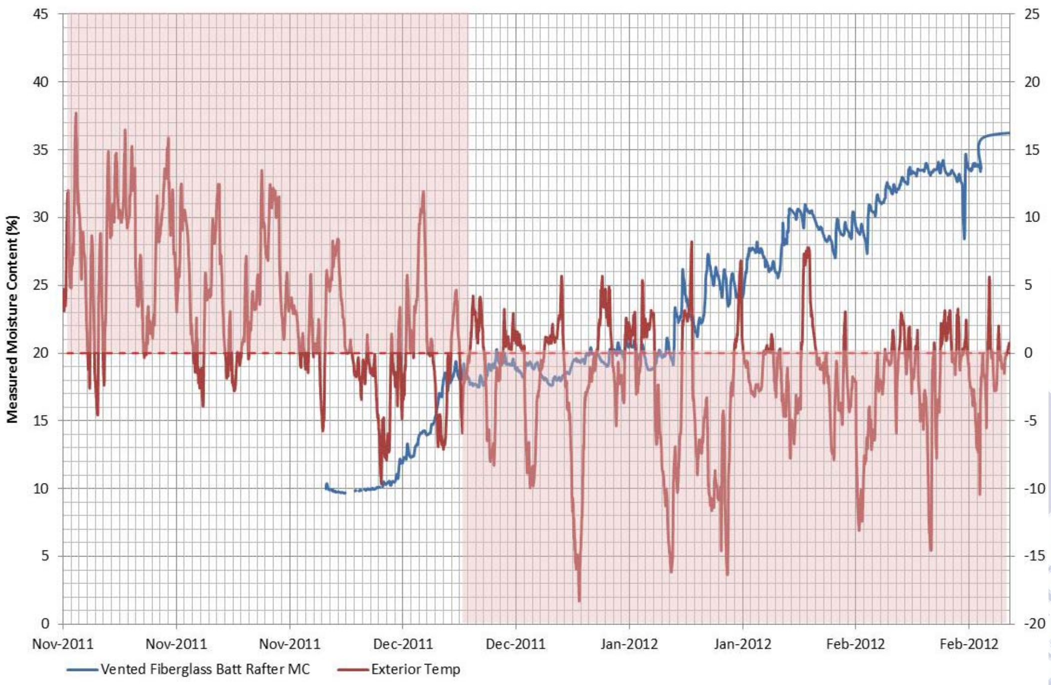

Figure 18 : Analysis of rafter moisture content peak in ventilated fiberglass roof assembly

2.2.4 Measured Relative Humidity

Relative humidity sensors were installed in the insulation in all roof assemblies, in the interior void between the insulation and interior drywall if applicable and in the ventilated cavity if applicable.

The measured relative humidity data for the unvented closed-cell spray foam assembly (Figure 19) shows that the relative humidity measurements in the foam are low for the entire analysis period.

The measured relative humidity data for the vented closed-cell spray foam assembly (Figure 20) shows that the vented cavity is very similar to the exterior environment, and that there is no elevated relative humidity at the monitored locations in the closed cell spray foam.

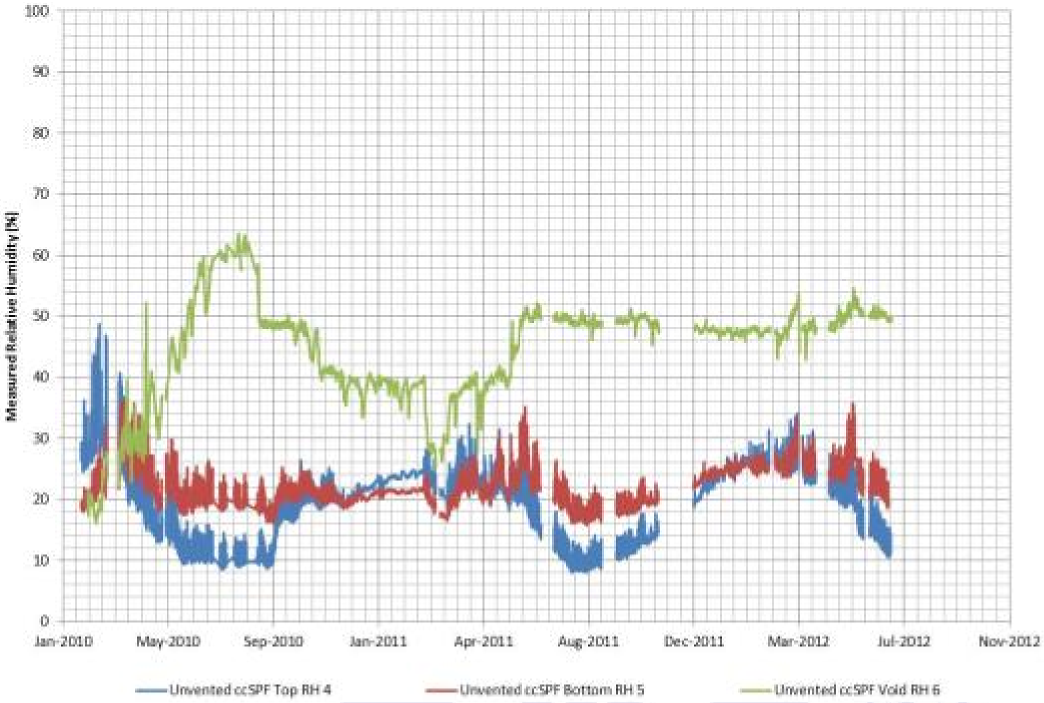

Figure 19 : Unvented ccSPF roof assembly - measured relative humidity

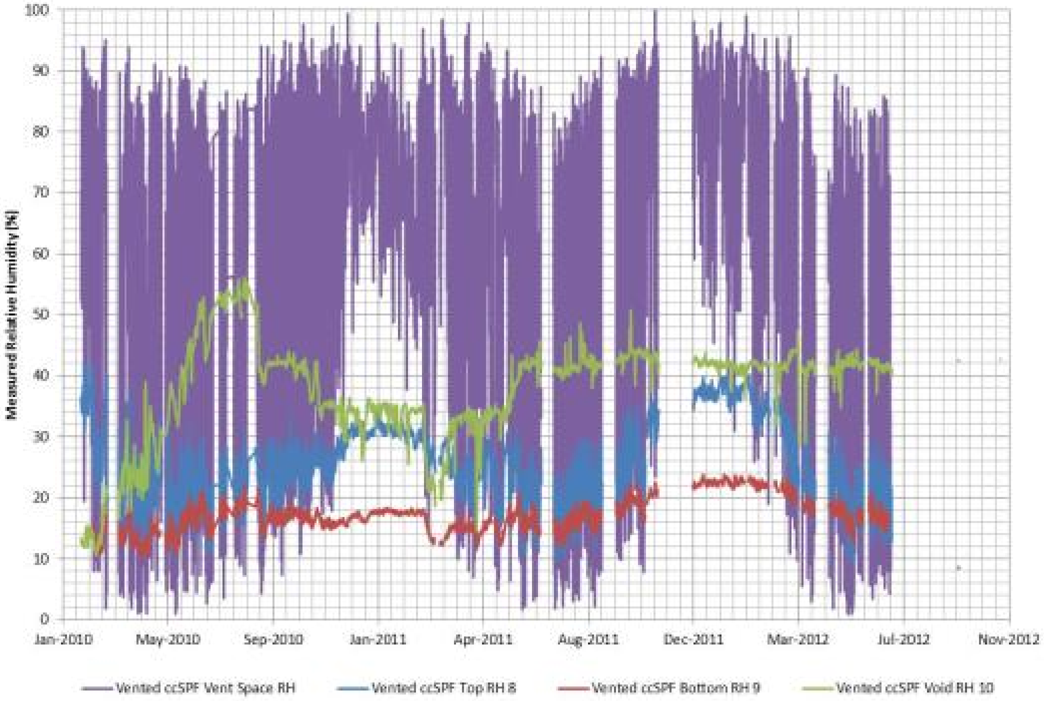

Figure 20 : Vented ccSPF roof assembly - measured relative humidity

In the vented fiberglass roof assembly, one RH sensor was installed in the ventilation cavity, and a second RH sensor was installed in the fiberglass batt insulation. The ventilation cavity appears to be well connected to the exterior. The measured relative humidity in the fiberglass batt is elevated compared to the ccSPF assemblies, and fluctuates much more, indicating moisture movement in the assembly. This movement could be convective looping, diurnal variations in the vapour pressure gradient, or connectivity with the ventilation cavity.

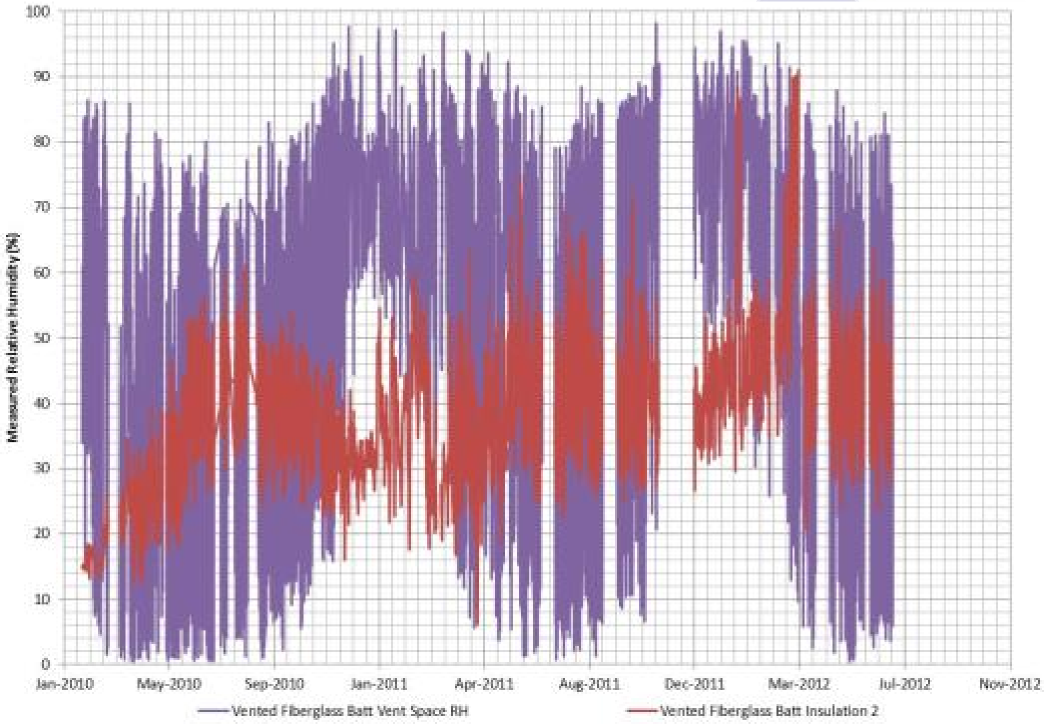

Figure 21 : Vented fiberglass batt roof assembly - measured relative humidity

The unvented open-cell roof assemblies are shown in Figure 22 for the painted foam and Figure 23 for the unpainted foam. The blue line in each of these graphs is the measured relative humidity in the spray foam near the exterior of the assembly. The trends are identical with increasing relative humidity in the winter months that correlates to the elevated sheathing moisture contents for the unvented open-cell assemblies earlier in Figure 16. The unpainted foam peaks approximately five percent higher in both measured winters which is a relatively insignificant difference, and could be a result of a higher relative humidity or a slightly different depth in the cavity.

The green line in the unvented ocSPF assemblies is the measured relative humidity in the space between the interior surface of the spray foam and the interior drywall. The trend between the two assemblies is similar although the measured RH in the painted foam assembly is approximately 10% higher throughout the entire year.

Analysis of the RH in the spray foam near the interior surface (red line) shows that the painted foam has slightly lower measured relative humidity in the winter months, and a higher relative humidity in the summer months indicating that the paint on the surface may be having a small effect on the relative humidity near the interior edge of the foam.

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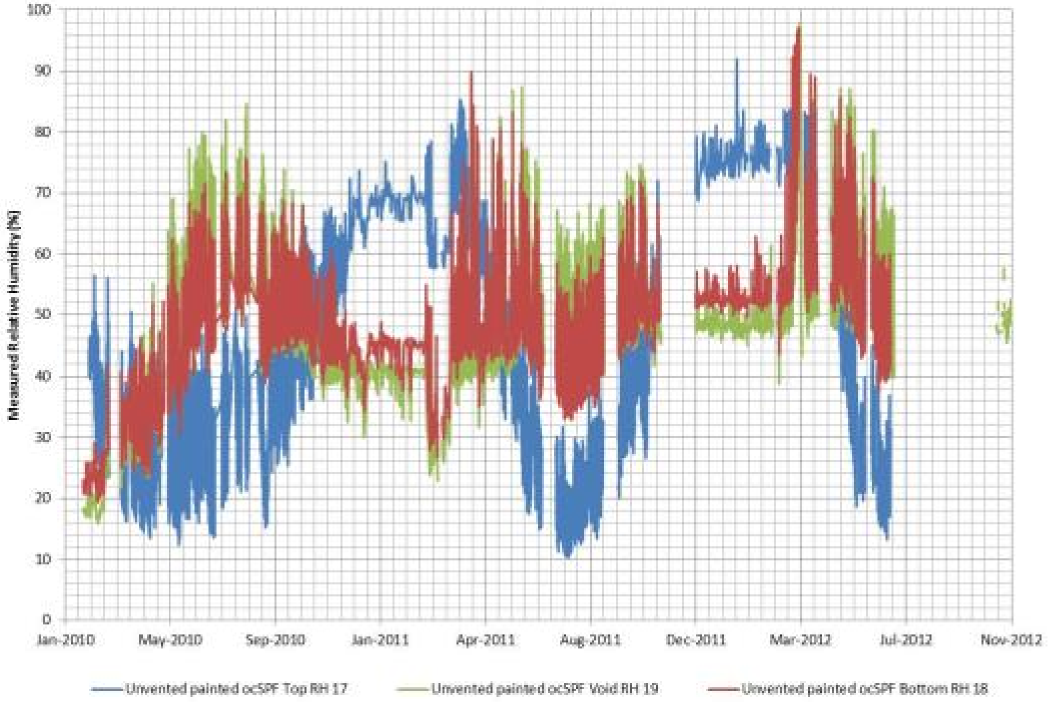

Figure 22 : Unvented painted ocSPF roof assembly - measured relative humidity

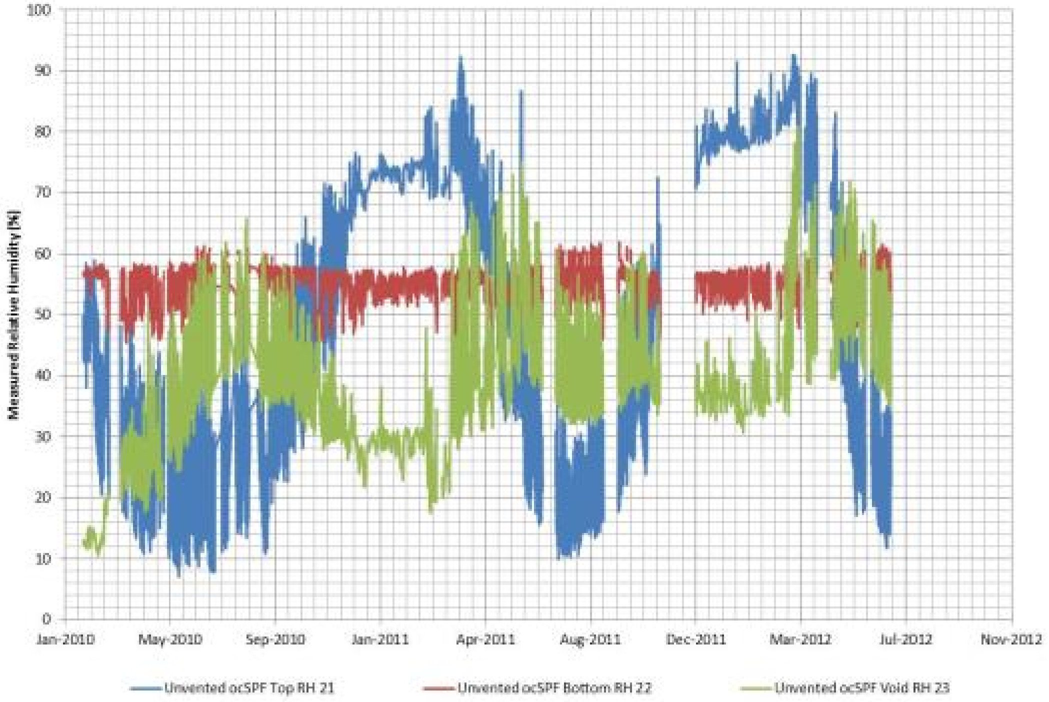

Figure 23 : Unvented ocSPF roof assembly - measured relative humidity

The measured relative humidity in the vented ocSPF assembly is shown in Figure 24. The vent space relative humidity failed during installation. The blue line shows the measured relative humidity near the exterior surface of the open-cell foam near the interface with the baffle. The relative humidity near that surface is quite high during the first winter at an interior relative humidity of 40%, and condensation would have occurred in the second winter (wih an interior relative humidity of 50%).

One hypothesis is that this elevated relative humidity may have been caused by a relatively vapour impermeable baffle, and the inability for water vapour to redistribute. Similar test results were observed in previous test wall analysis with the side by side comparison of walls with OSB, and walls with low permeance foam sheathing. In the previous wall study, the wall with exterior insulation sheathing and no OSB, there was no redistribution available for the water vapour, and condensation occurred. In the wall with OSB, vapour was able to redistribute, the RH did not reach 100%, but the moisture content of the sheathing increased.

This previous wall test result is similar to the difference in results between the vented and unvented ocSPF roofs. In the unvented roof assembly, the spray foam and water vapor in contact with the roof sheathing redistributes in the sheathing, increasing the moisture content but decreasing the relative humidity. In the vented roof assembly, the foam and water vapor are in contact with the non-hygroscopic plastic baffle, so the moisture cannot redistribute and the relative humidity reaches 100%.

The relative humidity measurements near the interior surface of the foam and in the void to the interior of the foam are similar to the unvented ocSPF assembly in Figure 23, although the void RH does not fluctuate as much in the warmer spring and fall for the vented ocSPF. This may be because the inward vapour drive effects of the unvented ocSPF are decreased with the ventilation in the vented ocSPF and the rejection of some heat from the assembly reducing vapour pressure gradients.

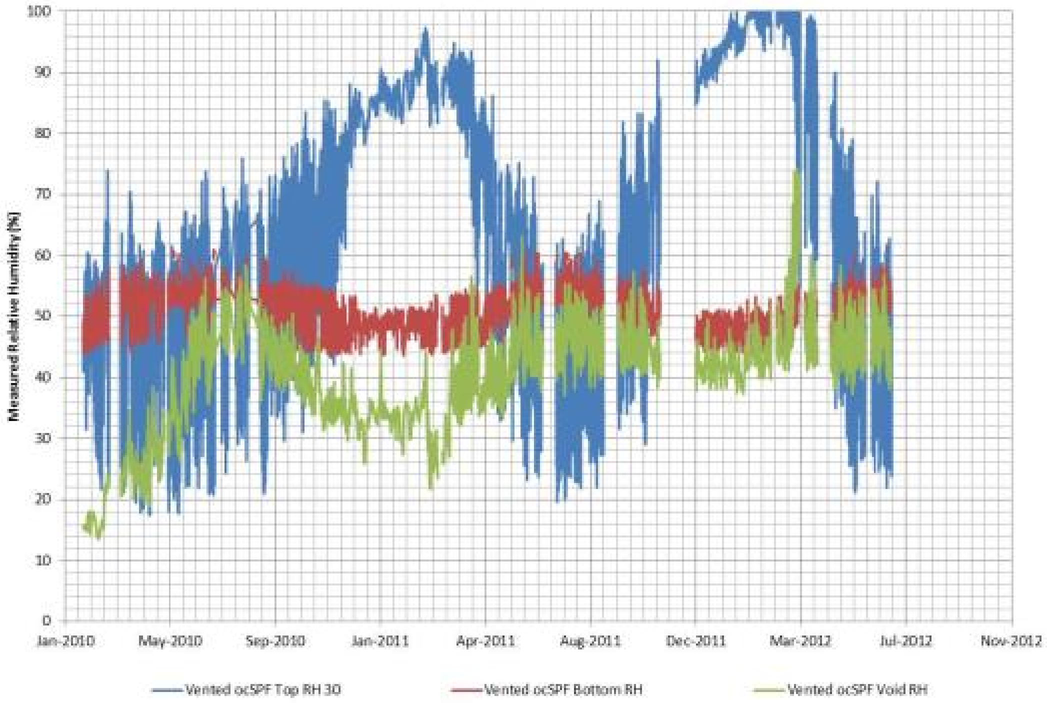

Figure 24 : Vented ocSPF roof assembly - measured relative humidity

2.2.5 Intentional Wetting Events

In the summer and fall of 2010 water was added to the wetting systems in direct contact with the exterior surface of the roof sheathing. This is intended to simulate a deficiency in the roof resulting in a leak underneath the shingles.

Figure 25 shows four wetting events of 30 mL to the wetting systems, and two wetting events of 60 mL injected into the wetting system. There was no measured moisture content change following the first three wetting events of 30 mL, and only a small increase (~2%) following the fourth wetting of 30mL. When 60mL was injected into the wetting system in September, there was a corresponding increase in the moisture content, but the peak measured moisture content did not exceed 12%. Similarly in October, a 60 mL wetting event to each roof assembly produced a response in the moisture content measurement but did not exceed peaks of 14% moisture content. As mentioned previously, these all remain within the safe moisture storage levels for wood sheathing.

A total of 240 mL of water was applied to the sheathing of each of the roof assemblies between August 25 and October 1, 2010, and there was no significant increase in measured sheathing moisture content during that period of intentional wetting.

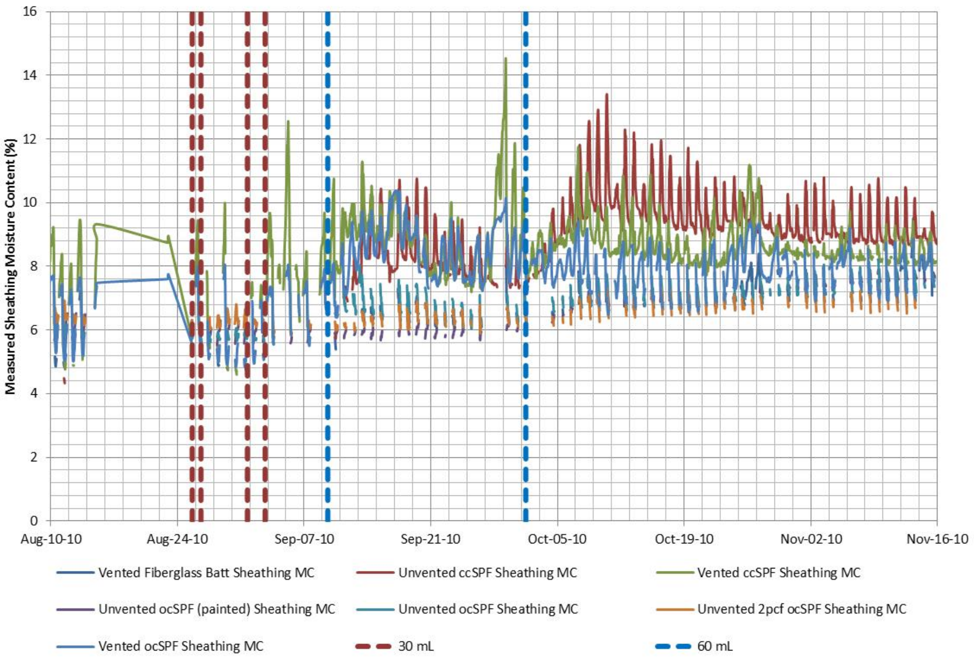

Figure 25 : Measured sheathing moisture content during intentional controlled wetting events

2.2.6 Summary

The sheathing moisture content analysis showed that there were elevated sheathing moisture contents for both the painted and unpainted unvented ocSPF roof assemblies under the tested boundary conditions, and there were no elevated sheathing moisture content measurements for the other test roof assemblies.

The rafter moisture content analysis of the vented fiberglass assembly showed that there was an elevated moisture content greater than 40% likely indicating the presence of liquid water potentially as condensation rundown.

This condensation could be the effect of a very air and vapour open insulation material resulting in convective looping between the warm and cold surfaces of the roof assembly. The condensation could also be a result of a relatively vapour impermeable ventilation baffles , and may not be removing moisture from the roof assembly, but instead protecting the roof sheathing from moisture moving through the roof assembly like a cold-sided vapour retarder.

Analysis of the measured relative humidity in the roof assemblies showed elevated relative humidity in both the unvented and vented ocSPF roof assemblies. In the unvented ocSPF roof assemblies, this elevated relative humidity corresponded to elevated sheathing moisture contents, but in the vented ocSPF with a ventilated baffle, the relative humidity reached 100% and may have resulted in high moisture levels on the interior face of the baffle within the ocSPF foam.

There were no predicted moisture related durability issues in the vented or unvented ccSPF roof assemblies indicated by moisture content or relative humidity measurements during this monitoring period.

3 Hygrothermal Simulations

This chapter presents the results of a set of hygrothermal simulations undertaken to support the measured data of the field investigation described in Chapter 2. These simulations also allow the prediction of performance for identical roof systems under various interior relative humidities in various cold climates.

3.1 Validation of Model

The WUFI 5.1 Pro computer program was used to model the test roofs. 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. 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 for the ocSPF roof assembly from the University of Waterloo test hut investigation. The spray foam material properties were modified to match those provided by manufacturers, where they differed from WUFI. 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.

The correlation between the measured data and the hygrothermal simulations is excellent considering all of the possible variables, material data, and boundary conditions that can be manipulated. The measured sheathing moisture content from the unvented open-cell foam roof was used for comparison from the first two years. The first year, the interior RH was 40% and the second year, the interior RH was 50% (Figure 26). One year of monitored exterior conditions from the BEGHut recorded data was used for both years in the hygrothermal simulation, so small differences could be a result of the different exterior weather conditions in the measured and simulated data.

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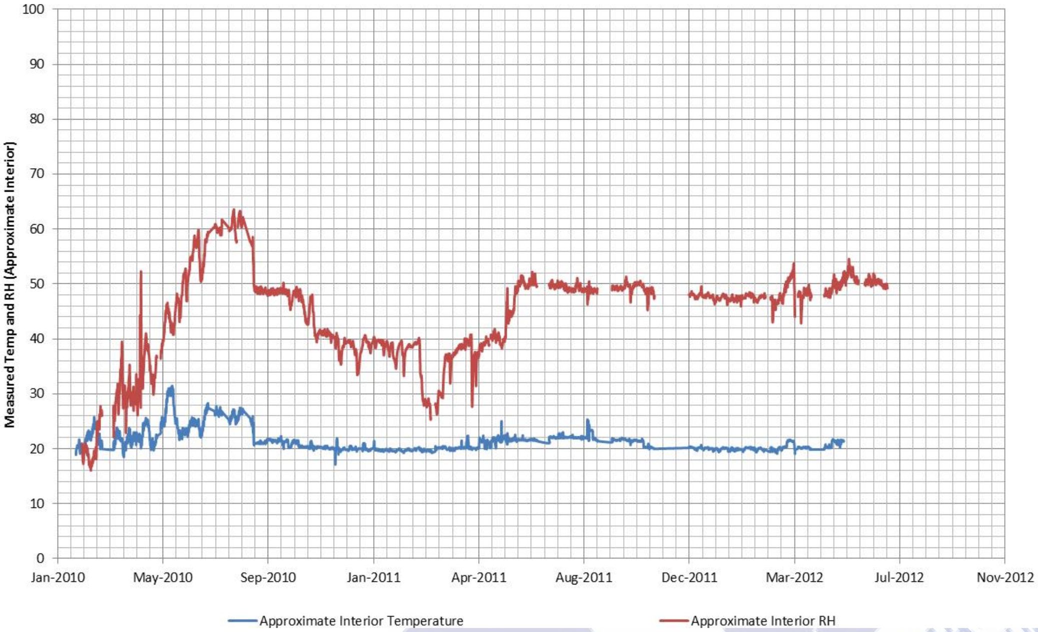

Figure 26 : Approximate interior relative humidity and temperature

Correlation of roof measurements with hygrothermal simulations can be more difficult than wall correlations because night sky cooling plays a significant role in the temperatures and moisture contents of the sheathing, and average values were used in the BEGHut data for the hygrothermal simulation because the night sky cooling effects are not measured at the BEGHut.

The green line in Figure 27 is the measured sheathing moisture content in the ocSPF roof assembly. And the blue and red lines are the predicted sheathing moisture content at 40% interior RH and 50% interior RH respectively. The flat-line area on the measured data at approximately 6% is a result of meeting the bottom end of the resistance measurement system employed.

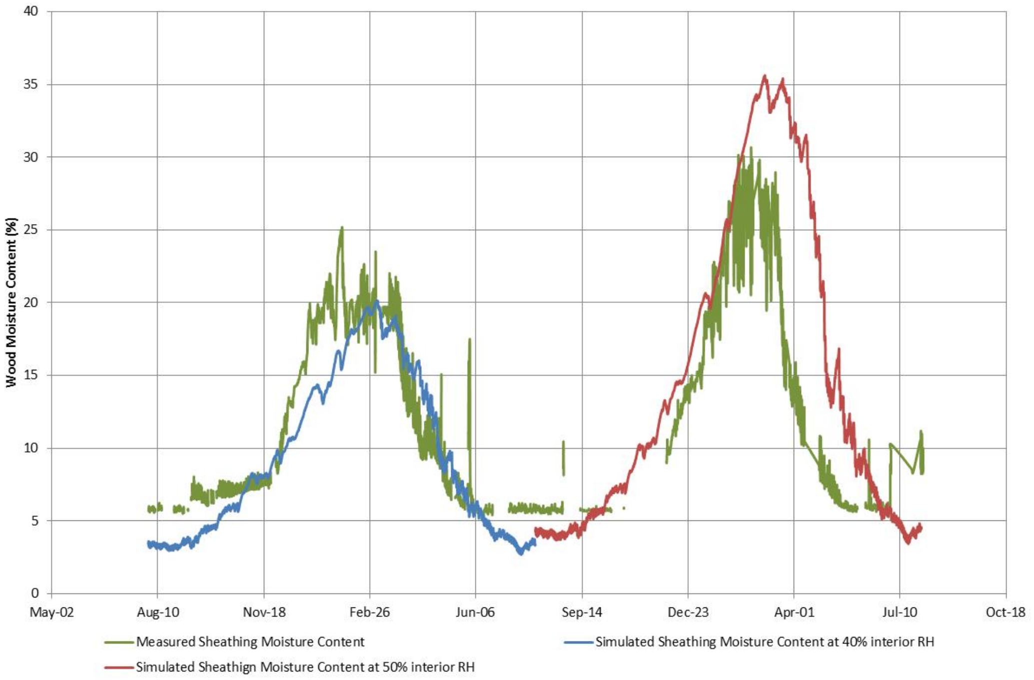

Figure 27 : Comparison of measured and simulated sheathing moisture content in the unvented ocSPF roof

3.2 Hygrothermal Simulations of all Roof Assemblies in Different Climates

The correlation between the field measurements and hygrothermal simulations in the previous section demonstrates that careful application of the WUFI hygrothermal model allowed for the prediction of measured roof performance. This section of the report extends the results from the experimental program to a wide range of roof types and climates

Seven different roof assemblies identified previously were parametrically modeled in different Canadian climates. Based on BSCI's experience with hygrothermal simulations and enclosure monitoring, we used the worst case scenario for the simulations to achieve a conservative prediction of performance. In this analysis that means we used:

- North orientation (least solar energy for drying)
- 12/12 roof pitch (45°) to further limit the solar energy.

All of the other parameters used in the simulation were chosen to most closely match the roofs monitored in the University of Waterloo BEGHut. The only change made across the different climate zones was a decrease to the interior relative humidity in the very cold climates of northern Canada.

For all of the vented roofs, a WUFI ventilation rate of 50ACH was chosen. This represents an airflow velocity of approximately 0.22 ft/s (0.07 m/s) assuming a 16 foot length (4.9m) of rafter.

For this analysis the insulation was assumed to be in direct contact with the vented cavity and not separated by a baffle. The material properties of the baffle are unknown, but further work could be done to determine if there is a predicted effect on the performance of the roof assembly from different types of ventilation baffles.

Unlike wall simulations, the performance of roof simulations is significantly affected by clear sky radiation effects on the surface also referred to as night sky cooling, which can lower the roof temperature by several degrees beyond the ambient exterior temperature, potentially resulting in further condensation of any water vapour.

3.2.1.1 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 28).

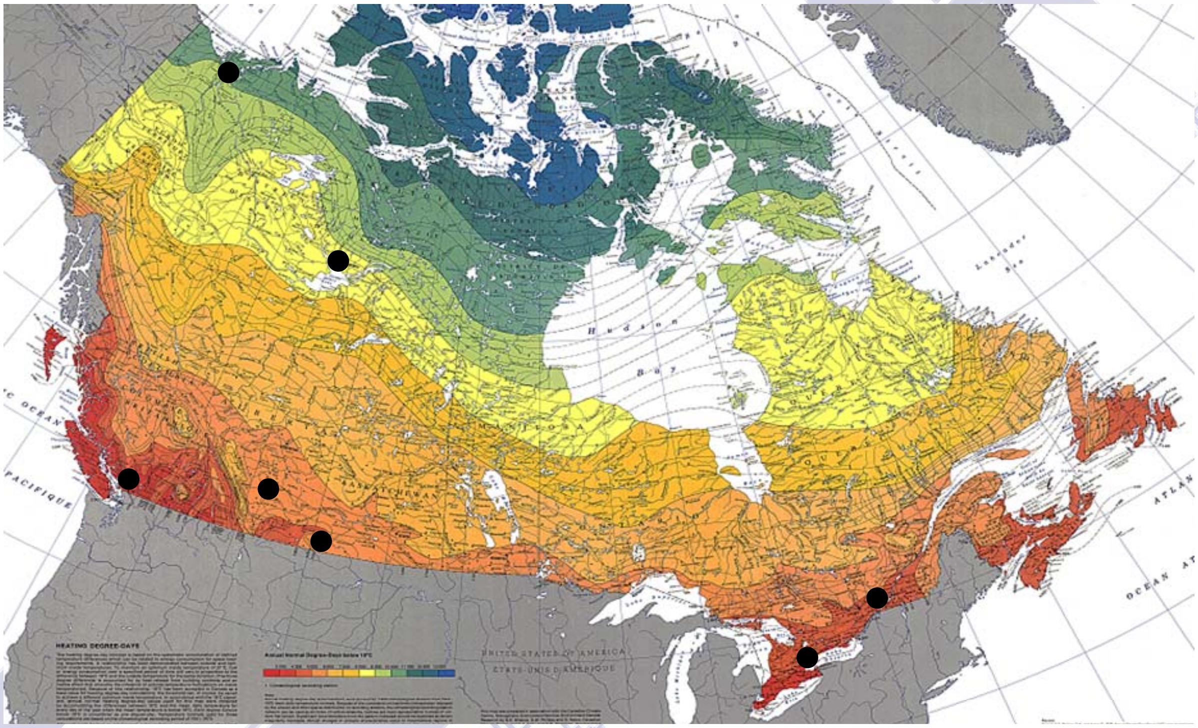

Figure 28: Canada Heating Degree Days and Simulation Cities (National Atlas of Canada, 5th ed.)

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, and this information is summarized in

Table 3.1. 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 28). 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 3.1 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 3.2 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 3.1: 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 3.2: Summary Climate Statistics for Cities in WUFI Simulations

Representative Locations	Vancouver	Toronto	Ottawa	Calgary	St. John's	Quebec City	Winnipeg	Yellowknife	Inuvik
Nominal Heating Degree Days (<18°C)	3000	4000	4500	5000	5000	5000	6000	8000	10,000
HDD<18°C in WUFI Climate File	3346*	4385*	4974*	5770*	5269	5410	6480*	8291**	9977**

*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.

3.2.1.2 Indoor Climate

The temperature for interior conditions in all simulations was set at 22°C with an annual variation of 1°C, Figure 30. Each climate category was modeled with three interior climate conditions – low, medium and high indoor relative humidities (Figure 29,

Table 3.3). 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. Although it is not recommended that any interior RH be above 40% during the winter in cold climates, the models were run above this level to stress the enclosure and to represent what has been found in measured data from some homes.

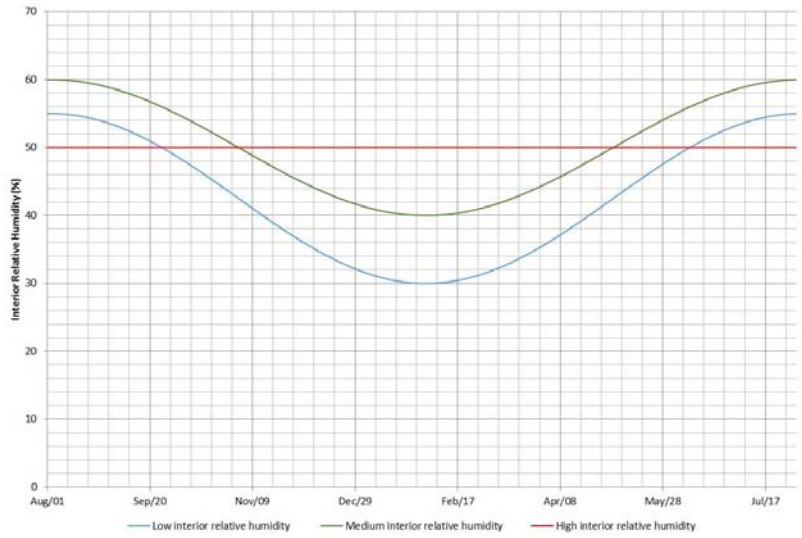

Figure 29 : Simulated interior relative humidity conditions

Table 3.3: 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 30.

Project/Case: SPUF HDD 4000/Open Cell 5.5" - 30/55% RH

Outdoor Climate (Left Side) | Indoor Climate (Right Side)

Map/File | Sine Curves | EN 13788 | EN 15026 | ASHRAE 160P

WTA Recommendation 6-2-01/E: User Defiinied Sine Curve Parameter

Temperature / Relative Humidity

Temperature

Adjustments

Mean Value [°C]	22
Amplitude [°C]	1
Day of Maximum	8/1/2008

☐ constant

Relative Humidity

Adjustments

Mean Value [%]	42.5
Amplitude [%]	12.5
Day of Maximum	8/1/2008

☐ constant

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

3.3 Simulation Procedures

All of the roof simulations began with a constant temperature of 22°C across all components.

The simulations were conducted for more than one year to ensure they reached equilibrium and the annual variation in moisture content was constant. The initial conditions may have been varied to make it easier for the assembly to reach equilibrium.

The roof sheathing was divided into two layers, an interior 3mm layer, and exterior 8 mm layer. In our experience, monitoring the interior 3mm layer more accurately represents the moisture content in the OSB, because moisture will condense and accumulate on the interior most surface, and the entire thickness of the OSB is rarely engaged and at equilibrium. Using the interior 3mm as the indicator of moisture content results in higher predicted moisture contents than using the entire thickness, but this is more realistic of what's actually occurring, and does match the measured moisture contents in the validation of the model done previously.

The interior latex paint layer was assumed to be approximately 5 US perms (287 ng/Pa•s•m^2). Latex paint is assumed to be a US Class III vapour retarder which is between 1 US perms (57.4 ng/Pa•s•m^2) and 10 US perms (574 ng/Pa•s •m^s). No sensitivity analysis was conducted on the drywall interior paint in this study, but this may have an effect on the moisture accumulation in some roof assemblies.

For the purposes of the hygrothermal simulation, it was assumed that the vapor control paint applied to the surface of ocSPF was 1 perm (57.4 ng/Pa•s•m^2). Most vapour barrier paints are tested by applying the paint to a plastic film, and not tested on absorptive hygroscopic materials. Care should be taken when specifying a vapour retarder paint that it actually meets the criteria when installed on a substrate different from a plastic film.

The physical characteristics of the most critical components in the hygrothermal simulations are shown in Table 4.

Table 4 : WUFI material data for simulations

			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)
	thickness, t [m]		0.14	0.09	0.09	0.05	0.14	0.001	0.013	0.011
	thickness, t [in.]		5.5	3.5	5	2	8	6 mil	0.5	7/16
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
Thermal Resistance - metric, m^2·K/W	RSI	=t/k	4.00	2.57	3.75	2.08	3.33	0.00	0.06	0.12
Thermal Resistance - imperial, hr·ft^2·°F/Btu	R-value	=RSI·5.678	22.7	14.6	21.3	11.8	18.9	0.0	0.4	0.7
Vapour Properties										
Water Vapor Diffusion Resistance Factor	VRDF	=185/μ	1.30	1.30	89	89	5.80	50000	8.3	812.8
Vapor Diffusion Thickness	Sd value	=185/M	0.2	0.1	8.0	4.4	0.8	50.0	0.1	9.0
		=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
Permeance US perms			17.7	27.5	0.3	0.7	2.7	0.1	30.6	0.4
Permeance, ng/Pa·s·m^2	M	=μ/t	1016	1581	16	42	157	4	1755	20
Other Properties										
Bulk Density, kg/m^3	ρ	-	30	30	39	39	7.5	130	850	650
Porosity, m^3/m^3	Ψ	-	0.99	0.99	0.99	0.99	0.99	0.001	0.6	0.95
Specific Heat Capacity, J/kg·K	c_o	-	840	840	1470	1470	1470	2300	850	1880

3.4 Analysis Results

The analysis results from the hygrothermal simulations are shown in Table 5.

The hygrothermal analysis showed that vented closed cell spray foam roof assemblies will perform well in all simulated climates.

The unvented closed cell worked well at all interior relative humidity levels in Vancouver, Toronto and Ottawa. In the colder climates of St.John's, Calgary, Quebec City, and Winnipeg, the elevated interior relative humidity did result is some predicted elevated sheathing moisture contents, but all of these cold cities were predicted to perform well at a reasonable interior relative humidity. It is not surprising that there are predicted moisture related issues at the high relative humidity (50% all year) in these climates. At the medium relative humidity, there were also some predicted elevated sheathing moisture contents, but it is important to remember that this analysis is conducted at the worst case scenario. The reason for the predicted elevated sheathing moisture contents seems to be a combination of the North orientation, steep pitch, and night sky radiation effects. If the orientation is changed to South, and all other variables are kept the same, the results can be seen in the sensitivity analysis section.

Vented open cell spray foam roof assemblies were predicted to work well in all climate zones up to and including Winnipeg, because the ventilation kept the interior surface of the roof sheathing dry. Based on the field testing, there may be elevated relative humidity at the interface between the baffle and the spray foam depending on the baffle properties. In the intial WUFI analysis, there was no layer included in the assembly for the baffle.

The unvented unpainted open cell spray foam with only a latex paint vapor control layer on the drywall (Class III), had predicted elevated sheathing moisture contents as warm as Vancouver with an elevated interior relative humidity.

The unvented open cell spray foam with an airtight polyethylene vapor barrier had significantly improved predicted performance compared to the unvented open cell with only latex paint vapor control. There were no predicted elevated sheathing moisture contents until the climates of Yellowknife and Inuvik with interior poly.

The open cell foam with a 1 US perm (57 ng/Pa•s•m^2) coating on the foam had improved performance compared to the unpainted open cell assembly, and worked in Ottawa with the recommended winter time interior relative humidity.

The ventilated fiberglass assembly had good predicted performance in all climate zones up to and including Winnipeg. The ventilation of the fiberglass removed all moisture in the simulation that diffused from the interior, and it was assumed that there was no air leakage from the interior in this assembly. It is unlikely that the air leakage would be nonexistent in reality. Using a code required polyethylene air/vapor barrier in the vented fiberglass assembly, and assuming it was airtight, reduced the predicted risk to safe levels, even in the extreme cold climates. Air leakage will move a significant amount of moisture, and fiberglass roof assemblies with poly should be expected to have some amount of air leakage.

Table 5 : Simulation Summary Results

Moisture Content (MC) in Wood Roof 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

🟩 = MC < 20%, no mold growth

🟨 = MC is 20 to 28%, potential for mold growth

🟥 = MC > 28%, moisture problems expected, this design is NOT recommended

Cathedral Roof Construction					Vancouver			Toronto			Ottawa			St. John's			Calgary			Québec City			Winnipeg*			Yellowknife			Inuvik		
					HDD 3000			HDD 4000			HDD 4500			HDD 5000			HDD 5000			HDD 5000			HDD 6000			HDD 8000			HDD 10000		
Contents of Cavity		Depth of Cavity	Ventilation	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 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%
Spray Polyurethane Foam (SPF)	2.0 pcf Closed Cell^3	5" R30	Ventilated Continuous Baffle	ccSPF	🟩 13%	🟩 13%	🟩 13%	🟩 10%	🟩 10%	🟩 10%	🟩 10%	🟩 10%	🟩 10%	🟩 11%	🟩 11%	🟩 11%	🟩 10%	🟩 10%	🟩 10%	🟩 10%	🟩 10%	🟩 10%	🟩 9%	🟩 9%	🟩 9%	🟩 18%	🟩 18%	🟩 18%	🟩 12%	🟩 13%	🟩 12%
		5" R30	Non-ventilated	ccSPF	🟩 11%	🟩 14%	🟩 14%	🟩 10%	🟩 13%	🟩 13%	🟩 12%	🟩 14%	🟩 14%	🟩 15%	🟥 43%	🟥 46%	🟩 15%	🟥 39%	🟥 39%	🟩 13%	🟩 19%	🟨 20%	🟩 13%	🟨 21%	🟨 22%	🟥 >60%	🟥 >60%	🟥 >60%	🟥 >60%	🟥 >60%	🟥 >60%
	0.5 pcf Open Cell	8" R30	Non-ventilated	interior poly	🟩 13%	🟩 13%	🟩 13%	🟩 13%	🟩 13%	🟩 13%	🟩 13%	🟩 14%	🟩 15%	🟩 14%	🟩 15%	🟩 16%	🟩 15%	🟩 16%	🟩 17%	🟩 14%	🟩 14%	🟩 17%	🟩 13%	🟩 14%	🟩 15%	🟨 21%	🟥 52%	🟥 55%	🟥 51%	🟥 >60%	🟥 >60%
		8" R30	Ventilated	latex paint	🟩 13%	🟩 13%	🟩 14%	🟩 11%	🟩 11%	🟩 11%	🟩 11%	🟩 11%	🟩 11%	🟩 12%	🟩 12%	🟩 12%	🟩 10%	🟩 11%	🟩 13%	🟩 11%	🟩 11%	🟩 12%	🟩 11%	🟩 13%	🟩 14%	🟨 24%	🟨 27%	🟥 31%	🟩 18%	🟨 25%	🟨 28%
		8" R30	Non-ventilated	1 US perm paint on foam	🟩 12%	🟩 17%	🟩 18%	🟩 13%	🟨 24%	🟨 28%	🟩 15%	🟥 30%	🟥 32%	🟨 27%	🟥 >60	🟥 >60	🟥 30%	🟥 >60%	🟥 >60%	🟥 32%	🟥 >60%	🟥 >60%	🟨 24%	🟥 59%	🟥 60%	🟥 >60%	🟥 >60%	🟥 >60%	🟥 >60%	🟥 >60%	🟥 >60%
		8" R30	Non-ventilated	latex paint	🟩 17%	🟥 30%	🟥 35%	🟨 25%	🟥 40%	🟥 50%	🟥 38%	🟥 52%	🟥 54%	🟥 35%	🟥 >60	🟥 >60	🟥 51%	🟥 60%	🟥 >60%	🟥 39%	🟥 55%	🟥 58%	🟥 51%	🟥 56%	🟥 57%	🟥 >60%	🟥 >60%	🟥 >60%	🟥 >60%	🟥 >60%	🟥 >60%
Fiberglass Batt		9 1/4" R30	Ventilated Continuous Baffle	interior poly	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 12%	🟩 12%	🟩 12%	🟩 19%	🟩 19%	🟩 19%	🟩 16%	🟩 16%	🟩 16%
		9 1/4" R30	Ventilated Continuous Baffle	latex paint	🟩 16%	🟩 17%	🟩 17%	🟩 14%	🟩 14%	🟩 14%	🟩 13%	🟩 13%	🟩 13%	🟩 14%	🟩 14%	🟩 14%	🟩 13%	🟩 13%	🟩 13%	🟩 14%	🟩 14%	🟩 14%	🟩 14%	🟩 15%	🟩 16%	🟨 27%	🟥 31%	🟥 33%	🟨 21%	🟨 26%	🟨 28%
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)			St. John's (4881) Trois-Rivières (4929) Calgary (5108) Prince George (5132) Sherbrooke (5151) Québec City (5202) Sudbury (5343)			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. Roofs are residential wood frame with dark asphalt shingles with a 12/12 pitch 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. Effective Air Barrier is assumed to be installed, as is proper rain control

c. Results assume no air leakage from the interior space into the roof assembly

Specific notes:

1. Apply SPF directly onto back of exterior sheathing, or against interior surface of baffle
2. MC values are for inner 3mm of OSB sheathing
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)

* - CWEC data was used for the analysis in Winnipeg, as the predicted moisture content values appeared to be more realistic than the WUFI weather file based on our expereience and the results of other simulated cities.

3.5 Sensitivity Analysis

A sensitivity analysis is determined by taking one variable that was a constant in the analysis, like North orientation, and changing it to a different orientation for a small sample of the analysis to determine the effect.

Sensitivity analysis was conducted on the orientation for the Calgary simulations, and on the ventilation rate in the vented roof assemblies in Yellowknife.

3.5.1.1 Orientation

The results in Table 5 for Calgary, were repeated on the south orientation to see what effect on performance there would be in the hygrothermal simulation. The moisture contents decreased significantly on the south orientation for all cases because of the increased solar energy for drying. Unvented ocSPF still had significantly elevated moisture contents when the peak wintertime RH was above 30%.

Table 6 : Analysis of predicted performance related to orientation

Cathedral Roof Construction					Calgary (North)			Calgary (South)		
					HDD 5000			HDD 5000		
Contents of Cavity		Depth of Cavity	Ventilation	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%
Spray Polyurethane Foam (SPF)	Closed Cell^3	5" R30	Ventilated 2" Continuous Baffle	ccSPF	10%	10%	10%	5%	5%	5%
		5" R30	Non-ventilated	ccSPF	15%	39%	39%	7%	9%	9%
	Open Cell	8" R30	Ventilated	latex paint	10%	11%	13%	5%	5%	5%
		8" R30	Non-ventilated	1 US perm paint on foam	30%	>60%	>60%	28%	46%	46%
		8" R30	Non-ventilated	latex paint	51%	60%	>60%	19%	32%	43%
Fiberglass Batt		9 1/4" R30	Ventilated 2" Continuous Baffle	interior poly	🟩	🟩	🟩	🟩	🟩	🟩
		9 1/4" R30	Ventilated 2" Continuous Baffle	latex paint	13%	13%	13%	-	-	-

3.5.1.2 Ventilation Rate

To determine the impact of ventilation, the ventilated roofs were simulated in Yellowknife and differences in predicted roof sheathing moisture contents were observed with an increase in roof ventilation from 50 ACH to 100 ACH. These values correlate to 0.22 and 0.44 ft/s. 100 ACH is possible in a windy environment with a temperature gradient, but is not likely to be a continuous airflow rate. In all three ventilated roof assemblies, the sheathing moisture content peaks were reduced fairly significantly with increased ventilation.

Table 7 : Analysis of predicted performance related to ventilation rate

Cathedral Roof Construction					Yellowknife 50 ACH			Yellowknife 1000 ACH		
Contents of Cavity		Depth of Cavity	Ventilation	Type of Vapour Control	Low RH 20/50%	Med. RH 30/55%	High RH 50%	Low RH 20/50%	Med. RH 30/55%	High RH 50%
SPF	Closed Cell	5" R30	Ventilated 2" Continuous Baffle	ccSPF	18%	18%	18%	14%	14%	14%
	Open Cell	8" R30	Ventilated	latex paint	24%	27%	31%	15%	15%	15%
Fiberglass Batt		9 1/4" R30	Ventilated 2" Continuous Baffle	latex paint	27%	31%	33%	17%	17%	17%

3.5.1.3 *Sensitivity Analysis of Calgary unvented CCSPF with medium interior RH*

A comparison was conducted of multiple variables for the unvented closed cell spray foam assembly in Calgary with a medium interior relative humidity level. The worst case scenario variables are North orientation, 12:12 pitch, night sky radiation active, and a cold climate data file in WUFI. All of the predicted moisture content curves are at equilibrium, and this may take several years to achieve. By changing each of the worst case scenario variables, one at a time, the predicted equilibrium moisture contents were all quite safe from a moisture related durability perspective.

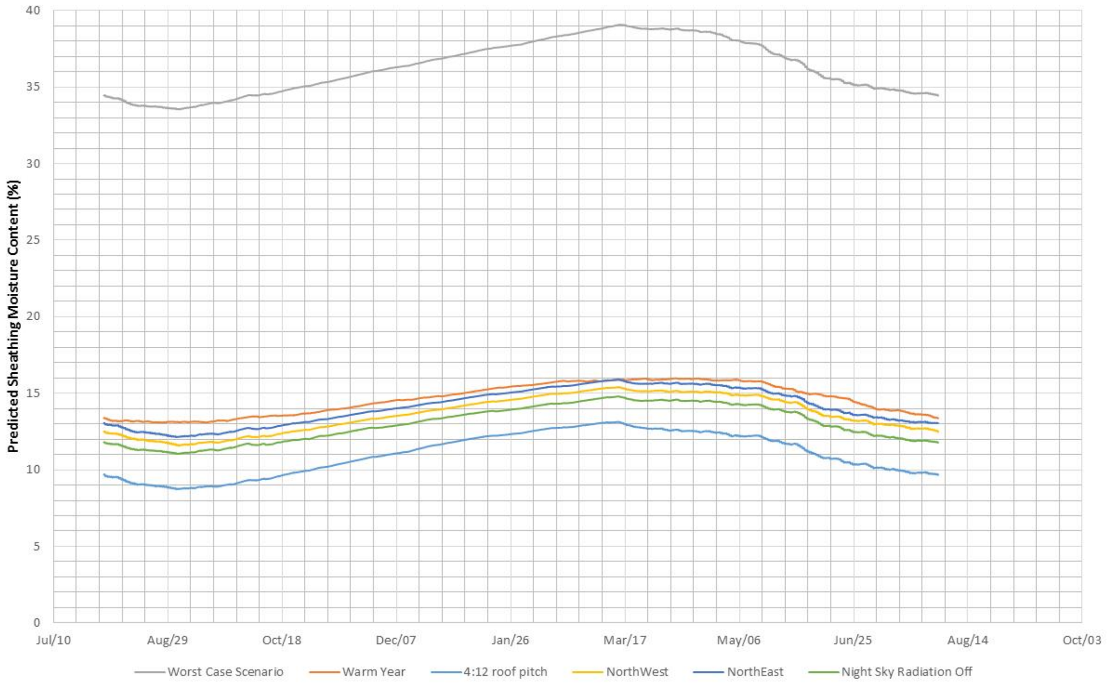

Figure 31 : Comparison of worst case scenario with different experimental variables

4 Conclusions and Recommendations

Findings from each element of this study, and conclusions that can be drawn from the findings, are summarized below.

Field testing at the University of Waterloo BEGHut suggest the following:

- No issues or concerns were found with ccSPF vented or ccSPF unvented roof assemblies at 40% or 50% interior relatively humidities in Waterloo, Ontario
- No issues or concerns were found with fiberglass vented assemblies using an interior polyethylene air and vapour barrier at 40% or 50% interior relatively humidities in Waterloo, Ontario. The polyethylene air and vapour barrier was well sealed with no penetrations.
- Elevated sheathing moisture contents were measured in the painted and unpainted ocSPF roof assemblies with an interior relative humidity of 40% and 50% in subsequent winters in Waterloo, Ontario.
- The added latex paint layer to the interior surface of the ocSPF foam did not show evidence of reducing the risk and may have affected the drying rate in the summer months
- Further analysis should be conducted on the vapour permeance of ventilation baffles and the effect of moisture accumulation in an cathedral ceilings with continuous baffles
- Several intentional controlled wetting events did show some correlation to increased sheathing moisture content, although the increase in moisture content was not significant.

Hygrothermal analysis was also conducted. When interpreting these results and making conclusions regarding the in service performance, it should be noted that all of the spray foam cathedral roofs assume there are no defects in the spray foam, and that all wood-to-wood connections where there is no spray foam are sealed to be air tight, so that there is no air leakage to the roof sheathing from the interior. In the assemblies with a polyethylene air and vapour barrier, the polyethylene sheet is assumed to be completely air tight with no penetrations or air leakage of interior air. As well, the hygrothermal simulations were done as a **conservative worst case scenario** on the north orientation with a relatively steep angle to minimize the impact of solar energy and drying.

Within these limitations, the following conclusions can be drawn:

- Vented ccSPF simulations showed no risk of moisture accumulation in the roof sheathing and any of the simulated climates.
- Vented fiberglass roof simulations with an interior polyethylene vapour barrier showed no risk of moisture accumulation in the roof sheathing. Again, this analysis assumes there is no air leakage past the interior air barrier that would allow warm humid interior air into the roof cavity. In reality, this is difficult to achieve.
- Vented ocSPF worked well in simulations except the extreme north, although test hut measurements showed more analysis may be required into the material properties of the ventilation baffles and their influence on moisture accumulation within the foam at the interface of the baffle.
- Unvented ccSPF worked well in every location except for the extreme north of Canada when the interior relative humidity was reasonable and recommended. In

the cities of St. John’s, Calgary Quebec City, and Winnipeg, there were some predicted elevated sheathing moisture contents at interior relative humidities that are higher than recommended.

- The unpainted unvented ocSPF assemblies had issues in nearly every city, both with and without elevated interior relative humidity levels. By adding an interior polyethylene air and vapour barrier, the predicted moisture related issues were addressed except for Yellowknife and Inuvik.
- There was a small improvement in predicted performance with a 1 perm paint layer added to the interior surface of the unvented ocSPF compared to the latex paint vapor control assemblies, but this assembly still had predicted moisture related issues in most of the same cities, starting in Vancouver.

In combination, these conclusions lead to the following recommendations:

- Vapour control is needed for unvented ocSPF cathedral ceilings to reduce the risk in all cities in Canada. The amount of vapour control is dependent on the climate zone.
- Vented ccSPF can be installed in any climate zone to the code required minimum thickness to meet the R-value requirements.
- It appears that vented ocSPF will perform well in all cities as cold as Winnipeg, but it is recommended to conduct further research on the effect of the ventilation baffle vapour permeance on moisture accumulation and vapor diffusion in the assembly.
- Unvented ccSPF is predicted to perform well in all cities except Yellowknife and Inuvik with a recommended interior relative humidity. If the interior relative humidity is increased beyond the recommended, there may be moisture accumulation in the sheathing of the worst case scenario assembly, but sensitivity analysis showed that if the worst case scenario is not constructed, there is significantly less chance of moisture accumulation in the sheathing.