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Literature Review Report | Project 11237.000

American Chemistry Council - Unvented Roof Literature Review

To Mr. Stephen Wieroniey
American Chemistry Council
700 2nd Street, NE
Washington DC 20002

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RDH Building Science Laboratories
167 Lexington Court #6
Waterloo ON N2J 4R9

Contents

1 Introduction

The objective of this report is to review the practice of unvented roof assemblies and conduct a review of relevant literature. The focus of this review is residential sloped wood roof assemblies in Canada. Little technical information could be found on low slope roof assemblies where spray foam was installed directly to the underside of the roof deck. RDH has reached out to professionals in the industry and was unable to find any studies or technical data regarding spray foam in residential low sloped (flat) roofs.

The reviewed literature includes both Canadian and US building codes, modeling of roof performance, field studies, and other research and technical reports.

In some cases, reports and studies will be referenced from other parts of North America and the world. Climate zones from ASHRAE 90.1(similar to National Energy Code of Canada for Buildings, NECB) will be used and are shown in Figure 1 with Canadian cities referenced. It's important to remember that even though some of the studies referenced below were undertaken in the United States or Europe, they were chosen because the boundary conditions (indoor and outdoor temperature and humidity, wind, rain, etc.) are similar to those in Canada.

Figure 1: Climate zone map of Canada

2 Ventilated Roof Assemblies

Typical wood framed pitched roofs (Figure 2 and Figure 3) and low slope roof assemblies include ventilation. Ventilated roofs are the most common type of roof assembly on wood framed residential construction, and the only type prescriptively allowed by the National Building Code (NBC) of Canada. Ventilated roof assemblies rely on openings typically at the soffits, and near the ridge in sloped roofs. Ventilation in low slope roofs usually occurs at the soffits or overhangs, and sometimes at doghouses in the middle of the roof.

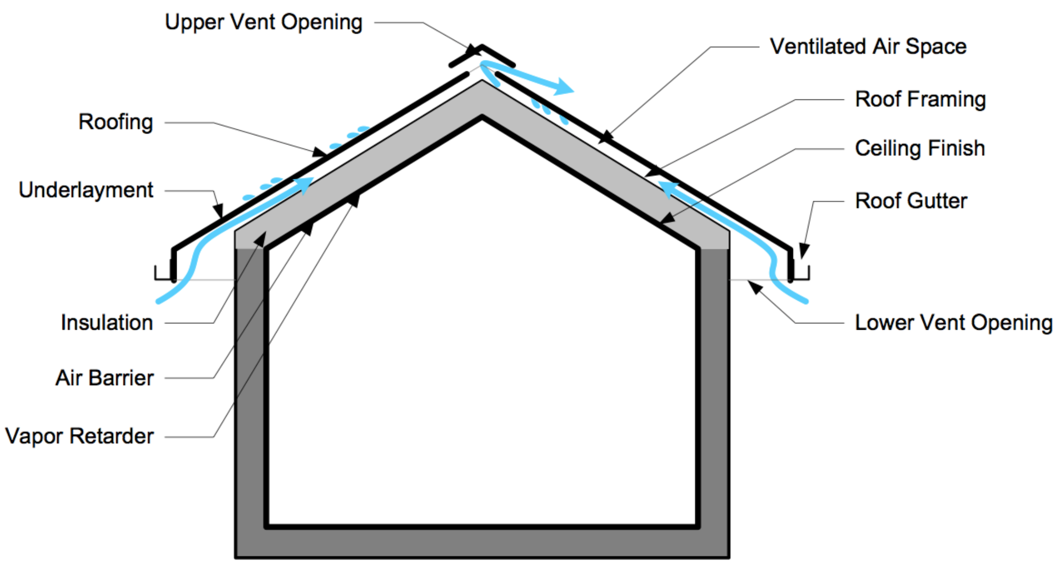

Figure 2 : Ventilated cathedral ceiling (Schumacher 2008)

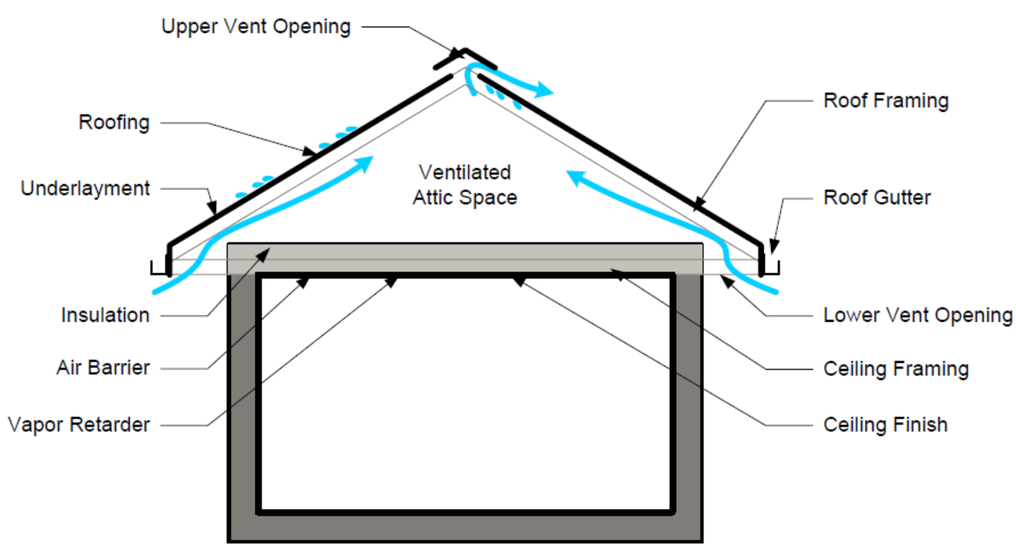

Figure 3 : Ventilated attic assembly (Schumacher 2008)

2.1 Attics

Historically, ventilated attics have been shown to be a durable, energy efficient way to create a pitched wood-framed roof system. Using this method, a large R-insulation can be installed on top of the ceiling of the living space in an attic to achieve high R-values. Ventilation of the attic space with outside air helps minimize some common attic and roof performance problems including moisture accumulation in the sheathing, ice damming, etc. Ventilated attics work well in nearly every climate zone with the exception of high humidity cold coastal regions (Roppel 2013) and some parts of the Far North (Climate Zone 8). The main advantages of ventilation in attics are generally reported to be:

1. Removal of moisture from the attic space, which may be a result of air leaks from the living space or construction moisture, to minimize condensation and moisture accumulation.
2. Removal of heat from the attic space to minimize ice damming in winter.
3. Reduction in shingle temperature thereby improving shingle durability.

Rose and Tenwolde (1999, 2002) showed that while ventilation is important and should be used if possible, especially in cold climates, other factors may be more critical to typical attic issues, such as moisture accumulation and ice damming, than attic ventilation alone. The main causes for most moisture related problems in roof assemblies are the interior relative humidity in the occupant space, closely followed by a lack of airtightness at the ceiling plane with air leakage from the interior into the attic/roof space.

There are numerous reasons an unvented attic roof assembly may be desired instead of a ventilated one. These include limiting wind-driven rain penetration through soffit vents in hurricane areas; limiting burning embers from entering in forest fire prone areas; and, wind-blown snow accumulation, particularly in extreme cold climates with typically lighter snow density (CMHC 2001). Physics, field experience, and a significant amount of published research all suggest that unvented, wood-framed pitched roofs can be designed and built to perform reliably, durably, and at a high level.

The idea that interior humidity control and airtightness are critical to the performance of ventilated attics is not new. Rowley et al. (1939) concluded that interior relative humidity control was an effective way to reduce condensation in roofs and walls. A paper by Jordan et al. (1949) involved taking moisture readings in three attics in Madison, Wisconsin, during the winter months. It was found that condensation only occurred in the attic with high humidity in the living space implying a connection between the attic space and interior living space below. Hinrichs (1962) made the correlation between interior humidity and airtightness when he noted that the air infiltration through the ceiling into the attic was the major source of condensation, he therefore concluded that a vapor retarder (not installed as an air barrier) was not a dependable means of attic moisture control. Dutt (1979) wrote that an airflow retarder was required in the ceiling in addition to a vapor retarder.

2.2 Low Slope Roofs

Low slope roofs are typically constructed as ventilated roof assemblies although they are not affected by stack effect pressures that often drive ventilation in sloped roof assemblies along with wind pressures. Very little research has been conducted into the performance of ventilated low slope roof assemblies, although experience has shown that moisture accumulation, and poor ventilation can be common on low slope roof assemblies. No moisture measurement or research on spray foam installed to the underside of a low slope roof assembly could be found during the literature review, although some studies in Europe on low slope roof assemblies, roofing colour, and vapor control are relevant to the roof durability discussion. A large research project regarding low slope roofing is currently ongoing with RDH Building Science, and Morrison Hershfield for Canadian Mortgage Housing Corporation (CMHC).

3 Building Codes

In Canada, under Part 9 of the NBC, unvented roof assemblies are not prescriptively permitted, as stated in (9.19.1.1).

> 1) *Except where it can be shown to be unnecessary, where insulation is installed between a ceiling and the underside of the roof sheathing, a space shall be provided between the insulation and the sheathing, and vents shall be installed to permit the transfer of moisture from the space to the exterior.*

The International Residential Code (IRC) in the United States has developed a set of guidelines for unvented roof assemblies in all the North American climate zones (IRC Section R806.5). These unvented roof assemblies include unvented cathedral ceilings Figure 5, and cathedralized attics Figure 4. As noted in the schematic it is important that the attic space in a cathedralized attic be part of the interior conditioned space.

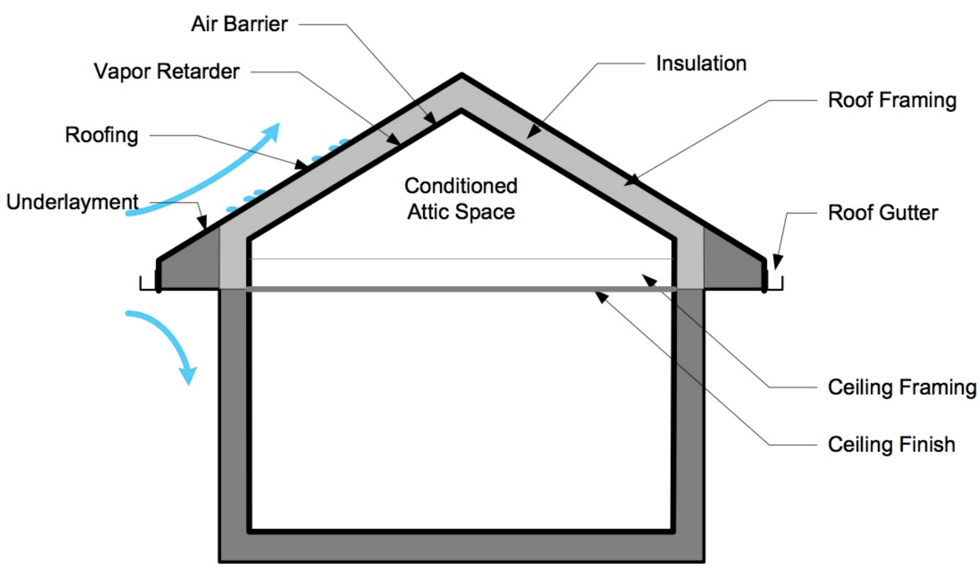

Figure 4 : Unvented cathedralized attic (Schumacher 2008)

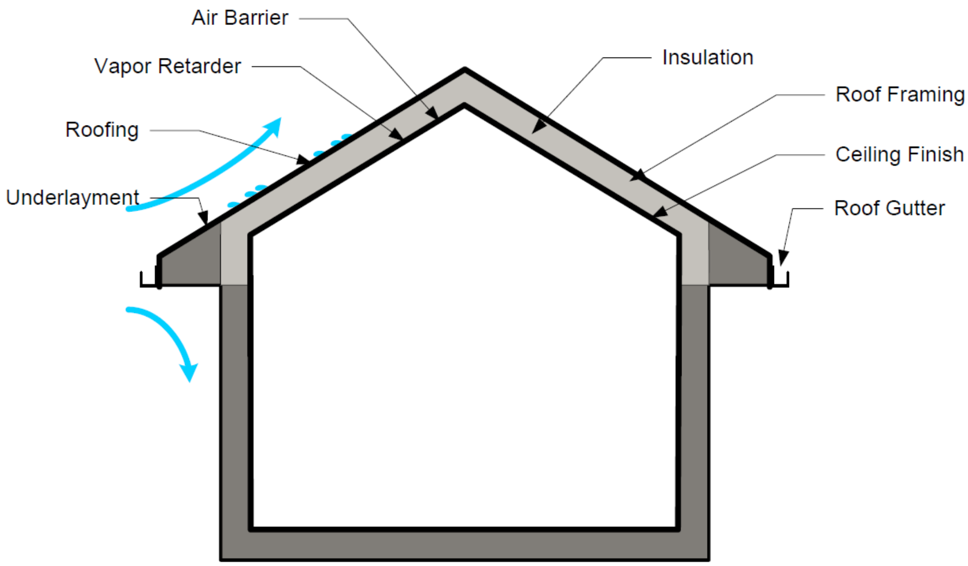

Figure 5 : Unvented cathedral roof (Schumacher 2008)

Some of the key criteria for allowing unvented roof assemblies in the IRC for cold climates (Climate Zones 5-8) include considerations for the air and vapor permeability of the materials in the assembly.

- Firstly, an interior Class I vapor retarder (<5.7 ng/Pa.s.m^2, 0.1 Perm) is not acceptable on the attic floor of the unvented cathedralized attic assembly or on the ceiling side of the unvented cathedral ceiling assembly. Instead, an alternate interior vapor control strategy is necessary as per below.
    - o *In Climate Zones 5, 6, 7 and 8, air-impermeable insulation shall be a Class II vapor retarder (5.7 to 57 ng/Pa.s.m^2, 0.1 to 1 Perm) or shall have a Class II vapor retarder coating or covering in direct contact with the underside of the insulation. (R806.5 [4.])*

However, Climate Zone 4C is missing from the list in relation to Canadian climate zones, and 4C often poses challenges because it can get quite cold, but also is expected to have higher interior relative humidity loads as a result of the higher humidity coastal location.

Other summarized criteria related to the air permeance of the unvented roof insulation that are stipulated in the IRC Section R806.5 number 5 include:

- Air-impermeable insulation shall be applied in direct contact with the underside of the structural roof sheathing.
- If air-permeable insulation is installed in direct contact with the underside of the structural roof sheathing, rigid board or sheet insulation shall be installed directly above the structural roof sheathing to a specified R-value based on climate zone.
- If a combination of air-permeable, and air-impermeable insulation is used, the air-impermeable insulation shall be installed directly to the underside of the structural roof sheathing as specified in IRC Table

> R806.5 for condensation control. The air permeable insulation shall be installed directly under the air impermeable insulation.

IRC Table R806.5 specifies a minimum R-value of rigid board insulation on the exterior of the sheathing, or air impermeable insulation on the underside of the sheathing for each climate zone, but does not provide a ratio of the amount of insulation required to address potential condensation and moisture accumulation. This means that if an unvented roof with higher than code specified R-values is constructed, the minimum R-value of air impermeable insulation specified in the table may not be enough to minimize the acceptable risk of moisture accumulation.

The guidelines for unvented roof assemblies have been in the IRC since 2006 and are based on building science moisture physics and field experience of unvented roof assemblies. As with all roof (and wall) assemblies, successful performance is still reliant on quality construction practices and controlled interior humidity at assembly-appropriate levels.

4 Unvented Roof Research Studies & Field Monitoring

There have been several studies conducted on unvented roof assemblies, most of which are on sloped wood framed roof assemblies. These studies are a combination of moisture monitoring studies as well as hygrothermal modeling simulations that predict performance. Most of the research found relates to spray polyurethane foam in residential sloped roofs and there does not appear to be much exploration into SPF in low slope roofs.

The moisture content of the wood-based sheathing is often used as the performance criteria because the sheathing is the first location where vapor diffusion and air leakage condensation would occur in a cold climate during the heating season. Generally, under normal conditions, the following criteria are used to assess the risk of various test wall assemblies (Straube et al 2010):

1. Peak sheathing moisture content less than 20% - no mold growth, very little risk

2. Peak 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 corrective action be taken.

3. Peak sheathing moisture content >28% - moisture related problems are expected and this design is not recommended.

Predicted wood moisture contents of wood-based sheathing are generally assessed with respect to relative risk as opposed to judged on some pass/fail criteria. The predicted moisture content should be kept in context and good scientific 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 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.

A second more sophisticated evaluation criteria that is becoming more common is the Finnish Valtion Teknillinen Tutkimuskeskus (VTT) Technical Research Centres' Improved Model to Predict Mold Growth in Building Materials (Viitanen and Ojanen 2007). This model is based on calculating empirical regressions of actual mold growth on building materials in varying climatic conditions by considering the temperature and relative humidity at the surface of the material. The sensitivity of the material (typically "sensitive" for wood-based sheathings) is also required for this analysis. While the VTT model results do not necessarily guarantee the presence of mold, they do provide a greater degree of reliability than categorical limits. The mold index will take into account all hours of the year that the relative humidity and temperature are ideal for mold growth, and can evaluate the seasonal impact of wetting and drying cycles. The VTT model output is a mold index, summarized in Table 1. Mold index values less than 3 are generally not visible to the naked eye, and therefore mold indices greater than 3 are often considered a fail.

TABLE 1: MOLD INDEX FOR THE VTT MODEL (VIITANEN AND OJANEN, 2007)		
INDEX	GROWTH RATE	DESCRIPTIONS
0	No growth	Spores not activated
1	Small amounts of mold on surface (microscope)	Initial stages of growth
2	<10% coverage of mold on surface (microscope)	--
3	10%-30% coverage of mold on surface (visual)	New spores produced
4	30%-70% coverage of mold on surface (visual)	Moderate growth
5	70% coverage of mold on surface	Plenty of growth
6	Very heavy and tight growth	Coverage around 100%

Schumacher and Reeves (2007) conducted an analysis of an unvented cathedral ceiling insulated with 0.5 pounds per cubic foot (pcf) open cell (oc) SPF in Vancouver, British Columbia, Climate Zone 4C. There was no polyethylene vapor barrier installed in the roof assembly. Data was collected over the course of the first two years that the house was occupied. During the first winter, the moisture content of the North-facing roof sheathing rose to 17-24% while the moisture content of the warmer and solar dried South-facing sheathing only rose to 12-14%. The monitored data suggested that the interior dew point and outward diffusion through the half-pound open-cell SPF plays an important role in the winter sheathing moisture content levels. During the first winter, the construction moisture was still drying out, and the heat recovery ventilator (HRV) was not switched to 'winter' mode until December which decreases the interior relative humidity. As a result the moisture levels inside the house were slightly elevated and the interior dew-point temperature exceeded 7˚C for approximately 41% of the hours. This corresponds to an interior relative humidity of approximately 40% at an interior temperature of 22˚C. During the second winter, the interior moisture levels were lower (dew-point temperature exceeded 7˚C only 17% of the hours) with similar exterior conditions, and the North and South facing roof assemblies reached moisture contents of 15-17% and 11-13% respectively. The sheathing moisture contents decreased, and the sheathing was dry in the monitored locations during the summer months resulting from inward vapor drive from the summer time conditions. Samples of foam were removed following the first winter to make a visual inspection of the plywood roof sheathing. None of the openings showed any signs of mold or decay on the plywood roof sheathing. The interior surface of the plywood was clean and seemed like new. Note that the interior humidity levels in this home were managed with ventilation to be lower than many residences in the Lower Mainland.

Rose (2001) reported on a test hut study in Champaign, Illinois (Climate Zone 5) that contained a combination of ventilated attics, unvented cathedralized attics, ventilated cathedral ceiling and unvented cathedral ceilings. The roof sheathing of the unvented cathedralized attic and the unvented cathedral ceiling assembles had slightly higher peak shingle temperatures than the conventional ventilated attic base case. This study did not include moisture monitoring.

Ueno and Lstiburek (2015) conducted a study of unvented roof assemblies with fibrous insulation in Houston, Texas (Climate Zone 2), and Chicago, Illinois (Climate Zone 5). Even though no SPF was used in this study, the failure mechanisms and issues associated with unvented roof assemblies with fibrous insulation are explained. The objective was to understand the long-term moisture performance with fibrous insulation, which could allow for widespread application of a low-cost technique without potentially compromising building durability. Seven test roofs bays were constructed, one vented cathedralized attic, and six unvented with a combination of dense-packed cellulose and fiberglass. Other experimental variables included a breather mesh ventilation under the shingles, and a vapor permeance vent at the ridge that allowed water vapor to pass, but was constructed as a water and air control layer. This research was meant to stress the roof assemblies with moisture with only one winter of availability to monitor moisture. The only interior vapor control was latex paint on the drywall, and the interior relative humidity was maintained at 50% for most of the winter. For the Chicago climate, 50% RH is considered very high, but has been measured in newer air tight houses with ventilation issues. Under these conditions, all roofs (with air and vapor permeable insulation) except the vented cathedral assembly experience wood moisture content and RH levels high enough to constitute failure. The unvented fiberglass batt roofs had wet sheathing and mold growth but no structural failure. The cellulose roofs had only slight issues, such as rusted fasteners, staining, and sheathing grain raise, despite the extreme moisture conditions measured. This difference was ascribed to cellulose's borate preservatives (borate salts added as a fire retardant and antifungal agent), its airflow-retarding properties, and its ability to safely store small amounts of incidental moisture. Based on the high interior moisture loading (50% RH) of this test, none of these unvented assemblies are recommended by Ueno and Lstiburek. These include unvented cellulose roofs; although minimal actual damage was observed, all monitoring results indicated very high-risk conditions for long-term durability. The failure mechanisms were caused by the movement of moisture by both vapor diffusion and air movement through the insulation. Closed cell spray foam is both an air barrier, and vapor barrier, which would have restricted the movement of water to the sheathing, and resulted in much lower measured sheathing moisture contents and moisture accumulation from the interior.

Smegal and Straube (2014) reported on a study at the University of Waterloo Building Engineering Group Research Facility (BEGHut) on the border between Climate Zones 5 and 6. Six different cathedral ceilings (all approximately R30) were constructed and instrumented for moisture and temperature conditions. The roof assemblies are shown in Table 2, below. The only roof with a polyethylene vapor barrier was the vented fiberglass roof assembly. It is generally reported that latex paint on drywall has a vapor permeance of approximately 570 ng/Pa.s.m^2 (10 US Perms). Although painted drywall samples were collected during deconstruction, their vapor permeance had not yet been tested as this paper was written.

TABLE 2 : CATHEDRAL ROOF ASSEMBLIES (STRAUBE AND SMEGAL 2014)				
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	Drywall
Vented Fiberglass (VFG)	R30 (~9 ¼”)	Yes	Polyethylene sheet	ocSPF
Unvented Painted Open Cell (NOCP)	R30 (~8”)	No	Painted foam and drywall	ocSPF
Unvented Open Cell (NOC)	R30 (~8”)	No	Latex paint on drywall	ocSPF
Vented Open Cell (VOC)	R30 (~8”)	Yes	Latex paint on drywall	SPF

The ventilation gap in all ventilated assemblies was provided by installing Durovent® polystyrene baffles from the soffit continuously to the upper roof vent, to provide a clear path for ventilation. Venting hole sizes were calculated based on the code requirement and drilled out at the soffit and at the top of the rafter bay. The SPF insulation was sprayed directly against the baffles and the fiberglass insulation was installed in contact with the baffles. During deconstruction, there was some evidence of deformation of the baffles as a result of the adhesion and curing of the SPF, although all of the ventilation paths still appeared to be continuous and were not affected by the installation of SPF in this case.

The interior relative humidity was set at 40% for the first winter which is slightly above the recommended interior relative humidity for cold climates (the NBC assumes 35% RH in Part 9), but not unusual in many houses. The second winter, the interior RH was increased to 50% and there was an increase in the moisture accumulation and measured moisture content of the sheathing in some assemblies (as well as persistent condensation on double glazing). The roofs were disassembled and inspected after seven years of exposure.

The measured sheathing moisture content was the main criteria for evaluation of the roof assemblies. Both of the unvented ocSPF roof assemblies with only latex paint vapor control had elevated sheathing moisture contents during both winters, with higher sheathing moisture contents the second winter with a higher interior RH (Figure 6). Neither the unvented closed cell (cc) SPF nor any of the vented roof assemblies experienced any elevated sheathing moisture contents; generally, MC levels did not exceed 13% even with an interior relative humidity of 50% during the second winter.

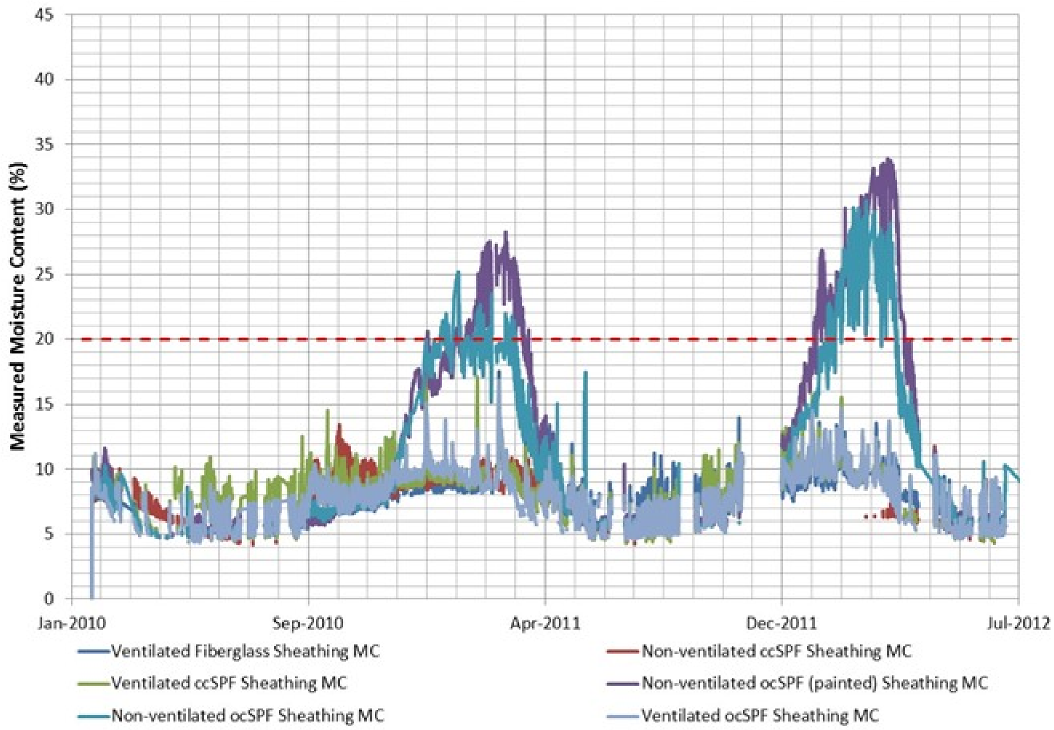

Figure 6 : Measured roof sheathing moisture contents for six full scale cathedral roof assemblies

Analysis of the rafter sheathing moisture content, and the relative humidity within the cavity insulation was also undertaken. The rafter sheathing moisture content (Figure 7) showed that there were elevated moisture contents in the ventilated fiberglass roof assembly indicative of liquid water on the rafters. The moisture content was only slightly elevated the first winter at an interior relative humidity of 40%, but in the second winter, the rafter moisture content reached approximately 40% at the monitoring location. This assembly had a polyethylene air and vapor barrier sealed to the framing, and no intentional penetrations of any kind for lights, wiring, etc. It was found during the roof deconstruction in 2017 that there was significant moisture accumulation and staining on the rafters, and the sheathing at the sides of the ventilation baffles. The sheathing above the baffle was well preserved as a result of the ventilation inside the baffle. There was also evidence that a significant amount of water had run down the polyethylene vapor barrier to the bottom of the cathedral ceiling over the years of operation. None of the other roofing assemblies had elevated rafter moisture contents, although the non-ventilated ocSPF assembly did have measured moisture contents of approximately 17% during the second winter.

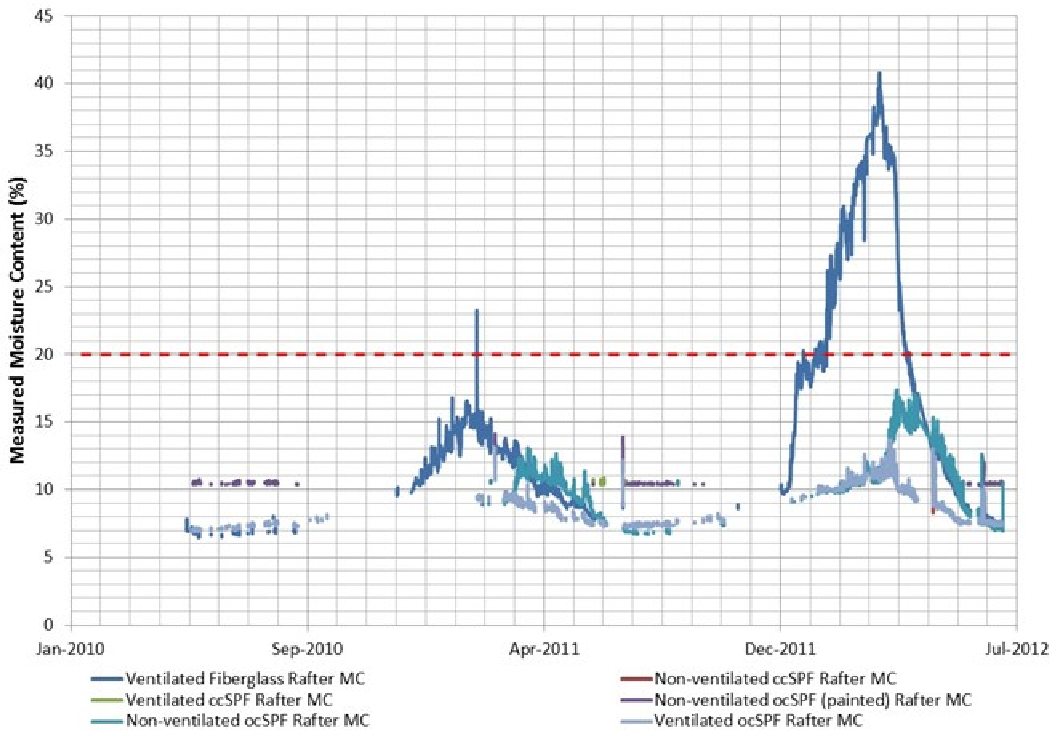

Figure 7 : Measured roof rafter moisture contents for six full scale cathedral roof assemblies

The conclusions based on the monitoring were as follows:

- There was no indication of any elevated moisture or long-term durability risks in the vented and unvented ccSPF cathedral ceiling roofs.
- There were elevated roof sheathing moisture content levels, and elevated relative humidity levels within the SPF in both (painted and unpainted) unvented ocSPF assemblies although the assemblies dried completely in the summer months. There was no observed sheathing damage after seven years. These assemblies require more vapor control on the interior although adding an interior low-permeance layer also hindering drying to the interior, as it would be a double-sided vapor barrier assembly. A smart vapor barrier may be beneficial in this assembly for performance and durability.
- In the vented ocSPF assembly, there was no elevated sheathing moisture content. However, due to the low vapor permeance of the baffle (measured to be 213 ng/Pa.s.m^2 [3.5 US Perms]), moisture did accumulate at the SPF to baffle interface, and there was evidence of condensation and drainage during the deconstruction. This suggests that more vapor control than just latex paint would be recommended on the interior.
- In the vented fiberglass roof assembly, there were no observed elevated sheathing moisture content measurements within the ventilation baffle, although there were elevated rafter moisture contents, and deconstruction showed a significant amount of staining, and water damage on the sides of the baffle where the sheathing was exposed and

on the rafter. There was also significant moisture at the bottom of the roof assembly where condensation had drained and collected at the bottom of the roof. This condensation and moisture accumulation was likely as a result of a small amount of air leakage from the interior, even with careful installation and a continuous polyethylene and drywall layer with no intentional penetrations.

As part of the research program, the results of the roofing study were used to correlate a hygrothermal model using WUFI Pro and the results were extrapolated to other regions of Canada covering all of the climate zones. For this analysis, the worst case realistic construction and boundary conditions were used to provide a conservative prediction of performance. A sensitivity analysis was included to show how the performance of the roof assemblies in all of the climate zones would vary under 'better than worse case' scenarios to provide context to the results. Good judgment is required in interpreting the hygrothermal analysis data.

A summary of the conclusions for the hygrothermal analysis using the conservative worst case scenarios for moisture accumulation in all Canadian climate zones shows that:

- Vented ccSPF simulations showed no indication/evidence of moisture accumulation in the roof sheathing for any of the simulated climates including Climate Zone 8.

- Vented fiberglass roof simulations with an interior polyethylene vapor barrier showed no indication/evidence of moisture accumulation in the roof sheathing although this analysis assumes there is no air leakage past the interior air barrier and in reality we know it is, practically speaking, difficult to achieve such airtightness with polyethylene sheet in typical construction.

- Vented ocSPF worked well in simulations although no baffle layer was entered into the model initially for this study, which in the field study was shown to trap and accumulate moisture. This could be added for future hygrothermal analysis.

- Unvented ccSPF worked well in every location except the extreme north (Climate Zone 8) when the interior relative humidity was limited to reasonable levels. In some Climate Zone 7 cities, with elevated interior relative humidity, there was long-term predicted moisture accumulation in the sheathing under conservative modeling criteria. A sensitivity analysis with 'better than worse case' scenarios often significantly improved the predicted durability of the assembly.

- The unvented ocSPF model exhibited moisture accumulation issues in nearly every city, both with and without elevated interior relative humidity levels. In Vancouver such as system performed well with an interior relative humidity of 35%, but showed durability risk at an interior relative humidity of 60%. The NBC of Canada suggests a maximum reasonable interior relative humidity of 60% in Vancouver because of the warmer winters in Climate Zone 4C, compared to the rest of Canada.

One unplanned, but realistic source of moisture in roofs are small rain leaks. **Grin et al (2013)** conducted hygrothermal analysis as part of a study on SPF insulation under roof sheathing for the Department of Energy Building America Program in the United States. For the hygrothermal analysis component of this study the durability of the roof sheathing was predicted in Miami, Seattle, and Minneapolis for various levels of water leakage past the asphalt shingles directly into the wood sheathing with SPF insulated unvented roof assemblies. In some cases all of the insulation was SPF, and in others, it was a hybrid approach with SPF and fibrous insulation which met the requirements of the International Residential Code (IRC) for unvented roof assemblies (R806.5). The amount of water passing through a roof system is difficult to quantify, but hygrothermal modeling was possible using ASHRAE 160, TMY2 and U.S. Climate Normals weather data, and WUFI weather data. WUFI 5 was used to determine the effect of 0.01%–1.00% of rainfall entering the unvented roof system as a leak and coming in contact with the wood-based roof sheathing.

The 2012 IRC-compliant roofing system in Minneapolis using closed ccSPF on plywood sheathing with cellulose insulation on the interior has the capability according to the modeling to safely dry 53 oz (1.6 L) of water through a 4-ft^2 area of plywood per year. Moisture contents >20% were seen during the modeling, but the systems were typically able to dry during the summer and return to <8% moisture content (MC). Within the Seattle analysis, the ccSPF insulated OSB-sheathed roofs were able to handle up to 1% rainwater leakage, while the ocSPF roof experienced elevated MC when more than 0.6% rainwater leakage was introduced into the system. This is due to both rainwater leakage and outward vapor drives during the heating season. The ocSPF roofs dried out much more readily than the ccSPF roofs. The Miami analysis showed that both ccSPF and ocSPF roofs dried, even up to 1.5% rainwater leakage, although both experienced more short-term fluctuation than similar roofs in the Seattle climate.

Interior RH can directly affect the sheathing MC in all scenarios and the report recommends that wintertime RH in Climate Zone 6 homes should be maintained at <40% - a limit that is typical for standard houses in this climate zone. Wintertime RH levels higher than this typically result in window condensation, wall and foundation assembly hygrothermal performance issues even in high performance enclosures. Orientation and sheathing materials create variations within the system, but these variations are relatively small compare to the type of SPF and vapor permeance coatings used.

This study by Grin et al. shows that drying of rainwater leakage is possible even through ccSPF, as long as there is no vapor barrier installed on the interior of the roofing assembly to stop the movement of inward drying water vapor.

Straube et al (2010) conducted a hygrothermal modelling study including all the US climate zones, a range of interior humidity levels and numerous arrangements and types of insulation in sloped roof assemblies. The results showed that so long as airtightness is provided and wintertime humidity is controlled, numerous unvented solutions using either ocSPF or ccSPF, or a combination of SPF and fibrous insulation can be successful. Climate, the solar properties and exposure of the roofing, along with the air and vapor permeance of the insulations and interior humidity are the most important factors to be considered in the design of moisture-safe unvented roof systems. The full report should be reviewed for a summary of the predicted moisture performance of all roof assemblies.

TABLE 3 : MATRIX OF CLIMATE ZONES, ROOFING, R-VALUE (2010), AND INSULATION TYPES MODELED FOR SLOPED ROOF ASSEMBLIES.

DOE ZONE AND CITY (12 VARIABLES)	CODE REQUIRED R-VALUE (2010)	ROOFING TYPE (4 VARIABLES)	INSULATION TYPE (8 VARIABLES)
1 Miami	30	Dark Asphalt	Spray fiberglass (1.8pcf)
2A Houston	30	Tile (ventilated)	1” ocSPF + spray fiber glass
2B Phoenix	30	Light metal	1” ccSPF + spray fiber glass
3A Atlanta	30	Cedar shakes	2” ccSPF + spray fiber glass
3C San Francisco	30		Full-depth ocSPF
4A Kansas City	38		Full-depth ccSPF
4A Boston	38		Kraft-faced batt
4C Seattle	38		Full depth cellulose
5A Chicago	38		
5B Denver	38		
6A Minneapolis	49		
7 International Falls	49		

One study on unvented low slope roofs with mineral wool batt insulation conducted in Europe by **Nusser et al. (2010)** investigated the measured performance differences between full scale test hut roofs with the following experimental variables:

- Different interior smart vapor barrier membranes (SVR). A smart vapor retarder is a material with vapor permeance that changes as a result of the surrounding relative humidity; more vapor permeable at higher RHs and less vapor permeable at lower RHs
- Different shading of the roof influencing the solar absorption and roofing membrane temperature
- Different roof sheathing types

Data was collected for 17 months on the full-scale roof assemblies, and it was concluded that roof assemblies with low temperatures on the roof, whether from shading, or a green roof leads to high and long lasting relative humidity in the cavity. For this reason, Nusser concluded that green roofs, enduring shading of the roof or membranes with a low solar absorption coefficient (very light coloured), should be avoided, to decrease risk, in unvented low slope roof assemblies.

Another study on the impact of different roofing membranes was conducted by **Buxbaum et al. (2013)** in Europe. The objective of the study was to analyze the hygrothermal performance and durability of unvented wood framed low slope roofs with cool roofing membranes using hygrothermal simulations. The assemblies consisted of a roofing membrane, oriented strand board (OSB) roof sheathing, 400mm of cellulose insulation, a vapor retarder of 0.025 Perms and an OSB interior layer. The main focus was on the drying potential of selected roof variable. In addition, roof assemblies were investigated at the Austrian BSRTU Building Science Research & Test Facility to analyze measured performance differences.

In the modeling component of the study it was found that the roofing assemblies with the light grey and dark grey membranes showed more drying, a lower total water content over time, and decreased moisture risks than the white roofing membrane as a result of the higher surface temperature, increased temperature gradient and drying towards the interior, although slow with an interior vapor barrier.

In the field study component of the research, the results were similar to the hygrothermal modeling analysis. It was concluded from the data analysis that the different colour roof membranes are significantly influencing the external roof surface temperatures due to the solar absorptivity. The differences in roof surface temperature strongly influenced the moisture migration and accumulation and therefore the durability performance of low-sloped roof construction. Light-coloured and especially white “cool” roofing membranes are reducing the effect of solar absorption and inward drying, hence drying of the roof assembly is limited and moisture related problems are likely to occur.

Kehrer and Pallin (2013) also found in their hygrothermal study that the colour and solar reflectance of the roof surface is very important. The amount of accumulated moisture is almost doubled in cool roof construction compared to a traditional black roof under certain modelled parameters, but the factor of safety with moisture related durability is higher in all low slope roofs with high solar absorbing black roof membranes.

A study by **Geving et al. (2013)** analyzed the performance of unvented roof assemblies with either an SVR or polyethylene film on the interior as the vapor control. The insulation in the unvented assemblies was either fiberglass batt or expanded polystyrene (EPS). The plywood sheathing was given an elevated initial moisture content so the drying of the roof assemblies could be measured and compared during summer time drying conditions. The roof assemblies with the polyethylene vapor barrier on the interior were the slowest to dry. The different smart vapor retarders had a range of drying but were far faster than the roof assemblies with the polyethylene. A similar ongoing study at RDH Building Science Laboratories in Waterloo, Ontario (Climate Zone 5/6) is being conducted on two roof assemblies with different interior vapor control and intentional wetting within the roofing insulation. The roof assembly with an interior smart vapor control layer dries very quickly in the summer months compared to the roofing assembly with the interior vapor barrier.

Based on building science physics, experience, and the United States IRC Building Science Consulting Inc (BSCI) and Building Science Corporation (BSC) authored a spray foam guide in Canada for the Canadian Urethane Foam Contractors Association (CUFCA). The guide (Smegal et al. 2013), discusses SPF use in all areas of a home, with specific guidelines and notes for each climate zone from Climate Zone 4 to 8. With respect to roofs it covers vented attics, unvented attics (cathedralized or conditioned attics), unvented cathedral ceilings, and vented cathedral ceiling and cathedralized attics. The guide shows which spray foam assemblies are recommended in each climate zone, as well as general cautions on interior relative humidity, and notes related to vapor control, R-value ratios, and the vapor and air permeability of insulation types.

5 In-service Inspections

In-service inspections are important to understand various aspects of moisture-related performance in the enclosure. They can confirm predictions, or lead to a better understanding of what's occurring in constructed assemblies. There are not a lot of documented cases of in-service inspections of SPF in unvented roof assemblies, although what could be found is included here. It may be beneficial to confirm our understanding of these roof assemblies by making more openings in SPF insulated unvented roof assemblies, in particular in the colder or more challenging climate zones such as Climate Zone 7.

Rudd (2005) conducted a field survey of four unvented cathedralized attics in Minnesota and Wisconsin in April 2004, and one cathedralized attic in Massachusetts in March 2004. All of these roofs were located in cold climates and investigated in the spring to indicate any possible moisture accumulation during the winter without time for the assembly to dry in the summer months. All five of the unvented cathedralized attics were insulated with low-density, ocSPF. No other vapor control was identified in the report for these roof assemblies. The SPF was removed near the ridge and moisture contents of the sheathing were measured with a pin type moisture meter. Sheathing moisture contents were higher on the north-facing roofs ranging from 20% to 40% MC, while the south-facing orientation ranged from 7% to 23% MC in all five houses. The sheathing moisture contents were the highest in the houses that had abnormally high indoor relative humidity levels as a result of basement flooding and/or poor ventilation in the home. Despite the high measured sheathing moisture contents, it was reported that there were no observations of fungal growth or wood deterioration.

Schumacher (2015) conducted a survey of existing unvented roof assemblies in Vancouver and the lower mainland in 2015. Three buildings were chosen to make opening into their ocSPF insulated unvented assemblies during May 2015. The observations are summarized below.

> Building 1 – The building was a decade old; the ocSPF had been installed as a cathedralized attic five years prior. Inspection openings were made at two locations on the north-facing slope and two locations on the south-facing slope. There was no other vapor control besides the ocSPF, and the conditions in the attic were the same as the interior of the building. No visible mold was observed on the exposed plywood sheathing. On the north-facing slope, the moisture content of the sheathing was around 12%, and it was approximately 7% on the south-facing slope.
>
> Building 2 – ocSPF had been installed for three years at a thickness of 4-6 inches on the roof sheathing. The roof assembly has a very low slope (close to flat), and the roof assembly did not include a polyethylene vapor barrier. The structure was quite airtight without an operating ventilation system. During the site visit, the interior RH was 70% and the interior dewpoint was 13°C. There was no visible mold on the sheathing on either

of the two inspection openings, and sheathing moisture content measurements were 16% and 15% in the two openings.

Building 3 – The building had an ocSPF insulated unvented cathedral ceiling with scissor trusses. The roof assembly did not use a polyethylene vapor barrier but the ceiling was finished with painted drywall. It is generally accepted that drywall with latex paint is approximately 10 US Perms (570 $ng/Pa.s.m^2$). The indoor humidity was measured to be 50% during the investigation and moisture contents of 10% were measured in the plywood sheathing near the ridge.

Grin et al (2013) conducted an extensive study of unvented roof assemblies with spray foam insulation applied to the roof sheathing as part of the Department of Energy Building America program in the United States. This study included 11 exploratory openings of 11 in-service roof systems in July of 2012. Some of the roof assemblies were constructed with ocSPF, and some were constructed with ccSPF. One roof in Climate Zone 7 was constructed with ocSPF installed over ccSPF. The investigations involved removing a sample of SPF from the underside of the roof sheathing, and taking a moisture content reading. Nine of the investigations were conducted in cold climates ranging from Climate Zones 4C to 7. There was a range of construction strategies, including unvented cathedral ceilings, and cathedralized attics, both ocSPF and ccSPF were used. All locations had MCs well within the recommended range for wood-based sheathing, keeping in mind it was the middle of the summer, and in some roof assemblies, elevated wintertime moisture contents may have dried. One location had some documented performance issues as a result of ccSPF sprayed onto wet roof sheathing, but besides that, it was documented that there were no other visible signs of moisture damage at any of the opening locations.

6 Summary and Interpretation

Sufficiently serious defects in construction can cause any assembly or part of assembly to fail. What follows assumes that there are no serious defects in construction.

6.1 Building Codes

While Canadian Building Codes currently do not have prescriptive provisions for unvented roof assemblies, the IRC in the United States provides prescriptive guidelines for unvented roof assemblies based on industry experience, hygrothermal analysis and moisture physics. The guidelines for unvented roof assemblies cover all North American climate zones, and explain how to choose the amount, location, and type of insulation based on its air and vapor permeability. As the IRC has allowed unvented roofs and cathedralized attics since 2006, there would be a significant history of experience to help identify potential performance problems established through code-based practices. An improvement to the IRC Table R806.5 would be to specify R-value ratios instead of specify R-values of air impermeable foam as part of the roof assembly to account for differences in High-R roof assemblies.

6.2 Boundary Conditions and Material Choices

The literature review revealed common themes in the success of unvented roof assemblies: appropriate interior relative humidity and a very airtight interior air barrier layer. In the notes section to Part 9 (9.25.5.2) of the NBC of Canada, it is explained that the monthly average vapor pressure difference across the enclosure during the heating season should not exceed 750 Pa, which translates into an interior relative humidity of 35% in colder climates, and 60% in mild climates. This means that in Climate Zones 5 and 6, the recommended wintertime relative humidity is 35%, in Climate Zone 4, the winter time relative humidity may be as high as 60% (even though that would not be recommended), and in Climate Zones 7 and 8, the interior relative humidity should be 30% or less. These relative humidity limits means that any special use areas within the same building such as pools, saunas, steam showers etc have not been considered in this report and would require specialized design.

Airtightness is critical to the performance of all roof assemblies, both ventilated and unventilated. Air leakage can result in condensation on the roof sheathing as water or ice, and moisture accumulation and durability issues.

It should be noted that both ocSPF and ccSPF are considered air barrier materials, but require correct installation, and in most cases, some combination with other materials to adequately form an air barrier system at the roof assembly. Problems can arise where SPF in combination with other components, such as where multiple side-by-side framing members do not form an air barrier, and condensation and moisture accumulation have occurred.

Some of the studies investigated reducing durability risk by increasing drying in unvented roof assemblies by use of an SVR on the interior of the assembly. The vapor permeance of the SVR can meet the Canadian building code requirement for a vapor barrier under ASTM E96 dry cup test conditions (≤60 ng/Pa.s.m^2) but have an increased vapor permeance in the presence of high humidity that can allow any trapped moisture in the enclosure assembly to dry. It has been shown that good performance can be achieved without the use of an SVR, however the use of a SVR will increase the factor of safety for moisture durability.

It was also noted in some studies that the colour and solar exposure of the roof membrane affected drying of any moisture in the roof assembly. This is not typically an issue in sloped residential roof construction as nearly all sloped residential roofs in Canada are dark in colour, however in the low slope roofing market, white "cool" roof membranes are more common. White roof membranes may result in an improvement in building energy use, but they do not heat up as much in the sun, and therefore do not have the same drying potential as dark systems. Because in cold climates, there can be an increase in the sheathing moisture content during the winter months as a result of a vapor pressure gradient and vapor diffusion, then providing summer time drying decreases the risk of long term durability issues. There is no requirement of roof membrane colour in the code, although the research shows darker, unshadowed roofs do have an increased factor of safety for moisture durability. In one reviewed study (Nusser 2010), green roofs were considered "shadowed" since the solar energy doesn't get to the roofing membrane and sheathing.

6.3 Open Cell Spray Polyurethane Foam

The hygrothermal analysis, field studies, and in-service investigations have shown that unvented open cell spray foam roofs can be installed in Climate Zone 4C (i.e. Vancouver and Seattle) the Vancouver area (Climate Zone 4) with only painted drywall (two layers of latex paint) on the interior. The success of this assembly will strongly depend on the interior relative humidity being maintained at a reasonable level by using appropriate ventilation strategies. Using a calibrated model for Vancouver roof performance (Smegal and Straube, 2014), it was shown that at a wintertime interior relative humidity of 35% there were no elevated sheathing moisture contents, but at an interior wintertime relative humidity of 60% with only latex paint vapor control, the predicted sheathing moisture content exceeded 30%. As mentioned previously, the National Building Code of Canada mentions in the notes for Part 9 (9.25.5.2) that the winter time interior relative humidity in milder climates (ie. Vancouver) can be as high as 60%.

To increase the factor of safety and decrease the risk of moisture accumulation, a Class II (5.7 – 57 ng/Pa.s.m^2) or smart vapor control layer could be installed on the interior. Unpublished research by Building Science Consulting Inc, has shown that it can be very difficult to meet the Class I or Class II (<1 Perm or 57 ng/Pa.s.m^2) vapor barrier requirements by applying vapor barrier paint to drywall, or the surface of foam.

In Climate Zones 5-6, interior Class II vapor control (<1 Perm or 57 ng/Pa.s.m^2) or a smart vapor barrier is required and these roofs can be successful. A double vapor barrier ie. 6 mil poly (Class I vapor control, <0.1 Perms, <5.7ng/Pa.s.m^2) on the interior, and asphalt shingles on the exterior, can however be problematic in the event that some moisture inadvertently enters the roof assembly. A smart vapor barrier should minimize the risk associated with the use of traditional interior polyethylene vapor barriers. The risk of moisture accumulation in the wood based exterior sheathing associated with construction defects in the interior air and vapor barrier increases as the climate gets colder. In the far north Climate Zones 7-8, there is very little drying available to the roof assembly and care is required to minimize the risk of potential moisture accumulation.

Vented ocSPF roofs can be successful in all climate zones provided that the material forming the ventilated cavity (ie. ventilation baffle) is not a vapor barrier and thus allows condensation within the spray foam (observed in the University of Waterloo BEGhut roof study). The baffle must be more vapor permeable than the ocSPF but also rigid enough to withstand deformation as the foam is curing (ie. unfaced cardboard baffles or other vapor permeable materials). It has been demonstrated that interior vapor control should be used for vented open cell roof assemblies in Climate Zone 5 and greater. As with all types of ventilated roof assemblies, in some regions in Canada where ventilation may bring moisture into the roof assembly, unvented assemblies may be preferred.

6.4 Closed Cell Spray Polyurethane Foam

The literature review of in-service investigations, field studies and hygrothermal analysis shows that sloped wood framed unvented closed cell spray foam roof assemblies will perform well in Climate Zone 4 through 7 provided recommended interior relative humidity is maintained during cold weather.

The only identified limitation to the use of unvented ccSPF is in extremely cold climates (ie. Climate Zone 8) and high interior relative humidities (specialized buildings like museums or pools, 35% in zone 8). There is very little inward solar drying in Climate Zone 8 relative to other climate zones.

Vented closed cell spray foam assemblies can be successful in Climate Zone 8 as an alternative to unvented ccSPF assemblies. The baffles must be strong enough to support the curing of closed cell spray foam without deforming, and inadvertently blocking the ventilation path.

7 Conclusions

This review of unvented sloped wood-framed roofs in cold climates has reviewed several hygrothermal and field studies predicting and measuring the performance of unvented roof assemblies with spray foam. This report also summarized some in-service openings of both open cell and closed cell spray foam unvented roof assemblies in cold climates.

In general, the field studies and in-service investigations showed good performance typically with no visible signs of moisture damage. The SPF installations that were investigated were installed in an airtight continuous manner without obvious defects. Even in cases where there were measured elevated sheathing moisture contents above recommended levels, it was documented in the reviewed reports that there were no visible signs of moisture damage of the sheathing at the opening locations.

This study shows that the construction industry has the required information and experience from Canada and the United States to design successful unvented roof assemblies for all climate zones in Canada with proper design and construction technology. While ccSPF can be used in most residential applications with few caveats, ocSPF requires more care in the selection and construction of effective interior vapor control.

If you have any questions following your review of this report, please do not hesitate to contact us by phone or email.

Yours truly,

Jonathan Smegal | MASc.
Associate, Senior Project Manager
jsmegal@rdh.com
519 342 4731
RDH Building Science Inc.

John Straube| Ph.D., P.Eng
Reviewed by

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