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STATE OF THE ART REVIEW OF UNVENTED SLOPED WOOD-FRAMED ROOFS IN COLD CLIMATES

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ABSTRACT

Typical residential house construction in North America has long had vented attics above living space with the insulation and air control layer at the ceiling plane of the living space. Except for documented wintertime condensation issues in cold climates, such vented attics generally perform quite well, provided that they are ventilated adequately and air leakage from the interior is prevented. However, architects and designers are moving away from empty attics by using the attic space as conditioned storage or bonus rooms, or by designing larger interior volumes with cathedral ceilings. The practical challenges of ventilating cathedralized attics and cathedral ceilings have been significant, both because of increased geometrical complexity and because of the number of penetrations typically required for services.

Spray foam has been used successfully in tens of thousands of unvented roof assemblies throughout North America but some concerns remain in the building industry that these assemblies are inferior to ventilated roof assemblies. The National Building Code of Canada, in particular, makes it difficult for designers to use unvented roof assemblies, even using designs that are approved in similar building codes in the United States and have been proven to be durable, high-performing options.

Over the past decade, the authors have been directly involved with studies of both 0.5 pcf (8 kg/m^3) open cell spray foam, and 2.0 pcf (32 kg/m3) closed cell spray foam in unvented roof assemblies in various climates with continuous monitoring of temperature and moisture conditions. This paper provides a literature review of research that has been conducted on wood-framed sloped unvented roof assemblies, but will focus on results from a field monitoring study of sloped unvented wood roofs in partnership with the University of Waterloo, as well as a field survey that opened roofs and removed samples from aged unvented roof assemblies.

VENTILATED ROOF ASSEMBLIES

Historically, ventilated attics have been shown to be an effective enclosure design for a pitched wood-framed roof system. Using this method, a large amount of insulation (typically fiberglass or cellulose) can be installed on top of the ceiling of the living space in an attic to achieve high R-values (Figure 1). In a ventilated attic, the air control layer separating the interior from the exterior is located at the ceiling plane, and exterior air enters the attic at the lower vent openings, usually at the soffit. The air moves through the attic and exits at the upper vent opening near the ridge. The air moves through as a result of wind pressures, stack effect, and occasionally mechanical fan pressures.

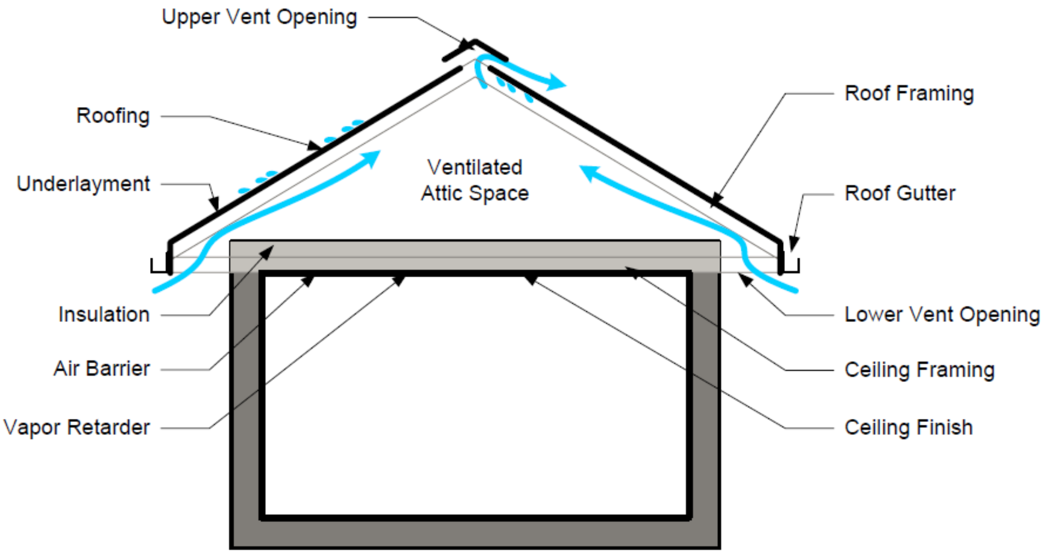

Figure 1: Ventilated attic assembly (Schumacher 2008)

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.

However, other factors may impact these issues more than attic ventilation alone. Rose and TenWolde (1999, 2002) showed that while ventilation is important and should be used if possible, especially in cold climates, the main causes of moisture-related problems in attics and roofing assemblies are the interior relative humidity in the occupant space coupled with a lack of sufficient airtightness at the ceiling plane.

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 below. Hinrichs (1962) made the correlation between interior humidity and airtightness when he noted that air infiltration through the ceiling into the attic was the major source of condensation; he therefore concluded that a vapour retarder (i.e., 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 vapour retarder.

Ventilated cathedral ceilings, as shown in Figure 2, have become increasingly popular as a means of increasing ceiling height and architectural interest. Such roofs are a much more compact enclosure assembly with all of the control layers for air, vapour, heat, and water between the sloped ceiling of the cathedral ceiling and the roof deck. This compact assembly also requires a minimum continuous air gap from the lower vent opening to the upper vent opening in each joist space. These spaces can be maintained with vent baffles, or by ensuring enough space between the insulation and the roof deck. These ventilated cathedral roofs can often be more problematic than ventilated attics because it is difficult to ensure that the minimum vent openings exist in every rafter bay all the way from the bottom to the top. The ceiling plane, which should be airtight, is often perforated with lights, speakers, and other equipment, and can overload the assembly's limited ventilation drying with interior moisture. Often, the insulation in a ventilated cathedral ceiling is air- and vapour-permeable fibrous insulation, and there have been many observed cases of moisture condensation and accumulation in these assemblies as a result of an inadequate air barrier combined with inadequate ventilation. Increasing ceiling airtightness, and increasing cathedral ceiling ventilation (via cross-strapping and larger ventilation gaps) can together overcome these limitations.

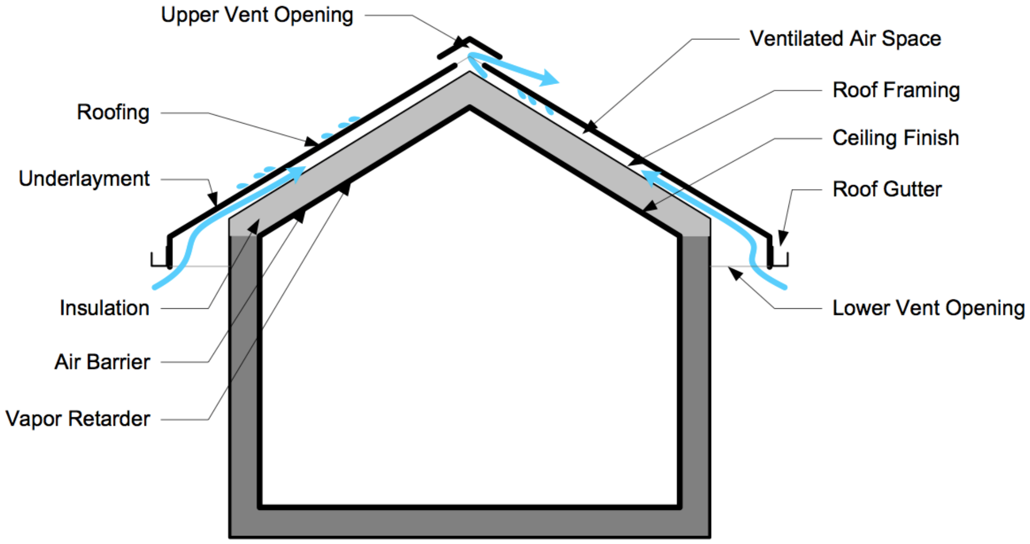

Figure 2: Ventilated cathedral ceiling (Schumacher 2008)

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, preventing burning embers from entering wood structures in forest-fire-prone areas, and reducing 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 design and built to perform reliably, durably, and at a high level.

It should be noted that among the most durable unvented roof assemblies are ones where all, (or a significant portion) of the insulation in the roof is installed in a continuous manner on the exterior of the roof sheathing, keeping the sheathing warm, minimizing thermal bridging, and removing the risk of condensation and moisture accumulation in the roof sheathing and assembly (Garden 1965). However, it is recognized that due to height restrictions on buildings, geometric complexities, and the cost of installing exterior roofing insulation, unvented roof assemblies with the insulation below the roof deck are often a more desirable construction alternative.

BUILDING CODES

In Canada, under Part 9 of the National Building Code, unvented roof assemblies are not prescriptively permitted, as stated in (9.19.1.1 pp. 9-105):

> 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 developed a set of guidelines for unvented roof assemblies in all North American climate zones for the 2006 IRC (IRC Section R806.5). A map of the climate zones with Canadian cities is shown in Figure 3. Canada is almost entirely in Climate Zones 5-8, except for a very small portion in the Lower Mainland of British Columbia, including Vancouver. Unvented roof assemblies covered by the IRC include unvented cathedral ceilings (Figure 4), and cathedralized attics (often referred to as unvented attics) (Figure 5). As noted in the schematic in Figure 5, the attic space in a cathedralized attic must be part of the interior conditioned space and will require some amount of air distribution, similar to other interior spaces.

Figure 3: RDH climate zone map of Canada

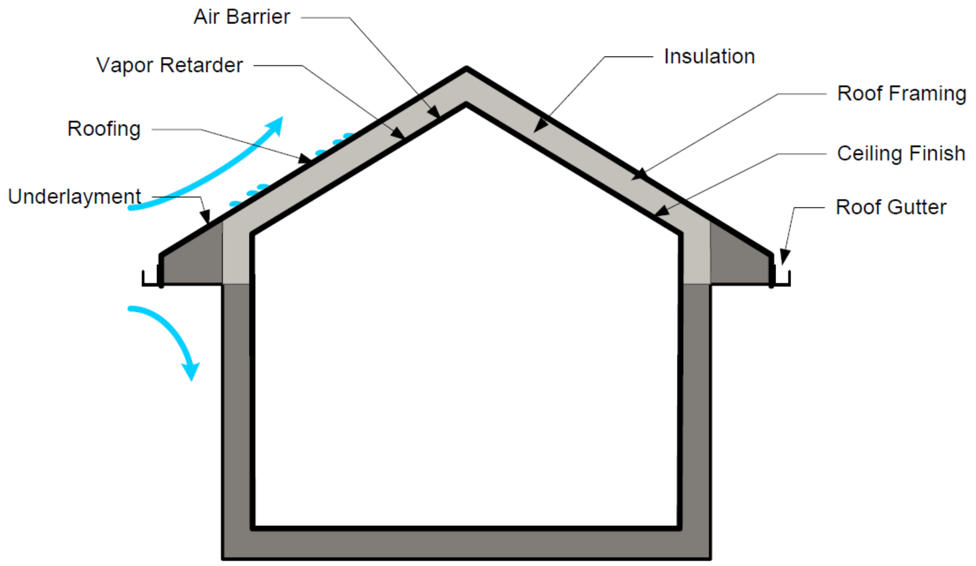

Figure 4: Unvented cathedral ceiling (Schumacher 2008)

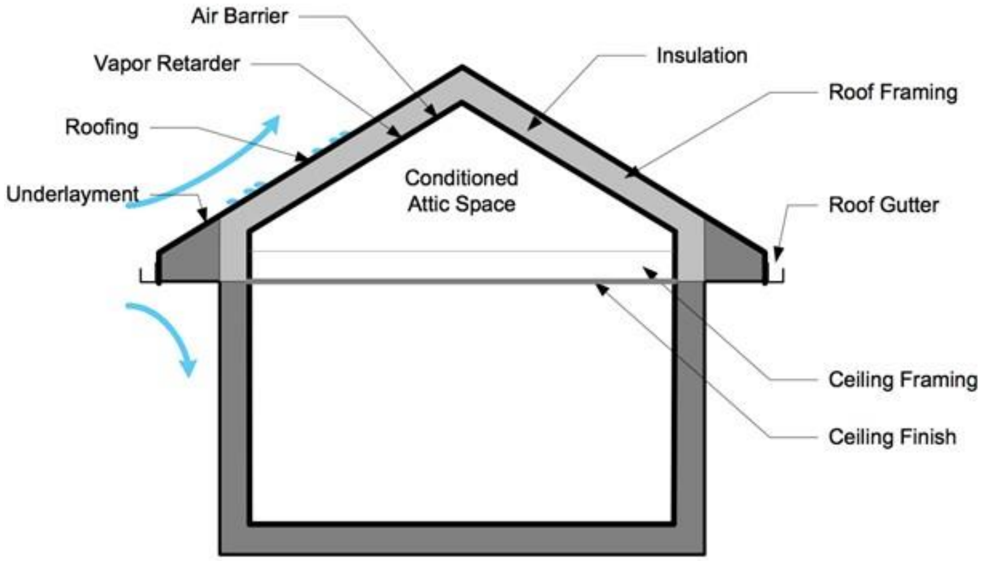

Figure 5: Unvented cathedralized attic (Schumacher 2008)

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 vapour permeability of the materials in the assembly. The code states that there can be “No interior Class I vapour retarder (<5.7 ng/Pa.s.m2, 0.1 Perm) on the attic floor of the unvented cathedralized attic assembly or on the ceiling side of the unvented cathedral ceiling assembly” (IRC Section R806.5 number 2).

In other words, the IRC recognizes that it is important to allow any moisture in these roof assemblies to dry to the interior, and hence to build enclosures without a vapour barrier on both sides of the assembly.

The IRC specifies the type of insulation for cold climates (Climate Zones 5, 6, 7, and 8) to specifically address the amount of possible vapour diffusion from the interior to the exterior roof sheathing:

> In Climate Zones 5, 6, 7 and 8, air-impermeable insulation shall be a Class II vapour retarder (5.7 to 57 ng/Pa.s.m^2, 0.1 to 1 Perm) or shall have a Class II vapour retarder coating or covering in direct contact with the underside of the insulation. (IRC Section R806.5 number 4)

However, Climate Zone 4C is missing from the list, 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 criteria related to the air permeance of the unvented roof insulation are stipulated in the IRC Section R806.5 number 5, including:

- 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 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. However, it 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 is constructed with R-values higher than code, the minimum R-value listed in the IRC 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.

UNVENTED ROOF RESEARCH STUDIES & FIELD MONITORING

There have been several studies conducted on sloped wood-framed unvented roof assemblies. These studies are a combination of moisture monitoring studies and hygrothermal modeling simulations that predict performance.

The moisture content of the wood-based sheathing is often used as the performance criteria because the sheathing is the first location where vapour 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 for 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 moisture contents of wood-based sheathing are generally assessed with respect to relative risk as opposed to judging 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 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 pcf (8 kg/m3) open cell spray foam in Vancouver, British Columbia, Climate Zone 4C. There was no polyethylene vapour 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, solar-dried, south-facing sheathing only rose to 12-14%. The monitored data suggest that the interior dewpoint and outward diffusion through the open cell spray foam play important roles in the winter sheathing moisture content levels. During the first winter, construction moisture was still drying out, and the heat recovery ventilator (HRV) was not switched to 'winter' mode until December. The winter mode uses a lower interior relative humidity setpoint as the indication for ventilation. As a result, the moisture levels inside the house were slightly elevated and the interior dewpoint temperature exceeded 7°C (44.6°F) for approximately 41% of the monitored hours. This corresponds to an interior relative humidity of approximately 40% at an interior temperature of 22°C (71.6°F). During the second winter, the interior moisture levels were lower (dewpoint temperature exceeded 7°C [44.6°F] for only 17% of monitored 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 vapour drive from the summertime 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 via ventilation to be lower than many residences in the Lower Mainland.

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 or RSI 5.3) were constructed and instrumented for moisture and temperature conditions. The roof assemblies are shown in Table 2 below. The only roof with a polyethylene vapour barrier was the vented fiberglass roof assembly. It is generally accepted that latex paint on drywall has a vapour permeance of approximately 570 ng/Pa.s.m^2 (10 US Perms). Although painted drywall samples were collected during deconstruction, their vapour permeance had not yet been tested as this paper was written.

Table 2: Cathedral Roof Assemblies (Straube and Smegal 2014)

Test Assembly	Insulation	Ventilation	Vapour Control	Air Control
Unvented Closed Cell (NCC)	R30 (~5”) (RSI 5.3)	No	ccSPF	ccSPF
Vented Closed Cell (VCC)	R30 (~5”) (RSI 5.3)	Yes	ccSPF	ccSPF
Vented Fiberglass (VFG)	R30 (~9 ¼”)(RSI 5.3)	Yes	Polyethylene sheet	Polyethylene sheet
Unvented Painted Open Cell (NOCP)	R30 (~8”) (RSI 5.3)	No	Painted foam and drywall	ocSPF
Unvented Open Cell (NOC)	R30 (~8”) (RSI 5.3)	No	Latex paint on drywall	ocSPF
Vented Open Cell (VOC)	R30 (~8”) (RSI 5.3)	Yes	Latex paint on drywall	ocSPF

The ventilation gap in all ventilated assemblies was provided by installing commercially available polystyrene baffles from the soffit continuously to the upper roof vent, ensuring 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 spray foam 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 spray foam, although all of the ventilation paths still appeared to be continuous and were not affected by the installation of spray foam 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 National Building Code 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 open cell spray polyurethane foam (ocSPF) roof assemblies with only latex paint vapour 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 spray polyurethane foam (ccSPF) nor any of the vented roof assemblies experienced any elevated sheathing moisture contents; generally moisture content (MC) levels did not exceed 13% even with an interior relative humidity of 50% during the second winter.

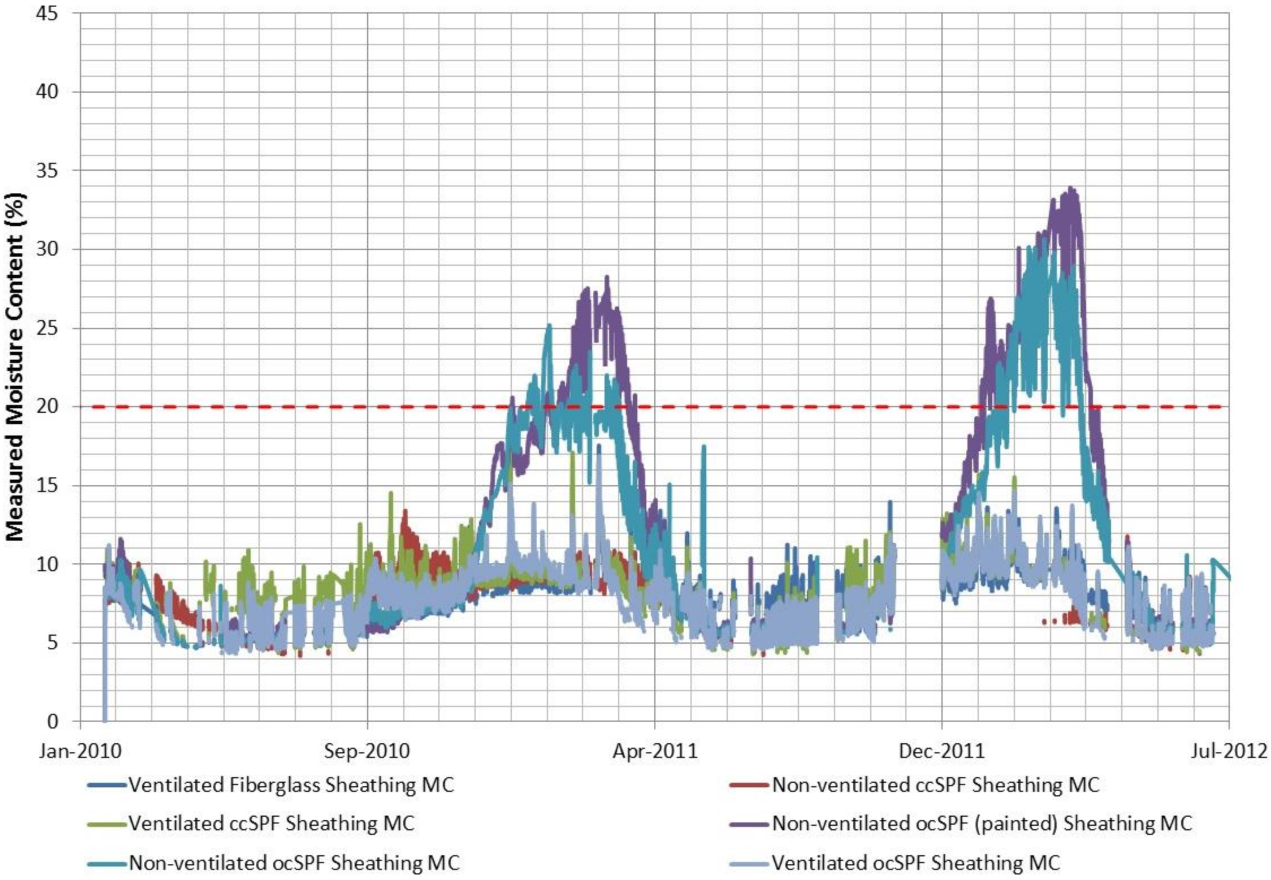

Figure 6: Measured roof sheathing moisture contents for six full-scale cathedral roof assemblies (Straube and Smegal 2014)

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 vapour 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 remained in good condition as a result of the ventilation inside the baffle. There was also evidence that a significant amount of water had run down the polyethylene vapour 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.

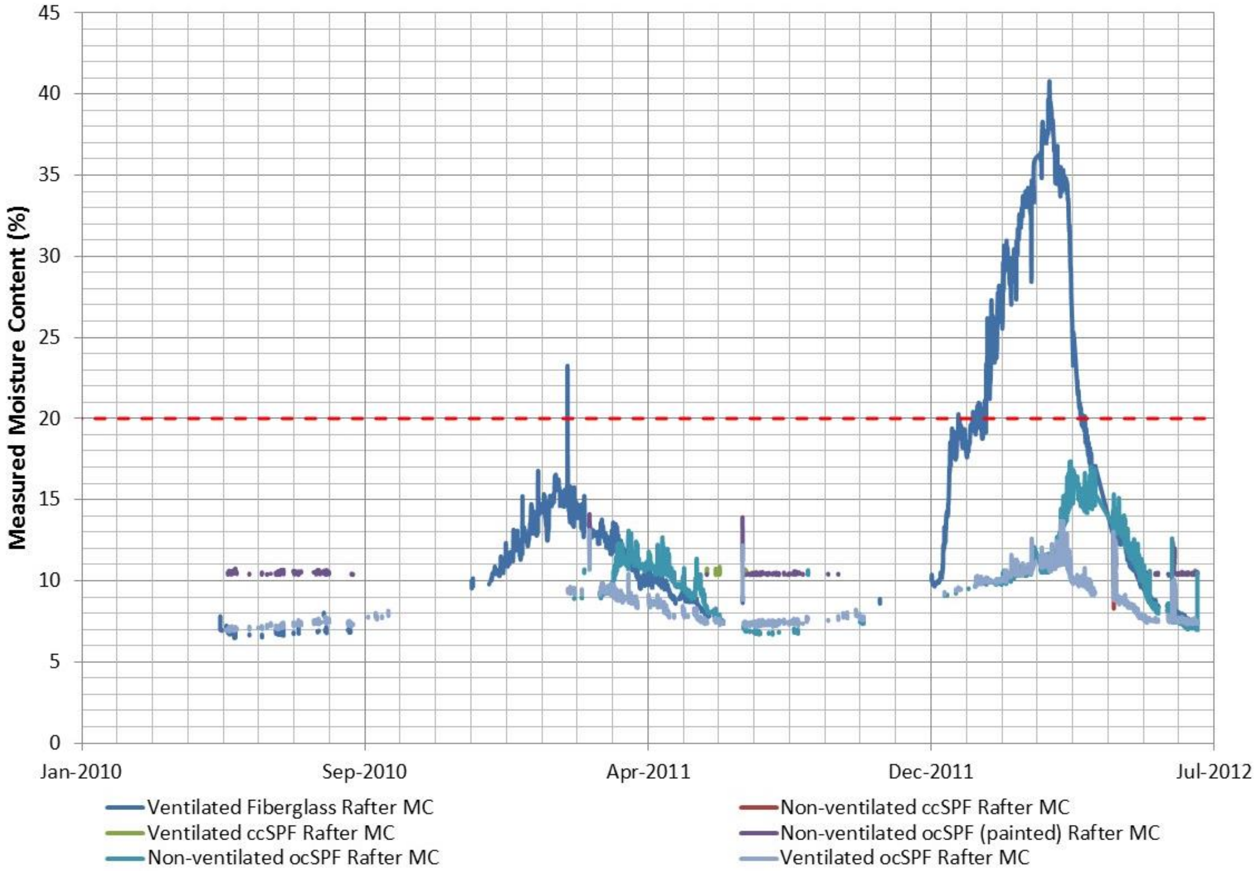

Figure 7: Measured roof rafter moisture contents for six full-scale cathedral roof assemblies (Straube and Smegal 2014)

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 closed cell spray foam cathedral ceiling roofs.
- There were elevated roof sheathing moisture content levels and elevated relative humidity levels within the foam in both (painted and unpainted) unvented open cell spray foam assemblies, although the assemblies dried completely in the summer months. There was no observed sheathing damage after seven years. These assemblies require more vapour control on the interior, although adding an interior low-permeance layer also stops any drying to the interior. A "smart" vapour barrier may be ideal in this assembly for performance and durability. Smart vapour barriers are materials that have a variable vapour permeance: a low vapour permeance when the surrounding RH is low, as is typical at the interior of most enclosures, and a higher vapour permeance when the surrounding RH is high, as would occur if there was a source of moisture on one side of the material.
- In the vented open cell spray foam assembly, there was no elevated sheathing moisture content. However, due to the low vapour permeance of the baffle (measured to be 213 ng/Pa.s.m^2 [3.5 US Perms]), moisture did accumulate at the foam-to-baffle interface, and there was evidence of

condensation and drainage during the deconstruction. This suggests that more vapour control than just latex paint would be recommended on the interior.

- In the vented fiberglass roof assembly, there were no 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 a result of a small amount of air leakage from the interior over several years, 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 (https://wufi.de/en/software/wufi-pro/) and the results were extrapolated to other regions of Canada covering all of the climate zones. For this analysis, 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 worst-case" scenarios to provide context to the results.

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 risk 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 vapour barrier showed no risk of moisture accumulation in the roof sheathing, although this analysis assumes there is no air leakage past the interior air barrier. In reality it is difficult to achieve perfect airtightness with polyethylene sheet in typical construction.

- Vented ocSPF worked well in simulations, although the initial model for this study did not include a baffle layer, which in the field study was shown to trap and accumulate moisture. Baffles could be added for future hygrothermal analyses.

- Unvented ccSPF worked well in every location except the extreme north (Climate Zone 8) when the interior relative humidity was limited to reasonable (30-35%) levels. In some Climate Zone 7 cities, with elevated wintertime interior relative humidity (≥40%), there was long-term predicted moisture accumulation in the sheathing under conservative modeling criteria.

- The unvented ocSPF model exhibited moisture accumulation in nearly every city, both with and without elevated interior relative humidity levels. In Vancouver such a system performed well with an interior relative humidity of 35%, but showed durability risk at an interior relative humidity of 60%. The National Building Code 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 spray foam 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 for spray foam insulated unvented roof assemblies in Miami (Climate Zone 1), Seattle (Climate Zone 4C), and Minneapolis (Climate Zone 7), for various levels of water leakage past the asphalt shingles applied directly into the wood sheathing. In some cases, all of the insulation was spray foam, and in others, it was a hybrid approach with spray foam and fibrous insulation which met the requirements of the International Residential Code (IRC) for unvented roof assemblies (Table R806.5). The amount of water passing through a roof system is difficult to quantify, but hygrothermal modeling was possible using ASHRAE 160, TMY2, 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 cell spray polyurethane foam (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 (0.37m2) 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% 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 moisture content (MC) when more than 0.6% rainwater leakage was introduced into the system. This is due to both rainwater leakage and outward vapour drives during the heating season. The ocSPF roofs dried out much more readily than the ccSPF roofs during warmer and sunny weather. 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 and 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 compared to the type of SPF and vapour 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 vapour barrier installed on the interior of the roofing assembly to stop the inward movement of drying water vapour.

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. The results showed that so long as airtightness is provided and wintertime humidity is controlled, numerous unvented solutions using either open or closed cell spray foam, or a combination of spray foam and fibrous insulation, can be successful. It was found that climate, the solar properties and exposure of the roofing, and the air and vapour permeance of the insulations and interior humidity are the most important factors to be considered in the design of moisture-safe unvented roof systems.

Table 3: Matrix of climate zones, roofing, R-value (2010), and insulation types modeled for wood-framed sloped roofs. (Straube et al. 2010)

DOE Zone & City (12)	Code Required R-Value	Roofing Type (4)	Insulation Type (8)
1 Miami	30	Dark asphalt	Spray fiberglass (1.8 pcf)
2A Houston	30	Tile (ventilated)	1” ocSPF + spray fiberglass
2B Phoenix	30	Light metal	1” ccSPF + spray fiberglass
3A Atlanta	30	Cedar shakes	2” ccSPF + spray fiberglass
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	–	–

There is also a group of other research studies and reports regarding roof performance that do not include sloped wood-framed roofs or spray foam, but do provide useful insight into roof performance parameters. For example, one study of 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 different amounts of solar absorption, and different interior smart vapour barrier membranes. It was concluded that low temperatures on the roof, whether from shading or a green roof, lead to high and long-lasting relative humidity in the cavity.

On a similar topic to Nusser et al., 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 (white) construction compared to a traditional black roof under certain modeled parameters, but the factor of safety with moisture-related durability is higher in all low-slope roofs with the high solar absorption of black roof membranes.

Buxbaum et al. (2013) also looked at the effect of roof membranes on low-slope roofs in a two-part study in Europe. 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 compared to the white roofing membrane, as a result of the higher surface temperature, increased temperature gradient and drying towards the interior (although inward drying was slow with an interior vapour barrier). In the field study component of the research, the results were similar. It was concluded from the data analysis that the different coloured roof membranes were seriously influencing the external roof surface temperatures due to solar absorptivity. The differences in roof surface temperature strongly influenced moisture migration and accumulation and therefore the durability performance of low-sloped roof construction. It was found that light-coloured and especially white “cool” roofing membranes can reduce the effect of solar absorption and inward drying, hence drying of the roof assembly is limited and moisture-related problems are likely to occur.

Even though the previous three studies focused on low-slope roof assemblies, all roofs could be critically affected by the conclusion that roof membrane colour and amount of solar energy significantly affect drying and long-term durability. This conclusion does not currently play a significant role in the North American wood-framed sloped housing market, where most of the roofs, especially in cold climates, are dark in colour, but it is still important to keep in mind in cases where roof membranes are lighter in colour.

Another study on low-slope roofs that could provide some general insight into long-term moisture durability was conducted by Geving et al. (2013) who investigated the performance of unvented roof assemblies with either a smart vapour retarder or polyethylene film on the interior as the vapour control. The plywood sheathing was given an elevated initial moisture content so the drying of the roof assemblies could be measured and compared during summertime drying conditions. The roof assemblies with the polyethylene vapour barrier on the interior were the slowest to dry. The different smart vapour 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 commercial low-slope roof assemblies with different interior vapour control and intentional wetting within the roofing insulation. It was found that the roof assembly with an interior smart vapour control layer dries very quickly in the summer months compared to the roofing assembly with the interior vapour barrier.

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 is occurring in constructed assemblies. There are not a lot of documented cases of in-service inspections of spray foam 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 spray foam 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 (Climate Zone 7) and Wisconsin (Climate Zone 7) in April 2004, and one cathedralized attic in Massachusetts (Climate Zone 5) in March 2004. All of these roofs were located in cold climates and investigated in the spring to find any possible moisture accumulated 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 (0.5 pcf [8 kg/m^3]), open cell sprayed polyurethane foam. No other vapour control was identified in the report for these roof assemblies. The foam 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 20-40%, while the south-facing orientation ranged from 7-23% 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) wrote a summary report on unvented ocSPF roofs in Vancouver and the Lower Mainland (Climate Zone 4C). This paper included past research as well as observations made at three buildings where inspection openings were made in unvented ocSPF roof 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 vapour 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 – Open cell SPF 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 vapour 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 vapour 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 a comprehensive 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 Zone 4C to 7. There was a range of construction strategies, including unvented cathedral ceilings and cathedralized attics. All locations had MCs well within the safe 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 problems 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.

CONCLUSIONS

This state-of-the-art 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 paper also summarized findings regarding 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 spray foam 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 research that there were no visible signs of moisture damage of the sheathing at the opening locations.

The building science research and papers reviewed for this study suggest that the construction industry has the required information and experience from Canada, the United States and elsewhere to design safe 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 vapour control.

Future Research

In conducting this review, some questions or uncertainties have arisen where more publicly available information would prove helpful to designing and specifying unvented roof assemblies in cold climates:

- Are smart vapour retarders helpful in reducing the risk of moisture accumulation in wood-framed sloped unvented spray foam roof assemblies? All of the research found regarding smart vapour retarders was for low-slope (flat) roofs.
- Can paint be applied to the surface of ocSPF to effectively reduce vapour diffusion into the spray foam of unvented roof assemblies? It is clear that vapour control is required in many regions with ocSPF unvented roof assemblies. Does paint that is advertised as vapour barrier paint perform as an adequate vapour control?
- For vented open cell spray foam roof assemblies, the research showed moisture accumulation as a result of a foam vent chute. What vent chute material will improve the performance of vented ocSPF roof assemblies?
- There is a lack of measurement and investigation information of unvented spray foam roofs in cold climates that have been constructed for many years. It would be useful to conduct more in-service openings of spray foam assemblies after years of operation in cities in Climate Zones 6 and 7 to expand the database and knowledge of spray foam performance?

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