

Why Wood Frame Attics Get Wet & Moldy in the Pacific Northwest

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Abstract

Over the past several years in the Pacific Northwest there has been a trend of increasing reporting and repair of moisture problems within attics below sloped wood frame roofs. The problem consists of seasonally wetted roof sheathing and mold contamination occurring within the wood frame attics of many newer houses, town houses, and multifamily building complexes. Often these problems are attributed to rainwater ingress through the roof assembly, inadequate ventilation of the attic space, and/or condensation associated with air leakage from the conditioned indoor spaces or from ducts; however, detailed investigation and testing of many of these attics has found that these factors cannot account for the observed problems. Instead, wetting from other sources, including condensation of outdoor attic ventilation air caused by night sky cooling, and in some cases rainwater ingress through asphalt shingles is hypothesized. These roofs and attics are generally constructed to meet current building code and third-party roofing warranty requirements.

These roofing problems are proving to be a significant burden on homeowners and warranty insurers. Numerous warranty claims have been filed for moisture ingress and mold issues within attics. Repairing moisture damage within attics is costly and a significant inconvenience to property owners and the warranty provider. Furthermore, the success of many of these repair efforts has been poor, with mold growth recurring a few years after a full remediation and air sealing work has taken place. This suggests a presence of other underlying wetting mechanisms.

In an effort to further understand the cause of attic moisture problems and develop potential remediation solutions, the authors undertook a research study and field monitoring program in Vancouver, BC. The study investigated sheathing moisture absorption caused by night sky cooling and ventilation air condensation as well as the impact of shingle underlayment types on potential exterior moisture sources. The study included both a controlled field exposure study to measure the moisture contents, temperatures, condensation, and mold growth on several roof test huts as well as supplemental laboratory testing. The primary objective of this study was to conclusively demonstrate that sloped wood frame attic roofs constructed according to best practice guidelines experience moisture-related problems even in the absence of interior moisture sources and with unrestricted ventilation.

This paper summarizes the key findings of this study and elaborates on the contribution of night sky condensation and exterior wetting sources. This study also addressed the efficacy of wood surface treatments with respect to preventing mold growth on the underside of the roof sheathing.

Introduction

Moisture problems in sloped wood frame attic roof assemblies are common and typically manifest as mold growth and the degradation of the roof sheathing. Often this type of damage is attributed to rainwater ingress through the roof assembly, to inadequate ventilation of the attic space, condensation associated with air leakage from the interior spaces or ductwork, or to the re-entrainment of humid exhaust air into the vented attic space (e.g., from soffit exhaust fans). Figures 1 through 4 provide example photographs of typical mold growth and damage patterns found within ventilated attics from some newer residential buildings in the Pacific Northwest, Climate Zone 4C (temperate marine). In many cases the mold growth does not lead to structural damage of the sheathing or necessarily create health problems (ACOEM, 2003; Lstiburek et al, 2008), but it is nonetheless perceived to be a possible health risk to the occupants or a property value risk to the owners.



Figure 1: Locally stained and wet sheathing and frost due to condensation of humid air leaking from a poorly sealed bathroom exhaust fan and duct.



Figure 2: A wood frame attic with widespread stained, wet, and deteriorated sheathing from persistent indoor and exhaust duct air leakage and poor attic ventilation



Figure 3: Locally stained, wet, and deteriorated sheathing from water ingress around a plugged dryer exhaust duct boot



Figure 4: Stained and damp sheathing only on the north slope of a very well-ventilated wood frame attic not obviously linked to conventional wetting mechanisms and hypothesized to be caused by night sky condensation of outdoor ventilation air. Note that the staining is more apparent on the sapwood versus the heartwood.

In recent years, there has been a trend toward highly insulated attics, which seemingly correlates with increased observations of moisture problems in wood frame attics, particularly in the Pacific Northwest (Dell et al. 2011, Roppel et al. 2013). This is not unlike problems observed in the past in other similar marine/temperate climate zones in Sweden (Arfvidsson and Harderup 2005, Hagentoft and Kalasgasidis 2010). Improvements in attic construction practices and materials in the past decade have typically lead to decreased interior air leakage in to attics due to improved ceiling airtightness, with the consequent decrease of the attic moisture load, as illustrated in Figure 5. Concurrently, attics were also constructed with more insulation (i.e., R-40+) to reduce the building's energy consumption. This has led to less heat loss into ventilated attics during cold weather and, as a side effect, has reduced the drying capacity of the roof sheathing. This has the effect of potentially exacerbating any inherent but otherwise undetected moisture problems. As more insulation is added to these attics and further air sealing efforts are undertaken, these attics approach a state of being able to function completely independently from the building on which they are constructed, as is shown schematically in Figure 5d.

This decoupling effect has both positive and negative implications for the performance of the roof sheathing and on the risk for wetting and associated damage. Phenomena that may previously have been masked by excessive heat loss in older, poorly insulated and air-leaky attics can become apparent in modern well-insulated and airtight attics. In addition, changes to plywood roof sheathing material properties over the past few decades (e.g., species and relative levels of heartwood and sapwood from later-growth timber) may also be contributing to the current moisture issues.

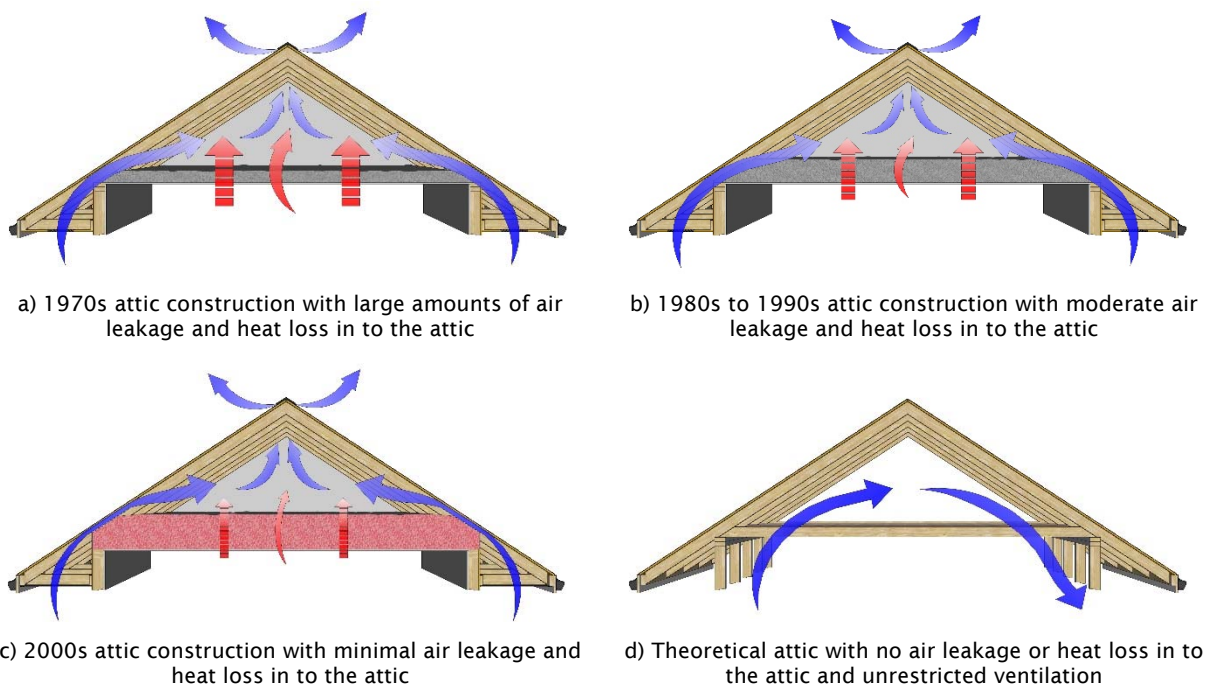


Figure 5: Schematics showing historical ventilation, insulation, and air leakage arrangements for attics (a, b, and c) and for a theoretical attic (d). Blue lines represent ventilation airflow into and out of the attics, red dashed lines and curved lines represent heat loss and air leakage respectively into the attics from the interior.

Detailed investigations and testing of many of these attics has shown that the traditional wetting mechanisms cannot account for the observed mold growth (as shown in Figure 4). Moisture-related problems have been found to occur in the absence of rainwater ingress, relatively airtight ceiling planes, and code-required attic ventilation rates or those required by third-party warranties. Consequently, we hypothesize that other mechanisms are affecting the moisture performance of these roof assemblies and, specifically, the roof sheathing.

When the traditional damage mechanisms are eliminated, two remaining potential sources of moisture have been identified:

- Outdoor attic ventilation air condensing on the underside of the sheathing due to night sky cooling.
- Inward vapor diffusion or seepage through wetted shingles and underlayment.

Condensation due to night sky cooling occurs when the roof sheathing temperature falls below the ambient dew point temperature as a result of net radiative heat loss to the much cooler night sky. This condensation (and potentially frost) on the underside of the sheathing is absorbed and increases the sheathing moisture content. A sufficiently elevated sheathing moisture content may create conditions suitable to support mold growth. The hypothesized inward vapor diffusion wetting mechanism is a process by which precipitation and surface condensation is absorbed by the shingles or collected in gaps between the shingles and driven into the roof assembly as vapor when subjected to elevated temperatures (e.g., solar heating).

In an effort to further understand the cause of the observed moisture-related problems in attics and to assess potential solutions for new or existing buildings, the authors undertook a research study to investigate the potential moisture sources and methods for mitigation of mold growth and prevention of degradation. This research consisted of both a controlled multiyear field exposure study and supplemental laboratory testing.

Objectives & Methodology

The primary objective of this study was to conclusively demonstrate that sloped wood frame attic roof assemblies experience wetting in the Pacific Northwest despite the elimination of typical indoor-based moisture sources. Further, this wetting cannot be prevented by ventilation alone. Once this was established, this study worked to identify and evaluate the critical wetting mechanisms and to assess the application of various wood treatment products to the sheathing to prevent mold growth and sheathing degradation. The field monitoring program to-date has progressed from September 2012 through to April 2014, capturing seasonal wetting over two winters. Within the second winter of the study, a vented shingle underlay was monitored as a possible night sky cooling decoupling measure (RDH 2014), though the results of this unsuccessful mitigation measure are not covered within this paper.

Concurrent field and laboratory research is ongoing by others locally including the Homeowner Protection Office (HPO), Morrison Hershfield, British Columbia Institute of Technology, and FP Innovations to investigate additional wood treatments and alternate mitigation strategies. Alternate roof configurations including unvented attics or exterior insulated roofs, while viable alternates to traditional ventilated attics, were not evaluated as part of this study.

Roof Hut Arrangements

To assess the field performance of wood frame attic roof assemblies with controlled parameters, four roof huts were constructed, each 6 feet wide by 6 feet long in plan dimension. The roof huts were constructed using ½" plywood sheathing, 2x4 wood framing, and dark-colored three-tab shingles. Three of the roofs were constructed at 3:12, 4:12, and 6:12 slopes, respectively, with standard asphalt-impregnated #15 roofing felt underlay, while the fourth control roof (CONT) was constructed at a 3:12 slope using an impermeable self-adhered membrane (SAM) underlay.

The four roof huts were placed on the open low-slope roof of a 2-story commercial building in Vancouver, BC, in order to expose them to exterior conditions while also decoupling them from the potential impact of a heated attic, indoor air leakage, duct leakage, or poor attic ventilation. Additionally, the installation of the self-adhered vapor-impermeable membrane on the control roof was intended to eliminate the potential for all wetting of the sheathing from the top of the roofs, including rainwater ingress and inward vapor diffusion. This controlled test hut approach allowed for evaluation of the field performance of these assemblies under unrestricted ventilation conditions (i.e. very well ventilated) while eliminating many of the conventional wetting mechanisms. The roof huts were constructed in late August, 2012, and were roofed by mid-September, 2012, under seasonally dry conditions.

The roof huts were arranged such that one side of the roof slope faces due north and one side faces south to investigate the impact of solar radiation on performance. The different orientations influence how the roof heats up and dries and gets wet and potentially how well the self-sealing stripping of the shingles engages. Photographs showing the construction of the four test huts are shown in Figures 6 through 8.



Figure 6: Roof huts under construction with plywood sheathing installed.



Figure 7: Three-tab asphalt shingles being installed by roofing contractor over #15 felt or SAM at the control roof.



Figure 8: Completed roof huts in place on low-slope commercial rooftop in Vancouver, BC.

Immediately after construction and before the onset of mold growth, various treatments were applied to test sections at the underside of the plywood sheathing in each roof on both the north and south orientations to assess their impact on reducing the long-term potential for mold growth and degradation. The efficacy of the treatments was assessed visually at regular intervals. The first round of wood treatments applied in October 2012 were:

- Sansin Boracol® 20-2
- Copper Naphthenate
- Bleach
- Thompson's WaterSeal®
- Kilz® Paint

A second round of wood treatments was applied in April 2013 after the first winter of wetting and when some mold growth was present on the sheathing; this consisted of:

- Zinc Naphthenate
- Sansin Boracol® 20-2 BD (added moldicide effect over 20-2 formulation)

Monitoring the Roof Huts

Temperature, moisture content, and relative humidity sensors were installed to measure the thermal and moisture profiles of the roof assemblies. The data were recorded with wireless data loggers.

Moisture pins were installed to monitor the moisture content of the plywood sheathing. Placement of moisture pins is critical in observing how wetting occurs; therefore, three sets of moisture pins were installed on each orientation of each test roof. The first set of moisture pins penetrated through all layers of the plywood in order to detect the worst-case moisture content in the sheathing. The second set of moisture pins were insulated and only exposed at the upper layers (outer 1/8") of the plywood to measure wetting from the exterior side. The third set of moisture pins penetrated only the bottom layers (inner 1/8") of plywood to measure wetting from the underside (e.g., night sky condensation). This arrangement of various moisture pin depths allows for monitoring moisture movement through the plywood sheathing. The sensors were placed near the center of the panels to eliminate edge effects. A standard 1/8" gap in the roof sheathing was included as part of the roof assembly near the sensors. A temperature sensor for moisture content calibration was installed within a small hole drilled into mid-depth of the plywood. Moisture content pins are referred to as MC and temperature as T within this paper.

Additional surface temperature, moisture content, and condensation sensors were installed after the first winter to refine the accuracy of the moisture content sensors and the potential for condensation/rain on the exterior of the shingles and the interior surface of the plywood. The moisture content sensors were installed using conductive epoxy to provide improved contact between the moisture pins and the plywood substrate, and like the inner moisture pins, these were installed to measure the moisture content of the surface of the sheathing.

Figure 9 shows a schematic of the moisture pin installation into the plywood, and Figure 10 shows photographs of the initially installed moisture content and temperature sensors.

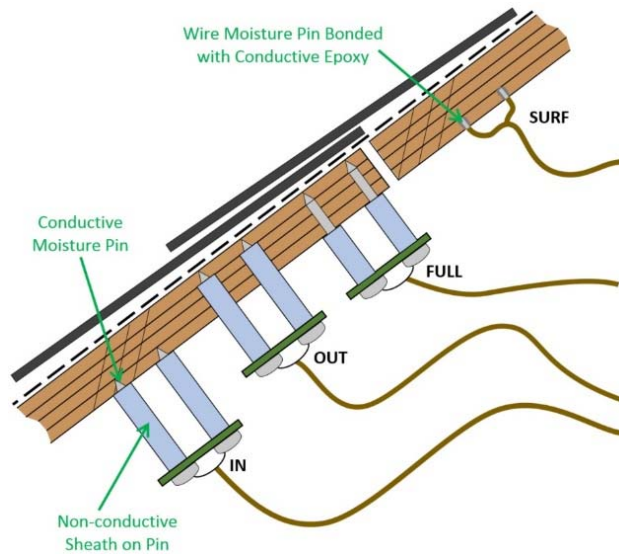


Figure 9: Schematic and coding of moisture pin installation at inner 1/8" (IN), outer 1/8" (OUT), and whole depth (FULL) of the plywood, and inner 1/8" of the plywood using pins installed with conductive epoxy (SURF).

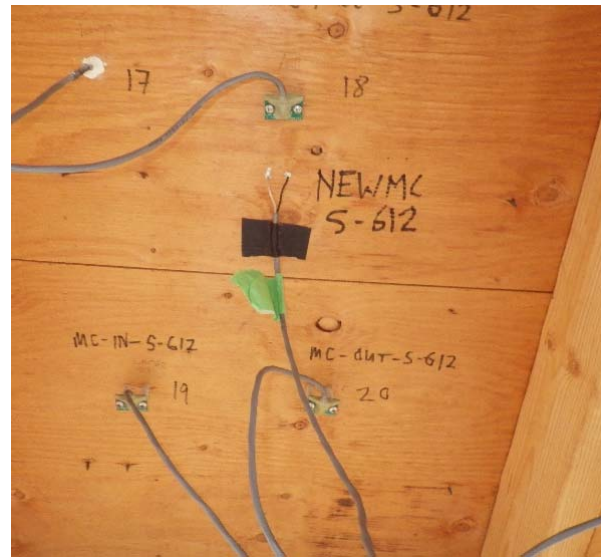


Figure 10: View of underside of south side of 6:12 roof hut showing placement of moisture pins and sheathing temperature sensors.

Field Monitoring Results & Analysis

The following sections present the exterior boundary conditions and theoretical equilibrium moisture levels, long-term sheathing moisture contents, and an evaluation of the wetting and drying mechanisms for the sloped roofs. The impact of the shingle underlayment is also assessed.

Overview of Exterior Conditions

Given the pertinence of the exterior climate to the performance of the test roofs, this section provides an overview of the exterior conditions at the test site in Vancouver, BC, where the roof huts are located. These roofs are not connected to interior spaces, and consequently there are no interior conditions to report.

The temperature and relative humidity were measured throughout the duration of the monitoring period (Figure 11). Even in the absence of condensation or other wetting mechanisms the moisture content of wood will vary with the relative humidity (RH) and temperature levels to which it is exposed. Consequently, using the correlation developed by Hailwood and Horrobin (1946), the equivalent moisture content (EMC) of the plywood sheathing can be calculated based on the ambient temperature and RH; this is also plotted in Figure 11. The EMC demonstrates the moisture content that wood would naturally experience under these environmental conditions without additional wetting.

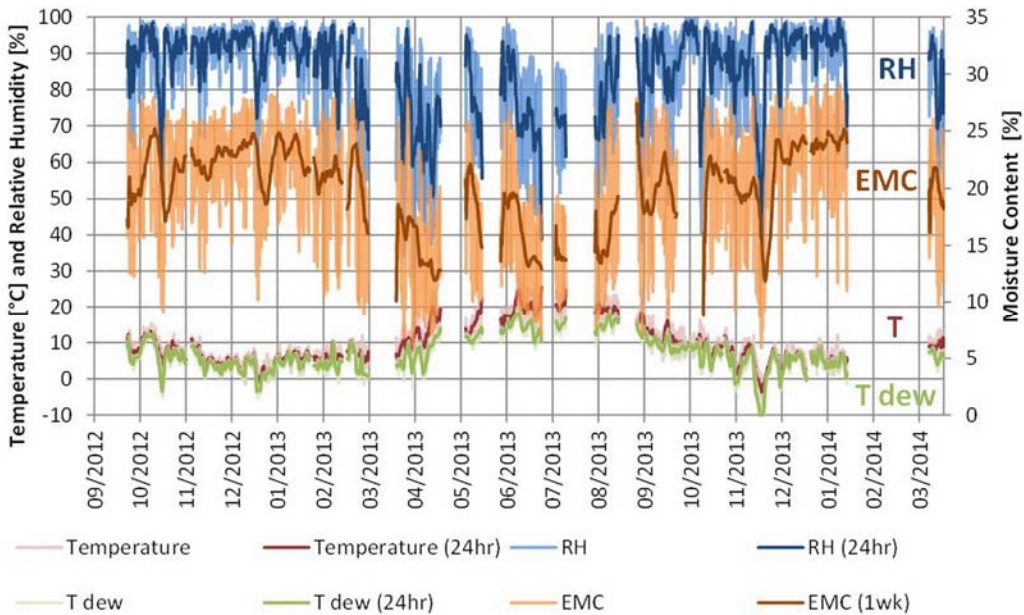


Figure 11: Temperature, Relative Humidity, and Equivalent Moisture Content, Hourly and 24hr/Weekly Averages for Monitoring Period.

Reviewing the climatic data shows that the EMC exceeds 20% MC throughout the winter due to natural exterior temperature and RH levels, even in the absence of wetting or drying forces. Wetting and drying mechanisms, however, have the ability to both increase and decrease the moisture content of the wood relative to EMC levels. These potential wetting and drying mechanisms include precipitation, condensation from night sky cooling, and solar radiation.

Within the Pacific Northwest, increased precipitation occurs in the winter with meager solar radiation, and in the summer there is less precipitation and significantly more solar radiation. These typical seasonal conditions have pronounced effects on the performance of the test roofs as discussed in subsequent sections.

Long-Term Sheathing Moisture Balance

The moisture contents of the plywood in the roof huts are influenced by a number of factors including the ambient RH, surface temperatures (e.g., due to solar radiation and angle to the night sky), and potentially wetting from sources such as inward vapor drive and condensation due to night sky cooling. Unlike an attic, these roof huts are not impacted by potential moisture from warm humid indoor spaces (air leakage or vapor diffusion), are not warmed by heat loss from the interior space, and are subjected to unrestricted ventilation.

Moisture contents below approximately 20% are generally considered safe from biodegradative mechanisms, whereas above approximately 28% (fiber saturation) there is risk of fungal growth and wood decay (Wang & Morris, 2011; FPIinnovations, 2014). A moisture content (MC) between 20% and 28% is considered cautionary, and wood decay can continue if present, though cannot typically be initiated if not already active. Another factor to consider is the surface RH of the air adjacent to the wood. High RH levels (typically above 80% RH, 100% RH in almost all cases when condensation occurs) can lead to surface fungal growth even if the wood moisture readings do not record high MC levels.

Comparison of the measured MC to the calculated EMC can provide insight in to whether additional wetting forces are acting on the sheathing. When the MC is above the EMC, it is likely that additional wetting is occurring from night sky cooling or inward vapor drive, and when the MC is below the calculated EMC, it is likely that additional drying is occurring from solar radiation heating. The monitored values for the full-depth moisture content pins for each of the three roof slopes and the control at the north orientation are presented in Figure 12. The south orientation shows very similar, albeit slightly drier results. Some gaps are present due to intermittent sensor malfunctions, and error readings were omitted from the plots.

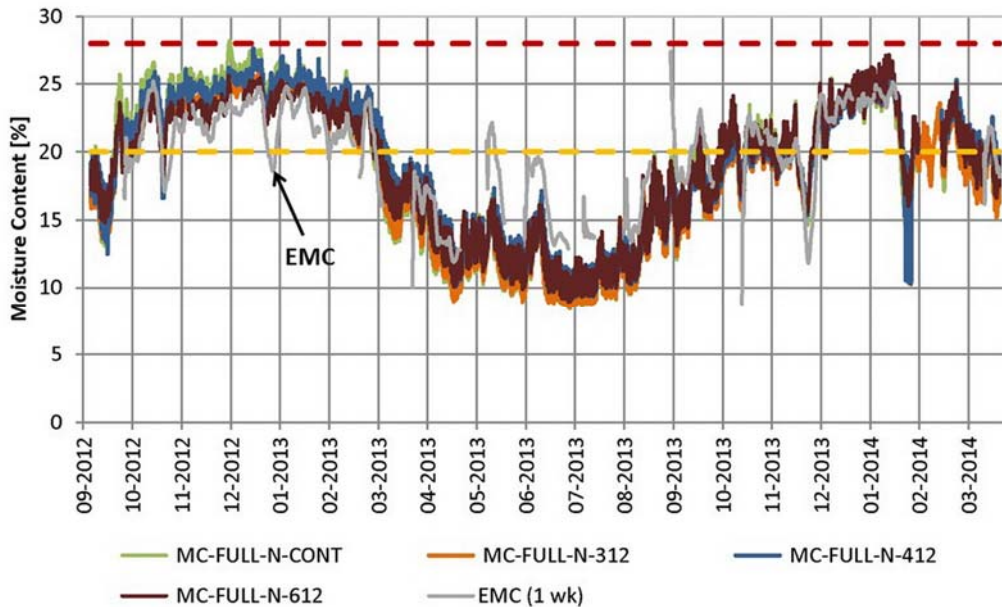


Figure 12: Moisture Content of Plywood Sheathing and Calculated EMC - North, Full-Depth MC Pins (FULL) - 2 Year data for the 4 Roof Huts.

In comparison with the equilibrium moisture contents generated from the ambient temperature and RH, evidence of wetting and drying effects are apparent. Elevated moisture contents in the winter (e.g., above 20% MC) exceed the predicted EMC, suggesting wetting in addition to absorption due to ambient RH levels. Conversely, summer moisture contents are lower than EMC values, suggesting additional drying from solar radiation heating.

Figure 13 provides the average seasonal moisture contents of the sheathing for each of the roof huts for the full-depth moisture content sensors at the north and south orientations. Average moisture contents for the inner and outer 1/8" depth of plywood are very similar, though they show more daily fluctuations.

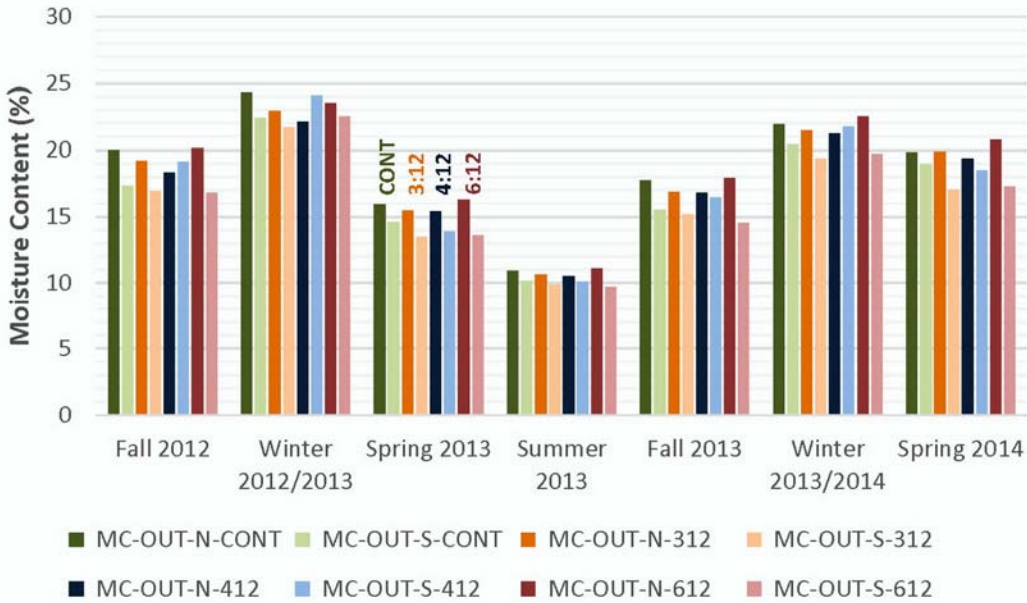


Figure 13: Seasonal Average Sheathing Moisture Content for North and South Elevations-Full Depth (FULL) for the 4 Roof Huts.

The general seasonal trends show summer drying and winter wetting consistent with the hourly trends shown previously in Figure 12. In addition, the north exposure is generally wetter than the south exposure, with a more pronounced difference for the steep-sloped roofs. Importantly, all three roof pitches exhibited the elevated moisture contents at certain times of the year, and the variation of the moisture content between roof pitches is not large enough to impact this more general trend.

The moisture content of the plywood in all of the roof huts appears to be most influenced by the ambient equilibrium moisture content levels. Moisture contents at all locations range between 20% and 30% during the rainy fall through spring months of October through March. The plywood moisture content at the start of the monitoring period in early fall started at 15% MC on average, increasing to above 20% during the rainy month of October, up to 30% at worst-case conditions in December and January. The moisture content was consistently at cautionary levels for fungal growth (above 20%) for the entire winter period (up to 6 months). These high moisture contents are consistent with data from other roofs monitored by the authors and others in the Pacific Northwest (Smegal et al, 2012, 2013; Dell et al, 2011).

The wetting and drying mechanisms that cause the observed moisture contents are examined in the following section.

Evaluation of Wetting and Drying Mechanisms

The increased moisture contents measured during colder periods and decreased moisture contents measured in warmer periods as compared to the EMC indicate that additional wetting and drying is occurring beyond the moisture balance with ambient RH and temperature. This study hypothesized that these mechanisms could potentially include wetting due to condensation

caused by night sky cooling, wetting due to inward-driven vapor caused by solar heat gains, and drying due to solar heat gains.

To examine these potential wetting and drying mechanisms, moisture contents and temperatures were analyzed.

Figure 14 shows the diurnal temperature variations for three nights, with October 3 and 4, 2014, experiencing condensation for the north orientation of the 3:12 roof slope. The moisture content is also included to demonstrate the effects of the condensation on the sheathing. Condensation occurs when the sheathing interior surface temperature is lower than the ambient air dew point temperature.

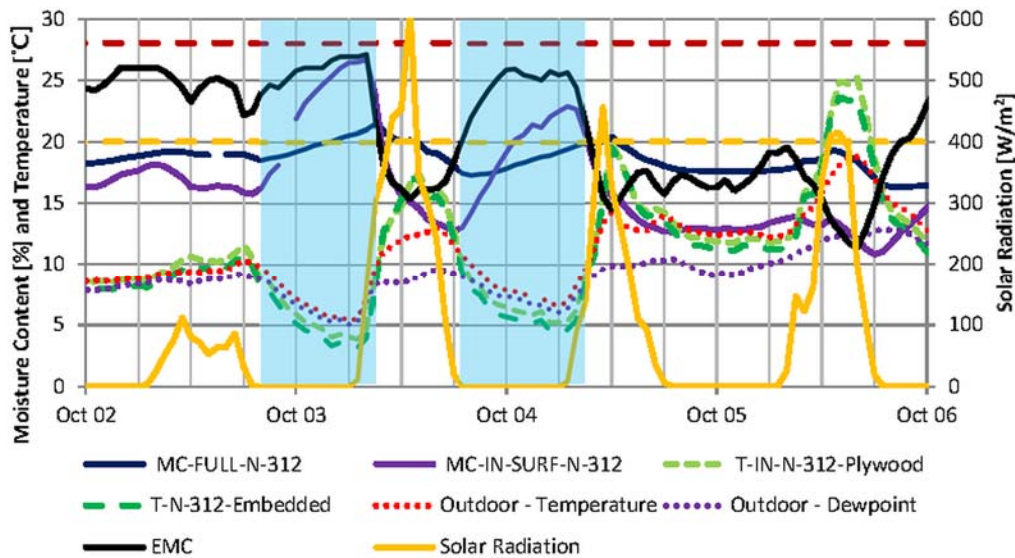


Figure 14: Diurnal temperature and moisture content variation in the north control roof on October 2 to October 5, 2013.

The figure shows a cyclical wetting and drying of the plywood sheathing. While the full-depth moisture content of the sheathing does not vary appreciably, the surface moisture content (which measures the outermost fibers of the plywood) does exhibit significant diurnal variations. It can be seen that incident solar radiation, even in the north orientation, causes the surface moisture content to drop by 10%. However, nighttime condensation increases the surface moisture content by nearly an equivalent amount.

The night sky cooling and subsequent condensation and frost formation was confirmed visually at multiple periods during the study. Photos showing the condensation and frost observed on January 2, 2013, are provided in Figures 15 through 18.



Figure 15: Frost on exterior of shingles during morning of January 2, 2013



Figure 16: Frost on exterior of shingles and impact of rising sun during morning of January 2, 2013



Figure 17: Frost on nail heads of south-facing roof slope on morning of January 2, 2013



Figure 18: Condensation on underside of plywood sheathing on morning of January 2, 2013. Note that surface condensation at this time only occurred on certain areas of the plywood and was affected by wood grain.

Interestingly condensation was mostly visible on areas of the plywood made of heartwood. This is likely because these areas are denser, have a lower permeability, and potentially include more water-repellant extractives. Consequently, the surface condensation absorbs less quickly in these areas than it does in the sapwood areas. The impact of this observation on mold growth is discussed later in this report.

Night Sky Cooling Condensation

Night sky cooling is a result of the cold, night sky absorbing infrared radiation emitted by the roofs. The degree of cooling on a roof depends on several factors, including on the presence of cloud cover, constituent material properties, and the roof's slope. This night sky cooling depresses the temperature of the roofs below the ambient air temperature. When the temperature depression drops the roof sheathing temperatures below the dew point of the ambient air, it can cause condensation (and frost when below freezing). The degree of night sky cooling can be quantified by measuring the temperature depression of the roof shingles compared to ambient temperatures. The slope of the roof, previous precipitation events, and thermal storage capacity of the roof assembly all have an impact on the degree of temperature depression.

The nighttime average temperature depressions for each of the roof huts was calculated and compared. A statistically significant difference was observed between the roof shingle temperatures on the 3:12/4:12 roof to the 6:12 roof, with the 6:12 typically experiencing less cooling than the other two roof slopes. However, while some temperature depression was observed at the sheathing, it was not statistically significant.

To further assess the effects of night sky cooling, an analysis of the total number of hours of potential condensation is shown in Table 1 for the wet winter period from December 2013 through January 2014. A histogram of the number of potential hours of condensation is also shown in Figure 19, with the darker-colored bar representing the sheathing temperature depression relative to ambient conditions and the lighter-colored bars representing the number of hours of potential condensation based on ambient dew point temperatures.

Table 1: Number of hours of condensation for December 2013 and January 2014.

ROOF	HOURS OF POTENTIAL CONDENSATION	TOTAL RECORDED HOURS	CONDENSATION FOR RECORDED HOURS
3:12 North Orientation	193	1394	14
3:12 South Orientation	201	1394	15
4:12 North Orientation ¹	-	-	-
4:12 South Orientation	219	1395	16
6:12 North Orientation	316	1396	23
6:12 South Orientation	320	1396	23

¹ Summary data were omitted due to an intermittently faulty sensor.

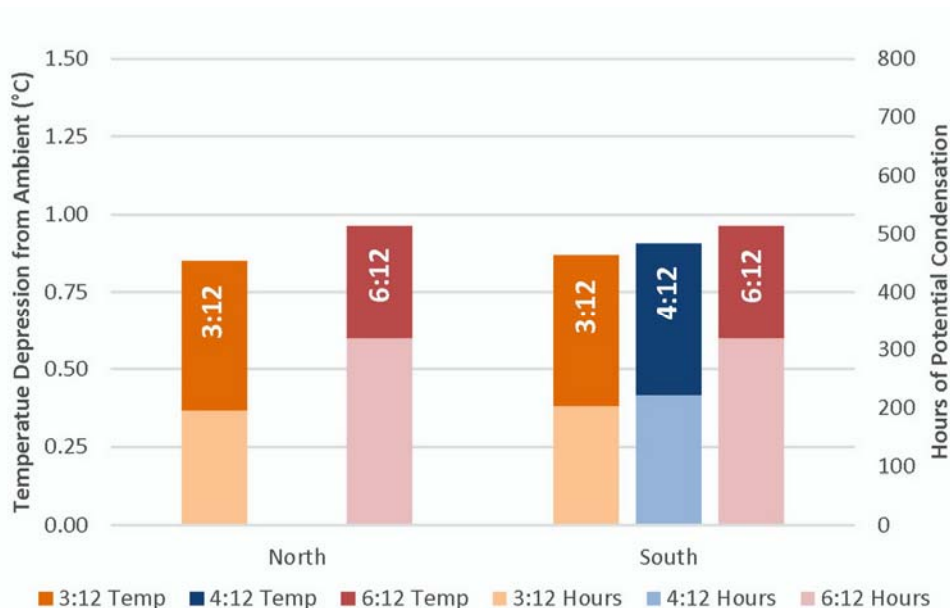


Figure 19: Number of Hours of Potential Condensation and Average Nighttime Sheathing Temperature Depression from Ambient for North- and South-Oriented Roofs for 3:12, 4:12, and 6:12 Roofs from December 1st, 2013 to January 31st, 2014.

The results indicate that there is an apparent temperature difference between the 6:12 roof and the 3:12/4:12 roof. Despite experiencing less of an effect of night sky radiation, the 6:12 roof assemblies are subject to increased hours of potential condensation.

Overall, condensation of moisture from the ambient air was observed on all of the test roofs due to night sky cooling of the roof sheathing. This cooling, and consequently wetting, mechanism significantly impacts the moisture content of the roof sheathing and may contribute to prolonged periods of moderate to high moisture content during which fungal growth can be supported. Consequently, it is likely that night sky cooling and associated condensation is a significant contributor to the moisture problems observed in sloped wood frame attic roof assemblies. These problems were observed on the test roofs despite elimination of other wetting mechanisms and unrestricted ventilation.

Impermeable vs. Permeable Shingle Underlayment

Two types of shingle underlayment were considered as part of this research: a permeable #15 roof felt and an impermeable 40 mil bituminous self-adhered membrane. The vapor-permeable #15 roof felt has a vapor permeance that ranges from approximately 0.5 U.S. perms under dry conditions up to 30 U.S. perms in wet conditions (Straube and Burnett 2005). The vapor-impermeable self-adhered membrane has a maximum vapor permeance of approximately 0.1 U.S. perms. An impermeable membrane eliminates any sources of exterior wetting, but also eliminates the potential for outward drying. The vapor permeable membrane allows for some vapor diffusion, which may result in some degree of wetting and drying to the exterior, but could also lead to increased wetting from the exterior due to inward vapor diffusion. To assess the impact of the permeance of these membranes on the wetting and drying characteristics of the roof assemblies, vapor-impermeable (control) and vapor-permeable (3:12) roof specimens were compared.

The moisture content of the outer sheathing layer for the impermeable and permeable roof assemblies for the north orientation are shown in Figure 20. Data for the south orientation is similar, though drier than the north due to solar radiation effects. It is important to note that a higher moisture content on the interior than the exterior could also indicate wetting on the interior, rather than indicating outward drying.



Figure 20: Moisture Content of Outer 1/8" of Sheathing for Impermeable and Permeable Underlayment, including Moisture Content Gradient, North Elevation, 2012/2013.

The figure indicates that the outer moisture content in the vapour impermeable assembly is consistently wetter than the permeable assembly. The increased moisture content of the sheathing in the control roof is likely a result of the inability of the sheathing to dry to the exterior. This finding suggests that exterior wetting from saturated shingles is not a significant cause of wetting of the exterior of the assembly and that instead the reduced outward drying increases the moisture content of the sheathing. However, this finding is for small, well-constructed, new roofs with no penetrations. Larger, less well-constructed, aged roofs which include penetrations are more typical of actual construction practice, and in these cases the improved water ingress resistance provided by the self-adhered membrane as compared to the roofing felt would likely outweigh the potential reduction in drying capacity.

Preliminary Performance of Applied Wood Surface Treatments

Monitoring and analysis demonstrates that sloped wood frame attic roof assemblies, as currently constructed, have significant risk of mold growth and degradation due to elevated moisture contents and that this cannot be prevented by ventilation alone. This section evaluates the preliminary performance of surface-applied wood treatments.

Surface mold growth can be modeled based on RH and temperature, among other factors. Temperature and humidity data were used to predict the theoretical mold growth in the roof huts. Using Viitanen's (2007) mold index, mold growth was predicted for the 3:12 and the 6:12 sloped roofs, in both north and south orientation, using the measured temperature and relative humidity data. The definition of the mold growth indices are shown in Table 2.

Table 2: Vittanen's Mold Growth Index Descriptions		
INDEX	GROWTH RATE	DESCRIPTION
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 (visual)	Plenty of growth
6	Very heavy and tight growth	Coverage around 100%

The model assumes that a certain amount of germination time is required prior to macroscopic mold growth. This is accounted for in the 0 to 1 mold index, whereby only microscopic observations could confirm the presence of mold. Subsequent indices from 2 to 5 cover the range of mold growth from less than 10% of the surface area to near complete mycelia matting. Note that based on environmental conditions, a maximum degree of mold can be supported; the calculations indicate a maximum mold index approximately 5. The results of the predicted mold growth are shown in Figure 22.

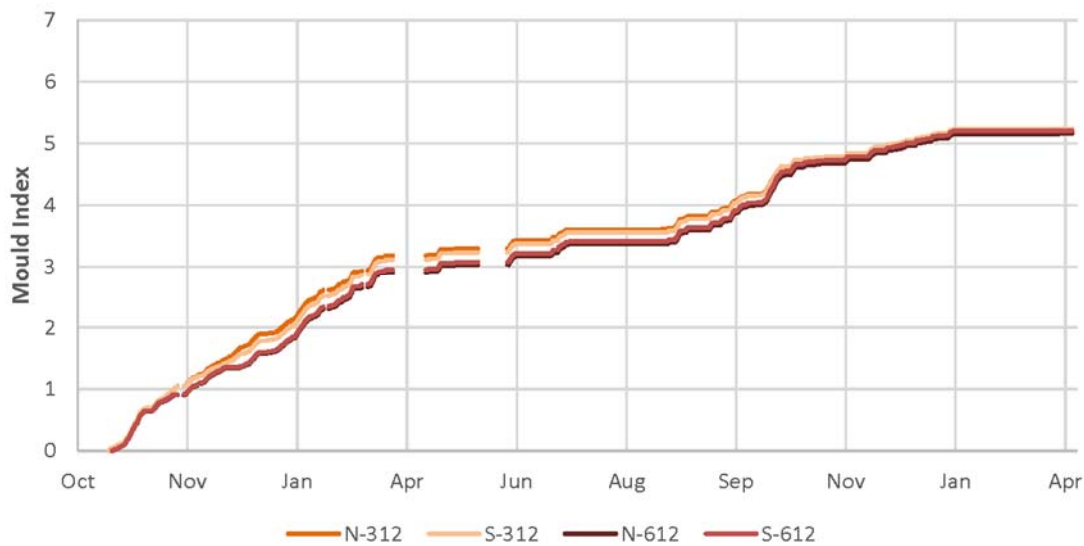



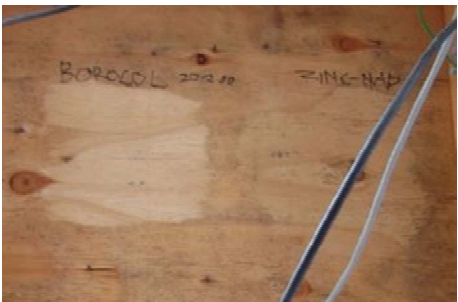


Figure 22: Mold Growth Index for 3:12 and 6:12 Roof Pitch for North and South Orientation

The results of the mold modeling suggest that the 3:12 roof pitch would exhibit slightly higher occurrences of mold compared to the 6:12 roof pitches. Similarly, mould growth was calculated to occur faster on the north orientation than on the south. Despite the predicted faster initial mould growth on the lower sloped and north facing roofs, after a period of 2 years, mould growth is predicted to reach its maximum on all of the roofs based on the substrate and the environmental conditions. It should be noted that mould growth reduction from high temperatures (>40°C) or dry periods (<80% RH) — which may cause cessation of mold growth or desiccation — was not included as part of this analysis.

The impact of surface treatments were analysed visually. Comparative photographs of the as-new and 1.5-year-old sheathing conditions for the different of treatments are shown in Table 3 for the north orientation of the 3:12 slope roof. Additional photos can be found in the full study report, though they show similar levels of final mold contamination.

Table 3: 3:12 Roof, As-New and 1.5-Year Condition		
North - Treatment Phase 1	2012/10/15	2014/04/07: 1.5 Years
		
North - Treatment Phase 2	2013/04/11: After First winter	2014/04/07: 1 Year
		

Consistent with calculated prediction, the north orientation exhibited the greatest degree of fungal growth on all three roof pitches, with the 6:12 roof showing the least amount of growth. The south-facing slopes were in generally better condition, with the 6:12 pitch similarly showing the least fungal growth. This is somewhat in contrast to the previously stated findings, which indicated lower moisture contents and fewer hours of condensation for the 6:12 roofs. Further investigation into the discrepancy between the visual fungal condition review and the potential number of condensation hours is required.

In regard to the efficacy of the fungal treatments, in general, the bleach and Thompson's WaterSeal® have to this point been inadequate in preventing fungal growth. In some cases, it appears as if the antifungal properties of bleach have primed the surface for a new wave of fungal colonization by eliminating the established fungi, resulting in more severe fungal growth than

the adjacent areas. The Boracol 20-2BD, Kilz® Paint, Copper Naphthenate, and Zinc Naphthenate seem to provide good resistance to fungal growth at this early stage. It is also obvious that products with mouldicides (e.g., Boracol 20-2BD and Kilz® paint) perform better than wood preservatives primarily designed to stop (Copper and Zinc Naphthenate). Nonetheless, longer-term field studies are required to ascertain whether repeated application is required to maintain the level of fungal resistance. A rating system was applied to the efficacy of each of the treatments for each roof hut orientation. The results are shown in Table 4.

Table 4: Visual Assessment of Surface Treatment Efficacy

Test Roofs (North & South)	Surface Treatments (left = North, right = South,)						
	Sansin Boracol® 20-2	Copper Naphthenate	Bleach	Thompsons WaterSeal®	Kilz® Paint	Zinc Naphthenate	Sansin Boracol® 20-2BD
Control							
3:12							
4:12							
6:12							

VISUAL ASSESSMENT SCALE

- Pristine or very light fungal growth
- Moderate fungal growth
- Significant fungal growth

Interestingly, visible fungal growth has not occurred to any significance on most heartwood sections of the plywood to date. This may be a result of the decreased moisture content (due to the presence of extractives) or the natural fungal resistance of heartwood. Further investigation is required.

The fungal growth on each roof hut sheathing was tested and determined to be primarily Cladosporium genus in all locations. Cladosporium is a mold genus that is known primarily for decomposition of dead organic plant matter and is commonly found outside.

Conclusions & Recommendations

The findings of this study clearly demonstrate that sloped wood frame attic roof assemblies experience wetting in the Pacific Northwest despite the elimination of typical moisture sources. Worse, this research indicates that the typical preventative approach of attic ventilation only exacerbates the problem. For the test roofs, this wetting—combined with seasonal fluctuation in the sheathing moisture content created by changes in ambient conditions—led to sustained periods in which the sheathing moisture content was sufficient to both allow for the initiation of fungal growth and sustain it.

The measurements indicate that the moisture content of the plywood is most closely related to outdoor climatic conditions, notably exterior ambient temperature and relative humidity, with the

moisture contents of all four roof assemblies surpassing 20% in the winter and drying out in the summer. Typically the north roof orientations experienced higher moisture contents than the south orientations for all of the different roof slopes. Only minor differences in the moisture contents based on roof slope were observed. This is despite the finding that the 6:12-sloped test roof experienced more hours of potential condensation than the 3:12 and 4:12 roofs did. Visual observations confirmed fungal growth on the sheathing of the test huts for all slopes and orientations.

These findings are of concern to the construction industry because sloped wood frame attic roof assemblies are the most prevalent type of roof assembly in low-rise wood frame buildings, and the cost to upgrade them to an exterior-insulated or unvented attic is often prohibitive, or in some cases, may not address all of the design issues. Furthermore, the ubiquitous use of these roof assemblies makes it highly unlikely that they will stop being used in the marketplace. Consequently, a method to prevent this mold growth is desired to address perceived health risks and associated impacts on property value.

One potential mitigation technique is the application of wood preservative treatments to the underside of the roof sheathing, and the efficacy of a number of these treatments was assessed as part of this study. The bleach, surface water seal, and non-fungicide wood treatment methods were not found to significantly mitigate mold growth and, in some cases, seem to exacerbate it. The capacity of the other surface treatments to mitigate mold growth appears promising, but further evaluation is required to ascertain long-term viability as well as the potential for use in remedial applications.

References

- American College of Occupational and Environmental Medicine (ACOEM), (2003), *Adverse Human Health Effects Associated with Molds in the Indoor Environment*, ACOEM Evidence-Based Statement, J. Occupational and Environmental Medicine, 45(5).
- Arfvidsson, J., Harderup, L., (2005), *Moisture Safety in Attics Ventilated by Outdoor Air*, Proceedings of 7th Nordic Symposium on Building Physics, Reykjavik, Iceland.
- Dell, M., Finch, G., Hubbs, B., Levy, A., (2011), *Performance Concerns with Wood Frame Attics*, Proceedings from 2011 RCI Symposium on Building Envelope Technology, Charlotte, North Carolina.
- FPIinnovations, (2014), *Technical Guide for the Design and Construction of Tall Wood Buildings in Canada –Special Publication SP-55E*, FPIinnovations, Pointe-Claire, Quebec.
- Hagentoft, C., Kalagasidis, A., (2010), *Mold Growth Control in Cold Attics through Adaptive Ventilation. Validation by Field Measurements*, Proceedings of the ASHRAE Buildings XI Conference, Clearwater Beach, Florida.
- Hailwood, A.J., Horrobin, S., (1946), *Absorption of water by polymers: Analysis in Terms of a Simple Model*, Trans. Faraday Soc. 84-102.
- Lstiburek, J., Brenna, T., Yost, N., (2008), *What You Need to Know About Mold*, Research Report-0208, Building Science Press, Westford, MA.

- Roppel, P., Norris, N., Lawton, M., (2013), *Highly Insulated, Ventilated, Wood-Framed Attics in Cool Marine Climates*, Proceedings of the ASHRAE Buildings XII Conference, Clearwater Beach, Florida.
- Straube, J., Burnett, E., (2005) *Building Science for Building Enclosures*, Building Science Press, Westford, MA.
- Viitanen, H., Ojanen, T., (2007), *Improved Model to Predict Mold Growth in Building Materials*, Proceedings of the ASHRAE Buildings X Conference, Clearwater Beach, Florida.
- Wang, J., Morris, P. (2011), Decay initiation in plywood, OSB, and solid wood under fluctuating RH conditions. International Research Group on Wood Protection, Section 2, Test Methodology and Assessment. 42nd Annual Meeting, Queenstown, New Zealand.