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Application of Spray Foam Insulation Under Plywood and Oriented Strand Board Roof Sheathing

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Building Science Corporation

October 2013

Building America
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Prepared for:

The National Renewable Energy Laboratory

On behalf of the U.S. Department of Energy's Building America Program

Office of Energy Efficiency and Renewable Energy

15013 Denver West Parkway

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NREL Contract No. DE-AC36-08GO28308

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Prepared under Subcontract No. KNDJ-0-40337-04

October 2013

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Definitions

BSC	Building Science Corporation
ccSPF	Closed-cell spray polyurethane foam
IRC	International Residential Code
MC	Moisture content, weight basis, usually in %
ocSPF	Open-cell spray polyurethane foam
OSB	Oriented strand board
RH	Relative humidity, reported in %
SPF	Spray polyurethane foam
TMY2	Typical Meteorological Year 2

Executive Summary

Unvented roof strategies with open cell and closed cell spray polyurethane foam (ocSPF and ccSPF) insulation sprayed to the underside of roof sheathing have been used since the mid-1990s to provide durable and efficient building enclosures. However, there have been isolated moisture-related incidents reported anecdotally that raise potential concerns about the overall hygrothermal performance of these systems. The incidents related to rainwater leakage and condensation concerns. Condensation concerns have been extensively studied by others and are not further discussed in this report (Straube et al. 2010).

This project involved hygrothermal modeling of a range of rainwater leakage and field evaluations of in-service residential roofs using spray polyurethane foam (SPF) insulation. All of the roof assemblies modeled exhibited drying capacity to handle minor rainwater leakage. All field evaluation locations of in-service residential roofs had moisture contents (MCs) well within the safe range for wood-based sheathing.

The quantity of water passing through a roof system is difficult to quantify, but hygrothermal modeling is possible using ASHRAE 160, Minneapolis Typical Meteorologial Year 2 and U.S. Climate Normals weather data, and WUFI weather data. WUFI 5 was used to determine the effect of 0.01% to 1.00% of the rainfall entering the unvented roof system as a leak and coming in contact with the wood-based structural roof sheathing. The 2012 International Residential Code-compliant roofing system using ccSPF on plywood sheathing with cellulose insulation on the interior has the capability according to WUFI to safely dry a leak up to 0.6% of the rainfall in Minneapolis. In Seattle the roof systems modeled were able to accommodate up to 0.6% for ocSPF and 1.0% for ccSPF and in Miami up to 1.5% could be dried out when using ocSPF. Assuming the recommended fully adhered membrane is properly designed, detailed, and installed water should have very little likelihood of ever entering the system through leaks. ocSPF dries more readily than ccSPF, but ocSPF allows more wetting of the sheathing during the winter months and accordingly requires a Class II vapor retarder coating directly applied to its interior surface as specified by International Residential Code. Interior relative humidity can directly affect the sheathing MC in all scenarios and hence wintertime relative humidity in a climate zone 6 home should be < 40%. Orientation and sheathing materials created variations within the system, but these variations were relatively small compared to the type of SPF and vapor permeance of coatings used. Oriented strand board (OSB) sheathing, ocSPF, and roofs facing north maintain the highest MCs, but all systems modeled were within the safe range for wood-based sheathing. Damage could occur where the volume of the leak, frequency of the leak(s), or quantity of interior moisture driven into the system are more than modeled in this study.

Explorations of 11 in-service roof systems were completed. The exploration involved taking a sample of SPF from the underside of the roof sheathing, exposing the sheathing, then taking a moisture content reading. All locations had MCs well within the safe range for wood-based sheathing. One full-roof failure was reviewed, as an industry partner was involved with replacing structurally failed roof sheathing. In this case the manufacturer’s investigation report concluded that the SPF was installed on wet OSB, based on the observation that the SPF did not adhere well to the substrate and the pore structure of the ccSPF at the ccSPF/OSB interface was indicative of a wet substrate.

1 Background and Significance for Building America

1.1 Introduction

Open cell spray polyurethane foam (ocSPF) and closed cell spray polyurethane foam (ccSPF) insulation sprayed to the underside of roof sheathing is a popular strategy for increasing roof insulation levels in all climate zones. Unvented roof strategies with spray polyurethane foam (SPF) have been used since the mid-1990s to provide durable and efficient building enclosures. However, there have been isolated incidents of failures (either sheathing rot or SPF delamination) reported anecdotally that raise some potential concerns about the hygrothermal performance and durability of these systems. The incidents were related to rainwater leakage and condensation concerns.

Condensation concerns have been extensively studied by others (Straube et al. 2010) and are not further discussed in this report.

It is unclear whether the rainwater leakage issues are a material issue, an application issue, both, or neither—or even whether issues actually exist in sufficient numbers to be of concern. The 2011 Standing Technical Committee on Enclosures has identified this as an important topic for additional research work (Lstiburek 2011).

The primary risks for roof systems are:

- Rainwater leaks
- Condensation from diffusion and air leakage
- Built-in construction moisture.

This report deals directly with rain and indirectly with built-in construction moisture. The technical approach used in this project combined hygrothermal modeling of a range of rainwater leakage scenarios, and field evaluations of residential roofs using SPF insulation.

1.2 Project Background

Spray foams have advantages over alternative methods with respect to providing air sealing in complex assemblies—particularly roofs. SPF can provide the thermal, air, and vapor control layers in both new and retrofit construction. In cases where mechanical systems are located in attics, moving the air control layer and thermal control layer to the underside of the roof deck has particularly large advantages compared to sealing and insulating attic ceilings and ductwork. In addition, it might not be desirable (in hurricane or wildfire areas) or practical (in retrofits) to add roof vents at soffit locations. Accordingly, there may not be any practical alternative to moving the air control layer and thermal control layer to the underside of the roof deck.

1.3 Relevance to Building America's Goals

The energy savings goals set by the U.S. Department of Energy's Building America program for both new and existing homes are 30%–50% relative to a home built based on the 2009 International Energy Conservation Code.

The insulation methods used to achieve the energy use reduction goals set out by the U.S. Department of Energy should not result in moisture-related durability risks or failures. Research into the performance of current recommended assemblies that use SPF should be completed, through theoretical modeling and field review of installed roof insulation methods, to determine if the recommended assemblies have long-term associated durability risks.

1.4 Cost Effectiveness

Durable assemblies exist for a long time and make the best use of construction resources. Because the assemblies last for a long time, their energy resource use should be considered over the life of the assembly, and should therefore be substantially reduced during the initial design. Improving the moisture tolerance and durability of an assembly is also necessary to determine the whole-house life cost.

The roof system's lifespan may be significantly reduced from durability flaws in the design. Replacement of a roof system due to a design flaw is costly and could be avoided with a thorough understanding of the system interactions. The cost effectiveness of this investigation is in the savings of never having to replace a roof system (framing, insulation, and sheathing) over the intended life of the house. According to Building Science Corporation's (BSC) experience it is estimated that the cost associated with replacing the roof framing, insulation, and sheathing for a typical home is on the order of $30,000–$50,000. Even in the case of localized bulk water leakage failures (approximately 2–10 ft^2) the costs to repair the roofing system (and the damage below it) can be very significant. These costs should be avoided with a long-term, durable, energy-efficient design and installation of the original roofing system.

1.5 Tradeoffs and Other Benefits

The increased R-value and airtightness of SPF roof systems improve energy efficiency and occupant comfort by reducing drafts and improving surface temperatures. The durability of these systems and their maintenance requirements and tolerance to the possible operating conditions within the home should be investigated.

1.6 Integration Opportunities

The information developed from this research will help enable the safe implementation of high R-value, airtight SPF roof systems on both prototype homes and homes in production-built communities.

1.7 Contact Information

The following are the BSC Industry Team members involved in this project:

Table 1. Industry Team Member Contact Information

Company Name	Team Member
Dow	Gary Parsons
BASF	Paul Campbell
Honeywell	Xuaco Pascual
Icynene	Paul Duffy

2 Experiment

2.1 Research Questions

The following research questions are answered by this project:

- Are there risks associated with installing SPF under plywood and oriented strand board (OSB) roof decks, specifically moisture and durability issues?
- Are roof leaks a serious problem with SPF roof assemblies?
- What is happening in these systems with high measured sheathing moisture content (MC) (i.e., 20+) but with no evidence of damage to the sheathing?
- Are there moisture durability risks associated with installing SPF under OSB roof decks in climates with high rainfall?

2.2 Technical Approach

This project hygrothermally modeled a range of rainwater leaks in code-compliant residential unvented roofs that used SPF insulation. Three climate zones were used in this analysis. In addition, field explorations were conducted of in-service residential roofs using SPF insulation. WUFI 5 hygrothermal modeling software was used for the analysis.

The hygrothermal modeling was used to determine drying potentials and assess the relative risks of rainwater leakage in SPF roof systems. Past field work and published work (Straube et al. 2010) has already addressed the condensation risks of various systems in various climate zones.

Hygrothermal modeling was conducted on roof assemblies located in the principal climate zones of interest defining building performance in the lower 48 states—a hot climate with significant rain (Miami), a cold climate (Minneapolis), and a marine climate with significant rain (Seattle). These locations "bracket" the expected in-service conditions of concern for unvented roof assemblies.

A number of roofs were reviewed to visually inspect the sheathing of in-service residential roofs using SPF against the underside of the roof sheathing. This enabled the correlation of modeled low sheathing MCs to in-service roofs with measured low sheathing MCs.

The field explorations were designed to provide information about the actual performance of roofs using SPF insulation. The isolated failures of SPF roofs have led some practitioners to believe that these systems trap moisture in the sheathing. The intent of the explorations of in-service roofs was to measure the sheathing MC and verify that it is within a safe level. Field explorations of installed ocSPF and ccSPF roof assemblies were conducted via visual inspection and core samples. Industry partners were approached to source specific installations of SPF under roof sheathing that could be investigated. The evaluations of the assemblies were based on visual examination of the materials, supported by quantitative moisture meter readings, and product sampling where necessary.

The field evaluation locations were selected based on availability and timing. All locations that were made available by the industry partners were evaluated.

3 Analysis Background

3.1 Unvented Roof Systems

A successful roof (or roof-ceiling assembly) will perform the following tasks:

- Provide a water management system to keep precipitation out.
- Provide an air barrier system between the indoors and outdoors.
- Provide a thermal control system to keep the heat out during the summer and retain heat during the winter.
- Provide a vapor control system to maintain a durable environment that does not allow condensation and does not promote mold growth.

BSC experience suggests that when failures occur in wood-frame roofs insulated with SPF at the deck, it is typically due to leakage of bulk water (precipitation), or vapor diffusion condensation. Vapor diffusion condensation can occur as an outward drive or as an inward drive. Proper roof enclosure system design can avoid the majority of failures. SPF insulated roofs are common in retrofit work. In retrofit work, the order of work to be considered is important. Health and safety issues must be addressed first and are more important than durability issues. Durability issues are in turn more important than saving energy. Lstiburek (2010) provides the background and approach for the preparatory work necessary prior to insulating an attic. The guide focuses on combustion safety, ventilation for indoor air quality, and attic ventilation for durability. The guide provides a scope of work and specification for the air sealing of many points of air leakage in common attic spaces.

Unvented attic assemblies, or cathedralized attics that move the insulation and airtightness planes to the slope, have been developed to overcome two major problems with vented attics (Figure 1). These problems are:

- Locating ducts/air handling units in the attic space causes major air leaks of conditioned air (and thus forced infiltration/exfiltration), and heat/loss gain through the ductwork.
- Designs with complex coffered ceiling planes, numerous penetrations by lights, speakers, vents, etc. make it practically difficult to achieve the airtightness required just below the insulation layer.

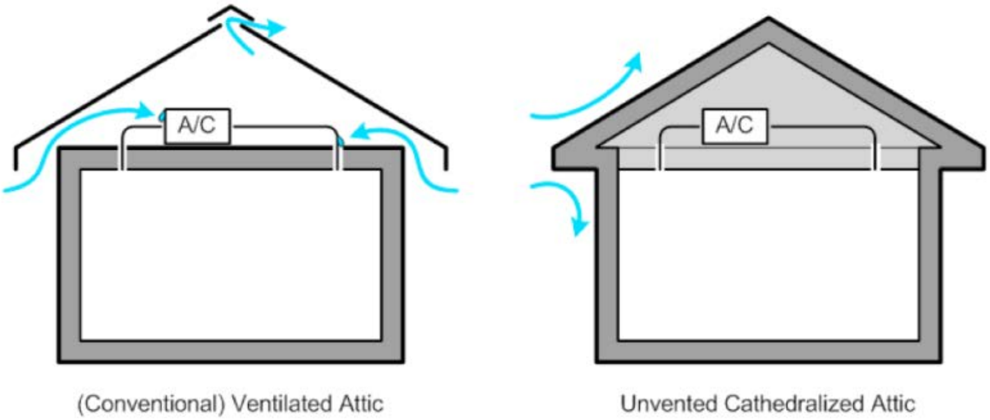


Figure 1. Cathedralized or unvented attics

All unvented attic and cathedral ceiling designs must provide for either a very high degree of airtightness or avoidance of condensation by warming sensitive surfaces. To meet durability goals in most applications, the airtightness must be provided by a continuous membrane—preferably adhered to the top surface of the structural roof deck and under rigid insulation that provides condensation control. In designs where the airtightness is provided between framing elements, SPF has been found to be a practical solution. However, all wood-to-wood joints in the framing must still be sealed. Figure 2 shows the application of SPF to form an air barrier in a hybrid roof system.

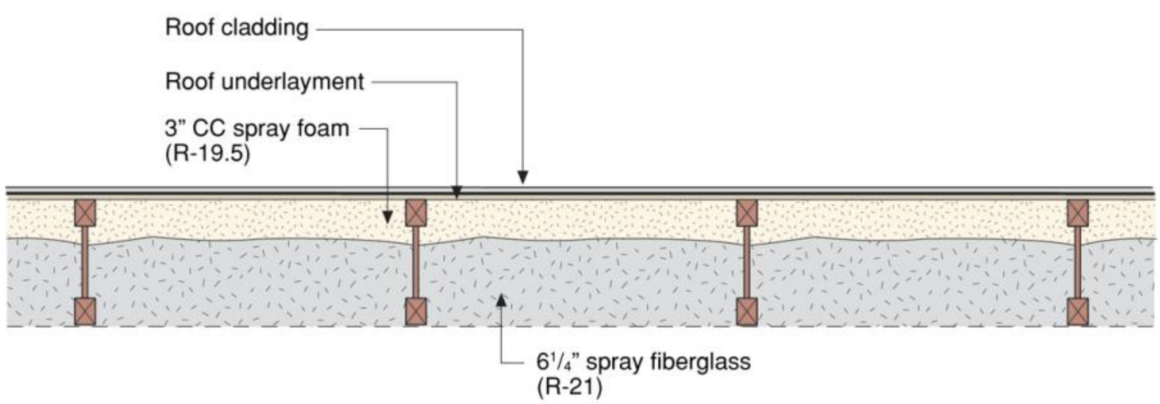


Figure 2. Example high-R hybrid unvented cathedralized ceiling/attic

3.2 Code Requirements for Roofs

The 2012 International Residential Code (IRC) defines vapor retarder class information. A vapor retarder is defined as: A measure of the ability of a material or assembly to limit the amount of moisture that passes through that material or assembly. Vapor retarder class shall be defined using the desiccant method with Procedure A of ASTM E96 as follows:

- Class I: 0.1 perm or less
- Class II: 0.1 perm to 1.0 perm
- Class III: 1 perm to 10 perms.

The IRC has had information on unvented attics for a few editions. The 2012 edition contains the following requirements, most notably the addition of the vapor retarder classes to R806.5 (4). The unvented attic and unvented enclosed rafter assemblies section R806.5 is as follows (ICC 2012).

R806.5 Unvented attic and unvented enclosed rafter assemblies. Unvented attic assemblies (spaces between the ceiling joists of the top story and the roof rafters) and unvented enclosed rafter assemblies (spaces between ceilings that are applied directly to the underside of the roof framing members/rafters and the structural roof sheathing at the top of the roof framing members/rafters) shall be permitted if all the following conditions are met:

1. The unvented attic space is completely contained within the building thermal envelope.
2. No interior Class I vapor retarders are installed on the ceiling side (attic floor) of the unvented attic assembly or on the ceiling side of the unvented enclosed rafter assembly.
3. Where wood shingles or shakes are used, a minimum ¼ in. (6mm) vented air space separates the shingles or shakes and the roofing underlayment above the structural sheathing.
4. In Climate Zones 5, 6, 7 and 8, any air-impermeable insulation shall be a Class II vapor retarder, or shall have a Class II vapor retarder coating or covering in direct contact with the underside of the insulation.
5. Either items 5.1, 5.2 or 5.3 shall be met, depending on the air permeability of the insulation directly under the structural roof sheathing.

    5.1 Air-impermeable insulation only. Insulation shall be applied in direct contact with the underside of the structural roof sheathing.

    5.2 Air-permeable insulation only. In addition to the air-permeable insulation installed directly below the structural sheathing, rigid board or sheet insulation shall be installed directly above the structural roof sheathing as specified in Table R806.5 for condensation control.

    5.3 Air-impermeable and air-permeable insulation. The air-impermeable insulation shall be applied in direct contact with the underside of the structural roof sheathing as specified in Table R806.5 for condensation control. The air-permeable insulation shall be installed directly under the air-impermeable insulation.

    5.4 Where preformed insulation board is used as the air impermeable insulation layer, it shall be sealed at the perimeter of each individual sheet interior surface to form a continuous layer.

The IRC for climate zones 1, 2, 3, and 4 requires that a Class I vapor control layer not be installed on the interior side of the assembly. This is to prevent inward driven moisture from being trapped in an assembly. Installing a low permeance vapor control layer on the interior in a cooling-dominated climate can quickly deteriorate the assembly.

Table N1102.1.1 of the 2012 IRC lists the thermal insulation requirements for each assembly. A summary of the requirements combining Table R806.5 and Table N1102.1.1 is shown in Table 2.

Table 2. 2012 IRC Table R806.5 and Table N1102.1.1 R-Values

Climate Zone	Minimum Rigid Board or Air-Impermeable Insulation R-Value	Total Required Installed R-Value
2B and 3B Tile Roof Only	0 (none required)	30
1, 2A, 2B, 3A, 3B, 3C	R-5	30
4C	R-10	30
4A, 4B	R-15	38
5	R-20	38
6	R-25	49
7	R-30	49
8	R-35	49

In cold climates it is important to note the ratio of vapor-impermeable to vapor-permeable R-values in Table 2. For cold climates the air-impermeable insulation is maintained at 50% or more of the total R-value of the roof system. This is for condensation control. When building high R-value roof systems, BSC recommends that this ratio be maintained or exceeded. If an R-80 cathedral ceiling or cathedralized attic is to be constructed in a cold climate, it is recommended that a minimum of R-40 (50%) be air-impermeable insulation installed and layered according to section R806.5 of the 2012 IRC.

For climate zone 1 (Miami hygrothermal analysis), R-5 air-impermeable insulation is required as a part of the R-30 roof. For climate zone 4 (Seattle hygrothermal analysis), R-10 air-impermeable insulation is required as a part of the R-30 roof. Because the roofs analyzed are intended to be as cost effective as possible, and because a normal pass of ccSPF is approximately 2 in., R-12 was used for ccSPF as the air-impermeable layer for Miami and Seattle. Due to the low incremental cost of ocSPF, an R-30 pass of ocSPF is used as the air-impermeable layer in lieu of a hybrid system in Miami and Seattle. For colder climates, alternate layers will be used to meet the IRC and optimize costs. These systems are discussed within the hygrothermal modeling section.

A roof that does not meet the IRC has the potential to have condensation within the assembly. As an example, the roof shown in Figure 3 was designed as an unvented roof assembly using ccSPF against the underside of the sheathing and batt insulation inboard of the SPF. The ccSPF in some locations was only 1 in. thick and R-28 batt was installed to the interior. The IRC requirement for climate zone 5 is R-25 for the SPF in this case and only R-6 to R-10 was present in this home. This resulted in condensation forming on the face of the ccSPF as the face of the SPF was colder than the dew point of the interior air. The quantity of condensation was further increased as the relative humidity (RH) in the house was quite high because drywall mudding and painting were underway. It is important for condensation control to maintain possible condensation surface temperatures above the dew point of the interior air.

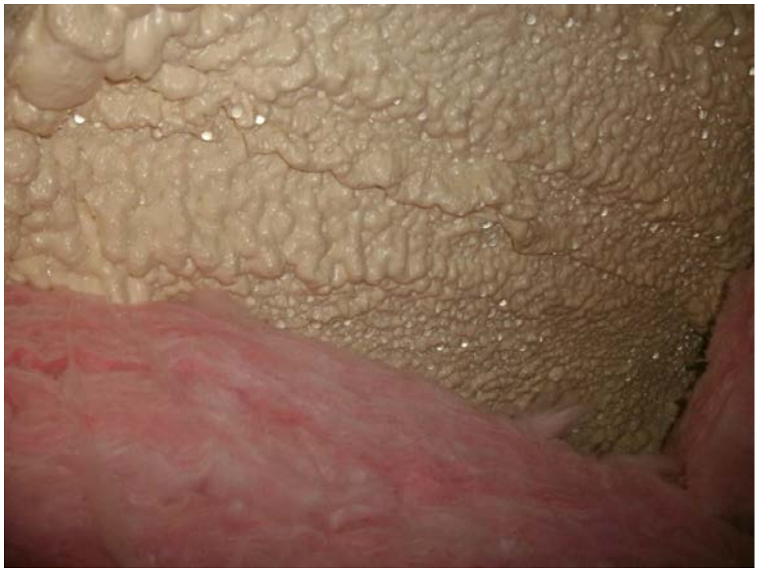


Figure 3. ccSPF unvented roof with condensation

3.3 Hygrothermal Fundamentals

Assessing moisture-related durability risks involves three different moisture processes: wetting, drying, and moisture storage/redistribution. These three processes in combination with the safe storage capacity of each component/material will determine the risk of moisture damage to an assembly. This report includes only a brief overview of the wetting mechanisms: they are covered in more detail by Lstiburek (2006) and Straube and Burnett (2005).

There are three main wetting mechanisms generally acting on the roof system. They are:

- Bulk water penetration from the exterior
- Vapor diffusion (from exterior or interior)
- Air-transported moisture (air leakage carrying moisture).

The first source of wetting is bulk water from the exterior. This can cause the greatest amount of damage in the shortest amount of time. The best strategy to avoid water ingress into the roof or living space from the exterior is to properly layer flashings, properly detail roof penetrations, and provide a properly applied water management system below the exterior water shedding layer. For SPF assemblies, a fully adhered membrane is recommended to be applied to the full area of roof structural sheathing for bulk water management before the roof cladding or shingles are installed. Vapor diffusion can be handled with a properly implemented vapor control system. For SPF assemblies, the vapor diffusion control is either provided by the SPF itself or through a vapor control layer in direct contact with the SPF. Air leakage and the associated possible condensation can be limited with a properly designed and installed air barrier system, and by maintaining possible condensation surface temperatures above the dew point of the interior air with proper enclosure design. For SPF assemblies, the SPF insulation serves as the air barrier.

Drying is important since nearly all building enclosures will experience wetting at some point. In roof systems, there is drying potential to both the interior and exterior if the enclosure design allows it. In the roofs modeled in this study the drying potential is inward as a fully adhered membrane is recommended beneath the roof shingles for bulk water management reasons and most such membranes are vapor impermeable.

The safe storage capacity (balance of wetting and drying) of an individual material or enclosure system is fundamental to good building design (Figure 4). It is rarely economical to build an enclosure with no risk of wetting; therefore, managing the risk is important. In any building enclosure, building materials should be chosen based on moisture tolerance that correlates to the risk of moisture accumulation in the enclosure.

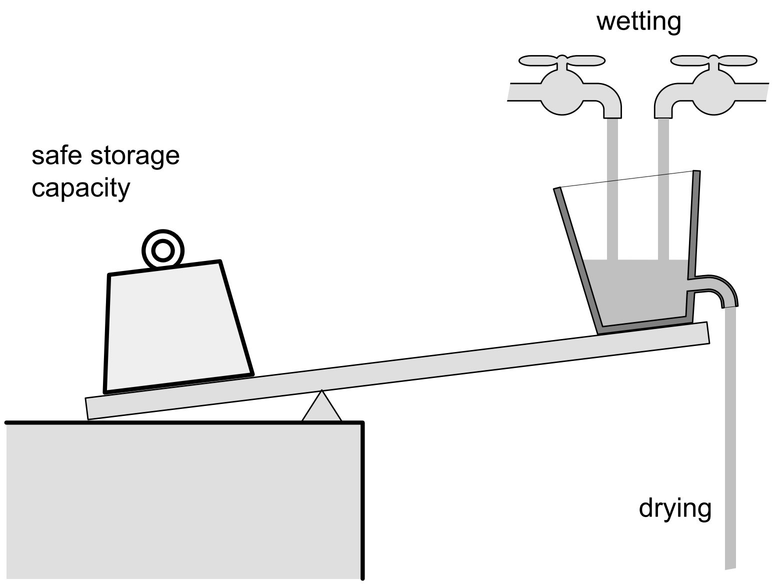


Figure 4. Moisture balance of wetting and drying

Hygrothermal modeling predicts the moisture-related risk associated with each roof assembly. During hygrothermal modeling, a key value monitored is the MC of the wood-based structural sheathing. Wood MCs of plywood or other wood-based materials such as OSB should not be judged on pass/fail criteria. When MC measurements are analyzed in the laboratory or in the field, the reading should be kept in context and good building science judgment is required to determine the moisture risk to the plywood or other wood-based material. For example, elevated wood MCs in the cold winter months are much safer from a mold growth perspective than similar MCs in the summer, when mold will grow more quickly. Also, high MC for a short period followed by drying is not necessarily risky, as wood-based materials are able to manage high MCs for short periods without exceeding the safe storage capacity of the assembly. In general, decay will not occur unless the MC is greater than fiber saturation for a prolonged period of time (Steffen 2000). Fiber saturation is commonly reached at an MC of approximately 25%–30% (Baker 1969).

The risk to the wood structural sheathing was assessed based on the following criteria based on Forest Products Laboratory (2010):

- Peak sheathing MC < 20%, no mold growth—very little risk
- Peak sheathing MC 20%–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
- Peak sheathing MC > 28%—Moisture-related problems are expected and this level of leakage for this design and location is not recommended.

4 Hygrothermal Analysis

4.1 Analysis Program

The analysis was completed using WUFI 5 hygrothermal modeling software. WUFI 5 is one of the most advanced commercially available hygrothermal moisture programs in use today. Its accuracy has been verified against numerous full-scale field studies of enclosure performance (roofs, walls, foundations, parking garage decks, etc.) over a number of years. It is one of the few models in the public domain that can properly account for adsorption of water vapor, absorption/redistribution of liquid water, and night sky radiation. Given the appropriate inputs, WUFI calculates heat and moisture flow every hour under the influence of sun, rain, temperature, and humidity. The material properties from WUFI's Generic North American Materials database were utilized for the simulation of the proposed roofs. The testing will not include extreme values usually associated with major disasters but it will include a portion of rainfall injected into the system to simulate a small leak past the rainwater management layers.

4.2 Boundary Conditions

Typical Meteorological Year 2 (TMY2), U.S. Climate Normals, and WUFI weather files were used for this analysis. The Minneapolis location (climate zone 6) was analyzed because colder climates can stress the roof sheathing more in terms of condensation potential as well as interior to exterior vapor drives. The Minneapolis systems were modeled with dark shingles on both north and south orientations on a 6/12 pitch. The north orientation would represent a worst case scenario with limited solar heating and drying. The Seattle (climate zone 4) and Miami (climate zone 1) roofs were modeled on the north orientation only and were modeled with OSB sheathing only, as these were found to be the most stressed material and orientation from the Minneapolis modeling.

The indoor conditions varied on a sinusoidal curve with a period of one year. The temperature was 68°F ± 2°F (20°C ± 1°C). For the Minneapolis modeling, the RH ranged from 30% in the winter to 60% in the summer for the standard humidity case. The RH ranged from 40% in the winter to 60% in the summer for the high humidity case. The 40% RH wintertime condition is generally considered beyond the upper level of recommended wintertime RH for cold climates in houses in general and creates a high-stress environment for all standard wall assemblies and is typically not seen in houses in cold climates. For Miami the RH ranged from 60% in the winter to 70% in the summer. For Seattle the RH ranged from 40% in the winter to 60% in the summer.

This modeling assumes good construction practices such as the materials are installed to the manufacturers' recommendations, and that interior RH is maintained at a reasonable level during the winter. Variations on the interior RH, and associated implications, are discussed. Each assembly starts with the sheathing MC at 18%, which is the maximum allowed by typical SPF manufacturers.

4.3 Roof Systems Modeled

The scope of this report includes only unvented cathedralized roof assemblies using SPF insulation. Two roofs have been analyzed—one using ccSPF and one using ocSPF. In BSC's experience these two roofs represent a significant portion of the production house roof construction options when using SPF under the roof sheathing and are regularly used in the deep retrofit home market. Both roofs incorporate the minimum required R-value of SPF (R806.5) and complete the R-value with netted cellulose insulation or fiberglass (N1102.1.1). BSC recommends that unvented roofs incorporating SPF insulation beneath the roof deck have a fully adhered membrane above the roof deck and below the roof cladding. This membrane is a secondary layer of drainage protection, but it is also good protection during construction before the roof cladding is installed. Keeping the roof dry before SPF installation is required by most insulation manufacturers. The basic modeled roof assembly is shown in Table 3:

Table 3. Basic Modeled Roof Assembly

Minneapolis Roof A	Minneapolis Roof B	Miami and Seattle Roof A	Miami and Seattle Roof B
Exterior air	Exterior air	Exterior air	Exterior air
Asphalt shingles	Asphalt shingles	Asphalt shingles	Asphalt shingles
½-in. plywood or OSB structural roof sheathing	½-in. plywood or OSB structural roof sheathing	½-in. OSB structural roof sheathing	½-in. OSB structural roof sheathing
R-25 ccSPF	R-25 ocSPF + 5 perm	R-12 ccSPF	R-30 ocSPF
R-24 fibrous air and vapor permeable insulation	R-24 fibrous air and vapor permeable insulation	R-19 fibrous air and vapor permeable insulation	
Interior air	Interior air	Interior air	Interior air

*Most Class II vapor retarder coatings when installed on ocSPF have an effective value of 5 perm.

4.4 Wetting—Rainwater Leakage

ASHRAE 160 (ASHRAE 2008) was used as a basis for choosing the quantity of rainwater leakage. Section 4.6.1 of the Standard discusses rain penetration:

"In the absence of specific full scale test methods and data for the as-built exterior wall system being considered, the default value for water penetration through the exterior surface is 1% of the water reaching that exterior surface. The deposit site for the water shall be the exterior surface of the water-resistive barrier. If a water-resistive barrier is not provided then the deposit site shall be described and a technical rationale for its selection shall be provided."

ASHRAE 160 states that "This standard deals with rain penetration in walls only. Roof systems are to be designed and built such that there is no rainwater penetration." However, this information was used as a starting point for the roof system hygrothermal modeling. WUFI has the capability to inject a percentage of the rainfall into the assembly in a specific location. ASHRAE 160 suggests that 1% of the rainfall that hits the surface passes the wall primary water shedding layer and is deposited on the drainage plane. For this modeling, parts of the 1% rainfall that pass the primary drainage plane are considered to leak past the fully adhered membrane on the roof sheathing and are hence deposited into the wood-based structural sheathing. A properly designed, detailed, and installed system should not be subject to any of the leakage discussed in this section, but it is important to understand the drying capability of the systems. The drying capability of the modeled roofs is shown based on the injection of water stemming from rainfall events in TMY2, U.S. Climate Normals, and WUFI weather data.

Table 4 shows the total rainfall for the year in Minneapolis and the average rainfall event according to TMY2 and U.S. Climate Normals data. Typically annual rainfall is reported in inches, but this information does not help many people understand the hands-on quantity of rainfall. Rainfall on a 4 ft^2 sloping area of roof (6/12 pitch) near the ridge was calculated. Four square feet was chosen, as in BSC's experience this is a typical area that is damaged by a roof leak. The annual rainfall on a 4 ft^2 roof area is almost 70 gal (260 L). This does not account for an area such as a valley or roof edge where there are concentrations from water run-down from the rest of the roof. The total rainfall in Minneapolis from these data is 27.5 in. and the average hourly rainfall is 0.22 in.

Table 4. Minneapolis TMY2 and U.S. Climate Normals Calculated Rainfall

	Total Annual Rainfall	1% of Annual Rainfall	Average Hourly Rainfall	1% of Average Hourly Rainfall
Gal/4 ft^2	69	1	0.5	0.01
oz/4 ft^2	8782	88	69.0	0.7
L/4 ft^2	260	2.6	2.0	0.02
mL/4 ft^2	259,943	2,599	2,044	20

Similar data to Table 4 were developed from WUFI for Miami and Seattle. Table 5 shows data developed from the Miami cold year weather file, which has significantly more rainfall than the warm year file. This was done to ensure a high-risk environment was modeled. Table 6 shows the data developed from WUFI for Seattle. Although the total annual rainfall increases for Miami and Seattle, the average rainfall decreases significantly from Minneapolis.

Table 5. Miami WUFI (Cold Year) Calculated Rainfall

	Total Annual Rainfall	1% of Annual Rainfall	Average Hourly Rainfall	1% of Average Hourly Rainfall
Gal/4 ft^2	209	2	0.2	0.002
oz/4 ft^2	26678	267	23.9	0.2
L/4 ft^2	790	7.9	0.7	0.007
mL/4 ft^2	789,676	7,897	706	7

Table 6. Seattle WUFI Calculated Rainfall

	Total Annual Rainfall	1% of Annual Rainfall	Average Hourly Rainfall	1% of Average Hourly Rainfall
Gal/4ft^2	112	1	0.1	0.001
oz/4 ft^2	14249	142	8.5	0.1
L/4 ft^2	422	4.2	0.3	0.003
mL/4 ft^2	421,780	4,218	253	3

4.5 Minneapolis Hygrothermal Results

One percent of an average rainfall event in Minneapolis is 0.7 oz (20 mL) per 4 ft^2 area and ASHRAE 160 assumes that this quantity passes the exterior cladding and lands on the drainage plane. For the roof systems analyzed, fractions of the ASHRAE 1% rainfall (ranging from 0.01% to 1.00% of total rainfall) is able to pass the fully adhered membrane and come in contact with the wood-based sheathing. This is the amount of water that is modeled and has to dry through the roofing system or accumulate and possibly cause damage. Figure 5 shows the correlated plywood sheathing MCs for 0.01%–1.00% rainfall leaks for the roof system described with ccSPF and cellulose insulation. Over the three-year analysis period, all of the injection scenarios are within the safe range and are not maintained above 25% MC. For the 0.80% and 1.00% cases there appears to be an increasing trend long term, which could likely lead to damage; the rest of the assemblies demonstrated a decreasing trend in MC.

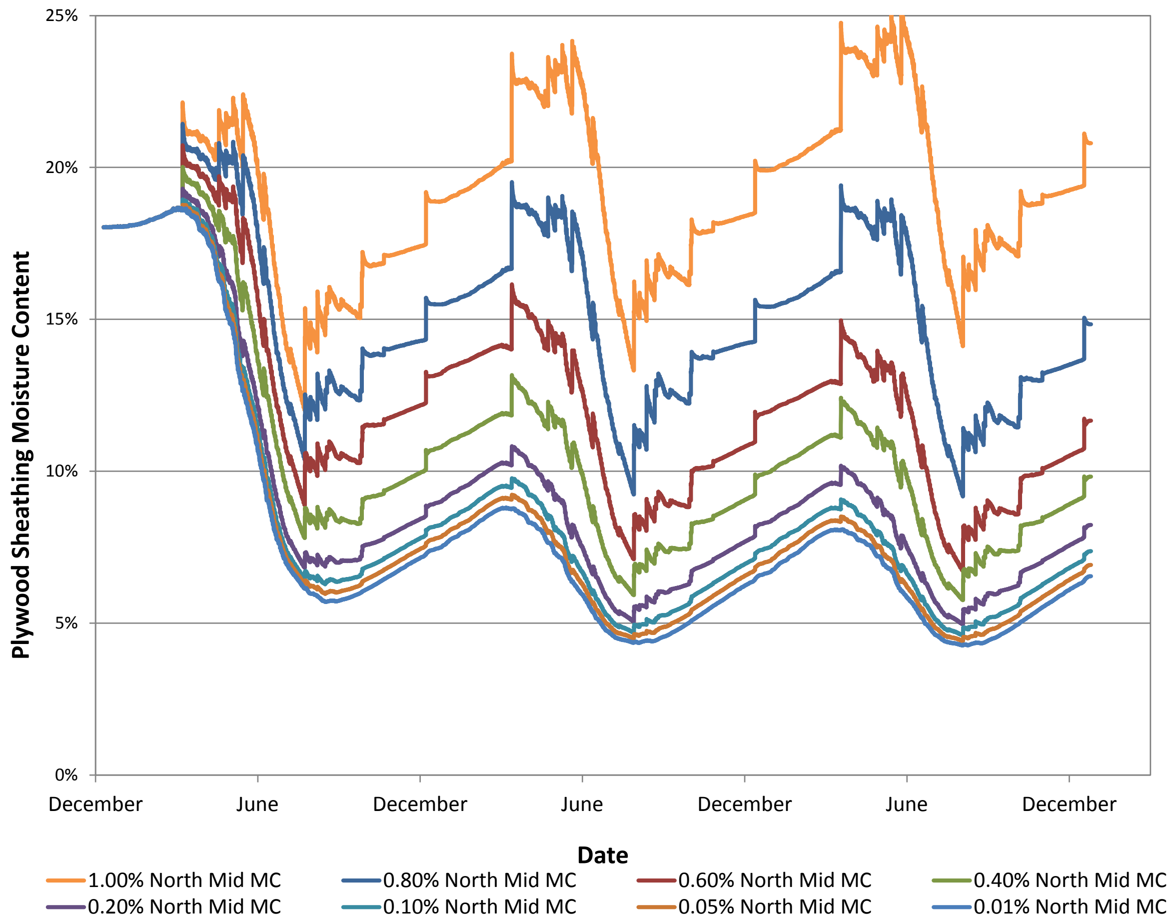


Figure 5. Minneapolis plywood sheathing MC of ccSPF unvented roof

To quantify the amount of water injected at the leak per year in each scenario Table 7 was developed. The 0.60% case, and cases less than that, have an overall trend of getting drier each year—i.e., the roof can manage the imposed water loads from a 0.6% rainwater leak. The roofing system using ccSPF and cellulose insulation on plywood sheathing has the capability, according to WUFI, to dry 53 oz (1.6 L) of water through a 4 ft^2 area of plywood per year. The graph also shows that the regular wettings from rainfall do not lead to accumulated moisture in the sheathing if the leak is < 0.6% of the rainfall. Assuming the fully adhered membrane is properly designed, detailed, and installed, these quantities of water have little likelihood of ever entering the system through rainwater leaks.

Table 7. Minneapolis Annual Rainfall Volume Calculations at a Roof Ridge

	0.01% of Rain	0.05% of Rain	0.10% of Rain	0.20% of Rain	0.40% of Rain	0.60% of Rain	0.80% of Rain	1.00% of Rain
Gal/4 ft^2	0.01	0.03	0.07	0.1	0.3	***0.4***	0.6	0.7
oz/4 ft^2	0.9	4.4	8.8	18	35	***53***	70	88
L/4 ft^2	0.03	0.13	0.26	0.5	1.0	***1.6***	2.1	2.6
mL/4 ft^2	26	130	260	520	1,040	***1,560***	2,080	2,599

Considering the 0.10% case, which is assuming 10% of the rain that passes the cladding can get past the fully adhered membrane, a sensitivity analysis was completed to determine the effects of roof orientation, OSB versus plywood sheathing, interior RH, and finally replacing the R-value of ccSPF with an equivalent R-value of ocSPF and two levels of class III vapor retarder.

Table 7 shows plywood sheathing MCs at 0.10% rainfall contacting the plywood on a north orientation and a south orientation with ccSPF and cellulose insulation. The graph shows that the north orientation increases the peak MC of the sheathing by up to 3% but that the sheathing MCs all remain well below any level of risk.

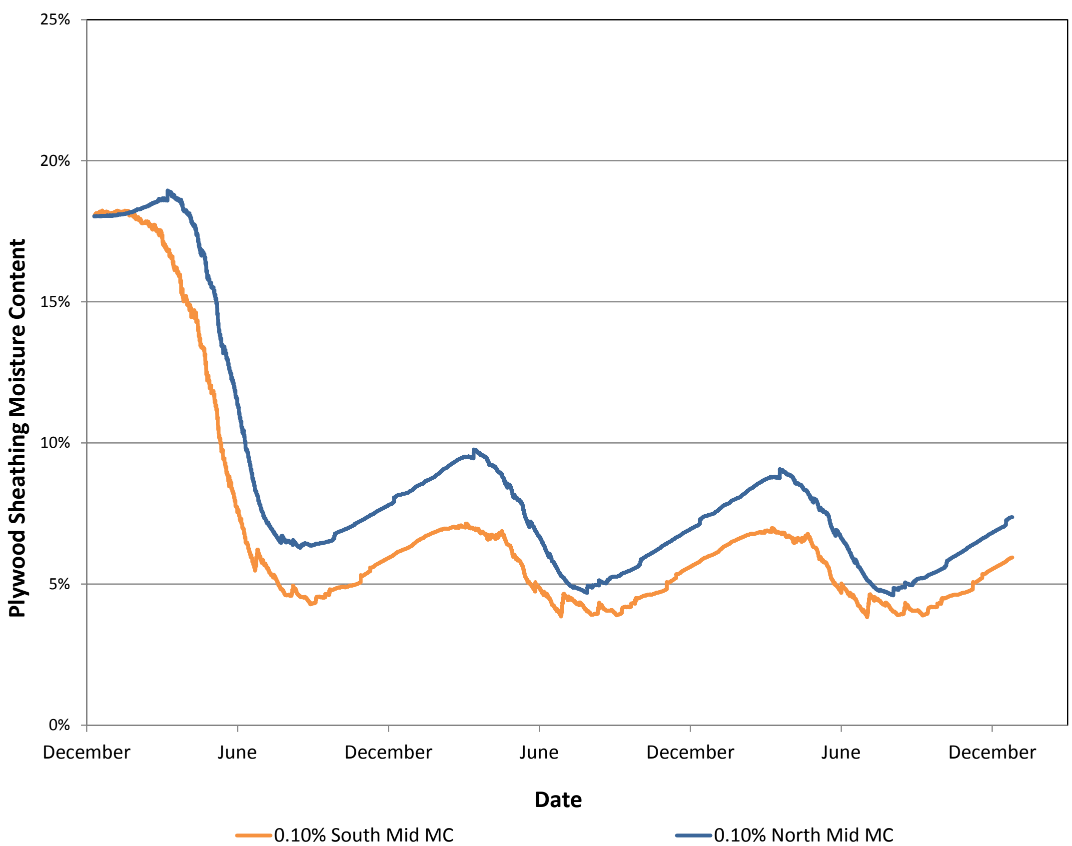


Figure 6. Minneapolis sheathing MC—north versus south

Figure 7 shows sheathing MCs at 0.10% rainfall contacting the sheathing considering OSB and plywood sheathing at ½-in. thick on the north orientation with ccSPF and cellulose insulation. The graph shows that OSB sheathing maintains 1%–1.5% higher MC than plywood, but also that the sheathing MCs all remain well below any level of risk.

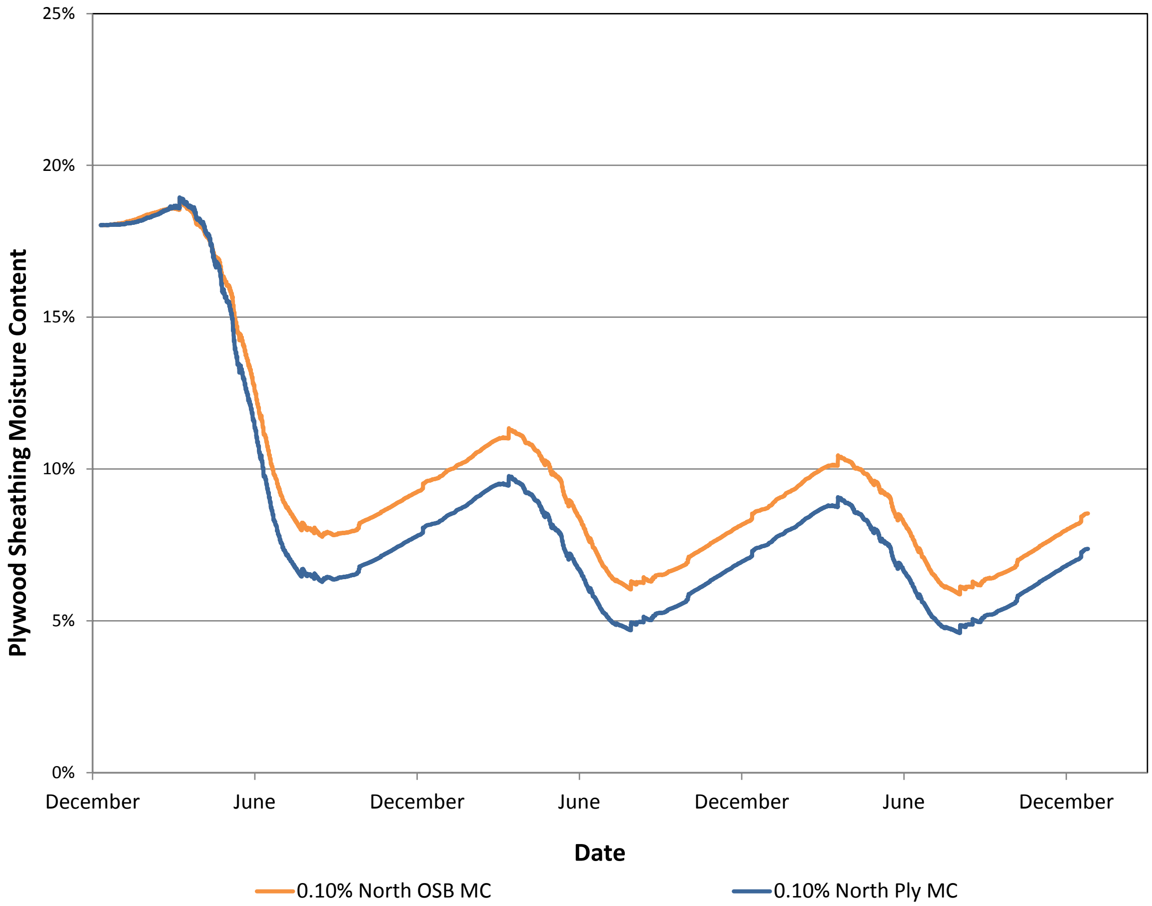


Figure 7. Minneapolis sheathing MC—OSB versus plywood

Peak plywood sheathing MC was affected by up to 1% when considering two interior RH scenarios (Figure 8). The first scenario allowed wintertime interior RH to fall to 30% while the second only fell to 40%. Both scenarios had summertime RH of 60%. In both scenarios the sheathing MCs all remain well below any level of risk.

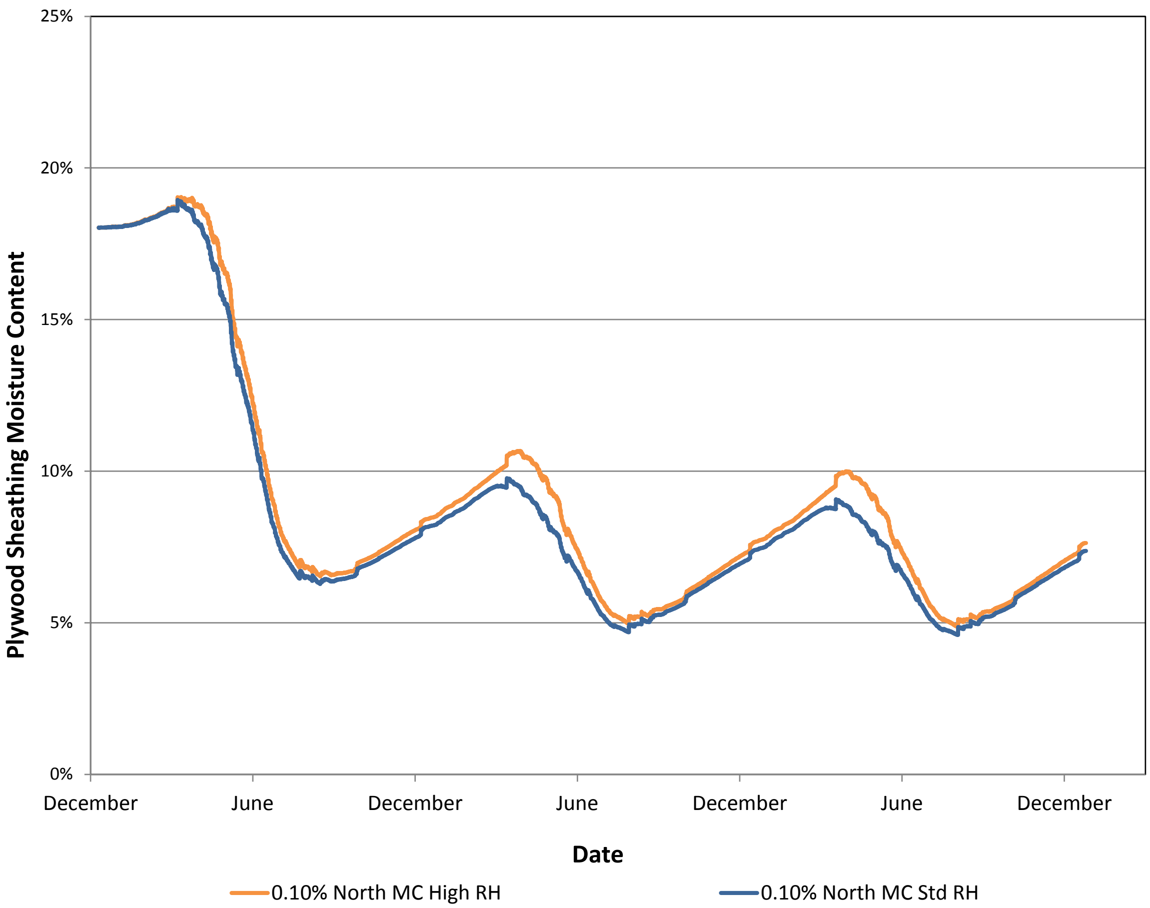


Figure 8. Minneapolis plywood sheathing MC based on standard and high interior RH

To determine if the interior RH affects a larger leak in a different way, the 0.60% leak was analyzed at the standard and high RH scenarios. As shown in Figure 9, the MC of the sheathing is affected only slightly more by the change in interior RH. The sheathing MCs all remain well below any level of risk.

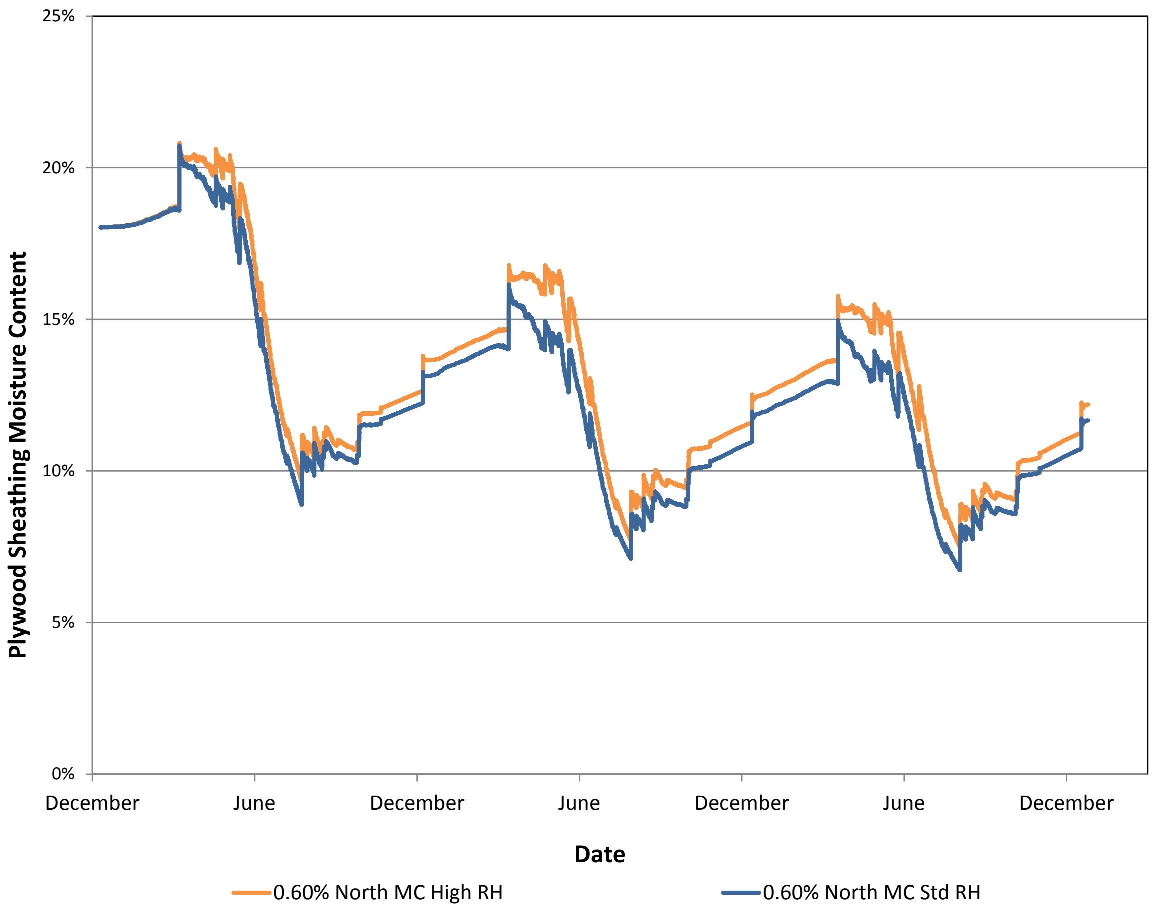


Figure 9. Minneapolis plywood sheathing MC based on interior RH—larger leak

The type of SPF was analyzed in Figure 10. The ocSPF in this case requires a Class II vapor retarder installed on the interior face of the insulation. A 5 perm coating was modeled, as this represents the actual effective achieved perm value based on BSC experience with spray-applied Class II vapor retarder coatings. Figure 10 shows sheathing MCs at 0.10% rainfall contacting the plywood sheathing on the north orientation. The ocSPF MC varies significantly more than the ccSPF, but both remain within safe wood MCs. The ocSPF dries much faster than the ccSPF during warm weather, but also has the ability to pass more moisture from the interior to the exterior during cold weather and hence the MC of the plywood increases significantly more during those periods.

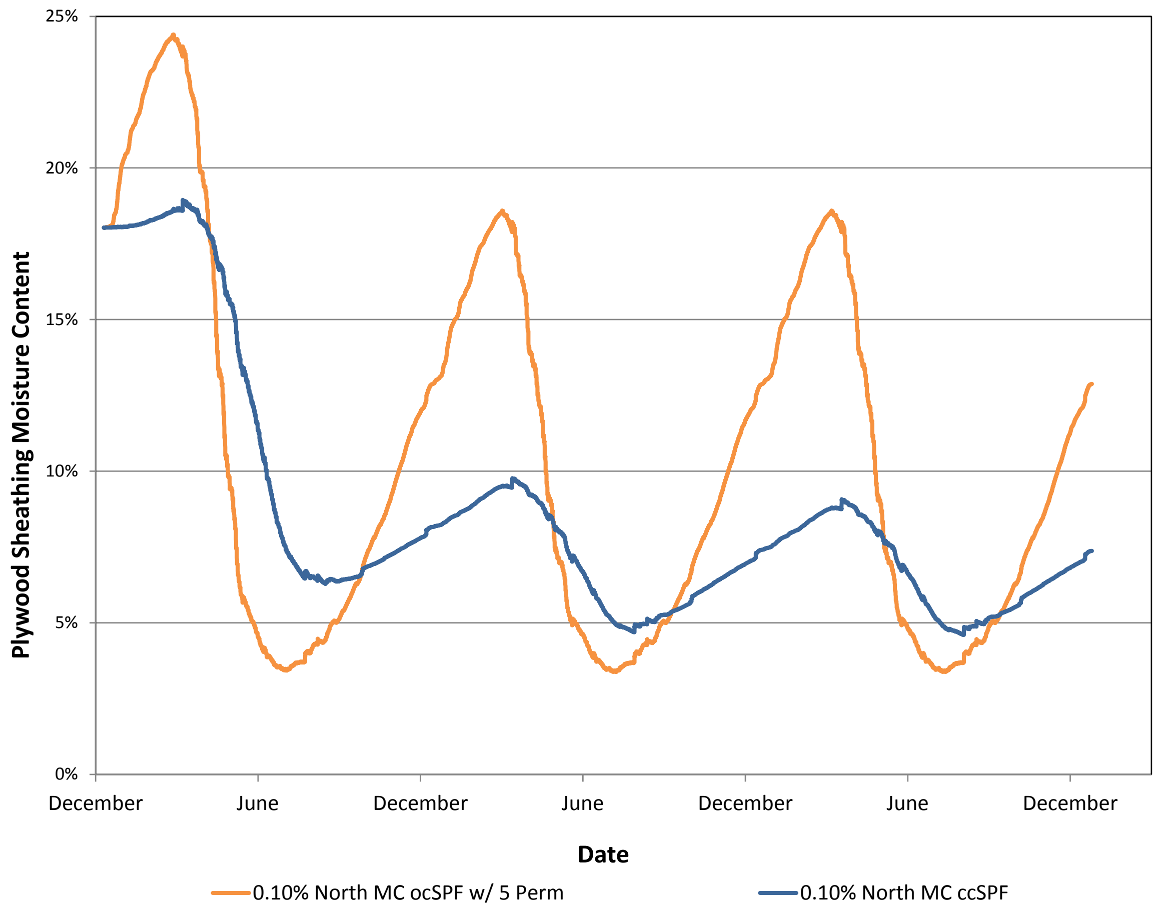


Figure 10. Minneapolis plywood sheathing with ccSPF and ocSPF

Because the ocSPF more easily tracks interior RH, a comparison using only ocSPF was completed. Figure 11 shows the effect of increased RH on a system using ocSPF and a 5-perm coating with a 0.10% rainfall leak. With elevated interior wintertime RH of 40%, the plywood sheathing MCs rise above 25%, but are not sustained for a significant period of time. If interior RH is kept below 35% in this climate zone, this system can operate safely.

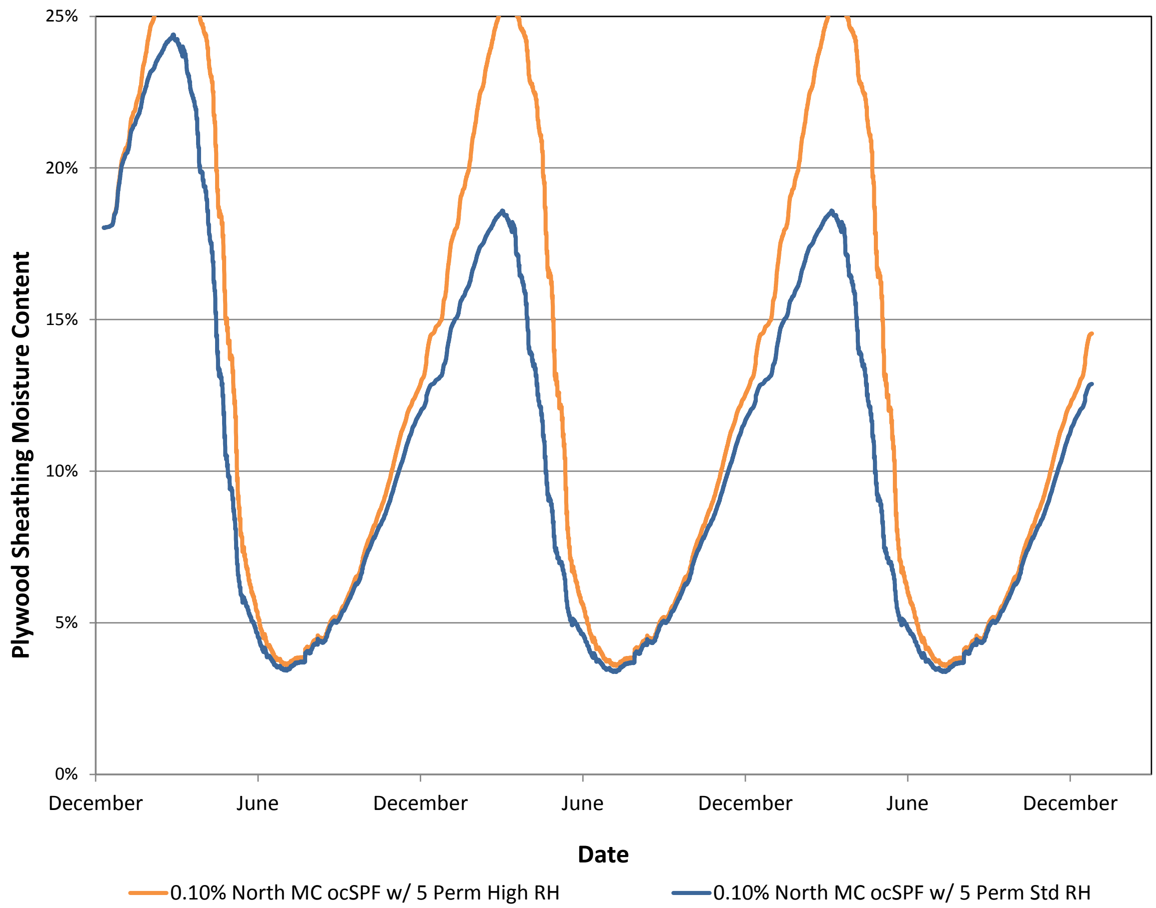


Figure 11. Minneapolis plywood sheathing MC ocSPF and high RH

The coating on the interior of the ocSPF plays a significant role in the vapor transmission from the interior to the exterior in a cold climate. The ocSPF system in Figure 11 was altered to include an effective 2 perm coating instead of the 5 perm coating previously considered. This was modeled and compared to the ccSPF system. With a 0.10% rain leak, the MC of the sheathing is shown in Figure 12. The 2 perm coating with standard RHs reduces the sheathing MC by almost 5%, while using ccSPF decreases it another 5%. Both the 2 perm coating and 5 perm coating on ocSPF dry the sheathing faster than ccSPF, but both get the sheathing wetter during cold weather than ccSPF.

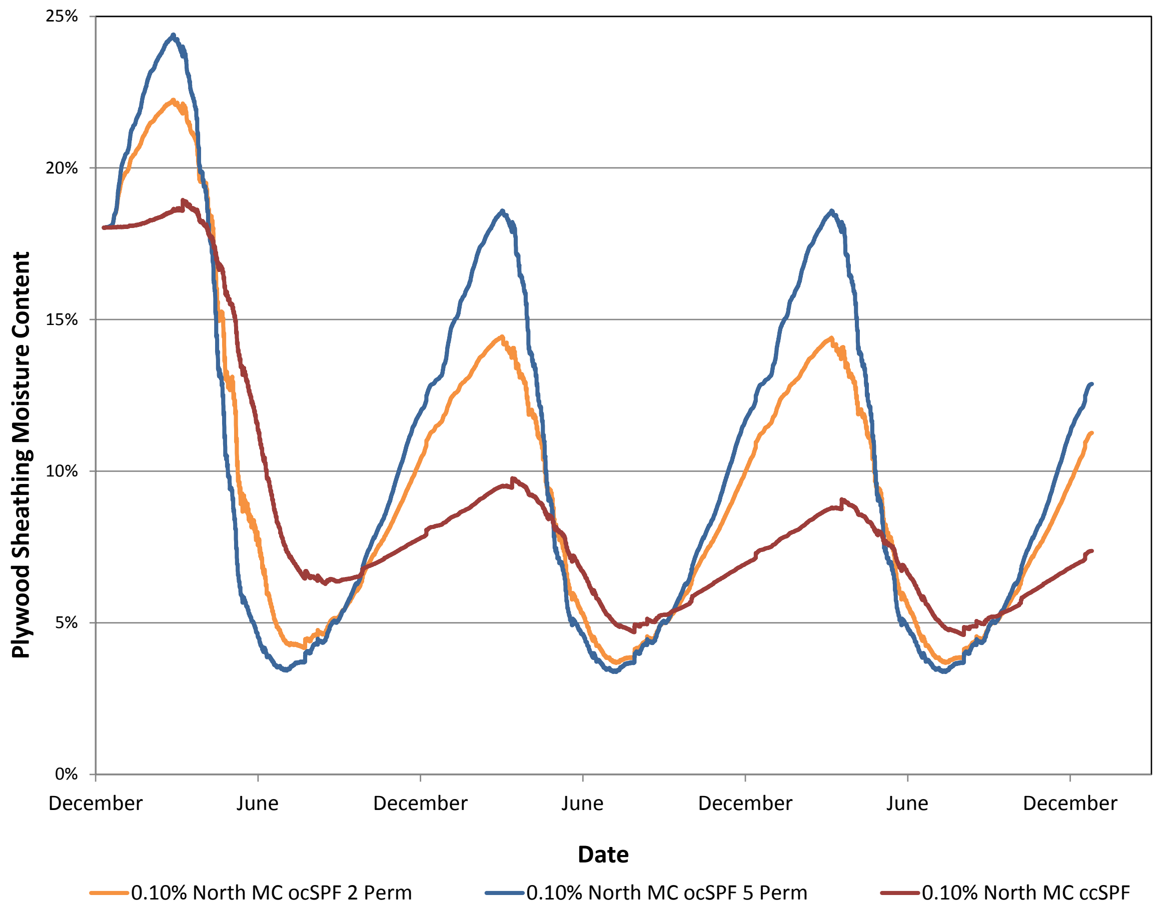


Figure 12. Minneapolis sheathing MC—ocSPF, 2 perm coating, and 5 perm coating

4.6 Seattle and Miami Hygrothermal Results

The modeling from Minneapolis showed that OSB sheathing on the north orientation was at the highest risk for deterioration. Based on this information, the roof systems in Miami and Seattle were modeled using OSB on the north orientation to evaluate the level of highest risk associated with rainwater leakage and its effect on the sheathing MC.

ASHRAE 160 assumes that 1% of an average rainfall event passes the exterior wall cladding and lands on the drainage plane. Rainfall sourced volumes up to that 1% are modeled assuming they pass the fully adhered backup drainage plane created by the adhered roof membrane and then come in contact with the wood-based sheathing. This is the amount of water that then has to dry through the roofing system or accumulate and possibly cause damage. Within climate zones 1 and 4 the vapor barrier requirements are such that no interior vapor control is required. This has positives and slight negatives, as is shown in the following figures.

Similar to the data shown in Figure 5, 0.1%–1% of rainfall was injected into the sheathing and the resultant wood MCs were compared. The Seattle modeling shows that a roofing system using ccSPF insulation against the underside of the roof sheathing and cellulose insulation was able to cycle 8%–24% MC with the influences of both indoor RH and up to the full 1% rainwater leak (Figure 13). The three-year analysis shows a drying trend of the system, although it is not recommended to allow MCs to regularly attain more than 25% for long durations, as occurs with the full 1% leakage. When the cellulose is replaced with fiberglass insulation (Figure 14) a very similar model is produced. In this system, cellulose and fiberglass perform nearly identically.

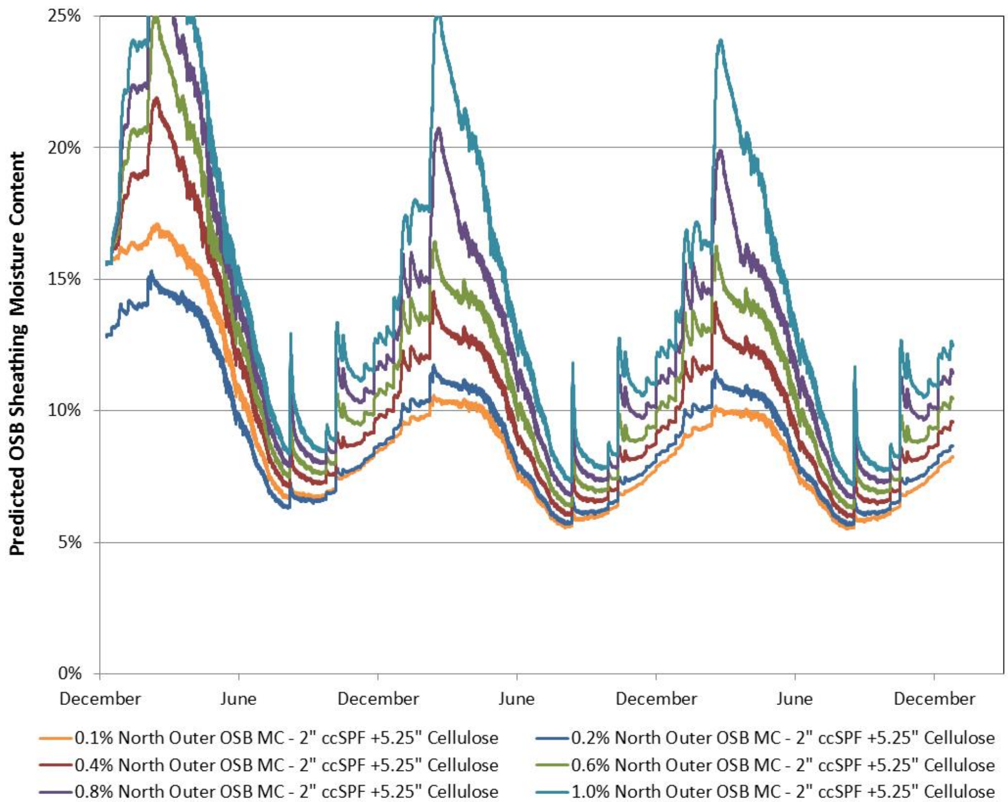


Figure 13. Seattle sheathing MC north 2 in. ccSPF + 5.25 in. cellulose

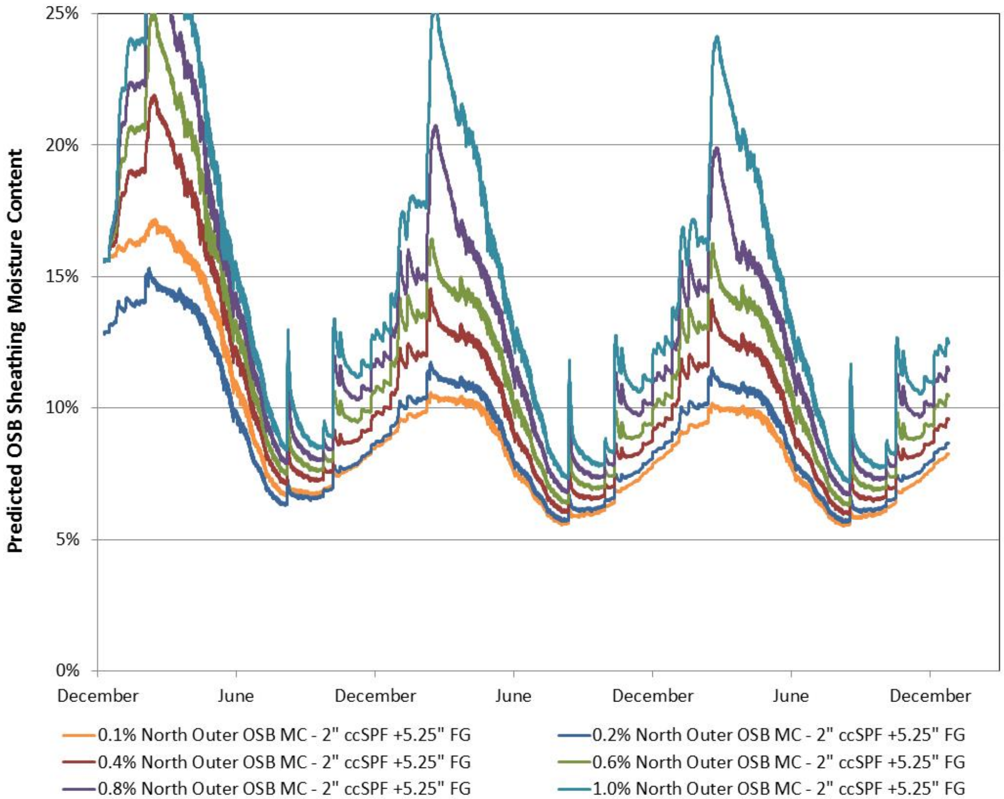


Figure 14. Seattle sheathing MC north 2 in. ccSPF + 5.25 in. fiberglass

Climate zone 4 is a difficult climate in that there is relatively continuous rain-based wetting as well as inward and outward vapor drives due to the heating and cooling of the homes during the alternating seasons. Figure 15 shows the sheathing MC as modeled between 0.1% and 1% of the rainwater. The modeling shows an increasing trend to the sheathing MC if more than 0.6% of rainwater leaks into the assembly. This correlates with the data analyzed for Minneapolis. In the Seattle case, both rainwater leakage year round and outward vapor drive in cold weather caused increased MCs in the sheathing while drying abruptly occurred during warm weather with the relatively high vapor ocSPF.

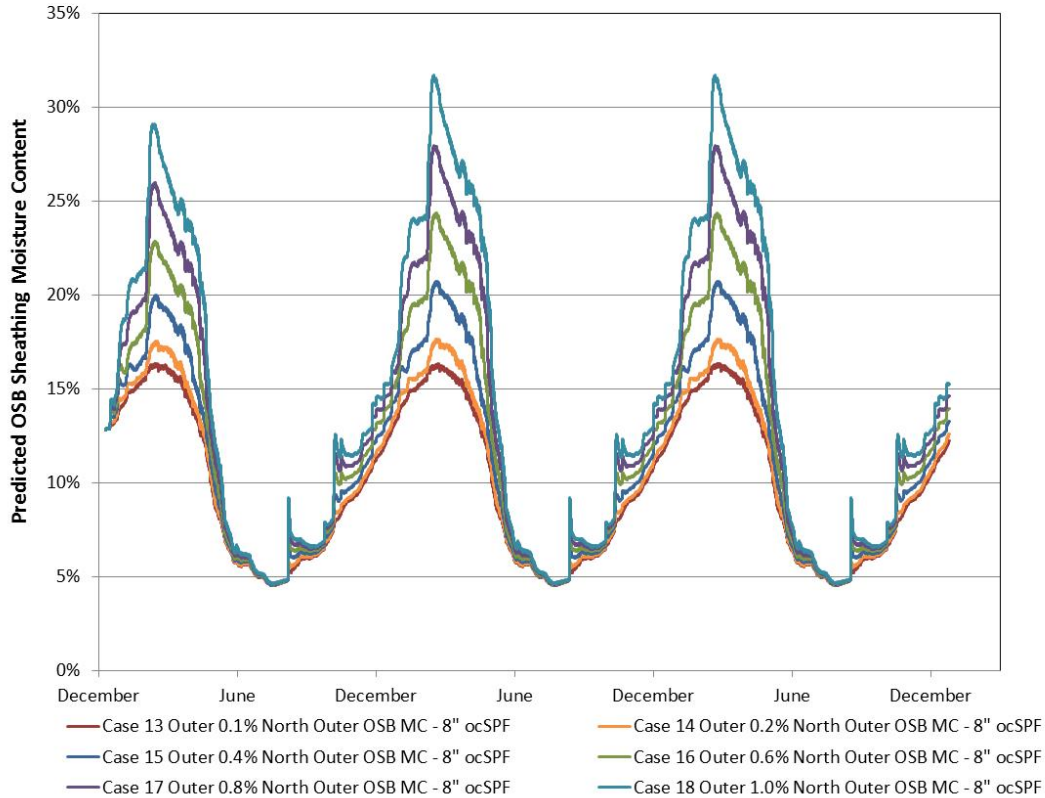


Figure 15. Seattle sheathing MC north 8 in. ocSPF

The Miami climate modeling shows that although the systems will be exposed to significant wetting throughout the year, there is also an equally large vapor drive produced by the heat and solar exposure, which forces the incidental moisture through the assembly and into the interior of the home. Figure 16 and Figure 17 are very similar graphs showing the sheathing MC of ccSPF-insulated unvented cathedralized roofs using cellulose and fiberglass insulation. Both systems safely dry out the full 1% of the rainwater leakage into the interior space. Figure 18 shows the sheathing MC for an ocSPF insulated roof in Miami and indicates that the full 1% rainwater leak is easily managed by the roof with significant inward vapor drives due to temperature and solar incidence with very limited outward vapor drives usually initiated by cooler outdoor weather.

The Miami modeling was then further stressed to determine its upper limit of wetting. Using the ocSPF case, the rainwater percentage was increased from 1% to 1.5%, 2.0%, and then 5%. Figure 19 shows the sheathing MCs for the high leak rates in Miami using ocSPF. At the 2% step the roof began to have extended periods of time with the exterior layer of the sheathing experiencing MCs above 25% and as such the dryable limit was chosen as 1.5%.

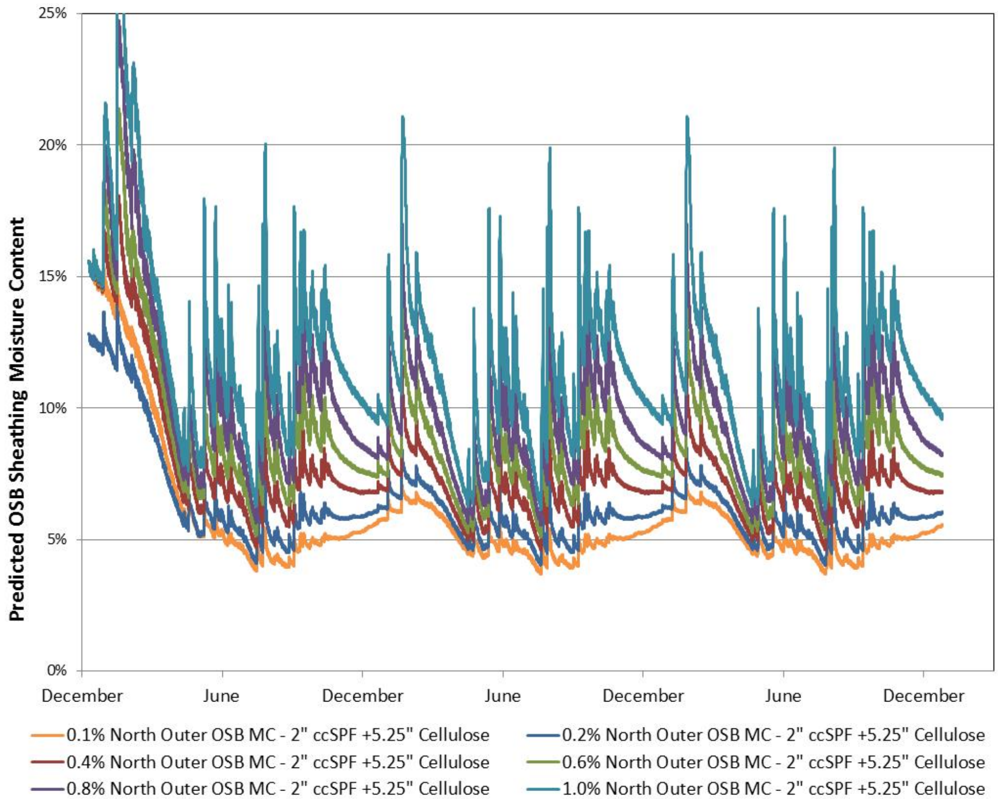


Figure 16. Miami sheathing MC north 2 in. ccSPF + 5.25 in. cellulose

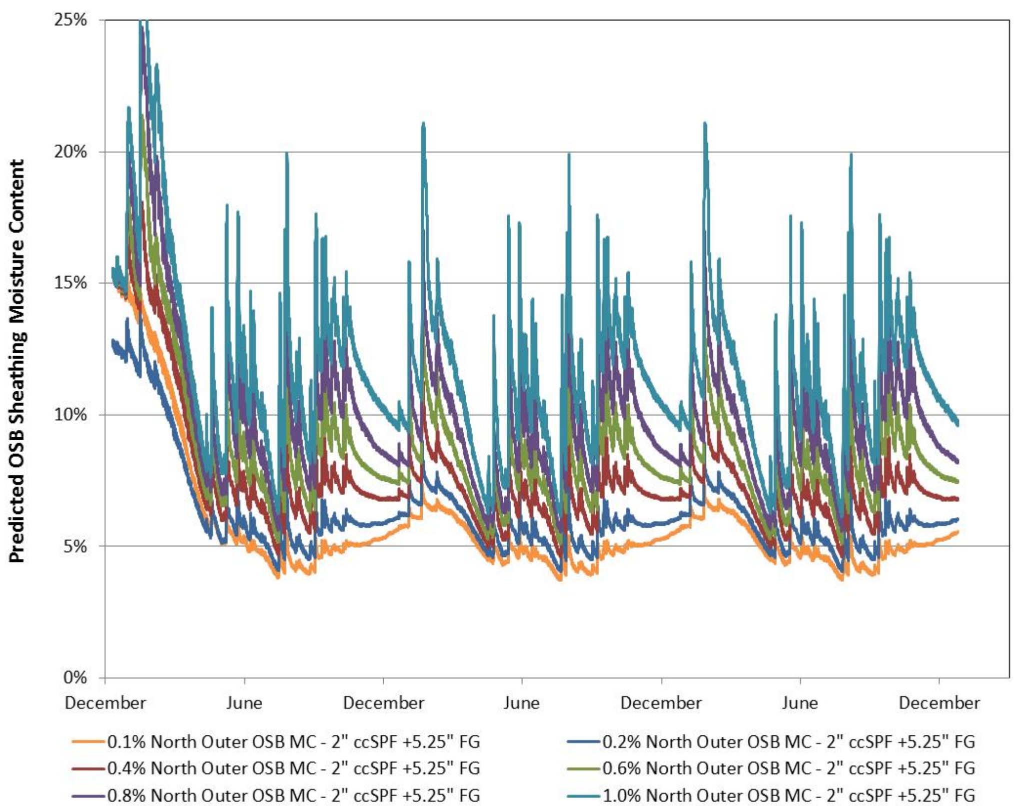


Figure 17. Miami sheathing MC north 2 in. ccSPF +5.25 in. fiberglass

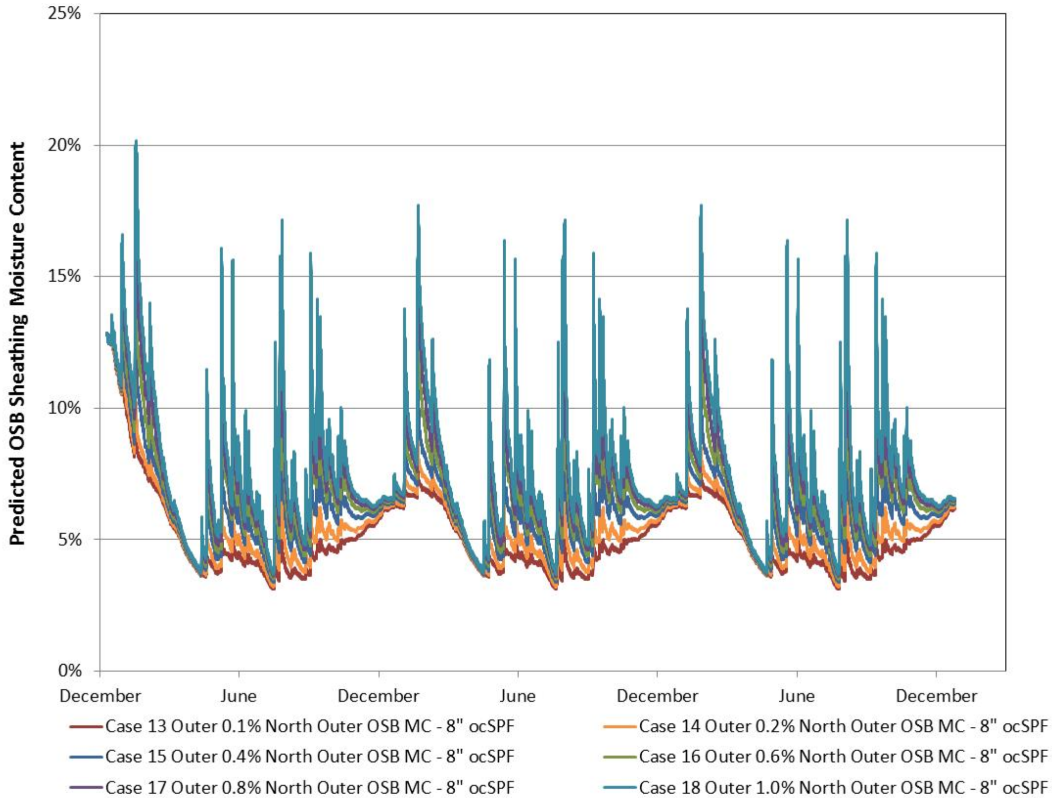


Figure 18. Miami sheathing MC north 8 in. ocSPF

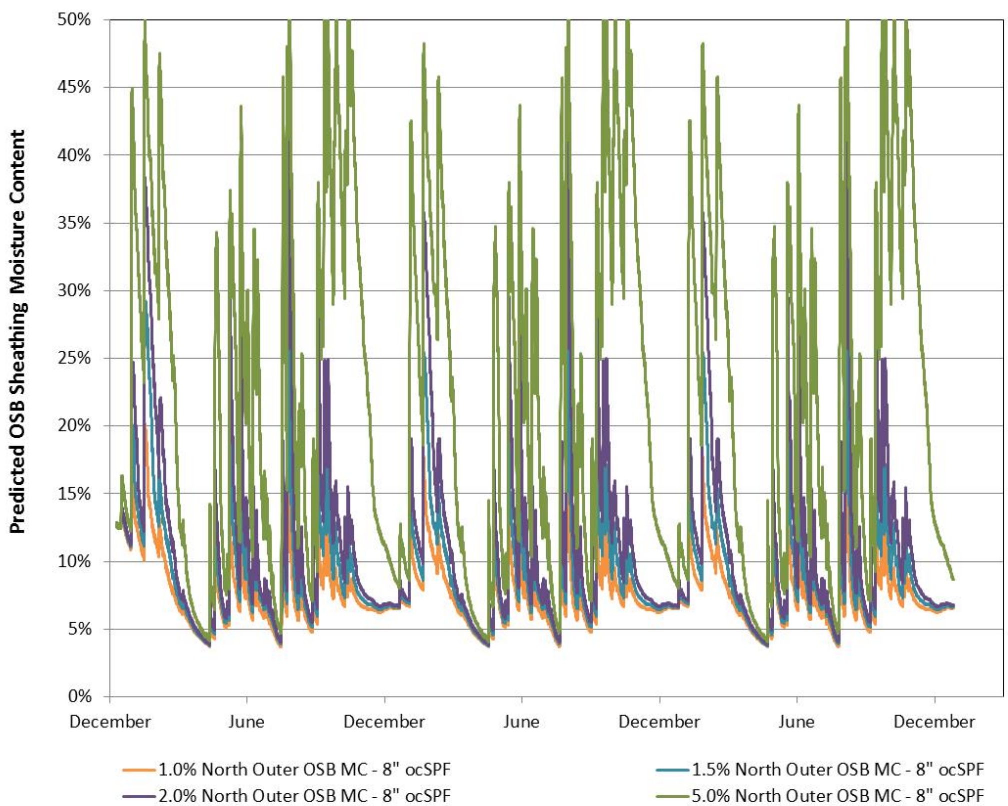


Figure 19. Miami sheathing MC north 8 in. ocSPF high stress

5 In-Service Roof Explorations

A number of roofs were reviewed to visually inspect the sheathing of in-service residential roofs using SPF against the underside of the roof sheathing. This enabled the correlation of modeled low sheathing MC to in-service roofs with measured low sheathing MC. The exploration consisted of the following:

- Attaining permission from a homeowner with an existing unvented roof using SPF insulation in contact with the roof sheathing
- Completing an invasive investigation on the roof from the interior
- Removing an area of interior drywall (if present)
- Removing fibrous insulation (if present)
- Removing a core of the SPF
- Inspecting the sheathing
- Taking an MC reading of the sheathing
- Taking photo documentation
- Repairing the area
- Documenting the results and roof system.

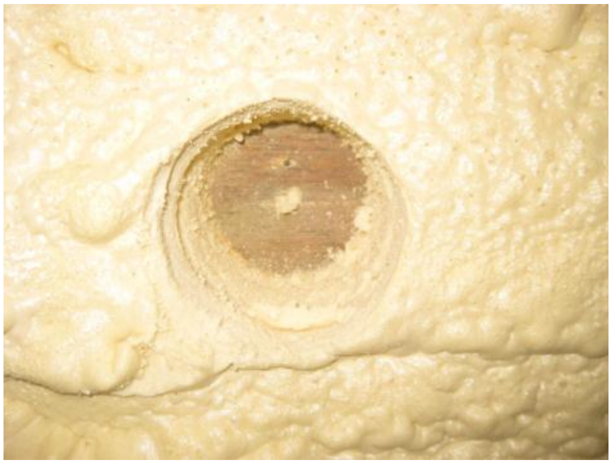
Eleven locations were reviewed. These locations span climate zones 2 to 7. Table 8 shows the list of houses and their locations.

Table 8. In-Service Exploration House List

House	Location	Climate Zone	Date of Site Visit
House 1	New Orleans, Louisiana	2	June 2012
House 2	New Orleans, Louisiana	2	July 2012
House 3	Coquitlam, British Columbia	4C	July 2012
House 4	Coquitlam, British Columbia	4C	July 2012
House 5	Westerville, Ohio	5	June 2012
House 6	Pontiac, Michigan	5	July 2012
House 7	Minneapolis, Minnesota	6	July 2012
House 8	Minneapolis, Minnesota	6	July 2012
House 9	Juneau, Alaska	7	July 2012
House 10	Juneau, Alaska	7	July 2012
House 11	Juneau, Alaska	7	July 2012

The following sections discuss each exploration, show photos where possible, and list the MC readings for each location. All sheathing readings, in all locations reviewed to date, are within the safe range for wood-based sheathing materials. Section 5.6 shows a failure of a SPF roof insulation system. In this case the manufacturer's investigation report concluded that the SPF was installed on wet OSB based on the observation that the SPF did not adhere well to the substrate and the pore structure of the ccSPF at the ccSPF/OSB interface was indicative of a wet substrate.

5.1 House 1: New Orleans, Climate Zone 2, June 2012



Description

- Built 2009
- Cathedralized attic
- R-21—~3.5 in. ccSPF below OSB roof sheathing

Exploration Findings

- All sheathing locations investigated are within safe MC readings

Exploration Location 1—North Lower

- 6% moisture content reading
- No visible signs of moisture damage

Exploration Location 2—West Upper

- 7.5% MC reading
- No visible signs of moisture damage

Exploration Location 3—East Upper

- 6.5% MC reading
- No visible signs of moisture damage

Exploration Location 4—West Lower

- 7.0% MC reading
- No visible signs of moisture damage

This information correlates well to modeling of warm locations with drives that enhance drying and have limited wetting.

5.2 House 2: New Orleans, Climate Zone 2, July 2012

Description
- Built 2009
- Cathedralized attic
- R-21—~3.5 in. ccSPF below OSB roof sheathing

Exploration Findings
- All sheathing locations investigated are within safe MC readings

Exploration Location 3—East Upper
- 6% MC reading
- No visible signs of moisture damage

Exploration Location 4—West Lower
- 7% MC reading
- No visible signs of moisture damage

This information correlates well to modeling of warm locations with drives that enhance drying and have limited wetting.

5.3 House 3: Coquitlam, Climate Zone 4c, July 2012

No photos available.

Description—North Upper Center Attic Bay
- R-20—~5.5 in. ocSPF with 2 coats latex paint below ½-in. OSB sheathing

Exploration Findings
- 8.7% OSB MC reading
- 8.1% OSB MC reading
- 7.5% OSB MC reading
- No visible signs of moisture damage
- OSB appeared clean and new looking

5.4 House 4: Coquitlam, Climate Zone 4c, July 2012

No photos available.

Description—North Upper End Attic Bay
- R-19—~5 in. ocSPF below ½-in. OSB sheathing

Exploration Findings
- 8.5% OSB MC reading
- 8.4% OSB MC reading
- No visible signs of moisture damage
- OSB appeared clean and new looking
- 9.2%, 10.1% framing bottom chord
- 12.4% framing mid-height
- 13.5% framing upper

5.5 House 5: Westerville, Climate Zone 5, June 2012

Description

- Built 2004
- Unvented cathedralized attic
- R-12—~2 in. ccSPF below roof sheathing
- R-28 fiberglass batt
- ½-in. drywall with latex paint

Exploration Findings

- All sheathing locations investigated are within safe MC readings

This information correlates well to modeling of cold climates with appropriate levels of vapor control.

Exploration Location 1—North Lower

- 13.5% MC reading
- This location had a roof leak in the 6 months before the MC reading

Exploration Location 2—North Upper

- 7% MC reading
- No visible signs of moisture damage

Exploration Location 3—South Lower

- 8% MC reading
- No visible signs of moisture damage

Exploration Location 4—South Upper

- 7% MC reading
- No visible signs of moisture damage

5.6 House 6: Pontiac, Climate Zone 5, July 2012

Description

- New Home January 2012
- Cathedralized attic
- R-40—~6 in. ccSPF below OSB sheathing

Exploration Findings

- Roof sheathing dry in all locations
- Roof sheathing structural failure

Exploration Locations

- OSB swelled and deteriorated
- During July exploration OSB was dry
- OSB was able to dry to the interior
- Roof sheathing MC < 6% in all locations when tested in July
- Roof sheathing was removed and replaced
- Manufacturer’s analysis report concluded that the SPF was installed over very wet OSB, which sealed in the liquid water causing the deterioration

5.7 House 7: Minneapolis, Climate Zone 6, July 2012

Description

- 1941, retrofit 2012
- Cathedralized attic
- R-21—~3.5 in. ccSPF below 1x board roof

Exploration Findings

- All sheathing locations investigated are within safe MC readings

This information correlates well to modeling of cold climates with appropriate levels of vapor control.

Exploration Location 1—Northwest Lower

- 9.2% MC reading
- No visible signs of moisture damage

Exploration Location 2—Southwest Lower

- 6.9% MC reading
- No visible signs of moisture damage

5.8 House 8: Minneapolis, Climate Zone 6, July 2012

Description

- Built 1914, retrofit January 2009
- Cathedralized attic
- R-21—~3.5 in. ccSPF below 1x board roof

Exploration Findings

- All sheathing locations investigated are within safe MC readings

This information correlates well to modeling of cold climates with appropriate levels of vapor control.

Exploration Location 1—North Upper

- 12.9% MC reading
- No visible signs of moisture damage

Exploration Location 2—North Upper

- 6.7% MC reading
- No visible signs of moisture damage

5.9 House 9: Juneau, Climate Zone 7, July 2012

Description

- Under construction 2012
- Cathedralized attic in heated garage
- R-15—~4 in. ocSPF below sheathing

Exploration Findings

- All sheathing locations investigated are within safe MC readings

Exploration Location 1—Southeast Lower

- 15.1% MC reading

Exploration Location 2—Southeast Upper

- 12.7% MC reading

Exploration Location 2—Northwest Mid

- 12.9% MC reading

5.10 House 10: Juneau, Climate Zone 7, July 2012

Description

- New home 2012
- Cathedralized attic
- R-19—~3 in. ccSPF below sheathing
- R-28—~7.5 in. ocSPF below ccSPF

Exploration Findings

- All sheathing locations investigated are within safe MC readings

Exploration Location 1—East Lower

- 16.9% MC reading (sheathing)
- No visible signs of moisture damage

Exploration Location 2—West Upper

- 15.1% MC reading (sheathing)
- 14.1% MC reading (framing)
- No visible signs of moisture damage

5.11 House 11: Juneau, Climate Zone 7, July 2012

Description

- Built in 2009
- Apartment above commercial paint supply store
- Cathedralized attic
- R-19—~3 in. ccSPF below sheathing
- R-20—~5.5 in. ocSPF below ccSPF

Exploration Findings

- All sheathing locations investigated are elevated. Due to the unique situation of the interior conditions, it is recommended that this location and its interior conditions be monitored further.

Exploration Location 1—South Mid

- 22.9% MC reading
- No visible signs of moisture damage

Exploration Location 2—North Mid

- 21.2% MC reading
- No visible signs of moisture damage

6 Conclusions

Unvented roof strategies with ocSPF and ccSPF insulation sprayed to the underside of roof sheathing have been used since the mid-1990s to provide durable and efficient building enclosures. However, there have been isolated moisture-related incidents reported anecdotally that raise potential concerns about the overall hygrothermal performance of these systems. The incidents related to rainwater leakage and condensation concerns. Condensation concerns have been extensively studied by others and were not discussed in this report (Straube et al. 2010).

This project involved hygrothermal modeling of a range of rainwater leakage and field evaluations of in-service residential roofs using spray foam insulation. All of the roof assemblies modeled exhibited drying capacity to handle minor rainwater leakage. All field evaluation locations of in-service residential roofs had MCs well within the safe range for wood-based sheathing.

Hygrothermal modeling was conducted on roof assemblies located in the principal climate zones of interest defining building performance in the lower 48 states—a hot climate with significant rain (Miami), a cold climate (Minneapolis), and a marine climate with significant rain (Seattle). These locations “bracket” the expected in-service conditions of concern for unvented roof assemblies.

The field evaluation locations were selected based on availability and timing. All locations that were made available by the industry partners were evaluated.

The quantity 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 in Minneapolis, Seattle, and Miami. The 2012 IRC-compliant roofing system in Minneapolis using 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. MCs > 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 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 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.

Assuming the fully adhered membrane is properly designed, detailed, and installed, these quantities of water have little likelihood of ever entering the system through rainwater leaks. The modeling showed ocSPF dries more readily than ccSPF, but ocSPF with a 5 perm coating or a 2 perm coating allows more wetting of the sheathing during the winter months.

Interior RH can directly affect the sheathing MC in all scenarios and BSC 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 RHs higher than this typically result in window condensation, wall and foundation assembly hygrothermal performance issues even in high performance houses.

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. The modeling showed that OSB sheathing, ocSPF with 5 perm coating, and roofs facing north maintain the highest MCs, but all systems were within the safe range for wood-based sheathing.

Explorations of 11 in-service roof systems were completed. The exploration involved taking a sample of SPF from the underside of the roof sheathing, exposing the sheathing, then taking an MC reading. All locations investigated had MCs well within the safe range for wood-based sheathing. One failure was reviewed, as an industry partner was involved with replacing structurally failed roof sheathing. In this case the SPF manufacturer's investigation report concluded that the SPF was installed on wet OSB based on the observation that the SPF did not adhere well to the substrate and the pore structure of the ccSPF at the ccSPF/OSB interface was indicative of a wet substrate. The other investigations were important to verify there have not been any hidden issues. Where a failure has occurred due to a rain leak, the volume of the leak, frequency of the leak(s), or quantity of interior moisture driven into the system, were likely significantly more than modeled in this study.

The following summarizes the findings of this research and how it relates to the questions.

Are there risks associated with installing spray foam under plywood and OSB roof decks specifically moisture and durability issues?

Based on this modeling there are no known risks with using SPF insulation under plywood and OSB roof decks if the following requirements are met:

- The installation complies with the 2012 IRC.
- A fully adhered leak-free roof membrane is installed.
- The roof sheathing is and framing dry below 18% before SPF installation.
- And when using ocSPF a low-perm Class II vapor retarder is installed where required.

Are roof leaks a serious problem?

Roof leaks can accumulate and be a problem if they allow > 1% of the rainfall to pass the drainage plane and deposit on the wood sheathing. Using the ASHRAE 160P criteria of a 1% rainfall leak past the exterior primary rain shedding layer, and assuming all of that 1% is able to pass the adhered roofing membrane to the sheathing, on the north orientation the leak can cause increased MC of the sheathing and may eventually lead to deterioration. If the leak is repaired, the systems analyzed in this report were capable of drying to the interior. If the leak is < 1%, most of the systems analyzed were able to repeatedly dry over time (Figure 5). Proper design and careful installation can limit if not eliminate roof leaks. Note that this is based on a climate zone with a moderate rainfall.

What is happening in these systems with high measured sheathing MC (i.e., 20+) but with no evidence of damage to the sheathing?

The ocSPF analysis section showed that depending on when the system was measured there is a significant fluctuation in the sheathing MC. There was a six-month swing from 4% MC to 25% MC repeatedly as the interior RH drove moisture into the assembly followed by drying of the assembly (Figure 11). The ccSPF did not experience such a fluctuation (Figure 8) and both systems dried to acceptable levels seasonally. Sheathing MCs > 20% can occur and if they have the ability to dry relatively quickly, the system will not experience damage. If the system maintains high MC, damage is likely to occur.

Are there moisture durability risks associated with installing spray foam under OSB roof decks in climates with high rainfall?

All of the roof assemblies modeled exhibited drying capacity to handle minor rainwater leakage. Based on this modeling there are no known risks with using SPF insulation under OSB roof decks if the following requirements are met:

- The installation complies with the 2012 IRC.
- A fully adhered leak-free roof membrane is installed.
- The roof sheathing and framing is dry below 18% before SPF installation.
- And when using ocSPF a low-perm Class II vapor retarder is installed where required.

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DOE/GO-102013-4257 ▪ October 2013

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