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Abstract:

Numerous arguments have been made in favor of the use of unvented cathedralized attic (UCA) assemblies in a variety ofclimates and applications. UCA assemblies, created by eliminating ventilation and by moving the thermal insulation and air barrier from the ceiling plane to the rafters, immediately below the roof deck, are increasingly common in low-rise residential construction in the hot-humid and hot-dry southern United States. Unvented cathedral ceilings (UCCs) are similar to UCAs with the exception that the interior finish is also installed on the underside of or between the rafters rather than on the underside of the ceiling joists or collar ties.

The test program described in this paper sets out to determine whether or not an assembly that meets the new IRC code requirements but is constructed without a vapor barrier and using an air impermeable, vapor permeable, low-density, open-cell sprayed polyurethane foam insulation can perform satisfactorily in the cold wet climates of Seattle, WA and Vancouver, BC (Zone 4C).

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ABSTRACT

Numerous arguments have been made in favor of the use of unvented cathedralized attic (UCA) assemblies in a variety of climates and applications. UCA assemblies, created by eliminating ventilation and by moving the thermal insulation and air barrier from the ceiling plane to the rafters, immediately below the roof deck, are increasingly common in low-rise residential construction in the hot-humid and hot-dry southern United States Unvented cathedral ceilings (UCCs) are similar to UCAs with the exception that the interior finish is also installed on the underside of or between the rafters rather than on the underside of the ceiling joists or collar ties. A more comprehensive explanation of these concepts is included in the Background section of the paper.

Recent changes to the International Residential Code (IRC) permit the construction of UCA and UCC assemblies. While no similar allowances have been made in any of the Canadian building codes, local building officials have permitted the construction of UCA and UCC assemblies in some jurisdictions. Section R806.4 of the 2006 IRC permits the construction of an unvented cathedralized attic or unvented cathedral ceiling with an air impermeable insulation provided that insulation is installed directly to the underside of the roof deck and is of sufficient thermal resistance to prevent the average monthly interior surface temperature of the foam from going below 7°C (45°F).

The test program described in this paper sets out to determine whether or not an assembly that meets the new IRC code requirements but is constructed without a vapor barrier and using an air impermeable, vapor permeable, low-density, open-cell sprayed polyurethane foam insulation can perform satisfactorily in the cold wet climates of Seattle, WA and Vancouver, BC (Zone 4C). Further details of the construction are provided in the paper.

A test house was constructed using the proposed UCC assembly and instrumented with sensors that measure temperature, relative humidity (RH) and moisture content (MC) within the assembly as well as basic boundary conditions such as indoor temperature and RH, outdoor temperature and RH, solar radiation, roof wetting (i.e. via condensation or rain). The sensors were monitored continuously by a monitoring system that could be accessed remotely without disturbing the occupants of the house.

Data was collected over the course of the first two fully occupied winters and analyzed. In the second summer, a visit was paid to the site to make some inspection openings, take some MC readings with hand-held meters and collect some painted drywall samples for permeance testing and wood sheathing samples for determining species calibrations for electrical resistances vs. moisture content. All of these activities are presented and discussed in this paper.

BACKGROUND

The ceilings of North American houses are increasing in both height and complexity. 57% of the respondents in the 2002 Builder Practices Survey (NAHB 2002) reported using ceiling heights of 9ft or higher. Similarly, 66% of the respondents of the 2003-2004 Consumer Preferences Survey (NAHB Economic Group, 2004) expressed a desire for ceiling heights of 9ft or more. These studies suggest a growing demand for

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larger volume spaces. One way of creating the feeling of larger space without significant increase in volume is through the use of varying ceiling heights (Wilson & Boehland, 2005). As ceiling planes are made higher and more articulated (e.g. through the incorporation of dormers, valleys, hips, etc.) they often require the construction of cathedral ceilings.

This type of ceiling construction is not restricted to the large semi-custom homes of the suburbs. In a June 2005 AIA survey (AIA 2005), 49% of respondents reported an increase in the number of finished basement and attic spaces. Cathedral ceilings are becoming increasingly common in the smaller homes of large urban centers as more homeowners finish attics to make the most use of limited available space.

Cathedral Ceilings

Cathedral ceilings represent the most compact form of roof used in low-rise residential construction. They are formed by applying the finish to the bottom of the rafters, thus minimizing the depth of the roof assembly and maximizing the volume of the living space. The design and performance of cathedral ceilings differ from conventional attics because there is limited depth available for the introduction of insulation or a ventilated airspace.

Ventilated Roof Assemblies

It is common to provide a ventilated airspace in attics or cathedral ceilings in cold climates to control ice dams by minimizing roof temperatures and to remove moisture that is introduced by warm, moist indoor air which leaks into the roof assembly (Figure 1). The practice of ventilating roof assemblies has been adopted by residential builders across North America and has been convention since the 1940s. Experience and research over the past 10 to 20 years have caused many to abandon ventilated roof assemblies in favor of unvented cathedralized attics (UCAs) or unvented cathedral ceilings (UCCs) (Figure 2).

Unvented Roof Assemblies

In hot climates, UCA and UCC assemblies prevent the warm, humid air from condensing on cool, inside drywall surfaces or on the cold surfaces of air conditioning ductwork (Lstiburek 2003). Similarly, Rose and TenWolde (1999) suggest that ventilation of roof assemblies in cold, wet climates can result in increased moisture levels and that unvented assemblies may mitigate this problem. In wooded areas, unvented assemblies may provide better protection from wildfire because there are no vents which can permit the entry of burning embers into the roof assembly (Rose and TenWolde 2002, Rudd 2003). In coastal areas, unvented assemblies are less likely to suffer from moisture problems related to wind-driven rain which can enter through vents and wet sensitive materials in the roof assembly (Lstiburek 2006). UCA and UCC assemblies are gaining acceptance and constructed in growing numbers in a range of climates.

Building Code Requirements

In the 2006 edition of the International Residential Code (IRC), Section R806.4, sentence 4 requires that unvented cathedralized attics be designed such that:

> In Zones 3 through 8 as defined in Section N1101.2, sufficient insulation is installed to maintain the monthly average temperature of the condensing surface above 45°F (7°C). The condensing surface is defined as either the structural roof deck or the interior surface of an air-impermeable insulation applied in direct contact with the underside/interior of the structural roof deck. "Air-impermeable" is quantitatively defined by ASTM E 283. For calculation purposes, an interior temperature of 68°F (20°C) is assumed. The exterior temperature is assumed to be the monthly average outside temperature.

Under this code provision, it is permissible to construct a UCA assembly using an air impermeable, low-density, open-cell sprayed polyurethane foam installed between framing members directly on the underside of the roof deck. This concept has been used as the basis for an unvented cathedral ceiling assembly proposed for houses in Seattle, WA and Vancouver, BC.

Proposed Unvented Cathedral Ceiling Assembly

The proposed UCC assembly, illustrated in Figure 4, is insulated using a low-density, open-cell polyurethane foam insulation and comprises (from outside to inside):

- Asphalt shingles
- 12.5 mm (1/2 in.) COFI plywood sheathing
- 38 x 89 mm (2 x 4 in.) strapping @ 406mm (16 in.) O.C.

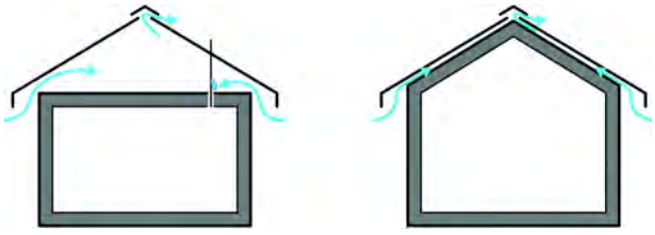

Figure 1 *Ventilated attic (left) and ventilated cathedral ceiling (right) assemblies.*

Figure 2 *Unvented cathedralized attic (left) and unvented cathedral ceiling (right) assemblies.*

- 38 x 228 mm (2 x 10 in.) rafters @ 406mm (16 in.) O.C.
- 266 mm (10.5 in.) of low-density, open-cell sprayed polyurethane foam
- No polyethylene vapor barrier
- 12.5 mm (1/2 in.) drywall painted

The IRC code requirement does not make any reference to the provision or exclusion of a vapor barrier. Some designers and contractors maintain that it is not necessary while others question this contention, arguing that the relatively high permeance of the interior drywall and the low-density, open-cell polyurethane foam make the roof sheathing in this system prone to excessive moisture content accumulation during the winter season. The need for additional vapor control is the focus of the research project described in this paper.

PREVIOUS RESEARCH

The hygrothermal performance of roof assemblies has been the focus of only a few North American field measurement studies. Parker and Sherwin (1998) studied the temperatures in 6 conventional ventilated roof assemblies installed in a test hut at Cocoa Beach, Florida, and noted the coolest temperatures in roof systems that had greater thermal mass, lighter colored roof coverings and higher ventilation rates. No moisture content measurements were made.

Winandy et. al. (2000) studied the temperature in 5 ventilated roof assemblies installed in matched south-facing test huts in Madison, WI and Starkville, MS. Black-shingled roofs were found to have peak daytime temperatures 5-10°C higher than lighter-shingled roofs in both climates; during the winter, roof sheathing temperatures were up to 20°C cooler in WI than MS. Moisture content measurements were made periodically using a hand-held electrical resistance MC meter. In non-humidified, ventilated MS attics, the roof sheathing MC ranged from 1.7% in the summer to 7.5% in the winter. In humidified, ventilated MS attics, the range varied from 4% in the summer to 17% in the winter. In non-humidified, ventilated WI attics, the range was from 6% in the summer to 13% in the winter.

Rudd (2005) conducted a field survey of four unvented cathedralized attics in Minnesota and Wisconsin (April 2004) and one such attic in Massachusetts (March 2004.) All five of the unvented cathedralized attics were insulated with low-density, open-cell sprayed polyurethane foam. Foam samples were removed within 1.5m (5 ft.) of the ridge, and the sheathing moisture content was measured with a hand-held electric resistance MC meter. Sheathing moisture contents were highest on north-facing roofs, ranging from 20% to over 40% while measurements on the south-facing roofs ranged from 7-23%. Rudd found that the sheathing moisture contents were highest in the houses that had abnormally high indoor RH levels as a result of flooding and/or poor ventilation.

Rose (2001) reported on one of the only studies to consider cathedral ceiling assemblies. A test hut was constructed in Champaign, Illinois with 3 conventional ventilated attic roof assemblies, 2 unvented cathedralized attic roof assemblies, 1 conventional ventilated cathedral ceiling assembly and 2 unvented cathedral ceiling assemblies. The roof sheathing of unvented cathedralized attic and unvented cathedral ceiling assemblies was 17.7-23.3% hotter than the conventional ventilated attic base case. No moisture content measurements were made.

RESEARCH PROGRAM

A project was conceived to extend past UCA and UCC moisture monitoring efforts to the coastal climate of the Pacific North West, and more specifically to measure the performance of the proposed unvented cathedral ceiling assembly. A vapor barrier was not used in the proposed UCC assembly. The combination of the painted drywall and the air-impermeable, low-density, open-cell sprayed polyurethane foam is intended to eliminate any convection of water vapor and control the outward diffusion of water vapor during cold weather. The vapor permeance of the interior layers of the assembly is sufficiently high to allow moisture in the sheathing to dry inward during warm weather or in the event of incidental wetting.

A manufacturer of foam insulations arranged for a test house in Vancouver and secured the necessary approvals from the building department. The research program and moisture monitoring system were designed, installed and monitored by the first author's building science consulting firm. The details of the research program, results and analysis are discussed in the sections that follow.

Objectives

The objective of the field monitoring project was to measure the moisture performance of the proposed UCC and to investigate the need for additional vapor control layers in order to determine if an assembly without these layers could safely accommodate the accumulation of moisture during the winter months and dry quickly enough during the summer months.

Approach

The experimental program was developed to monitor the moisture performance of the UCC using a series of temperature, humidity, moisture content and weather sensors so that the direction of moisture movement, driving forces and amount of moisture stored in the assembly could be determined.

A moisture monitoring system was designed and installed during construction of the UCC test house. The system allows temperature, relative humidity (RH) and moisture content (MC) to be measured at discrete locations on a 5 minute cycle. This method provides excellent temporal resolution but is limited in spatial resolution – sensors only respond to conditions in their immediate vicinity, so they must be located near the action to return useful results.

The indoor RH and temperature are monitored on two floors of the house; however, the indoor conditions are controlled by the occupants rather than the monitoring system.

The outdoor RH and temperature are also measured, as are the solar radiation on a horizontal surface and the incidence of wetting (i.e. incidence of rain or dew) on the roof slope. Wind speed and direction as well as quantity of rainfall are not measured.

Industry experience has demonstrated that stick-built assemblies insulated with sprayed polyurethane foam insulation have higher levels of airtightness than conventionally-constructed, batt insulated assemblies. No blower door test or sub-assembly air tightness tests were conducted on the UCC test house. It was assumed that air leakage did not have any effect on the measured performance.

One visit was made to the site during the second fully occupied summer to cut some openings in the assembly, conduct visual inspection of the plywood roof sheathing, make comparative measurements with hand-held meters and to collect samples of the painted drywall for permeance testing. It was not possible to collect samples of the plywood sheathing.

The permeance of the painted drywall samples was determined in the laboratory using ASTM E96 (dry cup method). Wet cup permeance tests were not conducted.

SETUP

The moisture monitoring system for the UCC test house is based on the techniques and equipment proposed by Straube et al (2002). Temperature (T) is measured using 10k NTC thermistors (accuracy +/- 0.2°C); relative humidity (RH) is measured using capacitive based sensors with onboard signal conditioning (accuracy +/- 3% between 10 & 90% RH); and moisture content (MC) is measured via in-situ electrical based resistance measurements between corrosion resistant insulated pins. Electrical resistance measurements were converted to %MC by weight, correcting for temperature and species using the Garrahan equation. The data acquisition equipment uses a 13 bit A/D with auto ranging (full scale of +/- 2.5 mV to +/- 2500 mV).

Moisture performance was measured at 4 locations on the north-facing roof slope and 4 locations on the south-facing roof slope as illustrated in Figure 3. Two wall locations were also monitored on each of the north- and south-facing walls, although these are not discussed in this paper.

Each monitoring location was given a unique name as an identifier (e.g. RSWU). The four characters of the identifier indicate whether it is a roof or wall location, the elevation, the lateral location and the vertical location. The identifier RSWU, for example, represents the Roof monitoring on the South face, at the West and Upper position.

On the south side of the house, the roof monitoring locations are in the storage room (RSWU & RSWL) and the hall (RSEU & RSEL), both on the attic (third) floor. On the north side, the monitoring locations are in the second floor landing

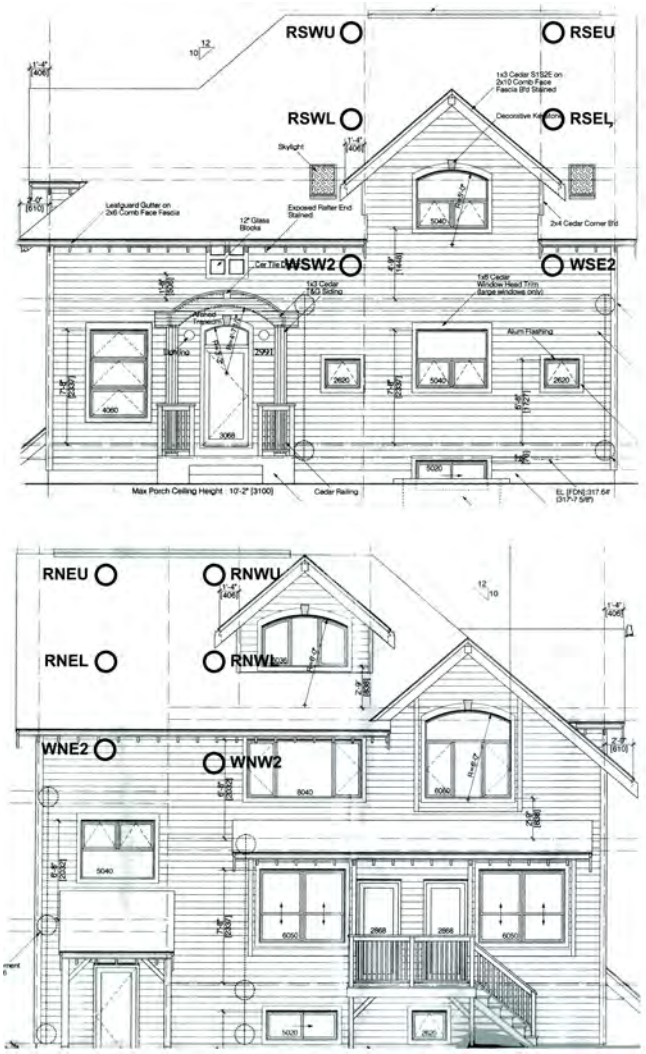

Figure 3 *South (top) and north (bottom) elevations showing approximate monitoring locations.*

(RNEU & RNEL) and in the seating area (RNWU & RNWL) on the attic floor. In all instances, the upper roof monitoring locations are 406 mm (16 in.) below the ridge line while the lower roof monitoring locations are 3.05 m (10 ft) below the ridge line.

In northern climates, the exterior sheathing moisture content is often used as the critical parameter for assessing the performance of roof assemblies that do not have vapor retarders. The MC & T of the sheathing are measured at all eight roof monitoring locations (the Basic Sensor Set). Additional measurements were made at the RNWU and RSWU locations (the Comprehensive Sensor Set): MC & T were measured near the interior edge of the rafter; RH & T were measured near the interior and exterior faces of the foam insulation. Figure 4 illustrates the layout of the comprehensive sensor set installed at the UCC assembly.

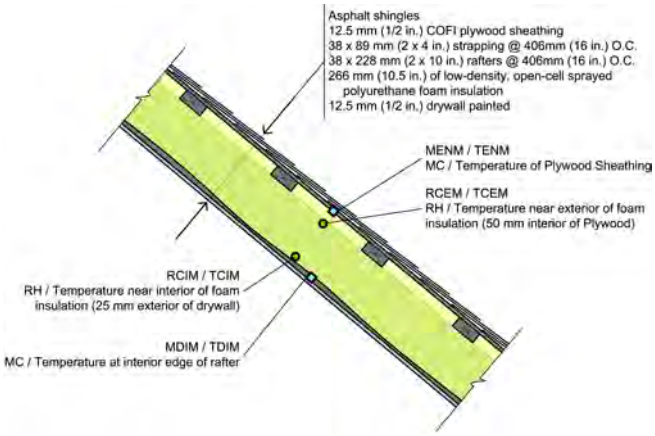

Figure 4 *Layout of comprehensive sensor set.*

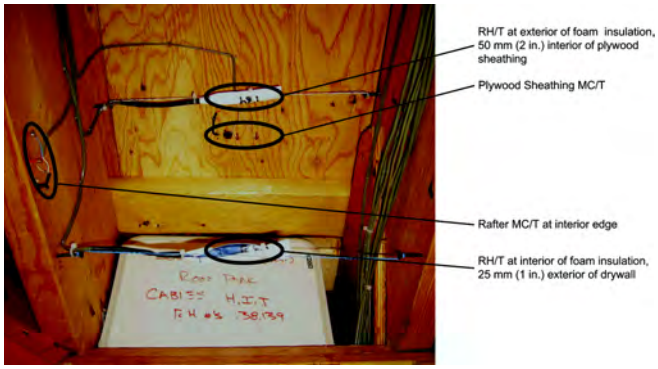

Figure 5 *Comprehensive sensor set installed on north-facing roof at west end, upper location.*

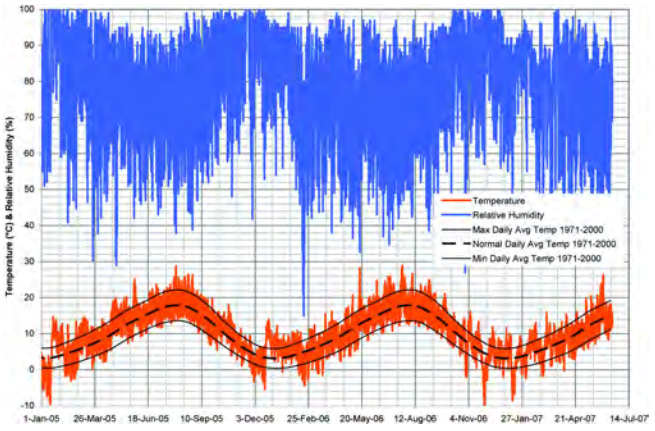

Figure 6 *Outdoor temperature and relative humidity.*

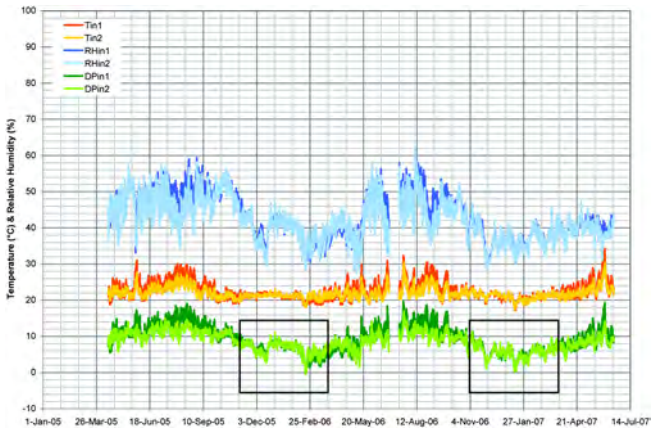

Figure 7 *Indoor temperature, RH and dew point.*

Figure 5 shows a photo of the sensors installed in the rafter bay at monitoring location RNWU. The rafters can be seen resting on the top of a load bearing wall. A 38 x 89 mm (2 x 4 in.) piece of strapping can be seen just above the whiteboard. The two RH/T sensor sets are packaged in a Tyvek® case to protect them from liquid water and the form insulation. They can be seen suspended on taught wires mounted at the appropriate depth in the rafter space. The low-density open-cell polyurethane foam easily envelopes these packages when it is applied.

The MC/T pins are installed so the active tip is 1/8in. (3mm) below the surface of the plywood and framing. An MC/T pair was installed at the inside edge of the rafter to check for any increase in moisture content associated with drying of the sheathing in the early summer.

RESULTS AND DISCUSSION

Data Collected by In-situ Monitoring System

Figure 6 shows the hourly outdoor temperature (orange trace) and RH (blue trace) recorded over the first two years of the monitoring program. The 3 black traces indicate the maximum, normal and minimum daily average temperatures from the 1971-2000 Canadian Climate Normals. For the most part, the 2006-2007 outdoor temperatures have been higher than suggested by the 30 year climate normals.

Figure 7 shows the hourly indoor temperature (2 middle traces), RH (2 top traces) and dew point (2 bottom traces) recorded at two locations in the house: location 1 (darker traces) is on the 3rd floor, in a sitting area next to the logging room while location 2 (lighter traces) is on the 2nd floor in the hallway outside the master bedroom. The house is heated with radiant floors, and year-round ventilation is provided by an HRV. A small, ductless split provides air-conditioning for only the master bedroom and dressing room.

As expected, temperatures and moisture levels are slightly higher at location 1 (on the topmost floor) during the summer months. Little difference can be seen between the conditions at the two monitoring locations during the winter months.

It is likely that construction moisture was still drying out in the first winter. This process would be accelerated by venti-

lating the house with drier (winter) outdoor air; however, the homeowner did not understand how to properly operate the heat recovery ventilation (HRV) system and did not switch it to 'winter' mode until December 2005. This switch was made in October 2006 so the unit ran at a higher ventilation rate for all of the second winter, and as a result, indoor temperatures were slightly cooler and RH levels at both locations were noticeably lower during the second winter. The dew-point temperatures were further analyzed for the periods indicated by the two black squares (Nov. 1st through February 28th of each winter).

Figure 8 shows the distribution of the outdoor and indoor dew-point temperatures for the period covered by Nov. 1st through Mar 31st of the 2005-06 and 2006-07 winters. There was little difference between the outdoor conditions in the first winter (06) and those in the second winter (07). Conversely, the indoor dew-point temperatures were noticeably lower the second winter. During the first winter, the interior dew point exceeded 7°C for roughly 41% of the hours while this threshold was exceeded fewer than 17% of the hours the second winter.

Figure 9 shows the daily average roof sheathing temperatures measured at East end of the house on the North-facing (blue traces) and South-facing roofs (orange traces). As expected, the South-facing roof experiences warmer temperatures than the North-facing. The 10/12 pitch of the roof is steep enough to allow the South-facing slope to capture the small amount of sunlight that is available in the winter so that it is remains slightly warmer than the North-facing, even during the colder winter months.

Figure 10 shows the distribution of the roof sheathing temperatures measured over the course of the monitoring (May 1st 2005 through May 1st 2007). Maximum roof sheathing temperatures are approximately 80°C and 50°C for the South- and North-facing roofs. The South-facing roof sheathing experiences roughly 2000 hrs/yr at temperatures over 20°C while the North-facing roof sees only 1500 hrs.

Figure 11 shows the daily average roof sheathing moisture content (MC) measured at the North-facing (blue traces) and South-facing (orange traces) over the two year monitoring period. Portions of three winters can be seen on the graph.

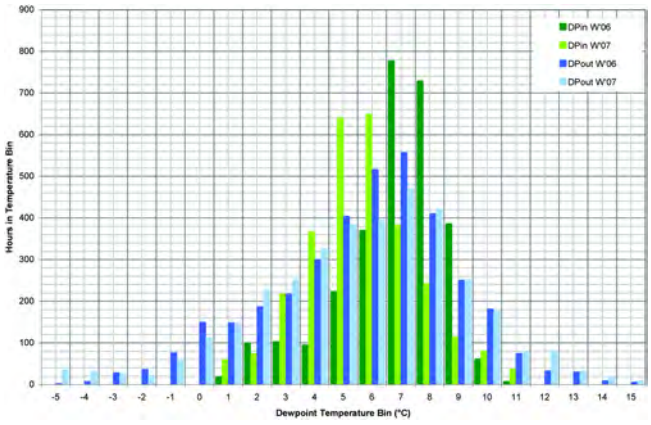

Figure 8 *Indoor and outdoor dew-point temperature distribution.*

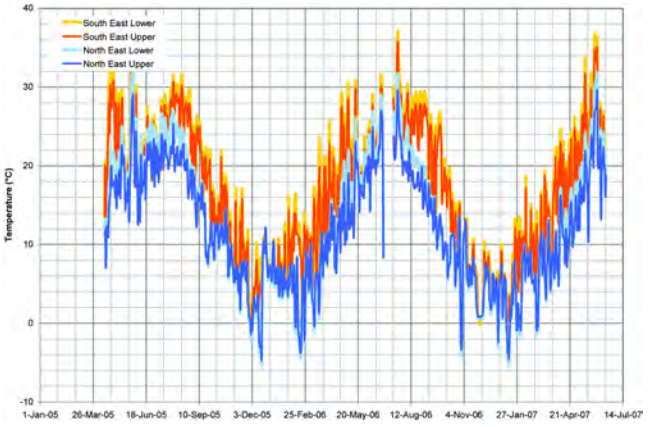

Figure 9 *Daily average roof sheathing temperature.*

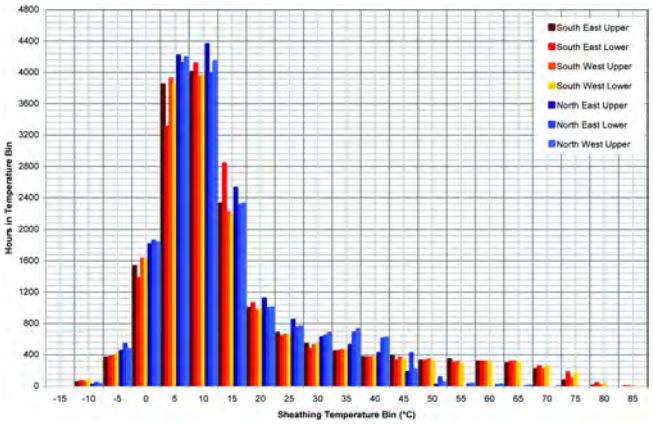

Figure 10 *Roof sheathing temperature distribution.*

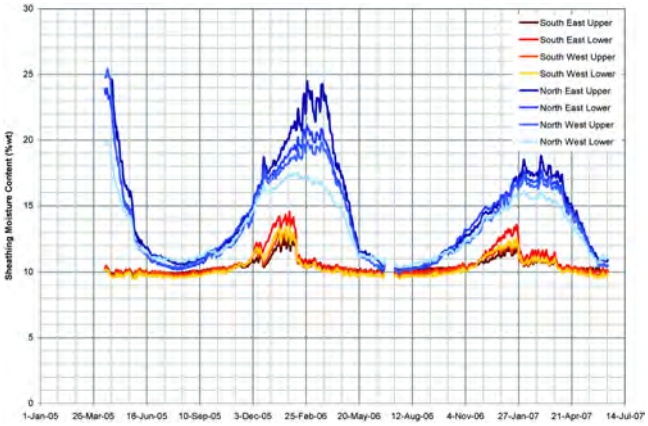

Figure 11 *Daily average roof sheathing MC (corrected for temperature and species).*

The North-facing measurement locations show initial high MC readings (e.g. in the range of 20-25% MC) as a result of high indoor moisture levels associated with the finish work (i.e. drywall mud, painting, cleaning, etc.) completed January through March of 2005. This effect could barely be seen on the South-facing roof which had dried significantly by the time power was supplied to the monitoring system.

The following winter (i.e. 2005-06, the first fully occupied winter), the sheathing MC at the North-facing locations increased by 7-14% to the high teens and low twenties while the sheathing MC at the South-facing locations only increased 2-4% to the low teens. The South-facing roof appears to dry quickly by mid February while the North-facing roof appears to increase in MC until the end of February and then dry down during mid March through mid May. Since the indoor conditions are similar for all monitoring locations, it is proposed that the increased solar exposure and average daily temperatures on the South-facing roof play a significant role in reducing the magnitude of the MC increase and accelerating the drying.

In the third winter (i.e. 2006-07, the second fully occupied winter), indoor moisture levels were lower and the increase in MC is not as significant. The sheathing MC at the North-facing monitoring locations increased 5-7% to the mid to high teens while the sheathing MC at the South-facing locations increased by 1.5-3%. Since the outdoor conditions were not significantly different from the previous year, it is hypothesized that the reduced interior dew point plays a significant role in the lower levels of moisture accumulation in the sheathing.

Field Visit

Some concern was raised over the elevated MC levels measured on the North-facing roof. A visit was made to the test house in early June 2006 (i.e. the second fully occupied summer) to make a visual inspection of the plywood roof sheathing. Roof test cuts were made through the drywall and the foam insulation at locations near RNEL, RNWL and RSWL. A plywood jig was used to cut a 150 mm (6 in.) diameter centerless core through the drywall so the finished drywall sample could later be used for permeance testing. These samples were sealed in plastic bags and placed in a wooden box to protect the painted surfaces from damage during shipping.

A 75 x 75 mm (3 x 3 in.) square hole was then cut through the depth of the foam insulation to expose the interior face of the plywood roof sheathing as seen in Figure 12. None of the test cuts showed any signs of mold or decay — the interior surface of the plywood was clean and the material resisted penetration of a pocket knife just as new plywood sheathing would.

The test cuts confirmed that there was good continuity of the sprayed foam insulation and a tight bond between it and the roof sheathing / furring, supporting the assumption that air leakage had no effect on the hygrothermal performance of the monitored roof assembly.

Vapor Permeance of Painted Drywall

The vapor permeance of the finished drywall samples was determined (using the ASTM-E96 dry cup method) to be approximately 450 ng/Pa s m (8 US Perms) for samples finished with 2 coats latex paint and 1500 ng/Pa s m (30 US Perms) for samples finished with a knock-down coating ('California Ceiling'). Both of these values were significantly higher than expected. The authors have measured a number of painted drywall samples from recent buildings and have noticed a higher trend than published permeance values. This may be attributable to changes in paint chemistry or application methods (i.e. adoption of airless spraying) typically used to paint new buildings.

Numerous vapor retarding primers are available that have a demonstrated permeance in the range of 35 to 57 ng/Pa s m (0.6 to 1 US Perms), 10 to 30 times lower than measured. Use of these primers will significantly reduce the diffusion during the winter such that the moisture content of the North-facing roof sheathing does not exceed 20%.

CONCLUSIONS AND RECOMMENDATIONS

Unvented cathedralized attics (UCAs) and unvented cathedral ceilings (UCCs) are increasingly common in low-rise residential construction. Recent changes to the International Residential Code (2006 IRC, Section R806.4) permit the construction of a UC attic or ceiling with an air impermeable insulation, provided that insulation is installed directly to the underside of the roof deck and is of sufficient thermal resistance to prevent the average monthly interior surface temperature of the foam from going below 7°C (45°F).

A UCC assembly was constructed at a test house in Vancouver (Zone 4C) using an air impermeable, vapor permeable, low-density, open-cell sprayed polyurethane foam insulation. A polyethylene vapor retarder was not used in the assembly. The interior finish layers (i.e. painted drywall) were intended to control outward diffusion of water vapor during cold weather and prevent moisture problems in the wood components of the assembly. A monitoring program was established to test this premise.

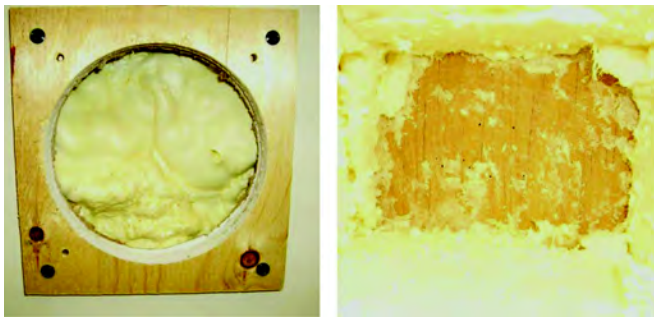

Figure 12 *Jig and core through drywall (left) and foam cut to interior face of plywood (right).*

The monitored data suggests that increased solar exposure and temperature dramatically affect the rate at which the roof sheathing dries in the summer and accumulates moisture in the winter. Construction moisture dried faster on the South-facing roof slope than the North – although both dried to approximately 10-12% MC by weight. During the first winter, the moisture content of the North-facing roof sheathing rose to 17-24% MC by weight while the moisture content of the warmer South-facing sheathing only rose to 12-14%.

The monitored data also suggests that interior dew point appears to play a significant role in the winter sheathing moisture content levels in the tested UCC assembly. During the first winter, the construction moisture was still drying out and the HRV was not switched to 'winter' mode until December 2007. As a result, the moisture levels inside the house were slightly elevated and the interior dew-point temperature exceeded 7°C for approximately 41% of the hours. Outdoor conditions were similar the second winter, but the HRV was operated in 'winter' mode from early in the fall so moisture levels in the house were more reasonable with fewer than 17% of the hours exceeding an interior dew-point temperature of 7°C. The second winter, the increase in sheathing moisture content was lower with the North- and South-facing roof sheathing reaching 15-17% MC and 11-13% MC respectively.

Through inspection openings, the foam insulation was observed to have good continuity (i.e. minimal voids) and strong adhesion to the sheathing and furring. None of the test cuts showed any signs of mold or decay, and the interior surface of the plywood appeared clean and sound.

ASTM E96 tests on samples collected from the test house revealed that the permeance of the finished drywall was several times higher than expected. It is recommended that a vapor retarding paint be used in similar assemblies in the Northwest to reduce winter vapor diffusion so that the moisture content of the North-facing roof sheathing does not exceed 20%.

Further analysis of the monitored data and comparison to hygrothermal computer simulations of the assembly performance are planned and may be presented in a future paper.

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