Attic Ventilation and Moisture Research Study

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Prepared for

BC HOUSING

Prepared by

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Acknowledgments

This research report was prepared by Morrison Hershfield for the Homeowner Protection Office, a branch of BC Housing. Special thanks are extended to Polygon Homes Limited for providing funding support for this project, and for the assistance with technical and construction expertise for the development of solutions outlined in this report.

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Summary and Significance of the Attic Ventilation and Moisture Research Study

The presence of moisture and mold growth in ventilated cold attics is not a new concern. Sources of moisture in attics include air leakage, roof leaks, wind driven snow or rain, ice damming, and the outdoor air ventilating the attic space. Canadian building codes include measures to minimize the entry of interior moisture into attics from air leakage and vapour diffusion. Our codes also have prescribed requirements on the size and location of vent openings in attics to promote ventilation.

The *Attic Ventilation and Moisture Research Study* was initiated in response to anecdotal observations that an unusually large portion of wood-framed buildings constructed in coastal climates exhibited mold growth on the roof sheathing of ventilated attics. The level of mold growth on the roof sheathing ranges from small isolated areas to almost complete coverage. Furthermore, it has been observed that in some recently constructed buildings the mold growth seemed to be concentrated near vent openings. In other words, mold seemed to be at locations that receive the most ventilation. This is contrary to current views that inadequate attic ventilation is a major cause of moisture collection and mold growth in attics and that the solution to problems related to moisture in attics is to increase attic ventilation.

Phase 1 of the *Attic Ventilation and Moisture Research Study* was to explore, via field testing and monitoring, the premise that in some maritime climates, mold growth in attics can occur even in buildings that fully comply with code requirements, without significant defects, with regard to controlling attic moisture levels. The research methodology is summarized as follows:

- ✓ Gain access to a recently constructed development with multiple similar units, which have mold growth concentrated at areas of high ventilation.
- ✓ Confirm, by test, that the venting areas of the attics meet code requirements.
- ✓ Confirm, by test, that the air leakage areas between the indoor space and the attic space are within the norms of good construction practice.
- ✓ Monitor environmental conditions, in the indoor and attic spaces, and moisture in wood materials in the attic of four sample units and in a "control" with a roof that was not attached to an indoor environment.
- ✓ Quantify the average attic ventilation levels and air transfer from the indoor space to the attic using tracer gases.

The key findings of this phase of the study were:

- ✓ In all the tested units, all of which had mold growth in the attics, the ceiling airtightness and attic venting area was consistent with code requirements and good building practice.
- ✓ The monitored units did not exhibit excessive indoor humidity.

- ✓ In the four units and the “control” roof not connected to a heated building, the moisture content of the attic sheathing reached, and spent significant time at levels recognized to support mold growth.

- ✓ For the attics, significant wetting events occurred with clear and cold nights, followed by sunny days.

- ✓ Tracer gas testing carried out in two periods, one week in December and one week in February, showed attic air exchange rates were low, in line with periods without wind (ranging from as low as 1 ACH to as high as 4.1 ACH). The results showed that, in these units, environmental driving forces for attic air exchange are low.

- ✓ Tracer gas testing showed that, in spite of good ceiling airtightness (confirmed by testing), air transfer from the living space to the attic was a significant fraction of the attic air exchange.

- ✓ In the tested units, air transfer from the attic to living space was very small. As such, any mold in the attic is not likely a significant source of biological contamination to the living space.

Phase 2 of the study focused on evaluating the factors that lead to moisture collection and mold growth in attics situated in coastal climates. The goal of Phase 2 was to identify both design solutions and treatments to minimize the potential for mold growth. Research activities included:

- ✓ In two of the units, the attic venting areas were altered and monitoring continued for another heating season.

- ✓ Heat, Air, and Moisture (HAM) computer simulation, calibrated to monitoring data, was carried out to evaluate the impact of varying levels of ceiling airtightness, indoor moisture levels, attic ventilation rates, sheathing thermal resistance, and insulation levels.

- ✓ A literature review and consultation with industry experts on the treatment of wood to resist mold growth.

- ✓ An evaluation of cost, practicality and effectiveness of design and treatment strategies to address mold growth in attics.

Key findings included

- ✓ While a dramatic reduction in insulation from current levels, back to levels before insulation was introduced in the 1990s, could reduce the potential for mold growth, there is effectively no difference in the risk of mold growth between current levels with R-30 insulation and going to beyond R-50 insulation levels.

- ✓ Ventilation of the attic via the attic vents is a principal source of moisture in attics in marine climates but it is also a necessary moisture removal mechanism. Modifications to the venting area and distribution do not appear to be a solution to avoid mold growth in cool marine climates.

- ✓ The addition of a thin layer of insulation outside the sheathing reduces the wetting potential of roof sheathings but warrants more study before becoming an accepted solution on its own right.

While a variety of solutions were examined, the general result of the analysis leads to the conclusions that there are two general ways of minimizing the potential for mold growth in ventilated attics in maritime temperate climates:

1. Avoid using ventilated attics by selecting and designing assemblies that do not require ventilation, such compact roof assemblies.

2. Treat wood roof sheathings, as a minimum, with moldicides and other products to increase the resistance of wood in ventilated attics to mold growth.

The first approach is generally limited to new construction and imposes changes and (usually) additional costs to current practice.

There are a number of products purporting to treat wood to resist mold growth. However, ongoing research is raising some questions about the ability of some to provide long-term resistance to mold growth in ventilated attics and address any environmental concerns that some may have with using chemicals to make wood sheathings more mold resistant. There will likely be some trial and error that will occur in practice until there are fully accepted products and procedures for treating wood in attics to address mold growth.

Since some consumers may be adverse to chemically treated wood or the possible requirement of ongoing treatments, industry needs to take a hard look at design options to avoid attics that require ventilation. The most feasible solution for low sloped roofs is to insulate outboard the roof structure with a conventional roof assembly. For a steep sloped roof assembly, the most feasible design alternative is an unvented roof assembly, which can also have other benefits like increased conditioned living space.

REPORT

Attic Ventilation and Moisture Research Study

Phase 1– Investigation and Measurement

Presented to:

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1. INTRODUCTION

The connection between hygrothermal performance and ventilation of attics of wood-framed sloped roofs has been studied for some time, reported to date back to the 1930's (Rose and TenWolde 1999 and 2002), and has steered our building codes to stipulate specific prescriptive requirements for the ventilation of wood-framed roofs.

Originally the sole purpose of attic ventilation appears to be to minimize condensation in attics (Rose and TenWolde 2002). Most Canadian research into attic moisture problems has identified that the leading cause of troubled attics and high sheathing moisture content is generally the transfer of moist indoor air into the attic space due to high indoor humidity (Forgues 1985, BLP 1991, Sheltair 1997). The intent of attic ventilation is to reduce the potential for problems by diluting interior air moisture sources and in theory to provide some drying of moisture in the attic. However, the level of drying is dependent on the temperature and moisture capacity of the attic air, and heat supplied to the attic from the conditioned space or from solar radiation heating up the roof surface.

Attic ventilation is firmly established as a critical element in residential roof construction, and lack of ventilation is routinely blamed for a variety of problems and failures. In addition to moisture control, attic ventilation is also cited to benefit summer cooling of the attic air and reducing cooling loads, minimizing ice dams in cold climates, and extending the service life of roof materials by reducing surface temperatures. The debate is ongoing on the real significance of some of these benefits and the mandatory requirement for venting for all types of roof construction has come into question (Parker and Sherwin 1998, Rose 2001, Rose and TenWolde 2002, Tobiasson et al 2001, Lstiburek 2006).

Despite steady attention to the subject over the decades, there is growing evidence that buildings seemingly built to code, in cool marine climates, are experiencing high incidences of moisture problems leading to mold growth in roof attics. Problems related to mold growth in attics are currently showing up in recently constructed wood-framed buildings in the coastal climate of British Columbia. This problem is not unique to our climate and construction practice. Surveys are showing that as many as 60 to 80% of the single family houses in the Gothenburg region of Sweden, also a cool marine climate, are showing significant mold growth (Arfvidsson and Harderup 2005, Hagentoft et al 2008, Hagentoft and Sasic Kalagasidis 2010, Hagentoft 2011). Coincidently, the frequency of reported attic moisture problems has increased as insulation levels in attics to address energy efficiency goals in both jurisdictions.

There are several factors leading to potential issues for highly insulated wood-framed attics constructed in cool maritime climates like coastal BC. The drying capacity of outdoor air during the winter is low because of constant wet conditions and the lack of sunshine hours limits the drying benefits from solar exposure. Furthermore, shading, on a site specific basis, can further reduce opportunities for drying from solar exposure. There is also less opportunity for heating from the conditioned space because of high insulation levels and low temperature differences between the conditioned space and attic for average conditions. Even small amounts of moisture transfer from the indoor to attic space can lead to problems, which is most likely to happen during the coldest weather when the moisture capacity of the attic air is lowest and stack induced pressure is the greatest.

There is a growing body of anecdotal information by visual reviews of recently constructed buildings indicating that:

1. Attic ventilation may not be helpful in controlling moisture in, and mold growth on, the wood sheathing and framing in well insulated attics located in cool maritime climates.

2. In some cases, attic ventilation may actually increase moisture in, and mold growth on, the wood sheathing and framing in well insulated attics located in cool maritime climates.

The visual evidence that attic ventilation might increase moisture and mold growth in some attics in cool marine climates is that staining is occurring at isolated soffit vent locations, the location where the ventilation rate should be the highest. Figure 1 illustrates the staining pattern seen in many attics recently reviewed in the Lower Mainland of BC.

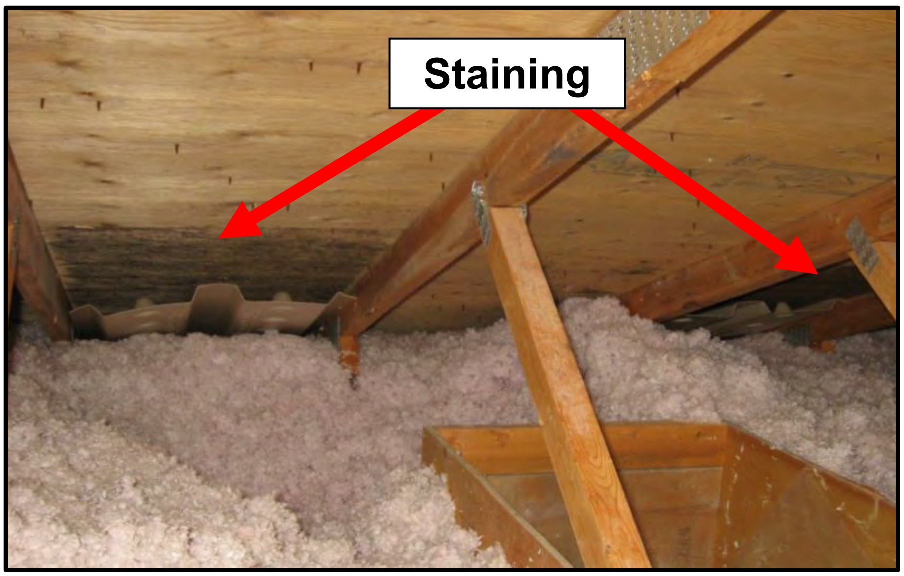

Figure 1: Staining (mold) at soffit vents in a recently constructed wood-framed attic

The hypothesis for these conditions is that the sheathing and framing can become colder than the surrounding air temperature and lead to wetting due to:

a) Cooling of the roof surface by radiation during clear nights.

b) Sheathing surfaces are cool, due to the thermal mass of the wood, relative to rising air temperatures in the morning due to solar exposure.

When the outdoor air is saturated - or even supersaturated - condensation or frost can form on the sheathing and framing in the attic even without a significant moisture contribution from inside the house. The theory is that the wood in the attic will pick up moisture as temperatures steadily drop in the winter, and average relative humidity rises in the attic space, to levels that any significant wetting event from condensation or frost will result in conditions optimum for mold growth (i.e. relative humidity 90 to 96%).

The key question that arises: Is there any ventilation configuration that will alleviate the occurrence of staining, at the location of expected highest ventilation rates, for attics with ceilings sealed to the standard of care of airtightness?

Morrison Hershfield Limited (MH) entered a research agreement with the Homeowner Protection Office, a division of BC Housing, to investigate attic ventilation and moisture in attics. The objectives of this study were to test the hypothesis presented above and to provide a complete understanding of the contributing factors leading to localized staining at soffits in wood-frame attics that appear to be built to code provisions for attic ventilation, areas and distribution, and ceiling airtightness. We set out to meet these objectives by conducting a comprehensive testing and measurement program of four attics that met the criteria of exhibiting localized staining at the soffits and were seemingly being built to current standard construction practices.

This study included the following tasks:

1. Literature review of research into moisture and ventilation of attics in cool marine climates

2. Visual review and selection of study units

3. Long term monitoring of air and surface moisture levels and temperatures in four attics and indoor spaces, as well as a control roof

4. Building characterization of the ceiling airtightness and ventilation areas using dual blower door fan depressurization

5. Smoke testing of ceiling air leaks under positive attic and negative house pressures

6. Tracer gas testing to measure air transfer rates from the indoor air to the attic space and the attic space to the outdoors

2. PAST AND CURRENT INDICATORS

Research of attics in cool marine climates has generally shown that moisture content levels of wood in the attic space can be expected to be greater than 20% kg/kg during the winter and levels greater than 30% kg/kg should not be uncommon (BLP 1991, University of Alberta 1993, Sheltair 1997, Chalmers University 2005 to 2011).

Field research of attics in Canadian marine climates, done in conjunction with cold climates, highlighted that high attic moisture content levels were coincident with high indoor humidity. These conclusions likely reinforced strategies to lower attic moisture conditions by lowering indoor humidity, providing airtight ceilings and the assumption that attic ventilation per code is sufficient to deal with small amounts of moisture transfer from the indoor space. In contrast, the University of Alberta (Forest and Berg 1993) predicted through a validated computer model that generally the 1:300 code requirement provides too much ventilation in Canadian marine climates (Vancouver, Halifax, St. John's) and the dominant moisture source for the attic is the outdoor air. Furthermore, they predicted that the ceiling airtightness had little impact on the sheathing moisture contents and virtually unaffected the quantity of moisture deposited by condensation. They suggested that sheathing moisture content can be reduced by sealing the attic or at least substantially reducing vent area by not installing any vents and relying only on the background leakage of the attic envelope.

The European experience has some similarities to Canada's, but with different approaches, responses and outcomes. A lot of work on ventilation and moisture in attics was conducted at the building physics lab at KU Leaven, Belgium in the 1970's, mainly as a result of complaints about mold and condensation in attics of shingled roofs (email correspondence with Hugo Hens). The results were never published in English but the reported conclusions of the research is that attic ventilation was seen as a risky approach in mild wet climates and it was better to provide an airtight ceiling, provide some thermal resistance outboard the sheathing to avoid radiation cooling, and avoid pressurizing the indoor space. The principle outcome of this work was that shingles lost popularity and attics became living spaces with cathedral ceilings gaining popularity.

In Sweden, there is growing concerns with mold growth in ventilated attics. These concerns are coinciding with increasing attic insulation levels to address energy efficiency demands. Currently the advice given to the Swedish building industry is to not provide too much ventilation or too little. Too high a rate combined with cooling by radiation results in high humidity, leading to mold growth, and too little ventilation is risky if there is construction moisture or moisture transfer from the indoors. Efforts have been made to demonstrate the benefits and feasibility of providing controlled ventilation in attics to control the risk of mold growth by ventilating only when the outdoor air has the potential to provide drying to the attic space. Chalmers University of Technology, in partnership with the Swedish building Industry, is also currently conducting research to develop information and tools for the design of cold attics. The project is set to answer questions about appropriate technological solutions that consider climatic conditions, construction techniques, ventilation systems and indoor conditions.

Table 1 summarizes the past CMHC sponsored research projects that measured and monitored attic conditions of several Canadian wood-framed buildings. The measurements from these studies provide a benchmark for comparison of measurements for our current study.

Table 1: Summary of CMHC Sponsored Research Projects of the Impact of Attic Ventilation for Canadian Marine Climates

Study	Description of Testing and Measurement Program	Key Findings and Conclusions for Marine Climates
Survey of Moisture Levels in Attics by Buchan, Lawton, Parent Ltd. 1991 (BLP)	• 15 attics in Ottawa, 5 in PEI • Attic ventilation and airtightness testing using a two fan pressurization approach • Air change sampling using tracer gases • Seasonal moisture content readings	• The ceiling airtightness ranged in most houses from 200 to 450 cm^2 at 10 Pa • Efforts to correlate the attic moisture levels to attic characteristics were inconclusive • 4 of 5 PEI houses had moisture content above 20% and 1 above 30% • Attic ventilation rates from 1 to 33 ACH; large variations correlated to wind speed, wind direction, and temperature difference between the attic and outdoors
Attic Ventilation and Moisture by the Department of Mechanical Engineering, University of Alberta. 1993	• Two test houses in Edmonton monitored over two winters, fan pressurization, ventilation rates using tracer gases • One house with no intentional attic ventilation openings and one with traditional venting • Validated heat-air-moisture model • Computer simulations, including marine climates	• Very good agreement between measured and simulated results • Attics should not be over-ventilated • Generally, the 1:300 code requirement provides too much ventilation • Attic moisture levels can be substantially reduced by providing a very small attic leakage area • This may be achieved by not installing any vents and relying only on the background leakage of the attic envelope • High pitched roofs will tend to have more moisture problems than low pitched roofs
Attic Ventilation and Moisture Control Strategies by Sheltair Scientific Ltd. 1997	• 4 attics in Vancouver, 4 in Edmonton • Half the attics had conventional ventilated attic spaces and the other half had no intentional attic ventilation • Monthly moisture content measurements • Airtightness and ventilation measurements using a two fan pressurization approach	• Elimination of all intentional attic venting area did not result in a trend towards either large reductions or elevations in wood moisture content • Wood moisture content in the attics peaked in January/February; 30% and 18% for conventional vented roofs and 25% and 15% for non-vented roofs • The truss moisture content was generally lower than the sheathing with no real differences between scenarios • The ceiling airtightness ranged from 185 to 350 cm^2 at 10 Pa • Attic ventilation rates from 11 to 31 ACH • Houses with high indoor RH showed higher attic moisture levels irrespective of attic ventilation or ceiling airtightness • Differences in wood moisture content in attics was not found to relate directly to differences in ceiling airtightness

3. STUDY OVERVIEW

3.1 Study Location and Unit Selection

The study units are in a townhouse development in Port Moody, BC. Each of the four units that are part of the study was selected from a larger pool of potential volunteers. All the buildings and units are of similar design and construction but completed in separate phases in 2004 and 2005.

The units were selected after a visual inspection of all the units that volunteered to be part of the study. The selection of units was based on apparent indoor humidity levels (signs of past condensation on windows), unit orientation (north-south or east-west), apparent venting area (venting on two sides or three), and level of staining at soffits. This work was completed in July 2011. Table 2 summarizes the conditions and occupancy of the test units recorded during the visual review of the suites. The exterior air temperature and relative humidity was 12°C and 97% RH. Figures and photos illustrating the unit orientations and elevations follow.

Table 2: Summary of Conditions and Occupancy at Visual Review

Unit	Indoor Conditions	Occupants	Staining
1	56% RH, DP 14.7°C, 25°C	1 child, 2 adults	very light staining, spots at one baffle
2	49.6% RH, DP 12.7°C, 24°C	2 children, 2 adults	light staining at baffles and next to joist
3	46.5% RH, DP 12.1°C, 24°C	2 adults	attic hatch by soffit; severe staining
4	48% RH, DP 12.14C, 23.9°C	2 children, 2 adults	heavier staining at baffles; ventilated at 3 sides

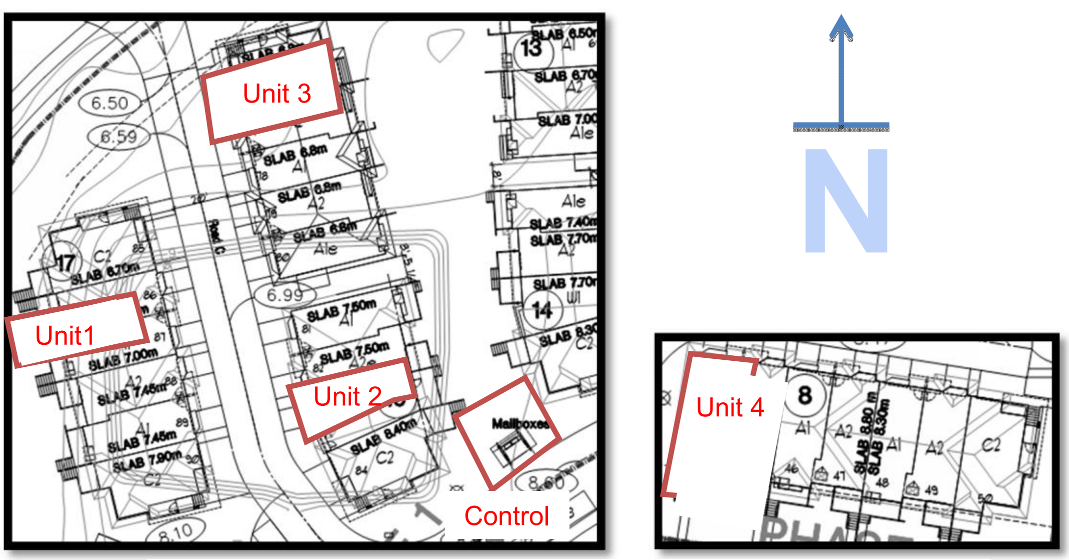

Figure 2: Site Plan and Orientation of Test Units

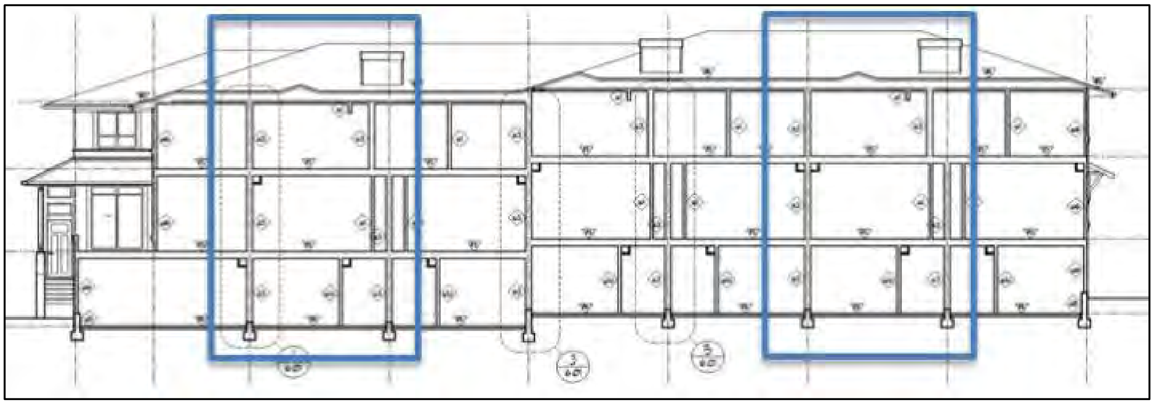

Figure 3: Building Elevation

Photo 1: *Test (Control) Roof Assembly with Unit 2 in the background*

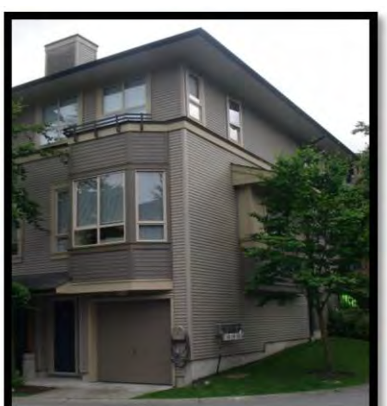

Photo 2: *End Unit 4*

Photo 3: *East Elevation of Unit 1*

3.2 Attic Construction and Ventilation

The attic construction and ventilation is typical of sloped roofs for wood-framed buildings in coastal BC. As required by code, the venting area is provided at the top of the attic near the ridge line (Photo 4) and at the bottom of the attic space at the soffits at opposite ends. The vents at the ridge are square low profile vents and baffles (Photo 5) are installed at the soffits. Unit 4 is the end of the building and is part of the hip roof end.

Dryer, exhaust, fresh air ducts and plumbing penetrate through the attic ceiling up through the roof. The dryer and exhaust ducts are insulated with fiberglass insulation wrapped in a polyethylene bag. The ceiling penetrations are sealed at the ceiling air barrier and to the metal ducts at the roof level with tuck tape (Photos 6 and 7). The attics are accessed through hatches that friction fit to a wood framed opening and batt insulation wrapped in polyethylene above the drywall hatch cover (Photo 8).

Drywall with taped joints separates the attics between units (Photo 9).

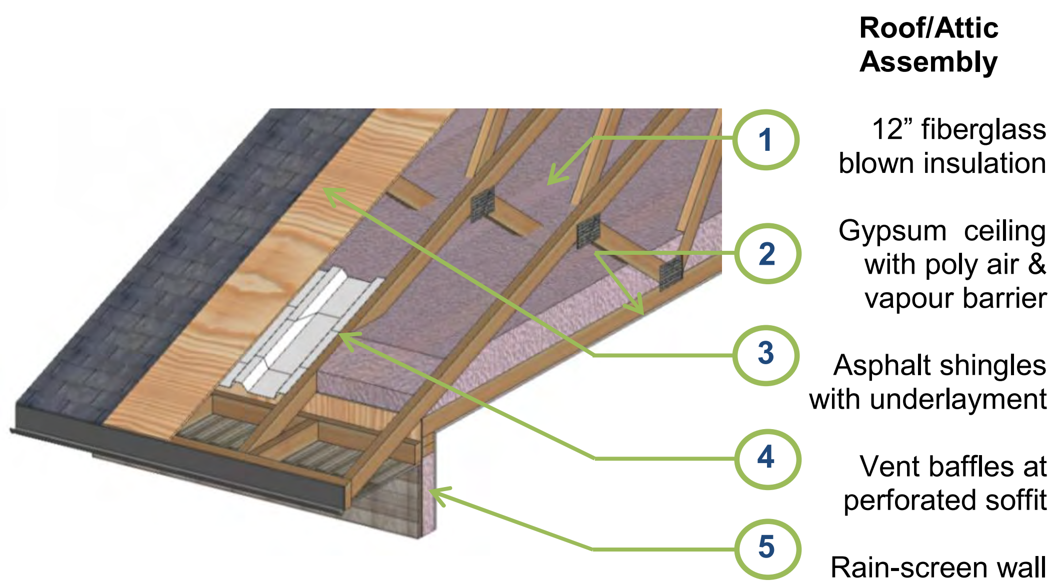

Figure 4: Attic Construction and Ventilation

Photo 4: *Roof Penetrations and Vent at Ridge*

Photo 5: *Baffle Vent at Soffit*

Photo 6: *Air Barrier Sealing of Dryer Duct Penetration at Ceiling*

Photo 7: *Air Barrier Sealing of Dryer Duct Penetration at Roof Sheathing*

Photo 8: *Roof Hatch*

Photo 9: *Drywall Fire Separation*

4. INVESTIGATION AND MEASUREMENT

This section describes the procedures of the investigation and measurement program conducted for this study to provide a complete understanding of the contributing factors leading to localized staining at soffits in wood-framed attics in coastal BC. Results, Analysis, and Discussion follow in later sections.

4.1 Building Characterization

The airtightness area of the ceiling interface between the indoor and attic space and the attic venting area were done using a two fan depressurization method. This method is similar to what was done in the past in the CHMC attic research studies (Sheltair 1989, BLP 1991, Sheltair 1997).

The primary purpose of conducting the airtightness and attic venting area measurements are twofold:

1. Provide an empirical basis to compare the relative airtightness of the attic ceiling to other buildings for a standard pressure differential, and

2. Confirm that the venting area meets or exceeds the code requirement of 1:300 venting area of the insulated ceiling area.

Two calibrated fans were required; one in the attic hatch and another in the main entry door. The fans were connected so that the fan speeds automatically adjusted until a target pressure difference was achieved in both the attic and indoor spaces. Equipment and assistance were provided by Retrotec Inc. This work was completed at the end of July 2011.

The first step was to pressurize the attic with respect to the outdoors. All the windows and doors were opened and the pressure difference was checked to ensure that there was no pressure difference between the indoors and outdoors. In the second step, both the attic and indoor space were pressurized to equal amounts with respect to the outdoors. This in theory yielded no flow across the attic-to-indoor interface, which allowed the attic air exchange rate to be determined. Then the flow across the attic-to-indoor interface was determined from the results of the first test. Figures 5 and 6 illustrate these procedures and calculations to determine the airtightness of the attic ceiling and venting area.

A pressure difference of 40 Pa was maintained for three of the units and generally the fluctuation in the air leakage area readings were fairly stable, less than 1.5%, indicating reliable measurements. Unit 4, however, has soffit baffle vents on three sides, the flow rates were significantly higher than in the other units, and a pressure difference of 40 Pa was not achieved. A pressure difference of 15 Pa was ultimately achieved but there was a lot of fluctuation in the readings. The fluctuation was so significant that the calculated attic-to-indoor interface value is unreliable because the fluctuation in the attic venting area was greater than the resolution of the ceiling airtightness area being calculated. However, the testing did confirm that the attic venting area at 15 Pa was much greater than required by code as will be discussed in section 5.

Figure 5: Building Characterization Step One, window and doors open, attic fan only

Figure 6: Building Characterization Step Two, window and doors closed, attic and house door fan

4.2 Smoke Test

Smoke testing was completed to visually inspect significant air leakage paths. This was done by filling the attic full of smoke by both positively pressurizing the attic with the fan in the attic hatch and negatively pressurizing the indoor air with the house fan. Smoke was visible coming through the fresh air grill in two units (units 2 and 3) and through the seal of the blower door to the attic hatch in all the units. The leakage at the attic hatch during the testing is not representative of actual conditions, but likely a source of some leakage from the indoor to attic space during normal conditions. The leakage at the fresh air grill was a result of the tape not being well adhered at the connection from the polyethylene insulation bag to the flange of the grill. The connections were sealed before the tracer gas sampling was completed in December as described in section 4.4. Figure 7 and photos 10 and 11 illustrate the locations with visual air leakage during the smoke testing.

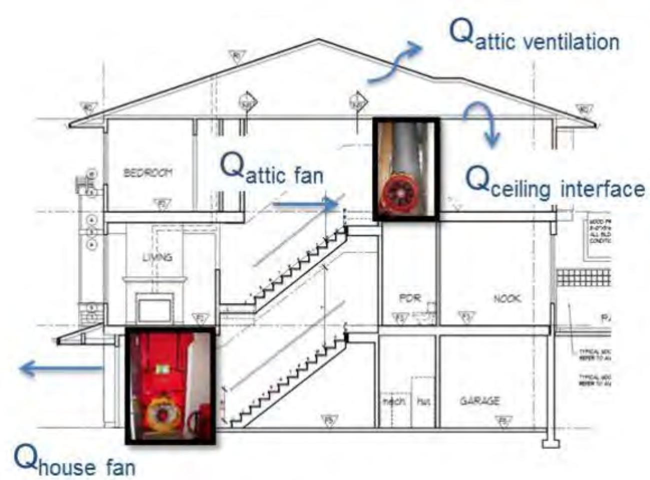

Figure 7: Smoke Testing with Negative Pressurization of the House and Positive Pressurization of the Attic

Photo 10: Fresh Air Grill with Air Leakage Path

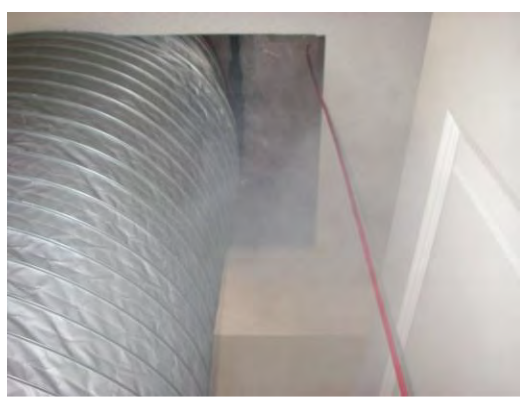

Photo 11: Air Leakage at Attic Hatch during Testing

4.3 Tracer Gas Testing

The air exchange rate of an attic is dependent on the weather and pressures across the roof assembly and the air transfer rate from the indoors to the attic is largely dependent on temperature differentials. The venting and airtightness areas provide an indication of the rates but are measured at specific pressure differentials. Tracer gas testing provides a means to determine average air transfer rates over a specific period of time.

Two key questions about attic performance were answered using the tracer gas sampling:

1. What is the attic air ventilation rate for real-life conditions?
2. What is the transfer rate of indoor air into the attic space?

The sampling was completed for two 1-week periods, December 8 to December 15, 2011 and February 20 to February 27, 2012. The air transfer rates calculated for these two periods represent average rates over these one week periods.

The tracer gas testing was done using a Perflourocarbon Tracer (PFT) method developed by Brookhaven National Laboratories (BNL). This method provides a convenient and practical method to measure air transfer rates in multi-zone buildings (Dietz et al 1985). Small passive sources and samplers are left in place for a period of time then sent to BNL to be analyzed and to determine the average transfer rates for a given period. PFTs are good tracers because they are very stable, not susceptible to oxidation in the atmosphere, and are present in the atmosphere at low levels. Low enough levels that small amounts of PFTs released in a building provide clear signals that can be easily and reliably absorbed by passive charcoal samplers. This method works on the steady-state assumption that over several days the average concentrations of the tracer vapour in a zone is equal to the emission rate of the tracer source, divided by the air leakage or infiltration rate. Knowing the rate from deployed passive PFT source and measuring the average concentration with passive samplers provides a means to calculate the air transfer rates.

Three types of PFTs were deployed in test units: on the second floor living room/kitchen, third floor hallway and into the attic. A small fan ran continuously in the attic to ensure the air was well mixed during the testing. Figure 8 illustrates the deployment of the tracers and samplers.

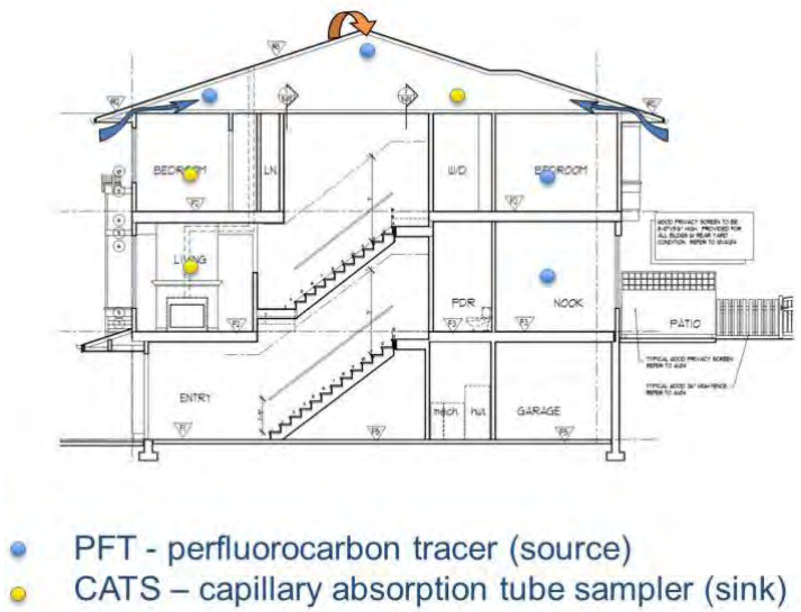

Figure 8: Tracer Gas Testing Experiential Program

4.4 Long Term Monitoring

SMT Research Ltd supplied and installed monitoring systems in the four test units and a control roof assembly not over conditioned space. Data was collected and downloaded to their website via the internet thus allowing the sensor readings to be reviewed every month. The sensors were installed in the units at the beginning of September and the end of September for the control roof. Readings were recorded every 15 minutes.

For each unit the following measurements were made:

Moisture content and temperature of the roof sheathing at three locations; at the vent baffles at soffit on opposite ends and the framing bay beside the baffles at the soffit (Photo 12);

a) Moisture content and temperature of top chord of truss at one location;
b) Condensation detection on sheathing at a baffle location;
c) Attic air temperature and relatively humidity;
d) Indoor air temperature and relatively humidity (Photo 13);

At the control assembly the following measurements were made:

a) Moisture content and temperature of the plywood sample installed at the underside of the roof underlayment (Photo 14);
b) Moisture content and temperature of a plywood sample with R5 rigid insulation installed between the underside of the roof structure and plywood sample;
c) Outdoor air temperature and relatively humidity (Photo 15).

Weather data was obtained from local environmental stations as needed for analysis.

Photo 12: *Sensor Set-up At Baffles*

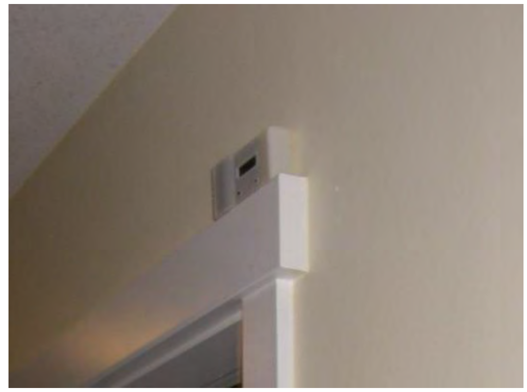

Photo 13: *Indoor Air Sensor*

Photo 14: *Control Assembly Sensors*

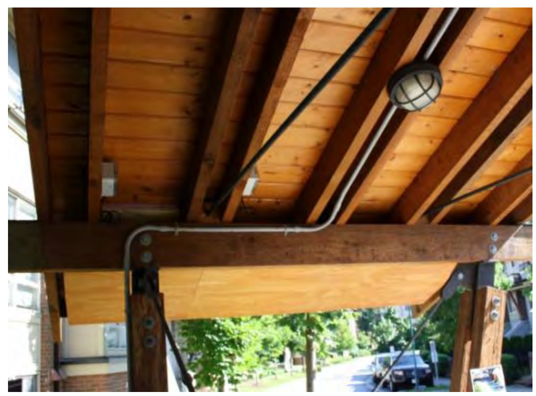

Photo 15: *Control Assembly Data Outdoor Air Measurements*

5. RESULTS

A summary of results of the testing and measurements is presented in this section. Analysis and discussion considering how the test and measurements is interconnected is presented in the next section.

5.1 Building Characterization and Smoke Testing

The attic venting area, including both intentional and unintentional openings, is presented in Table 3 for the measured pressure differential and is compared to the applicable required venting area required by code for the construction of the test attics (1:300 per insulated ceiling area).

Table 3: Measured Attic Venting Area compared to 1:300 Venting Area

Unit	Measured Venting Area	Insulated Area m^2 (ft^2)	Required Area (1/300 per insulated ceiling area)	% Measured Area / Required Area
1	2450 cm2 @ 40 Pa	60 (642)	1900 cm^2	129%
2	2435 cm2 @ 40 Pa	68 (728)	2160 cm^2	113%
3	3900 cm2 @ 40 Pa	57 (614)	1990 cm^2	196%
4	7530 cm2 @ 15 Pa	60 (642)	2315 cm^2	325%

The measured venting areas are higher than the average areas reported by the BLP (1991) and Sheltair (1997) studies and exceed the building code requirement by as much as three times.

The measured air leakage area for the attic ceiling, calculated normalized leakage area (NLA) and observations of the smoke test are summarized in Table 4. These values were derived using equation 43, Chapter 16 Ventilation and Infiltration, of the ASHRAE Handbook – Fundamentals to convert to a 10 Pa pressure differential basis.

Table 4: Measured and NLA Attic Ceiling Leakage Area and Smoke Test Observations

Unit	Measured Leakage Area	Calculated Normalized Leakage Area cm^2/ m^2 @ 10 Pa	Smoke Test Observations
1	110 cm^2 @ 40 Pa	1.6	Smoke at hatch
2	110 cm^2 @ 40 Pa	1.4	Smoke at hatch and the fresh air vent in the bedroom closet
3	160 cm^2 @ 40 Pa	2.2	Smoke at hatch and the fresh air vent in the washer/dryer closet
4	300 cm^2 @ 15 Pa	4	Smoke at hatch (less than others)

Comparison of the NLA values in Table 3 to the reported values in past Canadian studies (Buchan et al. 1991, Sheltair 1997, NRCan 1997) suggests that the ceiling airtightness of the units in this current study can be considered to have at least average airtightness levels, by Canadian standards, and a convincing argument can be made to classify the ceiling to attic interface as airtight.

The NLA values for units 1 and 2 are lower than all the leakage areas of the ceiling to attic interface for all the eight units measured in the Sheltair study, which is interesting because that study included three R-2000 houses[1]. Unit 4 with a NLA of 4, which is a less reliable value and likely lower in reality because of the difficulties identified in the previous section, is even lower than the measured R-2000 houses in Langley that were part of the Sheltair study.

Comparison of the reliable data for units 1 to 3, with NLA's 1.6 to 2.2, to the 1997 NLA Survey for whole building airtightness by National Resources Canada summarized in Table 5 further supports the argument that the study units have at least average airtightness at the ceiling to attic interface. The measured NLA's for the ceiling to attic interface of units 1 to 3 are close to the average NLA's for whole buildings but not for the R-2000 buildings. However, the ceiling interface NLA's for the study units are lower than all the R-2000 measurements in the Sheltair study, and built in the same period, and all R-2000 houses must meet a NLA of 0.7 for the entire house. Further recognizing that the normalized air leakage for the ceiling interface of a row townhouse with only 600 to 750 ft^2 area (55 to 70 m^2) and an attic hatch is likely higher than the overall whole building normalized area for detached homes, then there is a convincing argument that the ceiling interface are airtight for the study units[2].

Table 5: 1997 NLA Survey by National Resources Canada

Region	1981-1990	1991-1997	R-2000
B.C.	2.8	1.9	0.7
National	2.3	1.4	0.6

5.2 Tracer Gas Testing

The weekly average flow rates determined by tracer gas testing with comparison to the flow rates determined by fan testing at static pressure differentials are presented in Tables 5 and 6. In interpreting the results, it is important to keep in mind the objectives of the testing. The objective of the fan-testing is to provide an estimate of the attic venting and ceiling to attic air leakage areas, while the objective of the tracer gas testing is to provide the average air transfer rates over a specific time period. The purpose of comparing the flow rates is to show the relative difference and provide a general indication of the forces driving airflow compared to standard assumed pressure differentials.

1 Certified R-2000 houses must have airtightness testing to confirm that a level of airtightness of at least 1.5 ACH at 50 Pa or a NLA of 0.7 cm2/m2 (1.0 in2/100 ft2) is achieved.
2 This statement is largely based on recognizing the absolute leakage areas relative to the ceiling to wall area for the row townhouse, but it is also supported by the findings in the reference studies for detached houses (Buchan et al. 1991, Sheltair 1997).

The large difference between the attic venting rates suggests that on average there was not much wind pressure to induce ventilation during the tracer gas testing. Moreover, there were very few thermal forces to drive airflow through the attic. The average temperature difference between the attic and outdoor air was 1 to 2°C during the tracer gas testing periods, with periods during the nights where the attic air was below the exterior air temperature. The average wind speed, irrespective of direction, at a nearby weather station during the tracer gas testing was 0.6 m/s for the first period and 1.5 m/s for the second period. The test units are sheltered from the wind.

To demonstrate the order of magnitude flow rates derived by fan testing at a “standard” 4 Pa pressure differential, as presented in Table 6, we assumed an inlet area of half the total venting area. In reality, the inlet and outlet area are not likely equal and the airflows are much more complex than this simple extrapolation. The flow will be governed by the ratio of the inlet to outlet areas[3], the pressure distribution due to varying wind direction, and shelter provided by the adjacent row housing and woodland.

The average pressure difference due to wind was probably less than 0.5 Pa when accounting for the low wind speeds at the buildings during the tracer gas testing periods. This estimate is based on rough estimates for the pressure coefficients and shelter factors outlined in chapter 16 of the 2009 ASHRAE Handbook – Fundamentals. The flow rates determined by tracer gas testing and venting areas determined by fan testing appear to be aligned when the low wind speeds, shelter, pressure coefficients due to roof orientation and wind direction, and reduced inlet areas based on the venting area distribution are considered concurrently.

Table 6: Comparison between Measured Attic Ventilation Rates and Venting Rates Derived from Fan Testing

Unit	Tracer Gas Testing ACH (m^3/h)		Derived from Fan Testing, ACH (m^3/h) 4 Pa
	Round 1 (Dec. 8 to 15)	Round 2 (Feb. 20 to 27)	
1	1.2 (69.9)	1.0 (61.1)	8.3 (488)
2	1.3 (75.7)	1.2 (73.4)	8.3 (485)
3	2.6 (112.8)	3.7 (91.9)	18.2 (778)
4	4.1 (102.4)	2.1 (123.0)	58.7 (1475)

The attic ventilation rates measured by the tracer gases are in a range of 1 to 5 ACH, which represents 50% of the measured values in the Buchan et al. (1991) field study. The other reported ranges were 10% within 5 to 10 ACH, 30% within 10 to 15 ACH, and 10% greater than 15 ACH. The sampling period was one hour for the Buchan et al. (1991) study.

[3] Distribution of the intentional venting area in the attic is approximately 25% at the roof ridge and the remaining 75% distributed between the soffits at each end of the roof.

The ventilation rates are also within the range of 0 to 7 ACH measured for one of the research houses at the University of Alberta (Forest and Walker 1993) that had no intentional venting area added to the roof assembly. This is in contrast to a much wider range of 0 to 50 ACH for the attic with a venting area provided to meet the code requirement of 1:300 for the other research house. Given the wind exposure, the measured ventilation rates for this study are within the range of ventilation rates measured for the attic with a venting area per 1:300 for the University of Alberta study.

There was a temperature differential to drive air from the indoors to the attic, albeit less than the common assumption of 4 Pa. The average temperature difference between the indoor and outdoor air was between 13°C and 20°C for all the units during the two tracer gas testing periods. This temperature difference corresponds to a pressure difference, due to stack, between 1 to 2 Pa for a neutral plane level at 0.75 of the total building height.

The lower flow rates for the tracer gas testing compared to the fan testing can be fully explained by stack effect for the measured temperature differences with a neutral plane level in the range of 0.7 to 0.85 of the total building height. A NPL level in this range is consistent with NPL data for houses with exhaust systems, fresh air intakes and a chimney through the roof (NRCC 1995, ASRHAE 2009).

Table 7: Comparison between Measured Indoor to Attic Air Transfer Rates and Leakage Rates Derived from Fan Testing

Unit	Tracer Gas Testing CFM (m^3/h)		Derived from Fan Testing at 4 Pa CFM (m^3/h)
	Round 1 (Dec. 8 to 15)	Round 2 (Feb. 20 to 27)	
1	16.5 (28.0)	11.4 (19.3)	26.2 (44.5)
2	16.4 (27.8)	8.5 (14.4)	26.2 (44.5)
3	18.8 (32.0)	11.7 (19.9)	38.1 (64.7)
4	18.5 (31.4)	12.6 (21.4)	82.7 (140.5)

For the Buchan et al. (1991) study, the indoor to attic air transfer rate was determined by tracer gas testing for eight of the 20 units. The flow rate ranged from 2 to 85 CFM (3 to 144 m^3/h) and the average rate was 31 CFM (52 m^3h). The measured rates for the all the units in this current study are much lower than the average Buchan et al. (1991) measured rates. The rates are however higher, roughly double, than the 5 to 7 CFM (12 to 15 m^3/hr) measured for two research houses at the University of Alberta during extremely cold weather (1993).

5.3 Monitoring

This sub-section presents observations and analysis specific to the monitoring of the indoor, outdoor, attic and control spaces. Discussion of the monitoring in context to the other measurements, building characterization and air transfer rates, is presented in Section 6, Analysis and Discussion.

First, we note that there were many difficulties with the monitoring equipment during the winter of this study. Though this was disappointing and made the analysis more difficult, there was fortunately enough data to test our hypothesis and meet the objectives of this study. The periods of missing data will not be specifically highlighted in this report unless relevant to the discussion. Graphs showing the monitoring data for each sensor can be found in Appendix A.

Many of the previous Canadian studies indicated that moisture problems in attics were generally not evident without the presence of high indoor humidity. The units that were part of this study do not follow this trend. The measured indoor humidity during the heating season of 2011 to 2012, in all the units, is considered within normal operating conditions; higher moisture levels are often assumed for the design of building envelope assemblies. Table 8 summarizes the indoor conditions measured for the test units. A ∆VP of approximately 800 Pa is considered high, 550 Pa moderate, and 250 low (Roppel et al 2009, ISO 13788-01).

The difference in vapour pressure between the indoor and outdoor air, ∆VP, is a useful metric to categorize indoor moisture levels, since indoor relative humidity is variable depending on the outdoor conditions and indoor operating temperature (Roppel et al 2009). Comparing the ∆VP for the test units shows that the indoor moisture levels in the study units ranged from low to moderately high during the monitored heating season (December 1, 2011 to March 15, 2012).

Table 8: Measured Indoor Conditions

Unit	Average Temperature (°C)	Average RH (%)	95% Percentile Dewpoint Temperature (°C)	Average ∆VP (Pa)	95% Percentile ∆VP (Pa)	99% Percentile ∆VP (Pa)
Outdoors	**6.9**	**84.4**	**8.5**	**N/A**	**N/A**	**N/A**
1[4]	24.1	30.7	9.3	250	600	750
2	22.1	40.7	10.7	250	450	550
3	19.1	37.5	7.1	0	200	300
4	23.3	32.8	9.0	100	300	500

5.3.1 Long-Term Trends

The staining and occurrence of high sheathing moisture levels are correlated, but the highest moisture for the longest duration did not necessarily coincide with the most visible staining. For example the heaviest staining was observed at unit 1 at the east baffle, unit 2 at the east baffle, and unit 3 at the west baffle, but some of the highest moisture levels were recorded at units 1, 2, and 3 at the east non-baffle location[5]. Figure 9 summarizes the duration (hours) of elevated sheathing moisture levels and Table 9 summarizes observations of staining at the sensor locations at the start of

[4] Unit 1 has data only available for December 2011 and January 2012
[5] The sensors at Unit 3 west soffit, the location with the most visible staining, malfunctioned during critical wetting periods

the monitoring period. Pictures showing the condition of the wood at the time of the installation of the sensors are in Appendix B.

The general long-term trend of the sheathing and truss wood moisture levels during the monitoring period was the following:

- **East soffit, baffle and non-baffle**: the sheathing moisture levels were above 25% from the beginning of December to the end of February.
- **West soffit, baffle and non-baffle**: the sheathing moisture levels were above 20% MC but generally below 25% MC from the beginning of December to the end of February. The exception was unit 2, west non-baffle location, where moisture levels above 25% MC were recorded.
- **North soffit, non-baffle**: the sheathing moisture levels rose above 20% MC at the end of November; maintained levels around 25% MC until the end of January; and were trending below 20% MC at the end of the monitoring period (mid-March).
- **North soffit, baffle, and south soffit, baffle and non-baffle**: the sheathing moisture levels were generally below 20% MC during the monitoring period
- **Control assembly, insulated and un-insulated**: the sheathing moisture levels rose above 20% MC in October; maintained levels around 25% MC until the end of February; and were trending below 20% MC at the end of the monitoring period (mid-March).
- All the **truss** sensors were below 20% MC for the entire monitoring period.

Two significant moisture spikes occurred that affected the long-term sheathing moisture levels of the east soffit for units 1, 2, and 3 during the winter of 2011/2012. These events are discussed further in the next sub-section, diurnal wetting.

The west and south sheathing benefit more from solar heating than the north and east elevations, but all the elevations experience similar night sky cooling. Night sky cooling and solar heating are important factors for the elevated sheathing moisture levels, but exposure to outdoor air and moisture appears to be the critical reason for the elevated sheathing moisture levels. This statement is drawn from the observation that the control assemblies have moisture levels near 25% MC, regardless of thermal resistance outboard the plywood sheathing, and the control assemblies are strongly linked to the outdoor air and do not have any moisture source from the indoor air. The attic sheathing takes longer to reach elevated moisture levels than the control assembly sheathings, but eventually reaches similar levels as the sheathings absorb moisture with decreasing outdoor temperatures, ventilation, and higher relative humidity. Exterior air will pass the non-baffle locations, similar to the baffle locations but likely at different rates, because airflow is not greatly restricted by the insulation. The sheathing at the soffits will pick up the most moisture because this is the entry point of outdoor air and the coolest surface temperatures. Spikes in the sheathing moisture levels observed in the monitoring over a period of a day are presented in the next section.

Table 9: Staining Pattern Observed at Sensor Locations

Unit	Moderate to Heavy – Field Area Spotty or Covered	Light – localized at Fasteners	No visible Staining
1	East: baffle	East: non-baffle, West: baffle & non-baffle	East: truss West: truss
2	East: baffle	East: non-baffle West: baffle & non-baffle	East: truss West: truss
3	West: baffle	East: baffle & non-baffle West: non-baffle	East: truss West: truss
4	North: non-baffle	North: baffle	South: baffle &non-baffle South: truss

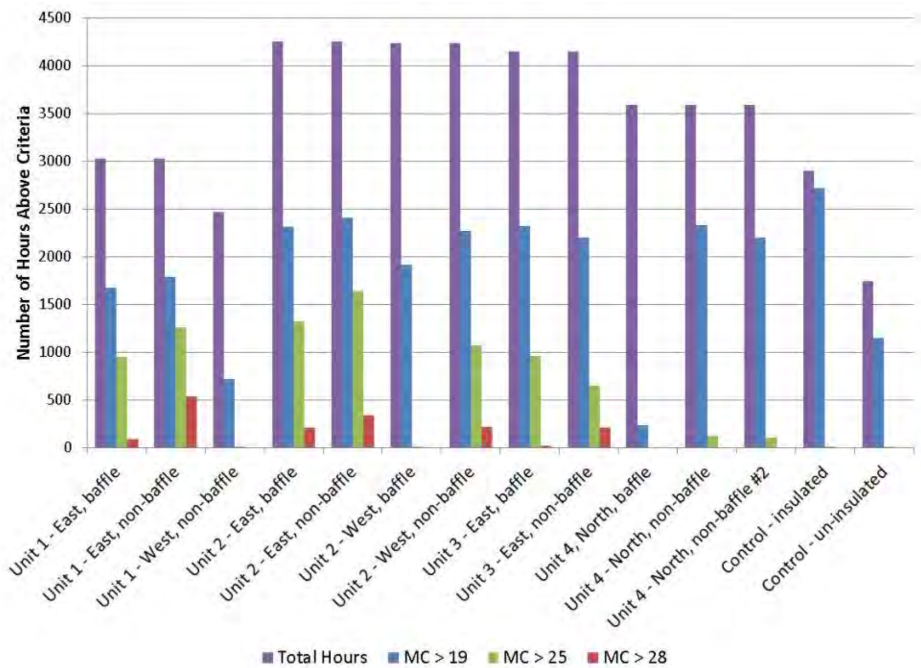

Figure 9: Duration of Elevated Sheathing Moisture Levels

Another important observation showing that outdoor air is the principal source of wetting of the attic sheathing is the attic air has essentially the same overall moisture level as the outdoor air. Figure 10 and 11 shows the attic air moisture content for unit 1 compared to the outdoor air moisture content. The time series graph in Figure 13 shows that the attic air follows the same trend as the outdoor air. The scatter plot in Figure 14 shows that, on average, the attic and outdoor air are at the same moisture levels, with the attic air being slightly drier than the outdoor air at high moisture content levels.

Note that the times where the attic air moisture content levels are higher than the outdoor moisture levels coincide with decreasing moisture content levels in the sheathing and elevated sheathing temperatures, i.e. moisture is driven out of/into the wood to/from the attic air depending on the relative difference in vapour pressures.

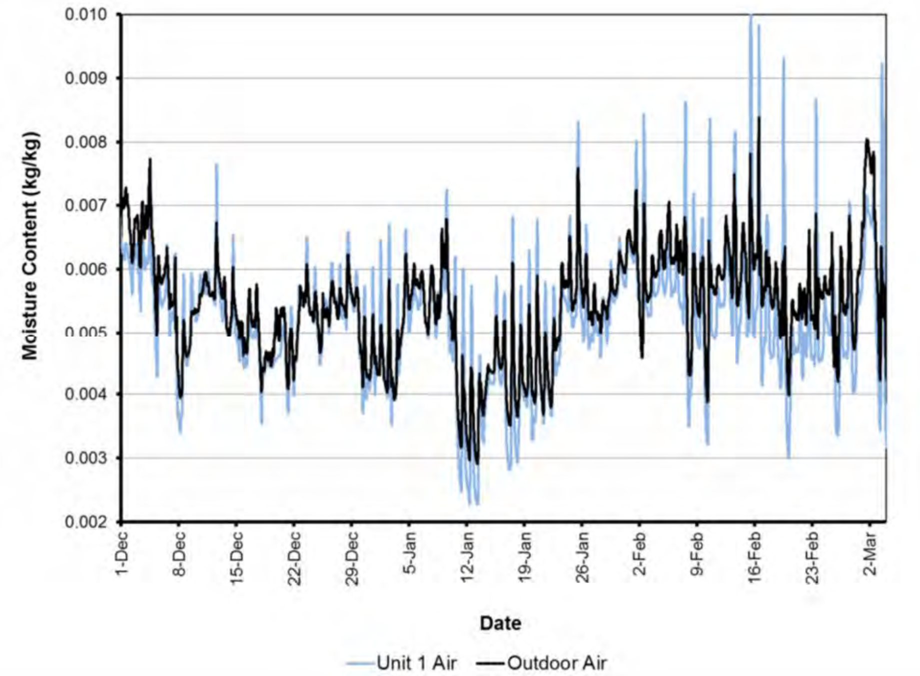

Figure 10: Unit 1 Attic and Outdoor Air Moisture Levels Per Time

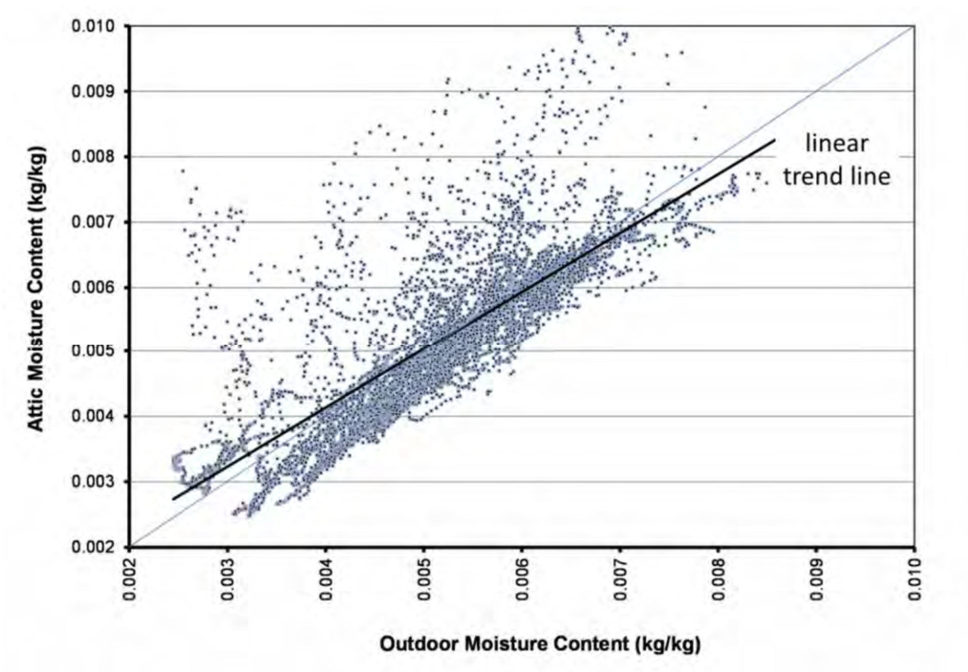

Figure 11: Unit 1 Attic versus Outdoor Air Moisture Levels

5.3.2 Diurnal Wetting

Sharp spikes in the sheathing moisture content occurred in all the units at the same time and appeared to happen when moisture was deposited by condensation or frost as a result of cooled attic air and surfaces by night sky radiation that was subsequently exposed to warmer humid outdoor air as temperatures rose in the daytime. Figure 11 illustrates these conditions for unit 1 on December 12, 2011. Review of the weather records for the night before this wetting event showed periods of clear skies during the night, and this was also the case for the night before the significant wetting period on January 12, 2012.

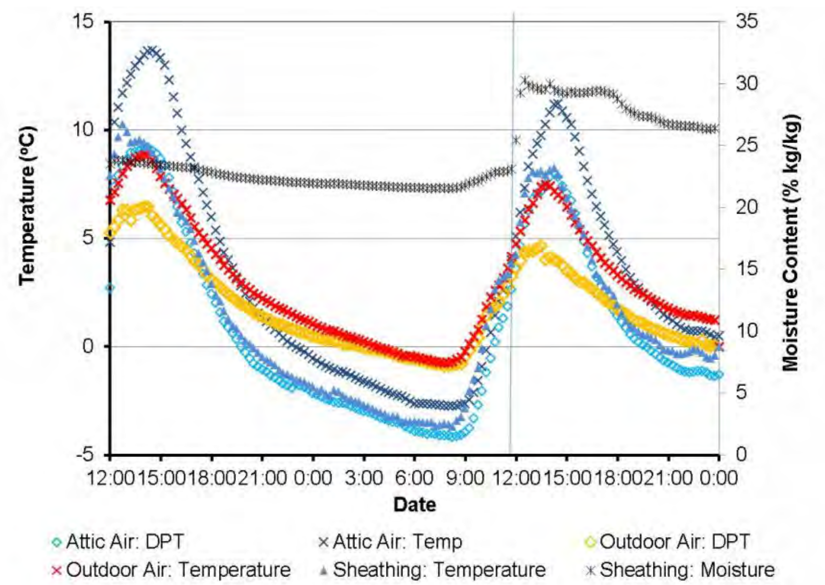

Figure 12: Unit 1 Sheathing Moisture Spike After Night-sky Cooling on December 12, 2012

6. CONCLUSIONS

The average attic ventilation rates measured in this study are low despite the abundant venting area. Nevertheless, these low rates appear to be sufficient enough to dilute any moisture transfer from the interior air to the attic space. The ceiling between the indoor and attic space appears to be relatively airtight, compared to other studies and expected values, and the transfer of air from the indoor to attic space does not appear to be a significant contributing factor to the moisture problems observed in the attics. Moreover, the average attic air moisture content is very close to the moisture content of the exterior air. Though the background moisture content of the attic sheathing appears to be largely dependent on the exterior air moisture levels, there are diurnal cycles due to daytime solar gains and nighttime radiative losses that result in differences of the sheathing moisture MC for the various locations. The fact that the moisture levels of the plywood sheathings in the control assemblies also reached elevated levels, up to 25% MC, suggests that higher ventilation rates will not significantly decrease the moisture levels in the attic and will not alleviate the occurrence of staining.

The attics in this study and the measured data are distinctive in the context of previous Canadian studies into the connection of attic ventilation and the hydrothermal performance of wood-framed attics because:

1. The attic construction with regard to controlling the heat-air-moisture flows represent current good practice
2. Venting areas and distribution are per or exceed code
3. A reasonable level of airtightness of the attic ceiling has been achieved
4. All ducts and plumbing that penetrate through the attic are brought up to the roof sheathing and are sealed, with no indication that they are contributing to higher moisture loads in the attic space
5. The indoor moisture loads are principally low to moderate levels
6. Despite all the above, the attics are getting wet leading to localized staining on the plywood sheathing near the soffits

The implication is that the provision of venting area and an airtight ceiling alone is not enough to limit mold growth in insulated wood-framed attics in marine climates. More ventilation will not solve the problem for attics constructed similar to the ones in this study and experience has shown us that less ventilation can lead to problems if an airtight ceiling is not achieved in practice.

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APPENDIX A – TRACER GAS RESULTS

A.1 1st Round December 2011 Installation Logs

Project Title: ______

House Description:
- ___ 1 Story
- X 2 Story
- ___ w /basement
- ___ split level
- X w /fireplace
- ___ w /woodstove

House ID: Unit 41 **# of Zones** ___

Start Date: 12/08/11 **Start Time:** 11:00 (am) pm (Circle one)

Stop Date: 12/15/11 **Stop Time:** 5:00 am (pm)

Zone # 1 **Zone ID** 2nd Floor **# of Sources** 1 **Source Color:** Brown
Avg Temp (°F) 75.5 (°C) 24.2 Volume (ft^3) 6991 (m^3) 198 # of CATS: 1

CATS ID	Room	Item Placed On	Source Location Room	Item Placed On
01715	Kitchen Island			

Zone # 2 **Zone ID** 3rd Floor **# of Sources** 1 **Source Color:** Purple
Avg Temp (°F) 75.5 (°C) 24.2 Volume (ft^3) 5175 (m^3) 147 # of CATS: 1

CATS ID	Room	Item Placed On	Source Location Room	Item Placed On
01012	Hall			

Zone # 3 **Zone ID** Attic **# of Sources** 1 **Source Color:** Red
Avg Temp (°F) 46.7 (°C) 8.1 Volume (ft^3) 2072 (m^3) 59 # of CATS: 2

CATS ID	Room	Item Placed On	Source Location Room	Item Placed On
00845	South			
01560	North			

Zone # ___ **Zone ID** ___ **# of Sources** ___ **Source Color:** ___
Avg Temp (°F) ___ (°C) ___ Volume (ft^3) ___ (m^3) ___ # of CATS: ___

CATS ID	Room	Item Placed On	Source Location Room	Item Placed On

Project Title: ____________________

House Description:
- ____ 1 Story
- X 2 Story
- ____ w /basement
- ____ split level
- X w /fireplace
- ____ w /woodstove

House ID: Unit 45 **# of Zones** 3

Start Date: 12/08/11 **Start Time:** 9:00 (am) pm (Circle one)

Stop Date: 12/16/11 **Stop Time:** 10:30 (am) pm

Zone # 1 **Zone ID** 2nd Floor **# of Sources** 1 **Source Color:** brown
Avg Temp (°F) 71.8 (°C) 22.1 Volume (ft³) 7841 (m³) 222 # of CATS: 1

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
00251	Family	Lamp		

Zone # 2 **Zone ID** 3rd Floor **# of Sources** 1 **Source Color:** purple
Avg Temp (°F) 71.8 (°C) 22.1 Volume (ft³) 5865 (m³) 166 # of CATS: 1

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
01082	hall	picture fram		

Zone # 3 **Zone ID** Attic **# of Sources** 1 **Source Color:** Red
Avg Temp (°F) 41.1 (°C) 5.1 Volume (ft³) 2072 (m³) 59 # of CATS: 2

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
03296		Truss east side		
00768		Truss west side		

Zone # ______ **Zone ID** ______ **# of Sources** ______ **Source Color:** ______
Avg Temp (°F) ______ (°C) ______ Volume (ft³) ______ (m³) ______ # of CATS: ______

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On

Project Title: ______

House Description:
- ___ 1 Story
- X 2 Story
- ___ w /basement
- ___ split level
- X w /fireplace
- ___ w /woodstove

House ID: Unit 51 **# of Zones** 3

Start Date: 12/08/11 **Start Time:** 10:00 (am) pm (Circle one)

Stop Date: 12/15/11 **Stop Time:** 5:30 am (pm)

Zone # 1 **Zone ID** 2nd Floor **# of Sources** 1 **Source Color:** Brown
Avg Temp (°F) 66.1 (°C) 19.0 Volume (ft³) 6710 (m³) 190 # of CATS: 1

CATS ID	Room	Item Placed On	Source Location Room	Item Placed On
00062	Kitchen Island			

Zone # 2 **Zone ID** 3rd Floor **# of Sources** 1 **Source Color:** Purple
Avg Temp (°F) 66.1 (°C) 19.0 Volume (ft³) 4946 (m³) 140 # of CATS: 1

CATS ID	Room	Item Placed On	Source Location Room	Item Placed On
00279	Hall			

Zone # 3 **Zone ID** Attic **# of Sources** 1 **Source Color:** Red
Avg Temp (°F) 43.9 (°C) 6.6 Volume (ft³) 888 (m³) 25 # of CATS: 2

CATS ID	Room	Item Placed On	Source Location Room	Item Placed On
00103	South side			
00156	North side			

Zone # ___ **Zone ID** ___ **# of Sources** ___ **Source Color:** ___
Avg Temp (°F) ___ (°C) ___ Volume (ft³) ___ (m³) ___ # of CATS: ___

CATS ID	Room	Item Placed On	Source Location Room	Item Placed On

Project Title: ____________________

House Description:
____ 1 Story
X 2 Story
____ w /basement
____ split level
X w /fireplace
____ w /woodstove

House ID: Unit 127 **# of Zones** ____

Start Date: 12/08/11 **Start Time:** 1:30 Circle one: am (pm)

Stop Date: 12/16/11 **Stop Time:** 9:00 (am) pm

Zone # 1 **Zone ID** 2nd Floor **# of Sources** 1 **Source Color:** Brown
Avg Temp (°F) 72.7 (°C) 22.6 Volume (ft³) 6993 (m³) 198 # of CATS: 1

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
00750				

Zone # 2 **Zone ID** 3rd Floor **# of Sources** 1 **Source Color:** Purple
Avg Temp (°F) 72.7 (°C) 22.6 Volume (ft³) 5176 (m³) 147 # of CATS: 1

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
00136				

Zone # 3 **Zone ID** Attic **# of Sources** 1 **Source Color:** Red
Avg Temp (°F) 46.5 (°C) 8.0 Volume (ft³) 2072 (m³) 59 # of CATS: 2

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
00114	North			
03105	South			

Zone # ____ **Zone ID** ____ **# of Sources** ____ **Source Color:** ____
Avg Temp (°F) ____ (°C) ____ Volume (ft³) ____ (m³) ____ # of CATS: ____

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On

A.2 1st Round December 2011 Brookhaven National Laboratory Data Analysis Report

Data Analysis Report

Terry Sullivan
Brookhaven National Laboratory

January 6, 2012

Vancouver Housing Study

Perfluorocarbon tracer (PFT) tests were performed in four housing units in Vancouver. These units have a garage and entrance to the living area on the first floor, a living area on the 2nd and 3rd floors, and an attic. The objective of the study was to measure the air exchange rates between the living area and the attic and the total rate of air exchange in the attic. The test plan placed a unique PFT source on each floor in the living area and the attic. PFT sampling was achieved using a Capillary Adsorption Tube Sampler (CATS) filled with a sorbing media. One CATS was placed on each level in the living area. A fan was placed in the attic to ensure good mixing in this zone. Two CATS were used in the attic. The sources and CATS samplers were in place for approximately one week to allow an approximation of average (e.g. steady-state like) conditions.

To calculate air exchange rates requires the volume of each zone, temperature, source release rate (dependent on temperature), duration of exposure and the measured PFT concentration. This information is entered into the AIMS computer program which can compute flows between zones for up to eight different source zones. Table 1 presents the volumes for each zone.

Table 1 Volumes of each zone in the analysis.

Volume (m^3)	2nd Floor	3rd Floor	Interior	Attic
Unit 41	198	147	345	59
Unit 45	222	166	388	59
Unit 51	190	140	330	43
Unit 127	198	147	345	25

The interior volume is the sum of the 2nd and 3rd floor volumes. The temperatures were recorded automatically every ten minutes. The average temperatures in the zones were used to estimate the source release rates. Analysis showed that for the range of temperatures in this study this leads to less than 2% error as compared to calculating a release rate at each of the more than 1000 measured temperatures. There was an issue with the temperature recorder in the attic of Unit 45 for the first few days. Examining the temperature plots of all of the attics showed that when the temperature recorder in Unit 45 was working, the temperature was almost identical to that in Unit 51. Therefore, the Unit 51 average attic temperature was used in the analysis. Table 2 provides the average temperature in each unit. The time of exposure of the CATS and location in each unit were documented on data sheets used in the field.

Table 2 Average temperatures.

	Interior Temperature (°C)	Attic Temperature (° C)	Exposure duration (hours)
Unit 41	24.2	8.1	174
Unit 45	22.1	6.6*	193.5
Unit 51	19.0	6.6	174.5
Unit 127	22.6	8.0	187.5

* Used Unit 51 value due to malfunction of the temperature probe during the first day.

The nominal source rates at 21.5 C are presented in Table 3. The same type of source was used in each zone of the four units. These are adjusted using the average temperatures in Table 2 to calculate the PFT release rate.

Table 3 Nominal source rates and CATS exposure duration.

Source	Zone	Location	Rate (nl/min)
PDCB	1	2nd floor	41.1
iPPCH	2	3rd floor	7.55
PMCH	3	Attic	26.4

Concentration Results

The samples were analyzed using a gas chromatograph at BNL. The total amount of tracer in pL/L (10^{-12}) for each location is presented in Table 4. Examining table 4 shows two interesting results. First, CATS 1082 is blank (highlighted in red). There was either a problem in deployment or analysis of this CATS and the results are not useable. The second fact is that although PDCB was released on the 2^nd^ floor (Table 3) it had a higher measured amount on the third floor. If the second floor air was well mixed (i.e. the tracer concentration was close to uniform on the floor) this could not occur. This suggests a short circuit pathway to the third floor between the source and the collection point on the second floor. Most likely this short circuit pathway is the stairs between the two floors. Considering that the air return ducts are in the top of the stairway at the 3^{rd} floor in all units further supports this theory. In Unit 45 there was an air return near the stairs on the 2^{nd} floor as well. In this case, the measured concentrations on the 2nd floor were similar to the measured concentrations on the 3^{rd} floor in the other units, further supporting the thought that the stairs act as a short circuit. In the three other units, the air return on the first floor was in the kitchen. Further, the ratio of source rate to concentration of the 3^{rd} floor PDCB and iPPCH and their sum:

	PDCB	iPPCH	Sum of 2
R = S/C =	2738/20.22	503/3.79	3241/24.01
=	135.4	132.7	135.0

Are essentially identical. This suggests that the 3rd floor concentration data are the appropriate measure of the average concentrations in the living area. Table 5 shows the PFT concentrations used in the analysis. These are based on the PFT volumes in Table 4, the PFT sampling rate based on diffusion, and the time of exposure. Table 5 combines the PDCB and iPPCH concentrations from the 3rd floor. .

Table 4 Measured PFT Concentrations (pL/L)

	CATS ID	Location	PDCB (pL/L)	iPPCH (pL/L)	PMCH (pL/L)
Unit 41	1715	2nd floor	4.01	2.34	0.14
	1012	3rd floor	20.22	3.79	0.19
	845	Attic	7.86	1.92	12.88
	1560	Attic	7.56	1.88	13.43
Unit 45	251	2nd floor	15.45	1.80	0.53
	1082	3rd floor	0.01	0.00	0.00
	3296	Attic	5.08	1.41	11.70
	768	Attic	4.82	1.34	11.32
Unit 51	62	2nd floor	5.33	1.08	0.12
	279	3rd floor	16.33	2.01	0.16
	103	Attic	4.04	1.17	7.37
	156	Attic	4.01	1.20	7.91
Unit 127	750	2nd floor	3.42	2.32	0.10
	136	3rd floor	15.12	2.97	0.12
	114	Attic	3.56	1.04	8.04
	3105	Attic	5.15	1.33	9.80

The agreement between the two locations in the attic indicates that this zone was well mixed except in Unit 127. The source rate for the interior zone was the sum of the PDCB and iPPCH values (Table 3) and the interior volume was the sum of the 2nd and 3rd floor volumes (Table 1).

Table 5 PFT effective concentrations (pL/L) used for air flow analysis.

	CATS ID	Location	PDCB + iPPCH	PMCH
Unit 41	1012	Interior	24.01	0.19
	845	Attic	9.79	12.88
	1560	Attic	9.44	13.43
Unit 45	251	Interior	17.23	0.53
	3296	Attic	6.49	11.7
	768	Attic	6.16	11.32
Unit 51	279	Interior	18.34	0.16
	103	Attic	5.21	7.37
	156	Attic	5.21	7.91
Unit 127	136	Interior	18.09	0.12
	114	Attic	4.6	8.04
	3105	Attic	6.49	9.8

Table 6 Interior zone infiltration rate (m^3/h) and ACH (h^{-1})

	Interior Infiltration Rate		Interior Air Changes per hour	
	m^3/h	SD	m^3/h	SD
Unit 41	135.8	16.6	0.39	0.05
Unit 45	176.4	21.8	0.46	0.06
Unit 51	145	17.8	0.44	0.06
Unit 127	169.1	20.7	0.49	0.07

Table 7 Attic zone infiltration rate (m^3/h) and ACH (h^{-1})

	Attic infiltration Rate		Air Changes per hour	
	m^3/h	SD	m^3/h	SD
Unit 41	70.2	5.3	1.19	0.11
Unit 45	69.9	5.3	1.19	0.11
Unit 51	75.7	5.6	1.28	0.12
Unit 127	112.8	9.7	2.62	0.26

Table 8 Air exchange between the interior and attic.

	Interior to Attic		Attic to Interior	
	m^3/h	SD	m^3/h	SD
Unit 41	28	3.6	2.0	0.3
Unit 45	27.8	3.7	8.2	1.3
Unit 51	32	4.2	3.0	0.5
Unit 127	31.4	9.6	2.2	0.5

Flow Results

Tables 6 – 7 document the flow results from the tests. Table 6 shows the infiltration rate for the interior of the building and the number of air changes per hour (ACH). Each of these measurements is presented with an estimate of the standard deviation (SD) based on uncertainties in the volume (5%), source rate (7%) and measured concentrations (10% or based on measured concentrations if more than one sample in the zone). This is for the two zones in the calculation (interior and attic). Table 7 shows the infiltration rate and ACH into the attic. The infiltration rates into the attics of Units 41, 45, and 51 were similar. The air exchange rate of the attic on Unit 127, which is half the size of the other attics, was higher. Table 8 shows the air exchange rate between the interior and attic in both directions. The air exchange rate between the interior and the attic was essentially the same in all units. The air exchange from the attic to the interior was similar in Units 41, 45, and 127 and substantially higher in Unit 45. The full output of results is provided in the EXCEL spreadsheet VANCOUVER.XLS.

The results in Table 6 – 8 are based on the 3rd floor data (2nd floor data for Unit 45 where the 3rd floor data was not useable). Using the average of the 2nd and 3rd floor data would not significantly change the results in Table 8. However, it would reduce the average concentration in the interior which would lead to higher predicted infiltration into the interior and higher flow rates from the interior to the attic.

A.3 2nd Round March 2012 Installation Logs

Project Title: ______

House Description:
- ____ 1 Story
- ✓ 2 Story
- ✓ w /basement
- ____ split level
- ____ w /fireplace
- ____ w /woodstove

House ID: 41 **# of Zones** 3

Start Date: Feb 20th/12 **Start Time:** 4:30 Circle one: am (pm)

Stop Date: Feb 27/12 **Stop Time:** 6:00 am (pm)

Zone # 1 **Zone ID** Attic **# of Sources** 1 **Source Color:** Red
Avg Temp (°F) 46.2 (°C) 7.9 Volume (ft^3) 2072 (m^3) 59 # of CATS: 2

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
03679	North	Joist		
03451	South	Joist		

Zone # 2 **Zone ID** 3rd Floor **# of Sources** 1 **Source Color:** Purple
Avg Temp (°F) 75.4 (°C) 24.1 Volume (ft^3) 5175 (m^3) 147 # of CATS: 1

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
06817	Hallway	Wall		

Zone # 3 **Zone ID** 2nd Floor **# of Sources** 1 **Source Color:** Brown
Avg Temp (°F) 75.4 (°C) 24.1 Volume (ft^3) 6991 (m^3) 198 # of CATS: 1

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
00862	Kitchen	Kitchen Island		

Zone # ____ **Zone ID** ____ **# of Sources** ____ **Source Color:** ____
Avg Temp (°F) ____ (°C) ____ Volume (ft^3) ____ (m^3) ____ # of CATS: ____

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On

Project Title: ____________

House Description:
____ 1 Story
✓ 2 Story
✓ w /basement
____ split level
____ w /fireplace
____ w /woodstove

House ID: 45 **# of Zones** 3

Start Date: Feb 20th/12 **Start Time:** 6:30 Circle one: am (pm)

Stop Date: Feb 27th/12 **Stop Time:** 6:30 am (pm)

Zone # 1 **Zone ID** Attic **# of Sources** 1 **Source Color:** Red
Avg Temp (°F) 47.5 (°C) 8.6 Volume (ft^3) 2672 (m^3) 59 # of CATS: 2

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
05050	South	Joist		
60001	North	Joist		

Zone # 2 **Zone ID** 3rd Floor **# of Sources** 1 **Source Color:** Purple
Avg Temp (°F) 71.2 (°C) 21.8 Volume (ft^3) 5865 (m^3) 166 # of CATS: 1

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
05305	Hallway	Picture frame		

Zone # 3 **Zone ID** 2nd Floor **# of Sources** 1 **Source Color:** Brown
Avg Temp (°F) 71.2 (°C) 21.8 Volume (ft^3) 7841 (m^3) 222 # of CATS: 1

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
04822	Living Room	light		

Zone # ____ **Zone ID** ____ **# of Sources** ____ **Source Color:** ____
Avg Temp (°F) ____ (°C) ____ Volume (ft^3) ____ (m^3) ____ # of CATS: ____

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On

Project Title: ____________

House Description:
- ____ 1 Story
- ✓ 2 Story
- ✓ w /basement
- ____ split level
- ____ w /fireplace
- ____ w /woodstove

House ID: 51 **# of Zones** 3

Start Date: Feb 20th/12 **Start Time:** 5:30 Circle one am (pm)

Stop Date: Feb 27th/12 **Stop Time:** 5:30 am (pm)

Zone # 1 **Zone ID** Attic **# of Sources** 1 **Source Color:** Red
Avg Temp (°F) 47.5 (°C) 8.6 Volume (ft³) 888 (m³) 25 # of CATS: 2

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
✓ 05105	North	Joist		
✓ 05658	South	Joist		

Zone # 2 **Zone ID** 3rd Floor **# of Sources** 1 **Source Color:** Purple
Avg Temp (°F) 67.8 (°C) 19.9 Volume (ft³) 4946 (m³) 140 # of CATS: 1

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
✓ 01997	Hallway			

Zone # 3 **Zone ID** 2nd Floor **# of Sources** 1 **Source Color:** Brown
Avg Temp (°F) 67.8 (°C) 19.9 Volume (ft³) 6710 (m³) 190 # of CATS: 1

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
✓ 01636	kitchen	kitchen Island		

Zone # ____ **Zone ID** ____ **# of Sources** ____ **Source Color:** ____
Avg Temp (°F) ____ (°C) ____ Volume (ft³) ____ (m³) ____ # of CATS: ____

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On

Project Title: ____________

House Description:
- ___ 1 Story
- ✓ 2 Story
- ✓ w /basement
- ___ split level
- ___ w /fireplace
- ___ w /woodstove

House ID: 127 **# of Zones** 3

Start Date: Feb 20th **Start Time:** 12:30 am (pm) (Circle one)

Stop Date: Feb 27th/17 **Stop Time:** 7:30 am (pm)

Zone # 1 **Zone ID** Attic **# of Sources** 1 **Source Color:** Red
Avg Temp (°F) 48.0 (°C) 8.9 Volume (ft³) 2072 (m³) 59 # of CATS: 2

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
00041	North	Post		
05975	South	Post		

Zone # 2 **Zone ID** 3rd Floor **# of Sources** 1 **Source Color:** Purple
Avg Temp (°F) 72.7 (°C) 22.6 Volume (ft³) 5176 (m³) 147 # of CATS: 1

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
05579	Hallway	wall		

Zone # 3 **Zone ID** 2nd Floor **# of Sources** 1 **Source Color:** Brown
Avg Temp (°F) 72.7 (°C) 22.6 Volume (ft³) 6993 (m³) 198 # of CATS: 1

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On
04607	Kitchen	Island wall		

Zone # ____ **Zone ID** ____ **# of Sources** ____ **Source Color:** ____
Avg Temp (°F) ____ (°C) ____ Volume (ft³) ____ (m³) ____ # of CATS: ____

CATS ID	Room	Item Placed On	Source Location Room	Source Location Item Placed On

A.4 2nd Round March 2012 Brookhaven National Laboratory Data Analysis Report

Data Analysis Report

Terry Sullivan
Brookhaven National Laboratory

March 20, 2012

Vancouver Housing Study

Perfluorocarbon tracer (PFT) tests were performed in four housing units in Vancouver during February, 2012. These units have a garage on the first floor, two floors of living area and an attic. The objective of the study was to measure the air exchange rates between the living area and the attic and the total rate of air exchange in the attic. The test plan placed a unique PFT source on each floor in the living area and the attic. PFT sampling was achieved using a Capillary Absorption Tube (CAT) filled with a sorbing media. One CAT was placed on each level in the living area. A fan was placed in the attic ensure good mixing in this zone. Two CATs were used in the attic. The sources and CAT samplers were in place for approximately one week to allow an approximation of average (e.g. steady-state like) conditions. These same units were tested in December, 2011 with identical placement of CATS and sources.

To calculate air exchange rates requires the volume of each zone, temperature, source release rate (dependent on temperature), duration of exposure and the measured PFT concentration. This information is entered into the AIMS computer program which can compute flows between zones for up to eight different source zones. Table 1 presents the volumes for each zone.

Table 1 Volumes of each zone in the analysis.

Volume (m^3)	2nd Floor	3rd Floor	Interior	Attic
Unit 41	198	147	345	59
Unit 45	222	166	388	59
Unit 51	190	140	330	25
Unit 127	198	147	345	59

The interior volume is the sum of the 2^{nd} and 3^{rd} floor volumes. The temperatures were recorded automatically every ten minutes. The average temperature in the zone was used to estimate the source release rates. Previous analysis showed that for the range of temperatures in this study this leads to less than 2% error as compared to calculating a release rate at each of the more than 1000 measured temperatures. There was an issue with the temperature recorder in the indoor space of Unit 41 and in the indoors and attic of Unit 51. However, temperature estimates were provided on the data sheets. Table 2 provides the average temperature in each unit. The time of exposure of the CATS and location in each unit were documented on data sheets used in the field.

Table 2 Average temperatures.

	Interior Temperature (°C)	Attic Temperature (° C)	Exposure duration (hours)
Unit 41	24.1	7.9	169.5
Unit 45	21.9	8.0	168
Unit 51	19.9	8.6	168
Unit 127	22.6	8.9	175

The nominal source rates at 21.5 C are presented in Table 3. The same type of source was used in each zone of the four units. These are adjusted using the average temperatures in Table 2 to calculate the PFT release rate.

Table 3 Nominal source rates and CATs exposure duration.

Source	Zone	Location	Rate (nl/min)
PDCB	1	2nd floor	41.1
iPPCH	2	3rd floor	7.55
PMCH	3	Attic	26.4

Concentration Results

The samples were analyzed using a gas chromatograph at BNL. The total amount of tracer in pL (10^{-12}) for each location is presented in Table 4. Examining table 4 shows that the interior concentrations were well mixed with similar values on the 2nd and 3rd floor. However, the PDCB released on the 2nd floor (Table 3) had a slightly higher measured amount on the third floor. If the second floor air was well mixed (i.e. the tracer concentration was close to uniform on the floor) this could not occur. This suggests a short circuit pathway to the third floor between the source and the collection point on the second floor. Most likely this short circuit pathway is the stairs between the two floors.

Table 4 Measured PFT Concentrations (pL)

	CATS ID	Location	PDCB	iPPCH	PMCH
Unit 41	862	2nd Floor	23.0	2.4	0.1
	6817	3rd Floor	29.3	4.0	0.1
	3679	Attic	7.8	1.3	21.6
	3451	Attic	7.9	1.3	20.5
Unit 45	4822	2nd Floor	33.9	2.3	0.1
	5305	3rd Floor	35.8	4.5	0.2
	5050	Attic	6.3	1.1	17.5
	1	Attic	6.4	1.1	17.4
Unit 51	62	2nd Floor	19.3	0.6	0.2
	279	3rd Floor	29.7	1.5	0.2
	5105	Attic	4.7	0.8	14.8
	5658	Attic	4.5	0.8	13.9
Unit 127	4607	2nd Floor	26.5	3.0	0.1
	5579	3rd Floor	29.2	4.3	0.1
	41	Attic	5.4	0.9	12.0
	5975	Attic	3.9	0.7	10.6

Flow Results

The Air Infiltration Measurement System (AIMS) computer code was used to calculate the overall infiltration rate and the infiltration rate into the interior and attic zones. Tables 5 - 8 document the flow results from the tests. Table 5 shows the overall infiltration rate and the number of air changes per hour (ACH) for the attic and interior zones. Each of these measurements is presented with an estimate of the standard deviation (SD) based on uncertainties in the volume (5%), source rate (7%) and measured concentrations (10% or based on measured concentrations if more than one sample in the zone). This is for the two zones in the calculation (interior and attic). Tables 6 and 7 show the infiltration rate and ACH into the interior of the building (Table 7) and attic (Table 8). Table 9 shows the air exchange rate between the interior and attic in both directions.

Table 5 Overall infiltration rate (m^3/h) and ACH (h^{-1})

	Overall Infiltration Rate		Overall Air Changes per hour	
	m^3/h	SD	m^3/h	SD
Unit 41	204	30.3	0.505	0.029
Unit 45	172.4	12.1	0.386	0.021
Unit 51	229.4	45	0.646	0.037
Unit 127	248.1	20.1	0.614	0.033

Table 6 Interior zone infiltration rate (m^3/h) and ACH (h^{-1})

	Interior Infiltration Rate		Interior Air Changes per hour	
	m^3/h	SD	m^3/h	SD
Unit 41	162.9	33.8	0.47	0.1
Unit 45	114.2	12.3	0.29	0.04
Unit 51	159.6	51.3	0.48	0.16
Unit 127	147.5	17.6	0.43	0.06

Table 7 Attic zone infiltration rate (m^3/h) and ACH (h^{-1})

	Attic infiltration Rate		Air Changes per hour	
	m^3/h	SD	m^3/h	SD
Unit 41	61.1	4.9	1.04	0.1
Unit 45	73.4	5.2	1.24	0.11
Unit 51	91.9	7.7	3.67	0.36
Unit 127	123	14	2.09	0.26

Table 8 Air exchange between the interior and attic.

	Interior to Attic		Attic to Interior	
	m^3/h	SD	m^3/h	SD
Unit 41	19.3	4.1	0.7	0.2
Unit 45	14.4	1.6	0.9	0.2
Unit 51	19.9	6.5	2.3	0.8
Unit 127	21.4	5.7	1	0.3

The full output of results is provided in the EXCEL spreadsheet Vancouver Feb 2012.XLSX.

The results in Table 5 – 8 are based on the combined concentration data from the two interior CATS located on the second and third floor of the units.

APPENDIX B– MONITORING DATA

B.1 Unit 1 Results

B.1.1 Unit 1 Sensor Placement

Figure B.1: Unit 1 east baffle

Figure B.2: Unit 1 east non-baffle

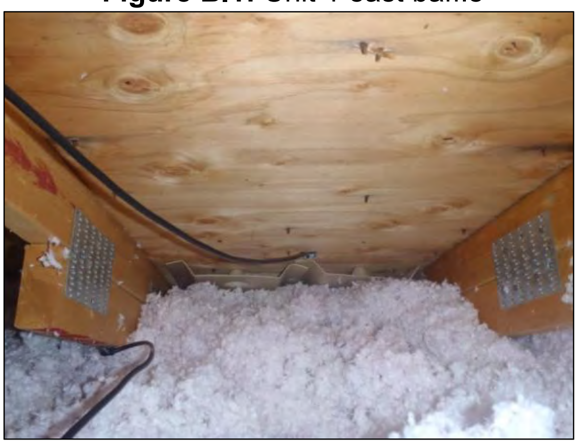


Figure B.3: Unit 1 west baffle

Figure B.4: Unit 1 west non-baffle

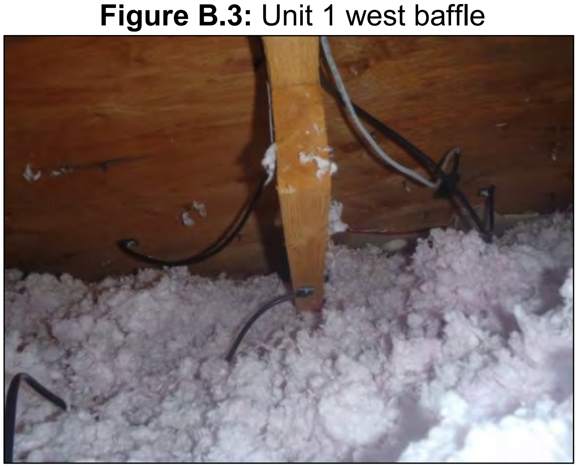


Figure B.5: Unit 1 east truss

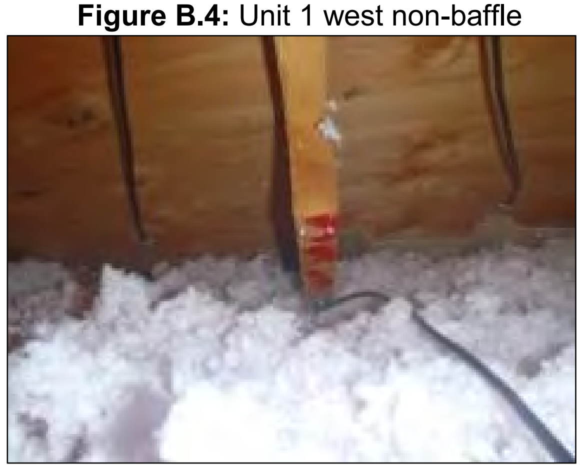


Figure B.6: Unit 1 west truss

B.1.2 Unit 1 Long Term Wood Temperature and Moisture Content

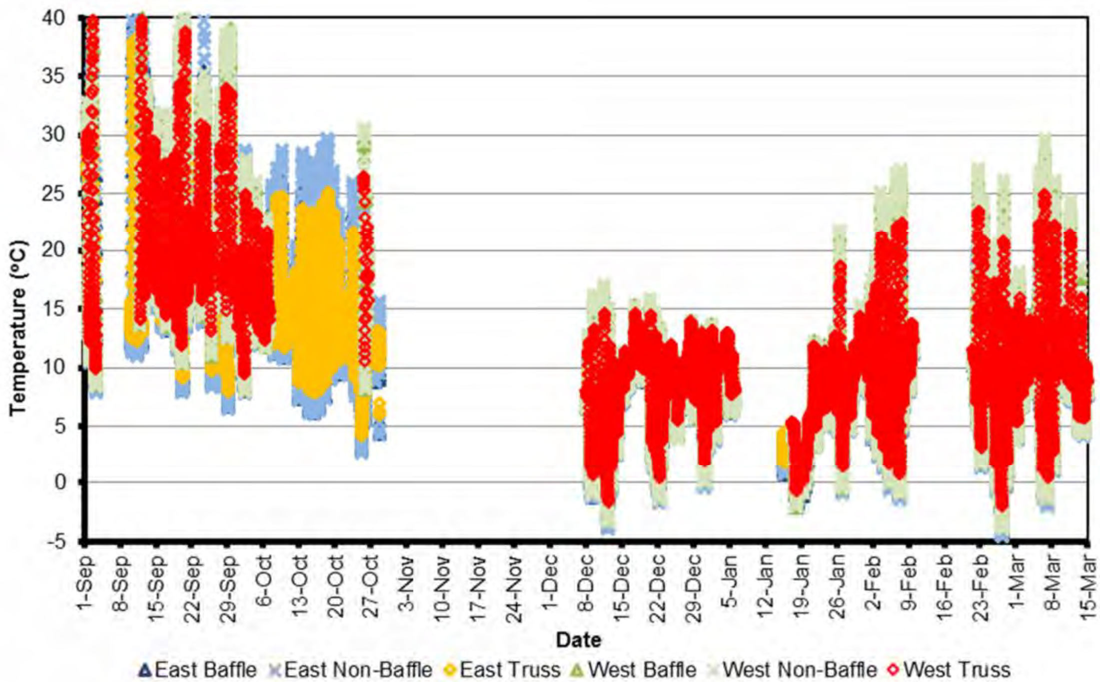


Figure B.7: Unit 1 long term wood temperatures

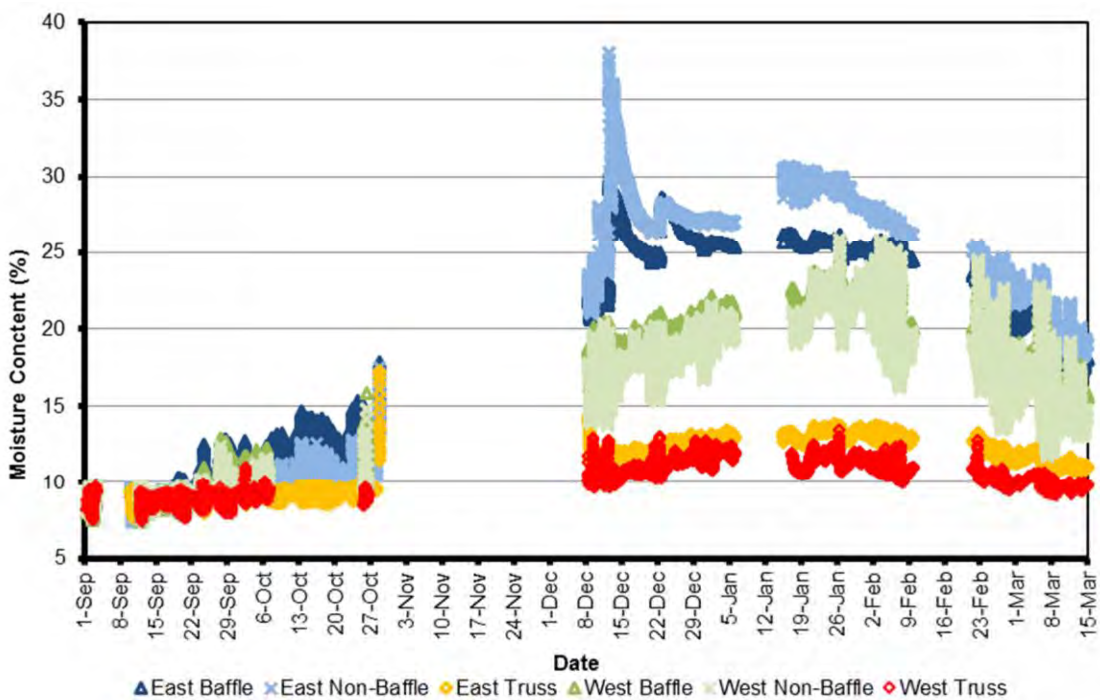


Figure B.8: Unit 1 long term wood moisture content

B.2 Unit 2 Results

B.2.1 Unit 2 Sensor Placement

Figure B.9: Unit 2 east baffle

Figure B.10: Unit 2 east non-baffle

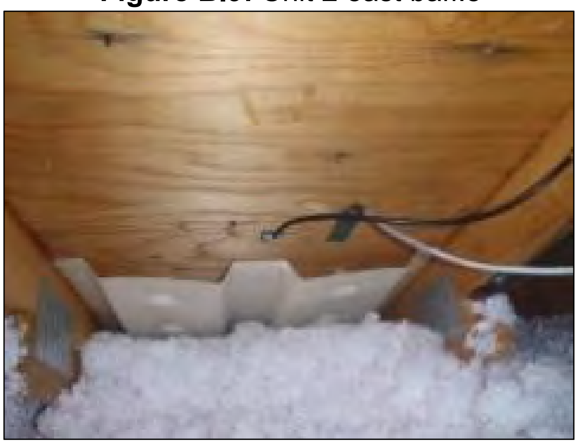


Figure B.11: Unit 2 west baffle

Figure B.12: Unit 2 west non-baffle

Figure B.13: Unit 2 east truss

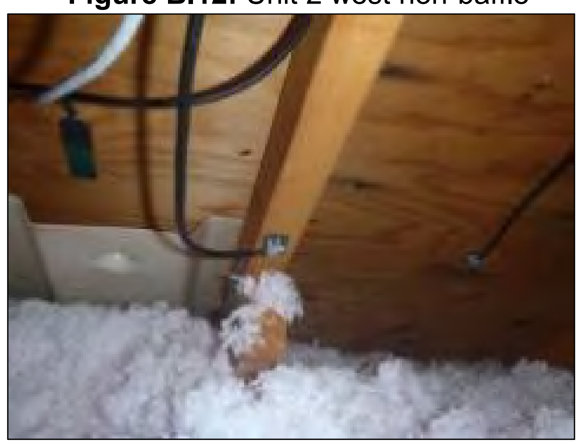


Figure B.14: Unit 2 west truss

B.2.2 Unit 2 Long Term Wood Temperature and Moisture Content

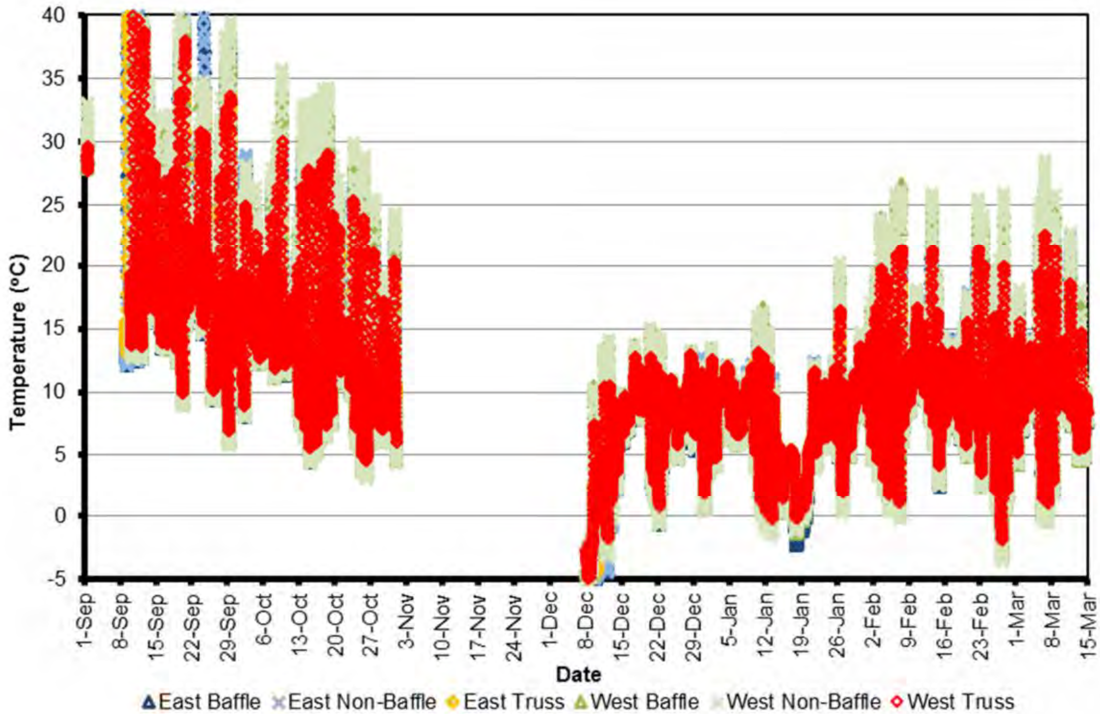
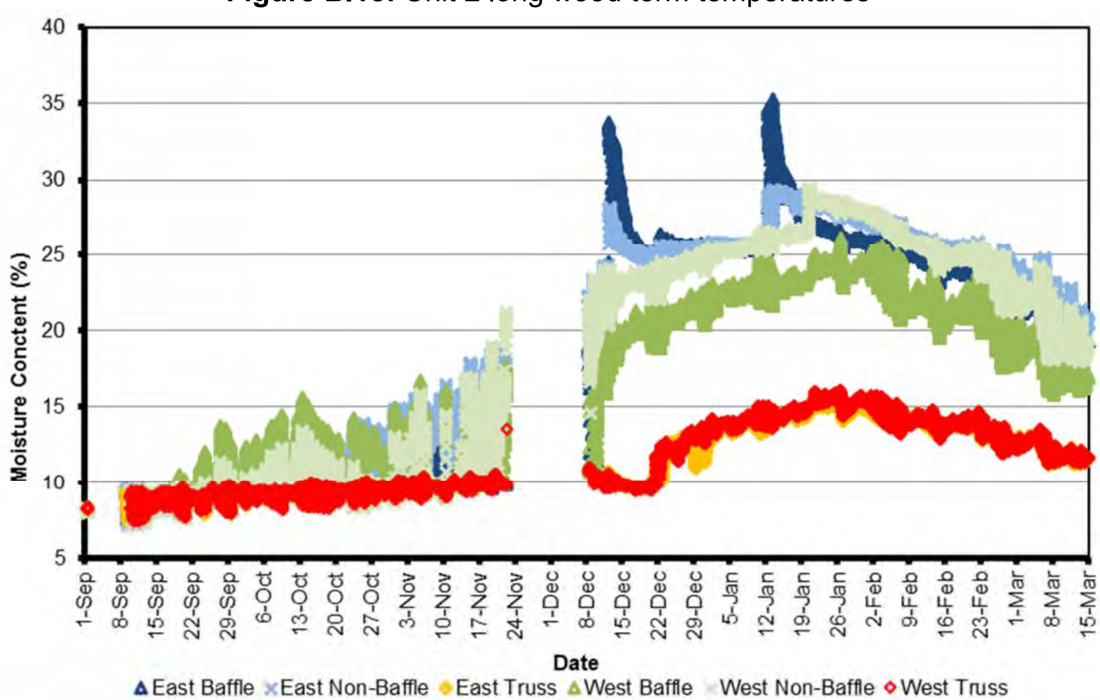


Figure B.15: Unit 2 long wood term temperatures



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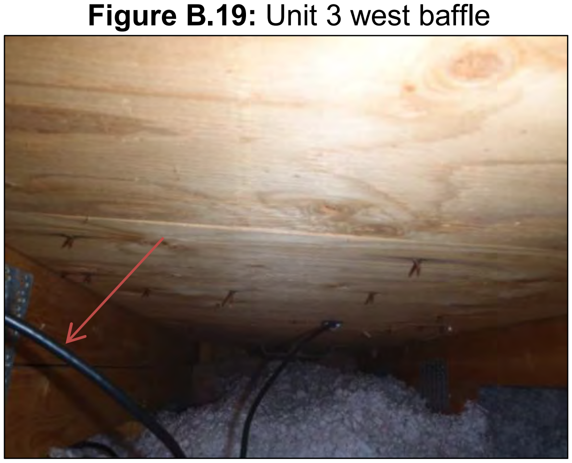

Figure B.21: Unit 3 east truss

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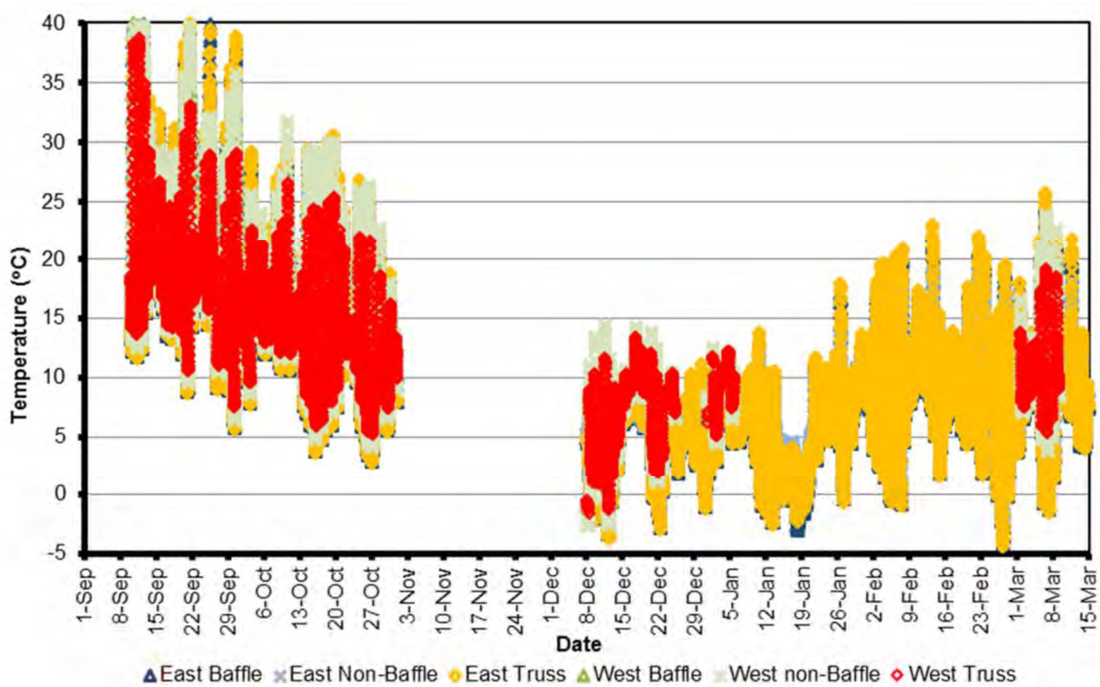
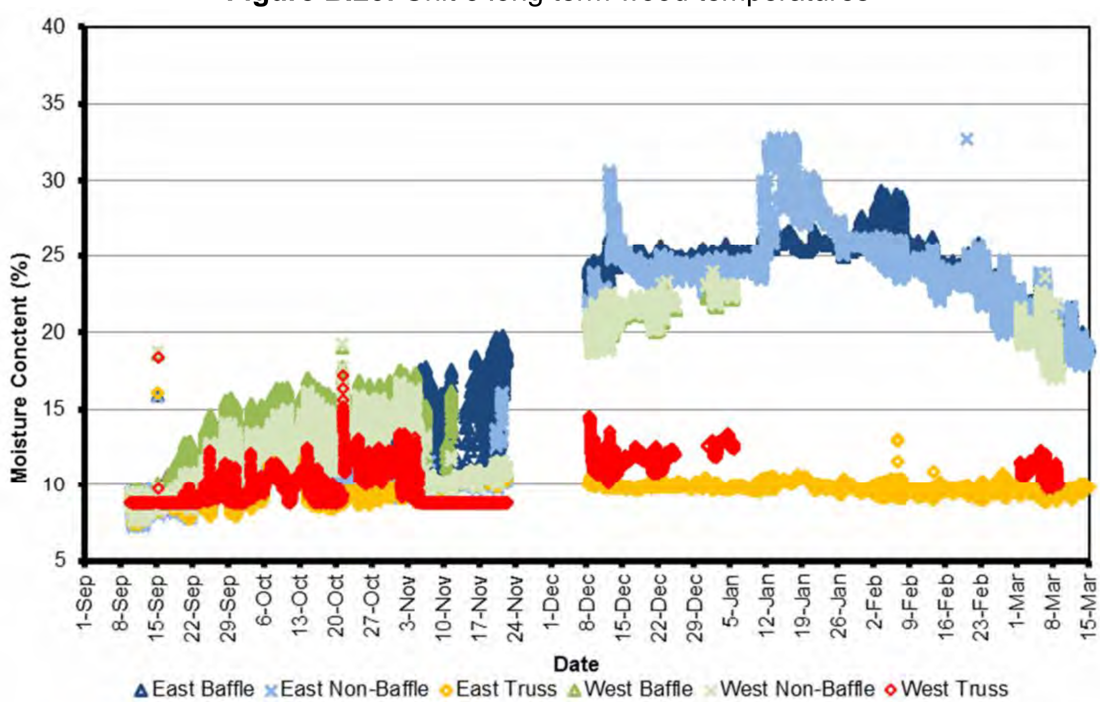


Figure B.23: Unit 3 long term wood temperatures



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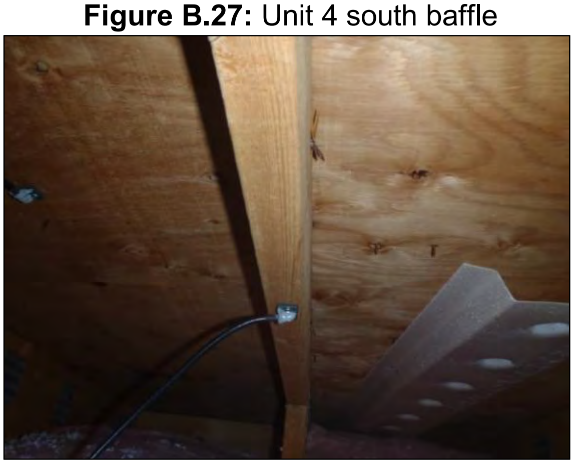

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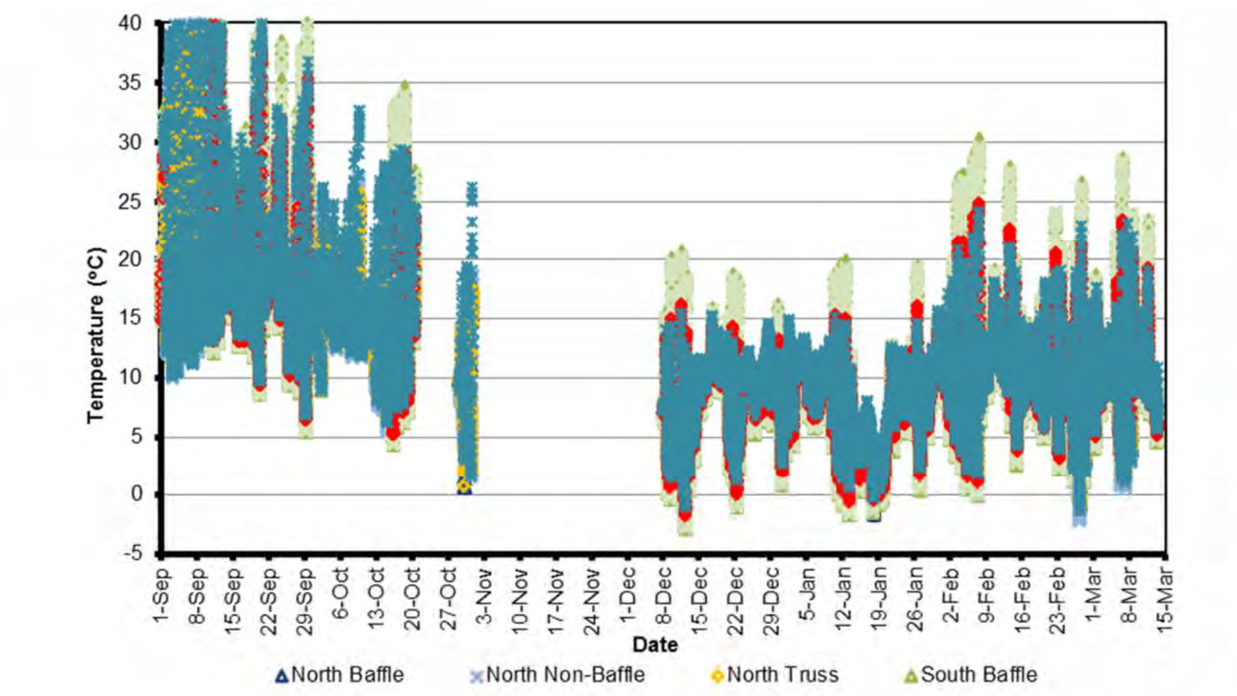

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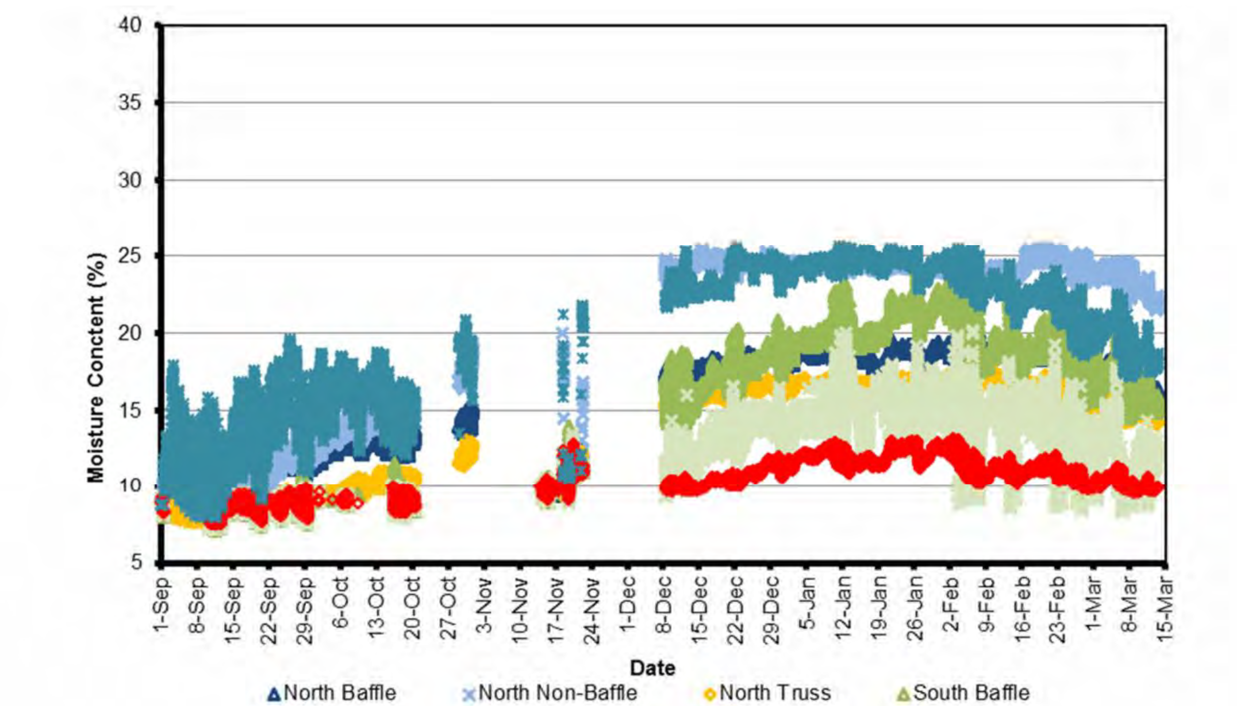

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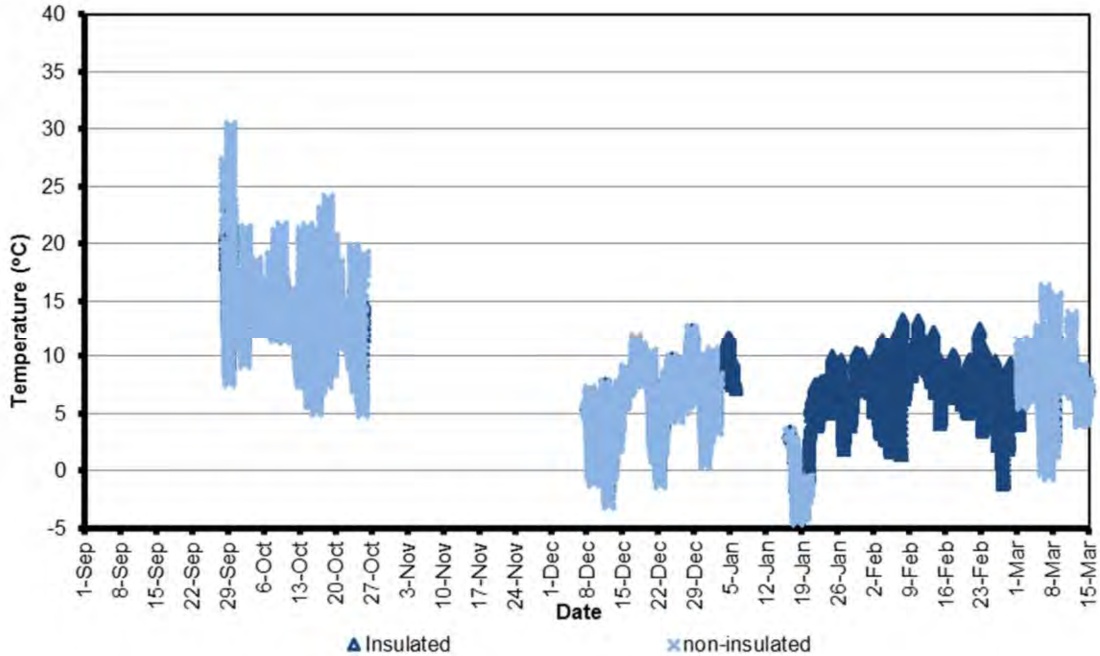

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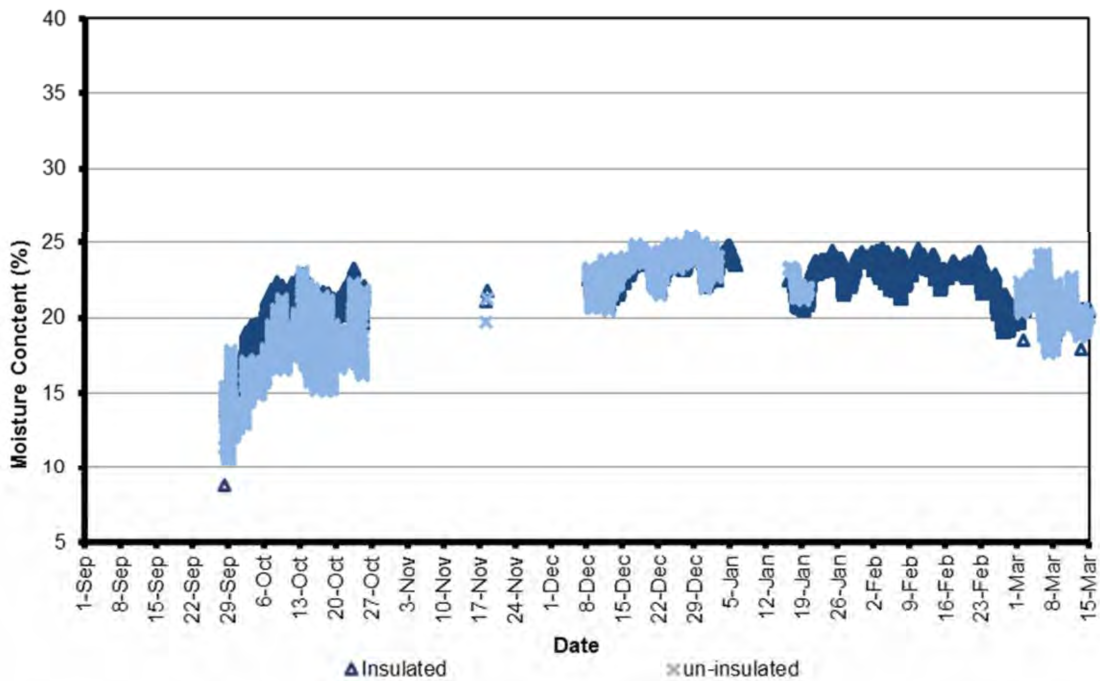

Figure B.36: Control long term wood moisture content

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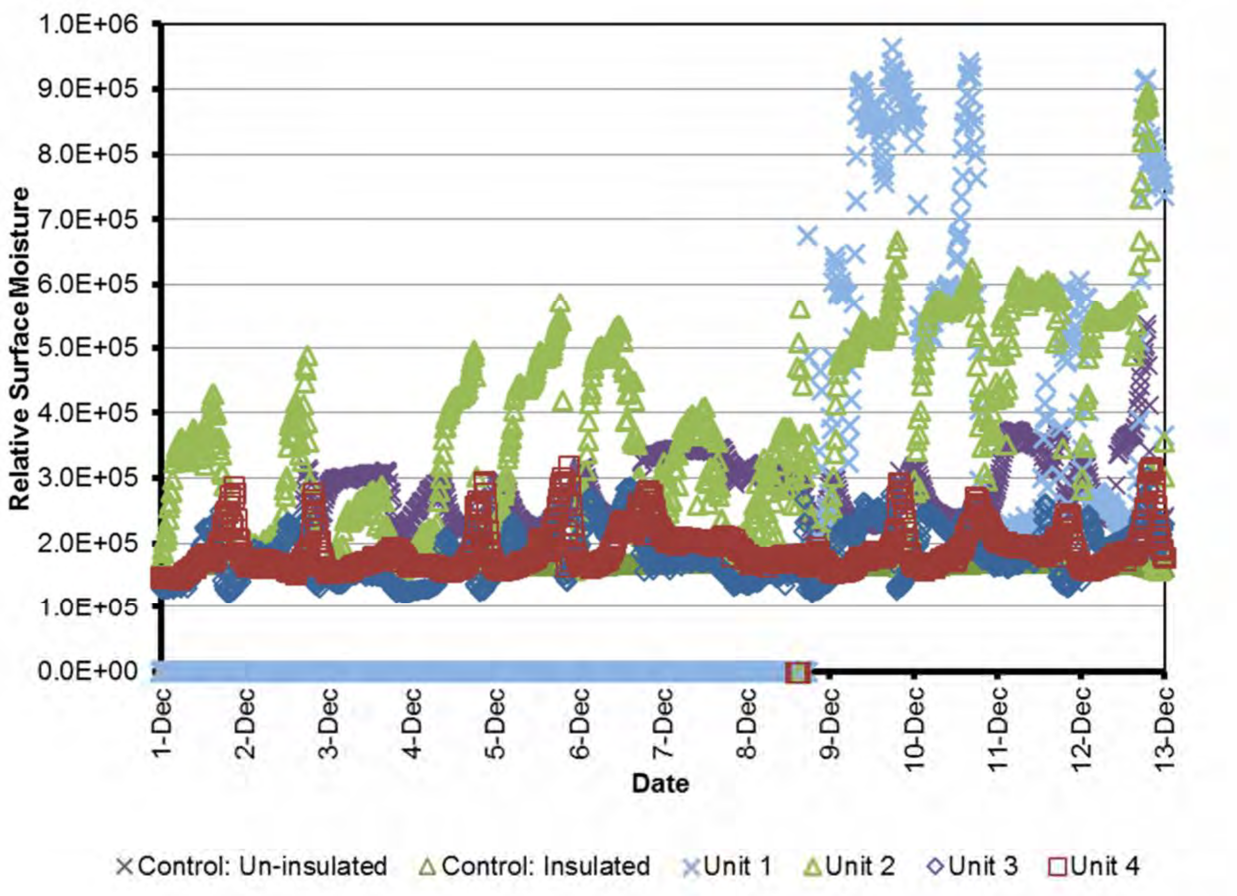

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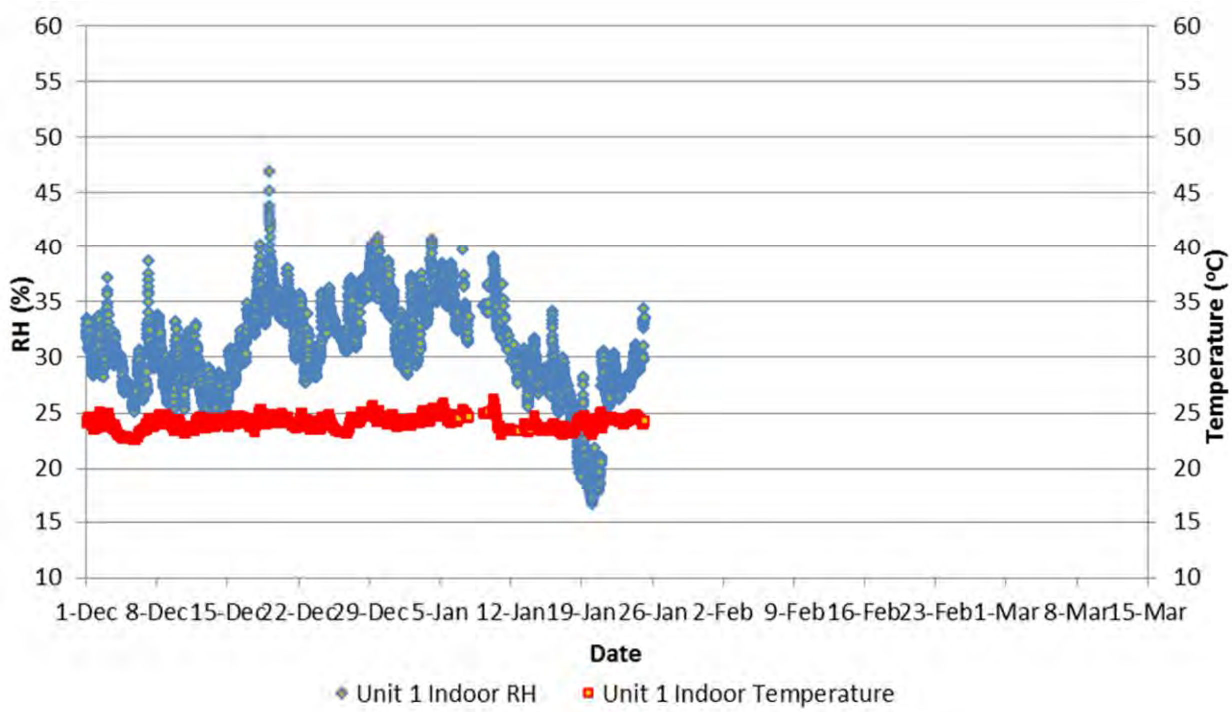

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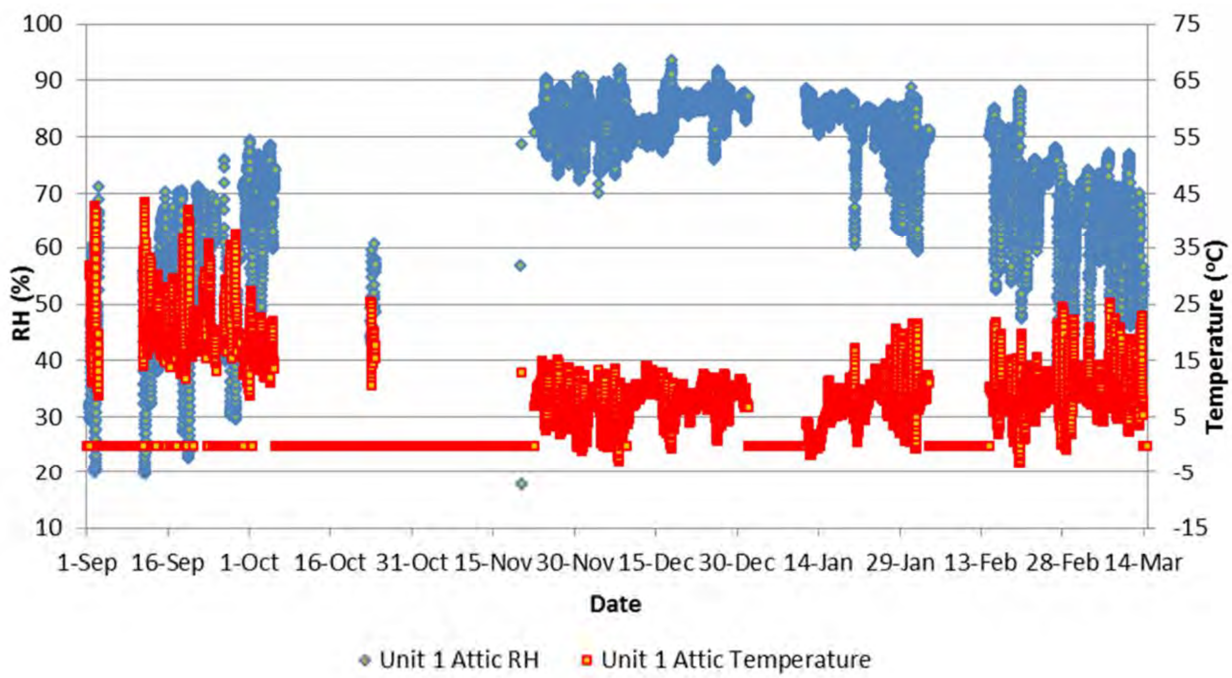

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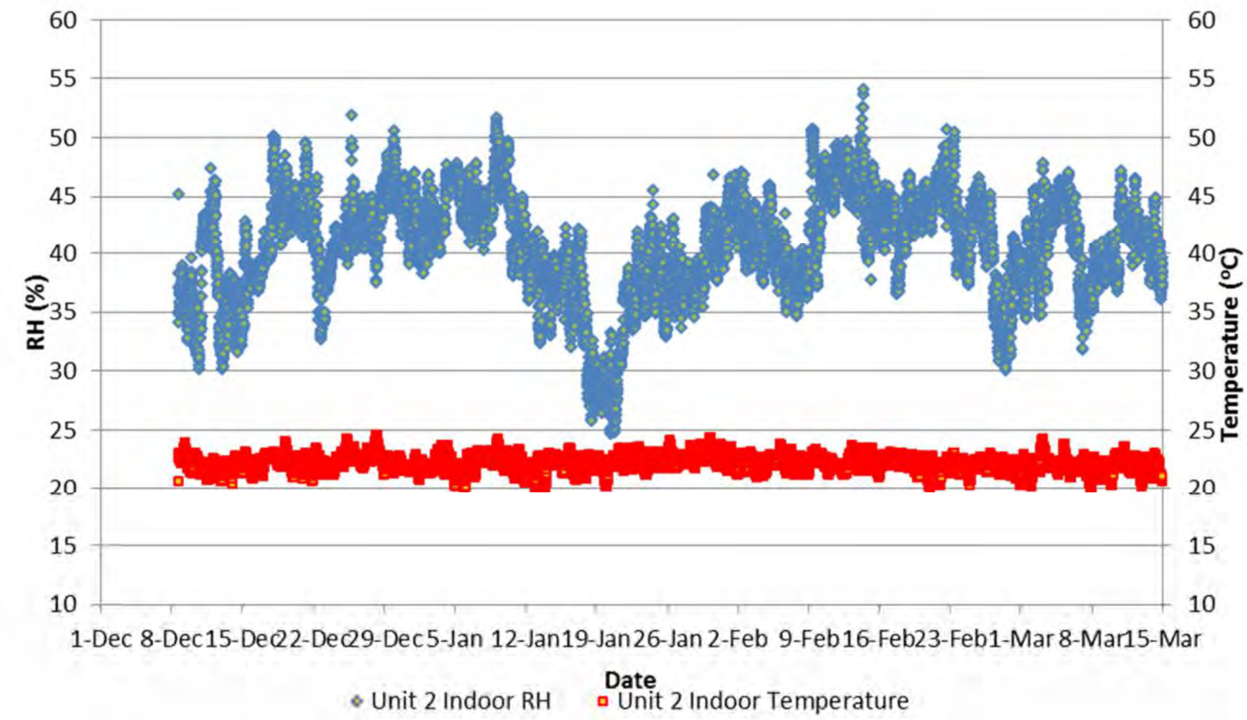

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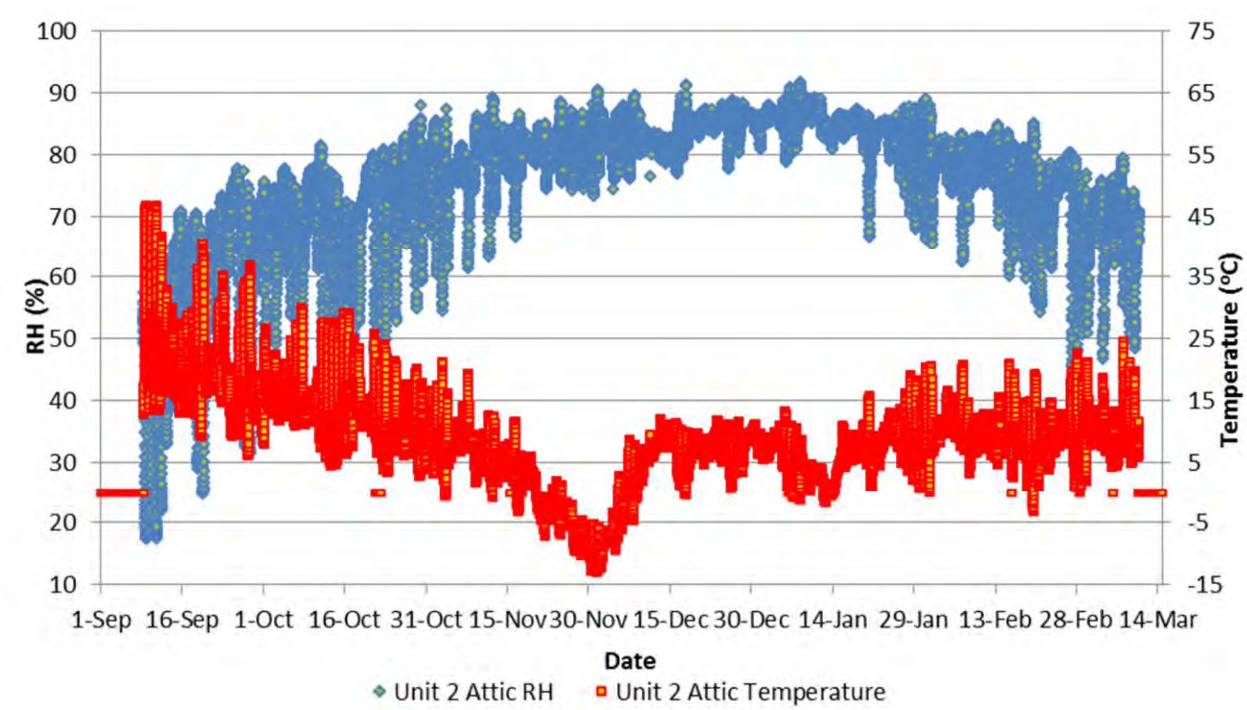

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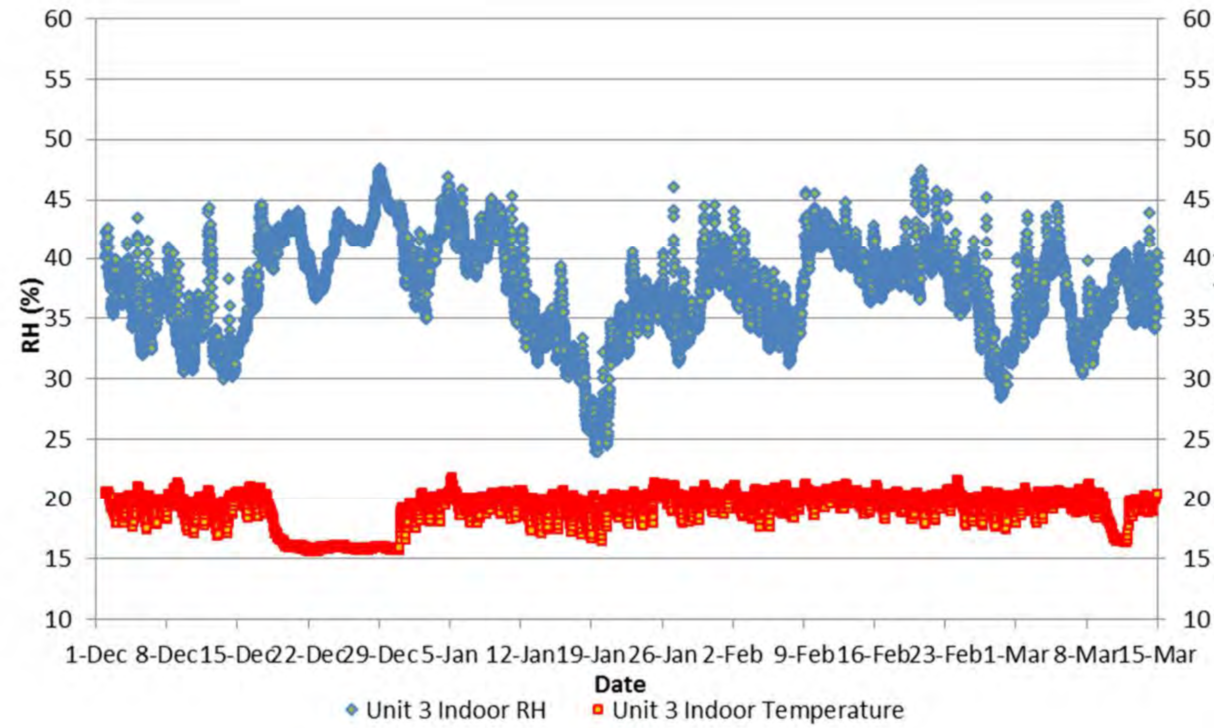

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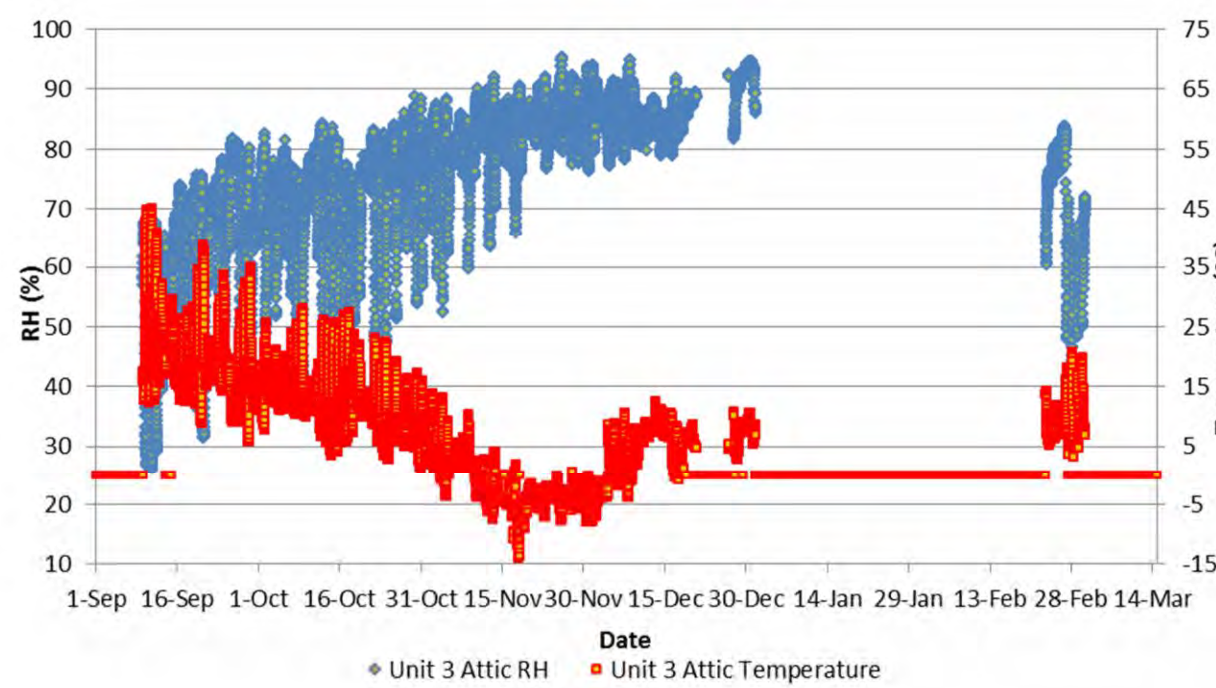

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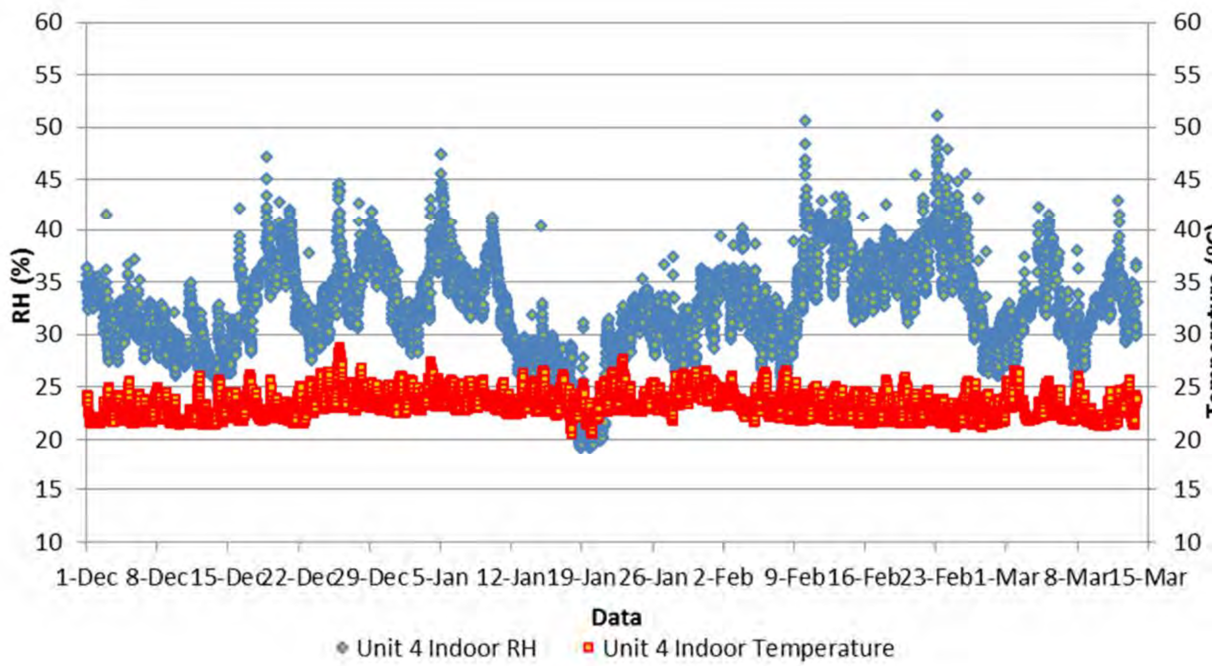

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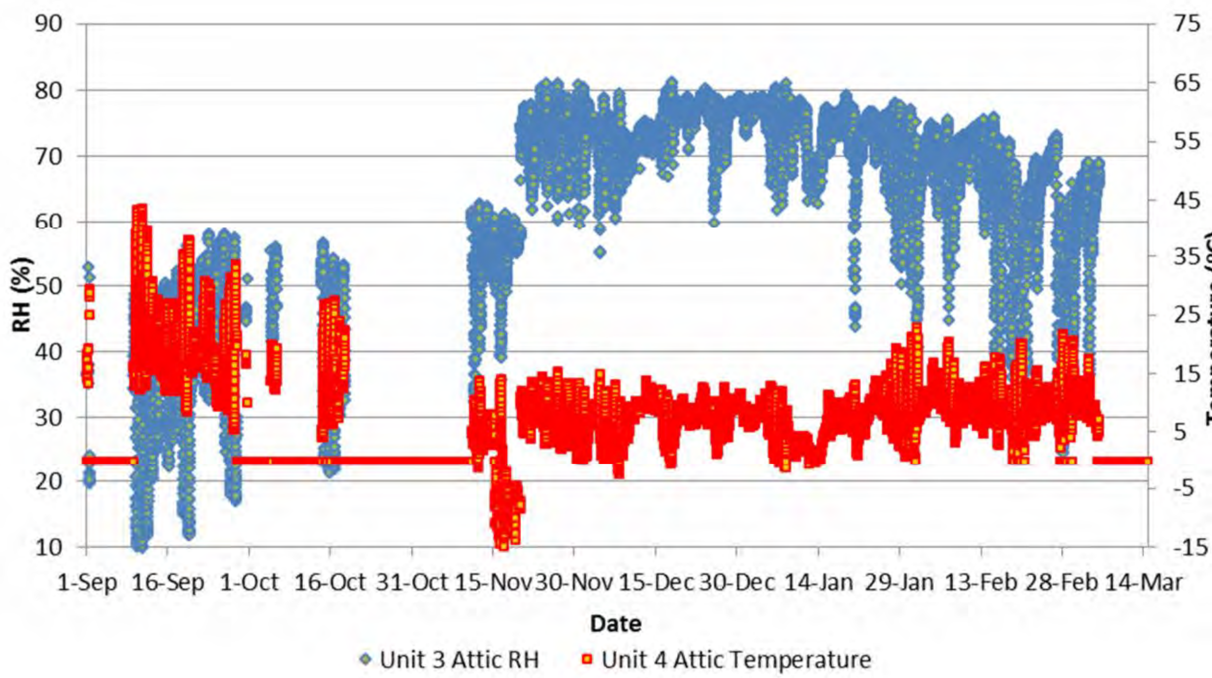

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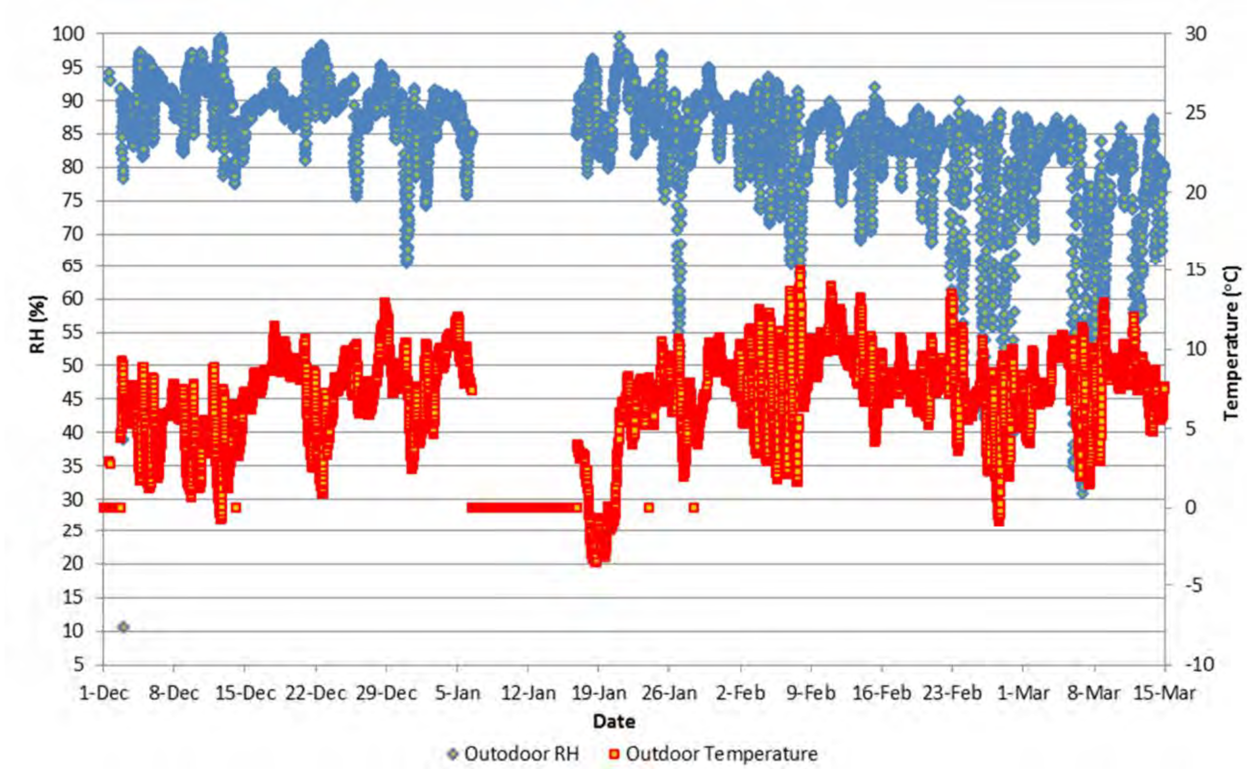

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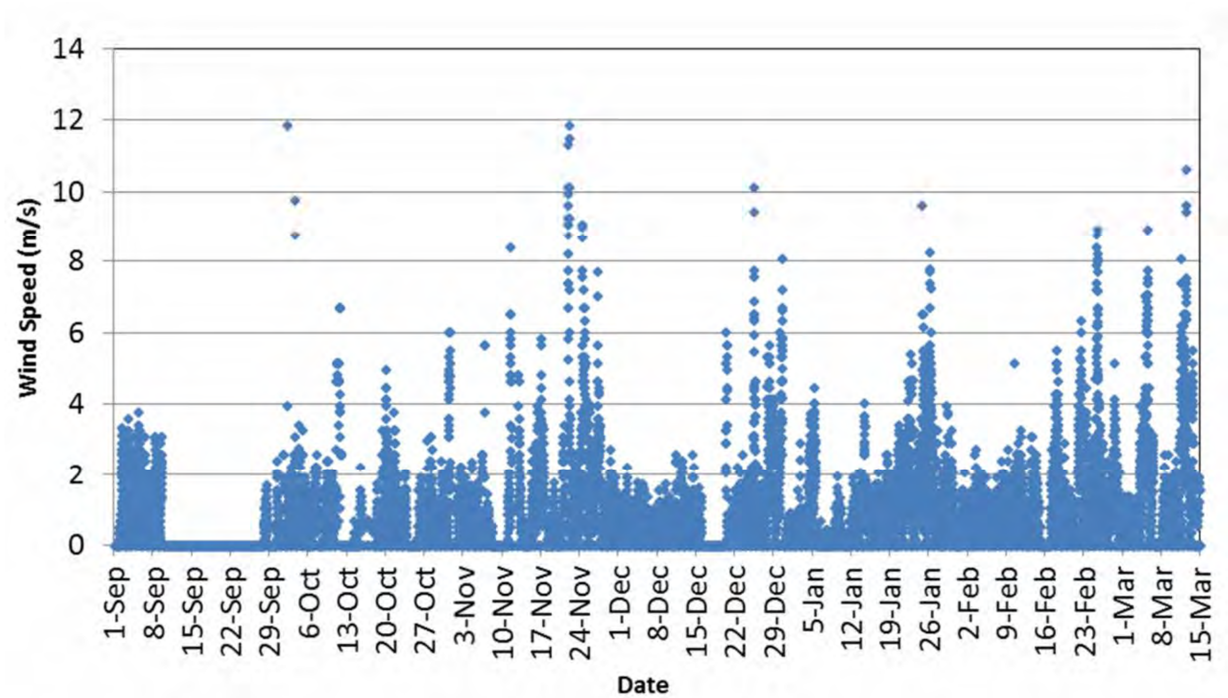

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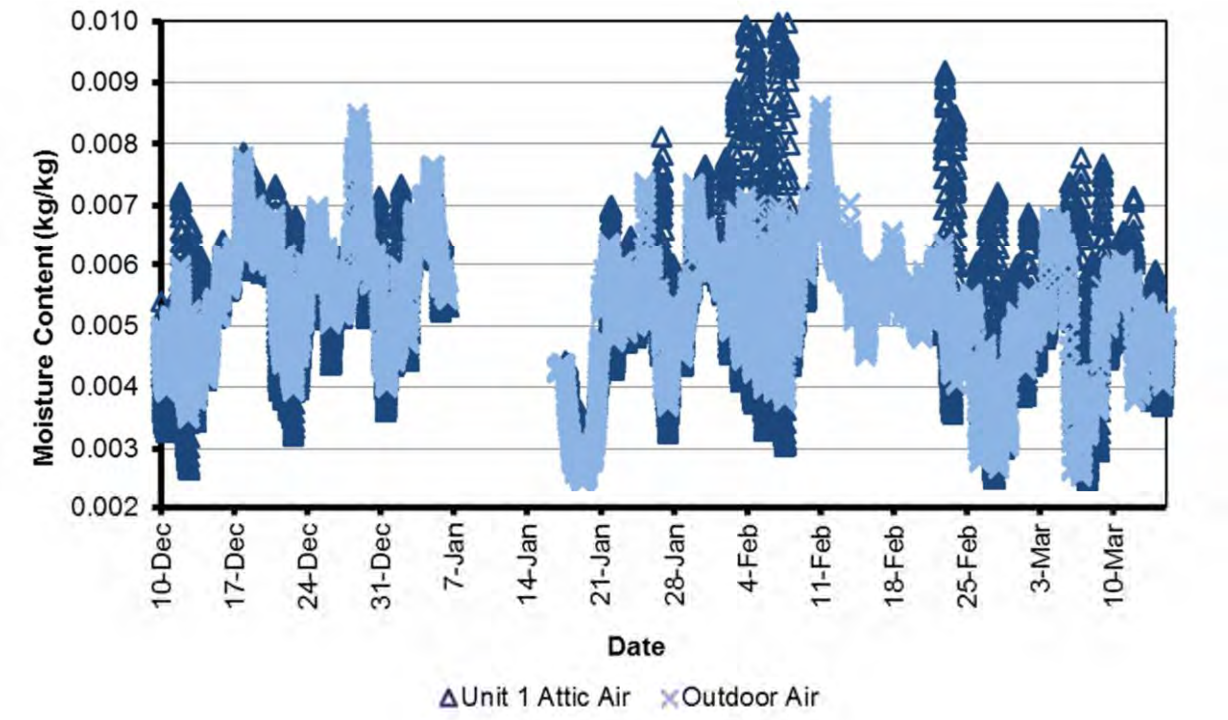

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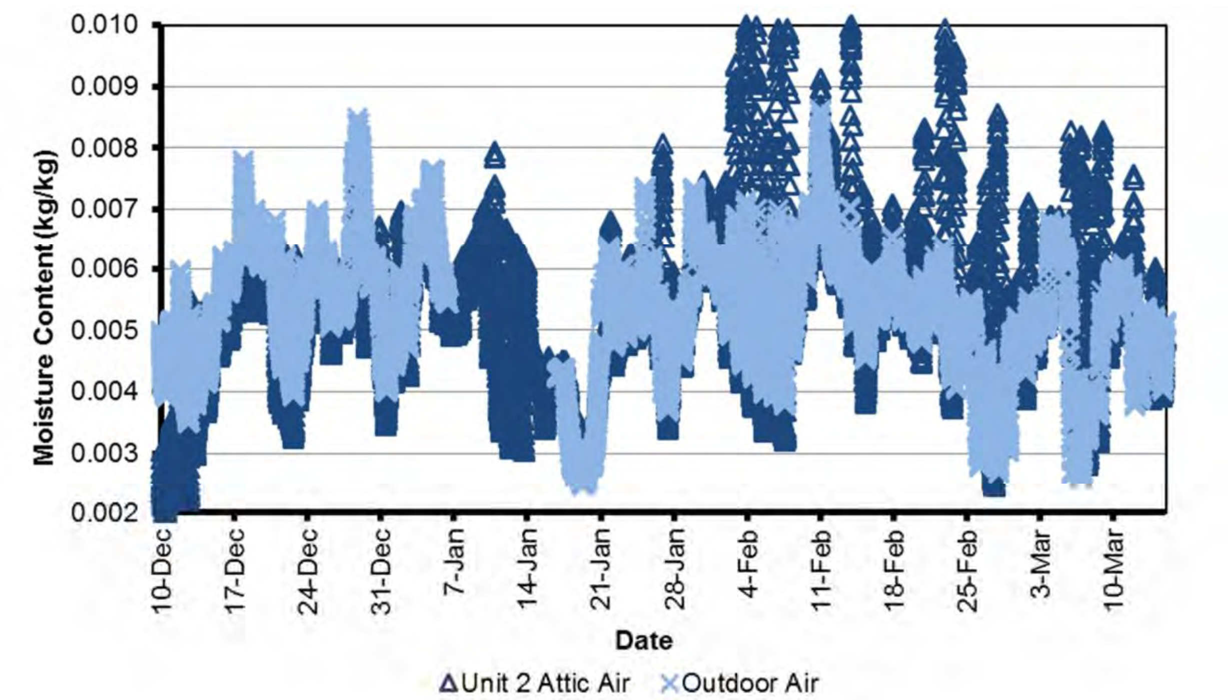

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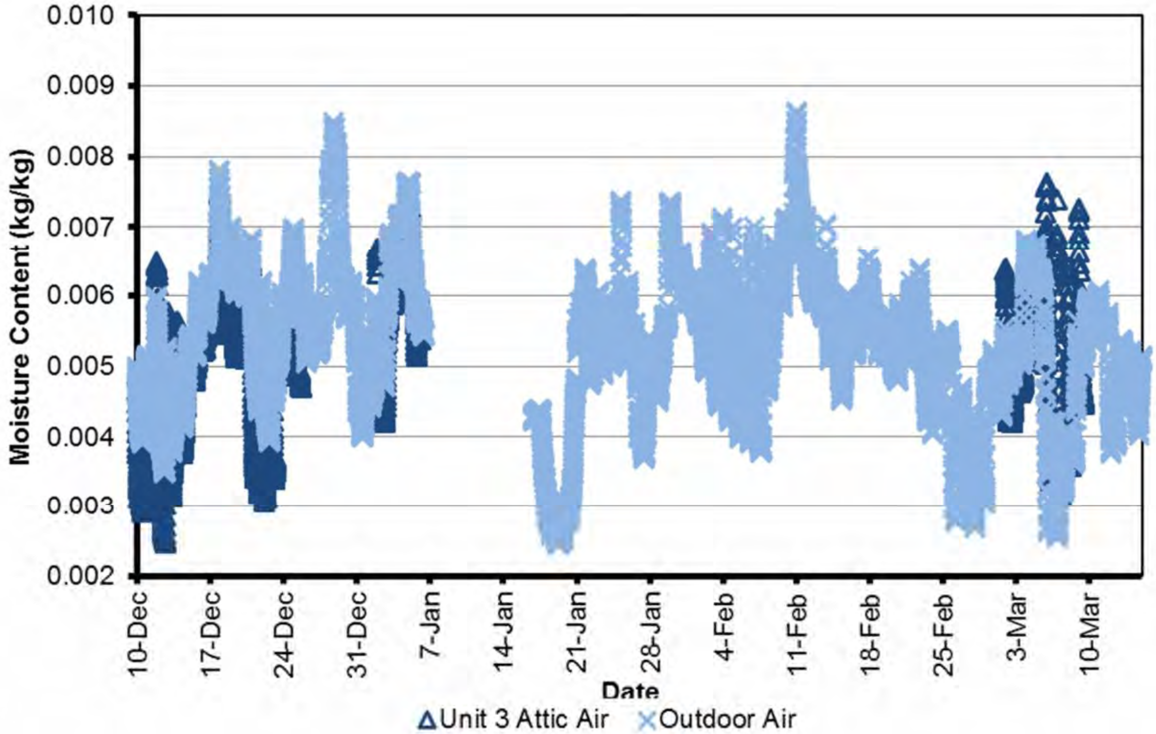

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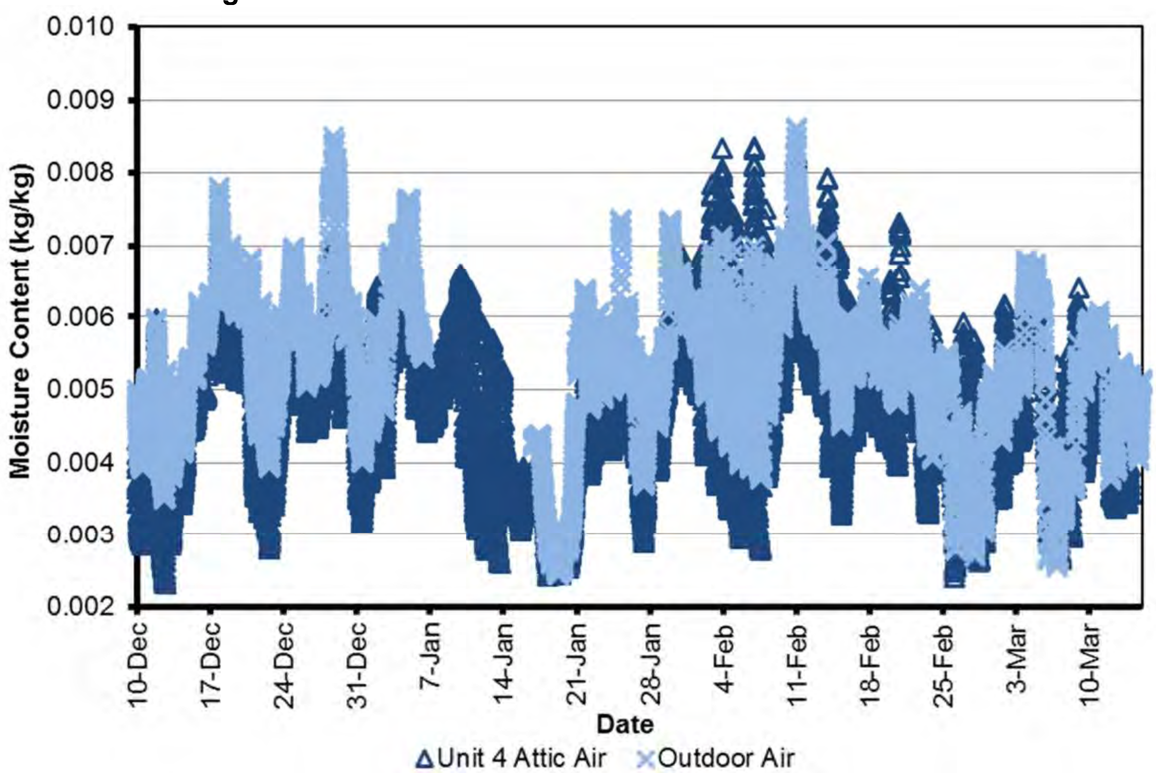

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REPORT

Attic Ventilation and Moisture Research Study

Phase 2 - Solutions

Service Contract Number 154452

Presented to:

Homeowner Protection Office
Branch of BC Housing
1701- 4555 Kingsway
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- FP Innovations (FPI) – technical expertise on the durability and performance of wood products and treatments in building construction
- Polygon Construction Management –construction practicality and costs of solutions
- UBC's School of Population and Public Health – expert opinion of health risks related to exposure of molds in buildings

EXECUTIVE SUMMARY

Phase one of the Attic Ventilation and Moisture Research Study tested a hypothesis that passive attic ventilation is not enough to control moisture in, and fungal growth, on wood sheathing and framing in well insulated attics in cool marine climates. This work highlighted that mold growth can be expected on untreated wood roof sheathings ventilated by outdoor air in the lower mainland of BC. More to the point, mold growth can occur in attics that comply with code requirements for ventilation and have reasonable levels of airtightness between the indoor and attic space. This is contrary to the prevailing Canadian assumption for cold climates that if the ceiling is reasonably airtight and you have the code required attic ventilation that there is little potential for moisture collection.

The visible presence of mold in buildings, which have no identifiable design deficiencies, is a concern to industry because many occupants and potential buyers naturally have concerns with any mold within attic spaces that are identified during building inspections. The visible presence of mold affects marketability, and ultimately property values, even if experts conclude that there is no real health risk or that surface mold growth will not lead to accelerated material degradation. Therefore, phase two of the study was commissioned to:

1. Answer questions regarding the relative influence of factors that affect mold growth in ventilated attics in the lower mainland of BC, and

2. Develop possible strategies to reduce the likelihood of visible mold growth and/or wetting occurring in wood-frame attics.

Additional monitoring and Heat, Air and Moisture (HAM) simulations were conducted to evaluate the factors that influence mold growth in ventilated attics and help guide solutions to address visible mold growth in wood-frame attics.

Additional monitoring showed that:

1. Mold growth can happen in our environment on roof sheathings that are completely decoupled from rain, therefore water absorption through asphalt shingles is not a significant contributing factor to localized staining, and

2. Adding additional venting area can help to dry the roof sheathing quicker but there is no real benefit in terms of reducing the occurrence of mold growth.

These conclusions were reached by looking at exposure time, temperature, and RH concurrently using a single indicator called the mold index. The mold index was utilized because the time of wetness was not enough to rationalize the differences of observed mold growth over two years of monitoring and measured moisture levels at various locations. Moreover, mold growth is equally dependent on exposure time, temperature, and RH. The mold index accounts for these factors concurrently and was shown to be a good yardstick that is able to explain the differences between the various locations.

HAM simulations were essential to identify the contribution that each factor has on the risk of mold growth, due to the complexity and quantity of interconnected variables. The first task of the HAM analysis was to confirm that all the field measurements, as a complete data set, are probable and demonstrate that a numerical model can closely simulate the measured response of the roof sheathing. Several models were evaluated, but ultimately EnergyPlus was selected for the HAM analysis and good agreement was shown between measured and simulated responses of the roof sheathing.

The validated HAM model (EnergyPlus) was utilized to evaluate the impact of varying levels of ceiling airtightness, indoor moisture levels, attic ventilation rates, sheathing thermal resistance, and insulation levels on moisture levels in ventilated attics. The key findings of the parametric study follow:

Attic Insulation – mold growth in ventilated attics would not be an issue if there was no insulation, but the risk of mold growth in insulated ventilated attics appears to have existed for at least 20 years. There is essentially no difference between R-30 and R-50, so there are no implications associated with going forward with adding more insulation to attics. There also does not appear to be any correlation to any recent code changes regarding insulation levels considering the 1994 BCBC required R-40 insulation for residential buildings for the lower mainland of BC (degree days less than 4500).

Attic Ventilation – attic ventilation can be the principal source of moisture in highly insulated attics. However, ventilation also has the potential benefit of drying wood in attics after wetting events, increased drying in the spring time, and taking away moisture due to air leakage from the interior space. Ventilation appears to be a net benefit. Moreover, there is no evidence to suggest that different requirements for venting area or distribution, which have been required by code for more than 30 years, will reduce the risk of mold growth in ventilated attics

Interface Leakage Area – air leakage from the interior to the attic can substantially increase the risk of mold growth on untreated wood in ventilated attics. Controlling air leakage through the ceiling is critical in minimizing mold growth in ventilated attics.

Indoor Humidity Levels – the simulations are confirming the findings of other Canadian studies. The risk of mold in attics is increased with elevated indoor humidity. Industry should not ignore that reducing indoor humidity will help reduce the occurrence and coverage of mold in attic spaces. Nevertheless, mold growth can occur in attics without high indoor humidity.

Sheathing Thermal Resistance – adding thermal resistance outboard the roof sheathing can reduce the risk of mold growth in ventilated attics, but require an airtight ceiling and low to moderate levels of indoor humidity to be successful.

Strategies to reduce the likelihood of visible mold growth and/or wetting occurring in wood-frame attics are outlined by a roadmap that identifies five broad strategies. These strategies are as follows:

Strategy 1. Treat wood sheathings with chemicals that make exposed surfaces unfavourable for mold growth for a broad range of environmental conditions.

Strategy 2. Provide insulating boards outboard mold resistant sheathings.

Strategy 3. Provide all the roof insulation outboard the roof sheathing, keep the roof structure warm and dry, and eliminate the need for a ventilated attic.

Strategy 4. Insulate the underside of the roof sheathing with foam and use an unvented roof assembly.

Strategy 5. Provide a mechanical system that controls air flow into the attic space and only ventilates when there is not the potential to add moisture to the attic space.

Feasible solutions that follow strategies 1 to 4 were defined and evaluated for cost, advantages and disadvantages, practicality, and expected performance. Solutions following strategy 5 were not defined and assessed based on considerations of the likely effectiveness and practicality of implementing these solutions for BC's climate and common construction practice.

A question leading from the evaluation of the solutions, and cost, is "can we learn to live with mold growth in attics?". If the public accepted the view that moderate levels of mold growth in attics are of little real consequence, then it might be possible to avoid the collective cost of implementing solutions in numerous buildings to resolve minor concerns in a few. This would likely be a long process of additional research to address concerns for health and a program of education and discourse with the public.

If the presence of mold in attics cannot be tolerated then the most practical solution, when considering costs vs. the significance of mold growth in attics, is to treat the roof sheathings with a moldicide. However, there is currently significant uncertainty around the available products that will provide long-term resistance to mold growth in ventilated attics in British Columbia. There will be likely some trial and error that will occur in practice until widely accepted products are established through testing and field demonstration projects.

The alternative to chemical treatments is to eliminate ventilation, and conditions favourable for mold growth, through design. The most feasible solution for low sloped roofs is to insulate outboard the roof structure with a conventional roof assembly. For a steep sloped roof assembly, the most feasible design alternative is an unvented roof assembly, which can also have other benefits like increased living space. However, there is a modest cost associated with unvented roof assemblies with insulation inboard the roof sheathing and requires enhanced design and field review compared to traditional construction.

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1. INTRODUCTION

Attic ventilation is a code requirement in residential wood-frame buildings in British Columbia. Attic ventilation is cited to be a benefit for moisture control, minimizing ice dams in cold climates, and extending the service life of roof materials by reducing surface temperatures.

Despite the collective acceptance of attic ventilation as a requirement, there is growing evidence of mold growth in attics in coastal BC that seemingly comply with code requirements for venting area and distribution, and indoor to attic interface airtightness.

Morrison Hershfield Limited (MH) entered a research agreement with BC Housing (HPO) to investigate the significance of attic ventilation to moisture levels in wood-frame attics in coastal BC.

1.1 Investigation and Measurement of Ventilated Attics in Cool Marine Climates (Phase 1)

Phase 1 of this study tested a hypothesis that passive attic ventilation is not enough to control moisture in, and fungal growth, on wood sheathing and framing in well insulated attics in cool marine climates. The outdoor air in cool marine climates is near or often saturated during the winter months. Monitoring and modeling shows that the wood in attics picks up moisture as temperatures steadily drop in the winter, and that average relative humidity (RH) in the attic space rises to levels that any significant wetting event, condensation or frost, can result in conditions conducive for fungal growth.

Phase1 demonstrated that staining of the roof sheathing can occur in attics that:

1. Represent current good practice with regard to attic construction for controlling heat, air, and moisture flows
2. Have venting areas and distribution (venting area provided at the bottom and top of the roof) that meet or exceed minimum building code requirements
3. Have a reasonable level of airtightness at the ceiling level
4. Are connected to indoor spaces with low to moderate humidity levels
5. Do not have excess moisture loads in the attic spaces from duct leakage, plumbing, or transfer of air from the indoor space.

1.2 Significance of and Solutions to Fungal Growth in Attics

The major reason for this study is the increasingly common observation of surface mold growth on the attic surface of wood roof sheathings of wood frame buildings in the Lower Mainland of BC. A perfectly valid question is “Does this matter? Is surface mold in the attic a problem?”

Some individuals believe that the presence of mold anywhere in a building is not acceptable and measures must be taken to eliminate mold growth in the building. Others note that mold located in attic spaces is unlikely to increase exposure of residents to fungal particles because air transfer between the indoor and attic space is predominately in the direction of the indoor to the attic space[1], and any transfer in the opposite direction should be insignificant. Tracer gas testing done in phase 1 supports this point.

Additionally, the dominant molds that have been sampled in many attics are non-pathogenic surface molds that are abundant in our outdoor environment[2]. Discovery of only common outdoor molds helps alleviate concerns for some individuals. However, the fact that more harmful molds are not often identified doesn't preclude their existence.

Another way of looking at the issue is to simply focus on marketability and the effect of molds in attics on property values. Many occupants and potential buyers naturally have concerns with any mold within attic spaces that are identified during building inspections. The visible presence of mold affects marketability, and ultimately property values, even if experts conclude that there is no real health risk or that surface mold growth will not lead to accelerated material degradation.

The visible presence of mold in buildings, particularly those recently completed and currently under mandated HPO warranty, which have no identifiable design deficiencies, presents a challenge to industry as there is no clear solution on how to eliminate the mold growth.

The objectives of phase two of this study is to:

- develop possible strategies to reduce the likelihood of visible mold growth and/or wetting occurring in wood-frame attics,
- evaluate the strategies using available information and modeling tools to identify possible solutions that:
  - have a high probability of being successful if implemented by industry,
  - can be applied to new and/or existing buildings,
- identify any risks with the various alternatives, and
- help guide decisions for any contemplated changes to the building code for wood-framed buildings in coastal BC.

[1] This is because both stack effect (i.e heat rises and cold air falls) and wind pressures create driving forces for air transfer in the direction of the indoor space to the attic.

[2] These molds are not considered pathogenic for humans, which means the mold do not cause sickness. However, some people are allergic to the spores of these molds similar to being allergic to pollen.

2. FACTORS LEADING TO FUNGAL GROWTH IN VENTILATED ATTICS

The first part of this report answers questions regarding the relative influence of factors that affect moisture levels and mold growth in ventilated attics. These answers support the solutions that are outlined in the rest of this report. The relative impact of ceiling airtightness, attic ventilation rates, sheathing thermal resistance, roof colour, and insulation levels in ventilated attics is established using monitoring data and validated Heat, Air, and Moisture (HAM) simulations.

Monitoring data is primarily from the test units presented in phase 1 of this study, over two winters (2011/2012 and 2012/2013). Additional monitoring data from another study is also presented to provide supplementary validation of the relative benefit that sheathing thermal resistance can have in reducing moisture levels.

Some of the questions regarding the relative impact of attic ventilation rates and sheathing thermal resistance can be answered through analysis of the monitoring data. However, the HAM simulations were essential to identify the contribution that each factor has on the moisture levels in ventilated attics, due to the complexity and quantity of interconnected variables. The HAM simulations helped make sense of the monitoring data and to confirm that the field measurements are plausible. Together, agreement between the field data and computational modeling provides confidence in the findings of this study.

2.1 Contribution of Mold Growth from Precipitation

Rain-water absorption of asphalt shingles has been suggested as a possible contributing factor to localized staining in attics in the lower mainland. The absorption of moisture through the asphalt shingles is clearly not a critical factor leading to mold growth for the units included in this study. New mold growth was observed on wood that was fully disconnected from direct precipitation and absorption as illustrated in the following photos. The key suggestion is that mold can grow on wood in our environment without getting wet by rain and subject to any additional moisture sources other than ambient conditions.

Photo 1: mold growth on the plywood cover below the sensor locations for the control roof assembly. This mold growth is after two winters exposed to ambient conditions at the study location.

Photo 2: staining of the backside of the plywood cover. Notice at the location where the plywood was in contact with the rafters is clean.

Photo 3: Mold growth on wood rafters and tongue and groove wood deck.

Photo 4: Mold growth on the plywood sample that is decoupled from the asphalt singles by a thick wood deck and 25 mm extruded polystyrene insulation.

From a broader perspective, absorption of moisture through the asphalt singles can be further discounted as a leading cause of mold in attics because staining is not limited to sloped roofs with asphalt shingles. Staining is also occurring in roof assemblies were absorption from precipitation is clearly not an issue, for example roof assemblies with waterproofing membranes.

2.2 Measured versus Predicted Performance

The primary performance criterion for this study is if the solutions identified in this report will be effective in eliminating the occurrence of mold growth in ventilated attics for code compliant buildings.

The factors that impact mold growth in attics are temperature, available nutrients, and moisture. Oxygen and spores are also necessary for mold growth but are abundant in attics ventilated with outdoor air, therefore they will not be discussed as a factor that can be controlled to eliminate staining for most scenarios. Most of the identified solutions will control one or more of these factors; temperature, nutrients, and moisture; to make conditions unfavorable for mold growth.

The measured performance for the monitored units includes surface temperatures and moisture content of the wood sheathing and framing. There is visual confirmation of the relative mold growth, and we have seen increased staining during the study period, but the specific conditions that initiated and promoted the mold growth on the sheathings cannot by identified by visual observations. We know that nutrients are readily available on wood sheathings and some of the differing quantity of mold can likely be explained by microscopic differences in nutrients and surface conditions due to the type of species, composition, sapwood vs. heartwood, manufacturing, and treatments. Nevertheless, mold growth will not happen without favourable **moisture** and **temperature** conditions for a sufficient amount of **time**.

A mold index, developed by VTT Technical Research Centre of Finland, was utilized to scale the observed mold growth and as a tool to provide a yardstick comparison between observed and predicted mold growth (Hukka et al 1999, Viitanen et al 2007)[3].

The mold index has the following scale:

0	No growth
1	Growth detected by microscope
2	Moderate growth detected by microscope (coverage more than 10%)
3	**Growth visually detected**
4	Moderate growth, 10 to 50% visual coverage
5	High growth, visual coverage more than 50%
6	100% visual coverage

The numerical model predicts the mold growth on wood surfaces that are subject to time varying temperature and relative humidity using empirical functions. These functions were derived by comprehensive laboratory testing that evaluated the time it takes for the various stages of mold growth to occur for different humidity and temperatures. Example curves for various conditions, extrapolated from the VTT work, for pine sapwood are shown in Figure 1 (Viitanen et al 2007).

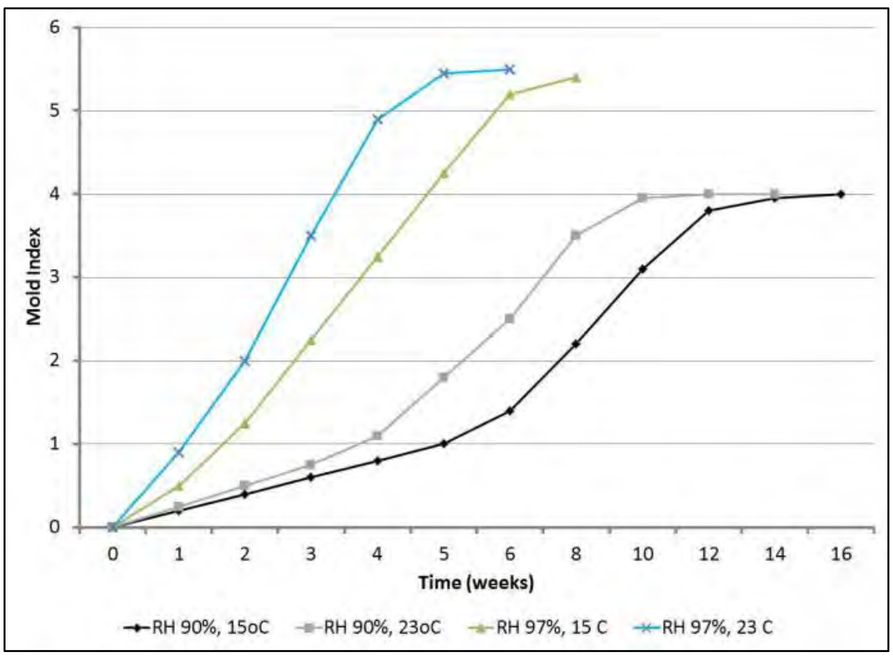


Figure 1: Predicted Mold Growth on Pine Sapwood

[3] There are other approaches and scales available (Clarke et al 1996, Sedlbauer 2001, Minchin et al 2008), but the mold index was determined to be the most convenient for the objectives of this study and compare observations and measurements to a predictive model.

The numerical model is intended to be for specific wood species (pine or spruce sapwood) and little has been done during periods of unfavourable conditions. Plywood or OSB sheathing in ventilated attics subject to real life dynamic conditions will have different responses, but follow similar trends (Viitanan 2007). Nevertheless, the mold index provides a general indication of the conditions necessary to initiate and sustain mold growth on wood materials, but should not be considered an absolute prediction of mold growth. For this study, the mold index is used as a yardstick to quantify and compare between measured and predicted conditions because exposure time, temperature, and RH are embodied within the index that yields a single value that is easy to interpret.

The critical threshold for this study is visually detectable mold growth, a mold index of 3, since this is the value associated with the initial appearance of visible surface mold. Keep in mind that the conditions favourable for surface mold growth are different than for decay (rot) fungus[4]. The characteristic surface molds that have been identified, for the studied units and similar attics, are moderately hydrophilic (like moisture). These surface molds can appear and grow on wood substrates under a wider range of conditions than decay fungus, i.e. without the presence of liquid water, if given enough time.

The mold index was used as a yardstick, to compare the measured conditions and observed mold growth because evaluating the time that the wood sheathings spent above specific moisture thresholds was not enough to explain the visible mold growth in the attics and control assembly. The mold index better explained the observed differences in staining at the varying locations and more definitive guidelines could be established. Further explanation follows.

Table 1 breakdowns the correlation between the observed staining and the corresponding moisture levels during the two monitored winters. The attics at locations with visible staining spent many weeks above 25% MC and days to several weeks above 28% MC. In contrast, the control assembly has visible staining after 2 years, but only spent a few weeks above 25% MC and was not subject to conditions above 28% MC. However, the sheathing of the control assembly spent more time above 20% MC and near 25% MC than compared to the attic roof sheathings.

A summary of the total hours above critical moisture content thresholds are found in Appendix A and a summary of the key findings that support the need for a better measuring stick, better than looking at moisture content in isolation, follow table 1.

[4] Decay fungi are a type of mold that will attack wood, consume the inner structure, and can lead to loss of structural strength. Surface molds live on the surface, stain the wood but do not consume the wood, and do not result in strength loss.

Table 1: Observed Staining and Measured Moisture Levels of the Plywood

Unit	Location	Observed Mold Index			Weeks above 25% MC		Weeks above 28% MC	
		at Nov. 2011	at Nov. 2012	at Apr. 2013	Winter of '11/'12	Winter of '11/'12	Winter of '11/'12	Winter of '11/'12
1	East Baffle	4	n/a	5	7.5	2	1	0.5
	East non-baffle	3	n/a	4	10	2.5	4	0.5
	West Baffle	< 3	n/a	<3	0	0	0	0
	West non-baffle	< 3	n/a	<3	0	0	0	0
2	East Baffle	4	5	5	7.5	9	1	2.5
	East non-baffle	3	4	4	9	11	2	2.5
	West Baffle	< 3	< 3	4	0	7.5	0	0.5
	West non-baffle	3	3	3	6	9.5	1	1.5
Control	With Insulation	0	n/a	4	0	2.5	0	0
	Without Insulation	0	n/a	4	0	3	0	0

A summary of the key findings that support the need for a better measuring stick, better than looking at moisture content in isolation, follow:

- Mold growth does not happen below 0°C and increasingly higher RH at the wood surface is needed to support mold growth for decreasing temperatures below 20°C (Haukka et al 1997, Viitanen et al 2007). The attic air fluctuated from below 0°C up to 15°C on daily cycles during the winter months.
- Visible mold growth will occur on wood when exposed to 90 to 95% RH (approximately equivalent to 18% MC to 25% MC for plywood), given enough time and favourable temperatures. The attic spaces were above 90% for a considerable amount of time.
- The wetting periods resulting in the moisture levels spiking above 28% MC for the attics were associated with clear nights below freezing and daytime roof sheathing peaking at 10 to 15°C.
- All the attic sheathing locations with staining had moisture contents above 28% MC for several days to several weeks, but both of the control roof scenarios did not reach moisture levels above 28% MC and still had visible staining after two years.

- The wood sheathings for the control roofs spent several more weeks above 19% MC compared to the attics, but generally spent several weeks less or no time at all above 25% MC.
- There were several locations in the attics that spent several weeks above 19% MC but these locations do not have any visible mold growth.
- It appears that wetting from condensation, resulting in roof sheathing moisture content levels above 28% MC, is an accelerant for mold growth and relates to more severe staining, but visible mold growth will occur at lower moisture thresholds given enough time.

These findings are significant when developing solutions to address visible staining in attics. For example, when evaluating the feasibility of adding thermal resistance outboard of the sheathing of a ventilated attic to eliminate wetting from condensation by night-sky radiation or establishing an appropriate testing protocol for evaluating coatings for wood in an attic environment.

The mold index accounts for exposure time, temperature, and RH concurrently and provides a single indicator for evaluating mold risk. This study is too broad, with too many unknowns, to predict absolute mold growth, because different types of wood substrates have different response functions. Nevertheless, the mold index, with generic functions for pine or spruce sapwood, appears to be a good predictor of conditions that will lead to visible mold (i.e. mold index greater than 3) and can explain the observed differences in staining at the varying locations. Graphs of the mold index over time for the monitored locations can be found in Appendix A.

Table 2: Observed vs. Predicted Mold Index

Unit	Location	Observed Mold Index			Predicted Mold Index	
		at Nov. 2011	at Nov. 2012	at Apr. 2013	Winter of '11/'12	Winter of '12/'13
1	East Baffle	4	n/a	5	4	4.5
	East non-baffle	3	n/a	4	3.5	4
	West Baffle	< 3	n/a	< 3	< 3	< 3
	West non-baffle	< 3	n/a	< 3	< 3	< 3
2	East Baffle	4	5	5	4.5	5
	East non-baffle	3	4	4	4.5	5
	West Baffle	< 3	< 3	4	< 3	4.5
	West non-baffle	3	3	3	4	5
Control	With Insulation	0	n/a	4	n/a	4
	Without Insulation	0	n/a	4	4	4

2.3 Monitoring Data

Monitoring continued during the winter of 2012-2013 at the test units identified in Phase 1 of this study. A description of the measurements and data from previous periods can be found in the Phase 1 report. For Phase 2, the attic venting area was altered in two units to investigate the relative impact attic ventilation has on moisture levels in the attics.

2.3.1 Impact of Venting Area

Monitoring continued in units 1 and 2 at the beginning of November 2012. The soffit venting was blocked in unit 2 by filling the voids with plastic bags filled with loose fill insulation. This work was done in-conjunction with servicing the monitoring equipment and continuation of the monitoring program. A button vent was added near the ridge of unit 1 at the middle of December 2012. Graphs showing the monitoring data for the period of November 2012 to the spring of 2013 can be found in Appendix A. The key findings related to changes made to the venting areas and how it relates to the effectiveness of ventilation follow.

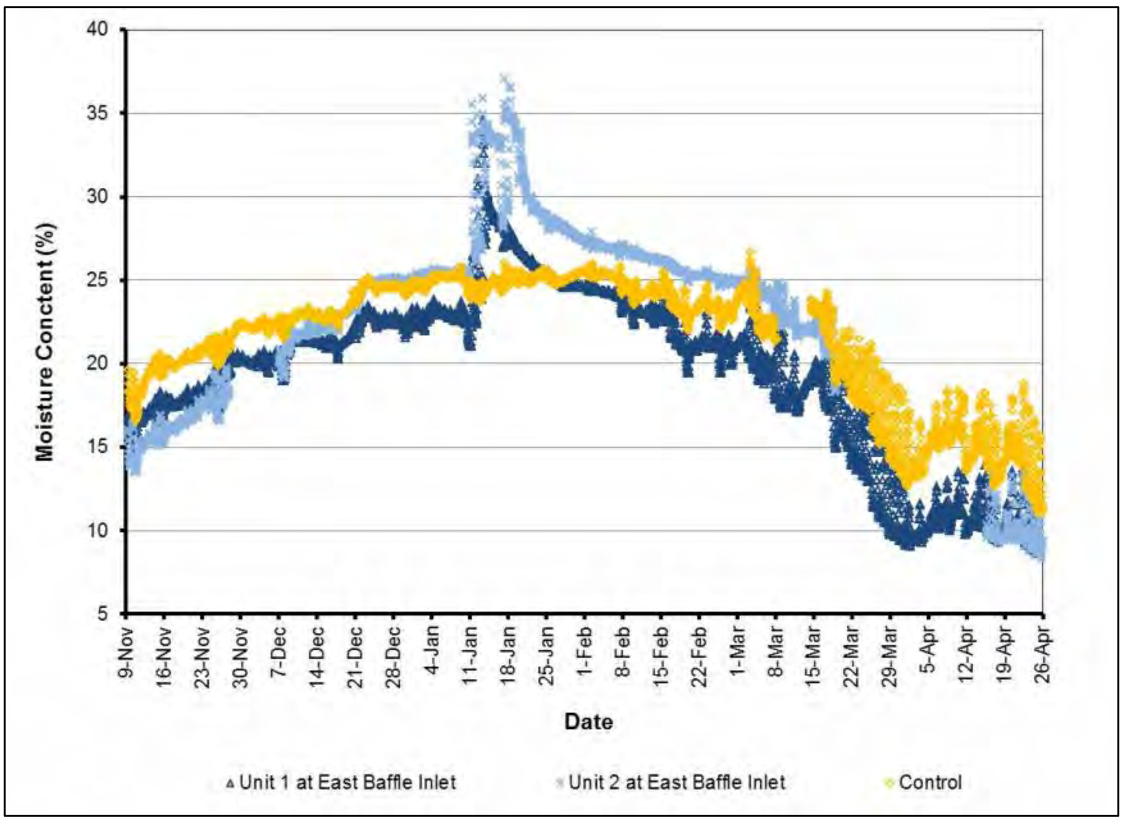


Figure 2: Moisture Content of Sheathings with Changes to Venting Area

Key Observations

Winter 2011/2013: The moisture levels peaked and remained at similar levels for both units, but unit 2 had higher peaks and had an extra wetting event.

Winter 2012/2013: during a 10 day period there was several consecutive cold clear nights when

- Unit 1 (additional vent) spiked less times than unit 2 (blocked soffit vents) and
- Unit 1 dried out more quickly than unit 2.

The moisture levels unit 1 dropped to similar moisture levels as the control assembly, one week after the wetting events. In contrast, moisture levels in unit 2 remained elevated at around 28% MC for several weeks longer.

Key Findings

There were similar differences between the two units for both winters, but it appears that the added ventilation area in unit 1 helped reduce moisture levels quicker than unit 2. However, there was no real benefit in terms of the mold index and the risk of mold did not appear to be reduced.

2.4 Validation of the Monitoring Data and Heat-air-moisture (HAM) Model

HAM simulations were essential for this study to identify the contribution that each factor has on the moisture levels in ventilated attics, due to the complexity and quantity of interconnected variables. The first task of the HAM analysis was to confirm that all the field measurements, as a complete data set, are probable and demonstrate that a numerical model can closely simulate the measured response of the roof sheathing.

Several models were evaluated to satisfy ourselves that we could meet the objectives of this task. This exercise highlighted the following key requirements of the HAM model to simulate the measured response of the wood sheathing:

1. The ability to directly simulate **transient pressure differentials** on the whole building and the resulting impact on the airflows and mixing of the attic air space.

2. Detailed calculations of the **radiation exchange** of the roof surface to the environment depending on the building orientation for each time step.

3. Simulate the movement and storage of heat and moisture in the roof sheathing with a complete coupling between the sheathing and attic air space.

Ultimately EnergyPlus was selected for the HAM analysis because the movement of air, dependent on varying pressures on the building, was deemed a principal factor in simulating the measured response. EnergyPlus has a comprehensive and validated air-flow network model that can simulate multi-zone airflows that are dependent on pressure differentials created from wind, forced air distribution systems, and thermal bouncy. The ability to properly account for airflow (air leakage from the conditioned space and ventilation) is fully coupled by a heat and moisture balance with heat and moisture flows to or from the roof construction. This coupling allows for the interaction of radiation heat transfer to the exterior, moisture storage within the wood, and moisture transfer between the attic space and wood sheathing to be directly simulated for varying rates of airflow. Accordingly, there was very good agreement between the measured and simulated response of the wood sheathing despite not having site specific data for radiation. A comparison of the measured and simulated moisture content for the roof sheathing to demonstrate this close agreement is shown in Figure 3. More details of the modeling approach and assumptions can be found in Appendix B.

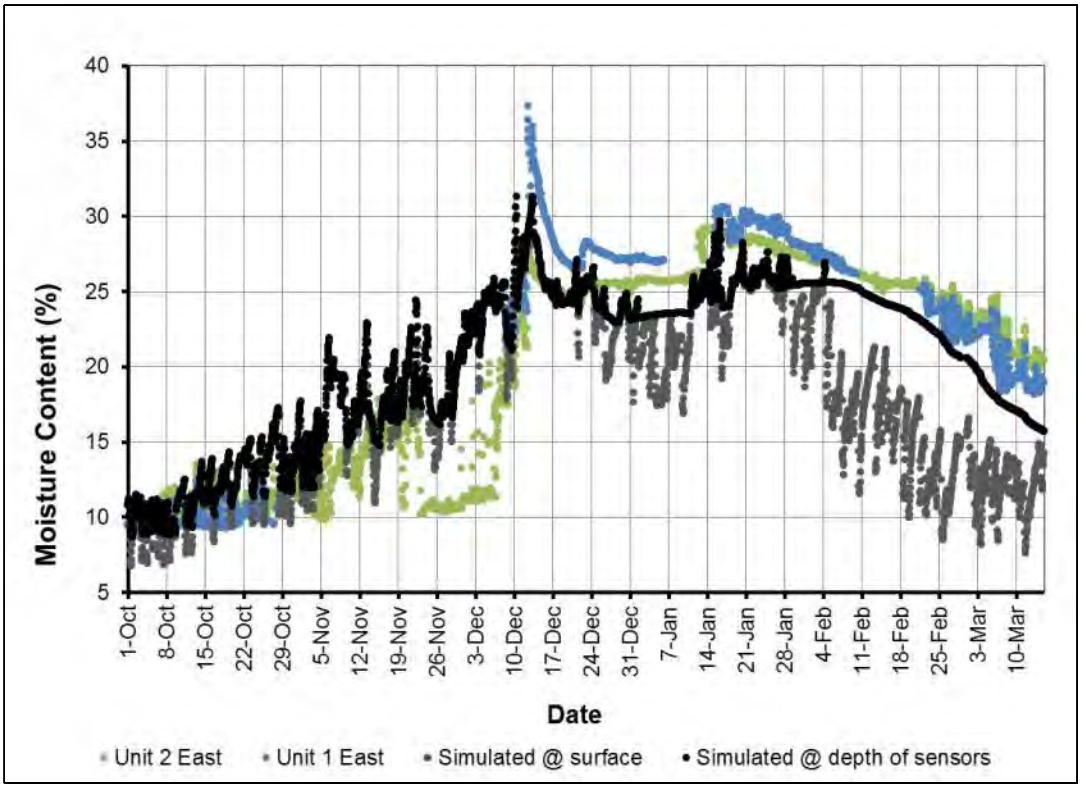


Figure 3: Comparison between the Measured and Simulated Moisture Content of the Roof Sheathing

2.5 Parametric Study

The validated HAM model using the same weather data was utilized to evaluate the impact of varying levels of ceiling airtightness, indoor moisture levels, attic ventilation rates, sheathing thermal resistance, and insulation levels on moisture levels in ventilated attics. A complete simulation matrix and results can be found in Appendix B. The key findings of the parametric study follow:

1. **Attic Insulation** – mold growth in ventilated attics would not be an issue if there was no insulation, but the risk of mold growth in insulated ventilated attics appears to have existed for at least 20 years. There is essentially no difference between R-30 and R-50, so there are no implications associated with going forward with adding more insulation to attics beyond R-30 levels. There also does not appear to be any

correlation to any recent code changes regarding insulation levels considering the 1994 BCBC required R-40 insulation for residential buildings for the lower mainland of BC (degree days less than 4500).

2. **Attic Ventilation** – attic ventilation can be the principal source of moisture in highly insulated attics. However, ventilation also has the potential benefit of drying wood in attics after wetting events, increased drying in the spring time, and taking away moisture due to air leakage from the interior space. Ventilation appears to be a net benefit. Moreover, there is no evidence to suggest that different requirements for venting area or distribution, which have been required by code for more than 30 years, will reduce the risk of mold growth in ventilated attics. Nevertheless, mold growth can be expected on untreated roof sheathings in ventilated attics in the Lower Mainland of BC, despite the net benefits of ventilation for conventional construction.

3. **Interface Leakage Area –** air leakage from the interior to the attic can substantially increase the risk of mold growth on untreated wood in ventilated attics. Effectively controlling air leakage is critical in minimizing mold growth in ventilated attics.

4. **Indoor Humidity Levels** – the simulations for our climate is partially confirming the findings for other Canadian studies. The risk of mold in attics is increased with elevated indoor humidity. Industry should not ignore that reducing indoor humidity will help reduce the occurrence and coverage of mold in attic spaces. Nevertheless, mold growth can occur in attics without high indoor humidity.

5. **Sheathing Thermal Resistance –** adding thermal resistance outboard the roof sheathing can reduce the risk of mold growth in ventilated attics. Adding R-2.5 insulation outboard the roof sheathing reduces the risk of visible mold growth but does not eliminate the risk of mold growth. Adding R-5 insulation minimizes the risk of mold growth for buildings with airtight ceilings and low levels of indoor humidity. Adding insulation outboard the sheathing up to R-5 is not effective in controlling the risk of mold growth in ventilated attics if the indoor humidity and/or interface leakage rates are high.

3. SOLUTIONS

This section outlines the available solutions that can be utilized to reduce the likelihood of fungal growth in new construction and addressing surface molds in existing attics. This section is organized as follows:

1. In Section 3.1, a roadmap of broad strategies is identified.
2. Then in Section 3.2, feasible solutions that follow each strategy are defined.
3. Then in Section 3.2, the incremental costs associated with implementing these solutions compared to current standard practice are presented.
4. Finally in section 3.4, an evaluation of the advantages and disadvantages, practicality, and expected performance of each of the solutions is presented.

3.1 Solution Roadmap

There are five broad strategies that can be applied to address fungal growth on roof sheathings:

Strategy 1. Apply treatments and coatings to create surfaces that are unfavourable for mold growth for a broad range of anticipated environmental conditions. For example, a treated wood sheathing surface that can be repeatedly exposed to condensation, long periods of high relativity humidity and dynamic roof temperatures without growing mold.

Strategy 2. Provide insulating boards and specify mold resistant sheathing outboard ventilated spaces. Liquid water is controlled by the insulating board by potentially two mechanisms, depending on the roof type. The principle mechanism of controlling exposure to liquid water, for all roof types, is keeping the roof sheathing temperature warm enough to eliminate wetting by night-sky radiation. A secondary mechanism of controlling exposure to liquid water, for sloped roofs with asphalt singles, is the insulating board will provide an effective capillary break between the sheathing and the shingles. The roof sheathings still should have mold resistance greater than unprotected sapwood. However, potentially different products can be used than the treatments required for Strategy 1, because exposure of the sheathing to liquid water will be minimized. Mold resistance of the sheathing can be provided by material selection, treatment, and/or coatings.

Strategy 3. The optimum solution from a technical and durability perspective is to provide all the roof insulation entirely outboard the roof sheathing, keep the roof structure warm and dry, and eliminate the requirement for ventilation.

Strategy 4. Insulate the underside of the roof sheathing with foam insulation to stop mold spores from getting in contact with the roof sheathing, while in service, and limit the available oxygen and moisture. Although mold will not likely grow on roof sheathings covered with foam insulation, the spray foam also provides a barrier between the wood sheathing and interior space. This barrier also alleviates concerns because there is no air path from the roof sheathing to the indoor space.

Strategy 5. Provide a mechanical system that controls airflow into the attic space and only ventilates when there is not the potential to add moisture to the attic space. This is engineered strategy that will require a lot more in-depth study; calibrated HAM modeling, field testing, and/or lab testing; before it is practical to implement in standard building practice in BC.

Table 3 summarizes the solution strategies with the variations and applications that are evaluated and discussed in more detail. Detailed descriptions of specific solutions that follow the broad strategies follow.

Table 3: Solution Roadmap Summary

Solution Strategy Category	Solution Strategy	Solution Variations	Application	
			New Construction	Existing Attics
Strategy 1: Treatments and Coatings	Create unfavourable surfaces for mold growth for a wide range of conditions, i.e. exposure to liquid water	• factory vs. site applied • low liquid and vapour permeance coatings • clear coatings with moldicide • preservative treatment	Yes	Yes with limitations to assessable site applications
Strategy 2: Insulating Board and Mold Resistive Sheathing	Warm the sheathing with insulating boards and specify mold resistant sheathings	• low vs. steep sloped roof assembly • treatments, coatings, and materials to resist mold growth	Yes	Limited to major renewals
Strategy 3: Exterior Insulated Roof Assemblies	Provide all the roof insulation outboard the roof sheathing	• low vs. steep sloped roof assembly	Yes	Limited to major renewals
Strategy 4: Insulate the Underside of the Roof Sheathing	Create additional barriers for mold growth	• un-vented steep sloped assemblies	Yes	Yes
Strategy 5: Control the ventilation	Provide mechanical ventilation of the attic space when conditions are favourable	N/A	Currently there is no practical application of this strategy for BC	

3.2 Solutions Definitions

In this section, solutions are defined that follow the viable strategies, 1 to 4, that are outlined in the Solutions Roadmap above.

There is a wide range of possible products that can be considered to meet the objectives of each strategy. The purpose of this study is not to systematically consider every possible variation. The intent is to identify solutions that are likely to be successful, given the current best available information, for common construction practice for wood-framed roofs in BC.

Further objectives are to target products that are readily available in BC[5], cost effective and practical, and/or provide a notable higher performance building envelope.

For the purpose of analyzing specific solutions, for cost and performance, we provided example products that meet the intent of the broad strategy. We have provided these example products to not only permit estimating the incremental construction costs but also to exemplify products that are commercially available in BC.

There are some alternative constructions and products that will improve the overall performance of the building envelope over the solutions that are defined in this report. Example improvements are increased durability of materials, tighter air barriers, and better protection of materials during construction. However, the solutions identified in this report are strictly defined by the risk of mold growth on the roof sheathing compared to the baseline case of a standard ventilated roof assembly. For construction cost estimates, the code minimums are used to establish cost effective solutions compared to the baseline case. The baseline assemblies are defined in section 3.3.

We must emphasize that the long-term efficacy of products to resist mold growth in ventilated attics subject to long-term high relative humidity and wetting by condensation has not been well established. We have identified products based on current readily available information. These solutions can provide a foundation for comprehensive testing and field verification studies that will be required to verify the long-term mold growth resistance of products for ventilated attics in BC. Unresolved research questions are outlined in Section 4. The reader should accept the uncertainty of the long-term resistance to mold growth of treatments in ventilated attics for our climate before implementing any of the solutions that rely on treatments.

Limitations of Long-term Mold Resistance of Wood Treatments for Ventilated Attics in BC

There is currently significant uncertainty around the available products that will provide long-term resistance to mold growth on wood products in the environments expected in ventilated attics in British Columbia. There are commercially available products that will likely work in practice. However, there are currently no widely accepted products that are supported by rigorous and comprehensive testing, and demonstrated field experience, in this application. In our opinion, widely accepted products will emerge when:

1. Commercial products are registered by Canada's Pest Management Regulatory Agency for controlling mold growth on wood products in attics.
2. Manufacturers support use of their product for attic applications through testing and long-term warranties for resistance of mold growth of common surface mold.
3. Validation of products through controlled and repeatable lab testing.
4. Verification of acceptable field performance through sustained elimination of mold growth and successful treatment of existing attics.

No one commercially available product currently satisfies all these requirements. The reader must accept this uncertainty when implementing any of the solutions that rely on wood treatments.

[5] Or can be expected to become readily available given enough demand

3.2.1 Strategy 1: Treatments and Coatings

Commercially available coatings or sealers bond, penetrate, and / or encapsulate active treatment agents to the wood surface and reduce liquid water absorption. These products can protect wood sheathings from mold growth during transportation, construction, and in service where wood is subject to high humidity or surface moisture for extended periods of time in service. Ideal products penetrate the wood to reduce liquid water absorption but have moderate to high vapour premeance to facilitate drying of the roof sheathing during favourable conditions.

Products that are promoted in preventing mold and decay fungi from growing on wood can include one or many active ingredients. The ones likely to be effective in attic applications contain ingredients specifically intended to resist the growth of surface molds (referred to generically as moldicides in this report). Research has shown that a mixture of active ingredients can improve the efficacy of moldicides (Viitanen 2002, Freeman 2008).

Active ingredients can include the same chemicals that are used for anti-sapstains and preservative treatments. Water repellents with high vapour permeance are also sometimes added to moldicide blends to reduce liquid water absorption, while allowing for drying by vapour diffusion. Low liquid water absorption can, in theory, minimize checking and splitting, which may make the moldicides more effective by not exposing untreated wood to the attic air.

Example active ingredients in commercially available moldicides, but not limited to, follow: 3-iodo-2-propynyl butyl carbamate (IPBC), didodecyldimethylammonium chloride (DDAC), disodium octaborate tetrahydrate (DOT), Chrolothalonil (CTL), propiconazole, and sodium carbonate. Wood preservative chemicals such as DOT have the added benefit of protecting against decay fungi, as well as surface molds.

Viable solutions following strategy 1 should have a moldicide with a preservative treatment that diffuses into the wood sheathing, since the roof sheathing can be exposed to repeat wetting by condensation and conditions where decay fungi will germinate. Low permeable coatings can increase mold growth resistance but is not necessary and cannot be relied upon alone. Additionally, viable treatments and coatings must be

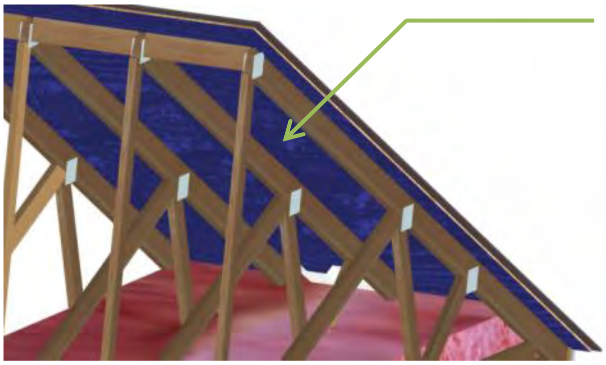
- Commercially available in BC
- Resist mold growth for the following conditions[6]
  - Condition 1: 30 weeks above 90% RH and temperatures up to 30°C
  - Condition 2: 10 weeks above 95% RH for temperatures up to 20°C
  - Condition 3: 5 weeks above 97% RH for temperatures up to 20°C
  - Condition 4: Periodic exposure to liquid water during conditions 2 and 3

There are some standard test protocols that cover some of these conditions (AWPA E24-06). Other conditions appear to be more severe than standard protocols in

[6] this is roughly based on measured conditions and doesn't necessary coincide with established tests

terms of humidity but not for temperature. Additional recommended research for mold testing of viable treatments is covered in section 4.

Solutions for New Construction



Solution 1.A – Apply an all in one treatment, moldicide, preservative, and low perm coating, to roof sheathing prior to delivery to job site. Example products are Bluwood.

Solutions for Site Applications and Existing Buildings

The remediation of attics of existing buildings requires cleaning and removal of stained areas to cosmetically address visible mold growth followed by a prevention strategy to control the re-occurrence of the fungal growth. While mold stains are often only cosmetic after treatment, failure to remove the stains may result in future misdiagnosis of active mold growth.

An ideal and practical method to clean mold in attics is a product that can be sprayed in a single application without requiring a rinse. Peracetic acid (PAA) appears to be a practical product to clean the roof sheathing because a single application is reported to be sufficient to remove black stains, requires no scrubbing or clean-up, the active ingredient is widely used in food processing and breaks down to oxygen and water, and can be applied with any sprayer. However, a commercial product does not appear to have been widely used to-date to clean mold in attics, but there is a product that is available in BC that is being marketed for this application.

An application of PAA using a sprayer is assumed to be part of all the solutions for existing attics. This is considered part of the baseline solution with consideration of the limited space in attics, turns black staining white, and cost.

Some organizations recommend that removal of mold is best done with soap, water, and scrubbing, due to health and safety concerns of the applicator when using chemicals like Chlorine. However, soap, water, and scrubbing is problematic in attics with low slopes near the soffit area. Health and safety concerns can be alleviated with appropriate personal protective equipment. Dry-ice blasting, or other media blasting, is another option. However, this method is more costly, cleaning up the mold is problematic, and proper clean-up requires temporary removal of the insulation.

Professional mold abatement companies typically follow protocols developed for mold abatement within the indoor environment (CSA 82-2004, Health Canada 2004, New York City Department of Health 2008). These protocols assume that the source of moisture be first stopped then remove the mold. The techniques and safety procedures for mold growth removal vary depending on the mold coverage.

However, these protocols are guidelines and all recognize that the guidelines are general and are not meant to exclude other similarly effective methods. Moreover, the protocols were developed for indoor environments and state that indoor humidity should be maintained at levels below 60% RH to inhibit mold growth. Deviation from these protocols is reasonable for ventilated attics because the humidity cannot be controlled per indoor standards and the transfer of air into the occupant space is controlled. Nevertheless, following these guidelines is recommended to maintain the safety of the workers performing the removal of the mold.

Solution 1.B – clean roof sheathing to remove staining and apply clear coating with moldicide and preservative treatment. Example products Concrobium® Mold Stain Remover (PAA) and Boracol 20-2BD (clear coating to control reoccurrence)[7].

3.2.2 Strategy 2: Insulating Board and Mold Resistive Sheathings

The sheathing can have, in theory, less mold resistance for this strategy than for a treatment only strategy (strategy 1). Mold resistance of the sheathing can be provided by material selection, treatment, and/or coatings.

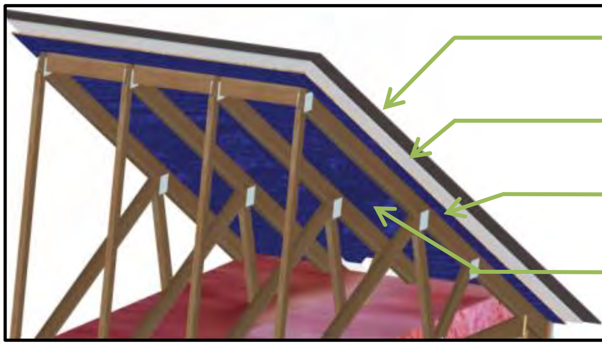
Viable solutions following strategy 2 must resist mold growth for the following conditions (this is roughly based on measured conditions and doesn't necessary coincide established tests):

- Condition 1: 30 weeks above 90% RH and temperatures up to 30°C
- Condition 2: 10 weeks above 95% RH for temperatures up to 20°C

There are a wide range of products available that satisfy these requirements. For the purpose of analyzing specific detailed solutions for cost and performance, we have provided two alternatives to have a base level cost comparison. These solutions have not been tested by time for this application so further research can be conducted to validate these solutions as presented in section 4. There are also theoretically more cost prohibitive solutions that follow this strategy, such as composite plastic sandwich panels, that can be used instead of wood sheathings. However, these solutions have been disregarded for further analysis because they do not meet the objectives of our target solutions as presented in the solutions roadmap.

[7] Boracol 20-2BD has been the industry standard for treating existing attics to control the reoccurrence of mold in ventilated attics. However, the long-term efficacy has been recently been called into question from preliminary findings of current research into the long-term efficacy of moldicides for ventilated attics in the lower mainland of BC. At this time there are no clear alternative commercially available products for existing buildings. Boracol 20-2BD is presented as an example product for existing buildings until conclusive and/or alternative products are available to industry in BC.

Solutions for New Construction and Renewals

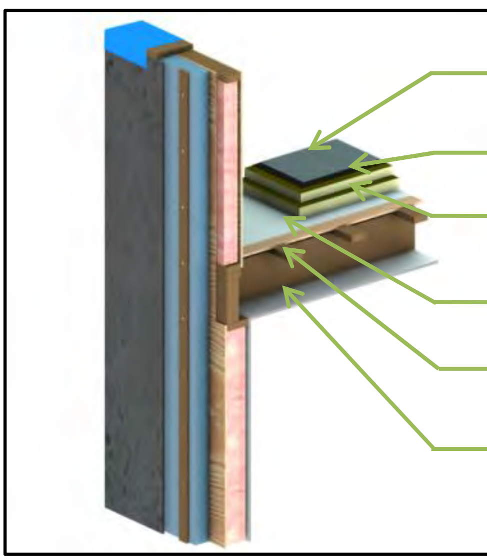


Solution 2 – exterior painted wood with moldicide a polyiso board outboard the roof sheathing. Example products are Rust-Oleum Zinsser Mold and Mildew-Proof Exterior Paint with R-5 Firestone Isoguard HD.

3.2.3 Strategy 3: Exterior Insulated Roof Assemblies

Strategy 3 is to provide all the roof insulation outboard the roof sheathing and eliminate the vented space below the roof sheathing. There are different requirements depending on whether the roof is a low-sloped or a steep sloped. This strategy is only appropriate for new construction and major renewals.

Solution 3.A – provide a conventional low-sloped roof assembly. For the purposes of cost analysis and identifying the minimum requirements, this solution assumes the following roof assembly.



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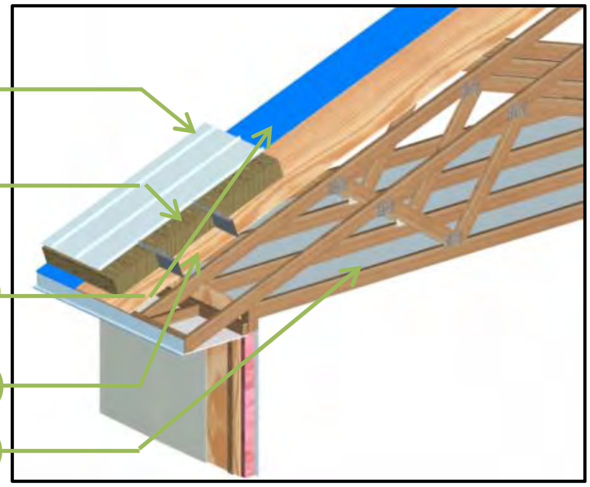
[8] As per Table 10.2.1.1.A in the 2012 BCBC for climates with degree days less than 3500, such as the Lower Mainland in BC. Less insulation is required for roofs with insulation above the roof deck when meeting code per ASHRAE 90.1 compliance paths.

Solution 3.B – provide an exterior insulated steep sloped metal roof assembly. This solution assumes metal roofing because this is the most cost effective solution of an exterior insulated steep sloped roof. For the cost analysis we have assumed a metal roof system with continuous z-girts with hidden clips as shown in the figure below.

Exterior

1. Metal roof system
2. Code minimum insulation[7] (R-28 Semi-rigid mineral fibre insulation)
3. Self-adhered SBS membrane (air, moisture and vapour barrier)
4. Plywood roof sheathing
5. Roof structure (trusses) with gypsum ceiling

Interior



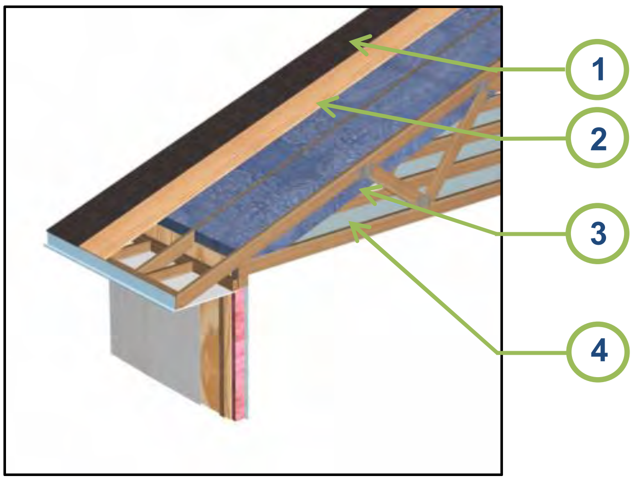
An exterior insulated asphalt shingle solution is also possible but requires wood decking for nailing the shingles to the roof and requires venting below the sheathing for Part 9 buildings. Venting requires strapping, or some other means to create the gap, outboard the insulation. All these add-ons make an exterior insulated roof assembly with asphalt singles cost prohibitive compared to a typical ventilated attic roof assembly. Moreover, mold growth will still likely happen on the sheathing with venting below the roof deck for an exterior insulated asphalt solution, similar to a ventilated attic roof. A solution following strategy 4, spray foam below the roof sheathing, is more practical if choosing to not vent below the roof sheathing. For these reasons, an exterior insulated asphalt roof assembly is not a practical solution to avoid mold growth on the roof sheathing and no further analysis is presented.

3.2.4 Strategy 4: Insulate the Underside of the Roof Sheathing and Cathedral Ceilings

Strategy 4 is to insulate the underside of the roof sheathing with foam insulation for truss roofs with attics or cathedral ceilings. These types of roofs are more difficult to inspect the roof sheathing compared to a typical ventilated attic, with access through hatches. Removing attic hatches and easy access can circumvent unnecessary alarm of mold growth within roof structures. However, mold growth is still as likely to occur on the roof sheathing as for any ventilated roof.

Solutions without any technical merit in controlling mold growth on the roof sheathing or are not practical for common residential construction are not further analyzed. For example, a detailed solution is not provided for unvented low-slope roof assemblies because this type of roof is not practical to a broad range of applications. This type of roof is not practical due to the risk associated with moisture held within in the system due to roof leaks and construction moisture, which can only be alleviated by an alternative solution and rigorous professional design and field review, following the requirements in Part 5 of the building code. Conversely, an unvented steep sloped roof assembly with asphalt singles is deemed practical because of less risk (probability and cost) associated with trapped moisture due to leaks and increasing acceptance of this type of assembly for standard wood-frame construction[9].

Solution 4 – provide an unvented steep sloped roof assembly. Medium density polyurethane spray-applied insulation is specified because the air and vapour barrier is provided by one material. Low density foam can also be used for this type of application but requires a separate material to achieve adequate vapour control. For the purposes of cost analysis and identifying the minimum requirements, this solution assumes the following roof assembly.



Exterior

1. Asphalt singles with underlayment
2. Plywood roof sheathing
3. 5 inches of medium density polyurethane spray-applied insulation (R-28 code minimum[6], air and vapour barrier)
4. Roof structure (trusses) with gypsum ceiling

Interior

3.3 Cost Implications

This section outlines the order of magnitude incremental cost estimates of implementing these solutions compared to current standard construction practice. Cost estimates are provided in tables 5 and 6 for three building types; a detached bungalow, townhouse, and an apartment. Descriptions and building sizes of the buildings follows.

Building Type 1: Two story, 2500 ft^2 detached bungalow, 1250 ft^2 roof/ceiling area

Building Type 2: Three story multi-unit townhouse, 5 units, 3250 ft^2 roof/ceiling area

Building Type 3: Four story multi-unit apartment, 60 residential units, 12,000 ft^2 roof/ceiling area

For the cost analysis, each solution is compared to a baseline standard constructed roof assembly as illustrated in Table 4 below. The incremental construction costs were derived using all the components that are identified in section 3.2 for each solution.

The surface area treated area of the roof sheathing for sloped roofs is the primary factor for incremental costs following strategies 1 and 2 but the ceiling area is also a primary factor of

[9] For example, our understanding is that the City of Vancouver is considering accepting this type of construction for part 9 buildings with conditions.

the incremental costs for strategies 3 and 4. The costs for the entire roof assembly have been normalized per a cost per total roof area to facilitate order of magnitude cost comparisons between the different solutions. Roof construction is often more complex than presented in these examples, with more slopes that result in more sheathing area per roof area. These differences will translate to different costs on a project specific basis. Nevertheless, the intent of these examples is to provide order of magnitude cost estimates to facilitate comparison between the various solutions.

Table 4: Baseline Roof Assemblies for Cost Estimates

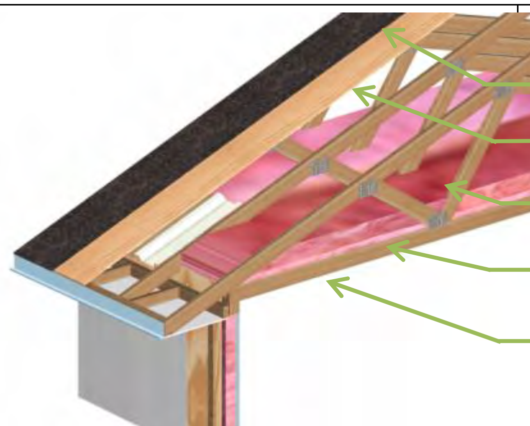
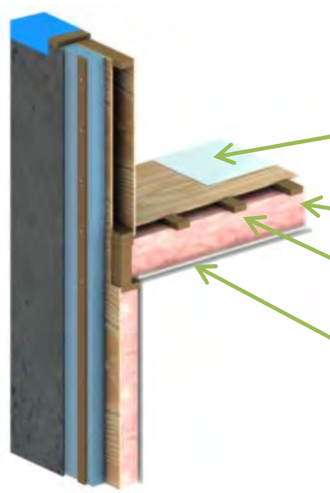
Baseline Steep-sloped Roof		**Exterior** 1 Asphalt singles with underlayment 2 Plywood roof sheathing 3 Code minimum insulation (R-40 or 11 inches of fiberglass batt insulation) 4 Roof structure (trusses) 5 Air and vapour barrier (polyethylene sheet) with gypsum ceiling **Interior**
Baseline Low-sloped Roof		**Exterior** 1 2 PLY SBS roof membrane (water penetration barrier and air barrier) 2 Code minimum insulation (R40 or 11 inches of fiberglass batt insulation) 3 Roof structure (trusses) 4 Air and vapour barrier (polyethylene) with gypsum ceiling **Interior**

Table 5: Incremental Cost for Solutions for Steep-sloped (4:1) Roofs

Strategy	Scenario	Incre-metnalC ost	New Construction			Existing Building		
			BLDG 1	BLDG 2	BLDG 3	BLDG 1	BLDG 2	BLDG 3
Strategy 1 Treatments and Coatings	**Solution 1A** all in one treatment prior to delivery to the job site.	$0.25 /ft²	$325	$850 or $170 /unit	$3000 or $50 /unit	N/A	N/A	N/A
	Solutions 1B cleaning and moldicide treatment at site	$3 /ft²	N/A	N/A	N/A	$4,000	$10,050 or $2010 /unit	$37,200 or $620 /unit
Strategy 2 Insulating Boards + Treatments	**Solution 2** mold resistive paint and insulation board	$4.5 /ft²	$6,000	$15,100 or $3,020 /unit	$55,800 or $930 /unit	N/A	N/A	N/A
Strategy 3 Exterior Insulated Assemblies	**Solution 3B** exterior insulated metal roof assembly	$15 /ft²	$19,500	$50,250 or $10,050 /unit	$186,000 or $3,100 /unit	N/A	N/A	N/A
Strategy 4 Unvented Roof	**Solution 4** unvented roof assembly with polyurethane spray-applied insulation	$7 /ft²	$9,000	$23,500 or $4,700 /unit	$86,700 or $1,445 /unit	$9,000	$23,500 or $4700 /unit	$86,700 or $1445 /unit

Table 6: Incremental Cost for Solutions for Low-sloped Roofs

Strategy	Scenario	Incremental Cost $ / ft^2	New Construction			Existing Building		
			BLDG 1	BLDG 2	BLDG 3	BLDG 1	BLDG 2	BLDG 3
Strategy 1 Treatments and Coatings	**Solution 1A** all in one treatment prior to delivery to the job site.	$0.25 /$ft^2$	$325	$825 or $165 /unit	$3,300 or $55 /unit	N/A	N/A	N/A
Strategy 2 Insulating Boards + Treatments	**Solution 2** mold resistive paint and insulation board	$4.5 /$ft^2$	$5,750	$14,750 or $2,950 /unit	$54,000 or $900 /unit	N/A	N/A	N/A
Strategy 3 Exterior Insulated Assemblies	**Solution 3A** conventional low-sloped roof assembly	New: $8.5/$ft^2$ Existing: $11/$ft^2$	$10,625	$27,625 or $5,525 /unit	$102,000 or $1,700 /unit	$13,750	$35,750 or $7,150 /unit	$132,000 or $2,200 /unit

3.4 Solution Synopsis

The advantages and disadvantages, practicality, and expected performance of the solutions were summarized as follows.

Cost

- Low - less than $5000 per unit for any of the building types
- Moderate - between $5000 and $10,000 per unit for any of the building types
- High -above $10,000 per unit for any of the building types

Construction Methods

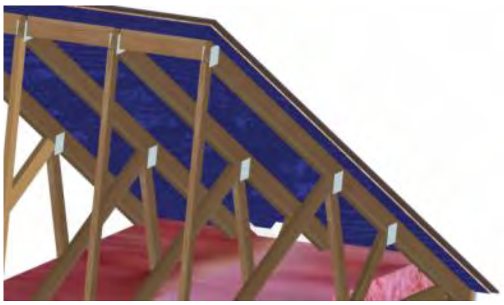
- Common – frequently used in construction with readily available materials
- Enhanced – new materials and/or sequencing will be introduced to standard construction
- Special – new construction methods and/or materials are required

Performance

- Proven – good performance is expected based on technical attributes and field experience
- Limited History – good performance is expected based on technical attributes but there is not a long history of demonstrated field experience
- Caution – some known performance problems are associated with this solution

Solution 1.A

Multi-functional Treatments for New Construction



Apply an all in one treatment to roof sheathing prior to delivery to job site. Bluwood is an example product.

Construction Methods: enhanced	**Performance**: limited history
Cost: Low (less than $2500 per unit)	**Uncertainties**: Acceptance by PMRA, validation by AWPA E24-06 testing, long-term mold resistance when subject to wetting by condensation.
Advantages: wood is treated for surface molds, decay, insects, and warranties are available for long-term performance. The treatment colours the wood so it is evident that the product has been applied. Application is done in a control setting.	
Disadvantages: only applicable for new construction.	

Solution 1.B

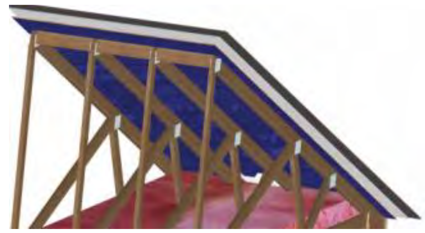
Wood Treatments for Existing Buildings

Clean staining on sheathing then apply clear coating with moldicide and preservative treatment. Example products are Concrobium® Mold Stain Remover (cleaning) and Boracol 20-2BD (clear coating)

Construction Methods: enhanced	**Performance**: limited history
Cost: Low (less than $2500 per unit)	**Uncertainties**: Acceptance by PMRA, validation by AWPA E24-06 testing, long-term mold resistance when subject to wetting by condensation. Effectiveness and corrosiveness of cleaning product for wood sheathings in attics.
Advantages: wood is treated for surface molds and fungal decay. The most feasible and practical solution for existing buildings.	
Disadvantages: inspecting the application of a clear coating is problematic. Application in the field in tight roof spaces is problematic.	

Solution 2

Insulating Boards and Paint for New Construction

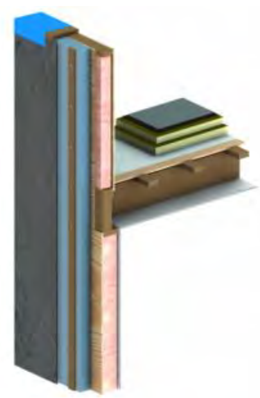


Apply an exterior coating (paint) with fungicide to the underside of the wood sheathing and install a polyiso board outboard the sheathing. Example products are Rust-Oleum Zinsser Mold and Mildew-Proof Exterior Paint with R-5 Firestone Isoguard HD.

Construction Methods: special	**Performance**: limited history
Cost: moderate (between $2500 and $15,000 per unit)	**Uncertainties**: Acceptance by PMRA, validation by AWPA E24-06 testing, long-term mold resistance when subject to extended periods of high humidity.
Advantages: Condensation on the underside of the sheathing is controlled by the polyiso board. The polyiso board provides an additional capillary break between the shingles and plywood. Inspection of paints is standard practice.	
Disadvantages: the presence of paint for this application might raise questions for future buyers (i.e. looks like something is being hidden). The sheathing is only treated for surface molds. Cost vs. risk compared to solution 1.	

Solution 3A

Conventional Low-sloped Roof Assembly



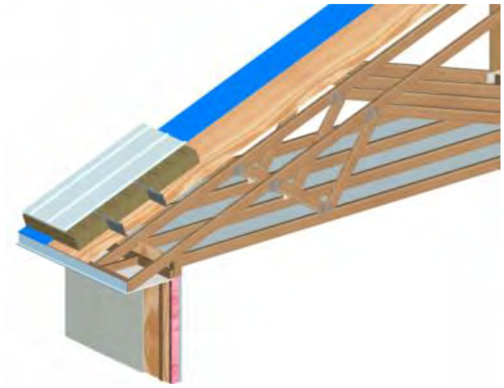
Exterior
- 2 PLY SBS roof membrane (water penetration and air barrier)
- Protection board
- Insulation
- Vapour barrier
- Roof sheathing sloped to drain
- Roof structure with gypsum ceiling

Interior

Construction Methods: common	**Performance**: proven
Cost: moderate (between $2500 and $15,000 per unit)	**Uncertainties**: none
Advantages: proven good performance.	
Disadvantages: roof membrane is exposed and traffic should be minimized on the membrane.	

Solution 3B

Exterior Insulated Metal Roof Assembly



Exterior

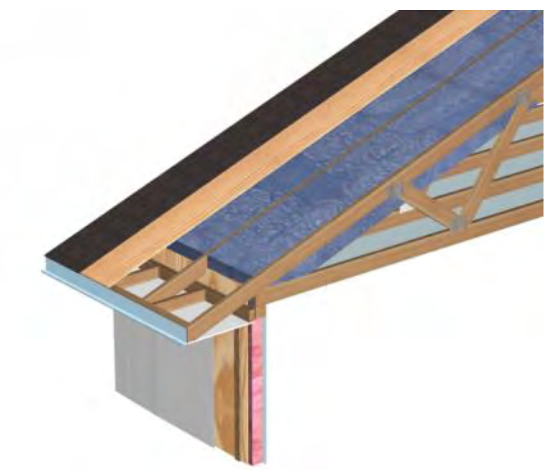
- Metal roof system
- Insulation
- Self-adhered membrane (air, moisture, vapour barrier)
- roof sheathing
- Roof structure with gypsum ceiling

Interior

Construction Methods: common	**Performance**: proven
Cost: high (more than $15,000 per unit)	**Uncertainties**: none
Advantages: proven good performance. Enhanced durability.	
Disadvantages: Cost. Not a direct comparison to standard asphalt single roofs.	

Solution 4

Unvented Sloped Roof Assembly



Exterior

- Asphalt singles with underlayment
- Roof sheathing
- Medium density polyurethane spray-applied insulation
- Roof structure with gypsum ceiling

Interior

Construction Methods: common	**Performance**: caution
Cost: moderate (between $2500 and $15,000 per unit)	**Uncertainties**: drying capability through asphalt singles
Advantages: excellent air barrier, insulation provides combined air and vapour barrier, can have a finished attic.	
Disadvantages: drying capability of roof sheathing.	

4. UNRESOLVED QUESTIONS AND FURTHER RESEARCH

This section identifies questions that are not answered by current knowledge and research that can be completed to answer these questions.

Can we learn to live with mold growth in attics?

There are reasons to believe that moderate levels of mold growth in attics are of little real consequence. If that could be confirmed, and the public accepted that view, it would be possible to avoid the collective cost of treating materials used in numerous buildings to resolve minor concerns in a few. This is likely to be a long process of:

- Research to confirm that mold growth in attics does not lead to health concern or accelerated deterioration of materials.
- A program of education and discourse with the public.

What is the long term efficacy of chemical treatments?

The identification of effective long lasting moldicides will be critical for addressing mold issues in existing buildings and important for new construction. However, there is currently significant uncertainty around the available products that will provide long-term resistance to mold growth on wood products in environments expected in ventilated attics in British Columbia. We envision more research in the following areas:

1. Validating products through controlled and repeatable lab testing
2. Demonstration projects to establish good practices for cleaning and treating wood products in attics and verifying acceptable field performance.

At the time of writing this report, testing was underway at FPInnovations to test the efficacy of various moldicides following AWPA E24. The next step following this work will be demonstration projects using the most promising products and/or blends.

The alternative to chemical treatments is to avoid the use of ventilated attics, and conditions favourable for mold growth, through design. A reason for avoiding chemical treatments is that some occupants might have similar concerns with chemical treatments as some occupants have with mold in attics. A question without direct answers is if there is potential of off-gassing of some chemical treatments in an attic environment and is it a health concern if there is off-gassing.

There are well established design solutions, but there are some questions and possible research that we see as being beneficial to continue to advance industry knowledge. For example, a comprehensive evaluation of the drying capacity of unvented roofs with asphalt shingles.

5. CONCLUSIONS

This study has shown that more ventilation will not solve the problem of mold growth in ventilated attics and experience has shown us that less ventilation can lead to problems when an airtight ceiling is not achieved in practice. There is still opportunity for debate as to whether surface mold in attics is really a problem and if anything really needs to be done besides acceptance that some mold growth is expected in ventilated attics in our climate.

If the presence of mold in attics cannot be tolerated then the most practical solution, when considering costs vs. the significance of mold growth in attics, is to treat the roof sheathings with a moldicide. However, there is currently significant uncertainty around whether the available products will provide long-term resistance to mold growth on wood products in ventilated attics in British Columbia. There will be likely some trial and error that will occur in practice until widely accepted products are established through testing and field demonstration projects. The alternative to chemical treatments is to eliminate ventilation, and conditions favourable for mold growth, through design. The most feasible solution for low sloped roofs is to insulate outboard the roof structure with a conventional roof assembly. For a steep sloped roof assembly, the most feasible design alternative is an unvented roof assembly, which can also have other benefits like increased living space. However, there is a modest cost associated for this alternative and in our opinion requires enhanced design and field review compared to traditional construction.

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Viitanen, H., "Mould Growth on Painted Wood", VTT Technical Research Centre of Finland, 2002.

Viitanen, H, T. Ojanen, "Improved Model to Predict Mold Growth in Building Materials", *Proceedings of the X International Conference on the Performance of the Exterior Envelopes of Whole Buildings*, 2007.

APPENDIX A: Monitoring Data

A.1 Change in Mold Index

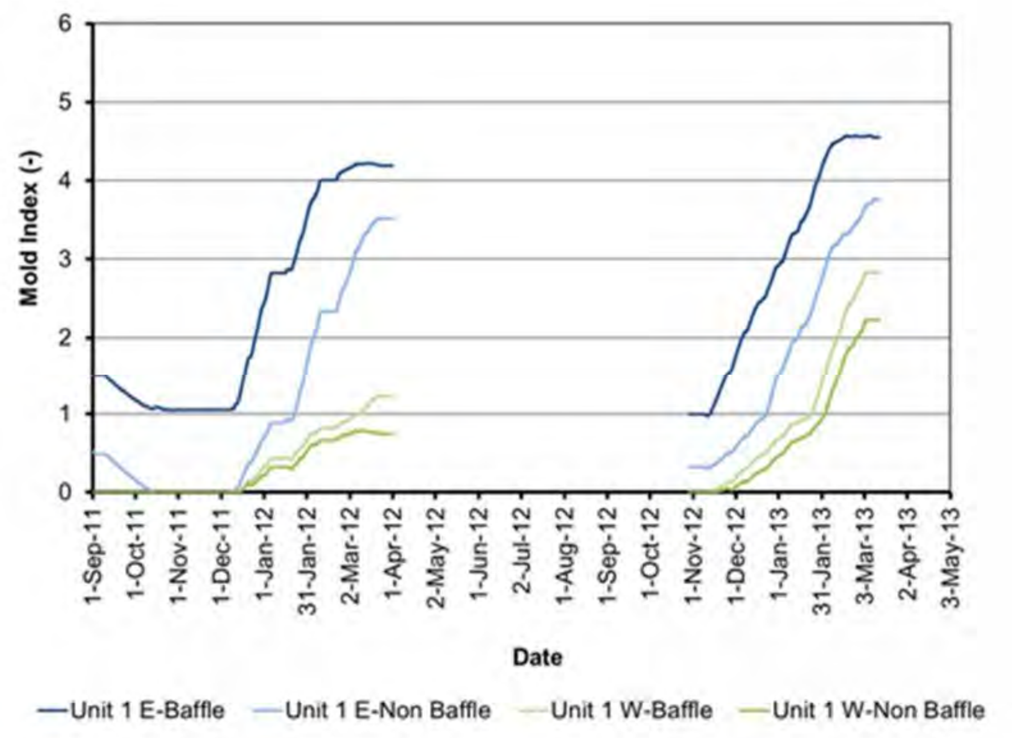

Figure A.1: Unit 1 Mold Index

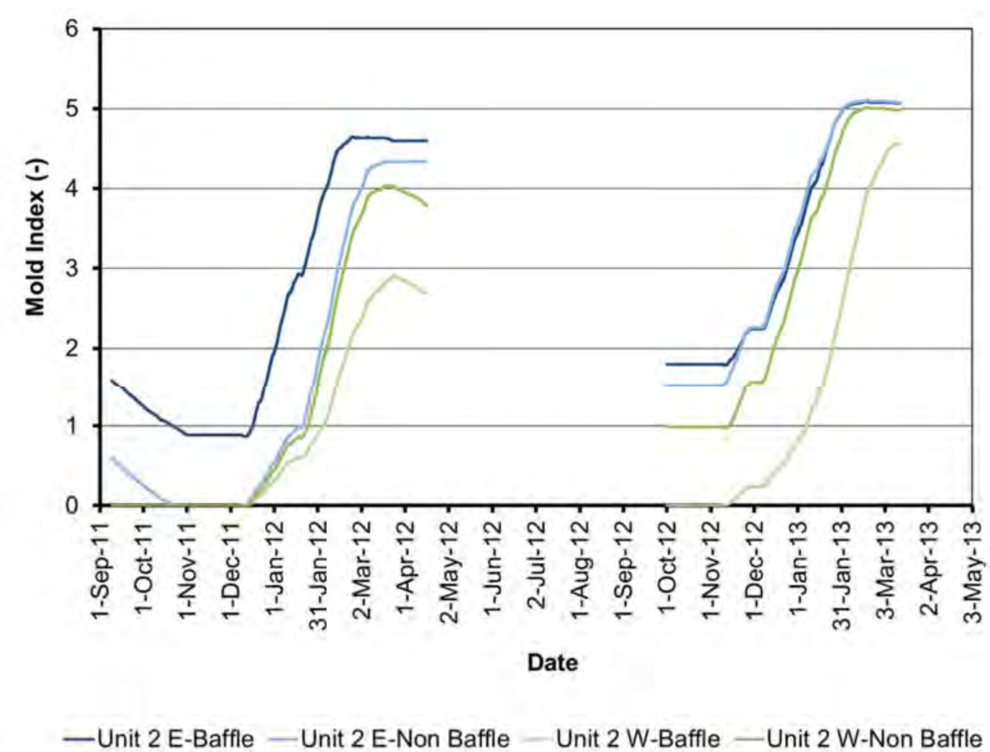

Figure A.2: Unit 2 Mold Index

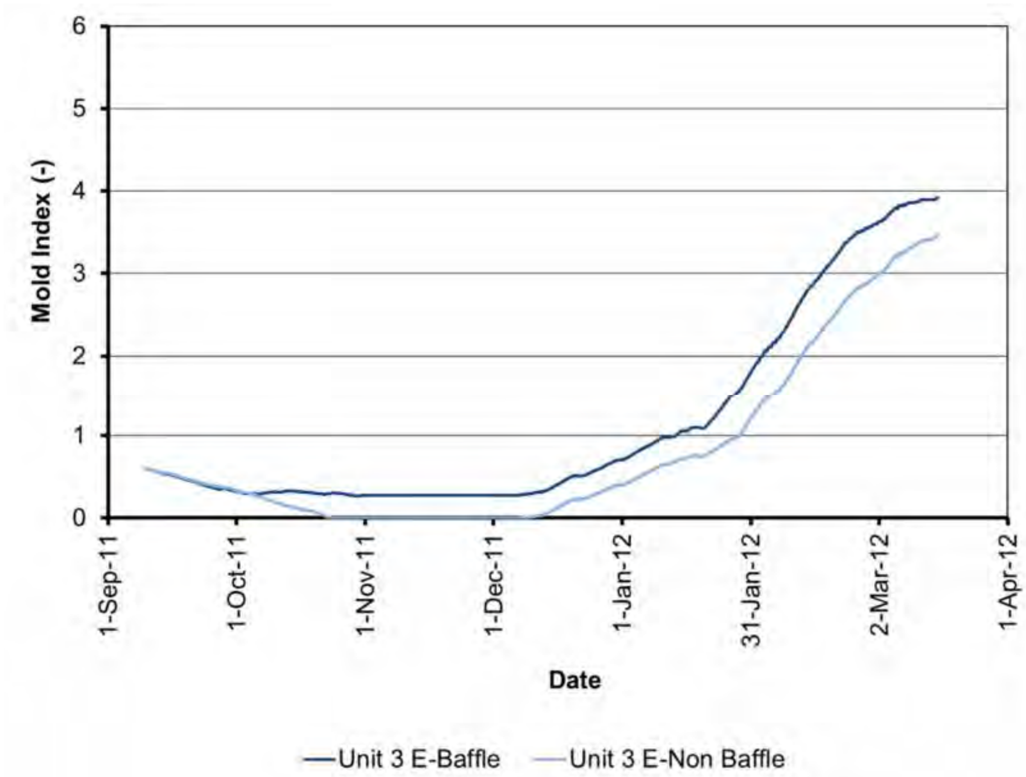

Figure A.3: Unit 3 Mold Index

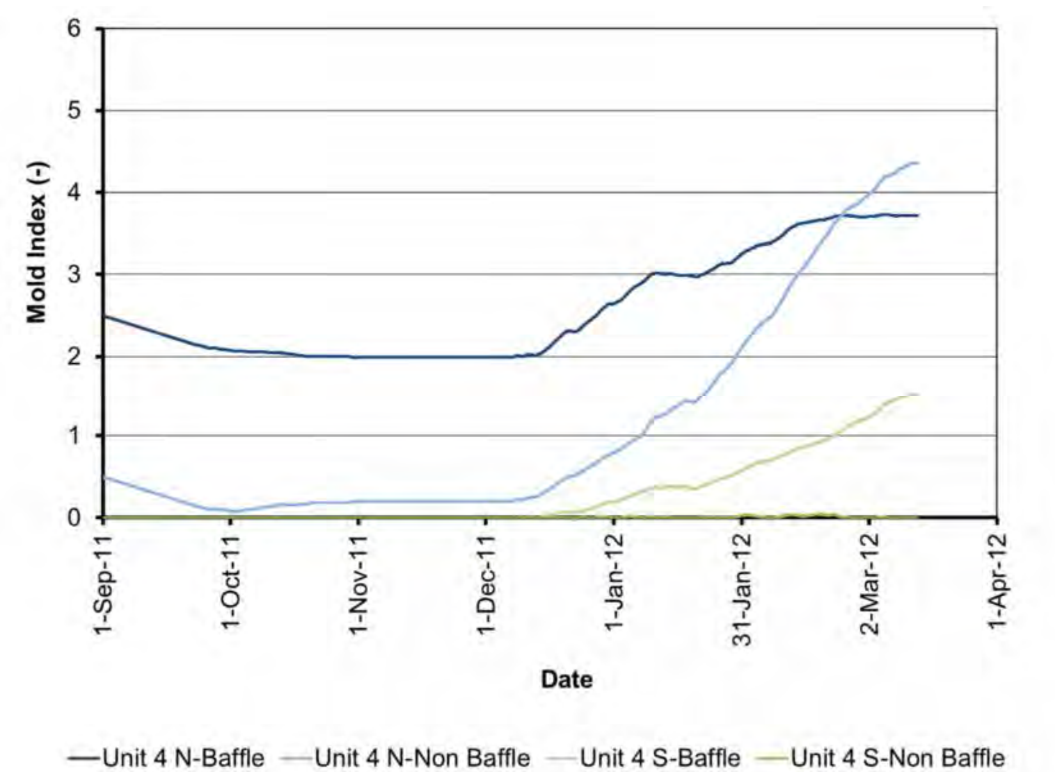

Figure A.4: Unit 4 Mold Index

A.2 Attic Wood Temperature and Moisture Content

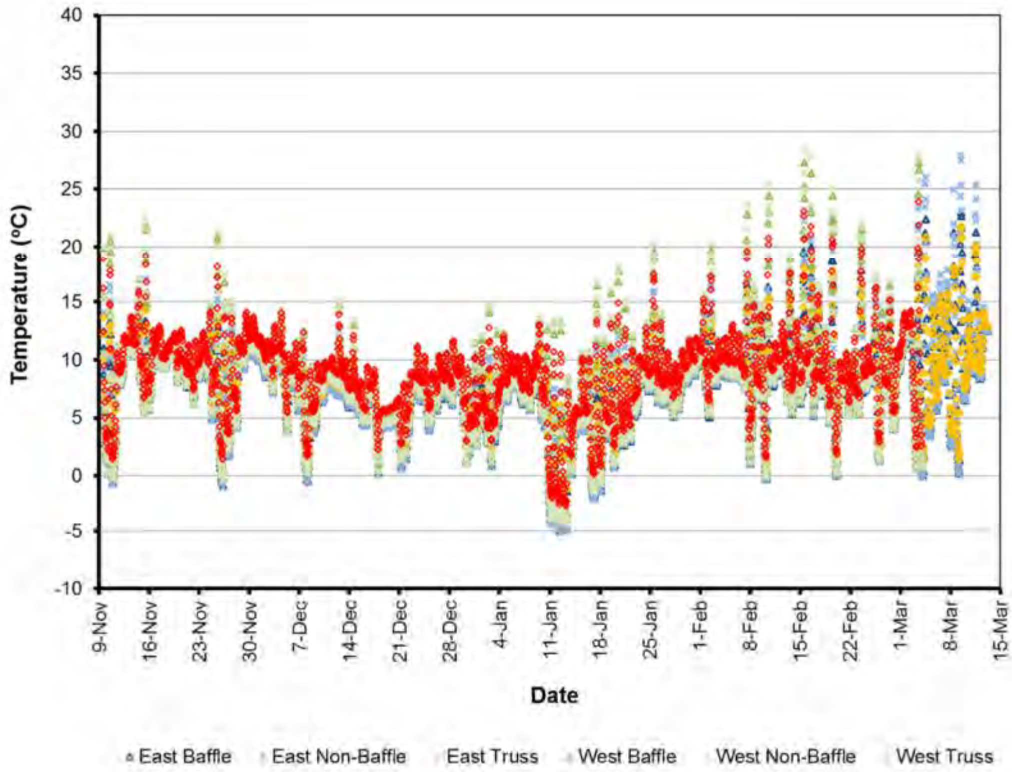

Figure A.5: Unit 1 Wood Temperatures for 2012 - 2013

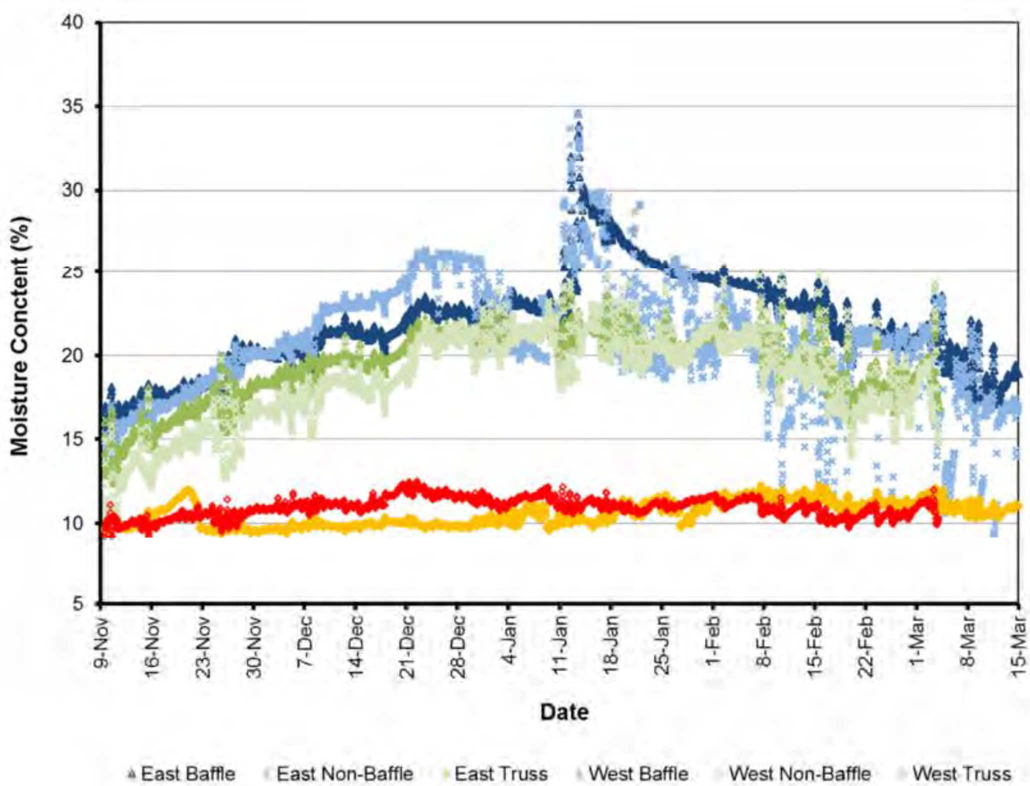

Figure A.6: Unit 1 Wood Moisture Content for 2012 - 2013

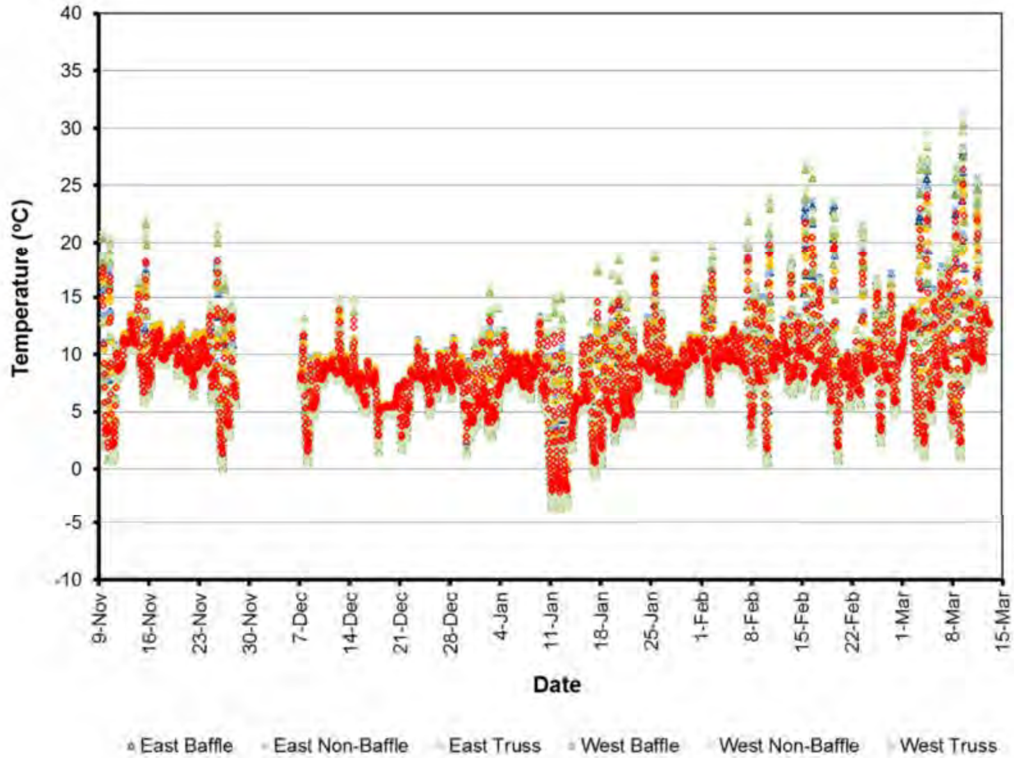

Figure A.7: Unit 2 Wood Temperatures for 2012 - 2013

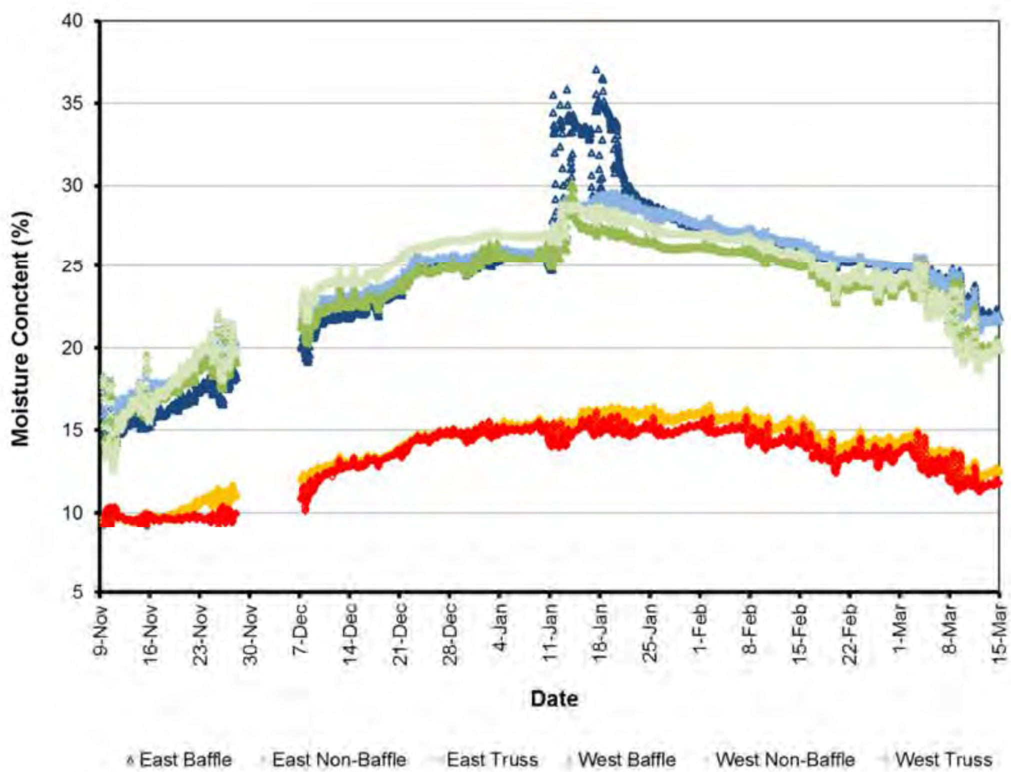

Figure A.8: Unit 2 Wood Moisture Content for 2012 - 2013

A.3 Attic and Outdoor Air Temperature and Relative Humidity

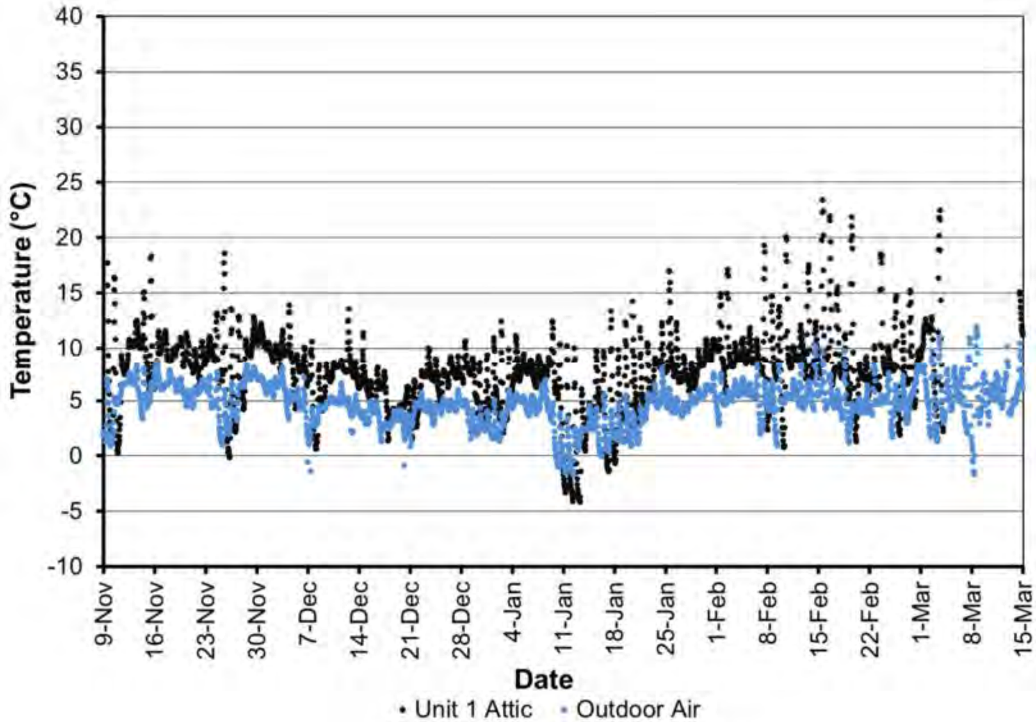

Figure A.9: Unit 1 Attic and Outdoor Air Temperatures for 2012 – 2013

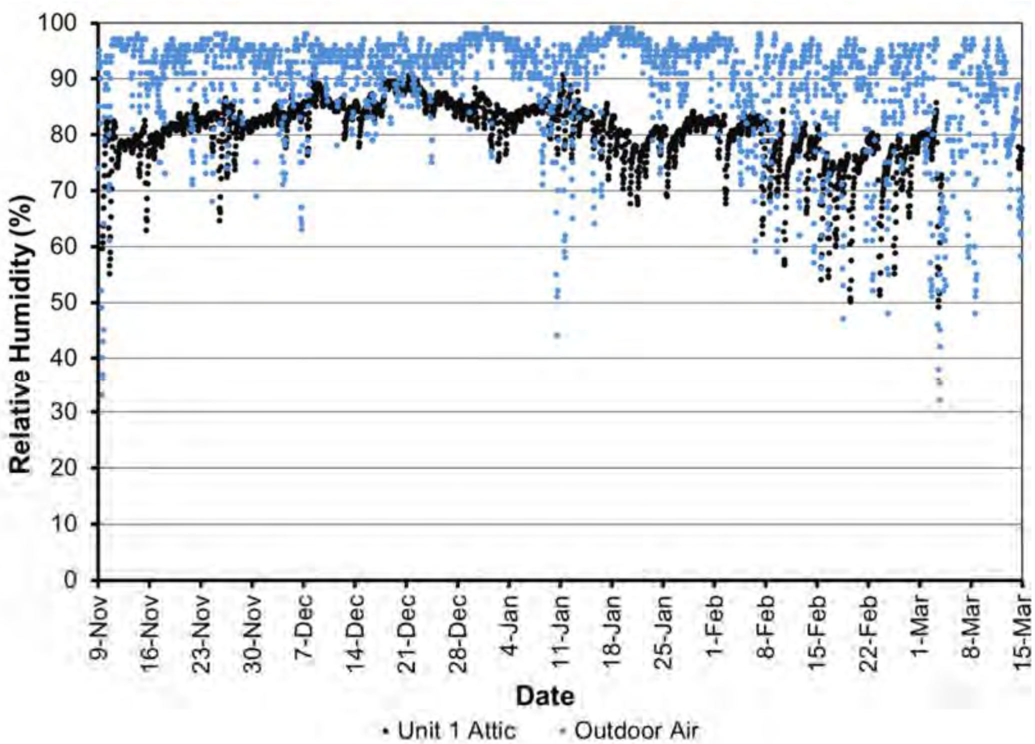

Figure A.10: Unit 1 Attic and Outdoor Air Relative Humidity for 2012 - 2013

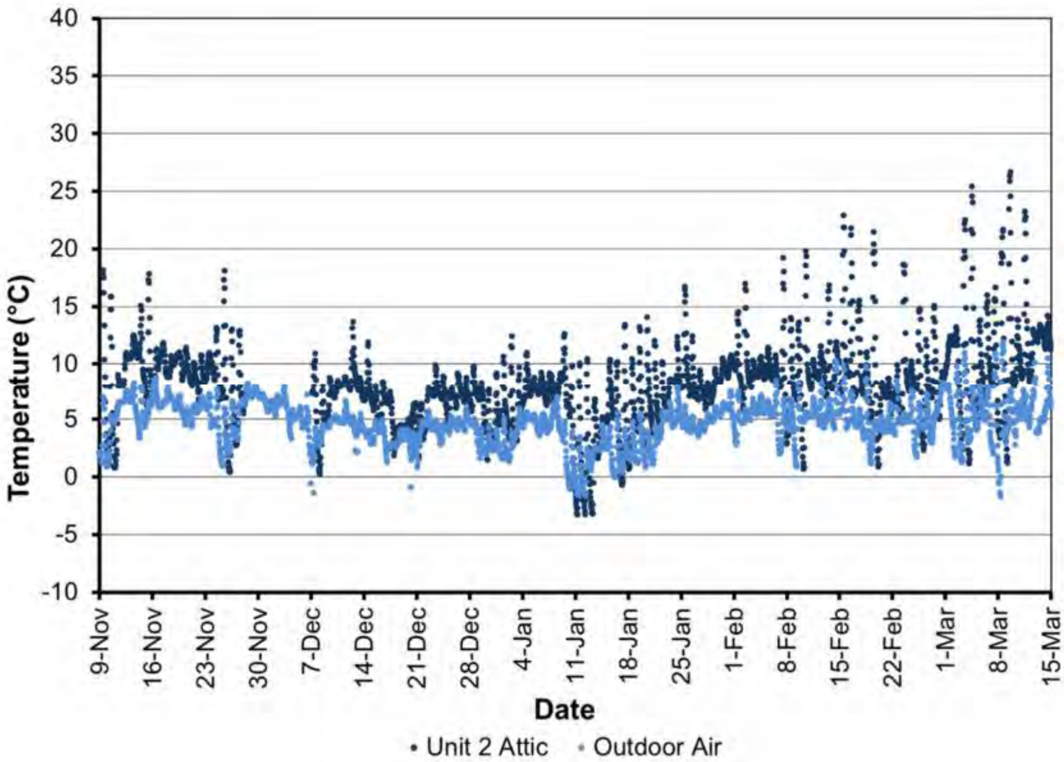

Figure A.11: Unit 2 Attic and Outdoor Air Temperatures for 2012 – 2013

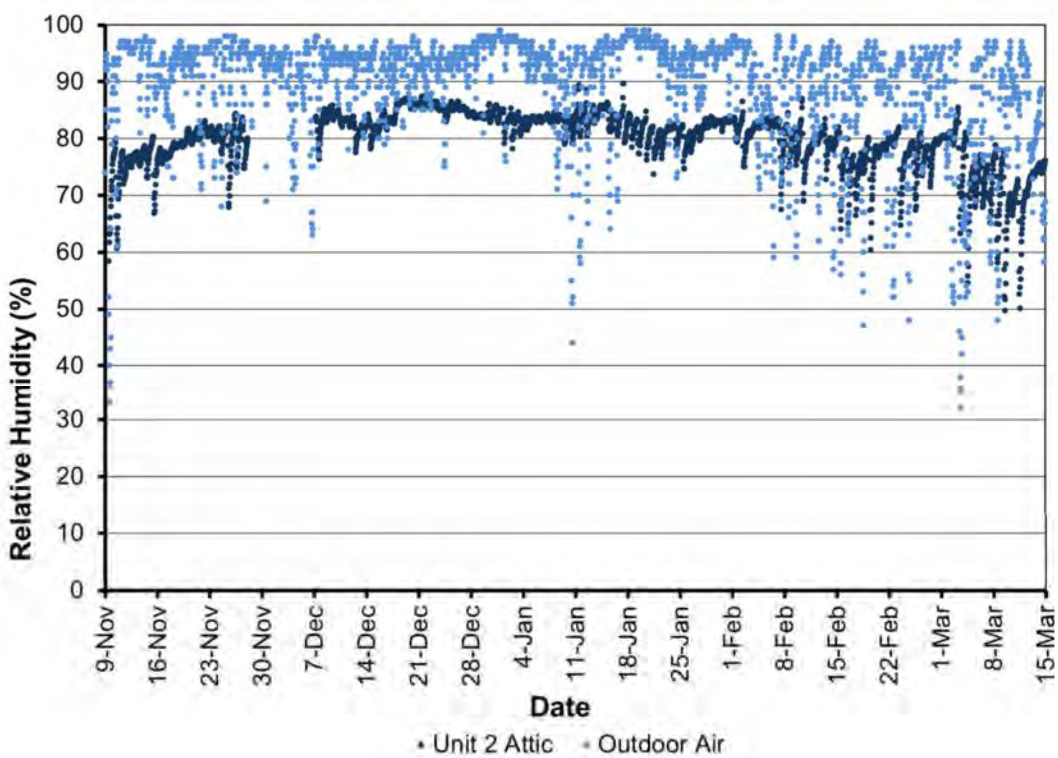

Figure A.12: Unit 2 Attic and Outdoor Air Relative Humidity for 2012 - 2013

A.3 Duration of Elevated Moisture Content

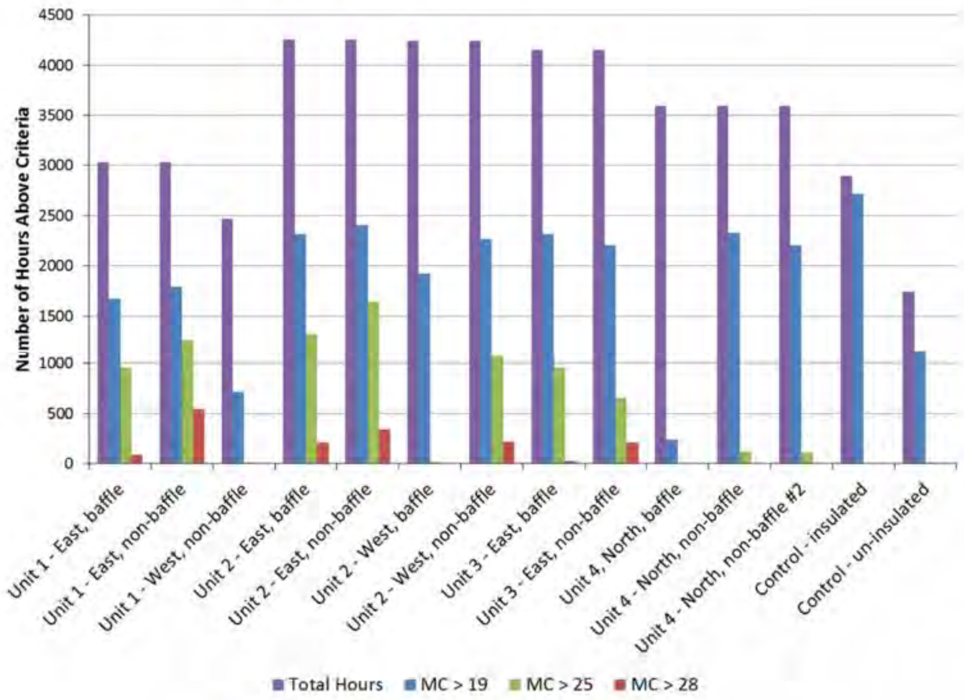

Figure A.13: Duration of Elevated Sheathing Moisture Levels for 2011-2012

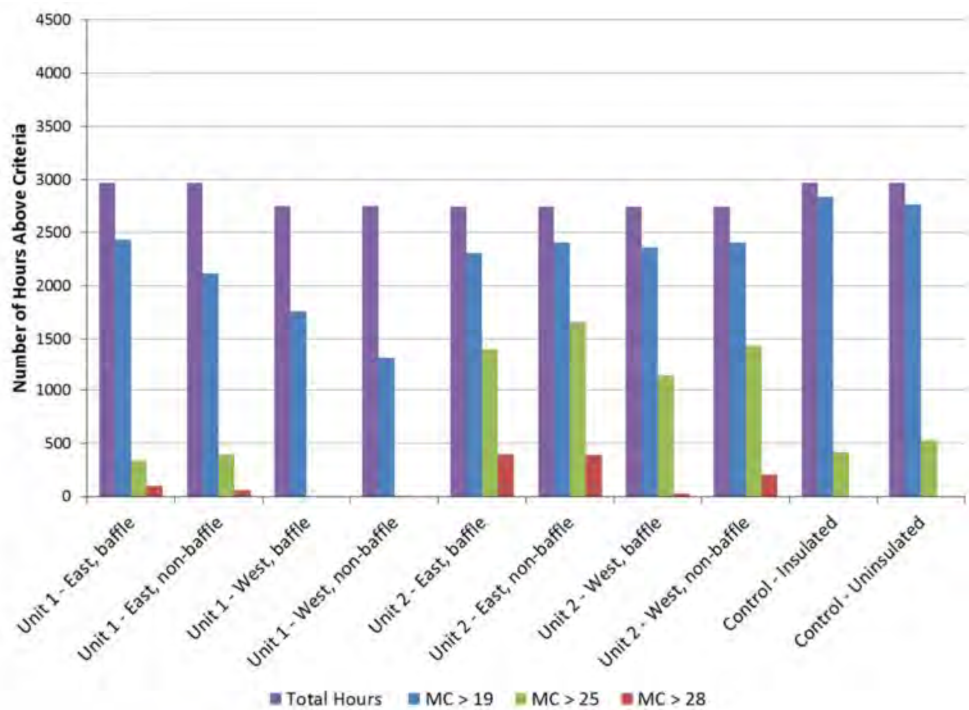

Figure A.14: Duration of Elevated Sheathing Moisture Levels for 2012-2013

A.4 Outdoor Air and Attic Air Moisture Levels

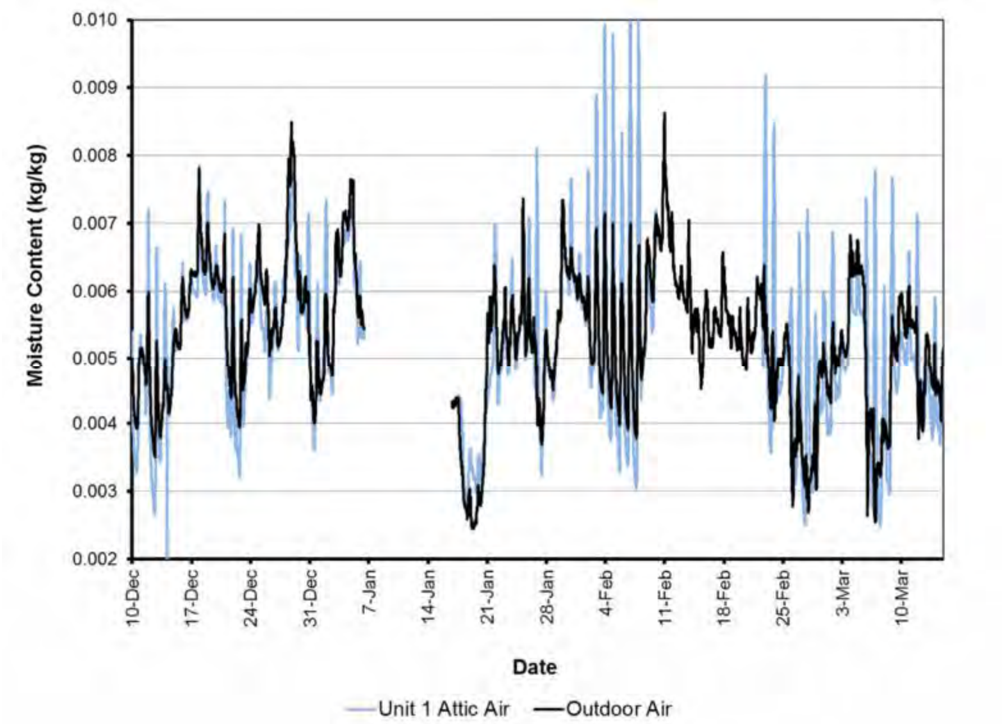

Figure A.15: Unit 1 Attic Air and Outdoor Air Moisture Levels per Time (Winter 2011 – 2012)

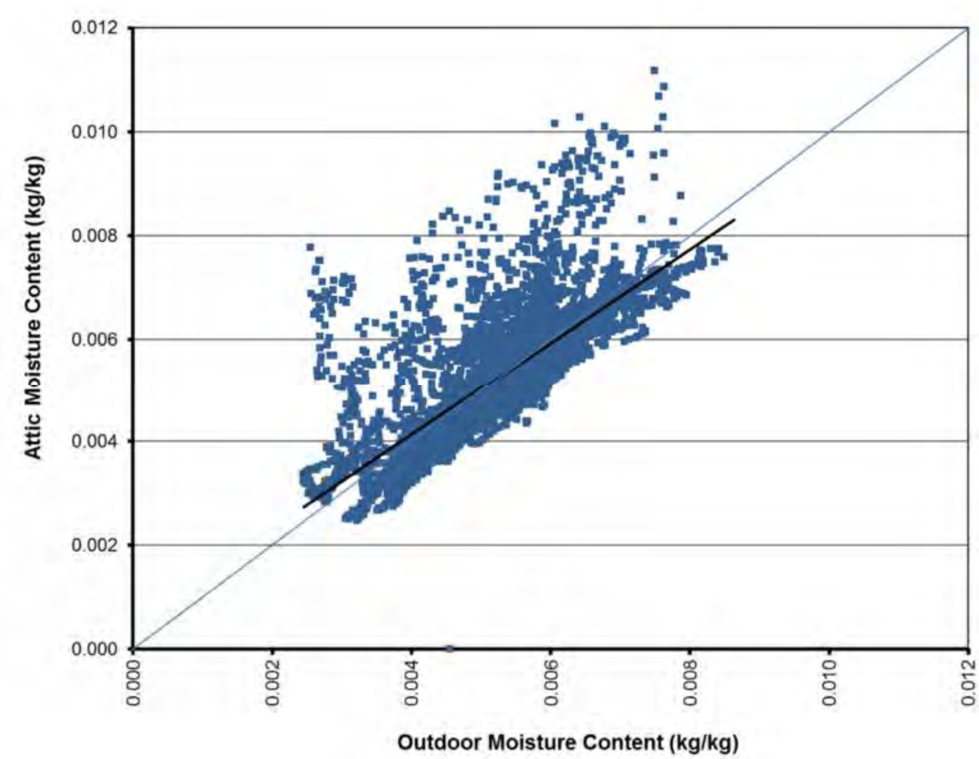

Figure A.16: Unit 1 Attic versus Outdoor Air Moisture Levels

Table A.1: Measured Indoor Conditions for the Winter of 2013-2014

Unit	Average Temperature (°C)	Average RH (%)	95% Percentile Dewpoint Temperature (°C)	Average ∆VP (Pa)	95% Percentile ∆VP (Pa)	99% Percentile ∆VP (Pa)
Outdoors	**4.7**	**89.9**	**5.8**	**N/A**	**N/A**	**N/A**
1	23.6	35.0	10.2	265	503	644
2	21.9	41.6	10.7	327	551	704

APPENDIX B: Heat-Air-Moisture (HAM) Simulations

MODELLING APPROACH

EnergyPlus was used to simulate the airflows into and from the attic and the hygrothermal behavior of the roof assembly. The simulation results were compared to monitoring data for two of the units in the study (Units 1 and 2). EnergyPlus is typically used for whole building energy simulations, however it also includes two modules which allows the simulation of multi-zone airflows coupled to the heat and moisture balance of the building envelope (Refer to the EnergyPlus Engineering Reference – The Reference to EnergyPlus Calculations dated October 1, 2013 for further explanation).

The **Heat and Moisture Transfer module** in EnergyPlus integrates the similar theory, calculation methods, and material properties as commonly used commercial hygrothermal software, such as WUFI. The Heat and Moisture Transfer model solves for temperature, moisture content, and relative humidity across the building envelope.

The **Airflow Network module** models airflows across surfaces depending on the pressures in the zones on either side of the surface, and a defined leakage area in the surface. Outdoor wind pressures are calculated based on the shape of the building, terrain, wind speed and direction, and wind pressures coefficients. The measured attic data came from units in the middle of a row of townhouses, so the entire building was modelled so that the wind pressure coefficients determined by the software were based on the geometry of the entire building. A representation of the building geometry used in the model in shown in Figure B.1.

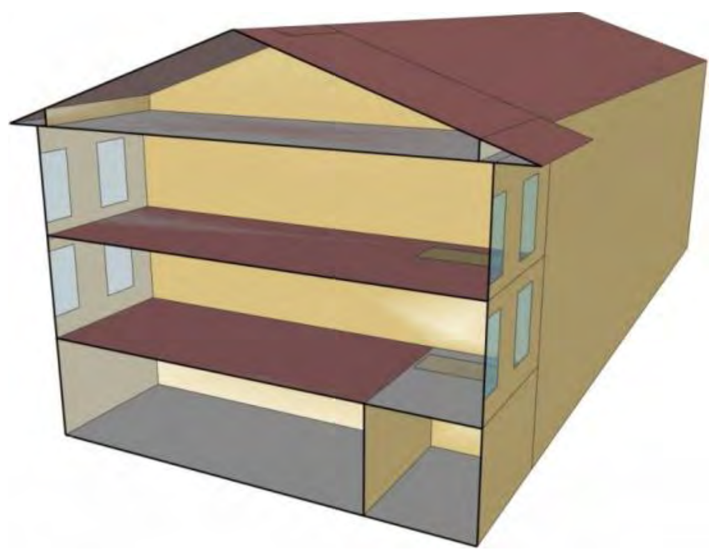

Figure B.1: Modeled Building Geometry

Weather Data

Weather data for Vancouver (CWEC energy simulation file) was utilized as a starting point for our analysis. The default CWEC data was customized with available site specific data for the winter of 2011 to 2012, and supplemented with cloud cover and solar radiation data from local weather stations. During the heating season, temperature and relative humidity were measured on site. At other times of year, the temperature and relative humidity were taken from nearby weather stations. Wind speed and direction were also supplemented using local weather stations. Considering the high wind speed at the airport compared to the relatively sheltered site location, the wind speed taken from the weather station were reduced by a quarter, which resulted in the attic ventilation rates fall within the same range as those measured during tracer gas testing.

The climatic data was further calibrated around the time of wetting events in order to get the same cooling of the roof during the night. This was done by taking the generic Vancouver CWEC data as a starting point for radiation data and was supplemented with order of magnitude cloud cover and solar radiation values that were recorded at nearby weather stations during the wetting events. The data was adjusted for actual conditions that had clear nights followed by sunny days and cloudy nights as per actual conditions during these time periods. This pattern causes the sky temperature to drop, thus cooling the roof, and then high temperatures to drive moisture into the attic space, then followed by average conditions with little capacity for drying.

Assumptions

The model required several key parameter inputs. Leakage and venting areas were required for the airflow network, and insulation levels and indoor air moisture sources affected the temperature and relative humidity of the attic air, impacting the attic sheathing hygrothermal behavior.

The effective leakage area of the attic was measured via a fan depressurization test, and the measured value, around 2400 cm^2 for both Unit 1 and 2, was used in the model. The leakage area was divided between baffles on either side on the attic, and a vent at the top of the attic. The vent was assigned an area of 420 cm^2, the sum of the three attic vents present in the unit. The remaining area was divided equally between the baffles on the east and west side of the unit.

The attic interface leakage area was modelled as 2 cm^2/m^2, which was higher than the measured value of 1.6cm^2/m^2 from the fan pressurization, but was rounded up to account for uncertainty in the fan testing.

The attic insulation level was modelled as R-30, the approximate level of insulation (loose filled fiberglass).

The building was modelled with forced air gas furnace and electric baseboard heaters for supplemental heating. The interior of the building was not modeled in detail to fully simulate the mechanical systems. However, the model was calibrated to simulate the measured indoor conditions and pressures differentials to drive air into the attic. The house was given a normalized effective leakage area that was air-tight (0.7 cm^2/m^2) and exhaust vents were modeled to a neutral pressure plane and air flow from the house to the attic that was aligned with experience and the tracer gas testing during the same periods.

Moisture was added to the indoor space so that the simulated vapour pressure difference between the house and outdoors resembled the measured conditions. A comparison between measured and simulated indoor moisture levels for Unit 1 follows.

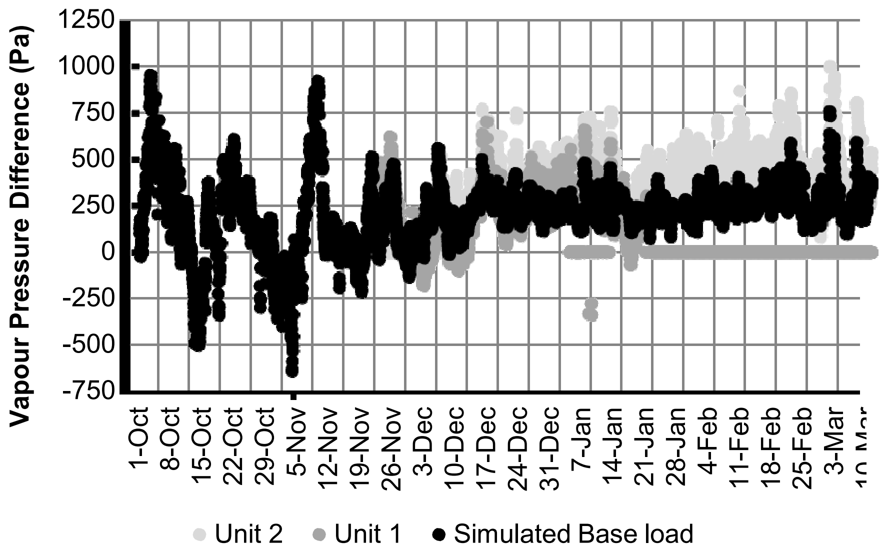

Figure B.2: Measured and Simulated Indoor to Outdoor Vapour Pressure Difference

Table B. 1: Simulated Indoor Conditions

Unit	Average Temperature (°C)	Average RH (%)	95% Percentile Dewpoint Temperature (°C)	Average ∆VP (Pa)	95% Percentile ∆VP (Pa)	99% Percentile ∆VP (Pa)
Outdoors	**5.4**	**85.8**	**10.1**	**N/A**	**N/A**	**N/A**
No Load	24.0	27.7	7.9	46	346	570
Base Load	24.0	34.0	9.6	208	480	702
High Load	24.0	44.1	11.8	467	732	932

Table B.2: Measured Indoor Conditions for the Winter of 2013-2014

Unit	Average Temperature (°C)	Average RH (%)	95% Percentile Dewpoint Temperature (°C)	Average ∆VP (Pa)	95% Percentile ∆VP (Pa)	99% Percentile ∆VP (Pa)
Outdoors	**4.7**	**89.9**	**5.8**	**N/A**	**N/A**	**N/A**
1	23.6	35.0	10.2	265	503	644
2	21.9	41.6	10.7	327	551	704

Simulation Matrix and Result Graphs

A simulation matrix was utilized to evaluate the impact of varying levels of ceiling air-tightness, indoor moisture levels, attic ventilation rates, sheathing thermal resistance, and insulation levels on moisture levels in ventilated attics. A simulation matrix outlining all the simulation cases follows on the next page.

Following the simulation matrix are graphs summarizing the roofing sheathing temperature and moisture content for each of the simulation cases. The conditions are reported for the sheathing inboard of the outdoor air inlet/outlet at the roof soffit for both the east and west sides of the roof.

Case ID	Parameter	Variable	Interface Leakage	Indoor Moisture	Attic Ventilation	Sheathing Insulation	Attic Insulation	Wind Speed	Building Orientation
1	Interface Leakage	0 cm^2/m^2	x	base	1/300, 2420 cm^2	R-0	R-30	weather data	ENE
2		2 cm^2/m^2	x	base	1/300, 2420 cm^2	R-0	R-30	weather data	ENE
3		5 cm^2/m^2	x	base	1/300, 2420 cm^2	R-0	R-30	weather data	ENE
4		10 cm^2/m^2	x	base	1/300, 2420 cm^2	R-0	R-30	weather data	ENE
5	Indoor Moisture	0 kg/day	2 cm^2/m^2	x	1/300, 2420 cm^2	R-0	R-30	weather data	ENE
2		11 kg/day	2 cm^2/m^2	x	1/300, 2420 cm^2	R-0	R-30	weather data	ENE
6		28 kg/day	2 cm^2/m^2	x	1/300, 2420 cm^2	R-0	R-30	weather data	ENE
7	Attic Venting Area	100 cm^2	2 cm^2/m^2	base	x	R-0	R-30	weather data	ENE
2		1/300, 2420 cm^2	2 cm^2/m^2	base	x	R-0	R-30	weather data	ENE
8		5000 cm^2	2 cm^2/m^2	base	x	R-0	R-30	weather data	ENE
2	Sheathing Resistance	0	2 cm^2/m^2	base	1/300, 2420 cm^2	x	R-30	weather data	ENE
9		R-2.5	2 cm^2/m^2	base	1/300, 2420 cm^2	x	R-30	weather data	ENE
10		R-5	2 cm^2/m^2	base	1/300, 2420 cm^2	x	R-30	weather data	ENE
11	Attic Insulation	R-0	2 cm^2/m^2	base	1/300, 2420 cm^2	R-0	x	weather data	ENE
12		R-10	2 cm^2/m^2	base	1/300, 2420 cm^2	R-0	x	weather data	ENE
2		R-30	2 cm^2/m^2	base	1/300, 2420 cm^2	R-0	x	weather data	ENE
13		R-50	2 cm^2/m^2	base	1/300, 2420 cm^2	R-0	x	weather data	ENE
14	Wind Speed	No Wind	2 cm^2/m^2	base	1/300, 2420 cm^2	R-0	R-30	x	ENE
2		weather data	2 cm^2/m^2	base	1/300, 2420 cm^2	R-0	R-30	x	ENE
15		high - factor 4	2 cm^2/m^2	base	1/300, 2420 cm^2	R-0	R-30	x	ENE

Case ID	Parameter	Variable	Interface Leakage	Indoor Moisture	Attic Ventilation	Sheathing Insulation	Attic Insulation	Wind Speed	Building Orientation
2	Building Orientation	ENE	2 cm^2/m^2	base	1/300, 2420 cm^2	R-0	R-30	weather data	x
16		NNW	2 cm^2/m^2	base	1/300, 2420 cm^2	R-0	R-30	weather data	x
17		WSW	2 cm^2/m^2	base	1/300, 2420 cm^2	R-0	R-30	weather data	x
18		SSE	2 cm^2/m^2	base	1/300, 2420 cm^2	R-0	R-30	weather data	x
19	Permeability of Shingles	5 ng/s m^2Pa	2 cm^2/m^2	base	1/300, 2420 cm^2	R-0	R-30	weather data	ENE
2		20 ng/s m^2Pa	2 cm^2/m^2	base	1/300, 2420 cm^2	R-0	R-30	weather data	ENE
20		500 ng/s m^2 Pa	2 cm^2/m^2	base	1/300, 2420 cm^2	R-0	R-30	weather data	ENE
21	High indoor humidity, sheathing resistance	n/a	2 cm^2/m^2	high	1/300, 2420 cm^2	R-2.5	R-30	weather data	ENE
22	Low venting area, sheathing resistance	n/a	2 cm^2/m^2	base	100 cm^2	R-2.5	R-30	weather data	ENE
23	High indoor humidity, low venting area, sheathing resistance	n/a	2 cm^2/m^2	high	100 cm^2	R-2.5	R-30	weather data	ENE
24	High interface leakage, high indoor humidity, high venting area	n/a	5 cm^2/m^2	high	5000 cm^2	R-0	R-30	weather data	ENE
25	High indoor humidity, high venting area	n/a	2 cm^2/m^2	high	5000 cm^2	R-0	R-30	weather data	ENE
26	High indoor humidity, high venting area, high wind	n/a	2 cm^2/m^2	high	5000 cm^2	R-0	R-30	high - factor 4	ENE
27	Low venting area, high sheathing resistance	n/a	2 cm^2/m^2	base	100 cm^2	R-5	R-30	weather data	ENE

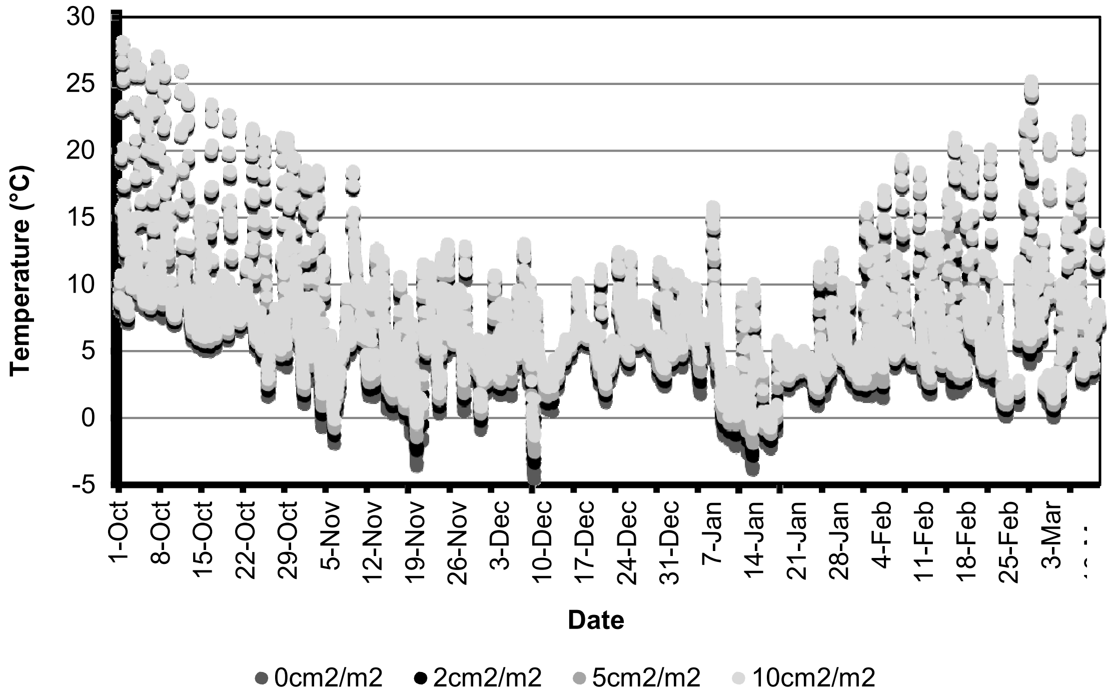

Figure B.3: East Roof Sheathing Surface Temperature for Different Rates of Interface Leakage (Case ID 1, 2, 3, 4**)**

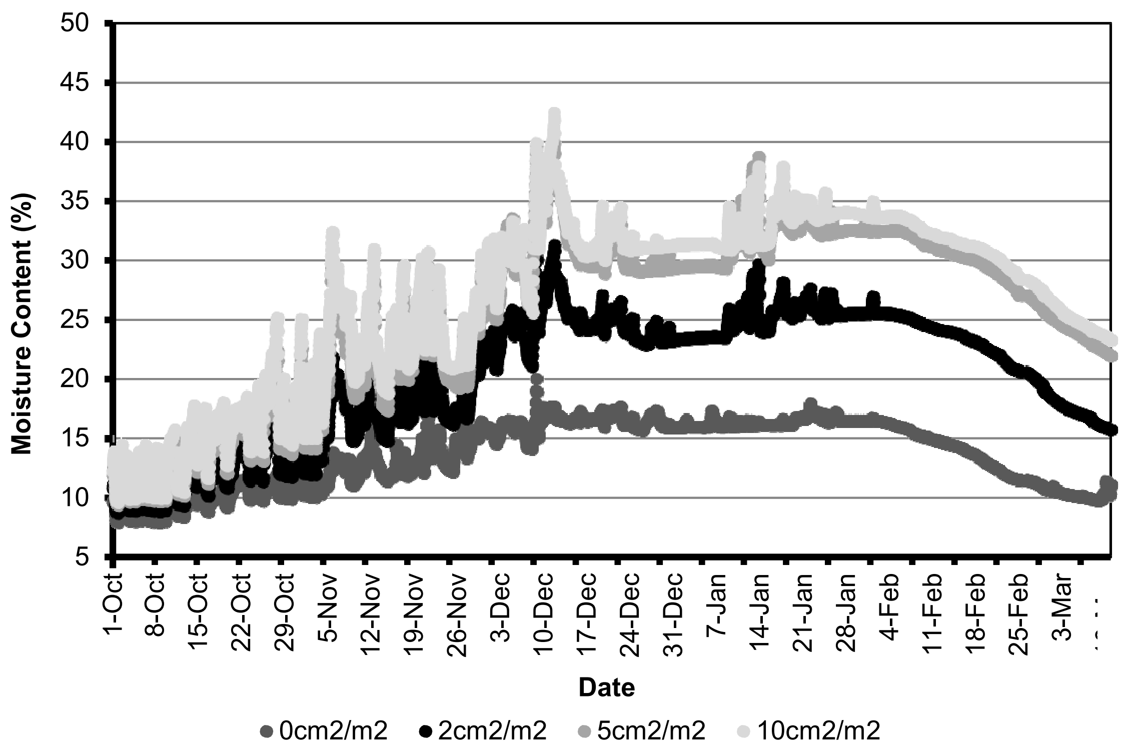

Figure B.4: East Roof Sheathing Moisture Content for Different Rates of Interface Leakage (Case ID 1, 2, 3, 4)

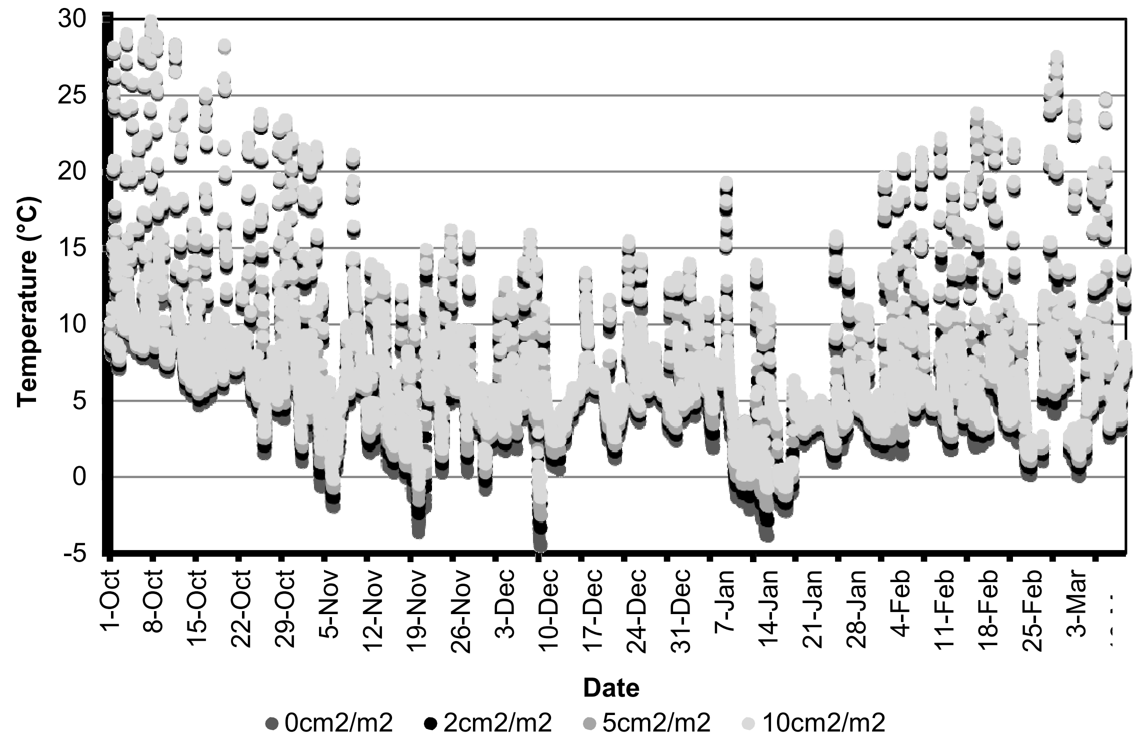

Figure B.5: West Roof Sheathing Surface Temperature for Different Rates of Interface Leakage (Case ID 1, 2, 3, 4)

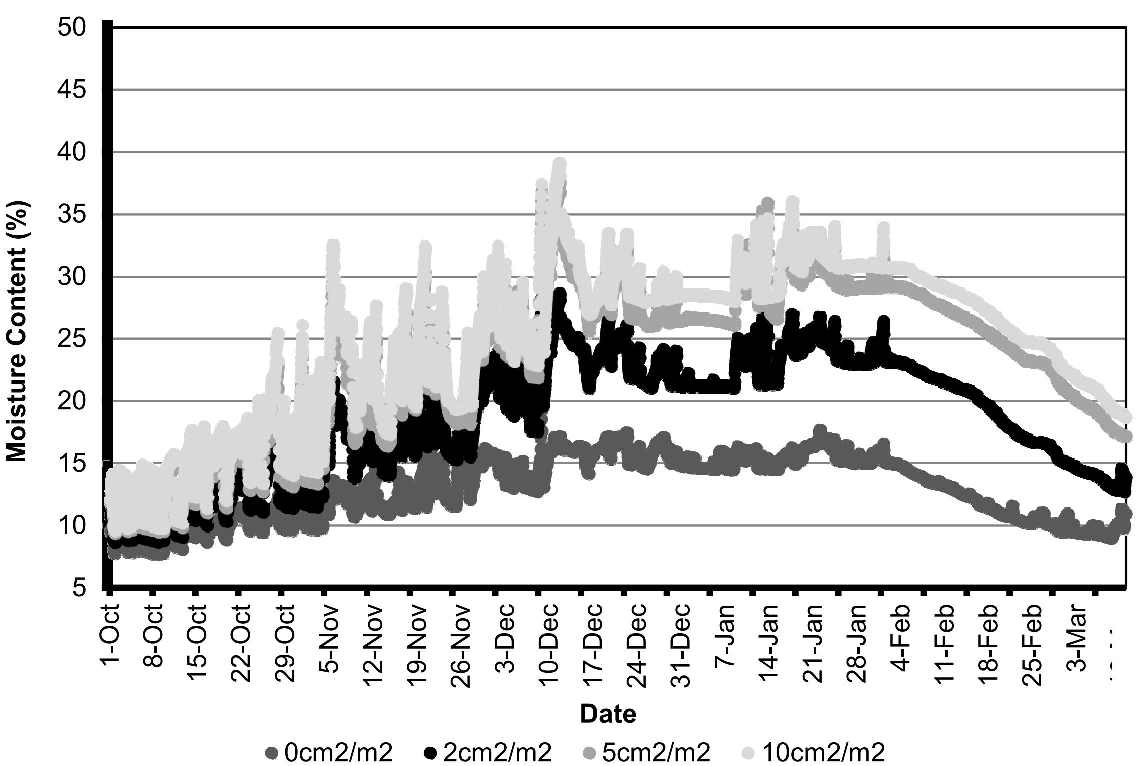

Figure B.6: West Roof Sheathing Moisture Content for Different Rates of Interface Leakage (Case ID 1, 2, 3, 4)

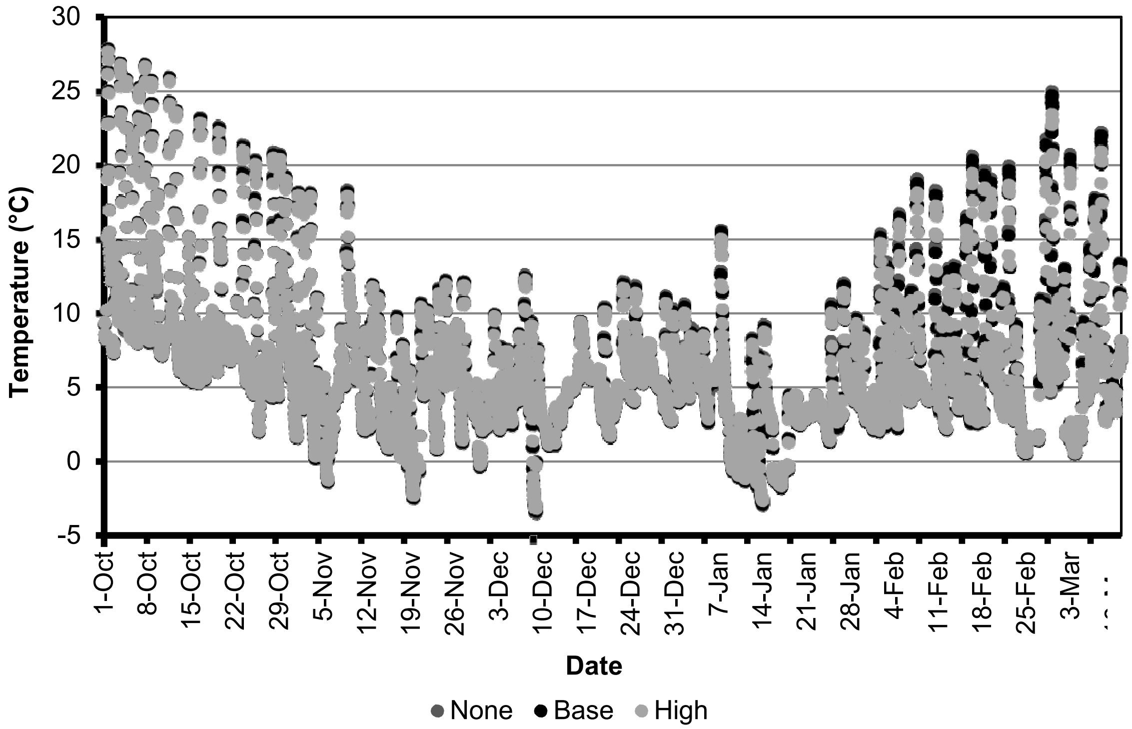

Figure B.7: East Roof Sheathing Surface Temperature for Different Indoor Moisture Levels (Case ID 5, 2, 6)

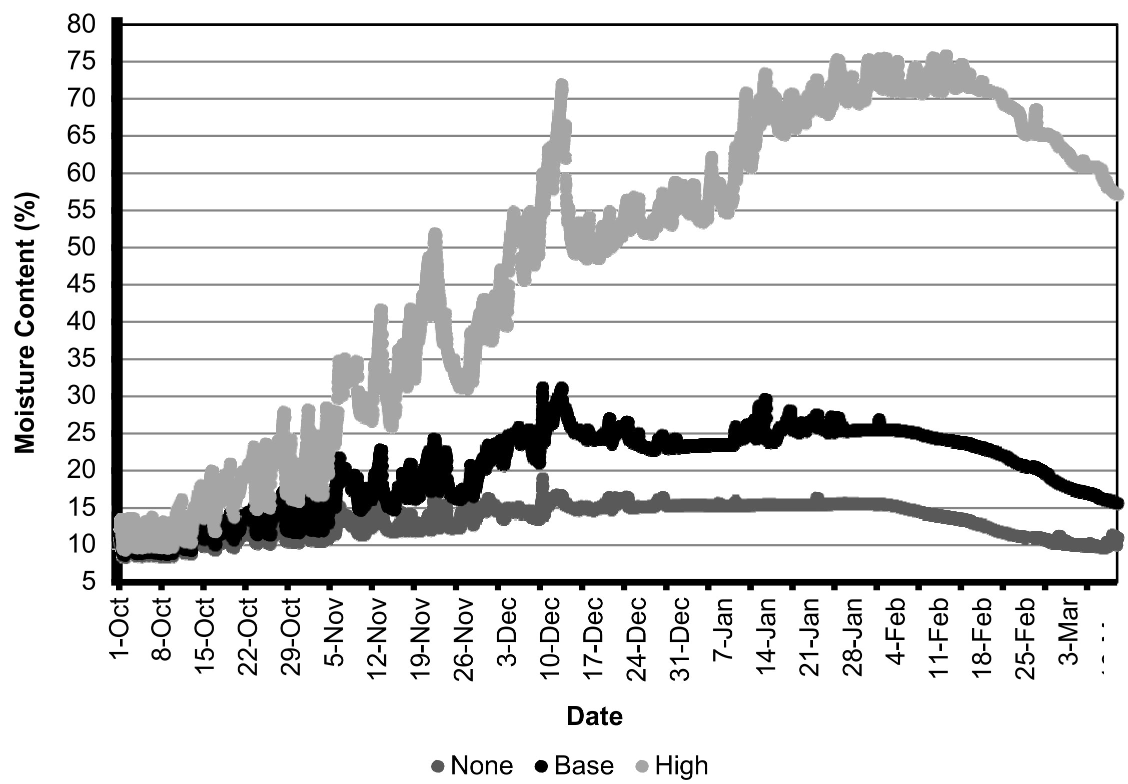

Figure B.8: East Roof Sheathing Moisture Content for Different Indoor Moisture Levels (Case ID 5, 2, 6)

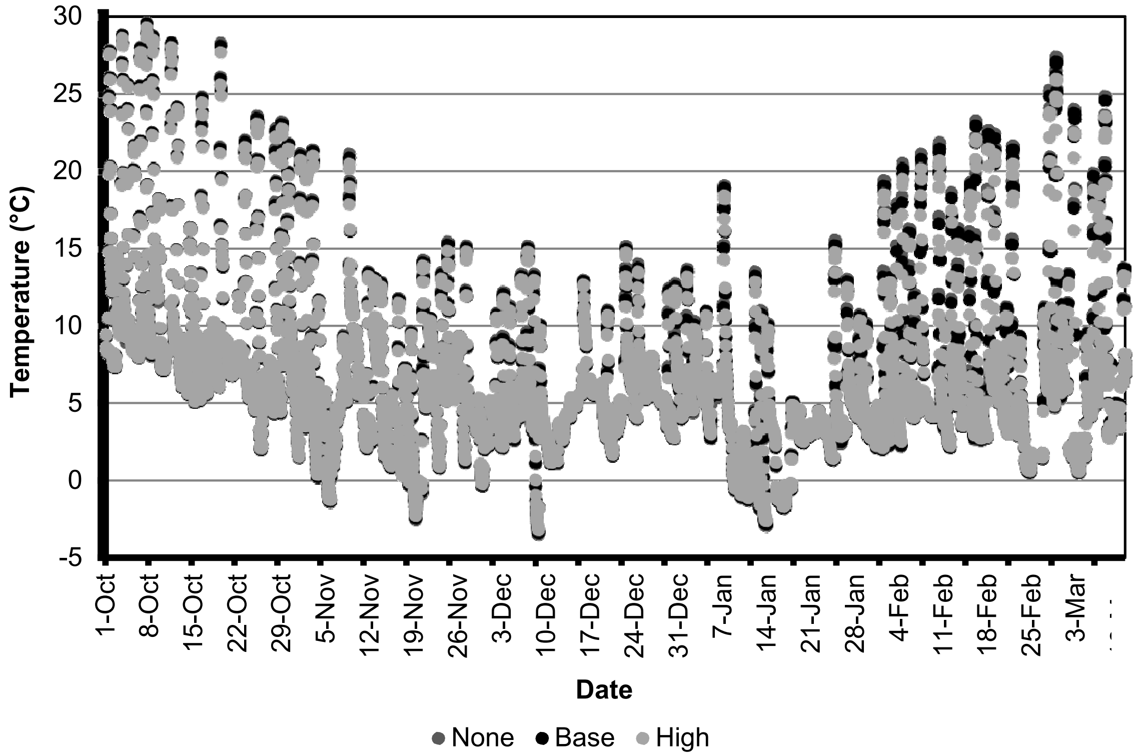

Figure B.9: West Roof Sheathing Surface Temperature for Different Indoor Moisture Levels (Case ID 5, 2, 6)

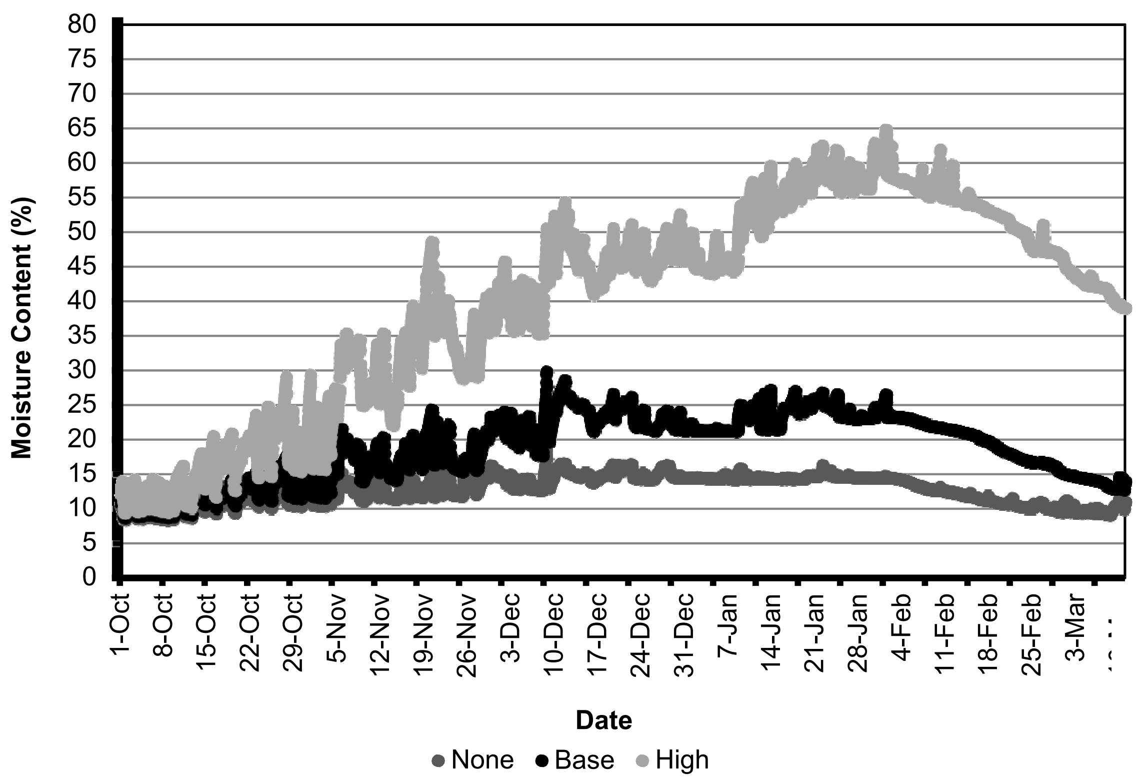

Figure B.10: West Roof Sheathing Moisture Content for Different Indoor Moisture Levels (Case ID 5, 2, 6)

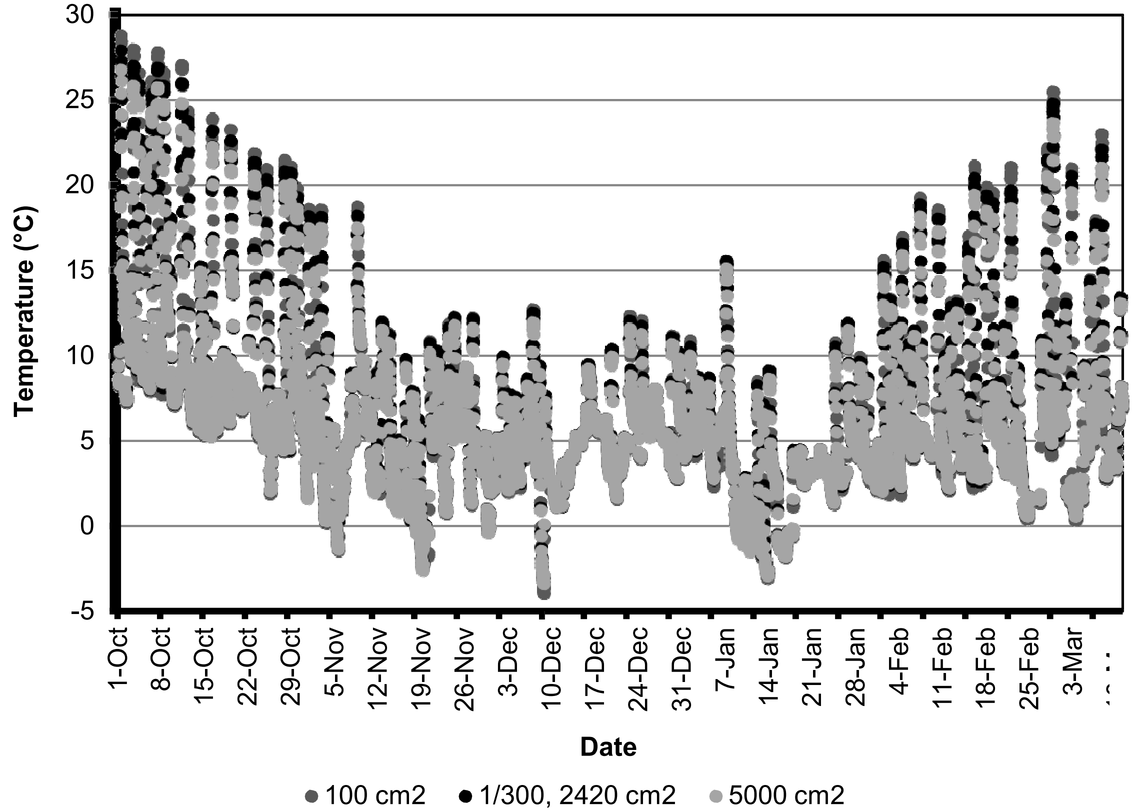

Figure B.11: East Roof Sheathing Surface Temperature for Different Venting Areas (Case ID 7, 2, 8)

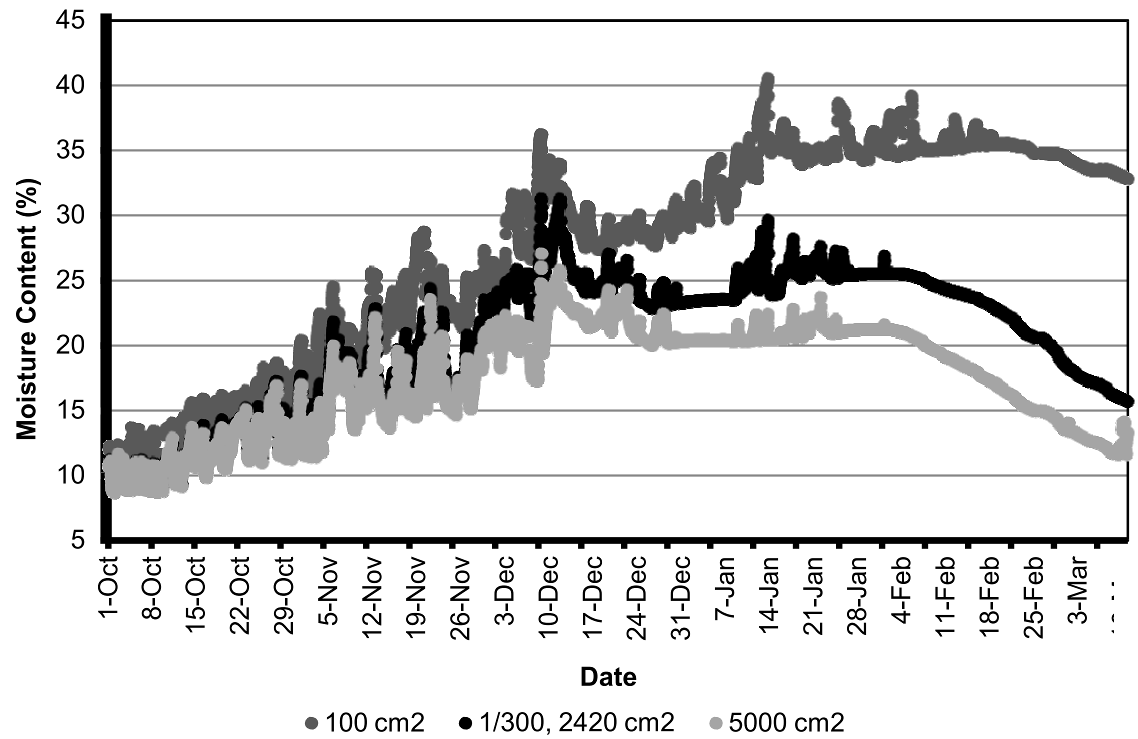

Figure B.12: East Roof Sheathing Moisture Content for Different Venting Areas (Case ID 7, 2, 8)

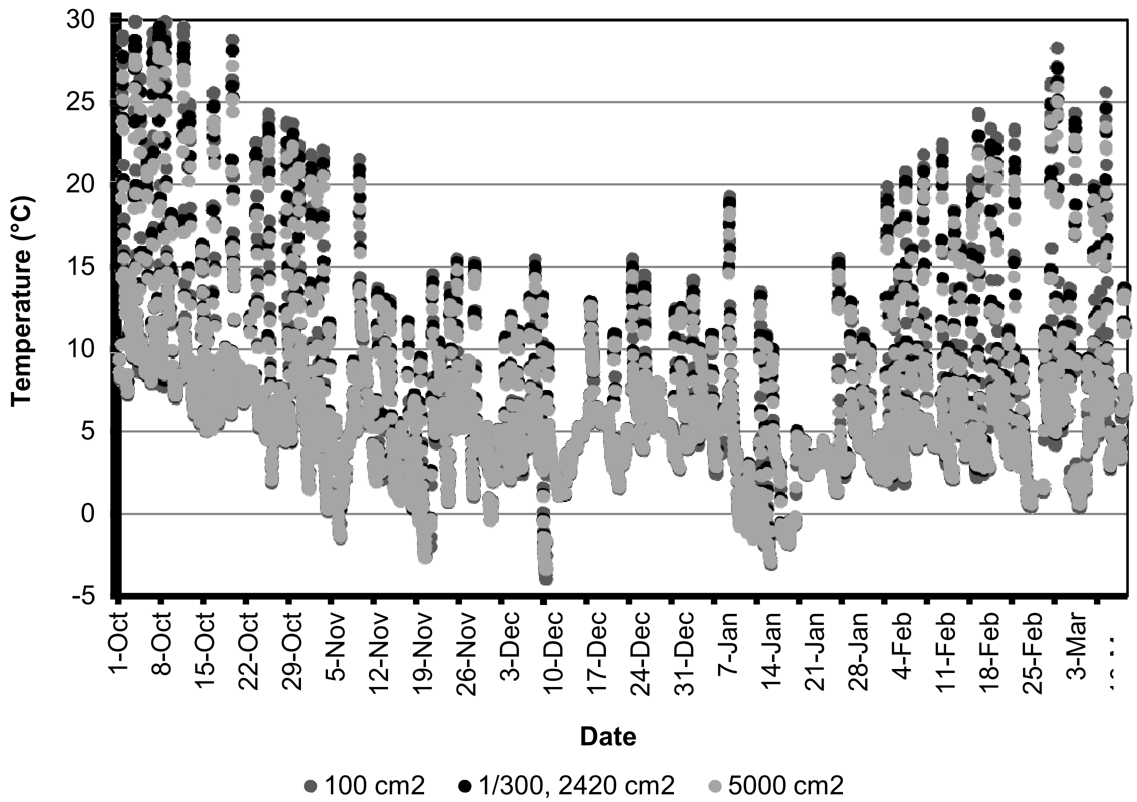

Figure B.13: West Roof Sheathing Surface Temperature for Different Venting Areas (Case ID 7, 2, 8)

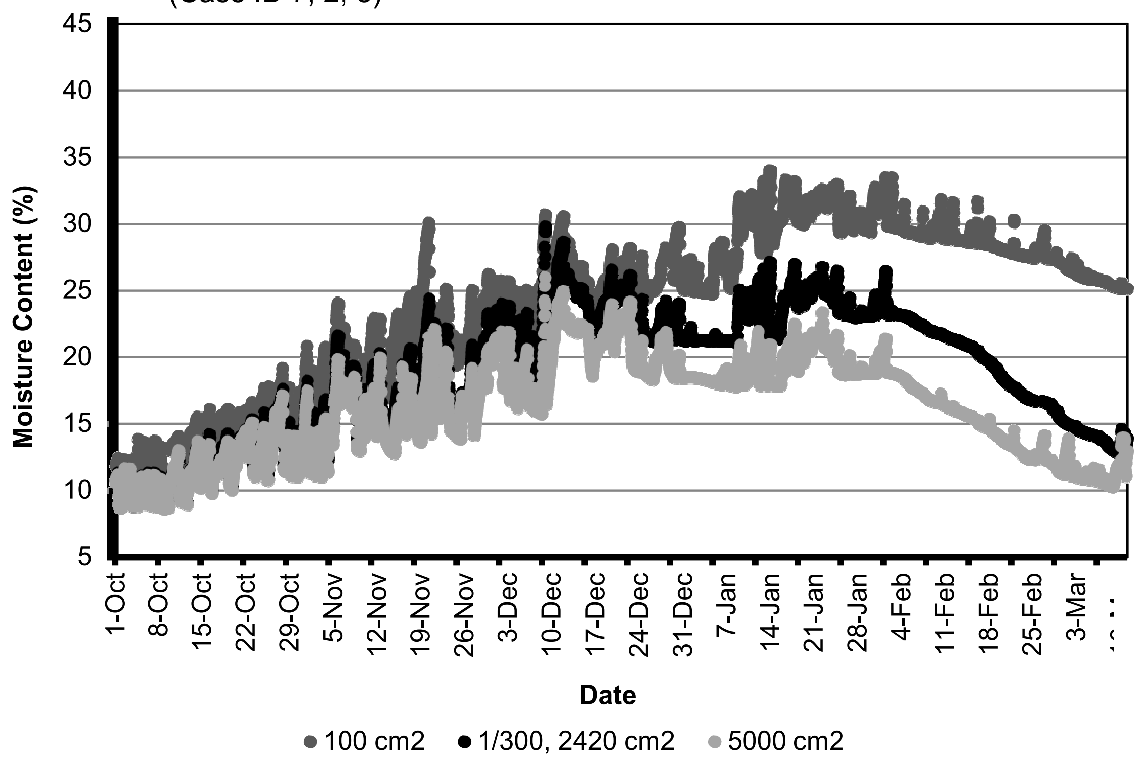

Figure B.14: West Roof Sheathing Moisture Content for Different Venting Areas (Case ID 7, 2, 8)

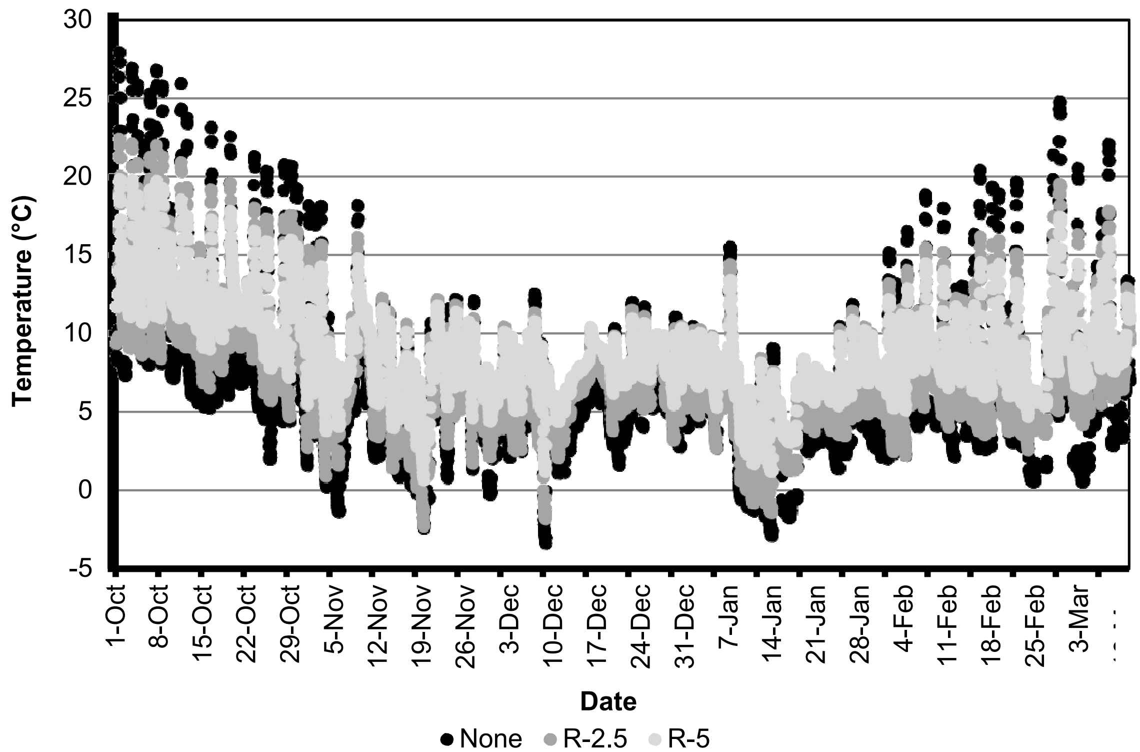

Figure B.15: East Roof Sheathing Surface Temperature for Different Sheathing Insulation Values (Case ID 2, 9, 10)

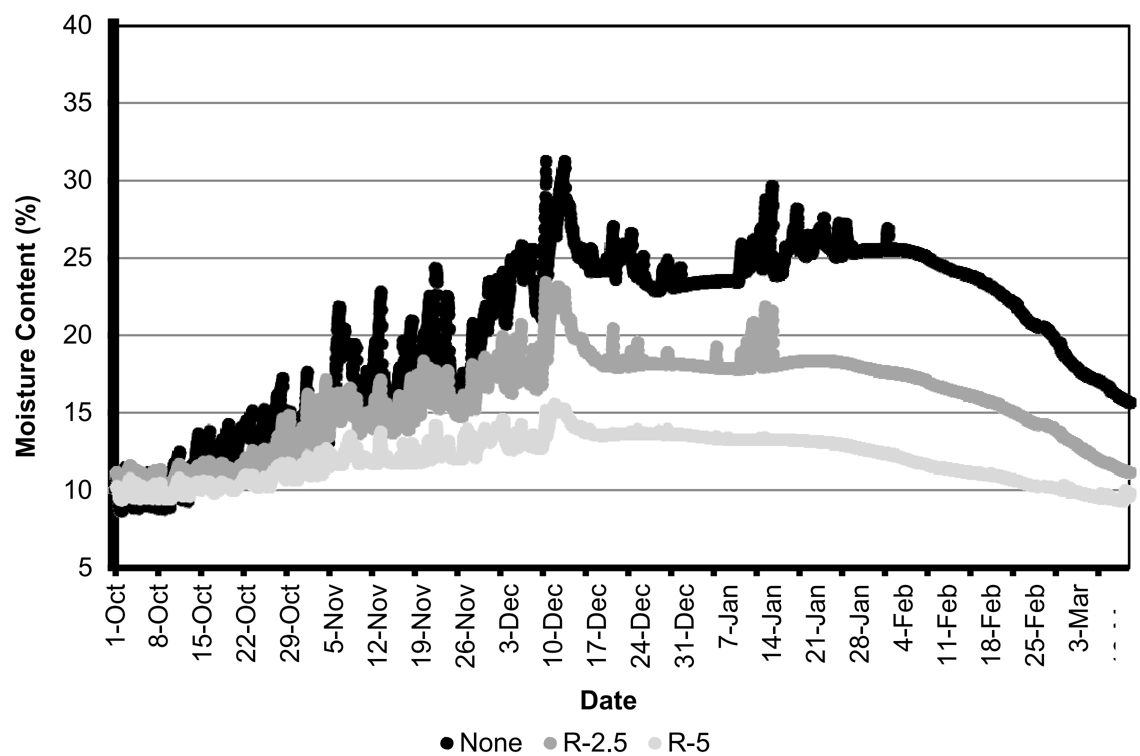

Figure B.16: East Roof Sheathing Moisture Content for Different Sheathing Insulation Values (Case ID 2, 9, 10)

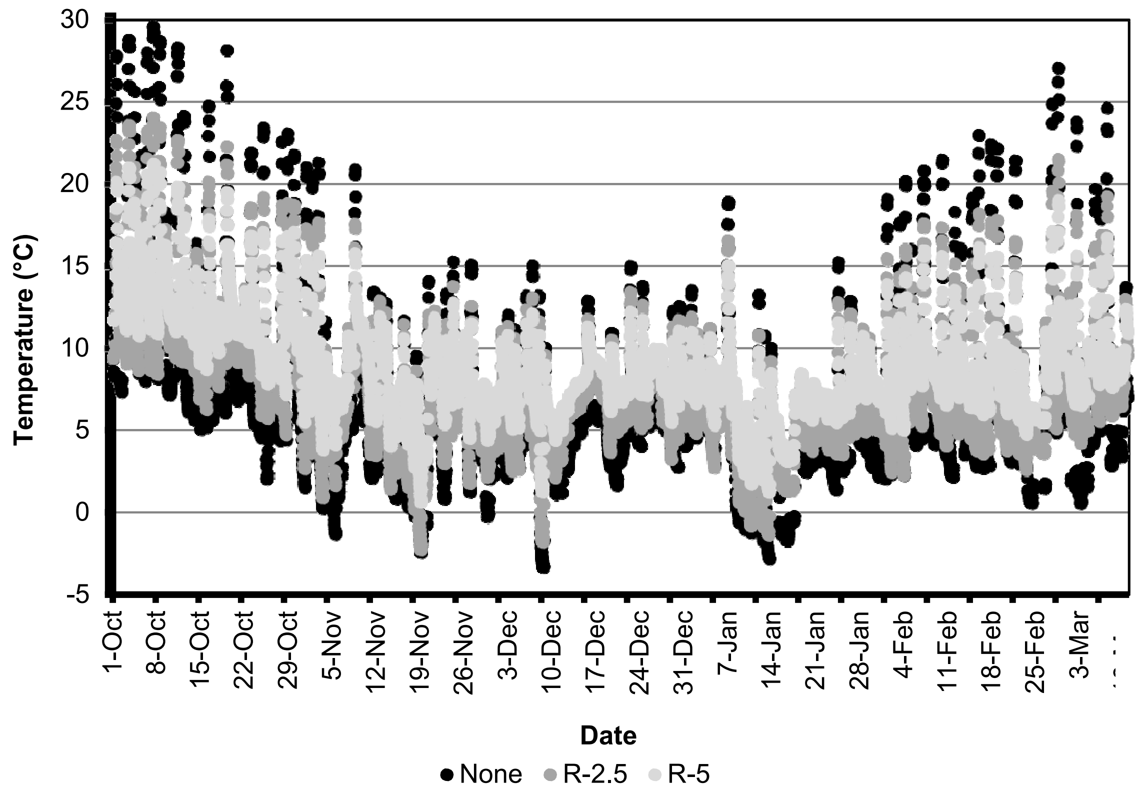

Figure B.17: West Roof Sheathing Surface Temperature for Different Sheathing Insulation Values (Case ID 2, 9, 10)

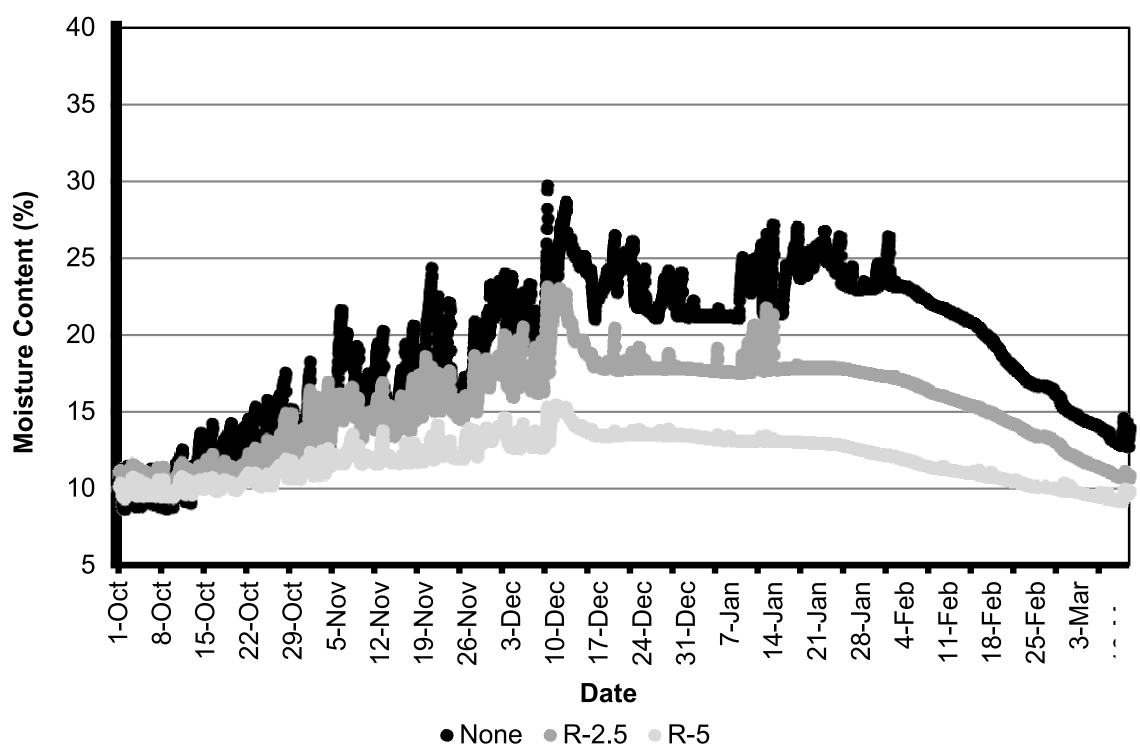

Figure B.18: West Roof Sheathing Moisture Content for Different Sheathing Insulation Values (Case ID 2, 9, 10)

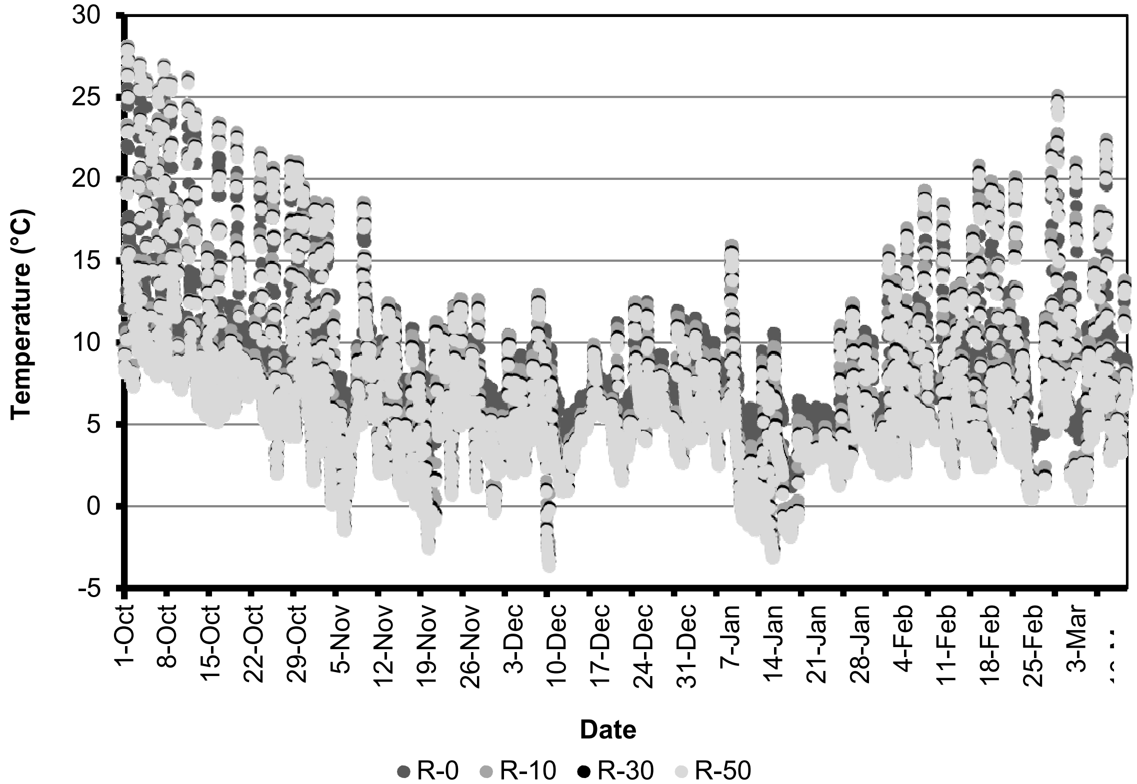

Figure B.19: East Roof Sheathing Surface Temperature for Different Attic Insulation Values (Case ID 11, 12, 2, 13)

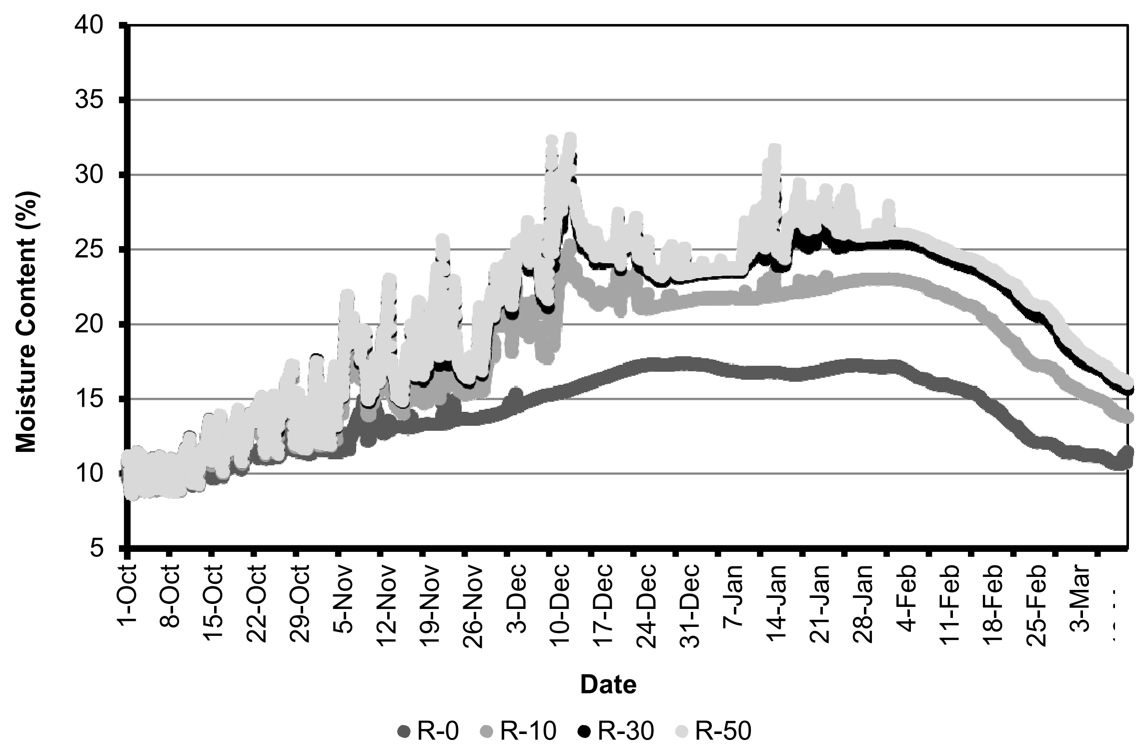

Figure B.20: East Roof Sheathing Moisture Content for Different Attic Insulation Values (Case ID 11, 12, 2, 13)

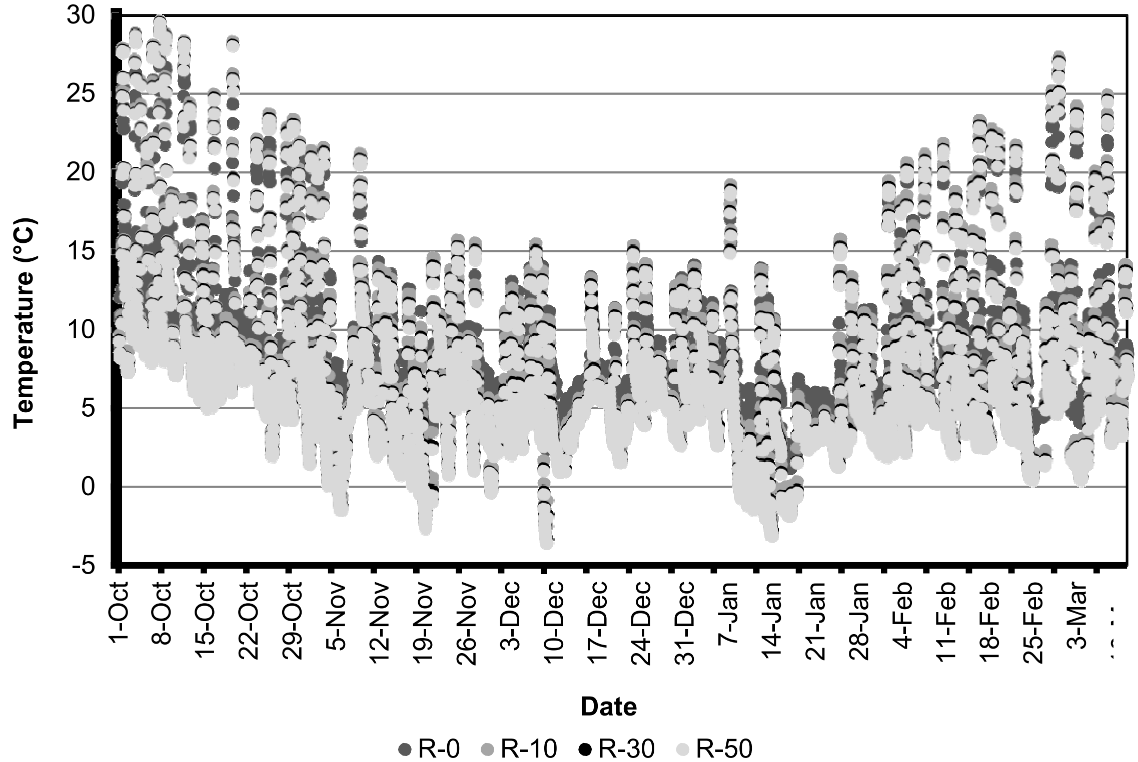

Figure B.21: West Roof Sheathing Surface Temperature for Different Attic Insulation Values (Case ID 11, 12, 2, 13)

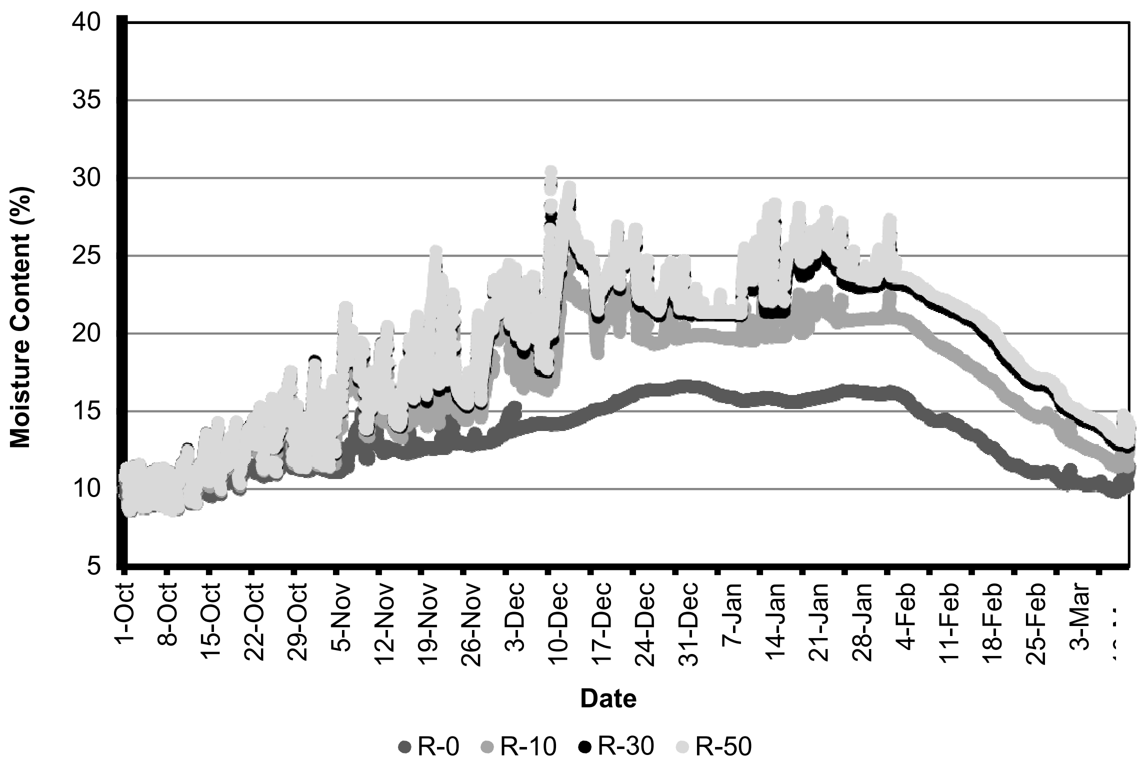

Figure B.22: West Roof Sheathing Moisture Content for Different Attic Insulation Values (Case ID 11, 12, 2, 13)

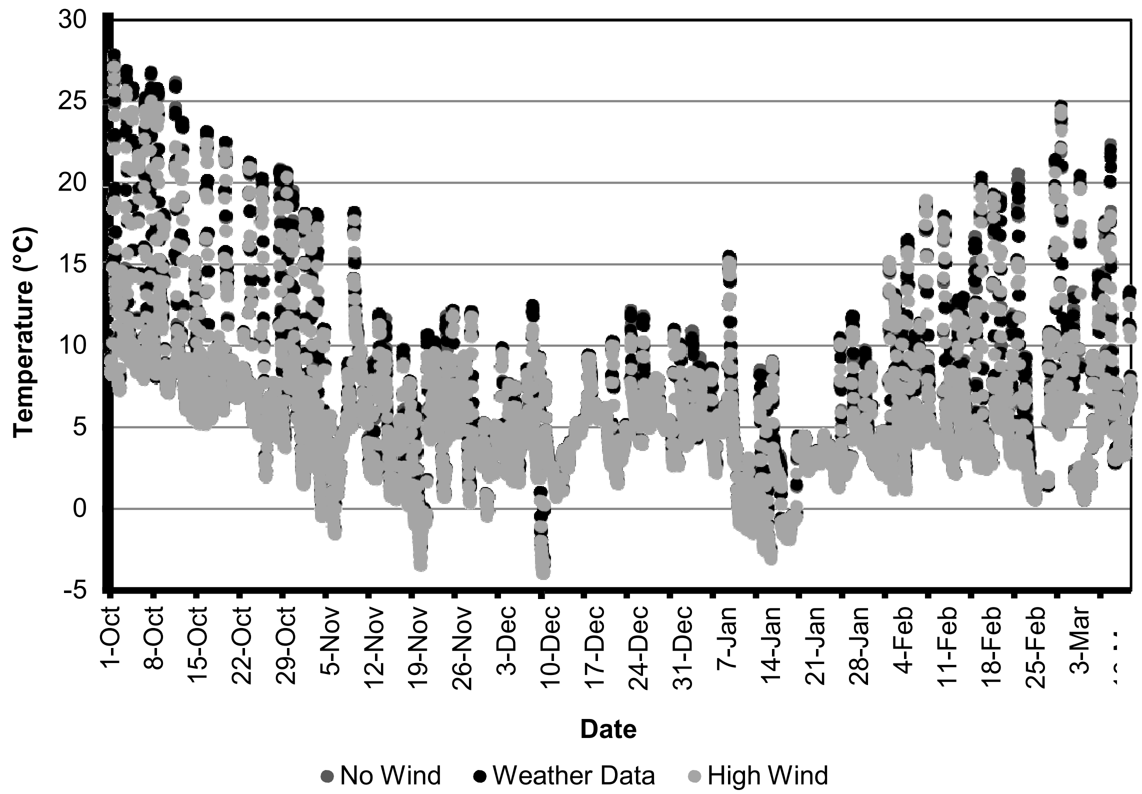

Figure B.23: East Roof Sheathing Surface Temperature for Different Wind Speeds (Case ID 14, 2, 15)

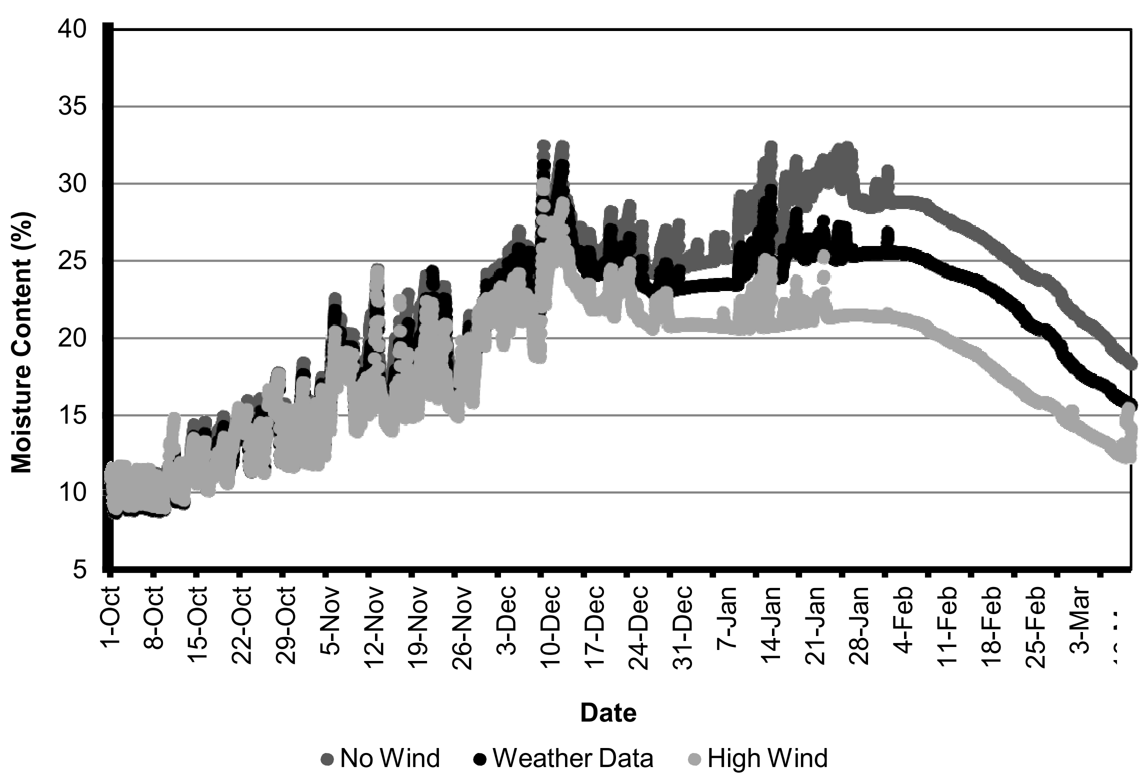

Figure B.24: East Roof Sheathing Moisture Content for Different Wind Speeds (Case ID 14, 2, 15)

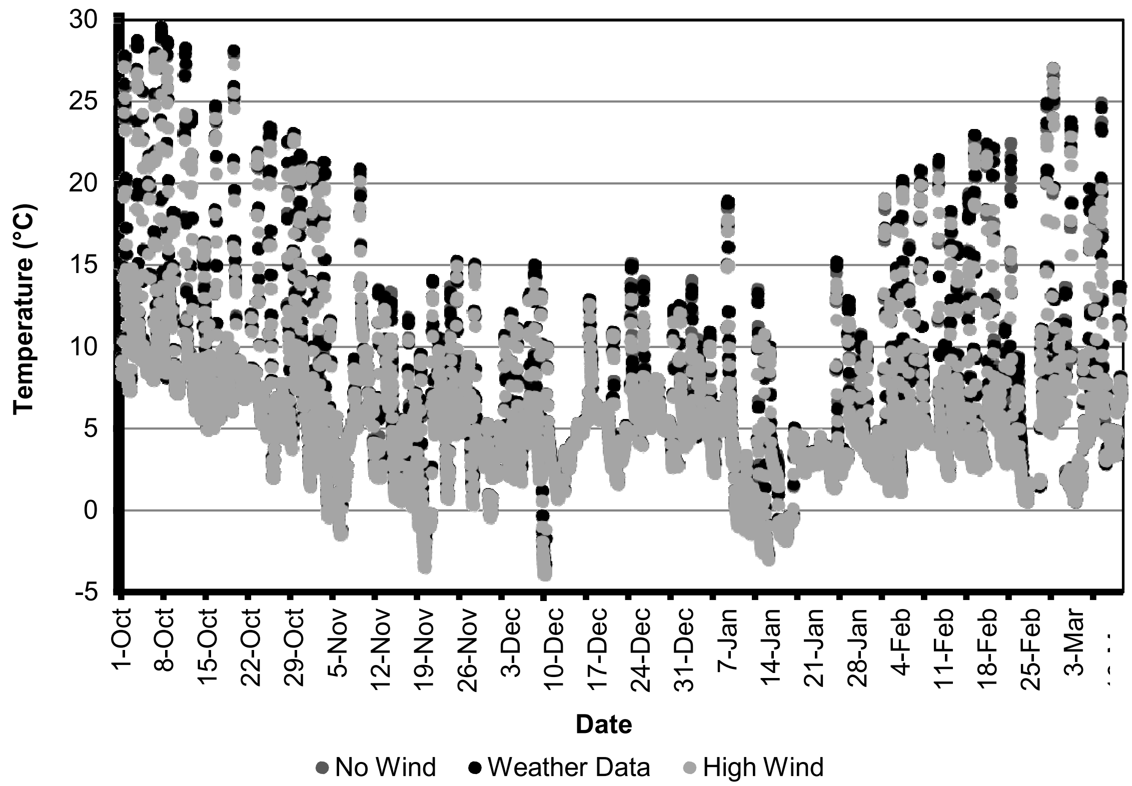

Figure B.25: West Roof Sheathing Surface Temperature for Different Wind Speeds (Case ID 14, 2, 15)

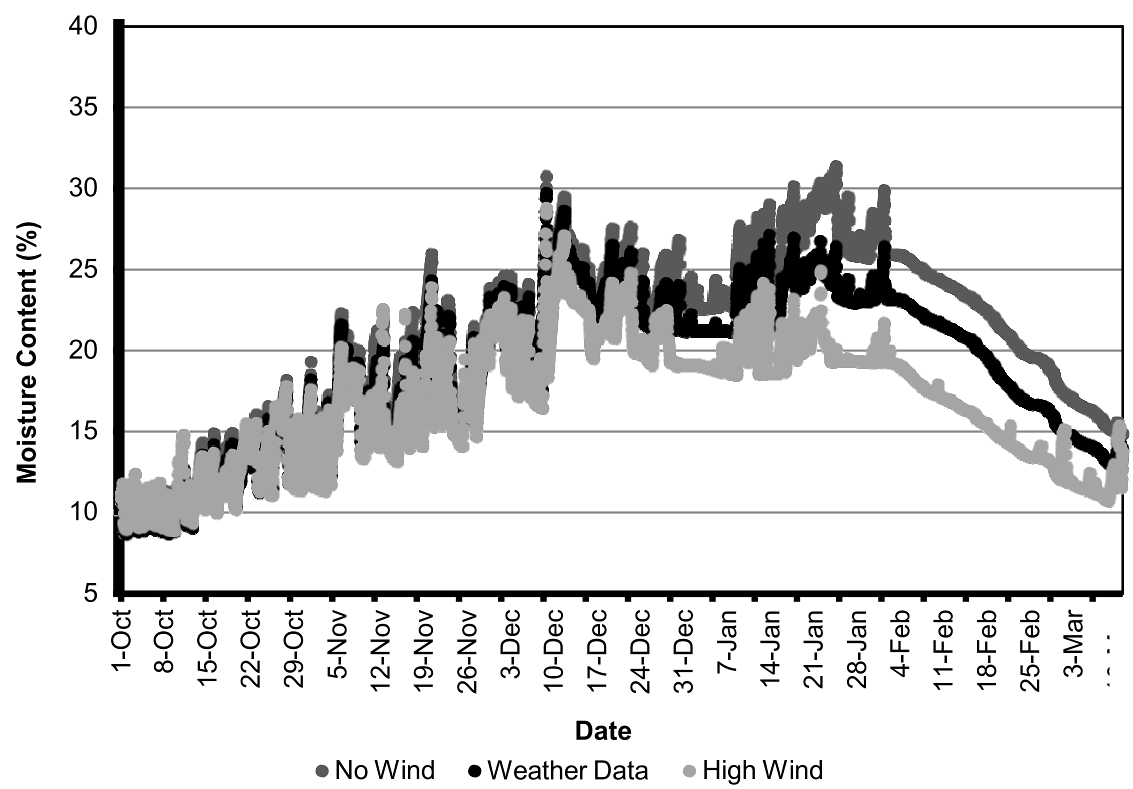

Figure B.26: West Roof Sheathing Moisture Content for Different Wind Speeds (Case ID 14, 2, 15)

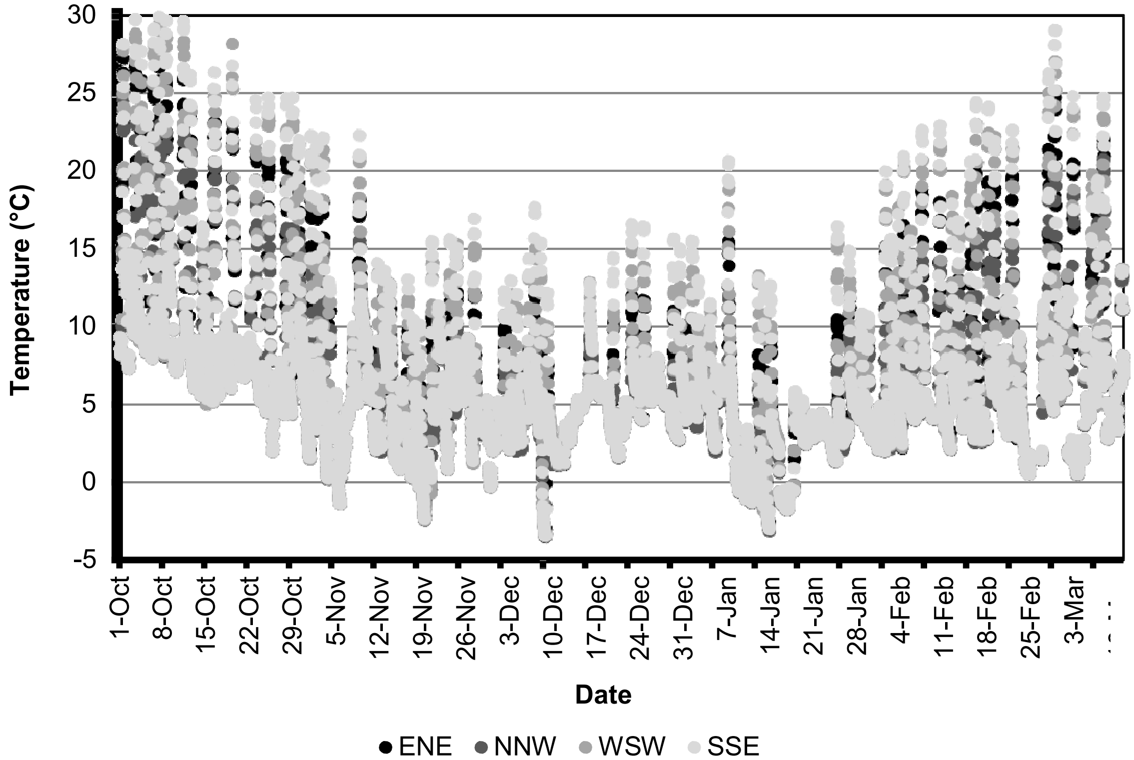

Figure B.27: East Roof Sheathing Surface Temperature for Different Building Orientations (Case ID 2, 16, 17, 18)

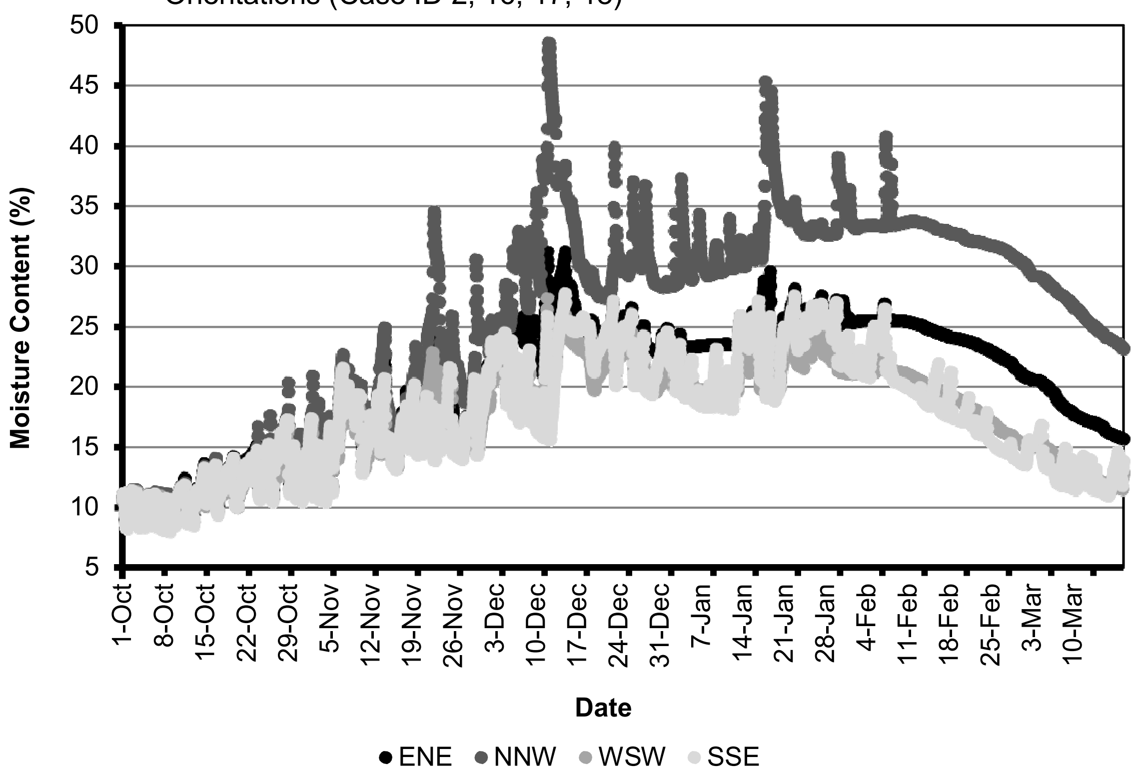

Figure B.28: East Roof Sheathing Moisture Content for Different Building Orientations (Case ID 2, 16, 17, 18)

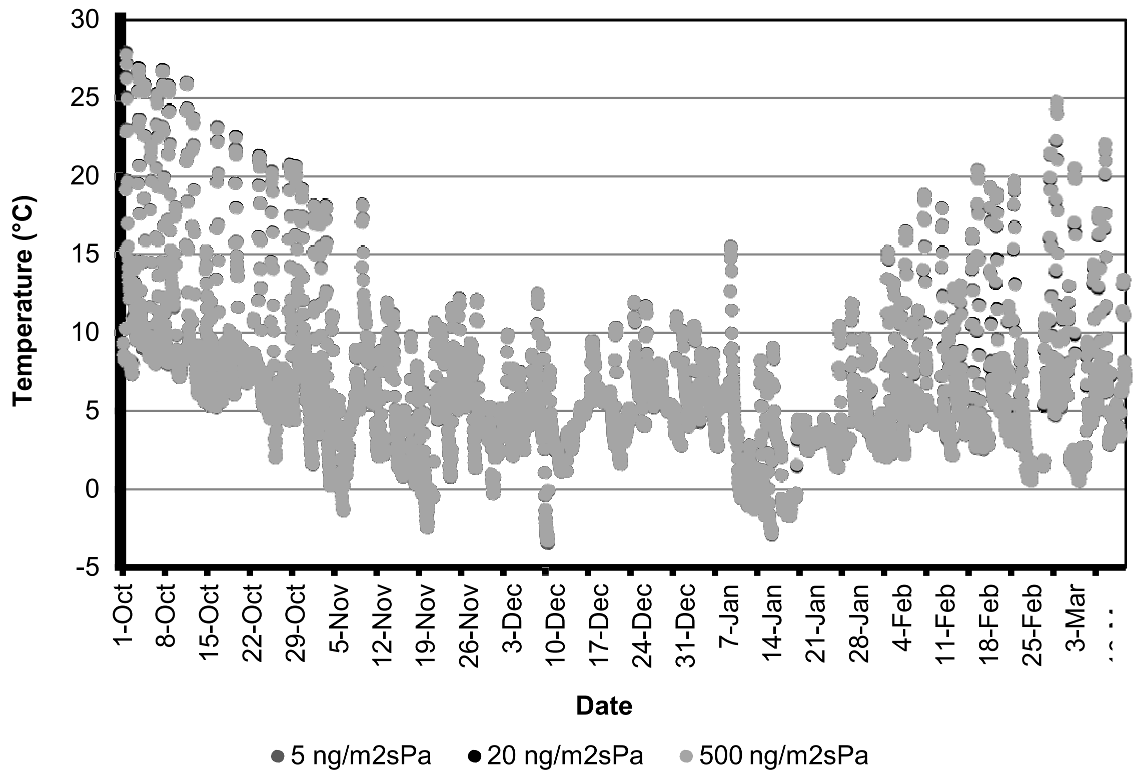

Figure B.29: East Roof Sheathing Surface Temperature for Different Shingle Permeability (Case ID 19, 2, 20)

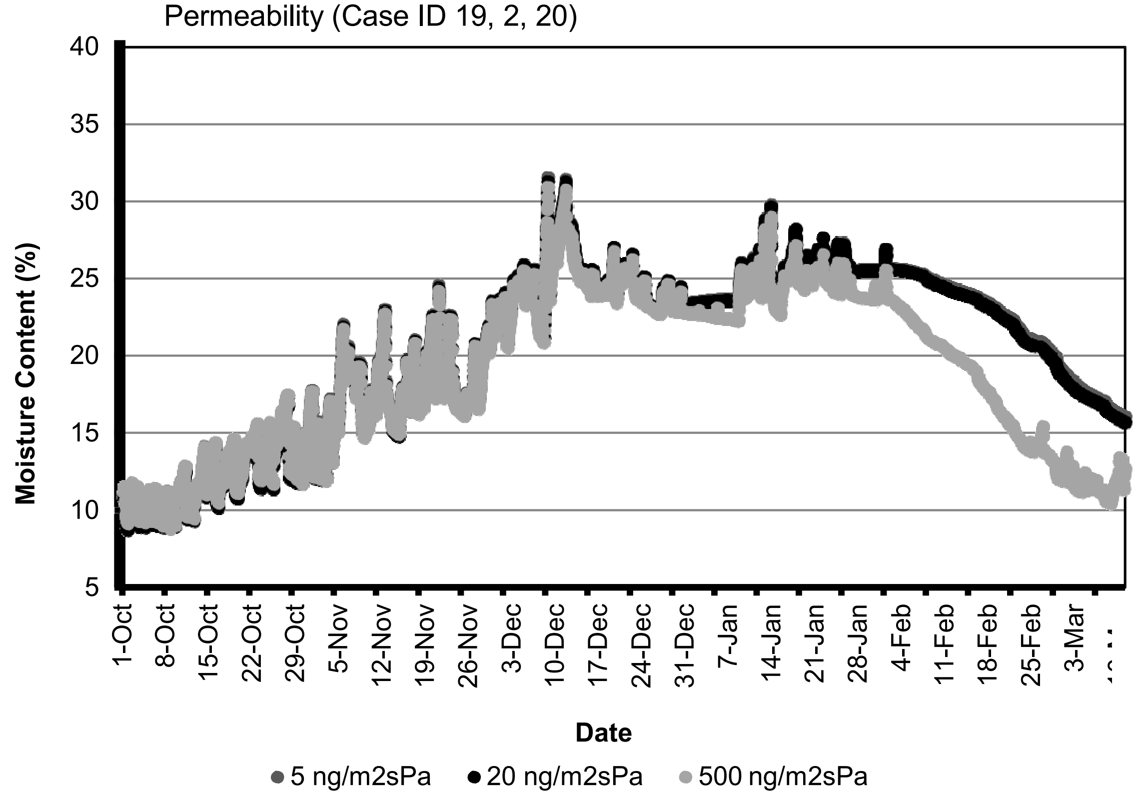

Figure B.30: East Roof Sheathing Moisture Content for Different Shingle Permeability (Case ID 19, 2, 20)

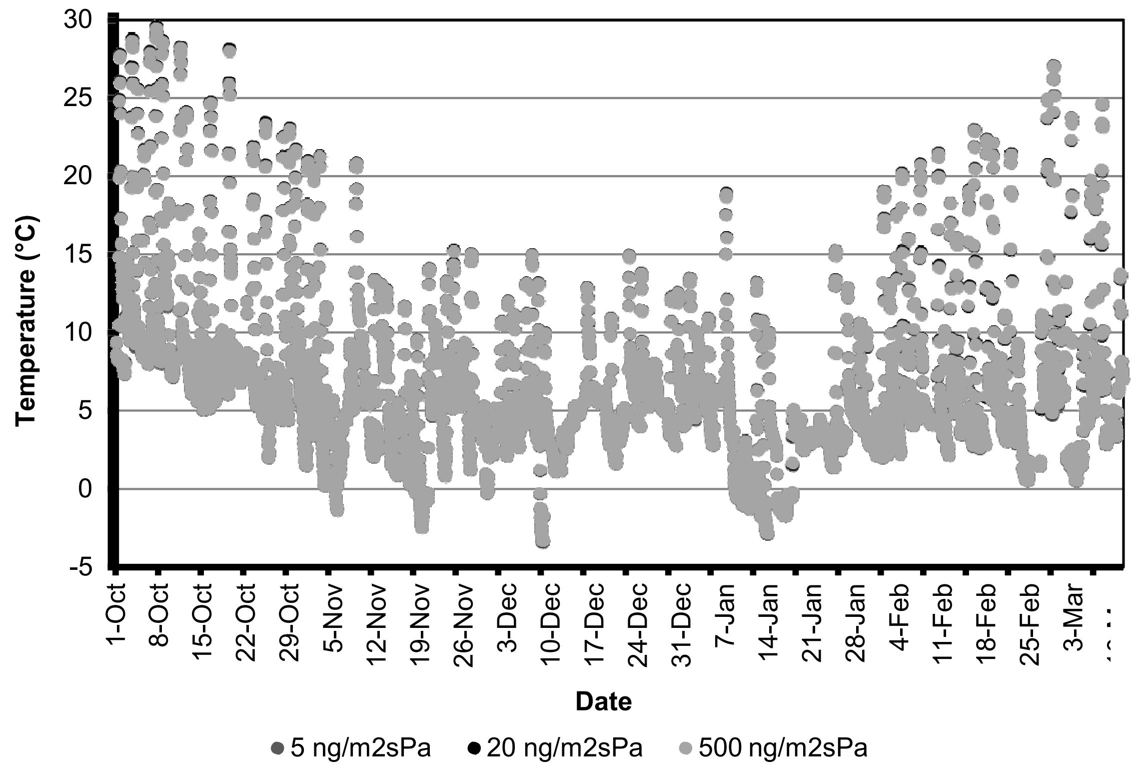

Figure B.31: West Roof Sheathing Surface Temperature for Different Shingle Permeability (Case ID 19, 2, 20)

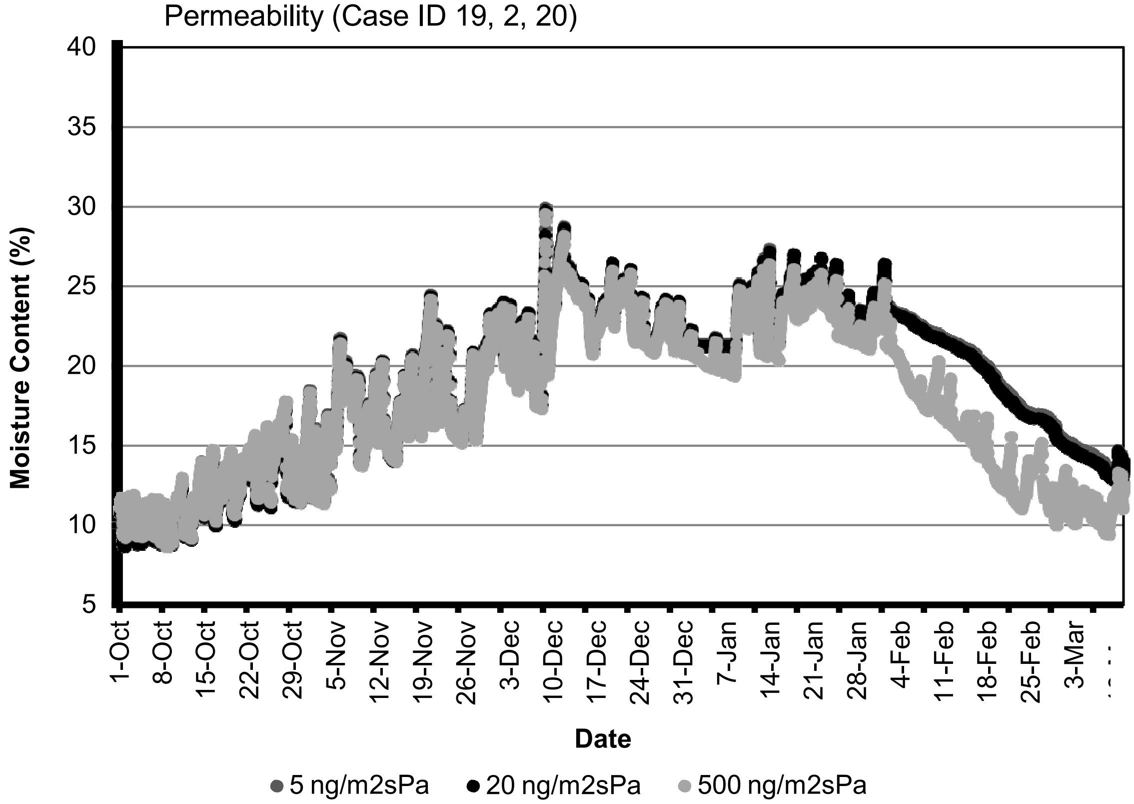

Figure B.32: West Roof Sheathing Moisture Content for Different Shingle Permeability (Case ID 19, 2, 20)

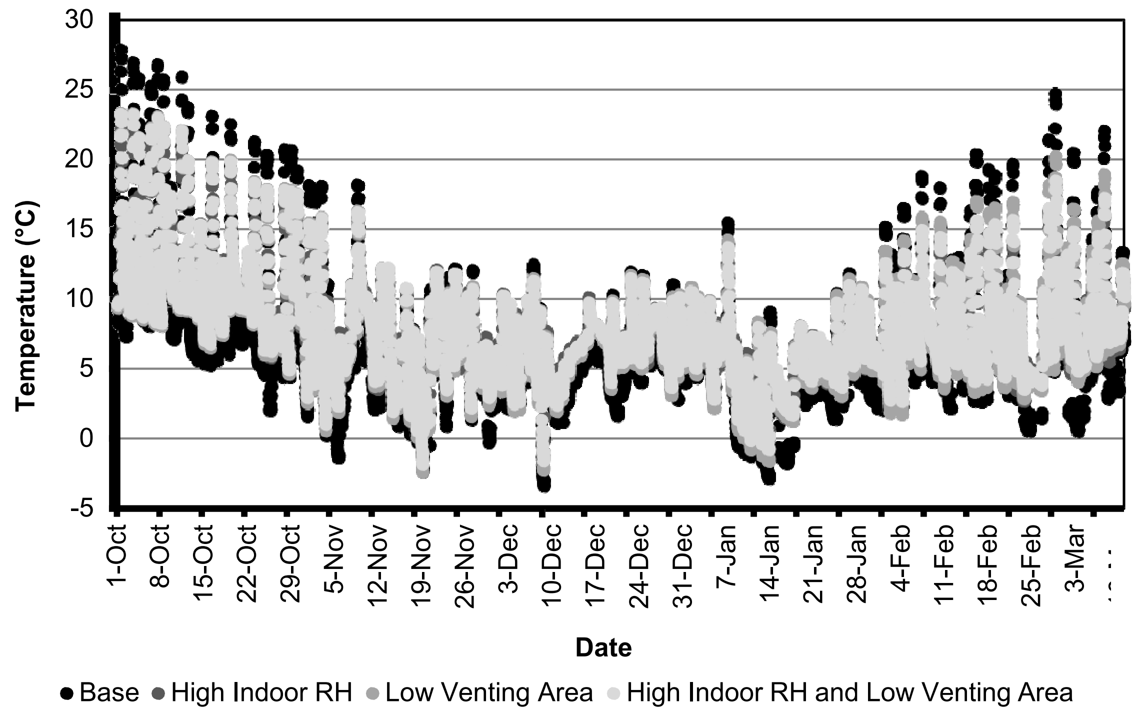

Figure B.33: East Roof Sheathing Surface Temperature with R-2.5 Sheathing Resistance and Permutations of Indoor Humidity, Interface Leakage Area, and Venting Area (Case ID 21, 22, 23)

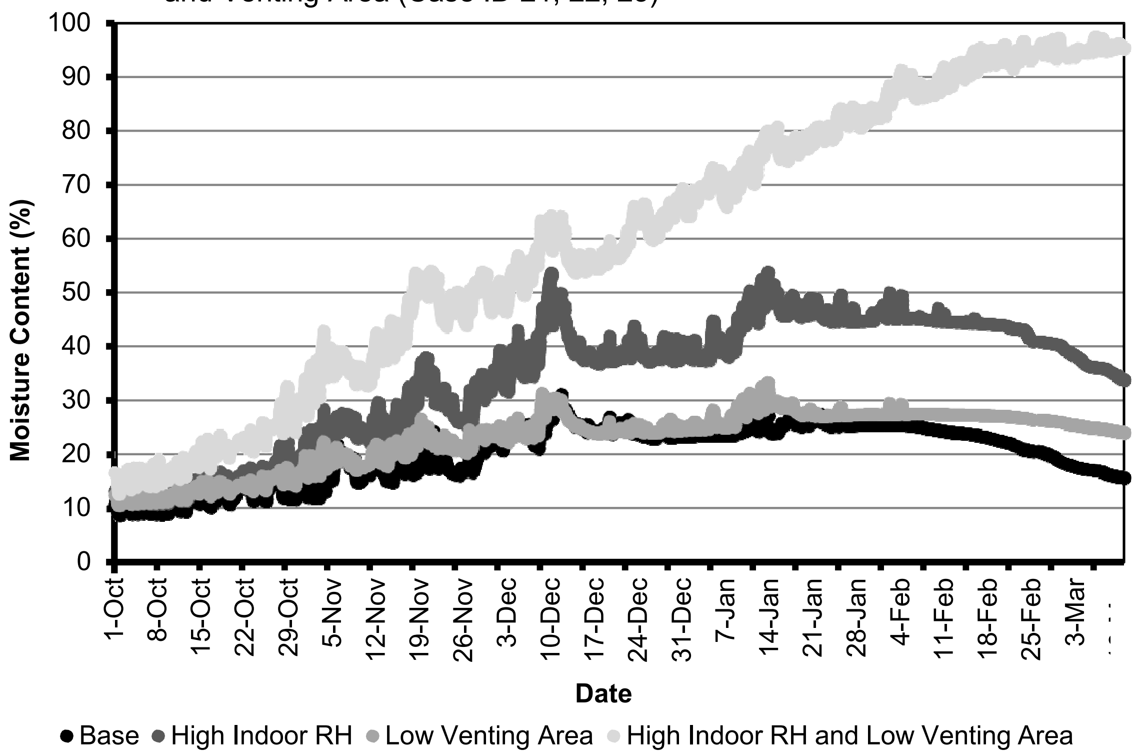

Figure B.34: East Roof Sheathing Moisture Content with R-2.5 Sheathing Resistance and Permutations of Indoor Humidity, Interface Leakage Area, and Venting Area (Case ID 21, 22, 23)

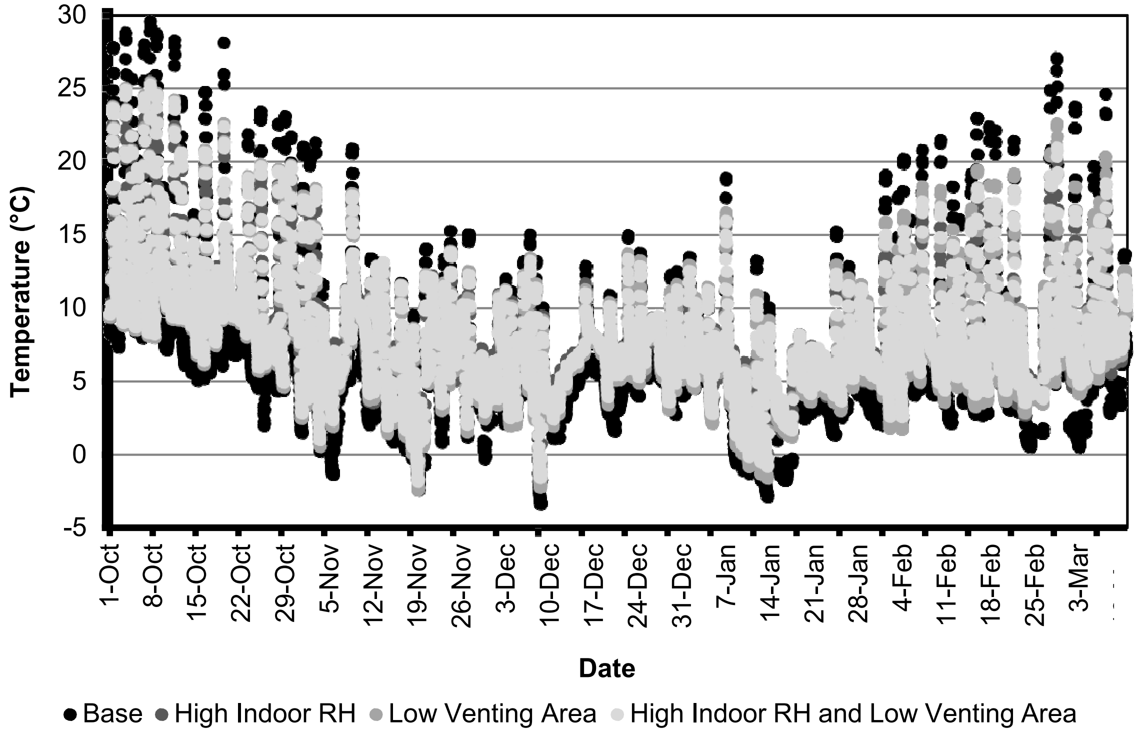

Figure B.35: West Roof Sheathing Surface Temperature with R-2.5 Sheathing Resistance and Permutations of Indoor Humidity, Interface Leakage Area, and Venting Area (Case ID 21, 22, 23)

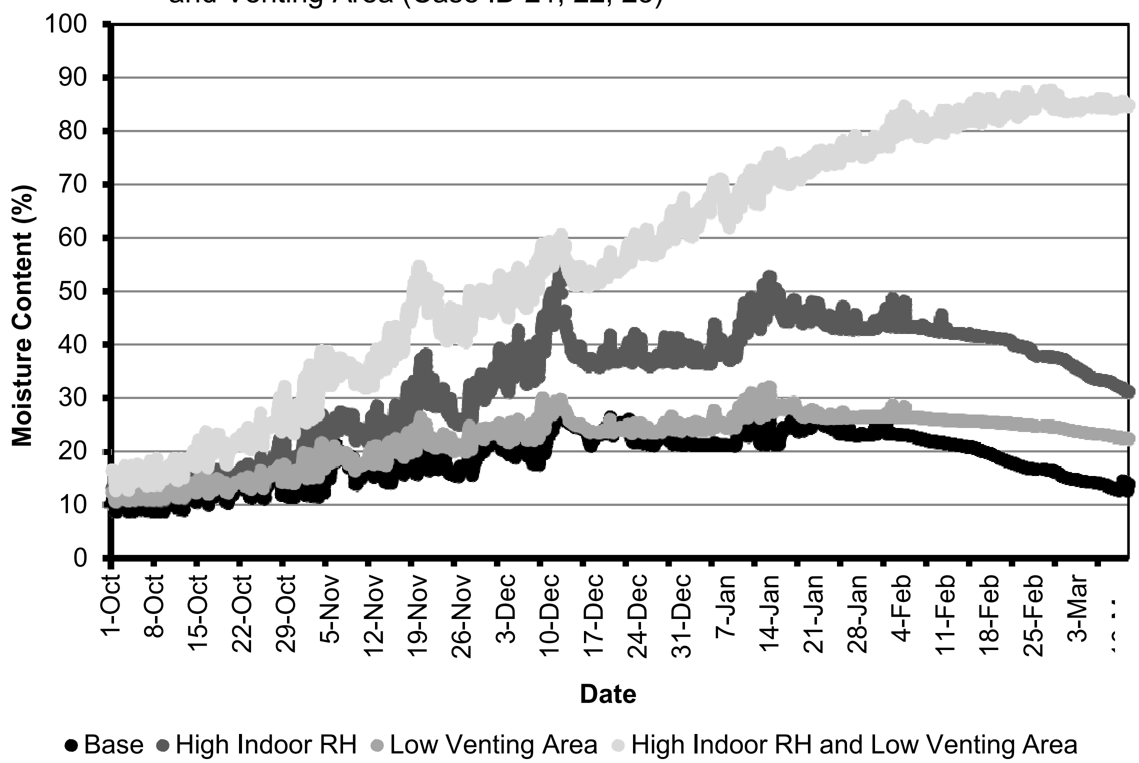

Figure B.36: West Roof Sheathing Moisture Content for Different Scenarios with R-2.5 Sheathing Resistance and Permutations of Indoor Humidity, Interface Leakage Area, and Venting Area (Case ID 21, 22, 23)

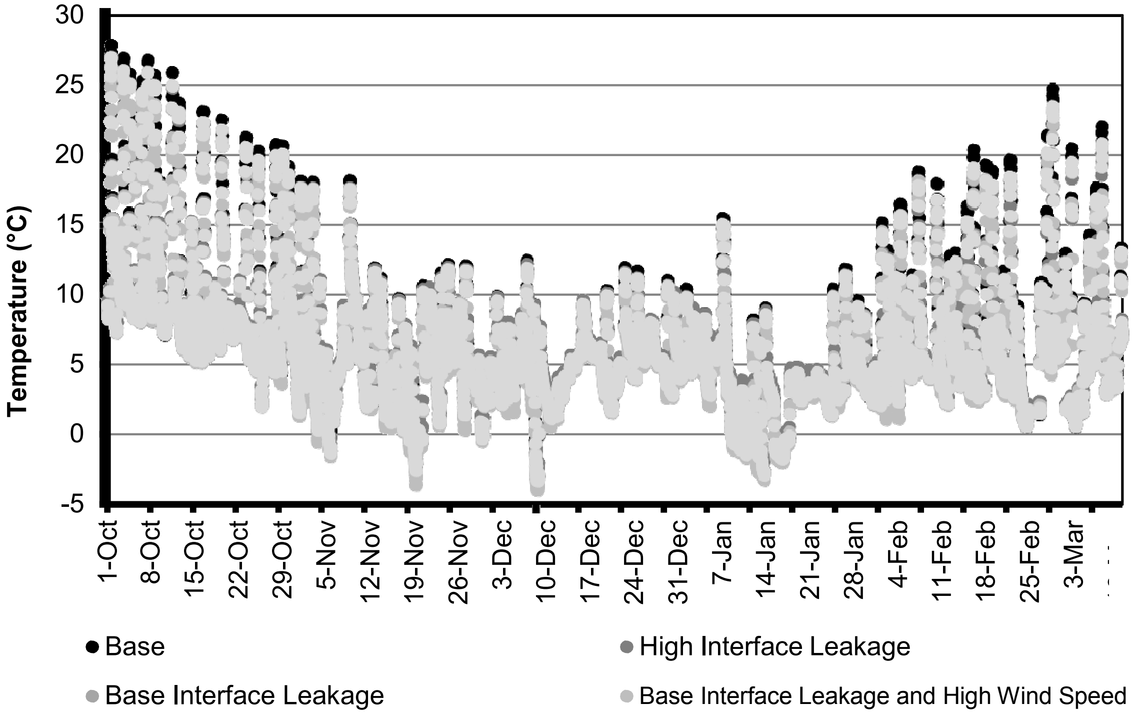

Figure B.37: East Roof Sheathing Surface Temperature with High Venting Area, High Indoor Humidity and Permutations of Interface Leakage Area and Wind Speed (Case ID 24, 25, 26)

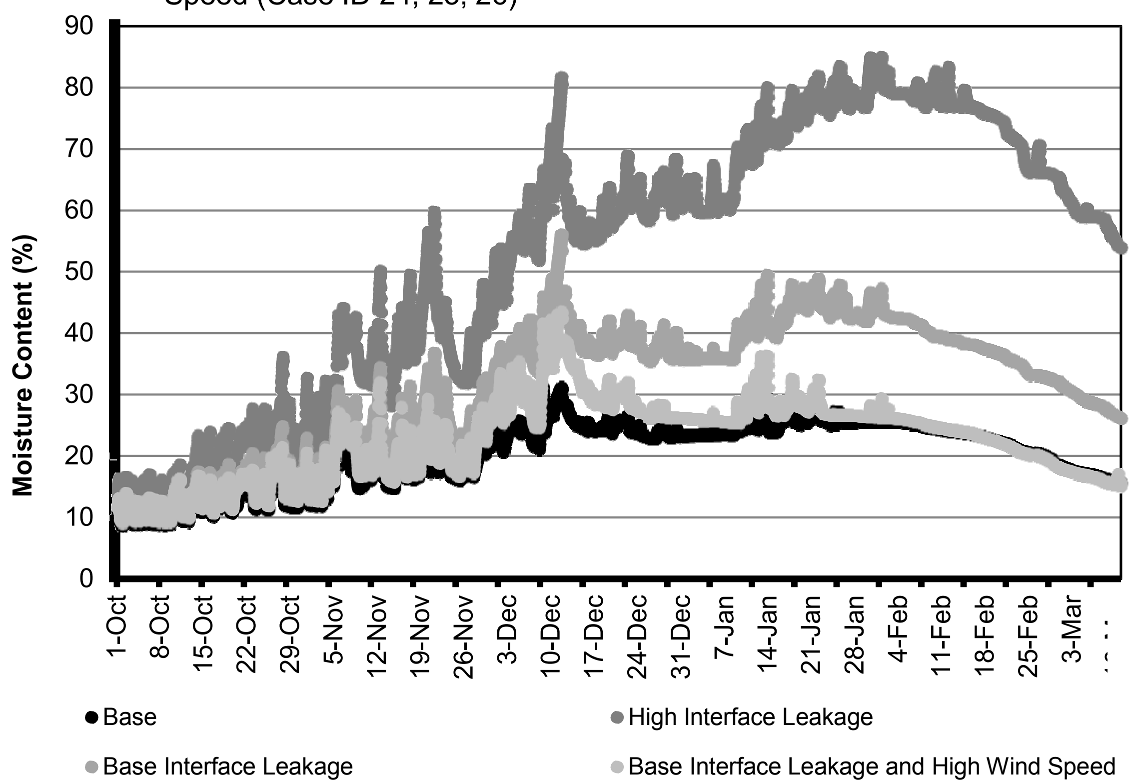

Figure B.38: East Roof Sheathing Moisture Content with High Venting Area, High Indoor Humidity and Permutations of Interface Leakage Area and Wind Speed (Case ID 24, 25, 26)

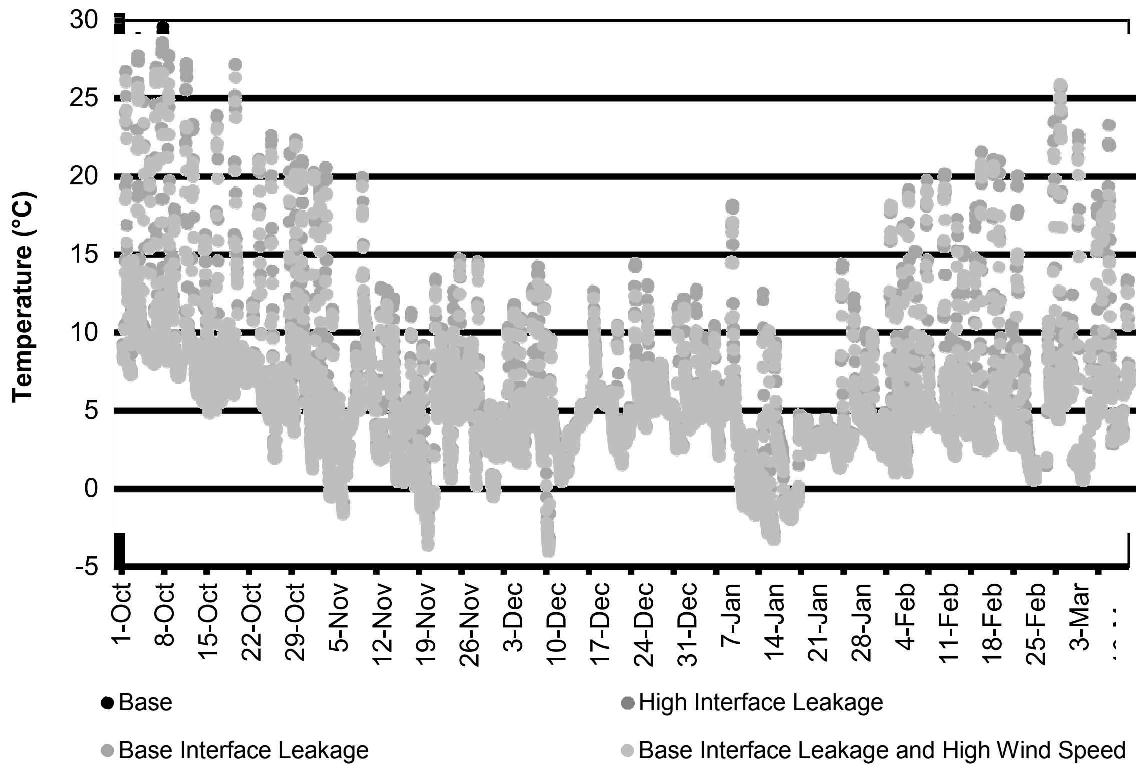

Figure B.39: West Roof Sheathing Surface Temperature with High Venting Area, High Indoor Humidity and Permutations of Interface Leakage Area and Wind Speed (Case ID 24, 25, 26)

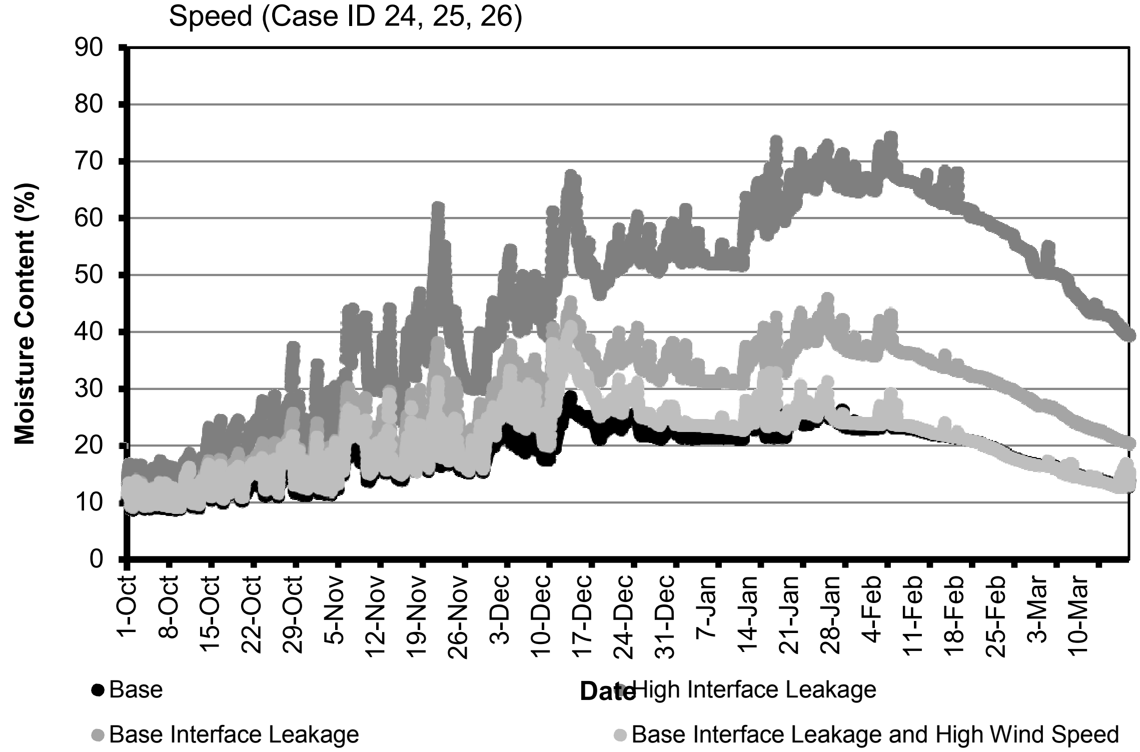

Figure B.40: West Roof Sheathing Moisture Content with High Venting Area, High Indoor Humidity and Permutations of Interface Leakage Area and Wind Speed (Case ID 24, 25, 26)

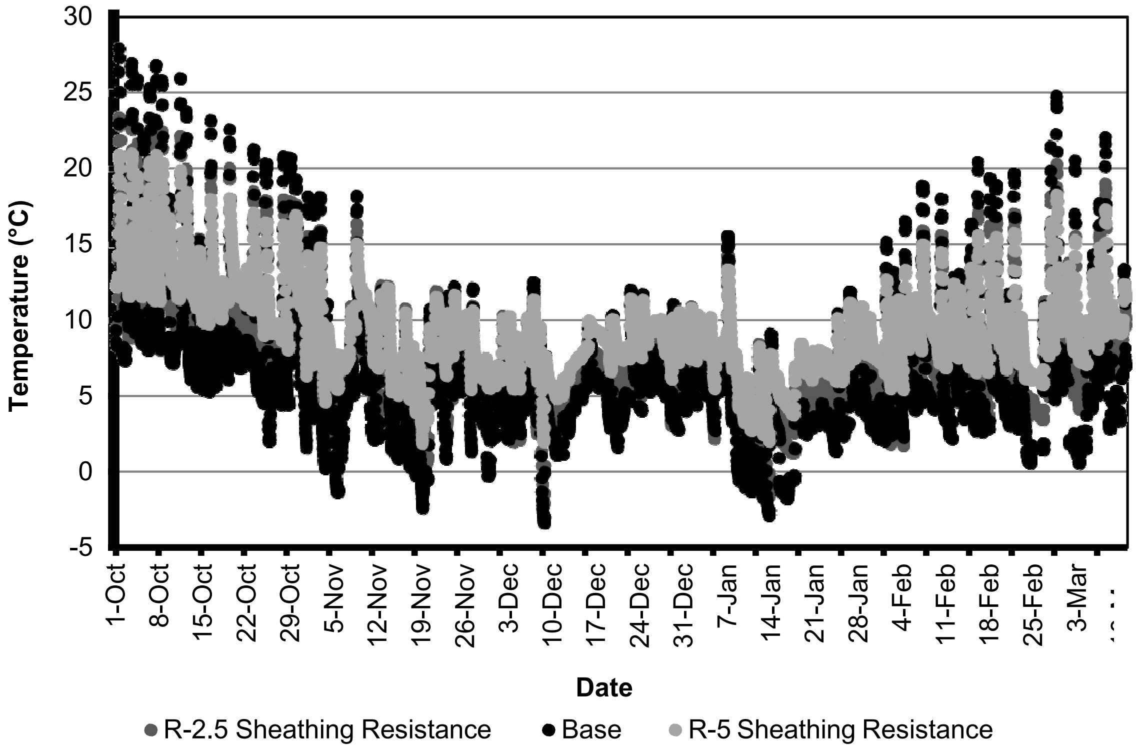

Figure B.41: East Roof Sheathing Surface Temperature with Low Venting Area and Permutations of Sheathing Thermal Resistance (Case ID 22, 2, 27)

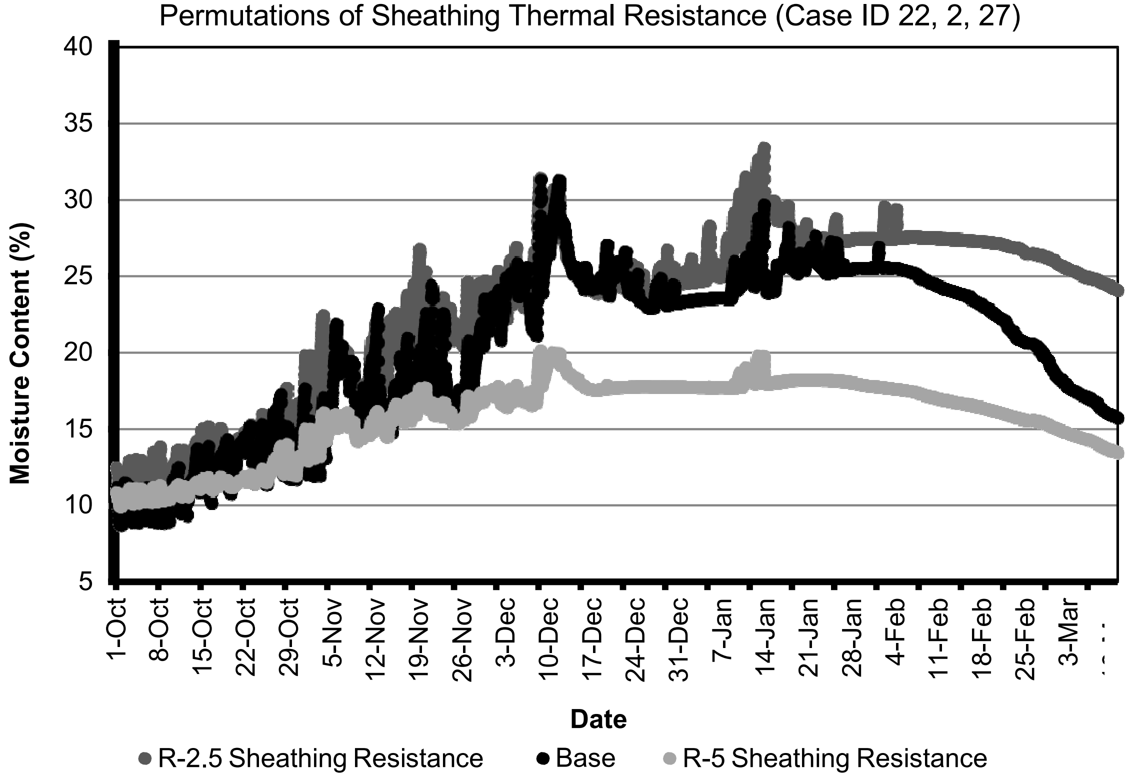

Figure B.42: East Roof Sheathing Moisture Content with Low Venting Area and Permutations of Sheathing Thermal Resistance (Case ID 22, 2, 27)

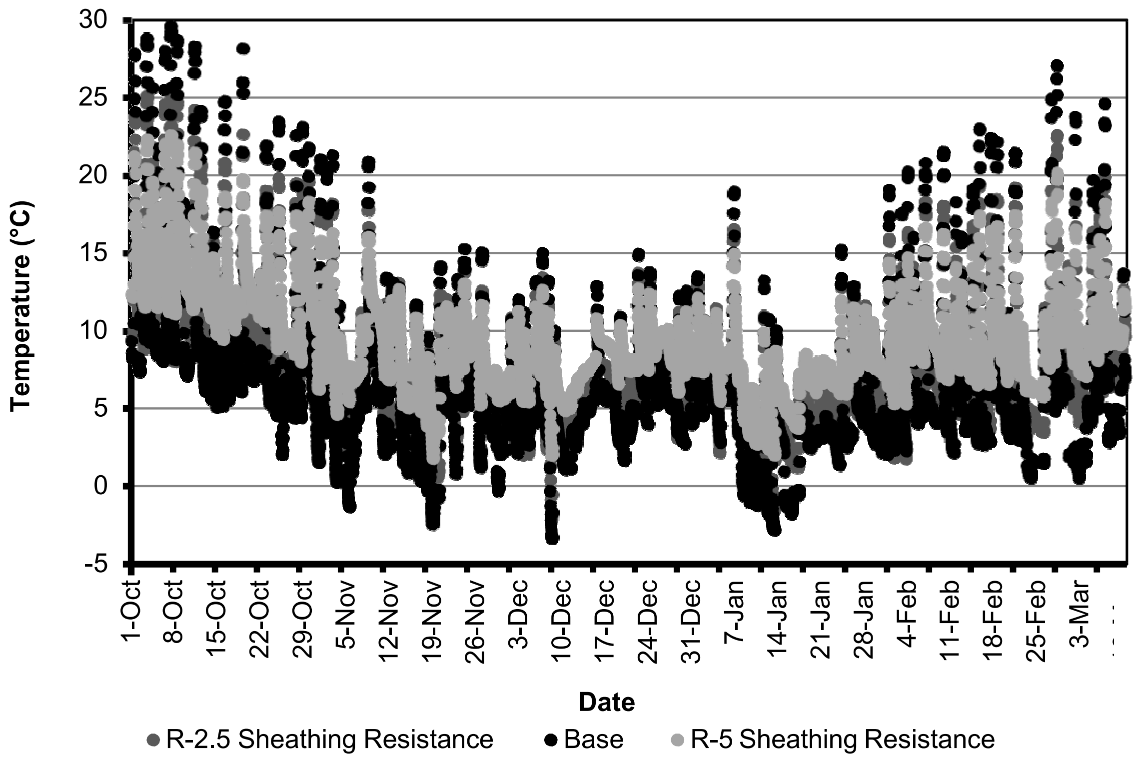

Figure B.43: West Roof Sheathing Surface Temperature with Low Venting Area and Permutations of Sheathing Thermal Resistance (Case ID 22, 2, 27)

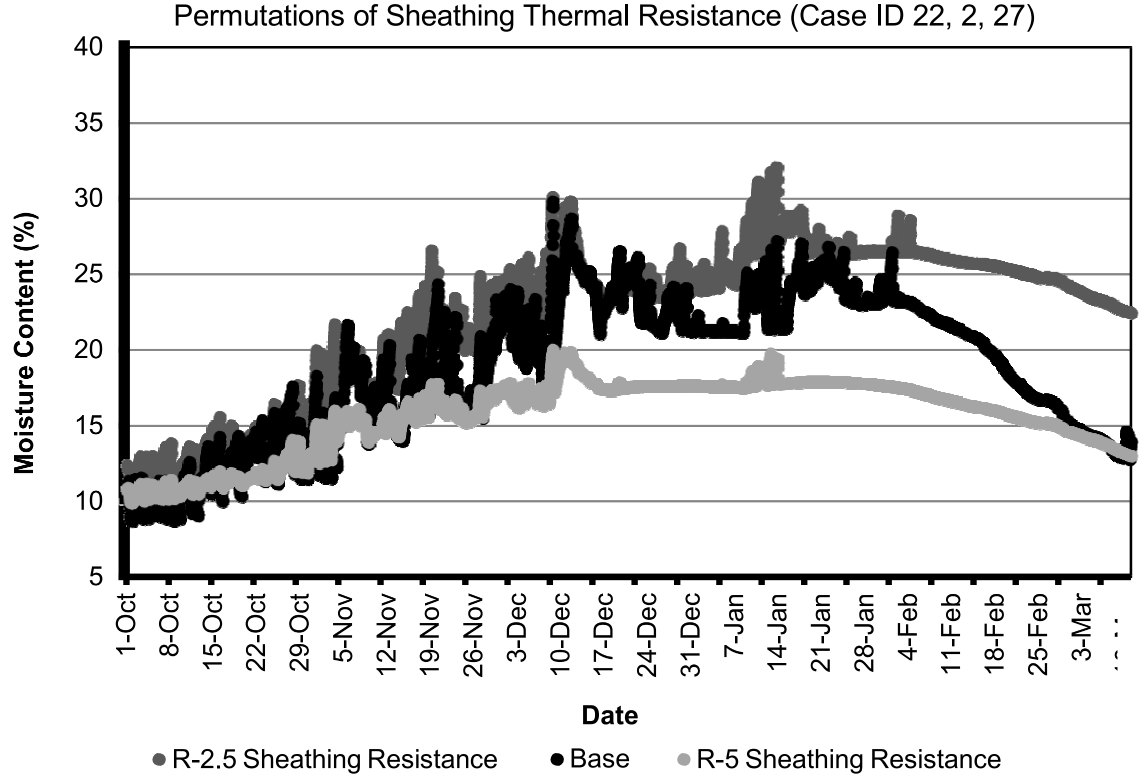

Figure B.44: West Roof Sheathing Moisture Content with Low Venting Area and Permutations of Sheathing Thermal Resistance (Case ID 22, 2, 27)