Highly Insulated, Ventilated, Wood-Framed Attics in Cool Marine Climates

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ABSTRACT

Attic ventilation is a firmly established requirement for residential wood-framed buildings. Attic ventilation is cited to be a benefit for moisture control, reducing cooling loads in hot climates, minimizing ice dams in cold climates, and extending the service life of roof materials by reducing surface temperatures. There is an ongoing debate on the real significance of some of these benefits and mandatory venting requirements.

Despite plenty of attention to moisture control and ventilation of attics, there is growing evidence that buildings, which are built to code in cool marine climates, have mold growth in attic spaces. Problems are being reported in marine climates in both Europe and North America.

The objective of this paper is to demonstrate how cold attic spaces, which are subject to high outdoor moisture levels and are built to code (ventilation area and distribution and ceiling airtightness) can still have moisture problems and to identify the contributing factors leading to mold growth. This paper covers a study in British Columbia, Canada of four attics and a control roof at the same location but not over conditioned space. Testing and measurements included long-term monitoring, air leakage and venting area characterization using dual blower door fans, smoke testing, and tracer gas testing to measure air transfer rates.

INTRODUCTION

The connection between attic ventilation and the hygrothermal performance of attics of wood-framed sloped roofs has been studied for many years, at least back to the 1930s (Rose and TenWolde 1999, 2002). Most building codes stipulate specific prescriptive requirements for the ventilation of wood-frame roofs.

Originally the identified purpose of attic ventilation appears to be to minimize condensation and moisture collection in attics (Rose and TenWolde 2002) which can lead to biological degradation of wood based material, corrosion of metals, and, most relevant to this paper, mold growth on wood surfaces.

The 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 in hot climates, minimizing ice dams in cold climates, and extending the service life of roof materials by reducing material 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).

Most Canadian research into attic moisture problems has identified that the leading cause of moisture troubled attics and high sheathing moisture content, with associated mold growth, is the transfer of moist indoor air into the attic space from high humidity indoor spaces (Forgues 1985; BLP 1991; Sheltair 1997). Attic ventilation is intended to reduce the potential for problems by diluting interior air moisture sources and in theory to provide some drying of moisture in the attic. The general assumption in Canada is that if the ceiling is reasonably airtight and you have the code required attic ventilation then there is little potential for moisture collection.

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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 did not affect 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.

There is growing evidence that in cool marine climates that buildings seemingly built to code are experiencing high incidences of moisture problems and mold growth in attics. In the coastal climate of British Columbia we are seeing problems related to mold growth in attics in many recently constructed wood-frame buildings. This problem is not unique to British Columbia's climate and construction practice. There is similar experience in Europe. 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 has steadily increased 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. 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. The ability to dry out materials is dependent on the temperature and moisture capacity of the attic air. High levels of insulation limit the heat supplied to the attic from the conditioned space. There is even visual evidence that attic ventilation might increase moisture and mold growth in some attics in cool marine climates. Figure 1 illustrates a staining pattern seen in many recent reviews of attics in the Lower Mainland of British Columbia. Mold growth is occurring at soffit vent locations, exactly where the ventilation rate should be the highest.

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, and
b. The thermal mass of the wood, relative to rising air temperatures in the morning due to solar exposure.

When the outdoor air is saturated, 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%).

There is a growing body of anecdotal information 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.

This paper summarizes a research study carried out in British Columbia, Canada, where comprehensive testing and measurements were conducted of attics in buildings that were seemingly built to code requirements and good practice with respect to attic ventilation area, venting area distribution, and ceiling airtightness, but still exhibited staining from mold growth.

SIGNIFICANCE OF MOLD IN ATTICS

One major reason for this study is the observation of surface mold growth on wood roof sheathings of wood frame buildings that seemingly meet code requirements with respect to ceiling air tightness and attic venting area. A perfectly valid question is "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 visible staining. Others note that mold located in attic spaces is unlikely to affect exposure in the occupied space because air transfer between the indoor space and attic is predominately in the direction of the indoor space to the attic space,[1] and any transfer in the opposite direction should be insignificant. Tracer gas testing done in this study supports this point.

Figure 1 *Staining (mold) at soffit vents in a recently constructed wood-frame project.*

Additionally, the dominant molds that have been sampled in many attics are 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 identified doesn't preclude their existence and cannot be relied upon to alleviate health concerns of occupants.

Another way of looking at the issue is to simply focus on marketability and property values. Many occupants and potential buyers naturally have concerns with any mold within attic spaces that are identified by building inspections. The visible presence of mold affects marketability, and ultimately property values, even if experts conclude there is no real health risk or cause for concern of accelerated material degradation.

The visible presence of mold in buildings without identifiable deficiencies or clear solutions presents a challenge to industry.

STUDY OVERVIEW

Study Location and Units

The study units are in a townhouse development near the ocean and surrounded by mountains. This is an area noted for persistent mist and fog. Attic surveys had identified many units in the complex that had surface mold growth especially near soffit vents. Each of the four units was selected from a larger pool of potential volunteers with this condition. All the buildings and units are of similar design and construction but completed in separate phases in 2004 and 2005.

The selection of study units was based on the apparent indoor humidity levels (signs of past condensation on windows), unit orientation (north-south or east-west), apparent venting area (venting provided on two sides or three), and level of observed staining at soffits. Table 1 summarizes the conditions and occupancy of the test units recorded during the visual review of the units. Figure 2 shows the site plan and location of each of the selected study units in the complex. Figure 3 shows the elevation drawings for the study units. Figures 4 and 5 show the north elevation of Unit 4 and the east elevation of Unit 1 for context.

Table 1. Summary of Conditions and Occupancy of Study Units

Unit	Indoor Conditions	Occupants	Staining
1	56% rh, DP 14.7°C, 25°C	1 child, 2 adults	very light
2	49.6% rh, DP 12.7°C, 24°C	2 children, 2 adults	light
3	46.5% rh, DP 12.1°C, 24°C	2 adults	severe
4	48% rh, DP 12.14°C, 23.9°C	2 children, 2 adults	heavier

The test (control) roof assembly shown in Figure 6 was selected because this sloped roof is not subject to moisture sources from an occupied space and has similar weather exposure as the test units. The wood sheathing tested in this assembly allowed us to evaluate the conditions of the roof sheathings in an attic with abundant ventilation. The test roof assembly included monitoring of plywood samples that were installed directly below the roof underlayment and at the underside of R-5 extruded rigid insulation that was attached to the underside of the roof structure. Figure 7 shows the plywood samples for the test roof assembly. This side by side comparison allowed us to also evaluate the impact that condensation due to night-sky radiation and rain-water absorption through the asphalt singles had on the wetting of the plywood samples.

Attic Construction and Ventilation

The attic construction and ventilation (shown in Figure 8) 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 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 are installed at the soffits. Unit 4 is the end of the building and is part of the hip roof end.

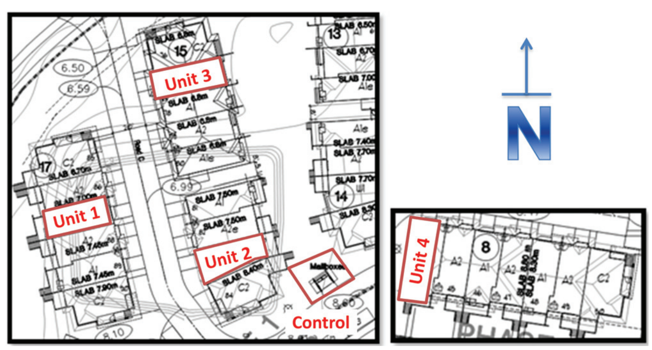

Figure 2 *Site plan and orientation of test units.*

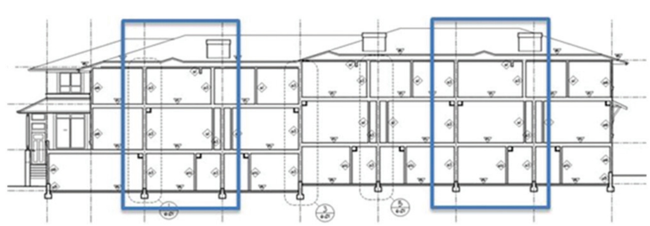

Figure 3 *Building elevation.*

1. This is because both stack effect (i.e., heat rises and cold air falls) and wind pressures (suction on the roof) create driving forces for air transfer in the direction of the indoor space to the attic
2. These same molds are also not considered pathogenic for humans, which means the molds do not cause infections. However, some people are allergic to the spores of these molds similar to being allergic to plants.

Dryer, exhaust, and fresh air ducts, as well as plumbing pipes penetrate through the attic ceiling and 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 contractors tape. 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. Drywall with taped joints separates the attics between units.

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-frame attics in coastal BC. Results, Analysis, and Discussion follow in later sections.

Building Characterization

The air leakage area of the ceiling interface between the indoor and attic space and the attic venting area was deter-

Figure 4 *End Unit 4.*

Figure 5 *East elevation of Unit 1.*

Figure 6 *Test (control) roof assembly with Unit 2 in the background.*

Figure 7 *Control assembly sensors.*

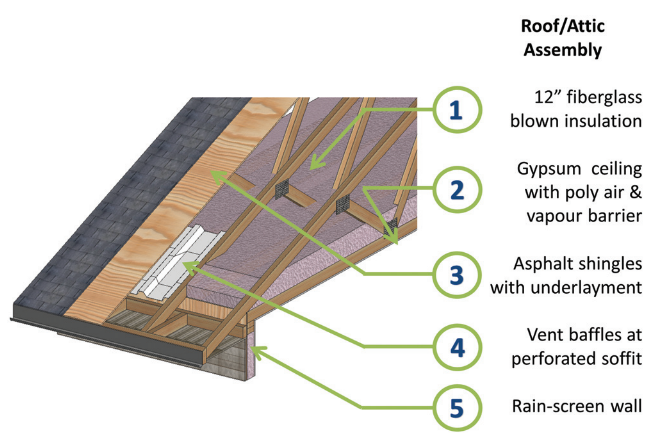

Figure 8 *Attic construction and ventilation*

mined using a two fan depressurization method. This method is similar to what was done in the past in previous Canadian attic research studies (BLP 1991; Sheltair 1997).

The primary purpose of conducting the air leakage 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.

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 9 and 10 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 fluctuations in the air leakage area readings were fairly stable, less than 1.5%, indicating reliable measurements.[3] Unit 4, however, has soffit 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 only 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 below.

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

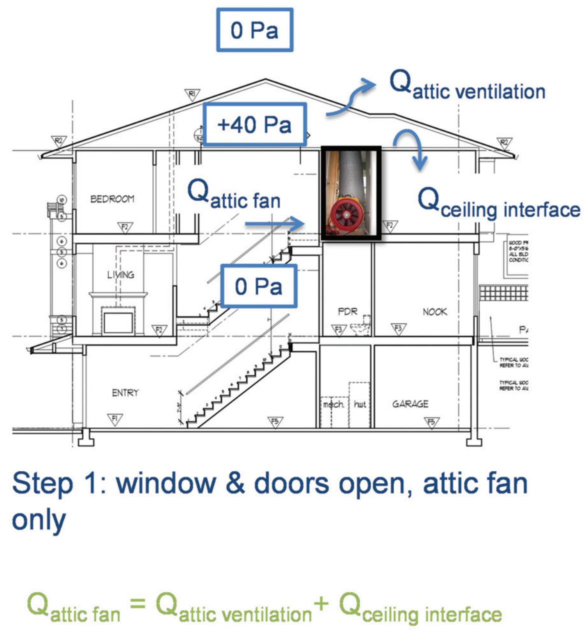

Figure 9 *Building characterization step one, window and doors open, attic fan only.*

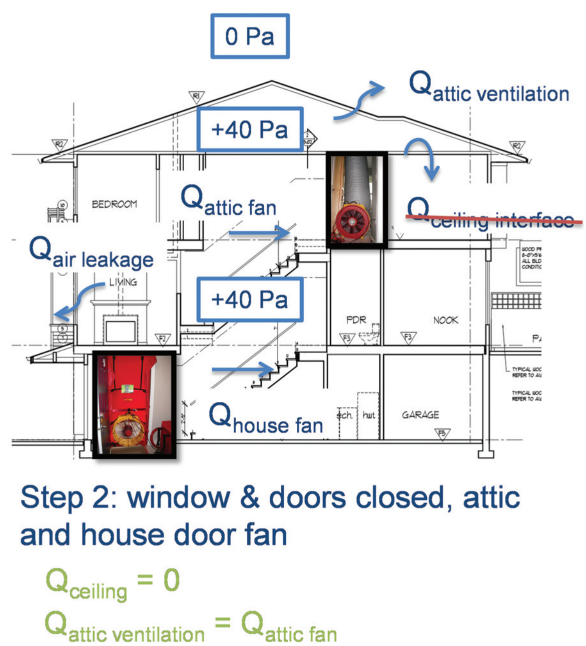

Figure 10 *Building characterization step two, window and doors closed, attic and house door fan.*

[3] A pressure differential less than 50 or 75 Pa was selected due to the limitations associated with the two fan setup, available power, the size of the venting areas, and ultimately the fan capacity (maximum 6300 cfm).

bag to the flange of the grill. The connections were sealed before the tracer gas sampling was completed in December as described below.

Tracer Gas Testing

The venting and ceiling air leakage 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 average 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 sources 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. No additional fans were added to the indoor space and the CATS (samplers) were placed at return air ducts to provide average mixing in the zone. Figure 11 illustrates the deployment of the sources and samplers.

Long Term Monitoring

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:

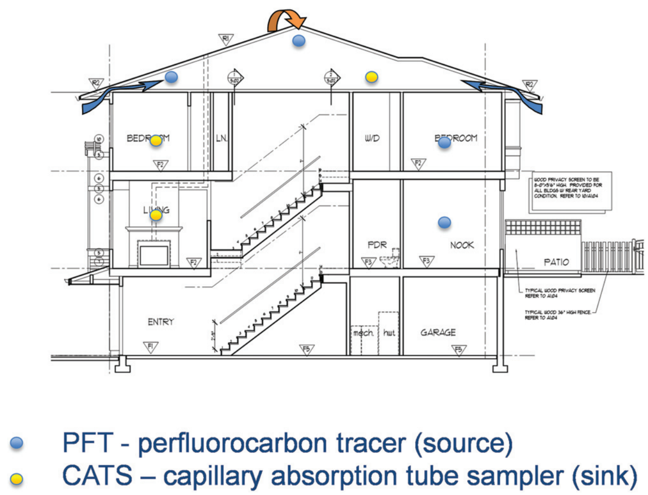

Figure 11 *Tracer gas testing experiential program.*

a. Moisture content and temperature of the roof sheathing at three locations, at the vent baffles at the soffits and at the framing bay beside the baffles at the soffit
b. Moisture content and temperature of top chord of truss at one location
c. Condensation detection on sheathing at a baffle location
d. Attic air temperature and relatively humidity
e. Indoor air temperature and relatively humidity

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
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

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

RESULTS

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

Building Characterization and Smoke Testing

The attic venting area, including both intentional and unintentional openings, is presented in Table 2 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).

The measured venting areas are higher than the average areas reported in 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 3. 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.

Comparison of the NLA values in Table 3 to the reported values in past Canadian studies (BLP 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.[4] 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.

Table 2. 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 area)	% Measured Area/ Required Area
1	2450 cm^2 @ 40 Pa	60 (642)	1900 cm^2	129%
2	2435 cm^2 @ 40 Pa	68 (728)	2160 cm^2	113%
3	3900 cm^2 @ 40 Pa	57 (614)	1990 cm^2	196%
4	7530 cm^2 @ 15 Pa	60 (642)	2315 cm^2	325%

Table 3. 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)

*Air leakage through surface(s), such as a ceiling surface, is commonly presented as NLA in previous Canadian studies and programs, therefore is continued in this paper. ΔP = 10 Pa, CD, 2 = 1, CD, 2 = 0.611, and n = 0.65 was utilized to calculate the NLA values.

Comparison of the reliable data for Units 1 to 3, with NLAs 1.6 to 2.2, to the 1997 NLA Survey for whole building airtightness by National Resources Canada summarized in Table 4 further supports the argument that the study units have at least average airtightness at the ceiling to attic interface. The measured NLAs for the ceiling to attic interface of Units 1 to 3 are close to the average NLAs for whole buildings but not for the R-2000 buildings. However, the ceiling interface NLAs 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 interfaces are airtight for the study units.[5]

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 period of time. 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.

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

Table 4. 1997 NLA Survey by National Resources Canada

Region	1981–1990	1991–1997	R-2000
BC	2.8	1.9	0.7
National	2.3	1.4	0.6

4. 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/m^2 (1.0 in2/100 ft^2) is achieved.

5. 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 (BLP 1991; Sheltair 1997).

Table 5. Comparison Between Measured Attic Ventilation Rates and Venting Rates Derived from Fan Testing

Unit	Tracer Gas Testing, ACH (m^3/h) Round 1 (December 8 to 15)	Round 2 (February 20 to 27)	Derived from Fan Testing, ACH (m^3/h) @ 4 Pa
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)

Table 6. Comparison Between Measured Indoor to Attic Air Transfer Rates and Leakage Rates Derived from Fan Testing

Unit	Tracer Gas Testing, CFM (m^3/h) Round 1 (December 8 to 15)	Round 2 (February 20 to 27)	Derived from Fan Testing, CFM (m^3/h) @ 4 Pa
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)

outdoor air was 1°C 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 wind.

To demonstrate the order of magnitude flow rates derived by fan testing at a "standard" 4 Pa pressure differential, as presented in Table 5, 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,[6] 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.

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 BLP field study (1991). 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 BLP study.

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).

For BLP study (1991), 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 BLP measured rates. The rates are however higher, roughly double, than the 5 to 7 cfm (12 to 15 m^3/h) measured for two research houses at the University of Alberta during extremely cold weather (1993).

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 later in the paper.

First, we note that there were many difficulties with the monitoring equipment during the winter of this study and con-

6. 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.

sequently there are holes in the data during various periods of the 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.

Monitoring continued the winter of 2012/2013 for Units 1 and 2 and the control roofs. The ongoing monitoring is exploring the impact of changes to the venting area. Unit 1 had an additional button vent installed at the ridge and Unit 2 had the soffit venting restricted by filling the free area with plastic bags filled with semi-rigid insulation.

At the time of writing this paper in January of 2013, the monitoring from the winter 2012/2013 was not comprehensively analyzed. We note that the general trends continue, but Unit 1 appears to have larger swings in moisture content and Unit 2 does not dry out as quickly after wetting events.

Many of the previous Canadian studies indicated that moisture problems in attics were generally not evident without the presence of high indoor humidity (BLP 1991; Sheltair 1997). 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 7 summarizes the indoor conditions measured for the test units. A ΔVP 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, ΔVP, 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 ΔVP 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).

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.[7] Figure 12 summarizes the duration (hours) of elevated sheathing moisture levels and Table 8 summarizes observations of staining at the sensor locations at the start of the monitoring period.

The correlation between moisture thresholds and staining provides a benchmark for the conditions favourable for mold growth. However, mold research tells us that exposure time, temperature, and RH must be considered concurrently when evaluating the risk of mold growth in attics (Haukka et al 1999; Viitanen et al 2007; Clarke et al 1996; Sedlbauer 2001). Moreover, analysis of the field monitoring data and visual observation of staining demonstrates the need to consider these factors together. An interesting finding was that the control assembly had visible staining after 2 years, but only spent 2 to 3 weeks above 25% MC. The control also was not subject to conditions above 28% MC and had more staining than wetter locations in the attics. However, the control assembly spent more time above 20% MC and near 25% MC than compared to the attics. These differences are explainable using a predictor, such as mold index (Haukka et al 1999; Viitanen et al. 2007), which accounts for exposure time, temperature, and RH concurrently, and will be discussed in future work.

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. Spikes in the moisture levels occurred on December 10 to 12th, 2011 and January 12, 2012. These events are discussed further in the next sub-section, diurnal wetting.

This winter (2012/13) moisture levels spiked to 35% MC in both the monitored units during a 10 day period, in the middle of January, when there was several consecutive cold clear nights. Unit 1 (additional vent) spiked less times than Unit 2 (blocked soffit vents) and dried out more quickly. Moisture levels in Unit 1 dropped to similar moisture levels as the control assembly in approximately 1 week period after wetting events. In contrast, the moisture levels in Unit 2 remain elevated around 28% MC at the end of January.

7. The sensors at Unit 3 west soffit, the location with the most visible staining, malfunctioned during critical wetting periods

Table 7. Measured Indoor Conditions

Unit	Average Temp., °C	Average RH, %	95% Percentile Dewpoint Temp.,°C	Average ΔVP, Pa	95% Percentile ΔVP, Pa	99% Percentile ΔVP, Pa
Outdoors	**6.9**	**84.4**	**8.5**	**N/A**	**N/A**	**N/A**
1*	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

*Unit 1 was only analyzed for December 2011 and January 2012

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.

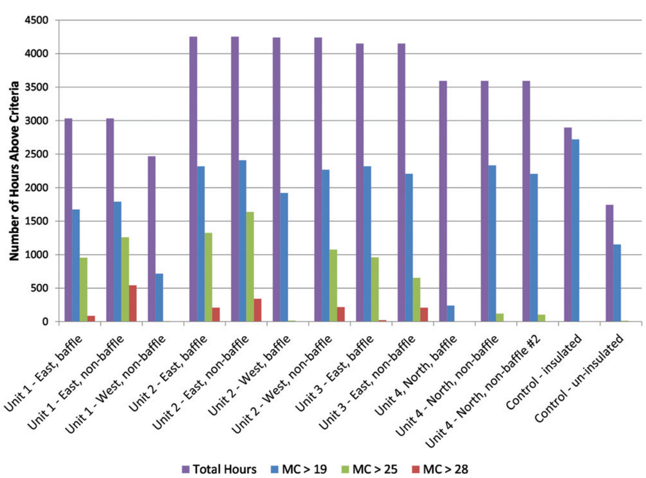

Figure 12 *Duration of elevated sheathing moisture levels.*

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. Figures 13 and 14 show 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).

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 surfaces cooled by night-sky radiation that was subsequently exposed to warmer humid outdoor air as temperatures rose in the daytime. Figure 15 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 and in January 2013.

ANALYSIS AND DISCUSSION

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 con-

Table 8. 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 and non-baffle	East: truss West: truss
2	East: baffle	East: non-baffle West: baffle and non-baffle	East: truss West: truss
3	West: baffle	East: baffle and non-baffle West: baffle and non-baffle	East: truss West: truss
4	North: non-baffle	North: baffle	South: baffle and non-baffle South: truss

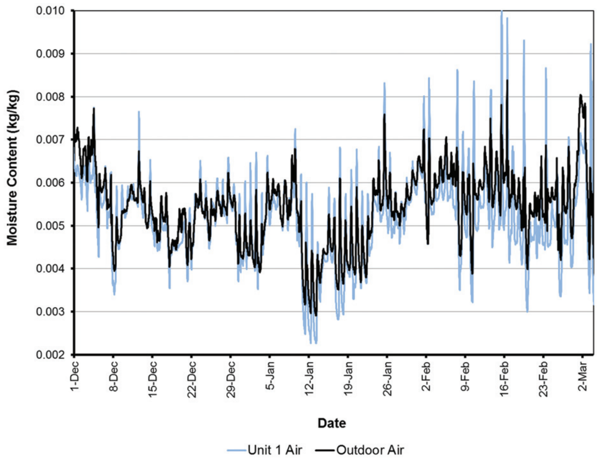

Figure 13 *Unit 1 attic and outdoor air moisture levels per time.*

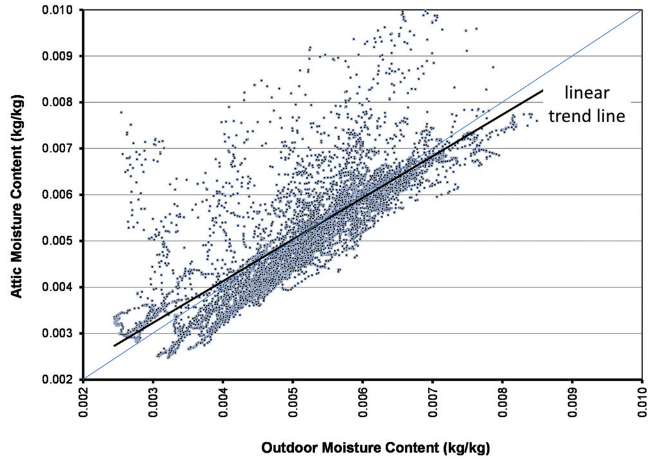

Figure 14 *Unit 1 attic versus outdoor air moisture levels.*

tent 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 testing and measurements completed for this study provided sufficient information to demonstrate how attics with ample venting area, subject to high outdoor moisture levels, can lead to mold growth in ventilated attics. A follow-up study is in progress and a summary of this work follows.

FOLLOW-UP STUDY

Visible mold in attics spaces for good and common construction practice without identifiable deficiencies or clear solutions presents a real issue for industry. This paper highlights this problem and provides an understanding of the contributing factors leading to visible mold in code compliant buildings. A follow-up study is focused on identifying solutions that industry can implement to respond to this issue, for both new construction and existing buildings. Included in the follow-up study is an evaluation of the impact of various parameters using a heat-air-moisture model that is validated and calibrated to the measured data presented in this paper.

The primary objectives of the follow-up study are to:

- develop strategies to reduce the likelihood of staining occurring and/or wetting in wood-frame attics,
- identify solutions that have a high probability of being successful if implemented by industry,
- identify any risks with the various alternatives, and
- help guide decisions for any contemplated changes to the building code.

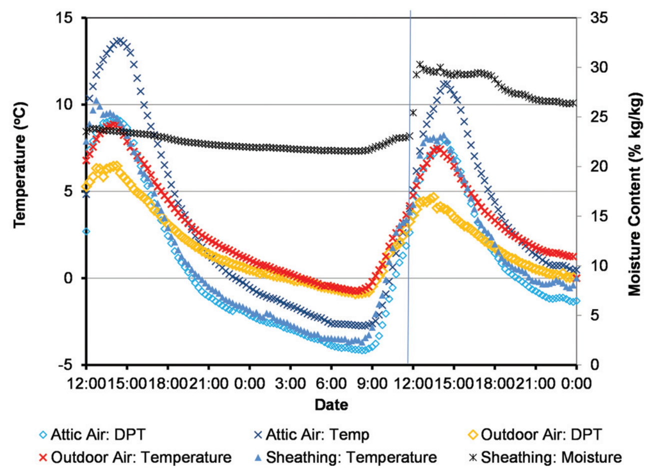

Figure 15 *Unit 1 sheathing moisture spike after night-sky cooling on December 12, 2012.*

Strategies and related solutions that are being explored, appropriate for the British Columbia costal climate, are as follows:

- **Strategy 1.** Apply treatments and coatings to create surfaces that are unfavourable for mold growth for a broad range of environmental conditions. For example, a treated wood sheathing surface that can be repeatedly exposed to condensation, long periods of high relative humidity and dynamic roof temperatures without growing mold.
- **Strategy 2.** Provide insulating boards and mold resistant sheathing outboard ventilated spaces. Liquid water is controlled by the insulating board by potentially two mechanisms, depending on the roof type. The principal 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 radia-

tion. A secondary mechanism of controlling exposure to liquid water, for sloped roofs with asphalt shingles, is the insulating board will provide an effective capillary break between the sheathing and the shingles. The roof sheathing still needs mold resistance greater than unprotected wood because of the exposure to high humidity for long periods of time, but does not need to meet the same requirements as the treatments 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 outboard the roof sheathing and keep the roof structure warm and dry.
- **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 and eliminates the air paths between the wood sheathing and interior space.

Other possible strategies that were considered but are not being followed up include:

- **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 an engineered strategy that will require more in-depth study; a calibrated heat-air-moisture modeling, field testing, and/or lab testing; before it is practical to implement in standard building practice.
- **Strategy 6.** Hide the mold growth. There are many types of roof constructions that follow this strategy that have similarities to the roofs covered by the other strategies. Examples are cathedral ceilings with ventilated cavities, low-sloped roof ventilated below the roof sheathing, and exterior insulated roofs with ventilated decking. The common theme is that inspection of the roof sheathing is more difficult and as a result is inspected with significantly less frequency than attic spaces with hatches. Consequently, these roofs are likely to circumvent unnecessary alarm of mold growth within roof structures. However, mold growth is still likely to occur.

A few of these strategies are already done in practice but a lot less frequently than conventional sloped ventilated wood-framed roofs, since generally all these solutions come at additional cost. Follow-up work is focused on identifying the cost-benefit of each solution for several scenarios; manufacturer and site solutions, low-slope and sloped roofs, and new and existing buildings.

Work also continues on validating a “whole building” heat-air-transfer model and evaluating the relative impact of ceiling airtightness, attic ventilation rates, sheathing thermal resistance, roof colour, and insulation levels on the moisture levels in ventilated attics. This effort is being supplemented through continued monitoring at the building site identified in this study, with different venting areas, and another location with low-sloped roofs with differing sheathing thermal resistance.

SUMMARY AND CONCLUSIONS

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 hygrothermal 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 control moisture, to limit mold growth, in insulated attics of wood-framed sloped roofs in marine climates, similar to Vancouver’s climatic zone. 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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- Polygon Construction Management—Construction practicality and costs of solutions
- University of British Columbia’s School of Population and Public Heath—Expert opinion of health risks related to exposure of molds in buildings

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