LONG TERM PERFORMANCE: UNVENTILATED WOOD FRAMED ROOFS USING POLYURETHANE FOAM

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ABSTRACT

Unventilated wood-framed roofs/decks, in which polyurethane foam (closed cell or open cell) is installed inboard of the roof/deck sheathing, are becoming more common in roof and deck applications in the Lower Mainland of British Columbia. In the flat roof/deck application, it has been seen as a viable alternative to ventilated roofs/decks in which ventilation, in general, has proven ineffective in dealing with incidental moisture. In the sloped roof application, it has been seen as a viable alternative to ventilated attics by locating the attic within the thermal envelope, thereby eliminating the potential moisture-related issues associated with ventilated attics.

It is acknowledged that spray foam can improve the airtightness of assemblies which, in turn, can help reduce the risk of moisture-related issues. That said, in the absence of a holistic approach in the design of roofs/decks using spray foam, the satisfactory **long-term performance** can be compromised. Such a holistic approach must take the following factors into consideration to ensure the overall successful long-term performance of the assembly:

- The possibility of imperfect installation or implementation of the environmental control layers (vapour retarder, air barrier, rain penetration control layer, and thermal insulation). Deficiencies can occur during construction or during in-service phases.
- Potential exposure to moisture sources other than rain and interior/exterior vapour, such as plumbing leaks, construction moisture, etc.
- Microclimate of each building (trees, overhangs, roof/deck finishing, etc.) and its impact on the solar drying potential.
- Lack of easy identification and location of possible future leaks, which can pose the risk of moisture being trapped for a long period before being discovered. This can lead to moisture-related damage including potential structural damage.

This paper explores the above four factors in relation to the unventilated wood-framed roofs/decks with polyurethane foam. Supported by physics, various site investigations, and in-depth hygrothermal analysis, this study examines the drying potential and tolerability of this assembly to construction and in-service moisture sources. In addition, the practicality and the ease of identifying, locating and repairing future leaks are discussed.

The study suggests that, under current practices, careful and holistic consideration of the above-mentioned factors is often not implemented during the design. Under the right conditions, this can pose the elevated risk of compromising the satisfactory long-term performance of these assemblies. This paper also presents

practical solutions on how to address these risks, followed by the consideration for the ease of locating and repairing future leaks.

BACKGROUND

When it comes to wood-framed sloped or flat roof assemblies in the lower mainland of British Columbia, one common practice over the years has been to install fibrous insulation (in the form of batt and loose fill) between the roof joists/trusses. In this interior insulated assembly, a vapour retarder and an air barrier are installed on the room side of the insulation. In addition, given that the roof waterproofing materials have very low vapour permeance, a ventilated air space is provided between the insulation and underside of the roof sheathing. The intent of the ventilated air space is to bypass the vapour diffusion resistance of the roof waterproofing materials and, as such, reduce the risk of condensation underneath the sheathing due to the incidental moisture that bypasses the vapour retarder and air barrier. The ventilation would also help in reducing the risk of ice damming in the sloped roof application, as well as reducing summer overheating in attics that are located outboard of the thermal envelope.

The above roofing assembly meets the building science principles as far as the four building envelope control layers are concerned. When installed properly, this assembly is expected to function as intended. That said, there are some shortcomings associated with this roof assembly in certain applications which are listed below:

- Flat roofs or decks: Ventilation has been found not to be an effective strategy in dealing with the incidental moisture in these assemblies (Ball, 1961). This has to do with the limited stack effect due to the small height of the ventilation gap, uncertainties in the wind and its directions, as well as limitations caused by surrounding obstructions as far as air flow is concerned. In addition, providing ventilation inlets and outlets in decks that are surrounded with walls and guard walls, poses constructability and aesthetic challenges.
- Sloped roofs with an attic outboard of the thermal envelope: Due to the added level of the thermal insulation in the attic ceiling as per the push for improving the energy efficiency, combined with the push to improve airtightness, the temperature of the attic is becoming colder than before (Hutcheon, 1995). In other words, attics are no longer benefiting from the passive heating that used to be available in the old days. This translates to reduced efficiency of the attic ventilation in addressing incidental moisture since, as the air temperature drops, so does its capacity to hold moisture.
- Air tightness: Sealed 6 mil polyethylene sheet has been one of the common methods of achieving the air barrier in these assemblies. Based on the experiences of the author, achieving effective and reliable long-term airtightness around ceiling penetrations and transitions is questionable under the current building practices and methods of application. One example is where pipes/ducts run through the interior partition top plates and then into the attic. Another example pertains to HVAC supply air inlet/outlet where the air seal between the duct and polyethylene sheet often gets cut during the installation of the ceiling board while cutting around these inlets/outlets.

As a result, the industry has been looking into alternative roof assemblies that would address the above challenges. One of the alternative roof assemblies that has been introduced in the construction market incorporates polyurethane spray foam, either closed cell medium density, or open cell low density with a vapour retarder paint, applied directly underneath of the roof/deck sheathing. This assembly is generally referred to as “unventilated roof”.

The proponents of this roof assembly are of the opinion that this is a good alternative to the ventilated roof assembly, and would address some of the challenges of that system. This is because:

- Due to its expanding nature, when applied properly, foam is expected to result in an effective air tightness in the ceiling and around penetrations.
- Given the high level of air tightness that is expected to be achieved with the spray foam when applied in sufficient thickness, the risk of incidental moisture reaching the roof sheathing due to air leakage is expected to be negligible. As such, provision of ventilation between the insulation and underside of the roof sheathing would not be required.
- In the sloped roof application, this design would allow for the attic to be located inside the thermal envelope, thereby eliminating the potential moisture-related issues associated with ventilated attics. In addition, HVAC equipment housed inside the attic will no longer need to be insulated and air tight and their efficiency will be increased.

The opponents of this roof assembly on the other hand, are of the opinion that there are some risks associated with this assembly, such as accumulation of moisture and the resulting damage to the assembly, as well as difficulty of identifying and addressing leaks in a timely manner.

Two insightful studies have been undertaken on the hygrothermal performance of the unventilated sloped roof assemblies using spray foam. The first study, performed by Straube et al. (2010), examines various simulations for each of seven climate zones in the United States and Alaska. The study focusses on exploring the risk of condensation due to vapour diffusion and air leakage. The second study, performed by Grin et al. (2013), examines the hygrothermal performance of these assemblies with the focus on various degrees of rain leakage. Three United States climate zones were used in the latter analysis, one of which includes a marine climate with significant rainfall. Seattle was selected as the representative city for this marine climate zone. Based on the author's experience, the findings related to Seattle in that study are sometimes referred to in discussions around the performance of unventilated roof and deck assemblies in the Lower Mainland due to similarities in the climates. However, the application of the findings of Grin's study to Lower Mainland of British Columbia must be done with caution and careful consideration for the following reasons:

- The unventilated closed cell foam roof used in the study for Seattle, is a hybrid assembly in which 2" closed cell foam is applied under the sheathing, followed by 5 ¼" fibrous insulation below the foam. Such hybrid assembly is generally rare in the Lower Mainland as the required thermal insulation is typically provided by applying the necessary thickness of the foam itself (5" or more depending on the thermal performance requirements). The thicker application of closed cell foam will have a direct impact on the inward drying of the incidental rain leakage, as is seen later in this paper.
- The unventilated open cell foam roof used in the Seattle study incorporates 8" of open cell foam with no vapour retarder paint, whereas such assemblies generally incorporate a vapour retarder spray paint in the Lower Mainland. The presence or lack of vapour retarder will have a direct impact on the winter wetting and summer drying of the assemblies.
- It is acknowledged that there are similar characteristics between the Seattle weather and that of the Lower Mainland. That said, the amount of annual rainfall varies depending on the location. For example, the annual rain in Vancouver is higher than that of Seattle (Environment Canada, n.d.; Shaw, 2017). Such a change will have an impact on the final analysis especially when the microclimatic aspects of the building site (surrounding trees, shades, etc.) are factored in.

- The study uses "average hourly rainfall event" for the hygrothermal modelling for Seattle. This is a reasonable approach that can provide reliable results in many cases. However, when it comes to locations that experience a high degree of rain, prolonged periods of sustained rain, and cloudy conditions such as Lower Mainland, using "average hourly rainfall event" in lieu of hourly rainfall, may not fully capture the actual performance of the assembly when it comes to worst-case scenario. For that reason, using the actual hourly rainfall data would be prudent.
- The study uses dark coloured shingles for a sloped roof orienting north. It is acknowledged that using a north-oriented roof is a sensible approach when it comes to analysing the assembly performance under worst-case scenario of reduced sun exposure. However, even when oriented north, the choice between dark and light-coloured shingles can have significant effect on the overall performance (Straube et al. 2010). For that reason, for locations that receive high rainfall, such as Lower Mainland, it would be prudent to use a roof shingle with light colour in modelling scenarios. This can also indirectly mimic the effects of the microclimatic of the building such as surrounding trees, etc.

This research study, conducted by the author, was initiated based on the information collected during:

- Site visits to several hundred single family wood-framed construction projects in the Lower Mainland.
- Consultation with a wide range of single family home builders, architects, and designers in the Lower Mainland.
- Interviews with multiple spray foam applicators involved in the single-family sector in the Lower Mainland.
- Conversations with some municipalities in the Lower Mainland as to the extent of the usage of unventilated spray foam roofs/decks in single family projects.

Based on the collected information (Heidarali, 2017a), it became apparent that unventilated spray foam roof and deck assemblies are being widely used in wood-framed construction projects in the Lower Mainland, especially in the single-family house sector. In addition, it was confirmed that in many cases, a holistic review and consideration is not implemented during the design and construction phases of these assemblies, which in some instances has led to performance failures. To that note, this research study performs a holistic review of the unventilated roof assembly in the Lower Mainland during the design, construction, and in-service phases.

This study is being conducted in several phases. This paper covers the first phase of the study and includes:

- Theoretical aspects of unventilated spray foam assemblies from the building science standpoint.
- Practical implications of the existing design and construction practices in the Lower Mainland, taking into account factors that can affect the overall long-term performance from moisture, thermal, accessibility, and constructability standpoint.
- Practical solutions for augmenting the long-term performance of these assemblies.

The remaining phases will capture the findings from site investigations during initial construction and in-service phases, as well as during renovations after multiple years of operation. The findings will be published in the future.

CONDENSATION CONTROL IN ROOFS: BACK TO BASICS

Thermal insulation was introduced in the building envelope assembly with the intent to reduce the transmission heat loss and gain through the building envelope, with a resultant improvement in the energy efficiency of the building. But, improving the energy efficiency is not the only impact that comes with the thermal insulation. Thermal insulation can also have an impact on the moisture performance of the assembly, and such an impact can be positive or negative depending on the location of the thermal insulation.

When the thermal insulation (with no resistance to vapour diffusion) is introduced inside a building envelope assembly (such as inboard of the roof sheathing), a large temperature gradient across the assembly will be developed. The temperature of the components outward of the insulation (such as roof sheathing) would now follow, more or less, the outdoor temperature, meaning the temperature of the roof sheathing would be very cold in winter. In cold climates, the air inside the heated buildings has higher humidity ratio ($kg_{water}/kg_{dry\ air}$) than the outside air during winter. As such, when the inside air reaches the components outboard of the insulation, which are at a much lower temperature than the dew point of the indoor air, condensation will occur.

As such, when it comes to the **interior insulated** building envelope assemblies in cold climates, the below considerations need to be taken into account in order to minimize the risk of condensation:

- **Consideration 1:** Install a material with sufficiently low vapour permeance, referred to as vapour retarder, on the high water vapour pressure side of the assembly (Hutcheon, 1995). In the context of the building physics, this generally translates to the room side of the thermal insulation. And,
- **Consideration 2:** Materials located outboard of the thermal insulation to have sufficiently higher vapour permeance than the interior vapour retarder to avoid the condition of double vapour retarder in the assembly. The intent is to reduce the risk of moisture accumulation and to permit the escape of water vapour by diffusion (Hutcheon, 1995). In the case of having a relatively low permeance material outboard of the thermal insulation, the diffusion resistance of such material must be bypassed by incorporating air movement behind that material. And,
- **Consideration 3:** Incorporate an air barrier in the assembly to minimize the exfiltration of the interior air towards the cold sections of the wall, where favourable conditions for condensation exists (Hutcheon, 1995).

Now that we looked into condensation control measures in interior insulated assemblies, we will turn into exterior insulated assemblies (insulation located outboard of the sheathing), and will explore the risk of condensation in these assemblies.

Unlike the interior insulated assembly where the sheathing temperature will follow that of the outdoor temperature, in an **exterior insulated assembly** the sheathing temperature follows the interior temperature, which is generally kept in the comfort range 18˚C or higher. This temperature is well above the dew point of the interior air. As such, the risk of condensation is eliminated (Hutcheon, 1995). With respect to Considerations 1-3 mentioned above, the implications of the condensation risk being eliminated are as follows:

- Consideration 1 (vapour retarder) is not a necessity.
- Consideration 2 (high permeance materials outboard of insulation) must still be met by this assembly to avoid the risk double vapour retarder, moisture accumulation in the insulation and the consequent reduction in its thermal performance.
- Consideration 3 (air barrier) would also not be applicable as far as the control of condensation is concerned. However, an air barrier would still be needed to minimize heat loss and gain, as well as to manage indoor air quality.

Now that we have covered the condensation considerations for both interior and exterior insulated assemblies, we will now look into the unventilated roof assembly and see how it relates to the context above.

The unventilated roof assembly is an interior insulated assembly, in which the insulation, in this case polyurethane foam, is located inboard of the roof sheathing and in direct contact with it. Its ability to address the three considerations listed above is explored below:

In the closed cell foam assembly, Consideration 1 (vapour retarder on the room side of the insulation) is provided by the foam itself, as this foam provides sufficient resistance to outward vapour diffusion, specifically when it is applied at thicknesses required by the energy efficiency requirements of the BC Building Code 2012. In the open cell assembly, a vapour retarder paint, sprayed over the inside face of the insulation, is claimed to serve as the vapour retarder for the assembly, although actual field performance of that needs to be closely looked at and evaluated. More on that to follow in the "Practical Considerations" section of this paper.

With regards to Consideration 3 (air barrier), both closed cell and open cell foam, when applied properly under proper surface condition and temperature, are expected to provide a high level of airtightness. Therefore, Consideration 3 is also addressed by these assemblies. That leaves us with Consideration 2.

As discussed earlier, Consideration 2 calls for materials outboard of the thermal insulation to have sufficiently higher vapour permeance than the vapour retarder on the inside. In unventilated assemblies, the permeance of the roof waterproofing membrane is much lower than that of the closed cell foam and the vapour retarder paint. This is contrary to Consideration 2 and therefore poses the risk of moisture accumulation in the assembly due to outward vapour diffusion during cold seasons. When sustained for a period of time, this moisture accumulation can pose the risk of moisture-related damages ("WUFI help", 2017a). Now the question that may arise is, "if these assemblies are susceptible to the risk of moisture accumulation, then how come they are widely used?" In order to answer this question, it is important to see how the sun interacts with these roof assemblies.

When sun hits the roof surface, it heats up the waterproofing membrane. Depending on the solar absorptivity of the membrane, its temperature can become much hotter than the outdoor air temperature (Stephenson, 1963). Given that the insulation is directly in contact with the roof sheathing (no air space in between), this increase in temperature is transferred to the sheathing. The combination of high temperature of the sheathing, as well as the accumulated moisture within it (as a result of the outward vapour diffusion), results in a very high water vapour pressure. Depending on the amount of moisture in the sheathing, this sun-induced water vapour pressure can be significantly higher than the vapour pressure inside the building. This

results in an inward water vapour flow (Baker et al. 1976), helping to dry the accumulated moisture towards the inside of the building. In other words, despite not meeting Consideration 2, unventilated roof/deck assemblies, can exhibit successful performance when sufficient sun drying potential is available.

Now the questions that may come up are:

- What degree of sun inward drying would be necessary to ensure satisfactory moisture performance?
- How sensitive are these assemblies to insufficient sun drying potential?

HYGROTHERMAL SIMULATIONS

In order to answer the above questions, a series of hygrothermal simulations were performed on two unventilated flat deck assemblies, one with closed cell foam (Assembly A) and one with open cell foam with one perm vapour retarder paint applied over the foam (Assembly B). These assemblies represent the majority of the unventilated foam deck assemblies, designed and constructed in the Lower Mainland (Heidarali, 2017a). To get a sense of comparison, the above simulations were also performed on an exterior insulated deck assembly, in this case a conventional assembly (Assembly C). Sd[1] =100 m (permeance of 2 ng/pa.m^2.s or 0.035 US perm) was assigned for the SBS modified bitumen self-adhered membrane over the plywood.

The simulations were performed using WUFI Pro 6.1 one dimensional heat and moisture modelling software, using Vancouver weather data. The materials were selected from the WUFI database. The moisture performance of these assemblies was evaluated under changes in the solar absorption of the waterproofing membrane: Low solar absorption of 0.2 was selected to represent light coloured roofing membrane or to mimic conditions where exposure to sun is low. High solar absorption of 0.8 was selected to represent dark coloured roof membrane.

The simulations were performed for four years under several variables including:

- No rain leakage versus 0.1% of the rain as leakage on the entire plywood sheathing thickness. The figure of 0.1% of the rain corresponds to approximately 1.17 kg of water spread over 1 m² of the plywood over an entire year. To get a practical grasp on this amount of leakage, it could be compared to a small bottle of water. When leakage does occur, it would be expected to be more than this amount, especially in areas of high and prolonged rainfall as those in the Lower Mainland. However, given the uncertainties associated with leakage, it was decided to use this rather conservative value in order to provide an unbiased analysis and yet get a practical insight.
- Exposure to humidity class 2 versus humidity class 4 under ISO 13788 standard. Humidity class 2 corresponds to dwellings with normal occupancy and ventilation, whereas, humidity class 4 corresponds to buildings with high interior humidity generation (ISO 13788, 2012).

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[1] Sd-value is referred to as vapor diffusion thickness and it is mainly used to characterise vapor retarders, vapor barriers, and surface coatings. Higher thickness translates to higher resistance to vapour diffusion ("WUFI help", 2017b)

- Change in the permeance of the waterproofing membrane. Sd = 100 m (permeance of approximately 2 ng/pa.m².s or 0.035 US perm) to represent a single layer of SBS-modified membrane versus Sd = 1500 m (permeance of 0.14 ng/pa.m².s or 0.002 US perm) to represent situations where several built-up layers of waterproofing membrane are in place (eg: re-roofing over existing roof waterproofing).

The thickness of the insulation in the open cell and closed cell foam assemblies is shown in Figures 1 and 2. The assemblies meet or exceed the thermal performance requirements under Zones 4, 5, and 6 of 2012 British Columbia Building Code, which is 4.67 (m².K)/W or 26.51 (hr.ft².F)/Btu. These insulation thicknesses are generally found in the unventilated roof and deck assemblies in the Lower Mainland. When it comes to the exterior insulated conventional assembly, the insulation thickness is selected in such a way (taking into account the available insulation thickness in the market) so that the nominal thermal insulation would be close to nominal thermal performance in the other two assemblies (Figure 3).

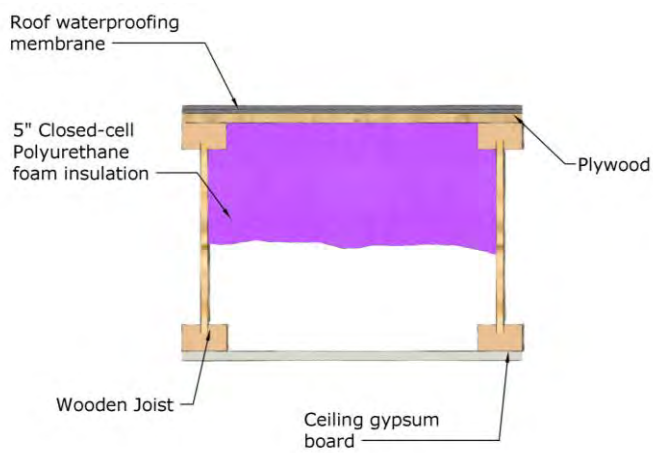

Figure 1: Assembly A

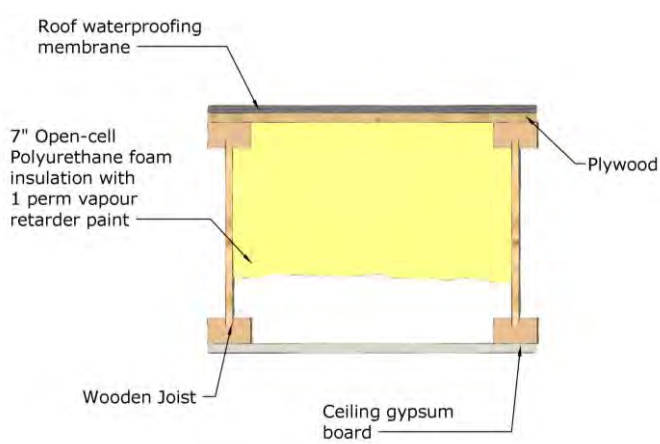

Figure 2: Assembly B

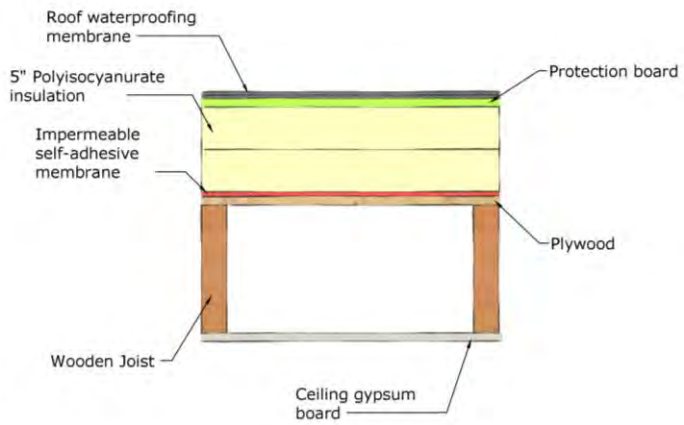

Figure 3: Assembly C

The analysis was performed using 48 simulations. In 24 simulations, no rain leakage was assumed in the assemblies, and then the performance of the assemblies was evaluated based on the change in the solar absorption of the waterproofing membrane, change in the vapour pressure difference across the assembly, and change in the permeance of the waterproofing membrane. Similar analysis was performed for the remaining 24 simulations, but this time a rain leakage of 0.1% was introduced across the whole plywood sheathing thickness. Figure 4 shows the results of the analysis of the plywood moisture content for all three assemblies without rain leakage, subject to interior humidity class 2 and with a lower diffusion resistance of the waterproofing membrane (Sd = 100m). By comparison, Figure 5 shows the results of the analysis of the plywood moisture content for all three assemblies with 0.1% rain leakage, but keeping the other criteria the same as Figure 4. These two figures were included in this paper as they demonstrate the behavioural trends of the assemblies under the most moderate conditions. All remaining figures showed the same trends but with more exacerbated effects as will be explained in the summary of findings below (Heidarali, 2017b).

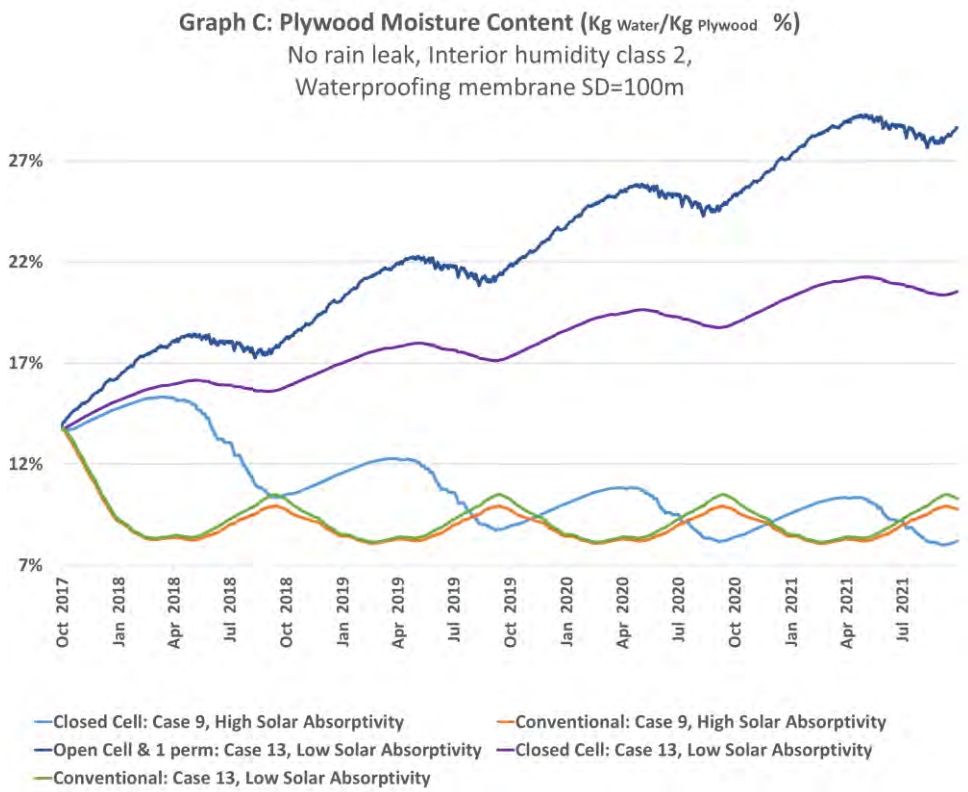

Figure 4: Plywood moisture content, no rain leakage

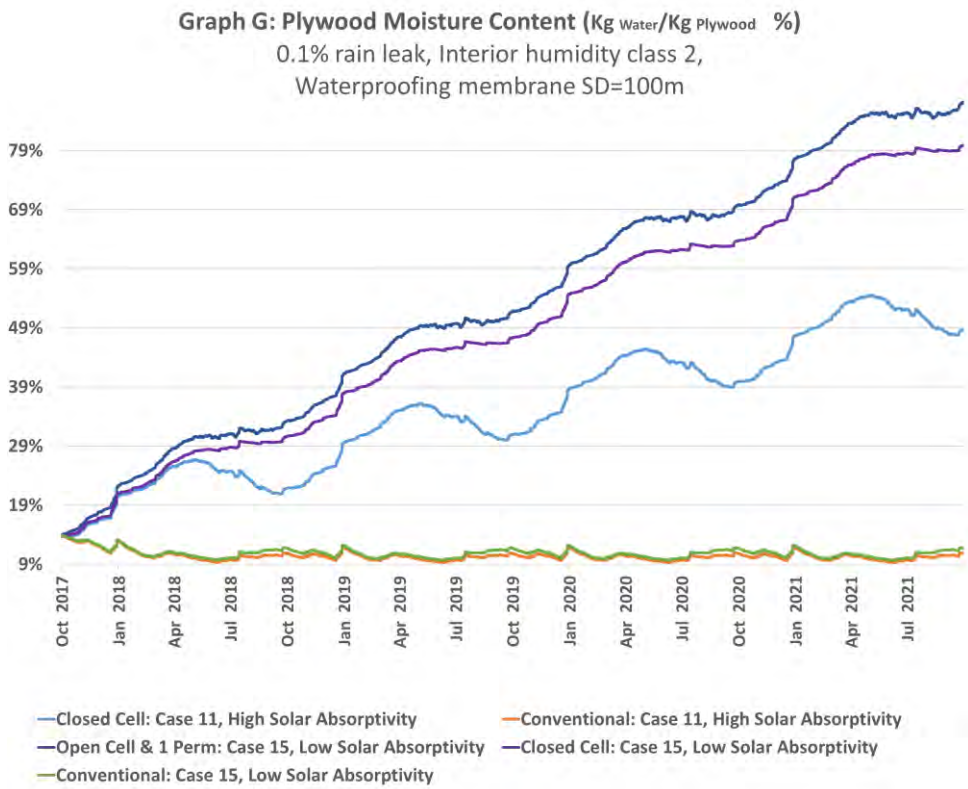

Figure 5: Plywood moisture content, 0.1% rain leak

Summary of findings Figure 5: Plywood moisture content, 0.1% rain leak for no rain leakage:

- When the solar absorption of the waterproofing is low (a = 0.2), there is an upward trend in the moisture content of the plywood sheathing in both open cell and closed cell assemblies in all scenarios. This was the case irrespective of the change in the vapour pressure difference (humidity class 2 vs 4), and irrespective of the diffusion resistance of the waterproofing membrane (Sd=100 vs Sd=1500). The upward trend in plywood moisture content is much higher when assemblies are subject to humidity class 4. This is expected since this humidity level translates to higher vapour pressure difference, leading to higher outward vapour diffusion.

- When the solar absorption of the waterproofing membrane is high (a = 0.8), the moisture content of the plywood sheathing in the closed cell assembly follows a downward trend. This was the case irrespective of the vapour pressure difference (humidity class 2 vs 4), and irrespective of the diffusion resistance of the waterproofing membrane (Sd=100 vs Sd=1500).

- One notable observation is the difference between the wetting and drying periods in the unventilated versus conventional assemblies. When the plywood in unventilated assemblies (open and closed cell) experiences the highest moisture gain towards the end of winter, the same plywood in the conventional assembly is experiencing drying and lowest moisture content during that period. This effect is more pronounced under humidity class 2 (normal humidity level) as can be seen in Figure 4. This is an interesting finding and has useful implications. The reason behind this opposing behaviour has to do with the location of the insulation. During cold seasons, the plywood temperature in unventilated assemblies will be very similar to cold outdoor air, and its corresponding high relative humidity, translating to high equilibrium moisture content in the plywood. On the other hand, plywood in the conventional assembly in winter, is exposed to warm indoor air and its corresponding low relative humidity, translating to lower equilibrium moisture content during winter.

Summary of findings for 0.1% rain leakage:

- Irrespective of low or high solar absorption of the roof membrane, there is an upward trend in the moisture content of the plywood in the closed cell assemblies. This was the case irrespective of the vapour pressure difference (humidity class 2 vs 4), and irrespective of the diffusion resistance of the waterproofing membrane (Sd=100 vs Sd=1500). A similar upward trend is also present in the open cell assemblies when the solar absorption of the waterproofing membrane is low, again irrespective of the vapour pressure difference (humidity class 2 vs 4), and irrespective of the diffusion resistance of the waterproofing membrane (Sd=100 vs Sd=1500). The upward trend in plywood moisture content is much higher when assemblies are subject to humidity class 4. This is expected since this humidity level translates to higher vapour pressure difference, leading to higher outward vapour diffusion.

- Even when the solar absorption of the waterproofing membrane is high (a = 0.8), the moisture content of the plywood in the closed cell assembly follows an upward trend.

Summary of findings shared between no rain leakage and 0.1% rain leakage:

- When the solar absorption of the waterproofing membrane is low (a = 0.2), the plywood moisture content ends up being higher in the open cell foam assembly compared to the closed cell foam assembly irrespective of the change in the vapour pressure difference (humidity class 2 vs 4), and irrespective of the diffusion resistance of the waterproofing membrane (Sd=100 vs Sd=1500). One might have expected the opposite result given that the inward diffusion drying through the open cell foam and its one perm vapour retarder paint is higher than the closed cell foam. This is true; however, the caveat here is that when the solar absorption is low, the inward drying would also be reduced. As such, the inward diffusion drying would not be sufficient to overcome the higher rate of outward vapour diffusion in the open-cell assembly, resulting in accumulation of moisture in the plywood sheathing.

- Increasing the diffusion resistance of the waterproofing membrane from Sd = 100 m to Sd = 1500 m does not have a noticeable impact on the overall results in both the closed cell and open cell assemblies. This is because the permeance of the waterproofing membrane at Sd = 100 m, is already significantly lower than the interior vapour retarder in both assemblies, to a point that the majority of the vapour pressure drop occurs across the waterproofing membrane and not the interior vapour retarder. As such, further increasing the diffusion resistance of the waterproofing membrane is not going to have a noticeable impact on the distribution of the vapour pressure across the assembly.

- The plywood moisture content stays at a very low level in all the evaluated scenarios in the exterior insulated conventional assembly. The change in the solar absorption of the waterproofing membrane does not have a noticeable impact on the moisture content of the plywood. This is expected since the presence of the insulation outboard of the plywood sheathing reduces the rate of inward heat flow induced by the sun. The change from humidity class 2 to humidity class 4 only resulted in a small increase in the moisture content of the plywood. This is logical as the plywood is maintained at a warm temperature throughout the year.

It should be noted that the above Figures and discussions did not include the results of the plywood moisture content in the open cell foam assembly <u>under high solar absorption</u>. The reason for this is explained below:

One of the key criteria for checking the validity and reliability of the simulation in the WUFI software is to compare the <u>change in the "total water content"</u> (referred to as Balance 1) of the assembly, with the <u>sum of the "surface flows"</u> across the component surfaces (referred to as Balance 2). These two figures should be the same and if not, their difference must be "small enough" when compared to the <u>total water gained or lost from the system</u>, or when compared with the total water content of the assembly (Bludau, 2017). Determining "small enough" requires judgment and testing.

When high solar absorption rate (a = 0.8) was used for the waterproofing membrane in the open cell foam assembly with a one perm vapour retarder paint, the moisture content of the plywood sheathing showed downward trend when exposed to humidity level 2 under no rain leakage, upward trend when exposed to humidity 4 under no rain leakage, and upward trend when exposed to 0.1 % rain leakage for both humidity levels 2 and 4. When reviewing the water content balances to verify the validity of these results, a large difference between Balances 1 and 2 was noted. This was not the case when a low solar absorption rate was

selected for this assembly, nor was this the case for any other simulations under this study.

To troubleshoot this matter, a wide range of numerical adjustments and improvements were incorporated such as very fine grids, adaptive time step control, as well as incorporating the extended numerical settings such as symmetric diffusive part, pivoting in matrix solver, and rational interpolation in sorption isotherm. None of these measures managed to address this issue. After ensuring that the discrepancies did not have anything to do with the settings of the simulations, the author examined the physics surrounding the open-cell assembly when exposed to very high moisture and temperature gain and proposed the following hypothesis:

One perm vapour retarder paint has much higher permeance than that of the waterproofing membrane. This causes a large transfer of vapour from the inside towards the plywood during cold seasons, thus, posing significant increase in the moisture content of the plywood. When the solar absorption of the waterproofing membrane is high, the temperature of the plywood increases significantly higher than the ambient air temperature under sunny periods. The combination of high moisture in the plywood, and high temperature, produces a large inward vapour drive. Such inward vapour drive may sometimes be too demanding to be handled numerically, leading to either discrepancies in the water balances or high numbers of convergence errors.

To test the above hypothesis, an alternative simulation was performed, in which the one perm vapour retarder paint was replaced with a smart vapour retarder membrane, installed inboard of the deck joists. Smart vapour retarder's permeance changes in relation to the Relative Humidity (RH) it is exposed to: When exposed to low level of RH, the permeance of the material reduces, offering relatively high resistance to vapour flow. On the other hand, when exposed to higher levels of RH, the permeance of the material increases. Compared to one perm paint, this will result in reduction of outward vapour diffusion during winter while maximizing the inward vapour diffusion during summer. For these reasons, a smart vapour retarder membrane was selected to see if this change would address the water balance issues. It did. After incorporating this change, the water Balances 1 and 2 became equal, confirming the validity of the proposed hypothesis.

The author consulted with the software developers on these findings. The author was advised that these findings have led to important clues with regards to the performance of high porosity materials, when subject to a large amount of water vapour in their pores, and when subject to large changes in temperature. To that note, this matter is currently being investigated and tested by the software developers.

For the above reasons, the author decided not to include the plywood moisture content results for the open cell foam assembly under the condition of high solar absorption since the results were not reliable. Nonetheless, the recommendations set forward in this paper remain the same as they cover best and worst case scenarios for these assemblies.

PRACTICAL CONSIDERATIONS

The previous section provided an analysis on the hygrothermal performance of the unventilated deck assemblies under various environmental and assembly conditions. By choosing conditions that cover both ends of the spectrum, the study managed to provide a well-rounded picture that can give practical insight as to how assemblies may perform under many different conditions. This section is going to look into the

practical implications of the findings of the previous section, as well as issues such as the microclimate of the building, identification of future leaks, access to utilities, and vapour retarder spray paint.

1. Microclimate of the Building and its Relation to Sun Inward Drying

The above analysis demonstrated the sensitivity of the open cell and closed cell foam assemblies to the adequate level of sun drying potential. It can be concluded that the satisfactory performance of these assemblies relies strongly on the adequate exposure to the sun, as well as having a roof finishing with high solar absorption. Failing to have either of these, would pose the risk of moisture accumulation even under normal indoor environmental condition, compromising the long-term performance of the assembly. The moisture accumulation would be exacerbated in the presence of rain leakage, or other sources of incidental moisture.

The practical consideration of such finding is important when it comes to the microclimate of each building. Among the two components of solar radiation (direct and diffuse), the direct solar radiation is the most useful when it comes to inward drying potential. Surrounding trees, overhangs, projections, shading elements, neighboring buildings, etc., can reduce the exposure to the "direct" component of the solar radiation, and as such, the inward drying potential (Photo 1). Depending on the site condition, such reduction can be to a point that it negatively impacts the successful moisture performance of these assemblies. Decks under protection, in particular, such as those shown in Photos 2 and 3 demand the most attention.

In addition to the microclimate of the site, roof/deck finishing and colour can also impact the inward drying potential. For example, light colour roofing membrane, or in general high solar reflective roofing materials, reduce the inward drying, and pose the risk of moisture accumulation in the deck sheathing in both open and closed foam assemblies.

Photo 1: Shade provided by surrounding trees, neighbouring building along the back, and overhangs

Photo 2: Unventilated deck under protection (outside view)

Photo 3: Unventilated deck under protection (inside view)

2. Identification of Future Leaks

Ease of identification of future leakage (rain, plumbing, etc.) is another practical consideration that needs to be taken into account. As the simulations showed, even when the inward solar drying is maximized, there is a risk associated with trapping the rain or other leaks inside these assemblies, which over time, can contribute to the wood decay of the roof structural components (sheathing and joists), without being evident on the interior. This is an important consideration for builders and their liabilities, as delay in identification of leaks and their causes can result in costly repair.

3. Access to HVAC Ducts, Pipes, and Electrical Wiring

When it comes to the design of building envelope assemblies, the primary focus, as far as the building science community is concerned, has been on the required environmental control layers such as air barrier, vapour retarder, rain penetration control, and thermal insulation. However, this is only part of the equation. Another important consideration that needs to be taken into account is related to future access to plumbing pipes, wiring, and HVAC ducts that are housed within these assemblies.

When it comes to sustainable and durable building envelope design, considerations must be in place to allow for easy access to the HVAC ducts, wiring, and plumbing pipes whether it is related to future repairs, maintenance, alteration, etc. Those that have seen foam used in deck and flat roof assemblies, must have seen the end results after the foam application: the majority of the HVAC pipes, wiring and plumbing pipes get encapsulated in the foam (Photos 4 and 5). The solution of moving these elements to the lower section of the deck joist to avoid encapsulation in the foam is not practical from the structural standpoint in many cases.

Now, imagine one would need to get access to the plumbing pipes to address a shower leak. Locating the

pipes would be a tedious task and almost impossible without disturbing and removing a good portion of the foam. And, when it comes to removing the foam, this is a demanding task as per the experience of the author: In the case of closed cell foam, one would likely end up using a jack hammer to remove the foam. During this process, damage to adjacent wires and equipment in most cases is inevitable. Removal of the open cell foam would be easier, but still requires a significant amount of work and effort. And that would not be the end of the challenges. Once the repair is done, the insulation needs to be reinstalled. In the case of fibrous batt insulation, this is a rather straight forward process. However, when it comes to the foam, the installation demands special applicator, foam truck, sealing off the area completely to avoid the toxic gases spread inside the occupied building, and providing ventilation to remove the gases. The practical aspect of the latter during occupancy is questionable.

Photo 4: Duct prior to foam application

Photo 5: Duct covered by foam

4. Vapour Retarder Spray Paint

In the Lower Mainland, unventilated assemblies that incorporate low density open cell polyurethane foam generally incorporate a vapour retarder paint (typically one perm or less), applied over the inside face of the foam to serve as a vapour retarder. Those who may have witnessed the site application of this paint, including the author, may have developed questions as to the reliability and feasibility of this practice. A coloured foam does not necessarily mean that the effective vapour retarder is in place. Verification of the paint thickness on an uneven surface and its uniformity is practically challenging. In addition, the method of application plays a significant role in the end results: When applied in too many layers, it can negatively impact the inward drying potential. When too little of it is applied (as caused by spraying from the distance shown in Photos 6 and 7), it will not provide sufficient resistance to outward control. In other words, the actual field performance of this approach is subject to many uncertainties.

Some proponents of this approach are of the opinion that even if the vapour retarder paint is not perfect, it is not going to necessarily harm the system performance given that the air leakage (as the primary

mechanism of vapour transfer) is successfully managed by the foam. It is acknowledged that vapour diffusion has a very negligible role in water vapour transport compared to the air leakage. However, this holds true in assemblies where the materials outboard of the thermal insulation have a higher vapour permeance than the interior vapour retarder (Consideration 2 stated at the beginning of this paper). In situations where the permeance of materials outboard of the insulation is very low and much lower than the interior vapour retarder (such as waterproofing membrane), the role of the vapour diffusion becomes more pronounced as was demonstrated by the hygrothermal simulations. Failure to have an effective vapour retarder on the inside in these situations, can result in the risk of moisture accumulation in the sheathing, especially where adequate exposure to sun is not available. As seen in the simulations, under limited exposure to sun-induced inward drying potential, the unventilated assembly using open cell foam and one perm vapour retarder paint, exhibited the highest moisture accumulation in the sheathing among all the assemblies.

Photo 6: Application of vapour retarder paint over open cell foam

Photo 7: Application of vapour retarder pain over open cell foam

RECOMMENDATIONS

At the beginning of this paper, a background on the unventilated roof and deck assemblies using polyurethane foam insulation was provided. This was followed by the basic building science principles and considerations pertaining to condensation control in roofs in cold climates. Evaluation of the unventilated roof/deck foam assemblies was then undertaken with respect to these principles, followed by detailed hygrothermal analysis of these assemblies. This led to a discussion on the limitations of these assemblies and practical considerations that need to be taken into account in the design and construction of these assemblies.

This section of the paper is going to provide solutions and practical recommendations with respect to the design and construction of the sloped roof incorporating spray foam, as well as offer alternative solutions for the flat roof/deck assemblies.

Recommendations for Sloped Roof

The overall moisture performance of the unventilated sloped roof assembly using polyurethane foam can be improved by incorporating a drained air space between the sheathing and the roof waterproofing membrane. The drained air space can be achieved by installing a permeable roof membrane over the roof sheathing, followed by installation of strapping over it (Photos 8 and 9). In the case of asphalt shingles or any other finishing -that requires solid surfaces, an additional layer of sheathing and underlayment needs to be installed over the strapping. For solid roof finishes such as metal roof, the additional sheathing and roof underlayment would not be necessary as the metal panel can be fastened through the strapping.

It must be noted that the proposed cavity is not there for ventilation purposes although it can be designed to serve that purpose. The main intent of this air space is to provide a drainage path for incidental rain that bypasses the roof waterproofing system. The air space also bypasses the diffusion resistance of the components outboard of the insulation, making the assembly aligned with Consideration 2 covered earlier in the paper. By incorporating this strategy, the assembly will no longer be dependent on the availability of sufficient inward solar drying to function satisfactorily. In addition, it provides redundancy in the system in dealing with incidental rain.

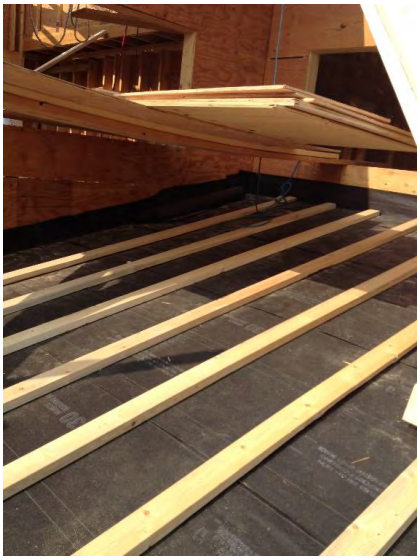

Photo 8: Strapping over roof felt

Photo 9: Strapping along the edge of the roof

When it comes to sloped roofs, two general configurations are available; attic and cathedral. In the sloped roof with an attic, there is plenty of room to install the HVAC ducts, plumbing pipes, and wiring inside the attic. As such, these will not be encapsulated inside the foam. In the case of cathedral roof however, the situation is different as the available space is determined by the roof joist depth. Running the HVAC ducts and plumbing pipes along the lower section of the joists in many cases is not practical due to the structural constraints (holes through the web of the joist need to be located as close as possible in the middle height of the joist). Therefore, to avoid being encapsulated inside the foam, the joists can be strapped down by installing 2” x 4” or 2” x 6” below the joists, resulting in a service cavity. This service cavity will provide sufficient room for the installation of ducts, pipes and wires below the foam. This strategy will provide easy access to these elements should a need to get to them be necessary. With the exception of pipes and ducts

that need to go up through the roof (leave a sleeve in place before hand), all the ducting, piping and wiring should then be installed after the foam is in place.

Some sloped roofs are designed with a very low slope. In fact, slopes as low as 2½" to 12" is commonly

Photo 10: House with 2½" to 12" sloped roof

Photo 11: Installation of 2 layers of 2 ½" polyisocyanurate insulation over the sloped roof

Photo 12: Installation of the SBS base sheet over the sloped roof

seen these days in the contemporary roof designs of wood framed residential buildings in the Lower Mainland. When it comes to these types of roofs, it would be prudent to consider the option of exterior insulation, instead of unventilated foam assembly or, any other interior insulated assemblies given the numerous benefits that they offer. Unlike steep roofs where the installation of the exterior insulation can be challenging for workers, low slope roofs provide much easier access. Photos 10 through 12 show an example of low slope roofs in a recently built custom house in West Vancouver. Exterior insulated conventional assembly was selected for these roofs.

2. Recommendations for Flat Roof and Deck

Incorporating a drained air space between the sheathing and the roof waterproofing membrane (similar to what was explained earlier), in theory, can also help improve the overall moisture performance of the

unventilated flat roof/deck assemblies. However, based on the author's experience and experiments, such practice comes with practical challenges in flat roof/deck applications. Some examples include sloping the air space, incorporation of drains in the air space to collect the incidental water, sourcing permeable underlayment that functions adequately in flat roof applications, and proper sealing of the strap penetrations. These are just some of the considerations that need to be allowed for, all of which pose constructability challenges, require substantial coordination, and are very costly solutions.

When it comes to flat roofs and decks, the option of exterior insulation seems to be the most logical and optimum approach. Not only does it come with several benefits from the thermal, moisture performance, and durability stand point, but also based on the author's experience, its cost can be very competitive with the unventilated spray foam assembly. This option would also allow for easy future access to the ducts, pipes, and electrical wiring inside the joist space. And last and somewhat foremost from the builder's stand point, all the building envelope control layers (air barrier, vapour retarder, insulation and rain penetration control) will be installed by one crew, the roofer. As such, in the case of a failure in the future, there would be one single point of responsibility.

There seems to be a hesitation to use the exterior insulation system in the deck assemblies (especially in single family projects), which stems from a misconception that "there is just not enough room to incorporate insulation outboard of the deck sheathing unless the deck ceiling is dropped". This misconception has led many builders to believe that the unventilated option would be the only available option for decks. The experience of the author has proved otherwise as described below.

Exterior insulation can successfully be implemented above the deck without the need to drop the ceiling, and yet still maintain sufficient clearance between the top of the deck and under the door. All it takes to make this happen is to have a meeting with the structural engineer, the architect and the builder at the beginning of the project to work out the details and coordinate this matter from the structural stand point. As an example, reducing the joist height to 2" x 8", combined with adding an additional one or two 2" x 6" plate under the door, can easily provide room for the installation of 5" to 6" of rigid insulation, while also leaving 2" to 3" of clearance at the bottom of the door. This solution is implemented in the two recently completed projects in West Vancouver as shown in the below Photos 13 through 16.

Photo 13: Smaller deck joists to accommodate exterior insulation

Photo 14: Smaller deck joists allowed for sufficient room to install exterior insulation over deck

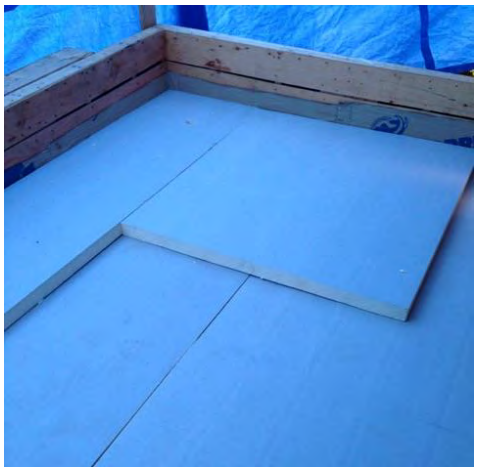

Photo 15: Two layers of 2 ½" insulation polyisocyanurate on top of the deck

Photo 16: Clearance between door and top of deck after installation of exterior insulation

Based on the experience of the author, some proponents of the unventilated roof assembly criticize the conventional assembly due to the insulation being sandwiched between two impermeable membranes, and the risk of rain leakage becoming trapped between the two membranes. As such, they are of the opinion that this roof option does not necessarily offer advantage over the unventilated foam assembly. It is acknowledged that the conventional deck assembly does not meet Consideration 2 stated earlier in the paper. It is also acknowledged that the risk of rain leakage becoming trapped between the membranes, and the consequent reduction of the insulation thermal performance is a concern. This, in fact, was one of the main reasons that led to the introduction of the inverted assembly. That said, despite this shortcoming, there are a wide range of advantages offered by this exterior insulated assembly that make it far superior to any interior insulated assembly including the unventilated assembly. These include resistant from the risk of condensation, ease of visual review of the wet sheathing from the inside and its ability to dry inward, reduced disruption to the interior of the building and occupants in the case of future leak repair, ease of future access to utilities inside the roof joists, and addressing the thermal bridging of the roof joists.

3. General Recommendations

- For unventilated assemblies using open cell foam, it would be prudent to incorporate a smart vapour retarder membrane in lieu of the vapour retarder paint. Given that the waterproofing membrane outboard of the foam has a very low permeance, incorporating a smart vapour retarder membrane would help address the shortcoming of the vapour retarder paint. The smart vapour retarder membrane not only provides sufficient reduction of the outward diffusion wetting during winter, it also maximizes the inward diffusion drying during summer. This membrane needs to be installed inward of the roof joists, and should be detailed as an air barrier (sealed at joints and penetrations). Failing to do so will result in the interior air bypassing this membrane via convection and coming in contact with the open cell foam, thus reducing the effectiveness of the smart vapour retarder membrane.
- When it comes to open cell or closed cell polyurethane foam, specific attention must be given to the mixing of the foam, surface condition and temperature, method of application, and ventilation during application. As such, it is critical to ensure that the foam application is conducted by approved and licensed applicators. Prior to the foam application, all the surfaces must be checked to ensure they are not wet or damp. The foam should only be applied when the rain penetration

control is completely in place at the field of the roof/deck assemblies, as well as at the transitions with adjacent assemblies.

CONCLUSION

To perform satisfactorily, the unventilated wood-framed roof/deck assemblies have a strong reliance on the inward drying induced by the sun. In addition, these assemblies can be sensitive to rain leakage or other incidental moisture, even when the exposure to sun is maximized. In this context, these assemblies somewhat rely on "perfection" to perform as intended, a condition that cannot always be relied upon.

When it comes to design and construction of these assemblies, a holistic approach needs to be implemented. In terms of moisture and thermal management, such a holistic approach should incorporate provisions that would make these assemblies tolerable to lack of ideal exposure to sun, and more forgiving to deficiencies in building envelope control layers and/or incidental leakage. This is especially important in the Lower Mainland of BC where prolonged periods of sustained rain and cloudy conditions are prevalent.

In addition, such a holistic approach should take into consideration factors beyond just moisture and thermal management. Ease of accessibility to HVAC ducts, plumbing pipes and wiring; ease of identification of future leaks and the associated repair; actual field performance of coatings applied to the foam; and long term durability are some of the key considerations that demand specific attention as far as sustainable roof design is concerned.

Based on the experience of the author in visiting numerous construction projects, the above holistic approach, in most cases, is not currently implemented in the design and construction of the unventilated roof/deck assemblies in the wood-framed construction of the Lower Mainland of British Columbia, in particular the single-family house sector. The unventilated roof/deck assemblies are currently seen and regarded as "a standard assembly", and "a solution for every application". The microclimate of buildings and its impact on the sun exposure does not seem to be given the required attention when it comes to the selection of these assemblies. Continuing on this path can open the door to unnecessary surprises down the road.

This paper discussed the practical challenges associated with the unventilated roof and deck assemblies using polyurethane open and closed cell foam, and it presented practical recommendations for addressing those challenges. These recommendations intend to improve the overall performance of these assemblies with the intent to improve long term performance, and reduce the risk of unnecessary surprises and costly repairs in the future.

When it comes to unventilated roof assemblies, the perspective of "a standard assembly and solution for all applications" needs to be replaced with a perspective that regards these assemblies as "a potential solution for certain applications". In other words, these assemblies need to be checked on a case by case basis. The role of engineers involved in these assemblies should be expanded beyond just simply inspecting the foam application and its thickness, to encompass all the considerations described in the holistic approach above. Builders and end-users must be provided with unbiased information pertaining to all aspects of these assemblies, including those covered in this paper, to help them make informed decisions.

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