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Proceedings

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Best Practices for a Successful Natatorium Enclosure

ABSTRACT

The indoor environment of natatoriums, or indoor pools, is typically characterized by elevated air temperatures and relative humidity (RH) levels. In climates with cool to cold winters, outdoor temperatures frequently drop below the dew point of the indoor environment. Where air leakage occurs in a natatorium in these climates, condensation can form within the enclosure, leading to premature failure of the building enclosure materials. Failures with multiple root causes (e.g., surface condensation, air leakage condensation, capillary contact with water, etc.) can manifest as rot/decay of the building (including structural elements), damage to finishes, dripping on the interior, corrosion of exposed metal, excessive condensation on glazing surfaces, etc.

In this paper, we consider existing natatorium design guidance and identify several areas where further clarification and additional guidance are warranted. We also present a series of forensic investigation case studies that reveal these patterns: moisture issues in natatoriums are typically related to some combination of inadequate air control at the enclosure and/or interior partition walls, poorly controlled or improper building pressure fields, mechanical system inadequacies, and thermal bridging.

We conclude with a summary of science- and experience-based best-practice recommendations for the successful design and construction of natatorium enclosures in both commercial and residential buildings. These recommendations are intended for use by the architects and mechanical designers doing the enclosure and HVAC design and the general contractors responsible for the on-site execution of the construction.

LEARNING OBJECTIVES

- » Identify high-risk enclosure details for air leakage and best practice air barrier system strategies.
- » Identify key high-level HVAC design requirements.
- » Verify building operation pressures by measurement and calculation.
- » Explain the main causes of natatorium building failures in cold climates.

SPEAKER



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Based in Waterloo, Ontario, for nearly 20 years, Jonathan Smegal is an associate and senior building

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Chris Schumacher is a principal and senior building science specialist with RDH Building Science Inc. His current work focuses on forensic investigation; testing and development of materials and systems; and applied hygrothermal analyses to address unique problems in new construction and existing building retrofit. Since 2001 Schumacher has led the design and implementation of dozens of lab- and field-testing programs for academic and government research; for industry-driven materials-and-methods demonstration projects; and for litigation- support work. He has a special interest in heritage buildings and enclosures, focusing on preserving their heritage features while designing updates to improve durability, energy performance, and occupant comfort. Through his work with three North American universities Schumacher regularly teaches undergraduate, graduate, and continuing-education courses on the topics of building science, enclosure design, enclosure performance, and hygrothermal analysis.



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INTRODUCTION

The indoor environment of a natatorium (indoor pool) presents one of the greatest moisture-related durability challenges to enclosures in cold climates. Temperature and relative humidity levels are elevated compared to typical commercial indoor environments (for example, living spaces and offices), resulting in a high indoor dew point. In high-humidity environments, the building enclosure is often subjected to interstitial condensation and moisture accumulation on indoor surfaces. These conditions often result in premature enclosure failures and, in serious cases, structural damage. This paper reviews strategies for successful natatorium enclosure design and construction as well as high-level design considerations for HVAC equipment. Other challenges and considerations for indoor pool environments, such as indoor air quality and corrosion of metals in the pool space as a result of chlorine exposure, are also important to the operation of a pool building, but these are not the focus of this paper.

Over the last two decades, we have participated in over two dozen projects involving the design or forensic investigation of pool buildings and other spaces that are characterized by high indoor temperatures and high relative humidity, resulting in high dew points. In most cases, moisture issues could have been reduced or entirely eliminated using best-practice design and construction details.

Our objective in this paper is to provide guidance on the key design criteria based on building science principles, field experience, and industry documents. This guidance is suited to both architects and general contractors.

INTERIOR ENVIRONMENT

The American Society of Heating, Refrigerating and Air-Conditioning Engineers' (ASHRAE's) HVAC applications guide recommends design conditions for different types of pool environments. The ASHRAE recommendations, reproduced in **Table 1**, consider different pool uses and recommend ranges for indoor air temperature, water temperature, and relative humidity. The different classifications of use suggest climate condition ranges appropriate for each expected activity level. The reader will note that this guidance provided by ASHRAE is not based on climate zones.

TABLE 1. Typical pool design conditions¹

Type of Pool	Air Temperature		Water Temperature		Relative Humidity
	°C	°F	°C	°F	%
Recreational	24 to 29	75.2 to 84.2	24 to 29	75.2 to 84.2	50 to 60
Therapeutic	27 to 29	80.6 to 84.2	29 to 35	84.2 to 95	50 to 60
Competition	26 to 29	78.8 to 84.2	24 to 28	75.2 to 82.4	50 to 60
Diving	27 to 29	80.6 to 84.2	27 to 32	80.6 to 89.6	50 to 60
Elderly Swimmers	29 to 32	84.2 to 89.6	29 to 32	84.2 to 89.6	50 to 60
Hotel	28 to 29	82.4 to 84.2	28 to 30	82.4 to 86	50 to 60
Whirlpool / Spa	27 to 29	80.6 to 84.2	36 to 40	96.8 to 104	50 to 60

Relative humidity is not a measure of the absolute amount of moisture in the air. By definition, it is relative to the temperature of the air, so on its own, it cannot be used to assess moisture risks. Dew point does provide a measure of the absolute amount of moisture available. Dew point is the temperature at which water vapor in the air reaches the saturation limit of the air and has the capability to condense on a surface. Hence, dew point is a convenient, more meaningful, and tangible parameter to use when comparing the interior moisture loads.

Typical industry standard and building code recommended indoor conditions for “normal” buildings in a cold climate are 20 to 22°C (68 to 71.6°F) and approximately 35% relative humidity (and lower in the far north). These indoor conditions result in a dew point of approximately 5°C (41°F). This is consistent with dew point values we measure in winter months in typical cold-climate commercial buildings with relatively high air leakage and ventilation requirements. As shown in **Table 1**, the indoor conditions for a pool are necessarily much warmer (to match the activity and clothing level) and at a higher relative humidity (owing to moisture from the pool).

Table 1 shows a range in relative humidity for all pools between 50% and 60%, although in cold climates we recommend keeping the relative humidity as close to 50% as possible. If a typical pool environment were considered to have an air temperature

of 28°C (82.4°F) and a relative humidity of 50%, the dew point would be approximately 17°C (62.6°F), which is 12°C (21.6°F) higher than that of a typical building. This means that in a natatorium, surfaces that are below 17°C (62.6°F) will have a high risk of condensation. Buildings exposed to cold-climate winters or having long periods of cold weather require best-practice design, material selection, and construction to prevent the humid indoor air from reaching surfaces that are near or below the dew point. The enclosure design is critical for all pool enclosures, both residential and commercial, to minimize the risk of condensation of the interior air on interior surfaces and within the enclosure. It is also critical to point out that to limit the rate of evaporation of the pool, which adds available moisture to the air and can exacerbate condensation in the enclosure, the pool should be maintained at a temperature 2–3°C (3.6–5.4°F) below the air temperature. If the pool is maintained at a temperature above the air temperature, it will evaporate and increase the RH of the space substantially or add significant latent load to the HVAC system to meet the design RH requirements.

BEST-PRACTICE ENCLOSURE DESIGN

Continuous Exterior Insulation

Residential and commercial pool buildings can successfully use a range of enclosure materials (cladding,

insulation, control layers, and structure). Typical structural systems include wood, concrete, steel, and mass timber. However, we recommend that pool enclosures in cool to cold climates employ a layer of continuous exterior insulation (i.e., the thermal-control layer) and that this be installed over the other control layers (i.e., water and air control) and the structure. The use of continuous exterior insulation keeps the structure and all other materials inboard of the insulation warm, reducing the potential for condensation. This stands in contrast to the numerous cold spots that are presented when insulation is installed between the structural members. Further, the application of insulation in the stud cavities and other framing spaces serves to insulate the sheathing from the interior, making it colder and increasing the relative humidity and potential for condensation and moisture accumulation at the interior face of the sheathing.

Construction with continuous exterior insulation over the structure has been studied exhaustively over the past several decades. In 1964, Neil Hutcheon² showed how installing the insulation on the exterior of the structure kept the interior surfaces warmer, reducing the risk of condensation. This concept was further refined by others. Alberta Infrastructure’s Chris Makepeace³ promoted the idea of the PERSIST (Pressure Equalized Rain Screen Insulated Structure Technique) wall assembly in 1998. In Alaska, similar exterior insulation strategies have been referred to as the REMOTE (Residential Exterior Membrane Outside-Insulation TEchnique) wall.⁴ Building Science Corporation’s Building Science Insight 001⁵ employs the same principles in describing “the perfect wall” strategy. Many others have documented research and summarized theory and guidance to maximize the benefits of this construction strategy.^{6,7,8,9}

A conceptual representation of an ideal exterior insulation strategy is illustrated in **Figure 1**. The image shows a schematic identifying the structural, finish, and control layers in the enclosure. The structure (concrete masonry unit [CMU], steel, wood,

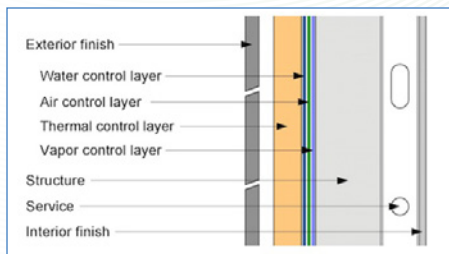


FIGURE 1. Schematic for an exterior insulated enclosure wall assembly.

insulated concrete form, mass timber, etc.) is covered with continuous water, air, and vapor control layers, which are all covered by continuous exterior insulation. The insulation could be rigid foam, semi-rigid stone wool, or medium-density (i.e., 32 kg/m³ or 2 pcf) closed-cell spray polyurethane foam (ccSPF). This strategy ensures the air barrier system is well supported by the structure and protected from temperature fluctuations and ultraviolet light. When this strategy is used in design and the structure is well constructed, issues with the wall assembly are rare because of the continuity of the control layers. However, as is typical with enclosure issues, the problems often occur at penetrations and transitions, which is why it is critical for the designer to provide clear, constructible details for all penetrations and transitions within the enclosure.

Air Barrier System

One of the most critical components of a natatorium's enclosure design and construction is a continuous air barrier system. The air barrier system must be continuous on all enclosure surfaces around the pool, including the roof, the exterior walls, and any interior partition walls that separate the pool space(s) from adjoining spaces having different uses (e.g., offices, community room, gymnasiums, and especially ice rinks). The design and construction of the air barrier system in a pool building in a cold climate demands a higher standard of care than typical construction, as even small imperfections can result in substantial failures. Designers and builders frequently struggle to achieve the required airtightness. Many in the industry remain confused regarding the roles of air and vapor barriers,

and this confusion is propagated in manufacturers' literature, industry guidance documents, construction drawings, etcetera. An air barrier is always needed, must be continuous, and, in a cold climate, must be located on the warmer side of the enclosure to avoid re-entrant looping condensation. A vapor barrier is usually required for pool buildings and can be the same material as the air barrier, but it does not necessarily have to be.

As an example of the confusion in literature and guidance documents, consider the *2011 ASHRAE Handbook – HVAC Applications*,¹ which states that "failure to install an effective vapor retarder will result in condensation forming in the structure, and potentially serious envelope damage," but it does not make any statements regarding the need for a continuous air barrier system within the enclosure, which is even more critical than vapor control.

Figure 2 illustrates how much more water vapor can be moved by air movement than by vapor diffusion, further emphasizing the need for a continuous air barrier membrane in the enclosure. Depending on the height of the space, stack effect can be substantial and cause continuous air leakage through the roof system.

In 1966, Kirby Garden wrote *Canadian Building Digest 83* on the topic of indoor swimming pools.¹⁰ Garden wrote, "Air leakage, a very prominent mechanism operating in most

buildings, transports water vapour into walls and roofs, producing interstitial condensation." Garden also discussed the importance of preventing air movement from the swimming pool space to other adjoining spaces in the building.

Other publications have also emphasized how critical the air barrier system is. In 1990, Madeleine Rousseau of the National Research Council published an article in *Home Builder Magazine*¹¹ regarding design and construction solutions to problems with indoor swimming pools. Rousseau stated correctly that an airtight assembly, or air barrier system, is required to control condensation. She expanded further on that, writing, "To obtain an airtight assembly over the enclosure, connect wall or roof air barrier materials to other air barrier materials in floors, windows, and skylights and seal the joints with sealants, adhesive membranes or gaskets." She provided a simplified cross-section view of a house with a pool that identified an airtight compartment around the pool space with a continuous air barrier system and separate mechanical system from the rest of the building.

Paul Totten, in 2007,¹² also wrote on the importance of properly designed and constructed air barrier systems in pool enclosures as well as the need for review and oversight of the construction of the air barrier system.

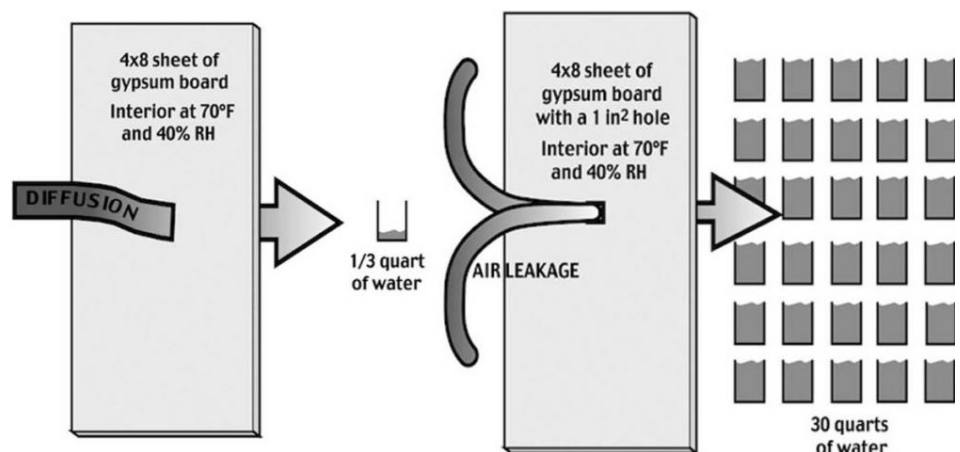


FIGURE 2. Illustration explaining the relative water vapor movement from vapor diffusion and air leakage. Source: buildingscience.com.



FIGURE 3. Staining from the roof on the interior structure.



FIGURE 4. Rotting of the wood at the exterior of the roof assembly.

POOL AIR LEAKAGE CASE STUDIES

We offer the following case studies to further consider the importance of thermal and air control in the building enclosure assemblies of natatoriums and pool buildings.

Case Study 1: Wood-Framed Resort Pool in the Northeastern US

Case Study 1 is a wood-framed pool building within a ski resort located in the northeastern US. The owners had observed some dripping and staining from the roof assembly onto the glulam structural beams of the building (**Figure 3**), and the exterior roof surface on the north side of the building appeared to be uneven. The key issue related to enclosure durability was air leakage condensation that led to moisture accumulation in the roof and, to a lesser extent, in the walls. The panelized wood framed roof construction was assembled on the ground as panels adjacent to the building and lifted into place onto the glulam beams. The panels themselves were constructed to be quite airtight: they were constructed with 10 in. (254 mm) engineered wood joists (e.g., TJIs) and were nearly full of ccSPF insulation. ccSPF insulation is an air and vapor barrier; however, at any joints where there is no insulation, such as panel joints, air control must be maintained. Continuity of the control layers between panels can be a challenge. In this case, when the panels were set on the glulam structure, the air barrier was not made continuous between the panels. This allowed

the slow movement of moisture-laden air through the gap between the panels, which reached the cooler roof surface and then condensed. The moist conditions resulted in rot and decay of the wood materials in the roof assembly at the joints between the panels (**Figure 4**), which slowly spread to the rest of the panel. The deterioration was greatest on the north orientation, which is to be expected due to the lower amount of solar energy available for drying. The deterioration was so widespread that there was some concern about the roof collapsing. Dark drips stained the sides of the glulam beams due to the condensate that eventually started rotting out the wood in the roof and turned the condensate a

dark brown color when it drained back into the building. The glulam beams were structurally sound, just stained, so the remediation involved replacing the roof with panelized wood-framed construction. The replacement required careful air barrier continuity detail at the joints, as shown in **Figure 5**, and a completely exterior insulated roof assembly.

Case Study 2: Commercial Pool Building in Southwestern Ontario

Case Study 2 was a project completed in 2019. Situated in southwestern Ontario, this project reminded us that even before the completion of the project and the operation of the building, care is required during construction. The structure was constructed, and the windows and membranes were installed. In many locations, exterior insulation was also installed. The pool had been mostly filled with water to ensure there were no issues with the pool systems, although the mechanical systems were not fully installed and functional. One of the exterior walls of a lower roof area had a self-adhered air/vapor barrier installed on the exterior of the gypsum sheathing and the steel stud to the exterior of a CMU structural wall. We observed that the self-adhered membrane had become loose over the entire wall surface and was no longer supported by the

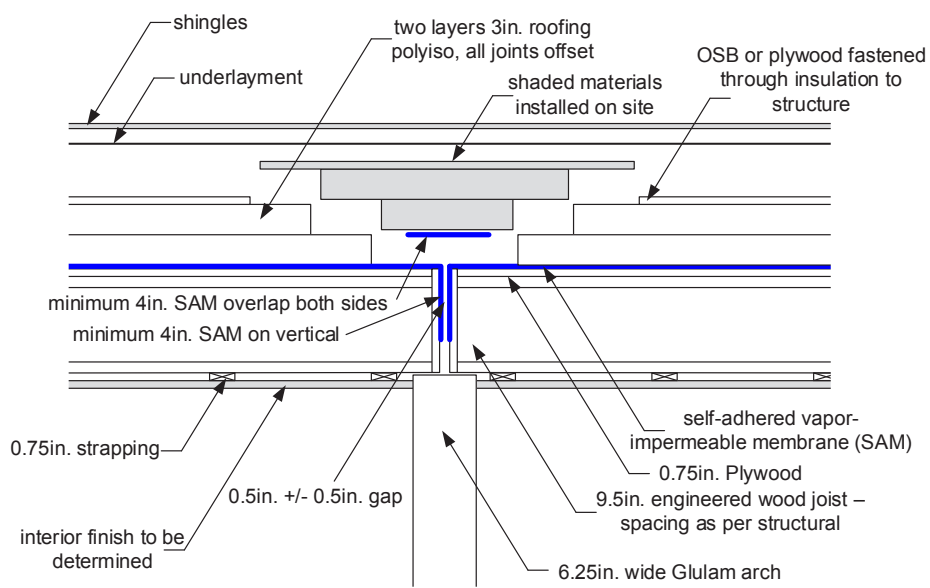


FIGURE 5. Schematic of the roof repair ensuring the air barrier continuity on the warm side of the insulation.



FIGURE 6. Mounding on ice formed when air leaked from the common areas and the pool leaked into the ceiling above the ice rink, condensed, and dripped onto the ice.

gypsum. Further investigation identified that it was not the membrane that had released, but the facer on the gypsum sheathing, and the gypsum core was wet. This failure occurred because the self-adhered membrane was a cold-sided vapor barrier during the winter. Air leakage pathways around the CMU wall extended into the void space, and since the continuous exterior insulation had not been fully installed, it resulted in failure of the wall assembly. Water was accumulating within the exterior gypsum, causing the facing to separate from the core. The repair involved a combination of strategies. First, ccSPF was installed into the void from the exterior, improving the thermal control, reducing the air leakage, and significantly reducing the void space. New gypsum was installed, and a vapor-permeable air/water barrier was installed in this area of the wall to increase the future safety factor of the assembly, particularly to take advantage of the vapor-permeable stone wool continuous exterior insulation. A more comprehensive quality control process using building pressurization and thermal imaging was conducted to assess and improve the air barrier system in other areas of the building while the air barrier system was exposed.

The requirement for airtightness of the interior partition walls surrounding a pool is important in buildings with adjacent spaces to limit the transport of odors, chloramines, and moisture.

Case Study 3: Community Center Pool Space Adjacent to Ice Rink Near Toronto, ON

Case Study 3 was a project in 2006 at a community center north of Toronto that included a pool and ice rinks in the same building, separated by a foyer space. The issue at this building was mounding on the rink ice overnight (**Figure 6**). The mounding was greatest at the end of the rink closest to the foyer and pool and diminished with distance from the foyer. Our investigation determined that air leakage pathways were created on the interior near the roof of the building where the partition walls were not air-sealed to the underside of the roof. These pathways allowed moisture from the pool space and foyer area to



FIGURE 7. Water accumulation and damage in the parapet, and the backer observed on the Blueskin air barrier.

pass through the common space and into the roof assembly above the ice rink. It condensed and dripped onto the ice through the joints of the interior finish, resulting in mounds that formed every night.

Case Study 4: Community Center Pool in Southwestern Ontario

Case Study 4 is a pool in southwestern Ontario that had condensation drainage coming out of the roof assembly at the lower portions of the roof. The architectural design for the roof and the roof-to-wall transition looked adequate: a self-adhered membrane transition from the wall to the roof, underneath the parapet, creating continuity between the roof and wall. However, when the parapet and adjacent roof were opened, it was discovered that the backer had not been peeled from the self-adhered membrane (**Figure 7**). The membrane was not adhered, and further, there were structural penetrations through the membrane that were not sealed. This resulted in air leakage pathways into the parapet from the interior space. The schematic in **Figure 9** shows the air leakage pathway along the structural connection to the parapet. Condensation on the underside of the roof membrane was guiding water directly to the roofing assembly and saturating the coverboard and roofing insulation. Condensation was also draining back to the interior of the building, staining window mullions and the pool deck (**Figure 8**).



FIGURE 8. Staining inside the pool area running down steel columns from the parapet.

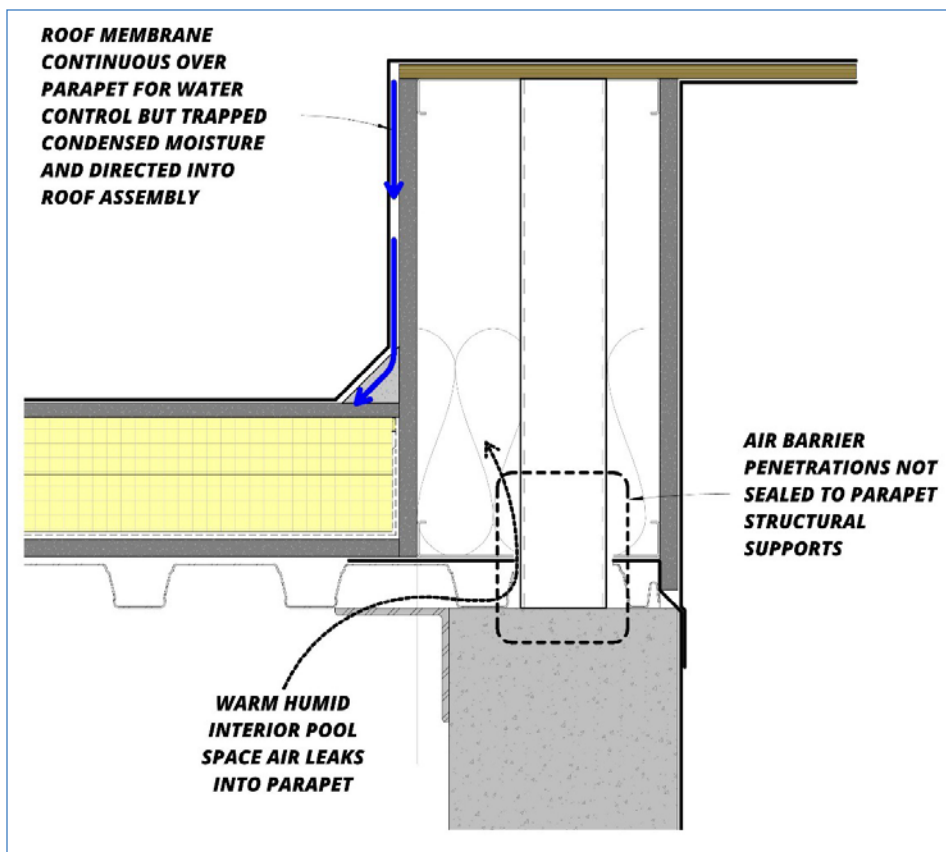


FIGURE 9. Schematic of the air leakage pathway and condensation that saturated a large percentage of the roofing insulation in the roof assembly.

THERMAL BRIDGING

Thermal bridging is another important consideration for the design and performance of pool enclosure assemblies. Ideally, thermal bridges are addressed in the design phase of a project, when they are easiest to remedy. They become difficult to manage once they are constructed. Often, the structure will pass through the insulation layer of the enclosure to support components of the building on the exterior, such as soffits, or other architectural details. In some cases, structural thermal breaks can be integrated into the structural design to reduce thermal bridging through the enclosure early in the design phase.

POOL THERMAL BRIDGING CASE STUDIES

We offer the following case studies to further consider the impact of thermal bridging on building enclosure assemblies of natatoriums and pool buildings.

Case Study 5: Community Center Pool in Chicago, IL

Case Study 5 is a pool in Chicago that had issues with both air leakage and thermal bridging from the hollow structural section (HSS) that connected

to the structure on the interior of the enclosure while also supporting the soffit. Significant condensation and dripping on the interior of the enclosure at this HSS was a result of a combination of thermal bridging and air infiltration. The infiltrating air combined with thermal bridging cooled the interior steel surfaces sufficiently in the winter time that interior air condensed on the surfaces. The initial design was for the entire soffit to be wrapped airtight in self-adhered membrane and connected to both the roof and the wall, but the air barrier layer was not continuous. Air flowed into the soffit through the hollow HSS and then into the building. Fortunately, the pool had been operating correctly under negative pressure (as discussed later in the paper) since it was constructed; otherwise, there would have been significant moisture damage to the soffit space. The recommended fix for this issue (**Figure 10**) was to ensure the air barrier was continuous at the plane of the enclosure with a fluid-applied membrane (green coating showing past the ccSPF on the roof deck) and spray foam on the wall and in the metal deck flutes, and to entirely wrap the soffit HSS structural members in ccSPF.

Case Study 6: Single-Family Residence with Pool Near Toronto, ON

Case Study 6 is a residential pool building north of Toronto. The residents were previously unable to use the pool in the



FIGURE 10. Closed-cell spray polyurethane foam (ccSPF) was installed above the windows at the transition between the metal roof deck and the enclosure over the green fluid-applied air and water barrier. ccSPF was also installed around the entire length of the HSS supporting the soffit and connected to the interior structure to minimize thermal bridging.



FIGURE 11. Illustration of wintertime stack effect with naturally occurring drawing of air in the bottom of the building and exhausting it out the top. Source: finehomebuilding.com.

wintertime because of the considerable dripping within the space as a result of poor design and construction details in the enclosure. The structure was steel with wood-framed infill and a vented cathedral ceiling. The roof needed significant improvements to the thermal control. To minimize the disturbance to the interior, the exterior surface of the roof was removed, and ccSPF was used to insulate the roof assembly and encapsulate all the structural steel components within the roof assembly before the roof was reassembled. Following the reinstatement of the roof, the condensation and dripping from the interior of the roof was almost completely repaired. One area had been missed by the contractor, which was evidenced by thermal imaging of the interior surface of the roof. That small section of the roof was reopened, and additional spray foam was installed around the thermal bridge to reduce the heat transfer in the problem area to eliminate the dripping on the interior.

HVAC DESIGN

This paper is intended to be largely focused on the building enclosure and not a discussion of HVAC equipment. However, there are some high-level HVAC considerations that are important to consider early in design as well as during forensic investigations of

moisture issues because they are related to successful enclosure performance.

Building Depressurization

The ASHRAE HVAC applications guide¹ states that “pool and spa areas should be maintained at a negative pressure of 15–40 Pa relative to the outdoors and adjacent areas of the building.” This negative pressure is provided to prevent chloramine odor migration. While controlling odors in adjacent spaces is recommended, the more important reason for depressurization is to control the movement of interior air-based water vapor into the enclosure and reduce the risk of moisture durability issues. Quantifying

the depressurization may require the engineers and trades commissioning the HVAC equipment to use different tools because it was found through the case studies that large HVAC balancing is completed to within ± 0.1 in water column, which equates to only 50Pa of accuracy.

Both Perkins+Will¹³ and Jason Der Ananian¹⁴ described the importance of depressurizing the pool space relative to the exterior and to adjacent spaces to reduce the risk of interior moisture entering the enclosure. Achieving depressurization becomes easier with greater levels of airtightness.

When completing both the design and repair work on pool buildings, it is our

experience that it is often difficult to convince the mechanical contractor to provide depressurization of the pool space. We often get pushback from the contractor, even when the symptoms and evidence of moisture issues indicate that pressurization is contributing to the reported issues.

Stack Effect

The other key criterion to keep in mind when determining the enclosure pressure is the stack effect within the building.

Stack effect is the term given to the naturally occurring interior pressures in a building related to the height of the interior space and the temperature gradient across the enclosure.

Figure 11 shows an illustration of typically occurring stack effect pressures during the winter months in a cold climate. Warm air is more buoyant; it rises to the top of the building and finds its way out through holes in the air barrier system. Replacement air is then drawn in at the bottom of the building. Positive air pressures push air out on the top of the building, while negative pressures pull air in at the bottom. The amount of pressure formed increases with building height as well as with greater temperature gradients between the interior and exterior. Stack effect pressures at the top of the building are the greatest in the coldest winter months. Therefore, they need to be considered when the pressure measurements are taken to ensure that the building is negatively pressurized all year round. Pressure measurement should be done during the winter months when it is cold

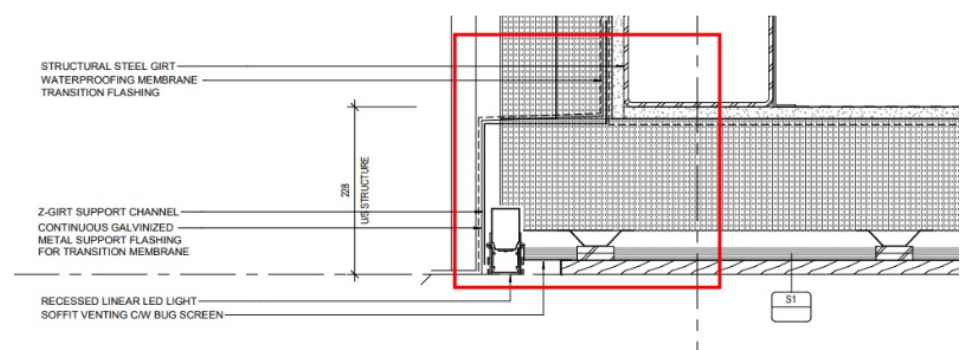


FIGURE 12. Many of the light fixtures at the perimeter of the soffit were filling with water and failing because of air leakage from pressurization of the building.



FIGURE 13. Photograph of water within the light fixtures at the edge of the soffit.

outside to confirm that the building depressurization is still effective even when the stack effect pressures acting within the space are the greatest.

POOL PRESSURE FIELD CONTROL CASE STUDIES

We offer the following case studies to further consider pressure field control and its impact on the building enclosure assemblies of natatoriums and pool buildings.

Case Study 7: Community Center Pool in Nova Scotia

Case Study 7 is a newly constructed pool in Nova Scotia, completed in 2022. Lights at the perimeter of the soffit space above the entrance were filling with water and failing. Unfortunately, due to COVID-19, we were unable to travel to the site to do the investigation ourselves. Instead, we assisted remotely with the investigation. The conditioned soffit was part of the interior space and wrapped in self-adhered membrane as well as continuous exterior insulation (**Figure 12**). The lights were well protected from driving rain events, and there was no correlation between rain events and water in the light fixtures. The accumulated water was most likely a result of warm, moist interior air being pushed along the electrical wiring pathway through the air barrier discontinuity into the light fixtures, resulting in condensation and

moisture accumulation. **Figure 12** shows a section of the exterior edge of the soffit with the membranes on the gypsum sheathing, and over the flashing, and thick layers of continuous exterior insulation. **Figure 13** shows a photograph of water accumulated in the light fixture at the edge of the soffit.

Our recommendation was to negatively pressurize the pool space to prevent moisture-laden interior air from entering the light fixtures. The mechanical contractor assured us that the pool space was depressurized and was not willing to make any adjustments to the mechanical system. A simple assessment, holding the exterior door open an inch, resulted in air moving out of the building, readily confirming that the space was, in fact, positively pressurized at grade.

To ensure that a building is depressurized correctly, the recommended pressure must be measured across the enclosure with

a manometer and not determined by measuring the flow rates at the mechanical equipment. We have found that many times, the HVAC contractor will provide evidence of depressurization by using measured flow rates of supply and exhaust, but these do not always correlate to the desired enclosure pressures.

AIR DISTRIBUTION OVER WINDOWS

HVAC design and distribution are also factors contributing to window condensation issues. As a result of the high interior moisture loads, it is common in cold climates that the glazing systems' surface temperatures will fall below the dew point for extended periods. The risk of condensation on glazing systems can be countered with high-performance glazing and framing systems, but reducing condensation more commonly relies on air distribution over the glazing from the HVAC system.



FIGURE 14. Fans were added during the building repairs to blow air directly over the windows to reduce condensation on the interior surfaces of the windows.

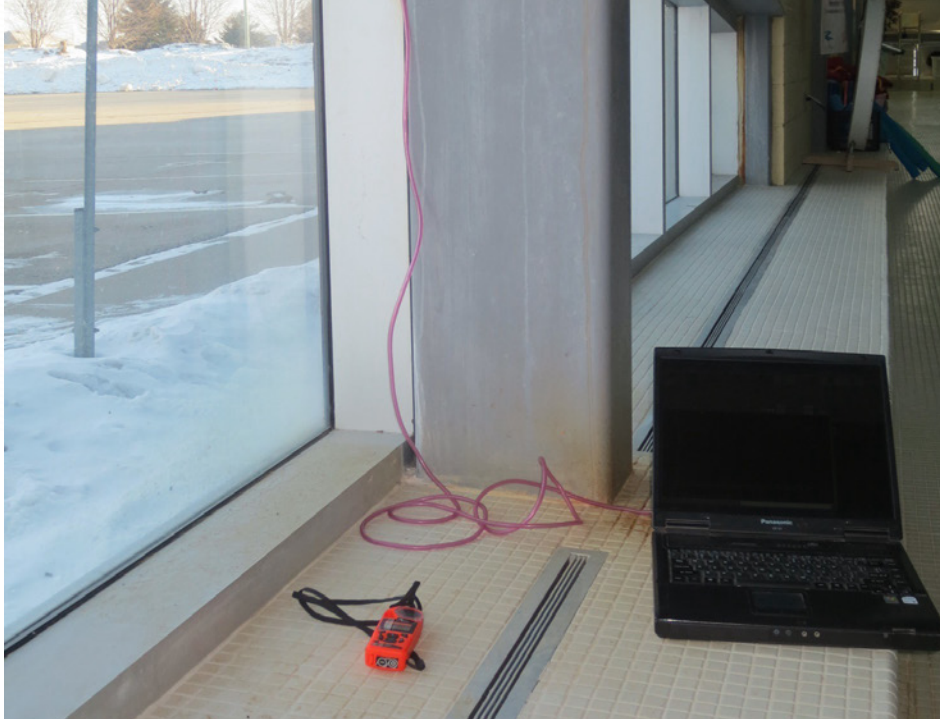


FIGURE 15. Linear grilles adjacent to the windows are designed to apply airflow to the window area, reducing condensation.



FIGURE 16. Around the windows, there was greater mortar damage and efflorescence as a result of the lack of deficient air barrier details.



FIGURE 17. At the top of the wall, icicles, wetting, efflorescence, and mortar damage were all present as a result of air leakage.

POOL AIR DISTRIBUTION CASE STUDIES

We offer the following case studies to further consider HVAC system air distribution and its impact on the performance of building enclosure assemblies in natatoriums and pool buildings.

Case Study 5 (Revisited): Community Center Pool in Chicago, IL

Case Study 5 in Chicago, previously discussed because of the thermal bridging and air leakage at the soffit, also had issues with condensation on the windows. The lack of air distribution from the mechanical system over the

windows and the deep interior mullions disrupted the airflow, promoting condensation. As part of the repair strategy for the building, additional fans, separate from the HVAC supply ducts, were installed specifically to blow air over the windows (**Figure 14**).

Case Study 4 (Revisited): Community Center Pool in Southwestern Ontario

Case Study 4, previously discussed because of the moisture accumulation in the parapet and roofing, also had issues with mechanical distribution. Air supply grilles and ductwork were provided around the perimeter of the pool with linear diffusers to supply air to the glazing at floor level (**Figure 15**).

A few years following the construction of the building, there were some issues with the masonry on the exterior of the building with crumbling mortar as well as staining of the masonry, mostly around windows (**Figure 16**). The parapet cap was removed during inspection to look down into the drainage/ventilation cavity behind the masonry. The air coming out of the gap was humid and smelled of chlorine. The high humidity air in the masonry veneer cavity resulted in icicles and moisture accumulate at the top of the wall under the parapet flashing during the winter time (**Figure 17**). The masonry wall issue was the result of a combination of factors, including, most importantly, the lack of air barrier continuity. However, it also involved installation deficiencies in the HVAC ductwork, since in some locations, the air from the ductwork was blown directly into the brick veneer cavity, resulting in premature failure of the masonry on the building. The building repairs included air barrier replacement and improvements to control airflow and eliminate air exfiltration.

Case Study 8: Multi-Family Building with Pool in Vancouver, BC

In Case Study 8, the importance of air movement over the interior of glazing was highlighted. The design of the visually stunning Butterfly Westbank pool project in Vancouver did not follow the best-practice recommendations of keeping window areas small and of providing large ducts with lots of air to the window areas. RDH Building Science worked with a company that provided extensive computational fluid dynamic analysis modeling on the airflow, analyzing interior surface temperatures to determine the best strategy to provide airflow over the glazing with the concealed ductwork. Many iterations and variables were run in the analysis, with two of the simulations shown here.

Figure 18 shows the model output for the plan view of the roof. The entire roof/skylight area is red, indicating condensation is expected to cover the entire skylight/ceiling assembly.

Figure 19 shows the predicted surface temperature and condensation results with a higher temperature set point as

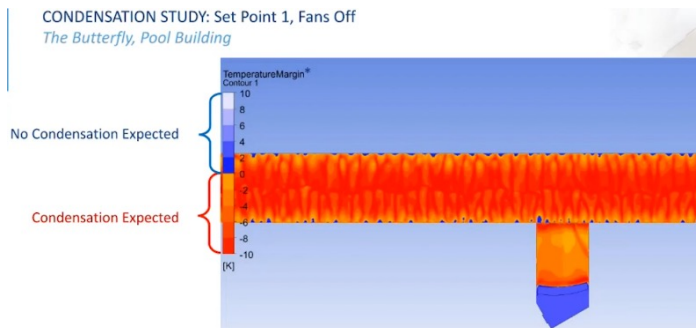


FIGURE 18. The predicted temperature margin and condensation risk on the skylights of the pool without any fans indicates that the other ceiling will be covered in condensation.

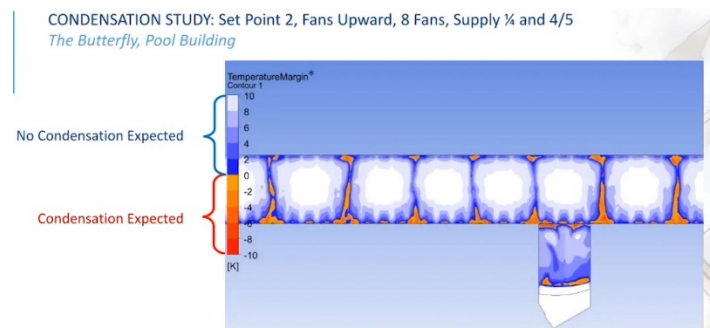


FIGURE 19. The predicted temperature margin and condensation risk on the skylights of the pool with a higher temperature setpoint and additional fans shows a significantly decreased risk of condensation.

well as additional fans blowing air over the glazing surfaces. This approach significantly reduced the predicted condensation risk over most of the skylight/ceiling of the pool space, as indicated by the mostly blue and white coloration of the surfaces.

RECOMMENDATIONS FOR POOL ENCLOSURE DESIGN

The authors have been involved in many natatorium enclosure designs and failures over the past two decades. Our experiences are distilled into the following seven recommendations that will minimize the risk of enclosure and durability issues in a pool building.

- 1. Early Design:** Communicate the importance of the key design criteria such as continuous exterior insulation, continuous air barrier system, and accurate construction details early in the process when these strategies can still be incorporated into the project budget and construction scope.
- 2. Continuous Exterior Insulation:** Wrapping the structure in control layers and installing continuous exterior insulation with as few penetrations as possible is typically the lowest-risk design for all enclosures, especially buildings with high-humidity interior environments, like pools, in cold climates.
- 3. Thermal Bridges:** Limit all thermal bridging through the insulation layer as much as possible in design. In instances where the structure must pass through the insulation layer, design structural thermal breaks or other strategies to control the interior surface temperatures of the structural elements.
- 4. Continuous Air Barrier System:** We have concluded based on the case studies as well as other previous research that a continuous air barrier system across all surfaces of the enclosure (that is, roof, walls, floor, and partition walls) that is also continuous at all penetrations, such as windows and doors, is required to be nearly perfect to minimize the risk of enclosure durability issues.
- 5. Negative Pressurization of the Building:** In a cold climate, to minimize the risk of interior air

entering the enclosure, the pool space should be kept at a negative pressure, which will reduce the risk of condensation of interior air within the enclosure. This is a requirement for pool buildings.

- 6. Airflow over Glazing:** Windows in pool buildings in cold climates often require air to be directed at the surface of the windows to minimize condensation on the interior surfaces.
- 7. Construction Quality Control:** It is crucial to always be aware during construction of the modifications/penetrations to the air barrier system. Any penetrations that are required should be reported and tracked, and repairs should be done by the responsible trades. Airtightness testing with the use of thermal imaging or tracer smoke can also help identify potential air leakage pathways and is recommended as a quality control tool prior to covering the air barrier system, although this is often difficult in reality due to construction sequencing on the project.

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The History of Roofing in One Building Since the 1970s—Actually!

ABSTRACT

This paper presents a case study of a commercial building that has encapsulated a good part of the history of roofing in Canada since the 1970s. This extraordinary example of roof life management for a shopping center highlights the evolution of roofing technologies and roof system types available from the early 1970s through 2019, the roof renewal processes that took place during several phases of repair and maintenance, and the positive and negative impacts that past decisions have had on the performance of the roof and the building's structural condition.

The paper begins by outlining Canadian commercial roofing history since the 1970s. Next, the processes of roof condition assessment—including information-gathering and testing methods that facilitate analysis of roof systems in place—are briefly discussed. The case study describes the client's concerns, the testing conducted, the test findings, and how the project team determined the steps now being carried out to address the long-term issues. Many commercial-type buildings across Canada have roofing assemblies that have outlived their original intended service lives and now need extensive repairs. The lessons from this example may be of value to consultants and owners alike.

SPEAKER



Jean-Guy Levaque,
F-IIBEC, RRC, RRO,
Arch Technologist
[Pretium Engineering Inc.](#)

As a specialist roofing consultant with more than 42 years of construction experience and more than 34 years of roof consulting

expertise, Jean-Guy Levaque has been providing valuable and practical solutions to high-profile national clients for existing building retrofit and new construction projects. A fluently bilingual consultant, he has an in-depth knowledge of the roofing industry and is widely recognized throughout Canada, the US, and internationally. Levaque strives to understand the needs of clients, and is dedicated to providing the best solutions, with integrity and honesty.

LEARNING OBJECTIVES

- » Discuss important milestones throughout the history of roofing since the 1970s.
- » Identify key elements of roof systems, roof evaluations and assessments, and report presentations to clients.
- » Self-evaluate present practice in roof assessments and decision-making processes on replacement of roofs.
- » Recognize challenges in the analysis of multiple parameters to attain a final recommendation.

Through a unique opportunity, this paper explores the trajectory of commercial roofing practices in Canada since the 1970s, as illustrated by the history of a single roofing system. It examines advancements in roofing materials, technologies, design approaches, and roof installation procedures, tracing the evolution from traditional roofing to the roofing systems we see today.

Furthermore, the paper presents assessment practices for roof refurbishment and alterations, providing insights into the methodologies and considerations involved in evaluating aged roofs, and the importance of thorough inspection, data gathering, and analysis in informing decision-making processes related to roof renewal.

A detailed case study shows the history of commercial roofing in one building. This case study offers a microcosm of roofing evolution, illustrating the lifespan of roof systems, the challenges encountered over time, and the strategies employed for refurbishment and alterations. Through this lens, the paper offers practical lessons and valuable insights for building enclosure consultants, building owners, and industry professionals engaged in managing and maintaining aging roof structures.

ROOFING HIGHLIGHTS IN CANADA SINCE THE 1970S

Between the 1970s and today, roofing options in Canada have transitioned from limited roof membrane and insulation choices to a wide variety of materials and applications. The following is a brief review of the

evolution of roofing practices during this period.

1970S

During the 1970s, built-up roofing (BUR) membranes dominated the commercial low-slope roofing market (**Fig.1**). This traditional approach, although widely used, presented a distinctive set of challenges, including issues related to installation, maintenance and upkeep, weight, and long-term performance. The range of available insulation materials was also limited, with glass fiber and wood fiber being the primary choices. There was little emphasis on thermal efficiencies during this time. It was common to see a roofing assembly with an *R*-value of 5 (or less).

In the late 1970s, oil embargoes led to rising costs of heating and cooling in buildings. This economic pressure drove the construction industry to explore alternatives and innovations aimed at improving the energy efficiency of new and existing buildings.

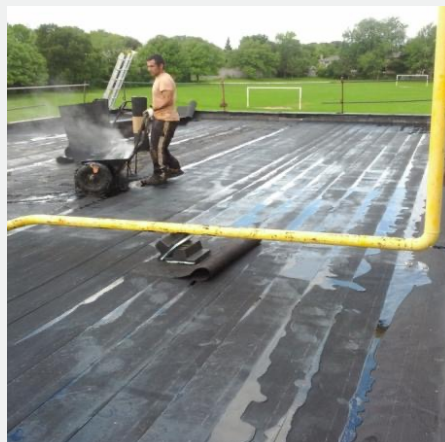


FIGURE 1. Built-up roof membrane application – *Pretium Eng. project*

EARLY 1980S

The early 1980s posed significant challenges for the roofing industry in Canada; in particular, soaring interest rates exceeding 20% hindered borrowing and investment in construction projects. This financial climate led to a temporary slowdown in roofing activity, prompting the adoption of makeshift solutions or “Band-Aid” approaches to roof maintenance.

In this era, alternative roof membranes, including modified bitumen (MB), were introduced and single-ply membranes such as ethylene propylene diene monomer (EPDM) and polyvinyl chloride (PVC) were adopted on a limited basis. However, BUR systems continued to dominate the industry because they were still relatively inexpensive.

Escalating heating and cooling costs provided incentives for the industry to focus on thermal efficiencies and drove efforts to improve insulation performance. However, the pursuit of higher *R*-values, such as R10, inadvertently exacerbated roof membrane failures, by exposing BUR membranes to the elements and removing them from the internal heat sources, leading to accelerated chemical degradation in membranes, increased risk of splitting, reduced impact resistance and increased risk of slippage,¹ underscoring the importance of balanced design considerations and compatibility between insulation and roofing membranes.

MID-TO-LATE 1980S

A construction boom fueled demand for roofing materials and technologies, with greater emphasis on alternative

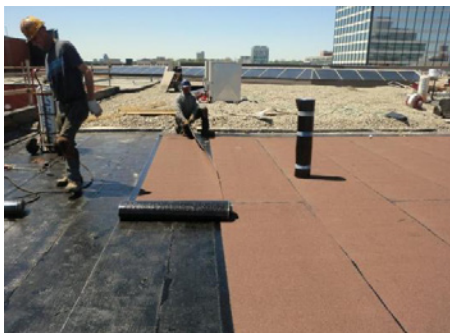


FIGURE 2. Modified bitumen roof membrane application – Pretium Eng. project

roof membranes, including MB (Fig. 2) and single-ply membranes (ballasted EPDM) or PVC. However, the dominance of BUR persisted, albeit with gradual diversification in some markets.

Expansion of insulation choices presented both opportunities and pitfalls. While options like glass fiber, wood fiber, expanded polystyrene (EPS), and extruded polystyrene (XPS) provided greater flexibility, the untested and untried use of certain insulation materials, notably XPS beneath BUR roofs, resulted in catastrophic failures due to the different coefficients of thermal expansion between XPS and BUR membranes.¹

New types of insulation materials emerged that provided lightweight, cost-effective, high *R*-value solutions. Phenolic insulation and polyisocyanurate (ISO) insulation effectively became the insulation materials of choice for many projects. The marketing for these two types of insulation was competitive, along with EPS, and their use became more popular in some areas of Canada where they were marketed more effectively. Phenolic insulation was less expensive and provided a higher *R*-value per inch than ISO insulation.

EARLY 1990S

The early 1990s was a period of refinement in roof system details, prompted by failures in nonreinforced PVC and EPDM seams, as well as other installation and manufacturing setbacks. However, the roofing

industry faced economic headwinds due to a recession, so stakeholders were compelled to seek cost-effective solutions. Similar to the early 1980s, this economic environment led to the proliferation of short-term repair strategies.

Amid rising concerns over energy efficiency and escalating heating/cooling costs, there was a push toward achieving higher levels of thermal efficiency, with *R*-values ranging from *R*-15 to *R*-20 becoming the norm. This heightened focus on energy conservation propelled innovation in insulation materials and installation practices and technologies. ISO and EPS insulation started to take over the insulation market, whereas the use of phenolic insulation declined and was then eliminated, driven by a failure of the product and resulting major legal disputes. “In contact with moisture, phenolic insulation is highly corrosive to metal fasteners, stress plates, and even the steel roof deck.”² Also in this era, the popularity of glass fiber waned due to cost considerations.

MID-TO-LATE 1990S

In the mid-to-late 1990s, thermoplastic polyolefin membrane (TPO) (Fig. 3) was introduced as a low-cost alternative to other types of roofing membranes.

ISO insulation remained the go-to choice for many roofing applications,



FIGURE 3. TPO roof membrane application – Pretium Eng. project

although there were ongoing concerns regarding production issues, particularly related to an industry switch of blowing agents from ozone-depleting trichlorofluoromethane (CFC-11) to Hydrochlorofluorocarbons (HCFC-141b) to Hydrocarbons (Pentane) to meet environmental requirements.³ Thermal value remained in the *R*-15 to *R*-20 range.

MB roof membranes were becoming more popular in many parts of Canada; the advantages of MB membranes were ease of application, some redundancy, less weight than BUR, and marketed performance. Costs of MB roofing systems started to go down to become more competitive with BUR options.

2000 TO 2010

The first decade of the 21st century was a period of adaptation and innovation in the roofing industry in Canada, characterized by both challenges and advancements across various fronts.

One significant challenge faced during this period was the impact of labour shortages, driven by the retirement of experienced roofing professionals and a shortage of young skilled workers wanting to enter the roofing market. Ideally, the roofing industry should have improved its efforts to attract and train new talent to ensure the continuity of roofing operations. However, while some parts of the country are acting on this, not enough has been done and labour shortages have been a constant problem to this day.

BUR roofing systems lost market share, MB systems continued to grow in popularity, and the use of single-ply membranes, including TPO, increased in some markets and building types. Advancements in installation technologies further streamlined the application of single-ply membranes, enhancing their efficiency and reliability.

ISO remained a popular insulation option despite production challenges related to blowing agents (see late 1990s above). Mineral fiber insulations, although more costly and heavier than ISO, offered alternative solutions.

Composite insulations were introduced during this period. These composite boards, composed of multiple layers of insulation and/or overlay boards, offered enhanced thermal performance and durability compared with traditional insulation options, with controlled adhesive applications in the manufacturing process being one key benefit. However, this advancement in roofing insulation technology was not widely adopted because of higher manufacturing costs, and the industry having trouble understanding labour cost benefits to offset the manufacturing costs.

While there was a continued emphasis on thermal efficiencies, with target *R*-values ranging from *R*-20 to *R*-25 becoming increasingly common, the pace of improvement plateaued somewhat during this decade. The lack of scientific data showing payback benefits was in part the problem. However, the persistent rise in heating and cooling costs underscored the ongoing importance of energy conservation and efficiency measures in building design and construction.

2011 TO 2020

The period from 2011 to 2020 was a time of significant shifts and challenges in the Canadian roofing industry, driven by factors such as labour shortages, technological advancements, environmental and sustainability concerns. Skilled labour shortages continued to pose a challenge, prompting the industry to seek government solutions for recruitment.

The insurance industry exerted pressure on the use of open-flame roofing systems, leading to stricter regulations and a shift toward safer alternatives (flameless solutions). Testing of insulation thermal values became a focal point to optimize energy efficiency and reduce heating and cooling costs. Advancements in insulation materials and adhesives played a crucial role in enhancing the performance and durability of roof assemblies.

The use of ISO insulation was widely adopted, although there were concerns about its performance and

thermal loss over time, and in extreme temperatures.^{4,5} Composite insulations, despite their potential benefits, failed to gain market traction to the extent expected. Challenges regarding adhesive quality and application led to installation failures and reliability issues.

The emergence of composite membranes and overlay boards offered versatile solutions for roofing applications, as these materials could meet diverse project requirements and be used in a range of environmental conditions. Additionally, roofs evolved into multifunctional platforms, serving not only as protective barriers but also as spaces for renewable energy generation, green roofs, and recreational amenities.

2020 TO THE PRESENT

The onset of the COVID-19 pandemic in 2020 brought unprecedented challenges to the roofing industry, including major supply chain disruptions in materials, increased labor shortages, and significant increases in roofing costs (labor and materials).

Climate change events have put renewed focus on sustainable roofing practices and resilience against extreme weather events. Concerns about the future climate issues has further underscored the importance of thermal efficiencies and resilience, and the roofing industry has focused on upgrading *R*-values to *R*-25 and above. Regulatory bodies are now considering the development and enforcement of energy standards for the refurbishment of existing roofs. It is important to note that more than half of the buildings in place today will still be there in 20, 30, or even 40 years.

A new generation of roofing contractor leaders is emerging, and they face even greater labour shortages, climate change issues, rising costs, and a large roof building inventory to renew. Standards such as CSA A123.26, *Performance Requirements for Climate Resilience of Low Slope Membrane Roofing Systems*,⁶ outline performance requirements for climate-resilient roofing systems, guiding industry practices toward greater sustainability and adaptability.

ASSESSMENT PRACTICES FOR ROOF REFURBISHMENTS AND ALTERATIONS

Assessment practices for roof refurbishments and alterations are crucial for ensuring the effectiveness, longevity, and safety of roofing systems. The following are common assessment methods employed in the industry.

Visual Assessments (Noninvasive)

Visual inspections are the most basic and commonly used method for evaluating the condition of roofing systems. Roofing professionals visually inspect the roof surface and flashings, looking for signs of damage and deterioration; defects such as cracks, seam failures, blisters, and punctures; drainage issues such as pooling or ponding water; debris and vegetation growth; and other evidence that the roofing system may be compromised. Visual inspections are clearly important for evaluation; however, they are limited to observable areas and depend on the experience and judgment of the inspector.

Roof Thermography (Noninvasive)

Thermographic imaging, also known as infrared thermography, is a non-invasive technique in which infrared cameras are used to detect temperature variations across the roof surface and underlying materials. This technology can identify areas of thermal anomalies, which helps the inspector investigate problems such as moisture infiltration, insulation deficiencies, or thermal bridging that exhibit distinct temperature patterns. By visualizing locations of specific anomalies, thermal images facilitate

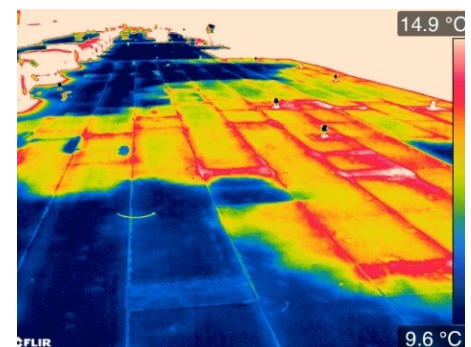


FIGURE 4. Roof Thermography scan – Pretium Eng. project



FIGURE 5. Cut tests – Pretium Eng. project

targeted repairs or upgrades. For example, thermographic scans can be used to assess the effectiveness of roof insulation by identifying areas of thermal loss or inadequate insulation coverage (gaps) (Fig. 4).

To correctly interpret thermal images, the inspector needs expertise to distinguish between genuine anomalies and false positives caused by environmental factors or surface conditions and confirm findings by cut tests / probes.

Cut tests (Destructive)

Roof cut tests are used to confirm findings from thermography scans and noninvasive tests, and to assess the composition and condition of roof systems (Fig. 5). By physically cutting the layers of roofs down to the deck, and examining the roof layers, inspectors can evaluate the presence of moisture, insulation layers, thickness and deficiencies, the adhesion or fastening of components, and other issues.

In cases where there are multiple layers of roofing materials, inspectors may need to use step cuts to evaluate each layer individually. This process helps inspectors assess the condition of each layer, identify any deficiencies or damage, pinpoint where moisture damage occurs, and determine the need for repairs or replacements.

Other Testing Methods

Other roof testing methods have various advantages and limitations. Examples of noninvasive methods that can be carried out on various roof assembly types include capacitance testing, nuclear testing, and electronic



FIGURE 6. Aerial view of shopping centre – Google image

leak detection. As technology advances, new testing methods that offer improved accuracy, efficiency, and safety may emerge.

Wind uplift testing assesses the ability of roofing systems to resist wind forces and prevent wind-driven rain infiltration. Various testing methods, such as field uplift testing (using a fastener pull-out tester, uplift portable tester, or wind uplift chamber) and laboratory simulations, help determine the wind resistance of roofing assemblies.

When selecting testing methods, it is essential to consider the specific requirements of each roofing project and chose methods that align with project goals, budget constraints, and regulatory requirements. Additionally, it is crucial to engage qualified professionals with expertise in roof testing and diagnostics to ensure that results are accurate and support an informed decision-making process

regarding roof repairs, maintenance, or replacements.

The following case study has used some of the test methods identified above to suit the project needs and the client’s budget.

CASE STUDY

In 2022, Pretium Engineering Inc., an Ontario-based specialist building science, mechanical and structural consulting engineering firm, was tasked with conducting a comprehensive review of the roofing systems of a shopping center located in Canada (Fig.6). The project involved a total roof area of approximately 740,000 ft² (68,700 m²) divided into 91 roof sections. There were structural concerns related to snow load. No roof replacement work had been undertaken since 2019, and several roofs needed attention.

The project objective was to develop a long-term plan for roof maintenance and replacement, ensuring the continued functionality, durability, and sustainability of the roofing assets. An assessment report was issued in 2023.

This case study explores the building’s roofing history, assessment findings, and maintenance planning process undertaken to address the distinctive challenges and requirements of the shopping center. Initially, a visual review was carried out, followed by more comprehensive assessments with roof thermography scans and cut tests.

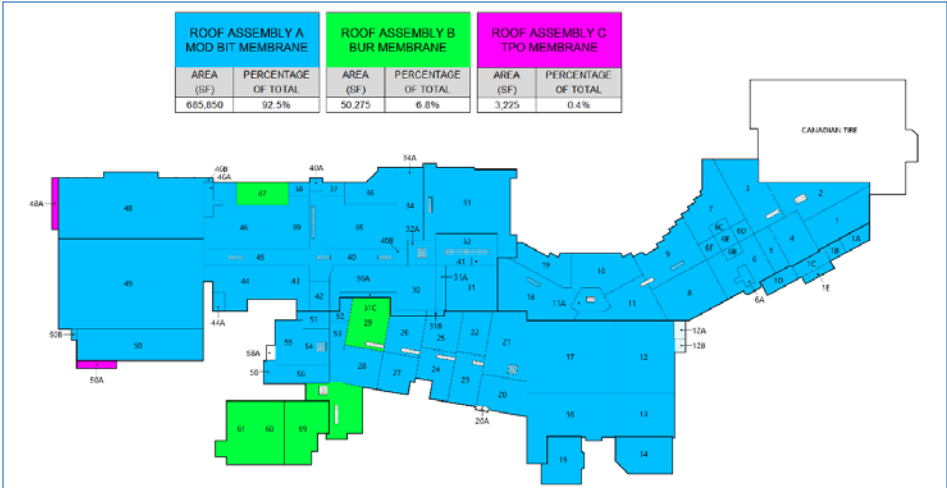


FIGURE 7. Roof plan showing the initial visual findings

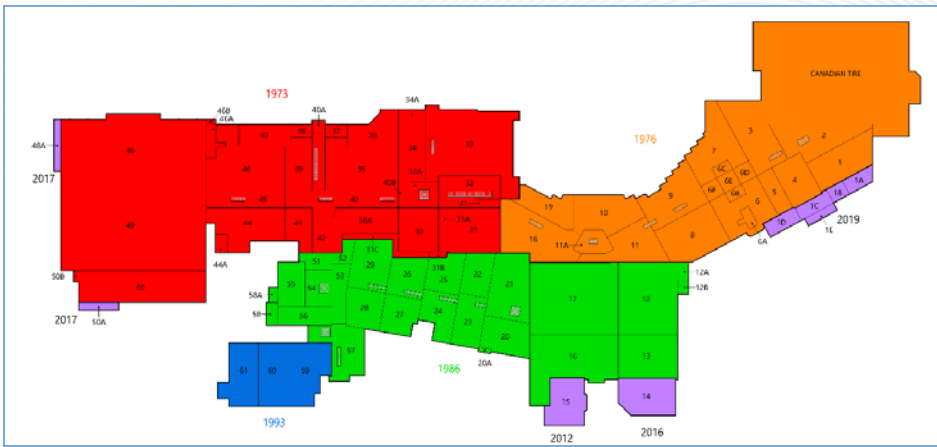


FIGURE 8. Construction sequences for the shopping center.

Additionally, through interviews with the client's management and historical records review, Pretium traced the evolution of the roofing systems since the shopping center's construction. Construction phases on the shopping center dated back to 1973. Over the years, the roofing systems have undergone various modifications, repairs, and replacements, resulting in a complex landscape of roofing materials and configurations. This historical context provided valuable insights into the performance and durability of the roofing systems.

FIRST VISIT: VISUAL ASSESSMENT

During an initial walkthrough to visually inspect the shopping center's roofs in 2022, we observed what we thought were three primary types of roofing systems:

- » Most roof surfaces (more than 92%) consisted of MB membrane roof assemblies, which initially appeared to be in fair to good condition.
- » BUR membrane roof assemblies with gravel surfacing comprised about 7% of the total roof area. These BUR roofs appeared aged, with visible signs of wear and deterioration. However, evidence of leaks was minimal.
- » The single-ply membrane roofs, represented by the pink areas on the roof plan (**Fig. 7**), constituted approximately 0.5% of the total area and were typically newer than the other parts of the roofing system.

Given the visual review of the roofs and the minimal reported leaks in the building, it was reasonable to assume that the shopping center's roofing systems were generally in good condition, especially considering the predominant presence of MB membrane roofs.

However, the visual review provided only a surface-level assessment, and further testing and inspection were necessary to fully evaluate the condition of the roofing systems and identify any underlying issues or areas in need of attention. When we conducted other types of tests, including roof thermography scans and cut tests, the information obtained led to dramatically different conclusions, regarding both the roof system types and the conditions of the roofs.

INSIGHTS FROM THE SHOPPING CENTER'S CONSTRUCTION HISTORY

As noted previously, investigation of the building's construction history, spanning from 1973 to 2019, gave us valuable insights into the evolution of the shopping center and its roofing systems (**Fig. 8**). Detailed records from the client on phases of building expansions helped us understand the chronological development of the shopping center and its roofing systems. However, we found that the inspection records were not always accurate, and, in many instances, the roof systems identified in documentation were not the roofs in place.

Each phase of construction introduced new roofing systems and modifications to existing roofs. Figure 8 shows the construction sequencing. This phased development approach and ongoing roof replacement program resulted in a mix of roofing materials, technologies, and installation methods across the shopping center's roofscape.

Because construction spanned multiple decades, the shopping center's roofing systems were subject to evolving building codes, standards, and industry practices. As a result, we found that the roofing systems installed during different construction phases varied in terms of design, materials, and compliance requirements.

Over the years, advancements in roofing technology and materials may have also influenced the selection and installation of roofing systems. We found that newer construction phases featured modern roofing materials and technologies, while older sections had legacy systems as well as roof retrofit work completed over time.

SECTION-SPECIFIC FINDINGS

Roofing from the Initial Construction

The first phase of construction in 1973 occurred in a period characterized by options in roof membrane types and insulation materials that were more limited than those available currently. During this time, roofing technology was relatively basic, and the available materials were often traditional and straightforward. **Figure 9** shows the areas of the shopping center roof from the first phase of construction.

We used cut tests to evaluate the roofing assemblies in some of the 1973 roof sections. In these sections, all the original roofing assemblies were in

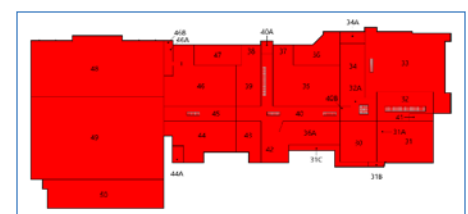


FIGURE 9. 1973 – First Phase of Construction – Pretium Eng. project



FIGURE 10. Cut test verification of roof assemblies – *Pretium Eng. project*



place, and several roofs had additional roof systems installed at various stages since 1973. The following findings from the cut test at roof section 46 represent the typical scenario for the sections of the roof that date back to 1973 (**Fig. 10**):

- » Second roof—overlay assembly (added circa 2002), featuring:
 - Two-ply MB membrane
 - ½-in. (13 mm) thick wood fiber (wet) overlay board with an R -value of R -1
- » First roof—base assembly (installed 1973 and left in place but with the gravel surfacing removed), featuring:
 - Multiple BUR membrane (scraped)
 - No overlay board
 - 1 in. (25 mm) thick glass-fiber insulation with an R -value of R -4
 - No vapor retarder
 - Steel deck

The glass fiber insulation in the 1973 roofs was commonly used during this period due to its thermal resistance properties. Note that there were minimal insulation alternatives available at the time. Using insulation with an R -value of R -4 was a common industry practice at the time.

It is notable that no vapor retarder was installed. Vapor transference was not well understood in the 1970s, and many roofs installed in that era did not have vapor retarders.

A MB overlay roof assembly was installed in 2002 directly over the original (BUR) system. All components of the old roof were left in place (except for some loose ballast). This new MB roof added board with an R -value of R -1, providing a minimal R -5 value. The decision to remove the gravel surfacing from the original BUR system and install an overlay assembly with an MB membrane may have been driven by the need for a cost-effective solution to address aging and deteriorating roofing conditions. By installing a new membrane over the existing substrate, the overlay assembly aimed to improve waterproofing and extend the lifespan of the roofing system at a relatively low cost.

Wet insulation was found in the second roof, while the insulation below in the first roof remained dry. No leaks were reported in these roofs. This evidence indicated that the original roof was preventing water intrusion, while the second roof was failing in areas. This was a very common finding among

the roofs at the property with multiple roofing systems in place.

Roofing Upgrade of 1973-Phase Roofs in 2001

In three large roof sections the original 1973 roof was replaced in 2001, with the entire roofing system being removed down to the deck (**Fig. 11**). The client reported that the replacement of the roof in 2001 coincided with a change of tenants, and the roofing upgrade may therefore have been driven by the need to meet specific tenant requirements.

The cut tests at roof section 49 identified the following roof assembly characteristics of these roof sections:

- » Total R -value of insulation = R -15
- » First roof—base assembly (circa 2001), featuring:
 - MB membrane and overlay composite board composite (mechanically fastened base sheet)
 - Two layers of 1.5 in. (38 mm) thick polyisocyanurate insulation for an R -value of R -15
 - Kraft paper vapor retarder
 - Steel deck
- » Total dry weight: 3 lb/ft² (14.6 kg/m²)
- » Total weight at wet areas was not known

The replacement of the BUR system with a MB system reduced the roof system weight by 60%, from 8 lb/ft² to 3 lb/ft² (39 to 14.6 kg/m²)

Extensive deterioration of the cap sheet granules at the fastener/plate locations raised concerns about the long-term performance and durability of the roof. The deteriorations seemed to be a result of thermal bridging at the fasteners for the mechanically fastened MB base sheet, and we recommended that conditions be closely monitored for roof system wind uplift and membrane performance.

The replacement of other roof sections was a greater priority, and so we proposed the following options to address the observed deterioration and concerns about long-term performance:

- » Additional layers of membrane could be added over the existing MB

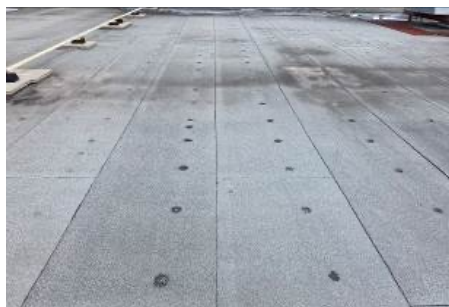
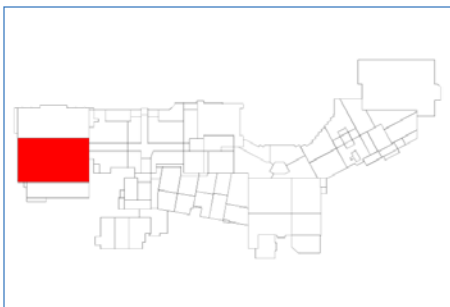


FIGURE 11. Roof Section 49 plan location and photo – *Pretium Eng. project*

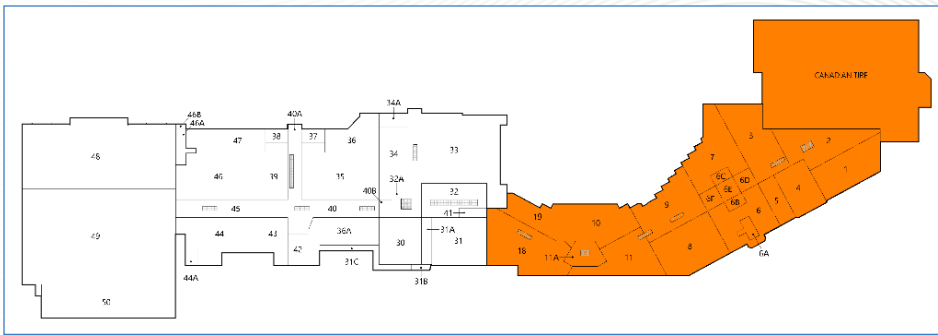


FIGURE 12. Shopping center diagram showing the 1976 expansion in orange.

system to enhance waterproofing and protect against granule loss. However, this approach might not address underlying issues and could increase the dead load further.

- » The existing MB membrane could be removed and more insulation could be added before a new membrane was installed. This option could address performance concerns and increase energy efficiency.

Roofing Installed in the 1976 Expansion

During the expansion that occurred in 1976, three years after the initial construction phase, insulation in the installed roofing systems was upgraded from 1-in.-thick glass fiber with an R -value of R -4 to 2-in.-thick insulation with an R -8 value.

All roofs of the 1976 expansion (**Fig. 12**) were later resurfaced, with the original BUR roofs remaining in place. The decision to overlay installed roofs with additional roofing layers over time is a common choice. The objective is to extend the lifespan of the roofing systems and address evolving maintenance and performance needs.

The cut test identified the following roof assembly in roof section 6, which was representative of many of the roof sections that were initially installed in this expansion phase and subsequently had additional roof systems installed at later times:

- » Total R -value of insulation = R -8 to R -9.3
- » Second roof—wet overlay assembly (added circa 2006), featuring:
 - MB membrane

- ½ in. (13 mm) perlite overlay board (wet), with R -value of R -1.3
- » First roof—dry base assembly (installed in 1976 and left in place, with gravel surfacing removed), featuring
 - Multi-ply BUR membrane (scrapped)
 - 2 in. (51 mm) thick glass fiber insulation with an R -value of R -8
 - No vapor retarder
 - Steel deck
- » Total dry weight: 12 lb/ft² (58.6 kg/m²)
- » Total weight (at wet areas): 14 lb/ft² (68.4 kg/m²)

Roofing Installed in the 1986 Expansion

The expansion of the shopping center in 1986 marked another major development in the building's construction history, increasing the mall's total surface area significantly (**Fig. 13**).

Cut tests identified that most roofs in this section had their original roof

assemblies in place, and several of these roofs had additional roof systems installed at various times since 1986.

The following assembly at section 21 represented the worst-case scenario:

- » Total R -value of insulation = R -25 to R -26.2
- » Third roof—moist second overlay assembly (added circa 2014), featuring
 - MB membrane
 - ¼ in. (6 mm) hick asphaltic overlay board
- » Second roof—moist first overlay assembly (added circa 2000), featuring:
 - Multi-ply BUR membrane plus gravel, with loose gravel removed
 - ½ in. (13 mm) thick wood fiber (wet) with an R -value of R -1.2
- » First roof—dry base assembly (installed in 1986 and left in place), featuring
 - Multi-ply BUR membrane plus gravel, with loose gravel removed
 - 3.75 in. (95 mm) thick phenolic insulation with an R -value of R -25
 - Kraft paper vapor retarder
 - Steel deck
- » Total dry weight: 23 lb/ft² (112 kg/m²)
- » Total weight (at wet areas): 27 lb/ft² (132 kg/m²)

The installation of a BUR system with phenolic insulation during the 1986 expansion represents a significant advancement in roofing technology for that time period, achieving an impressive R -value of R -25. However, it is important

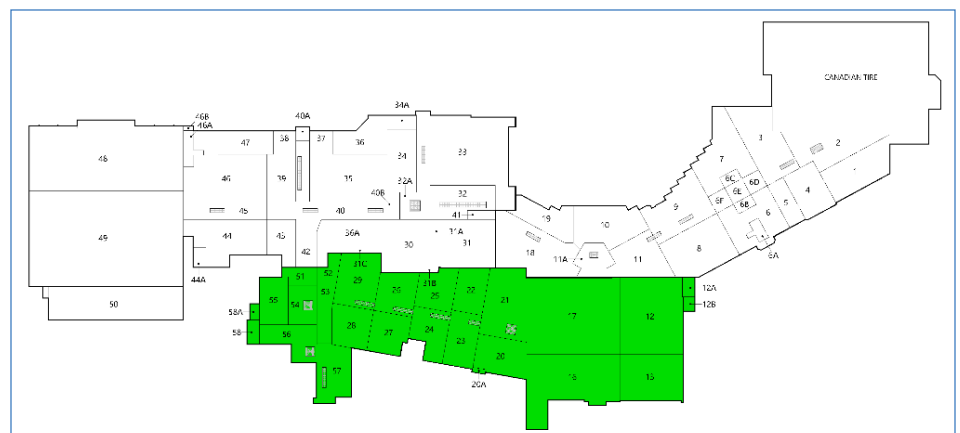


FIGURE 13. Shopping center diagram showing the 1986 expansion in green.

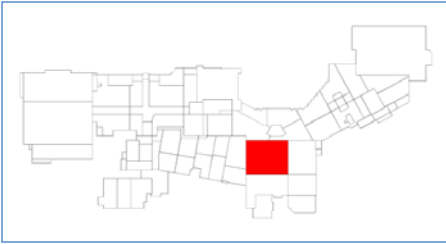


FIGURE 14. Shopping center diagram showing section 17 in red.

to recognize that while phenolic insulation offers excellent thermal performance, it has proven to be the wrong insulation choice because it reacts to moisture absorption by becoming corrosive, affecting any metal surfaces (e.g., screws, metal deck) that come into contact with the wet insulation.

The past decisions to overlay the roofs of the 1986 expansion reflects a common practice in this part of the country (confirmed by interviews with the client and local roofing contractors) aimed at extending the lifespan and enhancing the performance of roofing systems. However, the addition of a BUR overlay in 2000 and another MB roof in 2014 added between 190% to 240% more weight to the roofing structure compared to the original assembly. This substantial increase in weight places significant strain on the structural capacity of the building, potentially exceeding design limits and compromising the integrity and safety of the structure. These findings were reported to the client's structural engineers for their review and actions.

Cost considerations may have influenced the decision-making process to leave existing roof assemblies in place, and

to add secondary roofs, potentially prioritizing short-term cost savings over long-term performance and durability.

The overlay assembly installed circa 2014 included a 6-mm-thick (¼-in.) asphaltic overlay board, which served as a protective and insulating layer between the membrane and the underlying roofing components. This was a common practice of the time in this part of the country.

2007 Replacement of Roof Section 17

In 2007, some of the 1986 construction-phase roofs in one wing were entirely replaced with an MB system (Fig. 14, 15). According to the client, the decision to replace the roofing coincided with a change in tenant and overall renovation to the wing.

The cut tests identified the following roof assembly at roof section 17:

- » Total *R*-value for insulation = *R*-16.2
- » First roof—dry base assembly (installed in 1986), featuring:
 - MB membrane with mechanically fastened base sheet
 - ½ in. (13 mm) thick wood fiber overlay board with an *R*-value of *R*-1.2
 - Two layers of 1.5 in. (38 mm) thick polyisocyanurate insulation with a total *R*-value of *R*-15
 - Kraft paper vapor retarder
 - Steel deck
- » Total dry weight: 3 lb/ft² (14.6 kg/m²)

In discussions with the client, we concluded that the original BUR roof (with possible phenolic insulation) may have been removed completely and replaced with the new MB roof

assembly to address the problems with phenolic insulation (well known by 2007). This change decreased the overall *R*-value in this wing, from *R*-25 to *R*-15, and reduced the weight of the roofing system from approximately 8 lb/ft² to 3 lb/ft² (39 kg/m² to 14.6 kg/m²).

Roof section 17 and the adjacent sections appear to be good candidates for eventual roof resurfacing. In approximately 6 to 8 years, the client could consider salvaging all materials and installing one or two more plies of MB membrane to extend the life of the roofing system by another 20-plus years, or remove the MB membrane, add insulation to enhance the system's *R* value and a MB membrane.

Roofing Installed during the 1993 Theater Expansion

The decision to install BUR systems for the new movie theaters in 1993 was most probably determined by cost. BUR remained a popular choice for certain applications due to its low cost and proven long-term durability.

Figure 16 shows the theater sections, all of which had the original roofing assemblies in place. The cut tests identified the following roof assembly in these three roof sections:

- » Total *R*-value for the insulation = *R*-12.5 to *R*-14
- » Roof assembly (circa 1993), featuring:
 - Gravel surfacing
 - Multi-ply BUR membrane
 - ½ in. (13 mm) thick wood fiber insulation (damp or wet) with an *R*-value of *R*-1.2
 - 2.5 in. (64 mm) thick

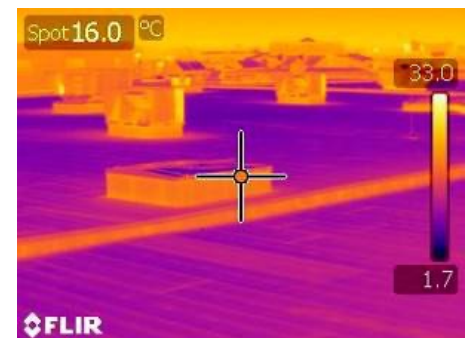
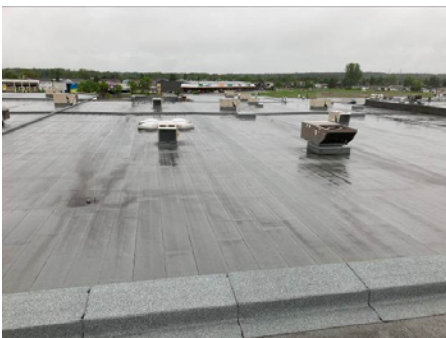


FIGURE 15. Section 17 overall photo, cut test photo and thermal scan – Pretium Eng. project

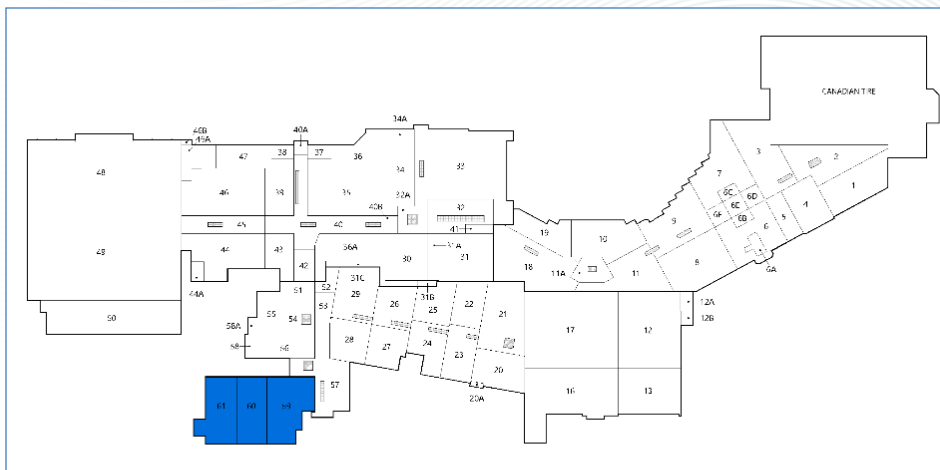


FIGURE 16. Theatre roofs 1993 expansion, plan location, test cut and thermal scan – Pretium Eng. project

polyisocyanurate insulation with an R -value of R -12.5

- Kraft paper vapor retarder
- Steel deck
- » Total dry weight: 7 lb/ft² (34 kg/m²)
- » Total weight (at wet areas): 10 lb/ft² (49 kg/m²)

These roofs were approximately 30 years old and showed signs of extensive

wear, with gravel easily removed from flood-coated felts, bare felts visible in areas, and some wet areas identified by the scans. Some leaks had been reported, primarily at flashing locations and areas around deteriorated HVAC units and ductwork.

As other roofs were prioritized for more immediate work and based on ongoing uncertainty of the tenant's

intent to remain, we recommended that some preventive maintenance be carried out to help prolong the service life of the roofing system and prevent further deterioration. We noted that the roofs in these sections were ideal candidates for resurfacing while salvaging good insulation and vapor retarder materials. Preventive maintenance would be critical until such work could be carried out.

Roofs Installed between 2012 and 2019

Between 2012 and 2019, several smaller additions were added to the shopping center (**Fig. 17**).

2016 Addition

This addition, identified as section 14, has a MB roof system in place (**Fig. 18**).

The cut test identified the following characteristics of the roof assembly:

- » Total R -value of insulation = R -16.2
- » First roof—base assembly (installed circa 2016):
 - Mechanically fastened MB membrane
 - ½ in. (13 mm) thick wood fiber overlay board with an R -value of R -1.2
 - Two 1.5 in. (38 mm) thick layers of polyisocyanurate insulation with a total R -value of R -15
 - Self-adhered MB vapor retarder
 - Deck: Steel deck
- » Total dry weight: 4 lb/ft² (19.5 kg/m²)

The roof was only 7 years old. No thermal anomalies were identified during the review, indicating that the roof system was functioning adequately in terms of thermal insulation and energy efficiency. The assembly, with a good vapor retarder, two layers of ISO insulation, an overlay board, and an MB membrane, would be a good candidate for future roof resurfacing.

2017 TPO Roofs

A cut test was not carried out at the TPO roofs, so the roof system components were not confirmed (**Fig. 19**). These roofs are smaller and are located over storage and exterior canopy areas.

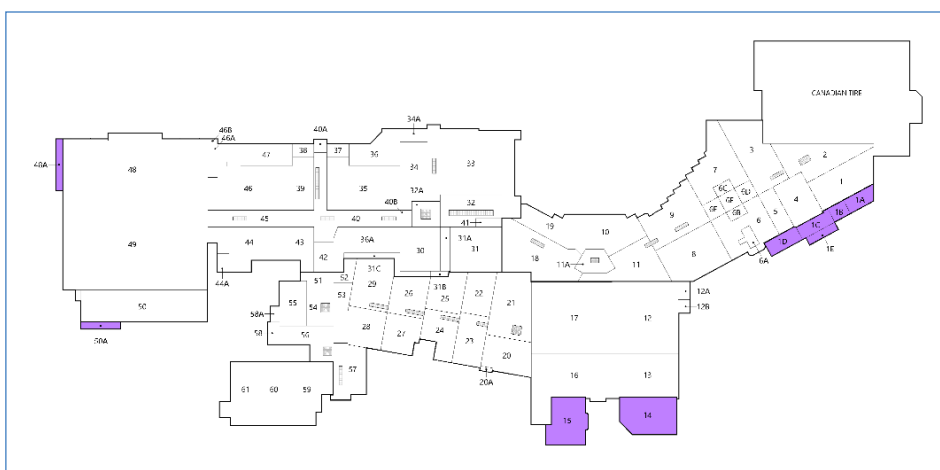


FIGURE 17. 2012 to 2019 additions – Pretium Eng. project

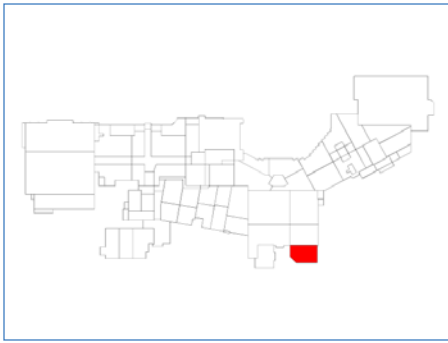


FIGURE 18. 2016 addition - plan location and overall photo – Pretium Eng. project

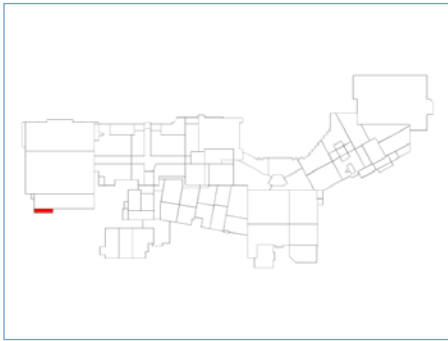


FIGURE 19. 2017 TPO roofs – Plan location and overall photo – Pretium Eng. project

2019 Addition (Five Roof Sections)

The roof systems installed in 2019 are the latest additions (**Fig. 20**). The cut tests identified the following typical roof assembly, with all dry components:

- » Total *R*-value of insulation = *R*-20
- » Roof assembly (installed circa 2019), featuring
 - MB membrane
 - ¼ in. (6 mm) thick asphaltic overlay board
 - Two layers of 2 in. (51 mm) thick polyisocyanurate insulation with a total *R*-value of *R*-20

- Self-adhered MB vapor retarder
- Steel deck
- » Total dry weight: 5 lb/ft² (24.4 kg/m²)

These roofs were only 4 years old. No thermal anomalies were identified during the review, indicating that the roof system was functioning adequately in terms of thermal insulation and energy efficiency. The assembly, with a good vapor retarder, two layers of ISO insulation, an overlay board, and an MB membrane, would be a good candidate for future roof resurfacing (in 16 to 20 years), salvaging all roof system components and adding one or two plies of MB membrane.

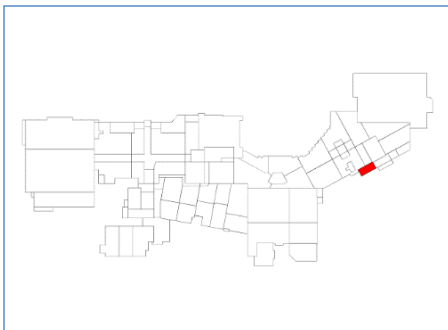


FIGURE 20. 2019 addition – plan location, overall view and cut test – Pretium Eng. project

SUMMARY OF ACTUAL ROOF SYSTEM ASSEMBLIES

After carrying out the roof thermography scan and test cuts at more than 80% of the roof sections, we determined that there were actually six types of roof systems, instead of the three types first identified during the visual review.

Figure 21 shows the results, which are color-coded as follows:

- » **Blue:** Single-assembly MB membrane roofs weighing 3 to 5 lb/ft² (14.6 to 24.4 kg/m²). These lightweight roofs cover approximately 41% of the total area.
- » **Green:** Single-assembly BUR membrane roofs weighing 7 to 9 lb/ft² (34 to 44 kg/m²). These heavier roofs cover approximately 6% of the total area.
- » **Yellow:** Double-assembly MB membrane roofs weighing 11 to 14 lb/ft² (54 to 68 kg/m²). These roofs cover approximately around 47% of the total area.
- » **Orange:** Double-assembly BUR membrane roof weighing 12 to 23 lb/ft² (58.6 to 112 kg/m²). This heavy roof section covers approximately 2% of the total area (replaced in 2024).
- » **Red:** Triple-assembly roof, with MB membrane over two layers of BUR membrane, weighing 14 to 27 lb/ft² (68 to 132 kg/m²). These roofs, which were the heaviest of all roofs, covered approximately 3% of the total area and were replaced in 2024.
- » **Pink:** Single-ply TPO membrane roofs, which were the lightest among the identified assemblies, with a weight of approximately

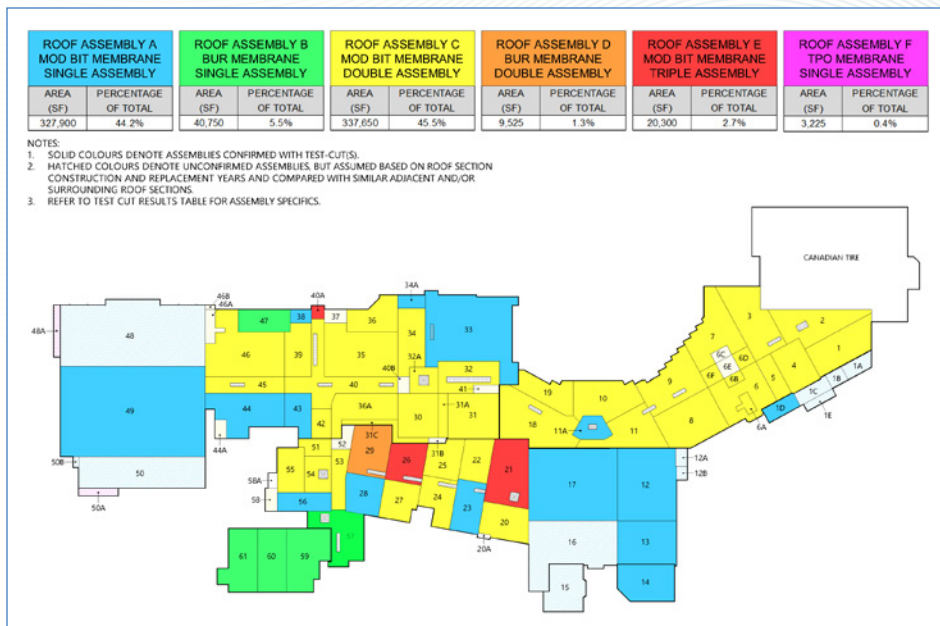


FIGURE 21. Diagram of shopping center showing the six types of roofing systems.

3 lb/ft² (14.6 kg/m²) These roofs cover approximately 0.5% of the total area.

PRIORITIZING INTERVENTIONS BASED ON ROOF SYSTEM DEAD LOADS AND ROOFING CONDITIONS

The recorded actual weights of the roof assemblies highlight significant variations in dead loads across the property (**Fig. 22**). These findings were shared with the client's structural engineers

to reassess structural capacities and prioritize roofing interventions.

In sections where multiple layers of roofs were installed over the original roofing, recorded weights ranged from 3 to 28 lb/ft² (15 to 136 kg/m²). The dead loads calculated by the client's structural engineers based on these actual weights of the roof systems were significantly greater than the loads indicated by the assumed weights of 5 to 8 lb/ft² (24.4 to 39 kg/m²).

Therefore, the engineers reassessed the structural capacities of the roofs. This recalibration was crucial for ensuring the safety and stability of the building under the increased loads imposed by the roofing assemblies.

Collaborative efforts with the client and structural engineers are underway to prioritize roofing interventions based on factors such as weight, roof system performance, and structural considerations. This strategic approach helps allocate resources effectively and addresses critical areas of concern first.

Thermography scans and cut tests were instrumental in identifying wet areas and confirming the composition of roof systems. These diagnostic tools provided valuable insights for informed decision-making regarding roof maintenance and replacements. The identification of wet areas within the roof assemblies prompted targeted repairs aimed at reducing roof weights and improving performance. By addressing moisture infiltration issues, these repairs mitigate further structural strain and prolong the service life of the roofs until replacement becomes necessary.

In some roof sections, the installation of overflow scuppers is being considered to enhance drainage efficiency during periods of excess rainfall. This proactive measure helps prevent water accumulation, mitigate potential water damage, and alleviates additional weight on the roofs.

Figure 23 shows the stresses on the building as a result of the dead loads and identifies the priorities for roof-system weight reductions at key roof sections, with red areas being the most affected.

In anticipation of the structural review completed in 2024, several roof sections in the red zones were replaced in 2023 and 2024. Going forward, the roof replacement program will closely follow the structural plan priorities, while keeping in mind the deterioration of the roofs. This blended approach will eventually address all zones of concern.

Additionally, some structural reinforcement work is underway to address more critical areas. Planning for

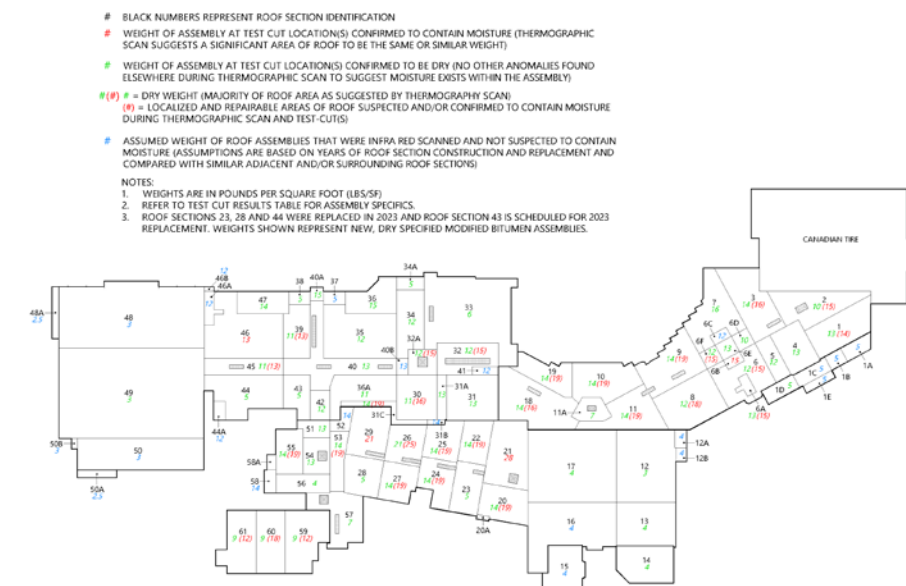


FIGURE 22. Diagram of shopping center showing the weights of the roofing systems.

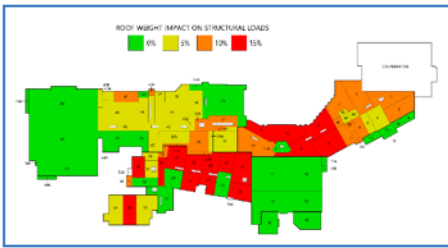


FIGURE 23. Diagram of shopping center showing the impact of roof weights on structural loads.

spot snow removal will also be done, as had been implemented for several years now by the property.

This entire process has required close collaboration among the roofing consultant, the structural engineers, and the property owners to develop and implement comprehensive solutions that address both roofing and structural considerations. This interdisciplinary approach ensures that the building's structural integrity will be maintained while addressing roofing issues effectively.

Figure 24 summarizes the estimated performance ratings for the identified roof assemblies based on their condition. The color coding reflects the overall condition ratings of the roof assemblies, from excellent (green) to poor (red). Most of the roofs (64%), representing an area of 473,000 ft² (44,000 m²) were rated fair to poor.

COMPREHENSIVE CAPITAL EXPENDITURE RENEWAL AND MAINTENANCE PLAN

Working with the structural plan and roof condition plan, we prepared a plan for a 15-year comprehensive roof capital renewal and preventive maintenance program for the client. (The time span of 15 years was requested by the client.) The plan (**Fig. 25**) provides a phased approach for work to be carried out that reflects the need for flexibility in determining which roof sections will be replaced in a given year. For example, phase 1 spans from 2025 to 2027, and within that phase, more than 17 roof sections could be replaced. Each year, the most critical roofs will be selected for replacement to work within the year's available budget.

The operating expense budget includes annual assessments, maintenance, and emergency repairs. The amount budgeted for operating expenses will decline over the years, as more capital expenditure work is carried out.

ROOF REPLACEMENT WORK UNDERTAKEN IN 2023 AND 2024

The existing roof system at section 28, which was installed during the 1986 phase, was replaced in 2023. The original roofing system had the following roof assembly (**Fig. 26**):

- Total *R*-value of the insulation = *R*-25
- Multi-ply BUR membrane
- A wet, 13-mm-thick (½-in.) wood fiber overlay board with an *R*-value of *R*-1.2
- 89-mm-thick (3.5-in.) phenolic insulation with an *R*-value of *R*-24; 20% of the insulation area was wet
- Kraft paper vapor retarder
- Steel deck with surface rust in some areas
- Total dry weight: 10 lb/ft² (48.8 kg/m²)
- Total Weight (at wet areas): 13 lb/ft² (63.5 kg/m²)

This roof had been scheduled for replacement since 2019. The insulation deteriorated and became saturated with moisture at the valley, affecting its thermal performance and contributing to potential corrosion and structural issues. Some leaks were identified and repaired locally over time. The roof weight was over the allowable structural load limits, so the loose gravel ballast was removed to reduce the weight until the replacement work started. It is interesting to see that the UV deterioration was not as intensive over a four-year period. The roof was scheduled for replacement in 2020, but replacement was deferred due to budget constraints until 2023.

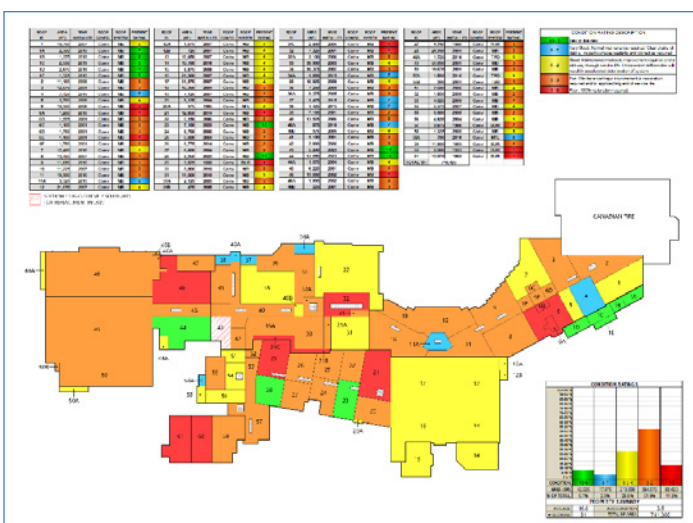


FIGURE 24. Performance ratings for the identified roof assemblies based on their condition.

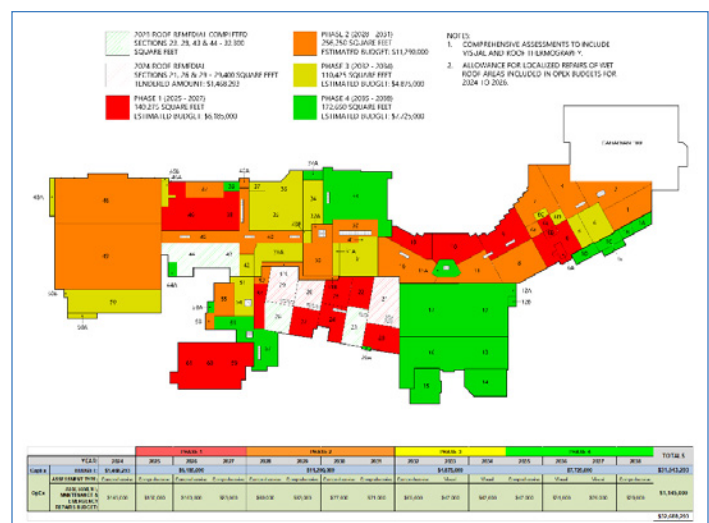


FIGURE 25. Operating and Capital Expenditure Plan – Pretium Eng. project



FIGURE 26. Roof Section 28 prior to replacement – Pretium Eng. project

No roof system components could be salvaged. The 2023 roof replacement maintained the same *R*-value (*R*-25), whereas the weight was reduced overall to 5 lb/ft², which is within the structural limits. The new roofing assembly is now composed of the following characteristics (**Fig. 27**):

- Single-ply MB membrane cap sheet
- Composite MB membrane and overlay board
- Two layers of 2.5 in. (64 mm) thick polyisocyanurate insulation with a total *R*-value of *R*-25 (design *R* value)
- MB self-adhered vapor retarder
- ½ in. (13 mm) thick gypsum core, adhered underlay board
- Steel deck
- (Total dry weight: 5 lb/ft² (24.4 kg/m²))

An emergency drainage overflow scupper was incorporated into the design to mitigate the risk of water accumulation during intense storms. This scupper provides additional



drainage capacity to prevent water ponding and minimize the potential for roof leaks or structural overload.²

Sacrificial MB membrane was installed at units and walkways to provide added protection against wear and tear around serviceable units and access points to the roof section.

CONCLUSION

The case study presented in this paper offers several key lessons that can be applied more generally to roofing evaluations and the development of strategies for maintenance, repair, and replacement projects.

Testing

On projects where historical documentation about roof assemblies are unreliable, it is important to invest in appropriate testing to collect the information needed to determine the weights, compositions, and performance of actual roofs. In this case, the client agreed early in the process to complete roof thermography and cut tests to help

evaluate the characteristics of the assemblies in place.

Evolution of Roofing Technology

When a project involves roofing systems installed across different construction phases, it is helpful to understand how roofing technology and materials have evolved over time, and what the industry was promoting and installing at various stages. On this project, we drew from our historical knowledge of roofing in Canada and local industry knowledge of similar work, while evaluating the types of membranes installed and the types of insulation used in the initial constructions stages and when subsequent roofs were installed over these original roofs.

Impact of Decisions Made Regarding Roof Replacement and Roof Overlays

This case study highlights how decisions made for short-term benefits may lead to serious problems over the long term. On this project, when aged roofs needed to be replaced, the older roofs typically remained in place and additional roofs were installed over them. These decisions, while probably economical at the time, adversely affected both the roofs' service lives and the building's structural integrity. As a result, the client must replace most of the roofs and address structural reinforcements. Salvaging options are very limited.

Similarly, the roof overlays selected for the shopping center were probably considered environmental benefits at the time. However, they have become performance, environmental, structural, and cost liabilities today.



FIGURE 27. Roof Section 28 after replacement - photos – Pretium Eng. project

Insulation and Energy Efficiency

The investigation of roofing systems from the different construction phases of the shopping center demonstrates how efforts to enhance thermal performance and reduce energy consumption have changed since the 1970s. Furthermore, the variations in insulation types and *R*-values seen in this case study highlight that projects may need multifaceted strategies to meet future energy-efficiency requirements.

Future Planning and Resilience

The property's roofing history underscores the importance of long-term planning and resilience in managing roofing assets. To the extent possible, it is important to anticipate future climate conditions, energy regulations, and technological advancements so that clients can make informed decisions about roof maintenance, upgrades, and replacements that will facilitate

the continued functionality and sustainability of the building. In this case, strategies to prepare for the future include installing overflow scuppers, repairing areas to prolong the service lives of roofs, increasing *R*-values when future roof remedial work occurs, designing for proper drainage, and installing roof systems and membranes that can be easily maintained and retrofitted.

Proper Roof Refurbishment Approaches

In creating the 15-year program for the client, we looked for opportunities to salvage roofing system components whenever possible. Unfortunately, as many of the roofs had multiple layers and added significant weights to the structure, most roofs could not be salvaged (the theatre roofs are one exception, as well as the newer installed MB roofs). However, the new and future replacement roofs will be designed such that the existing roof system

components can be left in place in the future, adding membrane layers to extend the roof service life.

Sustainable roof design practices

The case for salvaging roof system components is becoming increasingly compelling, especially considering the significant impact that salvage can have on sustainability, resource conservation, and overall building performance. Refurbishing roofs presents an opportunity to reduce the environmental footprint associated with construction activities. By salvaging materials and implementing sustainable practices such as carbon footprint reduction and end-of-life recycling, the roofing industry can contribute to overall environmental preservation and sustainability goals.

We all have a responsibility to act in the best interests of our climate and future generations of users of our buildings.

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Blindside Waterproofing Systems for Hydrostatic Conditions: Lessons Learned & Good Practices

ABSTRACT

In densely populated areas and where hydrostatic conditions exist, particularly near large bodies of water, the application of fully encapsulated blindside waterproofing systems, otherwise called “bathtubbing,” has become a common practice. As such, minimal standards exist for the performance of typical blindside waterproofing systems on a new construction project, let alone the more challenging “bathtub” application. A comprehensive approach is warranted in the selection and installation of waterproofing systems with consideration of construction challenges, performance requirements, and available options. With the use of alternative construction techniques, such as shotcrete in lieu of poured-in-place concrete for foundation walls, different challenges are experienced that require appropriate additional measures to reduce the risk of water leakage. This session presents the lessons learned from successful projects and projects with leakage issues as they relate to construction practices and detailing of the waterproofing system. The presentation will also discuss the findings from stand-alone mock-ups and follow-up full scale testing. Designers, consultants, and constructors will benefit from the session by better appreciating the challenges, risks, proper installation procedures, and mitigation measures in addressing failures of blindside bathtub waterproofing and thus propagating knowledge toward long-term performance.

SPEAKER



Christopher McConnell, BTech
EXP Services Inc.

Over his 10-years-plus career, Chris McConnell has gained experiences in a wide variety of fields and disciplines, including custom house design, general contracting, and consulting services related to noise, vibration, new construction, concrete rehabilitation, façade restoration, and waterproofing problem solving. He provides services to several types of clients in the commercial, industrial, and residential sectors, including services across Canada where he liaises with other EXP offices and manages the team remotely for highly successful projects. He is a graduate of McMaster University, where he finished summa cum laude in his bachelor of technology course.

LEARNING OBJECTIVES

- » Identify available waterproofing materials for blindside bathtub waterproofing systems.
- » Discuss perimeter foundation wall construction techniques and their implications on the selection of the appropriate blindside bathtub waterproofing systems.
- » Identify blindside bathtub waterproofing systems for best performance results based on construction challenges (pre-emptive versus reactive).
- » Explain the impacts of failure of the blindside bathtub waterproofing system, either due to construction practices or material selection.
- » Explore available options to resolve localized and systemic water leakage after installation.

INTRODUCTION

With the increasing demand for housing and expansive growth of multi-unit residential building (MURB) developments in downtown Toronto and neighboring communities, the number of below-grade levels, particularly for parking, continues to extend deeper. Blindside below-grade waterproofing has become an essential component of multi-unit residential building developments in constructing watertight foundation walls, primarily to accommodate parking spaces. The proximity of the communities in and around downtown Toronto to Lake Ontario has led to these below-grade assemblies inevitably reaching hydrostatic conditions with high water table conditions.

Given the current local municipal restrictions on collecting and discharging water around and below-grade foundations into the municipal storm and sanitary systems, all new buildings within the Toronto municipal area are required to be 100% watertight through an application method of below-grade waterproofing, widely known as "bathtubbing." This is achieved through a combination of excavations using caisson wall soil retention (tiebacks, rakers, and other retention methods), site dewatering (removal of active water to lower the water table during construction), raft slabs, and a waterproofing system that fully encompasses the below-grade structure ("bathtub" waterproofing).

To improve project schedules and reduce construction costs, developers consistently source alternative construction methods, and one such method is shotcrete. Shotcrete is a

method of concrete placement that has been in the industry for several decades and has recently been used for foundation wall construction with blindside waterproofing applications. Shotcrete allows for faster foundation wall construction, which allows for a reduction in the construction schedule. There are also the A-frame (Fig. 1) and the conventional poured methods (utilizing a wall form with threaded rods to hold forms in place) (Fig. 2). The A-frame allows for the construction of foundation walls that would produce the fewest penetrations through the blindside waterproofing. This is achieved by supporting the reinforcement cage above the forms and above the waterproofing system, and then removing the anchors when the next level is poured, allowing for waterproofing to be installed without penetration. The conventional poured method utilizes a threaded rod

technique that holds the interior form in place by anchoring it to the soldier piles. This method will require the securement of the form and the reinforcement bar cage through the membrane, and it will be necessary for the waterproofing to be detailed around them.

In addition to the construction methods, considering the water table for a specific site is also important. Understanding if a site has a high, medium, or low water table and the number of below-grade floors being constructed helps to identify what type of hydrostatic condition the below-grade floors will be under. Once the level of hydrostatic pressure is confirmed, selecting suitable materials and the details to accompany them is the next step.

With the new requirements needing "bathtub" application of blindside waterproofing and the condition

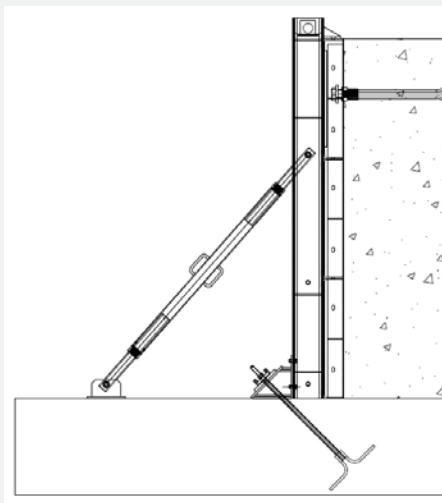


FIGURE 1. A-Frame for foundation walls construction method cross section

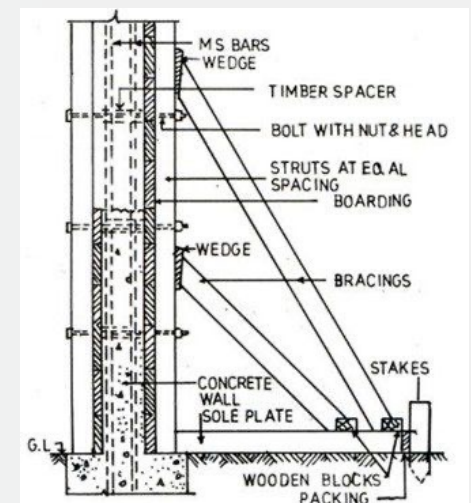


FIGURE 2. Conventional Framing for foundation walls construction method cross section

of hydrostatic pressure behind the foundation walls, shotcrete foundation walls have proven to contribute to failures in achieving the watertight condition required for the below-grade structure. The installation process of the shotcrete creates situations that are detrimental to the waterproofing adhesion process, wherein for most systems 100% adhesion is required to be an effective and reliable waterproofing system. Therefore, other means of construction, aside from shotcrete, are required to achieve a watertight condition for the blindside “bathtub” waterproofing systems.

WATERPROOFING MATERIALS FOR BLINDSIDE “BATHTUBBING”

Understanding the problem is only the beginning of establishing a path towards a successful watertight structure. To start, let us review the different types of waterproofing systems that are presented by their various manufacturers as being the right product for the site conditions. Some systems are sheet and liquid membranes that require 100% adhesion, while others require a two-stage system utilizing sheet membranes and a bentonite layer in hydrostatic conditions. The two-stage system is required to have a sheet membrane over the entire foundation wall structure but also requires a bentonite sheet layer within and just above the water table area. This additional layer of protection provides a back up to the main waterproofing membrane sheet. The bentonite is intended to swell and seal a breach in the main sheet reducing the possibility of water penetrating through the membrane and subsequently through the foundation walls.

There are several types of blindside waterproofing products, but the most common fully adhered systems are high-density polyethylene (HDPE) sheets, elastomeric sheets, Styrene-Butadiene-Styrene (SBS) modified bitumen sheets, bentonite sheets, and spray-applied elastomeric coatings. There are other waterproofing systems that are used in the industry that are not as common in the residential construction industry. These materials are thermoplastic polyolefin (TPO), polyvinyl chloride (PVC)

and Bentonite systems. These are not all fully adhered systems and depending on the soil and ground water conditions these systems may not be suitable for selection. With all the different types of materials, it is a challenge to know when to use which product to give the project the best chance for success.

The more we allow for a hydrostatic condition to occur around the below-grade structure, the higher the waterproofing system’s risk of failure. It has been recently identified that the use of drainage boards for the “bathtub” waterproofing systems can allow for water to flow freely around the structure and fill up with water to a point that is equal in elevation to the existing water table. Therefore, under these conditions, hydrostatic pressure has not been eliminated as intended with the introduction of a drainage board. If the drainage board can be eliminated and the waterproofing applied to a relatively smooth surface, this could reduce the amount of water directly behind the foundation wall and reduce the risk of excessive water infiltration. This can also be achieved by installing diaphragm soil retention walls, which have a higher strength than the conventional caisson walls we see in today’s construction. This can act as an additional line of

defense for keeping the water away from the foundation walls and assist the waterproofing system to achieve watertightness protection.

INVESTIGATION OF WATER INGRESS THROUGH FOUNDATION WALLS

Having had the opportunity to investigate a couple of structures with systemic failures of their waterproofing systems, we have begun to understand the causes of the failures and understanding these are common occurrences on construction sites. These failures are resulting in excessive amounts of water leakage through the foundation walls at cracks and construction joints. These investigations involved foundation walls constructed using a shotcrete method, and the structure was subjected to high water table conditions (high hydrostatic head). We utilized a number of non-destructive investigation methods for this investigation. One of the investigation techniques was the review of documentation from the construction process, such as third-party or Bulletin 19 (B19) field observation reports (Ontario requirement for new homeowner constructed developments), manufacturer reports, and a review



FIGURE 3. Shotcrete overspray on sheet membrane after form work was removed. No additional overspray removals were expected.

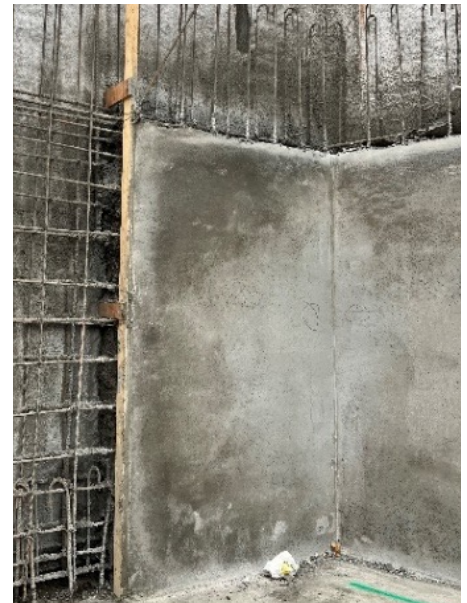


FIGURE 3. Shotcrete installation on sheet membrane and overspray is approximately 2 ft (0.6 m) beyond construction joints.



FIGURE 5. Water infiltration through foundation wall at column location.



FIGURE 6. Water infiltration through foundation wall cracks at corner.

of the dewatering decommissioning process. Using this information, we were able to identify suspected failure modes. Shotcrete foundation wall construction introduces several high-risk situations if not completed correctly or in the appropriate timelines. Due to shotcrete's low water to cement ratio, the dryer mix will cure much faster and will result in waterproofing adhesion failures if not applied in smaller increments. There is also the potential for rebar shadowing, unconsolidated material (voids), and overspray on the membrane creating a bond breaker within the waterproofing system, this has led to several failure modes of the waterproofing membrane not bonding as required and allowing for water travel through the foundation wall. If water leaks in the foundation wall are more localized and isolated, this could potentially point to a single failure mode as the source of the issue. One of the non-destructive testing methods we utilized to confirm a failure mode was ultrasonic pulse echo (UPE) analysis. The UPE analysis helped to assess the condition of the shotcrete while also identifying items such as tiebacks, potential waterproofing membrane failures, and the thickness of the walls at given locations.

During the review of the documentation, we were able to identify several areas where

the waterproofing was covered in overspray material from the shotcrete process (**Fig. 3 and 4**). This information helped us to see a possible correlation between some of the leak locations of the constructed walls (**Fig. 5 and 6**). We used this information to help in the selection of walls for the non-destructive investigation method utilizing the UPE analysis.

The UPE analysis provides information through acoustic stress waves from the interior surface of the foundation wall to the caisson wall and, in some cases, through the caisson wall. These waves help to locate defects or anomalies in the concrete wall that are dissimilar to solid concrete. This information can be utilized to extract information pertaining to the condition of the shotcrete, which identifies anomalies along the path of the UPE signal. A review of these results can tell us if there are areas of voids, cavities, or gaps in construction. We were able to use this information to not only find areas of concern in the shotcrete but also to find areas of membrane bonding issues, with a good degree of accuracy. In addition, we found and mapped out the locations of tiebacks where the signal reflection was much shorter due to the tieback being closer than the expected thickness of the foundation walls. Utilizing this process, we were able to

select locations to conduct concrete coring through the foundation wall to collect physical data and compare them with the analysis information.

Following the coring process, it was confirmed that the membrane had adhesion issues. This appears to have been caused by shotcrete overspray, unconsolidated concrete (voids) and material bonding issues with the dryer mix of the shotcrete. What we did not expect to find was that the shotcrete and liquid waterproofing materials that are used to detail tiebacks were not adhered, either. It was also discovered that one area had unconsolidated concrete at the backside of the foundation wall (**Fig. 7 and 8**), rebar shadowing had occurred (**Fig. 9 and 10**), and a waterproofing lap joint was not fully adhered (**Fig. 11 and 12**). The extensive water intrusion through the foundation wall was the result of several failure modes such as tieback anchors, unbonded membrane at shotcrete overspray locations, and partially bonded overlap joints. For more information on this subject please refer to my first paper published through the 16th annual Canadian Conference on Building Science and Technology titled "Lessons Learned – Moisture Ingress Protective Waterproofing Systems."

HOW TO REMEDIATE A SYSTEMIC "BATHTUB" WATERPROOFING SYSTEM FAILURE

As there are several products to waterproof the blind side of a below-grade structure, there are also several materials available to assist in remediating a systemic failure of the waterproofing system. A repair method called curtain grout injection uses the following materials currently on the market: bentonite polymers, acrylic/acrylates, polyurethane foams, and rubber polymer gels. These materials are either hydrophobic or hydrophilic in nature. Hydrophobic materials are those that repel water; while they will use some water for the activation process, once the curing process has begun, they will disperse water away. Hydrophilic materials are those that absorb water; they will use the water as part of the curing process and require moisture to maintain their gelatinous states. There

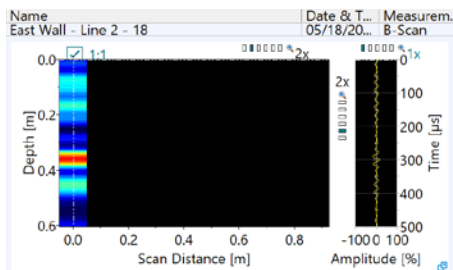


FIGURE 7. UPE analysis measurement at unconsolidated concrete location.



FIGURE 8. Extracted core from foundation wall showing unconsolidated concrete.

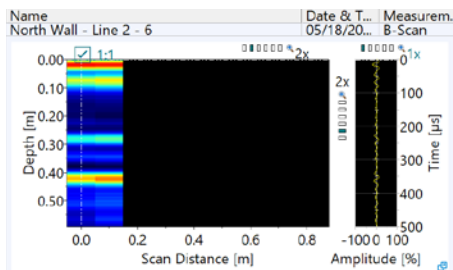


FIGURE 9. UPE analysis measurement at reinforcement bar shadowing location.



FIGURE 10. Extracted core from foundation wall showing reinforcement bar shadowing.

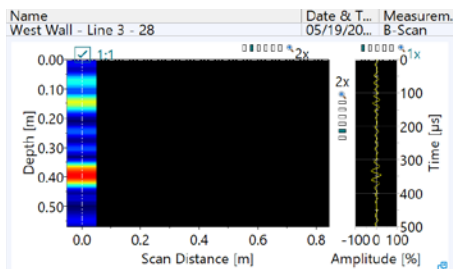


FIGURE 11. UPE analysis of concrete where lap detail and waterproofing adhesion failure were found.



FIGURE 12. Extracted core of foundation wall waterproofing where the membrane was not adhered due to shotcrete overspray.

membrane and construction system have failed to keep the building in a dry condition. Therefore, material warranty and material selection to accommodate the site conditions are critical to ensuring a successful remediation process. This is a scenario where one solution does not fit all, and therefore appropriate research into the product and retaining a consultant that has adequate experience is essential. Most of these materials require water to be present behind the walls during the injection process, which is beneficial, as dewatering the site after the structure is in place is extremely costly and difficult.

MATERIAL MOCK-UP PROCESS

We conducted a full-scale mock-up of four blindside “bathtub” waterproofing system material types on an A-frame and a conventional form and pour construction process. We incorporated the different types of details in the mockups that would reflect in-situ construction practices, such as pre- and post-applied penetrations, reinforcement anchors, tieback boxes, changes in surface elevation (soil retention), and smooth surface application (soil retention) without drainage boards. The intent of these mock-ups was to review the waterproofing systems following the installation of reinforcement and concrete for a 1.83 metre (6 ft) high wall with details reflective of real-world construction practices (as can be reasonably duplicated). The concrete was poured using a bucket attached to a crane to drop the concrete into the forms with no protection to the overlap waterproofing material.

Once the concrete reached acceptable structural capacity (confirmed using concrete cylinders cast for each wall) the backside of the forms where the waterproofing was installed against were removed. This exposed the waterproofing material which was bonded against the exterior face of the foundation wall mock-up. Following the exposure of the waterproofing materials, we removed the drainage boards where possible (some of the systems the drainage board are bonded to the membrane as part of the installation process) to expose

Hydrophobic Pros	Hydrophobic Cons	Hydrophilic Pros	Hydrophilic Cons
Pushes water away	Displaces water	Absorbs water; will continue to absorb water	Shrinks when it dries
Remains in a solid state, regardless of moisture presence	Has poor adhesion on wet surfaces	Is flexible and can bridge cracks	Loses flexibility when it dries
Becomes lighter than water when curing	Has poor flexibility after curing; cannot bridge cracks	Has better adhesion to wet surfaces	

are pros and cons to each material, and the site condition is critical to the selection of the appropriate materials.

The curtain grouting process is an intrusive procedure and will act as the new watertightness defense if the

the membrane at these drainboard locations. A visual and tactile review of the membranes took place to identify possible areas of debonding. Areas that were suspected of debonding were checked by completing a field adhesion test (the membrane was cut with a knife in a rectangle around the suspected area and grabbing the top of the cut section and attempting to remove by pulling perpendicular to the wall). A majority of the suspected areas were unbonded with some membranes performing better than others. A contributing factor to the unbonded waterproofing appears to be due to consolidation issues of the concrete (vibration was inadequate).

During the visual review we also noted that the top of the waterproof membranes were covered in concrete splatter from the installation of the concrete. Based on these findings the details and material selection are not the only major requirements but also the installation of concrete and the placement of the reinforcement within the foundation walls.

Lastly the walls were then sectioned off and laid down on their backs to facilitate the dissection and collection of the samples to be sent to an ASTM rated lab. We are having three tests performed for each membrane type: Hydrostatic Head Testing (ASTM

D5385 – Modified), Lateral Water Migration (AATCC TM127) and Concrete Adhesion ASTM D4541. These tests are to verify how the waterproofing would perform in the hydrostatic conditions of a blindside “bathtub” application including their ability to bond to post applied poured concrete. Quantitative test results are currently outstanding and will be received later.

HIGH TO MEDIUM HYDROSTATIC CONDITIONS

Understanding the performance of the materials and their restrictions can help in identifying what changes are needed to the design of the soil retention system and the selection of a framing method. In some cases the height of the water table could dictate which measures are needed to increase the chance of success. In a high to medium hydrostatic conditions, the water table could be four (or more), to two levels above the slab on grade. Understanding the site at the design stage and its expected hydrostatic condition is more important these days, due to the inherent risk it poses to ensuring the watertight condition of the below-grade structure. Upgrading the soil retention system to a higher-strength wall with water impermeability, specifically in the use of a Diaphragm wall, needs to be greatly considered. The implementation of this soil retention can allow for minimal damage to the caisson wall during the excavation process, resulting in a smoother surface. This will allow the waterproofing membrane to be installed directly on the wall without the use of a drainage board. Without the drainage board present, the chance for excess water to build behind the foundation wall will be reduced. Isolation of the tiebacks using tieback boxes is required at the structural design stage by the structural engineer. This detail will allow for the isolation of the tieback from the foundation wall embedment and remove the risk of difficult detailing of the tieback.

The use of A-frame construction to reduce the number of penetrations through the membrane will increase the chances of a successful watertight structure.



FIGURE 13. UPE Elastomeric Sheet Waterproofing Installed.



FIGURE 14. High-Density Polyethylene Sheet Waterproofing Installed.



FIGURE 15. UPE Elastomeric Spray Applied Waterproofing Installed.

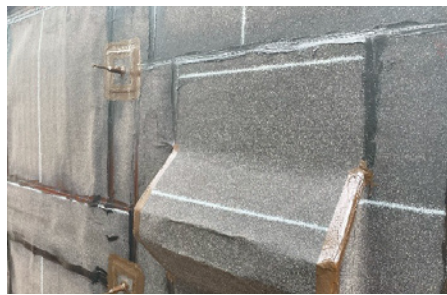


FIGURE 16. Styrene Butadiene Styrene Modified Bitumen Waterproofing Installed.



FIGURE 17. UPE Formwork in place for Pouring of Concrete from Bucket.



FIGURE 18. Concrete Splatter is found on overlap joint above the concrete pour.

The use of a dewatering system that carries the water behind the waterproofing system through the collection at pits can be very beneficial to the success of the waterproofing system. Some dewatering systems are completed with a series of water tubes and follow behind the waterproofing. However, this method requires that a large breach in the membrane be used to collect the tubes at one location from the dewatering wells. This penetration and method of dewatering can lead to water infiltration if the details are not completed adequately or if there is water coming through the dewatering system if it is not adequately sealed.

Finally, the selection of a waterproofing system that is designed and approved for these hydrostatic conditions is important. The system must be able to withstand the hydrostatic conditions at the weakest points of the system (that is, penetration details, lap joints, and repair patches). If the system cannot demonstrate successful applications in similar project conditions and the manufacturer cannot provide a letter of approval for the use of their system for your specific site conditions, a new material or system needs to be considered.

LOW TO MINIMAL HYDROSTATIC CONDITIONS

Low to minimal hydrostatic conditions can be considered with a water table being one to zero levels above the slab on grade, respectively. These conditions are at less risk of failure but still need to be given respect and attention to achieve the successful performance required. Use of the A-frame method in water table conditions for the site and tieback boxes are still recommended, but this process could potentially be modified in the non-hydrostatic levels. The membrane system will still need to be capable of preventing water infiltration, but the areas with no hydrostatic conditions may alter the manufacturers' requirements for a successful system. In these scenarios, it is often the under-slab waterproofing and the lowest level of the structure that are in the water tables. This will allow for a more conventional process for the levels above the water table that should be able to be performed as required.

CONCLUSION

Construction methods and blindside "bathtub" waterproofing systems have their appropriate uses, and knowing their limitations or restrictions is vital. Identifying the necessary construction methods early in the design stage can

reduce the risk of critical items during the construction process. It is necessary to select appropriate waterproofing systems with the intention to protect the reinforced concrete elements and reduce the moisture ingress into spatial conditions. The waterproofing of below-grade structures is successful only when it is done correctly the first time. Repairs or remedial measures to a failed waterproofing system applied to a buried structure are financially impractical from an excavation and repair standpoint. Remedial repairs from the negative side (interior space) by way of curtain grout injection can be a viable option, but they are very costly and intrusive due to the required process. The extent of water migration is dependent on the path that the water finds through the concrete elements and its ability to move laterally between the membrane system and the structure. If the waterproofing membrane system is not fully bonded to the structure, water can travel to areas that have a high risk of moisture ingress. Therefore, an appropriate material selection and construction methodology at the design stage, accompanied by quality control during the construction stage, is essential to mitigate potential failures of the waterproofing system and premature failure of the building components.

APPLICABLE STANDARDS

Ontario Building Code, 2012

ASTM D903-98(2017), Standard Test Method for Peel or Stripping Strength of Adhesive Bonds

ASTM D5385-93(2006), Standard Test Method for Hydrostatic Pressure Resistance of Waterproofing Membranes

ASTM E154-08, Standard Test Methods for Water Vapor Retarders Used in Contact with Earth under Concrete Slabs, on Walls, or as Ground Cover

ASTM E96/E96M-14, Standard Test Methods for Water Vapor Transmission of Materials

ASTM D412, Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers—Tension

ASTM D1970, Standard Specification for Self-Adhering Polymer Modified Bituminous Sheet Materials Used as Steep Roofing Underlayment for Ice Dam Protection

ASTM D4833, Standard Test Method for Index Puncture Resistance of Geomembranes and Related Products

ASTM D4068, Standard Specification for Chlorinated Polyethylene (CPE) Sheeting for Concealed Water-Containment Membrane

Decarbonizing Building Materials: Exploring the Embodied Carbon of Structure and Enclosure Systems

ABSTRACT

This session will explore the crucial role of engineers, architects, and design team members in the selection of low-carbon building materials to alleviate the environmental impact of both new and existing structures. A comprehensive overview of industry standards for life-cycle assessment (LCA) reporting, including ISO 14040 to 14044 environmental management, the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, up-front embodied carbon, and absolute embodied carbon intensity, will be discussed. This session is designed to equip design and construction teams with the knowledge needed to effectively implement LCA processes, thereby contributing to local and global efforts to combat climate change. By focusing on standards such as the Toronto Green Standard, LEED, and Canada Green Building Council's Zero Carbon Building – Design Standard, attendees will gain detailed insights into material selection and decision-making processes. Furthermore, practical solutions for reducing a building's environmental footprint will be presented. This session is essential for architects, engineers, contractors, and sustainability consultants seeking guidance on aligning their decisions with sustainability objectives. By exploring practical methods to mitigate carbon emissions, participants will position themselves to play an active and influential role in driving positive change within the construction industry.

SPEAKER



**Sean Moore, SEBT,
LEED AP BD+C**
[Pretium Engineering Inc.](#)

Sean Moore is a solution-oriented sustainability professional with 10 years of experience in sustainability consulting and a specialization in building material selection and life-cycle assessment. Moore has collaborated with interdisciplinary teams to implement innovative design and construction solutions across various building types. His expertise in LEED certification, zero carbon design, carbon, and energy optimization has guided projects to meet the highest levels of sustainable building and performance standards. Moore's deep commitment to environmental stewardship has played a pivotal role in advancing the integration of sustainable practices within the built environment.

LEARNING OBJECTIVES

- » Describe the process of embodied carbon reporting, including ISO 14040/14044, TRACI, and other life cycle assessment methodologies.
- » Discuss practical strategies for reducing the environmental footprint of buildings through the selection of low-carbon building materials, which can be implemented in their projects immediately.
- » Explain how the application of industry standards, such as the Toronto Green Standard, LEED, and CaGBC Zero Carbon Design enables informed decisions aligned with sustainability goals.
- » Explore methods to mitigate embodied carbon emissions to drive positive change within the construction industry.

WHAT IS THE URGENCY TO ADDRESS CLIMATE CHANGE AND REDUCE GREENHOUSE GAS (GHG) EMISSIONS?

Global temperatures, weather patterns, and seasons are experiencing significant changes, often referred to as global warming or climate change. This concern has prompted worldwide action to address and mitigate the impacts related to climate change. The US Environmental Protection Agency (EPA) and Environment and Climate Change Canada (ECCC) collaborate with global agencies as part of the Intergovernmental Panel on Climate Change (IPCC).^{1,2} The IPCC has continued to collect data on environmental factors since the mid-20th century, focusing on GHG emissions such as carbon dioxide (CO₂), methane, and nitrous oxide. This data is imperative for predictive climate modeling, which has shown that GHG emissions related to the Industrial Revolution and human activities have reached historically elevated levels compared to emissions over the past 800,000 years.^{1,2} According to the IPCC, human-induced warming had reached 1°C (33.8°F) above pre-industrial levels by 2017, with predictions of global temperatures rising between 0.1°C (32.18°F) and 0.3°C (32.54 F) per decade.¹

In response to these worrying trends, the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement, comprising 195 global members, have committed to climate change reduction goals.^{2,3} The primary objective is to curb the increase in global surface air and sea temperatures to 1.5°C (34.7°F) and

mitigate emissions through public and private collaboration to ensure that we can sustain a healthy planet for future generations. **Figure 1** illustrates an exponential increase in temperatures globally since 1940. This underscores the importance of mitigating emissions by reducing both operational and embodied carbon emissions.

ECCC COMMITMENTS⁵

Canada signed the UNFCCC Paris Agreement in 2015, and since then, Canada has implemented federal commitments to reduce GHG emissions compared to 2005 emission levels by 40% to 45% by 2030, while striving to achieve net-zero emissions by 2050. In 2021, Canada passed the Canadian Net-Zero Emissions Accountability Act, which ensures accountability and transparency as the country works with all levels of provincial and municipal government to deliver on aggressive targets.⁴

CANADA EMISSION PROJECT AND PROGRESS TOWARD 2030 CLIMATE TARGETS

ECCC and the Net-Zero Advisory Body were launched in February 2021 and are consistently tracking progress towards meeting reduction goals. **Figure 2** outlines historical and projected emissions for the benchmark period of 2005 to 2035.⁵

US NATIONAL CLIMATE TASK FORCE COMMITMENTS

The US signed and joined the UNFCCC Paris Agreement treaty alongside Canada in 2015.^{3,4} Since joining the treaty, the EPA and the White House have created a National Climate Task Force⁶ to address climate change, and they have developed the following goals:

1. Target a 50% to 52% reduction in GHG emissions by 2030 compared to 2005
2. Pursue 50% electric vehicle sales share by 2030
3. Achieve 100% carbon-pollution-free electricity by 2035
4. Target net-zero emission economy by 2050

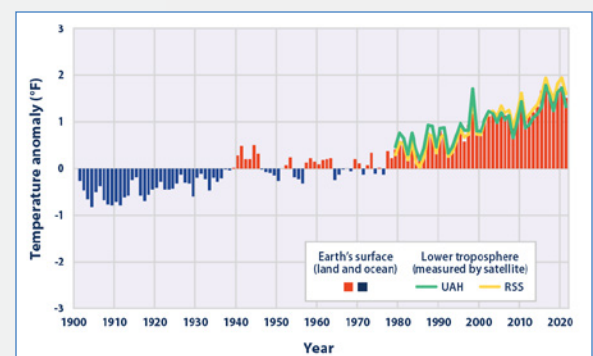


FIGURE 1. Global temperature trends.¹

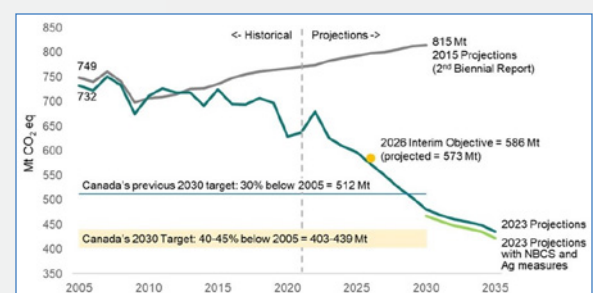
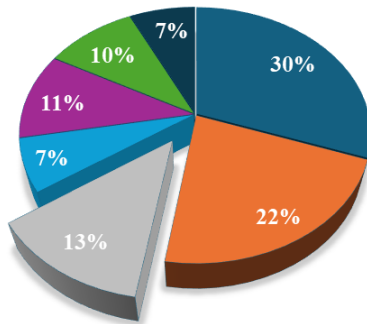


FIGURE 2. Canada emission projections.⁵

Canada GHG Emissions by Sector (2022)

Oil and gas Transport Buildings
Electricity Heavy Industry Agriculture
Waste and Other



U.S GHG Emissions by Sector (2022)

Oil & Gas Transport Buildings
Electricity Heavy Industry Agriculture
Waste & Others

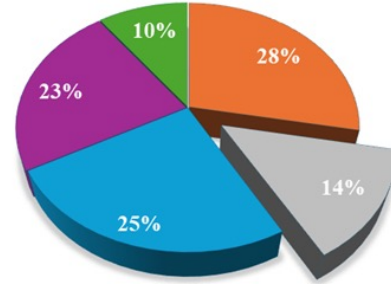


FIGURE 3. Canada greenhouse gas (GHG) emissions by sector.⁸

FIGURE 4. US greenhouse gas (GHG) emissions by sector.⁹

WHY IS LCA IMPORTANT?

To meet our global commitments to reduce GHG emissions, designing buildings to reduce operational and embodied carbon is vital to curb global temperature increase. According to the International Energy Agency, buildings account for approximately 28% of global carbon emissions,¹ which is correlated to the operational and embodied carbon emissions of buildings. In Canada, buildings contribute to 13% of GHG emissions, with 11% attributed to embodied carbon, making buildings the third-highest carbon emitter in the country. Similarly, in the US, buildings account for 35% of total GHG emissions, with approximately 8% linked to embodied carbon. Given these significant emissions, LCA is an assessment that allows design teams to make informed strategies to meet ambitious climate goals, such as Canada's target to reduce GHG emissions by 40% by 2030 and achieve net-zero emissions by 2050.⁵

Here are four reasons why conducting an LCA is valuable:

- 1. Quantifying Environmental Impact:** LCA facilitates the quantification of environmental impacts for buildings through their life cycle, including manufacturing, resource depletion, GHG emissions, and waste generation from construction and deconstruction of building materials.
- 2. Material Resource Efficiency:** Analyzing the entire life cycle of a building promotes resource

efficiency by exploring alternative design options and reducing materials, which can lead to cost savings while providing a more balanced use of resources.

- 3. Proactive Decision-Making:** LCA provides comprehensive data analysis to highlight key priorities and inform the decision-making process early in design. This enables architects, engineers, and the owner to compare distinct design options against baseline building archetypes while communicating the project's progress of reducing emissions through the entire process.
- 4. Regulatory Compliance and Certification:** LCA demonstrates compliance with increasing sustainability regulations to achieve green building certifications such as LEED, Toronto Green Standard (TGS), Canada Green Building Council's (CAGBC's) Zero Carbon Building – Design Standard, and additionally regions that have developed their own standards.

HOW CAN LIFE-CYCLE ASSESSMENT (LCA) PLAY A ROLE IN DECARBONIZING THE BUILT ENVIRONMENT?

LCA is a method used to estimate the environmental impacts of products, processes, and the primarily focuses on envelope and structure materials throughout the life cycle of a building. This life cycle goes from raw material extraction, manufacturing to disposal

and replacement. This comprehensive approach, often referred to as "cradle to grave" (A-C), helps with understanding the environmental footprint of different building materials. Peter Drucker who is an Austrian American educator, author and primarily focused on management theory stated, "You can't manage what you can't measure,"⁷ which highlights the importance of collecting and analyzing detailed data to make informed decisions. This is validated by conducting LCA, which assesses material manufacturing data from the industry to verify effective options to reduce embodied carbon emissions. When conducting an LCA, the scope of assessment must include a 60- to 100-year life cycle, which allows for quantified results of the up-front embodied carbon (A) to the end-of-life stage (C).

In North America, the building sector for both the US and Canada made up to 14% of the overall GHG emissions (Fig. 3 and 4).^{8,9} This may not appear significant in the overall breakdown of emissions, but since the population in North America is predicted to increase by 10.13 million by 2030,¹⁰ reducing the emissions for predicted building demand will be imperative when considering the practical strategies to meet emission reduction commitments.

WHAT IS THE LIFE-CYCLE STAGES OF BUILDING MATERIALS?

There are three main stages in LCA reporting methodology, with an additional stage that looks beyond

the 60-year life cycle. The assessment of the whole building's structure and building envelope covers the entire lifespan of each building product, from raw material extraction to end-of-life disposal. These stages include specific processes and activities that contribute to the overall environmental impact and follow International Organization for Standardization (ISO) reporting requirements.

Figure 5 displays the scope for product and building LCAs.

WHAT ARE THE INDUSTRY STANDARDS THAT GOVERN LCA?

Industry standards in North America follow ISO and are enhanced by regional and national green building standards. LCA was introduced as a tool for manufacturers of building products to increase transparency, primarily reported through Environmental Product Declarations (EPDs). The adoption of industry-wide and product-specific EPDs has provided more detailed insight and available resources for design and construction teams to conduct LCA and provide practical solutions. To provide an example of commonly used EPDs, the National Ready-Mix Association (NRMCA)¹¹ and the Canadian Ready-Mix

Concrete Association (CRMCA)¹² regularly updates their industry-wide EPD with the latest manufacturing and new mix design information. This governing body ensure that the latest in concrete mix design are reflected in EPDs, which LCA software providers include to assist design teams with accurate data to include in the assessment.

Below are the three main standards that govern both product and building LCA methodology.

ISO 14040/14044, *Environmental Management – Life Cycle Assessment – Principles and Framework*,¹³ *Life Cycle Assessment – Requirements and Guidelines*.¹⁴

These sections provide the foundational principles and framework for conducting LCA studies, including guidance on defining goals and scope, inventory analysis, impact assessment, and interpretation of results. The process included in this standard helps to supports the UN Sustainable Development Goals (SDG) 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), which aligns with Corporate Sustainability Reporting and Environmental Social Governance (ESG) initiatives.

ISO 21930:2017, *Sustainability in Buildings and Civil Engineering Works – Core Rules for Environmental Product Declarations of Construction Products and Services*.¹⁵

This standard provides a detailed framework for creating EPDs for construction products and services. It outlines principles and requirements for LCAs, including goal definition, life-cycle inventory analysis, life-cycle impact assessment, and result interpretation. The standard enforces consistent rules for data quality, system boundaries, and relevant environmental impact categories. This is important for LCA analyst and when selecting an appropriate software to conduct compliant analysis.

WHAT ARE THE DIFFERENT LIFE-CYCLE IMPACT CATEGORIES (LCICs)?

LCICs provide a consistent industry framework for assessing the environmental impacts associated with building materials.

Two primary methodologies used for LCIC reporting are:

- 1. Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), developed by the EPA.¹⁶
- 2. Center of Environmental Science, Leiden University (CML), often used in Europe.¹⁷

TRACI

The Environmental Protection Agency (EPA) developed the TRACI framework, which provides a set of impact assessment categories that quantify the environmental effects of pollutants and resource use. The main categories that are applied in most LCA software and required for green building certification are:

- 1. Global Warming Potential – Embodied Carbon
- 2. Acidification Potential
- 3. Eutrophication
- 4. Smog Formation Potential
- 5. Ozone Depletion Potential
- 6. Resource Depletion Potential

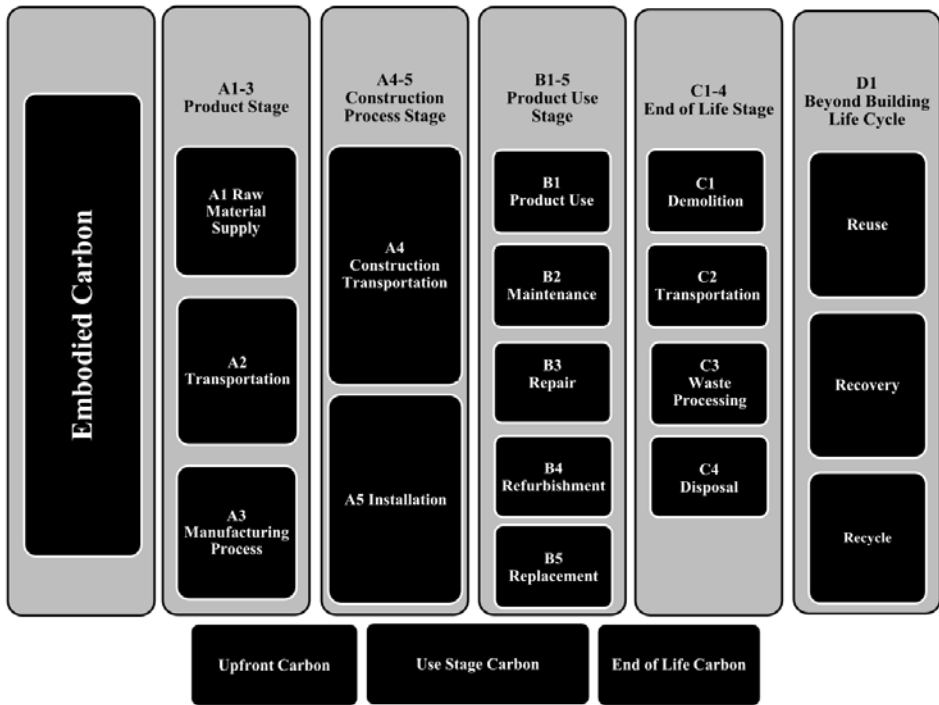


FIGURE 5. Life-cycle stages.

Based on the LCIC standards used in North America, the common goal is to quantify building material environmental impacts, which can be reported in many ways. Global warming potential (GWP), another term for embodied carbon, is a key metric, but LCA software can assess multiple LCICs. It is important to consider multiple impact categories when selecting environmentally preferred materials. For instances, choosing a different type of insulation, cladding, roof membrane, or structure may result in significant embodied carbon reduction but may increase the environmental impact in another category. The LCA software's are all capable of assessing multiple LCICs, so it is important to consider the entire environmental impact, while there's an opportunity to make an impact.

The LEED rating system has addressed this concern by first requiring

buildings to conduct an LCA, then reducing embodied carbon emissions, followed by receiving points for further reductions without negatively impacting other LCIC categories by more than 5%.¹⁹

Table 1 below summarizes the six (6) main TRACI LCICs and more human health effects as outlined by the CML.

WHAT ARE THE LCA REPORTING METRICS FOR REGIONAL AND NATIONAL STANDARDS?

Following the detailed summary of LCA background in this paper and how the standards are governed, it is important to know the final output requirements, which are outlined in Table 2. The embodied carbon reporting metrics vary depending on region and sustainable building certification program being pursued. It

is important to engage an experienced LCA professional that can help your team navigate the requirements and conduct the assessment as early in the design process as possible.

The key focus below is on the main embodied carbon metrics, thresholds, and LCA stages for:

- 1. TGS Version 4: Mid- to High-Rise Residential and Non-Residential
- 2. LEED Version 4.1 and Version 5
- 3. CAGBC Zero Carbon Building – Design Version 4
- 4. City of Vancouver Embodied Carbon Guidelines Version 1

WHAT ARE THE MAIN LCA SOFTWARE TOOLS AVAILABLE?

Integrated LCA software tools are necessary when assessing whole-building life cycle, as they allow users to model design options compared to an archetype baseline building to produce LCA results and reduction options. A full LCA is not necessary if you are looking to replace a specific product with an alternative but when assessing a complete retrofit or design of a new building, selecting the right LCA specialist and software is important. Software's provide compliant EPD and reporting metrics to ensure that LCA assessment provides the latest industry information, while including quantified material takeoffs and bill of materials to depict the building's design. Below is a list of whole-building LCA that are commonly utilized and follow standards that align with the standards included in **Table 2**:

- 1. Athena Impact Estimator for Buildings²⁴
- 2. One Click LCA
- 3. Tally

The above LCA software tools follow industry standards for reporting of multiple sustainable standards with varying integration capabilities. Athena Impact Estimator is a free software that is recognized for utilizing TRACI LCIC, with a focus on North American building construction. It includes industry-wide EPDs and product-specific EPDs for select suppliers. One Click LCA is a user-friendly software

TABLE 1. Environmental impact category summary

Environmental impact category	LCIC standard	Reporting metric	Environmental impact
Embodied carbon or global warming potential	TRACI	kg CO ₂ eq	Contributes to climate change by preventing heat from leaving the Earth's atmosphere ¹⁵
Acidification potential	TRACI	kg SO ₂ eq	Causes soil and water acidification, harming ecosystems, and aquatic life ¹⁵
Eutrophication potential	TRACI	kg N eq	Leads to excessive growth of algae, depleting oxygen and harming aquatic life ¹⁵
Smog formation potential	TRACI	kg O ₃ eq	Contributes to the formation of smog, causing respiratory and cardiovascular issues ¹⁵
Ozone depletion potential	TRACI	kg O ₃ eq	Leads to increased ultraviolet radiation reaching the Earth's surface, potentially causing skin cancer and harming ecosystems ¹⁵
Resource depletion	TRACI, CML	MJ	Focuses on the sustainability of resource use and the implications of depleting finite resources ¹⁵
Human health	CML	Disability-adjusted life years	Effects from air pollutants (for example, particulate matter, NOx causing respiratory diseases, cancers, and other health issues ¹⁶

Note: LCIC = life-cycle impact category; TRACI = Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts; CO₂ = carbon dioxide; SO₂ = sulfur dioxide; N = nitrogen; O₃ = ozone; CML = Center of Environmental Science, Leiden University, MJ= Mega Joules, NOx- Nitrogen Oxide.

TABLE 2. Embodied Carbon Reporting Metrics: Green Building Standards

Certification Standard	Options/Tiers	Reporting metric
LEEDv4.1¹⁹		
Building life-cycle impact reduction Whole-building LCA	(1–4 pts.) Path 1: Conduct an LCA (1 pt.)	1. Conduct an LCA for building and propose reduction strategies for A-to-C scope
	Path 2: LCA 5% reduction (2 pts.)	1. 5% embodied carbon reduction 2. 5% reduction in three other LCIC categories
	Path 3: LCA 10% reduction (3 pts.)	1. 10% embodied carbon reduction 2. 10% reduction in three other LCIC categories.
	Path 4: LCA 20% reduction and reused or salvaged materials (4 pts.)	1. 20% embodied carbon reduction 2. Include reused or salvaged building materials
LEEDv5²⁰		
Integrated Process Carbon Assessment Prerequisite	New prerequisite to conduct an LCA of up-front embodied carbon (A stage)	1. Provide total up-front embodied carbon emissions. 2. Add 0.5 times the GWP for building materials to account for up-front embodied carbon of MEP, interiors, and furnishings.
Reduce Embodied Carbon	Option 1: Whole-building LCA (1–6 pts.)	1. Path 1: 10% reduction (2 pts.) 2. Path 2: 20% reduction (3 pts.) 3. Path 3: 30% reduction (4 pts.) 4. Path 4: 40% reduction (5 pts.) 5. Add 1 pt. if the project shows a 20% reduction in three or more LCICs.
CAGBC Zero Carbon Building – Design v3²¹		
Embodied Carbon	Applicant must provide LCA reporting for life-cycle stages A to C	Applicant must report building embodied carbon intensity. Minimum performance: 1. 10% embodied carbon reduction 2. <500 kg CO ₂ e/m ² Innovation strategy: 3. Strategy 1: 20% reduction or <350 kg CO ₂ e/m ² 4. Strategy 2: 40% reduction or <240 kg CO ₂ e/m ²
CAGBC Zero Carbon Building – Design v4²¹		
Whole-Building Life Cycle Assessment (wbLCA)	Applicant must provide LCA reporting for life cycle stages A to C	Path 1: Embodied Carbon Intensity Maximum Limit 1. 425 kg CO ₂ e/m ² for all buildings except warehouse & distribution centres 2. 350 kg CO ₂ e/m ² for warehouse & distribution centres Path 2: Improvement Over Baseline 1. 10% embodied carbon reduction Innovation strategy options: 2. Limit upfront carbon emissions to zero or less. 3. 20% reduction or <350 kg CO ₂ e/m ² 4. <350 kg CO ₂ e/m ² for warehouse & distribution centres. 5. 40% reduction or <260 kg CO ₂ e/m ²

Table 2 continues on the next page >

TABLE 2. Embodied Carbon Reporting Metrics: Green Building Standards (continued from previous page)

Certification Standard	Options/Tiers	Reporting metric
Toronto Green Standard v4 ²²		
Embodied emissions	Tier 2: GHG 2.1: low embodied emissions	Conduct an LCA for up-front embodied emissions following CAGBC Zero Carbon Building – Design. Demonstrate embodied carbon intensity of <350 kg CO ₂ e/m ² .
	Tier 3: GHG 2.2: extra-low embodied emissions	Demonstrate embodied carbon intensity of 250 kg CO ₂ e/m ² .
City of Vancouver Embodied Carbon Guidelines Version 1.0 ²³		
Embodied carbon guidelines	Conduct an LCA for all new developments and report on embodied carbon intensity (kg CO ₂ e/m ²). Part 3 buildings must report whole-building embodied carbon results and set limits that building will not be more than two times the baseline as part of the building permit submission. It is likely that projects will be required to show a 10% or 20% reduction relative to baseline embodied carbon starting in January 2025.	

Note: LCA = life-cycle assessment; LCIC = life-cycle impact category; GWP = global warming potential; CAGBC = Canada Green Building Council; CO₂ = carbon dioxide; GHG = greenhouse gas, MEP= Mechanical, Electrical, Plumbing.

with subscription-based fees, and it can be integrated with CAD software, architectural bill of materials and reports for multiple international LCA reporting requirements. Tally is well-known for its integration with CAD software’s bill of materials, which can be directly imported from Autodesk software such as AutoCAD and Revit.

WHAT ARE THE KEY FOCUS AREAS TO REDUCE EMBODIED CARBON?

The process of reducing embodied carbon emissions can appear onerous, but when assessing different building types and locations, there are some main principles to consider even before conducting an LCA. To simplify the task of LCA, following the EPA’s Resource Conservation and Recovery Act’s 3Rs (reduce, reuse, recycle) principle when first considering a building project, helps to reduce excess materials, reuse existing material or salvaged structure. Following the initial steps of reducing building materials, is the consideration of structure and envelope, with optimized scenarios to include recycled content. Often many building materials already include recycle content, but by conducting an LCA, the analyst can assess the effect of location, suppliers and even specific products for materials such as: concrete, steel,

aluminum, insulation, fenestration, roofing membrane to find the optimal path to reduce the embodied carbon of your new construction or retrofit project. After considering opportunities to retrofit or adaptively reuse a building, performing an LCA is the best opportunity to quantify design strategies and propose reduction opportunities.

When acquiring property that may require demolition, assessing an envelope or structural retrofit or when advancing the design of a new-construction project, these fundamental principles should be considered to reduce the environmental footprint.

1. **Consider the 3Rs Principle:** Where there is opportunity to first reduce the use of new building materials, by reusing existing buildings, materials, this is the most impactful way to reduce the emissions of buildings. If this is not an option, then looking to reuse material or specify low-carbon materials should be explored. Finally, implementing circular economy principles, building materials recycled content or capability to be recycled or fixed towards the end of its service life should be explored.
2. **Engage an Experienced LCA/ Sustainability Consultant:** Engaging an experienced sustainability

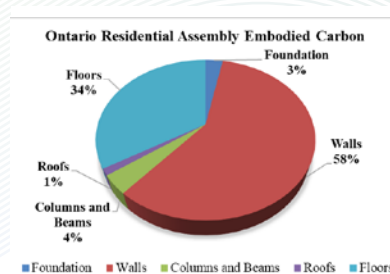
consultant early in the conceptual design phase enables the design team to adopt an integrated approach, addressing embodied carbon, energy performance, sustainability certification requirement, and local code requirements.

3. **Optimize Structural Design Early in the Design Stage:** Consider the following key areas:
 - a. Steel construction or prefabricated products (If applicable)
 - b. Lighter-weight and durable envelope cladding.
 - c. Opportunity for Hybrid timber versus steel or concrete
 - d. Reduce ceiling height
 - e. Reduce quantity of columns
 - f. Opportunity to include steel or timber in mechanical penthouse.
4. **Assess Slag Cementitious Content (SCM) Mix Designs:**
 - a. SCM content in the range of 15% to 25% is preferred for above-grade concrete slabs to meet high early strength development, rapid setting times, and desired finish requirements. If proper scheduling and concrete specification are developed, incorporating 25% to 35% SCM

content can be considered. The input of concrete suppliers and structural engineers is important when considering alternative mix-designs.

- b. SCM content of 25% to 35% often can be incorporated in below-grade footings, piles to reduce embodied carbon but must be assessed early and communicated on concrete setting times to ensure efficient construction and strength development.
- c. Portland limestone cement (GUL) over general use (GU) cementitious content alone can provide 5% to 10% embodied carbon reduction without introducing additional recycled content.

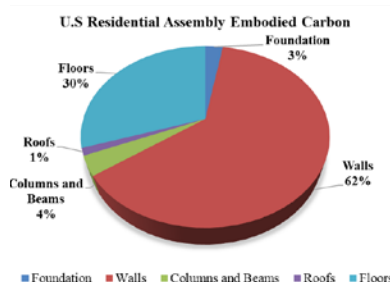
5. **Assess Building Insulation Type:**
It is important to assess against code requirements, sustainability requirements, and embodied carbon impact for optimal product selection. It is important to consider the insulation value (R-value), durability and embodied carbon impact of insulation since the wall assembly group comprised 58% to 62% of the overall buildings embodied carbon. Exploring options such as mineral wool, fibreglass but depending on the application you may require more wall cavity depth, material and potential for absorbing moisture over time. Selecting the right insulation type is dependent on energy performance goals, building code and the constructability when integrating into the overall assembly.
6. **Assess the Cladding Options:** The selection of cladding materials can make a huge difference in reducing the embodied carbon of building with over 50% of residential buildings surface area being wall area. Consideration of lighter-weight metal, fibre cement, EIFS, insulated metal panels (IMP), often provide significant reductions over masonry, precast and cement-based cladding.
7. **Provide regular LCA Updates:**
It is important to conduct LCA at a conceptual stage, design development and construction documents stage to keep stakeholders engaged and to ensure



LCA Measures	Unit	Total	Foundation	Walls	Columns and Beams	Roofs	Floors
Assembly %			3%	58%	4%	1%	34%
Global Warming	kg CO ₂ eq	8.11E+06	2.48E+05	4.72E+06	3.05E+05	1.06E+05	2.73E+06
Acidification	kg SO ₂ eq	4.36E+04	6.57E+02	3.20E+04	1.01E+03	6.30E+02	9.26E+03
HH Particulate	kg PM _{2.5} eq	9.74E+03	2.91E+02	4.93E+03	3.26E+02	4.14E+02	3.79E+03
Eutrophication	kg N eq	6.43E+03	1.45E+02	4.46E+03	1.63E+02	6.12E+01	1.60E+03
Ozone Depletion	kg CFC-11 eq	5.97E+00	7.04E-03	5.87E+00	7.43E-03	2.51E-03	7.82E-02
Smog	kg O ₃ eq	9.57E+05	1.76E+04	6.35E+05	2.79E+04	1.09E+04	2.65E+05
Primary Energy	MJ	8.50E+07	2.11E+06	5.31E+07	3.08E+06	2.30E+06	2.44E+07
Non-Renewable Energy	MJ	8.10E+07	2.01E+06	5.06E+07	2.90E+06	2.22E+06	2.32E+07
Fossil Fuel Consumption	MJ	7.03E+07	1.67E+06	4.45E+07	2.57E+06	1.86E+06	1.97E+07

Note: LCA = life-cycle assessment; CO₂ = carbon dioxide; SO₂ = sulfur dioxide; N = nitrogen; CFC = chlorofluorocarbon; O₃ = ozone.

FIGURE 6 & TABLE 3. Baseline residential assembly impact: Canada.



LCA Measures	Unit	Total	Foundations	Walls	Columns and Beams	Roofs	Floors
Assembly %			3%	62%	3%	1%	30%
Global Warming Potential	kg CO ₂ eq	8.90E+06	2.47E+05	5.56E+06	3.09E+05	1.06E+05	2.68E+06
Acidification Potential	kg SO ₂ eq	4.81E+04	8.98E+02	3.36E+04	1.26E+03	7.69E+02	1.16E+04
HH Particulate	kg PM _{2.5} eq	9.14E+03	2.22E+02	5.62E+03	2.48E+02	3.65E+02	2.68E+03
Eutrophication Potential	kg N eq	8.10E+03	2.45E+02	4.88E+03	2.65E+02	9.49E+01	2.61E+03
Ozone Depletion Potential	kg CFC-11 eq	2.86E+01	5.92E-03	2.09E+01	6.32E-03	2.18E-03	6.26E-02
Smog Potential	kg O ₃ eq	1.03E+06	2.30E+04	6.47E+05	3.37E+04	1.31E+04	3.17E+05
Total Primary Energy	MJ	9.19E+07	1.91E+06	6.28E+07	2.92E+06	2.34E+06	2.19E+07
Non-Renewable Energy	MJ	8.90E+07	1.83E+06	6.09E+07	2.78E+06	2.30E+06	2.11E+07
Fossil Fuel Consumption	MJ	8.41E+07	1.74E+06	5.76E+07	2.68E+06	2.00E+06	2.01E+07

Note: LCA = life-cycle assessment; CO₂ = carbon dioxide; SO₂ = sulfur dioxide; N = nitrogen; CFC = chlorofluorocarbon; O₃ = ozone.

FIGURE 7 & TABLE 4. Baseline residential building assembly impact: US.

that building materials selected align with the project's goals and considering the entire life cycle of the products selected.

WHAT ASSEMBLIES CONTRIBUTE THE MOST TO EMBODIED CARBON EMISSIONS?

When conducting an LCA, the building materials are inputted into an approved software by individual building material assemblies. Depending on the building type and performance requirements, the assembly groups' embodied carbon impact can vary but quantifying the biggest impact areas will assist in developing a project-specific strategy.

Overall, the results outlined in **Figure 6** and **Figure 7** below provide an example of LCA results, based on a conventional 30-story high-rise with 4 underground parking levels in North America. The LCA was conducted for both Canada and the US to demonstrate different approaches and design priorities depending on location and performance requirements.

To summarize the findings, the largest embodied carbon emissions for a high-rise residential building are in the wall assembly category (58% to 62%),

followed by concrete slab floors (30% to 34%) and then concrete columns (4%). Conducting an LCA for your retrofit or new construction will help to assess against industry benchmark and embodied carbon intensity metrics, to assist the team in to focus efforts to reduce the embodied carbon emissions and environmental footprint of the development.

WHAT LCA SOFTWARE WAS UTILIZED FOR THIS STUDY?

To perform accurate LCA analysis, following industry LCA requirements and TRACI reporting impact categories, Athena Sustainable Materials Institute's Impact Estimator for Buildings Version 5.5.0108 (Public Release) was utilized.²⁴ An archetype building for high-rise residential structure and envelope was used to provide a common scenario to demonstrate key focus areas and opportunities to reduce embodied carbon.

TABLE 5. LCA stage impact: residential baseline Canada

		Total Impact	Product (A1 to A3)	Construction process (A4 and A5)	Product Use (B1-B5)		End of life (C1 to C4)
Embodied carbon stage %		100%	73%	16%	3%		8%
LCA measures	Unit	A to C	Total	Total	Replacement total	Total	Total
Global warming	kg CO ₂ e	8.11E+06	5.91E+06	1.32E+06	2.32E+05	2.32E+05	6.51E+05
Acidification	kg SO ₂ e	4.36E+04	2.10E+04	1.28E+04	2.08E+03	2.08E+03	7.64E+03
HH particulate	kg PM 2.5e	9.74E+03	3.93E+03	8.20E+02	3.46E+02	3.46E+02	4.64E+03
Eutrophication	kg N eq	6.43E+03	4.78E+03	1.04E+03	6.30E+01	6.30E+01	5.43E+02
Ozone depletion	kg CFC-11e	5.97E+00	5.65E+00	2.86E-01	9.62E-03	9.62E-03	2.56E-02
Smog potential	kg O ₃ e	9.57E+05	2.99E+05	3.97E+05	1.68E+04	1.68E+04	2.45E+05
Primary energy	MJ	8.50E+07	5.65E+07	1.46E+07	4.40E+06	4.40E+06	9.48E+06
Non-renewable energy	MJ	8.10E+07	5.30E+07	1.44E+07	4.21E+06	4.21E+06	9.41E+06
Fossil fuel consumption	MJ	7.03E+07	4.41E+07	1.39E+07	3.02E+06	3.02E+06	9.25E+06

Note: LCA = life-cycle assessment; CO₂ = carbon dioxide; SO₂ = sulfur dioxide; N = nitrogen; CFC = chlorofluorocarbon; O₃ = ozone.

TABLE 6. LCA stage impact: residential baseline US

		Total Impact	Product (A1 to A3)	Construction process (A4 and A5)	Product Use (B1-B5)		End of life (C1 to C4)
Embodied carbon stage %		100%	74%	16%	3%		7%
LCA measures	Unit	A to C	Total	Total	Replacement total	Total	Total
Global warming	kg CO ₂ eq	8.91E+06	6.57E+06	1.40E+06	2.84E+05	2.84E+05	6.56E+05
Acidification	kg SO ₂ eq	4.81E+04	2.47E+04	1.35E+04	2.25E+03	2.25E+03	7.63E+03
HH particulate	kg PM 2.5 eq	9.17E+03	3.24E+03	8.24E+02	4.61E+02	4.61E+02	4.65E+03
Eutrophication	kg N eq	8.11E+03	6.04E+03	1.13E+03	3.70E+02	3.70E+02	5.70E+02
Ozone depletion	kg CFC-11 eq	2.87E-01	2.36E-01	1.24E-02	1.23E-02	1.23E-02	2.60E-02
Smog potential	kg O ₃ eq	1.03E+06	3.55E+05	4.16E+05	1.84E+04	1.84E+04	2.44E+05
Primary energy	MJ	9.19E+07	6.27E+07	1.55E+07	4.20E+06	4.20E+06	9.49E+06
Non-renewable energy	MJ	8.90E+07	6.00E+07	1.54E+07	4.09E+06	4.09E+06	9.47E+06
Fossil fuel consumption	MJ	8.42E+07	5.61E+07	1.52E+07	3.63E+06	3.63E+06	9.31E+06

Note: LCA = life-cycle assessment; CO₂ = carbon dioxide; SO₂ = sulfur dioxide; N = nitrogen; CFC = chlorofluorocarbon; O₃ = ozone.

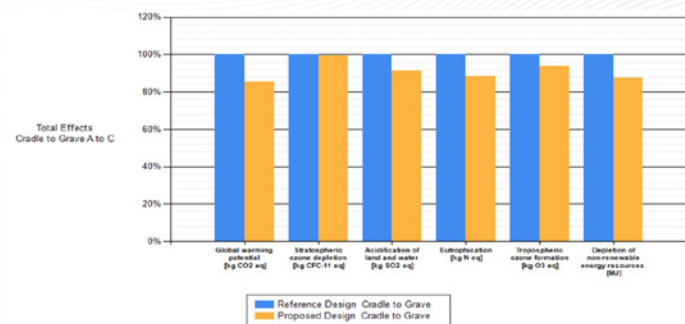


FIGURE 8. Optimal embodied carbon reduction scenario: Canada.

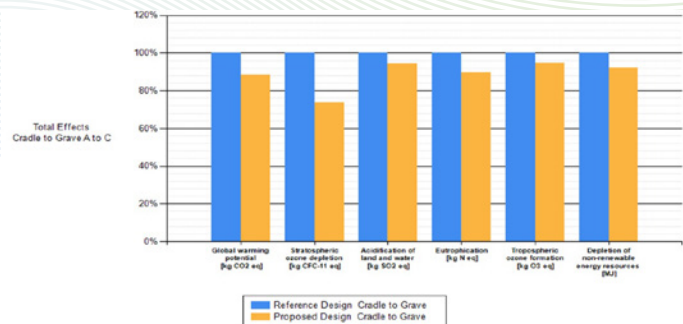


FIGURE 9. Optimal embodied carbon reduction scenario: US

TABLE 7. Embodied carbon reduction scenario: Canada

Summary Measure	Unit	Reference Design Total Effects Cradle to Grave A to C	Proposed Design Total Effects Cradle to Grave A to C	% Difference
Global warming potential	kg CO2 eq	8.11E+06	6.94E+06	-14.44%
Stratospheric ozone depletion	kg CFC-11 eq	5.97E+00	5.93E+00	-0.67%
Acidification of land and water	kg SO2 eq	4.36E+04	3.97E+04	-8.86%
Eutrophication	kg N eq	6.43E+03	5.67E+03	-11.84%
Tropospheric ozone formation	kg O3 eq	9.57E+05	8.97E+05	-6.22%
Depletion of non-renewable energy resources	MJ	8.10E+07	7.09E+07	-12.44%

TABLE 8. Embodied carbon reduction scenario: US

Summary Measure	Unit	Reference Design Total Effects Cradle to Grave A to C	Proposed Design Total Effects Cradle to Grave A to C	% Difference
Global warming potential	kg CO2 eq	8.90E+06	7.86E+06	-11.74%
Stratospheric ozone depletion	kg CFC-11 eq	2.86E-01	2.11E-01	-26.41%
Acidification of land and water	kg SO2 eq	4.81E+04	4.55E+04	-5.50%
Eutrophication	kg N eq	8.10E+03	7.25E+03	-10.45%
Tropospheric ozone formation	kg O3 eq	1.03E+06	9.78E+05	-5.35%
Depletion of non-renewable energy resources	MJ	8.90E+07	8.21E+07	-7.75%

WHAT LIFE-CYCLE STAGES CONTRIBUTE THE MOST TO EMBODIED CARBON EMISSIONS?

Assessing a building's performance for the entire life cycle gives a complete summary of the impacts from the initial product selection to construction, the operations/use stage, and end-of-life replacements. Table 5 summarizes a baseline high-rise residential building in Canada. This LCA study and output results follow industry standards and includes the assessment of life cycle stages A1 to C4. The upfront-embodied carbon of building materials accounts for 89% of the overall embodied carbon and 83% of the overall environmental footprint for all LCIC impact categories,

The same archetype building was also prepared in the US to provide a complete understanding of the differences in building material impact from Canada to the US. In comparison to the results from **Table 5**, the US breakdown for embodied carbon by stage in **Table 6** shows that the product stage accounts for 90% of the building's embodied carbon and 85% of the overall environmental footprint.

WHAT IS THE OPTIMAL EMBODIED CARBON REDUCTION STRATEGY?

Each building project is an opportunity to evaluate the impact of various design strategies on reducing embodied carbon. This paper proves that factors such as building type, location, and standards significantly influence the selection of optimal strategies. The author has conducted multiple scenarios based on a 30-story high-rise building in Toronto with a footprint of 625 m², a gross floor area of 20,000 m², and 4 underground parking levels. These embodied carbon reduction scenarios aim to achieve a 5% to 10% reduction in embodied carbon while aligning with an absolute embodied carbon intensity of less than 500 kg CO2e/m² per the CAGBC Zero Carbon Building – Design minimum embodied carbon performance requirement, as detailed in **Table 2**.

A practical scenario was created where no retrofit or reuse options were available, focusing solely on a new-construction high-rise development.

LCA software can also be used to assess existing building retrofits based on market trends for new developments in North America. The analysis assumes the use of concrete as the primary structural material and aims to meet energy performance targets for the American Society of Heating, Refrigerating and Air-Conditioning Engineers' Climate Zone 6 and follow Ontario Building Code Supplementary Standard – Energy Efficiency Requirements (OBC SB-10 standards for Part 3 buildings.

Assessing hybrid-timber structures is another option to be considered for other applications as codes progress to allow for timber above six stories, which was not considered in the analysis. Currently the application of hybrid-timber structures is more impactful when considering commercial office, low-rise, industrial, and institutional developments.

TABLE 9. Embodied carbon reduction assumptions: Canada

Reduction options	Baseline	Proposed	GWP reduction per assembly (%)	
Foundations	35 MPA CRMCA industry-wide EPD	35 MPA GUL 35% SL	26%	
Wall assembly	Steel stud, Stone veneer-faced precast concrete panels, mineral wool insulation, type-X gypsum	Steel stud (same), metal cladding (30 Ga), fiberglass insulation, gypsum (same)	9%	16%
Parking garage, cast-in-place concrete	30 MPA CRMCA industry-wide EPD	30 MPA GUL 35% SL	7%	
Window-to-wall ratio	60%	40%	16%	
Floors	30 MPA CRMCA industry-wide EPD	30 MPA GUL 25% SL	11%	
Roof	Built Up Roof with XPS insulation.	SBS Modified Bitumen, EPS insulation.	10%	
Column height and SCM	3.0 m (10 ft) 30 MPA CRMCA industry-wide EPD	2.75 m (9 ft) 30 MPA GUL 25% SL	8%	
Overall GWP Reduction			14.44%	
Baseline embodied carbon intensity (kg CO ₂ e/m²)			405	
Absolute carbon intensity (kg CO ₂ e/m²)			347	

Note: MPA = megapascal; CRMCA = Canadian Ready-Mix Association; Ga = Galvanized; GUL= Portland Limestone Cement

TABLE 10. Embodied Carbon Reduction Assumptions: US

Reduction options	Baseline	Proposed	GWP reduction per assembly (%)	
Floors	3000 PSI NRMCA industry standard EPD	NRMCA 3000 FA/SL-50	18%	
Foundations	NRMCA 5000 PSI industry standard	NRMCA 5000 FA/SL-50%	17%	
Column height and SCM	3.0 m (10 ft)	2.75 m (9 ft)	8%	
Window to wall (%)	Aluminum frame double-glazed argon fill 60% (W-W)	Aluminum frame double-glazed argon fill 40% (W-W)	16%	
Wall assembly	Steel stud, Stone veneer-faced precast concrete panels, mineral wool insulation, type-X gypsum	Steel stud (same), metal cladding (30 Ga), fiberglass insulation, gypsum (same)	5%	8%
Parking garage, cast-in-place concrete	NRMCA 4000 FA/SL-00	NRMCA 4000 FA/SL-40	3%	
Roof	Built Up Roof with XPS insulation.	SBS Modified Bitumen, EPS insulation.	3%	
Overall GWP Reduction			11.85%	
Baseline absolute embodied carbon intensity (kg CO ₂ e/m ²)			445	
Absolute embodied carbon intensity (kg CO ₂ e/m ²)			393	

Note: EPS= expanded polystyrene insulation; MPA = megapascal; NRMCA = National Ready-Mix Concrete Association; FA= Fly-Ash; Ga = Galvanized; GUL= Portland Limestone Cement; PSI= Pounds per square inch; SL= Slag; XPS = extruded polystyrene.

HIGH-RISE RESIDENTIAL LCA SUSTAINABILITY GOALS:

1. Reduce embodied carbon by 5% to 10%
2. Ensure all embodied carbon reduction scenarios align with reasonable energy performance targets and TGS Version 4 Tier 2 performance
3. Align LCA reporting with TGS Version 4, LEED Versions 4.1 and Version 5 reporting requirements
4. Reduce the environmental impact in embodied carbon and three other LCIC categories by a minimum of 5%

In the following pages, the results of LCA study for residential building in Canada and the US have been included to show optimal results to meet embodied carbon intensity requirements. **Figure 8** and **Table 7** below show the optimal embodied carbon reduction results for a building in Canada. Similarly, Figure 9 and Table 8 show the optimal results for a high-rise residential building in the US.

CONCLUSIONS

In conclusion, this paper highlights the opportunity that engineers, architects, and design team members have in specifying building materials that consider the environmental footprint

of the entire building's life cycle. The product stage alone makes up 89% of the embodied carbon. A summary of the LCA industry standards was provided to offer a better understanding of the latest reporting metrics and strategies to meet evolving green building standards.

Moreover, engaging an experienced sustainability consultant with experience in LCA early in the design phase will reduce the potential for costly changes further in development if embodied carbon was not considered. Engaging a sustainability consultant can help your team with assessing the embodied carbon, energy performance, sustainability certifications, and local requirements to provide practical and cost-effective solutions for your building. Some examples of impactful solutions outlined in this paper were:

1. Optimizing structural design early in the design stage
2. Assessing fly-ash and slag cementitious content options for concrete mix design in floor slabs and foundation between 25% to 35% GUL
3. Selecting high-performance insulation with manufacturer EPDs
4. Reducing the window-to-wall ratio between 40% to 60%

In high-rise residential buildings, the key focus area to reduce embodied carbon is within the wall assembly category, which consists of 58% to 62% of the overall embodied carbon. Next in priority is concrete floors (30% to 34%) and then concrete columns (4%), as outlined in Table 3 and Table 4.

Based on the LCA analysis and the summarized reduction options in **Table 9** and **Table 10**, no single measure can meet a 10% embodied carbon reduction or an embodied carbon intensity of 350 kg CO₂e/m² on its own. Therefore, assessing a building project's specific design and local requirements is crucial to decide the best approach to meet various industry standards such as TGS, LEED, CAGBC Zero Carbon Building – Design, and City of Vancouver Embodied Carbon Guidelines.

Lastly, when seeking effective ways to reduce embodied carbon, it's crucial to consider local building code requirements and consult with experienced professionals, including architects, structural engineers, building science experts, and sustainability consultants. This approach ensures that the building is safe, practical, and environmentally conscious.

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Airtightness: Ultimate Benefits and Decisive Stakeholders' Interests

ABSTRACT

Airtightness is essential to reduced energy consumption, occupant comfort, and building resilience as a whole. Revealed building energy use intensity (EUI) operational data are alarming. We should be able to work together to conquer the beast of air and energy leakage, but our expectations of air permeability in distinct components and buildings become blurred. Although anticipated conservation targets may appear achievable when projects are initiated, whole-building airtightness performance and resulting energy exhaustion reveal major misperceptions underlying applied methodologies.

Many construction stakeholders are not necessarily proceeding in harmony; designers, developers, and legislative entities confuse requirements and standards. To build a truly airtight building and cut down on wasted energy, it is important to plan carefully and use tools to find and seal up any gaps during construction.

In light of stakeholders' diverse interests and contributions toward achieving a specific enclosure performance, the research presented in this paper intends to clarify the most commonly utilized airtightness approaches in the construction industry. The analyses include commonalities and differences between testing parameters in various predominant standards, as well as subsequent energy consumptions/savings. The airtightness study will offer awareness for delivering continuous air-barrier, and propose practical paths toward sustainability.

LEARNING OBJECTIVES

- » Discuss developing codes and standards.
- » Compare energy conservation objectives.
- » Interpret parameters, measuring tools, and correspondences evaluation.
- » Manage authorities, builders, and public expectations.
- » Explore enabling feasibilities to achieve aimed performance.

SPEAKER



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1. INTRODUCTION

A common performance motivation axiom by Lord William Kelvin is “what cannot be measured cannot be improved.” Achieving airtightness performance (through whole-building testing) can initially appear demanding. Air-barrier assemblies and accessories are available, but integrating these into air-barrier systems, which comprise many connections, is still a challenge. This paper will review the history of developing airtightness requirements, with examples from whole-building testing approaches, while examining codes and standards.

Focus on airtightness testing of materials and assemblies has increased, but to date, mandatory whole-building airtightness has not been sufficiently adopted, particularly due to cost concerns. This paper will also discuss interests and joint tactics for officials, developers, consultants, contractors, and sub-trades in delivering and commissioning airtight enclosures. This research relates largely to Cool Temperate climate zones, as defined by the Köppen¹ climate classification, in which the coldest month has an average temperature below -3°C and the warmest month has an average temperature above 10°C . The scope of the manuscript is Canada-centric.

2. SIGNIFICANCE OF AIRTIGHTNESS

Airtightness in construction has numerous important benefits. Whole-building airtightness tests are sought by building physicists to help resisting vicious enclosure air leaks. Airtight

buildings provide several benefits for governments, owners, occupants, and other stakeholders.

2.1. Superior Indoor Air Quality

Airtight construction reduces the entrance of pollutants, allergens, and outside noise by regulating airflow and improving filtration and ventilation. Moreover, it enables the utilization of a 100% fresh-air-intake ventilation supply, while exhausting all used and possibly contaminated air. Heat Recovery Ventilator [HRV] and/or Energy Recovery Ventilator [ERV] sizes can be optimized, eliminating the need for recycled and makeup air filtering and their associated costs.

2.2. Improved Energy Efficiency

Airtight construction reduces energy consumption by minimizing heat loss or gain through air leakage. Air leaks are deemed responsible for 25–40% of energy losses in conventional construction.² Occupants will benefit from decreased heating and cooling expenses as well as a lower carbon footprint. Heating, Ventilating and Air Conditioning [HVAC] system design relies on the airtightness component, which is, unfortunately, most often predicted as an assumption to complete the energy modeling required for sizing heating and cooling equipment. Air leakage impacts ventilation equipment’s initial size and capacity, ultimate performance, and maintenance. Therefore, airtightness will provide stakeholders a lower initial building cost, improved performance of heating and cooling equipment, efficiency, life cycle durability [LCD] for maintenance and replacement. Unfortunately, energy modeling and energy balance software

are in weak declension with the calculated airtightness savings results; which means that their energy loss mechanisms and progressive algorithms aren’t based on the same physics principles that include air leakage/tightness measures.

2.3. Increased Durability

Airtightness assists in preventing moisture damage, which can cause rot, mold growth, and other harm to a building’s structure, including concealed components. Additionally, it prolongs the life of building components, such as insulation. Air leakage can result in degrading insulation’s effectiveness, by picking up its moisture. In colder seasons, when the interior has a normal relative humidity (RH) with an air pressure higher than the outdoor pressure, then moist air will flow from inside to outside, through gaps in the enclosure; it gets to cold cavities and surfaces, forming condensation on building materials outboard of the air control layer, including structural elements. This condensation can cause mold, mildew, and fungus, which may lead to health hazards, and corrosion of building components. This may result in deterioration of structural components, such as fasteners and anchors. Where the condensation is concealed, deterioration is usually undiscovered until a failure occurs. Early signs of deterioration of concealed materials are rarely revealed.

2.4. Enhanced Comfort

A building that is airtight keeps out drafts, cold spots, and temperature swings, contributing to a comfortable and consistent living space all year round.

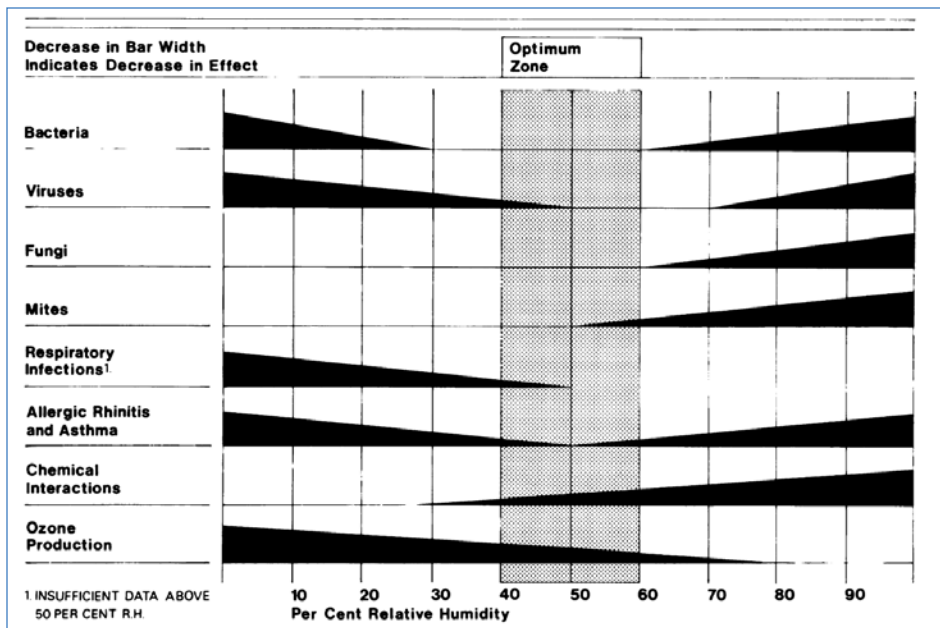


FIGURE 1. This chart suggests an optimum zone of 40 to 60% for relative humidity. Reproduced from Arundel et al. (1986).

Furthermore, thermal comfort is directly connected to RH. Humans' perception of warmth is influenced by the surrounding RH. It feels colder in dryer environments, and warmer sensations increase with elevated RH levels at a constant temperature. Our interviews with residents of a 33-story multi-unit Toronto residential building, built in 2010, confirmed unsuccessful efforts to increase RH to 30% at any point. Even with the use of a humidifier rated for a space four times the size, uncontrolled air leaks made it impossible to increase RH. Occupants had to turn their thermostats up to feel warmer in this relatively dry environment, which wasted energy. Therefore, airtightness is interrelated to energy savings through the RH / thermal comfort component.

2.5. Relative Humidity and Health

Health-related issues, such as dry, cracking skin; irritation of mucous membranes; eye dryness; respiratory infections; and static electricity generation, place limits on the acceptability of very low-RH environments. The optimal RH range was defined in Arundel et al.³ where epidemiological studies examined the relationship between the number of respiratory infections or absenteeism and the RH in buildings.

Arundel et al.'s results were presented in a chart that is now widely recognized by scientists, healthcare professionals, and some organizations such as The US Department of Energy. Some health factors get worse at lower humidity levels, some get worse at higher humidity levels, and some get worse at both ends of the humidity spectrum. These findings led to the conclusion that the ideal middle zone is between 40% and 60% RH. This would require humidification control, which is unattainable in air-leaky interior environments.

Hospitals and other healthcare buildings are specified for a minimum indoor air quality with a 40% RH. HVAC designers tend to lower RH parameters to 20% or 30% in other common buildings to make the enclosure less vulnerable to condensation, thereby sacrificing RH-related health and comfort necessities for building occupants. As Taylor⁴ states, "There is now overwhelming scientific evidence that a mid-range air humidity has significant benefits for human health. It is very possible for us to be managing the indoor air quality of our public buildings in line with this evidence. The time has come for regulations on indoor air quality to include a humidity level of 40–60% RH."

3. AIRTIGHTNESS METRICS

Various measuring methodologies have been used for reporting of airflow and airtightness. In the following section, we cover some of the units that are used to quantify air testing performance. These can serve as the basic measurements, with respect to developing trends and practices discussed further in our research. Our research will utilize the International System of Units [SI] units for further equations.

3.1. Air Permeability

Air permeability is a commonly used metric to quantify the airflow rate through a given area of element, expressed as the volume flow per hour (m^3/h) of air supplied to one side of the element by air-moving equipment, per square meter (m^2) of element area at a specified pressure difference at each side of the element: for example, $10 \text{ m}^3/\text{m}^2\cdot\text{h}$ @ 50 Pa differential.

3.2. Volume Flow Rate

This metric is defined as Q , a measure of the amount of air that flows through a specific space in a certain amount of time; for example, liters per second [L/s], m^3/h , or Cubic Feet per Minute CFM. It is normally expressed as $Q = v \times A$,

where

v = air velocity

A = cross-sectional area through which air is passing

3.3. Air Leakage Rate

Q_{AP} defines the airflow passing through the enclosure at a given pressure difference, from high- to low-pressure space.

3.4. Air Changes per Hour

Air changes per hour (ACH or air exchange rate) is the number of times that the total air volume in a space is completely removed and replaced in one hour. It can also be thought of as the rate at which outside air enters a space divided by the volume of that conditioned space, or as a measure of volume flow rate (m^3/h) at a certain reference pressure differential (for example, 50 Pa) per cubic meter of building volume (that is, Q_{50}/V or ACH_{50} , also known as N_{50}). The methodology

considers the building's interior volume of air that needs to be conditioned and, therefore, internal walls and floors are excluded. Voids within wall and floor constructions also are not counted. ACH is also known as the percentage of an enclosure's air that is exchanged in a time period.

Example: ACH or ACH_{50} or $N_{50} = 1.2 \text{ 1/h}$ or 1.2 h^{-1}

3.5. Equivalent Leakage Area

Equivalent leakage area $EqLA$ is a visual representation of air leakage as the area of a theoretical orifice in the building enclosure that would leak the same amount as all of the building's actual collective holes at a given pressure difference. $EqLA_{10} = 500 \text{ cm}^2$ (area @ 10 Pa pressure differential).

3.6. Effective Leakage Area

Effective leakage area $EffLA$ is similar to $EqLA$, but referenced in the American Society for Testing and Materials ASTM E779-10⁵ with a discharge coefficient assumption of 1.0 and a reference pressure of 4 Pa.

3.7. Normalized Leakage Area

Normalized leakage area NLA is the ratio of the equivalent leakage area $EqLA$ to the area of the building enclosure divided by enclosure area. Example: $NLA_{50} = \text{cm}^2/\text{m}^2$ (area @ 10 Pa pressure differential).

$$NLA_q = \frac{EqLA}{A} \quad \text{cm}^2/\text{m}^2$$

3.8. Normalized Flow or Air Leakage Rate

Normalized flow or air leakage rate NLR is the airflow at a given pressure differential divided by the area of the building enclosure area. Example: $NLR_{50} = \text{L}/(\text{s} \cdot \text{m}^2)$

Q = airflow [L/s], or the volume of the air per unit time required to maintain the pressure differential

ΔP = pressure differential; hence, $Q_{\Delta P}$ = airflow at a defined pressure differential

C = flow coefficient variable

N = dimensionless flow exponent

Examples:

$ACH = (3.6 \cdot \text{Airflow L/s}) / \text{Building Volume [Conditioned Space Only, internal walls and floors excluded]}$

$1 \text{ L/s} = 2.1188810952620662 \text{ ft}^3/\text{min}$ [CFM]

$NLR@50 = \text{L/s Airflow @50} / \text{Enclosure Surface Area}$

3.9. Air Changes per Hour $ACH_{\Delta P}$ Versus Air Leakage Rate $Q_{\Delta P}$ and NLR

Codes and standards may specify airtightness targets using ACH or air leakage rate. Although it is possible to convert between them for a specific building, it is not possible to apply a single conversion factor to all buildings. Conversion is a volume function—to-enclosure area ratio that varies with building height and shape.

While some experts believe that NLR is a more intuitive metric for air leakage, ACH appears to be more practical with regard to energy balance/modeling and consumption measurement, allowing for designs that accurately reflect heating/cooling demand.

4. RELATIONSHIP BETWEEN BUILDING ENERGY EFFICIENCY AND AIRTIGHTNESS⁵

Enclosure air leaks significantly increase heating and cooling energy demands, while airtightness leads to savings.

Figure 2⁶ shows the effects of airtightness on heating energy demand for an example six-story, 4700 m² multi-unit residential building in Climate Zone 4 with the following characteristics:

- » Effective RSI-4.4 (R-25) walls and USI-1.53 (U-0.27) windows
- » Heat recovery ventilation (60% efficient)
- » Drain water heat recovery and low-flow fixtures
- » Light-emitting diode lighting and occupancy sensors in corridors

Figure 2 demonstrates that exceeding the baseline normalized air leakage rate target of 2.0 L/s/m² can increase the energy required to heat a building by nearly 70%. However, improving airtightness and achieving a normalized air leakage rate of 0.5 L/s/m² can reduce this energy requirement by nearly 30%, thereby meeting energy efficiency

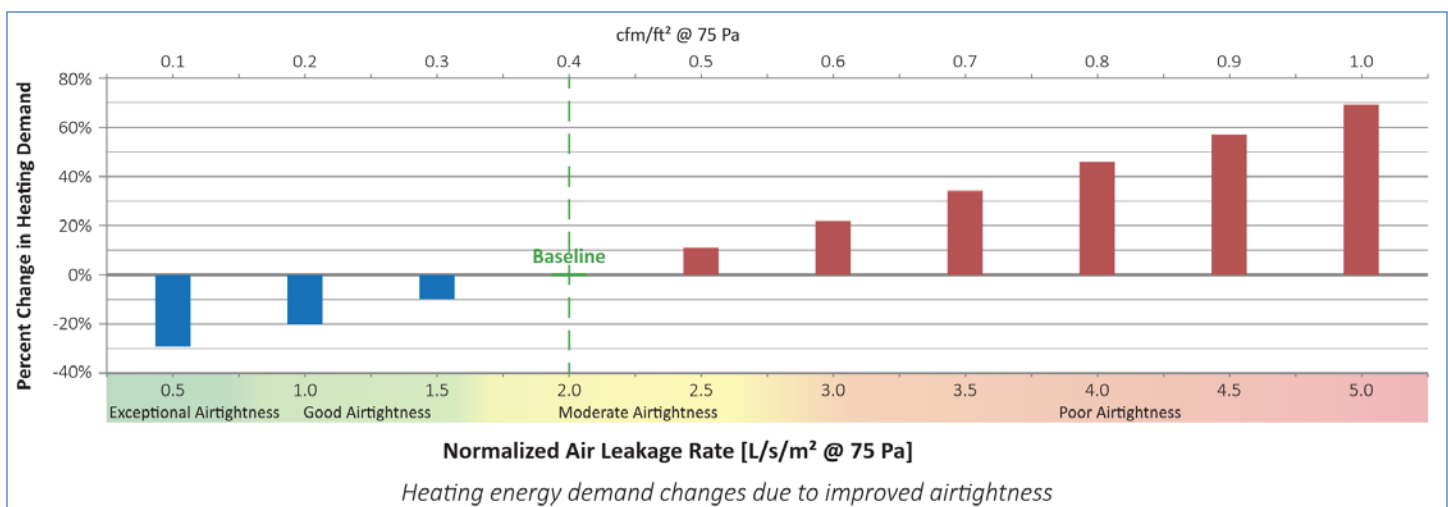


FIGURE 2. Heating energy demand changes due to improved airtightness.⁶

requirements and improving utility cost savings.

5. CODES AND STANDARDS RELATED TO WHOLE-BUILDING PERFORMANCE REQUIREMENTS

Reviews of Canadian national and provincial regulations and recognized standards show that historically, there has been no mandatory requirement for whole-building airtightness performance. This was the status until 2017, after which occurred the development of the British Columbia provisional step code, the Washington State Building Code with a voluntary airtightness target, and the higher levels [Version 3, Version 4, etc.] of the Toronto Green Standards (TGS), in addition to voluntary standards such as Energy Star, LEED, and Passive House. Progressive airtightness requirements appear as follows:

5.1. 1977 National Building Code of Canada (NBC)

Section 4.8, Wind, Water and Vapour Protection, subsection 4.8.1, Control of Condensation, states the following:⁷

"4.8.1.2 (1) ... the assembly shall be designed to prevent condensation by providing a continuous vapour and air barrier in the assembly ..."

The 1977 NBC notes that continuous air and vapor barriers are requirements for building assemblies as measures to prevent condensation in cases of temperature and water vapor pressure differentials.

5.2. 1985 NBC

Section 5.3, Control of Air Leakage, Subsection 5.3.1, Air Barriers, Article 5.3.1.1.(1), states the following:⁸

"The assembly shall be designed to provide an effective barrier to air exfiltration and infiltration, at a location that will prevent condensation within the assembly, through (a) the materials of the assembly, (b) joints in the assembly, (c) joints in components of the assembly, and (d) junctions with other building elements."

With its 1985 edition, the NBC's requirements start to dictate some performance expectations focusing

on building assemblies, components, and connections, and other building elements exposed to environmental differentials. But assemblies are here in silo, probably with some interface, and no mention of the continuous air-barrier nor a whole-building performance bar or testing requirements.

5.3. 1995 NBC

Section 5.4, Air Leakage, Subsection 5.4.1, Air Barrier Systems, Article 5.4.1.2, Air Barrier System Properties, states the following:⁹

"... sheet and panel type materials intended to provide the principal resistance to air leakage shall have an air leakage characteristic not greater than 0.02 L/(s • m²) measured at an air pressure difference of 75 Pa..."

Section 9.25, Heat Transfer, Air Leakage and Condensation Control, Article 9.25.1.2, General, states the following:⁹

"(1) ...any sheet or panel type material with an air leakage characteristic less than 0.1 L/(s.m²) at 75 Pa ..."

These requirements indicate that air leakage is a critical issue in building systems. For Part 5, the materials used to provide principal resistance must have an air leakage characteristic not greater than 0.02 L/(s•m²) at an air pressure difference of 75 Pa, and Part 9 calls for air leakage not greater than 0.1 L/(s•m²) at 75 Pa.

5.4. 2010 NBC

Section 5.4, Air Leakage, Subsection 5.4.1, Air Barrier Systems, Article 5.4.1.2, states the following:¹⁰

"...materials intended to provide the principal resistance to air leakage shall

a) have an air leakage characteristic not greater than 0.02 L/(s•m²) measured at an air pressure difference of 75 Pa, or

b) conform to CAN/ULC-S741, 'Air Barrier Materials – Specification'."

Article 9.36.2.9, Airtightness, states the following:⁹

"(1) The leakage of air into and out of conditioned spaces shall be controlled by constructing

a) a continuous air barrier system in accordance with Sentences (2) to (6), Subsection 9.25.3. and Article 9.36.2.10.,

b) a continuous air barrier system in accordance with Sentences (2) to (6) and Subsection 9.25.3. and a building assembly having an air leakage rate not greater than 0.20 L/(s•m²) (Type A4) when tested in accordance with CAN/ULC-S742, 'Air Barrier Assemblies – Specification,' at a pressure differential of 75 Pa, or

c) a continuous air barrier system in accordance with Sentences (2) to (6) and Subsection 9.25.3. and a building assembly having an air leakage rate not greater than 0.20 L/(s•m²) when tested in accordance with ASTM E2357, 'Determining Air Leakage of Air Barrier Assemblies'."

Part 5 of the 2010 NBC introduces CAN/ULC S741, Standard for Air Barrier Materials—Specification,¹¹ and allows testing of all these different materials to determine their performance against air leakage. Part 9 introduces CAN/ULC-S742, Standard for Air Barrier Assemblies—Specification,¹² and covers air barrier assemblies as combinations of air barrier materials and their accessories.

5.5. 2020 NBC

Part 5 Environmental Separation, Subsection A-5.4.1. The Article, A-5.4.1.1.(3)¹³, addresses *"Air Leakage Performance Classes for Air Barrier Assemblies which is CAN/ULC-S742." Article 9.36.6.3, Determination of Airtightness, states the following:*

"(1) Where airtightness is to be used as input to the energy model calculations, it shall be determined through a multi-point depressurization test carried out in accordance with CAN/CGSB-149.10, 'Determination of the airtightness of building envelopes by the fan depressurization method,' using the following parameters described therein:

a) as-operated, and

b) guarded or unguarded.

2) Except as provided in Sentence (3), where airtightness is to be used to demonstrate compliance with an Airtightness Level listed in Table 9.36.6.4.-A or 9.36.6.4.-B, it shall be determined through a single-point, two-point or multi-point depressurization test carried out in accordance with CAN/CGSB-149.10, 'Determination of the

airtightness of building envelopes by the fan depressurization method,' using the following parameters described therein:

a) as-operated, and

b) guarded or unguarded, as applicable.

3) Determining NLA10 using a single-point test is not permitted."

The 2020 NBC references in Part 5 CAN/ULC-S742¹² and, in Part 9, presents the method of testing the whole-building enclosure and provides an air leakage rate as per the standard CAN/CGSB-149.10,¹⁴ which is "a standard method of tests (SMOTs) for the determination of the airtightness of building envelopes. This Standard contains three test options, two types of assessments and, for attached zones, two pressure boundary setups. The test options are the multi-point test, the two-point test and the single-point test. The types of assessments are as-operated and closed-up. The pressure boundary set-ups are guarded and unguarded."

5.6. Excerpt from the 2020 National Energy Code of Canada for Buildings¹⁵ requirement Article 3.2.4.2. Air Barrier System, states the following:

"1) The air barrier system shall have a normalized air leakage rate not greater than 1.50 L/(s·m²) when tested in accordance with ASTM E3158, 'Standard Test Method for Measuring the Air Leakage Rate of a Large or Multizone Building,' at a pressure differential of 75 Pa, using the following criteria:

a) the building shall be prepared in accordance with the building envelope test described in the standard,

b) the air leakage test shall be conducted under both pressurized and depressurized conditions, and

c) the air leakage area used to determine the normalized air leakage rate shall include all the surfaces separating conditioned space from unconditioned space.

(See Note A-3.2.4.2.(1).)

2) The air leakage rates measured in accordance with Sentence (1) shall be averaged."

The NECB 2020 stated that the test building enclosure standards ASTM

E3158,¹⁶ "this test method is used to determine the airtightness of building envelopes or portions thereof by measuring the air leakage rate at specified reference pressure differentials."

5.7. Excerpts from Regional Whole-Building Airtightness Requirements

5.7.1. Vancouver For the city of Vancouver, BC, Canada, under the Vancouver Building By-law,¹⁷ the whole-building airtightness test is required to be conducted per ASTM E779,⁵ which is a test method that measures air-leakage rates in a building enclosure under controlled pressurization and depressurization.

Article 10.2.2.21, Building and Dwelling Unit Airtightness Testing, states the following:

"1) In a building required to comply with this Article, the building and dwelling units shall be tested for airtightness in accordance with

a) ASTM E779, Standard Test Method for Determining Air Leakage Rate by Fan Pressurization,

b) USACE Version 3, Air Leakage Test Protocol for Building Envelopes, or

c) airtightness protocol recognized by Natural Resources Canada for use in homes and buildings labeled under the EnerGuide for New Homes program..."

5.7.2. Toronto In the 2018 TGS Version 3, Tier 2, the city of Toronto required conducting a whole-building airtightness test, where Tier 2 was voluntary. The same requirement became mandatory in 2022 TGS Version 4 Tier 1. "The Toronto Green Standard Version 4 (2022) includes three tiers of performance with a focus on carbon reductions and green infrastructure enhancements. The key changes recommended are:

The energy performance of each tier moves up so that Tier 2 becomes the required Tier 1, Tier 3 becomes voluntary Tier 2 and Tier 4 becomes voluntary Tier 3 (the new highest performance level for near zero emissions)."¹⁸

As requirement of TGS V4, Tier 1, under Energy Efficiency Report Submission & Modelling Guidelines, under subsection

5.4.3,¹⁹ "Infiltration shall be modelled as per NECB 2015 at 0.00025 m³/s/m² at 5 Pa (0.05 cfm/ft² at 0.02 in w.c.) of total, above grade exterior walls, and windows area. Reduced air leakage rates may be modelled, provided the project team makes a commitment to achieve a minimum air leakage rate, to be confirmed by mandatory airtightness testing. Credit will be allowed down to the values required by Passive House, which approximately convert to 0.0001 m³/s/m² at 5 Pa. Air leakage testing values determined at 75 Pa can be approximately converted by multiplying the value by 0.112. For example, a tested value of 0.0015 m³/s/m² at 75 Pa would equate to 0.000168 m³/s/m² at 5 Pa, to be used in the model, instead of the 0.00025 m³/s/m² at 5 Pa indicated."

5.7.3. Requirements in further regions Recent projects in Washington, DC; Portland, Oregon; and Seattle, Washington, have required whole-building airtightness testing. The U.S. Army Corps of Engineers' (USACE's) requirements for new buildings and renovations have adopted an airtightness performance requirement of 0.25 cfm/ft² at 75 Pa (1.271 L/[s·m²]) maximum air leakage. The USACE Air Leakage Test Protocol is adopted in TGS with the ASTM E3158-18 standard.^{20,21}

6. EFFECTIVE PLANNING APPROACHES TO PRODUCE AIRTIGHT BUILDINGS

Planning for airtightness testing ensures that a continuous air barrier is considered throughout the design process. This means, among other benefits, less escape of expensive conditioned air and less outdoor make-up air to precondition at great cost. In this case, extracting energy while exhausting used indoor air, and adding such energy to outdoor air intake through heat exchanger units, renders the most efficiency.

Planning has to start earlier than the design stage. A commitment to build with airtightness in mind is fundamental. Whether the decision is made because of code requirements or to meet a certain efficiency goal or standard, owners and consultants must commit to their determination from the beginning.

Whole-building airtightness testing is required to ensure delivery of an airtight building. Energy modeling uses delivered test results to assess the building as a whole system, to ensure it meets the designed and, more importantly, constructed, performance requirements. The proposed planning approach tends to request more of two specific participants: consultants and general contractors. Their obligations will impact the financial planning discussed later in this paper. A careful feasibility and payback study is required, with the knowledge that construction stakeholders progressively joining the project will be affected and must be informed about the whole-building airtightness objective beforehand. The plan will not undermine each trade's individual obligation to pass standard airtightness tests for its own installed assemblies. Steps for airtightness testing vary depending on building type and size, and the testing standard used. **Figure 3** suggests practical steps. The process can apply to a variety of project delivery models, such as a stipulated price (design/bid/build), construction management, or design/build. Different delivery models may impose greater responsibilities on some participants than others.

6.1. Testing Frequency

Testing frequency depends on the targeted standard and methodology,

but also on the building's size and design. A minimum of three whole-building tests are deemed practical, with the first test conducted as soon as the enclosure is air-sealed, and air-barrier components and interfaces are still accessible. This allows for parallel qualitative testing, which is essential to remediate flaws if the quantitative test exceeds the allowable targets.

6.2. Testing Capabilities

A National Research Council Canada NRC 2015 survey²² identifies 49 companies with 127 locations across Canada reporting 36 locations with current capacity to complete Part 3 whole-building airtightness testing, while 91 locations had available expertise that could be developed if airtightness requirements came into effect. Potential future capacity was indicated by factors such as labs offering Part 9 of the Canadian building code airtightness tests, to offer Part 3 testing at different locations. Now in 2024, we are certain that capabilities have significantly increased, allowing room for price competition, although they already appeared sufficient in 2015.

6.3. Budgets

The same survey respondents identified building size, number of penetrations, and phased construction delivery as major cost factors. Major costs can be divided into three main categories:

1. Space preparation tasks, time, and laboratory/engineering;
2. Remediation tasks for resulting identified leaks; and
3. Delayed schedules (leading to increased costs) as a result of the previous two categories.

In this paper we are discussing smart scheduling with a built-in strategy to overcome the first category further. Nonetheless, the main cost for developers is fixing leakage problems. Improved design/detailing and sound air barrier construction practice should help manage the second and third categories. Typical defects appear at surfaces, sealed joints (including structural), penetrations (electrical, plumbing, HVAC), joints and interfaces between doors and windows, detached membranes (at substrates and overlaps), termination seals, screws, staples, loose clamps, missing or unadhered sealing tapes, cuts or holes in the air barrier, tongue-and-groove joints, and corner joints.

Contractors are improving test coordination with labs, who offer, for example, to start testing tasks in the evening, after conventional construction hours. Testing laboratories in 2024 suggest their own cost to be approximately \$10,000–15,000 for a 10-story building. Pending enclosure complexity and prebuilt provisions for compartmentalization, costs will vary. Associated costs to produce an airtight building aren't mainly for airtightness testing procedures, but in rectifying enclosures to achieve a continuous air barrier.

7. CASE STUDY: PERMEABILITY EXPECTATIONS OF AIR BARRIER COMPONENTS

A frequently conveyed myth in our building physics culture claims that an enclosure's air barrier system has three tiers: a material is incorporated into an assembly, which is interconnected to create an enclosure. Each of these supposed three tiers has a distinct measurable resistance to airflow. The permeability performance requirement decreases by one order of magnitude as the testing climbs up the chain to form the airtightness measurement for a building enclosure:

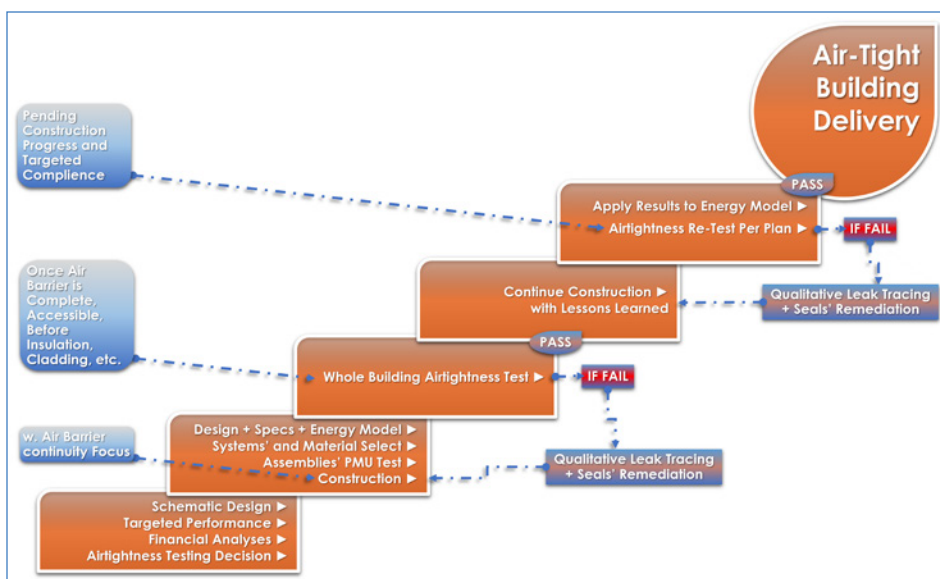


FIGURE 3. Project planning with consideration of building airtightness testing.

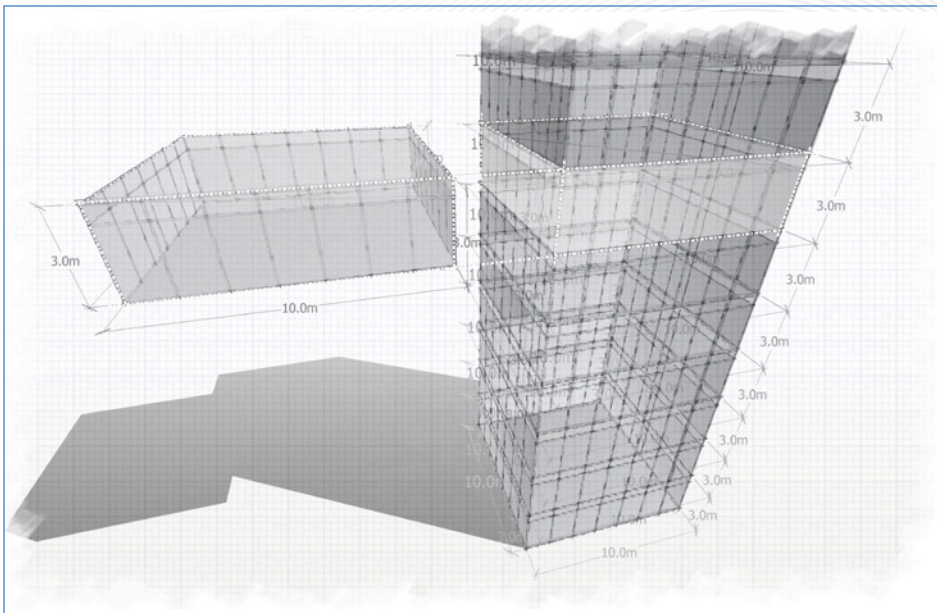


FIGURE 4. The proposed multi-story glazed enclosure structure, and extracted case study floor / level

Material 0.02 L/(s·m²)

Assembly 0.20 L/(s·m²)

Enclosure 2.00 L/(s·m²)

All items are tested at a pressure differential of 50 Pa.

In searching the literature, the authors were not able to locate any scientific basis for this myth, only remote correlations between separate codes and standards. For example, the National Building Code of Canada¹³ specifies that the principal air barrier material may have a maximum air permeance of 0.02 L/(s·m²) @ 75 Pa, and ASTM E1677-00, *Standard Specification for an Air Retarder (AR) Material or System for Low-Rise Framed Building Walls*,²³ calls for an assembly air permeance requirement of 0.30 L/(s·m²) @ 75 Pa.

7.1. Research Archetype

We are focusing on an individual level (that is, floor) of a multi-story building (Fig. 4) in our case study, with the hypothesis that the main vertical enclosure is completely created out of glazing assemblies. The footprint is 10 m × 10 m, and the height is 3 m for simplification.

Typically, North American Division 8 glazing specifications require an assembled architectural window to meet the following airtightness

performance requirements (at a static pressure differential of 300 Pa):

- » Air infiltration/exfiltration shall not exceed 0.3 L/s per square meter of fixed area; and
- » Air infiltration/exfiltration shall not exceed 0.5 L/s per square meter of operable glazing area.

Based on Individual Laboratory Chamber Testing with ASTM E283²⁴

Building enclosure air leakage behavior has a relatively linear relationship

between pressure and leakage volume or airflow. The test results²⁵ in **Figure 5**, also discussed in an Air Barrier Association of America (ABAA) 2017 conference,²⁵ are applied for theoretical extrapolation in the Passivhaus airtightness methodology. The relative ACH is realized, by mathematically interpreting an airtightness rating resulting from a physical test at a certain pressure to a targeted benchmark test pressure for rating's parallel analytics, and energy balance modeling comparisons.

7.1.1. Study Chronology While the threshold of air leakage rate is 0.3 L/(s·m²) at 300 Pa; and if ACH is rated at 50 Pa pressure differential (ACH_{50} or N_{50});

$$N_{50} = Q_{50} / \text{volume}$$

where

Q_{50} = volume flow rate in L/s or m³/h @ 50 Pa

Volume = building's clear interior conditioned volume

The allowable

$$Q_{300} \text{ per m}^2 = 0.3 \text{ L/s} \cdot \text{m}^2 = 1.08 \text{ m}^3/\text{h} \cdot \text{m}^2$$

$$Q_1 \text{ per m}^2 = 1.08 / 300 = 0.0036 \text{ m}^3/\text{h} \cdot \text{m}^2$$

Flow rate @ 50 Pa:

$$Q_{50} \text{ per m}^2 = 0.0036 \times 50 = 0.18 \text{ m}^3/\text{h} \cdot \text{m}^2$$

Glazing area = 40 m (perimeter) × 3 m (height) = 120 m²

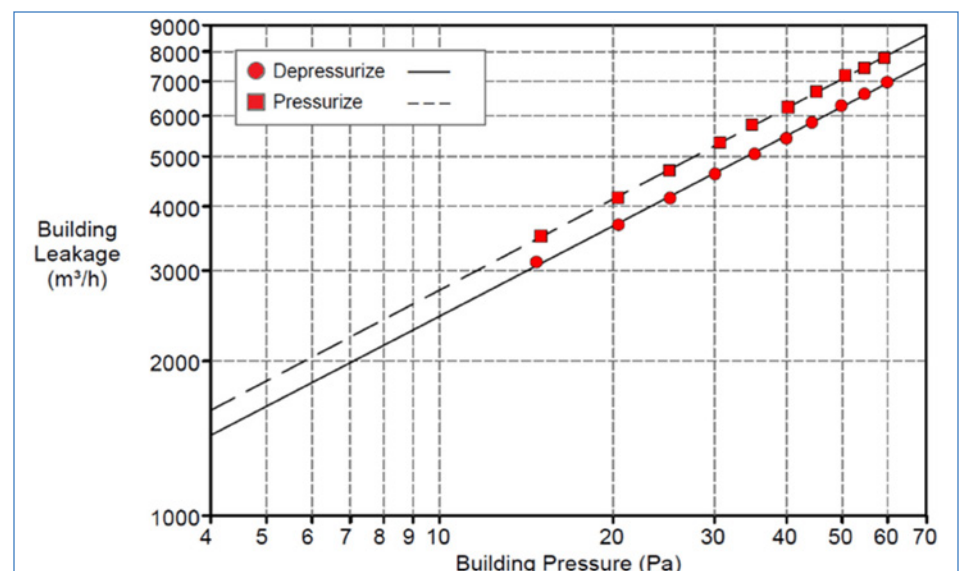


FIGURE 5. Example air leakage graph using the blower door test.

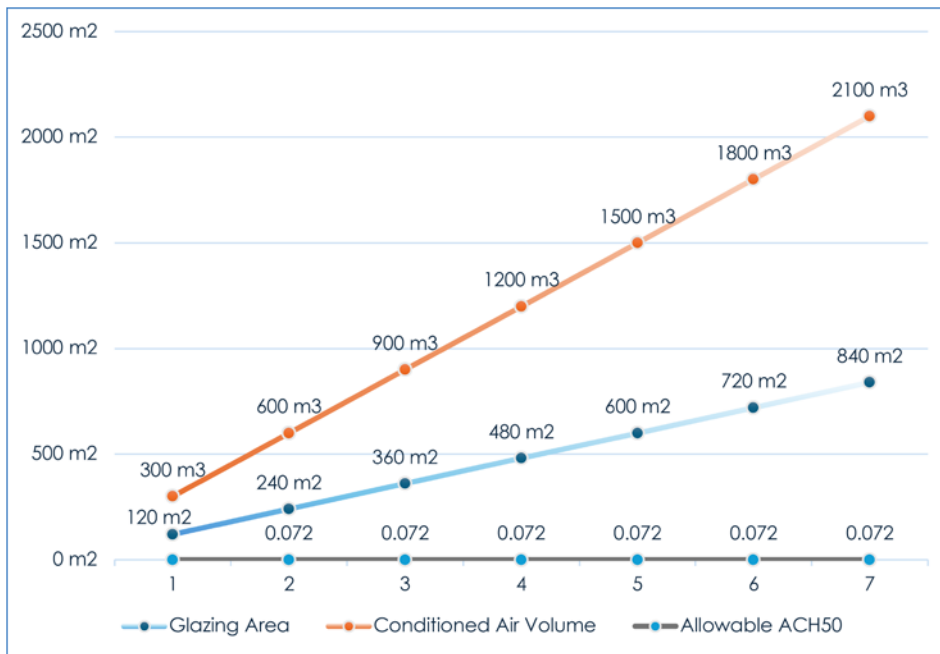


FIGURE 6. Constant allowable ACH_{50} versus increased glazing area + conditioned air volume.

Total leakage through the wall glazing:

$$= 0.18 \text{ m}^3/\text{h} \cdot \text{m}^2 \times 40 \text{ m} \times 3 \text{ m}$$

$$= 21.6 \text{ m}^3/\text{h}$$

Example specimen volume

$$= 10 \text{ m} \times 10 \text{ m} \times 3 \text{ m (floor height)}$$

$$= 300 \text{ m}^3$$

$$ACH_{50} \text{ or } N_{50} = Q_{50} / \text{volume}$$

$$= 21.6 \text{ m}^3/\text{h} / 300 \text{ m}^3$$

$$ACH_{50} \text{ or } N_{50} = 0.072 \text{ 1/h or } 0.072 \text{ h}^{-1}$$

Projects pursuing TGS Tiers 2 through 4 are meant to ensure buildings' air barrier continuity with enhanced resiliency.

The targeted testing threshold is proposed to be $Q \leq 2.0 \text{ L/s} \cdot \text{m}^2$ @ 75 Pa, and the test report will be required to be submitted to the City of Toronto for site plan approval.

If equivalent philosophy is applied in our case study, then

$$Q_{75} \text{ of } 2.0 \text{ L/s} \cdot \text{m}^2 = ACH_{50} \text{ of } 1.951 \text{ h}^{-1}$$

7.1.2. Study results and discussion A

fully glazed vertical building enclosure would have an allowable air leakage of $ACH_{50} = 0.072 \text{ h}^{-1}$, while the TGS target would be $ACH_{50} = 1.951 \text{ h}^{-1}$, which is 27 times the allowable glazing air leakage. This discrepancy raises several essential questions:

- » Why is a completely glazed enclosure wall required to meet an extreme ACH_{50} of 0.072 h^{-1} , or 3.69% of the total allowable air leakage?
- » In the "material, assembly, enclosure" categorization, what is the definition of the assembly?
- » Is it a window? Which size (minimum and maximum)?
- » Is a manufactured window, tested at $1500 \text{ mm} \times 1500 \text{ mm}$, for $0.3 \text{ L/s} \cdot \text{m}^2$ at 300 Pa air leakage equal to an entirely glazed enclosure constructed out of numerous individual glazed assemblies, with joints, corners, etc., for a total area of 120 m^2 ?
- » What air leakage rates would be expected from other assemblies within the same enclosure if it were not fully glazed?

7.2. Considering the High-Rise Area-to-Volume Ratio A/V

Utilizing the calculation for a multi-story building, with increasing enclosure surface area and conditioned air volume, we state that the airtightness requirement remains constant at $ACH_{50} = 0.072 \text{ h}^{-1}$ air exchange rate (Fig. 6), which is, interestingly, 12% of the $0.6 ACH_{50}$ Passive House threshold²⁶.

The transition joint between glazing elements and adjacent enclosure can be a source of air leakage. Even if glazing meets the air leakage requirements of ASTM E783²⁷ the test method only measures air leakage through the glazing product, not the connection integrity between the glazing and the rough opening. The testing lab can quantitatively and separately test each and make recommendations on how to remediate the transition seals if excessive air leakage is reported.

A widespread misconception relates air leakage primarily to buildings' glazing assemblies, which was recently proven erroneous on many fronts.²⁸ A Passivhaus project in Victoria, BC, Canada, was tested for quantitative whole-building airtightness analysis. Simultaneously, a qualitative air leak detection, using fog, was executed. One could identify some fog penetration through operable windows' hardware assemblies. The glazing contractor remediated the issue, and airtightness testing was repeated. Not surprisingly, the results hardly changed quantitatively. It may have been relatively easy to misjudge the innovatively thin and transparent glazing assembly, but the ACH numbers demonstrated that the major contributing air leaks were instead through unpredicted concealed opaque enclosure assemblies.

As Gord Cooke,²⁹ an engineer with 35 years' experience and airtightness field test expert, said, "Our glazing codes and standards [CSA A440] have done a very good job... windows don't make that much difference to the final airtightness results."

8. PATHWAYS FOR DISCUSSION TO ACHIEVE SUSTAINABILITY

A few matters of contention can be debated to create bridges allowing for irrefutable compulsory whole-building airtightness testing, helping chase the gaps and overcoming yet known hurdles.

8.1. Legislative Authorities

- » As per earlier Section [5] discussion, there are not nearly enough jurisdictions adopting codes or

standards that specifically mandate whole-building airtightness performance, beyond mention as a potential requirement. In the last ten years, surveys were conducted to capture national whole-building airtightness testing capabilities, and results were very encouraging. One could almost conclude that the industry was ready. By 2024, the industry has certainly improved the available education and resources on quantitative airtightness, thereby eliminating some stakeholders' alleged lack of capabilities as a reason to delay implementing a mandatory building requirement.

- » Sound clarifications can be provided for codes' or standards' vague airtightness requirements, and most importantly, for eliminating unscientifically justifiable leeway scopes around whole-building testing and delivering a prescribed airtightness performance. Today's buildings' EUI performances, or the lack thereof, demonstrate clear evidence that most risky alternative paths and trade-offs have been deliberately misused. Identifying the targeted ACH is the conformist way; tightening windows for deviations appears essential at this point.
- » Contractors often provide feedback, once the integration of whole-building airtightness testing is directed for project delivery, is that the resources are not available on the market. The fact is, they are available, based on several survey and questionnaire exercises.³⁰ What is not available is awareness among individual contractors/trades of the need to work together to achieve the end goal of a continuous enclosure's air barrier, without gaps.

8.2. Incentive Programs

- » Enbridge Gas provides commercial and multi-residential builders and developers with incentives up to \$45,000 for whole-building airtightness testing. The funds are thought to resolve issues and help ensure intended performance standards are achieved. And they also offer free technical and hands-on training to industry professionals

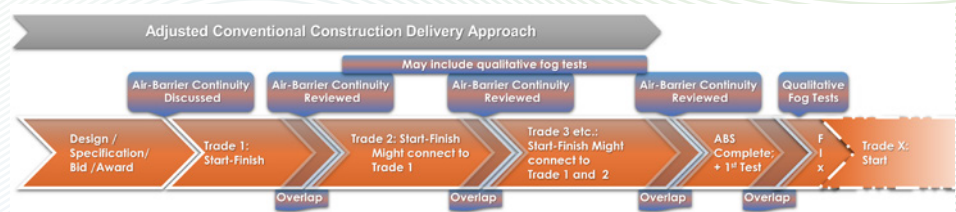


FIGURE 7. Example project delivery processes to ensure airtightness.

as part of the Commercial Airtightness Testing program.

- » Some cities and municipalities provide accelerated building permit and site plan approval processes, and enable tools to remove barriers to building with approved sustainability standards, which include mandatory whole-building airtightness testing and conditionally allowing height, rear yard, and building depth bylaw relaxations.

8.3. Immediate Stakeholders: Owner, Consultants, and Contractors

It appears to be the most challenging part of the equation, and it therefore needs careful consideration, starting at the decision-making stage.

8.3.1. Selective If whole-building airtightness testing is not a legislative mandatory project requirement, but is included in the project specifications, at the pricing stage, contractors may:

- » negotiate for testing of assemblies instead of whole-building, provided for each enclosure assembly from individual subcontractors, to suffice; and/or
- » offer a credit as a temptation to waive the testing; and/or
- » inflate delivery cost noticeably for undisclosed risks.

Our construction practices are unaccustomed to analyzed approaches and tools to deliver a continuous air barrier.

The owner must evaluate budgets and return on investment compared with the project objectives. Voluntary standards such as Energy Star, LEED, or Passive House might be sacrificed, along with their benefits. Pressure might be increased on consultants, including architects, to ensure receiving similar building performance without

the whole-building airtightness testing, which is illogical.

8.3.2. Compulsory If whole-building airtightness testing is a mandatory project requirement, at the budgeting stage, general contractors (GC) or construction managers (CM) may inflate delivery cost noticeably for undisclosed risks.

8.3.3. How Can Continuous Air-Barrier Delivery Risks Be Managed?

Beyond traditionally specified discrete assemblies' performance laboratory and site mock-ups, a risk management approach is essential. The following steps may apply:

- » Illuminate air-barrier continuity benefits at the project's beginning and provide a refresh session whenever new stakeholders or contributors join. And resolve petitions for joint end goal.
- » Simplify enclosure designs and dedicate particular attention to detailing both quantity and quality. Remember that missing or unclear details are likely to become vulnerable to air leakage, among other issues, when being executed on-site. Simplicity is significant, and on-site resolutions can be volatile.
- » Set a performance target, such as $ACH = 1.5 \text{ h}^{-1}$.
- » Implement air-zone compartmentalization principles in designing for large and/or more complex buildings. This will help also in building operation managing stack effect.
- » Identify all trades connecting to the air-barrier system.
- » Carefully select building enclosure systems, assemblies, components, materials, and accessories that form and attach to the air barrier. Reviews of materials' compatibility and

constructability sequence, and trial samples of materials, are essential.

- » GC and/or CM can create a trade-to-trade air-barrier transition assessment mechanism or plan based on detailed shop drawings. Queries to and between trades will likely arise during this process, which is desired, but that will resolve many problems upfront. The assessment must include connecting or penetrating trades such as plumbing and electrical, not only enclosure contractors. It will likely be a dynamic document or process that evolves with progress through the project's milestones.

8.4. Possible Benefits of Tested Projects over Untested Projects

The air-barrier transition evaluation might be a new process for some contractors, and might have some project budget implications, but it should not be significant, and cannot outweigh the substantial airtightness benefits. Scheduling has to consider the need for trade transition/connection time, but it should not necessarily prolong the construction initial schedule. The price of testing is an added cost, but is not comparable to the financial benefits of improved energy savings.

8.5. Necessary Stakeholders' Discussion

Elements that have the power to significantly impact project's course, while utilizing physics and finance as essential success tools:

- » Interface sharing assemblies' performance mock-ups can reveal unpredicted air-barrier installation challenges early on. Resolving and documenting those processes can confirm sound continuity. Clearly defining each trades' responsibilities will ensure continuity and ease the continuous air barrier construction progress.
- » The first whole-building airtightness test should be performed as soon as the airtight enclosure is complete and accessible, for visibility, adjustability, and modification. The first test does not have to be when the whole-building enclosure is completed. Large buildings can be tested in phases.
- » It is recommended to perform a minimum of three periodically progressive airtightness tests. The first one right after the air barrier is completed and still exposed, the second can be after the insulation and cladding to ensure no air-seals cuts or damages, with the third one being final and official. Pending projects' sizes and designs, the number of tests may vary for qualitative and/or quantitative purposes, and to ensure no undesired surprises appear at the final certification test.

CONCLUSION

There is solid evidence supporting the fact that airtight construction is feasible,

but it is definitely a significant shift in approach compared with conventional construction practice. Proven strategies for reducing air-barrier gaps will also reduce capital and operating expenses, and carbon emissions from most buildings. Airtight construction requires correct, simplified, detailed designs at transitions, with deliberate confirmation of materials' compatibility, and attentive and caring tradespersons to vigilantly execute connections and supervise overlaps, all of which will reduce the need for later remediation. Clear instructions preventing damaging tasks can protect the installed layer. Surprisingly, testing laboratories appear consistently occupied with isolated building assemblies' air testing; that is based on specifiers' directions. This practice is hindering essential progress toward complete building airtightness and distracting from the ultimate goal, which is whole-building performance.

All leaks contribute, but paying extreme attention to smaller leaks exhausts available resources and diverts focus from the main performance objectives. It is appropriate to remember that code committees voted against whole-building airtightness testing inclusion based on a limited testing resources argument, which was rendered as an inaccurate argument based on feedback from consultants and testing labs. We now wonder when NBC 2020 and NECB 2020 will be adopted for all building projects without delay.

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Thermal Performance of Spandrel Assemblies in Glazed Wall Systems

ABSTRACT

While the thermal performance calculation of discrete vision areas in curtain wall and window wall systems is well understood, the same cannot be said of opaque spandrels, the simulation of which often stretches the limits of common evaluation methods. Recently published spandrel simulation procedures continue to struggle with the following:

- » Calculating U-factors for nonstandard sizes, especially slab bypass or column cover configurations with high frame-to-center-of-spandrel ratios.
- » Capturing heat flow through adjacent assemblies.
- » Predicting interior temperatures, especially near corners and framing intersections.

As a result, there is confusion and inconsistent results in spandrel thermal performance values. Several studies show that conventional two-dimensional ("2-D") thermal simulations may overestimate R-values by more than 30% compared to physical testing or three-dimensional ("3-D") simulations.

This paper summarizes ongoing research, including a literature review, preliminary thermal simulations, and laboratory testing. The research objective is to develop improved thermal simulation techniques that more accurately represent the thermal characteristics of spandrel assemblies and their integration with the building envelope.

LEARNING OBJECTIVES

- » Identify the limitations of current thermal simulation methods for spandrel assemblies.
- » Evaluate the impact of ventilation in spandrel assemblies.
- » Discuss the experimental setup for performing laboratory testing.
- » Compare laboratory test results to thermal simulation results.

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INTRODUCTION

Glazed wall systems, such as curtain walls and window walls, comprise transparent, translucent, and opaque areas. The opaque areas, known as spandrel assemblies shown in **Figure 1**, are often used to hide building components such as slab edges, mechanical equipment, and suspended ceilings. Spandrels are increasingly insulated with the intent of improving thermal performance relative to the transparent portions of the glazed wall system. However, due to thermal bridging from the structural framing components that interrupt the insulation, spandrel thermal performance is often worse than expected. This can contribute to greater-than-expected building energy loss, unexpected condensation risks, and other performance issues.

There is a general notion that insulated spandrel assemblies may be evaluated using similar 2-D thermal simulation techniques as the vision areas of glazed wall assemblies since they are part of an integrated system with similar framing. However, components within spandrel assemblies,

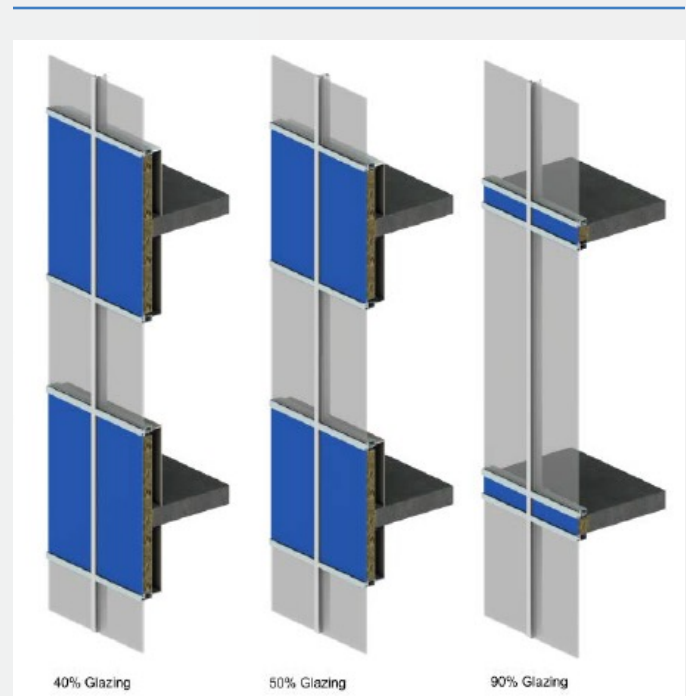


FIGURE 1. Various spandrel assembly conditions (blue) at slab edges.

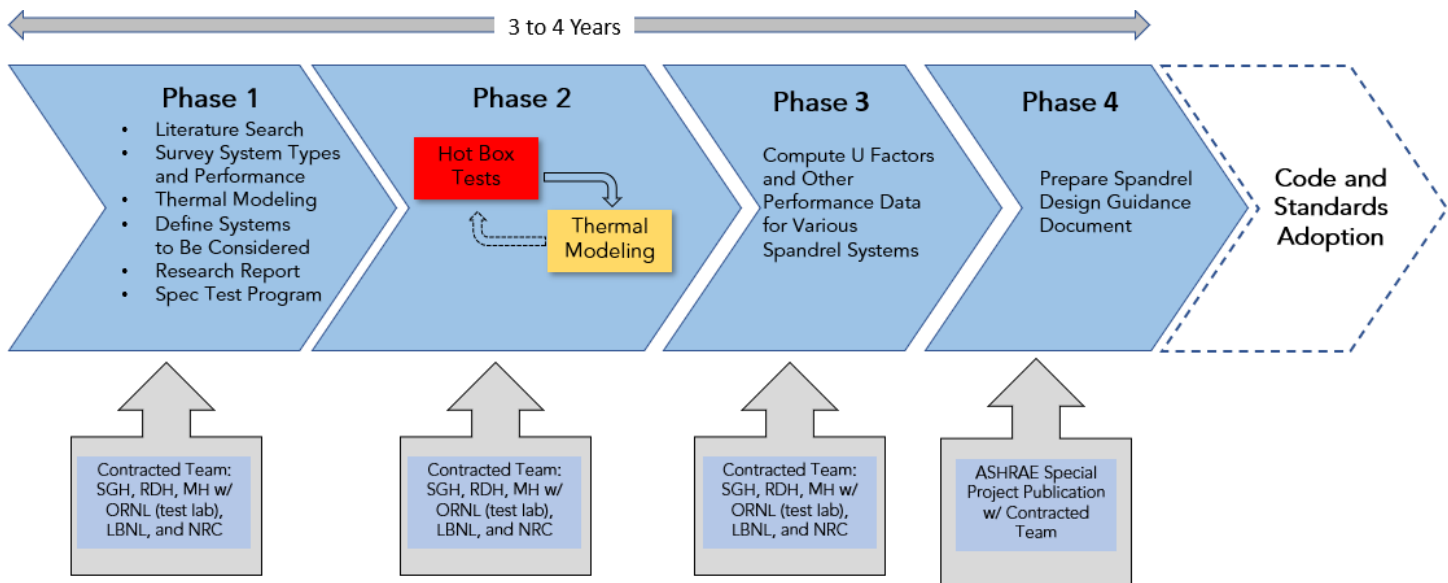


FIGURE 2. Project phasing plan.

the position of the insulative layers, and other construction realities differ significantly from vision areas. These differences result in heat flow paths that previous techniques struggle to capture effectively, leading to an overestimation of thermal performance by as much as 20% to 30% when compared to laboratory measurements.^{1,2} In addition, traditional thermal simulation techniques do not account for a number of conditions typically found in many buildings, such as the impact of nonstandard spandrel sizes and adjacent assemblies.

Without industry guidance to evaluate spandrel thermal performance under these conditions, many professionals struggle to provide accurate spandrel

U-factors for their projects, the impact of which is an overestimation of whole-building energy performance and a failure to achieve energy efficiency goals. Similarly, many building energy codes and industry standards do not include rigorous requirements to accurately evaluate spandrel thermal performance, making it difficult to enforce thermal requirements for spandrels. As whole-building energy performance comes to the forefront and building energy codes and standards become more stringent, the industry will inevitably recognize the impact of spandrel assembly thermal performance on whole-building energy performance and will seek accurate values for their designs.

order to address this shortcoming in industry knowledge, a multi-phased research program was created. A key differentiator is the intent of developing a procedure that is valid for the many potential spandrel conditions that may be applied to buildings. Another reason for this research is to foster innovation by providing the industry with an analytical means of assessing improvements in spandrel thermal performance. Jurisdictions may choose to recognize the performance of spandrels in different ways, including requiring the use of the procedure developed as part of this work or by setting targets independent from those of other opaque wall assemblies. With a standardized approach, codes,

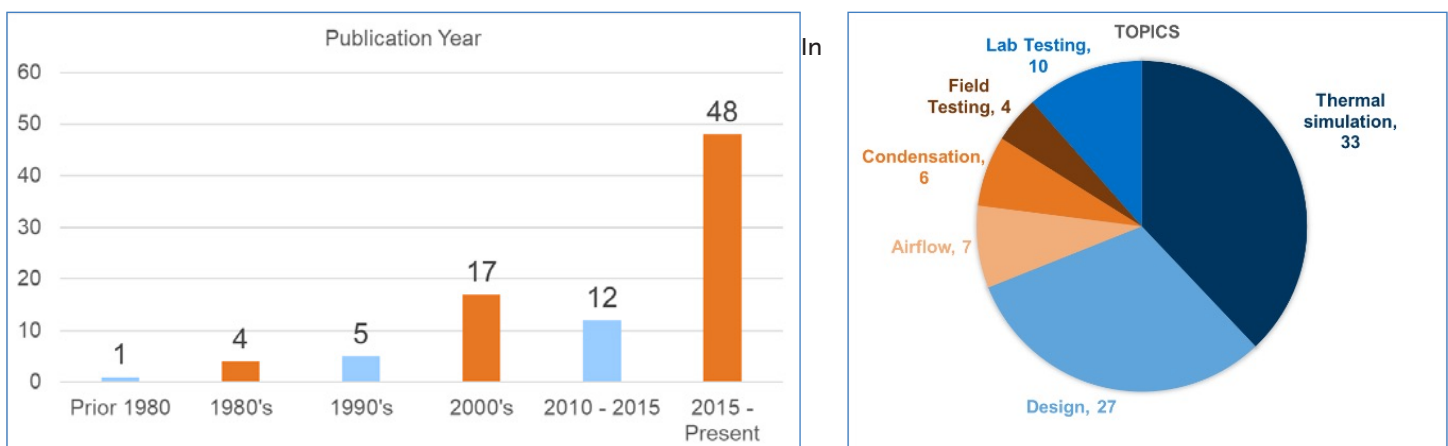


FIGURE 3. Breakdown of reviewed documents by publication year and topic from literature review.

TABLE 1. Industry gaps from the literature review.

Topic Area	Descriptions
Adjacent Assemblies	» What is the impact of adjacent assemblies on spandrel thermal performance? » What is the impact of the intermediate floor connected to window wall spandrel assemblies?
Thermal Evaluation Techniques	» How can the accuracy of 2-D thermal simulation methods, when compared to physical test results, be improved? » What are the impacts of contact resistance of components on thermal performance? » What is the accuracy of current industry standards and guidelines on simulating thermal performance compared to physical testing?
Spandrel Panel Construction	» How do size and configuration impact spandrel thermal performance? » What are the impacts of various spandrel components on thermal performance?
Overall Building Enclosure Thermal Performance	» What are the impacts of accurate spandrel thermal performance values on weighted U-factor calculations and envelope backstop calculations for building energy code compliance?

and standards can be tightened over time (for example, step/stretch codes, Passive House) and empower owners to prescribe and obtain desired levels of performance.

RESEARCH PROGRAM OVERVIEW

The research program’s main goals are to develop a validated thermal simulation procedure for evaluating the thermal performance of spandrel assemblies and to provide guidance on how to improve spandrel thermal performance.

To meet the study objectives, a multi-phased research program that includes a review of the current research and state of industry practice, laboratory testing, 2-D and three-dimensional (3-D) thermal simulations, and publication of a thermal simulation procedure as shown in **Figure 2**, was developed.

The scope of the research includes various glazed wall systems and spandrel configurations. The systems in the study include stick-built and unitized curtain wall systems, window wall systems, and next-generation designs, such as timber veneer systems and highly insulated unitized systems. Variations in spandrel configurations include spandrel insulation types, slab anchor types, cladding panel types, mullion wraps, and various backpan designs.

This paper summarizes Phase 1 of the study and includes a literature review,

an industry survey, an evaluation of the current state of practice, computational fluid dynamics (CFD) simulations, and the development of a test program. A summary of the scope and key results are presented in the following sections.

LITERATURE REVIEW

The researchers performed a literature review to discern the current state of understanding and research on spandrel thermal performance, including current research methods, evaluation standards and practices, and problems with spandrel design and associated solutions. The literature review included eighty-seven research papers, codes, standards, industry articles, and guidelines focusing on thermal simulation, condensation risk, airflow, and laboratory testing **Figure 3**.

From the literature review, the authors identified several gaps in the industry’s knowledge as it relates to accurate evaluation of spandrel thermal performance; these gaps are listed in **Table 1**. Findings from the literature review were used in the development of the test program and to focus research on key areas where additional industry guidance is required.

INDUSTRY SURVEY

The researchers conducted an industry survey to assess the prevalence of specific spandrel types and to assess

industry knowledge and expectations of spandrel performance. This survey was also performed to understand which systems and details are most challenging from the standpoint of thermal performance, as well as to understand potential innovation opportunities. The survey reached thirty-five industry professionals in various roles, including fourteen designers, sixteen contractors, and five industry organization representatives. Key takeaways from the survey results are listed in **Table 2**.

CURRENT STATE OF USE

Recognizing the importance of manufacturers’ role in advancing the state of the industry and in providing solutions for higher-performing spandrels, the researchers conducted a series of interviews with glazing system manufacturers. The focus of the interviews was to identify barriers to the future development of spandrel panels and to identify opportunities for innovation. The interviews were limited to those with relatively large manufacturers of spandrel assemblies. **Table 3** lists common themes that emerged from ten interviews.

In addition to the information gathered from the interviews, the researchers analyzed the prevalence of glazed wall systems in North America. Eight of the largest cities in North America were selected to review the prevalence of glazed versus non-glazed buildings

TABLE 2. Industry survey key takeaways.

Categories	Takeaways
Prevalence of Glazed Wall Systems	» Glazed wall systems are prevalent in modern construction. » Glazed wall systems are used in all eight The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) climate zones. » The most common glazing type is double-glazed insulated glazing units with a low-emissivity coating. » Unitized curtain wall is the most common type of glazed wall construction in downtown core areas. » Glazed wall systems are typically installed on buildings greater than twelve stories. » Glazed wall systems account for more than half of the exterior wall area on projects where they are included, with spandrel areas accounting for 40% to 60% of that area.
Prevalence of Spandrel Panels and Common Characteristics	» Glazed wall systems are primarily selected by the respondents for aesthetics, followed by speed and constructability. » Designers most often specify vented spandrels. In contrast, contractors show no preference for either vented or fully sealed spandrels. » Metal panel was the most commonly specified spandrel cladding, followed by shadow box.
Spandrel Panel Concerns and Innovation	» The most common issues were aesthetics, condensation, and glass breakage. » Thermal performance, code compliance, and lack of industry-accepted analysis techniques are a concern. » Insufficient market demand for higher-performing products, industry education, and lack of industry-accepted analysis techniques are the top three barriers to spandrel innovation
Spandrel Panel Thermal Performance	» Most are aware of the difference in thermal performance required of spandrel panels compared to transparent glazing. » The average reported thermal performance of spandrels varies widely in the industry, from R-3 (RSI-0.53) to R-10 (RSI-1.76). » Based on current technologies, most believe that a spandrel R-value between 5 (RSI-0.88) and 10 (RSI-1.76) is achievable but could be higher. » The most common analysis procedure is the American National Standards Institute/ National Fenestration Rating Council (ANSI/NFRC) 100 (2-D).

in downtown commercial areas. The cities reviewed were New York City, Phoenix, Houston, Chicago, Columbus, Jacksonville, Los Angeles, and Vancouver, British Columbia. The cities are all located in ASHRAE Climate Zones 2 to 5.

Results show that glazed wall systems represent roughly 40% of the building facade systems in downtown cores. Results also show that high- and mid-rise glazed buildings are dominated by curtain wall systems rather than window wall systems.

In summary, the industry appears to recognize that a 3-D thermal simulation procedure would produce more accurate results when compared to 2-D thermal simulations, but it is waiting for building codes and standards to “raise the bar.” In the absence of a more

accurate and enforceable standard, it is likely that the industry will continue to proceed with “business as usual.”

CFD SIMULATIONS

In response to the prevalence of vented and sealed spandrel assemblies

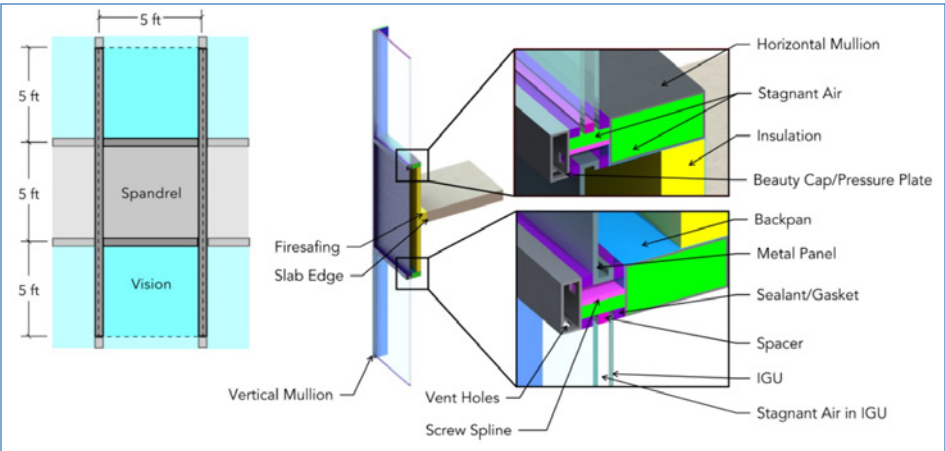


FIGURE 4. Three-dimensional computational fluid dynamics (CFD) simulation geometry (excerpts from CFD model).

TABLE 3. Summary of industry interviews.

Category	Common responses
Industry Knowledge	» Across the industry, there is limited knowledge of thermal modeling standards and resources specific to spandrel panels. » Misunderstandings persist regarding the difference between the one-dimensional center-of-spandrel performance and the effective thermal performance of spandrel panels (2-D or 3-D).
2-D Versus 3-D Modeling	» All the interviewed manufacturers report their performance based on 2-D thermal simulations. » Manufacturers identified access to 3-D performance data as a market differentiator but acknowledged the improved accuracy (and decreased R-value) as a risk when approaching markets or teams with a poor understanding of the results
Codes and Standards	» Impediments to innovation include current code language, which allows and sometimes requires less accurate 2-D thermal simulation or tabulated performance, and inconsistent enforcement of the existing performance documentation process. » Suggested solutions included code updates to recognize spandrels as a unique wall construction type and a standardized modeling procedure.
Innovative Technologies	» The most common areas of product development are limited to internal system components (for example, thermal breaks). » Achieving an “all-glass” visual intent is cited as a significant constraint when considering other areas of improvement (for example, exterior insulation).

highlighted by the industry survey, the researchers evaluated the impact of airflow through spandrel assemblies on thermal performance with CFD simulations. While the researchers anticipated this effect would be minimal based on previous studies of ventilated rainscreens, 3-D CFD simulations were performed, as shown in **Figure 4**, to quantify the potential impact of varying ventilation parameters and examine the need, if any, to adjust the test program design.

The 3-D CFD simulations evaluated the impact of airflow on spandrel panel thermal performance, specifically studying the impact of vent openings, air volume modeling assumptions, and film coefficients. Other variables that can influence airflow include spandrel panel size, cavity depth, frame type, backpan profile, insulation type, the roughness of surfaces enclosing the air cavity, and emissivity. However, these variables were all deemed secondary compared to vent openings and exterior air velocity and were excluded from the study at this time. The 3-D CFD simulations were compared to the 2-D finite element analysis (FEA) thermal simulations more commonly used by practitioners.

Based on the results of these simulations, the following conclusions were drawn:

- » Discrete vent openings in spandrel assemblies have a marginal effect on the average velocity and air temperature in the spandrel cavity and the simulated interior surface temperatures (less than 1°F (0.5°C) difference) and have little to no effect on the overall heat transfer across the spandrel assembly.
- » Simulated spandrel cavity temperatures using 2-D FEA and 3-D CFD simulations differ by as much as 19°F (10.5°C), notably near vent openings.
- » Interior convective film coefficients vary from floor to ceiling and are higher below the slab edge than above the slab edge. The common practice of using a single interior film coefficient does not account for such variations. In addition, the interior film coefficients vary with exterior air velocity but are much less pronounced.

– The CFD-calculated film coefficients in this study reflect an approximation of laboratory testing conditions, not real-world conditions. They should not be

compared to standard values, which are derived using different air velocities.

- » Overall thermal performance (that is, U-factor) varies minimally (0% to 6%) when calculated using 2-D FEA thermal simulations versus 3-D CFD simulations.

This agreement is generally supported by recent NFRC updates to spandrel simulation procedures and the associated physical validation testing. However, the authors note that this conclusion does not apply to typical installed spandrel conditions, which include elements not captured in the simulated configuration (e.g., deflection headers, adjacent glazed wall systems, etc.).

The primary differences between the 2-D FEA and 3-D CFD simulations are the geometry simplifications, radiative film coefficients, and air volume modeling assumptions used in the 2-D FEA thermal simulations.

Different levels of convective heat transfer exist within spandrel cavities depending on exterior wind velocity, but differences between ventilated and sealed panels are negligible, even at high wind velocities. Therefore, spandrel panel ventilation will not be

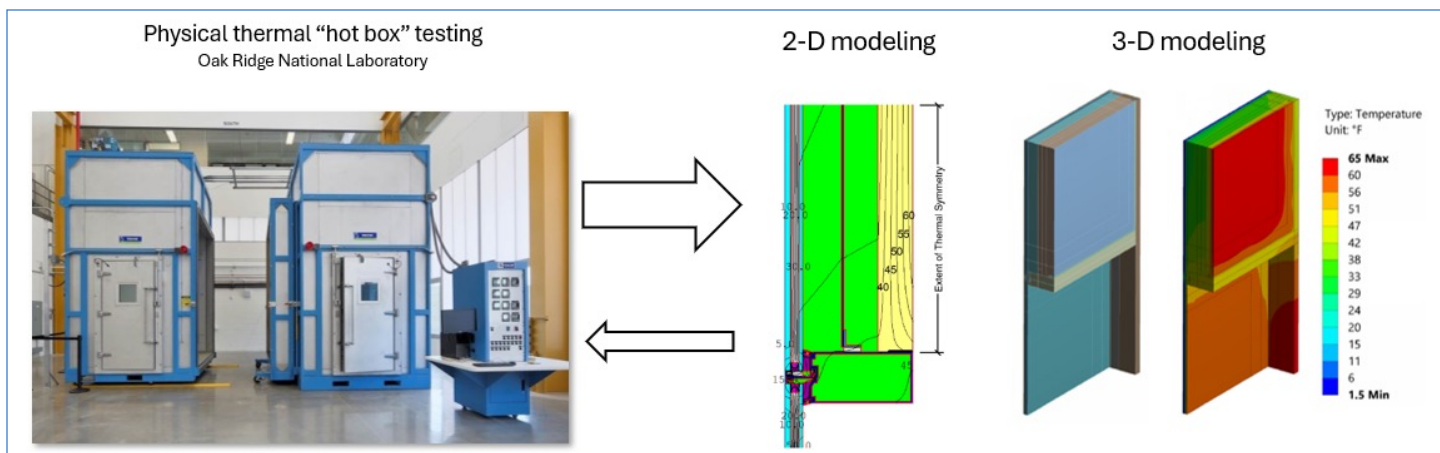


FIGURE 5. Left: Hot-box testing image, courtesy of Oak Ridge National Laboratory. Right: 2-D and (3-D) computational models.

considered in the laboratory testing program or in future simulations.

The 3-D CFD simulations in this study focused primarily on convection at two exterior air velocities. Additional study should be performed to evaluate the variability of interior convective air film coefficients based on geometric surface configurations and mechanical systems. In addition, future work on the subject should study the effect of radiative film coefficients and solar radiation (heat flux to simulate the solar heat gain).

LABORATORY TEST PROGRAM

The setup of the laboratory testing program was included in the first phase of the research program. The objective of the laboratory testing program is to provide data to validate 2-D and 3-D thermal simulation methods for the development of simulation guidelines to evaluate the thermal performance of spandrel assemblies **Figure 5**.

The laboratory tests are designed to cover multiple systems and configurations that are intended to capture conditions typically found in commercial buildings. These configurations include the impacts of:

- » Spandrel panel size.
- » Adjacent assemblies (for example, transparent vision glazing sections, non spandrel opaque assemblies).
- » Intermediate floor attachments and anchorages.
- » Spandrel construction (for example, backpan configuration, insulation

type, cladding type, interior wall construction).

- » Airflow around the spandrel assembly.

The impacts of the above factors have been missing from previous and current industry standards and research. As a result, there is little guidance on how to consider these factors when evaluating spandrel thermal performance through thermal simulations; this lack of guidance has led to confusion and improper evaluations in the industry.

The configuration of the test articles includes various spandrel panels at different sizes and a truncated reinforced concrete intermediate floor slab to simulate the impact of floor

slab anchorages and connections to glazed wall systems. This arrangement is shown in **Figure 6**.

The laboratory tests are being carried out at Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee, using hot-box equipment capable of testing large articles at steady-state conditions. Temperatures at critical locations will be measured and compared to 2-D and 3-D thermal simulations. The test procedures are similar to ASTM C1199 and ASTM C1363, with the exception that heat flow metering will not be required since only surface temperatures, air temperatures, and airflow around the test article will be measured. The articles will be tested under the conditions listed in **Table 4**.

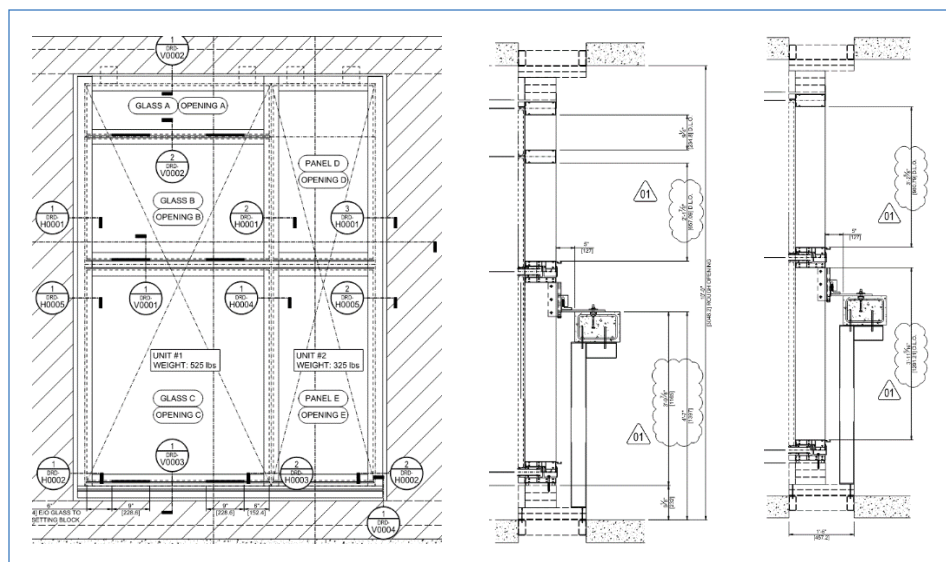


FIGURE 6. Left: Test article spandrel panel configuration. Middle and right: Section views of the test article.

TABLE 4. Laboratory test conditions.

Conditions	Temperatures	Airflow
Warm Side (Indoor)	100°F (37.8°C)	Natural convection conditions.
Cold Side (Outdoor)	35°F (1.7°C)	Winter wind conditions.

Over 150 sensors will be installed at critical locations in the test articles, as shown in **Figure 7**. The sensors are to be located at key areas such as the center of the panel, the edge of the panel, the glazed wall system frame, and intersections between horizontal and vertical mullions. The temperature sensors will measure temperatures throughout the components within the spandrel assemblies to capture the temperature profiles of the spandrel panels and overall system throughout the test.

The research program will test both curtain wall and window wall systems with various configurations and spandrel construction components, as shown in **Table 5**, through multiple rounds of hot-box testing at steady-state conditions. A total of six test articles and eighteen variations will be tested.

In order to evaluate the impact of various components on spandrel thermal performance, variations to the spandrel panel construction will be made to the test articles for multiple rounds of testing. These variations will consist of discrete modifications of key components and will not impact the common panel layout of all tested systems. Temperature and airspeed sensors will be placed on, within, and adjacent to each test article to capture data that can be compared to simulations.

All laboratory testing will be carried out as part of Phase 2 of the research project.

CONCLUSIONS

Phase 1 of the research program has identified many gaps within industry research and the state of practice

in relation to spandrel thermal performance within glazed wall systems. Some of the key findings of knowledge gaps within the industry from the literature review, industry survey, and interviews regarding the current state of use include:

- » Glazed wall systems are prevalent across North America.
- » Reported spandrel U-factors relying on 2-D thermal simulations may differ by more than 30% relative to 3-D thermal simulations and physical testing.
- » The impact of adjacent assemblies, such as vision glazing and slab edges on spandrel performance is not generally being accounted for, nor are they recognized by industry or the associated codes and standards.
- » Impediments to innovation include current code language, the lack of a procedure to accurately account for spandrel performance, and inconsistent enforcement of existing procedures.
- » Ventilation of spandrels has a negligible impact on the product U-factor and temperatures.

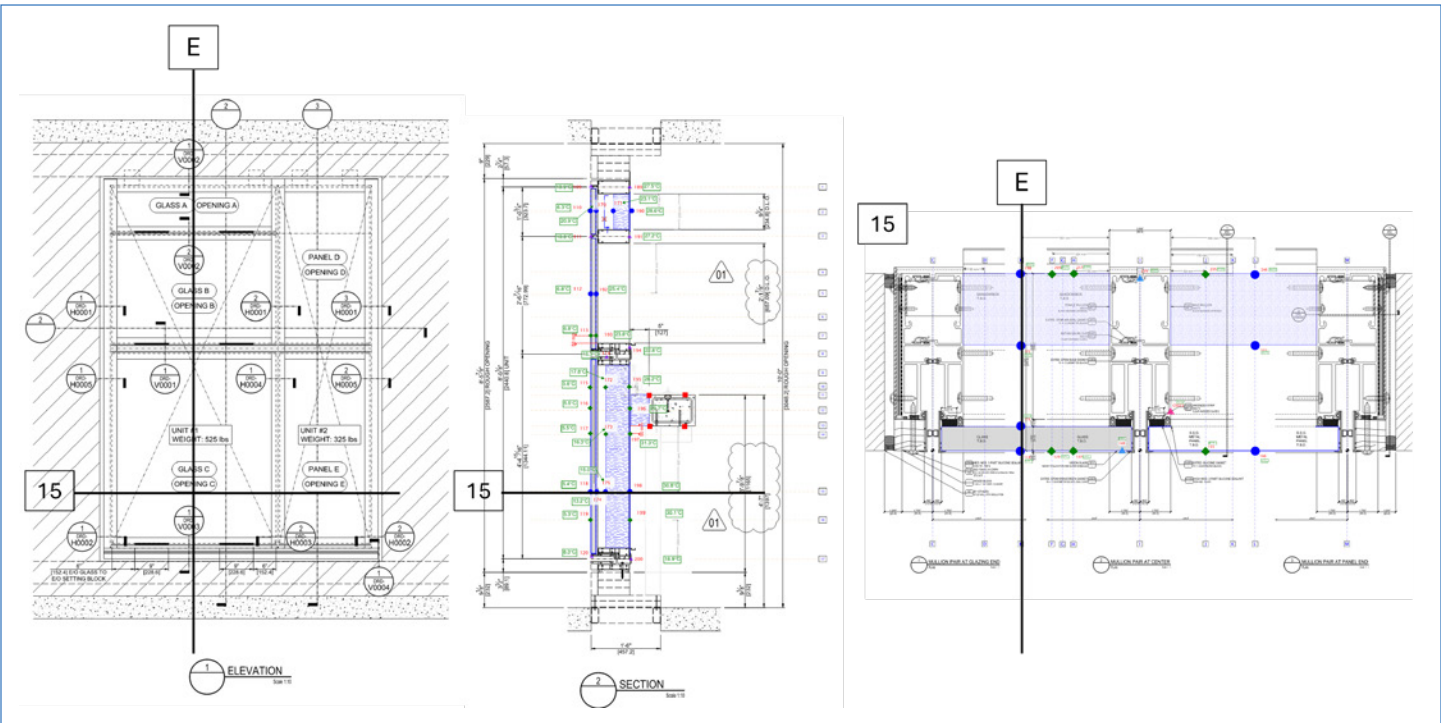


FIGURE 7. Left: Elevation view of temperature sensor layout. Middle: Section view of temperature sensor layout. Right: Chamber sensor layout.

TABLE 5. Proposed curtain wall and window-wall system test articles and variations.

Description	Description
Stick-Built Curtain Wall	Unitized Curtain Wall
» Thermally broken aluminum captured system. » Commonly used in industry. » Individual components installed on site.	» Thermally broken aluminum structural glazed system. » Commonly used in industry. » Prefabricated panels shipped to and assembled on site.
Window Wall (Top Slip Anchor)	Window Wall (Deflection Header)
» Thermally broken aluminum. » Supported on slab edge; mullion above and below slab. » Greater integration with intermediate floor slab; less space available for insulation, leading to greater heat loss.	» Thermally broken aluminum. » Significant interaction with intermediate floor slab. » More space for insulation outboard of slab. » Opportunity to thermally break deflection header.
Veneer System	Next-Generation High-Performance System
» Alternative to typical curtain wall systems allowing for wood or steel back sections. » Individual components installed on site.	» Industry state-of-the-art high-performance systems. » Aluminum-framed systems with insulation (R-40+).

These findings confirmed some of the industry gaps of the researchers and revealed additional gaps that the research program should address for the industry. One such topic was the impact of airflow through the spandrel in ventilated spandrel assemblies on thermal performance. 3-D CFD simulations were used to confirm whether ventilation through spandrel panels would impact thermal performance. Findings from the CFD simulations include:

- » Discrete vent openings in spandrel assemblies have a marginal effect on the overall spandrel assembly U-factor. Spandrel ventilation will not be considered in laboratory testing and future simulations.
- » Interior convective film coefficients vary from floor to ceiling and are higher below the slab edge than above the slab edge. The common practice of using a single interior film coefficient does not account for such variations.
- » Overall thermal performance (that is, U-factor) varies minimally (0% to 6%) when calculated at standard size and configuration using NFRC 100 procedures with 6 in. edge using 2-D FEA thermal simulations versus 3-D CFD simulations.

- » The primary differences between the 2-D FEA and 3-D CFD simulations are the geometry simplifications, radiative film coefficients, and air volume modeling assumptions used in the 2-D FEA thermal simulations.
- » Future CFD studies may assist with an investigation into interior/exterior air film coefficients, which have been shown to significantly impact interior temperatures of assemblies with relatively low R-values.

Based on these results, ventilated spandrels were not included in the test program. Instead, the test program focused on laboratory testing of six test articles with eighteen spandrel variations that represent various glazed wall systems and spandrel configurations. The test program will measure surface temperatures throughout the spandrel assemblies through multiple rounds of hot-box testing at steady-state conditions. The test articles will be arranged to include multiple spandrel panels of different sizes and a truncated concrete intermediate floor slab to evaluate the thermal bridging impact of slab anchorages and bypass details. The test articles will be designed such that multiple components may be replaced in between rounds of testing to allow for variations in spandrel components and configuration.

NEXT STEPS

The researchers have developed a detailed plan for Phase 2 in collaboration with the research team, test laboratory, and industry champion that includes testing and modeling of the six test articles, each with three variations, for a total of eighteen variants. Supplementing the measurements with 2-D and 3-D simulations will enable the development of procedures that can be universally applied, developed into standards, and adopted by building energy codes and standards. Specifically, Phase 2 will include the tasks noted below:

- » **Laboratory Testing:** Laboratory testing will be performed at ORNL and will collect temperature measurements for comparison with 2-D and 3-D simulations. A summary package that includes relevant documentation and measurements that enable independent researchers or professionals to conduct additional investigations or calibrate future 2-D and 3-D simulation techniques/ software will be provided.
- » **Thermal Simulations:** Construct 2-D and 3-D simulations of select details. Compare simulated and measured test results of select details. Detailed comparison will be provided in Phase 3.

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Adaptation of Low-Slope Roof Assemblies against Projected Climate Severities: Evaluation of a New Standard

ABSTRACT

The Ontario Building Code requires low-slope roof assemblies to withstand dynamic wind uplift according to National Building Code of Canada requirements and tested per the CSA standard A123.21, *Standard Test Method for the Dynamic Wind Uplift Resistance of Membrane-Roofing Systems*. This requirement has had a major impact on the roofing industry, obliging manufacturers to design, test, and determine the performance of complete roof assemblies. However, a recent project demonstrated a worst-case scenario: a series of errors involving a lack of project-specific wind resistance values in the design specification, use of questionable alternative methods of compliance presented by the manufacturer, and poor quality of material handling and workmanship by the roofer during construction resulting in failure after strong wind events. As the industry tries to cope with current code requirements to resist the climatic conditions based on the historic data, the effects of climate change expose the built environment to more-severe environmental stressors. Extreme weather events—including high wind speeds, intense rainstorms, heavy snowfalls, extended heat waves, and other stressors—are becoming more frequent and powerful. This paper discusses the evaluation of CSA A123.26, *Performance Requirements for Climate Resilience of Low Slope Membrane Roofing Systems*, an optional standard that builds on CSA A123.21 to address the impacts of projected wind extremes and heavy rainfall.

LEARNING OBJECTIVES

- » Recognize the designer's responsibility and means to include the project-specific wind uplift requirements for low-slope roofs.
- » Describe existing challenges in meeting the current building code in resisting wind uplift and the required due diligence.
- » Explain the CSA A123.26 standard.
- » Discuss the potential effect of the new CSA A123.26 standard on the industry.

SPEAKERS



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Sathya Ramachandran has 24 years of experience in building science consulting and research, with a focus on such high-performance goals as durability, resilience, energy conservation, and occupant comfort of building envelope assemblies. He has provided consulting services for various building types across North America and has advanced education in building science. He has strong knowledge, experience, and attention to detail in the areas of building science principles, material composition, regulations, different assemblies, and components. He is a voting member of the ASTM International E06 Committee for Performance of Buildings.



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Over his 30-year career, Bruno Bernard has developed an in-depth knowledge of roofing materials and their behaviour. Since 2016, he has headed the EXP roofing testing laboratory, the only laboratory recognized by UL DAP in Canada for the CSA A123.21 standard (Standard Test Method for Dynamic Wind Uplift Resistance of Membrane Roofing Systems). His duties include laboratory testing, in situ testing, and consulting expertise. He sits on the SIGDERS (Special Interest Group for the Dynamic Evaluation of Roofing System) committee and other related task groups.

In 1994, the National Research Council of Canada (NRCC) led the way to form a consortium-based research and development study group, the Special Interest Group for Dynamic Evaluation of Roofing System (SIGDERS), which includes representatives of manufacturers, contractor's associations, testing laboratories, homeowners, and insurance companies. The group's research led to the development of the CSA A123.21, *Standard Test Method for the Dynamic Wind Uplift Resistance of Membrane-Roofing Systems*,¹ which was first published in 2004 and subsequently revised in 2010, 2014, and 2020. Referenced in the *National Building Code of Canada (NBCC)*² since 2015 edition and adopted by the provincial codes, including the *Ontario Building Code (OBC)*,³ CSA A123.21¹ specifies the primary means of assessing a roofing system's resistance to counteract calculated wind loads and has become a pivotal point in the development of roofing specifications.

With the codification of CSA A123.21,¹ the design and construction of roof assemblies for buildings built in Canada are no longer a simple composition of layers of roof components, relying on the proprietary design of the system by the manufacturer. Low-slope roof assemblies, excluding protected roof membrane assemblies, are now required to resist the project-specific wind uplift loads of three different zones of a roof area: the field, edges, and corners. To meet this requirement, each of the project team members, including designers, manufacturers, and installers, must play a pivotal role. However, there have unfortunately been cases in which team members have not adequately

carried out their responsibilities, and a combination of errors and/or omissions have led to failures.

Addressing the project-specific challenges related to the wind load is a crucial starting point in achieving long-term durability of roof assemblies, but it is not the only concern. The other main challenge is to design roof assemblies that resist and manage precipitation. To address that challenge, project teams must take into account the NBCC² requirements for sizing drains and rainwater leaders. In addition, there are several qualitative measures followed in the industry that are either industry best practices or standards, including standards published by roofing contractors' associations, for example *Roofing Practices Manual of Roofing Contractor's Association of British Columbia*.⁴

With the changing climate and anticipated climate severities, there is a need to further enhance the above mentioned requirements for roof assemblies to resist increased wind load, to control and manage increased precipitation, and to counter increase in temperature from having an impact on the durability. To meet this need, NRC in collaboration with the SIGDERS committee has developed *Performance Requirements for Climate Resilience of Low Slope Membrane Roofing Systems* (CSA A123.26),⁵ which addresses the severities related to wind and rain.

THE PERFECT STORM— A CASE STUDY

On December 14, 2021, a six-storey multi-unit residential building under construction in the Greater Toronto Area reported roof damage caused



FIGURE 1. Failed roof assembly after heavy wind conditions

by a strong wind event (**Figure 1**). The fully adhered thermoplastic polyolefin (TPO) roof assembly over concrete deck with a layer of vapor retarder, two layers of polyisocyanurate insulation and a layer of high density polyisocyanurate coverboard had experienced wind uplift damages due to high wind conditions that reached up to 96.3 km/h, as recorded by the nearby weather stations. The damage covered approximately 15 per cent of the roof assembly, across four different locations. At first glance, the roof assembly failure appeared to be due to heavy wind conditions experienced at the time of the event that may have exceeded wind uplift design parameters. However, subsequent review determined that the wind conditions were found to fall within the expected wind load range for the site. The project experienced a series of missteps leading to the failure event, all potentially contributing to create a 'perfect storm' scenario. The potential contributing factors include: failure by the designer to specify project-specific wind uplift values in the design specification; alternative questionable methods of compliance employed by the manufacturer; and poor material



FIGURE 2. Poor installation practices observed and corrected



FIGURE 3. Exploratory opening investigation conducted post failure



FIGURE 4. Removal of failed roof for repair

handling, poor workmanship and poor quality control by the contractors during construction (**Figures 2, 3, & 4**). While the primary cause of failure can be attributed to one or more of the above missteps, this roof failure incident provided some insights that are valuable lessons learned. For further discussion of the issues noted herein, refer to the article by Ramachandran et al., “Wind Uplift Failure of a Roof Assembly: The Perfect Storm.”⁶

MEETING CODE REQUIREMENTS FOR WIND UPLIFT

To satisfy code requirements for wind uplift, designers must first calculate and/or use the available online calculator to determine the project-specific wind uplift values and include them in the project specifications. In addition, it is advisable for the designer to specify a requirement for the contractor to submit reports issued by third-party testing laboratories to confirm that the procured roof assemblies are rated to exceed the required project-specific wind uplift values. If the designer chooses to include basis-of-design roof assemblies in the specification, the designer may choose to research and/or work with manufacturers to identify rated roof assemblies that meet the project-specific requirements. Some manufacturers and third-party testing laboratories have posted online the roof assembly resistance reports with their ratings that can help the designer identify appropriate roof assemblies. NRC is in the process of developing a portal with database of tested roof assemblies from various manufacturers to provide a centralized resource. At the time of the roof assembly

procurement, the roofing contractor can work with manufacturers to identify a roof assembly that is rated to resist the project-specific wind uplift load requirements of all zones at each of the roof areas of the building, and present as a substitution request for designer’s approval.

While the selection of a rated roof assembly is an important step, the general contractor and roofing trade must take responsibility for good workmanship and the correct installation of the selected system. It is critical to follow the manufacturer’s instructions for the tested assembly, including the use of proper spacing, patterns, and installation timing for each of the components. Materials must be properly stored, and proper precautions taken at the time of installation to ensure the effective functioning of the components. For installation of assemblies during winter, those components that are affected by cold weather conditions, a winter-grade product as offered by the manufacturer is to be used. Additionally, crews must pay attention to details at the time of construction, such as temporary seals at perimeter scuppers and openings, and along end of workday assembly terminations, to avoid loss of integrity of the roof assembly due to inclement weather including extreme weather conditions that may occur during installation. Quality control measures by the general contractor and roofing trades are essential to verify that materials and components are properly installed. A general conformance review by the designer and a qualified consultant as required is imperative during construction.

CALCULATING PROJECT-SPECIFIC WIND UPLIFT REQUIREMENTS

The project-specific wind uplift load values are calculated based on load-resistance-factor design (LRFD) with inputs including the geographical location, terrain of the project site, openings in the building, height of the building, size of the roof area, and height of the parapet. NRCC has developed and published an online tool, Wind-RCI,⁷ that can calculate these values based on the user’s project-specific input. This tool can be used to calculate the required size or width and corresponding wind uplift resistance values for field, perimeter, and corner zones of each roof area, as required, based on the building information and site location characteristics. The online tool has limitations: it is not applicable to buildings exceeding 45 m (150 ft) in height, and it should be cautiously used for buildings located in dense metropolitan locations where micro-climatic site conditions may influence load values in ways not captured by the tool’s calculations, for instance locations that experience wind tunnel effects in downtown core of major cities. It is important to note that, as is the case with any tool, it is the user’s responsibility to verify the values generated by Wind-RCI.⁷

THIRD-PARTY LABORATORY TESTING TO RATE ROOF ASSEMBLIES

CSA A123.21¹ is a rigorous test method that simulates the effects of wind pressure on a roof assembly specimen. The test method is straightforward: a complete 3.7x7.3 m (12x24 ft) specimen composed of the layers of the tested

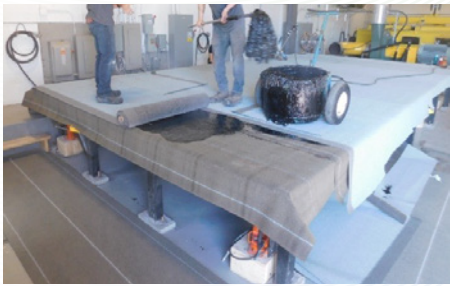


FIGURE 5. Installation of a roof assembly specimen.

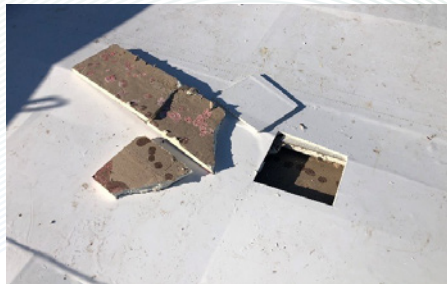


FIGURE 6. Airtight chamber mounted over the roof specimen.



FIGURE 7. Destructive testing upon completion of a test to evaluate the mode of failure.

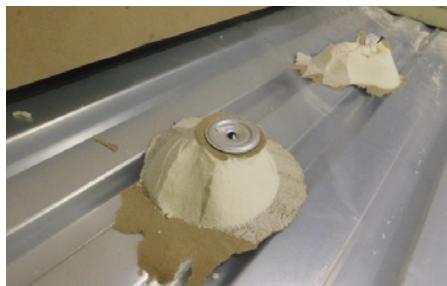


FIGURE 8. Mode of failure observed upon completion of testing

roof assembly, which may include a thermal barrier, a vapor retarder, insulation layers, cover board, and a roofing membrane system, is installed on a deck, usually of corrugated steel, attached to a specially designed test rig (**Figure 5**). An airtight chamber is then placed on the specimen to ensure airtightness at the junction where the chamber meets the bench (**Figure 6**). An air suction system and computer-controlled shutters modulate the pressure and duration of the vacuum created in the chamber, simulating the pressure effects experienced by roofs during their service life.

The test procedure consists of consecutive load cycles, in predetermined sequences, divided into five levels and two methods, and it is carried out to assess maximum stress until an evident roof failure is observed. The test may last up to 10 hours, depending on the performance of the assembly, during which time the test pressures and behavior of the roof specimen are constantly monitored. At the end of the test period, an investigation is carried out to understand the dynamics of the rupture, if any, and to assess possible

improvement options to enhance the performance of the assembly (**Figure 7 and 8**).

CHALLENGES EXPERIENCED IN MEETING THE WIND UPLIFT REQUIREMENTS

An issue experienced in the industry is for the designers to transfer the responsibility of determining wind uplift requirements to roofing contractors and/or manufacturers by referencing the building code in the specifications, rather than specifying the required project-specific wind uplift values. However, it is prudent for the designers to be informed of the code requirements and either verify the project-specific wind uplift values themselves or engage qualified professionals to provide verified values. Doing so eliminates ambiguity, upholds the standard of care, reduces risk and liability, and prevents cutting corners. In June 2018, the Canadian Roofing Contractors Association issued an advisory bulletin⁸ to communicate the responsibility of confirming project specific wind uplift loads lies with the designer and not the roofing contractor, and the reasoning for this design

responsibility has been dissected at length by Klassen in a 2021 article.⁹

In addition to verifying the project-specific wind uplift values, the designer must obtain test reports supplied by a third-party testing facility that uses apparatus properly calibrated as per the CSA A123.21¹ protocol, and verify that the tested rating of the proposed assembly meets the project-specific wind uplift load requirements for each of the roof areas for all zones. It is also important that the designer understands whether the manufacturer proposes to meet the requirements by using the extrapolation method set forth in the *Wind Design Standard Practice for Roofing Assemblies* (ANSI/SPRI WD-1).¹⁰ ANSI/SPRI WD-1 that provides calculation means to enhance securement. If that is the manufacturer's intention, the manufacturer should provide the details of calculation and any other information that the designer may require to assess the risk. The designer should assess the suitability of the extrapolation method by verifying the calculation and taking into account the mode of failure experienced during the original test. While the extrapolation method may be appropriate for mechanically attached roofing systems (MARS), it is not suitable in all circumstances for fully adhered roofing systems or partially adhered roofing systems (PARS). For instance, if a roof assembly's mode of failure is due to cohesive failure of one of the layers of a roof assembly at its ultimate capacity, improving the adhesion of the layers by reducing the spacing of the adhesives (which is a common approach for extrapolation) will not improve the overall performance of the roof assembly. Regardless of the amount and spacing of the adhesive, the roof assembly will experience cohesive failure of the layer at its ultimate capacity before reaching the project-specific wind uplift resistance values. The designer may specifically note that extrapolation methods of compliance and the use of noncalibrated testing facilities are unacceptable. The safest approach is to ensure that the rating of the proposed roof system is confirmed through third-party testing and meets or exceeds project-specific wind uplift resistance values for all roof zones.

While it is critical that the designer exercise prudence during the design stage and verification at the procurement stage, these precautions will not be sufficient if the installers on site are not informed of or do not follow the same configurations of assembly securements that were used for the tested specimen (i.e., if they do not use the same attachment methods for the roof assembly layers). To ensure that the constructed roof assembly meets the code requirements, it is imperative that the project includes standard of acceptance or mock-up reviews, general conformance reviews, and quality assurance inspections.

The wind uplift loads at the corner are typically higher than at the edge and field conditions. Therefore, there is technically an option to install a roof assembly at the field and edge conditions that is rated lower than the assembly for the corner conditions. Choosing to install varied assemblies at the field, edge and corner will have cost benefits, particularly on larger roofs. Such installations with varying performance ratings should be carefully evaluated on a case-by-case basis to verify that the variation will not have a performance impact at the transitions between the assembly types. Certain conditions may apply in projects that allow different roof assemblies for each of the zones; these conditions include maintaining the same roof composition for all zones in terms of materials, positioning of layers, and thickness of layers; maintaining a consistent thickness for all the assemblies; or using roof area dividers where variations are distinct.

PROJECTED CLIMATE SEVERITIES

In addition to meeting current code requirements, designers and contractors also need to understand that further enhancements to the way roof assemblies are constructed for long term durability may be necessary to prepare for climate-change-driven events such as intense wind storms, heavy precipitation and increased temperature. With the Earth's current surface temperature already reaching 1.5°C warmer than preindustrial levels, the occurrence of severe climate-

related conditions is anticipated immediately and throughout the course of the service lives of existing and to-be-built building stocks. Among building envelope components, roofs tend to be especially vulnerable to climate-related risks due to their exposure to increase and variation in temperature, windstorms causing wind uplift failures, and extended water and snow retention. According to Engineers Canada,¹¹

Engineers have a significant role to play in addressing climate change issues and incorporating them into engineering practice in Canada... Engineers, under their professional code of ethics, play a fundamental role in ensuring construction and operation are continuously adapted to the impacts of climate change to ensure public safety.

SCOPE AND APPLICABILITY OF CSA A123.26

To support the design community in countering the anticipated effects of climate severities, the Task Group on Climate Resilience of Low Slope Membrane Roofing Systems developed CSA A123.26⁵ under the authority of the Technical Committee on Bituminous Roofing Materials and the Strategic Steering Committee on Construction and Civil Infrastructure. The document was published in 2021 as a national standard that meets the Standard Council of Canada's requirements. The objective of CSA A123.26⁵ is to outline specific quantitative and qualitative requirements in the selection and detailing of low-slope membrane roofing systems to resist the impacts of anticipated climate severities. The standard addresses two main elements of the anticipated climate severities: wind and rain. Regarding wind, the pivotal requirement for the roofing system's long-term performance is resistance to wind loads, which includes the determination of project-specific wind uplift loads and selection of an appropriate assembly that can resist the determined load. Additional qualitative requirements in the standard are in line with the determined wind uplift loads. Regarding rain, the standard has design requirements for the roofing

system to collect, manage, and dispose of anticipated additional rainwater due to climate severities, as well as several qualitative requirements.

CSA A123.26⁵ provides three performance levels for low-slope membrane roofing systems: Bronze, Silver, and Gold. The Bronze level represents the current requirements included in the NBCC² and *National Energy Code of Canada for Buildings* (NECB),¹² which do not take into account anticipated future climate severities. The Silver and Gold levels include provisions to counter the impacts of anticipated climate severities and the level of resilience required for the type of building and use.

NRCC has developed an online tool, Climate-RCI,¹³ based on the information from Environment and Climate Change Canada. This tool allows users to input a building's location in Canada and select a magnitude of global warming (0.5°C to 3.5°C). Based on these inputs, the tool classifies the severity of wind, rain, and temperature for the building's location as normal, severe, or extreme. Additionally, the tool provides quantitative design parameters: 1/50 hourly wind pressure and 1/50 one day rain, representing a 50-year mean recurrence for wind and rain, respectively, and anticipated maximum daily temperature for heat. The tool then requires the user to select a resiliency index of 1, 2 or 3, wherein the selection of a higher resiliency index, means the intent to achieve higher roof resilience. Resiliency index 1 aligns performance requirements with current provisions of NBCC² and NECB.¹² Resiliency index 3 is defined as follows: "Roofing systems are fully functional with required performance for normal and emergency operations irrespective of the climate conditions. Damage to contents is minimal in extent and minor in cost. Resiliency index 2 is for any level of performance requirement between Resilience Index 1 and 3. The user should select the resiliency index based on the expected function of the building (especially importance category and risk) and the resiliency required in terms of recovering from disturbances and adapting to climate severity. After the resiliency index for the project is

Climate Category	Resiliency Index 1	Resiliency Index 2	Resiliency Index 3
Normal	Bronze	Silver	Gold
Severe	Silver	Silver	Gold
Extreme	Gold	Gold	Gold

FIGURE 9. The application of climate category and resiliency index to identify a roofing assembly’s performance level.

selected, the tool produces a summary of design parameters for the project, including required roof performance level, whether Bronze, Silver, or Gold.

When the combination of climate index and resiliency index identifies a Bronze level roofing system for the entered inputs, the performance requirements are the current NBCC² and NECB¹² requirements, and the project-specific wind uplift values can be determined using Wind-RCI.⁷ When the roofing system is classified as Silver, it is assumed that the roof assembly will comply with the NBCC² and NECB¹² requirements as well as some additional requirements specified in CSA A123.26.⁵ Similarly, in case of the Gold performance level, the roofing assembly must meet the Bronze and Silver level requirements plus additional requirements specified in CSA A123.26.⁵ In the event of a

conflict in requirements between the levels, the requirements of the highest level would take precedence. **Figure 9** illustrates the various relationships between the climate category and resiliency index in the selection of the required performance.

CSA A123.26⁵ is applicable to adhesive applied roof systems (AARS), partially adhered roof systems (PARS), and mechanically attached roof systems (MARS). An AARS involves using adhesives to bond the roofing layers, mainly the cover board and insulation, on to lower layers. A PARS involves using a combination of adhesive and mechanical fasteners to secure the roofing system to the substrate. In a MARS, the roofing system is secured to the substrate with mechanical fasteners such as screws or nails. CSA A123.26⁵ does not address the climatic adaptation requirements for

the structural support (deck) below the roof assembly, which should be handled through enhancements to the structural design of the buildings.

RESISTANCE TO WIND UPLIFT LOADS

Using Climate-RCI,¹³ by inputting the project location and global warming magnitude, designers can determine the qualitative severity of the anticipated future wind conditions as either normal, severe or extreme and a quantitative 1/50 hourly wind pressure. For instance, the severity and wind uplift pressure value for a project located in Toronto (City Hall) with a global warming magnitude of 2°C is ‘severe’ and 0.46 kPa (9.67 psf) respectively. For the same location and a global warming magnitude of 3.5°C the severity is ‘extreme’ and wind pressure value is 0.50 kPa (10 psf). The wind pressure value is then used to calculate the factored wind loads either following the procedure outlined in section 4.1.7 of NBCC² or using Wind-RCI.⁷ It is to note that the required performance level for the roof, whether Bronze, Silver or Gold may vary depending on the selection of Resiliency Index. **Table 1** presents the wind uplift pressures determined for a hypothetical building of 9 m (30 ft) height in Toronto (City Hall), and its

TABLE 1. Wind load determination for Toronto using Climate-RCI,¹³ Ontario

Global Warming Magnitude	Climate Severity for Wind	Wind Pressure Value	Factored Wind Uplift Load	Resiliency Index	Required Performance Level for Wind
Source: Climate-RCI ¹³			Source: Wind-RC ¹⁷	Source: Climate-RCI ¹³	
0.5°C	Normal	0.44 kPa	Corner -2.6 kPa Edge -1.3 kPa Field -1.0 kPa	1	Bronze
				2	Silver
				3	Gold
2°C	Severe	0.46 kPa	Corner -2.7 kPa Edge -1.4 kPa Field -1.1 kPa	1	Silver
				2	Silver
				3	Gold
3.5°C	Extreme	0.5 kPa	Corner -2.9 kPa Edge -1.5 kPa Field -1.2 kPa	1	Gold
				2	Gold
				3	Gold

Note: Above values are for a roof with no parapet

corresponding factored wind uplift loads and required performance levels for different resiliency indices.

WIND UPLIFT RESISTANCE AT CORNERS AND EDGES

The presence of roof parapets can significantly minimize the effect of wind load at the roof perimeters, i.e. corners and edges. When calculating the factored wind uplift loads per NBCC² or using Wind-RCI⁷ to meet current code (Bronze level), the presence or absence of a parapet is one of the factors in determining the project specific requirements. For instance, for the above Toronto example, the factored wind uplift loads for the roof assembly with no parapet are Corner -2.6 kPa; Edge -1.4 kPa; and Field -1.1 kPa. The same roof with a 1 m (3 ft) parapet will have reduced factored wind uplift values of Corner -2.2 kPa, Edge -1.3 kPa, and Field -1.0 kPa. While the presence of a parapet reduces the wind uplift loads within the roof area, the wind loads against the parapet cladding and its components, particularly the top edge of the parapet, will be higher and is to be determined. For instance, in the above scenario, the factored wind loads for parapet cladding and metal edge components will be -2.9 kPa in suction for Corner and -1.7 kPa in suction for Edge, and a positive load of 1.4 kPa at the face of the parapet.

For the Silver and Gold level roofs, the values determined are required to be

increased by 30% and 50% respectively if a parapet is not installed. **Table 2** below presents the wind uplift values for each of the performance levels for the above example.

The alternative option of installing a 0.9 m (3 ft) high parapet must be installed as an extension of the main structural system of the building and meet the determined wind uplift loads. Installation of a roof parapet as an extension of the main structural system poses challenges in achieving continuity of the air barrier at the intersection detail between the exterior wall and roof assemblies. Lack of air barrier continuity may contribute to wind uplift failures in addition to the potential condensation issues within the parapet assembly. Hence, the roof-to-exterior wall junction detailing at the base of a roof parapet installed as part of the main structural system requires special attention to ensure that the continuity of the air barrier is maintained.

In addition to the requirement to either install a 0.9 m (3 ft) high parapet or increase the performance requirements to counter the higher wind uplift loads for the roof perimeters, CSA A123.26⁵ includes a requirement to reinforce the field membrane termination using metal bars or plates with a maximum spacing of 152 mm (6 in.) to provide secondary protection against membrane lifting and peeling or pulling away from the roof perimeter. The required use of metal components to secure membrane

termination to the structural elements such as metal decks may cause some thermal bridging around the fasteners. However, the risk of wind uplift failures and consequential repair or replacement of roof assembly trumps the marginal increase of thermal bridging at the roof perimeters. Another possible challenge with the installation of term bars and plates is the potential inhibition of rainwater drainage. As an alternative to the requirement to install the term bar and plates, the standard includes an option to further increase the wind uplift loads for the perimeter zones by 30% for parapets with a height greater than 914 mm (3 ft) and 50% for parapets with a height lower than 914 mm (3 ft).

Wind uplift loads are significant at parapets, particularly at the top edges, which experience complex wind aerodynamics. Cap flashings, including cleats and their fasteners, require an appropriate thickness and attachment spacing to resist the determined wind uplift load requirements as that of the roof assembly. The wind forces on the parapet and cap flashing are complex and depend on the roof slope, parapet height, parapet shape, and internal pressure between the wall and edge metal. The cap flashings, particularly at the corners, have a high probability of failure, which can lead to further failure of the rest of the flashing, other parapet components, and the membrane of the roof system. In addition to the requirements listed in CSA A123.26,⁵

TABLE 2. Wind load determination for Toronto (City Hall), Ontario

Roof Performance Levels	Location-specific wind loads per Wind-RCI ⁷			Location-specific wind loads per Wind-RCI ⁷ and Climate-RCI ¹³ with increase of 30% for Silver and 50% for Gold		
	Field wind load, kPa	Edge wind load, kPa	Corner wind load, kPa	Field wind load, kPa	Edge wind load, kPa	Corner wind load, kPa
Bronze	-1.0	-1.3	-2.6	-1.0	-1.3	-2.6
Silver	-1.1	-1.4	-2.7	-1.43	-1.82	-3.51
Gold	-1.1	-1.4	-2.7	-1.65	-2.1	-4.05

Note: NBCC = National Building Code of Canada. 1 m = 3.3 ft; 1 kPa = 20.9 lb/ft².

Wind loads for Bronze categories are compliant with current NBCC requirements; wind loads for Silver and Gold categories are increased 30% and 50%, respectively, from the NBCC code requirements. 1 m = 3.3 ft; 1 kPa = 20.9 lb/ft².

refer to ANSI/SPRI ES-1, *Wind Design Standard for Edge Systems Used with Low Slope Roofing Systems*,¹⁴ for further guidance. The CSA A123.26⁵ requires that the membrane flashing be fully adhered on the vertical upturn of the parapet, and wrapped over the top edge of the parapet, with fasteners securing the membrane flashing through cleats to limit failure.

ROOFTOP ADD-ONS

A critical issue related to the rooftop add-ons is their resistance to wind uplift loads. With regard to the design of rooftop add-ons, CSA A123.26⁵ requires that add-on components and their anchorages meet the wind uplift load requirements for the roof assembly. For vegetated roof assemblies, CSA A123.26⁵ references CSA A123.24, *Standard Test Method for Wind Resistance of Modular Vegetated Roof Assembly*,¹⁵ to determine the project-specific wind uplift loads and airflow conditions for either the built-in-place vegetated systems or the modular vegetated system. The intent of the test is to evaluate the overturning and/or displacement of the vegetated roof components mounted on the roof assembly samples when wind uplift loads are applied.

When there are exterior-mounted rooftop units such as mechanical, electrical, and communications equipment, air intakes, vent stacks, guywires, or solar panels, the attachments for the rooftop units and the supporting frames can be insufficient or missing. When the wind uplift load exceeds the self-weight of a rooftop unit, the unit could tip over, causing damage to the roof membrane. While CSA A123.26⁵ includes some prescriptive requirements for the anchorage of rooftop units, the main intent is to design rooftop units, including their components and anchorage, to meet the wind uplift loads required for the roof assembly.

CSA A123.26⁵ also addresses an issue related to the rubbing of rooftop components against the roof membrane system causing reduced service life. The standard requires that gas lines are mounted on supports at

a minimum of 304 mm (12 in.) over the membrane surface to limit the potential for gas lines to rub against the roof membrane due to deflections between the supports. Similarly, the standard requires that lighting protection cables are secured to thermally nonconductive supporting elements to limit rubbing of the cables on the roof membrane. The minimum spacing requirements for the securement of cables are 914 mm (36 in.), 304 mm (12 in.), and 203 mm (8 in.), respectively, in the field, edge, and corner areas.

CSA A123.26⁵ addresses the common issue of corrosion of metal components in rooftop units and resulting damage to the roof membrane by requiring that rooftop units and their components, including body stands, anchors, and fasteners, be made out of nonferrous metals, stainless steel, or hot-dip galvanized steel with a coating designation of at least G-90.

RESISTANCE TO RAIN LOAD

Rainwater resistance of a roof assembly is a function of the watertightness of the membrane and flashings, the roof slope, drainage, flashing construction, and the ability of the system to evacuate the water.

The primary function of a roof assembly is to prevent precipitation from entering the space below by controlling and discharging the rainwater collected on the roof to either a storm water drainage system or the terrain adjacent to the building. To ensure that roof assemblies meet this objective, designers calculate rain loads and design a roof drainage system. The design process involves determining the appropriate number of drains and size of drains and scuppers, taking into account the roof slope, the type of roof finish, and the type of rainwater leaders. The number and size of drains are calculated based on the rainfall information from NBCC² and the maximum permitted hydraulic load of leader pipe available in OBC.³

The intent of the code is to ensure that the roof drainage system can carry off rainwater from the most intense rainfall that is likely to occur. Therefore, to meet current code requirements (which would be applicable to a

Bronze project), the designer needs to determine the maximum 15-minute rainfall intensity for the site location (1 in 10-year return), referred to as the "concentration time." This rainfall information can be obtained from Table C-2 in the NBCC² Appendix or the Ministry of Municipal Affairs and Housing's Supplementary Standard SB-1, Climate and Seismic Data.¹⁶ The hydraulic load in liters from a roof is equal to the maximum 15-minute rainfall intensity multiplied by the sum of area of the horizontal surface and one-half the area of the adjoining vertical surface (with the areas measured in square meters). For instance, based on the NBCC² Table C-2, the maximum 15-minute rainfall intensity (1 in 10-year return) for Toronto (City Hall) is 25 mm. NBCC² Table C-2 also provides information on 1-day rainfall that has 1 chance in 50 of being exceeded in any single year. The 1-in-50-year return value 1-day rainfall is used mainly to determine the additional (structural) dead load due to ineffective drains.

Anticipated rain loads for Silver and Gold level roof assemblies can be determined using the Climate-RCI¹³ tool. Unlike the NBCC² tables used for Bronze assemblies, Climate-RCI¹³ only provides 1-day rainfall projections. In absence of the maximum 15-minute rainfall intensity information, the extrapolation of 1-day rainfall data in the Climate-RCI¹³ tool is suitable as long as the structural systems will be designed to handle the weight of the projected 1-day rainfall. The 15-minute rainfall intensity can be calculated using the percentage difference between the 1-day rainfall data for Silver and Gold roofs from Climate-RCI¹³ and the 1-day rainfall values from the 2020 edition of NBCC.² Refer to **Table 3** showing an example of the rain load determination using extrapolation for 'severe' and 'extreme' conditions.

Table 7.4.10.9 of Ontario Building Code provides the maximum permitted hydraulic load drained to a horizontal storm drainage pipe at 2% roof slope. Based on the determined rain load, assuming a drain and leader size of 152 mm (6 in.) with a drain slope of 2% under the roof and a roof area of

TABLE 3. Rain load determination for Toronto, Ontario

Rain Load Calculation	
Roof Area	9290 m ²
15-minute rain intensity per NBCC ²	25 mm
One Day rainfall per NBCC ²	97 mm
15-minute rain intensity for 'severe' condition per Climate-RCI ¹³	Unavailable
One Day rainfall for 'severe' condition per Climate-RCI ¹³	116.69 mm
Extrapolated 15 min rain intensity = (25 mm * 116.69 mm) / 97 mm	30 mm
One Day rainfall for 'extreme' condition per Climate-RCI ¹³	126 mm
Extrapolated 15 min rain intensity = (25 mm * 116.69 mm) / 97 mm	32.5 mm

TABLE 4. Number of drains and drain size determination for Toronto, Ontario

Determination of Drains	
Volume of rainwater (9290 m ² x 25 mm = 232.25 m ³)	232,250 liters
Hydraulic load of 4 in. diameter drain/drainpipe and 2% slope of drainpipe per Table 7.4.10.9 in OBC ³	5,970 liters
Number of 4" drains = 232,250 liters / 5,970 liters	39 drains
Hydraulic load of 6 in. diameter drain/drainpipe and 2% slope of drainpipe per Table 7.4.10.9 in OBC ³	17,600 liters
Number of 6" drains = 232,250 liters / 17,600 liters	14 drains
Volume of rainwater for 'severe' condition (9290 m ² x 30 mm = 278.70 m ³)	278,700 liters
Number of 6" drains = 278,700 liters / 17,600 liters	16 drains
Volume of rainwater for 'extreme' condition (9290 m ² x 32.5 mm = 301.92 m ³)	301,925 liters
Number of 6" drains = 301,925 liters / 17,600 liters	18 drains

9290 m² (100,000 ft²), a total of 14 drains is required. Refer to **Table 4** showing comparative calculations for a 4" drain and for 'severe' and 'extreme' conditions.

ROOF DRAINAGE SYSTEM DESIGN

The intent of the building code is to discharge rainwater off the roof at the earliest possible time, but without adding stress to the drainage system during rapid acceleration of rainfall intensity; this purpose is achieved by allowing a certain amount of time for the rainwater to flow across and down the roof before it enters the gutter or drainage system. To determine the drain size and number of drains for an effective rooftop drainage system,

the building code directs the designer to use the maximum 15-minute rainfall intensity and hydraulic load calculations.

In addition to the current building code requirement, CSA A123.26⁵ prescribes maximum runoff for rainwater by limiting the distance between the roof perimeter and drains and limiting the spacing between the drains. For roofing systems in the Silver category, the standard specifies that water on the surface cannot run more than 10.7 m (35 ft) to a drain and scupper. In the Gold classification, the maximum distance to a drain or scupper is 6.1 m (20 ft). Analysis shows that this maximum water runoff distance requirement overwrites the current

code, adding a significant number of drains to the roof and limiting the current industry practice of using two-directional slopes and valleys. When the limiting distance for maximum runoff for rainwater is applied, to a 9,290 m² (100,000 ft²) roof, 45 roof drains are required for a roofing system in the Silver category. The SIGDERS committee intends to review this CSA A123.26⁵ requirement given the impracticality of such an installation, questionable performance in terms of thermal bridging, and challenges related to the continuity of air barrier and waterproofing. Also, this drainage system requirement conflicts with the intent of the building code to reduce overstress on the drainage system.

**RAINWATER RUNOFF
MANAGEMENT ON
ROOF SURFACES**

Current industry practice in roof drainage design is to achieve a 2% minimum positive slope toward roof drains; typically, the roofing system will have two-directional drainage achieved using sloped structure toward a central valley with crickets built using tapered insulation at the center that lead runoff water to drains. This industry practice is further reinforced in CSA A123.26,⁵ which requires that roofing assemblies in the Silver and Gold categories achieve the minimum 2% positive slope for the main roof surface, which also includes a back slope at the crickets that is double the slope of the main roof. The Gold requirement prescribes that the entire roof structure to have a minimum of 2% positive slope.

Current industry practice also limits the interference to free drainage on the roof surface by suitably positioning rooftop units, rooftop accessories, and other openings or by using crickets around such interferences. For effective management of the drainage path, CSA A123.26⁵ includes a prescriptive requirement to position rooftop units, rooftop accessories, and other openings a minimum of 1.8 m (6 ft) away from roof drains, low points, or valleys to avoid restricting the flow of water to drains or scuppers.

RAINWATER DISCHARGE

Ensuring the effectiveness of drains and scuppers is a critical part of handling the discharge of rainwater. In addition to a prescriptive requirement for the minimum drain diameter, CSA A123.26⁵ includes several qualitative requirements for drains, such as the requirement for a sump at drains, specifications regarding the size and slope of the sump, and installation of strains and screens with specific material choices and securement. CSA A123.26⁵ requires a minimum drain diameter of 76 mm (3 in.) for roofing assemblies in the Silver category and 102 mm (4 in.) for those in the Gold category. A sump is required at each main drain measuring minimum 1.2 x 1.2 m (4 x 4 ft), with a minimum 4% slope toward the drain. In the Silver and Gold classifications, every drain is required to have a corrosion-resistant metal strainer that is compatible with the adjacent materials and secured in place, and there must be drain screens secured to the drain strainers in a minimum of four locations to catch roof debris. These screens must be at least 609 mm (24 in.) in diameter and made from a corrosion-resistant material that is compatible with the adjacent materials. The screen must be installed with a zinc strip to minimize the unintentional growth of vegetation.

In alignment with the current industry practice to install secondary drainage for every roof area, CSA A123.26⁵ includes requirement to install secondary drains or scuppers to manage the overflow of rainwater in case of drain failures. The standard requires a minimum scupper opening height of 102 mm (4 in.) for roofing assemblies in the Silver classification and 152 mm (6 in.) for those in the Gold classification, and it prescribes that a scupper must be installed a minimum of 51 mm (2 in.) above the finished roof surface with proper flashing detail and located at the lowest point of roof or roof perimeter. The standard also prescribes that the width of a scupper opening must not be less than the circumference of the roof drain in the same roof area. However, upon evaluation, it was noted that a requirement to install scuppers with a

width equal to the circumference of the main drains is excessive. For instance, the circumference of a 76 mm (3 in.) diameter drain is greater than 228 mm (9 in.) and the circumference of a 101 mm (4 in.)-diameter drain is greater than 305 mm (12 in.) This requirement is currently being reviewed by the SIGDERS committee for modification; in future editions of CSA A123.26,⁵ the requirement may specify that scuppers must have the same diameter as the main drains or a diameter equal to the height of the scupper.

Regarding the rainwater discharge onto grade, CSA A123.26⁵ calls for the termination of drainpipe 457 mm (18 in.) above grade with an elbow extension of 914 mm (3 ft) from the building onto splash pads at the outlet and/or counter-flashings on the wall. While this arrangement is a common industry practice, the requirement in the standard reinforces the significance of keeping the water away from the building as it is being discharged.

CONTINUITY OF WATERPROOFING, AIRTIGHTNESS, AND WEATHER RESISTANCE

The CSA A123.26⁵ roof performance requirements for the 'Silver' and 'Gold' categories specify that roof membranes, flashing systems, and other roof penetrations must be designed to be watertight and comply with CAN/ULC-S742, *Standard for Air Barrier Materials—Specification*.¹⁷ These requirements align with current industry practices for waterproofing and air barriers in roof assemblies.

In addition, CSA A123.26⁵ includes requirements to enhance the weather resistance of roof assemblies by limiting the impacts of snow accumulation, wind-driven rain, and water splashing off the roof membrane surface. The current common industry practice is for a 203 mm (8-in.) membrane upturn at roof penetrations and openings, including skylights, fire walls, roof curbs, transitions, and changes in plane in the interior field of the roof. According to CSA A123.26,⁵ roof assemblies in the Silver category must have an upturn of 355 mm (14 in.) and

those in the Gold category must have a 457 mm (18 in.) upturn. The membrane upturn requirement on an exterior wall assembly within the field of a roof assembly may pose challenges when the insulation is positioned within stud cavities. It could create a situation in which vapor retarder is doubled in the wall assembly. The upturn for the membrane flashing at the parapets is required to be at 304 mm (12 in.).

INSPECTION REQUIREMENTS

The wind and rain sections of CSA A123.26⁵ both specify need for independent inspectors to conduct quality assurance observations. For the Silver category, the requirement is to retain an independent inspector for at least 25% of the days of work, during major stages of the roofing application, including completion. The intent is for the inspector to review whether the work conforms to the standard, to the applicable governing building code, and to any quality assurance metrics established by the design specifications. For the Gold category, the requirement is to retain an independent inspector for 100% of the days of work. CSA A123.26⁵ offers alternative options such as in situ testing of the roof assembly for wind uplift, leak detection system for rain penetration, and flood testing of penetration flashings to either substitute for or reduce the 100% inspection requirement. These alternatives are discussed in later sections.

CSA A123.26⁵ requirements for quality assurance inspections conveys the criticality of construction reviews for a proper installation of the roof assembly. However, when a building envelope consultant with expertise in roofing is involved in the project, the intent of this requirement can be met without engaging an independent quality assurance inspector. If the requirement were modified to include a review by the already involved building envelope consultant with expertise in roofing as an alternative to a quality assurance inspector, that would avoid duplication in some projects and thus lower the costs of Gold and Silver projects.

In addition to the construction reviews as mandated by the CSA A123.26,⁵

it is recommended to conduct the following: review of project specifications (including project-specific wind uplift loads); shop drawings and submittals; wind uplift resistance report from the third-party laboratory; and mock-ups to establish the standard of acceptance. The above is recommended to be conducted by a qualified building envelope consultant or an independent quality assurance inspector.

In Situ Negative Pressure Uplift Test Option

Annex B of CSA A123.26⁵ includes an alternative option for PARs and AARs to reduce the quality assurance inspections particularly related to wind uplift resistance for the Gold category. In lieu of construction reviews for 100% of the project days, in situ negative pressure uplift testing as described in Annex B of CSA A123.26⁵ allowing reduction of quality assurance inspections to 50% of project days. A minimum of two tests is required for every 5600 m² (60,300 sq. ft.) of roof area. The testing uses an in-situ pressure chamber, with deflection and pressure sensors mounted on the selected roof areas. The deflection of the roof membrane is monitored visually through a port and deflection sensor as the pressure differential is increased by increments of 720 Pa at 60-second intervals to a termination test pressure meeting project-specific requirements. While there is no direct correlation between this field test and the laboratory testing specified in CSA A123.21,¹ the in-situ testing results provide a good understanding of the performance of the roof assembly and may identify noncompliant installation.

Leak Detection System Option

Leak detection systems may be installed as an integral part of the assembly at the time of construction, or they can be installed using a nondestructive technique within one or two years after completion of construction. CSA A123.26⁵ specifies that an integral leak detection system installed during construction is suitable to reduce the Gold category requirement for quality assurance inspections from 100% to 25% of days.

Watertightness Testing Option

As an alternative option to the Gold category requirement of quality assurance inspection for watertightness on 100% of days, CSA A123.26⁵ allows the option of conducting flood testing. The specified testing method is a modified version of ASTM D5957, *Standard Guide for Flood Testing Horizontal Waterproofing Installations*,¹⁸ wherein a minimum test area of 3 x 3 m (9.8 x 9.8 ft) with at least one plumbing vent or any other roof penetration is flooded to a minimum depth of 25 mm (1 in.) for 24 hours to evaluate for water leaks.

While the test area is defined, the CSA A123.26⁵ standard does not indicate the number of such tests per roof or the number of tests for a certain extent of roof area. It is the authors opinion that the number of tests be determined by the number of roof areas defined by the direction of slope and the selection of the test area by the quality assurance inspector.

SUGGESTIONS FOR FURTHER DEVELOPMENT OF CSA A123.26 AND ASSOCIATED TOOLS

In general, CSA A123.26⁵ streamlines various requirements to meet the wind and rain effects of anticipated climate severities on roof assemblies. As the first design standard of its kind, it addresses several of the critical issues related to roof assemblies. However, it could be further enhanced to address the following:

- » Given the projected increase in temperature due to climate change, in addition to the measures to counter the high wind conditions and increased rainfall, the standard may include in the future additional requirements focused on roof membrane material performance countering the temperature increase. It is recognized that additional research is required in this regard.
- » Climate-RCI¹³ estimates anticipated climate severities for wind, rain, and heat; this tool may require further refinement to include additional metrics for freeze-thaw cycles, snow accumulations, hail, and so

on. Similarly, CSA A123.26⁵ could be expanded to include requirements to counter such climate severities.

- » CSA A123.26⁵ includes prescriptive requirements, both quantitative and qualitative, for the Silver and Gold categories, while defaulting to current codes and industry practices for the Bronze category. However, qualitative industry practices vary significantly across regions, provinces, and jurisdictions. It may therefore be prudent to revise the standard to document qualitative prescriptive requirements for the Bronze category. For example, the requirement for membrane upturns at penetrations might be specified.
- » CSA A123.26⁵ clearly illustrates the significance of the high wind conditions anticipated at the parapet and includes some recommendations for the structural integrity of the parapet assembly, membrane, and cladding components attached to the parapet, including cap flashings and their components. This topic, particularly the requirements for the substrate to which these components are secured, can be further detailed. Additional requirements could help address air-barrier continuity challenges at the base of parapet where the parapet is part of the main structure.
- » CSA A123.26⁵ may further develop the mounting requirements for rooftop add-ons, specifying whether they are allowed to be floating (not secured to the roof deck, but supported by self-weight or added weight) on the roof assembly or secured to main structural system. If floating, the standard may further include requirements about the required compressive strength of the roof assembly and components, and about required isolators to reduce damage to the roof assembly.
- » As discussed, CSA A123.26⁵ could be expanded to include requirements for specification review, preconstruction meetings, submittals (including the test reports), shop drawing reviews, and mock-up reviews for standard of acceptance. These requirements would be in addition to the requirements for

periodic quality assurance reviews. Also, as discussed, a review by a qualified building envelope consultant might be offered as an acceptable alternative to the requirements for third-party quality assurance inspections.

- » Considering that the intent of CSA A123.26⁵ is to help sustain the service life of the roof assembly, the standard may be expanded to include requirements for maintenance during operation, such as requirements for periodic reviews and predetermined maintenance activities, including repairs and renewals.

CONCLUSION

With the changing climate and the likelihood of adverse weather conditions in the future, the design and construction of roof assemblies capable of resisting project-specific wind uplift values as required by the building code is just a starting point to achieve durable and resilient roof assemblies with long service lives. CSA A123.26⁵ aims to enhance the resilience of roof assemblies, particularly low-slope membrane roofs, against future climatic conditions by incorporating anticipated wind and rain loads, using data from

Climate-RCI¹³ and improving the quality of roofing details. The requirements in the standard, both quantitative and qualitative, are intended to improve the performance of the roof assemblies and ensure durability by countering future climate severities, by reducing wind uplift failures, water ingress issues, safety issues, and maintenance. The standard also provides clearer guidelines for construction practices, which can support designers across regions, provinces and/or jurisdictions.

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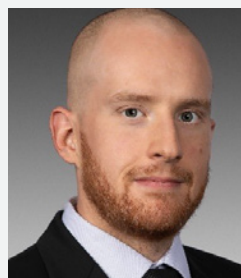
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Self-Adhered Membrane Applications: What Does It Really Mean to Stick?

ABSTRACT

This paper addresses the comprehensive evaluation of adhesives for self-adhered membranes in the construction industry. It recognizes that relying solely on peel adhesion tests overlooks critical forces that affect membrane performance. The session explores the current evaluation methods, their limitations and emphasizes the importance of considering alternate evaluation criteria including, shear forces, temperature fluctuations, and loading rates. Neglecting these factors can lead to reduced adhesion, membrane detachment, and compromised building envelope integrity. Intended for construction professionals, architects, and engineers, the session showcases advancements in adhesive testing technology and methodologies. Attendees will gain insights into assessing adhesive performance and its implications for long-term project success. By broadening the understanding of adhesive performance, attendees can improve the reliability and durability of self-adhered membrane systems, contributing to the sustainability and success of construction projects.

SPEAKER



**Cody Shelner, CABS,
LEED Green Associate**
[Functional Coatings by tesa](#)

Cody Shelner is an experienced expert in the pressure-sensitive adhesive and self-adhered membrane industry. With a background in mechanical

engineering, Cody has contributed significantly to the development of adhesive technologies for self-adhered membranes. His expertise lies in evaluating and testing adhesives under various forces and environmental conditions. He actively participates in industry associations and committees, working toward establishing standards and best practices. Dedicated to advancing the industry, He continues to drive innovation and collaborate with leading manufacturers and professionals to shape the future of construction materials.

LEARNING OBJECTIVES

- » Identify the limitations of relying solely on peel adhesion tests for evaluating adhesive performance in self-adhered membranes.
- » Evaluate the importance of considering shear forces, temperature fluctuations, and external loads in the comprehensive evaluation of adhesives for self-adhered membranes.
- » Analyze the potential consequences of neglecting critical forces on adhesive performance, including reduced adhesion, membrane detachment, and compromised building envelope integrity.
- » Apply advancements in adhesive testing technology and methodologies to enhance the evaluation of adhesive performance, ensuring proper membrane adhesion and improving overall project performance.

INTRODUCTION

Self-adhered membranes come in a variety of colors, sizes, purposes, and designs. Whether it is for window and door flashing, roof underlayment, roofing membranes, air barriers, or below-grade waterproofing, the product's fundamental design is a membrane with a pressure-sensitive adhesive (PSA) designed to adhere the membrane to a surface. Depending on the target application, the self-adhered membrane can be comprised of a variety of materials and if the membrane is not self-adhering on its own can be coated with a separate PSA to provide the adhesion. When combined, these materials provide a functional membrane that will be adhered to a variety of construction materials, hence the name *self-adhered membranes*. With one of the fundamental performance criteria of the membrane being its ability to adhere, it begs the question: What does it really mean to stick?

PSAs are developed to balance the performance of adhesion, cohesion, and tack. The adhesion of a pressure-sensitive compound is the ability of the material to interact with another material's surface. With a PSA, the interaction is not a curing process or a chemical reaction with the surface but rather an entanglement of the outer surfaces of the two materials, the strength of which is driven by the surface energies of the two materials. A high-surface-energy substrate will have a greater affinity for the adhesive and, as a result, a higher measured adhesion when measured by peel adhesion.

Figure 1 shows a typical orientation for a 90-degree peel adhesion test.

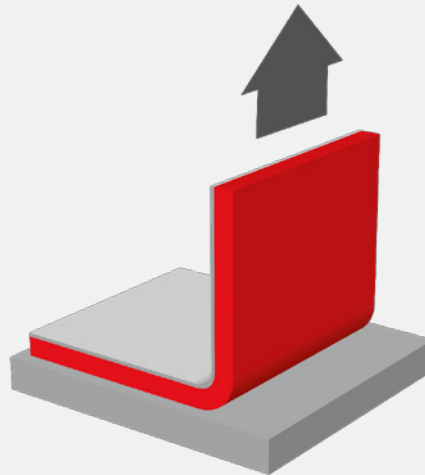


FIGURE 1. Typical 90-degree peel adhesion. (Courtesy of tesa tape Inc.)

Where adhesion is the affinity of the bonding substrate to the adhesive, cohesion is the affinity of the adhesive to bond to itself. This characteristic determines the inner strength of the adhesive layer and allows a PSA to maintain its integrity when external forces are applied.

Finally, the third main characteristic of any PSA, regardless of specific chemistry, is tack. This is the spontaneous ability of an adhesive to stick to a surface with no pressure applied or time to dwell on the surface. When handed a self-adhered membrane, the initial reaction by most people is to evaluate how sticky the material "feels"—this is often analogous to the amount of tack in the PSA. The evaluation of this property is performed in a lab scale using a variety of test methods. One such examples, as shown in **Figure 2**, is loop tack testing which applies a loop of the material to the testing surface with no pressure and

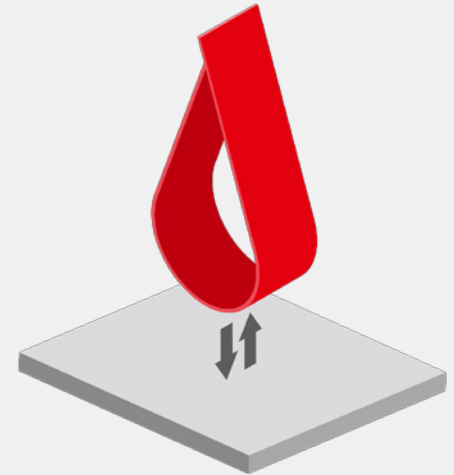


FIGURE 2. Loop tack measurement. (Courtesy of tesa tape Inc.)

immediately removes the material measuring the near instantaneous force of the adhesive on the surface.

CURRENT TEST METHODS

The current evaluation techniques vary between the different types of self-adhered membranes and the organizations that have developed the test methods; this paper will focus on commonly used ASTM test methods for evaluation of self-adhered membranes. These test methods are also often referenced in product specifications and acceptance criteria for self-adhered membranes in many applications. While it is common to use peel adhesion tests for product evaluations, it is important to note that not all peel adhesion methods are directly comparable or well understood. Separation rate, angle of peel, and sample preparation can all impact the expected comparability of the results.



FIGURE 3. Typical 180-degree peel adhesion. (Courtesy of tesa tape Inc.)

ASTM D903, STANDARD TEST METHOD FOR PEELING OR STRIPPING STRENGTH OF ADHESIVE BONDS¹

This test method, originally published as ASTM D903-46T and most recently approved in 2017, is commonly used to evaluate the adhesion of materials to construction substrates. The benefits of this method are its simplicity and its ability to be used on a wide variety of rigid and flexible materials. The drawbacks for building enclosure applications are the limit of the test being only approximately 180 degrees (**Figure 3**), the sample preparation recommendation for a single panel, and the limits when using extensible materials.

For thick membranes (typically over 10 mils), the impact of orienting the membrane at 180 degrees creates an outsized influence on the recorded bond strength due to the need to continually fold the material back on itself during the test. While still technically allowable, the ability to evaluate the adhesive performance is diminished by the increased load from orienting the membrane as required by the method. The extent of this impact is impacted by the stiffness of the membrane and the overall membrane thickness. This method also includes the recommendation of preparing the bonded material prior to cutting the sample material to size. This preparation also allows for damage to the edges of the bond line and the

underlying substrates, which can alter the measured strength of the bond. Last in this brief overview of the test method is the concern for extensible materials. When a material is able to elongate in the same force range as the peel test, the impact of peel strength and tensile strength of the elongating membrane are combined, and the rate of peel is altered by the extension of the membrane. The method correctly recommends reinforcement but gives no guidance on at what level the elongation of the membrane requires reinforcement and standardizes the criteria. This method also lacks a standardized approach to the sample preparation and pressurization of the material, leading to further variability.

ASTM D3330, STANDARD TEST METHOD FOR PEEL ADHESION OF PRESSURE-SENSITIVE TAPE²

Some of the concerns previously mentioned with ASTM D903 were addressed by the development of ASTM D3330. This test method includes six different methodologies for evaluating

the bonding strength of a PSA to a surface of interest, including both 90- and 180-degree angles, as well as specific methodologies for evaluation of a material bonded to its own substrate. This method also includes a variety of precautions when utilizing it for anything other than single product evaluations. Specifically, in Section 5.3, the method states that the peel methods (other than liner adhesion) cannot be used to compare to different products due to the difference in backings and adhesive stiffness causing changes in the resultant measured forces. Nonetheless, this method is referenced regularly to set the minimum standards for products, including AAMA, ICC ES, and ABAA material standards.

ASTM C794, STANDARD TEST METHOD FOR ADHESION-IN-PEEL OF ELASTOMERIC JOINT SEALANTS³

The inclusion of this test method in material standards for self-adhered membranes is a misapplication of a test method. This method is specifically written for the evaluation of joint sealants in peel. The entire methodology is based on the material being applied in an uncured state and embedding in the uncured material a reinforcement mesh to measure the peel value after a complete cure. The thickness of the joint sealant is defined by the test method, where for self-adhered membranes the thickness is determined at manufacturing not during the sample preparation. Without significant modifications to the test method for sample preparation, dwell time, application considerations, as well as the evaluation of separation (reinforcement failure, adhesion, cohesion, etc.) the method is not applicable as a self-adhered test method. With these modifications the test method then reflects other existing test methods (ASTM D 903 and ASTM D330).

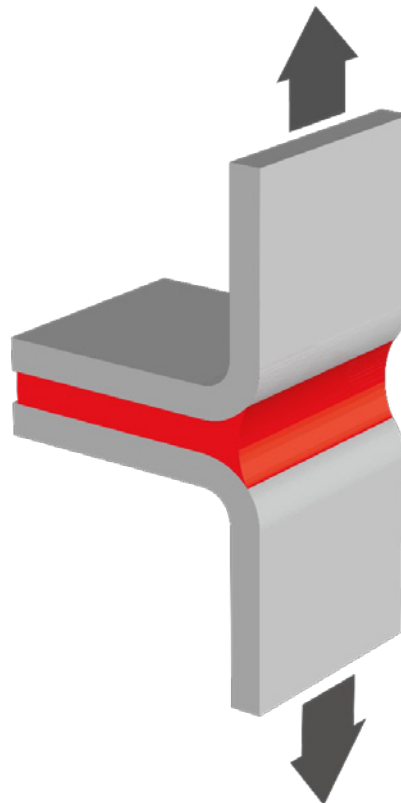


FIGURE 4. Example T-Peel configuration. (Courtesy of tesa tape Inc.)

ASTM D1876, STANDARD TEST METHOD FOR PEEL RESISTANCE OF ADHESIVES (T-PEEL TEST)⁴

T-Peel testing, as shown in **Figure 4**, is used to evaluate the adhesion of flexible materials in a T type configuration. This test method is another example

of misapplication of a test method without properly clarifying the deviations needed to use it as a method to evaluate the peel adhesion of self-adhered membranes. The method is designed to evaluate curable adhesive systems applied to flexible materials. In the introduction section of the test method care is taken to clarify the bonding condition, film thickness, layering of adhesive, cure times, etc., but these are material characteristics that are not relevant to pre-applied PSAs on a membrane. The method, if being utilized, must have a variety of modifications to consistently specify the sample preparation and testing parameters when utilized in the evaluation of self-adhered membranes.

ASTM D4541, STANDARD TEST METHOD FOR PULL-OFF STRENGTH OF COATINGS USING PORTABLE ADHESION TESTERS⁵

This test method was historically developed for the coatings industry and to use portable testing equipment. This testing is conducted by applying a test fixture to the surface to be evaluated, this fixture is typically glued to the exterior plane of the membrane, as shown in **Figure 5**. The fixture is then attached to the portable adhesion tester which can apply force (perpendicular to the membrane surface) and a balancing counter force outside of the tested area. These adhesion testers can be mechanical, pneumatically, hydraulically, or electrically actuated. This method can also be adapted to be used for self-adhered membranes, but a few necessary considerations are required. First, this portable adhesion testing is more relevantly used in a field applications rather than a laboratory environment due to the portability of the testing apparatus and the variability of the loading rate on the bonding line, specifically for the manually actuated adhesion testers. There are modifications that can be made to a constant-rate tensile tester that can allow for controlled rates of extension rather than relying on an operator for handheld or limited control for electrical, pneumatic, or hydraulic actuated testers. In a

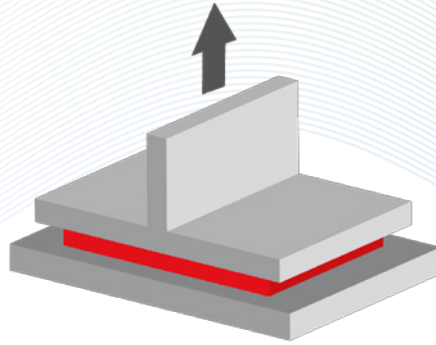


FIGURE 5. Asymmetrical loading of pressure-sensitive adhesive. (Courtesy of tesa tape Inc.)

laboratory environment when testing materials that are load rate dependent (self-adhered membranes) utilizing a constant rate extension tensile tester modified to run the test will ensure that the test is conducted at a repeatable speed. Additionally, the method was originally utilized for coatings that are uniform throughout their thickness, but when utilizing this method for materials that are composite in nature, care must be taken when evaluating the failure point of the sample, especially if the rupture occurs inside the composite membrane.

ASTM D7234, STANDARD TEST METHOD FOR PULL-OFF ADHESION STRENGTH OF COATINGS ON CONCRETE USING PORTABLE PULL-OFF ADHESION TESTERS⁶

Similar to ASTM D4541, this test method was developed to evaluate coatings, but specifically on concrete. This method is referenced in below-grade waterproofing material standards. For self-adhering membranes, many of the same concerns with this method persist as with ASTM D4541. Of note for this method was the work put into the appendix denoting the interpretation of failure modes of the bond (Appendix XI). Specifically, in the section on elastomeric coatings, which discusses the impact of edge peeling on the results for low-modulus elastomers. Most PSAs have similar performance at low loading rates which can impact the interpretation of the results.

NON-ADHESION TESTING

There are also a few test methods that evaluate the functional performance of an adhesive without specifically testing the adhesion of the material to the substrate. These test methods are also included alongside adhesion testing in material standards for a product, but rather than trying to directly evaluate the adhesion of the material these tests evaluate the functional performance of the self-adhered membrane in application. Two such examples are ASTM D7281⁷ for roofing membranes and ASTM D5385⁸ Modified for below-grade waterproofing. ASTM D7281 evaluates the performance of a seam of a roofing membrane (not necessarily a self-adhered membrane, but possibly) under ponding conditions and differential pressure. For a self-adhered membrane, this allows a functional evaluation of the ability for external and internal pressures to be withstood while maintaining a watertight bond. ASTM D5385 Modified allows the evaluation of a waterproofing membrane that has an intended leak point in a controlled location, the material is then evaluated for its ability to prevent the lateral passage of water between the membrane and the concrete. This test as well is not directly measuring adhesion but rather the ability of the adhesive solution to meet the core requirements of the application.

TESTING METHODS SUMMARY

The majority of test methods utilized for the evaluation of a PSA are peel forces applied at one or two orientations. This is evidenced by the results listed in unit force per unit width. This means that the evaluation is not of the performance of the material as a whole but rather the ability of the adhesive to resist loads directly at the bond line, which does not take into account the benefit or impact of the facer material, the ability of the membrane to spread loads, or other forces that are commonplace in application (such as shear, cleaving, or dynamic loading) and may bias results towards thicker products simply due to the force required to assemble a test sample in the required orientation.

SELF-ADHERED MEMBRANES IN APPLICATION

As previously discussed, self-adhered membranes may be and are utilized in a variety of building enclosure applications. As each application will have different contributing factors impacting the performance of a self-adhered membrane. Each application will have its own unique characteristics but there are many common characteristics that impact the performance of a self-adhered membrane. The characteristics discussed in the following sections are applicable to all building envelope applications and the evaluation and selection of self-adhered membranes.

FIELD OF SELF-ADHERED MEMBRANES

When utilizing a self-adhered membrane applied to a rigid structural material (roof deck, sheathing, foundation, etc.) as the substrate, when installed only the edges of the membrane can initiate a peel. As represented in the peel adhesion test methods, the material to fail in peel must have a portion or edge that is able to apply pressure (at a variety of angles) that will allow a liner peel force to be initiated. Since peel forces are not relevant at this location in the design, other forces must be evaluated. The first forces to consider are the shear forces on the membrane. These are any forces that result in a loading parallel to the bonded area. In the review of the current common test methods, none of them measure this characteristic directly. In vertical applications, this is initially from the weight of the material itself. Additionally, the material may experience shear loads from other materials that are bonded to the material, where the adhesive is the load-bearing pathway for the secondary material. There also could be shear loads from friction forces on the surface of the membrane; these can be caused by air moving past the membrane or other parallel loads applied to the surface of the membrane. These loads in the final design can be decreased by any fixturing that penetrates the membrane (brick ties, Z-girts, clips, etc.), which would support any shear

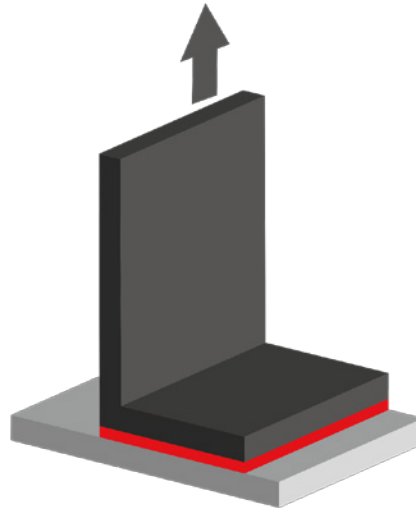


FIGURE 6. Asymmetrical loading of pressure-sensitive adhesive. (Courtesy of tesa tape Inc.)

loads. In horizontal applications, there is an additional shear load from pedestrians in areas where people may walk on the membrane.

In addition to the shear loads mentioned in the field of membrane, there are also perpendicular loads (often referred to as pull-off, tensile, uplift, etc.). The benefit of self-adhered membranes is that when they are exposed to these loads, they can dissipate the load over a large, bonded area rather than point loading in a mechanically attached system. These forces are most often driven by pressure differentials between interior and exterior conditions. When there is internal positive pressure and a pathway to the membrane (a hole, crack, gap, etc.), there will be a force exerted on the self-adhered membrane. The load is dependent on the pressure differential across the membrane and the impacted area of the membrane. An important distinction is that the force on the membrane is isolated to the area that is exposed to the pressure differential; in areas where the membrane is bonded to the rigid substrate, the rigid substrate will withstand the load from the pressure differential. The force is then dissipated to the surrounding adhesive by the membrane. This force, as applied, is not a peel, shear, or strict tensile load. This can be described as an asymmetrical tensile load or a

cleaving load as shown in **Figure 6**. This type of load will be a combination of peel, tensile, and shear loads at the same time. If there is a failure of the adhesive, the material will continue to balloon, resulting in a bubble behind the membrane. After the pressure load is removed, the membrane may then re-adhere, but the repeated loading may lead to degradation of the PSA.

EDGES AND TRANSITIONS

As with most other building envelope products, the transitions, terminations, and seams are the most critical areas for issues. Although peel is possible at the edges and transition points, the ways the materials are tested are also unlikely to be achieved (90- or 180-degree peel angle). Although the seams of the material are unlikely to peel at the tested angles, they are a critical interface for evaluation. One area of specific concern is a pressure differential at the lap seam. As discussed in the previous section, when a pressure differential is applied to a membrane that is not adhered to a rigid substrate, the membrane must then dissipate the load; this is even more critical when the load is applied at a seam or a transition. In addition to the previous loads at a seam, there is also a shear load on the two membranes at the seam, requiring sufficient shear strength in the adhesive to prevent the seam from bursting. This is applicable at all seams within a single material as well as transitions between different types of materials.

TEMPERATURE IMPACTS

The current test methods consider limited temperature exposure for adhesion. By default, these tests are conducted at room temperature (23°C 50% R.H.) but in practice these membranes will be exposed to a wide variety of temperature profiles. PSA tapes are temperature-dependent viscoelastic materials, which means that their ability to withstand loads is dependent on the temperature at which the load is applied. When exposed to elevated temperatures these adhesives will soften and lower their resistance to the variety of forces to which they are exposed. Conversely when the adhesives are exposed to

lower temperatures, they tend to become more rigid and can withstand higher forces than measured at room temperature. While more rigid the adhesives can also become more brittle so dynamic impact loads may cause a rupture in the bond. There is also a distinct difference between the temperature to which the adhesive is exposed and the temperature at which the membrane is applied. The same softening and hardening of the adhesive can occur prior to application but when applying the membrane, the softer adhesive will bond faster and result in an overall greater bond and the rigid cold adhesive may not bond at all depending on the temperature of application. Care must be taken that the loads described in the previous sections can and will be accommodated over the expected range of exposures and the impact of the temperature on each of these forces will be product dependent.

LOADING RATE

Another important characteristic to consider is the ability of PSAs to withstand extended loading times. The adhesives' resistance to all of the loads mentioned is rate dependent,

meaning that the rate at which the load is applied has a direct impact on the overall strength of the bond. Most often for PSAs, when a load is applied slowly, the overall strength measured is lower, and when the load is applied rapidly, the overall strength is greater. Also, the way the material fails can depend on the speed of application of the load as well with rapid application making the adhesive more rigid. The ratio between these loading speeds is not necessarily linear and consistent between different types of adhesives, so it is important to ensure that the rate of the bond is known (that is, long, slow load application versus rapid, dynamic loading), and the impact it may have on how an adhesive behaves must be considered.

LOADING DURATION

In addition to the load rate of the adhesive bond, it is also critically important to understand load duration. Static loads applied over a long period of time can result in creep of the bond line and failure at a much lower load than dynamic short term loading. This is critical for membranes where it is expected that there will be constant static loads on the bond that the

evaluation take into consideration the requirement to resist loads applied over a long duration rather than short term tests.

CONCLUSIONS

The evaluation of adhesives for use in self-adhered membranes is a multifaceted approach. The current techniques for evaluating bonds are limited to peel adhesion in various forms that are not often directly comparable. In practice, most adhesive bonds from self-adhered membranes are exposed to loads that require resistance in shear or tensile (pull-off) versus peel, and the testing techniques for self-adhered membranes are limited in their evaluation of these characteristics. In addition to the types of loads, it is important to consider and evaluate how these bonds will be able to withstand the applied loads over a wide variety of exposure conditions, as the adhesives used in these materials are dependent on the temperature at which the load is applied. Finally, the loading rates and expected loading times are necessary when holistically evaluating the bonding performance of a PSA.

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Anchored Brick Veneer: What Can Go Wrong and How to Prevent This

ABSTRACT

This paper will discuss a brief history and the sustainability of brick, present real-life examples of anchored brick veneer failures and deficiencies, provide an overview of code requirements, and discuss the best practices for the design of new anchored brick veneer. The costs to repair deficient anchored brick veneer can be substantial; a proper design will ensure a long-term and durable brick veneer system, with minimal maintenance.

LEARNING OBJECTIVES

- » Discuss key attributes, sustainability, and benefits of brick veneer.
- » Understand the material properties of brick veneer
- » Interpret the code requirements and the best practices for brick cavity wall drainage.
- » Identify common problems associated with various types of brick veneer failures and examples of what these deficiencies look like.
- » Learn about correlation issues with codes/standards.

SPEAKER



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on commercial and military buildings in the eastern United States. At Rimkus, he has experience with building enclosure investigation, property condition assessments, litigation, remediation design, and construction administration on commercial, military, and residential buildings. His investigative and design work includes wall cladding and roofing assemblies.

BRICK SYSTEMS

Anchored brick veneer, the focus of this article, is a cladding system that is designed with a structural back-up wall where the brick is then structurally tied (or anchored) to the backup wall. The brick veneer acts as a rainscreen, with an air cavity and water-resistant barrier that allows any rainwater that penetrates the brick veneer to migrate along the rear face of the brick toward a drainage system (flashing and weeps) that directs the rainwater to the outside. This system recognizes that brick and mortar are porous and manages the flow of rainwater, so it does not migrate into the backup wall or the interior of the building.

Composite brick walls are a structural system that utilizes the full thickness of the brick for the strength of the wall, and they are usually made up of two or more wythes (vertical columns of brick) that are fully mortared together. These wythes may be reinforced or plain (unreinforced). Composite brick walls are mass walls and were historically used in the construction of buildings until the mid-twentieth century (and are still used today). Composite walls absorb moisture yet are thick enough that the moisture is typically stored in the outer wythes of brick and then dries out between weather events. Flashing is still required at floor lines, parapets, and openings to direct absorbed moisture to the exterior as it migrates toward these areas.

ATTRIBUTES, SUSTAINABILITY, AND BENEFITS OF BRICK

Brick has many positive attributes, including aesthetics (warmth, beauty, and scale), long-term performance, and sustainability.



PHOTOGRAPH 1. The American Brewery, built in Baltimore, Maryland, in 1863 (Rebuilt in 1887).

Brick has been in use for thousands of years. Its origins can be traced back to 7000 BCE, when brick use was discovered in southern Türkiye. Early bricks were made from clay, and sun-dried to harden. Later, the ancient Egyptians mixed the clay with straw. (A similar process was used to make adobe, used by the Native Americans for centuries). In 3,500 BCE, fired brick was invented.¹

Examples of brick can be found throughout the world; however, one does not have to look far to see its beauty and contribution to our historic and contemporary architecture. For example, Baltimore, MD, has used brick for more than two (2) centuries (**Photograph 1**).

Brick is sustainable. According to the Brick Industry Association (BIA), brick is recyclable and can be reused

in construction or crushed and used for sub-base materials or permanent landscaping mulch. Brick contributes to energy efficiency by absorbing heat and releasing it later (thermal mass), has a long lifespan (100 years), and is easy to maintain.²

To fully utilize sustainability in brick, care must be taken to design the brick veneer for compliance with the codes and with a basic understanding of its material properties to avoid failures and costly repairs. For a material that, when properly designed and constructed, can last 100 years (or more), the benefits of sustainability are greatly compromised if failures appear within the first 10 to 20 years, or less, due to improper design and/or installation.

MATERIAL PROPERTIES

There are several material properties related to brick, including its compressive, shear and flexural tensile strengths, elastic modulus and the expansion of brick. These properties are primarily structural in nature and should be specified for its intended use by the designer. More detailed information regarding these properties can be found at the BIA, "Brick Masonry Material Properties," Technical Notes (TN), 3A³ and The Masonry Society (TMS) 402, 2022, Chapter 4.2.⁴

Temperature, moisture absorption, freezing, and creep cause material properties in brick to constantly move in different directions and at different rates. Brick continues to expand over time, and results in a net growth of brick compared to other materials like wood or concrete, that experience shrinkage as the wood dries out or as the concrete cures. Unlike concrete, brick is made



PHOTOGRAPH 2. Sealant separation at a window secured to wood framing due to shrinkage of the wood framing and expansion of the brick veneer. *Photo from Rimkus Archives.*



PHOTOGRAPH 3. Sealant separation at a window secured to wood framing due to shrinkage of the wood framing and expansion of the brick veneer. *Photo from Rimkus Archives.*

from clay. Brick or concrete will experience expansion and contraction due to temperature changes; however, brick will also gradually absorb moisture over time, causing it to expand (not shrink), reaching most of its maximum size within the first several years after installation. Brick will not return to its original size; the expansion due to moisture retains a net growth that is permanent. The expansion of brick due to temperature change is nearly the same as the expansion due to absorption of moisture. Two other components affecting the growth of brick are creep and freezing, though these have a smaller overall impact on brick. The designer should be familiar with the material properties of brick veneer when used with a wood-framed back-up wall, the brick veneer stresses at corners and openings and the best practices for sizing and placement of expansion joints to prevent unsightly cracks or gaps at window openings.

Properties of Brick Veneer Anchored with a Structural Wood-framed Back-up Wall

Wood framing will shrink as it dries out, in contrast to brick, which expands over time. Wood shrinkage adjacent to expanding brick should be accounted for at openings in the brick veneer or else sealant can split and result in gaps at windows, doors, and other sizable openings (**Photographs 2 and 3**). The

anticipated shrinkage of wood must be added to the calculated expansion of the brick veneer. Given the current trends to construct mid-rise buildings with wood framing that are typically 5- or 6-stories in height, the overall shrinkage of the wood is a

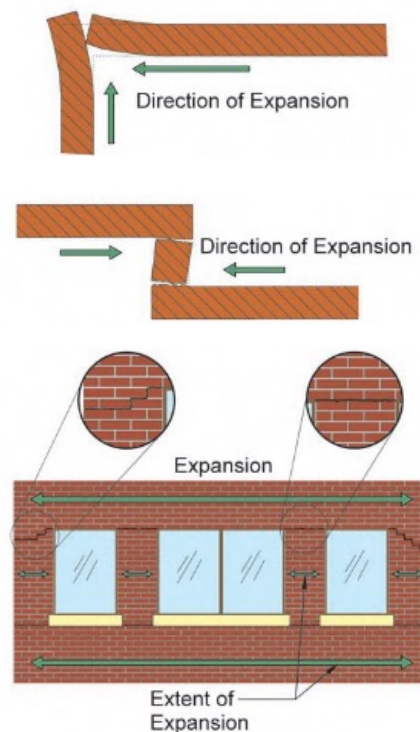


FIGURE 1. Movement of brick veneer at corners, offsets, and punched openings. *Image from BIA, TN 18A, pages 4 and 5, May 2019.*

function of its overall length and the deadload of the structure. Framing must be designed to minimize shrinkage and horizontal expansion joints, supported by steel shelf angles, are recommended at each floor to accommodate the anticipated net movement due to expansion of the brick and shrinkage of the wood framing or damage can occur.

Properties of Brick at Corners, Offsets, and Openings

How does brick veneer behave? The brick will move in all directions and stress tends to build up at building corners and openings⁵ (**Fig. 1**).

Designing for Expansion Joints

The movement of brick requires that large areas of brick veneer be divided up into smaller areas by installing expansion joints to minimize the stress on the brick veneer and prevent cracking. Adequately sized brick areas for appropriate stress relief are just part of the equation; how the brick is supported is just as important when it comes to minimizing stress due to differential building movements, deflection and/or movement of the supporting shelf angle. Assuming a 100-degree Fahrenheit (38°C) change in temperature as a rule of thumb, these factors together result in a combined movement of $0.0009L$ (where L equals the length of the wall, or the distance between expansion joints).⁶

So, what is the recommended expansion joint strategy? The BIA has the following recommendations for vertical expansion joints:⁵

- » Brickwork without openings: 25 ft (7.6 m.) o.c.
- » Multiple openings in brickwork: 20 ft (6.1 m.) o.c.
- » Widen the joints for parapet walls when the joints are more than 15 ft (4.6 m.) o.c.; or separate with a horizontal joint and then place another joint midway at the parapet wall.
- » Place joints at or near corners (within 2 ft) (0.6 m.), offsets, wall intersections, changes in substrate (backing system), and changes in brick support.

For horizontal joints:

- » Locate immediately below shelf angles with a minimum ¼ in. joint (0.6 cm.) and compressible filler within the joint.

When detailing the expansion joint, a backer rod and sealant must be provided to reduce moisture intrusion through the brick veneer and to reduce infestation by insects (you don't want a beehive behind your brick!). Some sealants can compress as much as 50%, so the calculated joint width should be doubled to accommodate the sealant.

It's not just the vertical joints where the sealant limitations must be factored into joint size. As noted earlier, brick moves in each direction, and an undersized joint can cause sealant to squeeze out of horizontal joints (**Photograph 4**).

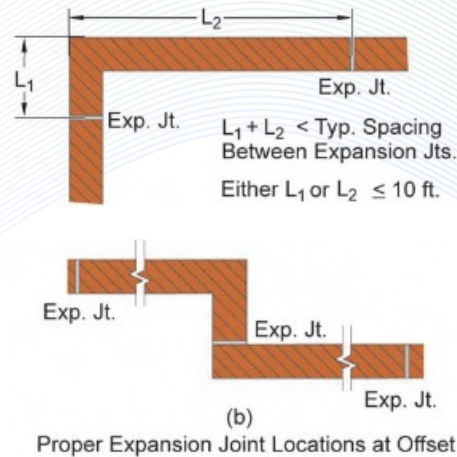


FIGURE 2. Expansion joints near corners and offsets. *Image from BIA, TN 18A, pages 4 and 5, May 2019.*

The horizontal joint should be located below the steel shelf angle with compressible filler.

Expansion Joints at Building Corners and Offsets

Placing the vertical expansion joint within 2 ft (0.6 m.) of the corner is preferred since it is convenient for a typical mason, who can reach 2 ft (0.6 m.) around the corner⁵ (**Fig. 2**).

The location of the vertical expansion joint from the corner, (2 ft or 0.6m.) is then added to the distance to the next vertical expansion joint on the adjacent wall so you do not exceed your calculated distance between expansion joints. Corner crack failures are usually located within 4 in. (10.1 cm.) of the outside corner (the nominal thickness of a brick) and are usually caused by insufficient

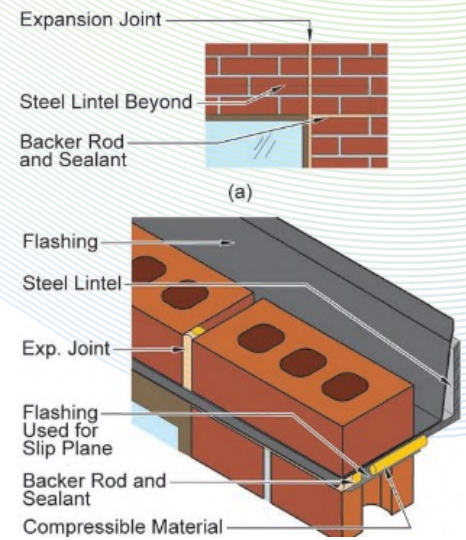
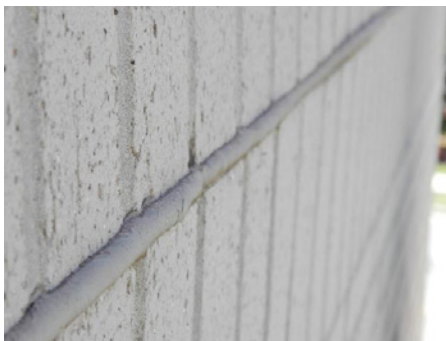


FIGURE 3. Detail of an expansion joint at a punched opening corner. *Image from BIA, TN 18A, page 6, May 2019.*

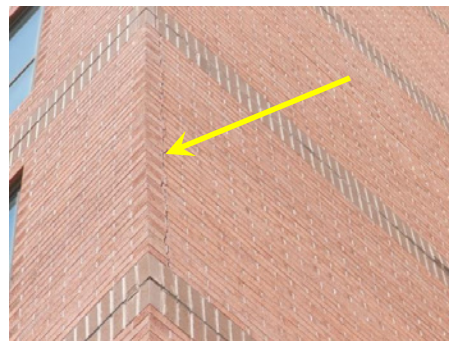
or lack of vertical expansion joints to accommodate movement (**Photographs 5 and 6**).

Expansion Joints at Punched Openings

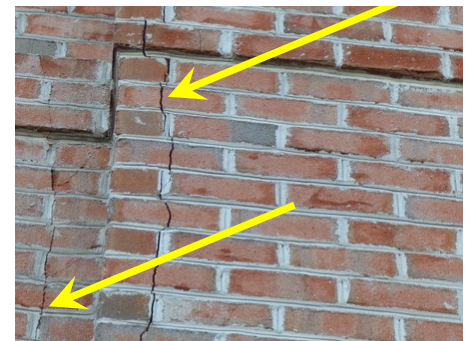
For brickwork with regularly spaced punched openings, the brick will move more above and below the openings (long brick panels) than between the openings (shorter brick panels)⁵. A natural location for the joint would be at the opening corner; however, the supporting loose laid lintel would require flashing to function as a slip plane on the expansion joint side of the lintel to move independently from the adjacent brick (**Fig. 3**). This allows the lintel bearing end that overlaps the vertical expansion joint to move independently from the movement in the adjacent brick.



PHOTOGRAPH 4: Compressed sealant at a horizontal movement joint. *Photo from Rimkus Archives.*



PHOTOGRAPH 5. A corner crack in the anchored brick veneer. *Photo from Rimkus Archives.*



PHOTOGRAPH 6. A corner crack in the anchored brick veneer. *Photo from Rimkus Archives.*

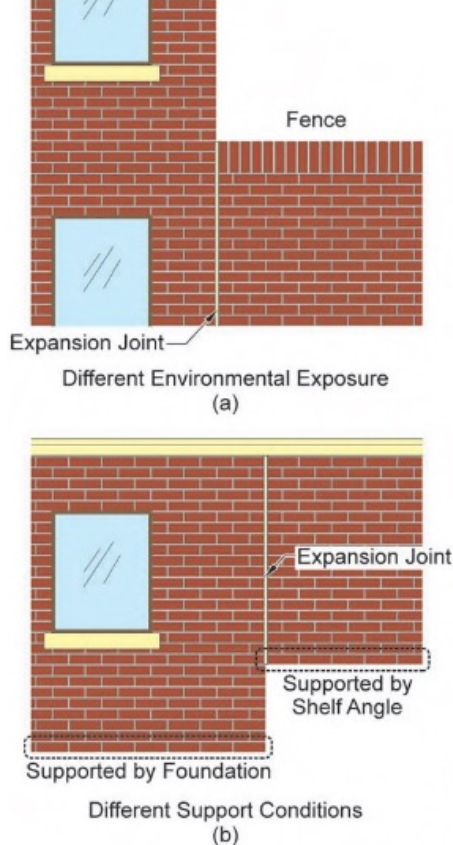


FIGURE 4. Expansion joints at different environmental exposure and support conditions. Image from BIA, TN 18A, page 6, May 2019.

Expansion Joints Differing Adjacent Conditions

Expansion joints should also be provided at different environmental exposures, such as a fence or parapet wall, or when supported by different conditions⁵ (**Fig. 4**).

BRICK VENEER CODE REQUIREMENTS

The building codes commonly used throughout the United States are the *International Building Code* (IBC) and the *International Residential Code* (IRC), each published by the International Code Council. Always verify with local jurisdictions regarding amendments and the currently effective edition of the code. For this presentation, the 2024 editions of the IRC and IBC were used. The IRC is limited to one- and two-family dwelling units that do not exceed three stories above grade plane.⁷ The IBC applies to all buildings, and you have the option to use the IRC if you have a residential building that meets the applicable limitations

noted above. Both codes include brick veneer requirements and also reference TMS 402 for specific brick veneer requirements. The 2022 edition of the TMS was referenced in this presentation. This article does not discuss the National Building Code of Canada or local provincial/territorial codes. The reader should consult with local codes for applicable guidance.

2024 IRC

The 2024 IRC allows the design of anchored brick veneer to comply with the prescriptive requirements within the IRC (Section 703.8) or applicable provisions of TMS 402 (2022),⁴ TMS 403 (2017),⁸ or TMS 404 (2022).⁹

The use of anchored brick veneer with a backing of wood-framed or cold-formed steel is limited to the “first story above grade plane and shall not exceed 5 inches in thickness.” Exceptions that allow the use of brick more than one story above grade plane include the following:

- » Buildings in Seismic Design Categories A, B, and C that are supported above a noncombustible foundation.
- » Detached one- and two-family dwellings in Seismic Design Categories D(0), D(1), and D(2) as permitted above a noncombustible foundation.

Generally, the exceptions allow the following:

- » Up to 30 ft (9.1 m.) and three stories in Seismic Design Categories A, B, and C if wood framed (plus an additional 8 ft (2.44 m.) at the gable end).
- » Up to 30 ft (9.1 m.) and three stories (plus an additional 8 ft (2.44 m.) at the gable end) in Seismic Design Category D(0) if wood-framed and each story does not exceed 11 ft 7 in. (3.5 m.) or up to 13 ft 7 in. (4.1 m.) per story if meeting specific exceptions. Cripple walls are not allowed. (A cripple wall is a type of raised foundation wall framed in wood that is susceptible to earthquake damage).
- » Up to 20 ft (6 m.) in Seismic Design Categories D(1) and D(2), or 30 ft (9.1 m.) (plus an additional 8 ft (2.44 m.) at the gable end), if wood-framed and the lower 10 ft (3.1 m.) has a backing of a concrete or masonry wall. Cripple walls are not allowed.

The fasteners for the ties must be secured to the structural stud or into a wood structural panel (Table R703.8.4[1]). Table R703.8.4(1) establishes the type of tie, fastener, and air space allowed for fastening to structural studs) (**Fig. 5**)

TABLE R703.8.4(1) TIE ATTACHMENT AND AIRSPACE REQUIREMENTS

BACKING AND TIE	MINIMUM TIE	MINIMUM TIE FASTENER ^a	AIRSPACE ^b	
Wood stud backing with corrugated sheet metal	22 U.S. gage (0.0299 in.) × 7/8 in. wide	8d common nail ^c (2 1/2 in. × 0.131 in.)	Nominal 1 in. between sheathing and veneer	
Wood stud backing with adjustable metal strand wire	W1.7 (No. 9 U.S. gage; 0.148 in. dia.) with hook embedded in mortar joint ^d	8d common nail ^c (2 1/2 in. × 0.131 in.)	Minimum nominal 1 in. between sheathing and veneer	Maximum 4 5/8 in. between backing and veneer
Wood stud backing with adjustable metal strand wire	W2.8 (0.187 in. dia.) with hook embedded in mortar joint ^{d, f}	8d common nail ^c (2 1/2 in. × 0.131 in.)	Greater than 4 5/8 in. between backing and veneer	Maximum 6 5/8 in. between backing and veneer
Cold-formed steel stud backing with adjustable metal strand wire	W1.7 (No. 9 U.S. gage; 0.148 in. dia.) with hook embedded in mortar joint ^d	No. 10 screw extending through the steel framing a minimum of three exposed threads	Minimum nominal 1 in. between sheathing and veneer	Maximum 4 5/8 in. between backing and veneer
Cold-formed steel stud backing with adjustable metal strand wire	W2.8 (0.187 in. dia.) with hook embedded in mortar joint ^{d, f}	No. 10 screw extending through the steel framing a minimum of three exposed threads	Greater than 4 5/8 in. between backing and veneer	Maximum 6 5/8 in. between backing and veneer

For SI: 1 inch = 25.4 mm.

a. All fasteners shall have rust-inhibitive coating suitable for the installation in which they are being used, or be manufactured from material not susceptible to corrosion.

b. An airspace that provides drainage shall be permitted to contain mortar from construction.

c. In Seismic Design Category D₀, D₁, or D₂, the minimum tie fastener shall be an 8d ring-shank nail (2 1/2 in. × 0.131 in.).

d. Adjustable tie pintles shall include not fewer than 1 pintle leg of wire size W2.8 (MW18) with a maximum offset of 1 1/4 inches.

e. Adjustable tie pintles shall include not fewer than 2 pintle legs with a maximum offset of 1 1/4 inches. Distance between inside face of brick and end of pintle shall be a maximum of 2 inches.

f. Adjustable tie backing attachment components shall consist of one of the following: eyes with minimum wire W2.8 (MW18), barrel with minimum 1/4-inch outside diameter, or plate with minimum thickness of 0.074 inch and minimum width of 1 1/4 inches.

FIGURE 5. 2024 IRC Table R703.8.4(1). Image cropped by Rimkus.

An air space of 1 in. (2.54 cm.) nominal is allowed for corrugated or wire ties, up to 4⁵/₈ in. (11.7 cm.) for smaller-diameter adjustable wire ties, and between 4⁵/₈ and 6⁵/₈ in. (11.7 and 16.8 cm.) for larger-diameter adjustable wire ties.

Each veneer tie shall support not more than 2.67 ft². (0.25 m²) of wall area and not exceed 32 in. (81 cm.) o.c. in the horizontal direction or 24 in. (61 cm.) o.c. in the vertical direction. In Seismic Design Category D or C (for townhouses) or in wind areas with design pressures exceeding 30 psf (0.48 kpa), then each tie shall not exceed 2 ft² (0.18 m²) of wall area.

What about drainage?

Section R703.1.1.1 states, “The exterior wall envelope shall be designed and constructed in a manner that prevents the accumulation of water...and a means of draining to the exterior water that penetrates the exterior cladding.”

Weep holes should be spaced at 33 in. (84 cm.) o.c. and located immediately above the flashing.

2024 IBC

The 2024 IBC differs from the 2024 IRC in that anchored masonry veneer requires compliance with Sections 1404.7 through 1404.10 as well as Sections 13.1 and 13.2 of TMS 402 (2022).¹⁰ For anchored brick veneer, IBC defaults only to chapters 13.1 and 13.2 of TMS 402, since Sections 1404.8 through 1404.10 are specific to anchored stone veneer, slab-type veneer, and terra cotta veneer.¹⁰ IBC Section 1402.2 requires exterior walls to include a drainage system that provides a means to drain water that enters the assembly to the exterior.

TMS 402

TMS 402 (2022)⁴ is used as a basis here, but other editions may currently be in effect, so the chapter numbers and requirements may differ from what referenced below. The requirements for brick veneer ties are primarily located in TMS 402 Chapter 13 (IBC requires compliance with Sections 13.1 and 13.2).

Section 13.1 includes general requirements for the system to comply with the weather, structural, fire, and

thermal requirements of the legally adopted building code. It requires the veneer to accommodate deformations and differential movement, states that the deflection of structural elements supporting masonry shall not exceed $L/600$ and includes loading limitations on the face of the anchored veneer within a 5 by 5-ft (1.5 by 1.5 m.) area. Section 13.1 also requires compliance with TMS 402 Part 1 and Chapter 4 which address contract document requirements, definitions, and quality assurance.

Section 13.2 provides the requirements for anchored masonry veneer. The code allows for two paths: Prescribed Design Method or Engineered Design Method. This article will generally address the Prescribed Design Method, as it relates to masonry with a running bond. A running bond is how brick is usually constructed, where the vertical joints in the row of bricks above and below a brick line up with the middle of the brick unit. The Prescribed Design Method includes Basic and Enhanced options, while the Enhanced path generally requires the ties to be spaced closer together to meet increased surface pressures and/or seismic design categories.

Regarding the veneer ties, the specified requirements for most uses include the following:

- » The thickness of the mortar bed joint should be at least twice the thickness of the veneer tie.
- » Deflection limits for the backup wall for wind and seismic loads
- » Requirements for lintels above openings
- » Isolation of the sides and top of the anchored veneer in Seismic Design Categories C, D, E, and F; support at each floor; and added movement joints.
- » For water penetration resistance, flashing and weep holes to resist water migration below the drainage plane (water-resistant barrier) with a minimum of 1 in. (2.54 cm.) air cavity and weep holes spaced no more than 33 in. (84 cm.) o.c.
- » General anchored veneer requirements (TMS Table 13.2.2.3)⁴:

Brick veneer can be anchored to a supporting backup wall using several types of acceptable brick veneer ties, depending on the substrate, height, and cavity width. The type of tie required depends on the use of the building (single-family home or not), and the type of structural backup wall (wood-framed, steel-stud framed, or concrete masonry unit). The appropriate veneer ties, including spacing requirements, and attachment are essential to the long-term performance of brick veneer. There are numerous types of acceptable veneer ties. Following are some basic examples.

- Corrugated sheet metal ties (for use on wood-framed residential buildings, 1 in. (2.54 cm.) cavity width and no more than 30 ft (9.1 m.) high or 38 ft (11.6 m.) at a gable end. The fasteners must be within 1/2 in. (1.2 cm.) of the right-angle bend (**Fig. 6**).
- Sheet metal ties (for use on wood-framed substrate, limited to 4 in. (10.1 cm.) cavity width and a height limit of 30-ft (9.1 m.) or 38 ft (11.6 m.) at the gable end. The ties come in corrugated or noncorrugated configurations (**Fig. 7**).
- Adjustable ties (for use on wood-framed/cold-formed/concrete, or concrete masonry unit substrates, limited to 4 in. (10.1 cm.) cavity width and up to 6 in. (15.2 cm.) cavity width with additional

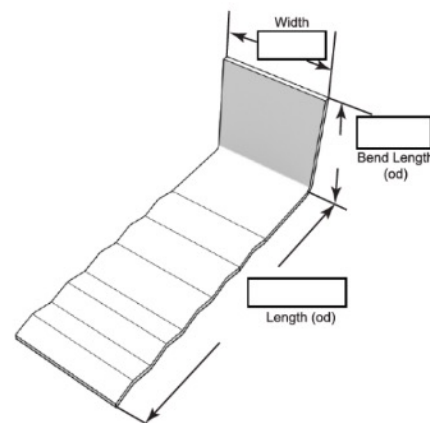
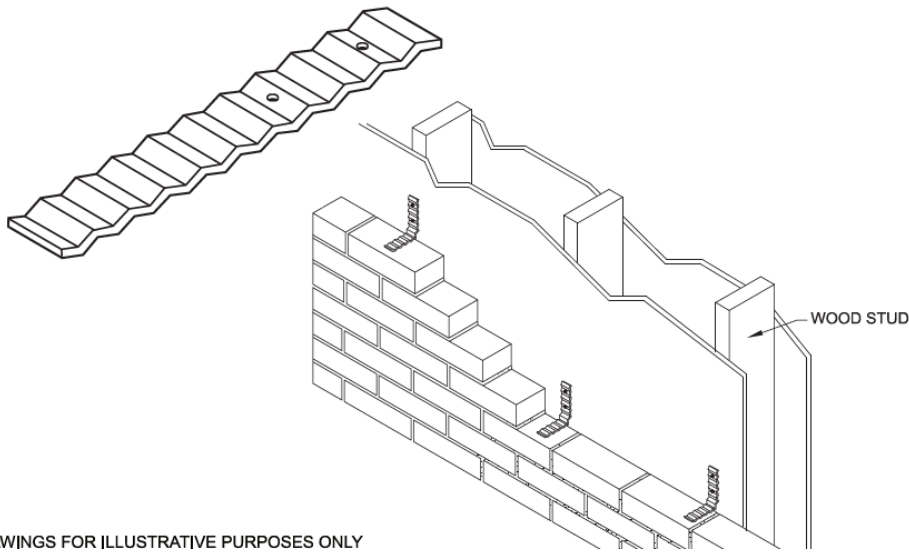


FIGURE 6. Corrugated sheet metal tie—Hohmann and Bernard product sheet. Image cropped by Rimkus.



DRAWINGS FOR ILLUSTRATIVE PURPOSES ONLY

FIGURE 7. Sheet metal tie—Heckmann Building Products sheet. Image cropped by Rimkus.

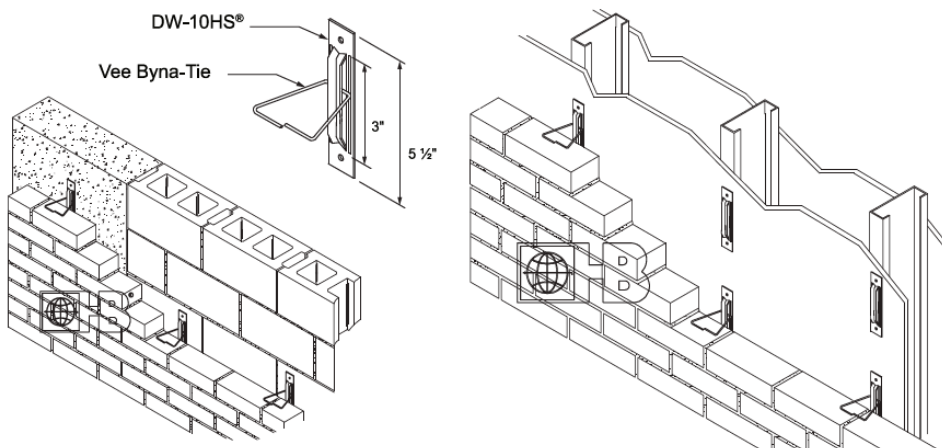


FIGURE 8. Adjustable brick tie—Hohmann and Bernard. Image cropped by Rimkus.

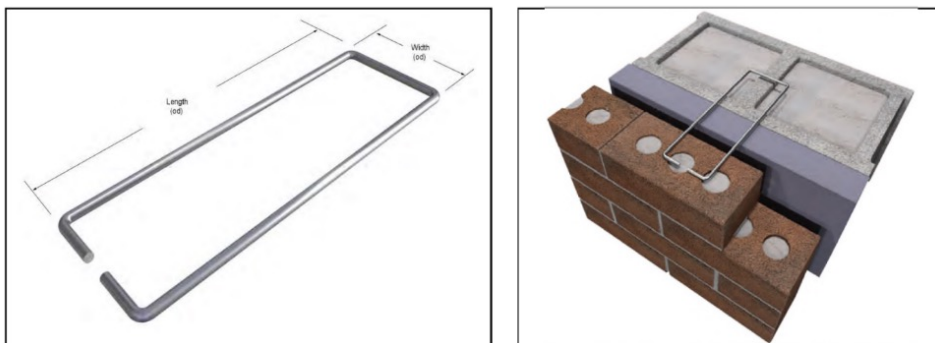


FIGURE 9. Nonadjustable unit wire tie—Heckmann Building Products cut sheet. Images cropped by Rimkus.

requirements). May exceed 30 ft (9.1 m.) or 38 ft (11.6 m.) at the gable end for wood-framed and cold-formed metal stud backing if designed for differential

movement and must meet pullout resistance requirements for concrete backing (**Fig. 8**).

- Adjustable, Unit wire and joint reinforcement ties (for use with

clay [brick] or concrete unit masonry substrates), limited to 6 in. (15.2 cm.) air cavity). Must meet pullout resistance requirements (**Fig. 9 and 10**).

- » Out-of-plane corbelling (per Section 5.6). Corbelling is the out-of-plane projection or recession of a row of bricks.
 - Solid units or units with holes grouted solid must be used.
 - The maximum projection from the face of the wall must not exceed one-half of the nominal brick wythe.
 - Each corbelled brick projection must not exceed one-half of the nominal unit height and one-third of nominal brick wythe.
 - Total corbelling is limited to no more than a 1 in. (2.54 cm) offset from rear face of brick units. This will generally be the limiting factor when modular size brick units are used.
 - Note: brick supported by steel shelf angles would “corbel” beyond the lip of the angle. This means a minimum of $\frac{2}{3}$ of the brick must be supported by the angle.
- » Fastener pullout resistance shall have a minimum design strength of 335 pounds (152 kg.) or an allowable load of 200 pounds (90.7 kg.).
- » Cavity width (not drainage space) is from face of framing, (not the face of the sheathing).
- » Veneer tie specifications (Table 13.2.2.4)
- » Veneer tie spacing requirements for Basic and Enhanced prescriptive design methods:
 - Basic: 2.67 ft² (0.25 m²) per tie, no more than 24 in. (61 cm.) spacing in either direction.
 - Enhanced: 1.78 ft² (0.16 m²) per tie, no more than 16 in. (40.6 cm.) spacing in either direction (this meets recommended spacing from manufacturers).

CAVITY WALL DRAINAGE

In addition to the requirements of movement joints, proper brick support, and the requirements for veneer ties

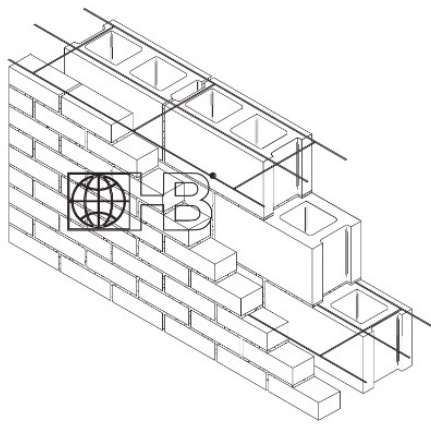


FIGURE 10. Ladder-type joint reinforcement tie—Hohmann and Bernard. Image cropped by Rimkus.

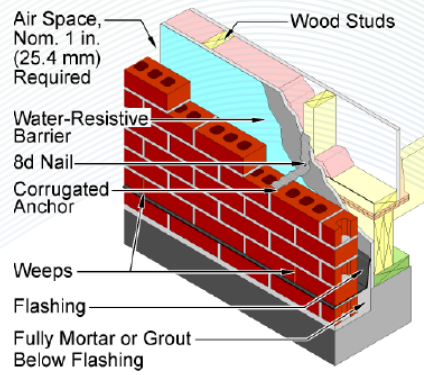


FIGURE 11. Brick veneer with wood framing. Image from BIA TN 7 page 3. Image cropped by Rimkus.

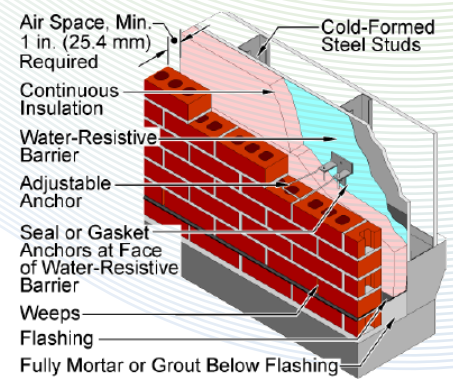


FIGURE 12. Brick veneer with cold-formed steel framing. Image from BIA TN 7, page 3. Image cropped by Rimkus.

and veneer tie spacing, the IRC, IBC, and TMS all have requirements for cavity wall drainage. Cavity wall drainage is essential to prevent the buildup of rainwater that may bypass any overlap joints in the water-resistant barrier or other flashing systems, resulting in corrosion of steel elements and fasteners and deterioration of the sheathing and framing. The BIA provides information on “proper design, detailing and construction to minimize water penetration into or through a wall system.”¹¹ (**Fig. 11 and 12**) This includes the following:

- » Through-wall flashing locations and installation and termination recommendations
- » Water-resistant barrier recommendations
- » Air-barrier recommendations
- » 1 in. (2.54 cm)-minimum drainage cavity
- » Weep requirements (referenced earlier)

Through-wall flashing is an impervious material of, and is essential for, the drainage system. Through-wall flashing materials may include sheet metal, flexible copper fabric, polyvinyl chloride, and bituminous (self-adhered) membranes. Through-wall flashing is required at the base of walls, windowsills, window lintels, shelf angles, projections, chimneys, tops of walls, and roofs. Flashing must extend vertically at least 8 in. (20.3 cm.) above the horizontal leg. The BIA recommends that a metal drip edge be provided at the exterior (**Fig. 13**).

The BIA recommends end-dams in flashing to prevent moisture from migrating behind the flashing. Weep tubes, or wicks should be spaced no more than 16 in. (40.6 cm.) o.c., and

open-head joint weeps no more than 24 in. (61 cm.) o.c. (closer than the 33 in. (84 cm.) maximum spacing allowed in the IRC and TMS) (**Fig. 14**).

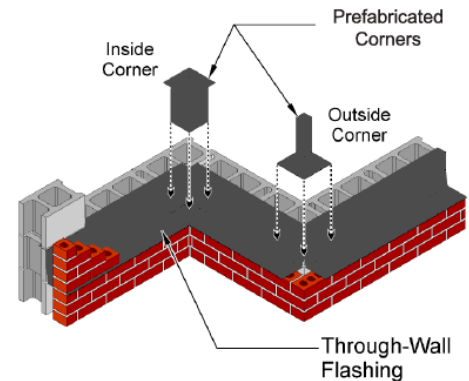
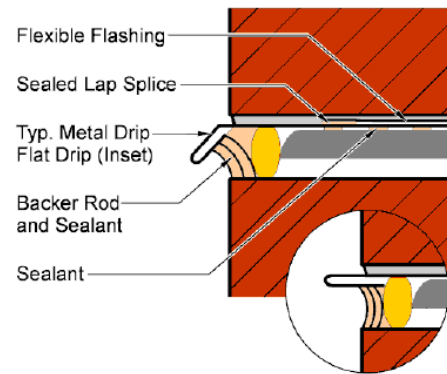


FIGURE 13. Drip edge and through-wall flashing. Image from BIA TN 7, page 6. Image cropped by Rimkus. The through-wall flashing selected must be compatible with other materials and components. The BIA recommends that the system of flashing, water-resistant barrier, sealants, and any adhesives and primer be sourced from a single manufacturer to confirm compatibility.

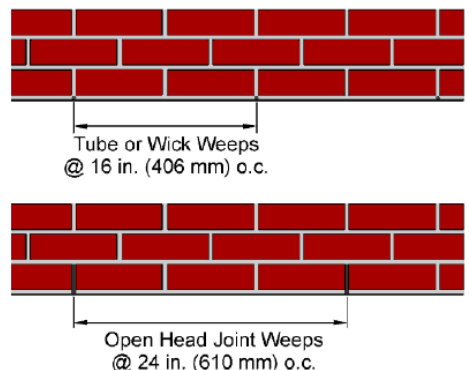
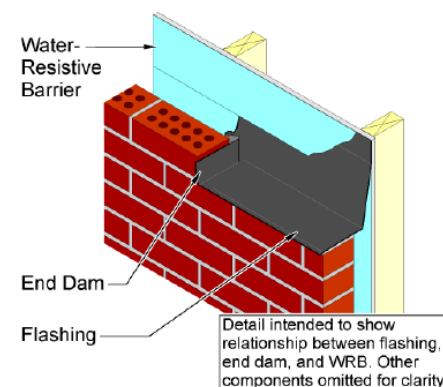


FIGURE 14. End dams and weep spacing. Image from BIA TN 7, page 7. Image cropped by Rimkus.

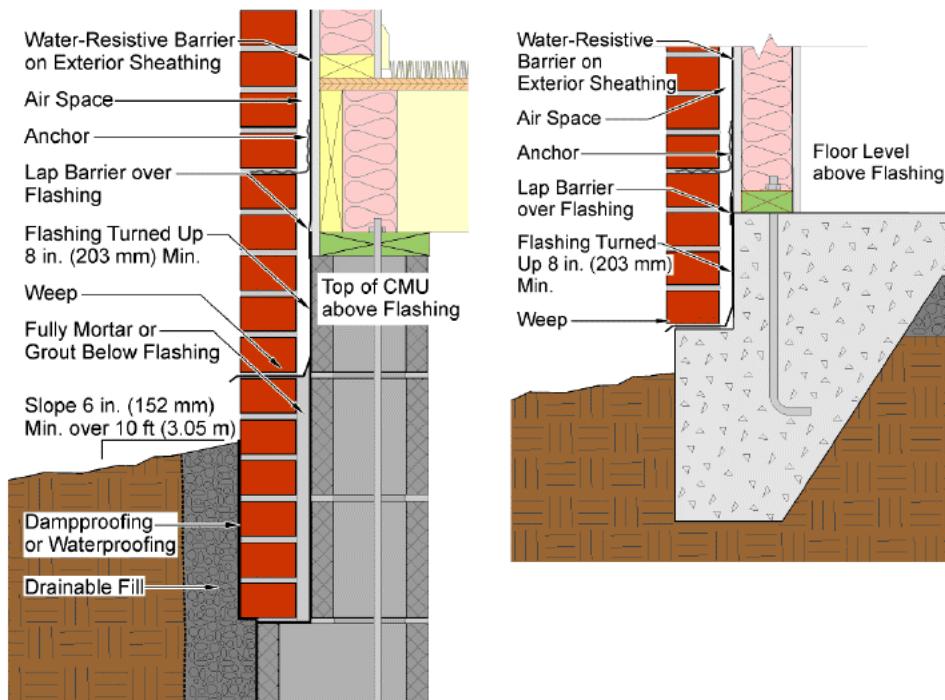


FIGURE 15. Base of wall flashing. Image from BIA TN 7, page 9. Image cropped by Rimkus.

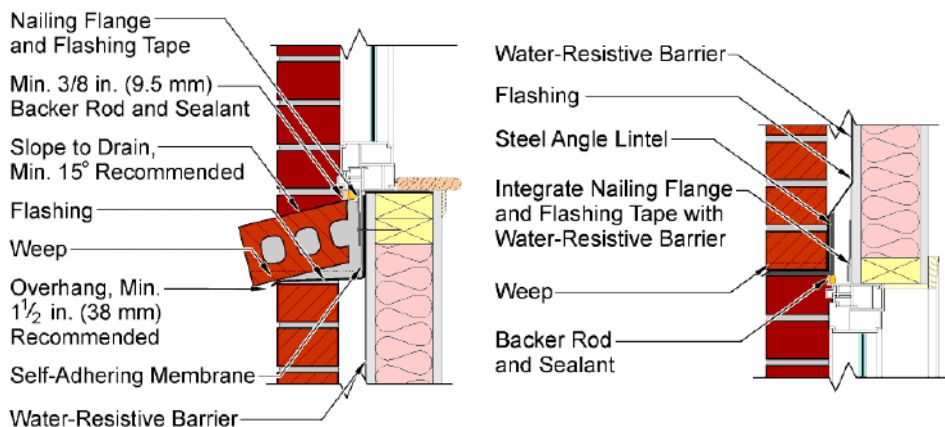


FIGURE 16. Windowsill and lintel flashing. Image from BIA TN 7, page 10. Image cropped by Rimkus.

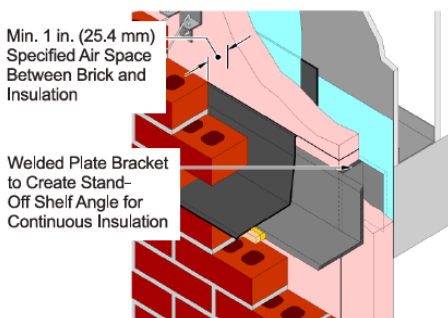


FIGURE 17. Stand-off steel lintel detail. Image from BIA TN 7, page 11. Image cropped by Rimkus.

There are several critical flashing locations that must be addressed. These include the base of the wall (no more than 10 in. (25.4 cm.) above grade; and consider ground treatment, such as mulch, and the slope of the grade). If the brick veneer extends below grade, then fully grout the collar joint below the flashing (**Fig. 15**).

Other critical areas include lintels, windowsills, and shelf angles. As noted earlier, provide for end dams at window flashing at windowsills and lintels (**Fig. 16 and 17**).

COMMON ANCHORED BRICK VENEER FAILURES

In addition to the corner cracks noted above, other examples of cracking include:

Stair-Step Pattern Cracks:

Stair-step-pattern cracks are usually wider on one end and can taper to a hairline width on the other end. They are typically caused by differential movement within the field of brick, either by unequal foundation settlement or by movement on one end or the other of the steel angle lintel due to insufficient torque of the anchor bolts. By pointing down in a perpendicular direction from the crack, one can approximate the location where the differential movement occurred (The IRC, IBC and TMS 13.1 require that the building meet structural requirements to limit differential movement) (**Photograph 7**).

Vertical Cracks

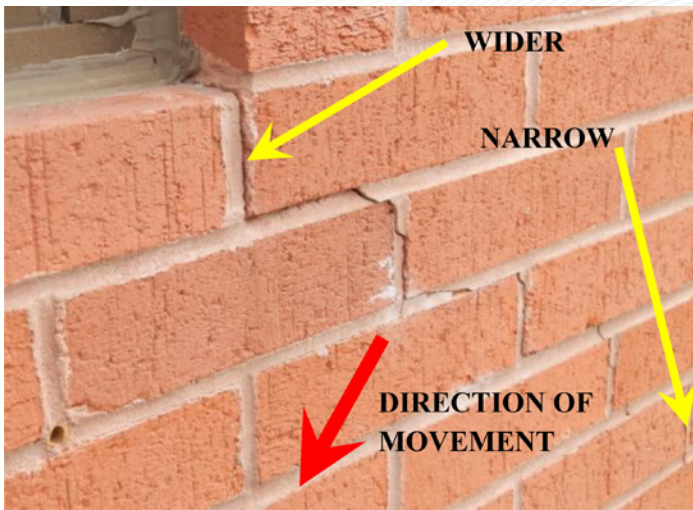
Vertical cracks are failures typically caused by an undersized steel angle (lintel). When the angle deflects, a vertical crack occurs that is wider at the bottom than at the top (The TMS limits deflection to $L/600$) (**Photograph 8**).

Horizontal Cracks:

Horizontal cracks are typically caused by insufficient or lack of horizontal movement joints, or movement of the shelf angle due to insufficient torque of the anchor bolts (The TMS contains commentary that references to the Brick Industry Association (BIA) Technical Notes 18A for expansion joint requirements) (**Photographs 9 and 10**).

Spalling:

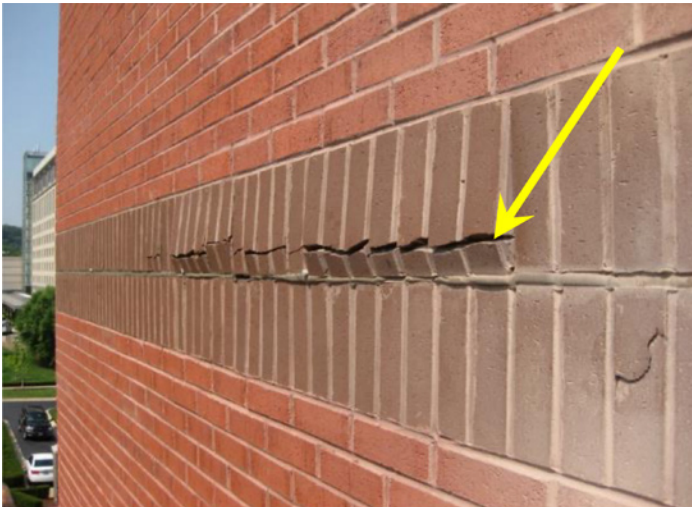
Spalling failure can be caused by several factors, such as age-related deterioration of the brick, or allowing it to retain moisture, become soft, or flake off brick fragments due to the freeze/thaw cycle (aka spalling). Nonpermeable paint can also trap moisture within the brick. Spalling can also result from inadequate allowance for movement joints or from embedded items within the brick. For historic brick buildings, the use of incompatible portland cement mortar over the existing



PHOTOGRAPH 7. A stair-step-pattern crack. *Photo from Rimkus Archives.*



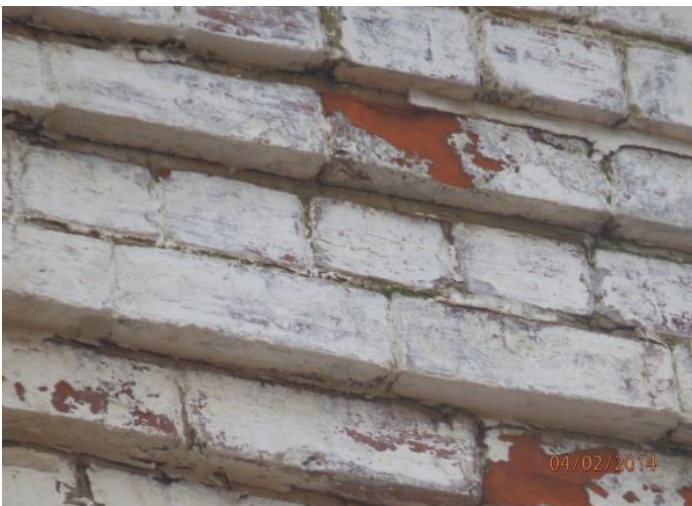
PHOTOGRAPH 8. A vertical crack. *Photo from Rimkus Archives.*



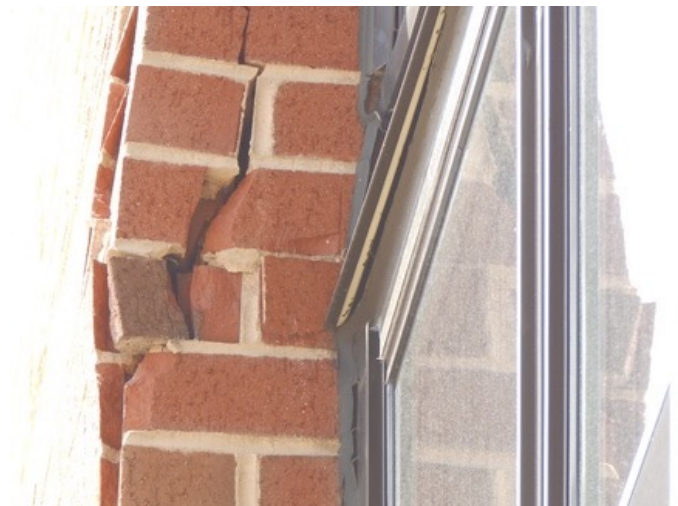
PHOTOGRAPH 9. A horizontal crack. *Photo from Rimkus Archives.*



PHOTOGRAPH 10. A view of the steel shelf angle below a horizontal crack. *Photo from Rimkus Archives.*



PHOTOGRAPH 11. Spalled brick. *Photo from Rimkus Archives*



PHOTOGRAPH 12. Spalled and fractured brick due to compression. *Photo from Rimkus Archives.*



PHOTOGRAPH 13. Bowed brick veneer. *Photo from Rimkus Archives.*



PHOTOGRAPH 14. Joint separation at the window in a bowed brick veneer wall. *Photo from Rimkus Archives.*



PHOTOGRAPH 15. A vertical crack in a bowed brick veneer wall. *Photo from Rimkus Archives.*

lime-rich mortar can result in spalling (for more information on spalling, see BIA TN 18A) (**Photographs 11 and 12**).

Bowed Brick:

Bowed brick veneer is typically caused by failed brick veneer ties, which allows the brick to move outward, resulting in separation gaps at the windows and vertical and diagonal cracks at the stress points (IRC, IBC and TMS specify requirements for brick veneer ties) (**Photographs 13 through 15**).

Efflorescence:

Efflorescence develops when excess moisture in the masonry causes the salts in the mortar and brick to dissolve and to crystalize on the surface as the moisture dries out. It appears as a white, powdery surface deposit (**Photograph 16**).

CORRELATION ISSUES WITH CODES/STANDARDS

The “cavity width” as defined by TMS varies when compared to “air space” as used in IRC are inconsistent when using corrugated sheet metal ties. Although TMS and IRC require a minimum 1 in. (2.54 cm.) drainage plane (air space in IRC), TMS limits the “cavity width” when installed on a wood-framed backup wall to 1 in. (2.54 cm.). The TMS cavity

width is from the stud face to the back face of the brick; effectively making the joint approximately ½ in. (1.3 cm.) when you subtract the sheathing. The TMS commentary says both requirements can be satisfied within the tolerances of each; yet tolerances are not clearly specified, other than that some mortar droppings are allowed within the air cavity. The TMS code allows an alternative to measure the cavity

width from the face of the sheathing if sheathing has a bearing stress of 100 psi (689 kpa) or the ties used to penetrate the sheathing to the light frame backing have a compressive strength of 200 psi (1379 kpa). Best practice is to provide at least a 1 in. (2.54 cm.) drainage plane and to meet the TMS strength requirements for the sheathing. Another option is to use an adjustable tie, where up to 6 in. (15.2 cm.) cavity width per TMS is allowed (the IRC allows up to 6⅝ in. (16.8 cm.).

There are variables for veneer tie spacing as noted in IRC and TMS. IRC allows the veneer ties to be spaced no more than 32 in. o.c. (81 cm.) horizontal and no more than 24 in. o.c. (61 cm) vertical, whereas TMS limits the spacing to no more than 24 in. o.c. (61 cm.) in either direction. The maximum brick area per tie in both codes is limited to 2.67 ft² (0.25 m²). For seismic zones, TMS limits the area per tie to 1.78 ft² (0.16 m²) and IRC limits this to 2 ft² (0.18 m²). Most exterior wall studs are at 16 in. (40.6 cm.) o.c. and given the modular size of brick (3 units per 8 inches or 2.67 in. (6.8 cm.) each), you can greatly simplify and satisfy all TMS and IRC requirements by spacing at 16 in. (40.6 cm.) o.c. each way. Also, a common recommendation from veneer tie manufacturers, is to space the ties at 16 in. (40.6 cm.) o.c. each way



PHOTOGRAPH 16. Efflorescence on the brick-and-mortar joint surfaces. *Photo from Rimkus Archives.*

(one tie for every 1.77 ft² (0.16 m²) of brick veneer).

IRC and TMS also specify that that weep holes can be spaced no more than 33 in. (84 cm.) o.c. BIA recommends that when wick weeps are used, spacing shall not exceed 16 in. (40.6 cm.) o.c.; when open-head-joint weeps are used, then spacing shall not exceed 24 in. (61 cm.) o.c. Use of weep tubes is not recommended by the BIA.¹¹ It is recommended that the designer comply with BIA recommendations, which are stricter than the IRC/TMS.

CONCLUSION

Designing for anchored brick veneer can be very complex due to the numerous code requirements. The proper selection of the brick veneer system, placement of flashing, and expansion joints are critical to the long-term performance of anchored brick veneer. The codes and industry standards noted in this paper vary in requirements, and the best practice would be to follow the strictest of requirements, identifying potential stress points in the brick veneer during

design and design and placement of expansion joints to minimize the stress and accommodate expansion. Provide clear details at all flashing locations and brick veneer expansion joints, locate all expansion joints on the exterior elevation drawings, and provide clear and concise specifications. Equally important is the need for active quality assurance observations during construction at regular intervals.

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Modeling, Simulation, and Measurement of a Full-Scale, Integrated Energy Efficiency-Retrofit Prototype for Single-Family Attached Residences in Cold Climates

ABSTRACT

Building energy retrofitting has been acknowledged as a critical path for achieving energy and environmental targets. Prefabricated panelized exterior insulated enclosure systems are emerging as a promising technology for retrofit solutions. However, there is a need to quantify panel performance relative to insulating value and airtightness. This paper presents a case study that investigated the use of numerical tools combined with in situ measurements to predict the performance of a full-scale, integrated energy efficiency retrofit assembly installed at Syracuse University's Building Envelope Systems Test (BEST) facility. The study investigated the impact of air leakage on hygrothermal performance under varying pressure differentials, using the Combined Heat, Air, Moisture and Pollutant Simulation for Building Envelope Systems (CHAMPS-BES) software program. The effective R-value was measured for a retrofitted panel system, including leakage and joint effects, and data were validated via field measurements. In the cold climate of Syracuse, New York, the overall retrofitting approach demonstrated an 80.3% reduction in total thermal energy use intensity (EUI), including 8.3% reduction from the enclosure retrofitting system and 72% reduction from a mechanical pod retrofitting system. If the approach were fully adopted to multiple residential building types across the United States, it could lead to significant reductions in carbon dioxide emissions with a potential annual energy savings of 531.05 TWh.

LEARNING OBJECTIVES

- » Identify and explain the key components of energy-efficient retrofitting technologies for residential buildings, with a focus on prefabricated panelized exterior insulated envelope systems.
- » Discuss the use of numerical tools for analyzing the hygrothermal performance of envelope retrofit assemblies by analyzing data from numerical simulations and field measurements, demonstrating competency in interpreting and applying results to real-world scenarios.
- » Assess the effectiveness of energy efficiency retrofitting measures in reducing energy use intensity, applying knowledge of relevant metrics and calculation methods to quantify potential energy savings accurately.

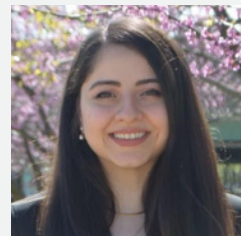
» Develop actionable strategies for promoting the adoption of energy-efficient retrofitting technologies in residential buildings, incorporating principles of sustainability to reduce environmental impact and foster long-term energy conservation efforts.

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INTRODUCTION

In the United States, buildings contribute to 38% of carbon dioxide (CO₂) emissions, consume 73% of total electricity, and account for 39% of total energy usage.¹ About 20% of that total energy is consumed by residential buildings. Residential buildings constructed before energy codes were established represent approximately 68% of all building stock in the United States,² and they often have significant air leakage and inadequate insulation. As a result, heating and cooling losses in these buildings can account for a substantial portion of utility bills. Deep energy retrofits that achieve significant reductions in energy used in for space conditioning and producing domestic hot water are needed to enable conversation of heating to clean energy without exceeding the capability of existing electric grids, and for reducing energy bills of households in historically underserved communities.³

The building enclosure is one of the main targets in energy retrofit projects to reduce overall energy consumption and the environmental impact of buildings, especially in cold climates.^{4,5} High-performance buildings incorporate a combination of tight building enclosures, mechanical ventilation, and energy-efficient components to ensure comfort, adequate airflow, and moisture control.⁶ In this context, prefabricated panelized exterior insulated enclosure systems are emerging as a promising technology for retrofit solutions.^{7,8} The project described herein focused on the design, development, and testing of proof-of-concept prototypes for a replicable, cost-effective “one-stop-shop” retrofit solution that addresses the need for innovation in integrated design, fabrication, and installation. The solution comprises a prefabricated modular exterior enclosure system that is compatible with a high-efficiency mechanical pod for heating, cooling, ventilation, and domestic hot water supplies.

The overall goal of this project was to develop a transformative solution for integrated whole-building energy efficiency retrofits of residences in cold

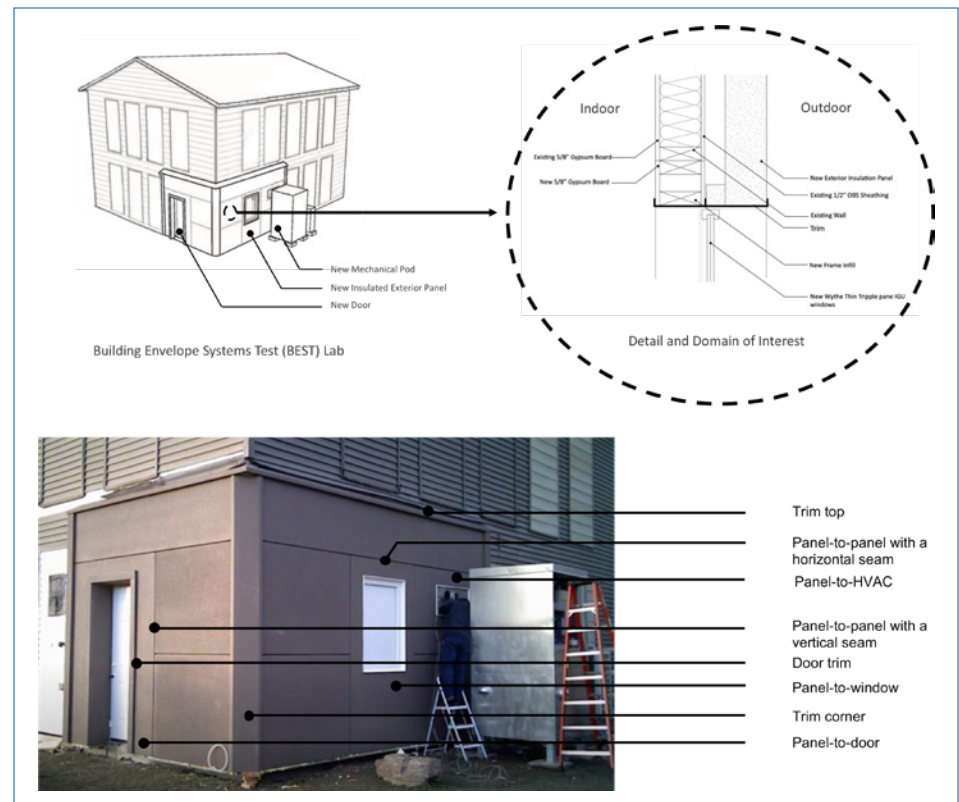


FIGURE 1. Schematic of the case study (top), and the completed prototype with different panel types and seam conditions (bottom).

or very cold climate regions; the first target was a solution for single-family attached residences with the potential of extending the approach to extend the approach to single-family detached homes and low-rise multifamily housing. The project team developed a novel highly insulated prefabricated modular exterior building envelope retrofit wall system and envelope-integrated HVAC system components that connect to a compatible and optimally-sized modular mechanical pod to deliver heating, cooling, ventilation, and domestic hot water.

Reviewing similar approaches of exterior building envelope retrofit wall systems,⁹ there is a need to quantify the panel performance relative to insulating value and airtightness.⁹ The primary research questions are: What is the impact of air leakage on the hygrothermal performance of a retrofitted panel system under varying pressure differentials? How do infiltration and exfiltration affect the hygrothermal performance? What is the effective *R*-value of the retrofitted panel system, including the effects

of leakage and joints? Therefore, this study measured the influence of air leakage on hygrothermal performance of a full-scale integrated energy efficiency retrofit assembly, installed at Syracuse University's Building Envelope Systems Test (BEST) facility, under different pressure differentials, modeled the effects of both infiltration and exfiltration using Combined Heat, Air, Moisture and Pollutant Simulation for Building Envelope Systems (CHAMPS-BES).¹⁰ It assessed the effective *R*-value of a retrofitted panel system, considering the effects of leakage and joints, and validated the results through the full-scale tests. In addition, an EnergyPlus model was developed.¹¹ This model was used to simulate the whole building energy savings potential (total thermal energy use intensity (EUI) reduction) of the retrofitted building prototype in comparison with a reference that represents existing conditions of the same type of buildings to assess the technical potential for energy-savings from all applicable buildings in the United States.

MATERIALS AND METHODS

This study evaluates the performance of an energy efficiency retrofit prototype using field measurements and modeling. The research was conducted at BEST facility, a state-of-the-art laboratory designed to simulate and measure the performance of building envelope systems. The research involved monitoring hygrothermal conditions in March 2022. The collected data validated a model-based evaluation methodology using the CHAMPS-BES software. Notably, the testing of the mechanical pod was not within the scope of this paper. This section is divided into four sub-sections, including (1) BEST Lab Setup; (2) Descriptions of the measurements; (3) effective R-value quantification; and (4) Modeling and simulation.

1. BEST Lab Setup:

The BEST Lab is a two-story building on the Syracuse University South campus, located at Syracuse, New York, that is a baseline residential building used for research and development related to building envelope systems and energy performance. **Figure 1** shows an overview the BEST facility (top left), lower corner section on the first floor used for testing (bottom) and the domain of interest for hygrothermal simulation (top right). The southeast corner room with two exterior walls exposing East and south was selected for the purpose of the full-scale prototype installation and testing of the integrated envelope and mechanical retrofit system. In the design of the panel layout, the objective was to maintain the minimum number of panels and seams to maintain thermal performance while considering impacts on aesthetics and cost. The panel layout and structural attachment system for the BEST Lab full-scale prototype test were driven by the overall building dimensions, foundation, existing wall assembly, elevation, locations of windows and doors. Panels were prefabricated for the installation and field testing at the BEST facility. Six mid-scale prototypes, for the integrated building envelope retrofit system, were designed and fabricated, and tested to represent varying panel types and

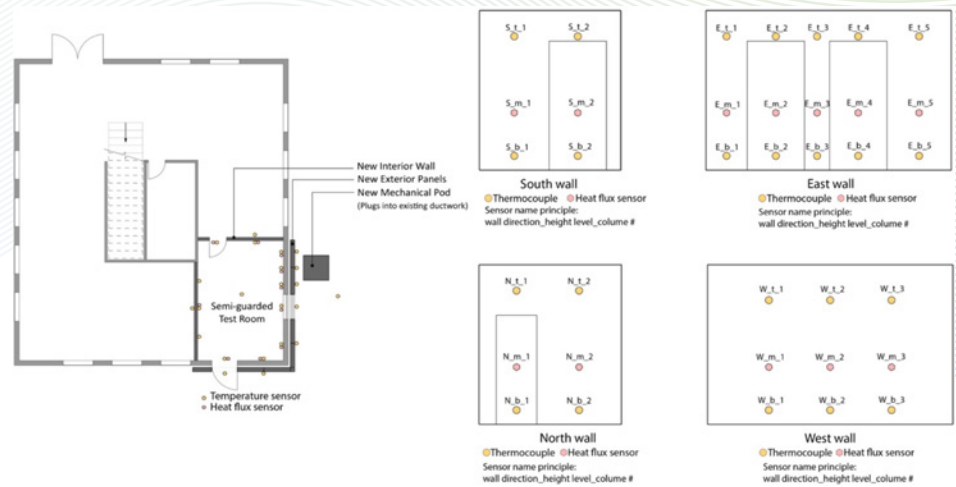


FIGURE 2. Sensor-mounting locations.

connections, including: (1) Opaque panel with no seams; (2) Panel-to-panel with a horizontal seam; (3) Panel-to-panel with a vertical seam; (4) Panel-to-panel with a vertical and horizontal seam; (5) Panel-to-window; (6) Panel-to-HVAC penetration. Two separate chamber tests measured thermal resistance and airtightness of each mid-scale prototype.¹² Thermal resistance and airtightness testing of panels with vertical, horizontal, and cross-joint seams showed anticipated decreases in thermal resistance and increases in air leakage compared with the opaque panel. Air leakage was especially greater than expected, with significant air-leakage at the vertical and cross-joint seams. The difference of results across panel types demonstrated the importance of compression in a panel module assembly and attachment strategy. It also informed a revised gasket strategy. **Figure 1** shows a photo

of the completed prototype on the BEST facility, with different panel types and seam conditions (bottom).

2. Descriptions of the measurements:

Type T Thermocouples and heat flux sensors were used to measure the exterior and interior surface temperatures and heat fluxes on the interior surface, in order to calculate the effective thermal resistance of the whole assemblies and to validate the hydrothermal simulations. An interior test room was constructed to setup a realistic experiment. A total of 59 sensors were mounted to the south, east, north, and west walls of the test room. The sensor mounting locations are shown in **Figure 2**. They were selected to include different type of wall sections (plain walls, door or penetration for the pod) and three vertical sections (top, middle, and bottom). The east wall contained

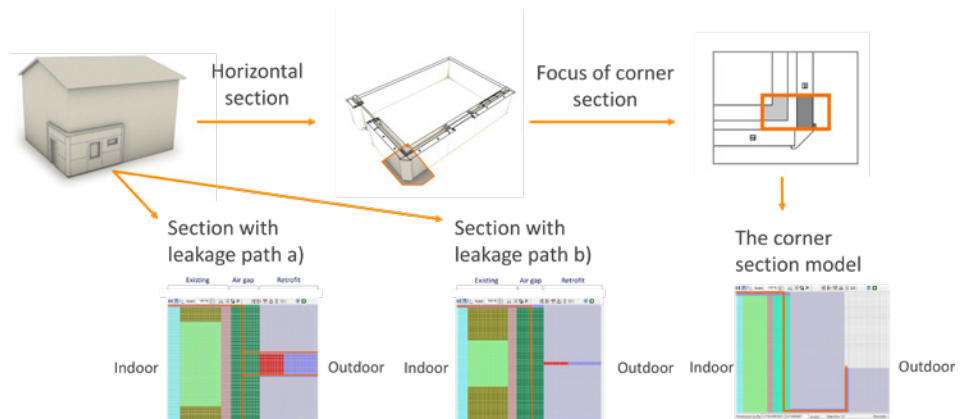


FIGURE 3. Overview of the modeling workflow and CHAMPS-BES simulation setup.

15 interior sensors, mounted in alignment with 15 exterior sensors. Each sensor on the east wall measured different panel conditions, for example an opaque structural panel, a panel with an opening for a window, and a panel with an opening for mechanical component penetrations.

The south wall contained 6 interior sensors, mounted in alignment with 6 exterior sensors positioned at an opaque panel area and at an exterior door. The north internal partition wall contained 6 interior sensors located at an internal door and an internal wall. The west wall contained 9 interior sensors. Additional thermocouples were used to monitor the indoor and outdoor air temperatures. The data acquisition was built using a Campbell CR3000 datalogger with three multiplexers. The data collection interval was 10 minutes.

3. R-value quantification:

The effective thermal resistance was calculated at each sensor location from measured in-situ temperature difference among indoor, air gap, and outdoor environment and heat flux data by using summation technique over time. The estimation of the effective thermal resistance R_e is calculated by using summation technique as below.¹³

$$R_e = \frac{\sum_{k=1}^M \Delta T_k}{\sum_{k=1}^M q_k} \quad (1)$$

where

R_e = thermal resistance, m^2K/W

M = number of values of ΔT and q in the source data

ΔT = difference in temperature between the indoor surface and the air

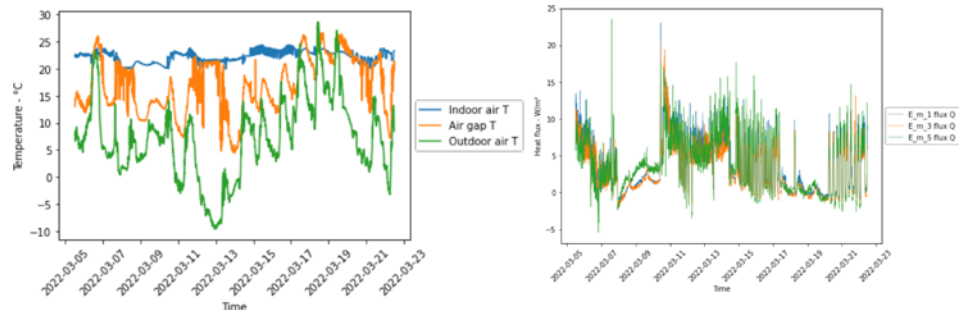


FIGURE 4. Thermal conditions for sections 1, 3, and 5 of the east walls during the running period: indoor temperatures, temperatures in the air gap between the existing exterior wall and the retrofitting panel, and outdoor temperatures (left); heat fluxes (right).

gap for the existing construction, K ; or difference in temperature between the air gap and the outdoor environment for the retrofitting plane, K

k = counter for summation of time-series data

q = heat flux, W/m^2

To determine the time to compute the estimated thermal resistance, the convergence factor CR_n was calculated using Eq. (2), where n is time units (12 hours).

$$CR_n = \frac{R_e(t) - R_e(t-n)}{R_e(t)} \quad (2)$$

At the selected time, CR_n remains below 0.1 for at least three periods of length n . The variance of R -values $V(R_e)$ is used at least two more times to evaluate whether the thermal resistance of the building component is acceptable or not. $V(R_e)$ is calculated as follows:

$$V(R_e) = [s(R_e)/\text{mean}(R_e)] \times (100\%) \quad (3)$$

where $s(R_e)$ is calculated with $(N - 1)$ degrees of freedom, and N is the

number of values of (R_e) ($N \geq 3$).

4. Modeling and simulations:

Advanced exterior enclosure retrofitting systems represent high thermal resistance. However, different insulation components are connected to each other using gaskets. Correspondingly, additional leakage around seams may affect the components' hygrothermal behavior. The main challenge of this problem lies in modeling of airflow through joints, cavities, and cracks, where determining the exact leakage path is difficult. Assuming a small path in the junction area with an airflow due to a pressure differential, heat and moisture transfer can take place between the flowing air and the building materials of the wall assembly. Therefore, in addition to the heat transfer behavior, analysis of the moisture accumulation (considering moisture sorption-retention curves of the materials) over time was needed.

The CHAMPS-BES software was used to simulate the combined heat, air, and moisture transfer through the wall

TABLE 1. Coefficients of variance and standard deviations (SDs) for R-values.

Wall sections	Existing construction			Retrofitting panel		
	R-value, m^2K/W	Coefficient of variance	SD, m^2K/W	R-value, m^2K/W	Coefficient of variance	SD, m^2K/W
E_m_1	1.53	3%	0.04	2.43	7%	0.16
E_m_3	1.76	2%	0.04	2.80	7%	0.21
E_m_5	1.48	2%	0.03	2.35	7%	0.17
Average	1.59	2%	0.04	2.53	7%	0.18

layers. The model has been built on the Delphin 5 program.¹⁴ The internal energy balance, air, and moisture mass balance are written as:

$$\frac{\partial \rho^U}{\partial t} = -\frac{\partial}{\partial x}(\mu j_{conv}^v + j_{diff}^Q + h j_{diff}^v) + \sigma_{ref}^U \quad (4)$$

$$\frac{\partial \rho^m}{\partial t} = -\frac{\partial}{\partial x}(j_{conv}^{ma} + \sigma_{ref}^{ma}) \quad (5)$$

$$\frac{\partial \rho^{mw+v}}{\partial t} = -\frac{\partial}{\partial x}(j_{conv}^{mw} + j_{conv}^{mv} + j_{diff}^{mv}) + \sigma_{ref}^{mw+v} \quad (6)$$

where

ρ^U = internal energy density, J/m³

μ = specific internal energy, J/kg

j_{conv}^v = convective water vapor flux, kg/(m²s)

j_{diff}^Q = heat conduction, J/(m²s)

h = specific of water vapor in J/kg

σ_{ref}^U = energy sources/sinks, J/m³s

ρ^{ma} = air mass density in reference volume, kg/m³

j_{conv}^{ma} = convective air mass flux, kg/(m²s)

σ_{ref}^{ma} = air sources/sinks in reference volume, kg/(m³s)

ρ^{mw+v} = moisture density, kg/m³

j_{conv}^{mw} = convective liquid (capillary) water flux, kg/(m²s)

j_{conv}^{mv} = convective water vapor flux, kg/(m²s)

j_{diff}^{mv} = diffusive water vapor flux, kg/(m²s)

σ_{ref}^{mw+v} = moisture sources/sinks in reference volume, kg/(m³s)

Figure 3 shows an overview of the modeling workflow. In this study, two different sections (a vertical section and a corner section) were analyzed. The three-dimensional (3-D) heat transfer problem for the corner was simplified and reduced to a 2-D problem. For the vertical section, two types of models—one without any leakage path (only energy balance), and one with leakage path (energy and air and moisture mass balances accompanied by interior and exterior air pressure boundaries)—were created. The actual leakage area ratio was calculated and was accounted for in the model geometry creation. Two difference leakage scenarios were considered: leakage path (a) was a symmetrical path and accounted for the leakage from the panel-to-panel

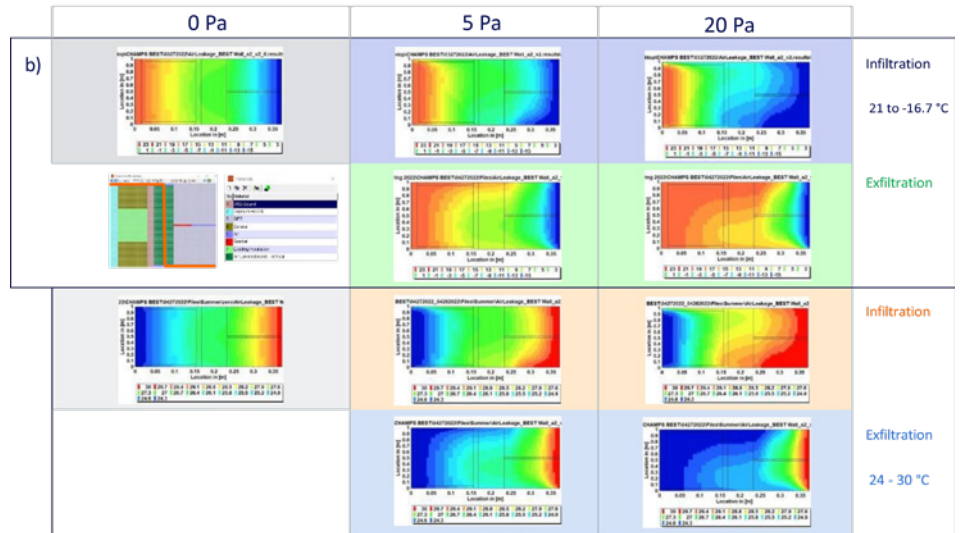
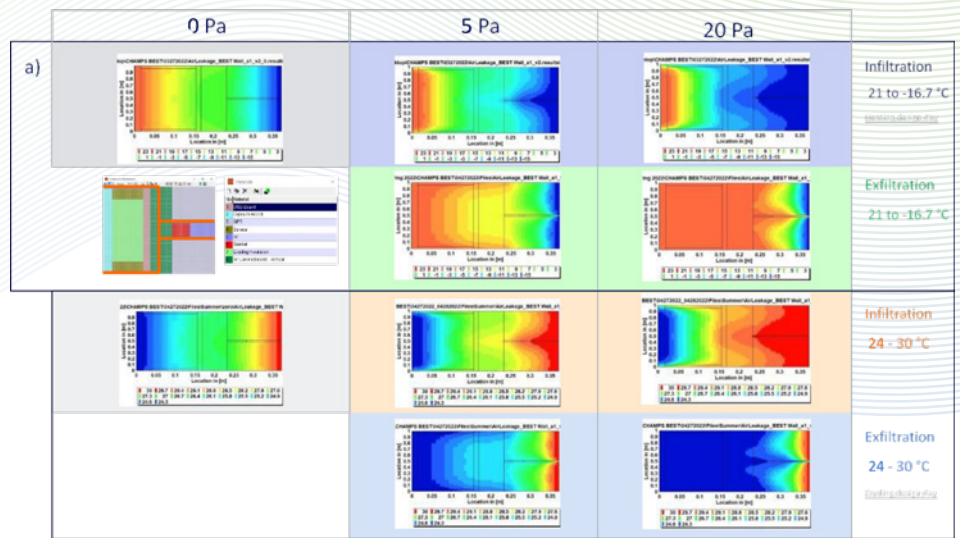


FIGURE 5. Temperature contours for the sections with leakage paths (a) and (b).

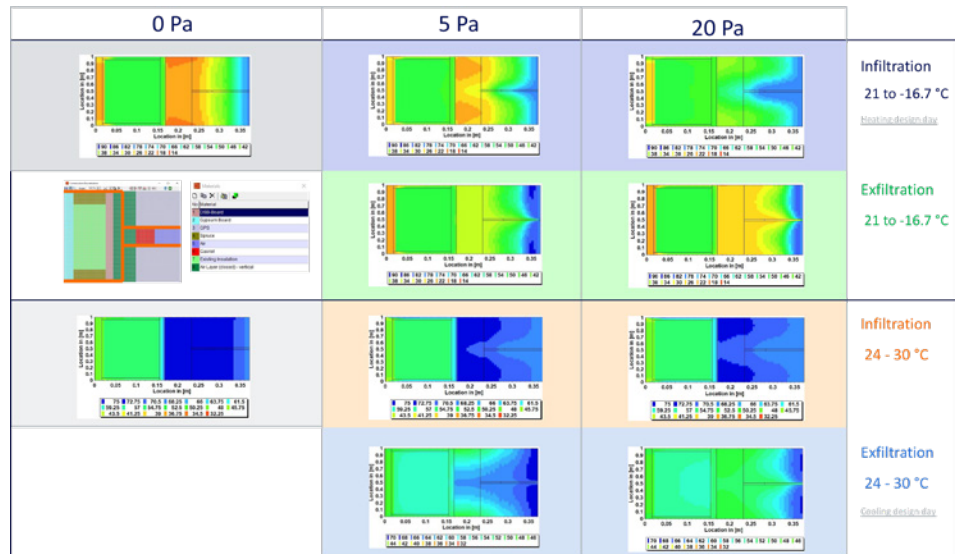


FIGURE 6. Relative humidity distribution for the sections with leakage path (a).

seam interfaces, and leakage path (b) was unsymmetrical.

Steady-state and transient simulations were performed. Material properties

TABLE 2. Summary of simulation results for the sections with leakage paths (a) and (b).

Leakage path (a)				
		Pressure difference, Pa		
Parameter	Location, mm	0	5	20
Gypsum temperature, °C	0	20.4	19.66	18.65
Oriented strand board temperature, °C	168.275	5.1	−3.45	−11.11
Air cavity temperature, °C	200.275	3.74	−6.55	−13.91
Inside panel temperature, °C	232.275	3.82	−4.75	−12.52
Outside panel temperature, °C	371.975	−16.5	−16.62	−16.7
Gypsum heat flux, W/m ²	0	4.82	10.64	18.1
R-value for existing structure, m ² K/W		3.46	2.46	1.8
R-value for retrofit, m ² K/W		4.2	0.95	0.15

Leakage path (b)				
		Pressure difference, Pa		
Parameter	Location, mm	0	5	20
Gypsum temperature, °C	0	20.4	20.04	19.44
Oriented strand board temperature, °C	168.275	5.38	0.65	−7.2
Air cavity temperature, °C	200.275	4.6	0.02	−8.03
Inside panel temperature, °C	232.275	4.25	−0.75	−8.82
Outside panel temperature, °C	371.975	−16.5	−16.6	−16.65
Gypsum heat flux, W/m ²	0	4.72	7.65	12.5
R-value for existing structure, m ² K/W		3.35	2.62	2.2
R-value for retrofit, m ² K/W		4.47	2.17	0.69

and parameters were obtained from the built-in libraries of CHAMPS-BES. Additional material properties were set based on laboratory measurements for the graphite polystyrene and

manufacturers’ data sheets for the gasket materials.

For the steady-state simulations, both winter and summer conditions were

analyzed. For the winter simulations, the indoor temperature was set to 21°C, and the indoor relative humidity (RH) was set to 25%. The outdoor temperature was assumed to be −16.7°C (heating design condition for Syracuse), and the outdoor RH was assumed to be 80%. The initial temperature over the whole wall was 0°C, and the initial RH over the whole wall domain was 55%. For the summer simulations, the indoor temperature was set to 24°C, and the indoor RH was set to 50%. The outdoor temperature was assumed to be 30°C (cooling design condition for Syracuse), and the outdoor RH was assumed to be 70%. The initial temperature over the whole wall was 22°C, and the initial RH over the whole wall domain was 55% for the summer simulations.

For the transient condition, the actual measured values were used to determine the simulated average heat flux over the interior surface and compare it with the average measured heat flux. For the models with leakage paths, interior and exterior air pressure boundaries were added (5, 10, and 20 Pa pressure difference), and both exfiltration and infiltration conditions were analyzed.

The energy-saving potentials were estimated by computer simulations using Design Builder/EnergyPlus software.¹¹ Simulations were performed to determine the annual thermal energy consumption for before and after the whole-building retrofit solution was applied. The baseline condition before the retrofit represents the median thermal EUI of the single-family attached building type in U.S.

RESULTS AND DISCUSSION

The air gap temperature followed the trend of outdoor air temperature in most cases (indicating the presence of infiltration airflow) with a few exceptions in which the temperature in the air gap was similar to the indoor air temperature (indicating the presence of exfiltration airflow). The heat flux variation was shown in Figure 4 (left), which correlated well with the indoor-outdoor air temperature difference, and was not obviously affected by the air gap temperature. This may be due to the

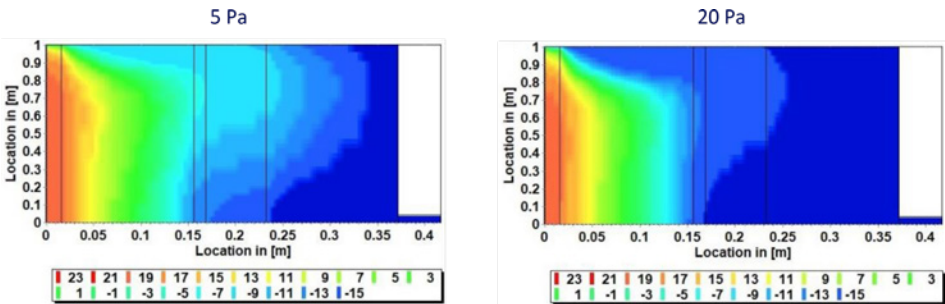


FIGURE 7. Temperature contours for the corner section.

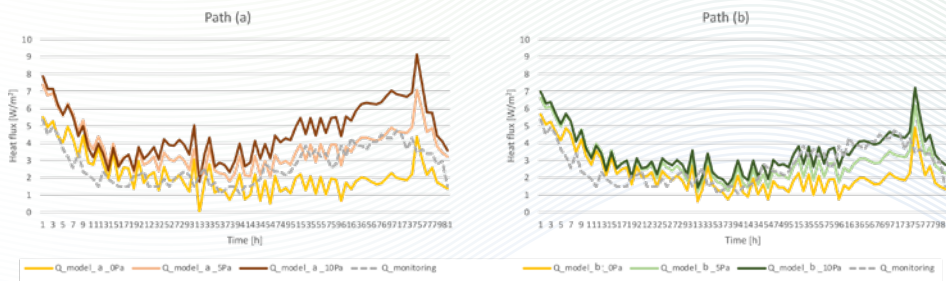


FIGURE 8. Comparison of simulated and measured interior heat flux data of 0-, 5-, and 10-Pa pressure difference scenarios for leakage paths (a) and (b).

TABLE 3. Summary of the error quantification results for the heat-flux comparisons.

	Leakage path (a)			Leakage path (b)		
	0 Pa	5 Pa	10 Pa	0 Pa	5 Pa	10 Pa
MAE, W/m ²	1.17	1.13	1.13	1.14	0.93	0.92
RMSE, W/m ²	1.42	1.39	1.39	1.39	1.16	1.16

thermal mass of the wall that made the heat flux less sensitive to the fluctuating air gap temperature due to infiltration/exfiltration. Even though section 1, 3, and 5 were at different locations, there were small differences among their monitored heat flux values. This indicated similar insulation performance of the opaque wall sections regardless of orientation and elevation.

Table 1 presents the coefficients of variance and standard deviations of *R*-values. The coefficients of variance were less than 10%; the mean *R*-values for the existing construction and the retrofitting panel were 1.59 and 2.53 m²K/W, respectively, with mean standard deviations of 0.04 and 0.18 m²K/W.

Figure 5 shows the temperature contours for the sections with leakage paths (a) and (b) for the three pressure-difference scenarios for the steady-state exfiltration and infiltration conditions. As can be seen from the comparison of the sections without and with leakage paths, the presence of an air leakage path significantly affected the contours. Because of the considered leakage paths, results from the scenario known as leakage path (a) represent more symmetric contours, and it was most severe for the 20 Pa pressure difference.

Figure 6 shows the simulated RH distributions for the sections with

leakage path (a) for the three pressure-difference scenarios for exfiltration and infiltration conditions. These distributions are notable given the severity of the influence of air leakage on the wall's performance.

Table 2 summarizes the simulation results for the sections with leakage paths (a) and (b). It shows that leakage effects on thermal resistance increased from 13% to 35% as pressure difference increased from 5 to 20 Pa. **Figure 7** shows the temperature contours for

the corner section for the 5- and 20-Pa pressure-difference infiltration conditions. The average interior heat fluxes for the 5- and 20-Pa cases were 13.87 and 20.58 W/m², respectively.

Then, the transient conditions were analyzed using the interior heat-flux data for the first four days of March. **Figure 8** shows the comparison of simulated and measured data for the 0-, 5-, and 10-Pa pressure-difference scenarios for leakage paths (a) and (b). **Table 3** summarizes the error quantification results for these comparisons. Field measurement data on temperature and heat flux validated the simulation results, with average mean absolute error of 1.07 W/m² and root mean square error (RMSE) of 1.31 W/m².

Figure 9 provides a comparison of the wall liquid content with and without leakage. The leakage model results of moisture for both scenarios (a) and (b) for moisture provide an overview of the differences over the four-day analysis period.

Step wise energy simulations were performed to determine the incremental thermal energy savings due to each retrofit strategy in comparison with the median thermal EUI baseline building conditions. These results were presented as an evaluation of various components of the retrofit prototype, based on the measured input

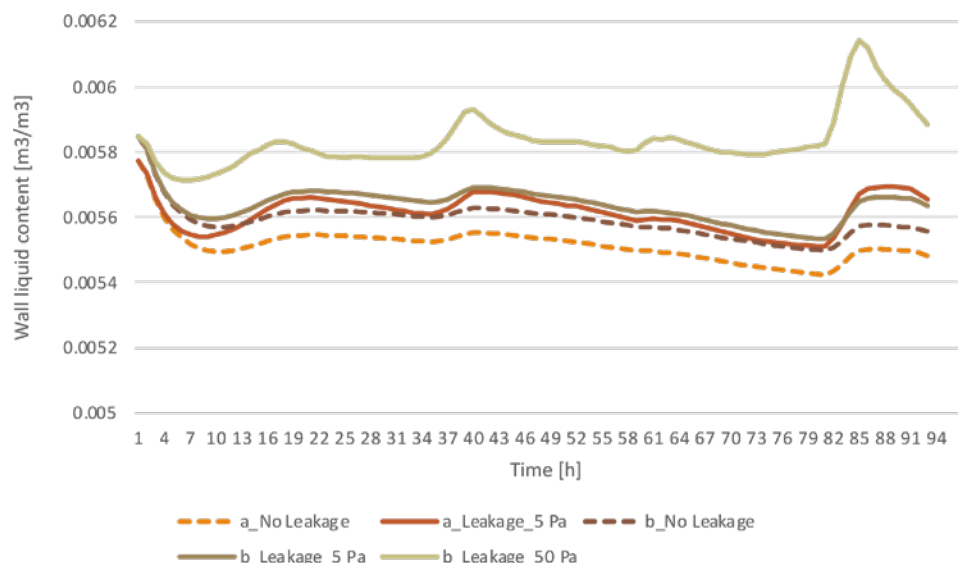


FIGURE 9. Comparison of the wall liquid content with and without leakage.

TABLE 4. Specific energy-savings for median thermal EUI single-family attached residences.

Retrofit strategy	Baseline ^a	Project goal	Achievable in Prototype	Specific strategies	Incremental annual energy savings	Energy savings subtotal
Airtightness	2.2 ACH ₅₀ ^b	1.05 ACH ₅₀	2.14 ACH ₅₀	Precompressed foam tape gasket solution, enclosure, integrated window and door installation	0.3%	8.3%
Insulation	R-value of 17 ^d	R-value of 30 (measured R-value = 27 ^e)	R-value of 16.97 ^g	Insulated prefabricated panel solution, including panelized roof modules	8%	
Heating equipment efficiency	80 AFUE ^d	3.0 COP	4.24 COP	Pod-based heat pumps	43%	72%
Cooling equipment efficiency	9.1 EER ^d	23 EER	23 EER	Pod-based heat pumps	0.5%	
Domestic Hot Water (DHW) efficiency	0.56 EF ^d	2.43 EF	2.43 EF	Pod-based heat pumps	28.5%	
Expected energy savings	--	75%		--	--	80.3%
Indoor air quality		<800 ppm of CO ₂		Pod-based energy recovery ventilation with heat-recovery efficiency of at least 80% and CO ₂ -enabled boost function		

a Baseline conditions for single-family attached building located at 150 Small Road, Syracuse, N.Y.

b Estimated airtightness level for single-family attached buildings in cold climate regions.

c Based on the target airtightness of maximum 1.0 L/s/m² exterior enclosure surface area at 50 Pa.

d 2014 Building America House Simulation Protocols by the National Renewable Energy Laboratory for buildings built between 1980 and 1989.

e Based on the midscale Building Energy and Environmental Systems Laboratory's chamber test results for retrofitting panels. (R-value of 27 was used as additional insulation from the panel.)

f Elimination of the top- and bottom-joint effects, which occupied 30% of the total joints by leakage area (total measured air leakage rate was 3.19 ACH50).

g Effective R-value for the retrofitting panel, ignoring the top- and bottom-joint effects.

values, and their combined effect on the building envelope performance and overall energy saving potential. However, they do not represent the results from the final retrofit solution. The final retrofit solution will be validated in the field. **Table 4** shows the impact of the enclosure and HVAC pod strategies, which provides 80.3% thermal energy saving after the retrofit. Improving the airtightness to 2.14 ACH50 leads to 0.3% reduction in thermal EUI. Then, adding the retrofit panel resulted in 8% reduction of the building's thermal EUI comparing to the baseline. A subtotal of 8.3%

thermal EUI reduction was achieved by retrofitting the envelope. It also shows the incremental thermal EUI reductions due to increased equipment efficiency for air heating (43%), cooling (0.5%) and domestic water heating (28.5%), with a subtotal thermal EUI reduction of 72% from the energy pod. From the total thermal EUI reduction (80.3%) from the integrated retrofit solution, 44.92% was from space heating, 0.70% from space cooling, 6.11% from ventilation, and 28.56% from the water heating energy reductions. It should be noted that the calculated R-value is lower than the target value and the airtightness level is

higher than the goal. The R-value for the retrofitting panel includes leakage and joint effects, and the analysis showed that 33% thermal leaks took place at the top and bottom boundaries of the retrofitting assembly due to insufficient insulation and sealing. As mentioned before, the reported results are based on the project prototype, but the final solution will be validated in the field. If the main issues are corrected, based on the project goal (values reported on the Project Goals column), 78% thermal energy is saved after the retrofit (savings of 14.4% from the enclosure system and 63.6% from the integrated HVAC pod).

CONCLUSION

This case study explored the significant potential of prefabricated, panelized exterior insulated enclosure systems for retrofitting single-family attached residences in cold climates. By integrating numerical tools with in situ measurements, the performance of a full-scale, integrated energy efficiency retrofit assembly was thoroughly evaluated. The research specifically focused on the impact of air leakage on hygrothermal behavior of the exterior insulated envelope systems. The effect of air leakage on hygrothermal behavior, especially moisture, was shown to be significant. CHAMPS-BES software enabled the testing of integrated retrofit walls compared with actual field testing, providing a

cost-effective way to predict assembly behavior. However, the airflow model (combining heat, air, and moisture transfer) required significantly more computational time than was need for the actual hygrothermal wall model (design without leakage). Although simulations of air leakage are more accurate, they are computationally complex and not typically considered for design and evaluation.

The energy model developed and applied for Syracuse, New York, estimated an impressive 80.3% reduction in thermal EUI through a retrofitting approach that included an exterior insulated panel system combined with enhanced mechanical equipment efficiency. The numerical modeling, simulation, and

measurements not only facilitated practical suggestions for strengthening building enclosure panel elements and evaluating retrofit solutions but also laid the foundation for methodological advancements in the design, construction, operation, and retrofitting of energy-efficient buildings.

ACKNOWLEDGMENTS

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Forward-Thinking, Solar-Ready Commercial Roof Design

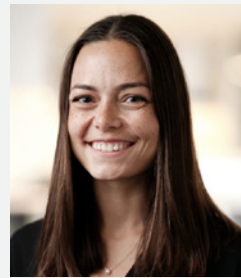
ABSTRACT

Recent energy conservation code updates in various jurisdictions require new and significantly altered roofs to be solar-ready. These updates exemplify the broader universal trend of incorporating sustainable practices into new construction. Although many of these codes avoid prescribing specific photovoltaic (PV) design criteria, they typically mandate the allocation of a portion of the gross roof area for future PV panel installation. Rooftop PV design is inherently multidisciplinary and influenced by various factors, many of which benefit from coordination with base building design decisions. Accordingly, a proactive approach during initial roof design contributes to a successful, predictable implementation process during future PV installation. The authors have compiled a set of forward-thinking, solar-ready roof considerations for commercial, institutional, and multifamily low-slope roofs that can guide design professionals and other project stakeholders, regardless of whether their jurisdiction regulates solar readiness.

LEARNING OBJECTIVES

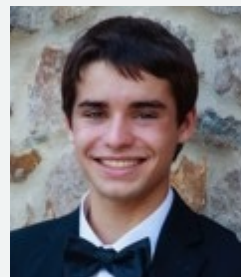
- » Identify the current available options for photovoltaic array support.
- » Discuss early design phase considerations related to rooftop solar that can impact the roofing assembly performance.
- » Identify how photovoltaic arrays can be effectively integrated with low-slope roofing systems.
- » Understand typical rooftop solar provisions in building codes.

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Recent energy conservation code updates in various North American jurisdictions have introduced requirements for new and significantly altered roofs to be solar-ready. In Appendix CB, the 2021 *International Energy Conservation Code* (IECC)¹ defines the term “solar-ready” as having “a section or sections of the roof or building overhang designated and reserved for the future installation of a solar photovoltaic or solar thermal system.” Currently, it is possible to approach the solar-ready requirement by denoting rooftop space for future PV panels on a roof plan, which is the minimum threshold for compliance. For example, the energy conservation code in Washington, DC² (where the authors reside), requires that the building design “show allocated space and pathways for future installation of on-site renewable energy systems... to cover no less than 25% of [the] horizontal projection of the gross roof area.” This and similar code provisions do not require rooftop renewable energy systems (e.g., PV panels) to be installed when the base building construction is complete.

The building owner will typically engage a PV vendor (many of whom can provide a variety of helpful “turnkey” services) when they are ready to implement the PV system. However, engaging a PV specialist after the base building construction is complete may result in a disconnect in timelines and communication with the base building project team members. In the meantime, simply allocating a portion of the gross roof area during the initial building design—though a productive incremental step toward increasing on-site renewable energy on new buildings—does not account for the multidisciplinary base building design decisions that must often be considered and coordinated for a successful future installation of PV panels. A Canadian Roofing Contractors Association article titled “Photovoltaics in Roofing”³ aptly notes, “If not carefully planned, not only can the hoped-for return on investment in solar quickly evaporate, it can result, instead, in significant financial loss and jeopardize the performance of the roof on which it was installed.”

A proactive approach during initial roof and building design can contribute to a successful and predictable implementation of rooftop PV panels, maintaining the roofing assembly’s performance and mitigating the potential for surprises, such as unexpected costs or constrained options to the building owner. These proceedings compile a set of forward-thinking, solar-ready roof considerations for low-slope membrane roofs (not including electrical design, which is outside the scope of this content) that go beyond roof area allocations and can guide design professionals and other project stakeholders, regardless of whether their jurisdiction regulates solar readiness. As a key member of multidisciplinary project teams for commercial, institutional, and multifamily base building designs, the building enclosure consultant is well-positioned to help keep these topics at the forefront of design/development teams’ thought processes.



FIGURE 1. Example rooftop PV arrays on racks.

ROOFTOP PV BASICS

It is helpful for the base building design team and other project stakeholders to embark on a solar-ready building design with a baseline understanding of PV technology and strategies available to attach the rooftop PV system.

Solar panels consist of PV cells designed to generate electricity when exposed to radiant energy, such as sunlight. Sunlight (i.e., solar radiation) is absorbed by the semiconductors that make up PV cells, resulting in electrical charges within the cells that then generate electricity.⁴ These PV cells are packaged together to create modules, which can be grouped into panels. The assembly of PV modules or panels with a support structure and other ancillary components (e.g.,

wiring, junction boxes, monitoring devices) is referred to as a PV array. PV arrays produce electrical power for the building, which can reduce the required demand for external energy from the local power grid.

PV arrays are typically supported by and attached to a framed structure referred to as a rack (**Fig. 1**). Attaching the rack to the building structure is a critical design decision that impacts various aspects of the roofing assembly. The most common attachment methods include ballast, dunnage/stanchion, mounts with through-fasteners, and hot-air-welded clips. Thin-film PV laminates, some of which can be adhered to thermoset, thermoplastic, or modified-bitumen membranes

under the umbrella of the building-integrated PV philosophy, have not been part of the authors' projects in recent years and are therefore outside the scope of these proceedings.

In a ballasted assembly (**Fig. 2**), the PV rack is typically attached to plastic or metal trays that are loaded with concrete blocks, pavers, or other weights to secure the PV assembly and counteract wind uplift pressures. Typically, ballasted PV assemblies have a low profile, and the panels are close to the roof membrane. This approach avoids rack/mount penetrations through the roofing membrane, minimizing the opportunity for such penetrations that, if poorly flashed, can act as vulnerabilities for water leakage. Ballasted PV systems are also typically the most economical attachment method. However, ballasted systems have several disadvantages that must be considered. Since the PV panels are close to the roofing membrane and the ballast trays rest on the membrane, this approach can impede roof drainage and cause heat buildup between the PV panels and the membrane, which can negatively impact the PV panel and roofing performance.⁵ Additionally, the PV assembly must be removed to access the roofing assembly for maintenance, repair, or replacement. Finally, the ballasted trays can shift in service, especially if adequate expansion/contraction measures are not designed into the system, potentially abrading or damaging the membrane.

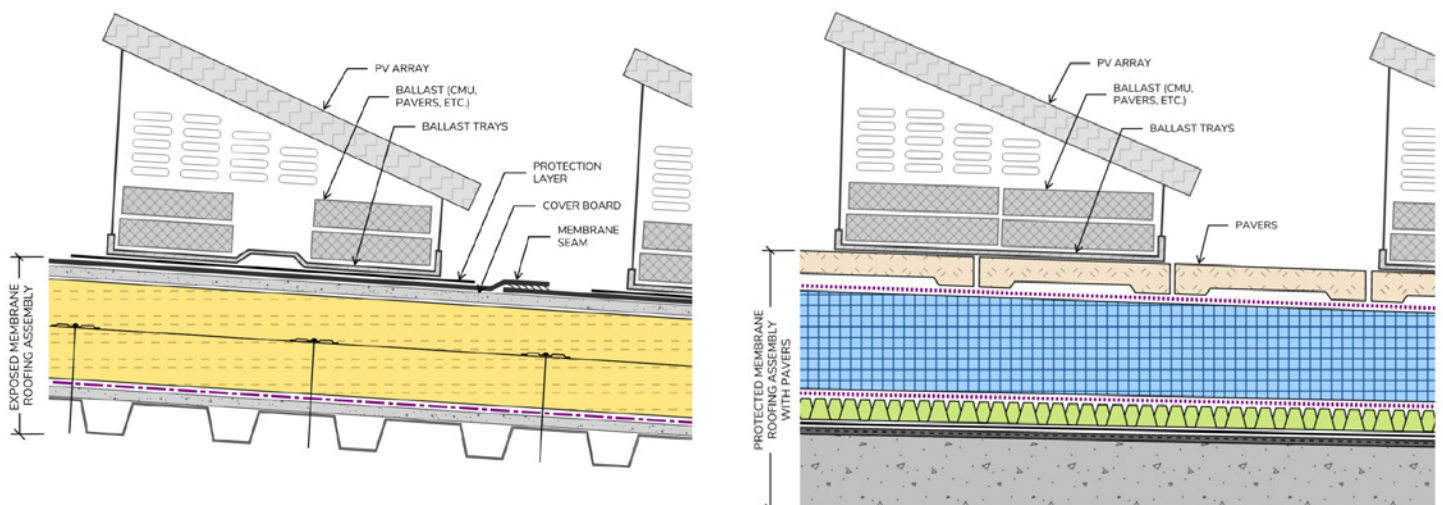


FIGURE 2. Example representations of ballasted PV assemblies over exposed membrane (left) and protected membrane (right).

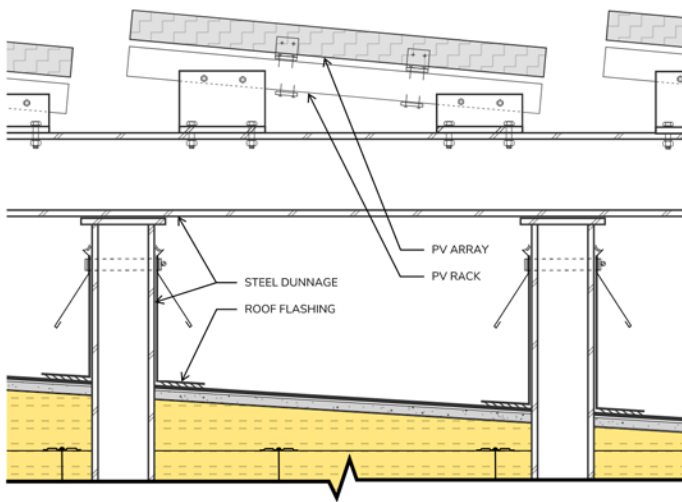


FIGURE 3. Example representation of dunnage PV assembly.

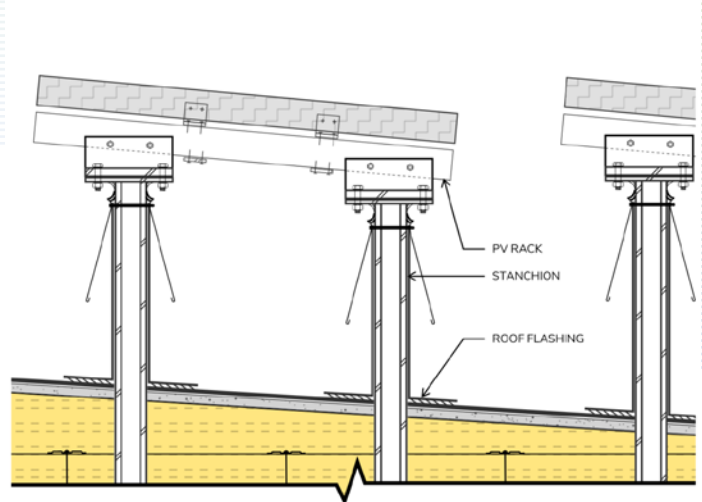


FIGURE 4. Example representation of stanchion PV assembly.

In a dunnage approach (**Fig. 3**), the rack is mechanically attached to steel framing and localized posts (e.g., at the corner of each dunnage frame) that transfer the PV system's structural load to the building, often at underlying columns. Like dunnage (but with increased roofing penetration frequency), stanchions (**Fig. 4**) are composed of a series of repeating small-diameter posts that transfer the structural load to the roof deck or building structure. Both dunnage and stanchions elevate the PV panels above the roof surface. This allows for beneficial airflow under the panels and, depending on how tall the dunnage system is, allows for roof maintenance, repair, or replacement without disrupting the PV assembly. For both dunnage and stanchions, the posts are flashed with roofing membrane in a detail that, provided it follows the

membrane manufacturer's instructions, is typically warrantable.

Another attachment option, for which commercially available options and partnerships with membrane manufacturers have increased in recent years, is PV roof mounts with through-fasteners (**Fig. 5**). These mounts generally consist of metal disks that attach to the roof deck and either rely on a gasket seal for water tightness or include an integral flange of exposed membrane roofing (e.g., polyvinyl chloride [PVC], thermoplastic polyolefin [TPO], modified bitumen) that is adhered or heat-welded to the roofing membrane. Manufacturers of through-fastened mounts typically have slope limitations (e.g., 2:12 maximum or 1:12 at areas of high snow load). This approach is generally more economical than dunnage/stanchions but requires

numerous penetrations through the roofing membrane and may have limited structural capacity relative to other attachment methods. Unless each mount is raised onto a curb, the systems may present an increased vulnerability to water leakage versus the dunnage/stanchion approach. The membrane penetration points have varying sealing features, depending on the specific product, and their low position puts them in the roof's drainage path. This approach also has similar drawbacks to ballasted systems associated with the PV panel's low-profile above the roof surface.

For PVC roofing assemblies, hot-air-welded clips (**Fig. 6**) are another newer attachment option. These clips are proprietary (and consequently offered by limited manufacturers), and they avoid rack/mount penetrations through

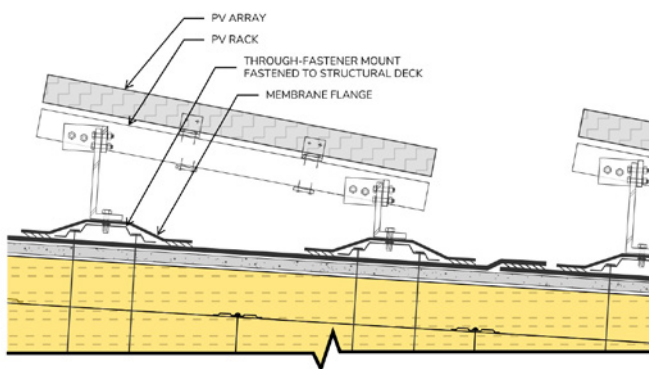


FIGURE 5. Example representation of through-fastened PV assembly.

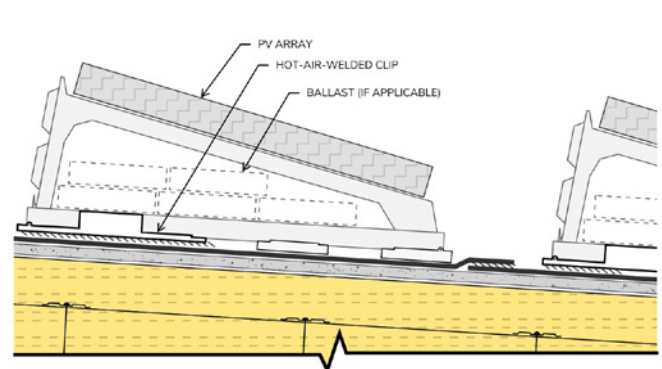


FIGURE 6. Example representation of hot-air-welded PV clip assembly.



FIGURE 7. Localized deflection and ponding under ballasted PV assembly.

the roofing membrane by using the roofing assembly to resist wind uplift pressures rather than attaching directly to the roof deck or building structure.

STRUCTURAL CONSIDERATIONS

Considering future PV installation during the base building structural design is essential to a holistic rooftop solar design. The building's structural system is interdependent with the attachments discussed in the previous section and may unexpectedly restrict the ability to install future PV panels if not sufficiently considered. The following sections discuss select base building structural considerations that the project's structural engineer can oversee.

Dead and Live Loads

Section 1606.4 of the 2021 *International Building Code* (IBC)⁶ requires that the weight of the PV array and its support system or ballast is included as a dead load when designing the roof structure. The design of the roof structure is, therefore, interdependent with the type of the future PV assembly. Ballasted systems, relative to other attachment systems, more uniformly distribute their dead load across the roof deck, while stanchion systems impose concentrated point loads on the building's structure at each post. Steel dunnage systems, which typically impose greater concentrated dead

loads than stanchions, consequently require particular coordination with the base building structure. Design professionals should consult with the building owner and structural engineer regarding what type of support system they envision for the future and plan accordingly by designing the base building structure with adequate reserve capacity for PV dead loads that can be reasonably anticipated. If dunnage systems are anticipated, the base building design may go so far as to identify specific future dunnage layouts and structural capacity at the associated future post locations.

Additionally, section 1607.14.4.1.1 of the 2021 IBC requires that the roof be designed for live loads both *with* and *without* the PV panels, so the base building structural engineer should capture future PV-related live loads for the area planned for future PV.

Deflections and Ponding

If the future PV will be a ballasted system, section 1607.14.4.5 of the 2021 IBC requires that the roof structure be designed and analyzed for deflections per section 1604.3.6 and ponding per chapters 7 and 8 of ASCE 7.⁷ The authors have investigated outcomes where the addition of a ballasted PV assembly resulted in ponding at areas of localized deflection in the roof structure (**Fig. 7**) and in the displacement of the roofing

base flashing at the perimeter of the roof, resulting in water leakage to the interior.

Wind, Snow, and Seismic Loads

Sections 3111.1.1 and 1607.14.4.2 of the 2021 IBC⁶ also require that rooftop-mounted PV systems be designed for wind loads in accordance with section 1609, which references chapters 26 to 30 of ASCE 7,⁷ and that snowdrift loads created by PV panels (if applicable) be included as dead load.

Besides the IBC, other industry codes and standards, such as those published by the ASCE (which the IBC references) and the Structural Engineers Association of California (SEAOC), include requirements or guidelines for the structural design of rooftop PV. The 2016 edition of ASCE 7, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, added new provisions for determining wind loads on PV panels. ASCE 7-16 also states that solar panels should be considered as roof projections that may cause windward drifts on the roof around them, and it includes provisions for how to calculate the snowdrift geometry and loading.⁷ Therefore, the base building design should assume a conservative weight for the solar-ready portion of the roof and/or perform a proof-of-concept analysis for the snowdrift of the future PV assembly. As always, project teams must utilize the latest applicable versions of codes and standards since their evolutions are likely to affect solar-ready building designs. For example, ASCE 7-22 includes increased structural design loads (e.g., snow loads and rain intensities) relative to earlier versions.

Where applicable, seismic loads must be considered as they relate to the PV array and the associated load path to the building structure. Three reports SEAOC has published provide structural seismic requirements for rooftop PV (PV-1),⁸ include requirements and recommendations for wind design for solar arrays (PV-2),⁹ and address key issues for evaluating the capacity of the building roof structures to support gravity loads imposed by PV arrays (PV-3).¹⁰ Even where these provisions are not triggered by a project's

governing codes, they can be helpful tools for design teams performing due diligence or proof-of-concept exercises to prepare a current base building for future rooftop PV.

FIRE-RELATED/COMBUSTIBILITY CONSIDERATIONS

Sections 1505.1 and 1505.9 of the 2021 IBC include requirements for fire classification of the roofing and PV assemblies based on the building construction type and reference additional requirements in the *International Fire Code* (IFC)¹¹ and standards by the National Fire Protection Association. When preparing a new building design that anticipates future rooftop PV, these provisions are worthy of an upfront understanding, particularly those related to firefighter access.

Access Pathways for Firefighters

Section 1205.3 of the 2021 IFC¹¹ requires pathways to support firefighters accessing roofs with PV arrays. These requirements vary between Group R-3 buildings (mainly smaller residential buildings) and all other buildings (which include commercial construction). For commercial roofs, the code prescribes the following minimum pathway widths and spacing based on the location and application:

- » Minimum 6 ft wide perimeter pathway around the edges of the roof (exception: where either axis of the building is 250 ft or less, the width may be reduced to 4 ft).
- » Minimum 4 ft wide interior pathways at minimum 150 ft intervals, in a straight line to roof standpipes or ventilation hatches, around roof access hatches, and (minimum one) pathway to the parapet or roof edge.
- » Minimum 4 ft wide pathways bordering all sides of non-gravity-operated smoke/heat vents.
- » Minimum 4 ft wide pathways on minimum one side of gravity-operated dropout smoke/heat vents.
- » Between array sections: minimum 8 ft wide pathway or minimum 4 ft wide pathway bordering 4 ft by 8 ft venting cutouts every 20 ft on alternating sides of the pathway.

The geometry of the roof and the layout of rooftop mechanical equipment and roof hatches can significantly impact and, in some cases, limit the layout of future rooftop PV, especially with consideration of the aforementioned access requirements. Accordingly, when determining the portion of the roof that will be allocated for future PV panels, it is prudent to conduct a proof-of-concept layout process that maps out these pathways, especially if the building owner is relying on the PV assembly to provide a minimum power output that is based on a panel layout that consumes the allocated square footage.

MECHANICAL, ELECTRICAL, AND PLUMBING CONSIDERATIONS

Electrical Pathways/Penetrations

The future rooftop PV system will require electrical conduits to route through the building and penetrate the roof, and some solar-ready roof designs generically require providing conduits with the base building project for the future PV. Deferring the identification of conduit pathways and penetration points/methods to the future can lead to limited choices and possibly compromised

decisions and performance problems. Therefore, it is good practice to incorporate these features, with some specificity, in the base building design. Regarding conduit runs in the building, allocate and label space within ceiling cavities, vertical chases, or other suitable pathways. Do not route electrical conduits through the roofing insulation above the structural roof deck; the authors have investigated existing buildings where this approach was used, resulting in a concealed safety hazard for future roofing contractors (**Fig. 8**). Moreover, the National Roofing Contractors Association (NRCA) also recommends against this practice, adding that conduits should not be routed through flutes in steel decks or directly mounted to wood decks.

Regarding electrical penetrations through the roofing assembly, collecting and routing electrical conduits through enclosures (either field-fabricated sheet metal using NRCA details or prefabricated using commercially available products [**Fig. 9**]) near or within the future PV area is a prudent feature to incorporate in the base design. The availability of these predetermined and reliable penetration points can help future



FIGURE 8. Electrical conduit on roof deck within roofing assembly.

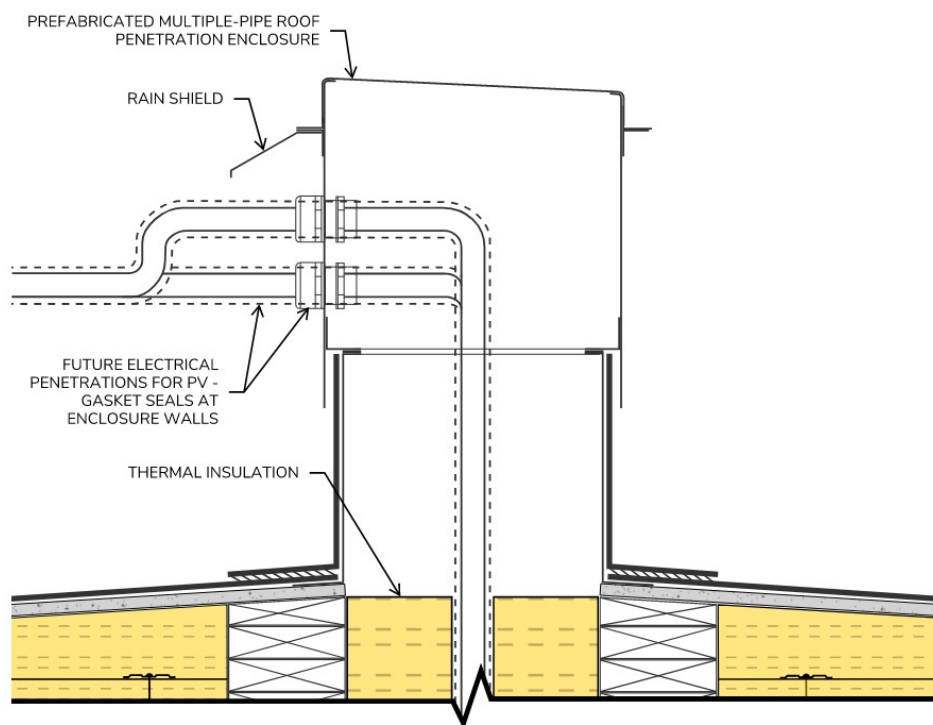


FIGURE 9. Example prefabricated enclosure for multiple-pipe/electrical conduit penetrations.

electrical contractors and roofing contractors avoid the temptation to use less-reliable penetration techniques such as pitch pockets, whose sky-facing sealant tends to deteriorate in service and cause water leakage vulnerabilities far faster than the surrounding roofing membrane.

Mechanical and Plumbing Equipment Layout

As described earlier, although the detailed layout of the future PV panels will likely not be included in the base building design, it is prudent to consider how the layout of the rooftop mechanical equipment may impact the available space for future PV. First, design teams should carefully consider whether mechanical equipment belongs on the rooftop in the first place or is better suited within a protected enclosure such as a penthouse, which is more conducive to a safe and recurring preventive maintenance program and less likely to be a source of water leakage through the roof. Design teams should endeavor to consolidate rooftop mechanical equipment, in part to minimize the number of access pathways required between and around

each unit, which can reduce the overall square footage of usable area for PV panels. Additionally, consider how large equipment (e.g., chillers or air-handling units) or mechanical penthouses or screen walls will cast shadows and position the PV area accordingly, since shading or otherwise obstructing only a small section of a PV module or panel can reduce its output.¹²

Roof Drainage Systems

The drainage strategy for the roof should be coordinated with the anticipated PV assembly support system and the locations of the solar-ready areas. The building code requires provisions for both primary and secondary (i.e., overflow) drainage on all roof areas. Roof drainage systems may include internal roof drains, through-wall scuppers, and/or gutters—all of which require access to inspect, maintain, and repair. It is prudent to avoid installing PV arrays over roof drains or blocking scuppers, especially with low-profile attachment systems (e.g., ballast, roof mounts, and clips) where routine maintenance is not possible without temporarily relocating the PV arrays to access the

drainage system, which would be costly and impractical.

ROOFING DESIGN CONSIDERATIONS

Single Ply Roofing Industry (SPRI) aptly characterizes the importance of roofing performance, even on roofs with PV: “The roof’s function is, first and foremost, to protect the building contents and its people from the elements.”¹³ This section discusses several factors directly related to designing the base building roofing assembly in the context of its future use under the PV assembly.

Alignment of Service Life

According to the NRCA, the service life of a typical PV assembly is approximately 25 years, and the service life of the average low-slope commercial roof is 17.4 years.¹² With that said, depending on the type/configuration of the assembly, membrane type, quality of installation, and degree of preventive maintenance, some roofing assemblies can functionally remain in service for 25 or more years. Endeavoring for the base building roof to last as long as possible is critical for establishing reasonable alignment with the service life of the future PV. Once the base building roof is installed below an allocated solar-ready area, the clock begins ticking toward misalignment of service lives until the PV is eventually installed. Misalignment (particularly if the PV implementation does not occur for several years) can result in a future scenario where costly removal and reinstallation of the PV assembly (especially for low-profile attachment systems) is required to accommodate the first roof replacement in the building’s life cycle.

Accordingly, enhancing the roofing assembly in the base building design to prioritize the length of its service life should be a design priority. Some fundamental strategies in this regard include the following:

- » Configuring the roof as a protected membrane assembly, where the membrane (e.g., a reinforced, monolithic fluid-applied waterproofing with a track record in this application) is protected

with overburden such as drainage composite, rigid and moisture-tolerant insulation, and a wearing surface. This approach typically lends itself more readily to roofs with a structural concrete deck than with a wood-framed plywood deck.

- » For single-ply roofs, specifying the thickest membrane in the manufacturer's standard offerings (e.g., 80 mil polyvinyl chloride or thermoplastic polyolefin instead of 60 mil).
- » Specifying a cover board below the roofing membrane for improved puncture resistance and load distribution (e.g., distributing the load from ballast trays in a manner that helps avoid localized insulation compression below the membrane and consequent localized ponding).
- » Specifying higher-compressive-strength insulation (e.g., 25 psi instead of 20 psi).
- » Including robust flashing detailing at all penetrations (e.g., avoiding pitch pockets, specifying prefabricated flashing boots, and specifying counterflashings at all penetrations to shield the underlying base flashing).
- » If considering a ballasted system for the future PV, fully adhering the cover board instead of mechanically attaching it since the shifting of the ballast can cause the roofing membrane to abrade against the fastener plates for the cover board.

Roofing Assembly Warranty

In addition to pre-PV-install inspections and other solar-related prerequisites, roofing manufacturers generally have requirements related to the composition of the roofing assembly. Base building design professionals should consult the basis-of-design roofing manufacturers to understand how the installation of future PV panels may impact the roofing warranty and what provisions are necessary to maintain the warranty at that time. For example, some manufacturers have specific guidance regarding membrane attachment and other roofing design enhancements described in the previous section. Additionally, some

roofing manufacturers have limitations on the roofing attachment options that they allow under their warranty, which may inform the structural design of the base building.

Insurance Requirements

FM Global, a commercial property insurance company, requires adherence to specific standards for roofing materials and installation procedures on FM-insured buildings. FM Global has published these requirements via Property Loss Prevention Data Sheets. FM Global Data Sheet 1-15, "Roof-Mounted Solar Photovoltaic Panels,"¹⁴ incorporates requirements related to fire and natural hazards for the design, installation, and maintenance of all roof-mounted PV panels, and this standard was updated in January 2023. FM Global mandates provisions that affect the base building design, including prohibiting multi-ply roofing assemblies (e.g., modified bitumen) under PV panels, requiring specific design parameters such as factors of safety (which can affect structural load reactions to the base building structure), and requiring additional ballast (where ballast is applicable) at specific portions of the PV array. If a building is insured by FM Global, then it is critical for the base building design team to coordinate with FM Global Approvals staff and the pertinent data sheets to ensure the design complies with all FM Global requirements and will be able to comply with any future requirements during the PV installation.

Roof Maintenance

SPRI recommends that PV array racks be installed with enough clearance above the roof membrane for maintenance/servicing, limiting PV arrays over field seams and penetrations so that they are accessible, and protecting high-traffic areas with walkway pads.¹³ Similarly, the NRCA recommends rack-mounted PV systems on support stands (e.g., stanchions) or on curbs with a minimum clearance of 30 inches from walls, curbs, or adjacent racks and enough room underneath to facilitate preventive maintenance, repairs, or replacement.¹² In section 9.7 of the *NRCA Roofing Manual: Membrane Roof Systems—2023*,¹⁵ the

NRCA provides guidelines for clearance above the roof surface for equipment support stands based on the width of the equipment.

BUILDING USAGE AND MAINTENANCE CONSIDERATIONS

Though it should, roofing design does not always consider how the building will actually be used and maintained, including maintenance of rooftop equipment and maintenance of the facade. To help base building design teams avoid imposing future unnecessary constraints on the building owner, this section highlights considerations related to fall protection required for future work on low-slope roofs and considerations related to future facade access.

Rooftop Fall Protection Requirements

The U.S. Occupational Safety and Health Administration (OSHA) sets and enforces standards to ensure safe and healthy working conditions for workers. OSHA's general industry standard (§1910.28)¹⁶ includes regulations, which were updated in 2017, for work on low-slope roofs of existing buildings. The standard essentially prescribes that employers of those working on low-slope roofs are responsible for providing their employees with an approved fall protection system where fall hazards are present. Key aspects of OSHA 1910.28's provisions for work on low-slope roofs include the following:

- » If a worker is less than 6 ft from the roof edge, they must be protected by a fall protection system such as a guardrail or personal fall arrest/restraint system.
- » If a worker is more than 6 ft and less than 15 ft from the roof edge, either they need a fall protection system (as described above) or the employer may implement a designated area (e.g., warning line system) if the work is both infrequent and temporary.
- » If a worker is more than 15 ft from the roof edge, then, at a minimum, the employer must implement and enforce a work rule prohibiting employees from going within 15 ft of the roof edge without some form of fall protection.

Additionally, sections 1015.6 and 1015.7 of the 2021 IBC require guardrails whenever components that require service (e.g., rooftop mechanical equipment and PV panels) or roof hatches are located within 10 ft of a roof edge, with the exception that guardrails are not required if personal fall arrest anchorage connector devices are present to protect workers in the defined edge zone.

A fall arrest/restraint system typically consists of a body harness, lanyard, and anchorage to the building. In conjunction with designating solar-ready roof areas and with consideration of complying with the aforementioned standards/code provisions, it is prudent for design professionals to incorporate guardrails, fall protection unit anchors, or travel arrest/restraint systems in the base building design to facilitate safe access of roof areas for future workers, including PV technicians.

Facade Access

Similar to planning for future roof access, it is prudent to consider how the facade of the building will be accessed for future inspections, maintenance, and repairs. While shorter buildings may be serviced via mobile elevated work platforms (e.g., scissor lift or boom lift) or scaffolding, taller buildings in dense urban areas may require facade access from the roof. Workers descending the face of the building, either via a hung platform (e.g., suspended scaffolds) or rope descent, would require personal lifelines and anchor points, and other equipment that is worthy of

coordinating with the solar-ready roof area to minimize the chances of conflict with future PV panels. For example, suspended scaffolds (i.e., swing stages) need unobstructed rooftop edge space to erect the suspension system (e.g., beams and counterweights). Also, the suspension system requires independent anchorage (i.e., tiebacks) and a pathway for the tieback cables to attach to a suitable independent anchor. Design professionals should consider conceptualizing and/or overlaying these pathways on an anticipated PV panel layout to avoid future facade access limitations for the building owner.

OTHER RESOURCES

As rooftop PV has become more common in recent decades, various agencies and industry associations have published helpful resources for building owners and design professionals. For example, the National Renewable Energy Laboratory, affiliated with the Department of Energy, has several guides that enumerate high-level considerations, discuss policy updates, and provide cost-benefit analyses for building owners. Building owners and design professionals may benefit from these resources in addition to those listed at the end of this paper.

CONCLUSION

When tasked with solar-ready low-slope commercial, institutional, or multifamily building designs, project teams (aided by the guidance of the building enclosure consultant) can contribute

to a successful future PV and roofing system by considering the following forward-thinking steps:

- » Work with the project's structural engineer of record and other team members (including PV specialists) to conceptualize the future PV support system and its various loads so they can design the base building structure with adequate reserve capacity that meets the code and avoids performance issues.
- » Identify mandatory access/maintenance pathways to prepare for future compliance with fire codes, coordinate with rooftop equipment and roofing maintenance needs, and inform the solar-ready area designated in the base building design. Also, consider how the roof and facade will be accessed, in conjunction with considering how the PV array will be accessed, when laying out solar-ready roof areas.
- » Design the roofing and rooftop MEP systems in the base building with the future PV system in mind rather than entirely deferring PV-related considerations such that they are not able to be coordinated with base building decisions.
- » Specify a durable roofing assembly with enhancements that will prolong the roof's performance and service life (ideally meeting or exceeding the service life of the PV array) and meet roofing manufacturers' PV-related warranty requirements.

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Windows Installation Designs for Meeting Demanding Thermal Code Requirements

ABSTRACT

The building enclosure industry has been moving toward the use of exterior continuous insulation for decades now, and the thickness of the insulation required has been increasing. Thicker exterior insulation requires new design solutions for cladding attachments and penetration, such as window openings. Modern emerging building codes, such as the *National Energy Code for Buildings 2020* in Canada and ASHRAE 90.1-2022, *Energy Standard for Sites and Buildings Except Low-Rise Residential Buildings*, require that the considerable thermal bridging impact of window installation details be considered. Finally, the need to focus on the water and airtightness of window installations is now widespread, and new standards, such as CSA A440.6, *High Exposure Fenestration Installation*, provide requirements for demanding applications.

This paper reviews the design and construction challenges of window installation in walls with more than about 38 mm (1.5 in.) of continuous insulation. New products have become available that may help solve some of the challenges. The design process, technology, and techniques for ensuring water- and airtight installation while mitigating thermal bridging are presented, along with a range of thermal calculations and construction details to bring these solutions to life.

LEARNING OBJECTIVES

- » Explain how building codes are changing to require improved thermal performance by reducing thermal bridges.
- » Identify how the fundamental control layers maintain their continuity at the head and sill of typical windows.
- » Describe the limitations of common window buck solutions for window installation
- » Identify how some newly available thermally improved materials and products can be used to make window installation thermally efficient as well as air- and water-tight.

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The installation of windows in walls is a common enclosure design requirement and yet a common source of problems. The wide range of different types of walls, cladding, and windows results in a vast range of possible combinations. As a result, the design of the window-to-wall interface detail is commonly unique to each project. Adding to the design and construction challenges are the changing requirements for better insulation values and controlling (limiting) thermal bridging. Despite these realities, this paper proposes that there are standard design principles that can simplify and guide the design of these important details.

The design of a wall must of course be considered in the design of the window rough opening. Hence, the common features of wall assemblies will be briefly considered. An increasingly common approach to understanding building enclosure design is embodied in the "Perfect Wall,"^{1,2} which identifies the enclosure control layers and an arrangement that meets most requirements. Although the relative position in the wall of the functional layers shown in **Figure 1** is the best for most applications, variations are common. For example, modern walls may have a water control layer outboard of the insulation, not use a vapor control layer, or routinely add insulation within hollow support frames made of steel and wood. However, despite variations, the layers identified must be present in any functional enclosure assembly and will need to be identified to allow for the design of a proper window installation.

In Canada, Part 5 of the National Building Code explicitly outlines the

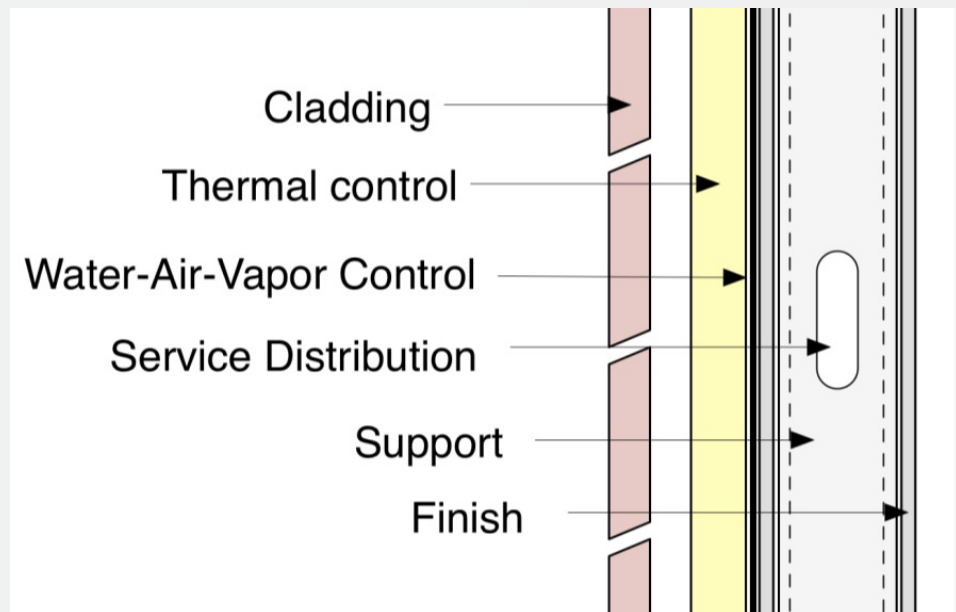


FIGURE 1. "Perfect Wall" enclosure design.

requirements for enclosures. Separate subsections describe thermal control (5.3), air control (5.4), vapor control (5.5), and water control (5.6).

The window, as part of the enclosure, must have all the same control layers. Like enclosure walls, windows may include additional functions, such as sound control, fire resistance, and impact resistance to respond to specific project requirements.

As society has demanded better energy efficiency and comfort, higher thermal performance has been required of enclosures. The building enclosure industry has been moving to the use of exterior continuous insulation for decades now and the thickness of the exterior insulation required has been increasing. Thicker thermal breaks and thicker insulated glazing units (that is, triple glazing) are the result of these same trends.

The framing component of vision framing can take on a bewildering array of shapes and numerous materials. However, for larger commercial and multi-unit residential buildings, shapes can be usefully categorized into four generic types: flanged, storefront, curtainwall, and solid (**Figure 2**). The locations of the control layers are not well identified for most window frame types, and this creates challenges for designing connections to the control and support layers of the surrounding walls.

Thicker exterior insulation requires new thermally efficient design solutions for cladding attachments and wall penetrations such as window openings. Modern emerging building codes, such as the *National Energy Code for Buildings 2020*³ in Canada and ASHRAE 90.1-2022, *Energy Standard for Sites and Buildings Except Low-Rise Residential*

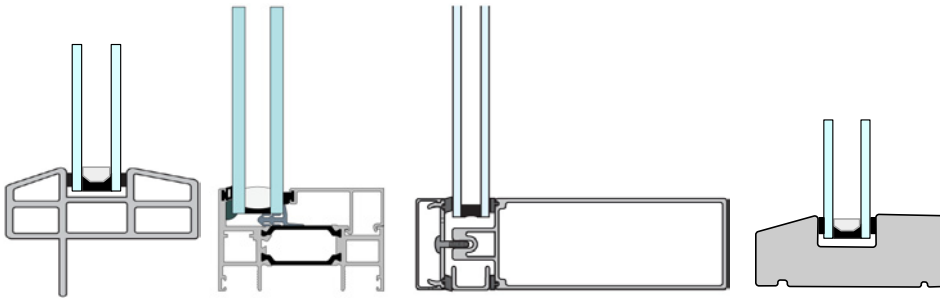


FIGURE 2. Four common categories of frame shape: flanged, storefront, curtainwall, and solid.

Buildings,⁴ require that the considerable thermal bridging impact of window installation details be considered.

The most critical function a window installation design must meet is that of structural support: if the window is not properly attached to a sufficiently strong enclosure support, failure will result in danger to life and safety. The primary life safety risk involves not in failing to resist the gravity load (which could cause the window to sag downward in its opening) but in the window falling outward (especially when that outward force is due to a human body). Design, construction, and inspection must always consider this structural function. Structural engineers specializing in window installation routinely provide designs to meet this need.

The remainder of this paper will focus on the air, water, and thermal control functions.

RAIN PENETRATION AND AIRTIGHTNESS

The second most important function of a window installation is to control rainwater penetration. This is a remarkably common defect observed routinely in practice. Windows and doors are routinely tested, in the laboratory, using standards such as ASTM E331⁵ since its introduction in the 1970s. Despite the widespread testing of window products for water penetration resistance, the poor control of rain penetration at windows has been well documented over the last 50 years, with surprisingly modern descriptions provided by Herbert,⁶ Scott,⁷ and Lies and Faith.⁸ Modern research has

increased over the last 25 years with dozens of published papers, such as RDH Building Engineering,⁹ Hardman and Katsaros,¹⁰ Lacasse,¹¹ and entire symposia subsequently devoted to the topic.^{12,13}

The need to focus on the water and airtightness of window installations is now widely accepted. ASTM E2112, *Standard Practice for Installation of Exterior Windows, Doors and Skylights*,¹⁴ has long guided installation. New standards, such as CSA A440.6, *High Exposure Fenestration Installation*,¹⁵ provide requirements for more demanding applications. The introduction to ASTM E2112-18 states, "Rainwater leakage has been the leading reason for dissatisfaction of building owners with performance of fenestration installations." This standard

explicitly only deals with walls that are drained (the term "drainage walls" is used) and face sealed (the term "surface barrier" is used) and does not directly address mass walls (the third rain control category) nor concealed perfect barriers (a type of perfect barrier rain control that does not place the barrier on the surface). More significantly, this widely used standard does not directly address airtightness or thermal continuity. Appropriate for its low-rise residential focus, most of the guidance provided relates to flanged windows. It is the authors' experience that in practice the ASTM E2112 standard does not provide sufficient guidance for designers of commercial non-flanged windows, and walls with exterior continuous insulation.

The airtightness of windows themselves is also tested (often using ASTM E283¹⁶), and windows are often rated for airtightness performance. However, the installation often results in air leakage around the window in the field. This air leakage is reported less often in the literature as a serious problem but can nonetheless result in durability impacts and increased heat flows.

In the authors' opinion, window frames and their rough openings should be assumed to allow rain penetration sometimes (often because of material

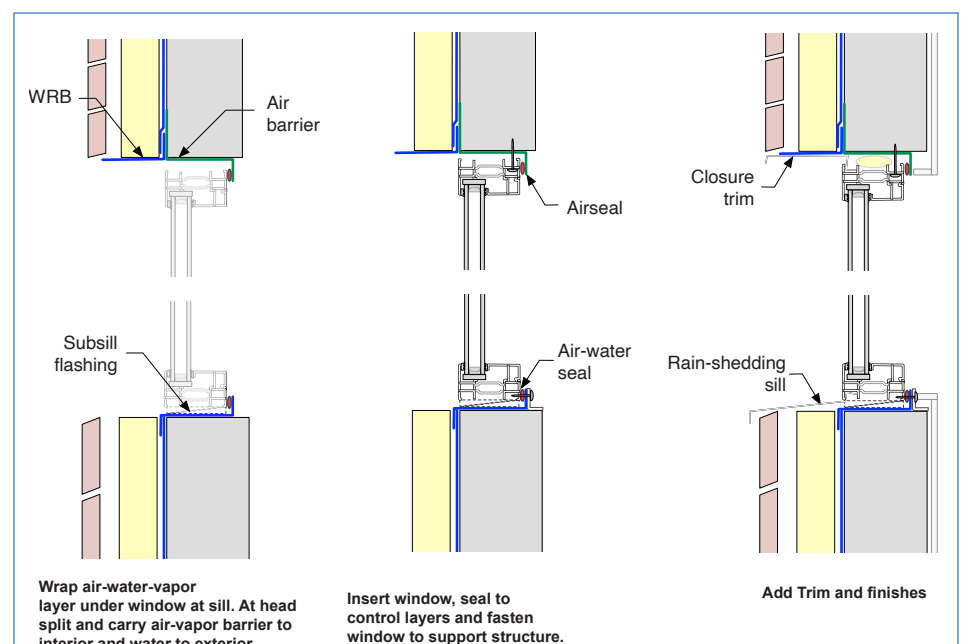


FIGURE 3. Generic punched window installation sequence.

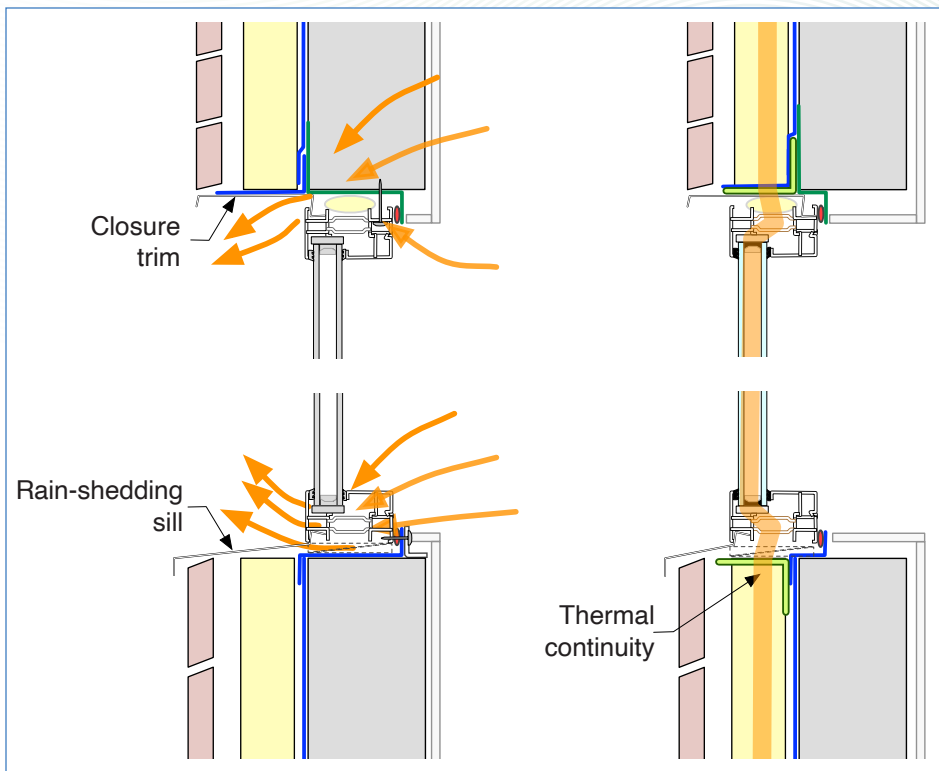


FIGURE 4. Thermal flanking can be avoided by ensuring alignment of thermal insulation.

deterioration over time or because of workmanship issues) and under some conditions (for example, hurricane-force-wind-driven rain). This leads to the recommendation that all rough openings should have water-resistant barriers applied and, most importantly, that drainage of the rough opening be provided and gross air leakage be blocked.

The purpose of any enclosure detail design between two distinct enclosure components is to connect the control layers of the two components, the interior and exterior finishes, and the structural components in a buildable and durable manner. When windows are connected to walls, it is recommended that the air control connection to windows be undertaken at the inside face of windows, and at the inner shoulder of the glazing rabbet for curtainwalls. For water control, the recommendation is to shed water to the exterior of unit frame at the head. At the sill, the water control should connect to the inside face of windows (or the inner shoulder of the glazing rabbet for curtainwalls).

The recommended approach to designing a window installation is shown in **Figure 3**. The air-water (and often vapor) control layer is wrapped under the window or door at the sill and raised upward and sealed to the inside of the frame for air barrier continuity. At the head, the water control is directed to the exterior and the air barrier is connected to the interior of the frame. Trims and finishes that are explicitly not

part of air, water, or thermal control are then added.

An inner air seal is provided around the entire perimeter, ensuring that air leakage is managed. While not always required, an upturned interior angle (or equivalent detail) is shown at the sill. Although this seal can be formed by the application of a backer rod and sealant in the rough opening, many window extrusion profiles (especially aluminum storefront sections of the type shown in **Fig. 3**) do not provide sufficient horizontal area for sealant adhesion. Sealing to the vertical inner surface is almost always possible and provides more than 1/2 in. of contact area for adhesion. An additional benefit of the upturn is that the air-water seal is not exposed to water that may accumulate on the rough opening sill: when exposed to air pressure, it will act across the inner seal and best practice is to limit water access to the air seal to limit air-pressure-driven water leakage.

MANAGING THERMAL BRIDGING

The installation of windows can locally increase heat flow. This is the definition of a thermal bridge. Building codes, such as NECB 2020¹⁷ and ASHRAE 90.1-2022,⁴ require the size of this thermal bridge to be estimated. Describing the methodology used to calculate and report thermal bridging is beyond the scope of this paper, but can be found in the codes and the standards they reference (for example, ISO 14683¹⁸ and



FIGURE 5. Steel angles provide structural support that allow windows to project outward, but impose significant thermal bridging.

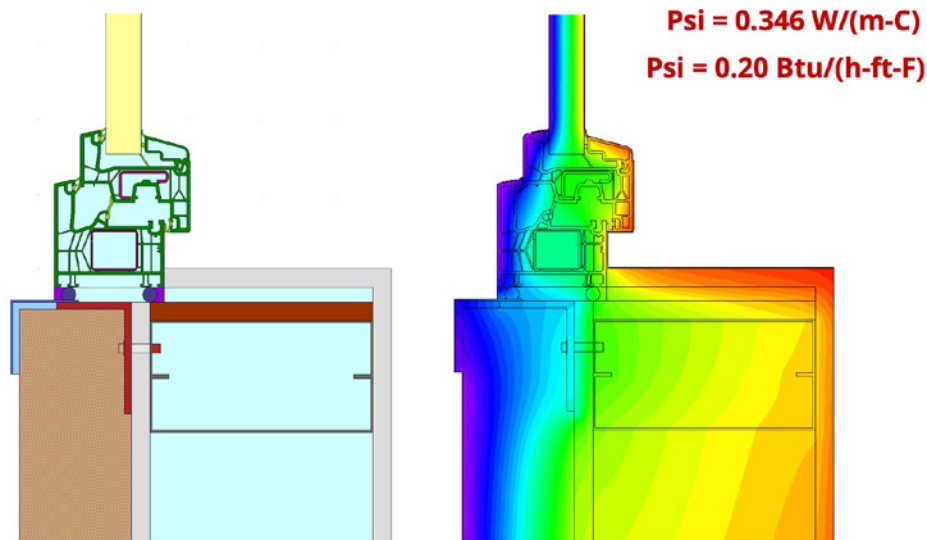


FIGURE 6. Thermal bridging calculation results for linear thermal bridging of steel window support angle.

CSA Z5010²⁵). In short, however, the increased heat flow caused by thermal bridging can be reported as an additional heat loss coefficient per length of sill, jamb, and head. The standard symbol used to describe linear thermal bridges is the Greek letter psi (Ψ), with units of $W/(m \cdot K)$ or $Btu/(h \cdot ft \cdot ^\circ F)$.

Research into the window-wall interface for North American building assemblies has been somewhat sparse, but several good references

exist.^{19–21} Increased heat flow around a window installation, often labeled as thermal flanking,² has more than just energy implications. Cold-weather condensation due to poor thermal control at window perimeters is an important problem that requires consideration (see, for example, Maref et al.²²).

The generic approach to detailing shown in the previous section manages air and water tightness very well.

However, the thermal continuity is lacking: that is, the thermal break in the window is not aligned with the thermal control layer. Thermal flanking can, in theory, be overcome by aligning the thermal break of the window with the thermal insulation layer(s) of the wall assembly (**Figure 4**). In modern wall assemblies with exterior continuous insulation, aligning the thermal breaks within aluminum window frames requires different solutions to ensure structural support.

A significant number of zero-energy and other low-energy buildings have been built with thick layers of exterior insulation for over 25 years. Hence, numerous techniques and details have been tried and tested on many jobsites. The earliest options developed were wood “bucks,” essentially sawn timber or engineered lumber frames that project outward from the face of the wall into the insulated cavity and provide support. This approach largely solves the thermal bridging issues, but the use of wood has significant limitations. Wood moisture movement routinely results in challenges during construction caused by warping and cupping. Before the window can be installed, the air-water membrane from the wall must be wrapped first outward and then inward, resulting in complex

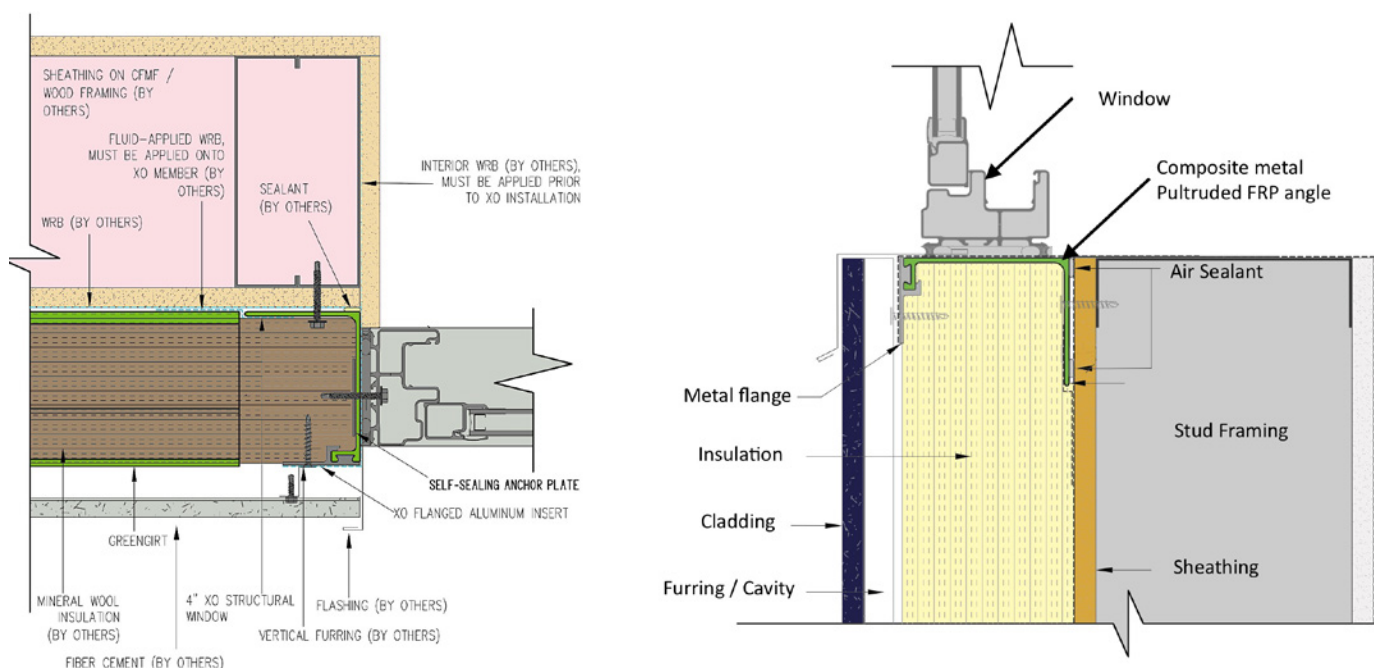


FIGURE 7. Example composite metal hybrid FRP angle window sill installation (Advanced Architectural Products, 2024).

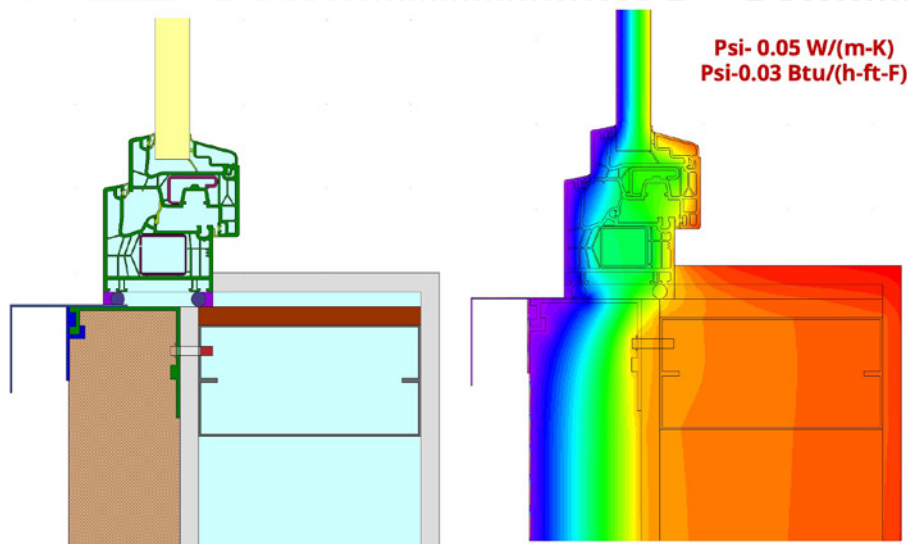


FIGURE 8. Thermal bridging calculation results for window sill installation using a composite FRP metal hybrid angle.

area would be $24 \times 0.30 = 7.2 \text{ Btu}/(\text{h}^\circ\text{F})$ and through the 20 feet of perimeter would be $20 \times 0.2 = 4 \text{ Btu}/(\text{h}^\circ\text{F})$. Thus, the total heat flow rises from 7.2 to 11.2, an increase of over 50%. Another perspective is that the additional heat flow caused by this window installation is equal to the heat loss through 60 square feet of R-15 opaque wall.

The limitations of the wood and steel angles have led to the development of alternative products. Polymer-based angles offer promise, as they are moisture-resistant and have inherently low thermal conductivity. However, polyvinyl chloride, used in many window frames, is not stiff or strong enough without large hollow sections, which complicate detailing, attachment, and installation. Pultruded fiberglass-reinforced plastics (FRPs) are also used in window frames and have much higher strength and stiffness. These offer promise, but have challenges associated with attachment: typical self-drilling screws and bolt holes have limited pullout strength due to cracking, fatigue, and temperature effects.

A pultruded FRP angle (sometimes used in a hybrid with metal) has recently been developed with sufficient strength and stiffness specifically for window installation (**Figure 7**). The thermal performance of this relatively slender and low-conductivity angle is very good. Thermal calculations using the same window and wall as before show almost seven times less thermal bridging than the steel angle design (**Figure 8**). Special aluminum inserts can be slid along the extrusion to significantly increase the load-carrying capacity at the sill for large and heavy units. These inserts increase the heat loss as point thermal bridges but are not usually required for common residential windows sizes and always cause less impact than a continuous steel angle.

The use of moisture-tolerant polymers allows the angle to be easily integrated with the air- and water-control strategy. In many scenarios, the easiest approach is to apply the air and water barriers as shown in **Figure 3**, and then apply the angles outboard of the membranes, followed by installation of the window and trim (left side of **Figure 9**) or

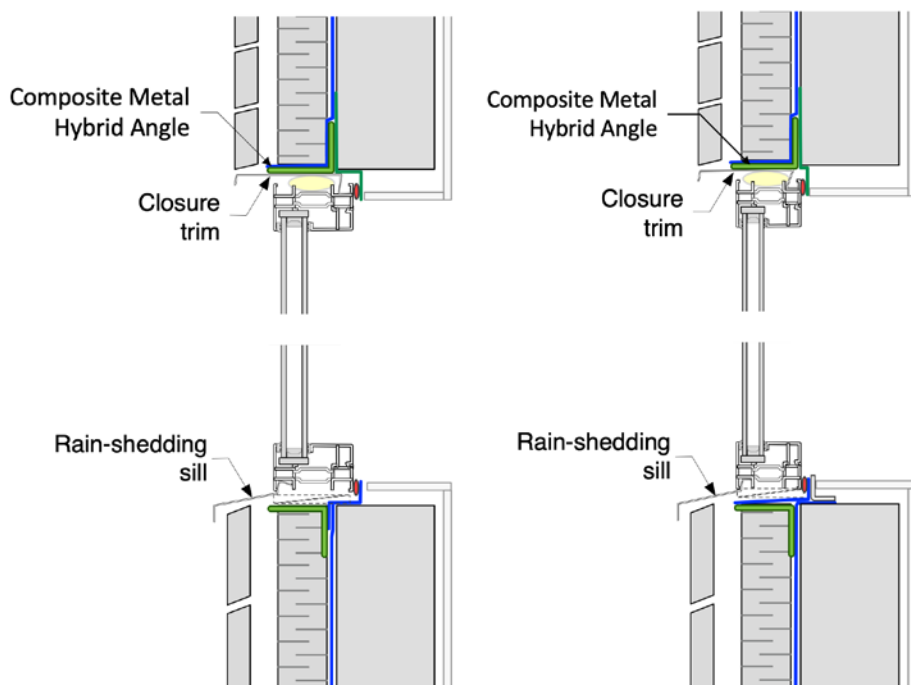


FIGURE 9. Integrating an air-water membrane with non-conductive structural angle.

membrane geometry, especially at the critical sill-to-jamb connection.

Alternative designs have used steel angles to support windows in alignment with the exterior insulation layer (**Figure 5**). These angles are dimensionally stable and strong, and, depending on their treatment and exposure, may not need to be protected with wrapped membranes. However, the thermal performance of these angles is very poor.

Figure 6 shows the results of a thermal analysis of a high-performance vinyl window in an externally insulated steel stud wall system. The thermal bridging due to the installation is predicted to be $0.20 \text{ Btu} / (\text{h}^\circ\text{F})$. The significance of this scale of impact can be appreciated by applying this calculation to a typical 4-foot-wide by 6-foot-tall high-performance commercial window with a U-value of $0.30 \text{ Btu}/(\text{h}\cdot\text{ft}^2\cdot^\circ\text{F})$. The heat flow through the 24-square-foot window

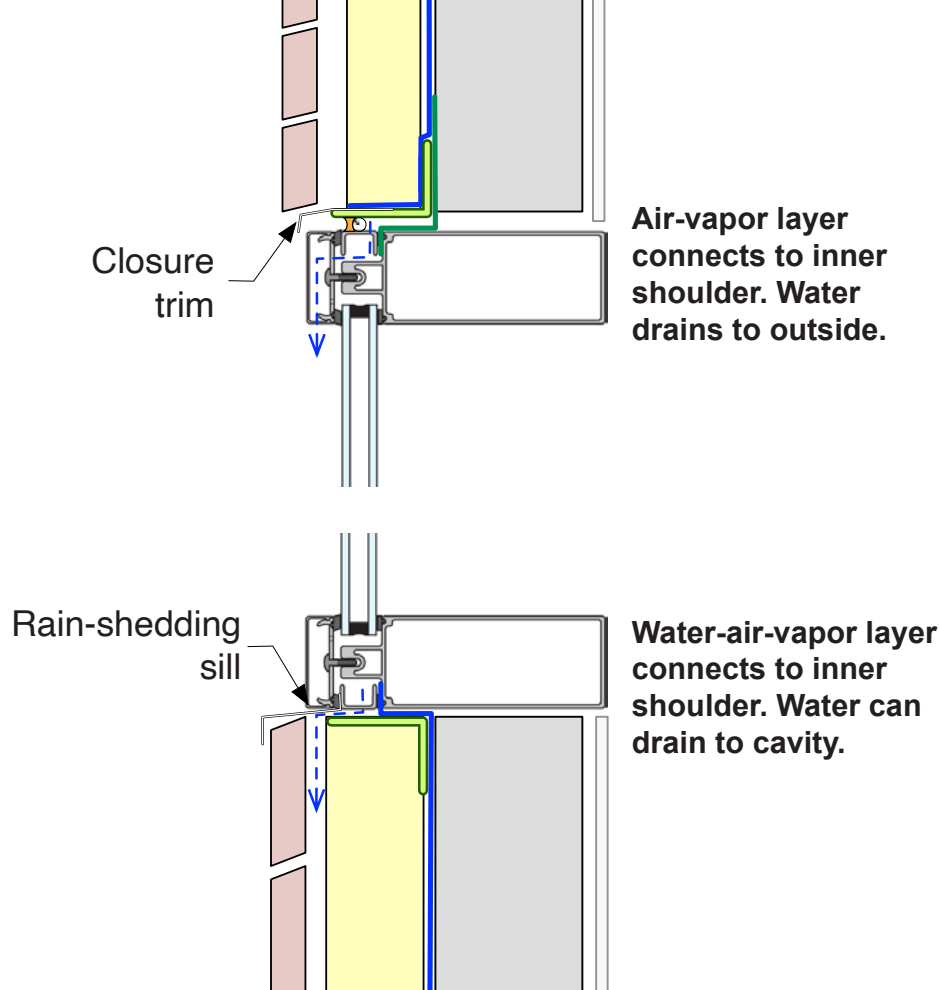


FIGURE 10. Generic curtainwall air-water-thermal integration with non-conductive structural angle.

integrated with a curtainwall **Fig. 10**. Alternatively, membranes can be added on top of the angle, provided the connection to the wall air-water barrier

is ensured.

Although most of the previous discussion has considered commercial

storefront-type windows, the recommended installation design can be applied to curtainwall-type framing as well. In the case of curtainwalls, the air-water barrier is connected to the inner glazing shoulder at the sill, and the water barrier is split to the exterior at the heads and jambs.

CONCLUSION

The installation of windows is a very important enclosure design detail that has become more challenging in light of changing thermal performance expectations and codes. Even without the need for more exterior continuous insulation, rain penetration at windows is a serious practical concern that must be addressed.

This paper has presented a series of recommendations for the generic design of window installations that meet the requirements of effective air and water penetration control. The impact of thermal flanking has been shown with the aid of representative calculations.

Finally, it was shown that the use of fiber-reinforced polymer angles can be a simple, powerful means of solving the combined challenge of air, water, and thermal control at punched window installations in modern wall assemblies with high levels of exterior continuous insulation.

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Achieving Building Envelope Durability Using CSA S478

ABSTRACT

The premature expense of rehabilitating buildings has been an issue for decades. In 1994, CSA produced a guideline document to improve building durability. In 2019, that guideline was upgraded to a consensus standard that is ready to be adopted by the model National Building Code of Canada (NBCC). CSA S478 provides a process for developing durability in the envelope of buildings designed under Parts 3, 4, and 5 of the NBCC and regulations using the NBCC. It responds to the requirements of NBCC 5.1.5.2 to provide durable design by setting out a standard way to demonstrate through the design process how to make the relevant elements in the building envelope achieve a target durability level. The standard is supported by all sectors of the design industry, including design professionals, insurers, and contractors, each of whom seeks an accepted process for achieving a target durability level.

Canadian Standards Association standard S478-19 is a comprehensive building enclosure design development and construction reference that assists designers, contractors, and users throughout the life of a building. This paper summarizes what the standard provides both in terms of directed obligations as well as detailed reference material to assist users of the standard.

LEARNING OBJECTIVES

- » Recognize that following the principles put forth in CSA S478 will reduce the risk associated with inadequate building envelope performance.
- » Explain how to employ CSA S478 in design and construction to achieve a durable building envelope.
- » Take the first steps in creating a durability plan for the life of the building to maintain the initial design objectives.
- » Discuss with the project team the benefits of employing a recognized standard for achieving the design and service life of building elements to manage risk, improve performance, and control unwarranted changes during construction.

SPEAKER



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BACKGROUND

The standards division of the Canadian Standards Association (CSA) develops consensus standards and guideline documents for, among other industries, the design and construction of buildings. Authorized by the Standards Council of Canada, CSA creates technical committees formed of industry experts representing various viewpoints affecting the standards or guidelines. These important documents are vetted by public comment and updated regularly to remain current and relevant. Many have been referenced in the National model and Provincial regulatory building codes and thus, as the latter, are the legal minimum requirement.

The origin of CSA S478, *Durability in Buildings*, was a guideline document prepared by a committee of experts and published almost 30 years ago as a first attempt at a document to address durability and premature deterioration issues throughout the life of a building. It grew from an industry demand to bring forth a set of recommendations to assist designers in creating durable buildings. CSA S478 was referenced in Part 5 of the Ontario Building Code (5.1.4.2(3) Resistance to Deterioration as a potential reference to designers. As a guideline document, it was not encumbered by the formalities of “standards language.” Rather, it provided good advice on best practices together with a comprehensive series of appended annexes giving summaries of the then-current research and procedural information directed at durable buildings.

Over the ensuing decades, resistance to build deterioration, in particular, the

building elements of the enclosure, deterioration remained an ongoing concern. Both social and financial costs for what was considered by most experts in the building science community to be premature building repair, costs to litigate recovery of damages arising from misdirected intentions, poor product selection, inappropriate design, and the growing concern about wasted embodied carbon in building products thrown away too soon, helped spark the desire to revisit the 1995 version of CSA S478. So, in 2017, I co-authored a white paper for CSA¹ on the transformation of the guideline into a standard and eventually became the first chair of that extensive rewrite. A rewrite was considered necessary because the guideline needed both updating and conversion to standards language such that it could be referenced by regulatory codes and design specifications. CSA S478 was first republished in 2019 and that remains the currently available version. It has not yet been adopted by the National model or provincial building codes but has been on the radar of many design professionals dealing with the challenges of durability and liabilities associated with premature deterioration.

PRIMARY ELEMENTS OF THE STANDARD

The standard deals with Part 5 buildings, that is, buildings that are greater than three stories or greater than 660 m² in building (footprint) area and not a hazardous occupancy. While the standard could be applied to Part 9 small buildings or houses, that has not been its intent. The standard places the primary focus on the building

envelope, members, connections, and components. It applies to both new and retrofit design practices.

As a key design consideration, the standard defines and distinguishes between the design and service life of the building and the components. It also suggests design life and proportionate service life periods but makes those decisions a subject of agreement between the designer and the owner. This distinction between suggested design and service lives provides the fundamental starting point for the selection of materials, geometric considerations, and processes used in the assembly of the building enclosure components. It also allows flexibility in selecting design life and thus component service life which dovetails into a risk management process for designers. More about that later in this paper.

While not a construction standard, CSA S478 provides construction process steps that will assist all parties to a building development or repair. Additionally, the standard gives owner operational steps to ensure the longer-term performance of building enclosure components and systems. Supplementing the design for durability for the building enclosure, these construction and operations initiatives form a full durability plan for the building throughout its design life.

The standard itself is quite short, being only 18 pages of standard requirements content; however, attached to the standard are 77 pages of non-mandatory (informative) Annexes. For example, Annex H gives a deep dive bibliography into available consensus standards and authoritative industry

guidelines. That compendium is given as a reference for use by designers to know they are using the best available information on building enclosure design and materials.

Additional Annex references provide information:

Annex A: How to Use the Standard together with a sample form for recording design and maintenance options forming part of a durability plan.

Annex B: Life Cycle Costs of Buildings, which refers to ISO 15686-5 2017 Buildings and constructed assets – Service life planning – Part 5: Life-cycle costing.

Annex C: Assessment of Environmental Conditions, discussing macro and micro environments, agents causing environmental actions (air, moisture, contaminants, soil, biological agents, temperature, solar radiation, and chemical incompatibility) as well as a discussion of the parameters affecting the structure environment such as driving rain index, the acidity of precipitation, time of wetness, exposure, freeze-thaw and severity classification for various materials of the assessed environmental conditions.

Annex D: Degradation Mechanisms and Mitigation Strategies for Building Materials, which incorporates a comprehensive table describing the mechanism and effect of failure, the necessary conditions for occurrence, mitigation methodologies, and selected reference material for various materials.

Annex E: Climate Change Effects on Durability of Building Materials and Building Elements, which gives an overview of the impact that climate change has as stated in research on climate change and describes the anticipated influence of degradation mechanisms for various materials and in various areas of Canada.

Annex F: The Building Envelope, which is an overview of good design practices for the various building enclosure components, walls above and below ground, roofs, windows and doors, soffits and cantilevered floors, and joints between these elements.

Annex G: Designer Considerations for Design Alternatives and the Quality Management Program, which describes risk areas and construction issues affecting quality management along with how designers can integrate quality management steps into the construction process.

CONTENTS OF THE STANDARD

The body of the standard lays out a simple yet effective process to arrive at a building enclosure design that results in a durable but cost-effective. Sections, in the standard are:

- 1 Scope:** to describe the purpose and what building elements are included and not included.
- 2 Reference publications and bibliography:** to list the numerous CSA, ASTM, EN, and ISO Standards specifically cited in the standard.
- 3 Definitions:** to identify the meaning of terms used in the standard.

These first three are standard clauses in all CSA standards tailored to suit the subject of the standard. The bespoke clauses set out for the standard follow. They are:

- 4 Fundamental durability requirements:** This section sets out the mandatory obligations for compliance with the standard in the following subsections:
 - 4.1 Durability and design service life:** This requires that buildings and their elements be conceptualized, designed, constructed, maintained, and operated in such a way that they will maintain the required resistance to the structure environment defined at the time of the design. This allows designers to incorporate design resilience in a manner to address their interpretation of the future environmental and physical loads under which the building must perform for the chosen design service life agreed to with the owner.
 - 4.2 Basic service life requirement:** The predicted service life shall meet its design service life. That is, no building is to be designed to fail before its intended useful life.
 - 4.3 Satisfying service life requirements – Agents and degradation:** The basic service life requirements are to be satisfied by taking into consideration all reasonably foreseeable agents and mechanisms of degradation and durability. A list of applicable clauses and Annex references are given. This direction requires that the designer knowledgeably consider the loads that are reasonably expected to affect the longevity of the elements proposed to form the building enclosure.
 - 4.4 Design compliance:** Options are given for determining the basic service life of the building. These are:
 - a. By designing protective mitigation to defend against loads and the consequences of those loads;
 - b. By specifying building elements that, without maintenance, will not degrade to failure during the design service life;
 - c. By specifying building elements that with scheduled and condition-dependent maintenance will not degrade to failure during the design service life; or
 - d. By providing a design such that degradation will not fail in the design service life.
 - 4.5 Fabrication and construction:** This leads the designer to Clause 9 which talks about the role of contractors, fabricators, and suppliers in the execution of the designer's overall quality management plan.
 - 4.6 Maintenance, repair, and renovation:** This tells designers that they shall provide a plan for execution by others to employ later in the life of the building to maintain the original durability plan developed by the architect.
- 5 Quality management during design, construction, maintenance, and operation:** This clause mandates that the designer is to determine and specify the quality management requirements to achieve durability for design, construction, operation and maintenance, and renovation and repair. It mandates that action items and documentation are necessary.

6 Design service life of buildings and building elements: These clauses describe design service life for the building and for building elements.

6.1 Buildings: At this time, the design service life for the building is set out in a table which suggests the appropriate life for different building categories with life spans ranging from 25 to more than 100 years. A copy of the table follows:

The range of life spans allows owners and designers to make rational choices concerning the durability of the building and focuses on the intended use as a metric. For example, the minimum life span for a small office building may reasonably be 25 years whereas the minimum lifespan for a residential building may be 50 years. Longer life spans may be chosen.

6.2 Building Elements: Clearly, some of the component parts referred to in this standard as building elements will have shorter service lives than the building. The standard addresses the life of building elements and the replacement or repair as factors to consider in the design and use of those elements. Factors to be considered include:

- The environmental and physical loads,
- The intended quality management procedures in the durability plan,
- The difficulty and expense of maintenance,
- The consequences of failure considering costs, disruption, and hazard to users,
- The availability of replacement components.

The life of the building elements is set out in terms of the replacement as a percentage of the life of the building. **Table 2**, below sets out various categories of failure in terms of the consequences ranging from minor to a risk to health and safety of users, injury, loss of life, loss of the asset, or a prohibitive repair cost. If an element falls into more than one category, the higher or highest category should be used. Where not possible to comply with the table, a life cycle analysis is to be conducted for the durability plan.

6.3 Specification of design service life: While a range of design life is given in **Table 1**, the designer is expected to establish the minimum design service life for the building under design. The designer does that through

Table 1
Categories of design service life for buildings
(See Clauses 6.1.2, 11.2, A.1, and A.2.2.)

Design service life category	Building type	Minimum design service life for building, years	Range of design service life, years
Short life	☐ Bunkhouses, sales offices ☐ Minor storage buildings	—	Up to 10
Medium life	☐ Low-hazard industrial ☐ Temporary buildings	10	10 to 25
	☐ Mercantile ☐ Medium-hazard industrial ☐ Business and personal services occupancies ☐ School portables	25	25 to 50
	☐ Low-rise commercial and office buildings ☐ Stand-alone parking structures* ☐ High-hazard industrial	25	25 to 99
Long life	☐ Single-unit residential ☐ Multi-unit residential ☐ Mid- and high-rise commercial and office buildings ☐ Post-disaster buildings (e.g., hospitals, power generating stations, public water treatment facilities, and emergency response facilities) ☐ Performing arts buildings, arenas, schools and colleges, and other assembly occupancies ☐ Detention, care, and treatment occupancy	50	50 to 99
Permanent	☐ Monumental and heritage buildings	100	100 to 300

* Parking structures shall have a design service life at least equal to the building they serve, except that parking structures serving long-life category buildings may be designed for medium life, provided that
a) they are not integral to the long-life superstructure; and
b) degradation of the parking structure will not adversely affect the building served.
See CSA S413.

consideration of the environmental and physical loads, proposed maintenance, and exposure conditions.

7 Predicted service life of building elements: The designer is to employ one or a combination of the following approaches, as applicable.

- Demonstrated effectiveness based on documented records of successful performance in the same or more severe environment and on information on degradation in literature, (Annexes D and H).
- Modelling applied where
 - a similar building element has been used in a similar or more severe environment has been successfully used,
 - a proven building element has been successfully used in a moderately different environment, or
 - an innovative building element is proposed to be used in a significantly different environment combined with laboratory or field testing for durability.

8 Design considerations: Innovative designs, systems, and materials are possible if they comply with applicable regulations. Materials are to be compatible physically and chemically considering environmental and physical loads.

TABLE 2. Categories of Failure (part 1 of 2)

Cate-gory of Failure	Conse-quences of failure	Description	Examples	Minimum Design Service Life of Building Element
1	Minor	Building element repair can be readily accommodated within routine maintenance	☐ Worn weatherstripping	Owner defined
2	Reduction in Serviceability State	Reduction in building element serviceability state without risk of failure of the building element, an adjacent building element, or the system in which it is included.	☐ Mortar joint degradation ☐ Sealant crazing ☐ Aesthetic degradation	
3	Reduction in Resistance Capacity Or Moderate Repair Cost	Reduction in the building element resistance capacity or performance without posing an unacceptable risk of failure of the building element, an adjacent building element, or of the system in which it is included. Or Repair to the building or building element could be moderately difficult in execution or accessibility (e.g. accessible from balconies, roofs, non-engineered scaffolding).	☐ Isolated roof leak in a conventional roof ☐ Leaking roof termination flashings ☐ Accessible thin membrane waterproofing on suspended slab ☐ Paint or coatings on serviceable elements (e.g., visible cladding surfaces)	20% of building design service life
4	Loss of Resistance Capacity Or High Repair Cost	Loss of building element resistance capacity or function. Or Repair to the building or building element could be costly because of difficulty in execution or accessibility issues (e.g. specialized equipment, engineered scaffolding, swing-stage use), or repair could require extensive use of materials or component replacements	☐ Roof replacement; ☐ Isolated roof leak in a protected roof membrane system that is difficult to access ☐ Concealed cladding attachments or guard elements that are easily accessible for inspection and repair ☐ Inner seal of a two-stage joint ☐ Insulating Glass Unit failure; ☐ Protective coatings on unserviceable elements (le.g., long-span roof over a pool)	Pod-based heat pumps

Detailing is to be clear, concise, and complete using drawings and specifications.

Buildability is required to achieve the necessary level of performance and reliability. For example, early input from contractors, fabricators, and suppliers, considering the sequence of construction, seeking input from building maintenance staff, and construction of mock-ups can provide important input.

Access for inspection throughout the service life and identification of building elements that require

special care should be part of the durability plan.

9 **Construction considerations:** The designer’s role during construction includes review of the contractor’s proposed changes to maintain compliance with the durability plan and confirmation that the quality assurance plan is maintained.

The contractors, fabricators, and suppliers also have a role. They are to review the design for execution of the durability plan and communicate concerns to the designer. They are to develop their quality control

procedures as set out in the durability plan, submit a quality assurance plan to the designer, and assign appropriate resources to implement that plan.

10 **Operation, maintenance, and inspection:** The operation and maintenance of the building shall not conflict with the durability plan. While it is acknowledged that designers do not control this portion of the life of a building, the premise of consistency in the purpose of the durability plan is important to the designer’s chosen service life.

TABLE 2. Categories of Failure (part 2 of 2)

Cate-gory of Failure	Conse-quences of failure	Description	Examples	Minimum Design Service Life of Building Element
5	Risk to health and safety of building users	Unacceptable risk for building users or the public (e.g., personal injury, biological growth potentially affecting human health, release of toxic chemical substances)	☐ Cladding falling hazards ☐ Examples shown for categories 6 and 7 that also pose a risk to health	100% of building design service life
6	Injury, loss of life, or loss of asset	Unacceptable risk of injury, loss of human life, or loss of building; building elements are hidden or not readily inspected	☐ Cladding primary support members and infill structural wall systems ☐ Cladding connectors and secondary support framing members ☐ Guard elements that are difficult to access for inspection and repair	100% of building design service life
7	Prohibitive repair cost	Extensive reconstruction require	☐ Waterproofing system below overburden ☐ Through-wall flashings and inaccessible drainage ☐ Elements of the building or building enclosure that are difficult or costly to access for inspection and repair on mid- and high-rise buildings ☐ Concealed sheathing, air barriers, and insulation ☐ Foundation wall waterproofing and dampproofing ☐ Corrosion of unserviceable elements	100% of building design service life

11 Repair work: Designers for repair work also have obligations under the durability plan. All repairs are to be based on an accurate diagnosis of the cause of degradation and the scope of repairs considering the extent of degradation on failure, impact on immediate and long-term use of the building, design service life of the repairs, and disruption of the use of the building during repairs. Work is to be done considering the scheduled design service life in the original durability plan with a revised durability plan created following Tables 1 and 2, where relevant.

12 Renovation: Buildings that are repurposed and renovated will require a revised durability plan which is to consider the revised use, environment changes and the impact of new work on other building elements.

SUMMARY OF THE PURPOSE OF CSA S478

In addition to the steps a designer can take to understand and develop designs that achieve a level of durability that aligns with the building’s intended function, the basic intent of the standard is to provide a coherent framework for designers to develop a durability plan that can be applied from the early design stages through the life of the building. Once the design for durability is complete, the durability plan a designer is to create includes:

- a) a maintenance plan
- b) a quality assurance plan
- c) an operation and maintenance manual,
- d) reference documentation supporting the chosen service life,

- e) a framework for compliance with the plan during renovation or repair, and
- f) quality control framework for construction in support of the overall plan.

CLIMATE CHANGE AND DESIGN LOADS

A key input to the design for durability is the prediction of design loads, both physical and environmental. The current design practice is to employ design tables included in supplements to the NBCC or applicable regulations. The physical loads on structural elements are those applied through use and are controlled through that use. The environmental loads are subject to the effects of climate change and are not established in model codes or applicable regulations. The impact of climate on building loads is discussed

in Annex E. That reference would assist designers in selecting appropriate environmental loads but with the proviso that there is no guarantee that those loads will be accurate.

Designers must consider that as the building ages, the resistance to environmental loads will probably decrease. Hence the need for routine inspections and maintenance as part of the durability plan. In addition, designers must consider that the conditions that impart environmental loads on the building and elements, will not remain static. Future changes to environmental loads are not currently incorporated into building enclosure design. For buildings with a design life of 25 years or less, that may not be critical. However, if the building is intended to have permanence with a design life of 100 or more years, a greater margin of resistance to degradation and applied environmental loads would be relevant. For example, substantial resistance to wind-driven rain loads in some geographic areas could direct the designer to increase the capacity to shed and drain water from walls and windows. Perhaps the design could choose the alternative approach which would be to increase the adaptive capacity of the building elements such that new components could be interchanged with greater ease than would normally be the case.

Adaptation, (or the ability to withstand future loads) and/or adaptive capacity to climate change, meaning the ability to swap in more or perhaps less resistance as may be appropriate, building elements would become among the considerations that a designer would put into the durability plan.

RISK AND LIABILITY CONSIDERATIONS

Failure of the building enclosure, be that through the roof, cladding, windows, doors, below-ground protection systems, or joints between has been a cause of major civil lawsuits for decades. That is a serious concern for both designers and their insurers. While most civil disputes have a conclusion in settlement of the matter through the various mediation and adjudication

processes that have taken deep root in the past 30 years, the most appropriate way to manage the risk of failure is to prevent the occurrence of failure in the most rational method available. Until the development of CSA S478 as a standard for fixing the intended durability in time and process controls, the debate about how long specific building elements should last, who was responsible for failure, and what the connections should be between owners, designers, contractors and suppliers, and users was left largely to forensic review of cause and effect.

Liability in terms of compensating for damage has been the result of costly dispute resolution processes that have little to do with the costs for design and construction and much to do with paying for investigation, repair which may conflict with the original design thinking, and jealous advocacy on positions. CSA S478 attempts to redirect the efforts to the design and construction stage. That reduces the uncertain risk and liability associated with alleged premature failure by providing documented support for the intended life and repair timing.

BUILDING CODES AND REGULATIONS

Building codes and regulations state what must be achieved. Those begin with the presumption that persons involved with design and construction will follow applicable statutes, design guides and standards. An omnibus standard for building enclosure durability asserting the obligations of various parties complete with a roadmap of how to achieve the foundational purpose of building codes and regulations has been missing from the landscape. This standard does not assert contractual obligations. That is not the form or purpose of CSA Standards. Rather it establishes various roles with duties that support an overall durability plan.

Building codes have historically not dealt with the cradle-to-grave life of buildings. They are largely about creation rather than use. While CSA S478 provides roles and duties to deal with maintenance and repair, fundamentally,

the standard is not in conflict with the objective of codes and regulations affecting design nor is it in conflict with the prevalent social imperative to become a more sustainable society. With the current emphasis on building sustainability and reduction in dismissal of embodied carbon, compliance with CSA S478 provides opportunities to reduce the creation of greenhouse gases by minimizing unintended and premature repair and replacement of building elements that should have lasted longer.

As of the writing of this paper, CSA S478 is not referenced in the National Building Code of Canada. Further, it has not been incorporated into provincial regulations and therefore is not the minimum legal requirement. Nonetheless, there is no debate that voluntarily following this standard will give all parties that have an interest in the durability of the building enclosure a more-structured, best-practice document on which to base decisions and arguments about durability.

REFERENCE

- 1 Genge, G.R. and Kerr, D.D., "CSA S478, Durability in Buildings, Transition into a Standard and Importation of Climate Change Issues, (*published for CSA S478 members only – distribution prohibited*), July 11, 2017.

Examining Methods for Preserving and Improving the Energy Performance of a Historic, Aluminum-Framed Curtainwall System

ABSTRACT

When compared with the modern curtainwall systems, historic, aluminum-framed curtainwall systems perform poorly with respect to energy transfer. These older systems are ideal candidates for replacement with more thermally efficient systems during building retrofits. However, there are situations where replacement of the curtainwall system is not feasible. When a facade is designated as historically significant by local preservation authorities, the appearance of the curtainwall system must be maintained. This requirement may be difficult to meet with modern replacement systems, and customization may be cost prohibitive.

This paper explores the energy savings of a method to thermally retrofit in situ a historic curtainwall framing system while maintaining the original appearance of the system. The change in thermal performance is modeled to estimate improvements that can be achieved when existing framing is retrofitted, and the estimated retrofit improvements are compared with the improvements that would be achieved by replacing the existing framing. Finally, an energy cost-benefit analysis is presented to account for embodied energy that would be associated with the new framing system used in the replacement option.

In the subject case, retrofitting of glazing attachment systems with modern materials while retaining the existing aluminum framing reduced the conductance of the system, but the improvement was limited given the geometry of the original aluminum framing. Thus, it was determined that the replacement option would offer greater benefit in this scenario.

LEARNING OBJECTIVES

- » Explain why historic curtainwall systems perform poorly compared to modern systems with respect to heat transfer.
- » Discuss the life-cycle analysis of glazing components and associated embodied energy.
- » Identify factors that impact a cost benefit analysis between retrofitting and replacing existing glazing systems.
- » Recognize how specific boundary conditions around existing glazing impact the practicality of replacement.

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When compared with modern counterparts, historic, aluminum-framed curtainwall systems perform poorly with respect to energy transfer. These older systems are ideal candidates for replacement with more thermally efficient systems during building retrofits.

However, there are situations where replacement of the curtainwall system is not feasible. When a facade is designated as historically significant by local preservation authorities, the appearance of the curtainwall system must be maintained. It is difficult to preserve the appearances of many historic curtainwall systems with typical replacement systems, and customization may be cost prohibitive. Boundary conditions can render replacement of the curtainwall system impractical if major interventions into the facade are required to remove and replace framing and associated anchorage.

This paper explores a method that was developed to thermally retrofit in situ a historic curtainwall framing system while maintaining the system's original appearance. The change in thermal performance is modeled to estimate improvements that can be achieved through retrofitting the existing framing and is compared to the improvement of new curtainwall framing. Finally, an energy cost-benefit analysis of retrofitting versus replacement is presented that accounts for embodied energy associated with the new framing system that would be used in a replacement project.

BACKGROUND

Water management has been an issue for curtainwall systems since they started to become common in the late 19th and early 20th centuries. Rehabilitation of these systems is not a new concept. Generally, owners have relied on sealants between framing and glazed components to prevent water penetration. Therefore, curtainwall systems require periodic maintenance over their service lives. Rehabilitation programs often involve replacement of glazing seals, frame joinery seals, and glazing units that have reached the end of their service lives. If the owner wishes to improve the thermal performance of the entire curtainwall system, glazing units are typically replaced with more-efficient insulating glazing units (IGUs).

In the late-20th century, curtainwall systems became fairly standardized. Before that time, curtainwall systems tended to be customized with unique framing and glazing systems. Those older curtainwall assemblies were built as an alternative to mass walls in buildings of various heights, and most of the custom systems used aluminum as the main frame material. Aluminum was desirable due to its high strength-to-weight ratio.¹ However, relative to almost all other building materials, aluminum has a very high energy conductance. Therefore, because frame materials have less thermal resistance than most glazing, aluminum-framed systems usually experience significant thermal bridging at their frames.² Thermal bridging can be reduced by incorporating relatively less-conductive materials, which are

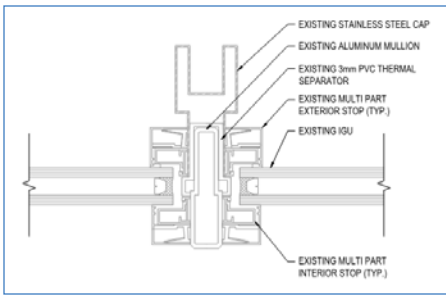


FIGURE 1. Plan Section View of a Typical Existing Mullion.

referred to as “thermal breaks,” in the frames. However, effective thermal breaks are often absent in early curtainwall systems.

When considering a project to update a facade that contains an older curtainwall system, it is desirable to improve the energy performance of the glazing system. Conceptually, designers have two options to improve the thermal performance of glazed portions of a facade. The existing curtainwall system can be replaced completely with a more energy-efficient system, or the existing system can be retrofitted such that it better resists energy transfer. In many cases, designers and owners only consider the incremental difference in conductance of the glazing system when comparatively evaluating these two options. However, for a more accurate comparison, the embodied energy of the replacement system and waste generated by removing the existing system should also be considered.

CASE STUDY

During a retrofit design for a commercial building located in the greater Toronto area, existing curtainwall located at the podium of a multiple building complex was considered. The curtainwall was designated as historically significant, and as such, the appearance of the curtainwall after the building retrofit must maintain proportions of the original system.

The curtainwall system, built circa 1960s, was assumed to be a poor energy performer given its age and configuration. The framing system was made of hollow aluminum mullions,

and glazing was captured by an intricate system of stainless steel and aluminum components forming multipart glazing stops on the interior and exterior. Stainless steel caps in a custom design contributed to the historic appearance of the building. The existing curtainwall system contained a polyvinyl chloride (PVC) thermal break wrapping the exterior portion of the mullion. Due to its orientation, the PVC thermal break did not mitigate energy transfer to modern standards, as heat energy could transfer around the thermal break through conductive materials.

Options to Improve Thermal Performance of the Frames

Two options were considered to improve the thermal performance of the curtainwall. The first option involved retrofitting the existing core framing system to improve its thermal performance. The second option was to replace the entire curtainwall system with a more thermally efficient modern system. An upgraded IGU was assumed as part of the retrofit in both options. Therefore, the thermal resistance of glazing was considered to be the same for both options, meaning that frame improvement options could be considered in isolation when comparing the choices.

Option 1: Retrofit the Existing System

Retrofitting an existing framing system of a custom curtainwall from the 1960s while maintaining the appearance of the original system can be challenging due to geometrical constraints. It was known that the original PVC thermal separator performed poorly since heat energy was able to bypass this component through metal glazing stop components. Replacing the glazing stops with a less-conductive material was of the utmost importance. The challenge was to do so while maintaining the original geometry of the mullion and using a material that could adequately transfer wind load.

Under the geometric constraints of the base situation, polyamide was chosen to replace the glazing stop as it is a relatively less conductive material but is still rigid enough to support glazing. The aerogel insulation was chosen for its low conductivity and to fit into the

tight space between the polyamide and the aluminum. Polyamide legs were required to transfer loads to the aluminum mullion/rail.

Another advantage of polyamide is that it is moisture tolerant. From a water management perspective, it was desirable to create a drained cap system because drained systems are known to perform better than face-sealed systems over the long term. In this option, intermittent weep tubes from the glazing pocket to the underside of the mullion would be required due to the geometry of the existing aluminum frame and the presence of the polyamide glazing stop.

Option 2: Replace the Existing System

The second option would involve replacing the existing system with a new, more thermally efficient curtainwall system. The existing aluminum frame contained a polyamide thermal break at the nose of the mullion. To recreate the existing look of the building, custom snap caps would be used, which would necessitate a captured system.

Discussion of Frame Improvement Options

From a heritage preservation perspective, retrofitting an existing framing system while maintaining the original appearance of the facade is the most desirable option. Preserving the facade is the most obvious benefit of retrofitting over replacing. Other benefits include extending the service life of the original system, which extends the use of the embodied energy from the production and installation of the original system.

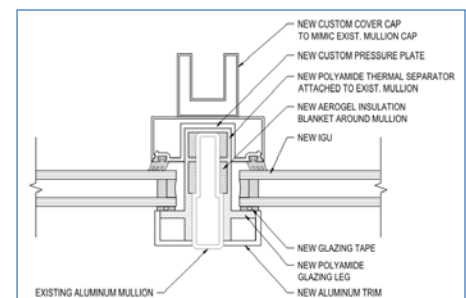


FIGURE 2. Plan Section View of a Retrofitted Mullion.

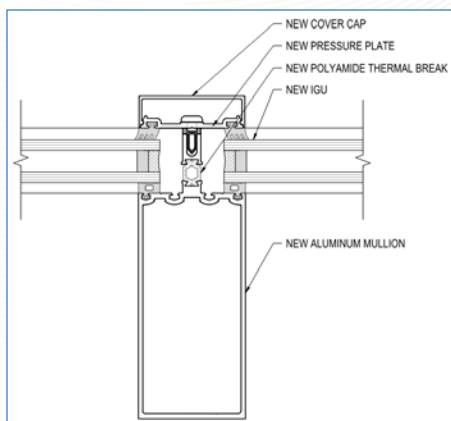


FIGURE 3. Plan Section View of a Replacement Framing System Mullion.

The benefits of retrofitting an existing curtainwall system generally align with the disadvantages of replacing the existing system. Because most historic curtainwall systems were customized, matching the appearance with an off-the-shelf system is impractical. The use of custom snap caps is one option a designer must mimic the appearance of an existing system. Whether such an approach will be accepted by preservation authorities is situationally dependent.

The relative thermal benefits of retrofitting and replacement are variable. Whereas the thermal performance of a readily available replacement system is well established, the thermal improvements of the retrofit option will depend on the original conditions and the retrofit design.

Thermal Modeling

To understand possible improvements of thermal performance of the two options as compared with the existing curtainwall system at the subject building, thermal model simulations of the existing base case, the retrofit option, and the replacement option were conducted. Four cases were modeled. The base case models the existing frame and glazing configuration. Case 2 models the existing framing system with a more thermally efficient IGU. Case 3 models the retrofitted existing frame system, and Case 4 models a replacement system. Given the age of the existing glazing system, replacement of existing IGUs is assumed.

Method

A two-dimensional thermal analysis of the different options was performed using WINDOW 7.7.10 and THERM 7.7.10 two-dimensional conduction heat-transfer analysis software programs created by the Lawrence Berkeley National Laboratory of the University of California. A typical curtainwall section (curtainwall intermediate rails and vertical mullion details) was modeled in THERM for each option. The thermal performance for each option was calculated using a weighted area method, in accordance with the National Fenestration Rating Council's *Procedure for Determining Fenestration Product U-values* (ANSI/NFRC 100-2017).³ Areas and U-values

were calculated for the frames, edge of glazing, and center of glazing to determine an effective U-value for each case.

Assumptions

The modeling assumed interior and exterior temperatures of 21°C and -18°C in accordance with simulation conditions in ANSI/NFRC 100. A single, fixed vision unit within the curtainwall, measuring 1200 mm wide and 1500 mm high, was modeled for each option. Where possible, typical material properties were used from THERM's standard database of material thermal conductivities. **Table 1** summarizes the thermal conductivities of the materials used. Refer to **Table 2** for IGU configurations used in the modeling.

The glazing was constant for cases 2, 3, and 4, and differences in thermal conductance of the system were assumed to be limited to the frame.

Results

Table 3 summarizes the obtained effective U-factors (R-values) for each case.

Case 4 (replacement option) yielded the lowest effective U-value of cases 2 through 4. This result can be attributed to the incorporation of a conventional thermal break, rather than a thermal separator. In case 4, the heat flow through the curtainwall frame is restricted directly by a thermal break in the frames. Additionally, this thermal break is aligned with the plane

TABLE 1. Thermal conductivities of materials used

Material	Thermal conductivity (W/mK)
Aluminum frames (oxidized, mill finish)	160
Existing aluminum stops	160
Stainless steel	17
Polyvinyl chloride thermal spacer/anti-rotation block	0.17
Gaskets and glazing tape	0.35
Retrofit polyamide thermal break	0.3
Aerogel blanket insulation	0.02

TABLE 2. Insulating glazing unit (IGU) configurations used in modeling

Base case IGU configuration	IGU configuration for cases 2–4
» 6.35-mm exterior glass lite » 12.7-mm air gap » 6.35-mm interior glass lite » Stainless steel spacer with polyisobutylene primary seal and silicone secondary seal » Center of glass U-value: 2.67 W/m²K	» 6.35-mm exterior glass lite, with low-E coating on surface no. 2 » 12.7-mm gap filled with 90% argon/10% air » 6.35-mm interior glass lite » Warm edge nonmetallic spacer » Center of glass U-value: 1.41 W/m²K

TABLE 3. Effective U-Values

	Base case	Case 2: New insulating glass units in existing frames	Case 3: Option 1 (retrofit existing system)	Case 4: Option 2 (replace existing system)
U-value W/m²K (R-value)	3.80 (R 1.5)	2.73 (R 2.08)	2.42 (R 2.35)	1.93 (R 2.94)
Centre of Glass U-value in W/m²K (R-value)	2.67 (R 2.13)	1.41 (R 4.02)	1.41 (R 4.02)	1.41 (R 4.02)
Reduction of Centre of Glass R-value	30%	49%	42%	27%

of the IGU to ensure that there are only limited heat-flow paths to bypass the thermal break or IGUs. In case 3 (retrofit option), the existing mullion extends well beyond the plane of the glass. Because the exterior cover cap generally approaches and remains the same temperature as the exterior air, the effectiveness of the thermal separator is limited by the thickness of the thermal spacer of the system, not by its length as would be the case with a thermal break.

The reduction of COG R-value results in **Table 2** also illustrate the gradual increase in thermal efficiency of the aluminum frames used in cases 2, 3, and 4. In this scenario, the reductions in COG R-value for cases 2 and 3 are similar, and significantly higher than the reduction for case 4. This finding suggests that the inefficiencies in the existing curtainwall framing have an impact on the potential effectiveness of a retrofit.

Energy Cost-Benefit Analysis

Considering modeled conductance of the curtainwall systems, we have determined that the replacement option outperforms the retrofit option. Therefore, replacing the existing

framing system with a new framing system would most substantially reduce energy flow across the wall assembly.

Major costs associated with replacing the framing system waste and energy during disposal of the original system, effort to install a replacement system (which may include significant anchorage modifications), and the embodied energy of the new system. Glazing is not considered in this analysis as it is held constant across frame options.

Embodied Energy of the Replacement Frame Option

The total embodied energy of an aluminum mullion typically used in curtainwall applications can be estimated to be approximately 200 MJ/kg.^{1,4} This estimate is from “cradle to gate”: it accounts for total energy used for raw supply and during production of the mullion, but it ignores energy used in delivery and installation. Given the sectional area of the mullion in question (ignoring the polyamide thermal break), one can calculate the embodied energy of a unit length of the mullion. **Table 4** shows the values used to estimate the embodied energy of the replacement option, which is approximately 656 MJ/m.

TABLE 4. Estimated embodied energy of a replacement frame

Density of aluminum, kg/m³	Energy density of aluminum mullion, MJ/kg	Estimated sectional area of mullion, m²	Embodied energy, MJ/m
2710	200	1.21 × 10 ⁻³	656

Energy Benefit of the Replacement Frame Option

The energy benefit of moving to the new frame option can be described by the improvement in modeled conductance, ΔU, which is defined as the difference in conductance (U-value) between the retrofit option and the replacement option:

ΔU = U_{Retrofit} - U_{Replacement} (1)

To determine the difference in heat flow across a unit area of retrofit and replacement curtainwall systems considered over time, the Toronto Canadian Weather Year for Energy Calculation (CWEC) data file⁵ was used. First, the difference in heat flow, ΔQ, between the two curtainwall systems was calculated by multiplying ΔU by the average change in temperature, ΔT (Kelvin), during a given time period:

ΔQ = ΔU × ΔT (2)

Multiplying by a given time period gives the heat flow over the time period. In the CWEC data file, average outdoor temperatures are given over an hour for one year. Summing the incremental heat energy flow for each hour period over a year gives the difference in energy flow over a year between the retrofit option and the replacement option.

Using this procedure, it was determined that the heat flow through the retrofit curtainwall system was approximately 210 MJ/m² more than the replacement system given the assumed constant internal design temperature of 20°C. As there were 3 m of frame per square meter of glazing in the models, we can assume that the difference in energy flow between the retrofit frame and the replacement frame is 70 MJ per meter of frame per year. **Table 5** shows the cumulative savings over assumed useful lifespans of the curtainwall.

Comparison of Embodied Energy of Replacement Frame to Benefit of Replacement Frame

The breakeven time frame for the incremental energy benefit in this analysis is approximately 9.4 years. That is the point where the estimated embodied energy for a unit length of replacement section is equal to the energy saved by using that section instead of the retrofit option.

TABLE 5. Energy savings based on service life

Assumed service life, years	Energy savings of replacement frames versus replacement frames, MJ	Difference between energy savings and embodied energy, MJ
10	702	46
20	1404	748
30	2106	1450
40	2807	2152
50	3509	2854

Comparing the embodied energy per meter to the energy benefit of replacement frames, we see that there is a net energy benefit to replacing the frames if the replacement framing system lasts at least 9.4 years.

Based on the difference in U-values between the retrofit and the replacement options, it is clear from the energy cost-benefit analysis that replacing the frames is a better long-term option than retrofit for the situation analyzed when considering energy use. Refer to **Fig. 4** that shows energy savings of the replacement system over 40 years compared to embodied energy of the replacement system.

Discussion

For the curtainwall system in this case study, the cost-benefit analysis takes into account the net energy benefit of retrofitting or replacing the framing system as well as the costs of embodied energy of the new framing system. It was determined that with an estimated 40- to 50-year lifespan for the new framing used in the replacement option, energy transfer savings for a replacement system outweigh the embodied energy of the replacement system.

The analysis presented here is for one frame retrofit option for one existing curtainwall. In this case, the constraints of the original system and the mandate

to keep the original proportions meant that the thermal performance that can be obtained from an off-the-shelf system could not be matched by the subject retrofit option. In other cases, it may be possible to use the energy cost-benefit analysis method to determine the target value improvement of a retrofit design and iterate with various options and models until targets are achieved.

Many older curtainwall sections are highly customized. If retrofitting options are not constrained by heritage geometry requirements, it is likely that substantially improved thermal performance of a retrofit mullion can be achieved by adding more-robust thermal management systems.

Considering the simplified analysis presented herein, the curtainwall assembly should be replaced. However, the analysis ignores some important considerations. In some situations, heritage requirements may dictate that the appearance of the facade cannot be altered. In some cases where strict heritage preservation requirements require that the appearance of the curtainwall must be maintained, the presented analysis suggests that thermal improvement on par with modern systems with efficient thermal breaks may not be possible. In that case, a retrofit method using moisture-tolerant materials with low conductivities is an option that will provide some energy savings.

CHALLENGES WITH RETROFITTING

When using the retrofit approach, it can be difficult to incorporate water penetration management techniques into the system. Thermal separators used in the assembly can impede water drainage. Additionally, moisture-tolerant materials must be used if drainage is desired. Geometry can restrict airflow and air pressures within a mullion that would help cavities drain.

Alternatively, a face-sealed approach to the retrofit can be considered. In this manner, all glass-to-metal and metal-to-metal interfaces at the exterior of the framing would need to be sealed with an ultraviolet-stable sealant. The long-term effectiveness of the approach

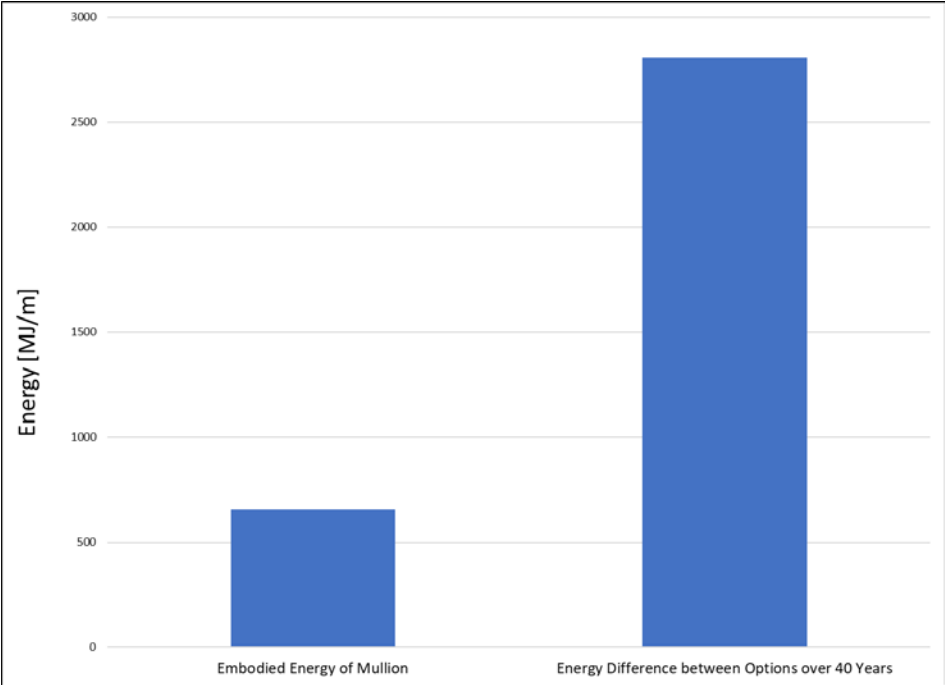


FIGURE 4. Comparison of energy between retrofit and replacement curtainwall systems.

partially depends on the scale of the project. The exposed supplementary seals become a maintenance item of the curtainwall system since the service life of the seals exposed to weather will be shorter than the service lives of the frame and glazing components. Replacement options that use readily available glazing systems with proven test data remove the uncertainties associated with a face-sealed approach.

ANALYSIS OF OTHER ASSEMBLIES

The analysis presented herein can be applied to any glazing system and is not limited to the retrofit of existing curtainwall systems. Window wall systems are candidates for frame rehabilitation, and the typical mullion profile and interior glazing method make it relatively easy to achieve water management of these systems.

LIMITATIONS

There are several limitations to the analysis. The materials chosen were from generic databases. The analysis looks at the situation purely from an energy perspective and ignores

monetary cost comparisons between the options. Assumptions were made to isolate the contribution of the frames to the difference in conductance for the various cases. While the glazing system is held constant, the interaction between glazing and relative conductance of the frames was not explored by varying the glazing configuration. Embodied energy is simplified into production of a new aluminum section and ignores waste associated with removing the existing system.

WHEN SHOULD RETROFIT BE CONSIDERED?

Given the original frame configuration, it would be difficult to achieve improved energy performance while maintaining the original appearance of the curtainwall system. A combination of factors led to this conclusion, including the original configuration of the curtainwall frame and glazing. It is likely that retrofits will be more attractive if all of the following are true:

- » Boundary conditions make replacement very costly or impractical.

- » Heritage requirements dictate the appearance of the facade cannot be altered.
- » Existing geometry is such that robust thermal breaks/separators can be added.

CONCLUSION

When considering thermal improvement options for existing glazing systems, it is important to take into account the embodied energy of a new system as well as differences in system heat energy conductance values for the various options under consideration. In the situation presented in this case study, an energy cost-benefit analysis indicated that the retrofit design was not the preferred option. Only one iteration of the design was analyzed; other retrofit designs that are more thermally efficient could be possible. Clear challenges exist when the thermal retrofit designer is faced with heritage preservation requirements with respect to historic glazing systems.

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Transforming 240 Markland Drive, Etobicoke: A Blueprint for Decarbonizing Multiunit Residential Buildings

ABSTRACT

Decarbonization within the built environment focuses on lowering greenhouse gas emissions primarily through fuel switching the building's mechanical systems from fossil fuels to electric power. The building envelope plays a significant role, as load reduction is often required to enable this change. This paper explores a 1960s building where deep retrofits to the existing building envelope were performed to optimize the building's new mechanical systems. The exterior masonry walls, windows, balcony slabs, roofs, joint sealants, and mechanical systems were in poor condition, providing the opportunity for the developer to revitalize the existing building and provide a new rental building on the adjacent land. Both buildings are/will be heated and cooled by a ground-source geothermal system. Wall overcladding, roof assembly replacement, and window and door replacement significantly increased envelope thermal performance and reduced air leakage, which decreased heating and cooling demands and reduced the number of boreholes required within the geothermal field. Peak electric demand was reduced, as post-retrofit utility bills show that energy consumption and peak electric demand dropped significantly compared to previous years. This paper will discuss sustainable design, demonstrating how future revitalization and development projects can help reduce the burden of the industry's electrification movement on local infrastructure.

LEARNING OBJECTIVES

- » Explain the concept of decarbonization in the built environment and its role as a model for community revitalization and benchmark for emulation.
- » Discuss the pre-existing building envelope systems/condition, pre-existing and retrofitted performance parameters, and the evaluations required to upgrade performance of the presented case study building.
- » Recognize the challenges involved with implementing new wall over-cladding, roof, and window/door systems within an occupied building.
- » Summarize the post-rehabilitation building performance, recognizing reductions in heating/cooling demands, energy consumption, and peak electrical demand.

SPEAKERS



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With over 17 years of experience, Blair Gamracy has worked on over 500 projects in new construction, building renewal, and enclosure

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INTRODUCTION

When the developer first laid eyes on the 1960s building (**Fig. 1**), the scene was far from inspiring. The building's exterior was marked by aged masonry walls, aging single-pane windows, and a failing roofing system. The mechanical systems within the building were outdated and inefficient. The lack of capital investment from the previous owner left the building aesthetically outdated and functionally deficient, presenting a challenging yet promising opportunity for revitalization.

Despite its declining state, the property held untapped potential. The developer saw beyond the immediate disrepair and envisioned a rejuvenated building that could set a new benchmark for low-carbon multiunit residential buildings (MURBs). Adjacent to the old structure and above the existing parking garage lay a parcel of land ripe for development. This land offered the opportunity for the developer to construct a complementary new MURB. The timing for this ambitious project was ideal, allowing the integration of modern design practices, performance improvements, and aesthetic upgrades. With the support of the surrounding community, the transformation began—a project aimed at not only revitalization and development but also reducing the burden of the industry's electrification movement on local infrastructure.

WHAT IS DECARBONIZATION?

Decarbonization refers to the process of reducing or eliminating carbon dioxide emissions produced by various human activities, particularly those associated with the combustion of fossil fuels



FIGURE 1. East elevation, preconstruction.

such as natural gas. Decarbonization is essential for mitigating climate change by curbing the release of greenhouse gases (GHGs), which contribute to global warming and related environmental impacts.

Decarbonization within the built environment focuses on lowering GHGs primarily through fuel switching buildings' mechanical systems from fossil fuels to electric power. The building envelope plays a significant role, as load reduction is often required to enable this change. Deep retrofits on existing building envelope systems are often required to improve energy efficiency and reduce overall demand and reliance on carbon-intensive fuels.

EXISTING BUILDING ENVELOPE AND MECHANICAL SYSTEMS

Exterior Walls

The exterior walls of the building were primarily clad with white-glazed brick masonry. The construction of the wall system consists of composite masonry, where the exterior wythe of the brick masonry is bonded to the interior wythe of concrete masonry units (CMUs). The exterior brick masonry and backup CMUs rest on exposed concrete slab edges and are tied to each other by header bricks (**Fig. 2**).

The wall was insulated inboard of the concrete block masonry units with 1.75 in. (45 mm) of expanded



FIGURE 2. Exploratory opening in brick masonry.

polystyrene (EPS) insulation and finished by plaster and lathe. The effective R-value of the existing wall system was estimated to be about 6.4 (RSI-1.13).¹

Conventionally reinforced concrete shear walls extend outboard of the exterior masonry walls and form the side walls of the balconies on the east and west elevations. The balcony slabs are extensions of the floor slabs and are constructed of conventionally reinforced concrete.

The brick and concrete shear walls showed signs of age-related deterioration. The exterior face of

the glazed brick had begun to spall in several locations, particularly at the upper floors of the building that have higher exposure to wind-driven rain. The suspected cause was freeze-thaw deterioration related to excessive wetting. The concrete on the shear walls had also started to spall in several locations, likely due to carbonation over years of service. Finally, the elastomeric joint sealants forming the control joints between masonry panels and around the perimeter of the window and door systems were generally cracked, crazed, and debonded from their parent substrates.



FIGURE 3. Existing in-suite windows and balcony swing doors.

Window and Door Systems

The existing in-suite windows were aluminum framed with a single-pane glass lite with exterior single-pane storm windows, installed over four single-pane operable sash sliders. The existing swing door systems consisted of full-height inward-swinging wood door slabs with exterior aluminum storm doors (**Fig. 3**). The window performance was calculated to be U-0.76 (USI-4.3) with a solar heat gain coefficient (SHGC) of 0.67.¹

There were several reports of water leakage through the existing window and door systems, as well as complaints regarding tenant comfort due to air leakage/drafts. Difficult operation of the sliding windows and swing door components were also reported, as the hardware had failed due to lack of proper maintenance.

Roof System

The roof system was a protected membrane roof (PMR) system. The system was comprised of a concrete deck, four-ply asphalt and felt membrane, 1.5 in. (37.5 mm) of extruded polystyrene (XPS) insulation, and gravel ballast (**Fig. 4**). The roof was estimated to have an overall thermal performance of approximately R-8 (RSI-1.41).¹ Active water leakage was reported into the mechanical penthouse and within several units directly below the roof.

Mechanical Systems

The building was heated by electric baseboard heaters and employed a central make-up air (MUA) unit, which did not provide fresh air during the heating months. Over half of the building's tenants had also installed portable air-conditioning units through their existing window systems for cooling.

DESIGN STRATEGIES AND INNOVATION

The success of the decarbonization efforts hinged upon innovative design interventions that addressed both aesthetic and performance considerations of this deep retrofit. Through strategic interventions such as wall overcladding, window and

door upgrades, and roof assembly replacement, the design team optimized the building envelope to effectively integrate advanced mechanical systems. Each design choice was carefully calibrated to optimize building performance while minimizing environmental impact.

Exterior Walls

The design team evaluated several options for wall overcladding. The team ultimately chose a drained exterior insulation and finish system (EIFS) due to its numerous benefits. The EIFS is lightweight and enhances resistance to air and water leakage, significantly reducing overall energy consumption. It also improves tenant thermal comfort and reduces the risk of exterior wall condensation. Additionally, the EIFS protects the masonry and concrete shear walls from further deterioration, thereby enhancing durability and lowering ongoing maintenance costs.

The EIFS overclad generally consists of 3 in. (75 mm) of EPS insulation covered with a reinforced cementitious base coat and a finish coat lamina. A liquid-applied air and water-resistive barrier is applied directly over the existing brick and reinforced concrete shear walls and floor slabs (**Fig. 5**).



FIGURE 4. Test cut within existing roofing system.

Due to the glazed brick and painted concrete substrates, qualitative bond and quantitative mechanical fastener load testing were conducted to identify effective EIFS attachment methods. The testing revealed that the EIFS should be both mechanically fastened and adhered with ribbons of the cementitious base coat for optimal performance.

The EIFS was integrated with the new window systems, resulting in enhanced

overall performance and increasing the effective R -value to 12.8 ($RSI-2.25$).¹

WINDOW AND DOOR SYSTEMS

The design team also evaluated several window and door systems. The team selected thermally broken aluminum-framed window and window-wall systems with double-glazed insulated glazing units (IGUs) for their many advantages over the existing window systems. The new systems meet the North American Fenestration Standard performance requirements for air and water leakage resistance, enhancing resilience and reducing overall energy consumption. Additionally, the thermally broken frames and IGUs improve tenant thermal comfort and reduce the risk of condensation on the window systems.

The window systems are generally comprised of fixed IGUs over four-sash operable windows to limit maintenance on the operable windows. The windows were installed in punched configurations and mulled to insulated swing doors at balconies.

Drained window-wall systems are used at the corridor windows on the south elevation. This approach was chosen to replicate the existing window systems that feature opaque spandrel panels bypassing the existing floor slabs.



FIGURE 5. Exterior insulation and finish system installation on the west elevation.



FIGURE 6. New residential window systems with sub-sill flashings.



FIGURE 7. New protected membrane roof system under construction.

At the ground-floor lobby and entrance vestibules, a thermally broken aluminum-framed commercial glazing system is used. This commercial system consists of fixed IGUs with thermally broken outward-swinging doors.

All glazing systems utilize sub-sill membrane flashings (**Fig. 6**) and transition membranes for critical barrier continuity to adjacent walls. These membranes are married into the adjacent air- and water-resistive barrier of the EIFS for improved air- and water-leakage resistance and to be in line with best-practice detailing.

The IGUs consist of two panes of annealed or tempered glass (depending on safety glass requirements), separated by a warm edge spacer. A low-emissivity coating is installed on surface #2 of the IGU, and the cavity is filled with argon. These improvements lead to increased performance with a U -value of 0.4 ($USI-2.27$) and a reduced SHGC of 0.40.¹

Roof Systems

The design team decided to maintain a PMR system due to its numerous benefits. PMR membranes have longer service lives as they are not subjected to extreme temperature variations. Additionally, the membrane is protected from physical damage caused by weathering, foot traffic, and other factors.

Although some existing components could be salvaged, the system's composition was changed to enhance

performance. The existing XPS insulation, which was bonded to the existing membrane and brittle from ultraviolet exposure, was in poor condition and could not be salvaged. A two-ply modified bitumen membrane was used over the existing reinforced concrete roof deck. A 4 in. (100 mm) layer of new XPS insulation was installed over a polyethylene separator sheet, improving the roofing system's thermal performance (**Fig. 7**). The existing gravel ballast was salvaged and supplemented with new gravel where necessary to meet wind uplift performance requirements.

Mechanical Systems

The electric baseboard heaters are replaced with ground-source heat pumps fed by a geothermal exchange field. The rooftop MUA units are replaced with an electric heating coil, direct-expansion cooling, and a 55% efficient energy recovery ventilator.

CHALLENGES WITH IMPLEMENTATION

Navigating challenges is an inherent part of any project, but challenges can be particularly pronounced in retrofit projects, especially ones as comprehensive as the deep retrofit executed at this building.

Tenant Engagement

While the roof replacement and wall overclad projects were primarily performed from the exterior of the building, the window and door

replacements and the mechanical retrofits were being performed within the building's interior and within occupied space. This involved a high level of coordination between various trades to ensure the sequencing of the construction activities had minimal impact on the tenants and their living conditions. Throughout the planning and construction stages, several town hall meetings were organized to communicate the design intent, phasing, and scheduling, as well as to answer questions from the tenants. Active resident engagement is pivotal for the project's success.

Local Bylaws on Combustible Insulation

Recent changes to the city's bylaws regarding the use of combustible insulation in an EIFS overclad presented additional challenges for the construction team. The EPS insulation utilized in the EIFS is classified as combustible foam plastic. However, once covered by the cementitious base coat, the EPS insulation within the specified system is fire protected, passing the required tests by Underwriters' Laboratories of Canada (ULC), notably CAN/ULC-S101-07, which assesses fire endurance tests of building construction and materials. This system is also compliant with the local *Ontario Building Code*.

Despite meeting these standards, the bylaw mandated the building owners to implement a temporary fire safety plan (FSP), incorporating alternative fire safety measures to mitigate fire hazards during construction. The bylaw's focus was primarily on the period during which the EPS insulation remained exposed before the installation of the base coat. Securing approval for the FSP necessitated coordination with local building and fire departments, as well as the trades involved in EIFS installation. Specific requirements of the FSP included limiting the duration of EPS exposure, capping the maximum dimensions for continuous EPS installation, and instituting a 24-hour fire watch. This resulted in significant changes to the typical installation practices for EIFS, but these adjustments were well accommodated by the EIFS subcontractor.

COVID-19 Pandemic

The deep retrofit was also performed during a period of global turmoil—the COVID-19 pandemic. The design phase commenced in 2020, followed by construction in 2021. This time frame had a significant impact on construction practices, available labor, and supply-chain interruptions, to name a few. The resilience and collaboration of the design and construction teams allowed the project to adapt to these challenges and ultimately achieve its goal of becoming a low-carbon citizen.

SUSTAINABILITY AND CLIMATE RESILIENCE

Geothermal Field

Both the existing building and the new adjacent development are/will be heated and cooled by a geothermal system incorporated into this project. The EIFS overclad and new window and roof systems significantly increased the exterior wall and roof *R*-values, decreased the mechanical heating and new cooling demands, and subsequently reduced the number of boreholes required to balance the geothermal field. The geothermal system allows full-building decarbonization through electricity use rather than relying on fossil fuels. This dramatically reduces operational carbon.

Climate Resilience

The building tenants will benefit from increased building resilience during extreme weather. In the event of power outages, the EIFS and roof insulation contribute to maintaining comfortable conditions for several days as opposed to hours.

Embodied Carbon

The EIFS overclad also dramatically reduced the embodied carbon for the overclad materials, as compared with other options that were considered.



FIGURE 8. West elevation, post construction.

The GHG reductions on site contribute to Canada's commitments to reduce carbon emissions. The building is now a low-carbon citizen and was zero-carbon certified by the Canadian Green Building Council in November 2023.

Electrical Demand

The deep retrofit work conducted not only lowered GHG emissions, enhanced building performance, and improved resilience, but it also reduced peak electric demand. Post-retrofit utility bills show that energy consumption and winter peak electric demand in Q1 2023 dropped by 56% (or 541,000 kWh) and 54% (or 433 kW), respectively, compared to Q1 2022. This reduction in peak electricity demand is especially important as Canada moves towards electrifying the building industry to meet the 2050 net-zero carbon target. Demand on the local grid is projected to increase drastically, and electrical infrastructure will need to keep up. The building's sustainable design demonstrates how future development projects can help reduce the burden of the industry's electrification movement on local infrastructure.

CONCLUSION

The transformation of this 1960s building is a testament to what can be achieved when vision meets innovation. From an outdated and inefficient structure, the building has been reborn as a model of sustainable design and performance (**Fig. 8**). The developer's commitment to integrating advanced technologies and sustainable practices has not only revitalized the building, but it has also set a new standard for new developments.

This project underscores the importance of deep retrofits in achieving environmental goals and showcases the potential of existing buildings to contribute to a sustainable future. As this building stands as a beacon of what's possible, it encourages other developers, designers, and communities to embrace the challenge of transforming our built environment for the better. By embracing innovation, collaboration, and a commitment to environmental stewardship, we can continue to drive progress towards a low-carbon future for all.

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Validating Thermal Performance of Existing Assemblies Using in Situ Measurements

ABSTRACT

In deep energy retrofits, the thermal performance of existing building envelopes is often difficult to determine with a high level of accuracy. For older buildings, the records of existing assemblies are often incomplete or inaccurate. To obtain greater baseline performance accuracy for energy models, in-field measurement tools can be used to obtain data on the thermal performance of the existing assemblies. For a known assembly, these field measurements assist in validating the U-factor estimates. If the field-measured U-factor consistently varies from the calculated prediction, those measurements prompt further study. For an unknown assembly, successful field measurements can provide approximate U-factor evaluation, validate assumptions, or identify anomalies requiring further investigation. Using case studies, this paper will summarize non-destructive methods utilizing a set of various field tools to measure the baseline U-factors for a range of existing buildings with various wall assemblies. The lessons-learned cover what can be achieved, the limitations of these approaches and tools, and ideas on improving the accuracy and precision of measurements. The key factors include the weather conditions, the interior conditions, thermal mass of the measured assemblies, and thermal profiles of the assemblies in question.

SPEAKER



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A highly motivated building enclosure consultant with RWDI's Philadelphia team, Shibe Huang possesses technical skills specific to high-performance buildings, energy code compliance, assembly performance analysis, and construction administration. With a background in architecture design, Huang has extensive experience in institutional projects and across all project phases. Her analytical skills and knowledge of building science and historic preservation contribute to a deeper understanding of building performance and help inform building designs. She holds a BArch from the University of Oregon and an MSD in environmental building design from the University of Pennsylvania.

LEARNING OBJECTIVES

- » Explain the benefits of utilizing in-situ measurements during an existing building restoration or deep energy retrofit project.
- » Summarize the key steps of implementing sensors to measure assembly conductivity in the field.
- » Describe heat flux patterns of various measurement conditions in typical wall and roof assemblies.
- » Utilize strategies described in the session to improve the accuracy of thermal evaluation for existing assemblies.

SECTION 1 BACKGROUND AND INTRODUCTION

The thermal performance of existing building enclosures is often difficult to determine with a high level of validity. This can create confusion and uncertainty in maintenance or retrofitting projects. For older buildings, the challenge to get information often comes from incomplete or inaccurate documentation. The reasons range from missing drawings to as-built conditions not matching record drawings, and undocumented later alterations from previous owners. When information about an existing enclosure is lacking, nondestructive measurement tools can be used in situ to collect data for use in the evaluation of thermal performance.

Before the heat flux sensor technology is applied to measurement conductivities, specialists can use several methods to analyze the thermal properties of building enclosures. Making assumptions based on incomplete record drawings is a valid way to analyze the thermal performance of the existing building envelope. Even without any record drawings, thermal analysis can still be efficiently done in collaboration with a historical expert familiar with the existing buildings' stock in this region. If the uncertainty due to incomplete information can impact the project significantly, destructive probes can be done easily to understand some situations, for example, the existence/ thickness of rigid insulation in a roof assembly, or the existence of fiberglass batt insulation in the interior metal stud cavities. With an analytical mind, tools like infrared cameras can also aid this process of using incomplete information to conclude the performance estimates.

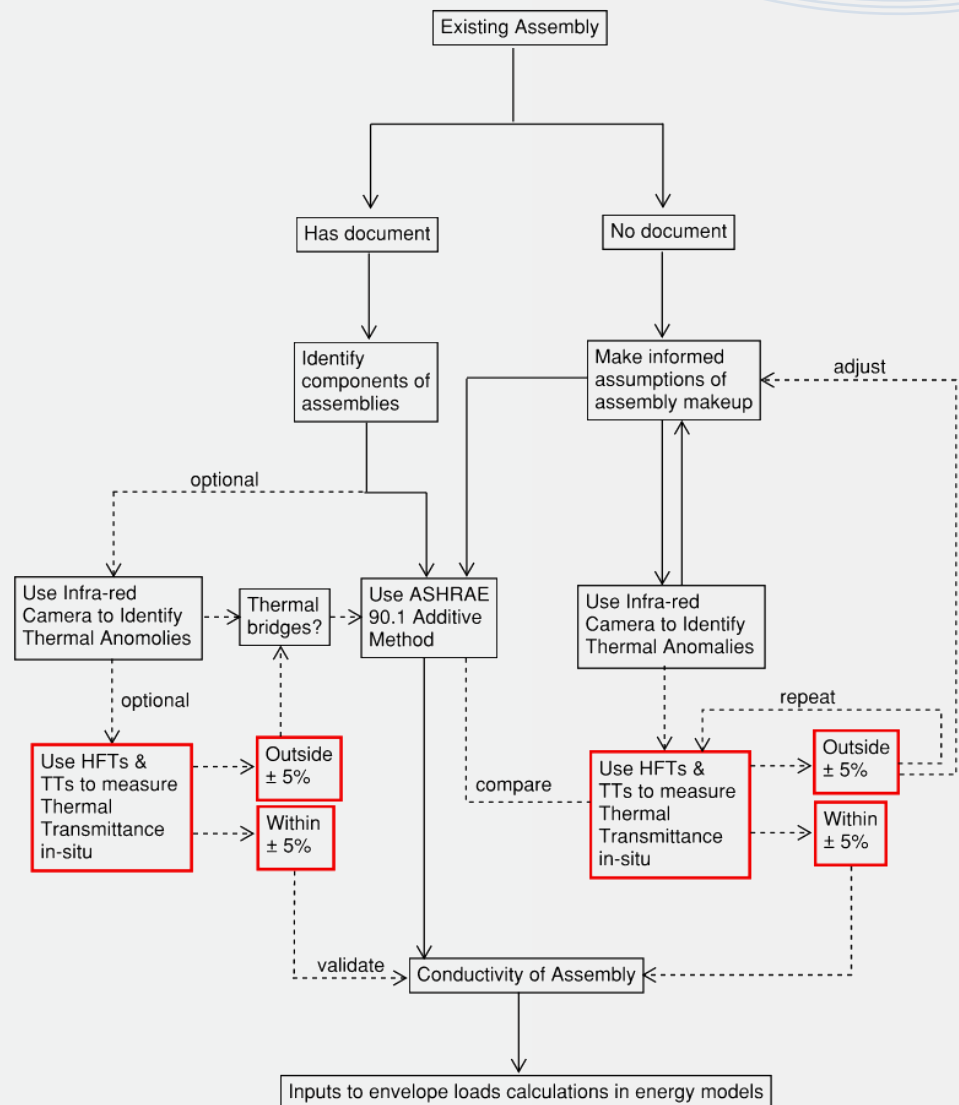


DIAGRAM 1. Typical workflow for determining the thermal performance inputs for energy models in known assemblies versus unknown assemblies. HFT = heat flux transducer; TT = temperature transducer.

(See the use of the infra-red camera in relationship to the heat flux tools in Section 3 Preparing to Implement Field Measurements.

Heat flux transducers (HFTs) and temperature transducers (TTs) can be especially useful for architects and

engineers when there are too many unknowns of the existing envelope. This study wants to position the in-situ measurement toolset as an enhancement to complement the typical workflow using assembly documentation research, infra-red

scans, and ASHRAE calculations. The field measurements can provide valuable information and confidence in the accuracy of assumptions based on field-collected data instead of dated un-verified information. See the summary of the enhanced workflow in **Diagram 1**. It is a typical workflow diagram to determine the thermal performance values of the enclosure assemblies. Using HFTs and TTs is an optional step in the thinking process and acts as an enhancement but not a replacement for the overall thermal analysis.

The outcome of the in-situ measurement is either thermal conductivity (U-factor) or thermal resistance (R-value), depending on the conventions. For most of the wall and roof assemblies, the measured conductivity is converted to thermal resistance (R-value) at the end of the data analysis process and shown in most of the charts included in this study.

All the case studies included in this study are extracted from measurements completed in my office. Since adopting the HFTs and TTs set to measure and analyze the conductivities in 2022, and so far, we have completed about 50 sets of measurements on various wall and roof assemblies. Most of the measurements were completed in wintertime. Most of the measured assemblies are opaque walls. A large portion of the measurements was taken amongst the portfolio of a college in Philadelphia, where a campus-wide energy retrofitting plan is currently

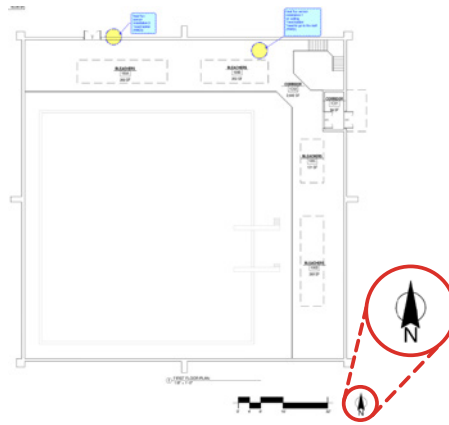


FIGURE 1. Floor plan of a sport facility, yellow circles are sensor locations.



FIGURE 2. Install sensors in the north slope under shade (wintertime), red arrow indicates the sensor location.

underway. The building use of the measured assemblies range from office, classroom, to residences.

SECTION 2 KEY STEPS TO IMPLEMENT IN SITU MEASUREMENTS

The procedure for using in situ measurements from HFTs and TTs to validate the conductivity of wall and roof assemblies can be divided into the following five steps.

Step 1: Understand the assembly by going through the workflow diagram presented in **Diagram 1**. Identify the goal of the measurement. If you have one set of equipment, prioritize the measurement of the field conductivity outside of the thermal anomalies. If multiple sets of equipment are available, expand the goal to include different thermal conditions adjacent to each other.

Step 2: Select measurement locations. Avoid direct solar radiation by deploying sensors in the north (**Figure 1**) or use the shades (**Figure 2**). The next section will discuss the use of a thermal camera in more detail to aid in selecting specific location.

Step 3: Install equipment. See **Figure 3 & 4**. Input conversion factor S as defined by the sensor manufacturer. Verify that the absorption rate of the HFTs matches the adjacent interior surface or surfaces. Validate initial readings, 15 minutes after the sensor installation.

Step 4: Collect data for more than 72 hours. The length of the measurement is 1) required if the results need to meet ISO 9869:1 and 2) more likely to produce a reliable result compared to a shorter measurement period. Record the weather conditions during the measurement period. Control the interior conditions to be as constant

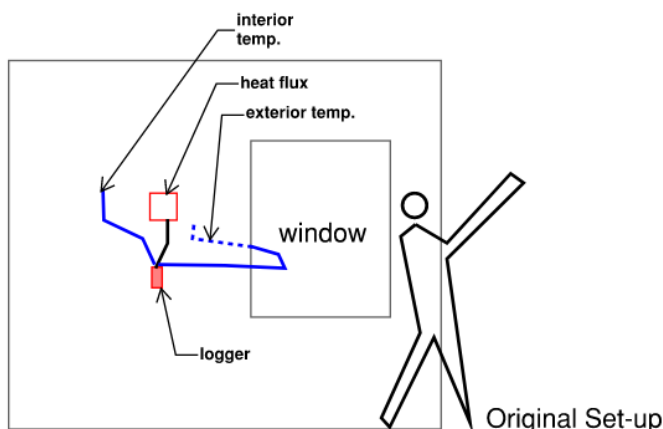


FIGURE 3. How to connect sensors at fenestrations.

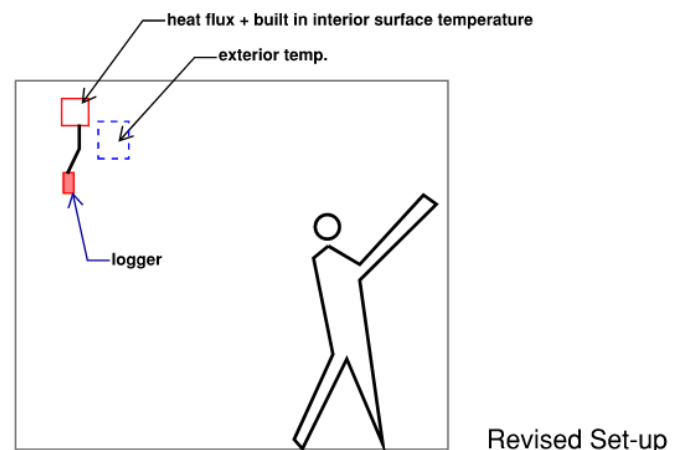


FIGURE 4. How to connect sensors without fenestrations.

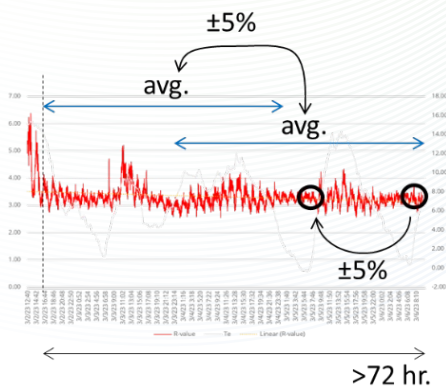


CHART 1. Example of a result chart with stabilized data.

as possible. Protect the equipment from being removed or damaged.

Step 5: Retrieve equipment and process data. To meet the criteria of standard ISO 9869:1, *Thermal Insulation—Building Elements—In-situ Measurement of Thermal Resistance and Thermal Transmittance*, the measured U-factor (See **Equation 1**) at the end of the test should deviate less than $\pm 5\%$ of the value obtained 24 hours at the beginning of the stabilized measurement; the first two-thirds of the overall measurement period should deviate less than $\pm 5\%$ of the last two-thirds of the overall measurement period. The overall standard deviation of the U-factor should be within 10% of the average value. (See **Chart 1** and **Table 1**)

EQUATION 1:

$$U\text{-factor} = \frac{\sum_{j=1}^n q_j}{\sum_{j=1}^n (T_{ij} - T_{ej})}$$

where

q_j = heat flux at time j

T_{ij} = inside air temperature at time j

T_{ej} = outside air temperature at time j

SECTION 3 PREPARING TO IMPLEMENT FIELD MEASUREMENTS

Before installing those tools, it is recommended by the standard practice guidelines^{1,2} to gather in situ information with an infrared camera. This field measurement tool can be used to identify thermal anomalies in opaque and nonreflective building enclosures, as it provides a two-dimensional temperature map of an exterior or interior surface in real time. Although the infrared camera reads specific surface temperatures, it tells if one section of the envelope is colder or hotter than the adjacent section, but it does not measure the conductivity of each section. For example, for a heated building, the lack of insulation in a portion of the exterior wall will likely show up as hotter surface in winter from the outside. The infrared camera may show the hotter portion being 5 degrees warmer than the adjacent portion. Therefore, the information is usually used only to compare the draw qualitative conclusions.

Thermal imaging can help identify conductive components of an opaque enclosure. For example, **Figure 5** is an infrared image of the exterior of a Philadelphia college dormitory, built in 1981, with a slate roof, a stucco wall at dormers, a stone wall, and wood windows. The image was taken in the winter, and analysis of the thermal patterns should exclude the reflection of the cold surroundings and the sky at the insulating glass units (IGUs) and metal downspouts (note the examples crossed out with white lines). Looking at the thermal image, it is apparent that the stone wall is conducting interior heat to the exterior more than the roof and the dormers. Therefore, the most conductive component of this building enclosure is the stone wall.



FIGURE 5. Exterior infrared image of a dormitory building at a college in Philadelphia, Pennsylvania, originally built 1981.

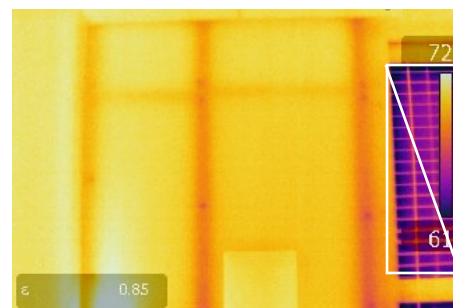


FIGURE 6. Interior infrared image of a wall of a college performance center and office in Philadelphia, Pennsylvania, originally built 1989.

Thermal imaging can also help identify the presence of insulation within a stud cavity. For example, **Fig. 6** shows an infrared image of an exterior wall taken in late winter from the interior of an office. The drawings on record indicated that the building, built in 1989, had metal studs at the interior. When analyzing the thermal image, the transmission of the cold surroundings or the sky should be excluded at the IGU (examples are crossed out with white lines). In this thermal image, profiles of the metal studs are apparent. Note that the field temperature between the metal studs is very close to the interior temperature captured at the interior wall surface to the left (72°F [22.2°C]). From this observation, it can be deduced that the heat loss to the exterior is very slow, and, therefore, the cavity between the metal stud walls is insulated.

Without quantitative values of the conductivities of the wall or roof,

TABLE 1. Example of converting measured data to desired result, following Equation 1.

time	Te	Ti	W/m2	Delta T	W/m2K	BTU/h ft °F	R-value
1/20/23 12:34	9.88	24.75	13.20	14.87	0.8875	0.1564	6.39
1/20/23 12:35	9.84	24.81	13.20	14.97	0.8819	0.1554	6.43

information from thermal images cannot be used directly as inputs to calculate enclosure loads in energy models. However, it serves an important role in determining where the heat flux sensor should be deployed because of two reasons:

- 1) Understanding the thermal anomalies help identify the components in the wall assembly. By itself it can add values to the workflow shown in **Diagram 1**.
- 2) To know the locations of thermal anomalies, so that the specific HFTs location can be selected.

SECTION 4 WAYS TO IMPROVE MEASUREMENT BASED ON TWO CASE STUDIES.

Field measurements of the HFT and TT will vary due to key factors such as the weather conditions, the interior air temperatures, thermal mass of the measured assemblies, and thermal profiles of the assemblies in question. The following case studies present a variety of real-world examples of these anomalies.

Case Study 1: Identifying the Conductivity of a Mass Masonry Wall

Being part of a campus aiming for net zero carbon by 2035, the project architect is looking to reduce the heating and cooling loads by insulating the existing envelope. The first step of the team was to understand the performance of the current envelope so that the energy modeler has adequate parameters to run analysis.

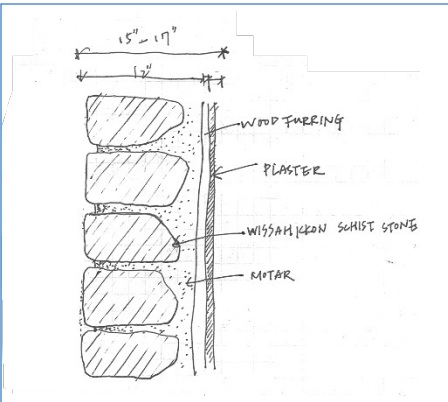


FIGURE 7. Assumptions about masonry assembly. Sketch by RWDI.

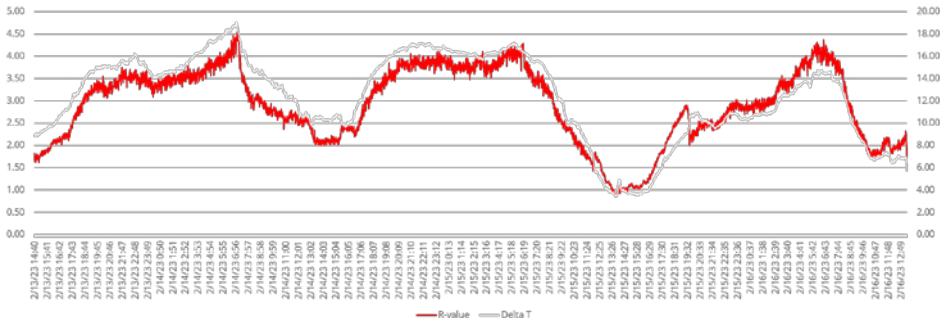


CHART 2. Thermal resistance based on measurements from heat flux and temperature transducers.

For a historic home built in 1724, there was no record of the construction or modifications to date. Based on the age of the building, it was assumed to be load bearing masonry. Assuming there is no interior insulation, the overall *R*-value is estimated to be *R*-1.5 ft²·°F·h/Btu (0.264 Km²/W).

An infra-red camera was used to identify the presence of insulation within the cavity (**Photo 3**). Because the surface temperature between the metal studs is lower than the interior temperature captured at the ceiling (at 72°F, 22.2°C), it was assumed that the heat loss at the cavity was faster than the wood furring, and therefore the cavity between the metal stud walls was un-insulated.

The HFTs & TTs tool set was deployed at the colder surfaces between the wood furring to eliminate the thermal bridging of the studs. Because the assembly is highly conductive. The tool set contributes to more than 1% additional resistance to the construction. The

thermal resistance of the HFT and adhesion tape were removed from the measured results based on ASTM C1046—21. The average measured thermal resistance with adjustment was *R*-1.71 ft²·°F·h/Btu (0.301 Km²/W). The standard deviation in the measurement of the thermal transmittance is 11.4% which exceeds the standard allowance for error (10%). The average measured thermal resistance is 12% greater than the assumed resistance based on the assumptions of the assembly materials. The existing assembly is measured to be slightly more insulating than the additive method prediction, which could be contributed to a thicker stone or the wood furring.

As demonstrated by this case study, using in situ HFT and TT tools cannot replace the process of component-based thermal analysis, but the field measurements can validate the outcome of the thermal analysis.

Case Study 2: Identifying the Conductivity of an Insulated Concrete Masonry Unit Wall

For a lecture hall built in 1995, the documentation indicated that the wall assembly was constructed of steel and concrete masonry units, exterior rigid insulation, and stone cladding over metal supports (**Figure 9**). The documentation also revealed many thermal bridges at the structural steel, corners, perimeter of fenestration, and penetrations that made a simple clear field value difficult to identify. The clear field area was so small that the measurements picked up heat loss thru the thermal bridges and through convection within the air cavity behind the interior gypsum board.



FIGURE 8. Interior infrared image of a historic home and office at a college in Philadelphia, Pennsylvania, originally built 1724.

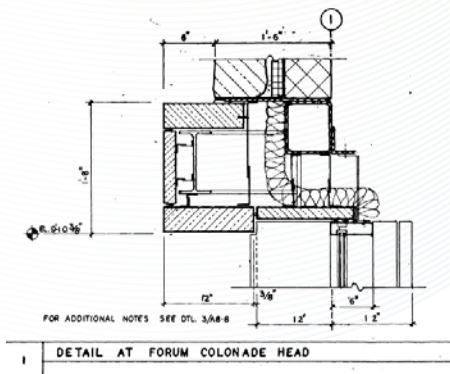


FIGURE 9. Exterior detail dated April 1, 1994. Source: Margaret Helfand Architects, Ehrenkrantz & Eckstut Architects, and Mary Miss Coe Lee Robinson Roesch Inc.

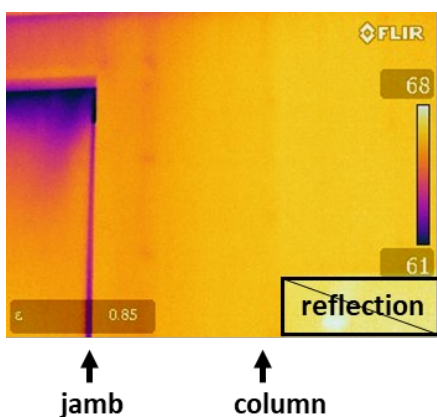


FIGURE 10. Infrared image of the measured wall.

At first, we were only using one set of HFTs, which was deployed outside of thermal anomalies based on the thermal imaging (**Figure 10**). When multiple sets became available, one of the sensors can be deployed at the thermal anomalies to understand the effect of thermal bridging.

If the additive method specified in Section A9.4 of ASHRAE 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*, were used on its own, it would produce an optimistic estimated R -value of 12.2 ft²·F·h/Btu (2.15 Km²/W), whereas the measured conductivity was only as high as 7.7 ft²·F·h/Btu (1.36 Km²/W). To capture the thermal bridges, multiple locations were selected, and a total of four measurements were taken to provide a relatively accurate measurement of the average conductivity of the

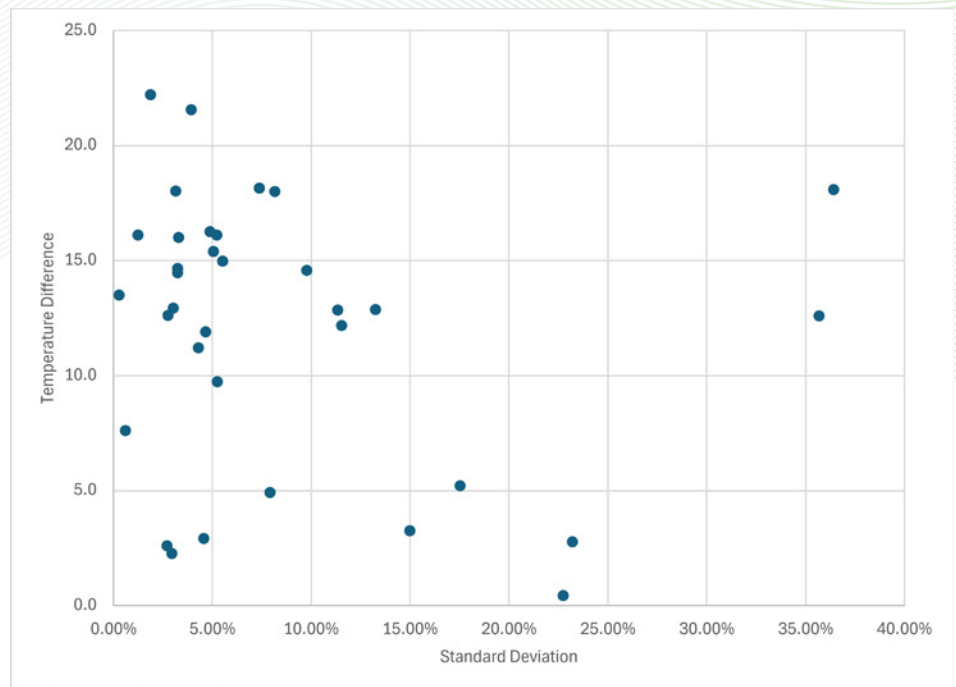


CHART 3. Scatter Diagram of Standard Deviation vs. Temperature Difference for Selected Measurements

exterior wall. This procedure eliminated the need to simulate the thermal bridges using THERM⁴ (or similar heat transfer simulation software programs developed for calculating conductivities of a certain geometries and materials in 2D or 3D). Now simulation process is yet to be automated, which can result in a more labor-intensive process to input a complex set of geometry into the model.

SECTION 5 FACTORS INFLUENCING THE PRECISION OF MEASUREMENTS.

5.1 the Difference between the Exterior and Interior Temperatures Differential

The ISO/ASTM standard requires maintaining interior-exterior temperature difference above 15°F (8.3°C). Depending on the climate, this limits the time during the year when measurements can be taken. Maintaining a minimum ΔT during seasons when heating or cooling is not being used. Based on the case studies, it was noted that a greater temperature differential often reduced the standard deviation of the HFT measurement, but 1) not the only factors or 2) the deciding factor to gain a set of data with less standard deviation.

Below is a scatter diagram (**Chart 3**) showing most of the measurements land within the 10% deviation range has at least 10-degree Fahrenheit temperature differential. However, a few cases that has much less temperature differential also managed to achieve the lower deviation with a much lower temperature differential. These are the cases where the assembly only contains one or two layers and does not contain thermal bridges.

When the 15°F (8.3°C) temperature differential couldn't be maintained consistently due to daily temperature changes, it was useful to double the measurement time to capture more data. Many of the selected installation conditions had noticeable day and night temperature differences. For examples, all the summer measurements in Philadelphia faced the challenge of inconsistent indoor-outdoor temperature differential (see **Chart 4**). The daytime temperature difference can usually reach 15°F (8.3°C) but not always constantly greater than 15°F (8.3°C) in the mornings and afternoons. At nights the temperatures differences sometime can reverse, where the outdoor becomes cooler than the indoor. It sometimes means the data was skewed,

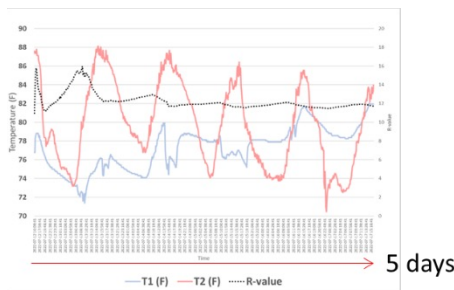


CHART 4. Extended measurement time in a mild climate. (Redline: outdoor, Blue line: indoor temperature, Grey line: Measured R -value)

especially around the tipping points of 0-temperature differential. However, successful measurements meeting the ISO/ASTM standards^{1,2} were completed at these challenging conditions before with extended time.

Selectively choosing data over a longer period does not meet ISO/ASTM standards^{1,2} and this method cannot be used to solely identify assembly thermal resistance. However, when dealing with fluctuating temperature difference, selectively crop out data around 0-temperature differential time can be useful in understanding the overall dataset. This is especially true for the assemblies that already had drawings and just in need of an order of magnitude for validations.

4.2 Weather Events that Had Limited Impact on Measurement.

Rain. When rain coincided with temperature changes, it appeared to have impacted the HFT measurement. However, when comparing two sets of measurements at the same location during different time periods, it was discovered that that rain event is not

necessarily impacting measurements. (See **Chart 5**)

SECTION 6 LIMITATIONS OF HEAT FLUX AND TEMPERATURE TRANSDUCERS AND ALTERNATIVE WAYS TO OBTAIN THE THERMAL PERFORMANCE OF EXISTING ASSEMBLIES

6.1 Translucent Assemblies

Like infrared cameras, HFTs and TTs are not suitable for the use on translucent assemblies. Even when HFTs are deployed at a shaded site, they will pick up heat transfer from ambient radiation, more than the conduction from the glass surface. Modifications such as taping or masking the outside of the glass can be made, but the modifications inevitably will change the original states of the assembly.

The most direct way to identify the properties of an IGU is to find the glass label by the manufacturer that is typically etched into a corner of the IGU. Alternatively, a glass thickness gauge meter can be used to identify the components within the glass unit; this meter usually can provide a reliable assumption of the low-e coating, the location(s) of the coating(s), and the width and type of gas of the gap. Information from an glass gauge meter are sufficient to provide an relatively accurate assessment of the thermal properties at the center of the glazing.

Metal Components

Another tricky component to measure with HFTs & TTs set are metal components, either metallic surfaces

or steel structure, because of the multidimensional heat flows created by highly conductive components.

To clarify, the tool set can be used on metal stud walls or roof with steel decks, where metal components are not in direct contact with the exterior or the HFTs and has its consistent heat flow pattern. This situation can be overcome by using the infra-red camera to identify the locations of the thermal bridges created by metal components within (see case study 2). Multiple measurements can be used to increase the confidence in the results.

However, if the interior surface is metallic, such as a curtain wall frame, the lateral conduction or interior radiative exchange can alter the measurement with numerous rapid fluctuations and make it difficult to identify heat flow patterns.

CONCLUSION

In-situ measurements using the combination of HFTs and TTs is a useful non-destructive method to determine the baseline thermal resistance for a range of existing building wall and roof assemblies. For an assembly with detailed documentation, these field measurements assist in validating the U-factor estimates. If the field-measured U-factor consistently varies from the calculated prediction, those measurements prompt further study. For an assembly with unknown makeup, successful field measurements can provide approximate U-factor evaluation, confirm assumptions, or identify anomalies requiring further investigation.

Setting up the HFTs and TTs in the field is critical to the success of the measurements. Skipping a step will likely result in inconclusive data or misinterpretation of the measurements. When the result does not meet the recommended 10% standard deviation by ASTM C1046-X4¹, the tool set will still reflect the real-time thermal behavior of the assemblies in question and provide insight of the thermal performance related to thermal mass or other factors that impact the heat transfer.

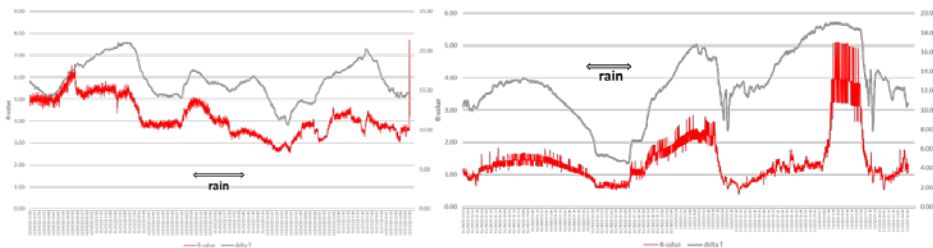


CHART 5. Comparison of two R -value measurements at the location of a masonry wall on different days. Red line: R -value, Grey line: temperature difference.

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- 3 ASHRAE. 2022. *Energy Standard for Sites and Buildings Except Low-Rise Residential Buildings*. ASHRAE 90.1-2022. Peach Tree Corners, GA: ASHRAE.
- 4 THERM. Computer program developed at Lawrence Berkeley National Laboratory (LBNL) Link: <https://windows.lbl.gov/therm-software-downloads>

Engineering Tomorrow's Envelopes: Smart Blue Roofs Pioneering Sustainable Building Practices

ABSTRACT

Urbanization has altered the hydrological cycle, increasing stormwater management challenges in densely populated areas. One emerging strategy to mitigate these challenges is the implementation of blue roof systems. Blue roofs, which temporarily capture rainwater and control its release, offer an innovative approach to managing rooftop runoff, reducing strain on municipal sewer systems and reducing flooding risk. This paper examines blue roof technology classifications, historical context, modern applications, Canadian codes and standards, and key design considerations through the lens of a detailed case study of a commercial building retrofit project in Mississauga, Canada. The case study illustrates the practical application of roof-integrated design blue roof principles, including structural analysis, membrane selection, drainage system design, leak detection mechanisms and construction procedures. By integrating blue roof technologies into urban infrastructure, cities can achieve synergistic benefits, including improved resilience, enhanced sustainability, and effective stormwater management.

LEARNING OBJECTIVES

- » Recognize and differentiate between Stormwater Detention Assemblies and Roof Integrated Design components in blue roof design.
- » Explain at regulatory requirements outlined in the *National Building Code of Canada* and *National Plumbing Code of Canada* regarding blue roof implementation.
- » Discuss at least two potential benefits of blue roofs in mitigating urban flooding and managing stormwater runoff.
- » Identify and explain the key differences between green and blue roofs.
- » Evaluate the feasibility of integrating blue roof systems and describe design considerations based on presented examples.

SPEAKERS



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His expertise extends to evaluating durability, energy efficiency, and occupant comfort implications in design and construction. He is a project director and has taken various leadership roles supporting the WSP National Technical Centres of Excellence.

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INTRODUCTION

Urbanization has altered the natural hydrological cycle, leading to significant challenges in managing stormwater in densely populated areas. The reduction in green spaces has resulted in increased surface runoff, higher solar radiation absorption, and diminished evaporation rates, all of which complicate water management in urban settings.¹ With climate change fueling more frequent and severe storm events, traditional stormwater systems are becoming increasingly inadequate, resulting in localized flooding that endangers public safety and property.^{2,3}

To address these challenges, there is a growing focus on blue roof technologies, which offer opportunities for managing rooftop runoff. Blue roof systems capture rainwater and store it temporarily, allowing it to evaporate, be stored for reuse, or be released over time to reduce the peak flow into the municipal stormwater system.⁴ Additionally, blue roofs enhance urban microclimates and conserve water by storing rainwater for irrigation and toilet flushing.^{1,5} They can also lower cooling demands through evaporative cooling during hot weather.¹ Research highlights the effectiveness of blue roofs in reducing stormwater runoff, especially in older urban areas with combined storm and sanitary sewers, where the risk of sewer overflows is particularly high.³

Given that low-slope roofs account for approximately 28% of urban surfaces in North America, according to satellite imagery studies, they represent an opportunity for stormwater management. This can mitigate environmental impacts and promote sustainable urban development amid ongoing urbanization and climate change.^{4,5}

TECHNOLOGY CLASSIFICATION

The concept of a blue roof has gained prominence as an innovation for stormwater management, setting it apart from traditional vegetative roofs. Blue roofs can be categorized based on their stormwater detention methods into the following designs:

Roof-integrated design (RID) utilizes either the entire roof or a portion thereof, with modifications made to roof drainage inlets to achieve a slower drainage rate into a leader pipe, allowing water to accumulate on the roof surface, as shown in **Figure 1**.

RID systems can be passive or active. Passive systems incorporate roof dams and checks or drain inserts with an orifice that reduces flow compared with conventional drains as shown in **Figure 2**. A check-dam system is constructed with a series of partitions or weirs, each fitted with openings at their lowest point. These openings are strategically created to avert the continuous water pooling and to facilitate a steady flow of rainwater toward the roof's drainage point.¹ On the other hand, active systems feature

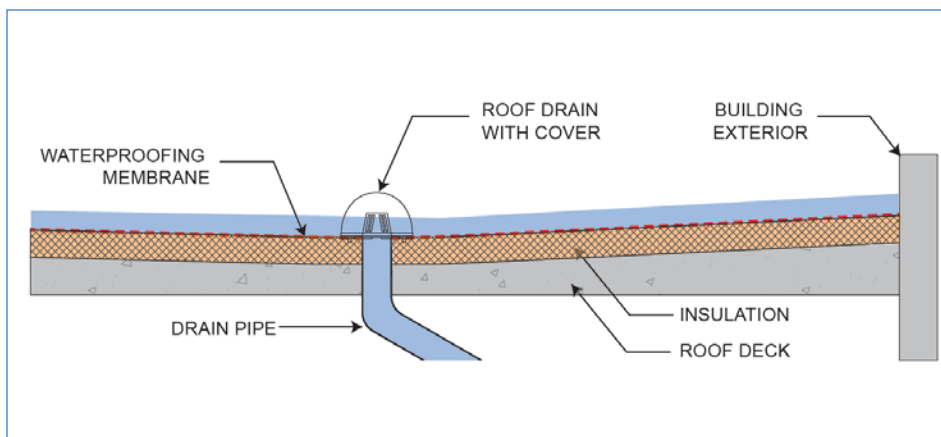


FIGURE 1. Roof-integrated design.

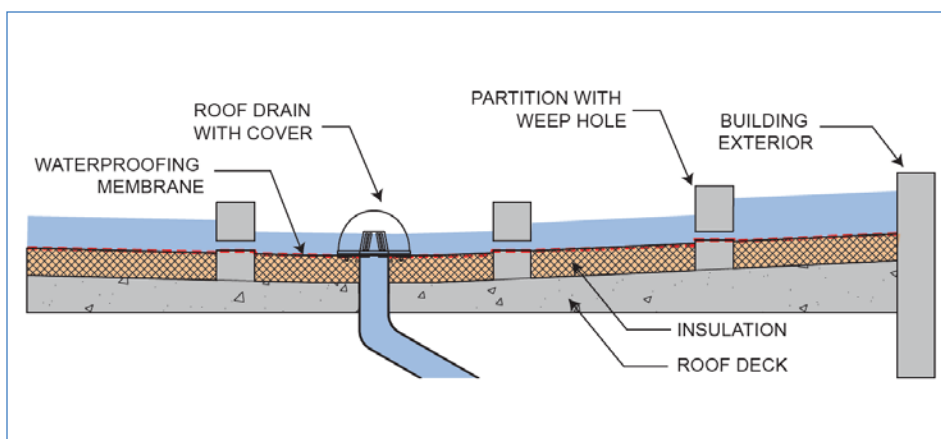


FIGURE 2. Check-dam system cross-section with multiple partitions.

remotely controlled valves often governed by programming to manage detention levels. These active systems may also utilize algorithms and sensors to adapt to varying weather conditions. By anticipating and responding to weather patterns, active RID systems optimize stormwater detention and release, mitigating the risk of overflow during intense rainfall events.⁴ Whether passive or active, RID necessitates a roofing systems capable of performing under volumes of ponded water for possibly extended periods of time as compared to typical low-slope roof system designs.

Modular tray design (MTD) incorporates modular systems, such as tray-based systems, which can be positioned on rooftops to store and manage stormwater. These trays are typically filled with porous media, enabling controlled drainage through weep holes at the base, complemented by various

outlet drains customizable to project requirements.⁴ The flexibility of this design allows for selective installation across diverse roof surfaces, particularly in areas with structural loading constraints or where rooftop equipment must be accommodated.⁴ The trays can either be freestanding, secured in place with weighted materials, or attached directly to the roof structure. MTD systems demand less maintenance than other methods; they can offer water detention capacity separated from the roofing membrane, making them a practical retrofit choice or an additional feature without necessitating extensive roof assembly modifications.⁴

"Blue-green" roofs integrate features of both blue and vegetative roofs by incorporating vegetation and growing medium layers above ponded water. 'Blue-green' roofs can either utilize roof-integrated or modular designs. They are designed similar to traditional

vegetative roofs but feature an expanded drainage layer, facilitating enhanced evapotranspiration and enabling a controlled, gradual release of stormwater.^{7,8}

HISTORY AND MODERN APPLICATIONS

Low-sloped roofs are defined by roofing membrane systems installed on slopes of 25% (1 in 4) or less.⁹ Flat roofs, a subset of low-sloped roofs, have a minimum slope of 2% (1 in 50) to ensure proper drainage.⁹ The historical use of low-sloped roofs can be traced back to ancient civilizations in the Mediterranean, Africa, and Asia, where the climate was conducive to such architectural designs.¹⁰ In contrast, regions with more severe weather conditions, characterized by heavy rainfall, traditionally favoured pitched roofs to prevent water accumulation and potential structural damage.¹⁰

The 19th century saw an increase in low-sloped roofs for residential buildings in urban areas across Europe and North America. Traditionally, these low-sloped roofs utilized tar and gravel surfaces, which provided an effective barrier against water as long as proper drainage was maintained. This method involved layering roofing felt, applying mastic, and embedding silver-gray gravel into the top layer to prevent the surface from drying out.¹⁰ However, these materials were less successful in colder climates, where ice dams and sagging could impede water flow and disrupt drainage.¹⁰ European construction laws influenced low-sloped roof trends to maximize building heights within city landscapes.¹⁰ Notable architects such as Le Corbusier and Frank Lloyd Wright also popularized low-sloped roofs in residential architecture during the early 20th century. Le Corbusier's "Five Points of a New Architecture," published in 1926, promoted low-sloped roofs' functional and aesthetic benefits, advocating for their use as gardens and terraces to reclaim urban green spaces.¹¹

The 1960s introduced bituminous felt roofing sheets, offering a lightweight and cost-effective alternative for roof coverage. Despite these advantages,

the material was prone to leaks and had a limited lifespan.^{12,13} This was due to the nature of the bituminous material, which could become brittle and crack under extreme weather conditions, leading to water ingress and damage. In addition to bituminous felt, other roofing systems, such as metal roofs and EPDM roofing systems were also being used.

In the 1970s, the roofing industry saw the advent of vegetative roofs, which were complemented by advanced waterproofing and drainage systems, culminating in the development of low maintenance 'extensive vegetative roofs' by the decade's end.¹⁴ In the mid-2000s, many municipalities across North America began encouraging vegetative roofs for new public and private buildings, recognizing the potential savings from reduced energy consumption, mitigation of the urban heat-island effect, and decreased stormwater infrastructure costs.¹⁵ In 2009, Toronto became the first city in North America to mandate vegetative roofs for certain new developments, along with stipulating minimum construction standards.¹⁶

In the 2010s, blue roofs emerged as an approach to stormwater management. The New York City Department of Environmental Protection conducted several pilot studies between 2011 and 2012 to evaluate the effectiveness of blue roofs. These studies involved the installation of various modular tray systems and check dam systems at multiple sites to monitor rainfall retention and detention rates. At one location, four different tray systems were tested at a community center to measure their outflow rates and assess performance. Similarly, at a storage facility on Metropolitan Avenue, the roof was divided into sections to test various drain inlet modifications and tray systems. These pilot projects consistently demonstrated peak flow reductions of 85% to 90%.¹⁷ However, the study did not explore the impact of different roof membrane types and their long-term performance.

Subsequent research has broadened the scope of blue roof studies. Campisano et al. (2020) conducted a full-scale

pilot installation of a MTD system on the University of Catania's campus in Catania, Italy. The study compared a section of the roof equipped with the MTD system against an unmodified section, observing an average of 54% retention efficiency and 72% detention efficiency for MTD system.¹⁸

Almaaitah & Joksimovic (2022) assessed a "blue-green" roof's hydrologic and thermal performance during a growing season in 2021 at the George Vari Engineering and Computing Centre at the Toronto Metropolitan University. The 'blue-green' roof was comprised of a 50 mm compost layer, a 250 mm substrate, a filter sheet, a 50 mm drainage layer, a root barrier, and a roofing membrane arranged from top to bottom. The membrane and drain system are not mentioned in the study. The research highlighted the roof's water retention capability, with average rates between 85–88% and peak stormwater attenuation of 82–85%.¹⁹ Temperature-wise, the study observed a mean air temperature reduction of 1.4°C to 2.5°C, varying with the type of vegetation.¹⁹ Notably, the cooling effects were more significant in the afternoon and evening, while a warming trend was noted in the early morning.¹⁹

While prototypes exist for tray systems, check-dammed systems, and 'blue-green' roofs, limited research and case studies exist for RID systems, flagging a potential area for further research and development. This gap in research limits practitioners' understanding of RID systems and their performance across various membrane types.

RELEVANT CANADIAN CODES AND STANDARDS

While specific standards for blue roofs have yet to be established within Canadian building codes and standards, the principles for general roof design remain pertinent. This section examines how existing roofing codes and standards can be adapted to blue roof applications, ensuring their functional and structural integrity.

The *National Plumbing Code* (NPC) 2020 contains provisions for roof drainage relevant to blue roofs. Section 2.4.10.4(1) determines the maximum

hydraulic load used to establish the minimum leader size for the roof drain. For roof drains with flow controls, the hydraulic load is determined using a 25-year rainfall intensity-duration-frequency curve provided by Environment Canada.²⁰ NPC clauses 2.4.10.4(2) and (3) stipulate that water stored on the roof should not remain for more than 24 hours and have a maximum depth of 150 mm (6 in.).²⁰ Additional clauses in the NBC 2015 specify the location of drains, which must be no more than 15 meters (49 feet) from the edge of the roof and no more than 30 meters (98 feet) from adjacent drains.²⁰ Additionally, overflow scuppers must be installed no more than 30 meters (98 feet) apart along the perimeter of the building to prevent structural overloading of the roof if drains fail.²⁰ However, the NPC does not mandate specific roofing membranes.

Many regionally specific codes, such as the 2012 *Ontario Building Code* (OBC), share requirements comparable to those of the NPC drainage guidance. The distinction lies in the sourcing of environmental data, where references in the OBC must adhere to the Ministry of Municipal Affairs and Housing (MMAH) Supplementary Standard SB-1 instead of NPC data.²¹

Different municipalities and regions may also have specific stormwater management and retention requirements. For example, the Toronto Green Standard (TGS) Version 4 applies to new site plan applications for four-story or higher residential buildings and all industrial, commercial, and institutional (ICI) developments.²² Within the water quality and efficiency prerequisite WQ1.1, Water Balance, Quality & Quantity Control, there is a mandate to retain 50% of the total average annual rainfall volume, remove 80% of total suspended solids, and control *E. coli* for discharges to Lake Ontario or waterfront sites.²² Peak flow control is also required; however, challenges arise in implementing blue roofs under prerequisite WQ1.3, On-site Green Infrastructure, due to conflicting requirements, such as minimum vegetative roof coverage, which can be up to 80% of available roof space.²² These requirements pose challenges

in blue roof implementation, with the standard specifications supporting vegetative roof infrastructure. Designers may consider implementing blue roofs in the remaining available roof space or installing a hybrid 'blue-green' roof to meet the Toronto by-law requirements. The City of Toronto also has a Wet Weather Flow Master Plan, which sets wet-weather flow-management targets for water balance, quality, and quantity. Table 1 in Section 2.2.1, Water Balance, lists examples of on-site stormwater management practices depending on the type of land use.²³ For example, commercial and industrial buildings may implement vegetative roofs, rooftop restrictors, and rainwater harvesting.

CSA A123.26:21, *Performance Requirements for Climate Resilience of Low Slope Membrane Roofing Systems*, lists even more stringent recommendations related to drainage. The standard outlines the requirements for low-sloped membrane roofing systems to achieve different ratings related to climate adaptation. According to Clause 7.2.8, water should not run more than 10.7 m (35 ft) to a primary drain or scupper to achieve a silver performance rating.²⁴ For a gold performance rating, Clause 7.2.13 stipulates that water should not travel more than 6.1 meters (20 feet) to a primary drain or scupper.²⁴

CSA 478:19, *Durability in Buildings*, provides minimum requirements to assist designers in making design

decisions, reviewing construction, and performing building maintenance in existing and new construction projects.²⁵ Blue roofs can influence the lifespan and performance of a building due to their unique construction and environment. For example, Sections 4.3 and 4.4 of this standard state that all foreseeable agents and mechanisms that could impact durability and performance must be considered and accounted for during design, construction, repair, and maintenance.²⁵ Similarly, Section 8.3, clauses (b) and (c), specify that the materials selected must be appropriate for the structure's environment, design loads, and differential movements.²⁵ Section 4.6.2 stipulates that a maintenance and inspection plan should be developed for building components, including repair and replacement.²⁵ This makes proper material selection for the waterproofing membrane and a thorough maintenance and repair plan essential for blue roofs.

Leak detection is an important consideration for blue roof systems. It can provide quality assurance during construction and a mean of leak diagnostics and monitoring for the life cycle of the roof assembly. In considering leak detection during design, the following standards offer guidelines and requirements for electronic-detection components: ASTM D7877, *Standard Guide for Electronic Methods for Detecting and Locating Leaks in Waterproof Membranes*, and ASTM D823, *Standard*

Practice for the Use of a Low Voltage Electronic Scanning System for Detecting and Locating Breaches in Roofing and Waterproofing Membranes.^{26,27}

Lastly, CSA B805:22/ICC 805:22, *Rainwater Harvesting Systems*, provides comprehensive guidelines for the design, materials, installation, and operation of rainwater harvesting systems, covering potable and non-potable applications and water treatment.²⁸ It can apply to blue roofs if detained water is reused within the building for potable or non-potable uses.

CASE STUDY

Building Description

The Credit Valley Conservation (CVC) Head Office, located at 1255 Old Derry Road in Mississauga, Ontario, Canada, consists of two buildings, A and B, connected by a one-story corridor. Constructed circa 2010, Building A is a four-story steel-framed structure with a one-story garage on the southeast elevation (**Figure 3** and **Figure 4**). The floors and roof slabs are supported by steel beams connected to steel columns anchored to cast-in-place footings. Building A has three roof sections: the main roof (A-1), the garage roof (A-2), and the elevator pit room (A-3) as shown in **Figure 5**. Mechanical equipment on the west side of roof A-1 sits within an open-air screen enclosure. The approximate area of roof A-1 is 645 m² (6943 ft²).



FIGURE 3. CVC Building A - Overview



FIGURE 4. CVC Site Plan

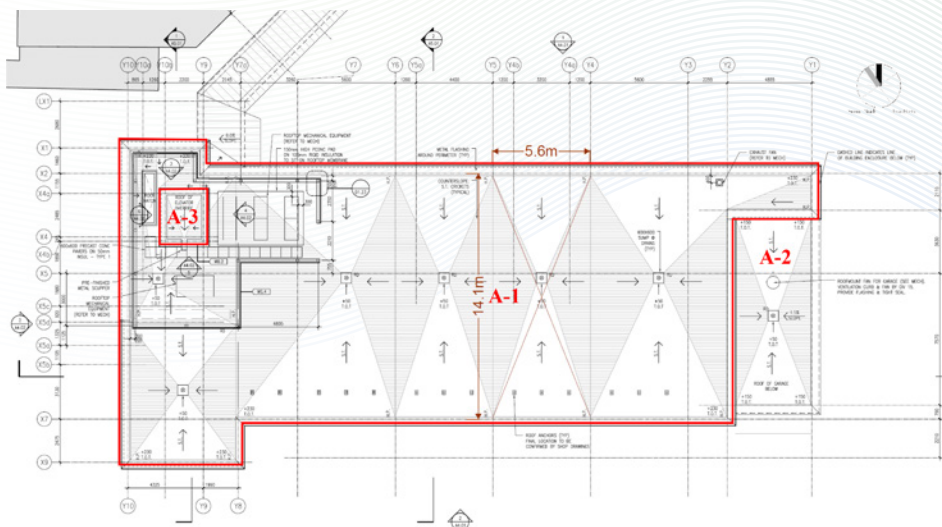


FIGURE 5. Building A – Existing Roof Plan

ROOF ASSEMBLIES

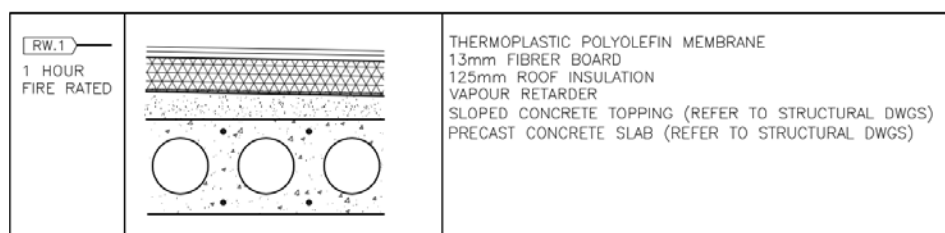


FIGURE 6. Existing A-1 roof assembly

The main roof structure of Roof A-1 comprises a 250 mm (10 in.) thick hollow-core slab. On top of the slab is a concrete topping that measures 230 mm (9 in.) at the perimeter, tapering to 50 mm (2 in.) at the center to facilitate drainage. The existing roof assembly is a conventional system that includes a self-adhered vapour barrier, 125 mm (5 in.) of EPS insulation adhered in place, and a 12.7 mm (½ in.) fibre board adhered in place. The system is capped with a single-ply fully adhered TPO membrane, as depicted in **Figure 6**.

Roof Section A-1 does not have overflow scuppers. The existing parapet height is 400 mm (16 in.). Building A has seven drains. The CVC Head Office Building A was designed in 2008 by Montgomery Sisam Architects Inc. Accordingly, the 2006 Ontario Building Code was the applicable building code at the time of design and permit issuance. Design loading was in accordance with Part 4 of Division

B. Environmental loading data for Mississauga was per Supplementary Standard SB-1.

Feasibility Study

Project Background

In October 2017, the CVC authority began exploring the feasibility of implementing an RID blue roof pilot project installation at their office building. This pilot project was seen as an opportunity to test the effectiveness of this emerging technology in managing storm peak load, reducing energy consumption, and determining the extent of non-potable demand which could be met by the existing rainwater harvesting (RWH) system.¹⁰ Over the following months, CVC engaged with internal and external stakeholders to refine the project concept and secure funding. Due to its size and relatively minimal mechanical and conduit congestion, Roof A-1 was identified as a candidate for the installation of the blue roof system.

In light of the prevailing code regulations in 2017, which allow a maximum rainwater drain-down time of 24 hours per day and a maximum roof rainwater level of 150 mm (6 in.), CVC entered pre-consultation and technical discussions with the City of Mississauga Building Department to determine the legislative requirements for a blue roof. In addition to comply with the general requirements of the OBC, two alternative solutions were proposed under OBC Division C to maximize the benefits of a blue roof.

The first alternative, Solution A, proposed extending the maximum allowable rainwater drain-down time to six days. This extension aimed to increase the amount of water stored while also including provisions for reducing the likelihood of mould or mildew growth and the risk of illness from unsanitary conditions caused by contaminated surfaces and vermin.²⁹ This latter concern is particularly pertinent in relation to Culex mosquitoes, whose larval development cycle can be as early as five days with favourable environmental conditions.³⁰ Culex mosquitoes in this region are known to carry the West Nile virus, and stagnant water without treatment may lead to increased larval development, potentially spreading the disease.³¹ According to this alternative solution, all accumulated rainwater must be treated every two days per CSA B805 standards to control bacteria and protozoa.^{28,29}

The second alternative, Solution B, suggested increasing the maximum allowable roof rainwater level from 150 mm (6 in.) to 250 mm (10 in.). The City of Mississauga requested a detailed structural assessment and the inclusion of additional overflow scuppers to manage this increased capacity and alleviate the risk of structural overloading on the existing structure.

Structural

The original structural deck was designed to accommodate dead, live, variable, and wind loads, according to the OBC 2012, table 4.1.2.1.A. Dead loads include the self-weight of the structure, permanent construction materials, roof assembly, overburden, rooftop equipment, and architectural

TABLE 1. Snow and rain loads as per Table 4.1.2.1A in 2012 OBC.²¹

City	Snow (without considering snow drift)		Water	
	Loading kPa (psf)	Precipitation mm (in.)	Loading kPa (psf)	Precipitation mm (in.)
Mississauga	1.28 (27)	130 (5.1)	1.11 (23)	113 (4.4)
Toronto	1.12 (23)	114 (4.5)	0.95 (19)	97 (3.8)

components. Live and variable loads account for occupants, movable equipment, and environmental factors such as snow, ice, and rain. For most roof structures, the variable snow or rain load is equal to or greater than the dead load, with the dead load calculated at 1.25 kPa (26 psf) and the variable load at 1.5 kPa (31 psf), per OBC Table 4.1.3.2.A.²¹

The rainwater storage capacity, integral to blue roof technology, imposes a variable load due to rain. Importantly, OBC Article 4.1.6.4.(3) specifies that snow and rain loads do not coincide and should not be combined in the same load calculation.²¹ Consequently, the capacity of an existing roof to support a rainwater storage capacity is equal to the design snow or rain load. Based on the 2012 OBC and regional precipitation data, hydraulic rain load calculations indicate that snow load typically governs design in Mississauga and Toronto, as shown in **Table 1**.

It is common practice that an increase of up to 5% in variable load is acceptable without requiring structural reinforcement, translating to increasing ponding from 130mm (5 in.) to 137mm (5.4 in.) in Mississauga. However, the CVC’s requirement to store up to the maximum allowable amount of water necessitated a detailed assessment and potential roof structural reinforcement.

Design loads for the Roof A-1 were calculated, factoring a basic snow load of 1.3 kPa, wind uplift of 1.3 kPa, and a basic superimposed dead load (SDL) of 1.6 kPa. Additionally, the average sloping topping dead load was 4.7 kPa, varying from 2.8 kPa to 6.6 kPa, as shown in **Figure 7**.

Accordingly, it was determined that the existing low-sloped roof can support basic seasonal blue roof technology without additional reinforcement, with a maximum snow load of 1.3 kPa plus 0.6 kPa in allowances or a maximum ponding depth of 180mm (7 in.). The blue roof system drains should remain opened to avoid ponding during the winter months.

Roof Assembly

Considering Roof A-1’s existing TPO roof assembly condition and performance risks, full roof replacement as part of the blue roof pilot was contemplated. Roof cut tests completed by CVC’s roofing contractor confirmed moisture present below the existing TPO membrane at several locations. Concerns were raised regarding risks and impact of future leaks below the new blue roof, including building operations disruption and hollow core structural roof slab deterioration. The CVC elected to replace the full roof assembly as part of

the blue roof project. Considerations and factors reviewed in making final new roof system design decisions are presented below.

Design

Overview

To implement the blue roof project on Roof A-1, a separation was needed to isolate existing rooftop building mechanical and weather monitoring instrumentation systems installed on the west section of the roof. Roof A-1 was divided, by a new segregation barrier, into two distinct areas: Zone 1 (the western third of the roof, which is to remain a conventionally drained low-sloped roof) and Zone 2 (the eastern remaining roof area designated for blue roof water retention), as depicted in **Figure 8**. Zone 3, the lower garage roof (Roof A-2), falls outside this project’s scope.

Roof Assembly

The new replacement roof assembly at Zone 2 (the blue roof area), as a retrofit, was to at least achieve the same thermal and condensation resistance performance levels of the existing TPO roof. Additional design decisions were guided by four key objectives established by the CVC. First was ensuring the new roof assembly can

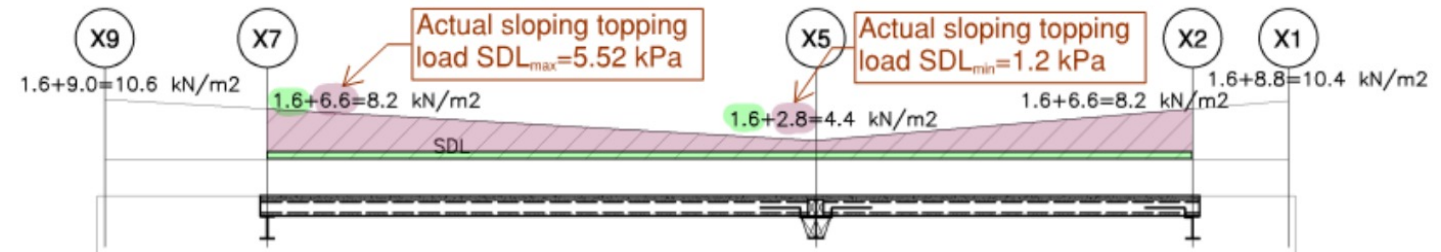


FIGURE 7. Superimposed dead load SDL cross-section diagram.

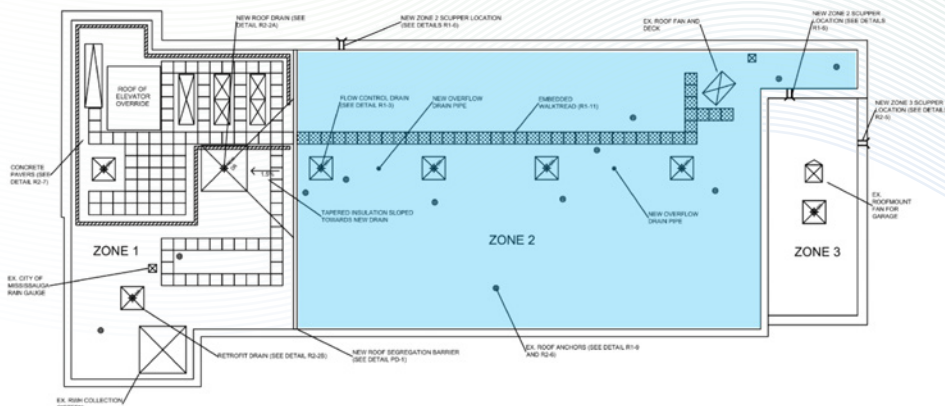


FIGURE 8. Roof Plan

allow for and perform under planned maximum water storage volumes, above the membrane, for prolonged periods outside of winter conditions. The second objective was maintaining high reflectivity white roof membrane surfacing design feature to reduce solar heat gain and building cooling energy loads. The third objective required that the roof membrane not impact the stored water's quality and resist potential chlorine and algicide water treatment additives. Finally, the roof membrane needed to withstand light foot traffic for demonstration and maintenance purposes.

For the new roof membrane, the design team considered fully adhered membranes with redundant, multi-ply, and seamless applications to improve leak resistance and roof durability. A summary of the options reviewed is provided in **Table 2**. All options included the same insulation and vapour barrier details.

Given the following considerations, Option 3 roof assembly including PMMA liquid-applied membrane system over 1-ply modified bitumen SBS base sheet

was ultimately selected.

- » The PMMA liquid applied membrane is installed in a seamless application and can withstand ponded water hydrostatic pressure anticipated in the RID blue roof pilot.³² Combined with a 1-ply modified-bitumen SBS base sheet below, Option 3's membrane system is multi-ply and redundant. The PMMA chemical structure consists of a polymer chains chemically bonded with one another, resulting in homogenous seamless installation.³² It also provides UV resistance and chemical stability, including at chlorine levels above expected treatment threshold of 1 mg/L (8.35x10⁻⁶ lb/gal).³²
- » Option 1 was not selected as the single-ply TPO membrane includes seams not suitable for prolonged periods of ponded water and lacks the multi-ply redundancy desired. In addition, TPO membranes tend to be more slippery when wet as compared to the other membranes considered, adding safety risk associated with occasional foot traffic outside designated walkways.

TABLE 2. Roof membrane design option.

Option No.	Description
1	Like-for-Like Single-Ply TPO Roof Membrane System
2	2-ply Modified Bitumen SBS Roof Membrane System
3	PMMA Liquid-Applied Roof Membrane System Applied over 1-ply Modified Bitumen SBS Base Sheet

» Option 2, although a multi-ply and redundant membrane system, it also includes seams. While there have not been specific RID blue roof studies related to the impact of ponding water on membrane seams, the Canadian Roofing Contractors Association (CRCA) advises against flood testing (i.e. ponding water) as a form of leak detection due to ponded water's hydrostatic pressure impact on seam bond.³³ In addition, modified bitumen cap sheets rely on embedded granules for UV protection. Under sustained ponded water, granules may become disturbed reducing the membrane's UV protection.

» Conventional BUR and ballasted roof assemblies were not considered as the gravel/ballast adds dead load decreasing available capacity for water storage.

Construction cost estimates were prepared for the three options considered. Option 1 was the least costly. Option 2 was ~20% and Option 3 was ~40% more costly than Option 1. All options included a white membrane and EFVM leak detection conductive medium.

The full new roof assembly is illustrated in **Figure 9**. On top of new self-adhered vapor barrier is an adhered in place glass-faced closed-cell polyisocyanurate foam core insulation layer. Above the insulation is a leak detection conductive medium (see section 1.3.3 below) an adhered in place asphaltic overlay board layer, composed of a mineral-fortified asphaltic core formed between two asphalt-saturated fiberglass mat reinforcements. The roofing membrane system includes a 1-ply torch-applied modified bitumen SBS membrane base sheet covered with the two-component PMMA liquid membrane with fleece fabric reinforcement. The PMMA membrane system resin is pigmented to result in designed high reflectively white finish.

At the parapets, above the PMMA membrane upturn height, the roof membrane is comprised of 1-ply torch-applied modified bitumen SBS cap sheet membrane installed over the modified bitumen SBS base sheet. The parapets

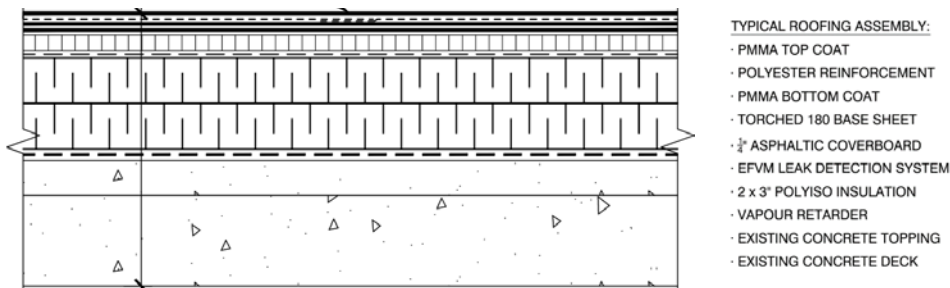


FIGURE 9. Final roof assembly.

are then protected with galvanized steel metal flashings. Roof designated walkways within the blue roof area are comprised of plastic bead and sand particles embedded into the PMMA top-coat during application.

All roof system components are specified by the same roofing manufacturer to maintain consistency and compatibility.

As with all considered assembly options, the final assembly was designed to meet the calculated wind uplift pressures and reviewed against relevant standards, such as CSA A123.21:20, *Standard Test Method for the Dynamic Wind Uplift Resistance of Membrane-Roofing Systems*.³⁴

Leak Detection

Leak detection and roof performance monitoring was added as a design objective to manage the risk associated with the planned ponded water over the roof assembly. Electronic leak detection (ELD) using electric field vector mapping (EFVM) system, meant as a diagnostics and monitoring tool, was integrated into the new roof assembly by introducing

an electronic-detection-conductive medium. ASTM Guide D7877 and ASTM Practice D8231 guided the electronic-detection-conductive medium selection and design.^{26,27} The conductive medium sits between the polyisocyanurate insulation and the asphaltic cover board, comprised of welded stainless-steel mesh. In consultation with the roofing membrane manufacturer, the conductive medium was placed below the coverboard instead of directly below the membrane system to protect the liquid applied membrane. The mesh grid, spaced out at 50 mm by 50 mm (2 in. by 2 in.), is connected through a contact plate and cable to a connection box. During ELD testing, a low-voltage charge is applied through the connection box via a portable pulse generator.

Roof Drainage and Scuppers

The new replacement roof assembly included the following drainage scope to accommodate the blue roof mechanical system design. **Figure 10** and **Figure 11** illustrate the blue roof drains connecting to the mechanical systems below the roof deck.

- » Upgrade the primary roof field drains, including adding a field drain within the blue roof zone, to tie-in the new roof assembly to the new blue roof mechanical sensors, valves, and water treatment/storage systems below the deck.
- » Add new field overflow drains equipped with extension pipes rising above the roof membrane up to the maximum planned blue roof water depth.
- » Add new overflow scuppers through the parapets set at the height of the maximum planned blue roof water depth.

The primary roof field drains control flow and pond water; and when the blue roof is inactive (e.g. in the winter months), they provide primary drainage to meet building design. These drains were retrofitted to include vandal-proof cast aluminum domes and hinged access gates, pan-formed aluminum drain bodies, and cast aluminum clamping rings. The retrofit drains connected to the rainwater leaders below the deck via mechanical coupling connections instead of U-flow friction insert seals as the pipes may experience high flow rate and temporary back-up conditions during blue roof drain down.

The overflow field drains and scuppers divert water, and meet the roof's drainage requirements, if the levels on the blue roof reach maximum planned storage capacity. The overflow scuppers cut into the parapets drain through downspouts terminating at grade as illustrated in **Figure 12**. They

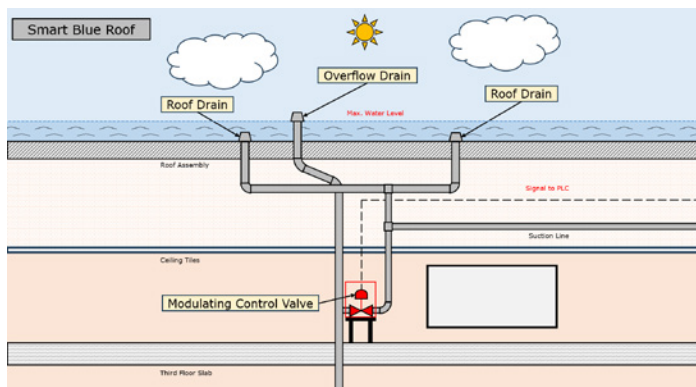


FIGURE 10. Rooftop drainage schematic³

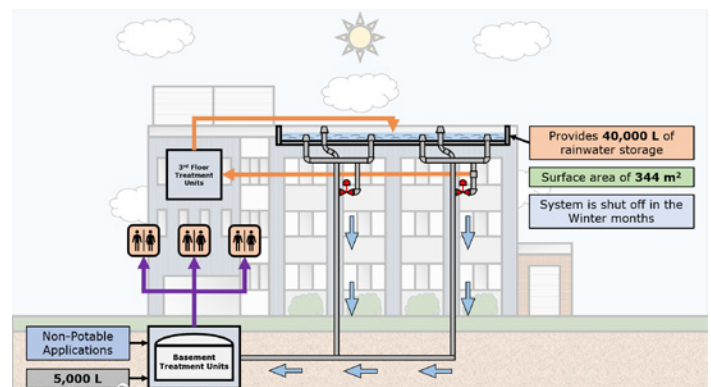


FIGURE 11. Blue roof mechanical system connecting to rooftop drains³

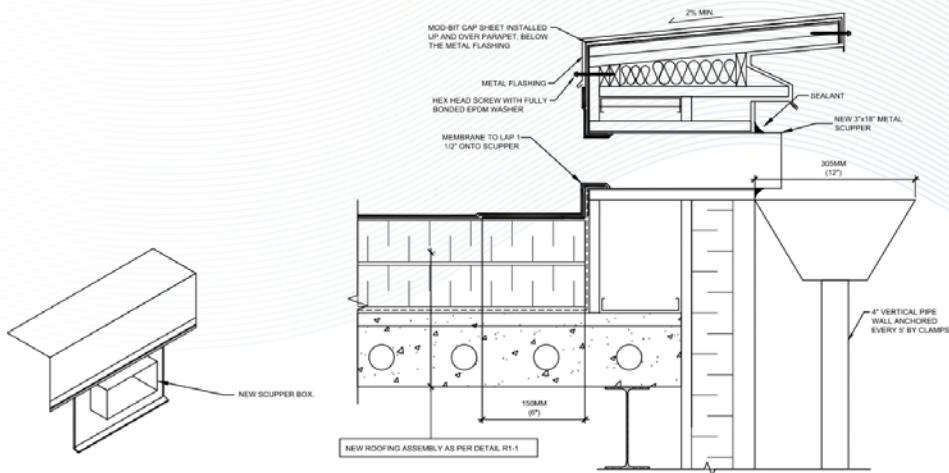


FIGURE 12. Scupper and parapet detail

were placed along the roof edge to make scuppers easier to inspect and were designed to complement the architectural style of the building, integrating with the overall design.

Construction

Construction commenced with removal of the existing roof assembly, followed by adjustments to existing roof anchors to extend them above the maximum planned water level. Surface preparation included cleaning and priming of the existing concrete surface for vapour barrier application, while insulation was installed staggered and tightly butted. ELD conductive medium mesh was installed followed by coverboard and 1-ply modified bitumen SBS base sheet. Surface cleaning was carried out to remove any loose granules, dust, or dirt, prior to the liquid applied PMMA system application. PMMA system application is sensitive to high temperatures, which could lead to improper curing. Ambient and substrate temperatures were closely monitored throughout the process to verify application conditions.

Uncovered concealed conditions during construction, including original structural roof deck precast panels construction tolerances, required some modifications to overflow drain and scupper levels to meet planned blue roof design water storage capacity loads. Multiple methods to validate final installed new roof membrane levels were employed. Based on these actual site conditions, final blue roof

water storage volume and overflow drainage heights were confirmed. Hand tape measurements, laser levels, and total station surveys were completed during several stages of the new roof assembly construction to confirm that the planned maximum storage capacity water levels were maintained.

After construction was completed and installation was commissioned, blue roof water flood testing was conducted to validate the roof and flow control systems integrity. Mobile truck pumped 16,000 litres of water onto the roof and systematic monitoring program was implemented to confirm the absence of leaks and proper operations of the mechanical systems.

Discussion

Implementing this blue roof pilot project at the CVC Head Office in Mississauga is testing this emerging innovative approach to urban water

management and climate resilience. It provided valuable insights into the feasibility and practicality of blue roofs installations in municipal settings, highlighting benefits and challenges encountered during the design and construction phases.

The pilot project incorporated an ongoing maintenance and monitoring program. The mechanical system includes drain sensors and control instruments to regulate flow. These components are scheduled for regular maintenance and monitoring to ensure proper performance. The roof assembly's embedded EFVM conductive medium allows for regular testing for moisture ingress and diagnostics in case of leaks.

Blue roofs by their design, increase the risk by intentionally ponding water. Structural load analysis, and incorporating redundancy and fail-safe mechanisms to the design manages the risks. The design includes two separate types of overflow drainage pathways (i.e. scuppers and drainpipes) to prevent water accumulation beyond safe levels. The roof membrane system and the drain sensors include intentional redundancy to manage risks over the life cycle of the design.

Preliminary analysis conducted by the CVC concluded that the blue roof pilot, in conjunction with their existing RWH, can harvest 8.84 m³/day of non-potable water, surpassing their current demand of 5.68 m³/day.³⁵ It is also projected to save approximately 11.6 GJ of energy annually, translating to 3,210 kWh of electricity and a cost reduction of \$302 annually due to the cooling effects



FIGURE 13. Roof assembly installation in progress



FIGURE 14. Blue roof flood testing in progress

of ponding water.³⁵ Accordingly, the system could reduce greenhouse gas emissions by about 0.2 tons of CO₂e annually.³⁵ CVC has installed monitoring equipment to gather data over the next two years to confirm these projections. Over the coming years, the CVC aims to evaluate the total volume of stormwater diverted from the storm sewer system, monitor roof surface temperatures reduction due to the blue roof, estimate annual water savings from rainwater reuse, and calculate energy savings from rooftop evaporative cooling.³⁵ In addition, TMU is researching this pilot project. Their primary objective is to investigate the public health hazards related to standing water on the roof and consider strategies to mitigate such risks.³⁶ They will also assess the rationale of the 24-hour time limit

for standing water described in the Ontario Building Code.³⁶ The authors of this paper will continue to review and monitor the roofing assembly and its long-term performance.

CONCLUSION

Intentionally ponding water on building's roofs commands greater interrogation of each design element. Designers need to re-consider some of the conventional wisdom and accepted best practices in managing water on roofs. Instead of efficiently moving water off the deck, as most roofs are designed, risk management is employed to sustain ponded water for prolonged periods.

Blue roof systems can present a promising mitigation strategy to the pressing challenges of urban

stormwater management, exacerbated by urbanization and climate change. Through comprehensive understanding of technology classification, historical context, modern applications, and case studies, the impact and risks of this innovative approach on buildings can be managed.

ACKNOWLEDGMENTS

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