High performance roofing and walls technologies. Task 1: literature review on curtain walls

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High Performance Roofing and Walls Technologies

Task 1 — Literature Review On Curtain Walls

Report No. A1–002844-01

Anca D. Galasiu, Wahid Maref and Hamed H. Saber

9 June-2015

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Table of Contents

List of Figures

Summary

This report is the first in a series of reports forming part of a joint project between the National Research Council Canada (NRC) – Construction and Natural Resources Canada (NRCan), Program of Energy Research and Development (PERD) on "High Performance Roofing and Walls Technologies" (A1-002844). The project aligns with the NRCan and NRC-Construction research priorities, addressing the thermal performance of commercial curtain wall systems, a widely used building envelope technology.

The overall objective of the project was to improve the thermal efficiency of commercial building envelopes. Commercial wall assemblies include a wide variety of wall systems, however, the current work addresses only approaches that would improve the effective thermal resistance (R-value) of Curtain Wall Systems.

In commercial buildings, curtain walls often cover a significant part of the building envelope. As such, their impact on the overall performance of the building is important. In order to evaluate, compare and improve the design of curtain wall systems one needs insight into the different calculation and evaluation methods, and the state-of-the-art of their thermal optimization.

The project includes the following five tasks:

- Task 1: Curtain Walls Literature Review
- Task 2: Curtain Walls and the National Energy Code for Buildings 2011
- Task 3: Thermal Optimization in Curtain Walls: Part I - Modelling
- Task 4: Thermal Testing and Optimization in Curtain Walls: Part II - Experiment
- Task 5: 3D Modelling of Curtain Walls

This report is a deliverable of Task 1: Curtain Walls Literature Review. In this report, a literature review was conducted to identify existing knowledge in the area of commercial curtain wall assemblies, including installation methods and state-of-the-art technologies, essential in guiding improvements in the thermal performance of building envelopes. This report focuses mainly on design considerations with respect to the curtain walls thermal performance, and summarizes information from academic publications, relevant sector/industry guides and standards, and selected commercial sources.

The report presents an overview of the following aspects:

- Curtain walls systems designs and installation methods (e.g., face-sealed, water-managed, pressure equalized rainscreen systems);
- Primary functions of curtain wall system components (e.g., vision panels, spandrel panels, frame, etc.);
- Individual performance requirements of curtain walls (e.g., control of air leakage, heat flow, rain and snow penetration, control of water vapour diffusion);
- Implementation of the National Energy Code of Canada for Buildings (NECB, 2011) on curtain wall design. Approaches that would improve the curtain wall thermal resistance to meet the minimum NEBC code requirement were addressed in previous work by Cornick (2013);
- Laboratory/field testing and computer modelling of curtail walls thermal performance, air leakage, water penetration resistance and condensation potential. Limitations of both laboratory and field performance tests, as well as comparisons between simulation results and physical testing are discussed. Computer simulations combined with standard tests of glazing products can be used to determine the overall U-factor of curtain walls, based on an area weighted U-factor of the framing, the glazing edge and the center of glazing regions. Selected examples of building envelope modeling studies, as well as proposed research work related to curtain walls are provided;

- Overview of recent research efforts undertaken in the field of fenestration products, the vision area of a curtain wall system being the most critical component in terms of heat loss;
- Overview of novel and emerging glazing and curtain wall technologies that have entered or are beginning to enter the market (e.g., dynamic glazing transmittance, double-skin systems, building integrated photovoltaics, BIPV).

From a regulatory point of view, this review found that in North America there are no codes or test methods exclusively dedicated to curtain wall systems. The American Architectural Manufacturers Association (AAMA) and the National Fenestration Rating Council (NFRC) are the primary bodies that regulate the window and curtain wall industry in the United States. In Canada, there is no industry standard for the performance of curtain wall systems, however, standards for the performance of windows are established by the Canadian Standards Association (CSA). Laboratory and field performance testing are established by the American Society for Testing and Materials (ASTM).

Overall, the literature review highlighted the importance of using a holistic approach when evaluating the thermal performance of curtain walls systems. Specific standards for curtain wall applications ought to be developed and harmonized in terms of thermal and energy performance, similar to the calculation methods for thermal resistance of building envelope assemblies and the requirements for air barrier assemblies defined in Part 9 of the National Building Code.

On-going work within the current project includes the thermal modelling of curtain wall systems configured as a complete (one-piece) assembly, as an example of an integrated approach to using CFD modelling within the NRC hygrothermal numerical model, hygIRC-C. The results of this model applied to curtain wall systems will be documented in a subsequent report.

Acknowledgements

This work forms part of the National Research Council Canada (NRC) Construction project on High Performance Roofing and Walls Technologies, NRC Project A1-002844, supported by Natural Resources Canada (NRCan), Program of Energy Research and Development (PERD). The authors are very thankful for all the financial contributions and thank Dr. Abdelaziz Laouadi and Dr. Michael Lacasse (NRC Construction) for their detailed review of this report.

High Performance Roofing and Walls Technologies –

Task 1 – Literature Review on Curtain Walls

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High Performance Roofing and Walls Technologies

Task 1 – Literature Review on Curtain Walls

Final Report Task 1

Anca D. Galasiu, Wahid Maref and Hamed H. Saber

1. Introduction

Curtain walls are thin, lightweight, metal-framed walls, consisting of a grid of vertical and horizontal mullions infilled with transparent or opaque panels made of lightweight vision glass, spandrel glass, metal, thin stone, composite materials and plastics. The curtain wall frame is attached to the building structure but does not carry the loads of the building floor or roof. Curtain walls act as a weather barrier for the building, minimizing air and water infiltration and providing light to the interior space. The loads of the curtain wall due to gravity and wind are transferred to the building structure usually at the floor line. Metal-framed wall systems date back to the 1930's, when new sheet-metal technologies and mass production in the automobile and airplane industries also paved the road for new developments in the building construction sector. The curtain wall technology developed rapidly after World War II, when the supply of aluminum became available for non-military use and large area of glass became possible with the discovery of the glass float process (or the Pilkington process, named after the British glass manufacturer Pilkington, which pioneered the technique in the 1950s). The United Nations headquarters, built in New York City between 1949-1952, featured the first complete glass curtain wall. Advances in insulated glazing (e.g., insulating glass units - IGUs – with gas or air-filled space between two or more panes of glass), as well as novel air conditioning and insulation technologies also addressed many of the heating and cooling issues associated with large glazed areas. During the last three decades curtain walls have become increasingly popular in the building construction industry and are considered one of the most significant developments in contemporary architecture.

Curtain walls combine many elements together and there are many factors that can affect their performance or lead to their deterioration. For example, one of the major causes of defects of the curtain wall frame and the panel materials is the failure of the gaskets and seals that connect these components. Gasket and sealant material selection and installation is critical in preventing air and water infiltration. Moisture can enter a curtain wall system and condensation can form on or between the panes of glass. Deformations of the frame can also occur if the water expands during the freeze-thaw cycles. Air leakage can generate drafts or hot/cold spots at the panel edges, which increases the heating and cooling costs. Both air and water leakage can contribute to indoor air quality problems by supplying moisture for mold growth. Water or condensation can remain hidden within the curtain wall system and not become evident until other wall components show significant deterioration, requiring costly repairs or replacement.

Therefore, preventing water and air penetration is of primary importance when designing and constructing curtain wall facades (Vigener & Brown, 2012; Sanders, 2006) or any component of a given building envelope. In addition to the environmental loads (wind, exterior precipitation, solar radiation, heat, air and water vapour flow), curtain walls must also be durable, have sufficient structural strength, respond appropriately to earthquakes and blasts, resist the spread of fire, control sound and vibration, control light, control odours.

In regions with harsh climatic conditions, a substantial amount of energy is used for the heating and cooling of buildings (Al-Homoud, 2005). Although the situation differs from country to country, buildings are generally responsible for about 30-40% of the total energy demand (Vrachopoulos, 2012). In Europe, buildings are responsible for an even higher energy use (40-50%) and the largest share of energy is used for heating (European Commission, 2010). The design of building enclosures with the intent of achieving energy savings can help reduce the building operating loads and the demand for energy over time (Saber, 2011 & 2012). Thermal insulations are major and obvious contributors and a practical and logical first step towards achieving energy efficiency, especially in buildings located in sites with harsh climatic conditions. This can be achieved by increasing the effective thermal resistance (R-value) of the building envelope. Nevertheless, some building envelopes include curtain walls, and large glazed areas and windows contain enclosed airspaces. The thermal resistance of an enclosed airspace depends on the emissivity of all the surfaces that bound the airspace, the size and the orientation of the airspace, the direction of the heat transfer through the airspace, and the temperatures of all the surfaces that define the airspace. Assessing the energy performance of a curtain wall system requires an accurate determination of the R-value of the enclosed airspaces.

2. Types of Curtain Wall Systems

Based on the method of fabrication and installation, the majority of curtain walls installed in Canada and the United States are classified into the following three categories: stick systems, unitized (or modular/panel) systems, and structural glazing systems.

2.1 Stick systems

Stick systems are installed and assembled together on the building structure floor-by-floor, piece-by-piece (generically referred to as sticks; see Figure 1). The frame may be fabricated in a shop environment; however, the other components of the curtain wall, including the glazing, are generally installed in the field. This type of systems can be low cost, using components of standard designs produced in bulk quantities requiring a short time for design and fabrication. They are fairly flexible in terms of creating various building shapes, forms, colours and appearances, and are easy to replace, modify or maintain. However, the installation of stick curtain walls components, which also includes the use of anchors, connectors, setting blocks, corner blocks, pressure plates, caps, gaskets and sealants is labour-intensive. These systems also present a higher risk of air and water penetration or leakage, as the joints between the frame (mullions) and the panels are done on-site and rely on qualified installers to ensure that seals are properly installed. The performance of curtain wall stick systems depends significantly on the quality of workmanship.

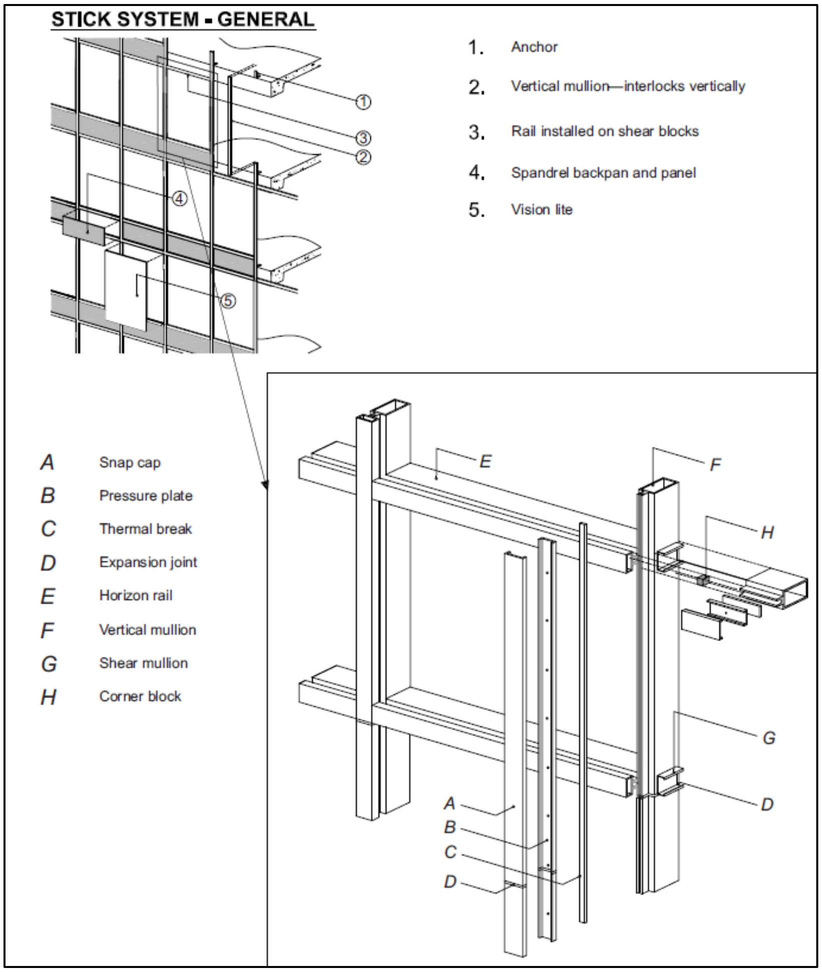


Figure 1: Stick-built Curtain Wall Systems configuration and installation (source: CMHC Guide, 2004)

2.2 Unitized systems

Unitized systems are composed of large modular pre-fabricated glazed units delivered to the construction site for installation. Vertical and horizontal units (typically one story tall, 1.5-2 meters wide) connect together like the pieces of a puzzle, generally providing high performance in terms of water and air leakage due to the factory-controlled environment where they are produced, and the exclusion of numerous components needed on-site by stick-built curtain wall systems. They are also not as labour-intensive during installation, but require the use of lifting appliances and powered mobile equipment. Replacements are also more problematic due to the interlocking nature of the modular units that require proper dimensional accuracy. These systems also present an additional challenge compared to stick built systems, requiring three joints along every mullion and rail (two glasses to aluminum joints and one joint at the junction between the half mullions and half rails) as compared to two joints along every mullion and rail. This increases the potential for air and water leaks by 50%, and if a leak developed at the third joint, there is usually no practical method of accessing the in-between panel joint for repair, unless a serviceable joint system design was specifically provided (Sanders, 2006). Figure 2 shows a Unitized Curtain Wall Systems configuration and installation.

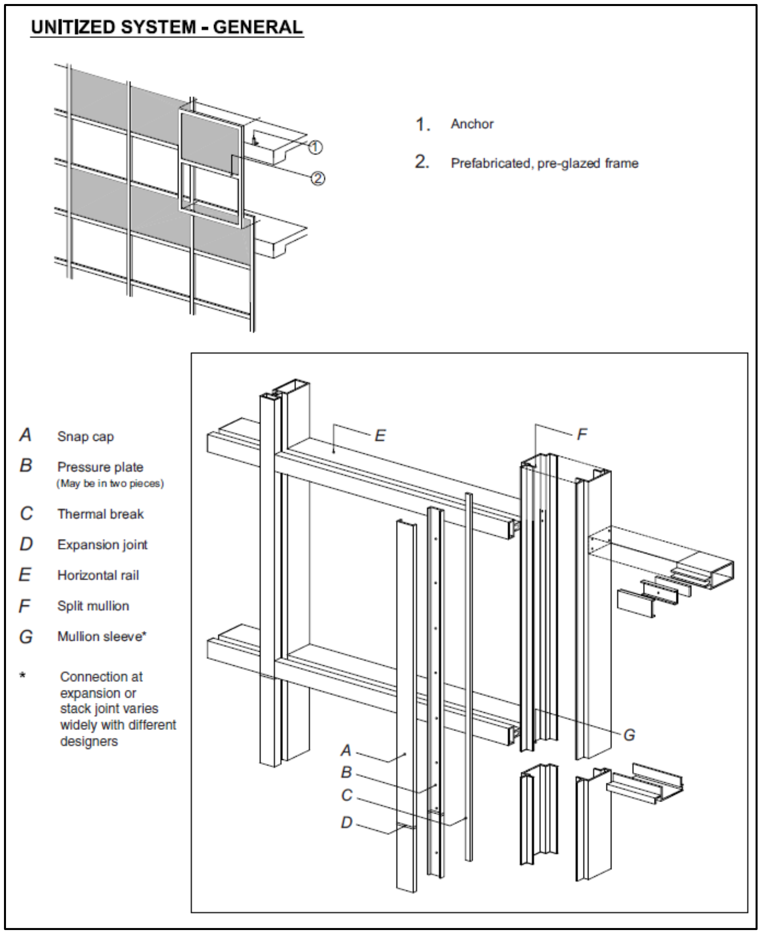


Figure 2: Unitized Curtain Wall Systems configuration and installation (source: CMHC Guide, 2004)

Traditional curtain faring may be built as a "stick system" but the use of unitized systems provides better quality control, while the pre-assemblage of small or large units (typically floor-to-floor) reduces the constraints for field or construction site storage. Figure 3 shows the installation of a glazed unit (McFarquhar, 2012).

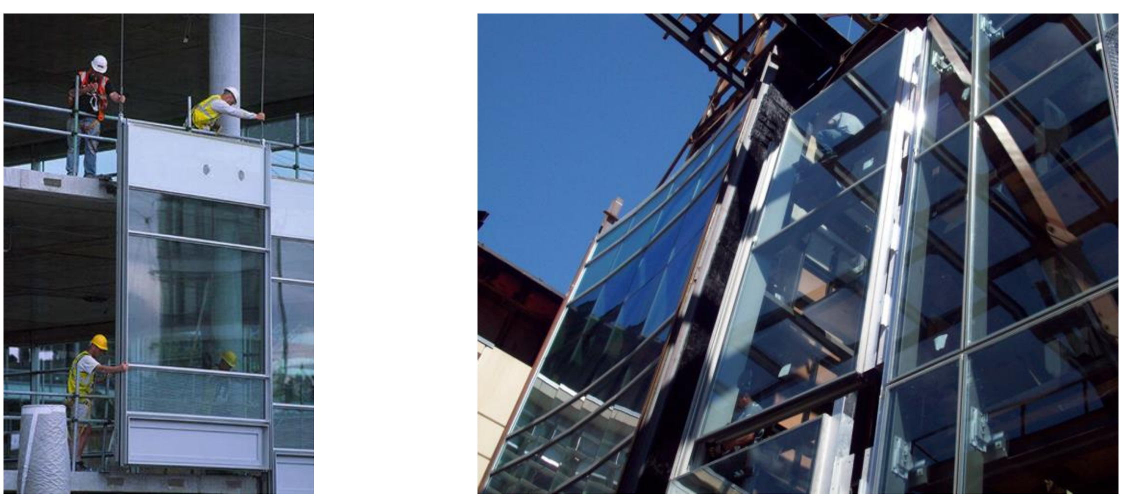


Figure 3: Glazed Unitized/Panelized System (source: Dudley G. McFarquhar, 2012)

2.3 Structural Glazing Systems

Structural glazing systems comprise frameless glazing in which each glazing unit is supported by point fixings, normally bolted connections. The glazing units may be supported individually from a separate framed structure similar to that shown in Figure 4.

There are two types of structural glazing:

- Structural Glazing Systems
- Structural Silicone Glazing Systems

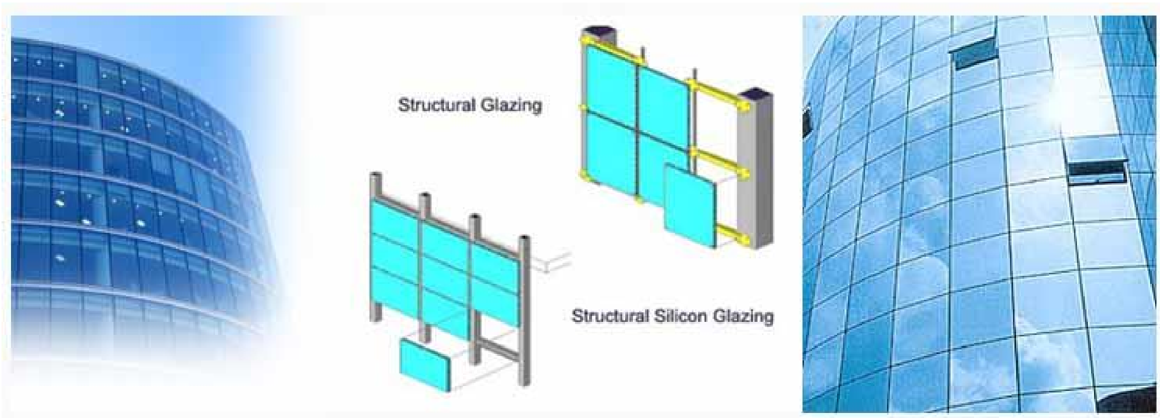


Figure 4: Curtain Walling (Structural Glazing) (source: http://www.tropicalalum.co.tz/?page_id=23)

2.3.1 Structural Glazing Systems

Structural glazing systems are a variation of stick curtain wall systems, designed to maximize the glazed area of the curtain wall system resulting in a building with an even glazed appearance with limited or reduced opaque areas. In these systems the glass unit is bonded to the frame, the aluminum mullions joining together through a vertical joint system, and the gaps between the glazing panels being sealed on the outside with structural silicone sealant (See Figure 5 (a) & (b)). The inner light of the glass unit is held apart from the vertical mullion with a gasket or spacer tape.

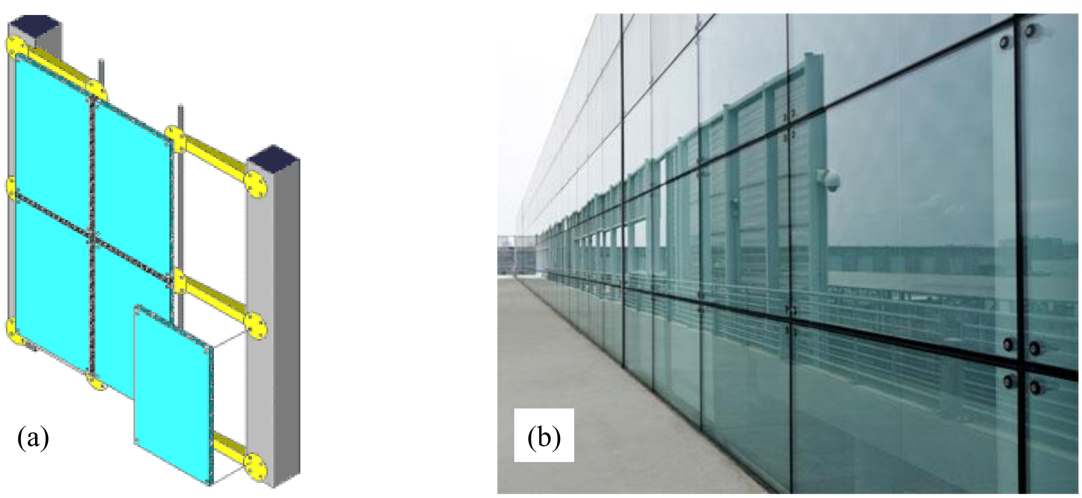


Figure 5: (a) Structural Glazing, (source: http://www.cwct.co.uk/design/options.htm); (b) Structural Glazing Curtain Wall Systems (source: http://www.hdwalls.xyz/images/structural-glazing-curtain-wall-systems-supplier

2.3.2 Structural Silicone Glazing

Structural sealant glazing is a method of bonding the glazing units to the frame. This has the advantage that the glazing appears from the outside of the building to be frameless (called also curtain walls with "invisible" mullions or transom curtain walls). In practice, the glazing is bonded to a carrier frame bolted to a framing system similar to that of a stick curtain wall. The glazing may be bonded on two edges (and framed on the other two) or it may be bonded on four edges (See Figure 6 (a) & (b)).

In Canada, stick systems are typically used in lower rise buildings. As the building height and footprint increases, the use of unitized systems also increases. Most of the very large or very tall curtain wall buildings constructed in Canada since the mid-1980s use the unitized system (CHMC, 2004). Structural glazing systems have also become increasingly popular (e.g., Ottawa Convention Centre, ON, built 2009-2011, http://glassmagazine.com/article/commercial/most-innovative-curtain-wall-project-118737).

(a) (b)

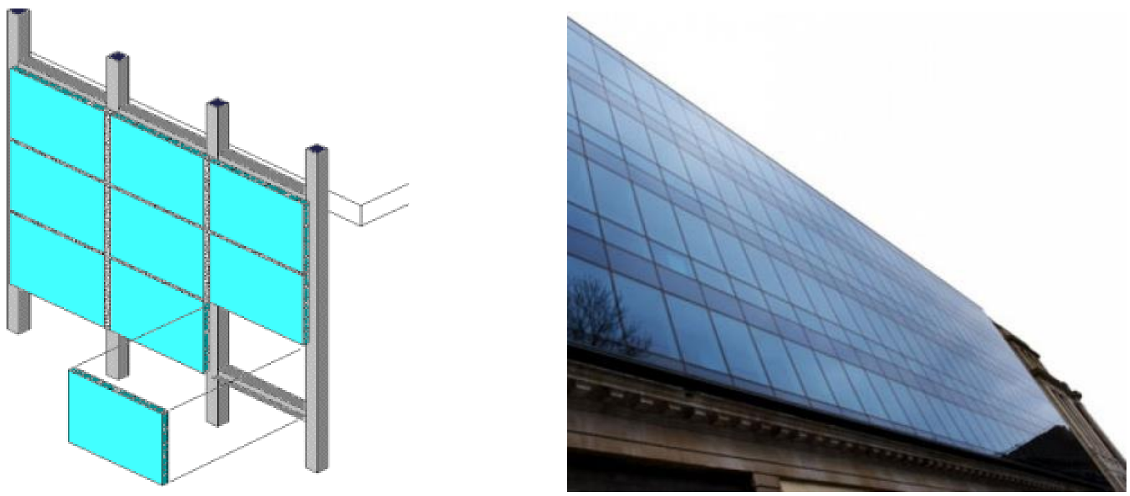


Figure 6: (a) Structural Silicone Glazing, (source: http://www.cwct.co.uk/design/options.htm), (b) Structural Silicone Glazed (SSG) Curtain Walling Suites (source: http://www.hdwalls.xyz/images/structural-silicone-glazed-ssg-curtain-walling-suites)

3. Description of Curtain Walls

In its basic form, a curtain wall consists of a metal frame (mullions) and a combination of transparent (vison glass) and opaque (spandrel panels) infill panels. The primary materials used are aluminum, steel and glass, along with secondary materials such as sealants, rubber gaskets and insulation products. The frame is attached to the building floor slabs and can have a tubular- or open-shaped profile. Clear glass panels are used as infill to provide vision (IGU: insulated glass units). Coated glass or panels made of metal, stone, plastics, ceramics, or other suitable materials, are used for opaqueness and are called spandrel panels (Figure 7). The weight of the entire assembly is taken up at each floor level and the wind loads must be resisted by the individual panels and these in turn transferred to the mullions themselves.

3.1 Vision Panels

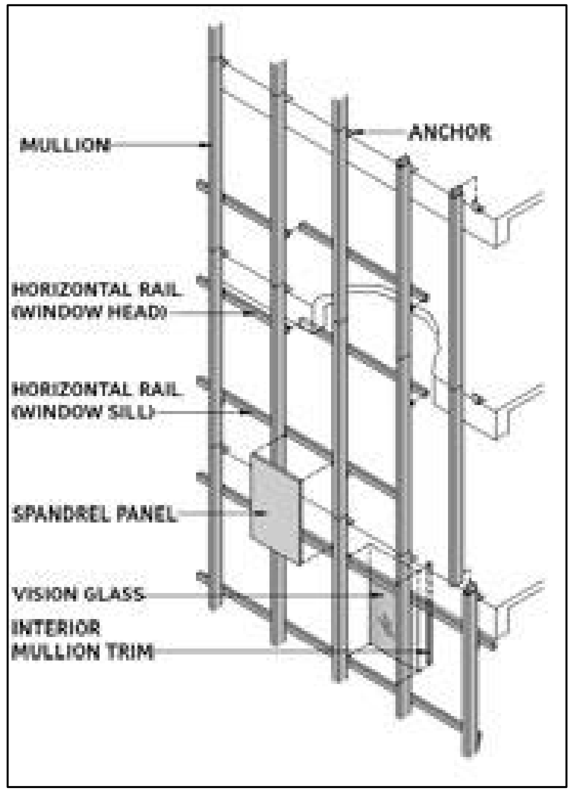


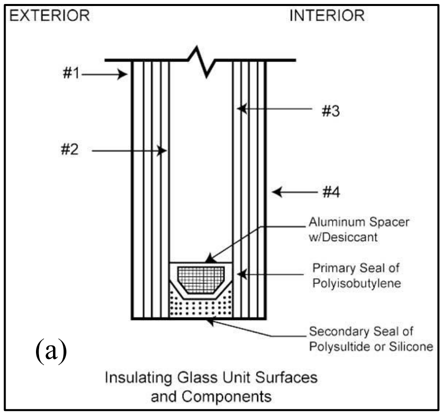
Figure 7: Basic components of a typical curtain wall system (source: Sanders, 2006)

Generally, due to its brittle nature, glass is significantly affected by the presence of cracks and defects, stresses such as those that arise due to impact, bending and point loads, as well as wind and thermal loads. Therefore, the vision glass used in curtain walls requires special designs and considerations in terms of safety, stability, impact-resistance, durability and cost. *Float, sheet or plate glass* breaks into large and sharp pieces or fragments, which constitutes a safety hazard. *Annealed float glass* withstands wind loads and some thermal loads relatively well; however, when used with coatings, tinted or in insulating glass units (IGUs) the thermal stresses rise considerably. To increase resistance to thermal breakage, annealed glass is factory-treated using a heat-tempering process and becomes heat-strengthened glass or tempered glass. *Chemically strengthened glass* involves chemical tempering instead of heat tempering and is similar to tempered glass in its qualities and uses. *Laminated glass* is made of two or more layers of glass with an invisible plastic interlayer, usually polyvinyl butyral (PVB), which keeps the glass from shattering. Combining laminated and tempered glass in a single pane produces a very strong and secure glazing product. *Tinted (green, bronze, grey, blue) glass* and *reflective glass* is used to control the solar and light transmittance, as well as for aesthetic reasons (Sanders, 2006).

3.1.1 Insulating glass units (IGUs)

Insulating glass units (IGUs) are the standard vision units used in curtain wall systems and have three basic components: *the glass, the edge spacer and the edge sealant* (Figure 8). IGUs are made of two or more panes of glass with hermetically sealed dry-air or gas-filled space(s) between them, which improves their energy efficiency. Argon is the most popular gas fill due to its low cost and UV-stability, as well as its colorless, non-corrosive and non-toxic nature, followed by krypton or more rarely, xenon, used mostly in narrow IGUs. The use of inert gas reduces the heat transfer through the glass due to its low thermal conductivity (the wider the gap between the panes, the lower the level of the transferred heat). Krypton and xenon have considerably lower thermal conductivities than argon, however, they are considerably more expensive than argon.

Reflective and low-emissivity (low-e) coatings (of very thin pure metal or metal oxide layers) can also be applied for solar (ultraviolet and infrared radiation) control, as either hard (e.g., cobalt, iron, chrome, tin) or soft coat (e.g., silver, copper, chrome, titanium, stainless steel) products. Soft coats are vulnerable to scratching and corrosion and are sealed within the air space in the IG unit (surface 2 or 3). Reflective coatings act like a mirror reflecting the heat back to the exterior, whereas low-e coatings reflect the heat back to the warmer side, reducing either the solar gains in the summer or retaining the interior heat in the winter and increasing the overall IGU energy efficiency. When combined with the thickness of the glass



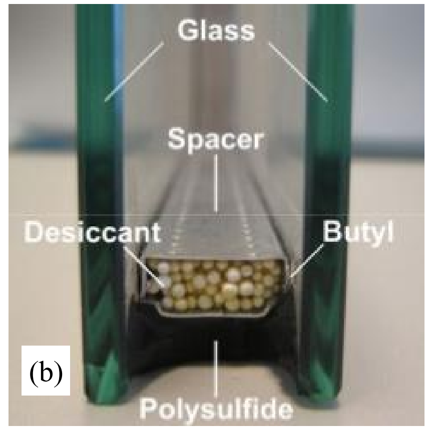


Figure 8: Components of a standard double-pane glass insulating unit (IGU) (source: (a) http://www.insuliteglass.com/insulating.html); (b) http://www.slideshare.net/VinaySrivastava7/microsoft-power-point-facade-presentation-compatibility-mode

panes, the overall thickness of an IGU lies generally between 22-25 mm for 3 mm plate glass, and 28-31 mm for 6 mm plate glass. Suspended coated films between the inner and outer panes can be used to replace the third and fourth pane of glass and reduce the IGUs overall weight. Typically, standard double-pane IGUs consisting of two clear uncoated glass panes with air in the cavity have U-factors of 2.85 W/m^2K (R-values of 0.35 m^2K/W). Standard double-pane IGUs filled with inert gas have lower U-factors between 0.2-0.5 W/m^2K (R-values 2-5 m^2K/W). Triple-pane glazings have U-factors ranging between 0.16-0.25 W/m^2K (R-values 4-6 m^2K/W), however, their thickness and weight makes them uncommon in standard curtain wall applications (Lux Research, 2012).

Traditionally, *spacers* have been made of aluminum or galvanized steel. However, metal spacers have high thermal conductivity and act as a heat conductor, undermining the ability of the IGU to reduce the heat flow, resulting in condensation at the bottom of the sealed unit because of the heating/cooling loss through the window. To reduce the heat transfer through the spacer and increase the overall IGU's thermal performance, spacers can be made of less-conductive materials such as pre-desiccated structural foam and thermoplastics (warm-edge technology).

IGUs for curtain wall applications are produced with *double-seal designs*, which use a primary sealant (polyisobutylene) as a barrier to vapour flow, and a secondary sealant to hold the unit together (hot melt butyl, polysulphide, polyurethane and silicone). In addition, IGUs used for structural glazing systems (where the glass is adhesively bonded to the framing) differ from non-structural silicone glazing. In this case, the secondary seal of the IGU must be made of silicone, silicone being the only edge seal material that has adequate UV durability and strength for such applications. The width of the secondary seal must also be designed to accommodate the wind loads (beyond the dimension needed to accommodate the normal internal stresses in the IGU), which results in a secondary seal of at least 6 mm in width and a dual sealed silicone unit (CHMC, 2004). Black anodized edge spacers are usually used in structural glazing systems to give the appearance of large or continuous glass.

Additional information about window spacers and edge seals can be found in the state-of-the-art review by Van Den Bergh et al. (2013).

3.2 Spandrel Panels

Spandrel panels are commonly used to cover construction elements and materials on the outside of a building. Heat-strengthened (tinted or opaque) *spandrel glass* is the most commonly used, as well as the best performing spandrel material in terms of wind and thermal loads. Reflective or film (ceramic) coatings and insulation can make the spandrel glass perform more like a wall than as a glass pane. Metal or stone panels are also used as spandrel infills. Metal panels are usually made of aluminum, or of sheets of steel or aluminum and a core (e.g., composite panels). The most common stone used in curtain wall applications is granite (CHMC, 2004).

3.3 Frame

The most common framing material for glass and metal curtain wall systems in North America is an aluminum extrusion (e.g., alloy AA6063). In some applications fiberglass framing is also used.

Anchors are used to cast or drill the curtain wall frame into the building floor slabs. Rubber gaskets or tapes made of neoprene, ethylene-propylene-diene-monomer (EPDM) and silicone are used in the joints to cushion the glass edge and prevent metal contact that may lead to breakage, and to seal the glass perimeter to prevent water penetration and air leakage. Gaskets rely on their elasticity and interface pressure to create and maintain a seal, however, they can dry, shrink and crack, creating small openings through which air, water or moisture can enter and damage the integrity of the curtain wall system. Corners are the most susceptible areas for water and air leakage. In cold climates, a special treatment is applied at both the exterior gaskets to address water penetration, and at the interior gaskets to address air leakage. Obtaining adequate performance from the joints at the interface between the curtain wall and the building is of utmost importance (CHMC, 2004).

Figure 9 shows a typical wall section of a stick-built curtain wall system. The air barrier plane includes the:

- Glass of the IGU
- Seal between the glass and the aluminum mullion
- Aluminum of the mullion
- Seal between the aluminum mullion shoulder and the back pan
- Metal liner of the back pan
- Seal between the bottom of the metal pan, and
- Shoulder of the mullion, which connects with the glass of the sealed unit below.

The leakage of air at the glass aluminum joint is minimized with either a wet or dry seal. In a unitized curtain wall system, the mullions are split and, therefore, include an additional air barrier joint between the half mullions. This joint is usually hidden and inaccessible once assembled (Quirouette, 1982).

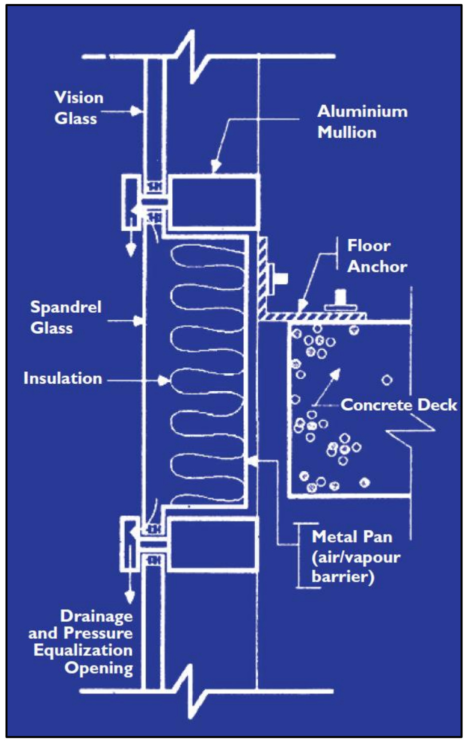


Figure 9: Wall section of a typical stick-built curtain wall system (Quirouette, 1982)

4. Curtain Wall System Designs for HAM Control

The previous section presented the different types curtain wall systems, along with their components, functionality and installation. The following section describes the curtain wall designs in terms of ***Heat, Air and Moisture (HAM) control***.

Curtain walls must meet the same basic performance criteria as all types of walls; however, the non-absorbent nature of glass and metal-frame imposes special constraints on their design. For example, water penetration must be controlled by either a seal or by drainage, as glass and spandrel panels cannot absorb and store water for re-evaporation as is the case for masonry or stone walls. When rain and wind impinge on the surface of the curtain wall, water may be pushed into the glazing cavity through gaps in the outside seals, where it can accumulate and overflow into the building at the floor, ceiling or window head.

The window frame design is also significantly important, as the frame's thermal performance is usually the main cause for a window's low overall thermal transmittance. The Passivhaus Institute in Germany states that windows (glazing and frames combined) should have U-factors lower than 0.8 W/m^{2}K, which generates the need for highly insulating frames with U-factors in the range of 0.7-1.0 W/m^{2}K (Gustavsen et al., 2010).

There are three types of curtain wall system designs: face-sealed, water-managed and pressure-equalized rainscreen systems. Pressure-equalized rain screen systems provide the highest level of protection to air and water infiltration, followed by water-managed systems as the next most reliable, and face-sealed as the least reliable.

4.1 Pressure-equalized rain screen systems

Pressure-equalized rain screen systems are designed to block all of the forces that can drive water through any available leakage path into the building (kinetic, gravity, capillary, action tension, surface tension, pressure gradients due to wind and rain). The inside of the glass unit, the glazing pocket and the interconnecting gasket or wet seal function as an air barrier. The outside of the glass unit, the exterior glazing materials and the exposed face of the aluminum framing function as a rain screen, shedding the water away. A pressure-equalization compartment is formed in the glazing pocket between the rain screen and the air barrier, which reduces the water penetration by equalizing the pressure differential. Weep holes are provided to act as vents for air movement between the exterior and the glazing pocket, and to prevent water entry into the glazing pocket. All interfaces between the adjacent units (IGU, spandrel, mullions, etc.) are isolated and are made air tight with plugs or seals, maintaining the continuity of the air barrier (Figure 10 and Figure 11)

Pressure-equalized rain screen systems require sophisticated design and detailing. An analysis of the time and spatial distributions of the wind pressures that takes into account the aerodynamic characteristics of the building is needed to develop an effective strategy. Designers often confuse rain screens with drain-screens and add unnecessary cost to low-rise buildings where the latter strategy is sufficient.

Figure 11 shows a curtain wall detail as a partial rain screen. The rain screen concept can be applied to curtain walls to create a wall assembly made of a face-sealed system (the glazing unit), a rain screen wall (the spandrel panels), and a set of rain screen joints. The wall section shows how the spandrel works as a rain screen wall. The spandrel glass panel is the cladding, and a pressure-equalization cavity (P.E. Air Chamber) is formed between the spandrel panel and the metal back pan. The air barrier incorporates the back of the sealed glazing unit, the shoulder of the sill mullion, the back pan, the shoulder of the header mullion, the back of the next glazing unit, and so on. Seals are required to maintain the air barrier continuity, consisting typically of a wet sealant (glazing tape) or a gasket installed between the window face and the mullion shoulder, and glazing tape or sealant installed at the joint between the back pan and the mullion.

4.2 Water-Managed Curtain Walls

Water-managed curtain walls include systems where the water drains from the glazing pocket, but no air barrier is provided between the glass units and the spandrel units and, therefore, a larger amount of water enters into the system and must be drained. The pressure differential between the glazing pocket and the interior may also be sufficiently high to drive the water vertically, beyond the interior gaskets, which can result in water ingress.

4.3 Face-Sealed Curtain Walls

Face-sealed curtain walls depend on a continuous and perfect seal between the glass units and the frame, as well as between all the frame members, which affects their long-term reliability.

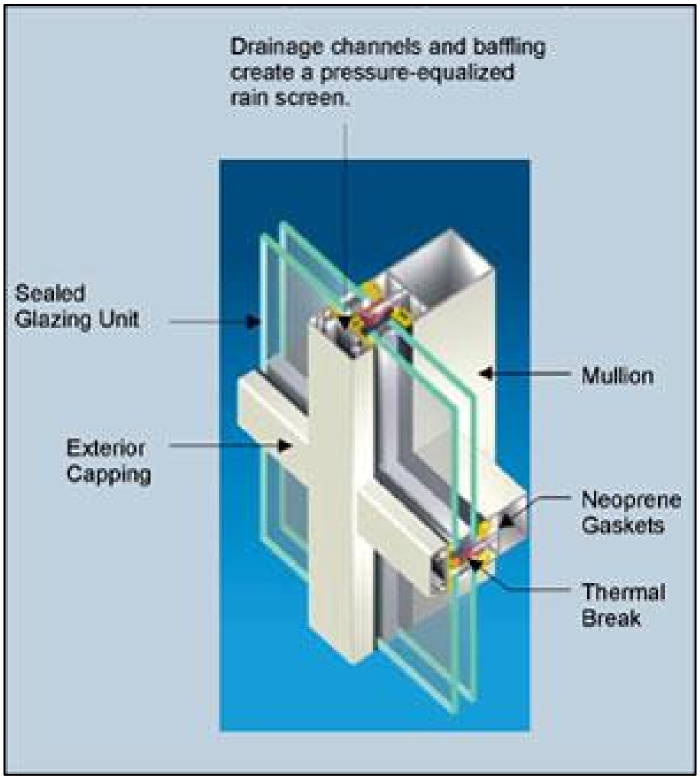


Figure 10: Manufactured Curtain Wall Systems achieving a pressure equalized rain screen (source: http://www.canadianarchitect.com/asf/enclosure_design_strategies/enclosure_strategies/enclosure_strategies.htm)

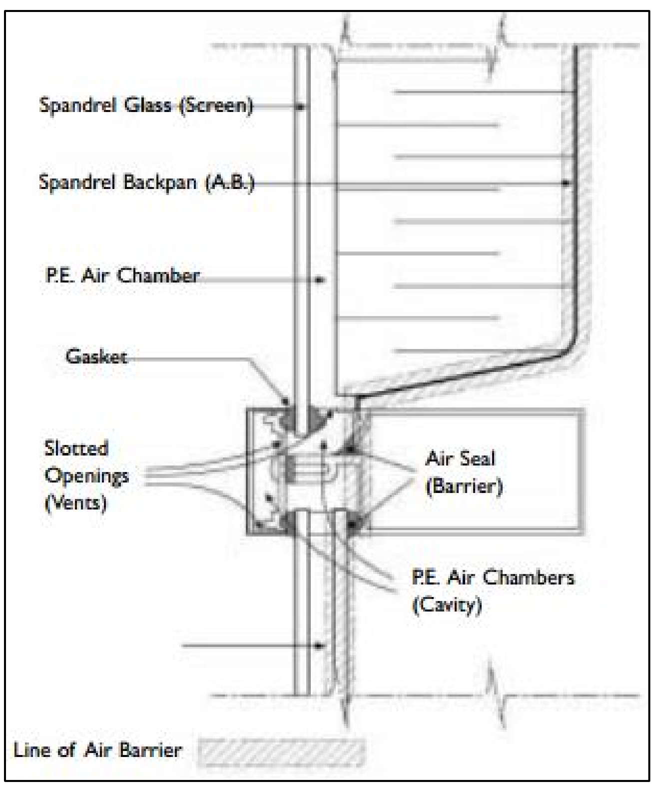


Figure 11: Rain screen concept applied to a curtain wall (source: https://www.cmhc-schl.gc.ca/en/inpr/bude/himu/coedar/upload/The-Rain-Screen-Wall-System.pdf)

4.4 Performance Requirements for Curtain Walls

Curtain walls must meet many individual performance requirements, including (but not limited to):

- Control of air flow and air leakage;
- Control of heat flow;
- Control of rain and snow penetration, and;
- Control of water vapour diffusion.

Each is discussed in turn.

4.4.1 Control of air flow and air leakage

Control of air flow and air leakage is achieved through the continuity of the air barrier between the glass panel, the air seal at the shoulder flanges of the mullion, the aluminum section to the other flange surface, the air seal between the lower shoulder flange of the mullion and the metal pan of the spandrel glass (pane), the metal pan, the air seal to the next mullion connection, and so on (Figure 12-(1)). The connections or interface joints between the curtain wall system and the other parts of the building (e.g., parapets, corner interfaces, grade connections, masonry walls, precast panel interfaces, steel sidings, soffits, sloped walls, glass roofs, etc.) also require special design considerations to ensure the continuity of an adequate air and thermal barrier connected to the curtain wall. Additional information on this topic can be found in Quirouette (1982) and Goncalves & Rousseau (2007).

4.4.2 Control of heat flow

Control of heat flow is achieved through use of insulation behind the spandrel glass or the opaque panels.

4.4.3 Control of rain and snow penetration

Control of the rain and snow penetration is based on the "rain screen principle", mentioned above and characterized by a pressure-equalization cavity behind the exterior surface, connected to the exterior but sealed as tightly as possible from the building interior (Figure 12-(2)).

4.4.4 Control of water vapour diffusion

Control of water vapour diffusion is met through the incorporation of a water vapour barrier positioned on the warm side of the insulation material.

Special considerations must also be given to the installation of the curtain wall assembly to ensure adequate performance. Issues that can impact a correct installation may be due to tolerances between the curtain wall components and the supporting building structure, improper construction sequencing, damages from other trades, installers' lack of understanding of the curtain wall design, poor construction practices, all of which can result in modifications to the curtain wall system, the adjacent systems, and the integration between the systems. Deviations from the original design, if not properly addressed, can cause performance failures of the curtain wall system. For more information on this topic see Peevey (2011).

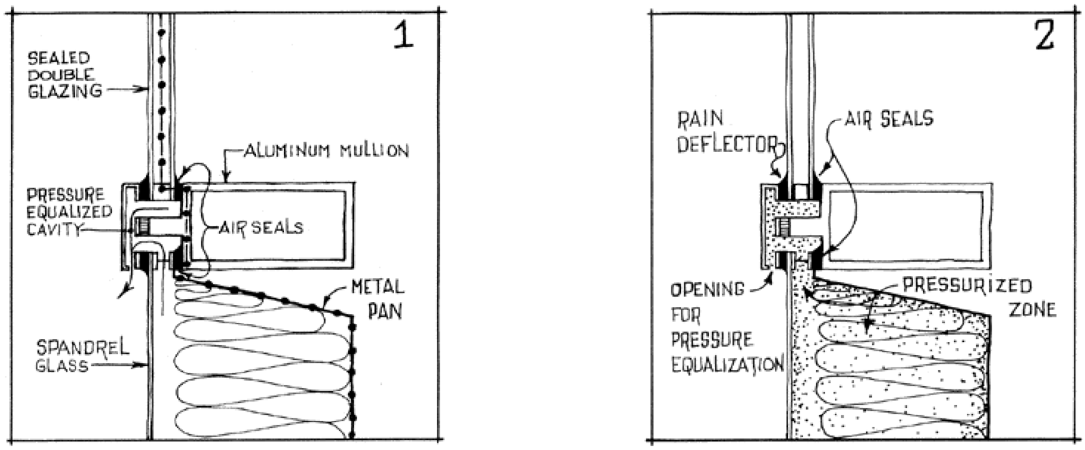


Figure 12: Illustration of curtain wall air barrier (1) and the rainscreen system (2) (source: Quirouette R., 1982)

5. Curtain Walls Performance as Addressed in Codes and Standards

The United States and Canada have industry standards which establish stringent performance requirements and testing methods for windows and curtain walls. The American Architectural Manufacturers Association (AAMA) and the National Fenestration Rating Council (NFRC) are the primary bodies which regulate the window and curtain wall industry in the United States. In Canada, there is no industry standard for the performance of curtain walls; however, standards for the performance of windows are established by the Canadian Standards Association (CSA). In addition, testing methods to evaluate both laboratory and field performance are established by the American Society for Testing and Materials (ASTM) in both the United States and Canada (Goncalves & Jutras, 2007).

5.1 The National Energy Code of Canada for Buildings (NECB 2011)

The National Energy Code of Canada for Buildings (NECB, 2011) provides the minimum requirements for the design and construction of new energy-efficient buildings, covering the building envelope, HVAC systems, water heating, lighting, provision of electrical power systems, and motors. To date the NECB code has been enforced only on federally owned buildings, with Ontario being the only province that has adopted it in its provincial code. The City of Vancouver and the province of British Columbia use ASHRAE Standard 90.1-2007 Energy Standard for Buildings except for Low-rise residential buildings. The other Canadian provinces have no enforceable building energy performance standards referenced in their provincial codes (McDonell, 2012).

A cursory survey of a few major curtain wall manufacturers indicated that meeting the prescriptive requirements of the NECB should not be problematic for the industry. In Europe, the much more stringent energy codes have not been an obstacle to the curtain wall industry and, in fact, these codes have stimulated much innovation in products and design (Cornick, 2013).

For vision glass, the maximum overall thermal transmittances (U-factors) of 1.6 W/m^{2}K and 2.4 W/m^{2}K for climate zones 8 and 3, respectively, are within the range of commercially available high performance systems. However, the requirement for the opaque spandrel panels, which range between 0.315 W/m^{2}K (R18) to 0.183 W/m^{2}K (R31), may require thicker units than normally used. Required insulation thicknesses for spandrel panels would range between 76 and 131 mm for climate zones 3 and 8, respectively, using current insulation products. The spandrel thicknesses may become problematic when attempting to trade-off the vision glass area with an increased spandrel panel U-value.

The challenge for the curtain wall industry comes with the desire to exceed the maximum allowable Fenestration and Door to gross Wall area Ratio (FDWR). Ultimately this will require:

- The use of triple, quadruple or multiple layers through the combination of glass and/or thin films with low emissivity and spectrally selectively coatings and/or vacuum evacuated glazing;
- Optimization of the vision glass areas (i.e., using energy simulation tools to tailor the vision glass to the orientation of the building to minimize heat losses or gains);
- Significantly improved thermal break systems;
- Significantly improved spandrel panels, potentially incorporating vacuum insulated panels;
- Double skin façades;
- Better building optimization where the HVAC systems are better suited to high performance envelopes; elimination of perimeter zones for example can offset the cost of the envelope.

5.2 Standards

5.2.1 Standards for Laboratory Performance

Figures 13 to 15 show examples of mock-up installations conducted at the Air-Ins Laboratory, Building Envelope Laboratory and Consulting (CLEB), Varennes, QC, Canada.

The following North American industry standards are commonly used to establish *laboratory performance criteria* for windows and curtain walls:

- **AAMA/NWWDA-101:** Voluntary Specifications for Windows and Glass Doors; Outlines laboratory performance requirements with regards to resistance to water penetration, air leakage resistance and wind load resistance for windows and glass doors (United States).
- **CAN/CSA-A440:** Windows; Outlines laboratory performance requirements with regards to resistance to water penetration, air leakage resistance and wind load resistance for windows (Canada).
- **AAMA 501:** Methods of Test for Metal Curtain Walls; Outlines laboratory performance requirements with regards to resistance to water penetration, air leakage resistance and wind load resistance for metal curtain walls (United States).
- **NFRC 102:** Steady-State Thermal Transmittance of Fenestration Systems; Outlines laboratory performance requirements with regards to thermal performance of fenestration products (United States).
- **NFRC 100-2014:** Procedure for determining the U-factors of fenestration products; Used to evaluate the thermal performance of window and curtain wall systems; Provides guidelines for product lines and custom products (e.g., address different sizes, select a test matrix, rules for extrapolation, etc.). For the simulation and calculation of individual window frames the document refers to ISO 15099. Only area-weighed methods are allowed (United States).
- **AAMA 1503:** Voluntary Test Method for Thermal Transmittance and Condensation Resistance Factor for Windows, Doors and Glazed Wall Sections; Outlines laboratory performance requirements with regards to thermal performance and condensation resistance of windows, doors and glazed wall sections (United States).
- **CSA/A440.2:** Energy Performance of Windows and other Fenestration Products; Outlines laboratory performance requirements with regards to thermal performance and condensation resistance of windows and other fenestration products (Canada).

Figure 13: Interior mock-up test (CAN/CSA-A440) at the Air-Ins Laboratory, Building Envelope Laboratory and Consulting (CLEB), Varennes, QC, Canada (source: Goncalves et al., 2007)

Figure 14: Exterior mock-up test (AAMA 501) at the Air-Ins Laboratory, Building Envelope Laboratory and Consulting (CLEB), Varennes, QC, Canada (source: Goncalves et al., 2007)

5.2.2 Standards for Field Performance

Figure 16 shows an example of field testing of a curtain wall resistance to water penetration.

The following North American industry standards are commonly used to establish *field performance criteria* for installed windows and curtain walls:

- **AAMA 502:** Voluntary Specification for Field Testing of Windows and Sliding Glass Doors; Outlines field performance requirements with regards to resistance to water penetration and air leakage resistance for windows and glass doors (United States).
- **AAMA 503:** Voluntary Specification for Field Testing of Storefronts, Curtain Walls and Sloped Glazing System; Outlines field performance requirements with regards to resistance to water penetration and air leakage resistance for Storefronts, Curtain Walls and Sloped Glazing Systems (United States).
- **CAN/CSA-A440.4 (appendix D)**: Field Testing of Window and Door Installations; Outlines field performance requirements with regards to resistance to water penetration and air leakage resistance for windows and doors (Canada).

Figure 15: Environmental test chamber (CSA/A440.2) at the Air-Ins Laboratory, Building Envelope Laboratory and Consulting (CLEB), Varennes, QC, Canada (source: Goncalves et al., 2007)

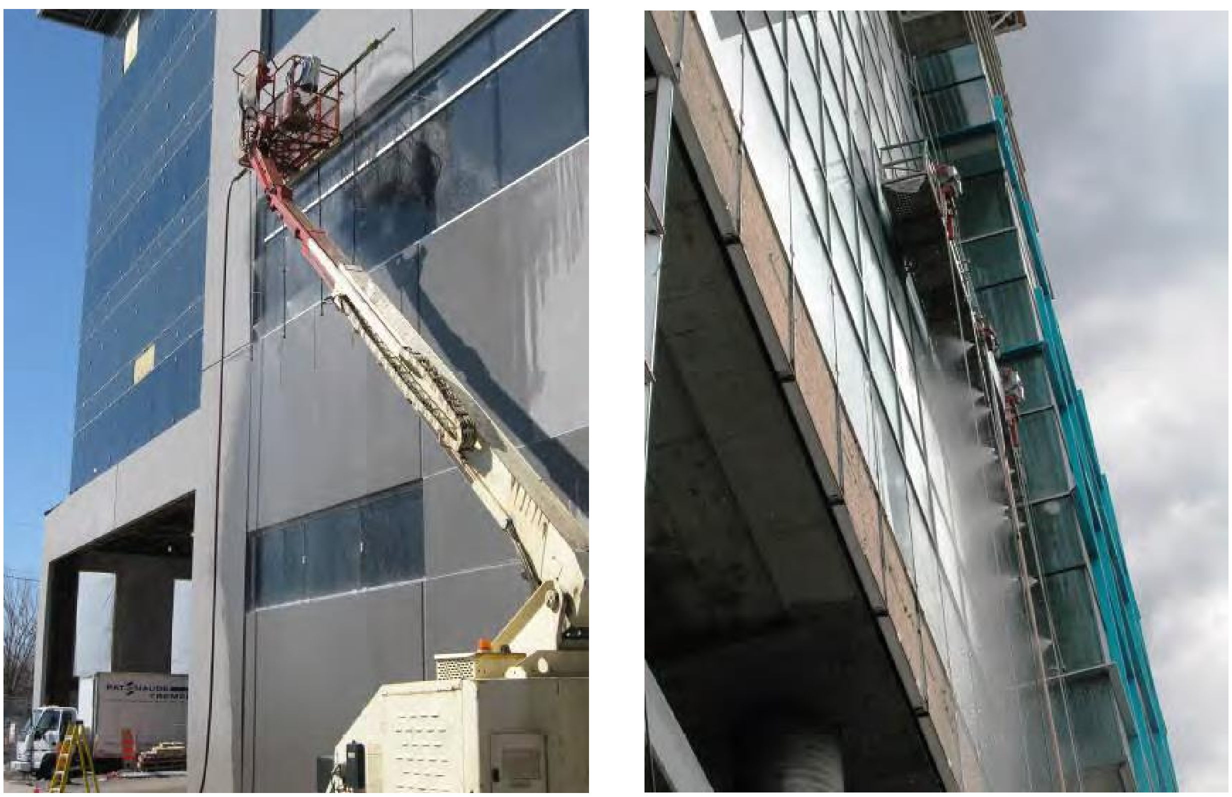


Figure 16: Field testing (CAN/CSA-A440.4) for resistance to water penetration (source: Goncalves et al., 2007)

5.2.3 Other Guidelines and Standards related to Curtain Walls and Glazing

Other organizations that provide information, guidelines or standards related to curtain walls and glazing include:

- **CSA/CGSB Standards** (Canadian Standards Association / Canadian General Standards Board) develops standards for construction materials. Laws and regulations in most municipalities, provinces and states in North America require certain products to be tested to a specific standard or group of standards by a nationally recognized testing laboratory. Currently forty percent of all the standards issued by CSA are referenced in the Canadian legislation.
- **ASTM Standards** (American Society of Testing Materials), Glass and Glazing Standards.
- **GANA** (Glass Association of North America), Glazing manual.
- **AA** (Aluminum Association), Aluminum Design Manual.
- **ACI** (American Concrete Institute), ACI-318-08, Building Code Requirements for Structural Concrete and Commentary.
- **IBC-ASCE 7** (International Building Code & American Society of Civil Engineers), Standard for Minimum Design Loads for Buildings and Other Structures.
- **Building Design Guide Industry Standards** (e.g., National Institute of Building Sciences (NIBS) - Building Envelope Design Guide for Curtain Walls; Marble Institute of America (MIA) - Standards of Natural Stone Workmanship and Practice, etc.).

As of Jan. 1, 2011, the Government of British Columbia has legislated that every new glazing system installed in the province must have a U-value below 2.85 W/m^2K. Even in parts of the country where energy regulations are less strict, there has been an emphasis on improving the overall performance curtain wall buildings (Porayko, n.d.) http://www.glasscanadamag.com/content/view/1821/59/).

Presented solutions include:

- Thermally broken curtain wall systems instead of thermally improved systems (e.g., the Alumicor thermally broken stick built system design, Thermawall, which incorporates a structural polyamide thermal break and triple-sealed glazing units with two thermal breaks).
- Use of whole building 3-D rendering software and Building Information Modeling (BIM). Projects in the United States already mandate that all sub-trades use BIM software in order to qualify for tender submissions.
- Latest designs of frames have a higher performance thermal break that replaced the PVC material with a polyamide-based material (up to 3.5 cm wide) offering a thermal break of 80%. The wider the bar the greater the separation between the exterior aluminum and the interior frame tube. Polyamide is also very stable, resilient, and UV-resistant.
- Use of two thermal breaks designs, one in the front of the pressure plate screw stem and the other from the back of the stem to the frame tube to reduce the thermal transfer. The outer thermal break also serves as a seal against water behind the pressure plate and the snap cap.
- Use of four-sided structural glazing (capless 4SSG system), which have improved thermal resistance from the silicone sealant with foam backing being flushed with the face of the glass. The entire face of the 4SSG system acts as a rainscreen and a thermal barrier, and the gasket or silicone in line with the face of the glass acts as a thermal break. Low-e glass and high-performance spacer bar are still required and gas filled air space may also be a considered.

The Passivhaus standard is a voluntary standard originating in the German building housing sector, that targets an entirely energy-neutral approach to modern construction, primarily heated by passive solar gains and internal gains. Although not a curtain wall standard, the approach defined by this organisation has internationally raised the demand for innovative products and designs that would help meet its requirements even for commercial applications. The Passivhaus standard stipulates:

- Windows (glazing and frames combined) with U-factors lower than 0.8 W/m^2;
- Thermal bridging-free construction of less than 0.01W/m^{2}K;
- Airtight building shell lower than 0.6 ACH at 50 Pa;
- Annual heating requirement lower than 15kWh/m^2;
- Annual total energy lower than 120 kWh/m^2;
- Ventilation systems utilizing heat recovery with over 75% efficiency and have low electric energy use of 0.45 Wh/m^3.

The above requirements generated the need for highly insulating frames with U-factors in the range of 0.7-1.0 W/m^{2}K (Gustavsen et al., 2010). Simulation studies were conducted by Gustavsen et al. (2011) to identify frame and edge-of-glass materials with improved thermal performance than that of the best window frames and spacers commercially available. Research targets were proposed as follows:

- Spacer technologies with conductivity of 0.02 W/mK;
- Thermal break materials with conductivity of 0.005 -0.02 W/mK;
- Structural insulating materials and solid frames with conductivity of 0.03 W/mK;
- Low-e coatings (or pigments) for PVC/aluminum window frames with emissivity of 0.05
- Alternative frame designs/technologies (e.g., slim window frame made of glass fibre reinforced polyester (GFRP), (Applefield et al., 2010);
- Alternative window designs (e.g., Sashlite® vinyl window insulating glass technology where glass and sash are built together without the need for a separate spacer. Sashlite® windows' design and manufacturing eliminates the need for the window components to be constructed separately and then glazed into the sash profile (such as typical IGUs). Instead, the vinyl sash profile incorporates the spacer, and the two panes of glass are glazed directly into both sides of the sash. The technology results in windows with low U-factors when built with low-e glass and argon fill (0.28 W/m2K or lower), and 0.268 W/m2K, when the vinyl profiles are foam-filled (Sashlite, 2015).

6. Energy and Thermal Performance

This section focuses only on curtain wall systems energy and thermal performance, these being main curtain wall characteristics that will be assessed through laboratory/field testing and computer modelling in the next tasks of this project.

There are five key curtain wall components that significantly affect its energy performance*: the glazing, the gaskets, the sealants, the framing and the shading*.

6.1 Testing

Due to the repetitive nature of curtain wall design, which can result in small issues being reproduced numerous times, curtain walls are subjected to a greater degree of performance testing than other wall types. However, not all curtain wall projects require testing and for small building projects it is rare to specify testing as long as performance data is available from the curtain wall manufacturer.

Nevertheless, for large building projects or custom curtain wall designs, testing is often required to verify that all details meet or exceed the performance requirements. In some jurisdictions all curtain walls must be tested regardless of design (Quirouette, 1982).

Performance testing of curtain walls is conducted in laboratories (for product development or to evaluate specification compliance) or in the field (for quality assurance). Along with other performance criteria (related to strength, durability, fire, sound, vibration, light etc.), the design of a curtain wall system includes requirements for air leakage control (air barrier), vapour diffusion control (vapour barrier), heat loss/gain control (insulation and thermal breaks), and rain and snow penetration control (rainscreen principle). Although all of the listed requirements are important with respect to performance, focus will mostly be given to aspects related to air leakage and thermal performance.

Thermal performance can be evaluated by both testing and computer simulation. Air leakage and water penetration resistance can be evaluated only by physical testing. The interaction of all the elements combined, including gaskets and seals, can only be reliably evaluated by physical testing.

Kazmierczak (2010) stresses the significant gap that still exists between the expected and the actual performance of installed curtain wall systems and highlights the importance of testing in the quest to avoid curtain walls failures. Mock-up testing is crucial in assessing curtain wall systems and for producing the final design, especially when laboratory settings generally represent "the highest and best contractor's efforts on the largest and best (curtain wall) projects". Nevertheless, the author comments: "The owner of one of the largest wall mock-up testing laboratories in the world, where many of the most prominent building walls were tested, ranging from Sears Towers in Chicago to Petronas Towers in Kuala Lumpur, estimated in 2007 that 95% of walls tested in his laboratory failed their first tests….. If only 5% of the best walls passed their first mock-up test, how well would the average wall perform ? (when installed)".

6.1.1 Laboratory Tests

There are four basic standard curtain wall tests used to evaluate curtain wall performance in mock-up (sample) test programs (PWGSC/CHMC, 2004):

- **Air Leakage (ASTM E283)** – Test for Rate of Air Leakage through Exterior Windows, Curtain Walls and Doors.
- **Water Penetration (ASTM E331)** – Test for Water Penetration of Exterior Windows, Curtain Walls and Doors by Uniform Static Air Pressure Difference.
- **Water Penetration (AAMA 501.1**) – Standard Test Method for Metal Curtain Walls for Water Penetration Using Dynamic Pressure.
- **Structural Adequacy (ASTM E330)** – Test for Structural Performance of Exterior Windows, Curtain Walls and Doors by Uniform Static Air.

The laboratory tests listed above have the following limitations:

- They were developed as a means of ranking different wall systems to a common standard; there is not necessarily a correlation between a test result and the in-service performance;
- Standard tests provide only the minimum parameters to be used in a procedure; pressure differences, flow rates, durations and pass/fail criteria must be defined by the specifier;
- Testing in Europe and in the Far East is much more extensive and onerous than that typically completed in North America;
- Specifiers rely on standard procedures and the use of minimal or irrational test parameters that may drastically limit the usefulness of mock-up test programs;
- In Canada, great emphasis is placed on the rainscreen technology for water penetration control; however, there is no standard test that can be used to evaluate the actual pressure equalization performance, and neither of the standard water penetration tests listed above permits the evaluation of the pressure equalization characteristics. To properly evaluate the pressure equalization characteristics of a wall system, testing needs to be conducted without water, using measurements of air pressure differentials (only) across the air barrier and the cladding elements;
- Curtain walls are tested and often held to a high standard, however, the interfaces with the adjacent construction is rarely tested even though it should be part of the testing;
- Curtain walls are evaluated in accordance with one standard and the operable elements within the wall are often evaluated to a lesser standard.

6.1.1.1 Air Leakage

Ideally, the air barrier of the curtain wall system should be completely airtight, however, for practical considerations, complete airtightness is not possible. Therefore, the curtain wall must be designed to not leak air excessively. Control of air leakage is interrelated with the control of water penetration, where an impermeable plane is also used to provide an air flow barrier. Aside from directly controlling the passage of air through the wall, air leakage control also impacts smoke control, sound transmission, insect control and ice buildup. Air leakage is usually concentrated at joinery, seals and gaskets.

Air leakage is evaluated in accordance with **ASTM E283** (Standard test method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen), a laboratory procedure carried out on a representative sample of curtain wall installed in a test chamber. Testing of walls for air leakage in the field can be done but the experimental error is much greater due to the difficulty in isolating the air leakage caused by the lateral and vertical flow in the curtain wall framing.

In the laboratory, a sample curtain wall (representative of the materials and spans) is constructed and attached to a pressure chamber, and sealed at the perimeter connections. A pressure differential is created across the wall sample and the flow rate through the wall is measured. First, the wall sample is covered with a sheet of polyethylene film and the chamber is depressurized by an exhaust fan. The leakage of air from the exhaust fan (equal to the amount of air leakage in the chamber) is measured and recorded (i.e., the extraneous air leakage is determined). The polyethylene film is then removed and the test is repeated to determine the increase in air leakage. The difference between the two tests is the leakage of air that passed through the curtain wall system. If the air leakage exceeds the required maximum, repairs may be undertaken and the test repeated. Tests should be conducted to assess both infiltration and exfiltration.

The **ASTM E283** test method provides a common procedure to compare different wall systems. The test method does not provide specific testing parameters (pressure difference, number of cycles, wind speed, etc.) or a pass/fail criteria that might relate the test to expected climatic conditions. The required parameters for the ASTM E283 procedure are *the allowable flow rate* and the *pressure difference*.

Allowable flow rate: The National Building Code of Canada (NBCC) recommends a maximum air leakage rate for air barriers in insulated walls between 0.1 to 0.2 L/s-m^2 of wall, at a pressure difference equivalent to a 40 km/h wind (75 Pa). The Architectural Aluminum Manufacturers Association (AAMA) specifies a maximum leakage rate of 0.3 L/s-m^2 at 75 Pa for curtain walls. However, for the Canadian climate, a rate under 0.1 L/s-m^2 (equivalent to a leakage area of 10 mm^2/m^2) is recommended, to control ice buildup on the exterior of the curtain wall components, prevent condensation in the glazing cavities, and prevent condensation and rain penetration in the wall cavities below the glazing system (CHMC, n.d.).

Pressure difference: The AAMA and NBCC allowable leakage rate criteria are based on a 75 Pa pressure differential. However, the 75 Pa pressure does not reflect the long-term applied pressures on high-rise buildings, and higher pressure differences should be specified to reflect the expected *stack effect*, *mechanical pressurization* and *mean wind pressures* on the particular building. Pressure differences due to the stack effect arise due to the temperature and density difference between the air inside and the air outside of a building; in colder climates this effect is greatest in the winter months. Due to the stack effect air enters into the building at a lower level and flows out of the building at higher levels. The stack pressure is commonly estimated to be 0.11 Pa/°C temperature difference for every 3 m (30 feet) of storey height. In order to establish stack pressures for a particular building, the mean monthly temperatures are required (not the extreme design temperatures). In Canada a pressure based on the mean January temperature is considered appropriate. The level of mechanical (HVAC) pressurization also can vary widely and may increase the exfiltration at the upper floors of a building. Wind pressure data provided in building codes is sufficient for structural design but is not suitable for air leakage evaluation. A reference wind pressure based on the mean January wind speed, modified by the exposure and pressure coefficients in the building codes should be used. The Air Leakage test pressure should be calculated as the sum of the stack effect pressure, the mechanical pressure and the wind pressure.

6.1.1.2 Heat Flow and Thermal Bridging

Thermal bridging occurs when a more conductive (or poorly insulating) material allows an easy pathway for heat flow across a thermal barrier. Curtain walls include in their structure highly conductive materials such as aluminum, steel and glass. The control of heat flow through a curtain wall system depends on the size and arrangement of the wall components. From a thermal perspective curtain walls have three key zones: the *vision glass* area, the *spandrel* area, and the *frame*.

Vision Glass — In Canada, the vision glass area includes mostly sealed double-glazed IGUs, with triple-glazed being sometimes used. The thermal resistance (R-value) of an IGU depends on the number of air or gas filled spaces and the applied films, tints and coatings. Typical heat transfer coefficients (U-factors) are provided by IGU manufacturers (U-factor is equal to 1/R-value; R-values are usually used to express the insulation performance of building envelope components other than windows). However, these values define the thermal resistance of the IGU to heat flow more like an opaque assembly (or a glass assembly used under night-time conditions) and do not take into account the solar energy (heat gains) that is filtered into the building during daytime. Therefore, even in cold climates, the solar heat gain coefficient (SHGC) is considered the principal curtain wall design criterion. The thermal resistance and the solar heat gain characteristics listed in the manufacturers' literature apply to the center of the IGU. However, the glass edge (an area 65-75 mm wide around the perimeter of the unit) is much more conductive than the center region, due to the high conductivity of the glass edge spacer. Therefore, an area weighted average of the characteristics of the centre-of-glass and edge regions defines an IGU's overall thermal performance.

Thermal stresses caused by solar exposure are also one of the major causes of glass breakage. Some conditions that can lead to increased thermal stresses in the glass include: the *glass tint*, heat absorption increasing from clear to green to bronze to gray; the *coatings and films*, which increase the temperature of the glass and may double or triple the glass thermal stress; unnecessary *overlapping with the framing,* which increases the temperature difference between the center and the edge of the glass (e.g., low conductivity gaskets can be used to thermally isolate the glass from the frame, resulting in warmer glass edges and less temperature difference between the center of the glass and the edge); *interior heat traps*, caused by shading systems and an inadequate air circulation to remove the heat built-up behind the glass; closed shading blocking the heat flow to the glass, that in cold climates can result in condensation due to low glass temperatures.

Spandrel — The spandrel area (glass or opaque) of a curtain wall includes an outer cladding, an air space, insulation, and a metal (aluminum or galvanized steel) back pan. However, the incorporation of metal stiffeners and the non-typical perimeter condition results in a multi-zone area that performs much as the vision glass area. The thermal performance of the spandrel area is a function of the insulation and the air/vapor barriers, and is defined by an area weighted average of the center and the edge regions. Due to lack of adjacent interior air, spandrel areas are exposed to wide temperature and humidity fluctuations, which increase the risk for condensation. Back pans are attached to the curtain wall frame behind the spandrel areas and insulation is installed between the back pan and the exterior cladding to create an air/vapor barrier that prevents water infiltration. Water infiltration in opaque areas not visible from the interior can cause significant damage before being detected.

Frame — The aluminum frame is usually the weakest thermal element in a curtain wall system (aluminum has a very high thermal conductivity, about four times more than steel). The heat flow in the frame is mostly due to conduction, therefore, the addition of insulation into the hollow area of the framing is rather ineffective. Thermal breaks that slow down the heat flow from the warm region to the cold region can boost the frame surface temperature. However, in cold climates, insulating the mullions in the spandrel area may lead to excessive condensation if humid air from the interior comes in contact with the mullions. Generally, thin plastic thermal breaks having wide contact areas perforated with numerous screws that secure the pressure plate to the frame typically exhibit only a 6-10% improvement in thermal performance compared to a non-thermally broken frame, however, high performance thermal breaks composed of polyamide webs can increase the thermal performance to values approaching that of the center-of-glass. Thermally broken mullions with PVC, neoprene rubber, polyurethane or polyester-reinforced nylon inserts (between 0.6-2.5 cm thick or more) aim to keep the surface temperature above the dew point temperature of the air, while also protecting the frame from extremes of expansion and contraction (i.e., thermal loads in a curtain wall frame are also due to the relatively high coefficient of thermal expansion of aluminum; the expansion and contraction is accounted for by sealed spaces between the horizontal and vertical mullions).

Some curtain wall systems utilize pressure bars (also known as pressure plates) fastened to the outside of the mullions to secure the glass, and gaskets are placed between the pressure bars and the mullions to function as thermal breaks. Gaskets are also used to cushion the interior and exterior panes of glass. These systems require special design and construction to ensure the continuity of the gaskets at horizontal and vertical transitions (e.g., gaskets may be stretched during installation but will shrink back to their original length; they can also shrink with age and exposure to UV radiation, leaving a gap at the corners). Schwartz (2001) also remarks the importance of designing large weep holes that resist blockage and keep the cavities of the glass framing system dry. Larger weep openings are regarded by some as areas that allow more air infiltration and diminish the thermal and condensation resistance of the framing. However, such issues can be mitigated by the use of baffles, as small weeps tend to get blocked by debris and insects, increasing the likelihood of water penetration.

For more information on current research on curtain walls thermal bridging see Payette (2015) (http://www.payette.com/post/2365186-thermal-bridging-research-curtain-walls).

A document published in 2012 by the joint Structural Engineering Institute (SEI) /American Institute of Steel Construction (AISC) Thermal Steel Bridging Task Committee, in conjunction with the SEI's Sustainability Committee's Thermal Bridging Working Group, notes that none of the key codes and standards specifying baseline requirements for high-performance green buildings[*] currently address the thermal transmittance requirements of steel elements that bridge the building envelope. Discussions and proposals are underway to adopt thermal bridging provisions in future publication of these codes.

Morrison Hershfield (2011) notes that building energy standards such as ASHRAE 90.1-2007 recognizes the impact of thermal bridging by providing effective U-values for exterior insulated steel stud assemblies, which take into account the effects of the steel studs through the stud cavity. However, the authors comment that these values are for assemblies with continuous insulation outboard of the studs, assuming only the nominal value of the exterior insulation. The ASHRAE 90.1 standard does not provide guidance in addressing the thermal impact of the cladding support elements passing through the exterior insulation, such as the effective R- and U-values of steel stud assembly walls, or for different arrangements of cladding attachments.

[*] International Green Construction Code (IGCC); ASHRAE 189.1 Standard for the Design of High-Performance, Green Buildings Except Low-Rise Residential Buildings; and ASHRAE 90.1 Energy Standard for Buildings Except Low-Rise Residential Buildings

6.1.1.3 Overall Thermal Transmittance

As mentioned above, the thermal transmittance coefficient (U-factor) and the glazing solar heat gain coefficient (SHGC) are important characteristics that define the overall energy performance of curtain walls. Testing the overall thermal transmittance includes testing the heat flow due to conduction, radiation and convection. The following test methods are generally used:

- **AAMA 1503.1** - Voluntary Test Method for Thermal Transmittance and Condensation Resistance of Windows, Doors and Glazed Wall Sections
- **ASTM C177** - Standard Test Method for Steady State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded Hot Plate Apparatus
- **ASTM C1199** - Standard Test Method for Measuring the Steady State and Thermal Transmittance of Fenestration System Using Hot Box Methods
- **ASTM E1423** - Standard Practice for Determining the Steady State Thermal Transmittance of Fenestration Systems

Most mock-up testing procedures use a warm chamber placed on the interior surface of the wall and a cold chamber placed on the exterior of the wall. Thermocouples placed on the interior surfaces of the wall record surface temperatures for given cold chamber conditions. The overall thermal resistance and transmittance values are obtained based on the temperature difference at specific locations and the power flow measured by a warm chamber calorimeter. The principal limitation of this method is the size of the sample given that, originally, laboratory chambers were developed to test windows and cannot accommodate samples larger than 2.5 m^2. Full curtain wall modules can rarely be accommodated in laboratory size chambers.

6.1.1.4 Thermal Cycling

A sequence of thermal cycling is also frequently included in a test program, having the intent to cycle the wall through a range of exterior temperatures representative of the temperature extremes to which the wall will be exposed. The temperature cycles induce movements in the wall, and air leakage and water penetration tests provide the potential effect of these movements. To be effective, at least five cycles are usually completed, the length of each cycle depending on the features of the wall, as more massive walls require longer to stabilize the temperatures. Thermal cycling is not normally conducted on small curtain wall samples, as the components are generally too small to move sufficiently.

6.2 Field Tests

Field testing of curtain wall a system is generally conducted as part of quality assurance programs in new construction, or as part of an investigative program in existing buildings. Field tests include verifications of:

- Resistance to water penetration
- Resistance to air leakage
- Structural performance
- Thermal performance with respect to surface temperatures.

Typically, the performance of curtain wall components is evaluated in accredited testing laboratories prior to construction. However, site conditions, variations in the manufacturing process and the experience of the installation team are all factors that may impact the field performance of an installed system.

Therefore, in order to be representative, field tests usually incorporate all of the essential components of the curtain wall (e.g., test areas should be three glass bays wide in order to incorporate a central bay that includes all of the junction details; for unitized curtain wall systems, a vertical module joint should also be included within the test area; the height of the test area should include at least one expansion or stack joint, one spandrel section and one vision section; the height of the test area should be at least one full floor high; if the curtain wall is installed adjacent to another type of wall assembly, the interface detail should also be included within the test area, etc.). In accordance with the AAMA 502, the allowable rates of air leakage for field testing may be 1.5 times the applicable laboratory test rating, unless otherwise specified (Goncalves & Jutras, 2007).

6.2.1 Air Leakage

Field air leakage testing is specified in the following standards:

- **ASTM E283** – Standard Test Method for Determining the Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors (quantitative test method)
- **ASTM E783** – Field Measurement of Air Leakage Through Installed Exterior Windows and Doors (quantitative test method).
- **ASTM E1186** – Standard Practice for Air Leakage Site Detection in Building Envelope and Air Barrier Systems (chamber pressurization in conjunction with white smoke tracers method); Outlines the test method to qualitatively assess air leakage through exterior building envelope and air barrier systems in the field (qualitative test method). Pictures in Figures 17 and 18 are courtesy of Goncalves et al. (2007).

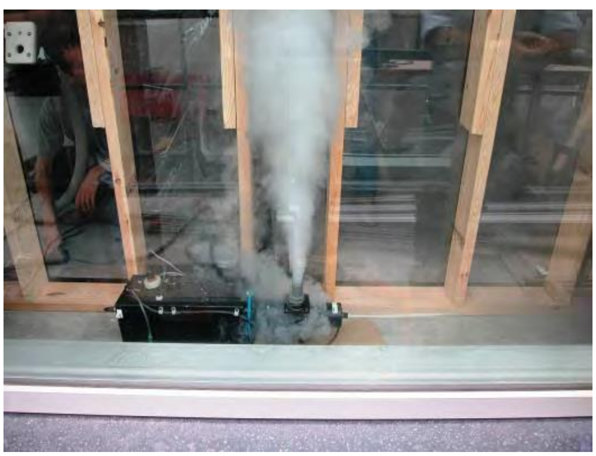


Figure 17: Portable smoke generator used to fill the test chamber with white smoke

Figure 18: Excessive smoke exfiltration visible on the exterior side of a curtain wall test specimen

Although the procedures for field air leakage tests are conceptually simple, the nature of most curtain wall assemblies makes reliable quantitative results difficult to achieve. The potential for lateral and vertical airflow or extraneous leakage occurring in the system is high and contributes to errors in the test procedure. Unless the curtain wall assembly can be isolated from extraneous airflow, quantitative field air leakage results should be interpreted with caution. Qualitative field air leakage testing can be conducted using testing chambers made of polyethylene sheet or plywood; however, attention must be paid to minimize any lateral air flow from the test area to the adjacent wall areas. A visual indication of air leakage can be achieved using a fog generator.

Figure 19: Interior Test Chamber used to test a portion of an installed curtain wall section (source: Goncalves et al. , 2007)

6.2.2 Thermal Performance

Thermocouples and remote data acquisition equipment are used to monitor curtain wall field thermal performance. The monitoring set-up includes measurements of the curtain wall surface temperatures, outside conditions (temperature, wind speed) and interior conditions (temperature, relative humidity). Monitoring of an installed system provides the most reliable measure of performance as all of the elements impacting performance are in place (finishes, heat supply, actual air circulation, etc.).

6.2.3 Thermography

Infrared thermography is used for qualitative assessments of curtain wall air leakage performance and the presence of moisture in exterior wall assemblies, in accordance with CAN/CGSB 149-GP-2MP - Manual for Thermographic Analysis of Building Enclosures standard. Because glass and metal curtain walls are lightweight structures with highly conductive components, the sensitivity of most modern scanning equipment can lead to misdiagnosis of small thermal bridges and air leaks. Therefore, the scanning protocol includes a two-steps procedure: the first step is conducted with the building at as negative an internal air pressure as possible, whereas the second step is conducted with the building at as positive an internal air pressure as possible. The variation in air pressures permits the identifications of thermal bridging and air leakage. Scanning is also used in curtain wall applications incorporating coated glass products, the small surface temperature differences detectable on the glass surfaces allowing the detection of IGUs installed backward or with missing coatings.

6.3 Computer Simulations

Computer simulations are the prevalent means of assessing curtain wall thermal performance and condensation potential. The modeling procedure involves the drawing of the frame section (complete with gaskets, thermal breaks and glass) and taking into account the conductivities of the curtain wall components, applying a temperature difference, and estimating the surface temperatures for comparison to psychometric charts. However, the interpretation of the output requires caution, as comparison of simulated results with physical test data has sometimes shown considerable error. Nevertheless, computer simulations, if used appropriately, can be very effective in evaluating the relative impact of changes on the thermal performance and the ranking of different designs (e.g., parametric studies). Nonetheless, even with accurate modeling, experience indicates that simulated surface temperature results should be reduced by 2°C for evaluation of condensation potentials using psychometric charts, and for critical installations, an even greater correction should be considered.

In addition, consideration should be given to the fact that simulations do not normally consider interior finishes or significant three-dimensional heat flow that can also have a significant impact on the curtain wall surface temperatures. Computer simulation combined with standard tests of glazing products can also be used to determine the overall U-factors of curtain walls, based on an area weighted U-factor of the framing, the glazing edge and the center of glazing region.

Energy Modeling can be divided into two types:

- Macro-modeling (e.g., EnergyPlus, DOE-2, etc.) used for whole building analysis and heat loss/gain calculations.
- Micro-modeling (e.g., THERM, hygIRC_1D, FEMAP, WUFI, Optics, Window, etc.) used for one-dimensional investigations of the performance of building components including built-in moisture, driving rain, solar radiation, long-wave emission, capillary transport and summer condensation optimization, or 2D and 3D finite-element modeling of thermal performance and heat-transfer in building components such as windows, walls, foundations, roofs, etc., where thermal bridges are of concern (i.e. hygIRC, hygIRC-C, etc.).

Selected examples of building envelope modeling studies recently completed, as well as proposed research work related to curtain walls are provided below:

Van den Bossche et al. (2015) — Conducted a comparative analysis of current European and North-American curtain wall systems in order to evaluate the thermal performance of existing curtain wall systems. When comparing existing, standard (i.e., not thermally improved) systems for both continents, the authors found that, generally, the European frames performed better and were more thermally efficient. A generic curtain wall frame was developed to investigate the influence of several design parameters on the thermal performance of the system.

Saber (2013-2015) —Saber conducted a comprehensive review of the thermal performance of enclosed airspaces, including computational and experimental methods for determining the effective R-value of enclosed reflective airspaces. Different parameters that affect the thermal performance of enclosed airspaces were discussed. The author provides practical correlations for the calculation of R-values for enclosed airspaces with different inclination angels and heat flow directions, as a function of the parameters that affect the thermal performance of an enclosed airspace: average temperature, temperature differential, aspect ratio, effective emittance. These correlations can be used by building designers and architects to determine the thermal resistance of building enclosures, and can be implemented in building energy simulation programs (e.g. ESP-r, Energy Plus, DOE, etc.).

As an example, Figure 20 shows the effect of the inclination angle on the air flow in an enclosed airspace including one surface with emissivity of 0.05 and the other surfaces with emissivity of 0.9. This figure shows the vertical velocity contours and the airflow field in the cavity for different inclination angles (θ) when the sample stack is heated from the top and the bottom. As shown, in the case of a sample stack heated from the top with θ = 30^{o} and a vertical sample stack heated from the left (θ = 90^{o}), a mono-cellular with one vortex cell airflow is developed in the air cavity. In the case of a sample stack heated from the bottom with θ = 30^{o}, a multi-cellular airflow is developed in the cavity with three vortex cells. For a horizontal sample stack (θ = 0^{o}) heated from the bottom and top, a multi-cellular airflow is developed in the cavity with six and two vortex cells, respectively. It has been shown that the value of the air velocity in the cavity is greatly affected by both the inclination angle (θ) and the direction of the heat flow through the sample stack. For a horizontal sample stack (θ = 0^{o}), the air velocity in the case of downward heat flow (sample heated from the top, v↑(max) = 0.6 mm/s) is much smaller than the air velocity with upward heat flow (sample heated from the bottom, v↑(max) = 18.7 mm/s). This is due to the fact that a downward heat flow encourages a relatively stable stratification of the air due to differences in buoyancy compared to the case with upward heat flow. Consequently, a sample stack with downward heat flow results in a greater R-value than that with an upward heat flow. Similarly, for θ = 30^{o}, the air velocity in the cavity of a sample stack heated from the top (v↑(max) = 10.6 mm/s) is also smaller than that of a sample stack heated from the bottom (v↑(max) = 14.1 mm/s). Therefore, the contribution of the middle layer to the R-value is greater for downward heat flow than for upward heat flow.

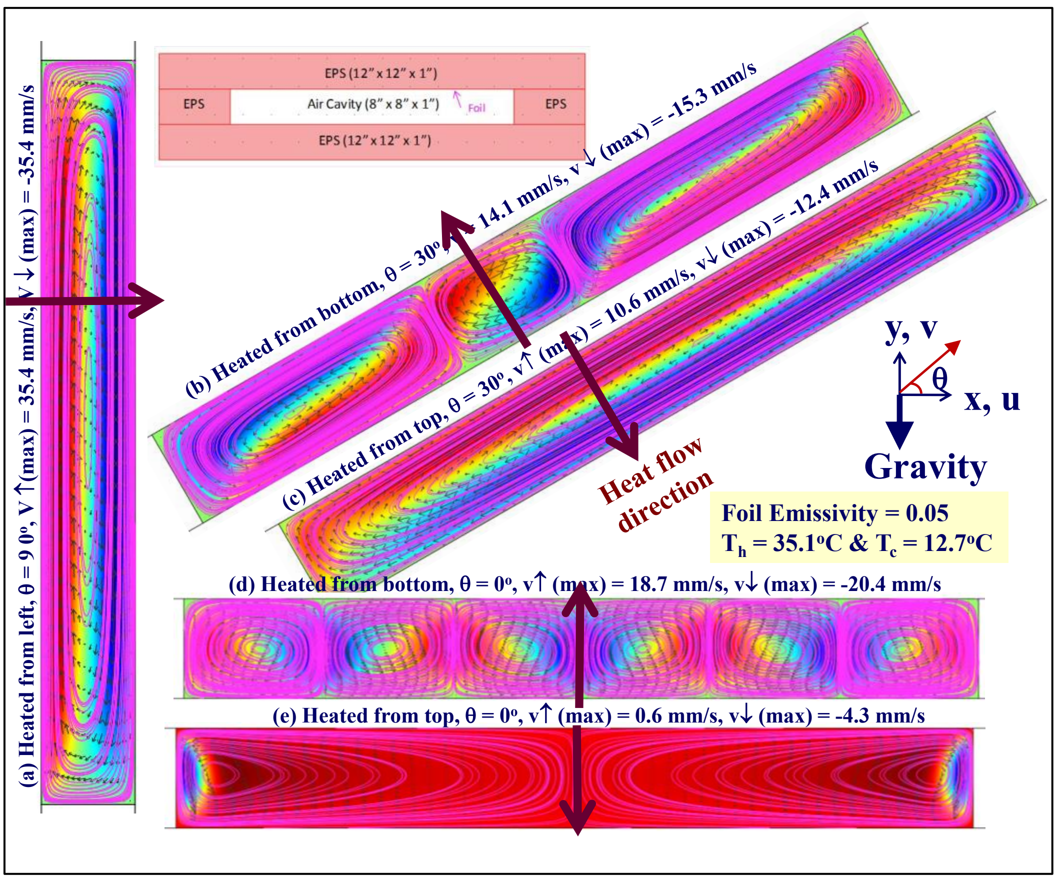


Figure 20: Vertical velocity contours and flow field in air cavity of sample stacks with different inclinations

Saber (2013a, b, c; 2014a, b) also investigated:

- the dependence of the R-value on the aspect ratio, A_R (A_R = length (H)/thickness (δ)) of the vertical enclosed airspaces (θ = 90°) (Saber, 2013a);
- horizontal airspaces (θ = 0°) with upward heat flow (Saber, 2013b) and downward heat flow (Saber, 2014a);
- high-sloped airspaces (θ = 45°) with downward heat flow (Saber, 2013c); and
- low sloped airspaces (θ = 30°) with downward heat flow (Saber, 2014b).

Those studies covered a wide range of enclosed airspaces for building applications:

- thickness, δ = 13 mm (0.5 in), 20 mm (0.75 in), 40 mm (1.5 in), 90 mm (3.5 in)
- length, H = 203 mm (8 in) – 2438 mm (96 in)
- average temperature, T_{avg} = 32.2 (90°F), 10.0°C (50°F), -17.8°C (0°F), -45.6°C (-50°F)
- temperature differential, ΔT = 5.6°C (10°F), 11.1°C (20°F), 16.7°C (30°F)
- effective emittance, ε_{eff} = 0 – 0.82
- aspect ratios, A_R = 16 to 188 for δ = 13 mm (0.5 in), A_R = 10 to 122 for δ = 20 mm (0.75 in), A_R = 5 to 61 for δ = 40 mm (1.5 in), and A_R = 2 to 27 for δ = 90 mm (3.5 in).

Depending on the thickness of the airspace and the operating conditions, Saber showed that the aspect ratio can have a significant effect on the R-value. Note that the effect of the airspace aspect ratio and the inclination angle of 30° on the R-values of enclosed airspaces are not accounted for by ASHRAE.

Arici et al. (2015) — Investigated fluid flow and heat transfer in double, triple and quadruple pane windows with air-filled gaps of 6 mm, 9 mm, 12 mm, 15 mm, 18 mm and 21 mm width, using a commercial CFD computer program ANSYS FLUENT 12.1. Four different outdoor temperatures corresponding to winter design dry-bulb temperatures of cities in different climatic zones were considered. Triple and quadruple windows including ordinary glass and low gap width glazing provided equivalent energy savings compared to double pane windows with large gaps and expensive low-e coatings.

Lawton et al. (2011) — Used a 3D finite element analysis heat transfer software package (Siemens PLM Software; FEMAP and Nx, with Maya's TMG thermal solver) to model thermal bridges at intersections to glazing assemblies and showed that the effects of the assembly details could potentially add up to 40% heat flow due to the window transitions. For example, a spandrel panel assembly with a thermal transmittance of U=0.048 was only U=0.127 (effective R-21 to R-8) when considering the thermally inefficient details; an improved U=0.065 (R-15) was obtained when a continuous metal flashing was removed. This work was part of an ASHRAE Research Project (RP-1365), Thermal Performance of Buildings Envelope Details for Mid and High-Rise Buildings, which had the objective to develop procedures and a catalogue that allows designers quick access to information related to thermal performance of building envelope components. Twenty-nine guarded hot-box test measurements were compared to simulated results and sensitivity analyses showed the importance of assuming appropriate values for contact resistance particularly between steel flanges and sheathings when modeling steel framed assemblies. The catalogue of 40 building envelope design details was developed based on a set of generic and common interface details suitable for mid- and high-rise construction. Temperature indices were provided for an approximation of surface temperatures due to average steady-state conductive heat flow in three-dimensions. However, heat and moisture storage effects, air transport, and localized temperature variations (for example, screws, surface resistances, moisture variations, etc.) were not modeled. The authors note that the surface temperatures can be used to evaluate condensation resistance using dew-points calculation methods, while being aware of their limitations.

Kumar (2010) — Compared 3D modeling of heat transfer effects in fenestration systems to 2D modeling results, including all three forms of heat transfer: conduction, convection and radiation. The study included multiple commercial fenestration products with a broad range of frame materials, spacers, insulated glass units and sizes. The Therm5/Window5 (2D) and GAMBIT / FLUENT (3D) software were used.

Gustavsen et al. (2008) — Highlighted the limitations of window heat transfer design tools and identified the following six priorities that would improve the modeling of low-conductance window frames: (1) Addition of 2D view-factor radiation to standard modeling and examination of the current practice of averaging surface emissivity based on area weighting and the process of making an equivalent rectangular frame cavity; (2) Assessment of 3D radiation effects in frame cavities and development of recommendations for inclusion into design fenestration tools; (3) Assessment of existing correlations for convection in vertical cavities using CFD; (4) Study 2D and 3D natural convection heat transfer in frame cavities for cavities that proved to be deficient; recommend improved correlations or full CFD modeling into ISO standards and design fenestration tools; (5) Study 3D hardware short-circuits and propose methods to ensure that these effects are incorporated into ratings, and; (6) Study the heat transfer effects of ventilated frame cavities and propose updated correlations.

Gustavsen and Thue (2007) — Used a commercial computational fluid dynamic program to study the effect of the horizontal aspect ratio on the heat flow through cavities with high vertical aspect ratio of the type typically found in vertical window frames with internal cavities. The authors concluded that in terms of heat transfer rates three-dimensional cavities with a horizontal aspect ratio larger than five can be considered as being two-dimensional cavities with an accuracy of 4%.

Kragh and Simonella (2007) — Modeled a single storey zone (6mx9m) of an open plan office building using an in-house software (E+TA ROOM) and found no direct correlation between the U-values of curtain wall components and the overall energy performance of the air-conditioned office space. The authors argued that it is not possible to thermally split curtain wall systems into windows and walls because of the interdependency of the heat transfer through the connected parts. They suggested that defining the required performance for the separate parts of the system is generally not meaningful, and highlighted the need to consider the curtain wall system as a whole (i.e., including the frames, infill panels, and glazing) when assessing the overall thermal performance. The authors also discussed the need for better integration of British codes and standards related to curtain wall design, highlighting their limitations and confusing regulations.

Curcija et al. (2004) — Developed a simplified component-based modeling methodology for predicting the thermal performance of different types of non-residential fenestration systems (i.e., casement windows, fixed windows, horizontal slider, sliding doors, swinging doors, curtain walls, combination windows, etc.) using real (manufacturer) thermal and solar-optical data of individual fenestration components (i.e., framing, glazing, spacer) to calculate the overall U-factor, SHGC and visible transmittance (VT) for best/worst case scenarios. Results compared well with detailed traditional modeling procedures (which require full numerical modeling of each component separately).

Griffith et al (1997) — Conducted an infrared thermography laboratory tests and computer simulations to investigate the thermal performance of different configurations of bolts and glazings on curtain wall samples. Experimental results were compared to 2D simulations approximating the thermal effect of bolts using the *parallel path* and the *isothermal planes* calculation methods. Results showed that stainless steel bolts affected the curtain wall thermal performance within 18% when spaced at least 230 mm apart (as specified by the industry standards). Performance increasingly worsened when the bolts were placed less than 230 mm apart or when steel bolts were used. The authors also noted that the isothermal planes method can be used with 2D heat transfer software typical of that used in the window industry to determine thermal bridging effects caused by bolts.

Curcija (unpublished)— In-progress research work at the University of Massachusetts on: convective models of complex fenestration systems including both the inside of the glazing cavity and the indoor/outdoor surfaces; modeling of vacuum glazing and fenestration products including vacuum glazing; development of models for dynamic systems (electrochromic, phase-change, etc.); extension of SHG to 2D and 2D modeling; integrated modeling of window-wall performance with whole building energy analysis.

André (2014) — Highlighted the importance of shifting from "*wall R-value thinking*" to "*whole building R-value*", especially for curtain wall projects, and looking at building envelope improvements as a whole to achieve energy savings, e.g., reducing the vision area, improving double low-e glass, substituting vision areas with skylights, spraying foam on spandrels backside, eliminating thermal bridging and losses at slab edges and window transition, investing in new glazing technologies such as dynamic glass, vacuum insulated glazing panels and triple glazing, and planning ahead by defining and analyzing options (including new products) early in the design process.

Arasteh et al. (2008) — Highlighted the need to improve building energy simulation programs to handle the performance of advanced fenestration products and make existing fenestration software capable of evaluating the thermal and optical properties over a wide range of environmental parameters instead of just calculating properties at design conditions. The results could then be used by building energy analysis programs to model the fenestration products, which would replaces traditional standard inputs such as the U-factor, SHGC and visible transmittance (Tvis).

Murray and Adams (2010) — Discussed the importance of micro-modeling of the curtain wall assembly to determine the relative benefits of each of the components (e.g., triple glazing, low-e coatings, warm edge spacers, fiberglass pressure plates, etc.) in the calculation of the system's overall thermal transmittance. Area discretization exposes the influence of the smallest system components, identifying potential thermal bridges, and presenting solutions for retaining the most of the nominal insulation value. Other sustainable solutions presented by the same authors include the use of photovoltaics and wooden frames. Figure 21 shows how much improvement has been achieved in fenestration industry since the 70s up to now, from a simple IGU to double or triple glazed IGUs, aerogel glazing, and vacuum glazing with a U-value of < 0.1. Figure 22 shows a conversion chart for vision glass, where, as an example, R3 glass may convert to an overall R2.5. Figure 23 shows a conversion chart for spandrel glass, where R15 spandrel insulation may convert to an overall R7.1.

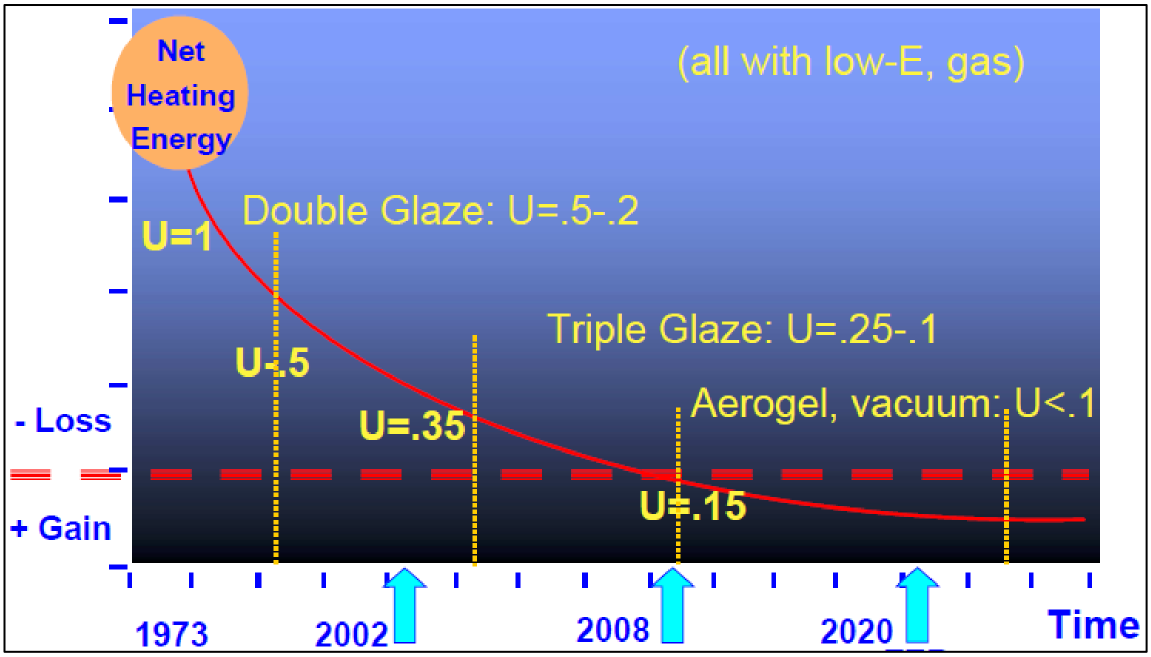


Figure 21: Impact of highly insulated glazing units on heating energy use (source: Murray & Adams, 2010)

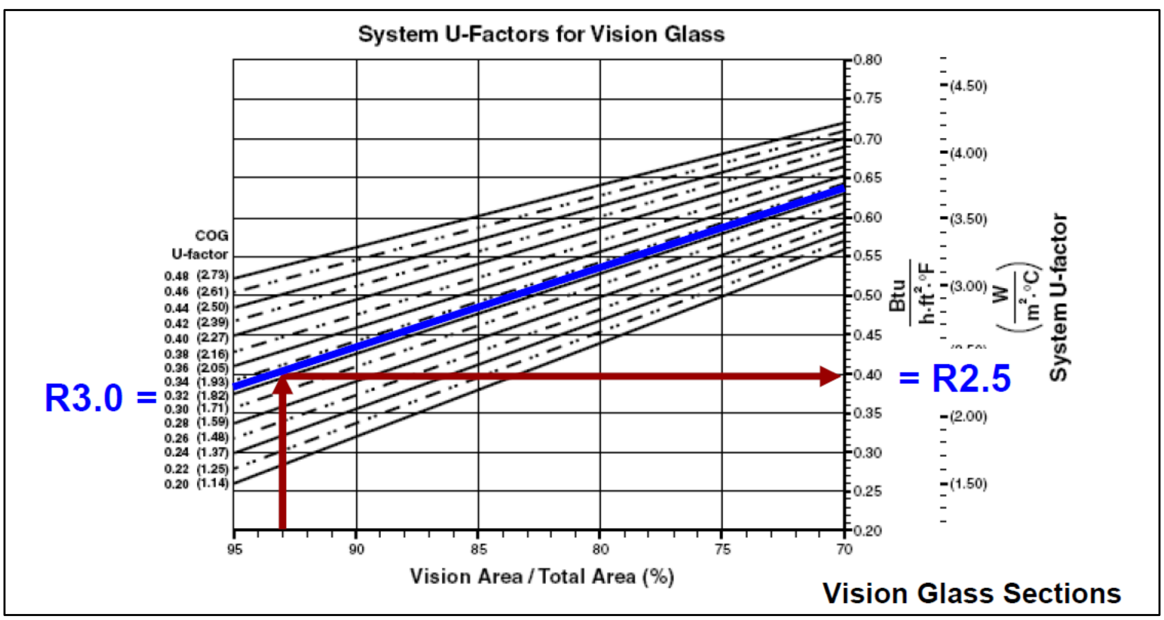


Figure 22: Conversion chart for vision glass (source: Murray & Adams, 2010)

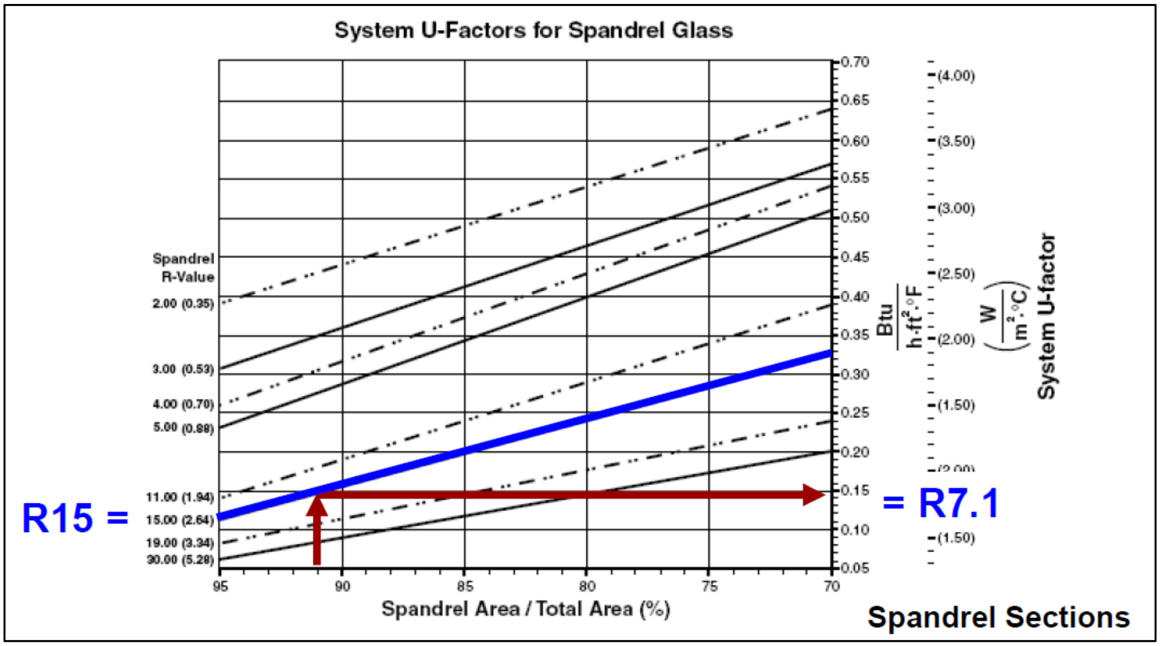


Figure 23: Conversion chart for spandrel glass (source: Murray & Adams, 2010)

7. Thermal Improvements

This section presents recent research work (including numerical simulations and physical testing) and novel design approaches that aim to increase the thermal performance of curtain wall systems.

McDonell (2012) lists the following main approaches that would improve the thermal performance of curtain wall systems to meet the energy code requirements:

- Smaller vision glass areas and larger insulated spandrel glass/opaque wall areas;
- Triple/quadruple IGUs, including products with suspended films and ceramic fritting for glare protection and high quality daylighting;
- Significantly improved thermal break designs for framing systems;
- Better quality and thicker insulation used in spandrel panels (with 100% vapour and air barrier to prevent condensation);
- Glass tuned based on the building façade orientation for a better control of winter passive solar gains and summer solar gains;
- Dynamically controlled exterior sunshades integrated with the curtain wall framing;
- Double-skin façade systems with passive ventilation and shading control;
- Occupant-controlled windows (even in high-rises);
- Integration of new technologies such as photovoltaic systems, vacuum glazing and variable glass tinting systems.

Ge at al. (2001) conducted an experimental study of temperature distribution across two mock-up curtain wall systems (3.8 m x 6.7 m), taking a holistic approach and including various design details including the glazing unit, the spacer, the thermal break material, and the back pan, all tested in an environmental chamber under steady-state and cyclic winter conditions. Temperature distribution on the glazing surface and the mullion section showed the magnitude of the impact that such design details can have on the thermal and condensation resistance of curtain wall systems. Testing conditions in the environmental chamber were 21°C (hot box) and -10°C, -18°C, -24°C, -32°C (cold box), as well as a sinusoidal profile used for the cycling test, developed based on weather files obtained from a Montreal, QC, weather station. Results showed that an improved curtain wall system (including a large thermal break of reinforced nylon in the frame section, a low-e argon-filled double glazing unit, a thermally broken aluminum spacer and an improved back pan design) provided a higher thermal resistance, warmer surface temperatures, and better resistance to condensation than a conventional design (with standard back pan design, conventional aluminum spacer, and a thinner thermal break in the frame section).

Straube (2008) investigated the impact of thermal bridging through commercial wall assemblies and heat flow through window systems calculated with an area-weighted average of the R-values of the windows and opaque wall sections. The results of a number of scenarios were plotted as shown in Figure 24 (Note that values are shown in United States customary units, R-values (Btu/ft^{2}h°F), U-factors (ft^{2}h°F/Btu), which are 5.678 times the SI values expressed as R-value (m^{2}K/W), U-factor (W/m^{2}K)). Curves 1 to 4 show the performance of a wide range of commercial enclosures with a wide range of cladding types. Curves 5 and 6 show significant improvements that are possible using best available thermally broken aluminum frames and high-performance glazing (U-factor=0.30). In all cases, high window-to wall ratios (WWR) generated high heat loss and heat gain.

- Curve 1 shows a standard U-factor=0.50 thermally-broken aluminum punched windows with air-filled double-glazed IGU in an R-12 batt-filled steel-stud brick veneer wall system (a real R-6 when thermal bridging is considered). The overall effective R-value of this wall is around R-3 to R-4 over the normal range of commercial window-to-wall (WWR) ratios of 25 to 50%.
- Curve 2 shows that increasing the R-value of the opaque wall to R-11 by adding an inch of foam on the exterior results in an increase of only R-0.5 to R-1.5 for the overall R-value for the same range of WWR.
- Curve 3 shows how significant an impact window performance can make even if a good wall is provided. An externally insulated R-16 wall, when mated with poor windows produces a vertical enclosure with an R-value of only R-3 to R-6 for the normal range of window areas.
- Curve 4 assumes a good-quality window frame with top quality glazing (low-e, argon-filled). The result for the overall vertical enclosure is still only R-4 to R-7.
- Curve 5 shows that even with an R-40 wall, the overall R-value will be in the R-7 to R-12 range for WWR of less than 40% (the highest ratio recommended for high-performance buildings). The grey curve below Curve 5 shows that decreasing the opaque wall R-value from R-40 to R-20 has little negative impact particularly at high glazing ratios.
- Curve 6 shows commercially-available low-e, argon-filled triple-glazed units in an insulated fiberglass frame, to deliver a U-factor of only 0.14. Even with a wall insulated to R-20, such a combination can deliver an overall R-value of R-12 to R-14, two to three times more than that of typical commercially available vertical enclosures.

Straube (2008) concluded that the overall R-value of modern commercial vertical enclosures is rarely over R-7, and more likely in the range of R-3 to R-5, whereas typical curtain wall systems have R-values of only R-2 or R-3. High performance systems using highly insulated (R-12) spandrel panels and best double glazing (with low-e and argon) may achieve R-4. Only a few systems (Kawneer 7550 series or Visionwall) can achieve R-6 to R-9. Super-windows with R-10 or R-12 and with dynamic shading to provide the capability of reducing the solar gain to less than 0.10 during bright sun and up to 0.60 or more during cloudy days. As well, other systems that incorporate light diffusing elements (Kalwall and Solera) and phase change materials (Glass-X) can reduce energy flows across daylight panels by a factor of 10. As such technology becomes more affordable and available, better thermal performance may be possible with higher WWR ratios.

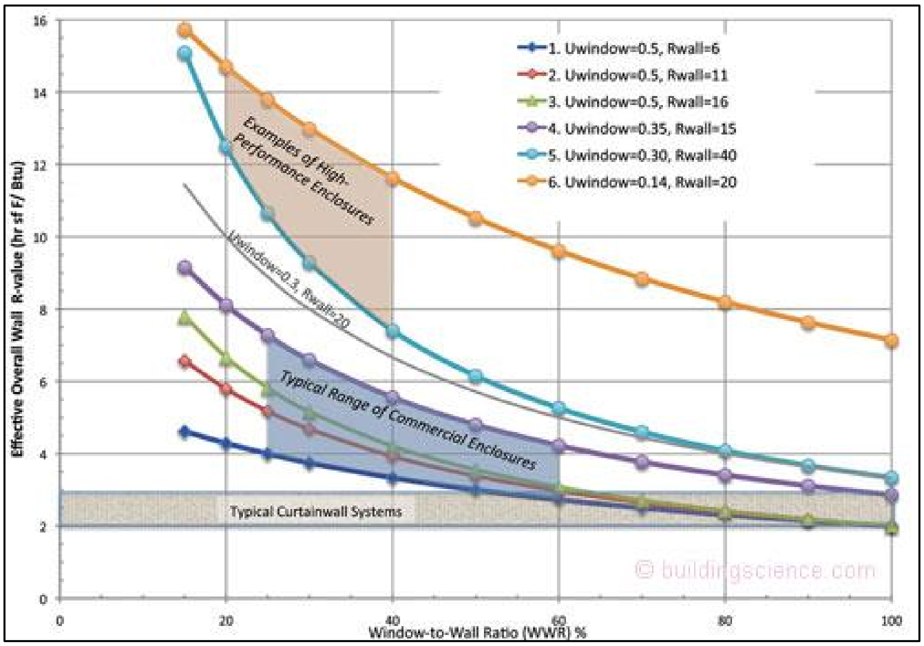


Figure 24: Impact of thermal bridging through commercial wall assemblies and heat flow through window system (source: Straube, 2008)

Van Den Bossche et al (2015) conducted a comparative analysis of existing European and North-American curtain wall systems to evaluate their thermal performance. A generic curtain wall frame was developed to investigate the influence of several design parameters on the thermal performance of the system. When comparing existing standard (i.e., not thermally improved) systems for both continents, generally, the European frames performed better and were more thermally efficient.

Two systematic differences are evident when analyzing a series of European and North-American curtain wall systems: (1) the location of the interior gasket; and (2) the more solid screw fin connection. In European systems there is an additional member in the interior aluminum profile that secures the gasket, whereas in North-America, this gasket is often installed directly into the aluminum structural member. Nonetheless, simulations showed that the profile member that secures the gasket (present in the European frame) does not have a major influence on the heat loss. The higher U-value of the North-American frames can thus be linked to the increased length of the screw fins.

A series of simulations were conducted to evaluate the influence on thermal performance of several design parameters: profile width and length, position of the insulating glass units, glass unit thickness, λ-values of screws and compartmentalization as well as several techniques to insulate the interior cavity. Results showed that the most influential parameters on the thermal performance of curtain wall systems are:

- Length of the screw fin
- Glass unit thickness
- Additional insulation in the inner cavity

To effectively design thermal optimized curtain wall frames, the parameters mentioned above should be combined into one optimal system. In this investigation, a minimum thermal transmittance of 1.485 W/m^2K, or a 62% decrease, compared to the reference value were attained. Further optimization of the inner cavity insulation might improve this value even more.

8. R&D Activities in the Fenestration Industry

The vision glazing is a critical component of curtain wall systems. In this section recent research efforts undertaken in the field of fenestration products are summarized, based on the state-of-the-art reviews by Galasiu et al. (2015), Jelle et al. (2012a, 2012b), Van den Bergh et al. (2013), Gustavsen et al. (2011), and Baetens et al. (2010a).

8.1 Multilayer Glazing

Insulated glass units are available in double (2 panes of glass) or triple glazing (3 panes of glass). Each pane of glass is separated by a spacer as well as a space filled with air or an inert gas such as argon, krypton or xenon (see Figure 25). Because of the number of glass panes and coating layers, triple IGUs have lower U-factors but also lower visible transmittances than double IGUs. Achieving the double glazing level of visible transmittance is proposed for improving the triple glazing performance.

Jelle et al. (2012a) conducted a state-of-the-art review to identify the window products with the lowest U-factor available commercially. The lowest center-of-glass U-factor found among all the glazing products reviewed was 0.28 W/m^2K (R-value=3.6 m^2K/W), characteristic of a double glazed product with polymer suspended film and xenon fill (called SeriousGlass 20) manufactured by Serious Materials. Suspended films located in-between the inner and outer panes reduce the window weight and allow for a larger gas cavity than common multilayer glazing due to the films being thinner than the glass panes; however, these types of IGUs have low visible transmittance (e.g. 23%), reduced durability and require special fastening systems to address the wrinkling of the suspended film. Vision wall also offered a similar product but with air fill, with a U-factor of 0.62 W/m^2K (R-value = 1.6 m^2K/W) and a visual transmittance of 50%.

The best high performance low-e triple glazing found by Jelle et al. (2012a) used krypton as the gas fill and had a U-factor of 0.49 W/m^2K (R-value = 2 m^2K/W) (Clima Guard N manufactured by Guardian Flachglas GmbH; iplus 3CE manufactured by Interpane Glas Industrie AG; and Top N manufactured by AGC Glass U.K.); The best performing low-e triple glazing with an argon fill had a U-factor of 0.64 W/m^2K (R-value = 1.56 m^2K/W) and a cavity thickness of 18 mm (12 mm wider than glazings with kypton fill (manufactured by Arcon Flachglas-Veredelung GmbH & co, KG). Conventional triple glazings have visual transmittances in the range of 70-72%.

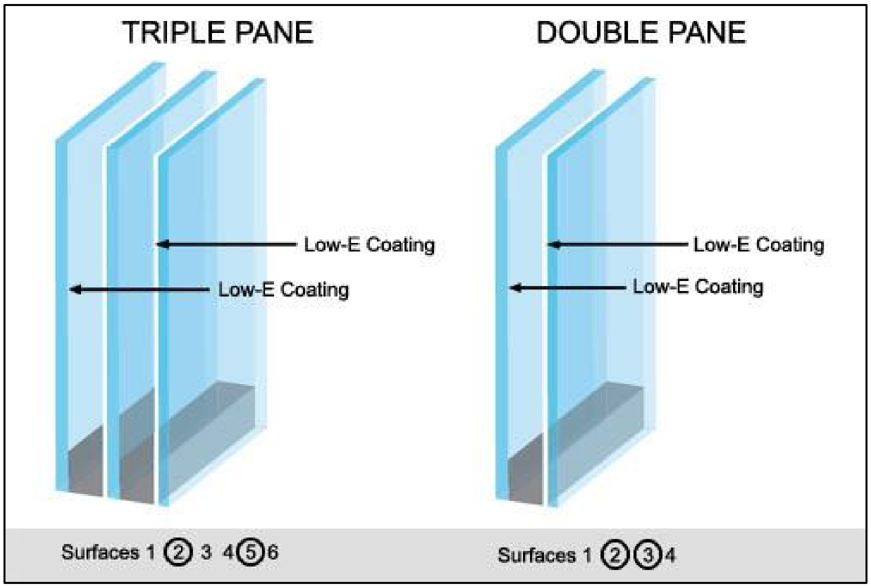


Figure 25: Double and Triple Glaze windows with low-e coatings (source: QualiGlass Windows & Doors Ltd)

8.2 Low-e Coatings

Jelle et al. (2011a) give examples of glazings incorporating hard and soft low-e coatings with low emissivity that are already available from various manufacturers, such as Pilkington glass KGlass with hard coating (e = 0.157); Opitherm S1 and S3 with soft coating (e = 0.013 and e = 0.037); Saint-Gobain glass Planitherm Total+ (e = 0.05) and Planitherm Ultra N (e = 0.03) with soft coating. However, research is still needed to improve the visible transmittance, the reflection of solar radiation (which is important in cooling dominated climates) and the durability of low-e coated glazing.

8.3 Dynamic Glazing

Dynamic glazing modifies its light and thermal transmission characteristics upon the application of a user-driven or automatic stimulation, changing from a transparent state to an opaque or tinted state and allowing the control of the amount of light and heat that passes through. Three different technologies are currently used to produce dynamic glazing: chromic, suspended particle devices and liquid crystal. The chromic technologies are further divided into four main categories: electrochromic (responding automatically to an electric signal), gasochromic (responding automatically to hydrogen gas), thermochromic (responding to changes in temperature) and photochromic (responding to changes in light).

Electrochromic glazing is considered by the building industry to be the most popular and promising of all dynamic window technologies, able to offer on-demand occupant control, high energy savings and good durability. The electrochromic technology uses electricity to change the colour and light transmission characteristics of transparent materials that change their optical properties in response to an electric field. At present, only four companies offer large-area electrochromic glazing, each using a slightly different approach for manufacturing (Sage Electrochromics, View Dynamic Glass, E-Control Glass, Gesimat).

However, most commercial electrochromic glazing products currently available absorb the solar radiation instead of reflecting it, re-emitting it towards both the outside and the inside of the space, which can potentially lead to overheating issues indoors. Reflecting electrochromic glazing has a large potential for solar control, as windows including this technology would block the solar radiation by reflecting it back towards the outside. Nevertheless, almost all research carried out to date addressed solar radiation absorbing electrochromic glazing and more research is needed in the field of reflecting electrochromic glazing, with only one company currently offering such a product (Guardian Industries / View Dynamic Glass). A typical electrochromic prototype is shown in Figure 26 and comprises of: K-Glass/ WO3 / electrolyte / ion storage (LiyV2Os) or protective layer (MgF2) / K-Glass. The speed of coloration and bleaching of an EC device is governed by the mobility of the metal ions intercalated into the electrochromic layer.

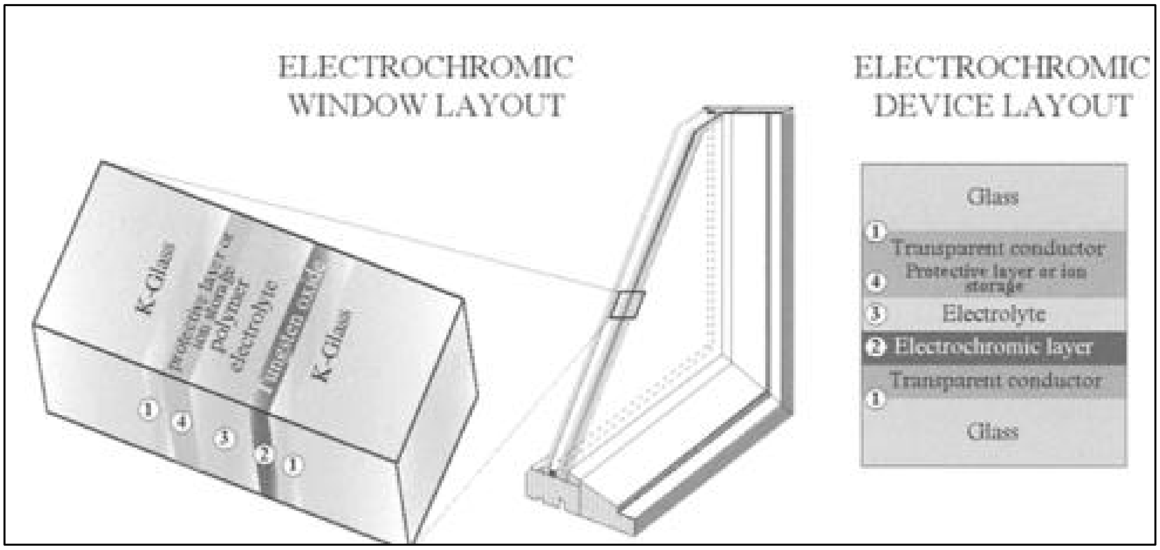


Figure 26: Electrochromic device layers and electrochromic window layout: Pilkington KGlass samples (source: Syrrakou, 2005)

Gasochromic glazing has the potential to be adopted in building facades due to its simpler structure and lower cost compared to electrochromic glazing. Its dynamic range is also larger (5-86%), however, not all electrochromic materials can be coloured with hydrogen gas, and limitations related to controlled gas exchange processes and stability over time also need improvement. Such window products are not yet commercially available but prototype units have been produced and are tested in Germany by AGC Interpane in collaboration with Fraunhofer Institute for Solar Energy Systems.

Thermochromic glazing exists on the market, but it responds automatically only to changes in temperature and cannot be controlled independently, which limits its effectiveness. Nevertheless, thermochromic glazing has a cheaper and simpler structure than electrochromic glazing and four companies currently offer such products: Pleotint, which makes a thermochromic film that can be laminated between two pieces glass and targets both new and retrofitting construction; Gesimat and GlasNovations. Another company, RavenBrick, is currently building an automated facility to begin the large-scale fabrication of a proprietary thermochromic window product. Prelco (Canada) offers a thermochromic window product that incorporates the Pleotint and RavenBrick TC films; Main obstacles for practical uses of thermochromic glazing include its critical temperature (which must be close to the comfort temperature of 20-25^{o}C), and low visible transmittance in the clear state (40-50%).

Photochromic glazing also cannot be controlled independently, responding automatically only to visible light. Canadian company Switch Materials developed a hybrid photochromic-electrochromic film, which responds to both light and electricity, displaying both photochromic and electrochromic properties. The technology is in prototype stage and is being tested in demonstration projects in Vancouver, BC, Canada.

Research activities in the field of dynamic windows focus mainly on developing new cost-effective technologies with larger dimmable ranges or improving the performance of the existing ones, and combining various smart glass technologies in multi-layer window systems that would provide full shading and privacy, an increased number of coloured states, increased colour uniformity during switching, and reduced defects in the device layers. In the building professionals opinion, the most desired properties of switchable windows are: integration with other coatings (e.g., low-e); glare reduction; consistent-looking tint changes regardless of window size; light control to any point between the tinted and the clear transparent state; high blockage of ultraviolet light; faster switching speeds (Baetens 2010a).

SPD (Suspended Particle Devices) glazing, as well as *LC (Liquid Crystal)* and *LCPD (Polymer Dispersed Liquid Crystal) glazing* are not expected to be adopted extensively in building facades due to: (1) continuous power consumption in the transparent state, operating at standard line voltage 110-220V AC; (2) concerns related to power outages, which would automatically switch the glass to an opaque state; and (3) concerns related to their long-term durability when used in exterior applications.

8.4 Air Sandwich Glazing

Sekisui Chemical Co. (Japan) manufactures a transparent, highly insulating and heat shielding light-transmitting (66%) material for windows, called the “Air sandwich”, with U-factors of 2.9 and 3.4 W/m^2K, for a 5-layer / 6-mm thick glass and a 5-layer / 4-mm thick glass, respectively, which can be installed by mounting to the interior side (room side) of the outer glass. The “Air sandwich” structure consists of multiple transparent plastic films stacked together with air layers in-between, and offers the equivalent of a double-glazed window performance with only 4-mm or 6-mm total thickness. The product targets the retrofitting market, enhancing the insulation of existing windows at only 60-80% of the cost of replacing the windows and frames with double-glazed windows. Further improvements of this product (or similar products) in terms of polymer degradation, the ability to maintain all films smooth and free of wrinkles, and an improved thermal performance (lower U-factors) are regarded as a possible alternative to window glass (Sekisui Chemical Co., 2015).

8.5 Vacuum Glazing

Vacuum-insulated glazing units (VIGs) have the air in the space between the two panes of glass extracted during the manufacturing process, creating a vacuum and providing a similar level of energy efficiency as double or triple glazing with only a quarter of the thickness of conventional double glazing. Because only a small vacuum is effective in reducing the heat losses by conduction and convection, the gap between the panes can be reduced to just 0.2 mm, giving the glazing unit an overall thickness of only 6 mm (same thickness as single glass). The glass panes are separated by a micro-spacer grid of low thermal-conductivity (0.5 mm diameter spacers set 20 mm apart). The edges of the unit are welded to achieve an airtight seal. Heat loss through radiation can further be limited by treating one of the glass panes with low-e coatings, similar to that used in conventional double and triple glazing (Low Energy House, 2013). Further information about vacuum glazing can be found in Baetens et al. (2010b) and Eames (2008).

Vacuum glazing (known also as glazing with an evacuated cavity between the panes) currently offers comparable U-factors to ordinary multi-layer glazing but with considerably less width and weight. Simulation studies showed that only one low-e coating with 0.02 emissivity can improve the thermal performance of vacuum glazing and offer U-factors of ~0.8 W/m^{2}K, which is considerably lower than the U-factors of any double glazed IGUs available today (Fang et al., 2007). Manz et al. (2006) also showed that a triple vacuum glazing with 16-mm width and stainless steel support pillars had centre-of-glazing (COG) U-factor lower than 0.2 W/m^{2}K when using 6mm/4mm/6mm sheets of un-tempered soda-lime glass and four low-e coatings (e = 0.03), which is lower than the U-factors of currently available triple IGUs. Guardian Industries announced the development of a prototype vacuum glass with a U-factor of ~0.5 W/m^{2}K or an R-value of ~2 m^{2}K/W (equivalent to R-12 ft^{2}h°F/Btu), similar to the insulation of typical brick or wood walls. The VIG consists of two 6 to 11 mm glass panes and a 0.25 mm space vacuum-sealed to 10.4 torr. In 2012, Rayotek Scientific announced a system that incorporates VIG spacers with sizes ranging from 0.5 to 1 mm, to be used in vacuum insulating glass windows (Rayotek Scientific, 2012; National Glass Association, 2012).

The best vacuum glazing found by Jelle et al. (2012a) was manufactured by Pilkington/NSG (SPACIA-21) (See Figure 27), using a combination of vacuum glazing and low-e glass with argon filling. The product has a width of 21 mm, which is considerably narrower than a conventional multi-layer glass (Planibel Low-e Tri manufactured by AGC Glass U.K) having the same U-factor of 0.7 W/m^{2}K (R-value = 1.4 m^{2}K/W) and a total thickness of 40 mm.

Regardless of the significant thermal performance advantages of VIG, more research is needed in the field of vacuum glazing edge seals and thermal expansion to bring these products to the commercial market.

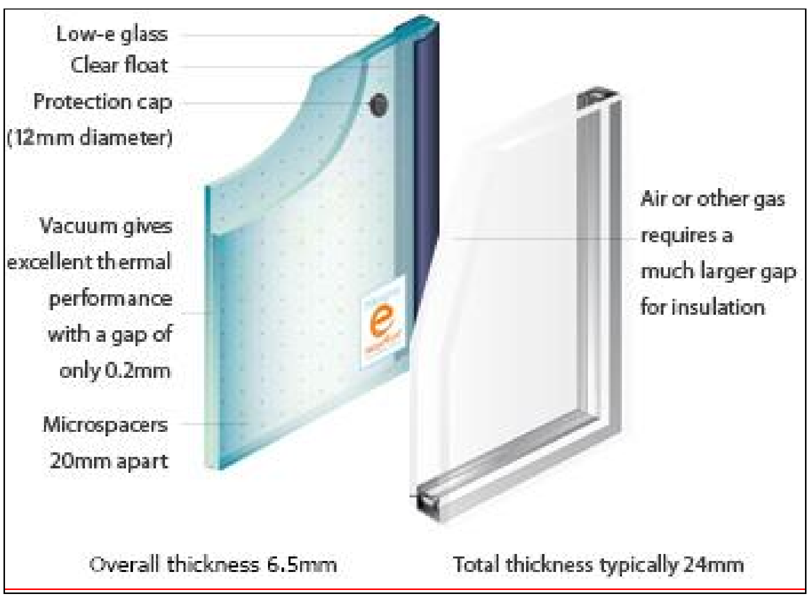


Figure 27: Pilkington Spacia™ vacuum glazing (source: Pilkington, 2013)

8.6 Electrochromic Vacuum Glazing

Papaefthimiou et al. (2006b) evaluated electrochromic vacuum glazing (ECVG) prototypes with dimensions of 400 x 400 mm, visual transmittance between 2% (tinted) and 63% (bleached), and U-factor of 0.86 W/m^{2}K, in real environmental conditions (See Figure 28). The results attested to the ECVG units durability and confirmed their potential to improve occupant thermal comfort and reduce the heating, cooling and lighting energy use. ECVG prototypes of 500 x 500 mm with two low-e coatings were simulated by Fang et al. (2010). Results showed that under winter conditions and with the EC layer opaque, the ECVG units with emissivity higher than 0.02 acted like a heating source for the indoor environment, the temperature of the indoor glass pane being higher than that of the indoor air temperature, due to the solar radiation absorbed by the low-e coatings and the EC layer. When the emissivity was lower than 0.02, the outdoor and indoor glass pane temperatures were similar. This technology is regarded as having great potential in the fenestration industry.

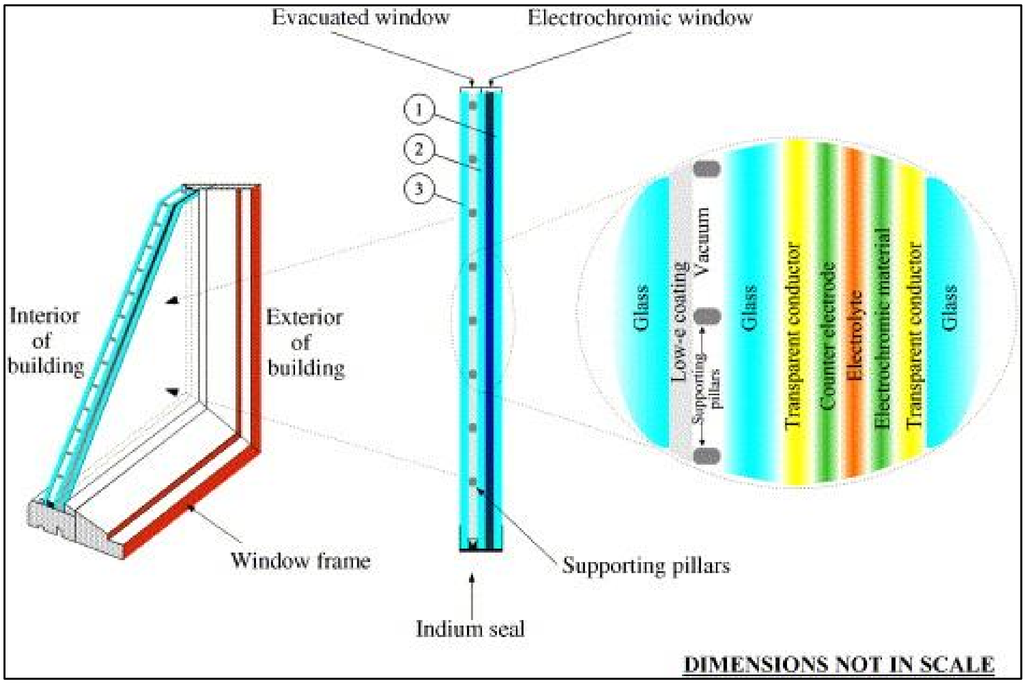


Figure 28: Electrochromic evacuated glazing (source: Papaefthimiou et al., 2006)

8.7 Aerogels

Aerogels are regarded as one of the most promising thermal insulation materials for building glazing due to their translucent characteristic, their already low U-factors (0.3 W/m^2K), and their potential for even lower U-factors (~0.1 W/m^2K) (Jelle et al., 2012a; Baetens et al., 2011; Bahaj et al., 2008; Schultz et al., 2005) (See Figure 29). The aerogel technology is relatively new in fenestration and promises low U-factors of ~0.1 W/m^2K (R-value=10 m^2K/W), however, this is usually obtained at the expense of the visible transmittance, as these glazings use translucent aerogel granules and are highly diffusing.

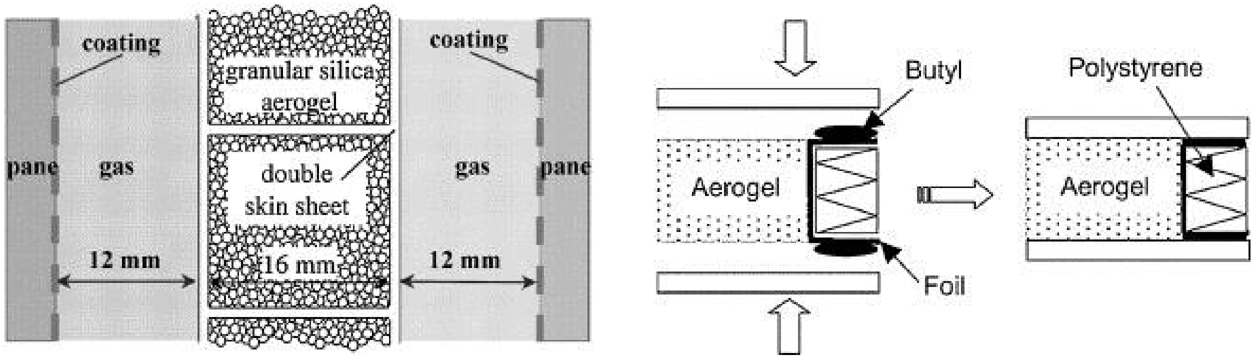


Figure 29: Cross-section through granular aerogel based glazing, consisting of two glass panels with a low-e coating on the inside, two gaps and an aerogel-filled PMMA double-skin-sheet (left) and cross-section of the monolithic aerogel based evacuated glazing (right) (source: Baetens et al., 2011)

In their review, Jelle et al. (2012a) found a silica aerogel glazing product manufactured by Cabot Corporation with a low U-factor of 0.3 W/m^{2}K (R-value=3.3 m^{2}K/W). Currently, only Cabot Corporation manufactures transparent and translucent aerogels for glazing and claims U-factors for its products between 0.25- 1.38 W/m^{2}K, and visible transmittances between 10-70% for its Nanogel® product. Advanced Glazings Ltd (North America) and Okalux (Europe) also offer customized aerogel glazing products, however, with lower visible transmittances between 7-59%.

More research is needed to obtain transparent aerogel glazing products with higher solar transmittance values than currently available (> 70%). Joint aerogel-vacuum glazing is regarded as a very advantageous solution.

8.8 Glazing Cavity Gas Fills

Most double and triple IGUs available on the market today use argon for cavity gas fills, and to a lesser extent krypton and xenon due to their rarity and higher cost (Figure 30). This figure illustrates the characteristics of a typical double-glazed window with a high-solar gain low-e glass with argon gas fill. These windows are designed to reduce heat loss but admit solar gain. High-solar-gain low-e glass products are best suited for buildings located in heating-dominated climates and are the product of choice for passive solar design projects. Researchers have been looking at ways to extract krypton and xenon from air at a cheaper cost (e.g., Cook and Griffiths, 2004; DOE, 2012) and vacuum glazing is seen as an improved alternative.

8.9 Spacers

In a state-of-the-art review on window spacers and edge seals, Van den Bergh et al. (2013) provided a detailed overview of commercially available systems and found that foam spacers (~0.15 W/mK) have a better thermal performance than thermoplastic spacers (~0.26 W/mK), and one composite spacer by TruSeal Technologies (Duralite) had a better thermal performance (0.08 W/mK) compared to both foam and thermoplastic spacers. No spacer systems on the market were found to utilize materials that have considerably lower thermal conductivities than the materials commonly used (e.g. polyurethane foam 26 mW/mK; aerogels 13 mW/mK). More research is also needed to improve the edge sealants and reducing or omitting the secondary sealant was found by the researchers to considerably improve the thermal performance in the edge-of-glass region. Spacer designs such as those by Cardinal Glass Industries (XL

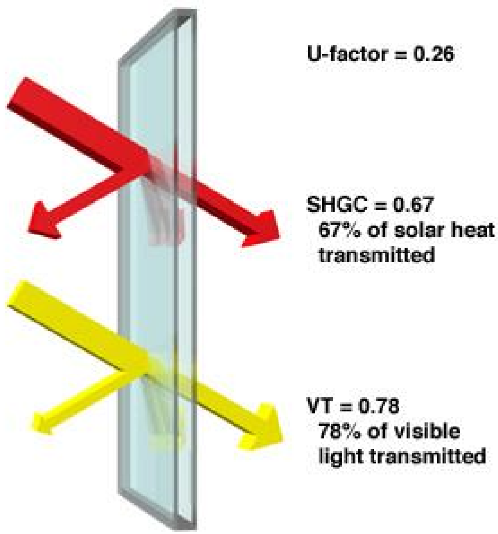


Figure 30: Double-glazed Low-e glass with argon gas fill Window with high solar gain†

Edge spacer made of stainless steel, PIB primary seal and Si secondary seal; Thermal conductivity 0.4 W/mK) were found to reduce the amount of applied secondary sealant. The best secondary sealant available today is made of butyl rubber (hot melt) and has a thermal conductivity of ~ 0.24 W/mK.

The best foam spacer found on the market by Jelle et al. (2012a) was manufactured by Edgetech, made from structural foam using warm edge technology (WET) and pre-desiccated to reduce condensation. Thermoplastic spacers made by ADCO North America Bystronic Lenhardt GmbH, Traco HQ and Manufacturing, Tremco Illbruck Ltd, and Viridian (0.28 W/mK thermal conductivity) also included desiccant material and WET. Among metal-based or metal-containing spacers the following types were highlighted: Swisspacer, Thermix, and TGI. Swisspacer is manufactured from special fibreglass and a composite material in two versions, one where the composite material is covered by an ultra-thin foil of aluminium and another using a thin stainless steel foil. Thermix is constructed from PVC (0.21 W/mK) and high grade steel (26 W/mK), and TGI spacers are manufactured of stainless steel (17 W/mK) combined with a high quality plastic polypropylene with low thermal conductivity (0.1-0.22 W/mK).

8.10 Frames

The best window frames found by Jelle et al. (2012a) had U-factors lower than 0.70 W/m^2K and were manufactured by:

- Bracia Bertrand Sp.J.
- PAZEN Fenster+Technik
- Stabalux GmbH
- Endl-Wagner GmbH
- Ing.-Büro A.Naumann&H. Stahr
- Internorm International GmbH
- NIVEAU FensterWesterburg GmbH
- RAICO Bautechnik GmbH

† http://www.efficientwindows.org/gtypes_2lowe.php

The lowest frame U-factor found was 0.61 W/m^2K, made of wood and manufactured by Stabalux GmbH. Best frames for glass façade systems were those manufactured by Endl-Wagner GmbH (U-factor 0.65 W/m^2K) and RAICO Bautechnik GmbH (U-factor 0.69 W/m^2K).

Research in the field of window frames mainly focuses on materials with low U-factors (e.g., Wan Abdul Rahman et al., 2008, simulation study of rice husk filled high-density polyethylene window frame; Appelfeld et al. (2010), study on glass fiber reinforced polyester window frames). Based on simulations studies Gustavsen et al. (2010, 2011) defined the research targets for window frame materials that would result in a better thermal performance than that of the best products available on the market today.

A new framing approach uses cast polyurethane covered in plastic, where polyurethane foam is poured into the window frame mold to create a solid frame, which is subsequently covered with a plastic layer, to produce a frame with a U-factor of 0.7-0.9 W/m^2K with a framing depth of only 9 cm. Research is underway to use the technology in frame profiles made of PVC with interior steel reinforcements and several air chambers; wooden frames with core insulation or sandwich structure; aluminum frames with insulation core; foam-filled plastic profiles. New and improved thermally broken frames are also emerging in the curtain wall industry (i.e., Schüco[‡] façades incorporate a newly developed insulation on the pressure plates surfaces - including the plate screws - with an overall U-factor=0.78 W/m^2K, when combined with a triple IGU of (1.20 x 2.50) m, 48 mm thick, U glass = 0.70 W/m^2K.) (See Figure 31).

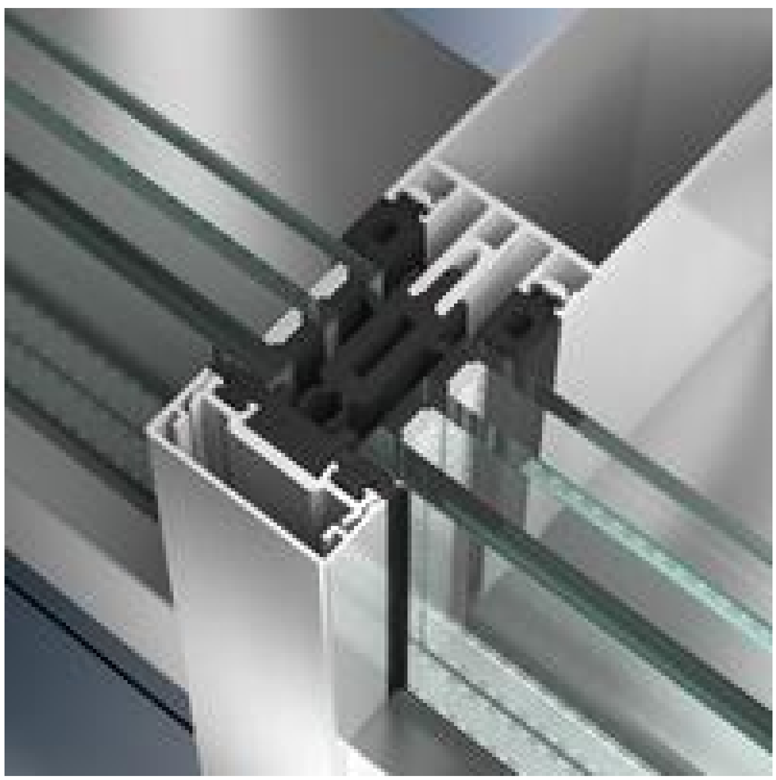


Figure 31: Schüco FW 50+.SI Curtain Wall Frame

[‡] http://www.schueco.com/web/uk/partner/fassaden/products/facades/aluminium/schueco_passivhaus_fasade

8.11 Phase Change Material (PCM) Glazing

GLASSX develops façade products that use phase change material (PCM), a technology based on a thin layer (16 mm) of a translucent material, which at room temperature (e.g. 24^{0}C) can absorb as much heat as a 250 mm thick concrete wall. The PCM layer can be installed separately or can be integrated with insulating glazing units. Phase change materials transition from a solid to a liquid state at a defined temperature and during the melting process, the material absorbs large amounts of thermal energy without becoming warmer. GLASSX uses Calciumchloridehexahydrate (CaCl2 6H2O), a nontoxic inorganic salt with a melting point of 24^{0}C. When the indoor temperature is beyond this temperature, the PCM melts and becomes translucent, transmitting most of the visible light and absorbing the infrared radiation completely. After eight hours, when the PCM is entirely molten and the outside temperature decreases below the melting point, the PCM material recrystallizes. GLASSX glazing units also come with an integrated shading solution consisting of transparent prisms located in the space between the outer glass panes (in the outermost air-gap), which allow solar gains in the winter but block the direct sun in the summer. Above 35° angle of incidence (in the temperate zone between April and September), the geometry of the prisms cause total reflection of the direct sunlight allowing only the diffuse light indoors.

Due to their ability to store and release energy, phase change materials (PCM) are likely to be applied increasingly in fenestration products. Efficient means of absorbing as much energy as possible from the solar radiation and releasing it back indoors when needed are sought, and various aspects related to the application of this technology to windows generated research interest (see studies by Jain & Sharma, 2009: Experimental solar transmittance measurements of commercial grade PCM; Ismail & Henriquez, 2001, 2002: Windows with moving PCM curtains; Merker et al., 2002a, 2002b: PCM shading systems).

8.12 Solar Cell Glazing

Materials used in solar cell thin-film technologies, sandwich cells, dye sensitized solar cells (DSSC) (See Figure 32) and other polymer-based solar cells (OPV – organic photovoltaic) continue to be one of the main focuses of research, as improved solar cell glazing products with higher transparency than currently available (> 50%) are being sought by the fenestration industry. Higher transparency decreases, however, the efficiency of the solar cells that cannot produce electricity from the visible part of the solar spectrum as the visible light is transmitted through the window. New technologies combining photovoltaic with electrochromic materials covering the entire glazing area have also generated great interest, however, optimizations are needed as the electrochromic properties of such devices were shown to lead to decreasing efficiencies of the embedded solar cells and vice versa (e.g., Huang et al., 2012; Ahn et al., 2007; Santa-Nokki et al., 2006; Huang and Chen, 2010). Limited supplies of tellurium and indium could also reduce the prospects for some types of thin-film solar cells, large-scale production could also be restricted by the silver required by solar cells, and recycling parts from old cells is encouraged (Jacobson & Delucchi 2009).

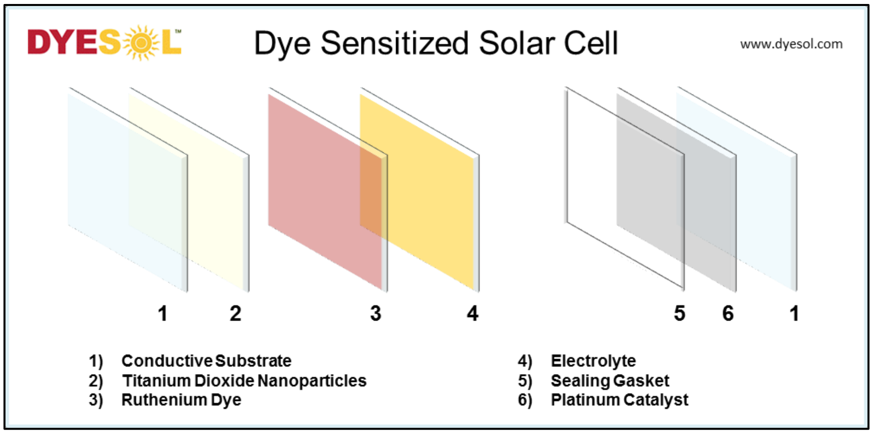


Figure 32: Basic structure of dye-sensitized (DSSC) solar cells (source: Dyesol, 2013); DSSCs are organic solar cells that offer a substantial price reduction (over thin-film silicon) due to an easy manufacturing process by roll-printing. DSSC solar cells usually include a layer of titanium dioxide (TiO2), a renewable and non-toxic white mineral used in white paints and tooth paste, and ruthenium dye sandwiched between glass sheets. This type of solar cell absorbs sunlight across the visible spectrum, produces electricity even in low light conditions, and can be directly incorporated into building glass facades.

8.13 Solar Shading Technologies

Glazing with built-in solar shading devices stand a good chance in gaining acceptance and popularity for use in building facades (i.e., newly patented technology used in the MicroShade product (See Figure 33), comprising a very thin and transparent layer of micro-lamellas built into two- or three-layer, low-e, glazing and angled to shade direct sunlight while allowing an unrestricted view. Further information about the thermal transmittance of high performance windows can be found in studies by Gustavsen et al. (2010, 2011), Ng et al., (2007), Collins & Simko (1998), and Simko et al. (1995).

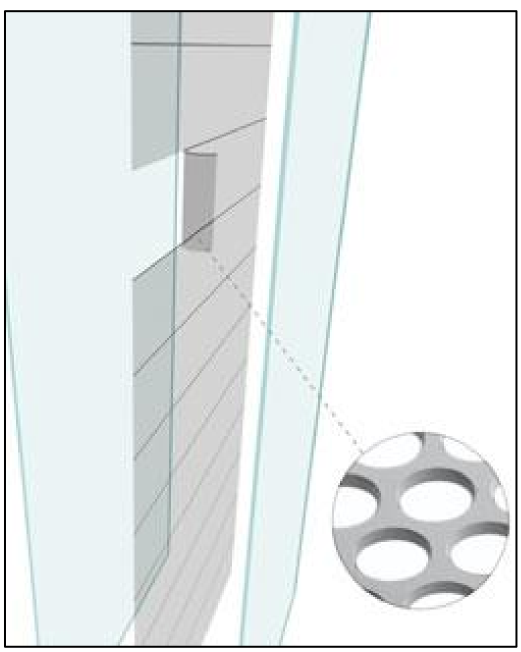


Figure 33: MicroShade - Solar Shading with Micro Lamellas (source: http://www.photosolar.dk/pages/id18.asp)

9. Innovative Curtain Walls

Below is a brief overview of other recent technologies that have entered or are beginning to enter the curtain wall market:

- Dynamic glazing transmittance
- Double-skin systems
- Building Integrated Photovoltaics (BIPV)
- Solar Thermal Curtain Walls (STCW)
- Adaptive Facades
- Frameless systems (Point-supported glass and structural glass mullions)

9.1 Dynamic Glazing Transmittance

Dynamic glazing transmittance – Employs the use of electrochromic, thermochromic and photochromic glazing. In their state-of-the-art reviews, Baetens et al. (2010a) and Jelle et al. (2012a) noted that only very few electrochromic windows manufactures produce large-area electrochromic windows with good durability and properties that meet the standard requirements for exterior building glazing. Thermochromic glazing responds automatically only to changes in temperature and cannot be controlled independently, which limits its effectiveness. The main obstacles for practical uses of thermochromic glazing include the critical temperature for transmittance modulation, which should be close to the ambient temperature, and a low visible transmittance in the clear state (currently < 0.5). Photochromic glazing cannot be controlled independently, responding only to UV and visible light. To date, the technology has been mostly used in eyeglasses and cost effective, large-size, durable photochromic glazing for windows is not commercially available.

9.2 Double-Skin Systems

Double-skin systems – Employ a ventilated space between the inner and outer walls. These types of systems have already been constructed in Europe and Asia where energy costs are much higher than in North America. Similar in concept to air-flow windows, the ventilated space conserves energy by tempering the temperature conditions inboard of the curtain wall. During the heating season, this space acts as a buffer between the exterior and interior. During the cooling season, warm interior air can be exhausted into this space. However, some authors argue that in cold climates, a less expensive way of achieving similar or greater energy savings, would be through the use of curtain walls with higher (over R-6) insulating values (Vigener & Brown, 2012).

9.3 Building Integrated Photovoltaics (BIPV)

Building Integrated Photovoltaics (BIPV) — Employ solar cells that generate DC electricity. Historically solar cells have been installed on horizontal surfaces, however, PV installed on tilted and vertical surfaces is gaining popularity (i.e., Schüco offers a BIPV option for a passive house façade, including mullions and transoms with cable ducts, cable guides and sleeves for cabling of PV modules). Another recent development includes the Texlon cladding system with copolymer Ethylene Tetra Fluoro Ethylene (ETFE, a material that does not degrade under UV-light) and integrated PV cells[§].

[§] http://www.etfe-mfm.eu/

Nevertheless, the current industry standard is to create building integrated photovoltaic (BIPV) glass modules by assembling together small opaque solar panels and window glass, which allows only the open areas of the glass to be fully transparent, providing overall transparencies below 0.5. Optimizations of such systems are still needed as, on one hand, the solar radiation used by the solar cells cannot be used for daylighting, whereas the overall (total area) efficiency of the glass-photovoltaic module is generally quite low due to the glass spacing between the photovoltaic cells. For more information, see studies by Ishikawa et al. (1996) and Yoshino et al. (1994) on PV module integration with curtain walls.

New technologies based on organic (OPV) and dye-sensitized solar cells (DSSC) show potential for fully transparent BIPV glass and inexpensive solar modules. However, both of these technologies typically have long-term durability issues with climate exposure and very low conversion efficiencies (2-7%) compared to traditional solar cells which have reached efficiencies between 8-18%. Recently, Dyesol announced DSSCs with a conversion efficiency of 11.3%, Oxford Photovoltaics achieved a 15.4% efficiency for its solar cells, and New Energy Technologies developed an OPV technology using a series of ultra-small solar cells (1 mm^2 single cell area, 100 nm thickness) applied on see-through glass or plastic substrates. These products are still in the R&D stage and significant breakthroughs are still needed. For additional information see the state-of-the-art review by Jelle & Breivik (2012c, 2012d).

9.4 Solar Thermal Curtain Walls (STCW)

Solar Thermal Curtain Walls (STCW) - employ the use of solar collectors installed as a building envelope or building facades module to generate shading and insulation while supplying domestic hot water. Figure 34 shows a stand-alone house with the solar collector integrated as envelope was constructed for investigating the thermal performance of solar thermal curtain wall.

Figure 34: Solar Curtain Wall System (source Li et al., 2015)

Figure 35 shows solar thermal curtain wall module which is actually a flat plate collector. It is composed of a layer of highly transparent glass sheet, a layer of highly absorptive plate, pipes and insulations. The plate is basically a tube-in-sheet-type plate.

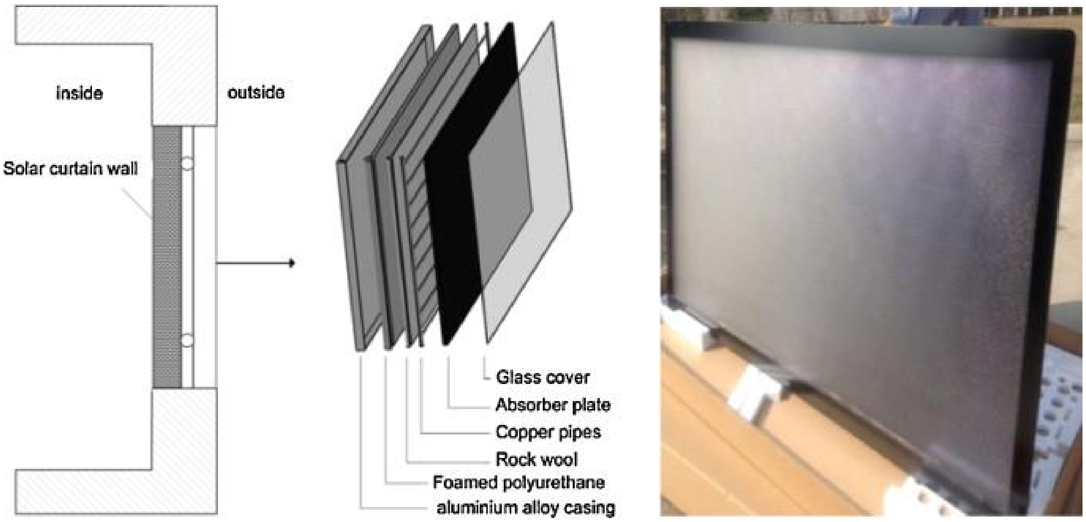


Figure 35: Structure diagram of the flat-plate collector (source: Li et al., 2015)

For more information see work by Li et al. (2015) who investigated the overall thermal performance of such a system integrated in the facade of a stand-alone house. The authors reported that the heat transfer coefficient of the STCW varied monthly and ranged between 1.99 W/m^2K (in August) to 0.86 W/m^2K (in January), and concluded that the annual performance of the facade-integrated solar curtain wall outperformed that of traditional walls in terms of heating/cooling load fluctuations and peak loads.

9.5 Adaptive Facades

Adaptive Facades — Optimize the light level, solar gain and thermal performance in real time responding to environmental changes (e.g., Adaptive Building Initiative (ABI)/Hoberman 2013 Patent; Tessellate stacked panels, built of metal or plastic, overlap resulting is a kaleidoscopic visual display of patterns aligning and then diverging into a fine, light-diffusing mesh[**]) (See Figure 36)

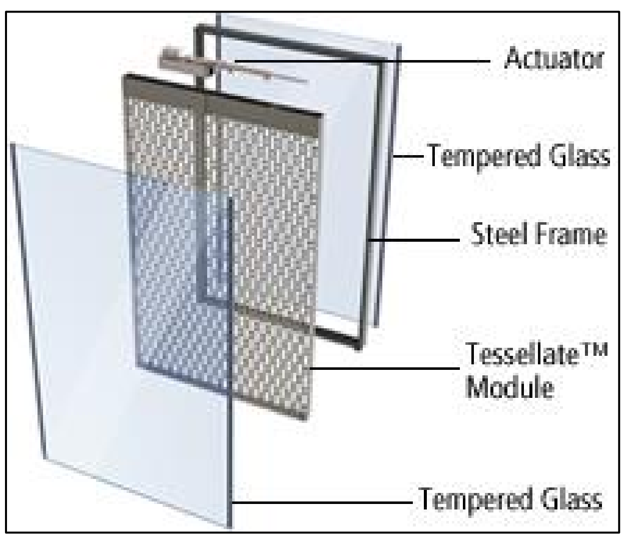


Figure 36: Tessellate Adaptive Facades System

[**] http://www.adaptivebuildings.com/tessellate-surface.html

9.6 Frameless Systems (Point-Supported Glass & Structural Glass Mullions)

Frameless systems (Point-supported glass and structural glass mullions) — Utilize glass panes fixed to a structural system at discrete points, usually near the corners of the glass panels (point-fixed). The glass is directly supported without the use of perimeter framing elements. These systems are different from the average structurally-glazed aluminum curtain walls, one of the biggest differences relying in the way the glass is supported. Aluminum curtain walls are held together on all sides by a cap, or from behind with structural silicone bonded back to mullions, whereas the point supported structural glass systems are anchored only at specific points, with silicone used as a weather seal between the joints[††]. See also Stackwall[‡‡], a structural wall system with glass panels joined to vertical glass mullions with metal patch fittings (Figure 37); and Enclos Glazing Systems[§§].

Figure 37: Oldcastle Building Envelope® Stackwall ® System

[††] http://wwglass.com/blog/post/what-is-a-point-supported-glass-system
[‡‡] http://www.oldcastlebe.com/products/structural-glass/structural/stackwall
[§§] http://www.enclos.com/service-and-technology/technology/structural-glass-facades/glazing-systems

10. Conclusions

This report is the first in a series of reports part of the NRC-Construction Project A1-002844, "High Performance Roofing and Walls Technologies". The main objective of the project is to improve the thermal efficiency of commercial building envelopes. This work reviewed existing knowledge on Curtain Wall Systems in an attempt to identify approaches that would improve the energy-efficiency, functionality and cost-effectiveness of the next generation of the curtain walls technology.

The literature review summarized information from academic publications, relevant sector/industry guides and standards, and selected commercial sources and focused mainly on identifying:

- Curtain walls weaknesses in thermal performance;
- Designs and methods for thermal performance optimization;
- Innovative insulation techniques and materials;
- Super-insulating or high efficiency glazing (with low U-factors);
- Junction details and attachments such as screws materials, length, spacing, frame dimension, glazing position in the cavity, and their effects on the overall thermal performance of a curtain wall system (i.e., U_{frame}).

The report provides descriptions of the designs and installation methods used in the curtain walls industry (e.g., face-sealed, water-managed, pressure equalized rainscreen systems); describes the primary functions of the curtain wall system components (e.g., vision panels, spandrel panels, frame, etc.); and reviews the curtain walls individual requirements for control of air leakage, heat flow, rain and snow penetration, and control of water vapour diffusion. Selected information on these topics was compiled from the best practice guide building technology "Glass and Metal Curtain Walls" (CMHC, 2014).

Curtain walls must meet the same basic performance criteria as all types of walls, however, the non-absorbent nature of glass and metal-frame imposes special constraints on its design. The repetitive nature of curtain wall design often result in small issues being reproduced numerous times, generating discrepancies between the expected and the actual performance of installed curtain wall systems. To avoid curtain walls failures, performance testing is usually conducted in laboratories (for product development or to evaluate specification compliance) or in the field (for quality assurance). Air leakage and water penetration resistance, as well the interaction of all the curtain wall components combined (including gaskets and seals) can only be reliably evaluated by physical testing. However, curtain wall thermal performance can be evaluated by both testing and simulations, and computer modelling combined with standard tests of glazing products can be used to determine the overall U-factor of curtain walls, based on an area weighted U-factor of the framing, the glazing edge and the center-of-glass regions.

A comparative analysis of European and North-American standard (not thermally improved) curtain wall systems found that, generally, the European frames perform better and are more thermally efficient. Two systematic differences were found: (1) the location of the interior gasket; (2) the more solid screw fin connection of the European systems, having an additional member in the interior aluminum profile that secures the gasket (in North-America, this gasket is often installed directly into the aluminum structural member). Simulations conducted to evaluate the influence on thermal performance of several frame design parameters (profile width and length, position of the insulating glass units, glass unit thickness, λ-values of screws and compartmentalization, as well as several insulation techniques of the interior cavity) showed that the profile member that secures the gasket (present in the European frames) does not influence significantly the heat loss. The higher thermal transmittance of the North-American frames was linked to the increased length of the screw fins. Overall, the following three parameters had the greatest effect on the thermal performance of curtain wall systems: length of screw fin; glass unit thickness; and additional insulation in the inner cavity. A minimum thermal transmittance of 1.485 W/m^2K (a 62% decrease from a reference value) was obtained. Further optimization of the inner cavity insulation is expected to improve this performance even more.

The literature review also showed that the vast majority of the glazing products commercially available consist of double or triple glazed insulated units. However, new products incorporating novel technologies are becoming more accessible and are showing improved reliability and stability. The demand for highly-insulating glazing technologies will also continue to increase.

Technologies that improve the heat transfer through windows by lowering its U-factor include insulating low-e coatings, suspended and applied solar control films, silica-based aerogels, phase change materials, and vacuum glazing. Dynamic glazing technologies (glazings able to change their optical properties in response to a stimulus such as an electric signal, temperature, light), as well as glazing with built-in dynamic shading, photovoltaic (PV) glazing or glazing incorporating organic (OPV) and dye-sensitized solar cells (DSSC), promising fully transparent BIPV glass and inexpensive solar modules, all have the potential to be adopted in building facades. However, most of these technologies are not yet fully developed and, in some cases, significant breakthroughs are still needed. For example, technologies based on organic (OPV) and dye-sensitized solar cells (DSSC) typically have long-term durability issues with climate exposure and very low conversion efficiencies (2-7%) compared to traditional solar cells, which have reached efficiencies between 8-18%.

Further fenestration R&D activities aim to:

- make dynamic glazing technologies energy efficient for cold climates;
- have larger dynamic ranges in order to admit as much daylight as possible in the highest transparent state, and reduce or eliminate the need for shading devices for solar radiation or glare control at the lowest visible transmittance;
- have faster switching speeds;
- have consistent-looking tint changes regardless of window size;
- have increased colour uniformity during switching;
- permit light control to any point between the tinted and the clear transparent state;
- offer higher blockage of ultraviolet light;
- have faster switching speeds;
- offer an improved lifespan and reliability over time;
- have less defects in the device layers;
- offer low installation costs, as in many cases the prospective energy savings do not justify the premium installations costs, which lead to long payback periods.

For vision glass, the maximum overall thermal transmittances (U-factors) of 1.6 W/m^2K and 2.4 W/m^2K for climate zones 8 and 3, respectively, are within the range of commercially available high performance systems. However, the requirement for the opaque spandrel panels, which range between 0.315 W/m^2K (R18) to 0.183 W/m^2K (R31), may require thicker units than normally used. Required insulation thicknesses for spandrel panels would range between 76 and 131 mm for climate zones 3 and 8, respectively, using current insulation products.

R&D activities also target improved materials and designs for spacers, edge seal systems and window frames, with lower thermal conductivity than currently available. In order to produce windows (glazing and frames combined) with U-factors lower than 0.8 W/m^2K, the following technologies are sought: (1) highly insulating frames with U-factors in the range of 0.7-1.0 W/m^2K; (2) spacer technologies with conductivity of 0.02 W/mK; (3) thermal break materials with conductivity of 0.005 -0.02 W/mK; (4) structural insulating materials and solid frames with conductivity of 0.03 W/mK; (5) low-e coatings (or pigments) for PVC/aluminum window frames with emissivity of 0.05.

Main approaches that would improve the thermal performance of curtain wall systems to meet the energy code requirements include:

- Triple/quadruple IGUs, including products with multiple layers through a combination of glass and thin films with low emissivity (low-e), and spectrally selective coatings or ceramic fritting for glare protection and high quality daylighting;
- Optimization of the vision glass areas (glass tuned based on the building façade orientation for a better control of winter passive solar gains and summer solar gains);
- Dynamically controlled exterior sunshades integrated with the curtain wall framing;
- Smaller vision glass areas and larger insulated spandrel glass/opaque wall areas;
- Better quality and thicker insulation used in spandrel panels (with 100% vapour and air barrier to prevent condensation), potentially incorporating vacuum insulated panels;
- Double-skin façade systems with passive ventilation and shading control;
- Occupant-controlled windows;
- Integration of new technologies such as photovoltaic systems, vacuum glazing and variable glass tinting systems (dynamic glazing);
- Significantly improved thermal break designs including (but not limited to):
    - improved frame designs with higher performance thermal breaks; high-performance spacer bars; gas filled air spaces;
    - two thermal breaks designs (e.g., one in the front of the pressure plate screw stem and the other from the back of the stem to the frame tube to reduce the thermal transfer, the outer thermal break also serving as a seal against water forming behind the pressure plate and the snap cap);
    - four-sided structural glazing (4SSG capless systems), which have improved thermal resistance from the silicone sealant with foam backing being flushed with the face of the glass (e.g., the entire face of the 4SSG system acts as a rainscreen and a thermal barrier, and the gasket or silicone in line with the face of the glass acts as a thermal break);

From a regulatory point of view, in North America there are no codes or test methods exclusively dedicated to curtain wall systems. The American Architectural Manufacturers Association (AAMA) and the National Fenestration Rating Council (NFRC) are the primary bodies that regulate the window and curtain wall industry in the United States. In Canada, there is no industry standard for the performance of curtain wall systems, however, standards for the performance of windows are established by the Canadian Standards Association (CSA). Laboratory and field performance testing are established by the American Society for Testing and Materials (ASTM).

The National Energy Code of Canada for Buildings (NECB, 2011), which provides the minimum requirements for the design and construction of new energy-efficient buildings, has been enforced only on federally owned buildings, with Ontario being the only province that has adopted it in its provincial code. The province of British Columbia uses the ASHRAE Standard 90.1-2007, while the other Canadian provinces have no enforceable building energy performance standards referenced in their provincial codes. The prescriptive requirements of the NECB should not be problematic for the industry, as the much more stringent European energy codes have not been an obstacle to the curtain wall industry in Europe and, in fact, these codes have stimulated considerable product and design innovations. For more information on the implementation of the National Energy Code of Canada for Buildings (NECB, 2011) on curtain wall design, as well as for approaches that would improve the curtain wall thermal resistance to meet the minimum NEBC code requirement see report by Cornick (2013).

Overall, the literature review highlighted the importance of using a holistic approach when evaluating the thermal performance of curtain walls systems. Specific standards for curtain wall applications ought to be developed and harmonized in terms of thermal and energy performance, similarly to the calculation methods for thermal resistance of building envelope assemblies and the requirements for air barrier assemblies defined in Part 9 of the National Building Code.

On-going work within the current project includes the thermal modelling of curtain wall systems configured as a complete (one-piece) assembly, as an example of an integrated approach to using CFD modelling within the NRC hygrothermal numerical model, hygIRC-C. The hygIRC-C numerical model, simultaneously solves the highly nonlinear two-dimensional and three dimensional Heat, Air and Moisture (HAM) equations that define the heat, air and moisture transfer across building components. The hygIRC-C model has been extensively benchmarked in a number of projects and has been used in several studies to assess the thermal and hygrothermal performance of conventional wall and roofing systems. The results of this model applied to curtain wall systems will be documented in a subsequent report (Saber et al., 2015).

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12. Standards Acronyms

Acronyms	Meanings
ASHRAE	American Society for Heating, Refrigeration and Air Conditioning for Engineers
AAMA	Architectural Aluminum Manufacturers Association
CSA	Canadian Standard Association
NFRC	National Fenestration Rating Council
CSA/CGSB	Canadian Standards Association / Canadian General Standards Board
ASTM	American Society of Testing Materials
GANA	Glass Association of North America
AA	Aluminum Association
ACI	American Concrete Institute
IBC-ASCE	International Building Code & American Society of Civil Engineers
MIA	Marble Institute of America
NIBS	National Institute of Building Sciences
NBCC	National Building Code of Canada
CMHC	Canadian Mortgage and Housing Corporation
SEI	Structural Engineering Institute
AISC	American Institute of Steel Construction

13. Standards and Titles

Standards	Title
AAMA/NWWDA-101	Voluntary Specifications for Windows and Glass Doors
AAMA 501	Methods of Test for Metal Curtain Walls
AAMA 501.1	Standard Test Method for Metal Curtain Walls for Water Penetration Using Dynamic Pressure
AAMA 502	Voluntary Specification for Field Testing of Windows and Sliding Glass Doors
AAMA 503	Voluntary Specification for Field Testing of Storefronts, Curtain Walls and Sloped Glazing System
AAMA 1503	Voluntary Test Method for Thermal Transmittance and Condensation Resistance of Windows, Doors and Glazed Wall Sections
AAMA 1503.1	Voluntary Test Method for Thermal Transmittance and Condensation Resistance of Windows, Doors and Glazed Wall Sections
ACI-318-08	Building Code Requirements for Structural Concrete and Commentary
ASHRAE 90.1	*Energy Standard for Buildings Except Low-Rise Residential Buildings*
ASHRAE 189.1	*Standard for the Design of High-Performance, Green Buildings Except Low-Rise Residential Buildings*
ASTM C177	Standard Test Method for Steady State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded Hot Plate Apparatus
ASTM C1199	Standard Test Method for Measuring the Steady State and Thermal Transmittance of Fenestration System Using Hot Box Methods
ASTM E283	Test for Rate of Air Leakage through Exterior Windows, Curtain Walls and Doors
ASTM E330	Test for Structural Performance of Exterior Windows, Curtain Walls and Doors by Uniform Static Air
ASTM E331	Test for Water Penetration of Exterior Windows, Curtain Walls and Doors by Uniform Static Air Pressure Difference

ASTM E783	Field Measurement of Air Leakage Through Installed Exterior Windows and Doors
ASTM E1186	Standard Practice for Air Leakage Site Detection in Building Envelope and Air Barrier Systems
ASTM E1423	Standard Practice for Determining the Steady State Thermal Transmittance of Fenestration Systems
CAN/CGSB 149-GP-2MP	Manual for Thermographic Analysis of Building Enclosures
CSA/A440.2	Energy Performance of Windows and other Fenestration Products
CAN/CSA-440	Canadian Standard for Windows
CAN/CSA-A440.4	Field Testing of Window and door Installations
IBC-ASCE 7	Standard for Minimum Design Loads for Buildings and Other Structures
NFRC 102	Steady-State Thermal Transmittance of Fenestration Systems
NFRC 100-2014	Procedure for determining Fenestration Product U-factors