UPGRADING THE PERFORMANCE OF HERITAGE WINDOWS TO SUIT MODERN DESIGN CONDITIONS: A CASE STUDY – FORMER US EMBASSY, OTTAWA

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ABSTRACT

100 Wellington Street was constructed in Ottawa, Ontario, Canada circa 1931 as the United States Embassy, and was occupied until 1997 when ownership was transferred to the Canadian Government. The Canadian Government was looking to repurpose this heritage-designated building to public "art gallery" quality space, capitalizing on its prominent location on the Ceremonial Route across from Parliament Hill.

With the proposed change to Gallery Space, the interior operating conditions were to be changed to add winter humidification, with museum quality controls on temperature and relative humidity variations. The heritage-designated windows, which consist of single glazed non-thermally broken bronze frames, needed to be assessed and potentially upgraded to tolerate the proposed interior operating conditions during winter design conditions in a cold weather climate. The challenge was to upgrade the air-tightness and thermal properties of the windows without negatively impacting on the heritage character of the building.

This paper will discuss how hygrothermal field monitoring and analysis was used to evaluate and quantify the performance of the original heritage windows and building envelope in relation to the proposed interior operating conditions. It will describe the window rehabilitation approach that was developed. The paper will also demonstrate the validity of the design concept through the construction and monitoring of a full scale *in-situ* mock-up. This paper presents the hygrothermal monitoring results of the window mock-up and discusses the strategies and concepts for dealing with similar heritage window upgrades in a cold weather climate.

INTRODUCTION

100 Wellington Street was constructed in Ottawa circa 1931. It is a three-storey (plus penthouse) building that is primarily clad with Indiana limestone, with bronze-framed "punched" windows. Located in downtown Ottawa, the building is situated in a prominent location across from Parliament Hill (photographs 1 & 2). It was designed by American architect Cass Gilbert in the Beaux-Arts style, as the first purposely constructed US Embassy in Canada. It served as the United States Embassy until 1997, when ownership was transferred to the Canadian Government. The Federal Heritage Buildings Review Office (FHBRO) of Canada has designated the building "Classified", for "*…its architectural importance, its historical associations and its environmental significance.*"[1] It is classified a Federal Heritage Building.

The Canadian Government, was looking to re-purpose the site, converting the building to "art gallery" quality space. The renovation, which would include the construction of a new five-storey addition, needed to balance the requirements for the upgrade of the original building while preserving the heritage defining characteristics. With the proposed change to Gallery Space, the interior operating conditions would be changed to add winter humidification, with museum quality controls on temperature and relative humidity.

[1] FHBRO Heritage Character Statement – 100 Wellington Street – FHBRO Number 84-27, 1998.07.20 (Revised)

Photograph 1: North & East Elevations.

Photograph 2: Close-up of East Elevation.

The region around Ottawa has extremes in weather in both summer and winter conditions. During the summer months, exterior temperatures of over 30°C (86°F) combined with relative humidity over 50% commonly occur during June and July. The “Canadian Climate Normals” note that the average daily maximum for July is over 26°C (79°F) and over 50% RH. For this reason, air conditioning is common in residential and accommodation occupancies. Dehumidification is not common for these occupancies, although it is common for office and larger institutional occupancies. During winter, exterior temperatures regularly reach below -20°C (-4°F) for extended periods, with the exterior air being nearly devoid of moisture. Rain can occur in all months of the year, with monthly averages from June through September over 85mm (3.4”). Snowfall averages over 55cm (21.6”) in December and January.

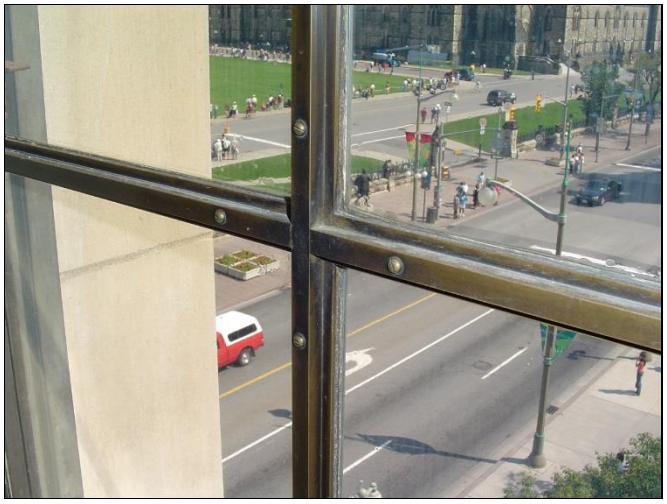
The envelope assemblies of the heritage building, including the windows, needed evaluation to determine if the proposed new design indoor environment could adversely affect their performance and/or ability to resist the imposed environmental loads. This information would be used to develop strategies to either upgrade or manage the impacts on the building envelope, while maintaining the heritage character. While the project considered the building envelope as a whole, this paper focuses on the evaluation and upgrading of the heritage windows to achieve the design objectives (i.e., to manage and control heat, air, vapour, and precipitation control). The following sections describe the evaluation, challenges, and implementation of the heritage window performance upgrades.

ORIGINAL WALL & WINDOW ASSEMBLIES

100 Wellington Street has a concrete encased steel-framed structure, founded on conventional cast-in-place concrete strip and spread footings. The building is clad on the north, east and west elevations with Indiana limestone. Brick masonry back-up, three to four wythes thick, is built tight against the back of the limestone and flush with the outside edge of the floor slab. A cavity air space, nominally 38 mm (1½”) thick, extends between floor slabs and separates the inside face of the brick masonry back-up from a wall of 75 mm (3”) thick terra cotta tile. The interior surface of the exterior walls are finished with plaster on metal lath, which is approximately 22 mm (7/8”) thick. The plaster wall finishes terminate at the underside of the plaster suspended ceiling which is approximately 1 m (39”) below the floor slab. The south (non-prominent) elevation has a similar composition except that it is clad with brick masonry rather than limestone.

The windows are single hung, vertical sliding windows with the lower sash operable and the upper sash fixed (photographs 3 & 4). The windows are constructed of non-thermally broken bronze frames. The operable sash is balanced using a conventional weight box system, with concealed weights and chain. Weather-stripping of the operable sashes relies on the double sash locks to compress the meeting styles together, and leaf-style metal weather-stripping at the sill.

Photograph 3: Typical bronze window.



Photograph 4: Close-up of bronze muntin bars, with single glazing

The building was originally heated with convection heaters, with individual temperature control valves, which are set into recesses below the windows. Ventilation air is supplied via diffusers located in the ceiling. The original building was not designed with (wintertime) humidification.

PROPOSED OPERATING AND ENVIRONMENTAL CONDITIONS

The operation conditions (controlled indoor environment) and the climate (uncontrolled environment) determine the thermal and moisture gradient across the building envelope and the potential for condensation. The transport mechanisms for movement of interior moisture are air leakage and vapour diffusion. The former is driven by air pressure difference through holes in the building envelope, and controlled by the air barrier system. The latter is driven by vapour pressure difference across materials and spaces and the vapour permeance of the materials, and is typically controlled by appropriate placement of low vapour permeance materials.

According to the statement of requirements, the proposed design indoor environment would be 35% RH at 22ºC, which has a dew point temperature of approximately 6ºC (43°F). Dew point temperature is the temperature at which air will become saturated and condensation can occur on neighbouring materials. In this case, condensation will occur when this condition air comes into contact with any surface at around 6ºC or colder.

As Ottawa is a cold weather climate, the critical design condition typically occurs during the winter season. The Ottawa winter thermal environment can be defined by the January design

temperature and by the heating degree-days. The former is a measure of condensation potential, while the latter is a coarse measure of how much condensation may occur. According to the National Building Code of Canada, the 2½% January design temperature for Ottawa is -25ºC[2].(-13°F) In other words, 2½% of the hours will be at or below -25ºC in an average January in Ottawa.

MONITORING OF EXISTING ENVELOPE PERFORMANCE

Heritage buildings, such as 100 Wellington Street, that did not include humidification in their original construction, would not have been designed to manage condensation of interior humidity during winter conditions. However, the construction of the building envelope may be such that there is an inherent resistance to condensation under winter conditions.

Excessive condensation must be avoided because adverse effects such as deterioration of building materials and/or the promotion of mold growth can arise from the accumulation of moisture under winter design conditions. The purpose for monitoring the hygrothermal performance of the actual construction is to determine the response of the building envelope to interior and exterior environmental conditions (temperature, vapour pressure, and air pressure), and to predict from the monitored results the conditions that the building envelope can support without adverse effects.

Hygrothermal monitoring is best completed with constant interior conditions (temperature, vapour pressure and air pressure). During the monitoring period, the temperature controls on the convection heaters below the window was set to maintain the interior temperature at 22ºC. Temporary local humidification was also used to maintain a constant relative humidity of 30%. The vapour pressure would be constant with constant temperature and relative humidity.

Sensors were installed to measure temperature gradient, vapour pressure gradient and air pressure gradient through the walls and across the windows in order to evaluate their hygrothermal response. The sensors were installed on the window frames and glazing (photograph 5). Similarly, sensors were installed through the wall assembly (photograph 6), including on the interior and exterior surfaces, as well as at the interstitial surfaces in the air space. We also installed temperature sensors to measure the effect of the heaters located below the windows, the ceiling diffusor, a wall return air vent and the underside of the concrete floor slab.

[2] National Building Code of Canada, Canadian Commission on Building and Fire Codes – National Research Council of Canada

Photograph 5: General set-up of monitoring equipment/sensors.

Photograph 6: Sensors mounted within wall

The sensors were read at ten-minute intervals for a period of nearly one month spanning from mid-December to mid-January. Hygrothermal monitoring ideally requires seven consecutive days with an exterior temperature below -10ºC (in a cold weather climate). However, such conditions were only present from January 6 to January 12. Notwithstanding this, from January 8 to January 11, the exterior air temperatures were near the Ottawa winter design temperature of - 25ºC.

ANALYSIS OF EXISTING ENVELOPE PERFORMANCE

Surface temperatures within a building assembly can be predicted from the Temperature Index ("I-value"). Temperature Index is a value that represents the relationship between a surface temperature on or within an assembly and the temperatures at its boundaries, such as the interior and exterior air temperatures. The Temperature Index for a surface within an assembly can be determined from the measured responses of an assembly to fixed boundary conditions.

The Temperature Index will be constant under steady state conditions. However, buildings seldom experience steady state conditions. Field monitoring provides data that allow instantaneous calculation of Temperature Index. Such values can be considered appropriate for "thermally light" assemblies such as glazing and windows as they tend to respond quickly to thermal changes. However, "thermally massive" assemblies such as masonry walls respond slowly to changes in interior and/or exterior temperatures due to their thermal lag.

We analyzed the monitored data to calculate the Temperature Index of the various assemblies. For the windows and glazing we were able to use the instantaneous values, but for the walls and slab we needed to determine the thermal lag in order to calculate the effective Temperature Index for these assemblies. These values were then used to predict the surface temperatures under the proposed winter design conditions (i.e., interior: 35% RH at 22ºC, exterior: -25ºC). A subset of these values are shown in Table 1 below:

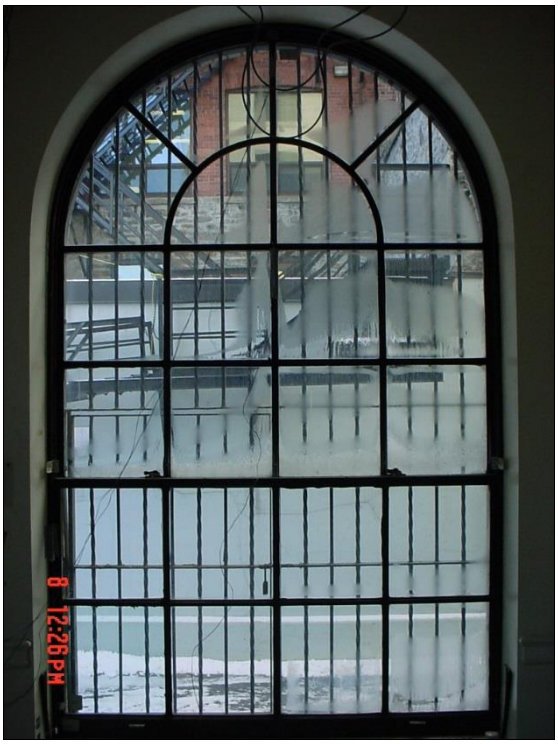
Table 1: Predicted Surface Temperatures Under Winter Design Conditions.

Location		Temperature Index	Predicted Surface Temperature
East Window	Window Sill	0.39	-7ºC
	Lower Glazing	0.47	-3ºC
	Window Head	0.71	8ºC
	Upper Glazing	0.70	8ºC
South Window	Window Sill	0.64	5ºC
	Lower Glazing	0.67	6ºC
	Window Head	0.73	9ºC
	Upper Glazing	0.72	8ºC

The measured thermal gradients through the various assemblies were then compared to the theoretical thermal gradients as calculated from the thermal resistance values as documented in the ASHRAE Handbook Fundamentals[3] (for steady state conditions). The close correlation between the measured and theoretical values validated the results of our monitoring and analysis.

It was noted that condensation and, in some cases, frost was observed on the windows during the field monitoring program (photograph 7). The locations where frost (and condensation) was observed, such as at the meeting rail and directly above the windowsills (photograph 8), were consistent with the locations predicted for condensation. Although not unexpected, our field monitoring and analysis confirmed that the thermal performance of the existing heritage windows is very poor, and without upgrades would not provide the required performance at or near the proposed winter design conditions.

[3] ASHRAE Handbook Fundamentals (SI Edition) – American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc.



Photograph 7: Typical condensation & frost accumulation.

Photograph 8: Frost observed at meeting rail.

Other data collected during our monitoring program related to air and vapour pressure differences. While more applicable to the evaluation of the opaque wall sections, this data was also used in the development of the recommended window perimeter and window-to-wall connection detailing.

Air Pressure Difference

The air pressure was measured on the interior, the interstitial space between the terra cotta and masonry back-up, and to the exterior. In general, the air pressure difference between inside and outside varied between -10 Pa and -20 Pa, where the air pressure difference between the room and the interstitial space remained relatively consistent at approximately 1 Pa. This demonstrated that cavity is effectively connected to the interior, and that the exterior cladding assemblies (limestone and brick masonry back-up) are the primary planes of air tightness for the walls.

Vapour Pressure

The vapour pressures measured in the east and south wall cavities were compared to both the interior and exterior data to determine the functional relationship. Our analysis determined that there is an appreciable drop in vapour pressure (and resultant dew point temperature of the air) from inside the room to the interstitial wall cavities. This analysis indicates that the interior painted plaster finishes on terra cotta tile were acting as an effective vapour barrier under winter design conditions.

BASIS FOR DESIGN

The hygrothermal monitoring and analysis of the windows at 100 Wellington Street conclusively determined that the original heritage windows, in their current state, would not perform under the proposed interior design conditions of 35% RH at 22ºC during winter. Accordingly, it was determined by the design team that the windows (and window-to-wall junction) would be thermally upgraded to provide effective hygrothermal performance at design conditions. There were a number of strategies considered, including;

- Replacement of the heritage bronze windows with more thermally efficient windows (frames and glazing), which would provide the required level of performance to support the proposed interior design conditions.
- Modification and upgrade of the existing heritage windows to improve the thermal performance of the windows through installation of improved glazing and modifications to the frame.
- Separation of the heritage windows from the conditioned space by either enclosing the exhibits in conditioned displays, or separating the exterior perimeter space in a "buffered" environment.
- Provide supplemental heat delivery to the windows and glazing to ensure that the surfaces remain above the dew point temperature of the air.
- And multiple combinations and variations of the above strategies.

The underlying premise of the overall project was to preserve the historical value and importance of the building. As *"…the original multipaned double-hung sash windows… are important character-defining features"*[4], the directive was that the windows must remain in place and effectively intact (e.g., maintaining as much of the original building fabric as reasonably practicable). Additionally, in keeping with the *Standards and Guidelines for the Conservation of Historic Places in Canada*[5], any changes to the windows would need to be completed in a manner that respected the original character of the windows and be reversible in the future. The relatively fine and thin detailing of the heritage sashes made them unsuitable to glazing modification without compromising their appearance and integrity, and glazing upgrades would not address the thermal inefficiencies of the non-thermally broken bronze frames.

DESIGN APPROACH

The design team determined that the best approach for 100 Wellington Street was to leave the original heritage windows in their unmodified state, and to install a new glazing system on the interior. This strategy would effectively result in the new interior window (the "primary" window) providing the required control of air leakage, vapour diffusion, and condensation control, and would make the original bronze windows effectively "storm windows". Included in the design were new induction heaters under the new interior windows. The space between the new and heritage windows would not be conditioned. The design team's solution effectively combined a number of the above mentioned strategies. The approach allowed the new glazing system to improve the overall thermal performance of the glazing system overall, and also separated the original windows from the new interior environment, thereby reducing the risks of condensation.

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[4] FHBRO Heritage Character Statement – 100 Wellington Street – FHBRO Number 84-27, 1998.07.20 (Revised)

[5] Standards and Guidelines for the Conservation of Historic Places in Canada, First Edition, Parks Canada, 2003

The fact that the original window frames were in remarkably good condition further supported the decision to retain the original windows.

With this approach, the desire would be to take advantage of the thermal benefit (albeit small) that the heritage windows would provide as a storm window (or secondary window). In order to provide this benefit, the heritage windows would need to provide a moderate level of air leakage control (i.e., maximum allowable air leakage rate of 8.35 m^3/h/m at 75 Pa[6]). However, in order to prevent moisture accumulation and condensation (or frost) between the primary and secondary windows, the secondary window must also be vented in a controlled manner (i.e., minimum air leakage rate of 5.00 m^3/h/m at 75 Pa[7]).

The following general parameters had to be considered by the design team:

1) The new interior glazing system must be effectively "invisible" from the exterior to protect the heritage nature of the facility.
2) The interior glazing system would become the primary window and therefore must effectively control air leakage, vapour diffusion, and condensation.
3) The new interior glazing system must provide all necessary transitions to the applicable portions of the opaque wall assemblies with respect to air leakage, vapour diffusion, and condensation.
4) The original heritage window must provide an appropriate level of air leakage control such that it provides thermal efficiencies without trapping latent air vapour, which could result in condensation in the interstitial space between the windows (eg., they must act as an effective storm window).
5) The new interior glazing system must be removable or operable to permit the regular cleaning of all four glazing surfaces. The size of the typical window (approximately 2000 mm tall by 1700 mm wide or approximately 78" x 67") further complicated this matter. And there were even larger windows on the ground floor level.
6) Regular blinds and black-out blinds were to be installed to the interior of the new window system to permit the regulation of daylighting as required the by the various exhibits.
7) The original windows were to be rendered inoperable in a manner that could be reversed in the future.

The project was also to include the upgrade of the mechanical systems, including new induction unit below the windows.

During the design development stage, it was determined that it was not practicable to use removable windows due to their size and weight. Accordingly, the decision was to utilize inward opening casement-style windows. The sash would be sized to cover the entire existing window opening, without any divisions, to ensure that the new window was not visible from the exterior. To minimize the profile of the new sash and frame, as well as to support the glazing loading, steel-framed windows were selected. Due to weight limitations, double glazing was selected rather than triple glazing. The entire system was to be mounted in a HSS structural steel frame

[6] CSA-A440.00 Windows/User Selection Guide to CSA Standard A440-00, Windows
[7] CSA-A440.00 Windows/User Selection Guide to CSA Standard A440-00, Windows

which would be concealed within the wall finishes. Typical details are provided in Figures 1 & 2, below.

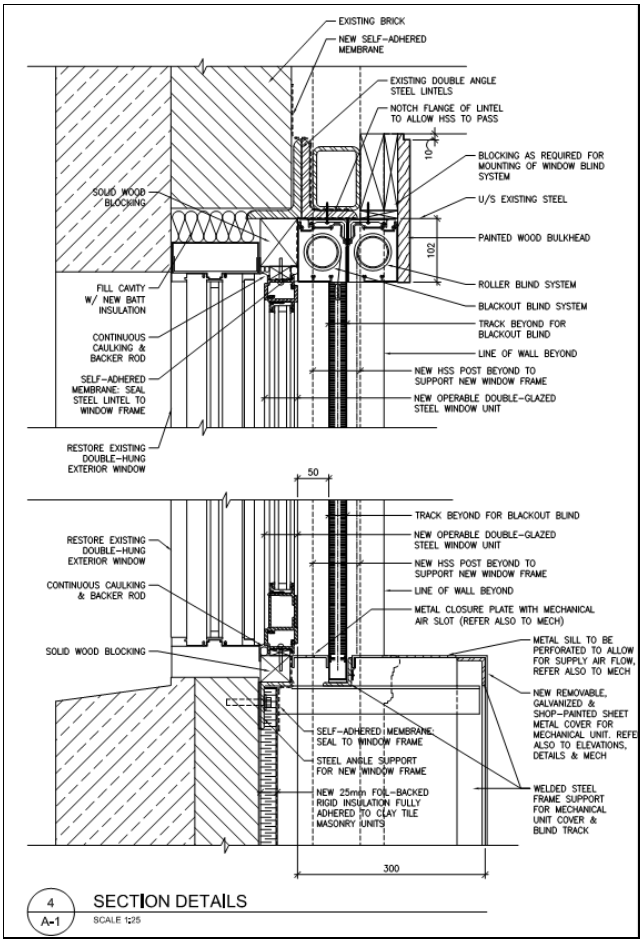


Figure 1: Section detail through new window* (courtesy Teeple Architects).

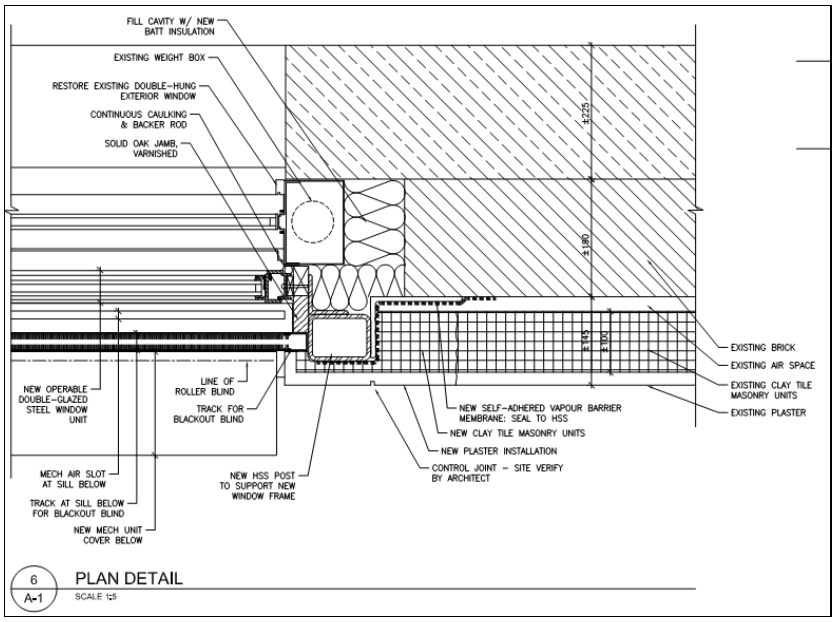


Figure 2: Typical jamb detail (courtesy Teeple Architects).

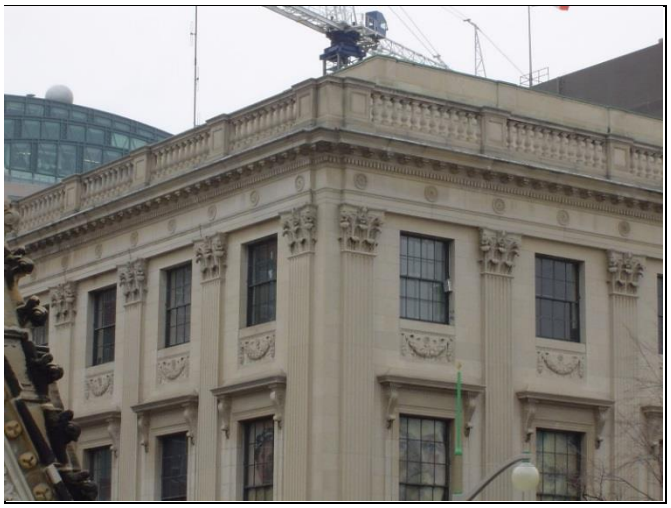
MOCK-UP VERIFICATION THROUGH FIELD MONITORING

In order to validate the design approach and to evaluate the effectiveness of the new window system, a full-scale mock-up was constructed *in-situ*. The mock-up included constructing a section of the proposed upgraded building envelope, consisting of; the modified exterior wall construction, two new windows to the interior of the existing windows (and the associated connections to the opaque walls), and the installation of new induction heating units below the windows, which would be representative of the planned mechanical upgrades.

Mock-up Construction

The mock-up was completed in a room on the third floor, northeast corner of the building (photograph 9). One of the windows was on the north elevation, with the second on the east elevation. The northeast corner was selected to minimize solar effects during monitoring. The location was also selected to permit the isolation of the windows and wall assemblies from the remaining building. Temporary sheet metal and membrane barriers were constructed in the interstitial wall cavity at the limits of the mock-up to prevent migration of air and vapour to the adjacent building areas (photograph 10). Openings through partition walls, unused plenums, interior doors, etc. were also temporarily sealed to help maintain stable interior set-point conditions.

The mock-up included the air barrier connection from the brick masonry back-up as it was determined to be the most air-tight element of the wall based on the field monitoring. Repairs to the interior finishes, including to the terra cotta blocks and plaster finishes were completed to provide continuity of the vapour barrier. During the repairs to the interior finishes, sensors were constructed into the interstitial cavity spaces for monitoring purposes (photographs 11 & 12).



Photograph 9: Mock-up located on 3rd floor NE corner.

Photograph 10: HSS frame and cavity divide.

Photograph 11: Sensors constructed into the wall cavity.

Photograph 12: Terra cotta and plaster finishes reinstated.

The HVAC mock-up included the installation of new induction units below the test windows. A temporary boiler unit was installed in the adjacent room to supply heat to the units (photographs 13 & 14). The appropriate supply and return plenums were connected to simulate the expected set-up of the intended mechanical system upgrades. A standalone humidifier was used to achieve the design relative humidity conditions.

Photograph 13: Temporary boiler unit.

Photograph 14: New induction unit.

A roller blind and black-out blind were installed at each window head, including the steel stud and gypsum board bulkheads. The blinds were installed to simulate actual usage of these elements, to determine what impacts they may have on heat delivery to the windows and the resultant impact on performance.

Hygrothermal Monitoring

Similar to the monitoring that was completed originally, we installed sensors to measure temperature gradient, vapour pressure gradient and air pressure gradient through the walls and windows in order to evaluate their hygrothermal response. The sensors were installed in the same general arrangement, with the addition of sensors installed in the cavity between the existing and new window systems, as well as on the new window assembly (photographs 15 & 16). As with the previous monitoring program, sensors to measure temperature (thermocouples), temperature and relative humidity (transducers), and air pressure (micro-manometers) were all utilized.

Photograph 15: Monitoring set-up.

Photograph 16: Thermocouples on window.

The sensors were read at ten-minute intervals (later changed to fifteen minutes) for a period of 18-days spanning from mid-March to early April. As previously discussed, hygrothermal monitoring ideally requires seven consecutive days with an exterior temperature below -10ºC (in a cold weather climate). However, such conditions were not present during the monitoring period. Generally the exterior temperature ranged between -5ºC and +5ºC, with the lowest recorded outdoor temperature being -9ºC, which was for a period of less than six hours.

The data was reviewed periodically during the monitoring period to ensure that the equipment was functioning properly and to look for anomalies or other indicators of problems. Early in the monitoring period it was discovered that there was a higher than expected air leakage rate into the interstitial space between the new and original windows. Upon detailed inspection it was discovered that the operable sash of the new window was not sealing properly in the closed position. We found that the weight of the sash had caused the hinges to deflect and sag preventing the proper fit and compression of the bulb gaskets. As the monitoring period was limited by the time of year, the decision was made to temporarily seal the sash rather than wait for a replacement sash to be fabricated.

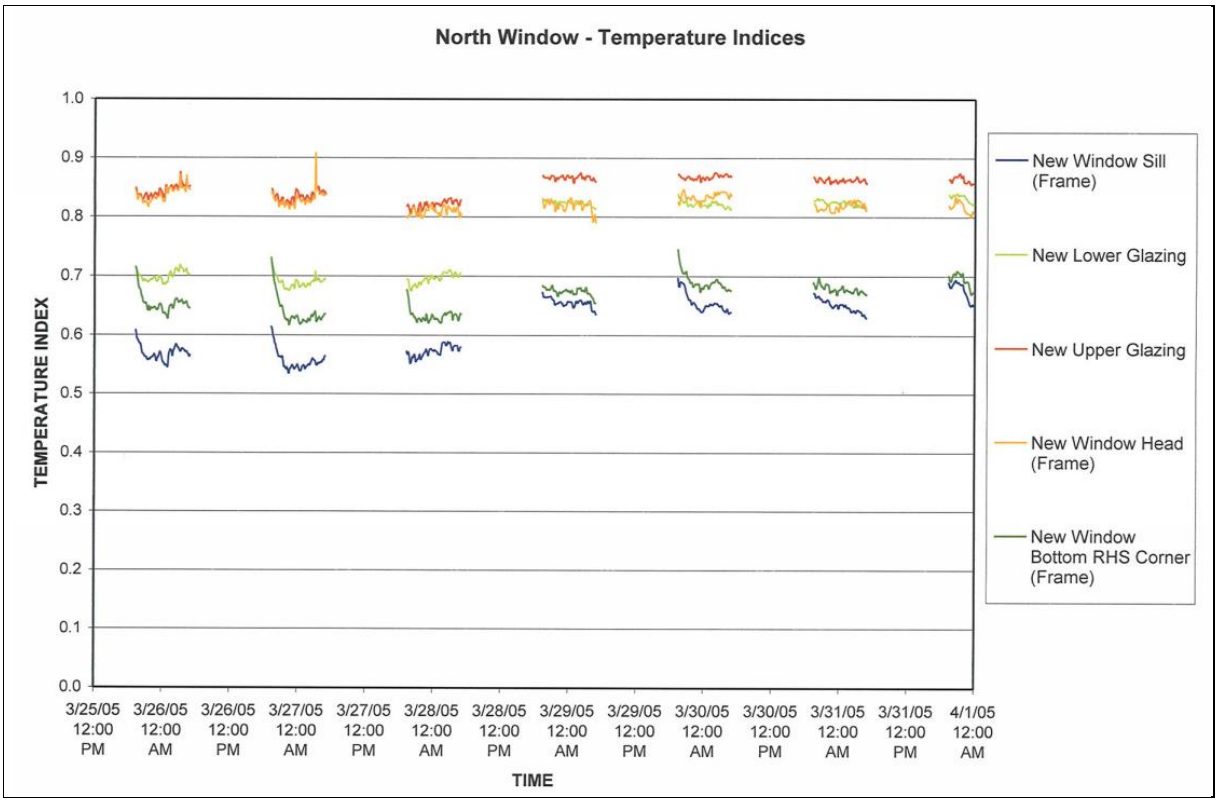
Minor modifications to the placement of some of the thermocouples and sensors were also made during the monitoring period. Additionally, the black-out blind in the north window was closed during the monitoring period to determine the impact it has on the performance of the window.

Analysis of Monitoring Results

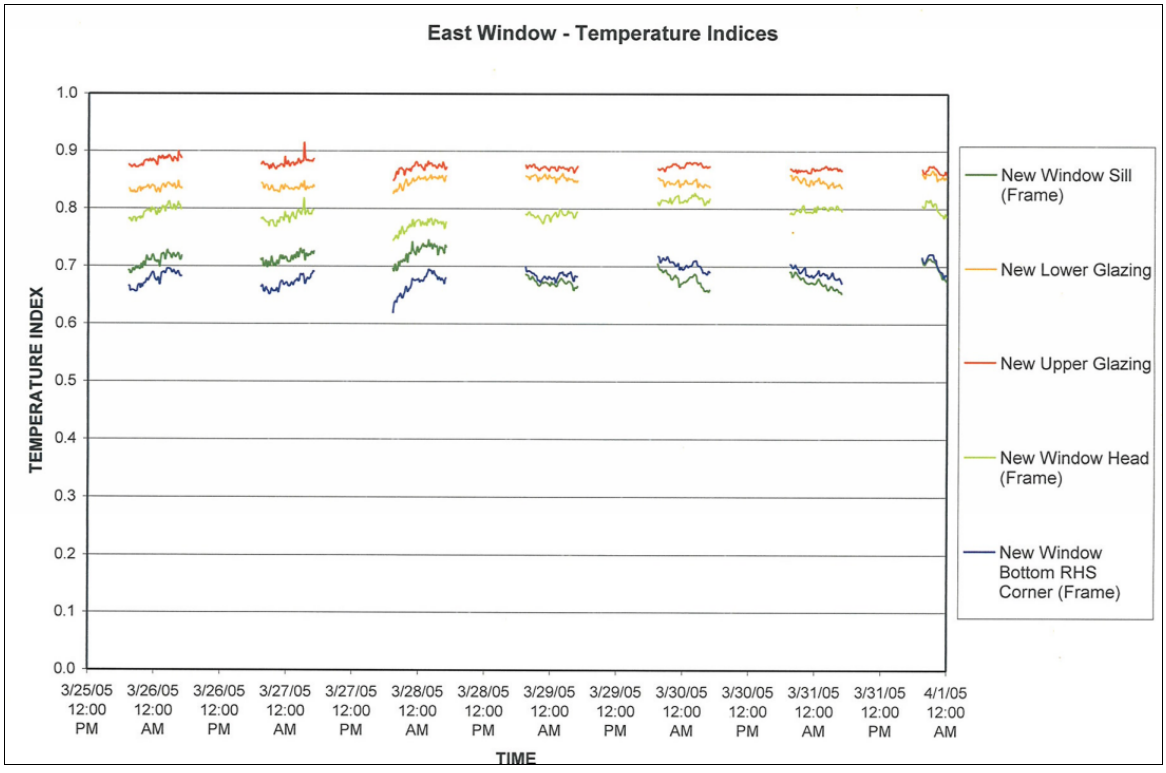
In analyzing the hygrothermal monitoring results, the various factors and constraints that may have influenced the results were assessed. These included;

- The exterior temperature never dropped below -10ºC during the monitoring period, impacting on the potential validity of the results. However, the impact on the temperature gradients would be less significant on the windows than the walls due to impact of thermal mass on the temperature lagging between these assemblies. However, using the previous results for guidance we determined that the results for the windows would be sufficiently accurate to predict the performance at design conditions.
- Construction moisture from the reconstruction of the terra cotta tile and plaster finishes remained in the interstitial cavity between the terra cotta and brick masonry back-up. As a consequence, the vapour pressure gradients and resultant evaluation of the vapour diffusion control of the reconstructed walls could not be properly evaluated based on the monitoring results.
- The grills for the heaters below the windows were not installed during the monitoring period as they were not available at the time of mock-up construction. It is therefore uncertain as to the influence that the grills will have on heat delivery to the windows.

The monitored data was analyzed to calculate the Temperature Index of the various assemblies. As the exterior temperatures were less than ideal, we focused on the nighttime data (as it had the lowest exterior temperatures) to determine the instantaneous Temperature Index of the glazing and window framing members (Graph 1 & Graph 2).



Graph 1: Temperature Indices – North Window.



Graph 2: Temperature Indices – East Window.

Using these Temperature Indices, we predicted that the surface temperature of the new window frames and glazing at winter design conditions would be above +12ºC for the majority of the surfaces. The exception was the sill of the new windows, which were measurably colder due to being "shaded" from the induction unit heat distribution. At these locations, the sill of the new window frame was predicted to be +5ºC at winter design conditions. As this is below the dewpoint temperature (6ºC), some condensation was a potential.

The results were also analyzed with the black-out blind in the closed position to determine the impact that this blind would have on the performance of the new windows. Using the resultant Temperature Indices, we predicted that the surface temperature of the new window frames and glazing at winter design conditions would be above +10ºC for the majority of the surfaces. However, similar to the condition when the blind was open, the predicted temperature of the sill of the new window was considerably colder than the remainder of the window. With the blackout blind closed, we predicted the temperature of the new window sill to be +2ºC at winter design conditions. At this temperature unacceptable levels of condensation were probable.

The sagging of the new sashes drastically impacted on the ability of the new windows to provide the desired level of air-tightness. As a consequence, significant amounts of moisture laden air was exfiltrating into the cavity between the new and heritage windows. The result was considerable amounts of condensation and frost, even during relatively mild exterior temperatures. The new windows effectively shade the heritage from heat delivery from the interior, resulting in these windows being colder than they originally have been. While the original heritage windows were intended to allow small amounts of moist air to vent the exterior, the amount of leakage into this space was more than it could tolerate. While increasing the level of venting between the windows would dissipate the moisture to the exterior, it would negate the thermal benefit (i.e., the ability of the heritage window to act as a 'storm window').

The monitoring also demonstrated that the proposed new mechanical equipment was able to maintain the temperature and relative humidity of the room air at the design set points, with the measured variance being within the allowable limits.

CONCLUSIONS & APPLICATION

The field monitoring and analysis confirmed that the thermal performance of the existing (unaltered) heritage windows is very poor when exposed to new indoor design parameters, and without upgrades would not provide the required performance at or near winter design conditions.

Our analysis of the data from the hygrothermal monitoring of the mock-up demonstrated that the thermal performance of the upgraded windows would generally be acceptable at winter design conditions. The exception being the temperature at the sill of the new windows, which was predicted to be lower than the dewpoint temperature of the interior air and therefore likely to have condensation. Additionally, these conditions are exacerbated by the use of the blackout blinds. In the closed position, the blackout blinds will further "shade" the windows from heat delivery and will likely result in unacceptable levels of condensation during winter design conditions.

A number of follow-up recommendations were provided to the design team, including;

- Redesign the interior new operable sash to prevent sag or deflection to ensure that it can be operated (for cleaning purposes only) while still maintain the required level of air-tightness.

- Re-evaluate the window options to find a more thermally efficient frame and sash. A more thermally-efficient frame will likely alleviate the condensation issues at the sill when the black-out blind is open.
- Confirm the effects of the proper grill on the induction unit on heat delivery to the window. If at all possible, improve the heat delivery to the sill of the window to minimize “shading”.
- Evaluate the possibility of directing more heat between the black-out blind and the new window. Conversely, restrict the use of the black-out blind to periods when the exterior temperatures are above approximately -5ºC.

This project identified a useful approach for measurement of *in situ* performance of existing walls and windows, analysis of resulting data, and field monitoring of a full scale mock-up such that appropriate design strategies can be developed for upgrading the performance of heritage windows in older buildings.

The project also demonstrated the significant value of constructing and testing a proposed mock-up, since issues such as the sagging of the operable sash and the impact of the black-out blinds may not have been realized unless tested. If the mock-up was not used, these issues would not have been identified until after construction was completed, and modification then would have become much more difficult and costly.

While the design concepts applied will vary from project-to-project to suit specific needs and environmental conditions, the process used to evaluate the original performance of the heritage building, develop design concepts, and evaluate them through *in-situ* testing and monitoring, is one that should be considered for dealing with similar heritage window (or envelope) upgrades in all climates.