

Evaluating the Field Performance of Windows and Curtain Walls of Large Buildings

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Abstract

The most common and costly problems associated with the in-service performance of the vertical building envelope of large buildings are related primarily with excessive air leakage and water intrusion. In particular, windows and curtain walls, as well as their interface with the adjacent wall construction, are determining elements in the performance of the vertical building envelope. Improved standards and design principles have contributed in significantly improving the performance of window and curtain wall systems, whether it is with respect to resistance to water penetration, air leakage resistance, wind load resistance or condensation resistance. The reality, however, is that many buildings of recent construction are still experiencing problems with the in-service performance of installed window and curtain wall systems. Typically, these problems are often the result of poor installation, fabrication and lack of adequate quality control.

This paper shall focus on evaluating the field performance of windows and curtain walls of large buildings 1) during the early stages of construction to validate as-built design and 2) during later construction stages as a quality control measure. Large scale field testing to assess building envelope performance in large buildings will be demonstrated through several practical case study examples.

The primary objective of this paper will be to provide an increased level of knowledge to the building community for an improved awareness of the benefits and limitations of the use of field testing in evaluating the field performance of the vertical building envelope of large buildings.

Keywords: building envelope, windows, curtain walls, field testing, air leakage, water infiltration.

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Introduction

Windows and metal & glass curtain walls generally represent as much as 50% to 100% of the exterior cladding of large buildings and are determining elements in the performance of the vertical building envelope. They are often an important architectural feature of a building and represent a significant portion of the overall cost of a building construction or renovation project. As a determining element in the performance of the vertical building envelope, they must be air and water tight, prevent condensation from occurring on the interior surfaces and resist wind load and other exterior forces acting on the building envelope. Given the ever growing complexity and variety of modern building envelopes, the evaluation of their performance in the pre-construction and construction phase is essential in order to avoid undesirable and costly problems during the service life of the building.



Figure 1: Metal & glass curtain wall - new construction (New York, NY)



Figure 2: Metal & glass curtain wall - building reclad (Montreal, QC)



Figure 3: Aluminum punch windows and precast concrete (Montreal, QC)



Figure 4: Aluminum punch windows and brick cladding (New York, NY)

Performance Requirements

Any form of water infiltration to the interior side of a building, excessive air leakage resulting in: 1) discomfort to building occupants; 2) the formation of excessive condensation on the interior side of the building or 3) the formation of icicles on the exterior side of the building, would be unacceptable to any building owner or occupant. This being said, one of the primary performance criteria for any window or curtain wall system is that they provide an appropriate level of resistance to water penetration and air leakage resistance.



Figure 5: Example of water infiltration within a curtain wall assembly.



Figure 6: Example of water infiltration at a punch window assembly.



Figure 7: Example of exterior icicle formation due to excessive air exfiltration within a curtain wall assembly.



Figure 8: Example of excessive interior frost formation due to excessive air infiltration at a window/wall interface.

Resistance to water penetration and air leakage resistance are obviously not the only performance criteria that need to be considered, however, the majority of the problems associated with the in-service performance of building envelopes are due to either water infiltration or air leakage issues. Other performance considerations include thermal performance, condensation resistance and wind load resistance.

Performance requirements need to be established for each project on a case by case basis, based on building height and geographic location, exterior and interior design parameters, as well as the type of building occupancy. The primary performance requirements which need to be established at the design phase of each project are as follows:

- **Wind load resistance:** The design pressures are typically established by the project's structural engineer and are based on the building's exposure classification, the building's height, type and configuration. The window and curtain wall components need to be designed to resist deflection and failure at the specified design pressure.

- **Resistance to water penetration:** Resistance to water penetration performance requirements will vary depending on the building's height, geographic location and exposure classification. In the United States, the resistance to water penetration rating is typically established as a function of the design wind pressure. In Canada, the CAN/CSA-A440 Standard includes a user's guide which recommends minimal performance levels for each major Canadian city based on geographic location and installation height.
- **Air leakage resistance:** Air leakage resistance performance requirements are often established by local building and energy codes and will vary for fixed and operable sections.
- **Condensation resistance:** Condensation resistance performance requirements will depend on the building's geographic location and climate conditions as well as the interior hygrothermal design conditions and type of building occupancy.

1. Industry Standards

Both the United States and Canada have industry standards which establish stringent performance requirements and testing methods for windows and curtain walls. In the United States, 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 Canada, standards for the performance of windows are established by the Canadian Standards Association (CSA). There is no industry standard for the performance of curtain walls in Canada. Testing methods to evaluate both laboratory and field performance is established by the American Society for Testing and Materials (ASTM) for both the United States and Canada.

The following is a list of the principal industry standards which are commonly used to establish the laboratory performance criteria for windows and curtain walls in North America.

- **AAMA/NWDA-101: Voluntary Specifications for Windows and Glass Doors**
Primarily 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**
Primarily 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**
Primarily outlines laboratory performance requirements with regards to resistance to water penetration, air leakage resistance and wind load resistance for metal curtain walls (United States).



Figure 9: Exterior mock-up test (AAMA 501) - Air-Ins laboratory.



Figure 10: Interior mock-up test (CAN/CSA-A440) - Air-Ins laboratory.

- **NFRC 102: Steady-State Thermal Transmittance of Fenestration Systems**
Primarily outlines laboratory performance requirements with regards to thermal performance of fenestration products (United States).
- **AAMA 1503: Voluntary Test Method for Thermal Transmittance and Condensation Resistance of Windows, Doors and Glazed Wall Sections**
Primarily 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**
Primarily outlines laboratory performance requirements with regards to thermal performance and condensation resistance of windows and other fenestration products (Canada).



Figure 11: Environmental test chamber - Air-Ins laboratory.

The following is a list of the principal industry standards which are commonly used to establish the field performance criteria for installed windows and curtain walls in North America.

- **AAMA 502: Voluntary Specification for Field Testing of Windows and Sliding Glass Doors**
Primarily 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 Systems**
Primarily 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**
Primarily outlines field performance requirements with regards to resistance to water penetration and air leakage resistance for windows and doors (Canada).



Figure 12: Field testing for resistance to water penetration.



Figure 13: Field testing for resistance to water penetration.

Field Performance Evaluation

The previous section of this paper highlighted the primary performance requirements and industry standards related to windows and curtain walls and are intended to provide the reader with some basic background on the subject, however, the main focus of this paper is the field evaluation of the performance of installed windows and curtain walls. Given the ever growing complexity and variety of modern building envelopes, the evaluation of the performance of installed windows and curtain walls in the pre-construction and construction phase is essential in order to avoid undesirable and costly problems during the service life of the building.

In most projects of any significance, the performance of the window and curtain wall systems which are to form part of the building envelope are evaluated in an accredited testing laboratory prior to construction. It is equally important, however, that the field performance of the installed products be evaluated as a quality control measure at different phases of construction. Site conditions, variations in the manufacturing process and the quality and experience of the field installation team are all factors which will impact the performance of the installed products or systems.

The first step when considering field testing is to identify test areas which are representative of the most common elements of the building envelope. Typically, field testing is usually limited to three to six test areas due to budgetary and scheduling constraints. It is therefore very important that the test areas be carefully selected in order to ensure a good sampling. The test areas should be selected based on the complexity of any given detail or condition as well as the frequency at which a given detail or condition is repeated throughout the project. Field testing should always include the interface between the window and/or curtain wall and the adjacent wall assembly in order to be representative of the entire installation. This interface is often the most critical element of any installation and may not have been validated by any form of laboratory testing prior to construction.



Figure 14, 15 and 16: Identification of representative areas for field testing (precast concrete / punch window wall assembly).

The test area for metal and glass curtain walls must incorporate all the essential components in order to be representative. The test area should be at least three glass bays wide as to incorporate a central bay which incorporates all the junction details. In the case of a unitized curtain wall system, 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, at least one spandrel section and one vision section. Typically, the height of the test area should be at least one full floor storey 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.



Figure 17: Identification of representative area for field testing (metal and glass curtain wall).



Figure 18: Identification of representative area for field testing (metal and glass curtain wall and adjacent masonry assembly).

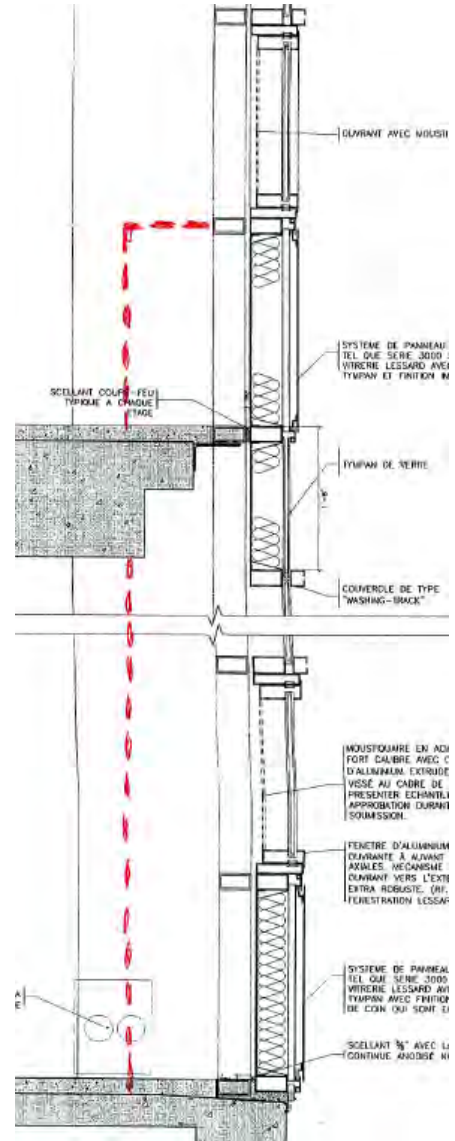


Figure 19: Vertical section illustrating location of test chamber and elements included in typical curtain field test.

1. Test Methods

The two primary criteria evaluated in the field are air leakage resistance and resistance to water penetration. The following are the principal standardized test methods used to evaluate these criteria in the field.

- **ASTM E783:** *Field Measurement of Air Leakage Through Installed Exterior Windows and Doors*
Outlines the test method for field measuring air leakage through installed exterior windows and doors. This test method is also used for measuring air leakage through curtain wall systems (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).
- **ASTM E1105:** *Field Determination of Water Penetration of Installed Exterior Windows, Curtain Walls and Doors by Uniform Static Air Pressure Difference*
Outlines the test method for the field determination of water penetration of installed exterior windows, curtain walls and doors.

Regardless of the three test methods noted above, a pressure differential must be created across the test specimen in order to simulate wind pressure. In order to create the required pressure differential, a test chamber is typically erected on the interior side of the test specimen. When exterior access is difficult, such as in the case of skylights, the test chamber can be erected on the exterior side of the test specimen. In certain cases, it may be possible to use high-power blower doors installed within a confined space. This method, however, is typically only used for forensic testing in occupied buildings. For new construction or major renovation projects, a minimum of three tests sequences should be foreseen as a quality control measure - at the very beginning of the project, midway through the project and near the end of the project.



Figure 20: Interior test chamber used to test a portion of curtain wall section.



Figure 21: Interior test chamber used to test a punch window assembly



Figure 22: Exterior test chamber used to test a skylight section.



Figure 23: High power blower door installed within a confined space adjacent to an exterior wall.

The test pressures are typically specified by the project architect and are different for the air infiltration/exfiltration test and the water penetration test. The air infiltration/exfiltration test is typically undertaken at a pressure differential of 1.57 psf (75 Pa) or 6.24 psf (300 Pa). The water penetration test is undertaken at pressure differentials varying between 6 psf (290 Pa) and 14.6 psf (700 Pa). The following table provides the wind speed equivalences for different pressure differentials.

Pa	kph	psf	in.H ₂ O	mph
75 Pa	40 kph	1.57 psf	0.30''H ₂ O	25 mph
137 Pa	54 kph	2.86 psf	0.55''H ₂ O	34 mph
144 Pa	56 kph	3.00 psf	0.58''H ₂ O	35 mph
150 Pa	57 kph	3.13 psf	0.60''H ₂ O	35 mph
180 Pa	62 kph	3.75 psf	0.72''H ₂ O	39 mph
200 Pa	66 kph	4.17 psf	0.80''H ₂ O	41 mph
216 Pa	68 kph	4.50 psf	0.87''H ₂ O	42 mph
252 Pa	74 kph	5.25 psf	1.01''H ₂ O	46 mph
288 Pa	79 kph	6.00 psf	1.15''H ₂ O	49 mph
299 Pa	80 kph	6.24 psf	1.20''H ₂ O	50 mph
300 Pa	80 kph	6.26 psf	1.20''H ₂ O	50 mph
324 Pa	83 kph	6.75 psf	1.30''H ₂ O	52 mph
360 Pa	88 kph	7.50 psf	1.44''H ₂ O	55 mph
383 Pa	90 kph	8.00 psf	1.53''H ₂ O	56 mph
384 Pa	91 kph	8.00 psf	1.54''H ₂ O	56 mph
396 Pa	92 kph	8.25 psf	1.59''H ₂ O	57 mph
400 Pa	93 kph	8.34 psf	1.61''H ₂ O	58 mph
431 Pa	96 kph	9.00 psf	1.73''H ₂ O	60 mph
467 Pa	100 kph	9.75 psf	1.88''H ₂ O	62 mph
500 Pa	104 kph	10.43 psf	2.01''H ₂ O	64 mph
503 Pa	104 kph	10.50 psf	2.02''H ₂ O	65 mph
539 Pa	108 kph	11.25 psf	2.17''H ₂ O	67 mph
575 Pa	111 kph	12.00 psf	2.31''H ₂ O	69 mph
600 Pa	114 kph	12.51 psf	2.41''H ₂ O	71 mph
700 Pa	123 kph	14.60 psf	2.81''H ₂ O	76 mph
750 Pa	127 kph	15.64 psf	3.01''H ₂ O	79 mph

Figure 24: Table of wind speed equivalences.

2. Air Infiltration/Exfiltration Test

As previously noted, air leakage testing is typically undertaken at a pressure differential of 1.57 psf (75 Pa) or 6.24 psf (300 Pa). In the United States, the AAMA 502 standard provides guidelines for allowable air leakage rates of installed windows and sliding glass doors. In accordance with the AAMA 502, allowable rates of air leakage for field testing shall be 1.5 times the applicable laboratory test rating, unless otherwise specified (see table below).

Product Designation	ANSI/AAMA/NWDA 101/I.S.2		AAMA 502	
	Allowable Air Leakage		Allowable Air Leakage	
	Test Pressure	Maximum Rate	Test Pressure	Maximum Rate
H-R15	75 Pa (1.57 psf)	1.5 L/s•m ² (0.3 cfm/ft ²)	75 Pa (1.57 psf)	2.3 L/s•m ² (0.45 cfm/ft ²)
SGD-LC25	75 Pa (1.57 psf)	1.5 L/s•m ² (0.3 cfm/ft ²)	75 Pa (1.57 psf)	2.3 L/s•m ² (0.45 cfm/ft ²)
C-C30	75 Pa (1.57 psf)	1.5 L/s•m ² (0.3 cfm/ft ²)	75 Pa (1.57 psf)	2.3 L/s•m ² (0.45 cfm/ft ²)
H-HC40	75 Pa (1.57 psf)	1.5 L/s•m ² (0.3 cfm/ft ²)	75 Pa (1.57 psf)	2.3 L/s•m ² (0.45 cfm/ft ²)
AP-AW40	300 Pa (6.24 psf)	0.5 L/s•m ² (0.1 cfm/ft ²)	300 Pa (6.24 psf)	0.7 L/s•m ² (0.15 cfm/ft ²)

Figure 25: Example of allowable air leakage rates depending on window classification (source: AAMA 502-02).

In Canada, the CSA A440.4 standard provides guidelines for allowable air leakage rates of installed windows, tested at a pressure differential of 1.57 psf (75 Pa), as outlined in the table below.

Window rating	Vertically and horizontally sliding window	Casement window	Projecting window	Fixed window	Tilt-and-turn window
Window size	$\leq 1.60 \text{ m}^2$	$\leq 1.12 \text{ m}^2$	$\leq 1.0 \text{ m}^2$	$\leq 4.0 \text{ m}^2$	$\leq 1.60 \text{ m}^2$
A1	16.60 m ³ /h	12.28 m ³ /h	10.60 m ³ /h	n/a	13.95 m ³ /h
A2	9.82 m ³ /h	7.26 m ³ /h	6.27 m ³ /h	n/a	8.25 m ³ /h
A3	3.27 m ³ /h	2.42 m ³ /h	2.09 m ³ /h	n/a	2.75 m ³ /h
Fixed	n/a	n/a	n/a	1.95 (m ³ /h)	n/a
Window size	$> 1.60 \text{ m}^2$	$> 1.12 \text{ m}^2$	$> 1.0 \text{ m}^2$	$> 4.0 \text{ m}^2$	$> 1.60 \text{ m}^2$
A1	2.79 (m ³ /h)/m	2.79 (m ³ /h)/m	2.79 (m ³ /h)/m	n/a	2.79 (m ³ /h)/m
A2	1.65 (m ³ /h)/m	1.65 (m ³ /h)/m	1.65 (m ³ /h)/m	n/a	1.65 (m ³ /h)/m
A3	0.55 (m ³ /h)/m	0.55 (m ³ /h)/m	0.55 (m ³ /h)/m	n/a	0.55 (m ³ /h)/m
Fixed	n/a	n/a	n/a	0.25 (m ³ /h)/m	n/a

Figure 26: Allowable air leakage rates depending on window classification (source: CSA A440.4-07).

When it comes to metal and glass curtain walls, the allowable air leakage rates are typically indicated in the architectural specifications and will vary depending on local building and energy codes and will also vary for fixed and operable sections.

The field air leakage resistance test consists of sealing a chamber to cover the interior or exterior face of the specimen to be tested, supplying air to or exhausting air from the chamber at a rate required to maintain the specified test pressure difference across the specimen, and measuring the resultant air flow through the specimen.

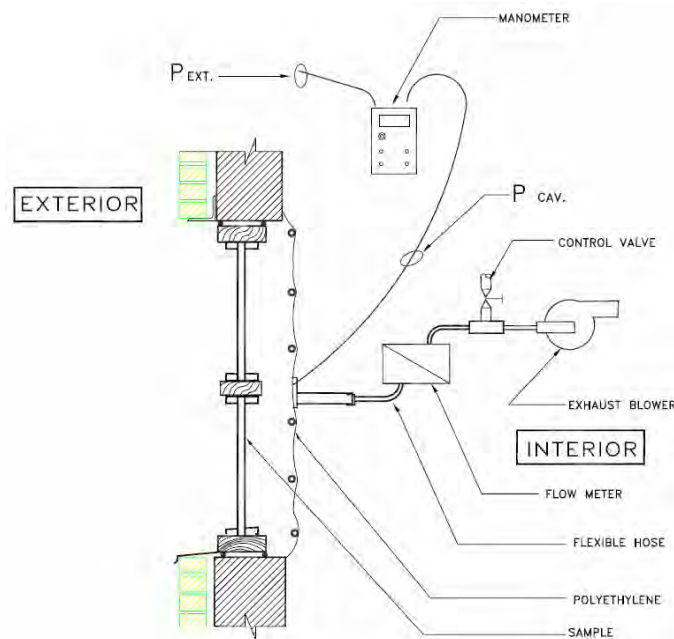


Figure 27: Typical set-up for field air leakage resistance test (source: CSA A440.4).

It is important to note that obtaining accurate air leakage results in the field is often difficult, particularly with curtain wall assemblies. Test results should be questioned when extraneous air leakage from either the test chamber and/or the confines of the test specimen significantly exceeds the allowable air leakage for the test specimen. Where it is not practical or possible to quantify air leakage, smoke exfiltration testing is an excellent alternative which can be used to qualify an air leakage problem. The smoke exfiltration test is undertaken by applying a uniform positive static pressure differential of 1.57 psf (75 Pa) across the test specimen and filling the test chamber with white smoke, using a portable smoke generator. The test consists of checking for any visible excessive smoke exfiltration from the exterior side of the test specimen.



Figure 28: Portable smoke generator used to fill test chamber with white smoke.



Figure 29: Excessive smoke exfiltration visible on exterior side of curtain wall test specimen.

3. Water Penetration Test

The field water penetration resistance test consists of sealing a chamber to the interior or exterior face of the test specimen to be tested, supplying or exhausting air to the chamber at the rate required to maintain the desired air pressure difference across the test specimen. Simultaneous to the application of air pressure difference, water shall be applied to the exterior face of the test specimen at the required rate (5 gal US/h/ft²) while observing for any water penetration at the interior.

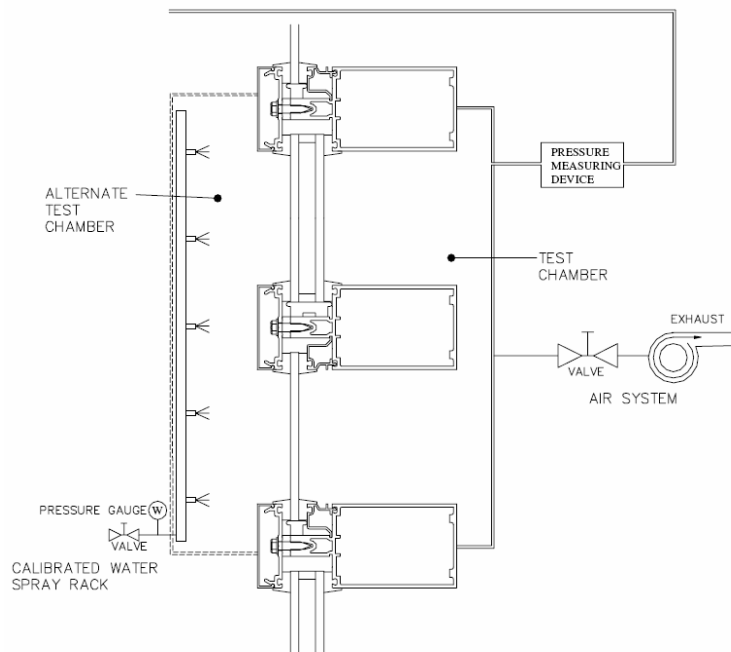


Figure 30: Typical set-up for field water penetration test (source: AAMA 503).

In the United States, the AAMA 502 standard provides guidelines for allowable water penetration resistance ratings of installed windows and sliding glass doors. In accordance with the AAMA 502 standard, water penetration resistance tests shall be conducted at a static test pressure equal to 2/3 of the applicable laboratory test rating, unless otherwise specified. In Canada, there is no provision in the CSA A440.4 standard for reduction in the field testing pressure.

For the water penetration resistance field test, a calibrated sprinkler rack is hung on the exterior side of the test specimen in order to apply a continuous and uniform water spray. It is important that sufficient water pressure is available on site in order to ensure that the required amount of water is sprayed on the entire specimen. When sufficient water pressure is not available on site, the use of a portable water reservoir and pump system may be necessary.

It is also important that the exterior temperatures be above freezing in order to run a water test. When undertaking a water test in winter conditions, a temporary heated enclosure should be installed on the exterior side of the test specimen.



Figure 31: Calibrated sprinkler rack hung from suspended scaffolding.



Figure 32: Calibrated sprinkler rack hung from motorized man lift.



Figure 33: Portable water reservoir and pump system.



Figure 34: Temporary exterior heating via test specimen.

4. Other Diagnostic Tools

Depending on specific applications, a variety of other diagnostic tools can be used to assess the performance of the vertical building envelope, whether as a quality control measure or for forensic purposes. For example, when attempting to pin point a specific water infiltration problem, the **AAMA 501.2** entitled *Quality Assurance and Diagnostic Water Leakage Field Check of Installed Storefronts, Curtain Walls, and Sloped Glazing Systems* can be used.

Infrared thermography is also used extensively in the building construction industry as a quality control and forensic tool to assess air leakage performance and the presence of moisture in exterior wall assemblies, in accordance with the **CAN/CGSB 149-GP-2MP** standard entitled *Manual for Thermographic Analysis of Building Enclosures*.



Figure 35: Diagnostic hose testing of curtain wall section.



Figure 36: Diagnostic hose testing window/wall interface.

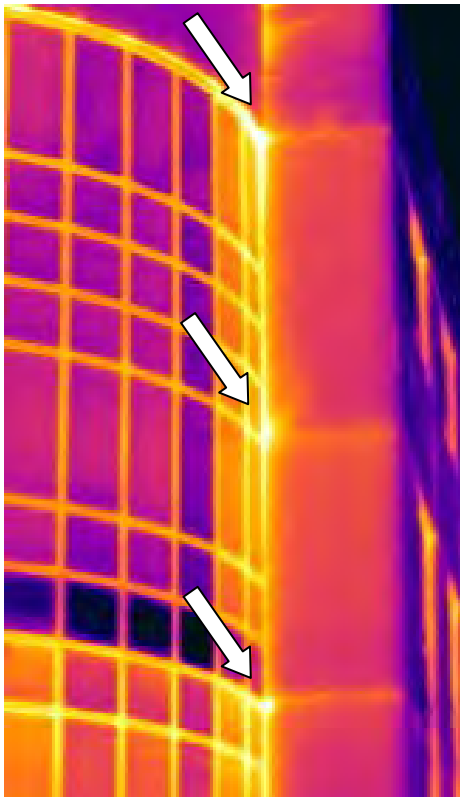
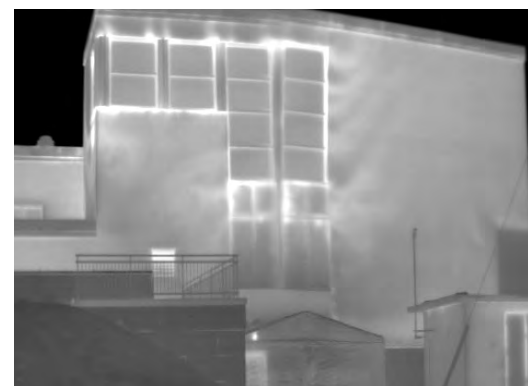


Figure 37: Thermographic image of excessive air leakage at the interface of the curtain wall with the adjacent wall assembly.



Figures 38 and 39: Thermographic image of excessive air leakage at the perimeter of the fenestration system.

Summary and Conclusion

Any form of water infiltration to the interior side of a building, excessive air leakage resulting in: 1) discomfort to building occupants; 2) the formation of excessive condensation on the interior side of the building or 3) the formation of icicles on the exterior side of the building, would be unacceptable to any building owner or occupant. This being said, one of the primary performance criteria for any window or curtain wall system is that they provide an appropriate level of resistance to water penetration and air leakage resistance.

In most projects of any significance, the performance of the window and curtain wall systems which are to form part of the building envelope are evaluated in an accredited testing laboratory prior to construction. It is equally important, however, that the field performance of the installed products be evaluated as a quality control measure at different phases of construction. Site conditions, variations in the manufacturing process and the quality and experience of the field installation team are all factors which will impact on the performance of the installed products or systems.

The first step when considering field testing is to identify test areas which are representative of the most common elements of the building envelope. The test areas should be selected based on the complexity of any given detail or condition as well as the frequency at which a given detail or condition is repeated throughout the project. Field testing should always include the interface between the window and/or curtain wall and the adjacent wall assembly in order to be representative of the entire installation. This interface is often the most critical element of any installation and may not have been validated by any form of laboratory testing prior to construction.

For new construction or major renovation projects, a minimum of three tests sequences should be foreseen as a quality control measure - at the very beginning of the project, midway through the project and near the end of the project.

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