A New Test Method for Quantifying Air Leakage of a Mechanically-Attached Roofing Assembly

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ABSTRACT

Wind flow over a mechanically attached roofing assembly (MAA) can lift the membrane and cause it to flutter or "billow." Air leakage into the assembly from the building interior is a concern for wind uplift resistance of MAAs. MAAs are a growing segment of the low-slope roofing market; however, there is no widely accepted standard specification or test method to quantify air leakage through them. An experimental procedure has been under development for quantifying the air leakage rate of MAA. Assemblies with two barrier types – conventional polyethylene film and reinforced modified bituminous film – were evaluated. Data clearly indicate that MAAs with barriers had lower air leakage rate than without. The air leakage impact on wind uplift resistance has also been evaluated under a dynamic environment. Assemblies with barriers performed better than the assemblies without one.

SPEAKER

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INTRODUCTION

Built-up roofing assemblies (BUR) have dominated the roofing industry for over a century (Baskaran, *et al.,* 1997). In the BUR, different plies of roofing felt are fully adhered to the substrate and this continuity offers significant resistance to air flow. Therefore, much research effort has been focused on system performance rather than the study of air leakage into the roofing assembly. In the 1970s, single-ply roofing systems emerged as the next generation of low-sloped roofing assemblies, replacing the labor-intensive BUR. Within the single-ply roofing systems, the membrane can be mechanically attached, fully adhered, ballasted, or air pressure equalized. The membrane can be a single-ply membrane such as PVC (polyvinylchloride), EPDM (ethylene propylene diene monomer), and TPO (thermoplastic olefin); or a two-ply as in the case of modified bituminous membranes. A roofing assembly in which the membrane is attached, through insulation and other components, to the structural deck at discrete points using fasteners is known as a mechanically attached assembly (MAA) and this system will be the focus of the present study.

Approximately one-fourth of North American low-slope/commercial buildings are roofed with MAA (NRCA 2004). Recent wind uplift performance studies of the MAA (Baskaran, *et al.*, 2006) identified that air intrusion into the assembly is one of the major factors that affects the performance. For airflow to occur, there must be both:

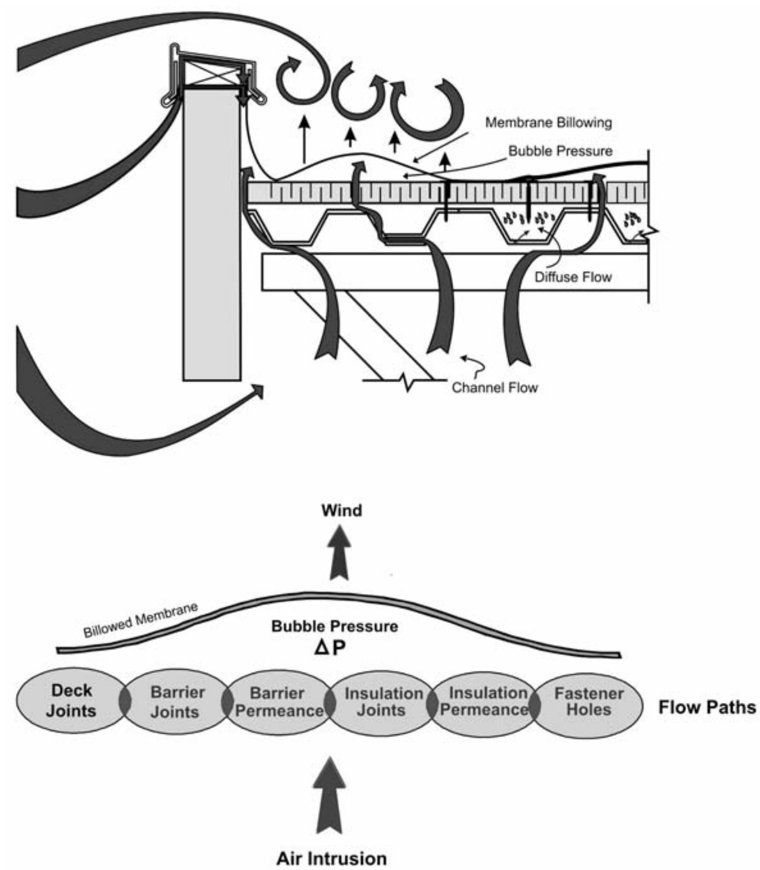


Figure 1 - Air leakage mechanism of MAA during wind uplift.

1. a pressure difference between two locations; and
2. a continuous flow path or opening connecting the locations.

MAA meet these two prerequisites during wind uplift conditions. *Figure 1* illustrates the airflow mechanism through MAA. The waterproof membrane, which acts as an air barrier/retarder, is placed on top of the insulation and attached to the structural steel deck using mechanical fasteners. The attachment locations are then overlapped and seamed. Wind-induced suction lifts the membrane and causes membrane elongation and billowing between the attachments. The magnitude of the wind-induced suction, the membrane's elastic properties, and the fastening pattern determine the deflection of the membrane billowing. The momentary displacement or billowing of the membrane creates a relative negative pressure below the lifted membrane and this draws indoor air into the roof, thereby satisfying the first prerequisite. The second prerequisite is met by the

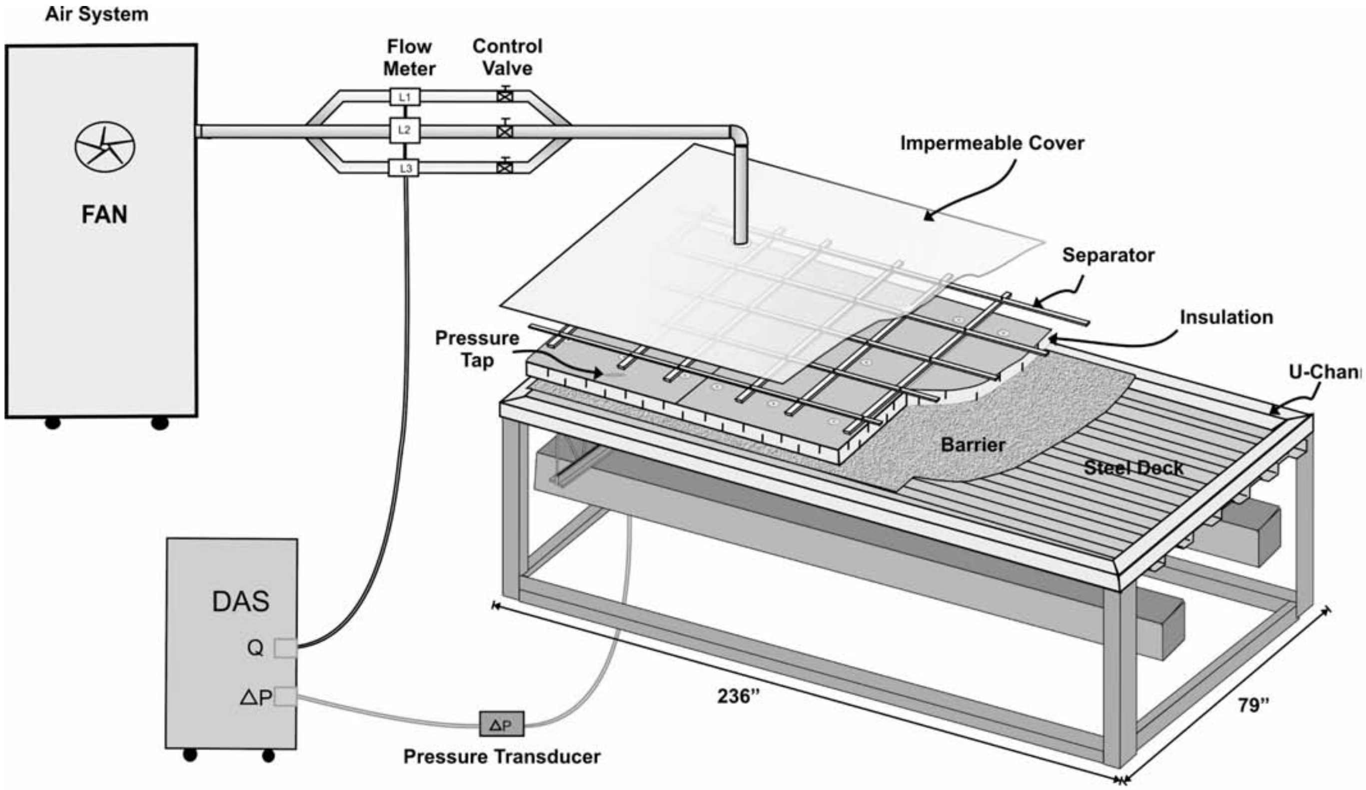


Figure 2 - Experimental set-up for determination of air flow resistance of roofs.

lack of airflow control at the deck level. Flow paths are created by the component's air permeability and joints/junctions/penetrations in the roofing assembly.

Despite the significance of air leakage on roofing systems performance, currently, no study exists in the literature (Molleti, 2006) that addresses the air leakage characteristics of a roofing assembly. Therefore, a research study was initiated at the National Research Council of Canada (IRC/NRC) with the objective of developing a new test procedure for air leakage quantification of roofing assemblies. This paper presents air leakage data from five roofing assemblies. It also compares the measured air leakage rates of the assemblies with the requirements prescribed in the codes.

EXPERIMENTAL APPROACH

Recently, Molleti and Baskaran (2006) reported the details of the newly developed air leakage test method for roofing assemblies. *Figure 2* illustrates the experimental setup developed for the air leakage quantification. As shown in *Figure 2*, the test frame has a dimension of 2 m x 6 m x 0.8 m (79 in x 236 in x 32 in). The test specimen/roof assembly is installed in the frame, which is supported on a lifting mechanism with adjustable jacks. This feature allows for investigating different roofing assembly thicknesses accommodating different roofing components.

The relevant experimental quantities to be determined in an air leakage test method are the applied test pressure difference and the corresponding volumetric airflow rate. The applied test pressure difference across the test specimen is detected by using Setra differential pressure transducers, which have a measuring range up to 10 kPa (200 psf) and an accuracy of 0.14% of the full-scale reading, and the corresponding airflow rate is measured using Merriam laminar flow elements with three flow ranges of 212 L/M (7.5 CFM), 1130 L/M (40 CFM), and 11300 L/M (400 CFM), depending on the air tightness of roofing assembly type. The output of the airflow and pressure measuring devices is connected to the data acquisition system (DAS), which records and plots the respective data on a GUI interface.

Following the experimental setup above (*Figure 2*), the present study quantified the air leakage rates of five roofing assembly configurations. The five roofing assemblies are:

- Assembly 1 (**A1**) - Steel deck and a layer of insulation

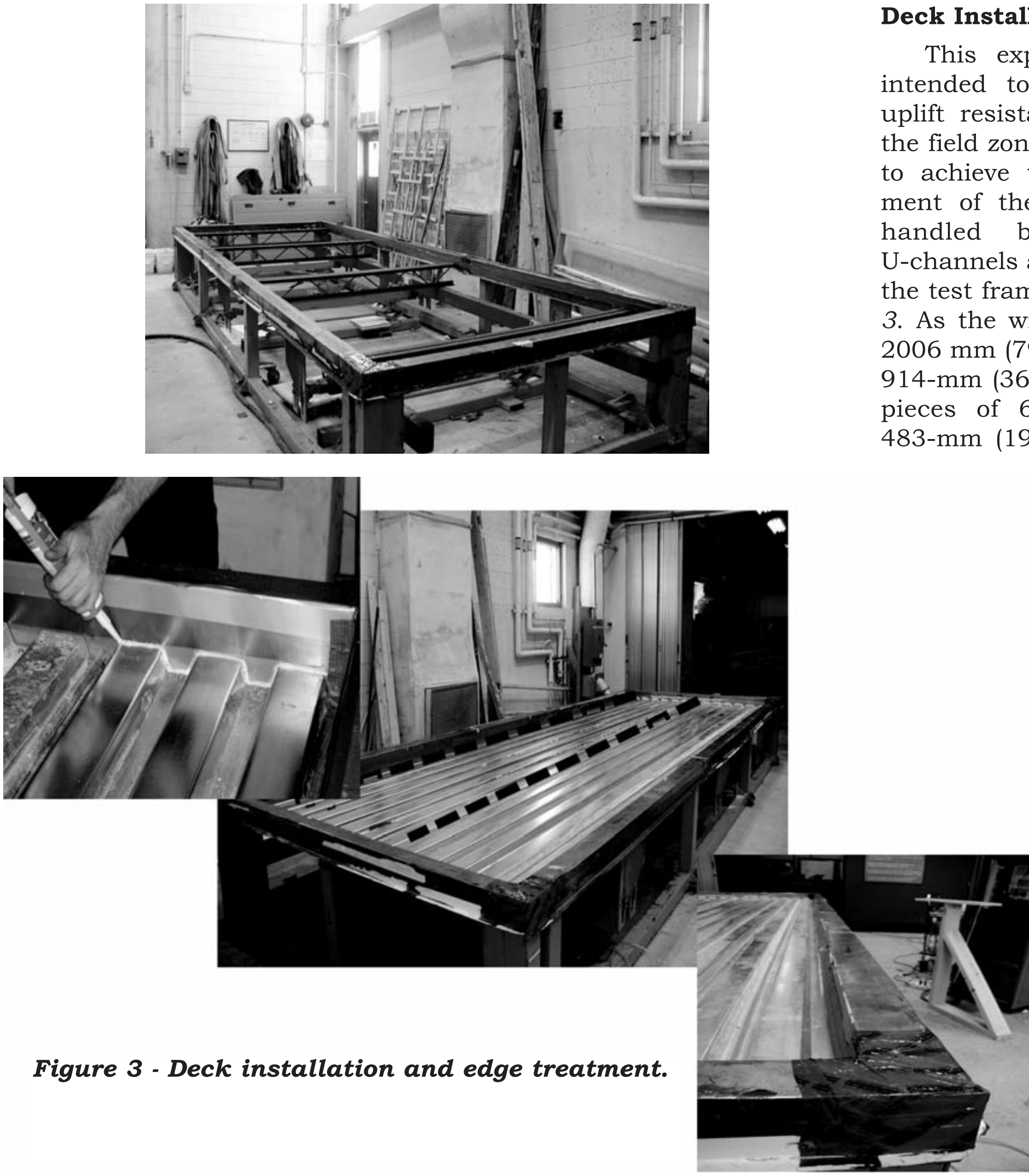


Figure 3 - Deck installation and edge treatment.

- Assembly 2 (**A2**) - Steel deck and two layers of insulation
- Assembly 3 (**A3**) - Steel deck, a layer of insulation, and building paper as a barrier/retarder
- Assembly 4 (**A4**) - Steel deck, a layer of insulation, and SBS-modified, self-adhered membrane sheet as a barrier/retarder
- Assembly 5 (**A5**) - Steel deck, a layer of insulation, and a 6-mil polyethylene sheet as a barrier/retarder

This experimental study was intended to measure only the air leakage associated with the field of the roof and it does not include leakage at the openings or perimeter of the roof. The experimental set-up assumed that in a roofing assembly, the continuous waterproof membrane is airtight and therefore it can be excluded from the investigation. Consequently, all the experimental mock-ups were constructed up to the insulation level. As the system installation is the same for all the tested assemblies, the construction procedure can be classified into five steps, noted below.

Deck Installation

This experimental set-up is intended to measure the wind uplift resistance associated with the field zone of the roof. In order to achieve this, the edge treatment of the test assembly was handled by installing steel U-channels along the perimeter of the test frame as shown in *Figure 3*. As the width of the table was 2006 mm (79 in), one full sheet of 914-mm (36-in) wide and two cut pieces of 610-mm (24-in) and 483-mm (19-in) wide steel decks were installed along the table length as shown in *Figure 5A* and *5B*. The steel deck was 0.76 mm (22-Ga) thick with a profile height of 38 mm (1.5 in) and a flute width of 150 mm (5.9 in). The black dotted lines indicate the deck overlaps. To eliminate the air leakage along the edges of the deck, the steel deck edges are butted to the U-channel and the gap between them was sealed using sealant and adhesive membrane as shown in *Figure 3*. Thus, the field zone of the roof is simulated, assuring that the airflow occurs along the steel deck seams and not the deck edges.

Barrier/retarder Installation

In the present experimental setup, “barrier/retarder” means a component installed in the roofing assembly to prevent airflow into the system. Three types of barrier/retarders are used:

1. Polyethylene film – single layer of 6 mil (0.006 in) sheet

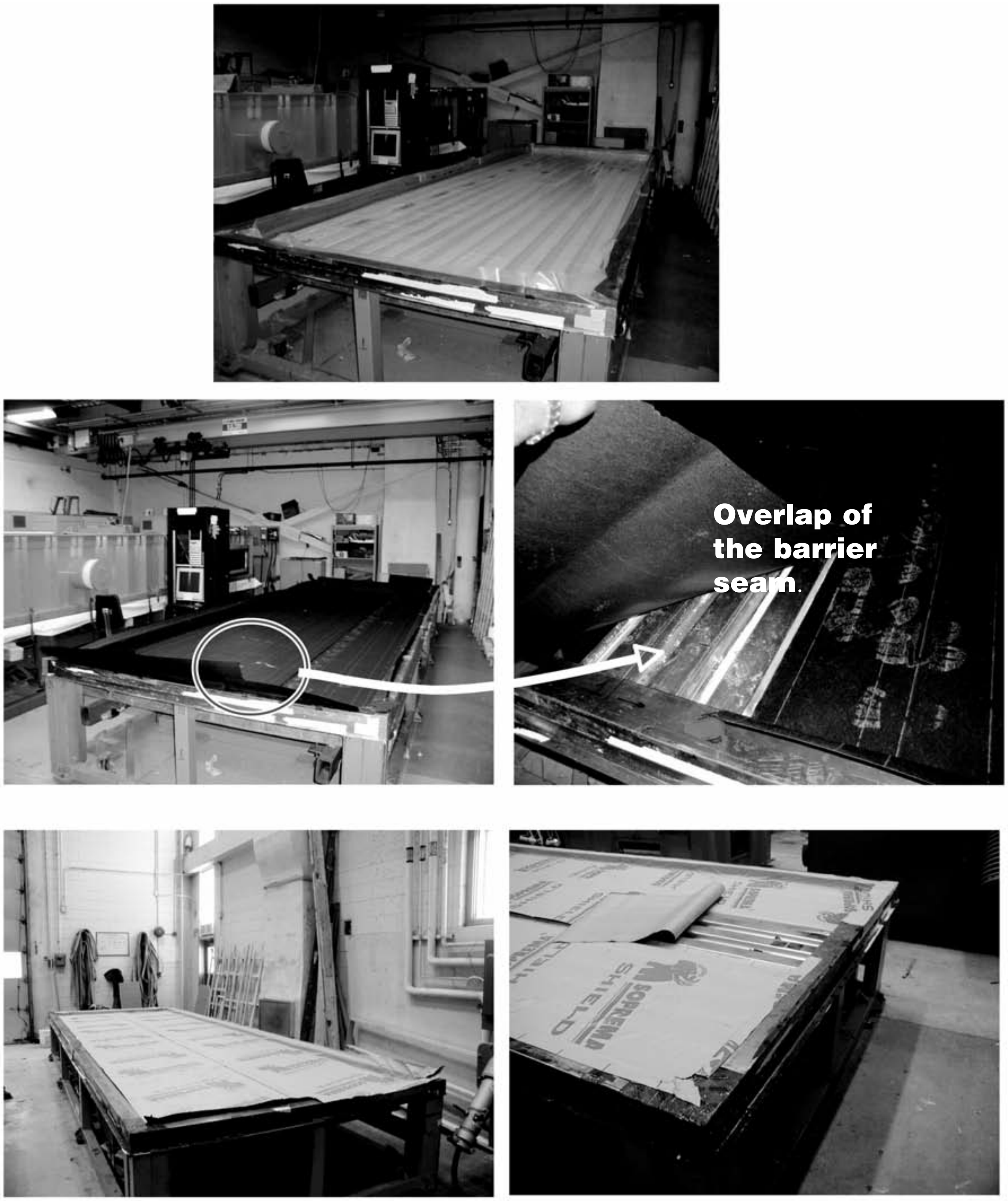


Figure 4 - Barrier installation.

2. Building Paper – 15 mil thick (0.015 in), asphalt-impregnated paper. It comes in a length of 44 m (144 ft) and width of 914 mm (36 in).
3. SBS modified self-adhered membrane sheet – 0.8 mm thick (1/32 in) self-adhered sheets. They are composed of SBS modified bitumen and surface reinforced, and come in strips of 1140 mm wide (45 in).

Figure 4 shows the installation of the three barriers/retarders. **A3** had building paper as the barrier/retarder and since the building paper comes in widths of 914 mm (36 in), two full sheets of 914 mm (36 in) and one cut sheet of 457 mm (18 in) were laid on the steel deck. The sheets had an overlap of 152 mm (6 in), and by using adhesive (vapor-block glue) the overlaps were joined. The edges of the building paper were pulled and bent at 90° over the U channel and sealed to the U channel as shown in *Figure 4*, and at the corners the building paper was cut at 45° and folded over the U-channel. **A4** had self-adhered membrane sheet (SAM) as barrier/retarder, and as SAM also comes in sheet widths of 914 mm (36 in), the installation procedure is similar to the building paper except this is a self-adhered film, which adheres directly to the top flange of the steel deck. For **A5**, a continuous sheet of polyethylene was installed on the steel deck. The edges of the polyethylene sheet were pulled and bent at 90° over the U channel as shown in *Figure 4*. The edge treatment of the polyethylene sheet was similar to the building paper in **A3**.

Insulation Installation

Figure 5 illustrates the cross section view of the two-insulation layouts and *Figure 6* shows the typical layout of insulation attachment. For all the five tested assemblies, 51-mm-thick (2-in) polyisocyanurate boards with a compressive strength of 170 Kpa (25 psi) were used as the insulation. In **A1, A3, A4** and **A5**, the insulation configuration was comprised of a layer of insulation with four full boards of 1219 mm x 2006 mm (48 in x 79 in) and one partial board of 1118 mm x 2006 mm (44 in x 79 in) installed with the long edges perpendicular to the deck flutes.

In **A2**, the insulation layout is similar to the former assemblies except that it is comprised of two layers of insulation in staggered arrangement. The insulation boards were mechanically fastened to the steel deck with 76-mm (3-in) diameter circular plastic plates and 127-mm (5 in) long fasteners. Each insulation board was attached with eight fasteners, a fastener density of one fastener per 0.3 m^2 (3.3 ft^2)

Figure 5A – One-layer insulation installation.

Installation of the Separator

With the insulation in position and fastened to the deck, a square, meshed wooden separator was installed on top of the insulation as shown in *Figure 7*. The role of the separator is to provide the gap or space between the test specimen and the impermeable cover for creating uniform differential pressure across the specimen and for allowing the airflow without any obstruction. A minimum gap of 50 mm (2 in) was maintained for this purpose. After the completion of the separator installation, two pressure taps were installed on either ends of the test specimen. These pressure taps measure the differential pressure across the test specimen.

Installation of the Impermeable Cover

A continuous sheet of impermeable cover as shown in *Figure 8* was laid on top of the separator. The overhang edges of the impermeable cover were adhered to the frame edges, thus eliminating any extraneous airflow into the test specimen. Provisions were made to install the flow measurement setup by making a 50-mm (2-in)

Figure 5B – Two-layer staggered insulation installation.

diameter opening on top of the impermeable cover. One end of the flow measurement set-up has an air filter, which was inserted into the test specimen, and the other end was connected to the air system. In between them, the flow-measuring device and the adjustable control valve were installed. The former measures the airflow rate and the latter controls the applied pressure.

RESULTS AND DISCUSSION

As discussed above, the relationship between the two parameters – namely, the differential pressure across the assembly and the volumetric airflow rate - characterizes the air leakage rate – of the assembly. To obtain these parameters, the following test procedure of depressurization technique was followed:

- Differential pressure in the range of 480 Pa (10 psf) to 2870 Pa (60 psf) in increments of 480 Pa (10 psf) will be applied across the assembly.
- At each applied target pressure, allow the pressure to stabilize for a minimum duration of 60 seconds
- After the pressure stabilization, the airflow measurements will be recorded for a minimum duration of 60 seconds.

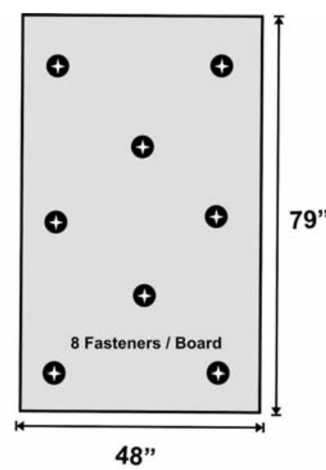
Following the above test procedure, the five assemblies were quantified for air leakage. All tests were carried out in an indoor laboratory environment (air pressure 101 kPa, ambient temperature 21°C, and air density 1. 202 kg/m^3). The tested assemblies can be categorized into two sets:

- Set 1: Assembly without barrier/retarder - A1 and A2
- Set 2: Assembly with barrier/retarder - A3, A4, A5

Figures 9 and 10 show a typical measured pressure and flow time histories of two assemblies – one without barrier/retarder (**A1**) and the other with barrier/retarder (**A5**), respectively. The pressure time history is a measure to verify whether the applied pressure equals the target pressure of the test protocol. The applied pressure at each pressure level is comprised of three parts: 1) pressure build-up, 2) pressure stabilization, and 3) pressure measured (Molleti and Baskaran, 2006).

As per the test procedure, the pressure is measured for a minimum duration of 60 seconds after it stabilizes. The pressure stabilization varies from assembly to assembly and is dependent on the airtightness of the tested assemblies, which leads to varying testing time as shown on the X-axis of *Figures 9* and *10*. Error analysis was performed between the target pressures and the measured pressure for all the assemblies. Data indicates that the measured pressure showed an error of 0.2% deviation from the target. As shown in *Figure 10*, the peaks in the pressure measurement for both the assemblies can be attributed to the manual operation of the control valve.

Note that these selected differential pressures are significantly higher when compared to existing



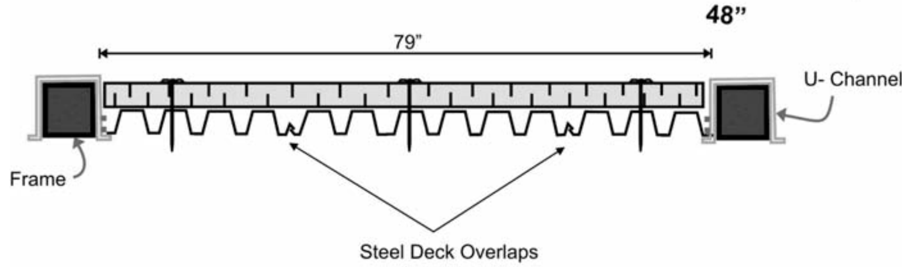


Figure 6A – One-layer insulation layout (front view along the table width).

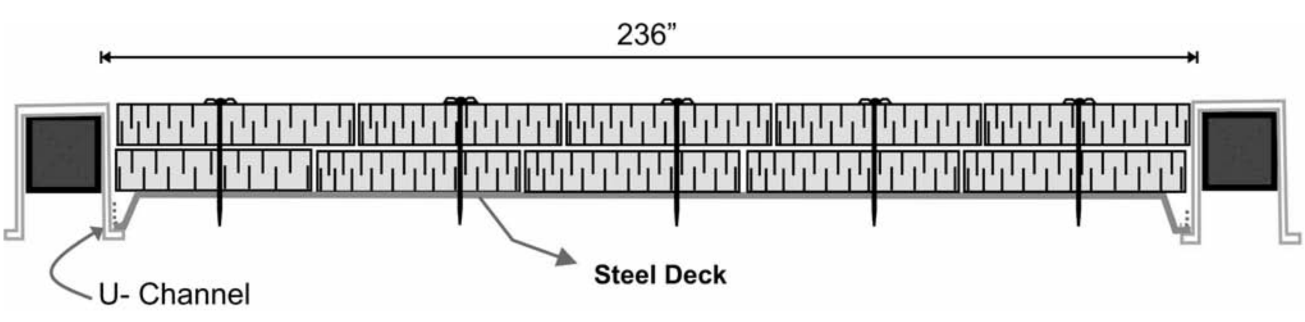


Figure 6B – Two-layer staggered insulation layout (side view along the table length).

Figure 7 - Installation of the separator.

wall test procedures. No specific pressure level was identified for representing the air leakage rate of roofs, similar to the case of wall assemblies at 75 P a (1.5 psf). The recently developed *Wind Design Guide* (Baskaran and Smith, 2005) provides a procedure for calculating wind-induced design pressure on roof coverings. Such a calculation procedure and practical input from the members of the ongoing consortia (see Acknowledgement section) will be used to reach consensus about the pressure level at which air leakage rates will be reported for the roof assemblies.

Figure 11 presents the measured air leakage rate of the five assemblies. Data clearly indicate that **A1** and **A2** without barrier/retarder had greater leakage rates when compared to the assemblies with barrier/retarder – namely **A3, A4,** and **A5**. The present study also attempts to answer whether the staggered arrangement of insulation boards as in **A2** can be as effective as that of having a barrier/retarder in an assembly. The comparison of the

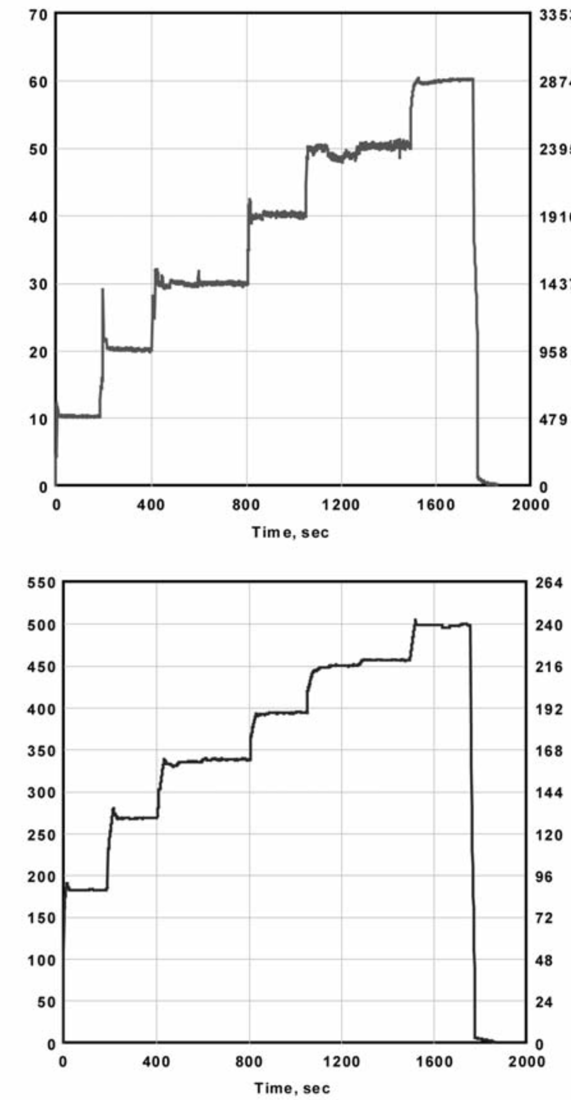


Figure 9 - Measured pressure and flow time histories of A1.

Figure 8 - Installation of the impermeable cover.

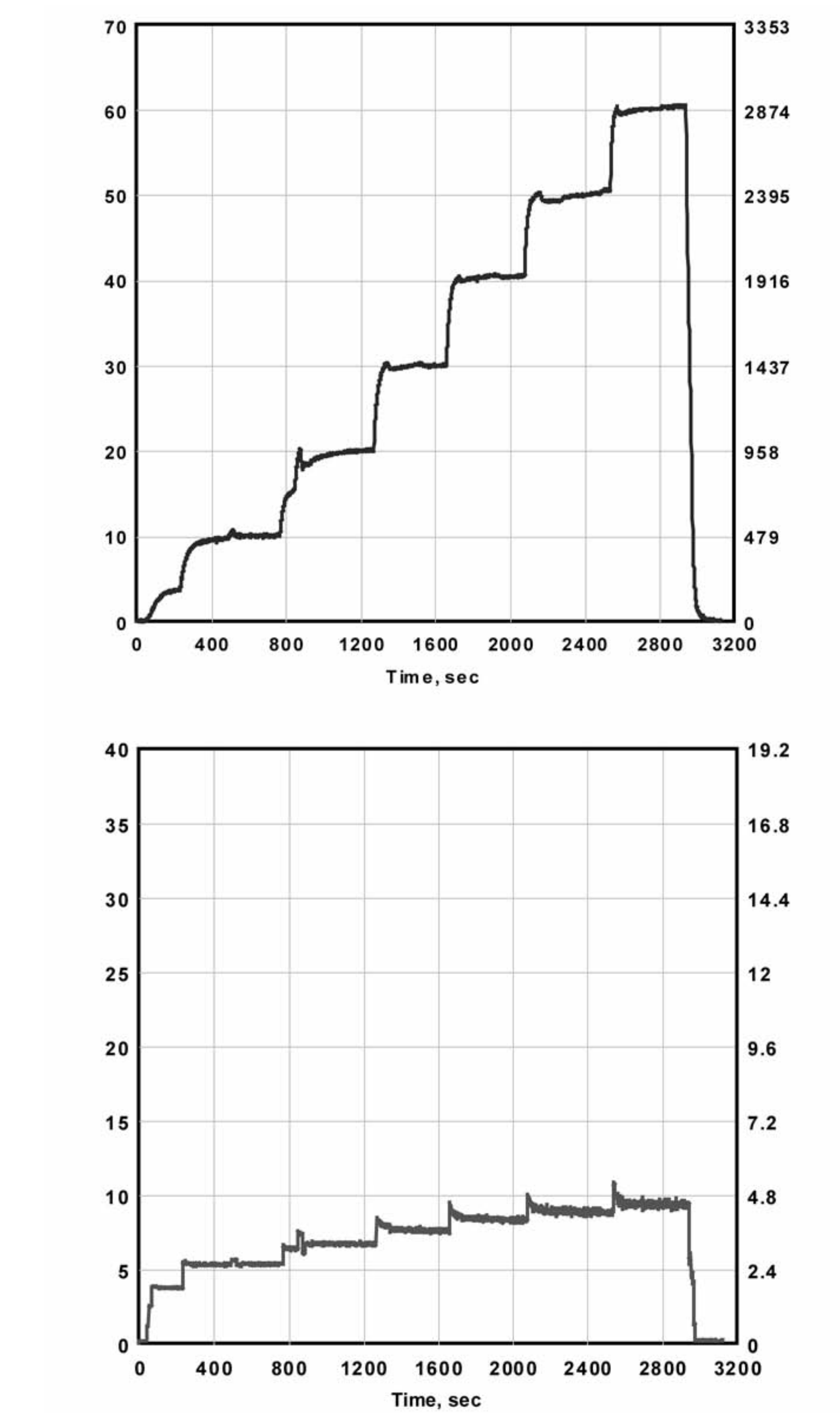


Figure 10 - Measured pressure and flow time histories of A3.

data from *Figure 11* points out that the staggered arrangement of insulation in **A2** certainly provided the air-retarding effect in comparison to **A1**; however, it proved to be not as effective as the assemblies with barrier/retarder (**A3, A4,** and **A5**).

It is also to be noted that in *Figure 11*, no air leakage data is presented for **A3** (with building paper) beyond 1440 Pa (30 psf). The reason was, during the air leakage testing of **A3**, at one corner, a 45°-cut made in the building paper opened up or enlarged. This led to a drastic increase in the airflow rate, and as a result, the test was stopped. Irrespective of this drawback, **A3** provided a good air-retarding effect up to 1440 Pa (30 psf).

To further illustrate the relative performance of the air-retarding effect of the different assemblies, *Figure 12* presents the percentage air leakage of the assemblies relative to **A1**. To get a better understanding, a typical pressure of 1440 Pa (30 psf) was selected for the following discussion. If it is assumed that **A1** without any barrier/retarder had 100% air leakage, then relative to the air leakage of **A1**, observations can be summarized as follows:

- **A2** with staggered insulation has 35% of air leakage of **A1** or air leakage reduced by 65%.
- **A3** with building paper has 10% of air leakage of **A1** or air leakage reduced by 90%.
- **A4** with self-adhered film has 6% of air leakage of **A1** or air leakage reduced by 94%.
- **A5** with polyethylene sheet has 2% of air leakage of **A1** or air leakage reduced by 98%.

The high leakage rate of **A1** can be attributed to the channel flow occurring at the deck and insulation joints. With the inclusion of another layer of insulation, **A2** did provide good air leakage resistance by reducing 65% of air intrusion; however, it could not be as effective as assemblies with a barrier/retarder. The channel flow between the joints in the insulation boards was providing the necessary flow path for air movement into the assembly. **A4** and

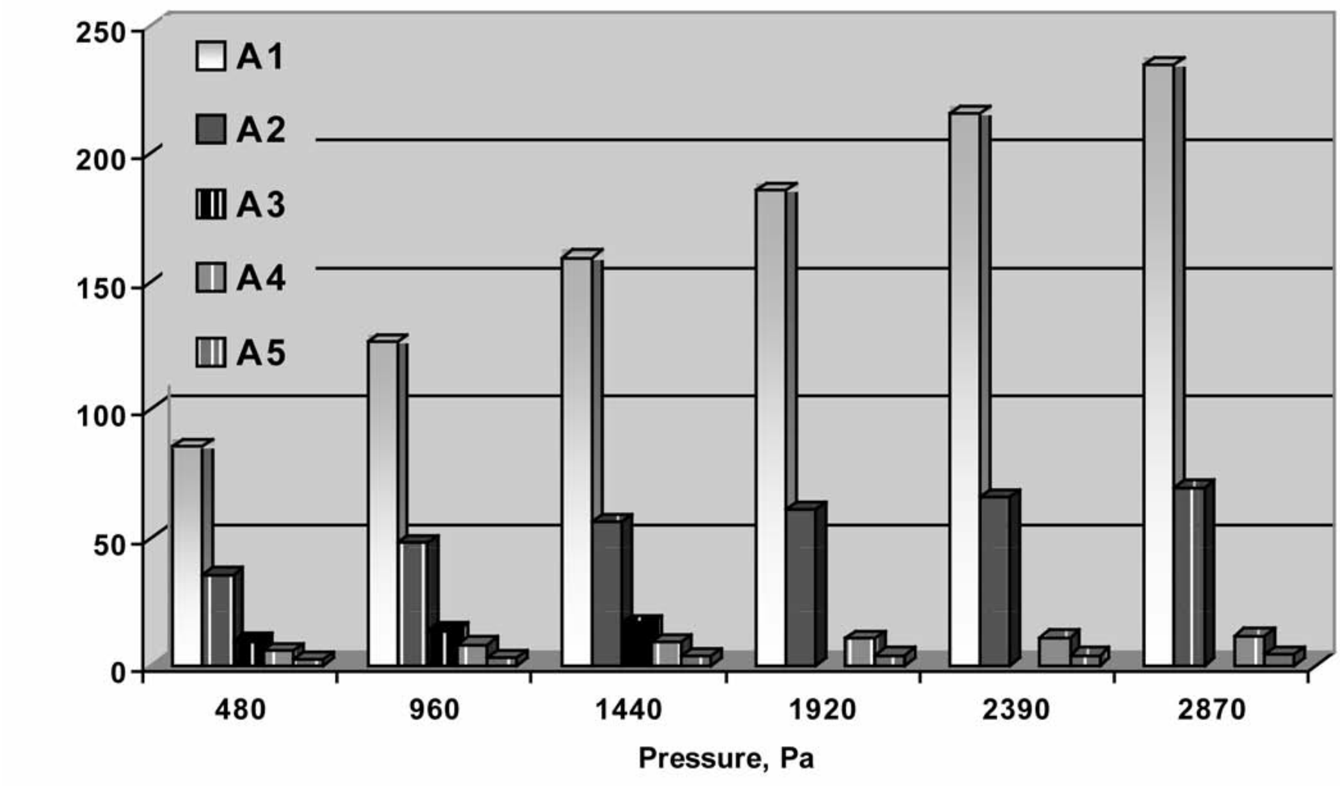


Figure 11 - Air leakage rate of the five tested assemblies.

A5, with self-adhered film and polyethylene sheet as barriers/retarders, showed good air leakage resistance. The reduced air leakage resistance of **A3** could be mainly attributed to the seam joints and corner edge treatments of the building paper. It should be noted that the building paper, being a soft material, if not properly installed has a tendency to tear. Within the assemblies with barrier/retarders, **A5** showed better air leakage resistance by reducing airflow by 75% and 60% compared to **A3** and **A4**. However, it should be noted here that the polyethylene sheet in **A5** was continuous without any seam joints, which represents the best-case scenario.

For an air barrier/retarder system in opaque, insulated portions of the building envelope, Part 5 of the NBCC (2005) recommends three permissible air leakage rates corresponding to various indoor humidity levels as shown in *Table 1*. To verify whether the tested assemblies comply with this code requirement, air leakage rates of the five assemblies were calculated at 75 Pa (1.56 psf) and compared with the NBCC [based on the laboratory testing condition, 0.15 L/s.m^2 (0.03 ft^3/min.ft^2) was selected] as shown in *Figure 13*. **A1** had a leakage rate of 2.52 L/s.m^2 (0.5 ft^3/min.ft^2), **A2** had 1.56 L/s.m^2 (0.31 ft^3/min.ft^2), **A3** had 0.30 L/s.m^2 (0.06 ft^3/min.ft^2), **A4** had 0.26 L/s.m^2 (0.051 ft^3/min.ft^2), and **A5** had 0.12 L/s.m^2 (0.023 ft^3/min.ft^2) respectively.

Codes of Practice and Standards	Warm Side Relative Humidity at 21°C	Recommended Maximum System Air Leakage Rate, L/(s.m^2) at 75 Pa
NBC (2005)	< 27%	0.15
	27 to 55%	0.10
	> 55%	0.05
ASTM*	None	0.3

*ASTM E1677-2005, Standard Specification for an Air Barrier (AB) Material or System for Low-rise Framed Building Walls.

Table 1: Recommended maximum air leakage rates as per the existing codes of practice and standard.

Comparison of these data with the NBCC indicates that none of the assemblies except **A5** comply with the NBBC code requirement. However, once again it should be remembered here that the assembly set-up of **A5** represents the idealistic construction procedure, having proper edge treatment and no seam joints, which has achieved its end

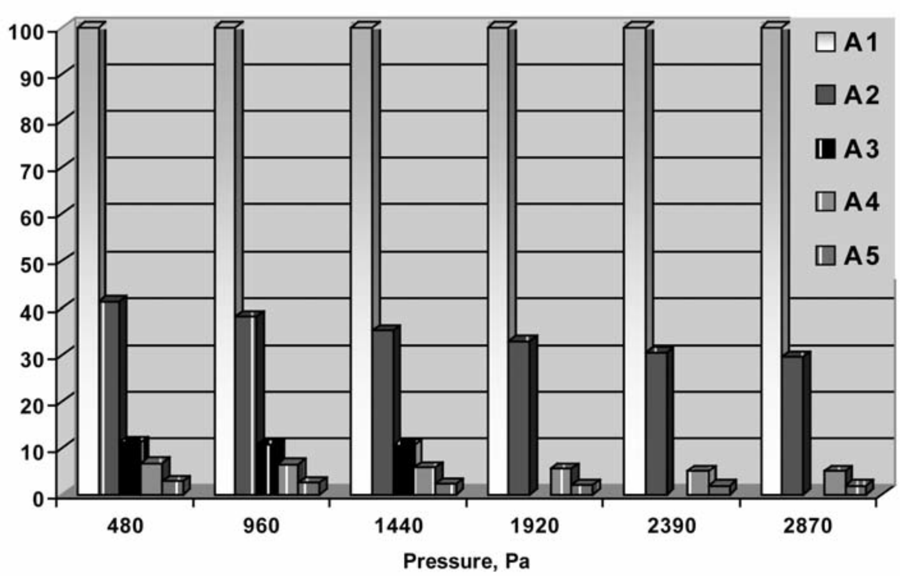


Figure 12 - Relative comparison of the air leakage resistance of the tested assemblies with respect to A1.

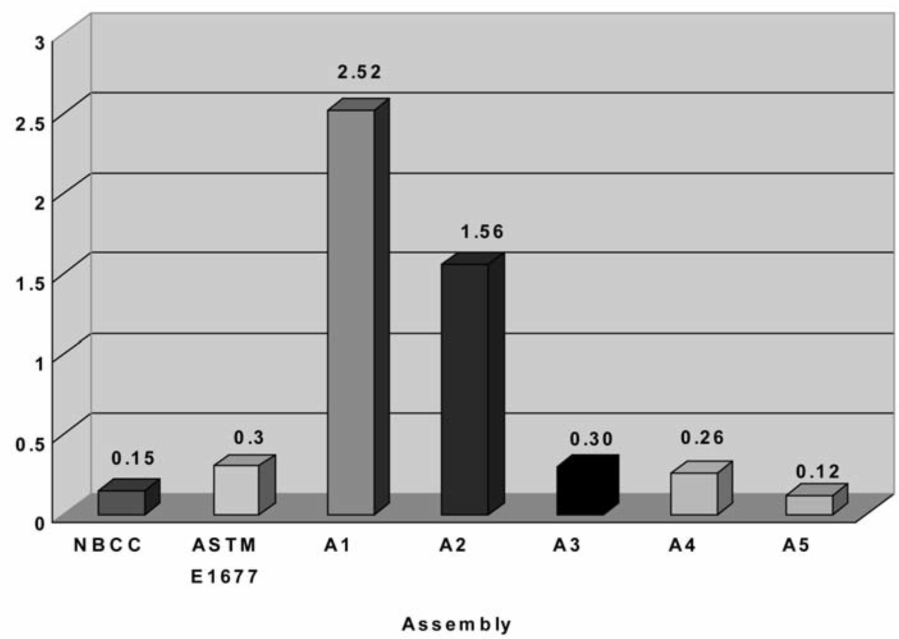


Figure 13 - Comparison of measured air leakage with the existing codes of practice and standard.

result demonstrating the significance of air intrusion.

Similarly, ASTM E 1677-2005, Standard Specification for an Air Barrier (AB) Material or System for Low-Rise Framed Building Walls, calls for an assembly air permeance requirement of 0.30 L/s.m^2 (0.06 ft^3/min.ft^2) at 75 Pa (1.5 psf). However, the standard restricts this permissible leakage rate to the opaque walls. Therefore, the comparison presented in *Figure 13* relative to ASTM E 1677 is not really applicable to roofing assemblies; however, it signifies the necessity of similar air leakage resistance requirement for roofing assemblies.

Analogous to ASTM E 1677, it should be noted here that the NBCC (2005) recommended air leakage rates are also the outcome of the research pertaining to walls, which have been generalized as a requirement for air barrier/retarder systems in opaque, insulated portions of the building envelope. Once again, though the comparison in *Figure 13* might not reflect the air leakage resistance requirement of roofing assemblies, it has clearly achieved its end result by demonstrating the significance of air leakage into the roofing assembly and the necessity of developing air leakage test standards for roofing assemblies with recommended design guidelines for barriers/retarders in the assembly. Additional research efforts are in progress in the enhancement of this test method, such as component requirements, structural capacity, installation techniques, and overall development of a standard for air barrier systems in roofing assemblies, which can lead to development of generalized "best practice," recommended air leakage rates for the air barrier systems of building envelopes.

CONCLUSION

Currently, no procedure or standard exists for quantification of air leakage through roofing assemblies. To quantify the air leakage performance of this roofing assembly, the authors have developed a test method. Based on this test method, the present paper investigated five roofing assemblies with and without barrier/retarder and quantified their air leakage performance. Data clearly indicated that assemblies without barrier/retarder had a high rate of air leakage, compared to assemblies with barrier/retarder.

The present experimental study also attempted to solve the myth that currently exists in the minds of some people in the roofing industry that the staggered arrangement of insulation boards can be as effective as that of having a barrier/retarder in an assembly. The reality was, the staggered insulation can indeed provide certain air-retarding effect; however, it cannot be considered as an effective barrier/retarder. Comparison of the measured air leakage rates of the five assemblies with the NBC (2005) recommended system air leakage rates clearly attested that except for the assembly with polyethylene sheet as a barrier/retarder, none of the other assemblies complied with the code.

In general, code requirement comparison clearly demonstrates the significant amount of air leakage into the roofing assembly and the necessity of an air barrier/retarder test standard for roofing assemblies. Development of this test method is a starting point for investigating the impact of air barrier/retarder systems in the roofing assembly performance, such as wind uplift performance, sustainable energy, moisture migration, and most important, increasing the longevity of the roofs.

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Building Owners

Canada Post Corporation, Department of National Defence, Public Works, and Government Services, Canada.

Industry Associations

Canadian Roofing Contractors' Association, Canadian Sheet Steel Building Institute, National Roofing Contractors' Association and RCI, Inc.

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