Air Intrusion Impacts in Seam-Fastened, Mechanically Attached Roofing Systems

By Suda Molleti, PEng;
Bas Baskaran, PEng; and Pascal Beaulieu

Figure 2 – Dynamic Roofing Facility – energy-efficient roof testing apparatus.

Editor's Note: This article presents the summary of a research study. A peer-reviewed paper on the study was published at the 15th Canadian Conference on Building Science and Technology in November 2017.

BACKGROUND

Air intrusion is termed as "when conditioned indoor air enters into a building envelope assembly [such as a roof (*Figure 1*)] but cannot escape to the exterior environment" (Molleti et al., 2009). In seam-fastened, mechanically attached roofing systems (MARS), the membrane's flexible and elastic nature and its attachment mechanism cause the membrane to flutter or balloon under the action of wind and mechanical pressurization. This volume change causes negative pressure or bubble pressure below the membrane, which is equalized by the air intrusion of the indoor conditioned air into the assembly.

The Special Interest Group for Dynamic Evaluation of Roofing Systems (SIGDERS) field measurement data indicated that the bubble pressure or the negative pressure below a fluttering membrane in mechanically attached roofing systems is around 30 to 35% of the suction pressure on the membrane. This pressure gradient is significant enough to cause air intrusion into the assembly. This intruded air is a binary mixture of dry air and water vapor; thereby, air intrusion becomes one of the major driving forces for the movement of moisture in the form of water vapor into mechanically attached roofing systems. Moisture can also migrate into the roofing system by means of water vapor diffusion during the winter season. All previous studies focused only on the diffusion process, which has often been blamed for condensation problems that might have been due to mass air movement by the air intrusion process. Controlling air intrusion is critical to ensuring good roofing system performance, because if left unchecked, it can have effects on wind uplift resistance, moisture accumulation,

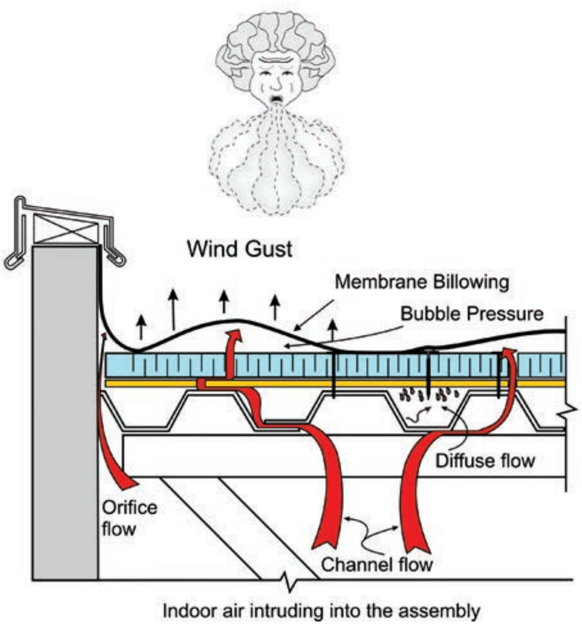


Figure 1 – Air intrusion in mechanically attached roofing systems.

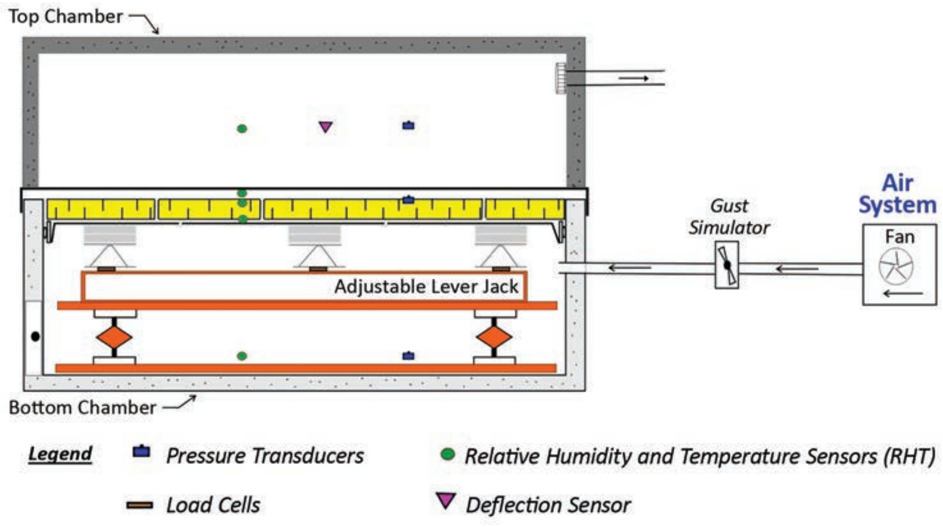


Figure 3 – Experimental setup for the hygrothermal testing.

and thermal resistance.

As of today, MARS have not been fully evaluated with regard to their moisture performance, particularly from the air intrusion process. The National Research Council of Canada (NRCC), in collaboration with the Canadian Roofing Contractors' Association (CRCA), the National Roofing Contractors Association (NRCA), the Roofing Industry Alliance for Progress, and the Single-Ply Roofing Institute (SPRI), addressed the issue of air intrusion and moisture movement in roof assemblies through a research and development project designated **A**ir Movement **I**mpacts on **R**oof Systems (AIR). The objectives of this research study are threefold: to understand moisture movement in MARS under the influence of air intrusion; to evaluate air intrusion mitigation factors; and to establish air intrusion limits for a code of practice.

This article presents the summary of this research study. A peer-reviewed paper on this research study was published at the 15th Canadian Conference on Building Science and Technology in November 2017.

EXPERIMENTAL APPROACH

Test Apparatus

The experimental study was conducted on the new Dynamic Roofing Facility's Energy-Efficient Roof Testing Apparatus as shown in *Figure 2*. This is an integrated test apparatus that has the capability to quantify all the energy-influencing parameters on roofing assemblies in one apparatus—namely air leakage, air intrusion, hygrothermal performance, and thermal performance. The major components are the insulated top and bottom chambers, air system, pressure-measuring apparatus, airflow-measurement system, temperature sensors, deflection sensors, humidity sensors, and data acquisition system.

The insulated top and bottom chambers have interior length and width dimensions of 20 ft. (6.10 m) and 8 ft. (2.44 m), respectively. The outdoor climatic conditions are simulated by a relative humidity (RH) and temperature conditioner with RH capability of 15% to 85% at an accuracy of ±0.5%, and temperature capability of -4°F to 158°F (-20°C to 70°C) with an accuracy of ±0.4°F (±0.2°C). The membrane assembly specimen to be tested is installed horizontally in the bottom chamber. The test specimen is supported on six load cells with a total capacity of 1323 lb. (600 kg) that are used to quantify the moisture performance of the roofing system following the gravimetric approach. The load cells have an accuracy of ±0.22 lb. (±100 g). *Figure 3* shows the test apparatus arrangement for this hygrothermal testing.

Test Specimens and Procedure

In this research study, 16 roof assemblies were tested. The performances of 12 key roof assemblies (*Table 1*) are discussed in this article. The assembly layout was comprised of (*Figure 4*):

- **Steel deck (22 Ga):** Mechanically fastened to the steel joist, spaced at 6-ft. (1.82-m) centers. The deck perimeter is air-sealed to the bottom chamber to ensure that the air intrusion occurs along the deck seam overlaps and not along the perimeter.
- **Vapor barrier/air retarder (VB/AR):**

Label	System details	Label	System details
S1	Thermoplastic (6 ft.) — 2 inch iso	**S7**	Thermoplastic (10 ft.) — 2 inch staggered iso
S2	Thermoplastic (6 ft.) — 4 inch iso	**S8**	Thermoplastic (6 ft.) — 2 inch iso, kraft paper adhesive seam
S3	Thermoplastic (10 ft.) — 2 inch iso	**S9**	Thermoplastic (6 ft.) — 2 inch iso, kraft paper seam tape
S4	Thermoset (10 ft.) — 2 inch iso	**S10**	Thermoplastic (6 ft.) — 2 inch iso, polyethylene seam tape
S5	Modified Bituminous (3 ft.) — 2 inch iso	**S11**	Thermoplastic (6 ft.) — 2 inch iso, self-adhered sheet
S6	Thermoplastic (6 ft.) — 2 inch staggered iso	**S12**	Thermoplastic (6 ft.) Vapor Diffusion — 2 inch iso

Table 1 – Description of tested specimens.

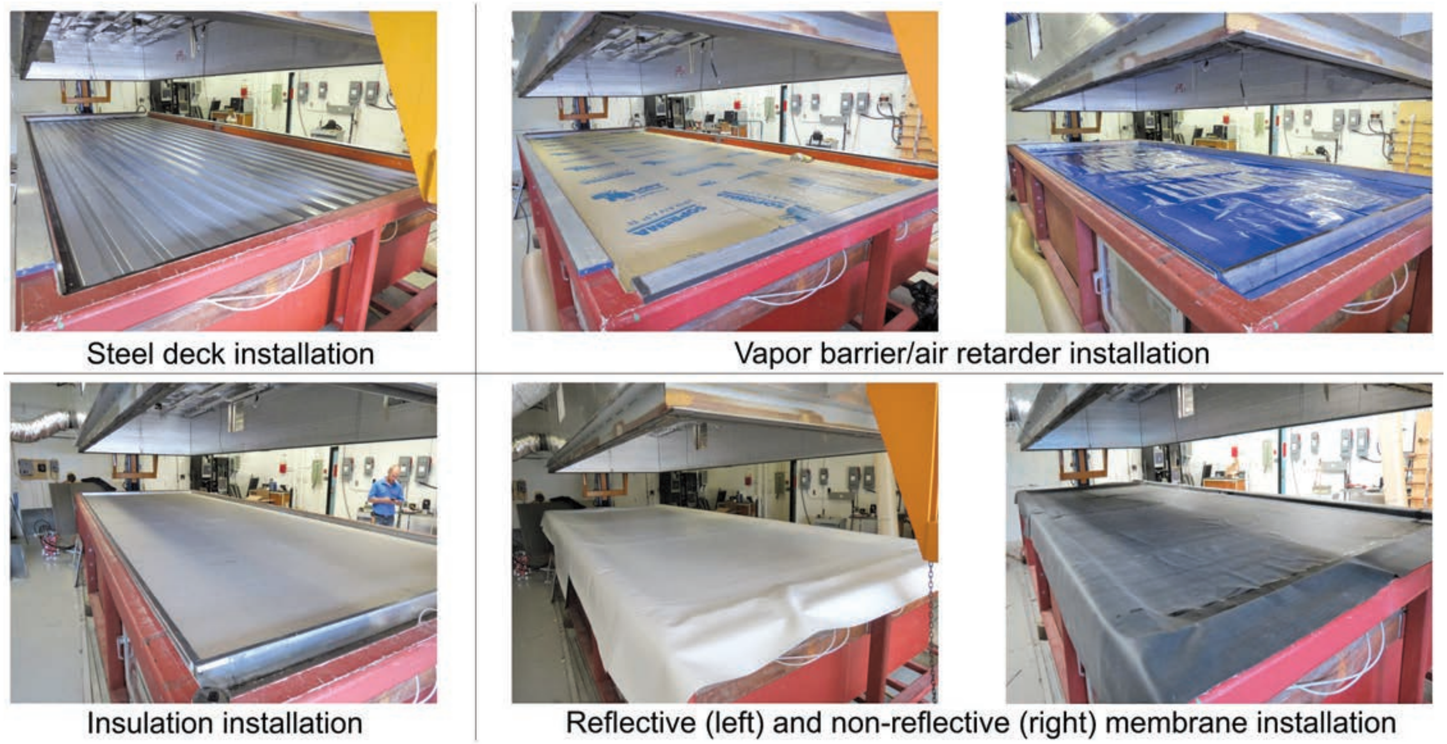
Dual-function vapor barriers (control vapor diffusion and air leakage) used in this study included asphalt-impregnated building paper (15-mil thick [0.38-mm]), self-adhesive sheet (40-mil [1-mm]), and polyethylene film sheet (single-layer of 10-mil [0.25-mm]). All vapor barriers were installed with 6-in. (152-mm) laps. With appropriate sealing techniques in the bottom chamber, the perimeter air intrusion along the vapor barrier edges was completely mitigated.

- **Polyisocyanurate insulation:** 4- by 4-ft. (1.2- by 1.2-m) boards, mechanically fastened to the steel deck with four fasteners per board. The insulation layout maintained a gap of ⅛ in. (3.1 mm) between the boards along the length of the table. Three insulation layouts were tested: single-layer, 2-in.- (51-mm-) thick; two-layer staggered insulation layout with each layer 2 in.- (51-mm-) thick; and a single layer of 4-in. (102-mm-) thick polyisocyanurate.
- **Roof membrane:** Three types of membrane roofing systems were tested, including thermoplastic, thermoset, and modified bituminous (mod-bit). Within the thermoplastic, a 45-mil PVC membrane with two sheet widths—6 ft. (1.8 m) and 10 ft. (3.0 m)—was tested. It was a one-sided weld (OSW) system. The thermoset systems were tested with a 45-mil reinforced EPDM as the waterproofing membrane with a sheet width of 10 ft. (3.0 m). The membrane attachment is a typical inseam attachment. The mod-bit membrane layout comprised a base sheet and a cap sheet. All the tested systems, irrespective of the membrane type, had a fastener spacing of 12 in. (305 mm).

Test Methodology

The potential condensation and moisture accumulation in MARS depends on the air intrusion rate, indoor conditions (temperature and RH), and outdoor conditions, including wind and solar loads. Based on ASHRAE Standard 62-1989 RH requirements, the indoor air conditions beneath the roofing system were set at 70°F (21°C) and 40% RH. The air pressure differences influencing the air intrusion rate are typically the wind loads acting on the roofing system.

Based on SIGDERS field-monitoring data from seam-fastened mechanically roofing systems, a suction pressure of 5 psf


Steel deck installation

Vapor barrier/air retarder installation

Insulation installation

Reflective (left) and non-reflective (right) membrane installation

Figure 4 – Test specimen construction.

(239 Pa) was finalized as the testing pressure on the roofing system. While this suction pressure might be higher than the daily pressures produced on a roofing system, it was adopted to be in agreement with ASTM D7586 test protocol that has 5 psf (239 Pa) as the lowest testing pressure. The gust duration for this testing pressure is set to 12 seconds.

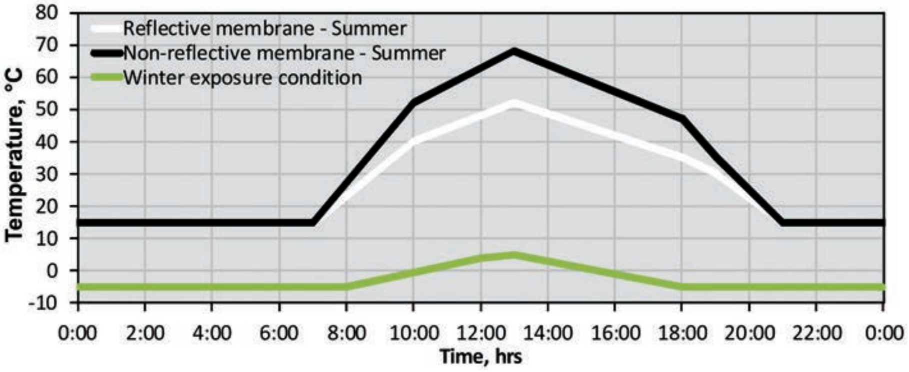


Figure 5 – Simulated diurnal summer and winter exposure condition.

Selecting experimentally feasible outdoor temperatures representative of those experienced by in-service roofs was necessary in this study. Relating to the solar absorptance of the membrane, the experimental testing for the summer conditions was finalized as 59°F to 118°F (15°C to 48°C) for roof assemblies with reflective membrane; and for roof assemblies with nonreflective membrane, the test conditions were set to 59°F to 154°F (15°C to 68°C). For the conditions designated as winter, irrespective of the membrane color, it was assumed the average roofing membrane temperature at night would be around 23°F (-5°C) and that, due to solar heating, it would rise during the day to about 41°F (5°C). *Figure 5* shows the simulated summer and winter exposure conditions.

Figure 6 – Systems responses after winter and summer cycle exposure conditions.

The test procedure involves measuring the air intrusion of the constructed roof system following the ASTM D7586 test protocol, and then subjecting the roof system to diurnal winter and summer exposure conditions with simultaneous application of wind pressures. At the completion of each cycle, the weight of the system is measured to determine the moisture gain and loss of the roof system.

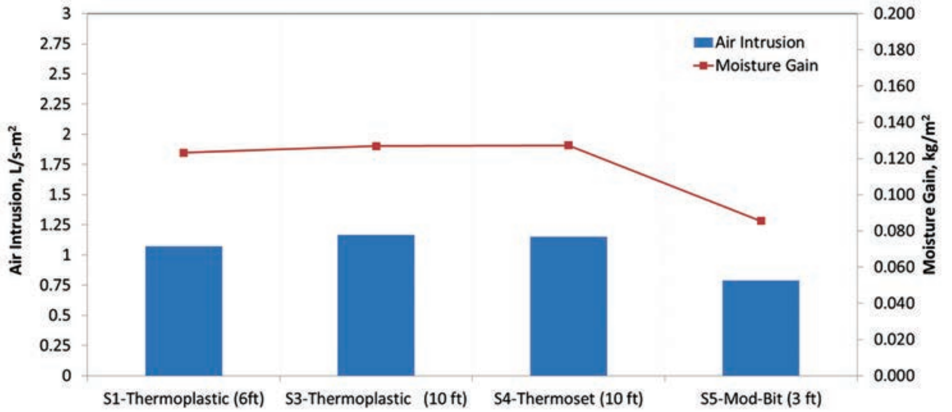


Figure 7 – Air intrusion vs. moisture gain in MARS – effect of sheet width and membrane type.

Air Intrusion Transports Moisture into MARS

For all the tested systems, the temperature and RH across different components of the roof system were measured and recorded. *Figure 6* shows the visual observations of the systems' responses at the end of the 24-hour winter cycle. All of the systems that had one layer of insulation and no vapor barrier showed frost formation along the sides of the membrane, and hand inspection under the membrane showed the presence of liquid water. At the end of the summer cycle, there was shrinkage of insulation observed in all of these systems.

Figure 7 shows the relation between air intrusion per gust and moisture accumulation that was measured from these systems. The moisture gain presented in the graph is the moisture accumulated over 24 hours of the winter cycle. The air intrusion data indicate that, with the increase in the membrane sheet width or fastener row spacing, the rate of air intrusion increases. The mod-bit membrane is a two-ply membrane with a granular cap sheet and base sheet. The weight of the mod-bit membrane (1.6 psf [7.81 kg/m^2]) is four times heavier than the single-ply membrane (0.4 psf [1.95 kg/m^2]). Being heavier, the mod-bit system measured less deflection under wind pressures, so the air intrusion was 25% to 30% less than the single-ply membrane assemblies, which translated into lower moisture gain.

In MARS, during the heating season, the membrane is the coldest part of the roof, and if it is below the dew point temperature, the air intrusion has the potential to cause condensation on the membrane underside. In all the systems shown in *Figure 7*, the accumulated moisture over 24 hours was above 0.02 psf (0.08 kg/m^2), and this weight is the combination of the liquid condensate and the moisture absorbed by the insulation facer and the insulation. Therefore, in heating-dominated climatic zones, MARS should be designed to minimize air intrusion into the systems.

Air Intrusion Transports More Moisture than Vapor Diffusion

In the current study, experiments were also conducted to differentiate the rate of moisture transport from air intrusion and vapor diffusion. Two systems with identical layouts provide the comparison between these two moisture-driving phenomena. With simulated diurnal winter conditions atop the roofing system and constant indoor conditions of 70°F (21°C) and 40% RH, there was a vapor pressure differential of 15 to 18 psf (718 to 862 Pa) across the system. This gradient allowed moisture movement of 0.55 lb. (250 g) over the 24-hour winter uptake period. There were no signs of frost formation or visible moisture under the membrane or on the insulation.

When a similar system configuration was subjected to wind conditioning of 5 psf (239 Pa), the bubble pressure or the differential pressure of 3 psf (144 Pa) across the system was able to drive 4.08 lb. (1850 g) of moisture over the same 24-hour winter uptake period. Frost and water were observed under the membrane and on the insulation. This sevenfold increase in the moisture gain clearly indicates that air intrusion in MARS is a major driving force of moisture into the system. This combination of air intrusion and vapor diffusion—as both mechanisms can operate at the same time—could be critical to initiate potential damage to the roofing components.

Air Intrusion Can be Mitigated by Proper Installation of Vapor Barrier/Air Retarder

Three commonly used vapor barriers—namely kraft paper, polyethylene, and self-adhered sheets—were tested to evaluate their functionality as air retarders in minimizing air intrusion into the roof assembly. All the vapor barriers were constructed with seam overlaps of 6 in. (152 mm). *Figure 8* compares the air intrusion and moisture performance of these four systems relative to a system without vapor barriers.

Systems with polyethylene and self-adhered sheets as vapor barriers completely mitigated air intrusion, demonstrating their air retarder functionality. With kraft paper as a vapor barrier, the seam overlap bonding techniques influenced the rate of air intrusion. The seam overlaps bonded by adhesive measured higher air intrusion compared to seam tape-bonding mechanisms. This could be attributed to the lack of proper bonding of the adhesive seams of the kraft paper, as the test was started immediately after construction without allowing curing of the seam adhesive. Using seam tape similar to that used in the polyethylene seams, the kraft paper decreased almost 97% of the air intrusion rate. The moisture gain comparison in these systems indicated that minimizing air intrusion can significantly reduce the bulk movement of moisture into the roof system.

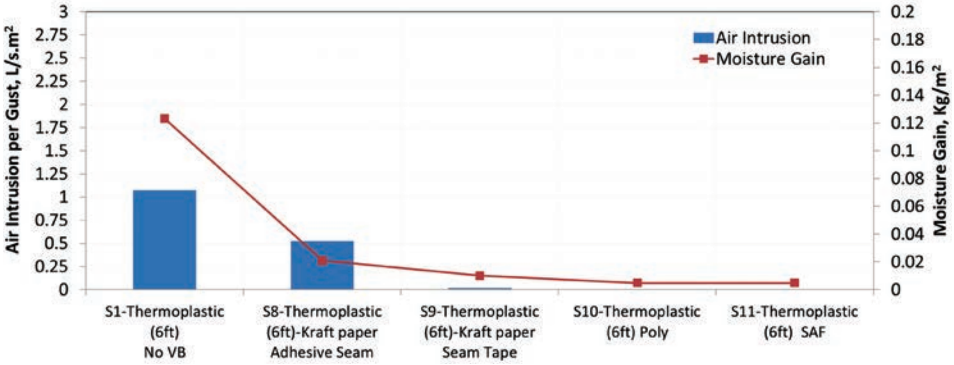


Figure 8 – Air intrusion and moisture performance of MARS with and without vapor barriers.

Air Intrusion Can Be Minimized by Installing Insulation in a Staggered Layout

A staggered two-layer insulation layout offsets the insulation joints and is a recommended approach for minimizing thermal bridging. In the current study, the staggered layout was evaluated for air intrusion performance relative to the one-layer insulation layout, and *Figure 9* shows their relative air intrusion and moisture performance. The staggered layout minimized air intrusion by almost 60% compared to the one-layer insulation layout, irrespective of the sheet width. Offsetting the insulation joints simulates channel flow paths, extending the length of the flow path for the air intrusion into the system. Within the same gust duration, if the flow path is increased relative to the membrane fluttering time or membrane response time, there could be less air intrusion. This is because the fluttering membrane might potentially push the air out of the roof system into the building interior before it reaches the coldest part of the system, i.e., the membrane.

Comparing the moisture accumulation at the end of a 24-hour winter cycle, systems with a two-layer staggered insulation layout had 60% less moisture compared to systems with a one-layer insulation layout. Unlike the latter, which experienced insulation shrinkage, there was no shrinkage observed in the staggered insulation layout systems, indicating that moisture and temperature play a role in the dimensional stability of the insulation boards. Although staggered insulation did show favorable results in minimizing moisture accumulation, the measured air intrusion of 0.08 cfm/ft^2 (0.77 L/s-m^2) was critical to initiate surface condensation.

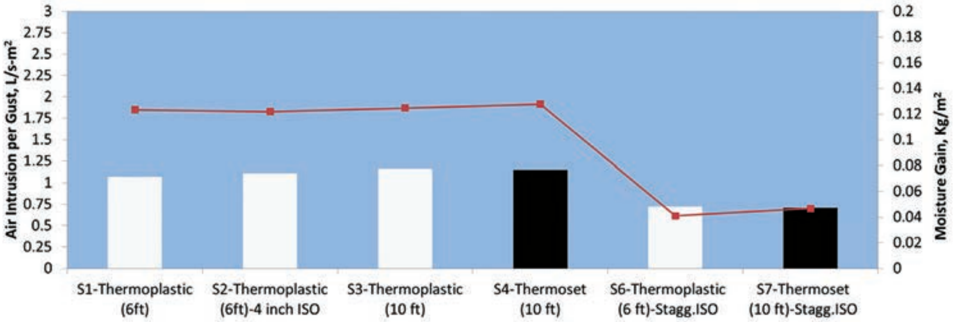


Figure 9 – Air intrusion and moisture performance of MARS with and without staggered insulation layout.

Air Intrusion Aids in Moisture Removal

Figure 10 compares the moisture performance of the reflective single-ply or thermoplastic systems, nonreflective single-ply or thermoset systems, and nonreflective two-ply or mod-bit system. In nonreflective membrane systems that had one-layer insulation layouts, the accumulated moisture in the winter cycle completely dried out in the 24-hour summer cycle from the combination of solar absorptance (higher membrane temperature) and air intrusion. However, in the reflective membrane systems, the same combination of solar absorptance (lower membrane temperature) and air intrusion removed only 50% of the moisture in the

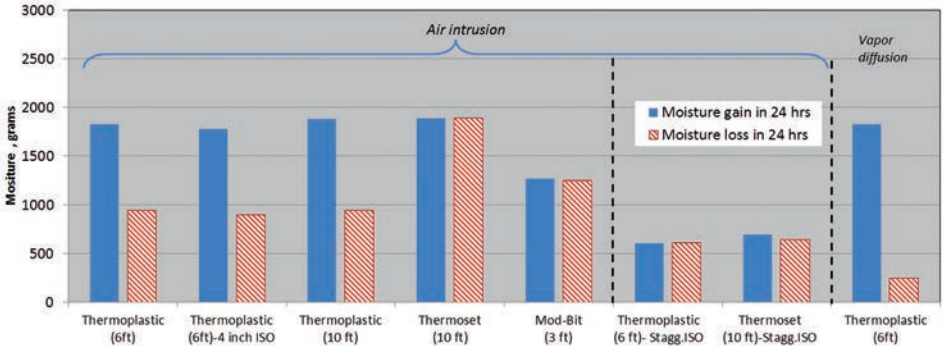


Figure 10 – Air intrusion aids in moisture removal.

same 24-hour summer cycle. Having similar air intrusion rates in both the single-ply membrane systems, the higher membrane temperature of the nonreflective membrane systems was critical in demonstrating complete drying within the scheduled 24 hours. However, with staggered insulation layout that allowed lower moisture intake, the same reflective membrane system demonstrated complete moisture removal within the 24-hour summer cycle. This indicates that if the air intrusion and moisture accumulation were minimized in reflective membrane systems, they could perform similarly to the nonreflective membrane systems without the concern of progressive wetting and drying.

The solar absorptance of a membrane definitely aids in moisture removal, but when combined with air intrusion, the rate of drying is expedited. Moisture removal by separate mechanisms of air intrusion and vapor diffusion was also investigated on a reflective membrane system. With the same membrane temperature, the process of vapor diffusion took seven days to remove the same amount of moisture that air intrusion removed in a day. In summary, air intrusion not only transports moisture into the roof system during the heating season, but also can contribute to drying of the system in the summer (cooling) season.

Air Intrusion Limits

Figure 11A shows the moisture gain of all the tested systems where air intrusion is the moisture-driving mechanism. By comparing the moisture accumulation data, a threshold of 0.01 psf (0.04 kg/m^2) could be identified as the critical moisture accumulation as highlighted by the dotted line in *Figure 11A*. It means that if the moisture accumulation is below this limit, there is potential for the system to dry out without any progressive accumulation of the moisture over the season.

Figure 11B plots the measured air intrusion for all the tested systems at the testing pressure of 5 psf (239 Pa). The joints of the structural deck are the primary flow paths for air intrusion, and if that air intrusion could be minimized to as low as 0.002 cfm/ft^2 (0.02 L/s-m^2) by a properly installed vapor barrier that also functions as an effective air retarder, the risk of condensation and moisture accumulation could also be minimized. This could be said to be a “no-condensation” criterion.

In Canada, it is mandatory to include a vapor barrier in most roof designs. NBCC and provincial codes allow vapor barrier-free designs under certain conditions. In the United States, there are no widely accepted guidelines for the inclusion of vapor barriers in low-slope roof assemblies. If air intrusion could be minimized to between 0.06 and 0.08 cfm/ft^2 (0.6 and 0.8 L/s-m^2), there would be minimal moisture accumulation, which might dry out in the cooling season without progressive wetting. If the air intrusion exceeds 0.08 cfm/ft^2 (0.8 L/s-m^2), as in the case of systems with single-layer insulation, there is potential for higher seasonal wetting in heating-dominated climatic zones, thereby decreasing the moisture tolerance of the system.

CONCLUSIONS

A new, unique test approach has been developed for evaluating climatic impacts on the hygrothermal performance of the roof system through simultaneous application of wind pressure, temperature, and RH conditions. The limitations of the current study are the extreme testing conditions discussed above. Therefore, the results presented in this report are applicable at these testing conditions only and might not be representative of on-site performance of the roofing systems. Based on this limited study, the following conclusions can be drawn:

- Membrane weight, sheet width, fastener row spacing, and membrane elasticity are some of the parameters that influence the rate of air intrusion into the roof assembly. Air intrusion and moisture accumulation in mod-bit systems was on average 25 to 30% less than in single-ply systems, owing to its higher material density.
- In the heating season, air intrusion at 5-psf (239-Pa) wind pressure transported sevenfold more moisture into the system compared to vapor diffusion. In the summer cycle or cooling season, air intrusion also helped to vent moisture out of the system at a faster pace compared to the vapor drive.

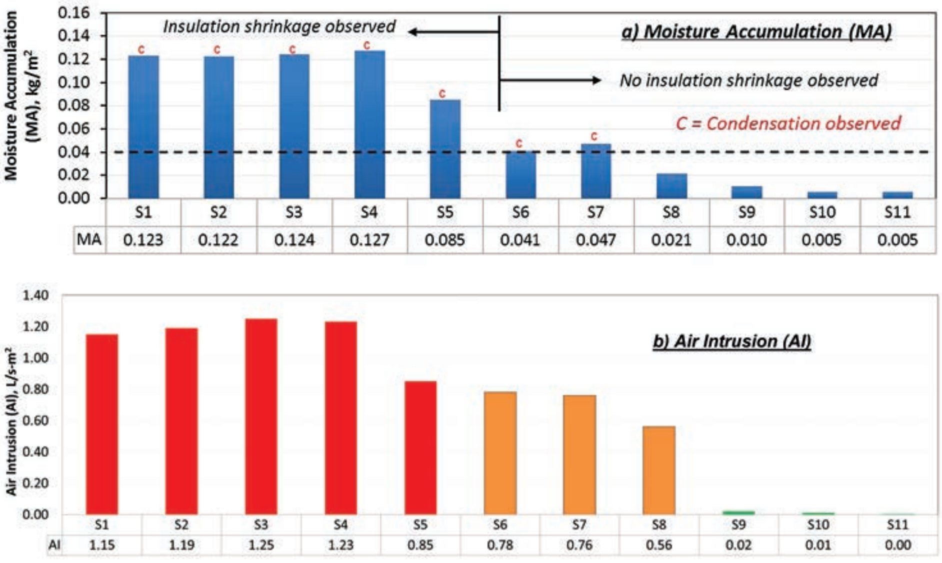


Figure 11 – Air intrusion and moisture performance of MARS.

- Three different vapor barriers—kraft paper, polyethylene film, and self-adhered sheet—were evaluated to quantify their performance as effective air retarders in MARS. Following proper installation techniques, these vapor barriers mitigated air intrusion into MARS, demonstrating their dual functionality, and all the tested MARS showed better performance with no condensation and moisture accumulation.
- A two-layer staggered insulation arrangement in membrane roof systems minimized air intrusion by 60%, transporting only one-third of the moisture compared to the one-layer insulation layout. Staggered insulation introduces channel flow in the system, increasing the length of the flow paths for air intrusion to respond to the fluctuating dynamic wind pressures. It should become standard practice rather than recommended practice.
- In the cooling season, the solar absorptance of the roofing membrane influences the rate of moisture removal or drying of the roof system, and when supplemented with air intrusion from membrane fluttering, the drying process could be further expedited.
- With a vapor barrier that also functions as an effective air retarder installed on the deck, air intrusion was very minimal (<0.002 cfm/ft^2 [0.02 L/s-m^2]). The mass flow of vapor was minimized, reducing the risk of condensation and moisture accumulation. When multiple layers of insulation were installed in a staggered arrangement, the air intrusion was minimized; however, the risk of condensation still exists with minimal moisture accumulation. This accumulated moisture could potentially dry out without any progressive accumulation. If air intrusion exceeds 0.08 cfm/ft^2 (0.8 L/s-m^2), there is potential for higher seasonal wetting, increased risk of surface condensation, and higher moisture accumulation. With more moisture accumulation, more drying time is required, therefore leading to potential disparity in the wetting-to-drying performance of the roof system.
- Although this study has been limited to one indoor RH condition and one type of insulation that is less absorptive, it would be ideal to validate this classification with other common insulation types and roof boards across the RH range of 30 to 60% recommended by ASHRAE 62.1 and the *ASHRAE Handbook*.

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Suda Molleti, PEng

Dr. Molleti is a research officer in the Performance of Roofing Systems and Insulation (PRSI) Group at NRC, where his work focuses on researching the wind-induced effects on low-sloped roofing systems and the thermal and hygrothermal performance of roofing systems. He is currently working on establishing energy ratings for roofing assemblies, wind performance of vegetated roof assemblies, energy and durability performance of PV-integrated roofs, and application of vacuum insulation panels in roofing systems. He is a member of the ASTM D08 and CRCA Technical Committees.

Bas Baskaran, PEng

Dr. Baskaran is a group leader with the NRC and an adjunct professor at the University of Ottawa. He is a member of committees at RCI, RICOWI, ASCE, SPRI, ICBEST, and CIB, and is a research advisor to various task groups of the National Building Code of Canada. He has authored or coauthored over 200 research articles and received over 25 awards, including the Frank Lander Award from the Canadian Roofing Contractors Association and the Carl Cash Award from ASTM. Dr. Baskaran has been recognized by Her Majesty Queen Elizabeth II with a Diamond Jubilee medal for his contribution to his fellow Canadians.

Pascal Beaulieu

Pascal Beaulieu is a technical officer in the Performance of Roofing Systems and Insulation (PRSI) group at the National Research Council of Canada. His work focuses on the wind-induced effects on low-sloped roofing systems and the thermal and hygrothermal performance of roofing systems. Pascal earned his degree in mechanical engineering technology from La Cité Collegiale.

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