Impact of Air Intrusion on Moisture Performance of Seam-Fastened Mechanically Attached Roofing Systems

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ABSTRACT

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) studied the issue of air movement in roof assemblies through an R&D project designated: Air Movement Impacts on Roof Systems (AIR). To quantify the impact of air intrusion on moisture transport, experimental work was conducted at the Dynamic Roofing Facility-Hygrothermal test chamber. A new hygrothermal test approach was developed to explicate the relationship between air intrusion and moisture accumulation in mechanically attached roofing systems. Membrane weight, sheet width and membrane elasticity influence the rate of air intrusion into the roofing system. Air intrusion and moisture accumulation in two-ply modified bituminous systems was on average 25 to 30% less than in single-ply systems due to its higher material density. Research showed that a properly installed vapor barrier can significantly minimize air intrusion into the roof system. A two-layer staggered insulation layout is found to reduce air intrusion by 60% as compared to one-layer layout. Irrespective of the membrane color, air intrusion during the winter cycle led to wetting of the system. In the summer cycle, the roof systems with reflective membranes that are constructed with one layer insulation took twice the time for drying compared to the roof systems with non-reflective membrane. However, when constructed with two-layer staggered insulation layout, the reflective systems demonstrated a minimum wetting-to-drying ratio of 1:1 performing similar to the non-reflective assemblies. The results presented in this paper are applicable at these testing conditions only and might not be representative to on-site performance of the roofing systems.

INTRODUCTION

In North America, low-slope membrane roofing assemblies can be classified into two categories according to the location of the waterproofing membrane. One is the protected roofing assembly, where the insulation is on the top with the membrane below it, and the other is the conventional assembly, where the membrane is on the top and the insulation is below. In the conventional assembly the membrane is exposed to external conditions such as wind, snow, rain, UV radiation and temperature changes. The membrane can be mechanically fastened, adhered or partially attached to the substrate. Where the membrane is mechanically fastened through the insulation and other components to the structural deck at discrete points using fasteners,

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the assembly is known as a Mechanically Attached Roofing System (MARS). The membrane can be single ply or two ply as in the case of a modified bituminous system. The present study focuses on seam-fastened mechanically fastened systems with single-ply and two-ply membrane. Approximately one fourth of North American low slope/commercial buildings are roofed with MARS.

With membrane roof systems, the waterproofing membrane is impermeable. If constructed properly, it can certainly perform as an air barrier and prevent air leakage (i.e., movement of air between indoor to outdoor and vice versa across the roof assembly) (Molleti et al., 2014, 2015). With mechanically attached roofing systems, because of the membrane's flexible and elastic nature and its attachment mechanism, the action of wind and mechanical pressurization can cause the membrane to flutter or balloon. The resulting volume change causes negative or bubble pressure below the membrane, which is equalized by the indoor conditioned air moving into the assembly, as shown in Figure 1. This concept is termed "air intrusion, where conditioned indoor air enters a building envelope assembly, such as a roof, but cannot leave the assembly to the exterior environment" (Molleti et al., 2010).

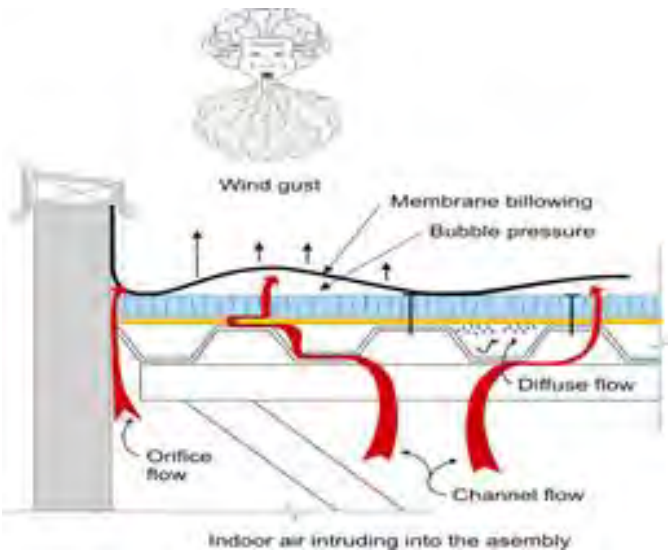


Figure 1: Air intrusion in mechanically attached roofing systems.

Controlling air intrusion is critical in ensuring good roofing system performance because if left unchecked, it can have effects on wind uplift resistance, moisture accumulation, and thermal resistance. Baskaran and Molleti (2003) demonstrated that minimizing air intrusion can increase the wind uplift resistance by 50%. A current research project, AIR, addresses the other impacts of air intrusion, namely the condensation and moisture accumulation, while a new project, "Energy Resistance of Commercial Roofs," will consider the energy impact.

The design of mechanically attached roofing systems has not considered the effects of air intrusion on performance (Hutchinson 2007). Cautions regarding its effects on wind-uplift performance and moisture performance are not new. Various technical notes, manuals and papers (NRCA Energy Manual 1989, Dregger 2002, Lstiburek 2008, Zarghamee 1990) have identified the above-discussed air intrusion effects on roofing assembly performance. However, no information was available regarding the extent to which air intrusion can occur in mec anically attached roofing systems and their sensitivity to air movement until the National Research Counci of Canada (NRC) initiated a ground-breaking study through the auspices of SIGDERS (Special Interest Group for Dynamic Evaluation of Roofing Systems).

MARS have not been fully evaluated with regard to their moisture performance, particularly from the air intrusion process. The NRC, 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 an R&D project designated: Air Movement Impacts on Roof Systems (AIR). The objectives of this research study are threefold: to understand moisture movement in MARS under the influence of air intrusion; to evaluate the influence of solar absorptance and vapor barriers/air retarders on mitigating the moisture accumulation and condensation potential; and to establish air intrusion limits for code of practice.

TEST APPARATUS AND EXPERIMENTAL EXPOSURE CONDITIONS

Experimental Test Apparatus

The experimental study was conducted on the new Dynamic Roofing Facility – Hygrothermal Test Apparatus, shown in Figure 2. The major components are the top chamber, bottom chamber, air system, pressure measuring apparatus, airflow measurement system, 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 top chamber has a height of 3 ft. (0.91 m) and it is operated by hydraulic lifts allowing it to move up and down. The bottom chamber is fixed to the ground and has a height of 3 ft. (0.91 m). Provisions are made for an opening on the side wall of the top chamber through which the air flow measurement system is installed and connected to the blower. The outdoor climatic conditions are simulated by a 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 ceiling of the top chamber is also fitted with infrared heaters, which have the capability to simulate membrane temperature up to 230°F (110°C).

The membrane assembly specimen to be tested is installed horizontally in the bottom chamber. It is supported by three joists placed 6 ft. (1.82 m) apart along the length of the table. The joists are supported on two longitudinal beams resting on a height-adjustable lever that permits testing of assemblies with different thicknesses. At the bottom of each joist, two 220 lb. (100 kg) load cells are installed; these are mechanically fastened to the beams. In total, six load cells with a total capacity of 1323 lb. (600 kg) are installed, used to measure the weight of the roofing system following the gravimetric approach. The load cells have an accuracy of ± 0.22 lb. (± 100 g). To simulate wind gusts, the bottom chamber is fitted with gust simulator and blower that have the capability to simulate static and dynamic wind cycles with a test pressure range up to 100 psf (5 kPa). The pressure measuring apparatus is a device for measuring the test pressure difference within a tolerance of ±2% of the reading or ±0.05 psf (±2.5 Pa). The airflow measurement system is a laminar flow measuring device that has the capability to measure airflow with an accuracy of 0.8% of the reading. The relative humidity and temperature sensors (RHT) are Vaisala HMP110 humidity and temperature probes which are used to measure the RH and temperature across the roofing system. These probes have a measurement range of 0 to 100% RH and -40°F to 176°F (-40°C to 80°C), with an accuracy of ±1.5% RH and ± 0.4°F (±0.4°C) respectively. The deflection sensors are lasers installed in the top chamber to measure membrane deflection. They have a measurement range of 10 in. (0.25 m) to 20 in. (0.51 m), with total range up to 30 in. (0.76 m). It has an accuracy of ±0.5% of the full scale reading. The data acquisition is a computer-

based system capable of simultaneously measuring the differential pressures, air intrusion, temperature, RH and membrane deflection as a function of time.

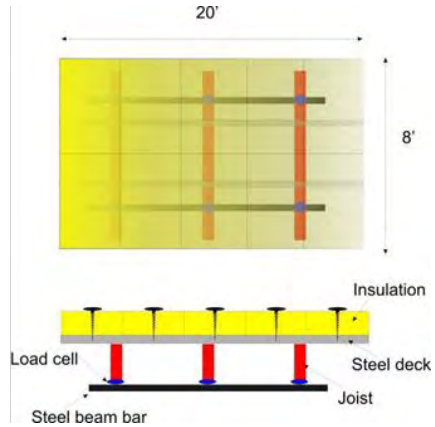


Figure 2: Dynamic roof facility hygrothermal test chamber.

Experimental Testing Conditions

The first criteria established were the indoor conditions. According to ASHRAE Standard 62-1989, relative humidity in habitable spaces preferably should be maintained at between 30% and 60%. In the present study, the assumption is that the roofing system is atop a commercial building, therefore, the efforts were to simulate realistic indoor conditions. In consultation with steering committee (SC) members for the project, indoor air conditions beneath the roofing system were set at 70°F (21°C) and 40% RH.

The movement of moisture via air intrusion is pressure dependent. The air pressure differences influencing the air intrusion rate are typically the wind loads acting on the roofing system. As part of the SIGDERS field monitoring objective, wind pressure measurements are being made on an ongoing basis on a Canada Post building in Vancouver that is roofed with MARS. Figure 3 shows measured peak pressure data on the three different roof zones, namely, corner, edge and field, characterized at different wind speeds and wind directions. With the wind speed ranging from 36 to 52 mph (58 to 84 kph), the peak pressures measured in the corner, edge and field are -8, -14 and -11 psf (-383, -670, -527 Pa) respectively.

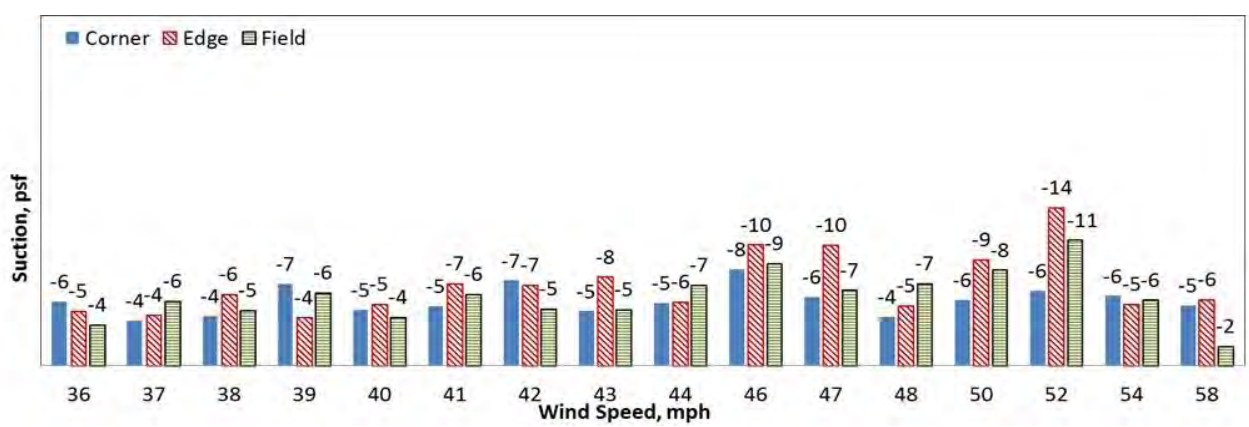


Figure 3: Measured peak pressures on MARS- Canada Post Building (YVR).

Irrespective of the wind speed, the average of peak pressures among the three zones varied from -6 to -7 psf (-287 to -335 Pa). A suction pressure of 5 psf (239 Pa) was finalized as the wind-induced pressure on the roofing system. While this suction pressure might be higher than the daily pressures produced on the roofing

system, it was adopted so as 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.

Selecting experimentally feasible outdoor temperatures representative of those experienced by roofs in service was necessary in this study. One of the objectives of the study was to relate the moisture tolerance of the roofing system with the solar absorptance of the membrane. Three types of membrane were tested – thermoset, thermoplastic and modified bituminous. Depending on the color, they have been categorized as non-reflective (black thermoset and grey modified bituminous) and reflective (white thermoplastic) membranes. In the current study, to simulate representative membrane temperatures, field-measured temperature data for both the thermoset and thermoplastic membranes were obtained as shown in Figure 4. These data were from two different unconditioned roof mock-ups installed side-by-side with thermoset and thermoplastic membranes. Based on this measure data, the summer conditions for the experimental testing was finalized as 59°F (15°C) to 118°F (48°C) for roof assemblies with reflective membrane, and 59°F (15°C) to 154°F (68°C) for roof assemblies with non-reflective membrane . For the conditions designated as winter, irrespective of the membrane color, it was assumed the average roofing 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). This temperature range represents the average winter temperatures in climatic zones 4 to 7. In the experiments, the roofing surface temperature was cooled or heated by air regulated in temperature simulating the winter and summer diurnal cycling temperatures. The relative humidity of the air in the top chamber was not controlled, since the roofing membrane constituted an almost perfect vapor barrier.

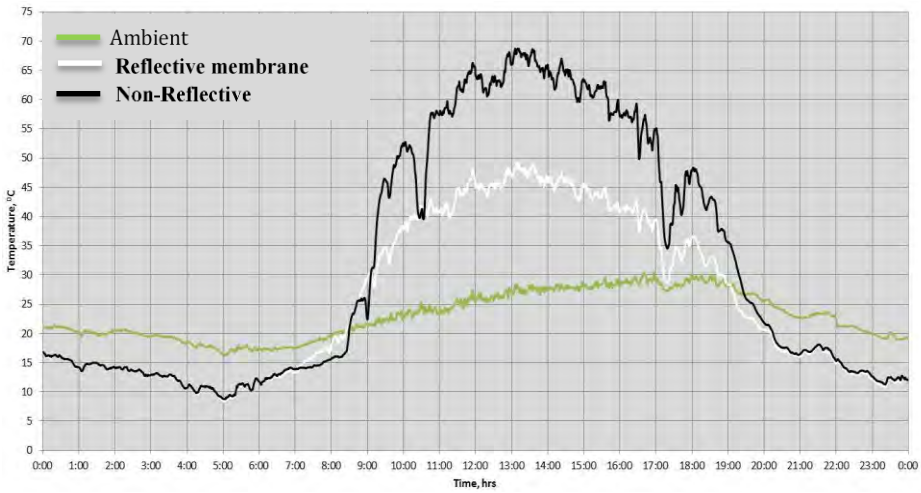


Figure 4: Measured in-situ membrane temperatures.

3. TEST SPECIMENS AND PROCEDURES

3.1 Description of Specimens

In the current study, twelve roofing systems were tested. As the roof installation is similar for all the tested assemblies the construction procedure is generalized and described below. Figure 5 illustrates test specimen installation procedures.

Table 1: Description of specimens

Deck Installation

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

For the test, the deck was constructed in accordance with field practice. The layout comprised steel joists spaced at intervals of 6 ft (1.8 m) o/c, and over them was installed a typical 22-Ga (0.76 mm) thick steel deck with a profile height of 1.5 in. (38 mm) and a flute width of 5.9 in. (150 mm). It had a yield strength of 80 ksi (552 MPa). The steel deck configuration comprised two sections totaling 20 ft (6.1 m) in length, equaling the length of the test chamber. The steel deck was fastened to the joist across each female flute or flange. 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.

Steel deck installation

Vapor barrier/air retarder installation

Insulation installation

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

Figure 5: Test Specimen installation

Vapor Barrier/Air Retarder Installation

A vapor barrier that has the capability to retard air movement (function as an effective air retarder) was installed in the roofing assembly to minimize air intrusion into the system. The following three types of vapor barriers: kraft paper (15 mil thick (0.015 in. (0.38 mm))), self-adhesive sheet (40 mil (0.04 in. (1 mm))), and polyethylene film sheet (single layer of 10 mil (0.01 in. (0.25 mm))) were used in this experimental study. All vapor barriers were installed with 6 in. (152 mm) laps. In the case of kraft paper the seams were joined either using adhesive or seam tape and in the case of polyethylene film sheet all the seam overlaps were sealed by a tacky tape. With self-adhesive film the seam overlaps were self-adhered. The perimeter edges of all three vapor barriers were not bent along the sides or cut at 45° in the corner, but they were laid in flush

resting on the lip of bottom chamber. The weight of the top chamber pressing down on the bottom chamber lip, provide an adequate air seal along the perimeter edge of the vapor barrier. This procedure was followed to prevent any perimeter air intrusion along the air retarder edges.

Insulation Installation

The insulation used in the study was the paper-faced polyisocyanurate (TYPE II, Class 1: ASTM C1289). It was obtained from one source. Three insulation layouts were tested – single layer of 2 in. (51 mm) thick, two-layer staggered insulation layout with each layer of 2 in. (51 mm) thick and a single layer of 4 in. (102 mm) thick polyisocyanurate. The insulation boards had a standard dimension of 48 in. x 48 in. (1219 mm x 1219 mm). The installation layout maintained a gap of 1/8 in. (3.1 mm) between the boards along the length of the table. The boards were mechanically fastened to the steel deck with 3 in. (76 mm) square metal plates and 5 in. (127 mm) long fasteners at a density of four per board.

Membrane Installation

Three types of membrane roofing systems were tested – thermoplastic, thermoset and modified bituminous. Within the thermoplastic, a 45 mil PVC membrane with two sheet widths – 6 ft (1.83 m) and 10 ft (3.05 m) – were tested. It was a one-sided weld (OSW) system. The thermoset systems were tested with a 45 mil ethylene propylene diene terpolymer (EPDM) as the waterproofing membrane with sheet width of 10 ft (3.05 m). The membrane attachment is a typical inseam attachment. The modified bituminous membrane layout comprised a base sheet and a cap sheet. The fastener row spacing is 35 in. (890 mm). After completion of base sheet installation, a coat of primer is applied on the base sheet top surface and following that a self-adhered cap sheet is installed. All the tested systems, irrespective of the membrane type, had a fastener spacing of 12 in. (305 mm). The roofing membrane for all the tested systems had an overhang of 1 ft (305 mm) around the table perimeter.

Test Procedure

The test methodology is designed as a diurnal temperature cycling where the roofing system is subjected to winter and summer cycles as shown in Figure 6.

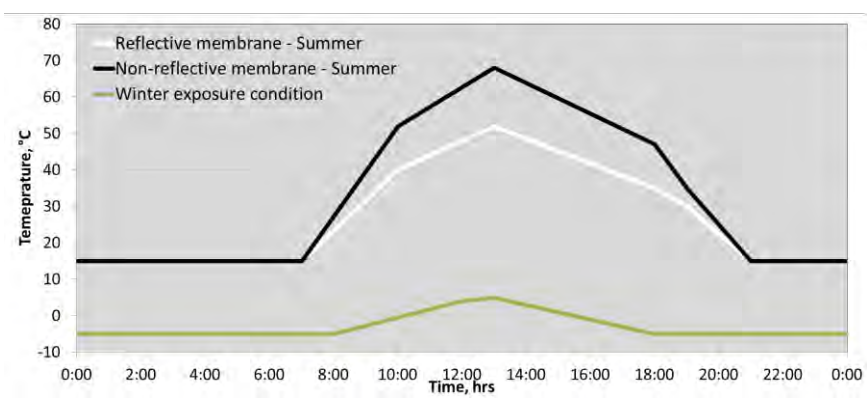


Figure 6: Simulated diurnal summer and winter exposure condition.

Moisture Movement due to Air Intrusion

After the installation of the roofing system in the bottom chamber is completed, the top chamber is lowered. Following the ASTM D7586 protocol, the air intrusion is measured to test pressures ranging from 5 to 25 psf (239 to 1197 Pa), and simultaneously the membrane deflection is also measured. After air intrusion quantification, the initial weight of the system is measured and recorded, W1. Following that the roof specimen is subjected to the winter conditioning cycle of 23ºF (-5ºC) to 41°F (5°C), with simultaneous dynamic wind conditioning at a test pressure of 0 to 5 psf (0 to 239 Pa) in the bottom chamber. All the parameters – bottom chamber pressure, bottom chamber temperature and RH, bubble pressure under the membrane, temperature and RH in the steel deck flutes, temperature and RH on the insulation, temperature and RH under the membrane, membrane deflection and top chamber temperature – are recorded. After completion of the 24 h winter cycle, the test specimen is lifted to obtain the weight, W2. The overhanging membrane around the table perimeter is then lifted and is visually inspected for condensation. All the observations are photographed and recorded.

The top chamber is again lowered and the temperature is set to the respective summer cycle for the reflective and non-reflective membrane systems. After attaining the target temperature of 59ºF (15ºC), the dynamic wind conditioning at the target pressure of 5 psf (239 Pa) is started in the bottom chamber. All the parameters described are recorded. After completion of the 24 h summer cycle, the test specimen is lifted to obtain the weight, W3. All the observations are photographed and recorded.

The difference in weight W2-W1 gives the moisture gain into the system after the winter cycle and the difference in weight W3-W2 reflects the moisture loss after the summer cycle. If the moisture loss equals the moisture gain, this indicates that the system is completely dry and further testing is not required. If they are not equal, the system is subjected to another round of the summer cycle. This process is continued until the system is completely dry. The membrane deflection is correlated with the applied suction and the corresponding air intrusion of the system is determined.

Moisture Movement due to Vapor Diffusion

The test methodology for vapor diffusion is similar to that for air intrusion as described above, except that no wind conditioning is applied in the bottom chamber.

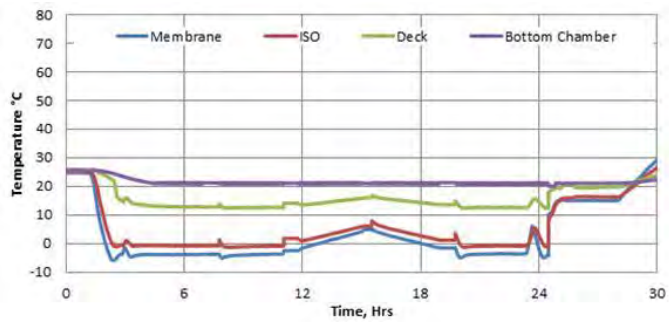
RESULTS AND DISCUSSION

Air Intrusion Impacts on MARS

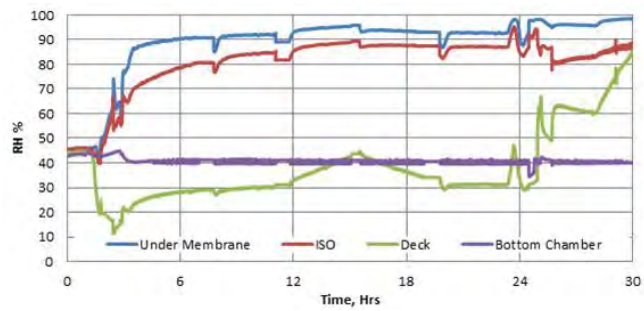
Moisture Movement and Condensation

In the current study, based on the bottom chamber steady state conditions of 70ºF (21ºC) and 40% RH, the dew point temperature of the air was 46ºF (8ºC). With the winter cycle set to a diurnal cycling of 23 to 41ºF (-5 to 5ºC), the temperature plane for condensation is at the insulation level within the system as shown in the temperature profile of System 1 (Figure 7a). From the RH profile shown in Figure 7b, the data indicate that the wind conditioning at 5 psf (239 Pa) pressure and the flow paths through the steel deck seams caused air intrusion into the system, increasing the RH under the membrane and on the insulation. Until 12 h, the membrane temperature (top chamber temperature) was at a steady state of 23ºF (-5ºC). The RH on top of the

insulation and under the membrane increased from an initial 40% to 85% and 90% respectively. Past the 12 h point, as the membrane temperature gradually increases from 23 to 41°F (-5 to 5°C), the RH on top of the insulation and under the membrane gradually increases to 90% and 95% respectively and it remains stable past 20 h where the top chamber temperature again drops down to 23°F (-5°C). At the completion of the winter cycle, i.e. at the end of the 24 h cycle, upon the opening of the top chamber, the RH under the membrane immediately ramped up close to 100% as shown in Figure 7b. The visual inspection (by lifting the membrane overhang sections along the table perimeter) showed frost formation along the sides of the membrane, and hand inspection under the membrane showed the presence of moisture as shown in Figure 7c.



a) Temperature Profile



b) RH Profile

c) Visual observations at the end of winter cycle

Figure 7: Moisture performance of a system after the winter cycle.

Figure 8 shows the relation between air intrusion and moisture accumulation that was measured from four systems without a vapor barrier. Within the 12 s gust duration, 6 s have been designed for ramping and holding the target pressure and the other 6 s are for depressurization. The measured air intrusion volume for each gust has been divided by 6 s to give the rate of air intrusion that enters into the roofing system as shown in Figure 8. The moisture gain presented in the graph is the moisture accumulated over 24 h within the winter cycle. The trend in the air intrusion indicates that an increase in the sheet width increases the rate of air intrusion.

Comparing the 10 ft (3.05 m) sheet thermoplastic and thermoset systems that are 45 mil singly-ply membranes, the measured data show that they have almost similar air intrusion rate and moisture gain indicating that membrane thickness might have a very minimal effect on the air intrusion rate. However, this needs to be verified by testing with thicker single-ply membranes. The modified bituminous 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)). With this high density, the mod-bit system measured lesser deflection and lesser volume, and the air intrusion was 25% to 30% less than the single-ply membrane assemblies and the same observed with the moisture gain.

In mechanically attached roofs, during the heating season the membrane is the coldest part of the roof and if it is below the dew point temperature, air intrusion has the potential to cause condensation on the membrane underside. In the tests conducted the accumulated moisture was above 0.02 psf (0.10 kg/m^2) and this weight is the combination of the liquid condensate and 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.

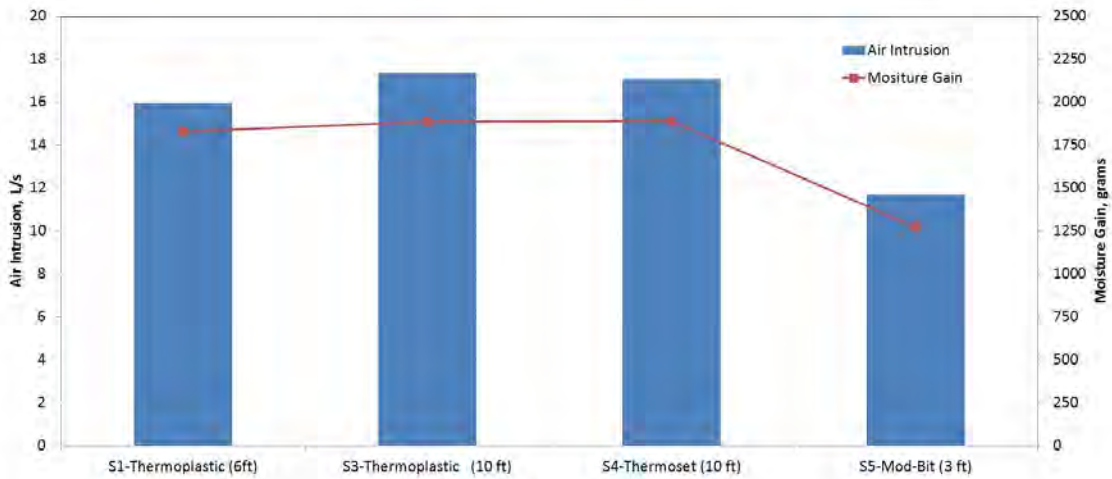


Figure 8: Air intrusion vs. moisture gain in MARS - effect of sheet width and membrane type.

Air Intrusion vs. 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 provide the comparison between these two moisture-driving phenomena. Both these systems had a 10 ft (3 m) PVC membrane while all the other components including the construction details are the same. With simulated diurnal winter conditions atop the roofing system and constant indoor conditions of 70°F (21°C) and 40% RH, there was vapor pressure differential of 15 to 18 psf (718 to 862 Pa) across the system. This moved the indoor air with higher vapor pressure into the roofing system that has lower vapor pressure, accumulating 0.55 lb (250 g) of moisture over the 24 h winter uptake period. There were no signs of frost formation or visible moisture under the membrane or on the insulation. When the similar system configuration is 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 h winter uptake period. Frost and water were observed under the membrane and on the insulation. This sevenfold increase in the moisture gain clear 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, the overall moisture accumulation within the system could be high enough to initiate damage to the roofing components.

Mitigation of Air Intrusion in MARS

Installation of Vapor Barrier/Air Retarder on the Steel Deck

Three commonly used vapor barriers were tested to evaluate their functionality as an air retarder in minimizing air intrusion into the roof assembly. S8 and S9 had kraft paper, S10 was constructed with polyethylene and S11 comprised self-adhered film. All the vapor barriers were constructed with seam

overlaps of 6 in. (152 mm). Figure 9 compares the air intrusion and moisture performance of these four systems relative to S1 that had no vapor barrier. The measured air intrusion of S8 was almost 80 times higher than in S10 and S11 and also was the moisture gain. This could be attributed to the lack of proper bond strength of the adhesive seams of the kraft paper as the test was started immediately after construction without any curing time for the seam adhesive.

After discussions with the steering committee, it was proposed to use seam tape for the kraft paper similar to S10 where the polyethylene seams were overlapped with seam tape. Following that approach, S9 was constructed and tested. The air intrusion reduced significantly from 0.06 cfm/ft^2 (0.56 L/s-m^2) measured in S8 to 0.002 cfm/ft^2 (0.02 L/s-m^2) in S9, an almost 97% decrease in the air intrusion rate. This validates the previous observation that the adhesive in the seam overlaps was the weakest link. The moisture gain comparison in S9, S10 and S11 relative to S1, indicated that minimizing air intrusion can significantly reduce the bulk movement of the vapor into the system.

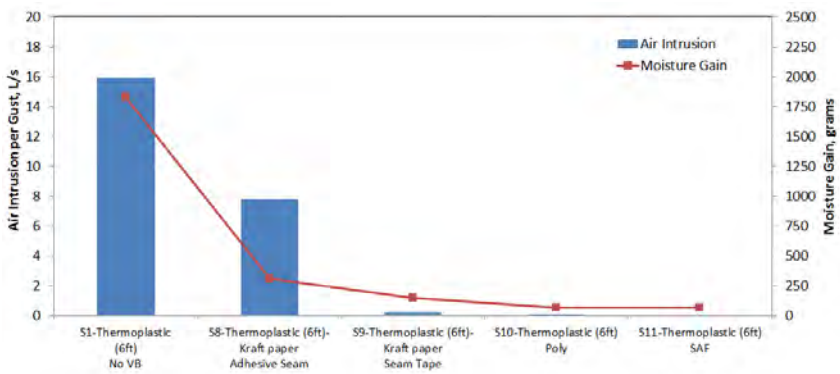


Figure 9: Air intrusion and moisture performance of MARS with an without vapor barriers.

Staggered Insulation 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. Figure 10 shows the air intrusion performance of S6 and S7 which had two layers of 2 in. (51 mm) thick insulation in staggered layout relative to that of S1, S3, and S4 which had one layer of 2 in. (51 mm) thick insulation, and S2 which had one layer of 4 in. (102 mm) thick insulation. The staggered insulation layout in S6 and S7 minimized air intrusion by almost 60% compared to the systems with one layer of insulation irrespective of the sheet width. This decline in air intrusion from the use of staggered insulation systems translated into lower moisture transport; only 35% moisture accumulation occurred within the 24 hr winter cycle compared to the systems with unstaggered layout. 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 will be less air intrusion as the membrane will push the air out of the roof system into building interior before it reaches into the coldest part of the system, i.e the membrane. Although staggered insulation did show favorable results in minimizing moisture accumulation, the air intrusion of 0.08 cfm/ft^2 (0.77 L/s-m^2) measured for the staggered insulation systems was critical to initiate surface condensation.

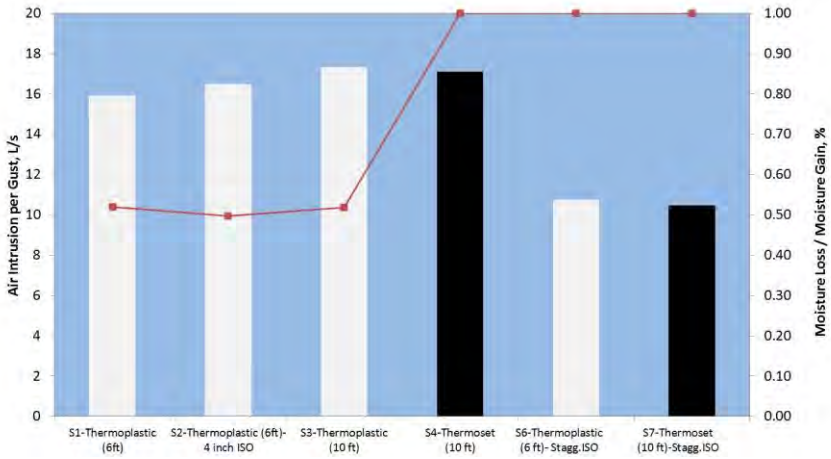


Figure 10: Air intrusion and moisture performance of MARS with and without staggered insulation layout.

Solar Absorptance of the Membrane

Figure 11 compares the moisture performance of the reflective single-ply or thermoplastic systems (S1 & S3), non-reflective single-ply or thermoset system (S4) and non-reflective two-ply or modified bituminous system (S5). It should be noted that all these systems had one layer of 2 in. (51 mm) thick paper-faced polyisocyanurate. As shown in Figure 11, there was only an 8% increase in the air intrusion rate between the 6 ft (S1) and 10 ft (S3) (1.83 and 3.05 m) sheet reflective single-ply systems, and therefore both of them showed almost similar moisture performance by gaining and losing the same amount of moisture within the 24 h winter and summer cycles. Both S1 and S3 required 48 h for complete drying while the non-reflective systems took 24 h. This minimum wetting-to-drying ratio clearly identifies the effect of membrane solar absorptance on the moisture performance of the roofing system in the heating season.

Although the thermoplastic system with one layer of insulation showed inferior performance with a higher rate of air intrusion and higher wetting-to-drying ratio, it showed better moisture performance with staggered two-layer insulation layout both in winter and summer cycles as shown in Figure 10. The staggered two-layer insulation layout, irrespective of the system type, mitigated almost 60% of the air intrusion into the system compared to the one layer insulation layout.

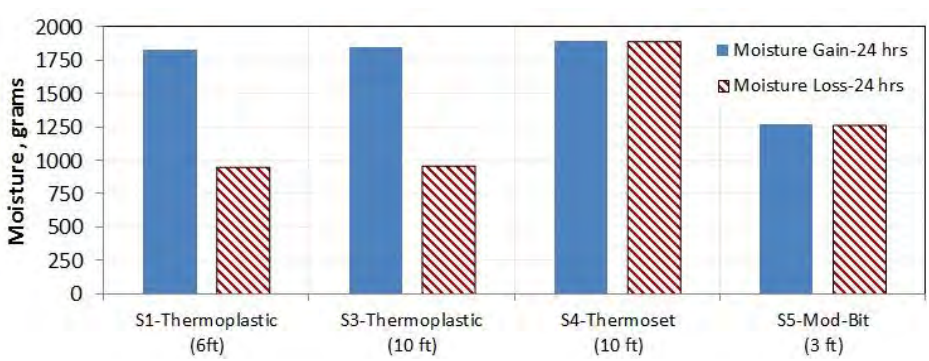


Figure 11: Comparison of moisture performance between reflective vs non-reflective membrane roofing.

In the thermoplastic system with staggered insulation, S6, this minimal air intrusion transported less moisture, accumulating only 1.34 lb (610 g) or 0.0084 psf (0.041 kg/m^2) over the winter cycle. In the summer cycle, the system completely dried out (100%) within 24 hrs, demonstrating a minimum wetting-to-drying ratio of 1:1. The moisture performance of S6 is a good example to show that with staggered insulation the potential for moisture accumulation can be minimized.

Air Intrusion Aids in Moisture Removal

From the above discussions, it has been observed that air intrusion could transport considerable moisture into the system. But air intrusion can also aid in taking moisture out of the system; this is demonstrated by comparing two systems (S1 and S12) that are identical with 6 ft (1.83 m) sheet thermoplastic membrane and one layer of 2 in. (51 mm) insulation without any vapor barrier. The winter cycle testing is the same for both the systems and the moisture gain was around 4.08 lb (1850 g). In the summer cycle, S1 is subjected to dynamic wind conditioning of 5 psf (239 Pa) while there is no wind conditioning in S12. Drying through the vapor diffusion process is the driving mechanism in S12. In the first summer cycle, the moisture loss in S1 was 2.09 lb (0.95 kg), which is 50% of the moisture gain, while the moisture loss in S12 was only 15%, i.e. 0.61 lb (0.275 kg). In the second round of the summer cycle, S1 completely dried out while S12 removed another 0.55 lb (0.25 kg) of moisture with RH under the membrane still at 60% during the peak temperature. 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.

Condensation and Air Intrusion Limits

Figure 12 shows the normalized moisture gain of all the tested systems where air intrusion is the moisture-driving mechanism. As indicated in the graph, there was condensation in Systems S1 to S7, while systems S8 to S11 had no sign of condensation. With moisture accumulation greater than 0.02 psf (0.08 kg/m^2), the non-reflective membrane systems, which had higher solar absorptance and higher temperatures, completely dried within 24 h compared to the reflective membrane systems, which took twice this time for drying. The reflective membrane system with staggered insulation that had a moisture accumulation of 0.01 psf (0.041kg/m^2) completely dried within 24 h, demonstrating a minimum wetting-to-drying ratio of 1:1. Therefore, 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 12a. 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 12b 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 VB-free designs under certain conditions. In United States, there are no widely accepted guidelines for the inclusion of vapor barrier in low slope roof assemblies. If air intrusion could be minimized to between 0.06 and 0.08 ft^3/s-ft (0.5 and 0.8 L/s-m), there will 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.

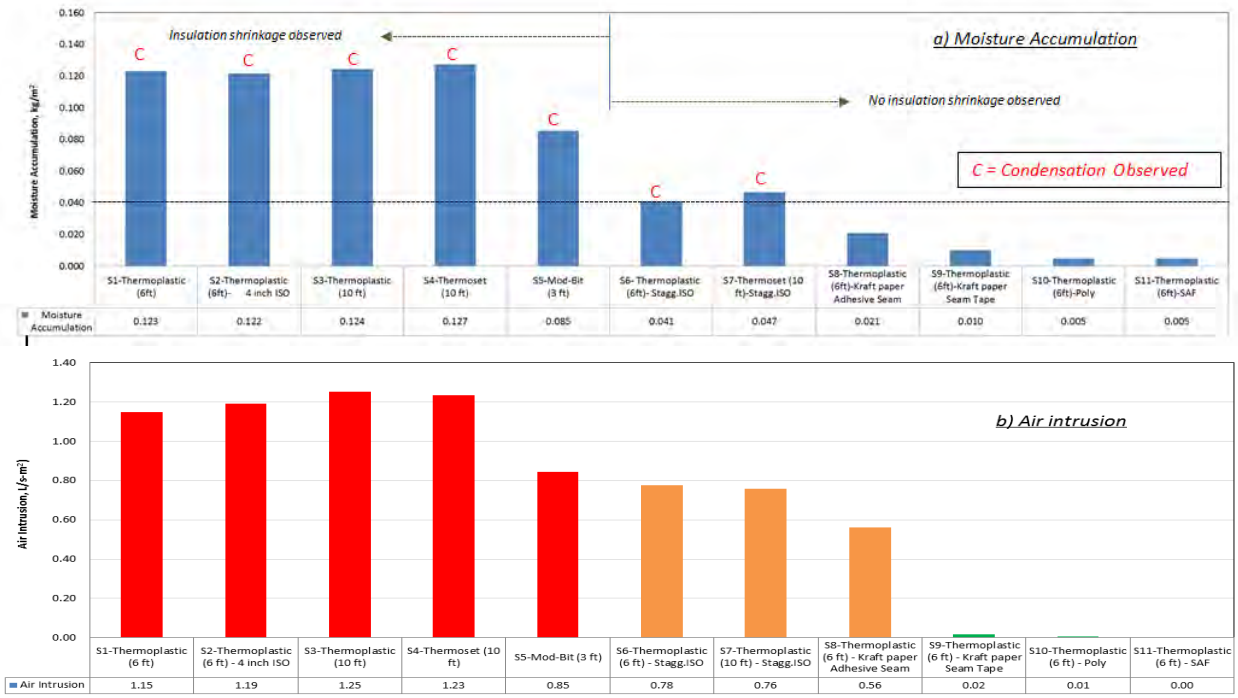


Figure 12: Air intrusion and moisture performance of MARS.

CONCLUSIONS

In the current study, the research focused on quantifying the impact of air intrusion on moisture movement and condensation within seam-fastened mechanically attached roofing systems with a view to establishing air intrusion tolerance limits for practice. 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 relative humidity 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 to on-site performance of the roofing systems. Based on this limited study, the following conclusions can be drawn:

- Membrane weight, sheet width or 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 modified bituminous 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 vent moisture out of the system at a faster pace compared to the vapor drive.

- Three different vapor barriers – kraft paper, polyethylene film and self-adhered sheet – were evaluated to quantify their performance as an effective air retarder. The seam overlaps of the kraft paper were identified as the weakest link but with proper installation technique it mitigated almost 100% of air intrusion into the system. All these systems demonstrated better performance with no

condensation and moisture accumulation.

- The combination of high solar absorptance and fluttering action associated air intrusion in membrane roof systems enhanced the rate of drying in non-reflective membrane systems compared to reflective membrane systems.

- 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.

- The critical threshold of moisture accumulation was determined as 0.008 psf (0.04 kg/m^2) for systems with polyisocyanurate insulation. If the moisture accumulation is below this limit, irrespective of the membrane color, i.e. reflective or non-reflective, the mechanically attached system has the potential for drying without progressive moisture accumulation.

- With a vapor barrier that also function 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 are installed in staggered arrangement, the air intrusion was reduced; however, the risk of condensation still exists with minimal moisture accumulation. This accumulated moisture could potentially dry out without any progressive accumulation.

- 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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