Air Intrusion and Its Effect on Moisture Transport in Mechanically Attached Roof Systems

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Abstract

About one fourth of North American buildings with low-slope roofs (4:12 or less) have mechanically attached roof assemblies, and their popularity continues to grow. In such systems, because of the flexible and elastic nature of the waterproofing membranes and their attachment mechanisms, wind and building mechanical pressurization from the interior causes the membrane to balloon or flutter. The membrane deflection's volume change causes negative or bubble pressure below the membrane, which is equalized by the indoor conditioned air moving into the assembly, which is termed "air intrusion." To measure air intrusion in mechanically attached roof systems, the National Research Council of Canada began an experimental study and developed control data as part of the Special Interest Group for Dynamic Evaluation of Roofing Systems (SIGDERS) research. To relate air intrusion to moisture transport in mechanically attached roof systems, a spin-off project began in collaboration with the Canadian Roofing Contractors' Association (CRCA), NRCA and four major roofing material manufacturers: Carlisle SynTec, Carlisle, Pa.; Dow Roofing Systems, Holyoke, Mass.; Firestone

Building Products, Indianapolis; and Sika Sarnafil, Canton, Mass. The paper discusses the research findings from this ongoing study, which addressed the following tasks:

- Test additional systems for air intrusion quantification and compare with the SIGDERS control data.
- Determine effects of air intrusion on moisture transport in mechanically attached roof systems compared with vapor transmission and establish air intrusion limits for potential condensation in these roof systems.

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Introduction

In conventional roof assemblies, the membrane can be mechanically attached, fully adhered or partially attached to the substrate. A roof 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 roof system. About one fourth of North American commercial buildings with low-slope roofs have mechanically attached roof systems with single-ply membranes (NRCA 2004).

With membrane roof systems, the waterproofing membrane is impermeable. If constructed properly, it certainly can perform as an air barrier impeding any air movement from the exterior environment to the interior and vice versa. The membrane, being the primary air barrier, can prevent air leakage in roof assemblies (Kalinger, 2008). With mechanically attached roof 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 balloon or flutter. The membrane deflection's 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, and this is termed "air intrusion: when the conditioned indoor air enters into a building envelope assembly, such as roofs, but cannot leave the assembly to exterior environment" (Molleti 2009). The pressure equalization depends on the air intrusion resistance of the subsurface components below the membrane (deck, insulation and any other installed roof components).

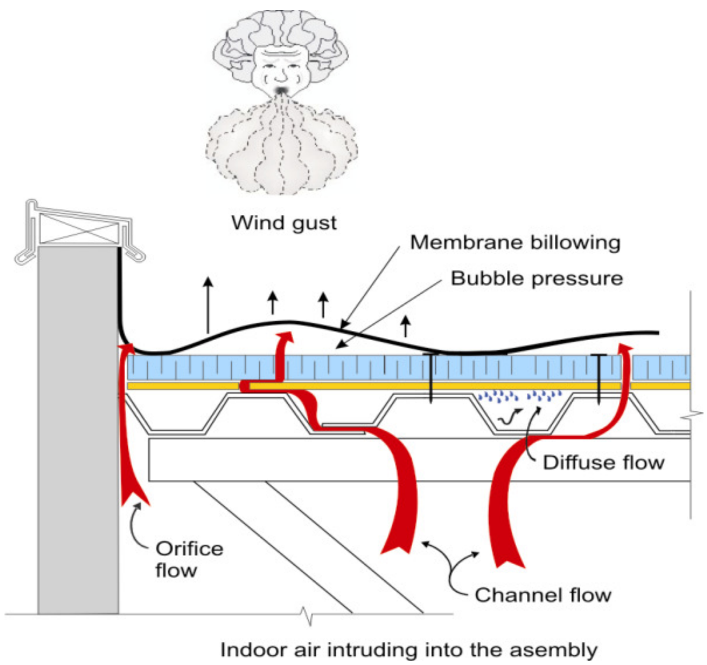


Figure 1: air intrusion in mechanically attached roof systems

Most mechanically attached roof systems have not considered the effects of air permeability on roof system performance (Hutchinson 2007). Cautions regarding air intrusion on wind-uplift performance and moisture performance are not new. There are existing technical notes, manuals and papers (*NRCA Energy Manual* 1989, Dregger 2002, Lstiburek 2008, Zarghamee 1990) that have identified the above discussed air intrusion effects on roof assembly performance. However, no information is available regarding the amount of air intrusion that can occur in mechanically attached roof systems and their sensitivity to air movement.

To measure air intrusion in mechanically attached roof systems, an experimental study has begun at the National Research Council of Canada (NRC) as part of the Special Interest Group for Dynamic Evaluation of Roofing Systems (SIGDERS) research. The control data from this experimental study was published in the January 2011 issue of

Professional Roofing, “How Much Air is Too Much?” (Baskaran and Molleti, 2010). To relate the control air intrusion data with moisture transport in mechanically attached roof systems, a spin-off project began in collaboration with the Canadian Roofing Contractors’ Association (CRCA), NRCA and four major roofing manufacturers: Carlisle SynTec, Carlisle, Pa.; Dow Roofing Systems, Holyoke, Mass.; Firestone Building Products, Indianapolis; and Sika Sarnafil, Canton, Mass. In the spin-off project, two tasks were undertaken and the paper discusses the research findings from this ongoing study. The tasks are:

- Air intrusion quantification of three different mechanically attached roof systems, with two different types of air retarders and cover boards; comparison of the measured data with the SIGDERS control data
- Small-scale experimental study to show the effects of air intrusion on condensation or moisture transport in mechanically attached roof systems compared to the vapor transmission and establish air intrusion limits for potential condensation in these roof systems

Air Intrusion Quantification

All the experimental testing was conducted at the Dynamic Roofing Facility – Air Intrusion (DRF-AI) Lab at the National Research Council of Canada. Research Report (RR-296) (Beaulieu et al. 2010) details the test setup and experimental procedure of the air intrusion measurements. The test apparatus consists of a movable two-section top chamber and a closed bottom chamber with each having a dimension of 20 feet (L) by 8 feet (W) by 3 feet (H) (6 m by 2.43 m by 0.91 m). The membrane assembly specimen is installed horizontally at the top of the bottom chamber. The bottom chamber supports a height- adjustable lever that can accommodate roofing assemblies with different thicknesses. The differential pressure across the test specimen is measured by installing two pressure measuring devices, one on top of the membrane and the other above the insulation. Air Intrusion measurements are made as per the ASTM standard – D7586/D7586M-11 Standard Test Method for Quantification of Air Intrusion in Low-Sloped Mechanically Attached Membrane Roof Assemblies, which recently became a standard from the D08-Roofing and Waterproofing Committee.

Using the DRF-AI test apparatus, three roof systems having dimensions of 20 feet (L) by 8 feet (W) were tested as follows:

RS1: Thermoset (TS) system with kraft paper as air retarder

RS2: Thermoset (TS) system with cover board

RS3: Thermoplastic (TP) system with polyethylene sheet as air retarder

The typical components used for the tested assemblies are a 22-gauge, 80 ksi steel deck; single layer of 48-inch by 48-inch by 2-inch (1220-mm by 1220-mm by 51-mm) polyisocyanurate insulation boards fastened with five fasteners per board; 6-mil-thick (0.15 mm)polyethylene sheet; and 3-mil-thick (0.076 mm) kraft paper as air retarders; and ½-inch- (12-mm-) thick high density (HD) cover board.

In the case of the TP system, a 6-foot- (1.8-m-) wide, 45-mil-thick (1.14 mm) PVC membrane was used as the waterproofing membrane with single-sided weld (OSW) seams. For the TS systems, a 10-foot (3-m), 45-mil (1.14 mm) EPDM membrane was used. The membrane was attached to the steel deck following the typical inseam attachment with tape adhesive. All three roof systems had a fastener spacing of 12 inches (305 mm) on center.

Following the ASTM D7586 test protocol, the three assemblies were tested for their air intrusion performance. As per the protocol, each specimen is subjected to negative pressures, ranging from 5 pounds per square foot (psf) (250 Pa) to 25 psf (1250 Pa) in increments of 5 psf (250 Pa). At the applied negative pressures, the membrane and insulation pressures and flow rates are measured. From the measured flow rate, the volume of air intrusion into the roof specimen is computed and as per the ASTM D7586, at the reference pressure of 25 psf (1250 Pa), the air intrusion volume is reported. Based on the reported air intrusion volume, Figure 2 compares the measured air intrusion volume of the three tested roof systems with SIGDERS control data; the results can be summarized as follows:

In Figure 2, the SIGDERS control data is categorized into three sections: “NoVB,” “WithSAF” and “Stagg.ISO.” The abbreviation “MB” represents the modified bitumen systems and TP and TS have been defined before as Thermoplastic and Thermoset systems respectively. Without any air retarder or air retarder at the deck level (No VB), the increase in the sheet width increases the air intrusion volume into the system. With a self-adhered film (WithSAF) as an air retarder, irrespective of the assembly type and configuration, the volume of air intrusion is minimized by more than 50 percent. Staggered insulation (Stagg.ISO) layout contributed in minimizing the air intrusion; the staggered insulation layout does not defend the air intrusion through the deck joints and only can dampen the air intrusion through the insulation joints. In other words, the staggered insulation layout rather that controlling the flow paths redirects the flow into the system through a channel flow path pattern, and the measured data verifies this rationale where the systems having staggered insulation layout had higher air intrusion compared to the systems with air retarder.

- however, its air intrusion performance varied relative to the membrane width, unlike the systems with self-adhered film.
- RS1 with 10-foot- (3-m-) wide thermoset membrane and kraft paper as air retarder controlled the air intrusion volume by 60 percent compared with the same system without any air retarder (TS-10 foot- NoVB); and in comparison with the TS-10 foot-SAF, RS1 had almost 3 times higher air intrusion, thus indicating the better air intrusion performance of SAF compared to the kraft paper.
- In RS2 with HD cover boards installed on top of the insulation, the measured air intrusion volume was almost similar to TS-10ft-NoVB, indicating that the staggered arrangement of cover boards on the top of the insulation would not minimize air intrusion into the system similar to the air retarder installed at the deck level. The deck overlap joints are the flow paths for air intrusion into the system, and with air retarder installed at the deck, the flow paths are sealed, minimizing air intrusion into the system. By installing cover boards on the insulation, the flow paths through the steel deck joints still are open, and the bubble pressure will draw the indoor air into the system through the insulation and cover board joints. The staggered cover board joints only will contribute to the rate of air flow and not to the volume of air intrusion.

- With polyethylene sheet installed as the air retarders in RS3, the air intrusion volume was controlled by almost 70 percent compared with TP-6 foot-NoVB. The polyethylene as the air retarder underperformed in minimizing air intrusion by almost 70 percent compared with the self-adhered film in TP-6 foot-With SAF.

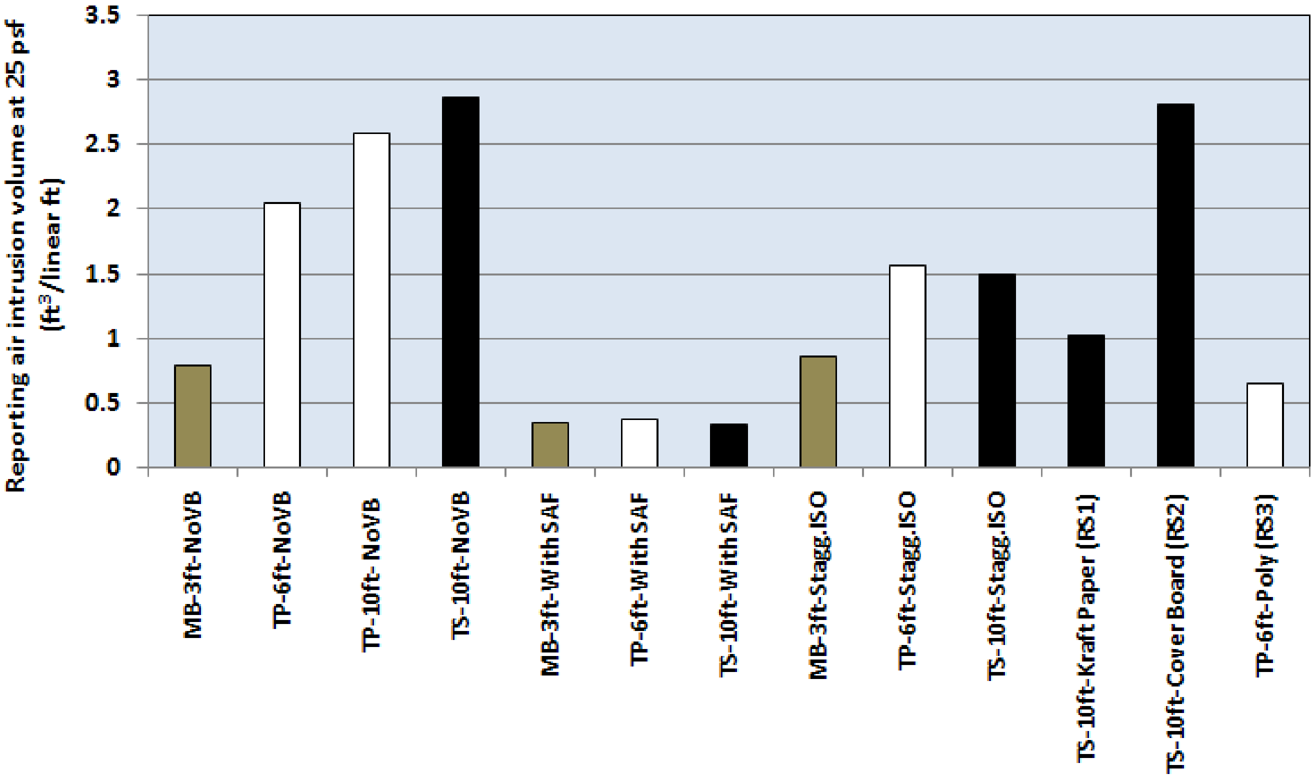


Figure 2: air intrusion VOLUME OF the MECHANICALLY ATTACHED ASSEMBLIES

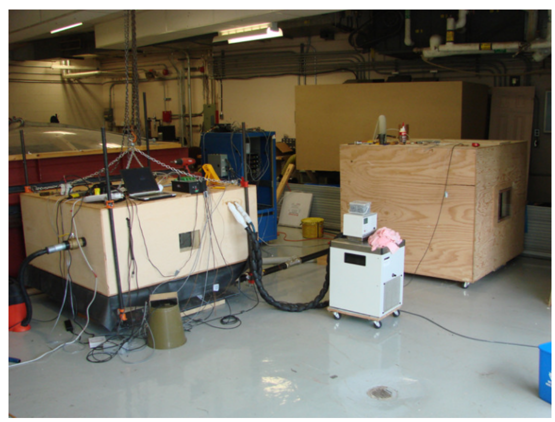
Effects of Air Intrusion on the Moisture Transport

For low-slope roof systems, it is estimated that energy losses are increased by 70 percent because of moisture accumulation in the insulation (Desjarlais 1998). When discussing moisture accumulation in roof systems, it is considered that moisture transport can result from membrane failures, edge failures, improper roof design or initial moisture concentration in roofing materials. Apart from the conventional moisture transport resulting from diffusion and vapor pressure differences, moisture accumulation resulting from air movement also can occur, and it can be of two orders of magnitude higher than moisture accumulation resulting from diffusion, depending on building climate (Wilson and Garden, 1965). As shown from the experimental data (Figure 2), air intrusion in mechanically attached roof systems potentially can carry moisture into the roof system.

Dew point is a temperature at which water vapor begins to condense. In roof systems, even though efforts are made to maintain the surface temperature within a roof assembly above the dew point, dew point temperature will occur somewhere within the assembly. The membrane's dynamic fluttering action can pump volumes of air into the system; when the warm, humid air, which holds a high content of water vapor, contacts surfaces at or below the dew point temperature, condensation on surfaces within the roof assembly can occur. This condensation can lead to wet insulation, reducing its thermal performance and affecting the roof assembly's durability and energy performance.

With control data obtained for air intrusion on some of the mechanically attached roof systems, it was imperative to understand its effects on moisture transport. A preliminary small-scale experimental study was conducted at the Dynamic Roofing Facility-Air Intrusion test facility at NRC.

Test apparatus**:** Figure 3 shows the cross-sectional view and picture of the test apparatus. It consists of an insulated top chamber, which is 48 inches (1220 mm) wide by 48 inches (1220 mm) long with a height of 20 inches (50 mm). A copper heating/cooling coil is installed in the top of the chamber to create the required testing temperature of -5 C (23 F), which is connected to a heating and cooling circulatory bath. The bottom supporting box is used for specimen support and connection of the flow measuring devices. To simulate different interior humidity conditions, the bottom chamber is connected to an insulated humidity chamber, where the humidity is controlled using a programmable humidifier and dry air line. The dynamic wind pressures are induced on the roof specimen using an air suction system, which is connected to manual ball valves to create the required suction pressure. The air intrusion volume is measured using laminar flow element, which is connected to the bottom supporting box. All the temperature, relative humidity, pressure and air flow sensors are connected to centralized data acquisition systems, which monitor and record the measured data.



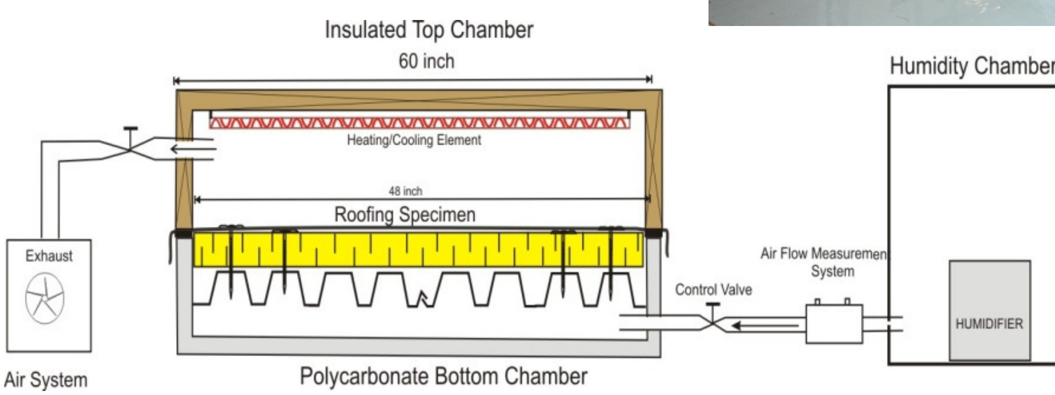


Figure 3: small-scale roof moisture test apparatus

Test specimens: From the air intrusion study (Figure 2), it was determined EPDM systems without air retarders have high air intrusion volumes compared with the other systems. Therefore, the small-scale study evaluated the EPDM systems for moisture transport. Four EPDM roof mockups with dimensions of 48 inches (1220 mm) by 48 inches (1220 mm) were tested in controlled laboratory conditions with simultaneous temperature, dynamic pressure and relative humidity. Figure 4 shows the specimen details. Specimens 1 and 2 (S1 and S2) have a steel deck as the structural substrate, 2-inch- (50-mm-) thick polyisocyanurate insulation as the thermal component and thermoset EPDM as the waterproofing component. The roof system configuration of specimens 3 and 4 (S3 and S4) is similar to those previously mentioned except the layout consists of 6-mil-thick (0.15 mm) self-adhered membrane as the air retarder. Figure 5 shows the typical construction of S3 with an air retarder. The steel deck layout consists of two cut sheets with one overlap joint in the middle as shown in Figure 5. The overlap joint is crimped in the middle and either ends and along the perimeter, and the deck edges are fastened and caulked with sealant to prevent air intrusion along the perimeter. Apart from the fastener penetrations, the steel deck's overlap joint is the major flow path for air intrusion. The insulation layout in all four specimens had four 22-inch by 22-inch (560-mm by 560-mm) boards. The self-adhered membrane in S3 and S4 had one overlap joint of 6 inches (150 mm) on the top flange of the steel deck. The membrane was attached to the steel deck following the typical inseam attachment with tape adhesive and fastener row spacing of 42 inches (1066 mm) and fastener spacing of 12 inches (305 mm) on center for all four specimens.

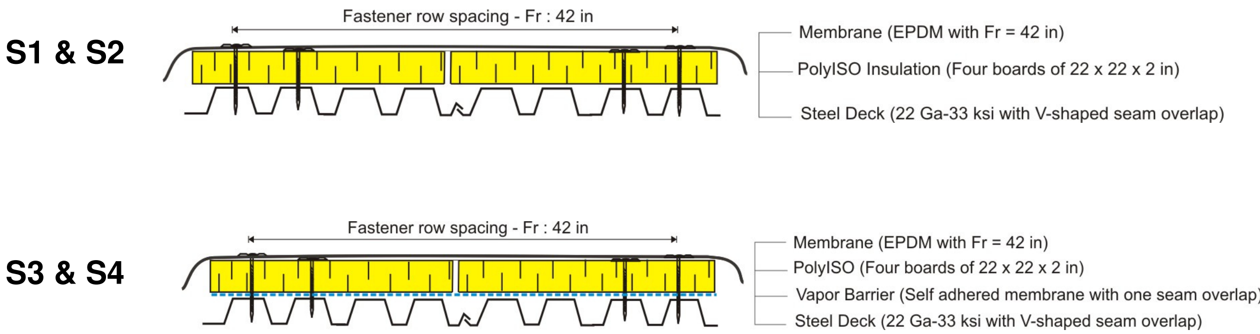
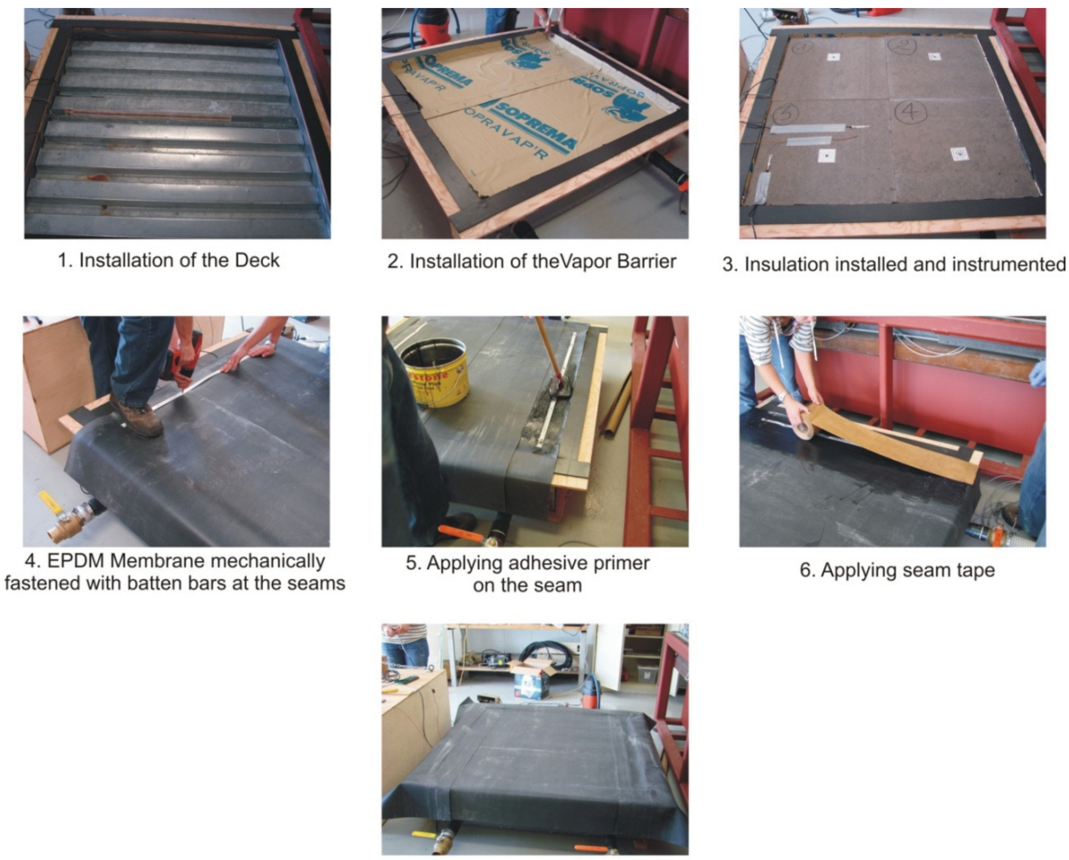


Figure 4: Tested roof specimens



1. Installation of the Deck
2. Installation of theVapor Barrier
3. Insulation installed and instrumented
4. EPDM Membrane mechanically fastened with batten bars at the seams
5. Applying adhesive primer on the seam
6. Applying seam tape
7. System instrumented and ready for test

Figure 5: typical specimen construction with an air retarder

Test methodology: The test methodology subjects test specimens S1 and S3 to temperature gradient without any suction pressure application, while S2 and S4 are tested with simultaneous temperature, dynamic suction pressure and relative humidity. With the insulation boards pre-weighed and the specimen constructed, the test begins by setting the temperature in the insulated top box to a target temperature of -5 C (23F) and the testing relative humidity to 25 percent in the humidity chamber. Once the temperature and relative humidity are stabilized, the CSA A123.21-10–Method 1-Level A dynamic load cycle is applied with15 psf: 400 gusts, 30 psf: 1100 gusts,45 psf: 600 gusts and 60 psf: 100 gusts for a duration of five hours, after which the test stops. The membrane is removed for visual inspection of condensation, and the insulation boards are weighed to measure the moisture content. After the weight measurements, the insulation boards are put back into the system, and the mockup is reconstructed for testing at the next humidity levels. Therefore, with an outside temperature set at -5 C (23 F) and indoor temperature maintained at 22 C (72 F), each specimen is subjected to four different humidity levels—25 percent, 35 percent, 50 percent and 65 percent—with dynamic pressure application at each humidity level. Following this procedure, each mockup was subjected to four days of testing.

Results and discussion

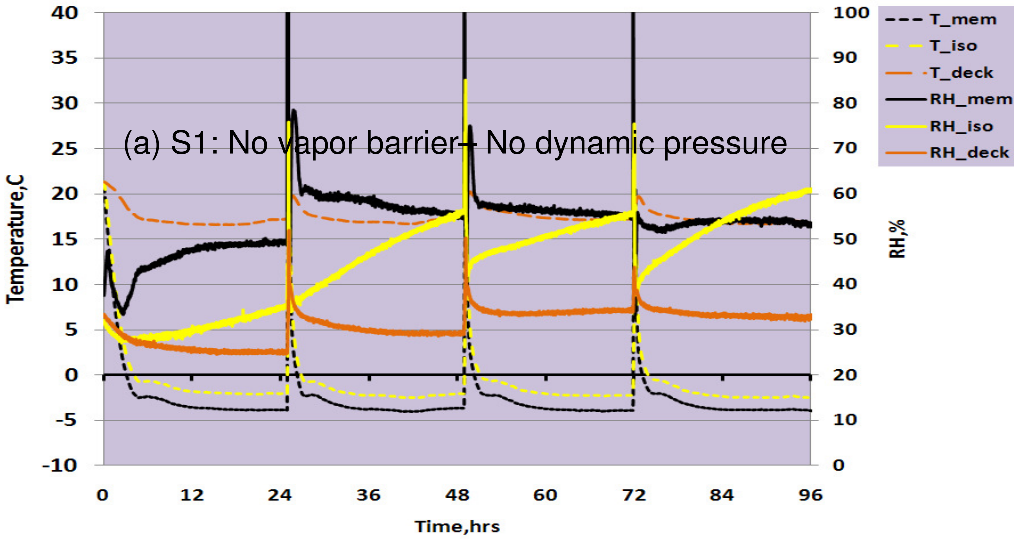
Figure 6 shows the measured response of the four tested specimens in terms of temperature and relative humidity (RH). In all four graphs, the dotted lines represent the temperature and the solid lines represent the RH. The important observations from this measured response are:

- In S1, which had no vapor barrier and no induced dynamic pressures, the vapor gradient from the heated interior toward the colder roof system would drive the moisture into the system. Based on the dew point temperature as shown in Figure 6 (a), it indicates the insulation is doing its job of shifting the dew point temperature from below the roof system to within the roof system. At 65 percent indoor RH for 24 hours, the steel deck measured a maximum RH of 32 percent, and the insulation ranged from 40 to 60 percent.

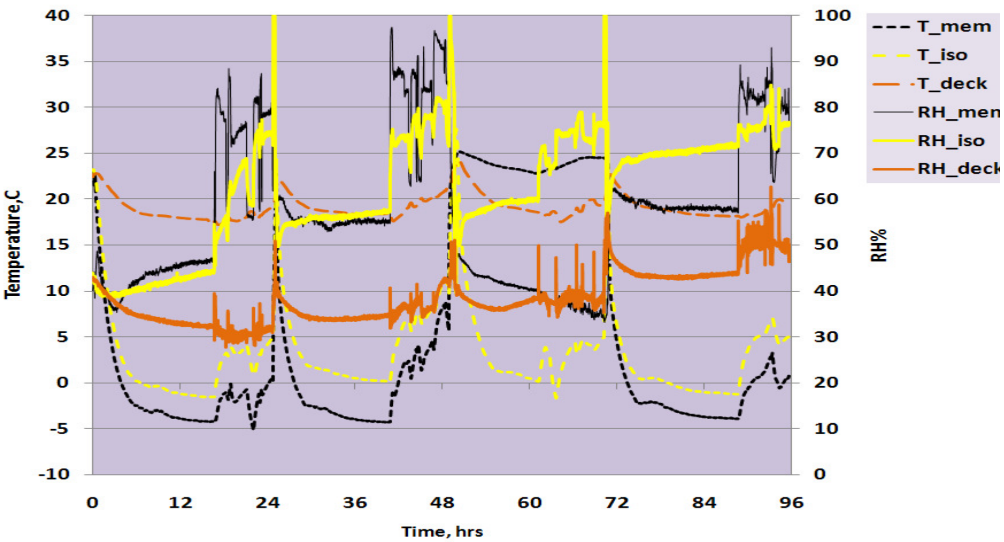
- In S2, at 25 percent indoor testing RH, the insulation RH at the beginning of the experiment was about 45 percent, and with dynamic pressure application, the insulation's RH increased to almost 75 percent, which is almost 70 percent higher than the original condition without any suction pressures. At 65 percent testing humidity level, the insulations' RH measured almost 85 percent. Another important observation to validate the air intrusion into the S2 is the rise in temperature of the membrane and insulation during the suction pressures. Warm indoor air intruded into the roof system, increasing the membrane and insulation temperature from -5 C to almost 5 C. The air intrusion also affected the steel deck; the steel deck's RH varied from 30 to 60 percent compared with the S1, where the steel deck's RH was 30 percent for all the indoor testing humidity levels.
- With a vapor barrier installed on the steel deck and without any dynamic pressure as in S3 (Figure 6 (c)), the vapor gradient is the driving force for the vapor transport similar to S1. However, compared to S1, at the 65 percent indoor RH, the steel deck's RH increased to 75 percent, which is higher than the RH measured on the steel deck in S1. The RH at the insulation level dropped compared with S1. The presence of a vapor barrier in S3 performed its function

of minimizing vapor transport into the roof assembly; as a result, there was lot of vapor movement into the steel deck flutes, which increase the steel deck’s RH.

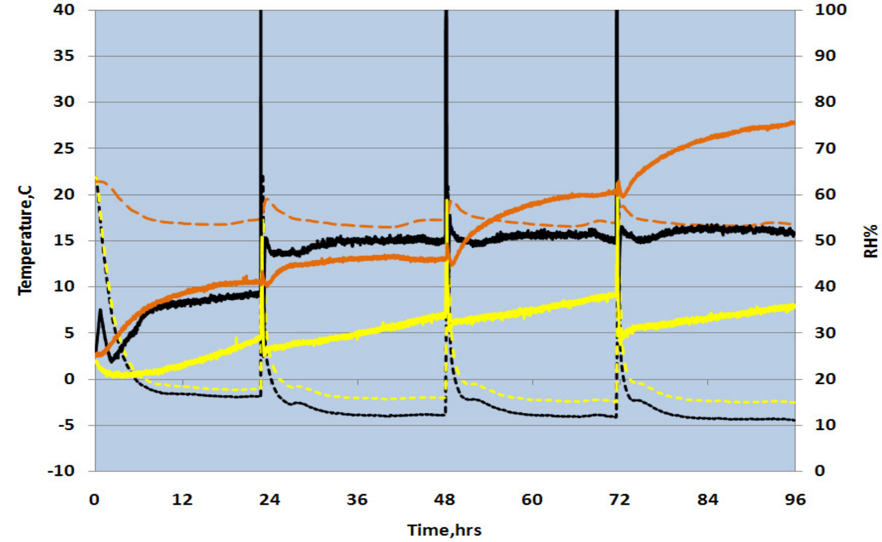
- S4 has a roof configuration layout similar to S3, except it is subjected to dynamic pressures of CSA A123.21-10. Although S4 had a vapor barrier at the steel deck, comparing its performance with S2 indicates that the RH of the insulation measured almost similar to the insulation’s RH of S2, ranging from 60 to 80 percent. This high RH within the insulation raised a question regarding whether this was a result of the fastener penetrations through the vapor barrier or the result of a breach in the vapor barrier. The steel deck’s RH was similar to S3’s, ranging from 50 to 80 percent, which was a result of the effects of the vapor barrier on the steel deck. During the suction pressures, the membrane and insulation temperature also increased by 2 to 3 degrees Celsius, indicating there was some kind of opening in the vapor barrier.



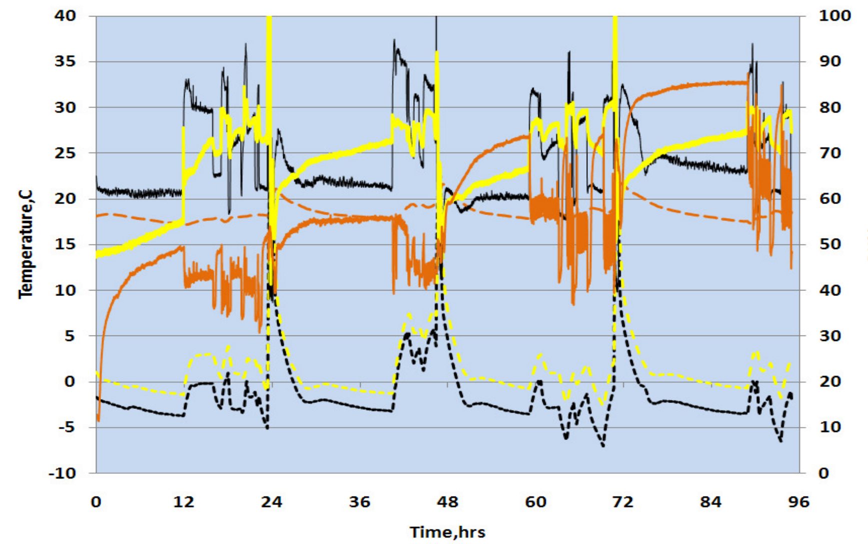
a) S1: no vapor barrier- no dynamic pressure



b) S2: no vapor barrier – with dynamic pressure



c) s3: With vapour barrier – No dynamic pressure



d) S4: With vapor barrier – With dynamic pressure

Figure 6: MEASURE RESPONSE OF THE FOUR TESTED SPECIMENS

Figure 7 shows the recorded visual observations during the test, and Figure 8 shows the measured moisture content of the four insulation boards at 50 and 65 percent indoor testing humidity levels. The moisture content is calculated based on the dry density of the polyisocyanurate insulation (Mukhopadhyaya et al 2007). Summarizing the results:

- At 50 percent and 65 percent indoor RH testing conditions, S1 without an air retarder and without suction dynamic pressures measured average moisture content of 0.36 percent.
- S2, with a roof configuration layout similar to S1, when subjected to suction pressures, measured moisture content of almost 8 percent in two boards and 3 percent in the other two boards at both RH conditions. From the visual observations shown in Figure 7 (b), at 35 percent indoor RH conditions, some condensation below the membrane and wet insulation was observed, which became more severe at 50 percent and 65 percent indoor RH conditions. Therefore, it clearly can be said that air intrusion in S2 was the contributing factor for condensation and high moisture content in the insulation.
- By installing an air retarder at the deck level and without any suction pressure, the average moisture content of the insulation boards in S3 was almost 0.08 percent at 50 and 65 percent RH conditions. Figure 7 (c) clearly shows there were no signs of condensation or wet membranes or insulation in S3.
- When the same system configuration was subjected to suction pressures as in S4, an average increase of 0.14 percent and 0.31 percent in the moisture content was measured at 50 and 65 percent RH conditions, which is comparatively low compared to S2. The air retarder, which primarily is a vapor barrier, is

successfully performing its dual role of vapor control (S3) and air intrusion control (S4). Upon closer examination of the air retarder, Figure 8(d) showed there was a breach in the air retarder during the installation, which might have provided the path for air intrusion into the system during the suction pressure application. The trapped air between two membranes (waterproofing membrane on the top and air retarder below) might have contributed to the wet insulation and slight increase in the insulation's moisture content.

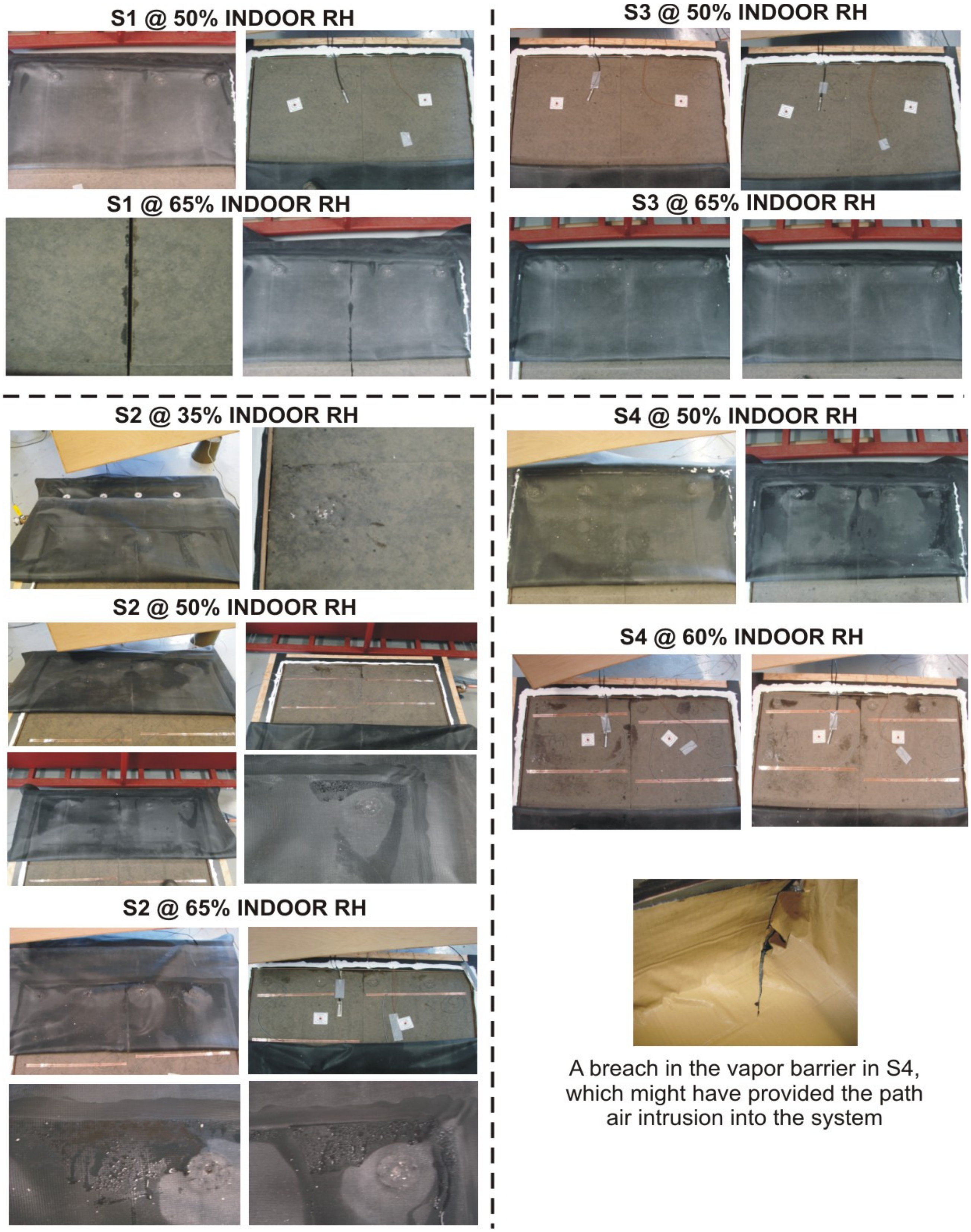


Figure 7: Visual observations for condensation within the system

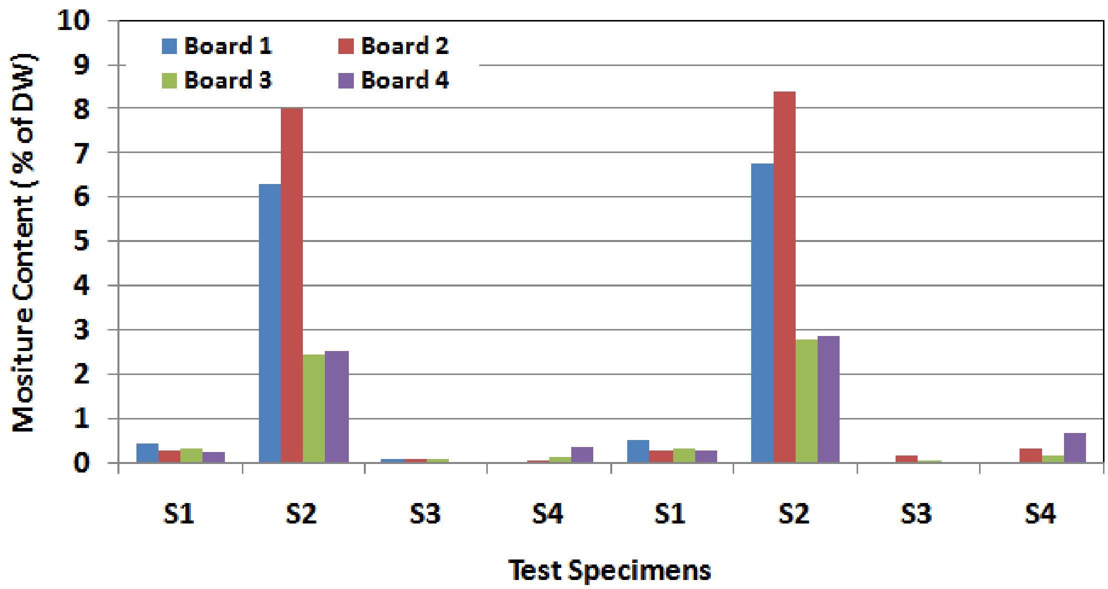


Figure 8: Measured moisture content of insulation boards

The experimental data clearly indicated that in S2 (without any air retarder), condensation started at the 50 percent indoor RH testing conditions. Based on the measured air intrusion volume, at 25 psf (1250 Pa) the reporting air intrusion volume of S2 is 0.42 ft^3/linear ft. Therefore, at an outside temperature of -5 C (23 F) and indoor conditions of 23 C (72 F) with 50 percent relative humidity, an air intrusion volume of 0.42 ft^3/ linear ft (11 L/linear m) could be a critical volume for potential condensation in mechanically attached roof systems. Plotting the air intrusion limit onto control data as shown in Figure 9 indicates that except for roof systems with a self-adhered film air retarder (SAF), all other systems are prone to potential condensation. With this benchmark data, further studies are required to be conducted using hydrothermal modeling to relate the air intrusion to long-term moisture gain and condensation using different environmental parameters and based on the critical air intrusion limit.

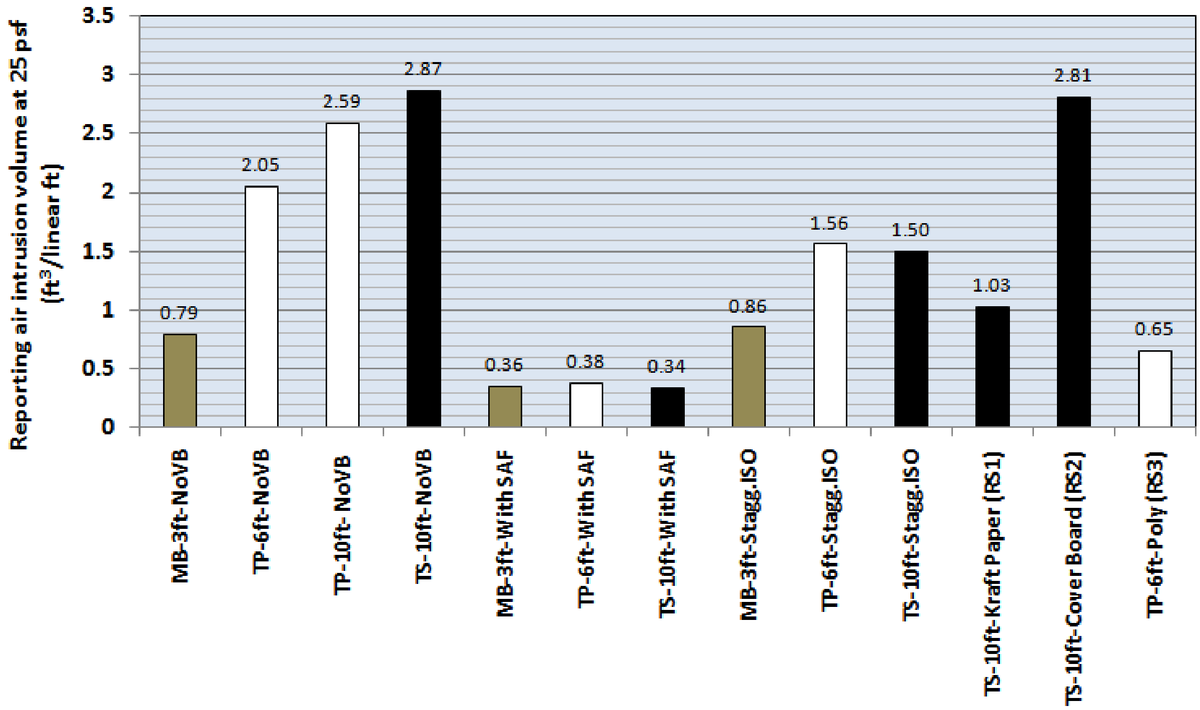


Figure 9: Air intrusion limit for potential condensation within the roof system

Conclusion

In collaboration with CRCA, NRCA and four major roofing material manufacturers, a research project focusing on air intrusion quantification and its effects on moisture transport was conducted. The research findings from this project can be summarized as follows:

- The kraft paper and polyethylene sheet minimized the air intrusion into the roof system with the polyethylene sheet outperforming the kraft paper; however, both air retarders underperformed compared with the self-adhered film air retarder.

- Installing HD cover boards on top of the insulation provided no resistance to air intrusion because the cover boards do not seal the primary flow paths of the steel deck unlike the air retarder installed at the deck level.
- The influence of air intrusion on moisture transport showed that without an air retarder in the system layout, there is a risk for potential condensation and increased moisture gain within the system, which is considerably high compared with the moisture gain resulting from vapor transmission.
- An air retarder at the deck level can minimize the moisture gain in the roof systems resulting from vapor transmission and air intrusion. However, trapped air resulting from air intrusion between two air retarders (membrane and air retarder at the deck level) within the roof system also can cause condensation.
- At an outside temperature of -5 C (23 F) and indoor conditions of 23 C (72 F) with 50 percent relative humidity, an air intrusion volume of 0.42 ft^3/ linear ft (11 L/linear m) could be a critical volume for potential condensation or moisture content increase in mechanically attached roof systems.

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