Final Report

Literature Review on the Performance of Residential Unvented Attics Constructed with Spray Foam in U.S. Hot-humid Climate Zones

Prepared for:
Stephen Wieroniey
Director, Center for the Polyurethanes Industry
Spray Foam Coalition of American Chemistry Council, Inc.
700 2nd Street NE
Washington, DC 20002
P: (202) 249-6604
stephen_wieroniey@americanchemistry.com

Prepared by:
Armin Rudd, Principal
AB Systems LLC
O: 717.867.0123
arudd@absystems.us

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1 INTRODUCTION

The Spray Foam Coalition (SFC) of the American Chemistry Council (ACC) sought to conduct a literature review of recent research pertaining to the performance of unvented attics constructed with spray foam in homes located in the U.S. hot-humid climate zones (CZ) (International Energy Conservation Code (IECC) CZ 1A, 2A, and part of 3A.) This literature review will start with documents appearing after the May 2005 report by Danny Parker (Parker 2005) to the Florida Department of Community Affairs entitled, "Literature Review of the Impact and Need for Attic Ventilation in Florida Homes."

Documents included in this literature review were drawn from private, public, and government sector buildings research organizations, engineering and trade associations, technical journals, conference proceedings, and International Code Council (ICC) building code language. In addition, efforts were made to identify documented field issues related to spray foam unvented attics in hot-humid climate zones, such as moisture accumulation and indoor air quality concerns. The purpose of this report is to summarize and discuss the individual document references.

2 UNVENTED, SEMI-CONDITIONED ATTICS

Stated simply, unvented attics are where the attic is sealed against air exchange to the outdoors and insulation is installed at the roof line rather than at the ceiling. Unvented attics are considered semi-conditioned because, with or without intentional space conditioning system airflow into the attic space, the attic space typically operates near the temperature of the actively conditioned living spaces below the attic.

In most cases, only ceiling gypsum board separates the attic from the living space, and, unlike for vented attics, no particular effort to air seal at the ceiling level is made or needed. With the thermal and air pressure boundaries at the roof line, conduction heat transfer through the ceiling gypsum board, and passively or mechanically induced air exchange, moderates temperature and humidity conditions between the two spaces.

The greatest advantage to employing the unvented attic construction strategy is to enclose space conditioning air distribution ducts and equipment inside conditioned space. If space conditioning ducts and equipment are located inside conditioned space by other means, the benefits of unvented attics diminish.

The Parker (2005) report and literature review did a thorough job of describing the unvented attic application and research results available at that time. The application has not changed since then, so there is no need to go into more detail about that here other than in the context of reviewing the more recent research, evaluations, and code changes.

While AB Systems agrees with essentially all of the conclusion items listed at the end of the Parker report, one conclusion item is elaborated on here:

a) Parker conclusion E2: *Sealed attic construction was measured in a realistic test in Ft. Myers, Florida to reduce space cooling by about 8%. Savings are less for very well sealed duct systems and more for poorly sealed ducts. However, savings would be negative if the duct system was otherwise within the conditioned space.*
   The savings may not be negative even with the duct system otherwise in conditioned space if the sealed attic construction made the house more airtight—reducing air leakage to outdoors. Although it is not impossible to achieve a low level of building air leakage to outdoors through the top of the building without the use of spray polyurethane foam (SPF), it is generally much easier to reliably achieve low air leakage using spray foam. The Parker report did not provide any test data on building air leakage for the different test homes, so it is not possible to evaluate that further in this case.

3 LITERATURE REVIEW

This literature review of references is organized by: Peer-Reviewed Papers; Reports; Case Studies; and Articles.

3.1 Peer-Reviewed Papers

3.1.1 Babineau, Francis, Jr. 2016. Cost-Effective High-Performance Unvented Attics.

Babineau reported that the most common method of constructing unvented attics (where the thermal boundary is shifted from the ceiling to the roof) in the U.S. is air-impermeable SPF. He goes on to report that the high material cost of SPF lends toward considering air-permeable fiberglass as a cost-effective material option for unvented attics in warm and dry climates. He describes methods of installation, thermal and moisture modeling to evaluate long-term material durability, and a warm-dry California case study project (climate zone 3B). The 13 inch thick roof insulation was R-38 unfaced fiberglass batts. The oversized batts were installed such that they touched at the interior face and were slightly compressed between the 2x4 truss top chords. The roof cladding was vented tile. Air sealing at the roof plane, eaves, and gable end walls was accomplished by canned SPF and caulk before installation of insulation, plumbing, electrical, and HVAC. Air sealing of penetrations was done again after installation of those items.

While the data reported in this paper were not from the hot-humid climate, it is interesting to note that even in the warm-dry climate, with modeled interior relative humidity (RH) ranging between 40% in winter to 60% in summer, the modeled roof sheathing RH exceeded 85% (about 15% moisture content) for 3 months (middle December to the Middle of March). Modeled roof sheathing RH peaked at the end of January at about 95% RH (about 24% moisture content). Babineau referred to these moisture performance results as acceptable but marginal. The results exceeded criteria by Straube et al. 2010 and Black and Straube 2007 which suggested that wood moisture content above 16% for more than 28 days may pose a risk of microbial growth on wood.

AB Systems would agree with the assessment of marginal based on the modeling results, especially since this was modeled in for a warm-dry, not warm-humid climate. However, actual testing and monitoring results would be more persuasive. It was reported that monitoring of the test house was installed as part of a separate study. Importantly, Babineau did not report which roof orientation was modeled. Roof orientation makes a significant difference in roof temperature and drying potential due to daily solar heating, with north being the limiting case. Hopefully, the monitoring study will consider the differences in roof orientation.

3.1.2 Miller, William, Andre Desjarlais, and Marc LaFrance. 2013. Roof and Attic Design Guidelines for New and Retrofit Construction of Homes in Hot and Cold Climates.

Miller reported on an unvented attic test done in a test facility in Charleston, South Carolina where open cell spray polyurethane foam (ocSPF) was sprayed under the roof deck. He reported that RH measurements at the top of the ceiling gypsym board—facing the unvented attic—reached 100% for brief periods on two days out of the 7 days reported in August 2012. Based on that, he reported that, “At this condition, water vapor is in equilibrium with liquid water and therefore all interior attic surfaces are wet!” However, Miller did not report having observed any physically wet attic surfaces. The RH measurement plots shown in Miller’s Figure 6 show that the attic air RH was only slightly lower than the attic-facing gypsum surface. The RH traces started at about 65% RH at midnight, then ramped up to a brief peak of 90-100% during sunshine hours, then ramped back down to where they began. This indicates that if any surfaces did reach water vapor saturation they also dried out quickly on a daily basis. One overcast day with relatively low insolation, the RH peak was 70-75%. This illustrated the understanding also previously held by others that solar heat was the force behind the moisture pulse in the unvented attic. Miller reported that the moisture could not have been from outdoor or indoor air. He stated that his field measurements imply that the actual moisture source was from previous rainwater that migrates to the underside of the shingles and underlayment, then solar irradiance drives the moisture through the roof sheathing and ocSPF. He did not discuss dew that typically collects on roofs each summer morning in warm-humid climates as a potential source of moisture in addition to rainwater. Miller did not discuss how the water migrates to under the shingles and underlayment, or whether that migration is in vapor or liquid form such as by capillarity. Miller did not discuss whether the moisture could be recirculated attic moisture moving in-and-out of the wood on a daily basis by sorption and desorption rather than a new source of moisture reaching the unvented attic space from outdoors.

Miller also reported that, "Colon (2011) field tested open-cell spray foam in a home in the hot muggy climate of south Florida. The roof deck was protected by an impermeable underlayment and the air-handler unit and ductwork were contained in the attic, yet moisture levels in the conditioned space increased above that measured *a priori* sealing the attic." However, the same Colon reference reviewed in this report showed no such reporting of that. That project was a new construction project, not a retrofit project. As such, there was no before and after monitoring, and no conditioned space moisture concerns were raised.

Miller went on to propose a new type of unvented (sealed) attic using materials he reported as being more affordable than ocSPF. This new type of sealed attic would actually be vented above an airtight spacer material separating blown or batt fiberglass insulation from the roof deck. The ventilated space created between the insulation spacer material and the roof deck would vent moisture he indicated to be migrating through the roof shingles, underlayment, sheathing, and the under-sheathing insulation. The proposed sealed attic design would also rely on conditioned supply and return air recirculated in the sealed attic for attic moisture management.

In his conclusions, Miller stated that, "For new construction, the best option is to keep the ducts out of the attic, make sure the attic floor is sealed, and add at least code level of insulation to the ceiling." From an energy perspective, AB Systems agrees with that, however, builders often consider keeping air distribution ducts out of the attic to be too expensive or impractical due to architectural constraints.

3.1.3 Miller, William, Sudhir Railkar, Ming Shiao, and Andre Desjarlais. 2016. Sealed Attics Exposed to Two Years of Weathering in a Hot and Humid Climate.

In this second paper by Miller, three test attics at a test facility in Charleston, South Carolina were compared. Two attics were constructed as unvented (sealed) attics, one with ocSPF and one with closed cell spray polyurethane foam (ccSPF). Another test attic was vented and served as the control. Each attic test bay was 12 ft wide and 21 ft deep with thermal and air exchange isolation between test bays. With a rafter run of 10.5 ft and relatively shallow 3:12 roof pitch, the height at the attic peak was 31.5 in. Table 1 summarizes the attic characteristics reported by Miller.

Table 1. Charleston, SC test attic characteristics reported by Miller

	Venting	Insulation	Roof sheathing	Shingle underlayment	Asphalt Shingles
Attic 1:	Vented, 1:300	R-38 fiberglass batts on attic floor	not reported	Vapor open, 16 Perm	Dark-colored asphalt shingles, 3% solar reflectance
Attic 2:	Unvented, sealed	R-22 ocSPF, 6" thick between 2x6 rafters and 1/2" under the rafters	plywood	15 pound felt paper, vapor open, 8 Perm	same
Attic 3:	Unvented, sealed	R-22 ccSPF, 4" thick between 2x4 rafters and 1/2" under the rafters	plywood	Vapor closed, 0.04 Perm	same

Noted is that Miller described the asphalt shingles as [water vapor] impermeable. However, in his 2013 paper he reported that his results implied that rainwater was migrating through the shingles, underlayment, roof sheathing, and ocSPF. Clarification would be helpful as to whether Miller expects that:

a) Only liquid water is migrating past the shingles and then water vapor is diffusing through the underlayment and shingles under high solar irradiance; or
b) Moisture is diffusing through wetted shingles under high solar incidence.

Research published by Railkar (2015) indicates that the former is not occurring, and research published by Boudreaux (2016) indicates that neither is occurring.

Detailed information on the instrumentation installed for monitoring the hygrothermal performance of the attic was reported. Measurements were taken on a 15 s interval and averaged over and recorded on a 15 min interval. Data was collected for over 2 years, between data collection started September 2013 and December 2015.

Miller reported mid-attic air RH data from June 30, 2014 to July 6, 2014. Table 2 organizes those results. For the ocSPF attic, on two days with high solar irradiance the attic air RH from midnight to noon was between 65-70%, while from noon to 8 pm the attic air RH ramped up to peak measurements showing 100% RH or higher with a 2-3 hour peak. Of course, it did not rain in the attic so the take-away is that the attic air RH became nearly saturated. On two other days with high solar irradiance the attic air RH from midnight to noon was between 65-70%, while from noon to 8 pm the attic air RH ramped up to peak measurements showing 85-90% RH with about a 1-2 hour peak. On three days with lower solar irradiance, the attic air RH from midnight to noon was between 65-70%, while from noon to 8 pm the attic air RH ramped up to peak measurements showing 70-85% RH with about a 1-2 hour peak. The attic RH measurements in the ccSPF attic were lower and the solar irradiance induced pulse moderated compared to the ocSPF attic.

Table 2. Mid-Attic Air RH from June 30, 2014 to July 6, 2014

		Peak Solar Irradiance (W/m^2)	Midnight to Noon mid-Attic Air RH	Noon to Midnight mid-Attic Air peak RH, peak duration
Attic 2 (ocSPF)	2-days	700-800	65-70%	100% or higher, 2-3 hours
	2-days	700-800	65-70%	85-90% 1-2 h
	3-days	500	65-70%	65-70% 1-2 h
		Peak Solar Irradiance (W/m^2)	Midnight to Noon mid-Attic Air RH	Noon to Midnight mid-Attic Air peak RH, peak duration
Attic 3 (ccSPF)	2-days	700-800	60-65%	70% 3-4 h
	2-days	700-800	60-65%	67% 3-4 h
	3-days	500	60-65%	63-66% 2 h

The researchers cut out a section of ocSPF from the north-facing orientation and inspected the roof sheathing and rafters. The underside of the roof sheathing was reported to be slightly wet to the touch and water marks were reported as being observable around the exposed rafters. That was explained as a two-dimension heat and moisture flow from the warmer roof sheathing in the center of the roof bay toward the cooler rafter.

More detailed explanation of the observed moisture accumulation would be useful. For example, was the water marking on the rafter or sheathing or both? Was there any sign of wood discoloration indicating any initiation of mold or decay? The photo shown in Figure 1 is hard to interpret, but it appears that the sheathing and rafters look dark and it is not clear in the report how old the rafters and roof sheathing were. What is the possibility that the water marks were pre-existing? Also, was the foam insulation removed at the peak of the attic or elsewhere? Were similar observations made on the south-facing orientation?

Figure 1. Taken from Miller et. al. 2016, Figure 5, showing the roof sheathing and rafters on the north-facing roof after two years of climatic exposure with ocSPF insulation removed for inspection

In AB Systems' experience, the greatest potential for finding wet roof sheathing would be on the north-facing roof at the end of winter when moisture from within the house and unvented attic could accumulate in cold roof sheathing. Building Science Corporation[1] made such inspections by removing ocSPF in unvented attics at two homes in north Florida at the end of February 2003. For discussion purposes on this topic, Table 3 shows the moisture content measurements taken with a Delmhorst BD-2100 pin meter. In House #1, the moisture contents and good condition of the wood materials were the same over the conditioned living space as they were over the unconditioned garage. In House #2, a trend of increasing moisture content was found on the north-facing roof. This agrees with Miller's (and other's) observation of two-dimensional moisture movement in-and-out of the roof sheathing and upward toward the attic peak in synchronization with solar irradiance influence. Neither of the two unvented attics showed moisture content measurements of any concern.

[1] The author of this report, herein referred to as AB Systems, was a Principal Engineer with Building Science Corporation at the time that work was done.

Table 3. Results of wood moisture content measurements taken by the Building Science Corporation in ocSPF sealed attics in Lake City, Florida on February 28, 2003

	Location description	Roof sheathing moisture content (%)	Framing moisture content (%)
House #1			
Location 1	insulated garage attic west-facing 8” down from peak	7 to 8	10 to 12
Location 2	living space attic west-facing 8” down from peak	7 to 8	9 to 10
House #2			
Location 1	living space attic north-facing 8” down from peak	14 to 16	7 to 8
Location 2	living space attic north-facing 30% down from peak	12 to 14	7 to 8
Location 3	living space attic north-facing 80% down from peak	11 to 13	9 to 10
Location 4	living-space attic south facing peak of hip	7 to 9	7 to 9

Miller reported monitored roof sheathing moisture content measurements from three days in October 2014. On a daily cycle, the moisture content was about 6% (typical of kiln dried wood furniture) from midnight to noon, then rising to about 11% (typical of aged framing lumber) by 6 pm, and back to 6% by midnight. None of those moisture content results presented any concern.

When the Charleston test facility study was completed, the shingles and underlayment were removed to inspect roof sheathing. The moisture content of all of the roof sheathing was reported to have been lower than the Delmhorst pin meter could measure except for at one plywood joint where the reading was a harmless 10-14% (the roof orientation was not specified). No reason as to an expected cause of that higher moisture content was given. One very small sized area on the topside of the roof sheathing (perhaps the size of a quarter judging from the photo) was reported and described as moisture damage. No reason was given as to an expected cause of that damage. Is it possible that the small area of damage was pre-existing, or due to an incidental shingle or underlayment defect due such as: under- or over-driven shingle nail, rip in the underlayment, shingle joints lining up too closely, etc. Without further support than offered, it seems that there may be no reason to believe that the small damage area had anything to do with the unvented attic.

3.1.4 Railkar, S., A. Desjarlais, A. Chich, and W.A. Miller. 2015. Thermal and hygrothermal performance of sealed and ventilated attics with and without breathable membranes in a hot and humid climate.

Railkar reported on data taken from the same Charleston, SC test facility that Miller reported on. The Railkar paper title and introductory parts of the paper indicated that sealed attic data was reported, however only data for vented attics was actually reported. Nevertheless, the vented attic roof sheathing partial vapor pressure data presented was helpful in understanding the improbability of any significant water vapor diffusion through asphalt roof shingles regardless of the underlayment water vapor permeance.

Partial vapor pressure was calculated from temperature and RH measurements and was used to identify differences in the moisture levels between asphalt shingle roof systems having different shingle underlayment over the roof sheathing. Partial vapor pressure data was reported for the topside and underside of the roof sheathing, with:

a) breathable underlayment (vapor permeable, Perm>10)
b) non-breathable underlayment (vapor impermeable, Perm <0.1); and
c) peel-and-stick membrane underlayment (no Perm value reported).

Test results showed a small increase in partial vapor pressure at the topside of the roof sheathing compared to the underside, and an even smaller difference between the three roof systems with different shingle underlayments. Although Railkar did not offer this assessment, his results would seem to indicate that moisture does not diffuse through asphalt shingles under hot-humid climate solar irradiance, and that would be applicable to both vented and unvented (sealed) attics.

If that is the case, then this would further confirm that the daytime moisture pulse observed in unvented attics is indeed the same attic air moisture repeatedly moving in and out of the wood sheathing and framing. The attic air moisture in that case would be either moisture generated in the living space below and rising into the unvented attic, or moisture due to unintended air exchange between the unvented attic and outdoors, or moisture initially built into the unvented attic, but not new moisture from outdoors diffusing through the roof system.

It is well understood that both ocSPF and ccSPF are air-impermeable based on the ICC code definition, and that ccSPF has lower water vapor permeance than ocSPF. While Miller (2016) showed that this short-peaked, diurnal in-and-out, two-dimensional moisture movement in unvented attics in hot-humid climates is muted by using ccSPF, using ocSPF has not been shown to cause damage (mold or wood decay) spanning two decades of unvented attic application in hot-humid climates. It is AB Systems' experience that there is not an important issue between unvented attics in hot-humid climates insulated with air-impermeable SPF of either open-cell or closed-cell type, but there is an important issue between unvented attics insulated with air-impermeable SPF versus air-permeable insulation due to increased two-dimensional moisture transport in-and-out and upward toward the peak with air-permeable insulation. Additional measures should be taken to lower attic air moisture levels if using only air-permeable insulation in unvented attics in hot-humid climates.

3.1.5 Pallin, Simon, Manfred Kehrer, and William A. Miller. 2013. A Hygrothermal Risk Analysis of residential unvented attics.

Pallin conducted a modeling study of unvented attics with both ocSPF and ccSPF insulation in IECC CZ 1 to 7. His focus was two-fold: roof sheathing moisture risk and space conditioning energy use. He varied a number of parameters but the most important parameter in terms of moisture risk was reported to be the vapor permeance of the insulation used to insulate under the oriented strand board (OSB) roof sheathing. Pallin reported that none of the 224 simulated unvented attics showed "any potential of developing mold on wood-based surfaces inside the attic," leaving only the risk of roof sheathing decay as the important consideration of moisture safety. He considered moisture content to be a common performance indicator for wood-based building material service life (Straube et al., 2010).

Even in CZ 1 to 3, unvented attics insulated with ocSPF were reported as a potential risk depending on the indoor moisture production rate. Relative to the indoor moisture generation rate, AB Systems has researched the need for and performance of residential dehumidification technologies (Rudd et al. 2013). Pallin used a “normal” indoor moisture generation rate of 15.8 lb/day which compared to a normal rate of 12 lb/day in the Rudd study based on a calibration of modeled to measured data. Pallin used a “high” indoor moisture generation rate of 33.6 lb/day which compared to a high rate of 24 lb/day in the Rudd study. AB Systems considers the high generation rate to be excessive and out-of-bounds for an annual simulation, but perhaps more reasonable for design-day dehumidification equipment sizing purposes. For that reason, simulation results using the high indoor moisture generation rate should be considered highly excessive and not likely to represent reality.

The Pallin study stated that most of his results showed the moisture content of the OSB sheathings varying between 13-17% moisture content annually. He also reported that 20–25% moisture content is commonly used as a critical upper limit to prevent decay of wooden materials (DIN 2012). Pallin concluded that “…every best-performing unvented attic roof is constructed with a closed SPF and with a low indoor moisture supply.” From a principles point of view, that may be true, but from an acceptable performance point of view, other constructions may be perfectly suitable.

Pallin provided results for Miami (CZ 1) and Atlanta (CZ 3, not strictly hot-humid climate). His results were presented as “Lowest and Highest Risk of Deterioration of the OSB due to the End Value of MC.” A significant shortcoming with Pallin’s report is that it was devoid of results data between the “best” and “worst” performing configurations. There would be many acceptable options between those extremes, but the reader is not provided that information. AB Systems considered it essential to the value of this report that at least the best and worst configurations for each of ccSPF and ocSPF should have been presented. However, not having that, one might possibly infer that the best and worst configurations using ocSPF, with the normal indoor moisture generation rate, in the hot-humid climate, would fall within the 13-17% moisture content range that Palin stated most of the results fell within. In comparison, the results presented for ccSPF in Miami and Atlanta showed that the moisture content started the simulation year at 16% and ended the simulation year at 13-14%.

Thermostat set point and supply and return air duct leakage were parametric variables modeled by Pallin. He reported that, thermostat set point and duct leakage had a low influence on the roof sheathing moisture content. However, he reported that duct leakage always had a positive effect on lowering roof sheathing moisture content in hot-humid climates. This reinforces AB Systems’ position that intentionally supplying a controlled amount conditioned air to unvented attics in humid climates can be an important moisture control strategy, especially to enhance construction moisture drying in the early months after closure.

A few conflicting statements appear in Pallin’s report, in the order they appear in the report, as follows:

1) “The shingles are assumed to be watertight and have a vapor permeance of 0.3 perm (sd = 10 m).”
2) “The roof shingle system of the simulated roof construction is simulated watertight and with a rather high vapor permeance.”
3) “It is also important to point out the risk when enclosing and organic material, such as the OSB, between two rather vaportight materials such as the SPF and the roof shingles.”

These statements seem to conflict in that in the first statement assigns a moderately low water vapor permeance to the shingles, but in the second statement the shingles are said to have a high vapor permeance, then in the third statement the OSB is said to be between vaportight shingles and vaportight [closed-cell] SPF.

The authors were contacted and clarification was made that "high" should in fact be "low" in statement 2) above.

Pallin mentioned a reference by Rudd (2005) that raised a question about the possibility for water vapor to breach the asphalt shingles. Rudd posed the possible mechanism whereby rain water or dew could be drawn into the shingle laps by capillary action, not sufficient to make the roof leak, but sufficient to cause solar heated water vapor flow upward above the shingle to the underlayment, through the underlayment, and into the roof system. Pallin considered that phenomenon possible, as did Salonvaara (2013), but did not have a way to account for that in his study. Others have studied that theory and concluded that moisture is not being driven through or around the shingles and through the underlayment by solar irradiance (Railkar et al. 2015; Ueno and Lstiburek 2015; Boudreaux et al. 2016).

3.1.6 Boudreaux, P., S. Pallin, and R. Jackson. 2016. Investigation of the proposed solar driven moisture phenomenon in asphalt shingle roofs.

Boudreaux reported on theoretical analysis and test data to evaluate the possibility of moisture transport past vapor-retarding asphalt roof shingles and more vapor-open shingle underlayment in unvented attics under the influence of solar irradiance, i.e. solar-driven moisture. While it seems that evidence is mounting that that is not happening, some of the statements and conclusions reported are discussed further here in order to hopefully bring more clarity.

In the abstract, Boudreaux stated, "Unvented attics perform well from this perspective, but from a moisture perspective sometimes homes with unvented attics have high interior humidity or moisture damage to the roof." It is presumed that Boudreaux was referring to relative humidity, but it is not clear whether Boudreaux is referring to high relative humidity interior to the living space or interior to the unvented attic. This is important since AB Systems is not aware of any reports of high relative humidity in the living space due to unvented attics and Boudreaux does not cite any. We would not want readers to draw unintended conclusions. Likewise, while there have been reports of high relative humidity in unvented attics, AB Systems is not aware of peer-reviewed reports of moisture damage to roofs in hot-humid climates due to the generally transient conditions of high relative humidity which peak for short periods due to solar irradiance then abate.

In terms of the theoretical approach taken to evaluate the question of solar-driven moisture into unvented attics, Boudreaux reported, "In conclusion, solar-driven moisture through asphalt shingle roof assemblies is unlikely because the capillary force is determined to be insufficient to drive substantial amounts of water all the way through the shingle gaps. Even if the shingle gap stayed filled with water, the impact on the moisture content of the sheathing would not be significant." However, the reader could benefit from some additional clarification. For example:

1) Boudreaux reported that he measured small gaps between the shingle laps that could have supported capillary suction, and then he reported some "valleys in the asphalt of different shingle samples" that were not deemed not likely to support capillary suction. What did those valleys look like? Were they large or small? Were they horizontally, vertically, or randomly oriented in the inclined direction of the shingles?
2) Regarding the adhesive strip that was considered to be a water dam, was it continuous or segmented as is typical?
3) Considering the statement, "Two simulations were performed; one with a liquid water filled interface between the shingle laps and one without any water between the shingles", combined with the illustration of Figure 3, it seems that moisture flow may have been modeled only perpendicular to

where the water layer was between the shingle laps. In other words, did the simulation allow for solar-heat-driven moisture flow both downward toward the lower shingle and up the incline past the shingle lap to where underlayment was directly exposed to the high water vapor pressure? Or was the solar-drive effect modeled only between the shingle laps? Of course, the most vapor diffusion would occur through the path of least vapor resistance, which would be directly through the underlayment in the area further up the incline from the shingle lap.

In terms of the experimental approach, Boudreaux reported that "there is no vapor drive into or out of the attic through the roof assembly, since no difference was seen in the humidity below the roof sheathing between the vapor permeable and impermeable underlayment." However, there were a couple of short-comings that should have at least been discussed, as follows:

1) The climate location of Knoxville, TN is not very similar to the hot-humid climate where unvented roofs are coated with dew nearly each morning during the comparatively extended summer.
2) The 1 inch thickness of low-perm ccSPF above the ocSPF was an atypical unvented attic scenario that would have muted the roof system moisture transport compared to all ocSPF. Is it possible that the moisture pulse signal was reduced enough by the ccSPF that significant moisture diffusion differences were not measureable in that experimental setup between the vapor open and vapor retarding shingle underlayments. Also, only one underlayment material described in the Table 2 material properties list.

Boudreaux reported that, "The sorption isotherms defined for wood explain the diurnal variation in attic humidity which has been attributed to solar-driven moisture. Sometimes called the ''ping-pong'' affect…" AB Systems agrees that it has been long well-known that there is a large solar-driven diurnal vapor adsorption/desorption effect that occurs in both vented and unvented attics affecting attic moisture levels. The research question became whether that was the only phenomenon affecting what we were measuring in unvented attics. The magnitude of the daily moisture pulse in-an-out of the unvented attic insulated roof assembly, and also accumulating upward toward the peak, seemed to indicate new moisture could be involved and not just the same old moisture bouncing back and forth and upward. It may be that the so-called "ping-pong" affect is all there is, however, Bourdreaux did not provide research results or a citation supporting how sorption isotherms for wood explain it all.

Boudreaux further stated that "…solar-driven moisture does not occur through asphalt shingle roof assemblies and so vapor impermeable membranes do not need to be installed on unvented attic roof assemblies…"

Note that AB Systems always recommends non-felt, synthetic shingle underlayment for unvented attics, not just because it is generally a Class II vapor retarder (0.1-1 perm), but because synthetic roof underlayment protects the roof much better during construction and from incidental water leaks after construction such as: under- or over-driven shingle nail, rip in the underlayment, shingle joints improperly lining up too closely, minor flashing defects, etc. Unvented attics are vulnerable to such incidental water leaks that would otherwise dry out and cause no problem with a vented attic. The use of better underlayment for unvented attics may be beneficial even if its lower permeance it is not needed to preclude moisture transport due to solar irradiance.

3.1.7 Salonvaara, M., A. Karagiozis, and A. Desjarlais. 2013. Moisture performance of sealed attics in Climate Zones 1 to 4.

Salonvaara conducted an unvented (sealed) attic modeling study primarily to evaluate the risks for high moisture content in the roof sheathing and for high relative humidity in the attic air. The insulation materials used were air-impermeable ocSPF and air-permeable fibrous insulation. His results showed that:

1) The insulation material water vapor permeance was a key factor in controlling roof sheathing moisture content, along with the attic-to-outside airtightness; and
2) “The sealed attic can experience elevated humidity at warm temperatures which can create favorable conditions for mold growth unless the attic is intentionally conditioned or via duct air leaks.”

Repeated here in Figure 2, Salonvaara provides useful and concise summary of the four major material property differences affecting the thermal and moisture performance of ocSPF and ccSPF.

1. Open-cell foam is light density (0.5 lb/ft^3 [8 kg/m^3]) and soft, closed-cell foam is more rigid and has higher density (2 lb/ft^3 [32 kg/m^3])
2. Open-cell foam has a lower R-value per inch (R-3.5/in. [RSI-20/25.4 mm]) than closed-cell foam (R-6/in. [RSI-34/25.4 mm])
3. Open-cell foam is vapor permeable (20–50 perm-in. [29–73 ng/smPa]), closed cell is vapor tight (1–2 perm-in. [1.46–2.92 ng/smPa])
4. In order to be an air barrier, 3.5–5.5 in. (89–140 mm) of open-cell foam and 1 in. of closed cell is typically needed to satisfy the air barrier material requirement 0.02 L/s·m^2 at 75 Pa (0.004 cfm/ft^2 at 0.3 in. H_2O) to be considered air-impermeable material per code.

Figure 2. Summary of the four major material property differences affecting the thermal and moisture performance of ocSPF and ccSPF from Salonvaara (2013)

3.1.8 Salonvaara, Mikael, Achilles Karagiozis, William Miller. 2016. Annual Energy and Heat Flows in Vented and Sealed Attics – Parametric Study - Climate Zone 2A.

In this study, Salonvaara modeled unvented and vented attics for energy performance but not for moisture durability performance. He reported that, “unvented attics mostly perform better than standard vented attics in the analyzed climates. However, vented attics with exceptionally well-insulated airtight ducts in the attic and ducts with higher thermal resistance can perform equally as sealed attics.”

3.1.9 Ueno, Kohta and Joseph W. Lstiburek. 2016. Monitoring of Two Unvented Roofs with Air-Permeable Insulation in Climate Zone 2A.

While this literature review is focused on SPF in unvented attics in hot-humid climates, and the roof insulation used in this research study was blown and sprayed fiberglass, this paper was included in the review to provide additional clarity in the field of unvented attics.

Ueno and Lstiburek studied two hot-humid climate unvented attic houses with unvented roof assemblies. One house was in Orlando and was occupied during testing. The other house was in Houston area and was unoccupied during testing. The water-resistant roofing material was concrete tile for the Orlando house and asphalt shingles in Houston. In both cases, the roof insulation was air-permeable fiberglass and an experimental vapor-diffusion vent was made along the hips and ridge. The purpose of the vapor diffusion vent was to vent moisture accumulated at the roof high points. The diffusion vent was made by leaving a gap in the roof sheathing, covered by an air-impermeable, water-resistant but vapor-open material.

Table 4 represents a tabular summary of the key test characteristics between the Orlando and Houston sites. Likely the most significant difference was the use of concrete tile in Orlando and asphalt shingles in Houston. The concrete tile would have moderated the environmental heating and cooling effects on the roof sheathing much more than asphalt shingles. Therefore, it is unknown how the results may have been different in Orlando with asphalt shingles. Concrete tile is uncommon in Houston, so asphalt shingles there are very representative of the building stock.

Table 4. Comparison of key test characteristics between the Orlando and Houston sites

	Orlando, FL	**Friendswood, TX (Houston area)**
IECC Climate Zone	2A	2A
Water-resistant roofing material	Concrete tile	Asphalt shingles
Roof underlayment	60 mil modified asphalt self-adhered membrane	#15 asphalt saturated felt
Roof sheathing	7/16" OSB	1/2"plywood
Air-permeable and vapor-open roof insulation	R-38 netted and blown fiberglass	R-38 spray applied fiberglass
Ridge diffusion vent	Yes, continuous slot, slightly off-ridge	Yes, continuous slot, slightly off-ridge
Hip diffusion vent	Series of 2" holes within 3' of peak	Yes, continuous slot
Intentional conditioned air supply to attic	None	None
Attic humidity control	None	Humidified in third winter to simulate occupant interior moisture generation
Occupancy	Occupied	Unoccupied

The Houston house was tested to have air leakage of 2.2 air changes at 50 Pa pressure differential (ach50) with the access hatch closed between the unvented attic and living space, and 2.5 ach50 with the hatch open. This indicated a house with low air leakage and reasonably low leakage in the unvented roof assembly itself. The Orlando house tested at 6.7 ach50 with both attic hatches closed and 7.6 ach50 with both hatches open. This indicated a high level of air leakage both in the house and the unvented roof assembly itself.

Houston Results

In a control portion of the unvented roof assembly that did not have a diffusion vent, east-facing roof peak relative humidity ranged from a high of over 95% RH in winter to a low of 40% RH in summer. This correlated with a roof sheathing moisture content high of 20% MC in the first winter when moisture of construction was a likely moisture source and 30% MC in the third winter when humidification for simulated occupancy was used. Moisture content fell to about 7% MC in summer.

In contrast, in the unvented roof assembly with diffusion vent, east-facing roof peak relative humidity ranged from a high of over 90% RH every day in winter and summer. This correlated with a roof sheathing moisture content high of 17% MC in the first winter when moisture of construction was a likely moisture source and 27% MC in the third winter when humidification for simulated occupancy was used. Moisture content fell to about 10% MC in summer. A particularly interesting observation is that the high vapor permeance of the diffusion vent system causes the roof peak relative humidity to spike above 90% RH almost every day, winter and summer, whereas without the diffusion vent that phenomenon is limited to winter. However, that brief peak RH excursion does not show a long-term effect on wood moisture content.

The authors stated that the unvented roof assemblies with diffusion vent exhibited drier conditions and that, "the diffusion vent roof shows greater moisture safety and less wintertime moisture accumulation than the conventional, unvented roof design." From observations of plotted data in Figure 9 and Figure 10 of the study, the durability differences between the unvented roof assemblies with and without the diffusion vent appear to be very small.

Ueno and Lstiburek also included an experiment at the Houston house to investigate the possibility of moisture uptake in the shingles being driven inward through the roof assembly. They did this by creating a vapor-closed box under a 2 ft portion of the roof to monitor any accumulating moisture gain inside the box from the exterior. The results indicated that:

a) there was no accumulating moisture gain; and
b) wood moisture content was not well correlated to exterior rain wetting events in most cases but well correlated with the 24-hour average sheathing temperature which was the same for measured locations outside of the box. This indicated that inward water vapor drive was not happening to any significant extent.

Orlando Results
Data was collected for two years. Winters in Orlando are significantly more mild than in Houston although both locations are in IECC Climate Zone 2A. Measured patterns in the first floor and second floor attics in Orlando were similar to Houston. High/low attic measurement pairs showed temperature and moisture stratification. The attics showed elevated moisture levels compared to the interior space, which was primarily attributed to moisture stratification not air leakage from the exterior. That was more pronounced in the second floor attic compared to the first floor attic. A strong diurnal swing was observed in attic dew point relative to the main interior conditioned space, from close to the interior space at night to as much as 27^{o}F higher in the day. That was attributed to roof sheathing moisture adsorption and desorption.

Comparing the unvented roof without a diffusion vent configuration to the unvented roof with a diffusion vent configuration, the following key observations were made:

a) Attic ridge RH and moisture content was high in both cases (above 90% RH and above 16% MC) but higher in the unvented roof without a diffusion vent. This trend was seen in both the first and second years but somewhat less in the second year.
b) The diffusion vent attic showed 30-40% RH swings everyday all year long with a relatively flat seasonal amplitude profile (daily averages ranging from 45% in summer to 70% in winter). The attic without diffusion vent showed 10-20% RH daily swings with a large seasonal amplitude profile (daily averages ranging from 30% in summer to 95% in winter).
c) Observations made after the monitoring period was over showed fungi growth on the interior surface of the insulation netting and on the vertical truss member near the ridge of the unvented roof without a diffusion vent. It was reported that there was no such fungi growth observed in the unvented roof with a diffusion vent.

Although somewhat less with the diffusion vent, accumulation of moisture in either case was reflective of previous unvented attic field work with fibrous insulation that resulted in failures, and especially correlated to first-winter effects where additional construction moisture is present. Intentional space conditioning of the attics was recommended to provide dehumidification.

AB Systems notes that a similar strategy is commonly used in sealed crawlspaces where conditioned air from the existing space conditioning system is supplied to the crawlspace, or unvented attic space in this case, in the amount of 20-30 cfm per 1000 ft^2 of crawlspace or attic floor area. That approach provides some moisture removal in summer via the air-conditioning system cooling coils, and provides heating to lower the RH in winter as well as some moisture averaging with the main interior space.

3.2 Reports

3.2.1 Colon, C. 2011. New Construction Builders Challenge: Sealed Attic and High Efficiency HVAC in Central Florida: AYear in Review

Colon reported on a slab-on-grade, concrete block wall, single-story new construction home in Rockledge, Florida. The unvented (sealed) attic in this home was insulated with R-27, air-impermeable ocSPF. The roof style was a simple full-hip, with a short section of ridge that, judging from the photograph, was about 12 ft long. AB Systems draws attention to the roof style only because it can be important relative to air-permeable unvented attic roof insulation strategies reviewed elsewhere in this report.

House construction was completed in March 2010 and monitoring instrumentation was installed the next month, recording data on a 15-minute interval. Temperature and RH sensors were installed in the indoor conditioned space, the unvented attic, and outdoors as part of the monitoring package. A plot of the 15-minute data showed that the interior conditioned space RH started out just below 60% in April, then steadily decreased to about 43% in December, then increased to about 53% in March-April. Considering the thousands of pounds of moisture that can dry out from new construction building materials in the first years (from concrete and masonry, wood, drywall joint compound, paint, etc.), that trend illustrated a nearly perfect response to indoor humidity control by the HVAC system. Some of that moisture is generated in the attic and some of it finds its way to the attic from below due to less dense moist air rising[2]. Note that the occupants kept a nearly constant cooling set point of about 73°F which allowed the cooling system to operate optimally for removing moisture.

Unvented attic relative humidity and temperature were measured at the attic peak and mid attic. In May 2010, the hourly average attic relative humidity was about 50% from 10 pm to 11 am, then ramped up to a little over 60% by 4 pm, then ramped back down to 50% by about 10 pm. A similar profile was recorded for the following months up through January 2011 except at progressively lower RH and with the ramping period being shorter and with less amplitude. From February to April 2011, the ramping period and amplitude progressively increased again to a little higher than it had been in May 2010. Though not mentioned by Colon, to AB Systems, the unvented attic RH increase in Spring 2011 was a typical and logical swing-season response as outdoor humidity rose but sensible cooling load was still low enough that moisture removal by cooling operation was not consistent. Colon reported two annual peaks in unvented attic RH—83% in May 2010 and 78% in April 2011. Neither the conditioned space RH nor the unvented attic RH was of any concern during the testing year. Even so, for unvented attics in humid climates, AB Systems always advises the introduction of 20-30 cubic feet per minute (CFM) of cooling supply air per 1000 ft^2 of unvented attic floor, at least for the first few months after the house is closed and conditioned. This is the same as for unvented crawlspaces. It is not for temperature control but to better manage moisture conditions in the unvented attic.

The interior conditioned space RH remained steady across the day and night, showing no RH pulse that would indicate either a cause or response to what was recorded in the unvented attic. Colon attributed the daily pulse in attic relative humidity to moisture sorption and desorption into and out of the wood framing materials, respectively. Moisture is desorbed from the wood into the attic as the wood is heated by the sun, then the relatively dry wood adsorbs attic moisture as the solar heat subsides and the roof cools down. Note that the

[2] Although not pointed out by Colon, his Figure 9 confirms the phenomenon of less dense moist air rising. The mid and high attic temperatures were the same across the day and night but the mid attic humidity ratio was lower than the high attic humidity ratio from about 1 pm to 7 pm.

roof will cool lower than the outdoor air temperature due to night sky radiation, and an unvented attic roof will cool lower than a vented attic roof due to the roof insulation. This wood framing moisture adsorption/desorption process is even more pronounced in vented attics where there is essentially an unlimited moisture source at night from outdoors. In unvented attics, in the absence of any moisture driven through the roofing materials, the moisture source is limited to moisture generated inside the house and moisture generated due to outdoor air exchange via natural infiltration and mechanical ventilation.

4 CONCLUSIONS

A summary of conclusion points resulting from this review of literature pertaining to the use of SPF in unvented attics in hot-humid climates follows:

1) There is modeled and measured evidence that there is a large but relatively short-peaked, diurnal increase in relative humidity, partial vapor pressure, and absolute humidity from approximately noon to evening hours in unvented attics constructed with ocSPF insulation. The increase in these values appears under the roof sheathing and in the attic air and responds with some delay to the magnitude of solar irradiance. From about midnight to noon these values in the attic air remain near or slightly above that in the conditioned living space air.
2) There is strong evidence that two-dimensional moisture movement in-and-out of the roof materials and upward toward the unvented attic peak is occurring in synchronization with solar irradiance influence. The in-and-out moisture movement mechanism is moisture adsorption and desorption. The amount of moisture movement occurs from least to most in air-impermeable ccSPF, air-impermeable ocSPF, and air-permeable fibrous insulation, respectively. Additional measures can be taken to lower attic air moisture levels if using only air-permeable insulation in unvented attics in hot-humid climates.
3) Evidence is mounting that moisture transport past the vapor-retarding asphalt roof shingles and the more vapor-open shingle underlayment is not happening in unvented attics even under the influence of solar irradiance. The moisture appears to be recirculated attic moisture moving in-and-out of the roof materials by sorption and desorption on a daily basis rather than a new source of moisture reaching the unvented attic space from outdoors.
4) Moisture content of the roof sheathing is the most important risk factor relative to moisture safety and the use of ocSPF in unvented-attics in hot-humid climates. The roof sheathing moisture content varies up and down below a critical range of about 20-25% with normal indoor moisture generation.
5) The most important factor in controlling roof sheathing moisture content is the water vapor permeance of the insulation installed under the roof sheathing. The higher the vapor permeance of the insulation installed under the roof deck the higher the roof sheathing moisture content, especially near the attic peak. Attic-to-outside air leakage is also a factor and it must be low.
6) A relatively small amount of conditioned air supply into the unvented attic air space, whether controlled or by duct leakage, has a positive effect on lowering roof sheathing moisture content and unvented attic air relative humidity in hot-humid climates. The higher the vapor permeance of the insulation installed under the roof deck the more important the conditioned air supply.

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