Investigation of the proposed solar driven moisture phenomenon in asphalt shingle roofs

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Abstract

Unvented attics are an energy-efficiency measure to reduce the thermal load of the conditioned space and decrease the space conditioning energy consumption by about 10%. This retrofit is usually done by spraying polyurethane foam underneath the roof sheathing, and on the gables and soffits of an attic to provide an air barrier and a thermal control layer. 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. As homes become more air tight and energy efficient, a better understanding of the hygrothermal dynamics of homes with energy-efficient envelopes become more important. One proposed reason for high unvented attic humidity has been that moisture can come through the asphalt shingle roof system and increase the moisture content of the roof sheathing and attic air. This has been called "solar driven moisture." Oak Ridge National Laboratory (ORNL) investigated this proposed phenomenon by examining the physical properties of a roof and the physics required for the phenomenon. Results showed that there are not favorable conditions for solar driven moisture to occur. ORNL also conducted an experimental study in a home with an unvented attic and compared the humidity below the roof sheathing before and after a vapor impermeable underlayment was installed. There was no statistically significant difference in absolute humidity before and after the impermeable underlayment was installed. The outcomes of the theoretical and experimental studies suggest that solar driven moisture does not occur in any significant amount.

Keywords

Building Envelope, Hygrothermal Analysis, Attics, Roofs, Moisture, Unvented, Sealed, Semi-conditioned

Introduction

Using less energy has many benefits including reducing the global warming potential, increasing the nation's energy security, and saving money for the end user. Consequently, the U.S. Department of Energy has a goal for decreasing the energy consumption of new and existing homes by 50% by 2030. This task will rely heavily on improving the thermal control layer and air barrier of the building envelope (walls, roof and foundation) and increasing the efficiency of space conditioning equipment, because space conditioning accounts for 54% of the total residential energy use (DOE, 2011).

One promising approach to improving the thermal resistance and airtightness of residential roofs is to encapsulate the attic by applying a thermal control layer and air barrier underneath the roof sheathing, on the gable walls and over the soffits (Rudd and Lstiburek, 1998). This can be done with different materials, but sprayed-applied polyurethane foam is commonly used. This approach moves the thermal control layer and air barrier from the attic floor plane to the attic ceiling plane, and can reduce the space conditioning energy when air distribution ducts are in the attic. Since the temperature differential between the duct air and attic air is decreased less energy is lost from the ducts. Also, since an unvented attic is better sealed from the outside than a vented attic, the whole house infiltration is usually decreased which further improves the space conditioning energy consumption (Hendron et al., 2003). The sealed attic design has been measured to save 8% in cooling energy in hot-dry climate zones (Hendron et al., 2003). Because of these benefits, unvented attics were incorporated into the International Residential Code sections R806.5 and N1102 in 2006 (IRC, 2015).

Despite the apparent energy savings, high relative humidity (>80%) and sheathing moisture content (> 40%) has been found in some unvented attics (Colon, 2011; Rudd, 2005; Aldrich et al., 2010). There could be multiple causes to these observed problems, many of which are not due to the inherent design of the unvented attic. For example, a design that works well in one climate might not work well in another climate zone. To better understand the variability of unvented attic durability, different parameters need to be studied to determine their effect on the performance of this attic system.

To that end, ORNL investigated the moisture sources that could cause high relative humidity in an unvented attic. Some have suggested that moisture may migrate through the asphalt shingle roof system and contribute to the elevated relative humidity in the attic (Rudd, 2005). Rudd proposed that dew on top of shingles could, by capillary action, be moved up the shingle laps where it is deposited between the shingles and underlayment. The sun would then heat the water to the point of evaporation after which the water vapor could be driven through the underlayment and into the roof sheathing. Similar phenomenon has been investigated and proven for other absorbent roofing materials (Cunningham et al., 1993). This phenomenon called solar driven moisture has led to recommendations that a vapor barrier should be installed under asphalt shingles when used with unvented attics (Rudd, 2005). This recommendation would significantly increase the cost of an unvented attic system. ORNL investigated the likelihood of the proposed phenomenon occurring from a theoretical and experimental standpoint and have reported the findings below.

Methodology

ORNL used two approaches to investigate solar driven moisture through asphalt single roofs. First the phenomenon was investigated from a theoretical standpoint to assess the likelihood of the phenomenon occurring from a physics standpoint. The idea proposed by Rudd, that liquid water is moved up the shingle lap by capillary suction, was investigated to determine if conditions existed on a roof for this to occur (Rudd, 2005). Then WUFI®2D 3.3 heat and moisture software was used to analyze the effects of an inward liquid or vapor drive on the moisture content of the roof sheathing. WUFI®2D has been validated previously (Oustad et al., 2005). For this simulation, data from a real home with an unvented attic was used. The measured climate from a weather station at the house was used as the exterior climate and the interior boundary conditions were based on temperature and relative humidity measurements from underneath the roof sheathing. The layer thicknesses for the simulation model corresponding to Figure 1 are 3 mm for the shingles, 1 mm for the felt underlayment, 13 mm for the Oriented Strand Board (OSB), 25 mm for the closed cell polyurethane spray foam and 138 mm for the open cell polyurethane spray foam. See the appendix for more information about the material properties used in the WUFI®2D simulation.

Secondly, the question was approached from an experimental standpoint. ORNL investigated three 223 m^2 test houses with simulated occupancy from 2009 to 2014. All homes had slab foundations, the same orientation and are located in the same neighborhood in Knoxville, TN. One of these homes had an unvented attic with a hybrid of closed and open cell foam applied on the underside of the roof sheathing and gable ends of the attic with all soffit, gable and ridge ventilation covered. The total air change per hour at 50 Pa (ACH_{50}) of the home was measured to be 3.5 ACH_{50}. A guarded blower door test was used to determine that about 25% of the total house leakage was coming from the attic roof, gables and soffits even though the attic had been sealed (Salonvaara et al., 2013). Heat and moisture was added to the space to emulate 3 people living in the home (Boudreaux et al., 2012).

Extensive temperature and humidity measurements were taken throughout the attic and interior of the home. Figure 1 shows the unvented attic roofing system with dark asphalt shingles, underlayment, oriented strand board (OSB) sheathing, closed cell polyurethane foam and open cell polyurethane foam. Before 2013, 15# felt paper underlayment (with a vapor diffusion thickness of 0.6 m) was used which is vapor permeable (Butt, 2006). In August 2013, the home was reroofed and a vapor impermeable underlayment was installed with a vapor diffusion thickness of 65.6 m.

The temperature and relative humidity was monitored at all points shown in black and gray in Figure 1 on the south facing roof between two rafters. The solid markers represent combination probes that include a Honeywell 192-103LET-AO1 that measured temperature and a Honeywell HIH-4000 that measured relative humidity. The markers with black borders are Campbell Scientific, Inc., HMP60 temperature and relative humidity probes that measure the outside and attic climate. The sensors were connected to a Campbell Scientific, Inc., CR1000 data logger with measurements recorded every 15 minutes. With these measurements the absolute moisture in the roof system could be compared before and after the vapor barrier was installed underneath the roof.

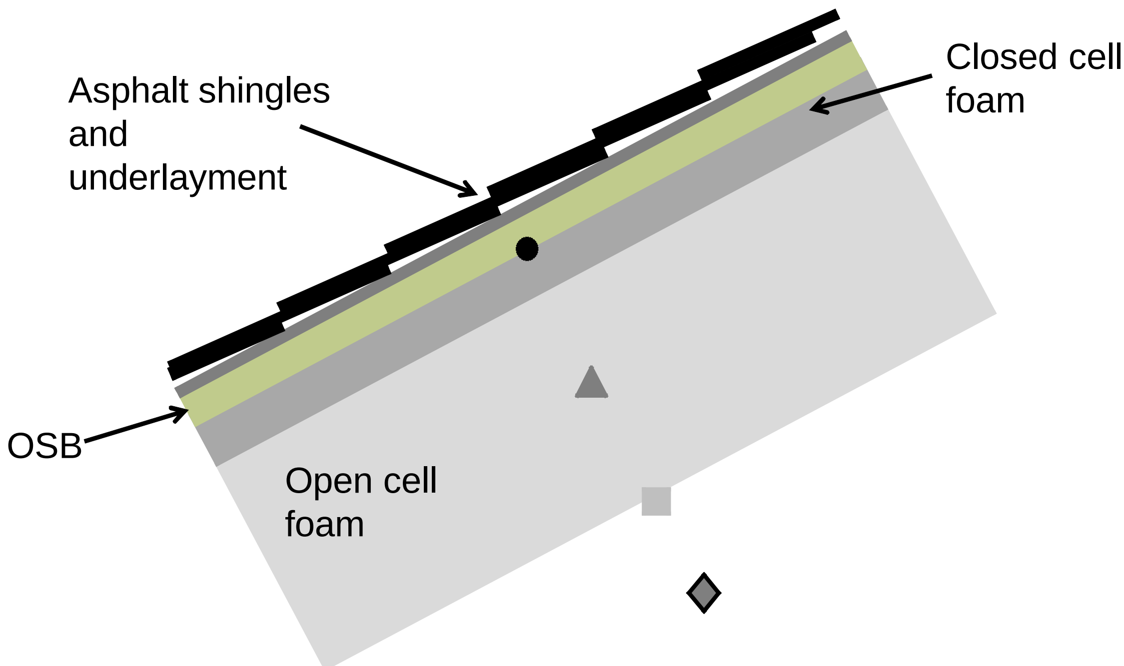
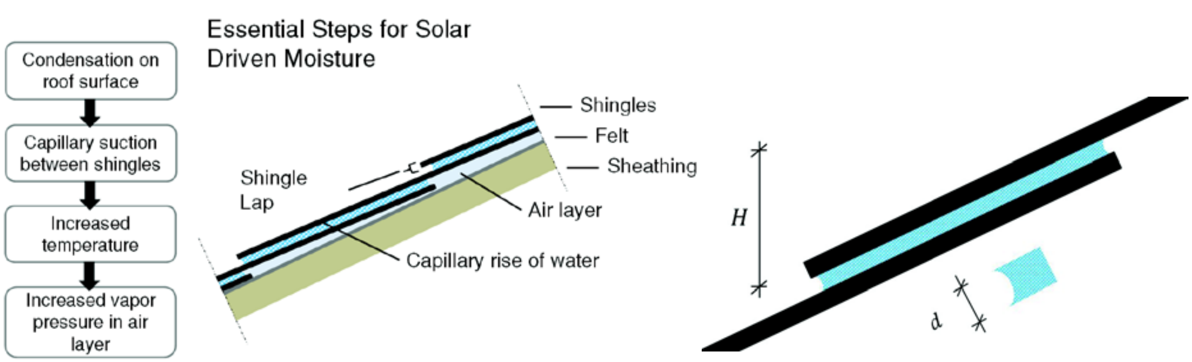


Figure 1. Schematic of the roof assembly materials with locations of temperature and relative humidity measurements.

Results

Can solar driven moisture occur from a strictly physical standpoint?

Solar driven moisture as discussed above requires certain physical characteristics to occur. The main characteristic that was investigated is whether favorable conditions are present for capillary action to draw water up the roof in the gap between where one shingle overlaps the one underneath it. It should also be noted that if liquid water should travel underneath the shingles then the underlayment should stop liquid water from reaching the sheathing. However, the vapor permeable felt paper does allow water vapor to move to the top of the roof sheathing surface. The potential effect of solar driven moisture was also investigated. Simulations were used to determine if the air layer above the sheathing had a high relative humidity how it would affect the roof sheathing and attic conditions. The essential steps for solar driven moisture to occur are described in Figure 2a.



a. b.

Figure 2. a. The four steps to solar driven moisture. b. Illustration of the suction height, *H,* and the gap distance between the shingle sheets, *d*.

Condensation on the roof surface is the first essential step for solar-driven moisture, which will occur if the surface temperature is below the exterior dew-point temperature. For the surface to cool, long-wave radiation exchange between the surface and sky must exist. This occurs when the sky has few clouds and then dew is maximized in light wind conditions (Richards and Oke, 2002). The south roof surface temperature of the unvented attic test home began being measured 20 May 2013. Since that day until 6 December 2013, 180 of the 201 days had at least three hours a night where the roof temperature was below the outdoor dew point temperature.

The next essential step for solar-driven moisture is for the condensed water to be transported between the laps of the shingles by a capillary force. For the likelihood of such a transport mechanism to be maintained, the capillary action of the physical shingle assembly needs to be determined. Equation 1 describes the suction height, H, that could possibly be achieved by capillary action (Hens, 2007):

$$H = \frac{2 \cdot \sigma \cdot \cos\theta}{g \cdot d \cdot \rho_{water}}, \qquad (1)$$

where σ is the surface tension coefficient, θ is the contact angle between the shingle surface and the water meniscus, g is the acceleration of gravity, ρ_{water} is the density of water, and d is the length of the gap between the shingles. Figure 1b describes the physical parameters. The gap distance between the shingles is not readily available in the literature. In general, θ can be assumed to equal zero (Hagentoft, 2001). After the known variables are inserted (σ (water to air) = $75.9 \cdot 10^{-3}$ N/m, ρ_{water} = 1000 kg/m^3, g = 9.8 m/s^2), the simplified expression of the suction height becomes Equation 2:

$$H = \frac{1.5 \cdot 10^{-5}}{d}\ [m]. \qquad (2)$$

According to Figure 2b, the suction height, which is also the required height to fully saturate the gap distance between the shingles, will depend on the slope of the roof. Therefore, a maximum gap between the shingles can be estimated for different roof slopes to maintain capillary suction. The width of a shingle is 0.34 m and with a 0.13 m exposure results in an overlap length of 0.21 m. The overlap length, together with a given roof slope, yields both H and d, as presented in Table 1. The slope of the roof will determine the required suction height to enable water to fill the gap between the shingles with water by capillary suction. The maximum gap distance to maintain capillary suction between the shingles is estimated for the roof slopes of 3:12, 4:12, 8:12, and 12:12. If the gap distance is larger than specified then the capillary force will not be strong enough to pull water up the gap.

Table 1. Summary of roof slope, capillary height, and maximum capillary gap distance[a].

Roof slope	3:12	4:12	8:12	12:12
Capillary height, *H* (m)	0.05	0.07	0.12	0.15
Maximum gap distance, *d* (μm)	≤ 305	≤ 234	≤ 133	≤ 105

[a]For a 0.34 m shingle width and an overlap of 0.21 m.

Table 1 shows that the maximum gap distance to allow for capillary suction between the shingle sheets is very small. This maximum gap distance, d, must not be exceeded; otherwise, the suction pressure will drop and a complete filling of the interface will not exist. To get a better understanding for shingle gap widths in the field the authors measured some asphalt shingle gap widths. Using feeler gauges the authors probed a few roofs and found that the gap distances were very small. As an example, for a 4:12 pitch roof, a 229 μm feeler gauge would not slip between the shingle laps. However, valleys in the asphalt of different shingle samples were measured as deep as 1 mm when using a depth gauge. Therefore regardless of the roof pitch the actual gap distance between the shingles is likely to exceed the maximum distances defined in Table 1 at some point along the path due to the rough surface of the asphalt shingle. In addition, the shingles are usually designed with an adhesive strip, which will most likely act as a dam to block liquid water from moving up the lap.

The above analysis shows that solar driven moisture does not likely occur as described by Rudd (Rudd, 2005). However, for the sake of argument let us consider that at in-situ conditions water vapor might somehow move through the asphalt shingle system and increase the humidity of the air layer below. This might be the case if the asphalt shingles are not providing an appropriate air barrier that might allow humid air beneath the shingles.

A two-dimensional simulation model was created in WUFI®2D 3.3, in accordance with Figure 3 to investigate the effects of a humid air layer between the shingles and roof sheathing. In order to establish the most favorable scenario for solar driven moisture, the lap between the shingles was assumed to be completely saturated with water at all times. The purpose was to study the effect of the relative humidity of the air layer underneath the shingles on the moisture content of the wood sheathing. Two simulations were performed; one with a liquid water filled interface between the shingle laps and one without any water between the shingles.

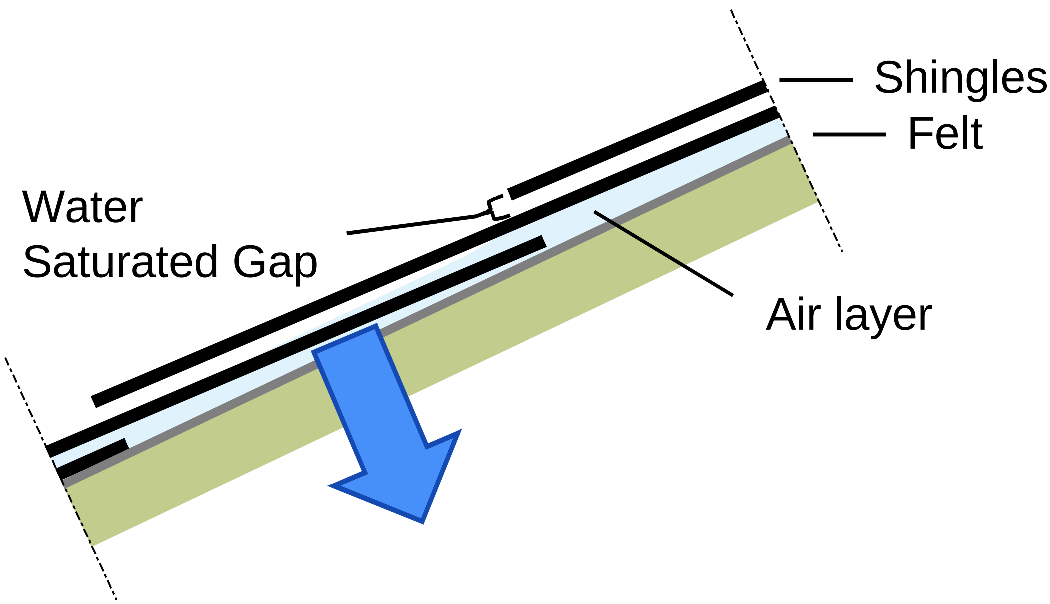


Figure 3. A two-dimensional model was created in WUFI® 2D to simulate an asphalt shingle roof assembly. A moisture source was added to the left side of the air layer, representing the assumed water saturated shingle lap. The arrow indicates the possible direction of water vapor diffusion.

The case assuming a saturated water layer could simulate the situation where capillary action is the cause for adding water vapor to the air layer or where the shingles might let humid air pass to the air space between the shingles and underlayment. This might also represent a scenario where the shingles have a high air permeance. The results from the simulations are presented in Figure 4.

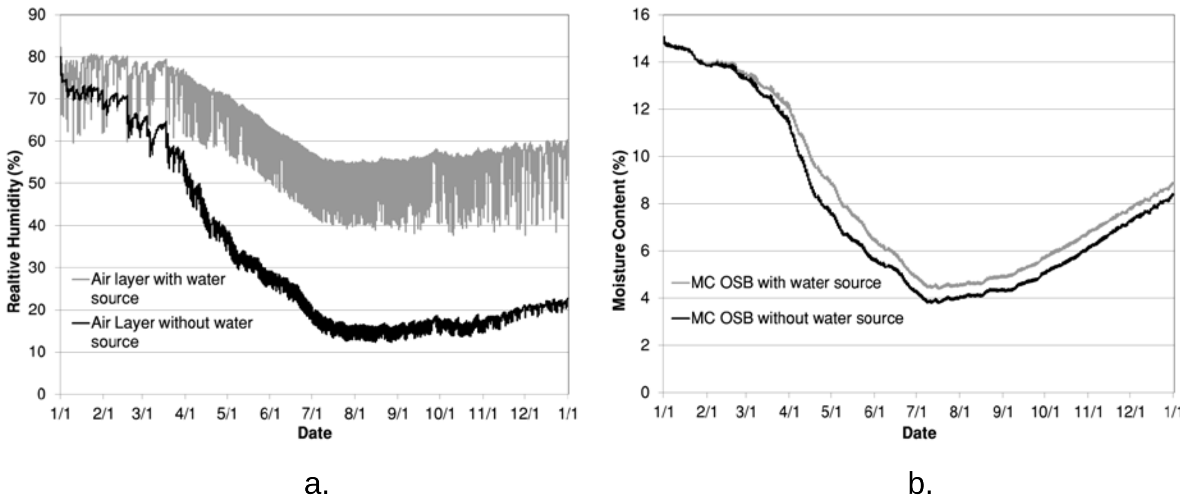


Figure 4. a. The annual variation in relative humidity of the air layer underneath the shingles with and without an assumed constantly saturated gap between shingles b. The annual variation of moisture content in the wood sheathing with and without a water saturated shingle gap

The relative humidity increases in the air layer with the existence of the water-saturated shingle interface as shown in Figure 4a. However, this increase is not sufficiently large to make a significant impact on the moisture content of the roof underlayment. According to Figure 4b, the moisture content of the wood sheathing only increases slightly by the existence of a constant liquid-water-saturated shingle gap. 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.

Does solar driven moisture occur in a real house with an unvented attic?

To further investigate the probability of solar driven moisture occurring, ORNL conducted an experiment on a real home with an unvented attic. Measurements of the absolute humidity in different locations in this home are shown in Figure 5. The measured diurnal variation in attic absolute humidity is shown for three sunny summer days in Figure 5. This diurnal variation has been attributed to solar driven moisture (Rudd, 2005). The partial pressure of water vapor at the different sensor locations correspond to the markers in Figure 1. Figure 5 helps in understanding how water vapor moves by diffusion in the roof assembly. Notice that when the sun is out the vapor moves from the roof sheathing to the attic, but during the night the vapor moves in the opposite direction. This also shows that the temperature of the roof sheathing directly affects the amount of moisture the sheathing can hold. This is described in the temperature dependent sorption isotherms defined for wood (Bergman et al., 2010). As the temperature of the sheathing increases the wood desorbs water vapor.

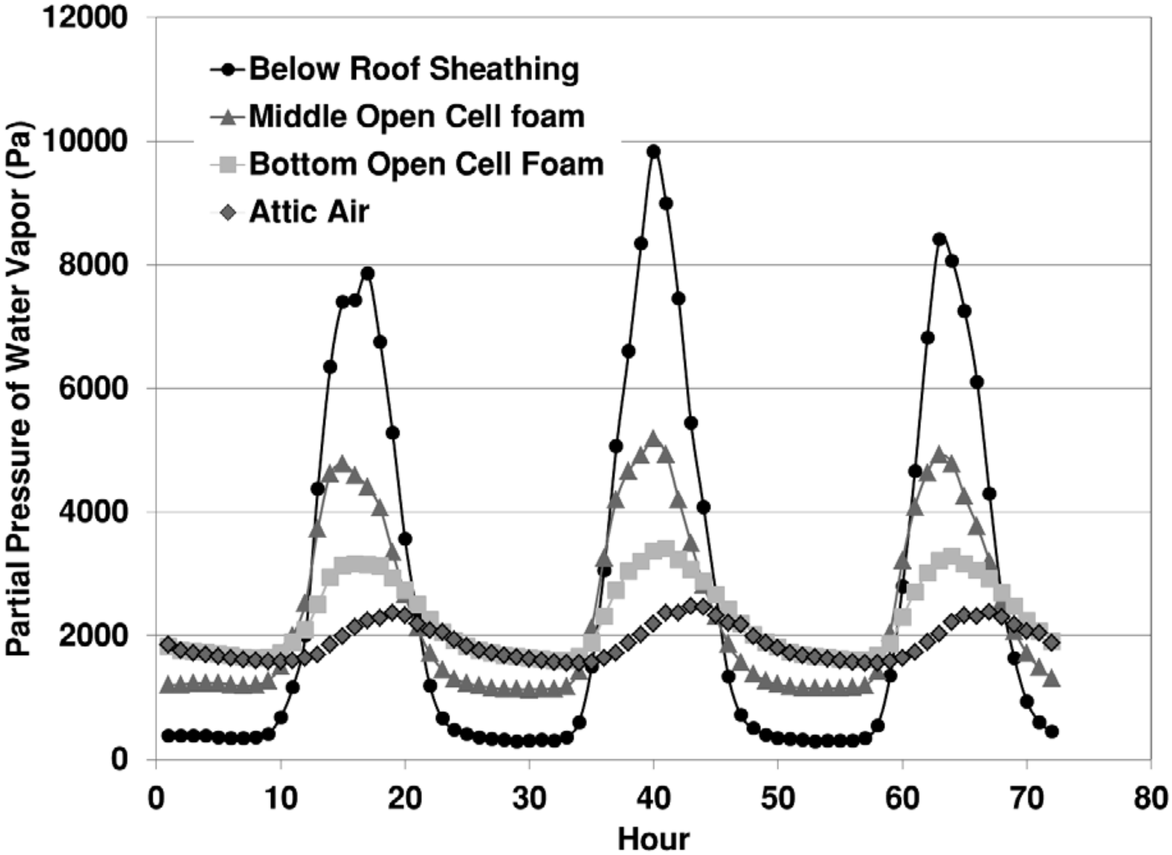
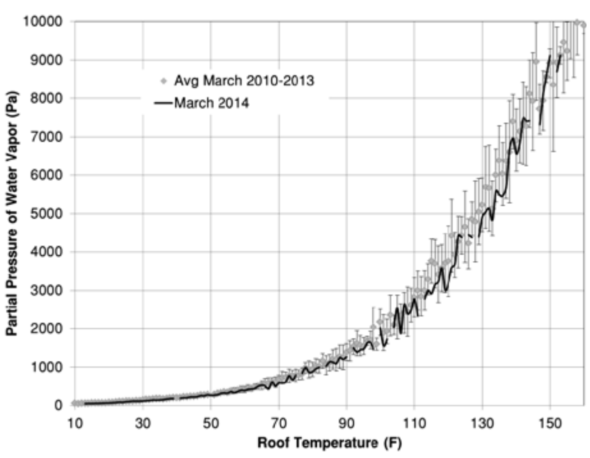


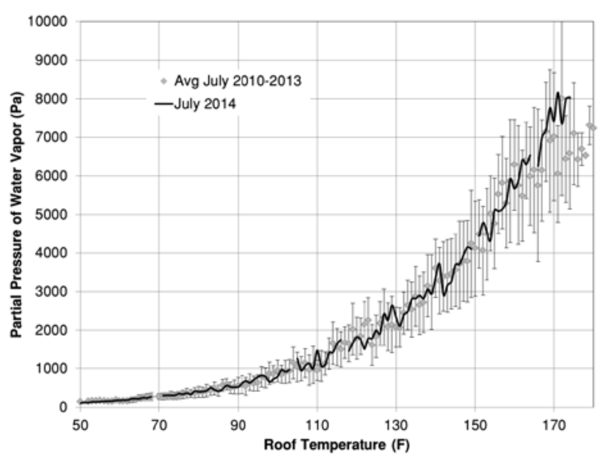
Figure 5. Partial pressure of water vapor at measurement locations throughout the attic and interior of the test home for three sunny summer days.

From construction in 2009 to July 2013, the unvented attic test home had 15# felt underlayment with a high water vapor permeance between the asphalt shingles and oriented strand board (OSB) roof sheathing. During August of 2013, the home was reroofed and a vapor impermeable underlayment was installed. The partial pressure of water vapor below the roof sheathing was compared before and after the reroofing to determine if solar driven moisture was occurring through the roof assembly. Since the measured absolute moisture under the roof sheathing is a function of sheathing temperature , ORNL compared the partial pressure of water vapor as a function of temperature for the same months before and after the addition of the vapor impermeable underlayment.

Figure 6 shows the temperature dependent partial pressure of water vapor for about 6 months (March) and one year (July) after the vapor impermeable underlayment was installed above the roof sheathing (black curve). The grey points are the average temperature dependent water vapor curve for the same month for the four previous years with a vapor permeable underlayment installed. The grey error bars represent ± 1 standard deviation from the average. Notice that the curve for the impermeable underlayment is within the bounds of one standard deviation from previous years with the permeable underlayment. Humidity was monitored for one year after the vapor impermeable underlayment retrofit and all months show similar results as March and July. This shows that there is no significant moisture source coming through the roof into the attic. If solar driven moisture was occurring, then the impermeable membrane would remove this moisture source and the temperature dependent vapor pressure would have decreased after installation of the barrier. This was not observed.



a.



b.

Figure 6. Temperature dependent partial pressure of water vapor before and after the impermeable underlayment retrofit. Plot a. shows the average partial pressure for March for the three years before the retrofit (gray markers) and for March 2014 (black line) which was 6 months after the retrofit. Plot b. shows the average partial pressure for July for three years before the retrofit (gray markers) and for July 2014 (black line) which was one year after the retrofit.

Conclusion

ORNL investigated the phenomenon of solar driven moisture through asphalt shingle roofs. This is important because as unvented attics become more popular it is imperative that they are designed to be durable to moisture as well as cost effective as possible. The phenomenon was studied from two standpoints. First it was studied from a theoretical standpoint to determine if the physical roof system allowed for capillary suction of water between the laps of the shingles (gap distance). Secondly it was studied from an experimental standpoint where the moisture level in the roof assembly was measured before and after a vapor impermeable membrane was installed under the shingles.

The authors have shown that from a theoretical standpoint, the gap distance between the shingles to maintain capillary suction is likely exceeded due to the rough nature of the asphalt shingle surface. Also if vapor moves below the shingles and humidifies the air space above the felt paper the effect on the roof sheathing moisture content is not significant.

Furthermore, findings showed that from an experimental standpoint the temperature dependent absolute humidity below the roof sheathing is unchanged whether the roofing underlayment is permeable or impermeable to water vapor. This suggests that there is not a significant moisture source coming into the attic from above the roof sheathing. Or more broadly, 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.

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, wood’s potential to hold moisture is temperature dependent. When wood gets hot it desorbs water; when wood cools it absorbs water. As the wood gets hot during the day the wood in the attic desorbs water – especially the roof sheathing. This same phenomenon happens in vented attics but the fact that the attic venting helps remove moisture and that the vented attic air temperature gets significantly higher than an unvented attic makes the affect harder to detect. Since the vented attic gets so hot, even though the absolute moisture in the attic rises during the day, the relative humidity goes down, which is opposite of what is seen in the unvented attic. Based on these finding, 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 to stop said phenomenon.

Declaration of conflicting interests

The authors declare that there is no conflict of interest

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Appendix

WUFI®2D 3.3 heat and moisture modeling software was used to simulate the relative humidity and moisture content of the building materials in the roof assembly based on measured outdoor weather conditions and the measured relative humidity and temperature below the roof sheathing. The simulation was run for one year of actual weather. The initial conditions of the simulation were set to 20°C and 80% relative humidity. Table A-1 below shows the material properties of each object in the WUFI simulation.

Table A-1. Material properties for the roof assembly moisture content simulation.

Building Material		**Asphalt shingle**	**Air Layer**	**Felt Under-layment**	**Oriented Strand Board (OSB)**	**Closed Cell Foam**	**Open Cell Foam**
Basic Parameters	**Bulk density [kg/m^3]**	280	1.3	715	630	39	7.5
	Porosity [-]	0.001	0.999	0.001	0.6	0.99	0.99

	Thickness [mm]	3	1	1	13	25	138
Thermal Parameters	**Heat capacity [J/kgK]**	1500	1000	1500	1500	1470	1470
	Thermal conductivity [W/mK]	12.0	0.047	4.0	0.13	0.025	0.037
	Moisture supplement [kg/m^3]	0	0	0	1.5	0.7	0.25
Hygric Parameters	**Sorption moisture at 80% RH [kg/m^3]**	-	-	-	95	1.12	0.21
	Water vapor resistance factor [-]	10000	0.79	993.17	650	70.6	2.14