Sealed Attics Exposed to Two Years of Weathering in a Hot and Humid Climate

William Miller, Ph.D.
Member ASHRAE

Sudhir Railkar, Ph.D.
Member ASHRAE

Ming Shiao, Ph.D.
Member ASHRAE

Andre Desjarlais, P.E.
Member ASHRAE

ABSTRACT

Field studies in a hot, humid climate were conducted to investigate the thermal and hygrothermal performance of ventilated attics and non-ventilated semi-conditioned attics sealed with open-cell and with closed-cell spray polyurethane foam insulation. In the ventilated attics the relative humidity drops as the attic air warms; however, the opposite was observed in the sealed attics. Peaks in measured relative humidity in excess of 80 – 90% and occasionally near saturation (i.e., 100%) were observed from roughly solar noon till about 8 PM on hot, humid days. The conditioned space of the test facility is heated and cooled by an air-to-air heat pump. The space was not occupied and had no interior moisture load due to occupancy. Moisture pin measurements made in the sheathing and absolute humidity sensor data from inside the foam and from the attic air show that moisture is being stored in the foam and the roof sheathing. The moisture in the foam diffuses to and from the sheathing dependent on the pressure gradient at the foam-sheathing interface which is driven by the irradiance and night-sky radiation. Ventilated attics in the same hot, humid climate showed less moisture movement in the sheathing than those sealed with either open- or closed-cell spray foam. The temperature measured on the underside of the sheathing was 10°C cooler (north-facing roof deck) and 20°C cooler (south-facing roof deck) for the ventilated attic as compared to the sheathing temperatures in the sealed attics. Foam was physically removed and moisture was observed around the rafter and sheathing interface. Observations, sheathing temperature and partial pressure measurements suggest two-dimensional heat and moisture flow that is cyclic moving in and out of the depth of the roof and that also moves along the plane of the sheathing towards the rafters. The use of permeable spray foam in a hot humid climate inadvertently allows moisture to be held against the roof deck. The moisture transfers back to the attic air as solar irradiance bears down on the roof.

INTRODUCTION

Roughly half of the 112 million U.S. homes were built from about 1960 till 1979 (U.S. Census Bureau 2013), and the prevailing building code was ASHRAE 1980 (ASHRAE 90-1980). Also single-family homes built with slab-on-grade foundations rose from 34% of all homes constructed in 1971 to 45% of all homes built by 2013 (U.S. Census Bureau 2013). In other words, by 2013, 45% of all new and existing homes in the southern and western U.S. had slab-on-grade foundations. In the colder northern climates, basements dominate about 80% of the residential market and a smaller percentage of HVAC systems are placed in the attics (CB 2013). Although as the demand and price for land rose, the percentage of 2-story homes built in the northeast jumped from 44% in 1971 up to 70% by 2013. These homes typically have a HVAC system per floor, and the unit conditioning the upstairs has its duct system in the attic, which raises the statistic for HVAC and ducts in attics to about 52% of all single-family homes.

William Miller is a Building Scientist employed at the Oak Ridge National Laboratory (ORNL). Andre Desjarlais conducts Program Development on behalf of the Energy and Transportation Division at ORNL. Sudhir Railkar is the Research & Development Manager for Steep Slope Roofing at GAF in Parsippany, NJ. Ming Shiao is a Materials Scientist working at GAF in Parsippany, NJ.

The convenience of the attic space appeals to builders, who all too often install the HVAC unit and the ducts in the attic to conserve living space while completing the rough-in at a low first cost. However, installing the HVAC and ducts inside an unconditioned and ventilated attic is not the most energy efficient option because of the extreme summer and winter operating temperatures occurring in the attic. Parker, Fairey and Gu (1993) simulated the effects of ducts on space conditioning Florida homes and observed that air leakage and heat transfer to the duct were major contributors to the peak electrical burden on the FL utility. Walker, I.S. (1998) in his bibliography of duct air leakage reports average measured leakage rates of roughly 7% to a maximum of 20% of the supply airflow. To improve envelope performance, researchers opted to literally encapsulate the HVAC and ducts by moving the boundary of the insulating planes to the roofline, gables and eaves of the attic. The concept was first introduced by Building Science Corp (Rudd and Lstiburek, 1998). They built and monitored test homes in a hot, dry climate and demonstrated that the prototype homes with unvented attics yielded significant cooling and heating energy savings over a conventional home with ventilated attic. Transforming residential attics into a non-ventilated semi-conditioned attic space has therefore gained approval among builders, Chasar et al. (2010). Boudreaux, Pallin and Jackson (2013) however recommend that sealed attics be conditioned to mitigate the moisture buildup issue as do Roppel, Norris and Lawton (2013). Building Science has successfully demonstrated a unique ridge vent that is vapor permeable but air impermeable, and can be used to vent moisture in sealed attics, Lstiburek (2015). However, field data demonstrating successful implementation in all climates are sparse and there still remains an educational gap in the best practices for builders. The dearth of data in hot, humid climates has caused confusion among builders and code officials because of the confounding variables affecting the hygrothermal performance of sealed attics.

NATURAL EXPOSURE TEST FACILITY

General Aniline and Film (GAF) and the Oak Ridge National Laboratory (ORNL) conducted field experiments at a natural exposure test facility (NET) located in the hot and humid climate of Charleston, SC, Figure 1. The study was conducted to better understand the effectiveness of various ventilation strategies and its impact on temperature and moisture management, Railkar et al. (2010). Two full years of field-testing were completed on different roof and attic constructions including two attics sealed with open cell spray polyurethane foam (ocSPF) insulation and closed cell spray polyurethane foam (ccSPF) insulation. All other attics were equipped with soffit and ridge ventilation set at an area ratio of 1:300 (i.e., 1 unit area of vent opening to 300 units of attic footprint).

Fig. 1. The southern exposure of the NET Facility in Charleston SC.

The attic of the NET was subdivided into seven attic modules. Barrier walls insulated and air sealed adjacent attics from each other. The barriers were made of R-15 expanded polystyrene insulation sandwiched between two pieces of oriented strand board (OSB). Different wall systems with brick and stucco claddings were similarly tested in previous field tests on the NET, Figure 1. During the course of the experiments an air-to-air heat pump maintained the interior ambient conditions at 23.9°C and 45 percent relative humidity. Salient features of the two sealed attics and a conventionally ventilated attic follow and are described in the sequence that they appear in Figures 1 and 2 (starting from the left).

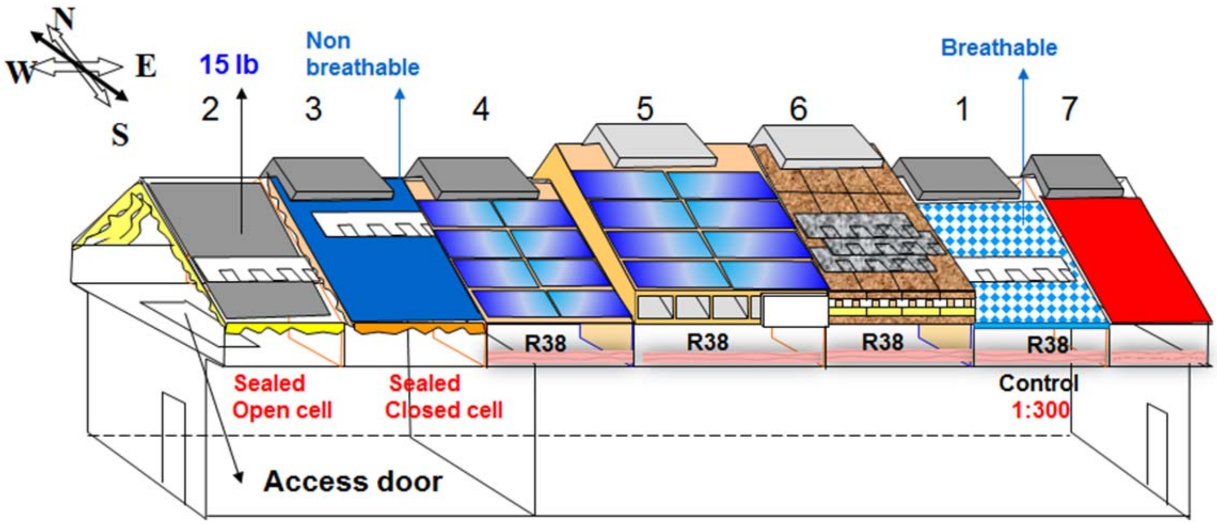

Fig. 2. Test attic assembly layout on NET Facility in Charleston SC.

Attic 2 [Sealed Attic (ocSPF)]: This attic had 6 inches of open cell spray polyurethane foam (ocSPF) adhered to the underside of plywood roof sheathing. The plywood was protected by 15 pound felt paper (8 Perm) and traditional dark colored shingles (impermeable) with solar reflectance of about 3 percent. The attic was not ventilated; it is sealed with R-22 ocSPF. The foam extended about ½-in past the 2 by 6 roof rafters to completely encapsulate the roofline. Foam was also applied to the west facing gable end of the attic bay. There is no insulation on the attic floor.

Tracer gas testing was conducted on the attic sealed with ocSPF to determine its air tightness to the conditioned space and to the outdoor environment under natural atmospheric pressures. The ASTM E 741 (2000) procedure was used to measure the airflow leakage by monitoring the decay rate of the tracer gas R-134a over time. The testing took 6 hours and yielded an air exchange rate of 0.25 per hour. Parker in his literature review reported that the Conservation Service Group (EDU 2005) evaluated air tightness of some 466 homes, 18 of the homes had attics sealed with spray polyurethane foam. The ACH of sealed homes was about 0.24, which is consistent with the present study.

Attic 3 [Sealed Attic (ccSPF)]: This attic is similar to attic 2 but is sealed with 4-in of closed cell spray polyurethane foam (ccSPF) installed to the underside of plywood roof sheathing. The ccSPF covered the 2 by 4 rafters of this attic bay. The plywood was protected by a non-breathable underlayment having a vapor permeance of 0.04. Traditional dark colored shingles with solar reflectance of about 3 percent were used as roof cover. The attic was not ventilated; it is sealed with R-22 ccSPF. There is no insulation on the attic floor. Barrier walls with R-15 insulation seal attic 3 from the adjacent attic assemblies #2 and #4. Air tightness of attic 3 has not been verified as of this report.

Attic 1 [Control Attic]: This attic had R-38 fibrous batt insulation installed on the attic floor. The sheathing was covered with a permeable membrane underlayment (16 perms) and traditional dark colored shingles with solar reflectance of about 3 percent. Appropriate length of soffit and ridge venting are added to obtain 1:300 ventilation. Tracer gas testing conducted on the ventilated attic yielded an ACH of 1.63.

INSTRUMENTATION

Micro-loggers were setup for remote acquisition and recording of field data. The loggers are equipped with 4 MB of memory, 32Bit relay multiplexers, rechargeable battery, a 115 Vac-to-24 Vdc transformer, modem, modem surge protector and associated cables. The micro-loggers scan all instrument data every 15 seconds and reduce analog signals to engineering units. Averages of the reduced data were written electronically to an open file every 15 min. Averages are calculated over the 15-min interval and are not running averages; they are reset after each 15-min interval. The electronic format is comma-delimited for direct access by spreadsheet programs.

During the construction of the NET facility, thermistors, humidity probes, heat flux transducers and static pressure sensors were installed at locations consistent from attic to attic to compare the performance of each attic bay. Figure 3 shows the placement of sensors in the two sealed attics. Table 1 describes the attic measurements, instrument range and uncertainty of measurement.

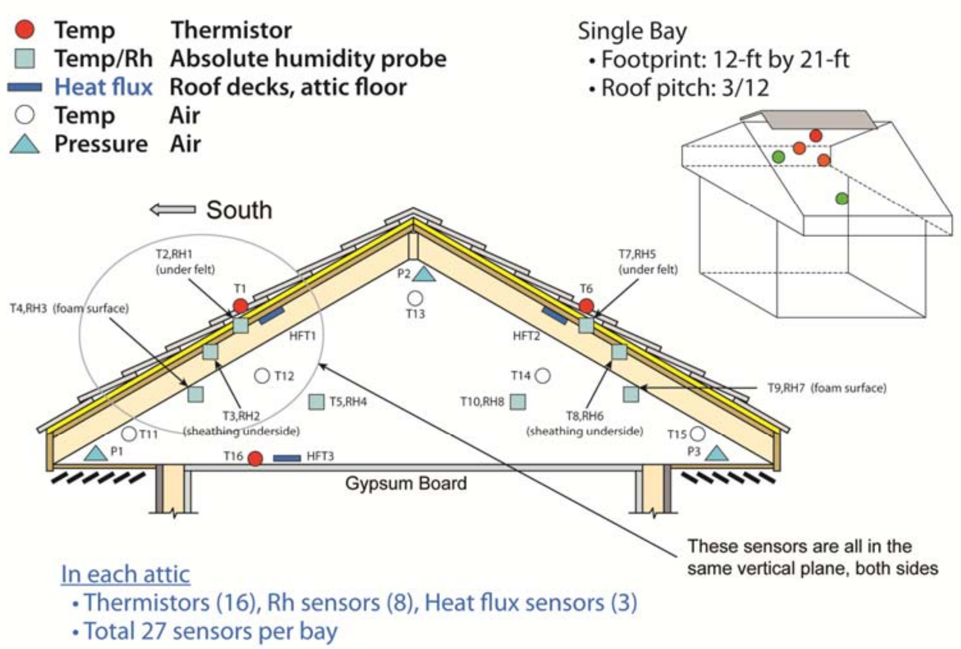

Figure 3 NET facility setup of instruments in the sealed attics 2 and 3 in Charleston, SC.

Absolute humidity sensors were fabricated using the technique described by Straube, Onysko and Schumacher (2002). A thermistor and relative humidity probe were packaged together in a vapor permeable and liquid water repellent cover fabricated from commercially available weather resistive barriers designed to allow passage of water vapor but not liquid water. Thermistor and humidity sensors were calibrated by ORNL Metrology in the above described vapor permeable protective sack.

The response of the thermistors was measured at the following nominal conditions; 15.8, 18.5, 21.2, 23.9 and 26.6 °C. All probes met the manufactures specification for the temperature response of +/- 0.2°C. Humidity sensors were checked at 25, 50, 75 and 90 % RH. The error in RH ranged from 2% of reading at 25% RH and 15°C to 6.5% of reading at 90% RH and 26°C.

The instrument setup for the ventilated attic differed slightly from that of the two sealed attics. The absolute humidity probe (T5, RH4) was placed on top of the R-38 fibrous batt insulation installed on the attic floor. The probe (T4, RH3) measured the temperature and relative humidity on a truss adjacent a roof rafter. All other instrument locations were the same as those placed in the two sealed attics.

Table 1. Descriptive and location of instruments in an attic bay of the NET facility in Charleston, SC.

Sensor ID	Sensor Type	Location	Measurement Uncertainty	Measurement Range
South-Facing Roof deck				
T1	Thermistor	Between asphalt shingle overlap	+/- 0.2°C	-60 to 150°C
T2, RH1	Absolute Humidity • Thermistor • Relative Humidity	Between underlayment & sheathing	+/- 0.2°C +/- 5%	-60 to 150°C 25 to 100% RH
T3, RH2	Absolute Humidity • Thermistor • Relative Humidity	Between underside of sheathing and spray foam	+/- 0.2°C +/- 5%	-60 to 150°C 25 to 100% RH
T4, RH3	Absolute Humidity • Thermistor • Relative Humidity	At foam surface adjacent the attic air	+/- 0.2°C +/- 5%	-60 to 150°C 25 to 100% RH
T5, RH4	Absolute Humidity • Thermistor • Relative Humidity	Attic Air	+/- 0.2°C +/- 5%	-60 to 150°C 25 to 100% RH
T11	Thermistor	Attic air near soffit	+/- 0.2°C	-60 to 150°C
T12	Thermistor	Attic air midway between soffit and ridge	+/- 0.2°C	-60 to 150°C
North-Facing Roof Deck				
T6	Thermistor	Between asphalt shingle overlap	+/- 0.2°C	-60 to 150°C
T7, RH5	Absolute Humidity • Thermistor • Relative Humidity	Between underlayment & sheathing	+/- 0.2°C +/- 5%	-60 to 150°C 25 to 100% RH
T8, RH6	Absolute Humidity • Thermistor • Relative Humidity	Between underside of sheathing and spray foam	+/- 0.2°C +/- 5%	-60 to 150°C 25 to 100% RH
T9, RH7	Absolute Humidity • Thermistor • Relative Humidity	At foam surface adjacent the attic air	+/- 0.2°C +/- 5%	-60 to 150°C 25 to 100% RH
T10, RH8	Absolute Humidity • Thermistor • Relative Humidity	Attic Air	+/- 0.2°C +/- 5%	-60 to 150°C 25 to 100% RH
T13	Thermistor	Attic air near ridge	+/- 0.2°C	-60 to 150°C
T14	Thermistor	Attic air midway between soffit and ridge	+/- 0.2°C	-60 to 150°C
T15	Thermistor	Attic air near soffit	+/- 0.2°C	-60 to 150°C
T16	Thermistor	On Gypsum board facing attic	+/- 0.2°C	-60 to 150°C

Heat flux transducers were placed on the underside of the south- and north- facing roof decks and on the attic floor, sandwiched between the gypsum ceiling and the R-38 batt insulation. A heat paste is used to reduce contact resistance between the HFT and the gypsum board. All transducers were calibrated in accordance with ASTM C 518-10 (ASTM 2010). R&D Services from Cookeville, TN used a Fox Heat Flow (FHF) meter having a 0.305- by 0.305-m footprint to measure the thermal resistance of batt insulation insulating the attic floor of attic 1, Table 2. Each HFT was placed in a 0.305- by 0.305-m (30- by 30-in.) guard made of gypsum board and from the same lot of batt insulation calibrated in the FHF meter. The HFT and checked batt insulation were later placed in the attic 1 bay. Use of the guard corrects for the shunting of heat flow around the transducer. The manufacturer states accuracy of their sensor as ±1% of full-scale reading with a sensitivity of about 4.1 W/m^2 per mV of signal (1.3 Btu/hr·ft^2 per mV). The stated time constant is ≤ 5s. R&D calibrations showed them to be accurate within ±5% of the instrument's reading.

Table 2. Calibration of fiberglass batt insulation used as guard for the ceiling heat flow of attic 1.

Specimen	Thickness	Density	Apparent Thermal Conductivity	Thermal Resistance
	(in)	(lbf/ft^3)	(Btu-in)/(ft^2 ·hr· ^{o}F)	(hr·ft^2 ·^{o}F)/Btu
13-3411	12.000	0.53	0.3056	39.3
13-3422	12.001	0.53	0.3417	35.1
13-3423	12.000	0.54	0.3448	34.8
13-3423	12.000	0.54	0.3448	34.8
1 in = 0.0254 m; 1 lbf/ft^3 = 16.02 kg/m^3; 1 (Btu-in)/(ft^2 ·hr· ^{o}F) = 1.442 W/(m·K) 1 (hr·ft^2 ·^{o}F)/Btu = 6.7 (m^2·K)/Watt				

Measuring the moisture content of wood is a key fundamental measure of hygrothermal performance, because the measure is directly relatable to the potential for mold growth leading to the decay of wood components. Viitanen (1997) reported fungus requires moisture content (MC) of 25-28% for growth. Details for the formulation and benchmark of an algorithm to compute moisture content is presented in Appendix A.

FIELD EXPERIENCE

Field testing and data collection started September 2013 and continued through December 2015. During the course of study two anomalies were observed in reduced data for the sealed attics: 1) during the warmer months the relative humidity of the attic air increased as the temperature of the attic air increased, and 2) the heat flow crossing the ceiling was more than double the ceiling heat flow measurements for ventilated attics having R-38 (IECC 2012 code) levels of insulation. Traditional dark colored asphalt shingles having a solar reflectance of 3 percent cover both sealed attics and the ventilated attic.

Sealed Attic — Relative Humidity Trends

Trends in attic moisture for the sealed attics differed from trends for the conventionally ventilated attics, Figure 4. The relative humidity in the attic sealed with ocSPF showed values in excess of 80 to 90% and occasionally near saturated air was measured during late afternoons on warm to hot days. In other words, the moisture content in the attic sealed with ocSPF was consistently high from solar noon to around 8 PM; example trends are shown for 7 contiguous June/July days in Figure 4. The attic sealed with ccSPF shows less of an increase in attic air relative humidity than that observed for the attic with ocSPF. Cloud cover dropped the solar irradiance during the week and the attic relative humidity also dropped below 70% for both sealed attics because the sun did not drive stored moisture from the plywood and ocSPF into the attic air. The trend in peak relative humidity was not observed in either sealed attic during the winter months. In comparison, the ventilated attic (Figure 4) shows drops in relative humidity as the attic air warms.

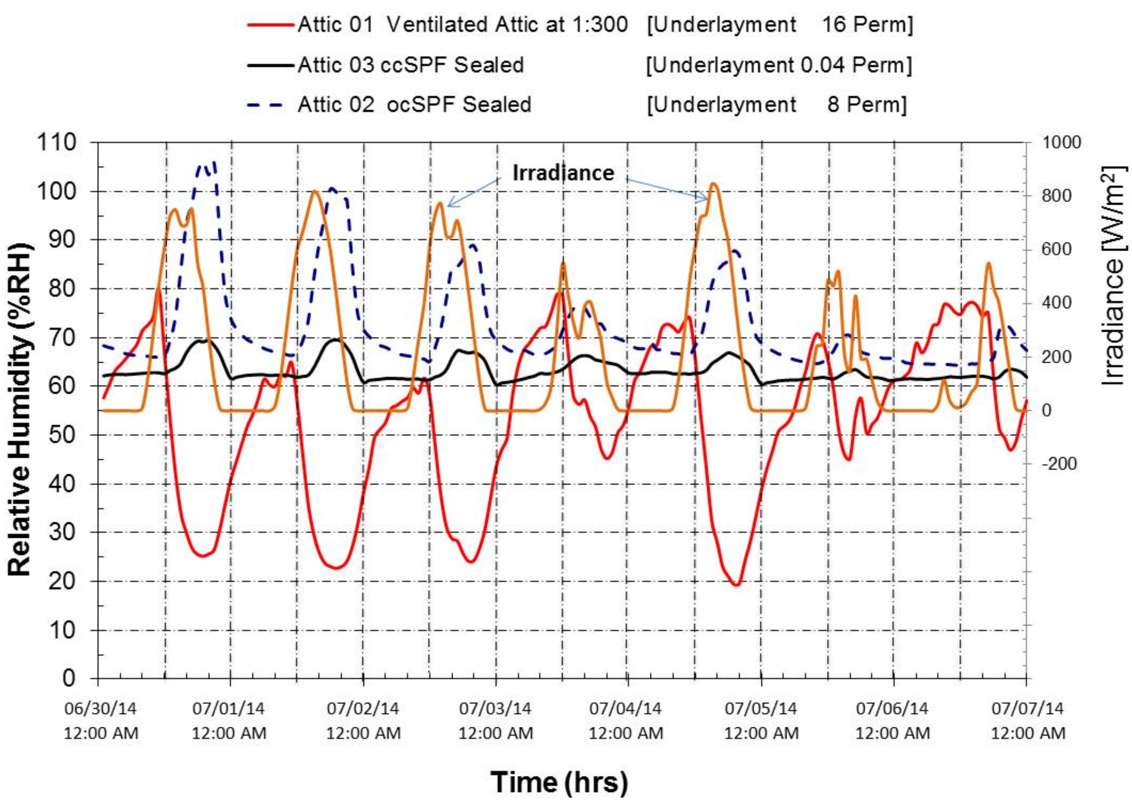

Fig. 4. Relative humidity of the attic air measured in the attics sealed with ocSPF and with ccSPF and also in the conventionally ventilated attic.

As temperature increases, the moisture bearing capacity of the air increases and by definition of relative humidity (partial pressure of water vapor in air to the partial pressure of water vapor at saturation for the same temperature and pressure of the actual state) it should drop not rise as observed in the sealed attics. Instrument measurements and data acquisition channels were checked for consistency. A portable relative humidity sensor yielded measures within 1 percentage point relative humidity of the field sensor. Next the portable sensor was held close to the ocSPF adhered to the south-facing roof deck. The test was made in October 2014 around 2 PM. The humidity readings began to steadily climb from 55% to 65% over a brief 10 minute period. The result indicated that moisture was being driven out of the foam as the sun heated the south-facing roof structure.

A section of the open cell spray foam was removed in August 2013 from between 2 by 6 rafters on the north-facing roof deck, Figure 5. The sheathing's underside was slightly wet to the touch. It is keenly interesting that water marks are observable around the exposed rafters. The thermal resistance through the depth of the rafters is much less than that of the foam insulation. Therefore the sheathing temperature at the rafter would be less than that measured between the sheathing and foam during daylight hours. Measurements show the underside sheathing in contact with foam to reach 60 to 70^{o}C during the summer. Hence there is a strong potential for 2-dimensional heat and moisture transfer with movement into the depth of the roof deck and along the plane of the sheathing toward the rafters.

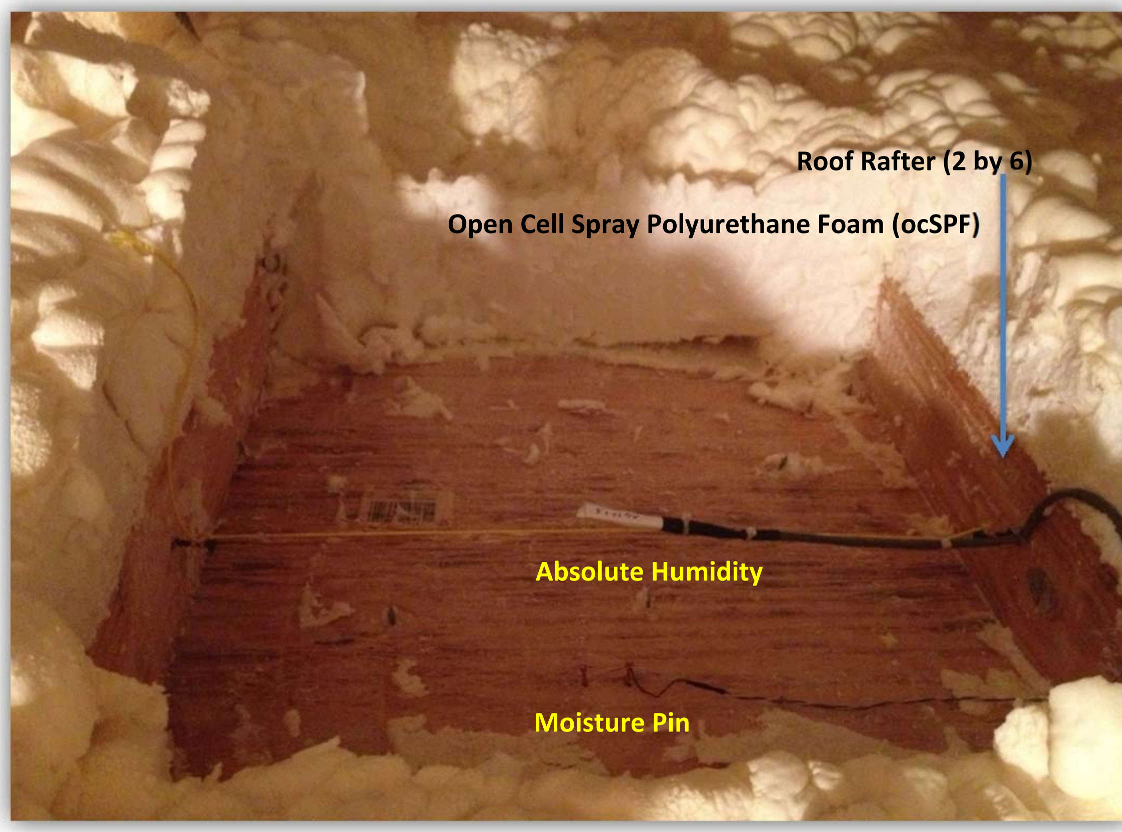

Fig. 5. The sheathing on the north facing roof deck. Open cell spray polyurethane foam insulation removed to inspect sheathing and add instruments after 2 years of climatic exposure.

Spray foam has a moisture capacity of only 0.33 kg per cubic meter of foam, while plywood at about 60% relative humidity has a hygroscopic storage capacity of 48 kg per cubic meter of wood. The wood is far more absorbent than the foam and as the sun drives moisture from the wood into the foam there forms a moisture layer at the wood-foam interface. Therefore moisture pins were nailed into the underside of the ½-in plywood prior to refilling the cavity with ocSPF, Fig. 5. Absolute humidity probes were also installed to the underside of the plywood, and mid-way through the depth of a new application of ocSPF foam and at the foam's surface adjacent the attic air.

The living space of the NET facility is comfort conditioned by a split-system air-to-air heat pump, which maintains moisture level in the comfort zone. Figure 6 provides measures of the partial pressure of water vapor computed from the absolute humidity probes placed in the living space, the outdoor air, the attic air, the surface of the ocSPF, mid-depth of the foam, the sheathing's underside and between the underlayment and topside of the plywood sheathing. Moisture content values of the sheathing are also illustrated on the secondary ordinate axis of Figure 6. Moisture content is adjusted for temperature, see Appendix A.

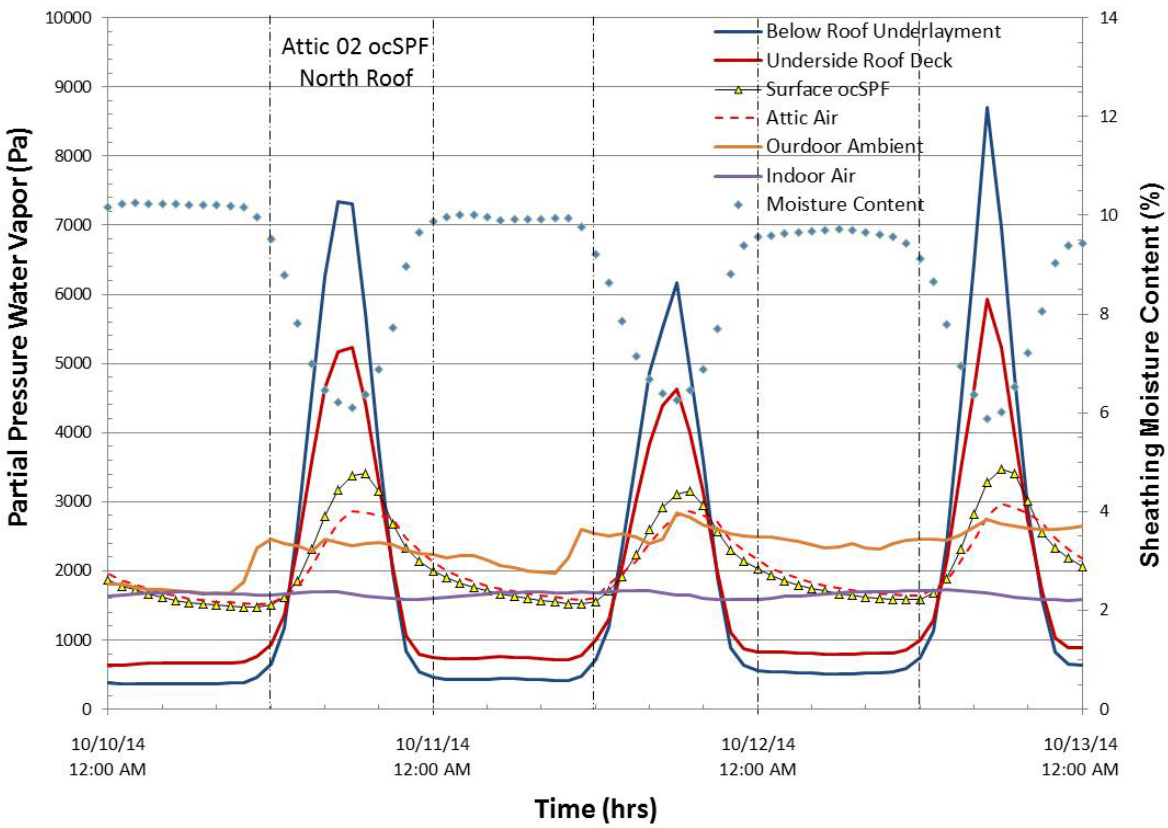

Fig. 6. The partial pressure of water vapor measured at various locations from the roof underlayment to the surface of the foam adjacent the attic air. Moisture content of the sheathing is shown on the secondary y-axis.

The absolute humidity probe yielding partial pressure of water vapor in the living space shows very little potential for moisture to diffuse from the conditioned space into the attic across the ceiling plane. For this study occupancy habits are not a factor because there were no internal moisture loads. The building owner had closed the water main during the field study because of construction and renovation of the high school adjacent the NET. It is also very interesting that around 4 to 8 PM the partial pressure of water vapor in the outdoor air is less than that of the attic air and also for that of the measures on or in the foam. At all other times the partial pressure of the outdoor air exceeds that of the attic air and that of the foam surface, Figure 6. Therefore during hours from about solar noon till about 8 PM, there is a potential, for moisture to diffuse from the plywood and foam into the attic air as actually measured earlier with a portable humidity sensor. During the evening, night-sky radiation cools the roof below the outdoor ambient and the lowest partial pressure is seen at night below the underlayment at the topside of the sheathing. At night the attic moisture is transported by air back into the foam and diffuses through the foam and into the plywood deck, Fig. 6. The following day the sun heats the roof and the moisture is driven back into the attic air thus explaining why the attic air moisture exceeds the moisture content of the outdoor air during the late afternoon immediately following peak irradiance.

The moisture content of the plywood (as measured with moisture pins) also verifies these moisture movements. During the heat of the day, the moisture content of the sheathing drops which implies that moisture moves from the sheathing into the foam. As the sun sets, the roof cools and moisture is reabsorbed from the attic air and the foam back into the roof deck. It is also keenly interesting to compare these moisture content measurements to the visual observation made when a portion of ocSPF was removed from the deck (Figure 4). The moisture pins are measuring the average moisture content through the thickness of the ½-in plywood. Removing the foam revealed the sheathing to be wet especially near the rafters. After completion of the field study, the roof shingles and underlayment were removed to verify workmanship of the roof, Figure 7.

Fig. 7. Condition of the ½-in plywood deck after 2 years of exposure. Replacement shingles and underlayment replaced Feb 2016.

A Delmhorst meter was used to measure the moisture content on the top side of the bare plywood deck. All meter readings showed both the south- and north-facing decks dry. Wood resistance was too high for the Delmhorst to yield a measurement. However the Delmhorst showed 10 to 14% moisture content at the abutting of two 4 by 8 plywood sheets where the plywood is nailed to the roof rafters.

Water damage was observed below and to the right of instrumentation placed in the north-facing roof deck, Fig. 6. The damage was near the same rafter shown in Figure 4 but was about 1.22-m below the instrumentation and about 1.6 meters up from the soffit.

Parsons and Drzyzga (2013) reviewed the challenges to sealing existing residential attics and concluded that air sealing the joint between the exterior sheathing and top plate when the exterior sheathing was not flush with the top of the top plate was problematic. They concluded it best to seal the gap from the exterior rather than from the confined interior space of the attic. Their observations are consistent with independent work conducted by ORNL on wall assemblies. The work of Hun, Spafford and Desjarlais (2014) concluded that the interface between the OSB and the top plates was responsible for most of the air leakage at the wall to roof joint and allowed the entry of unwanted moist air into the sealed attic.

Open cell SPF is very permeable being about 19 perms at a 3-in thickness; however ccSPF is only 0.5 perms for the same 3-inch thickness of closed cell SPF, Kumaran (2008). Therefore, it is very plausible that the ccSPF, being semi-impermeable, does not release as much moisture during times of peak irradiance as observed for the ocSPF, which, in turn helps explains the differences in humidity levels between the two sealed attics, shown back in Figure 4. Data similar to that in Figure 6 is highlighted in Figure 8 for the attic sealed with ccSPF.

The two graphs of the partial pressure of water vapor in the attic air and at the interior surface of the ccSPF show there is very little pressure gradient during the 3 contiguous days, Figure 8. Hence the flux of water vapor leaving the ccSPF is much less than that observed for the case with ocSPF. Also, the moisture content of the plywood sheathing (sealed with ccSPF) is seen to vary similar to that observed in Figure 6 for the plywood sheathing sealed by ocSPF. The variation in moisture content is about the same, changing from about 10% at night to 6% in the afternoon. There appears to be some moisture movement and storage in the ccSPF but it is not as large as that observed in the ocSPF case. The attic sealed with ccSPF had a non-breathable underlayment whose vapor permeance was only 0.04. Therefore moisture did not diffuse from above the asphalt shingles. Boudreaux, Pallin and Jackson (2016) conducted an experimental study on a sealed attic home and compared the moisture content below the roof sheathing before and after installing a vapor impermeable underlayment. They observed no statistically significant difference in absolute humidity before and after the vapor barrier installation.

Building Science recommended a vapor barrier be installed between the asphalt shingles and the roof deck (Research Report 0306, Feb 2003). They also stated that moisture condensing on the roof can be pulled by capillary forces through the gaps made by overlapping shingles and is then driven inwards as the sun heats the roof. Boudreaux, Pallin and Jackson (2016) examined the necessary physics for capillary movement of water within gaps made by shingle overlaps. They concluded the conditions are not favorable for the occurrence of solar driven moisture. The water stored in the plywood and foam does not come from the roof top. Plywood sheathing contains moisture; however, moisture is also coming from stagnant humid air within the attic that originates from the indoor conditioned space and/or the outdoor ambient. In the NET case the moisture originates from the outdoor ambient, leaks into the wall cavity of the exterior wall, around the top plate and into the attic.

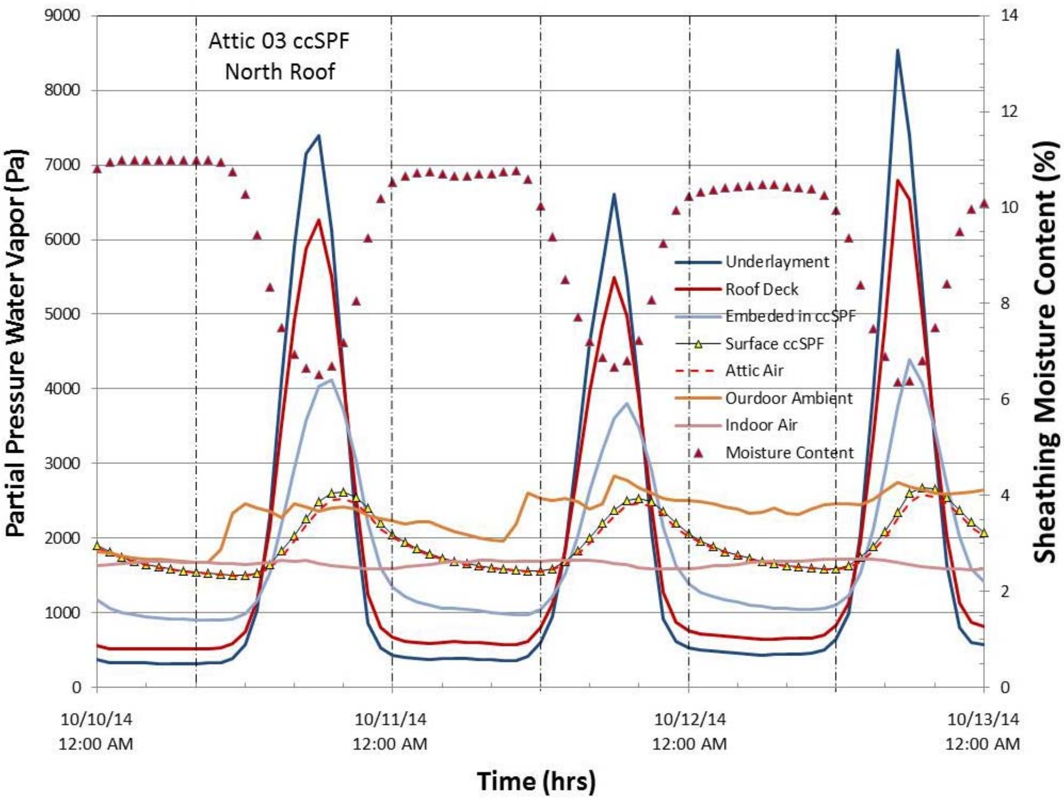

Fig. 8. The partial pressure of water vapor measured at various locations from the roof underlayment to the surface of the foam adjacent the attic air. Moisture content of the sheathing is shown on the secondary y-axis.

Moisture pin measurements are shown in Figure 9 for 3 contiguous days for the 3 attic systems to better understand the differences in water movement in the sheathing of the two sealed attics and the attic equipped with ventilation at 1:300. The data is corrected for temperature effects, see Appendix A. The moisture pin data for the two sealed attics is the same data as shown in Figure 6 for the attic sealed with ocSPF and in Figure 8 for the attic sealed with ccSPF. As stated previously, the movements of moisture in the roof decks of the two sealed attics are very similar in value and trends, dropping as the decks are heated by the sun and rising during the late evening/early morning hours as the night-sky cools the decks.

The sheathing of the ventilated attic also shows about the same moisture content during the late evening/early morning hours as seen in the sealed attics. However during periods of peak irradiance the ventilated attic does not drop as much as that measured for the sheathings of the two sealed attics. The underside of the sheathing in the ventilated attic is exposed to air while the sealed attics are covered by foam having a higher thermal resistance than air. Therefore the ventilation in attic 1 causes the temperature of the sheathing's underside to be about 10°C cooler than that of the sheathing covered by foam insulation. For the south-facing deck, the sheathing is 20°C cooler for the vented attic as compared to the sealed attics. There is less drive for diffusion from the plywood in the ventilated attic. Also the underside of the sheathing in the ventilated attic is exposed to air and its vapor diffusion resistance is of the order 0.006 (Pa·s·m) per ng as compared to a diffusion resistance for foam of about 0.4 (Pa·s·m) per ng, ASHRAE Fundamentals (2009). Therefore water vapor more readily moves from the sheathing into the air of the ventilated attic as compared to the two sealed attics. Temperature is therefore the driver. What is also very interesting is that all 3 sheathings have about the same moisture content during the late evening /early morning hours and the trends are repetitive over the 3 contiguous days of data. The moisture pins provide an average resistance measure of the wood that is made over the ½-in depth of the plywood sheathing. Moisture pin data for the south facing roof decks are very similar to that measured on the north-facing roof deck. However, the sheathing's underside temperature in the sealed attics was 20°C warmer on the south-facing deck than that of the sheathing in the ventilated attic.

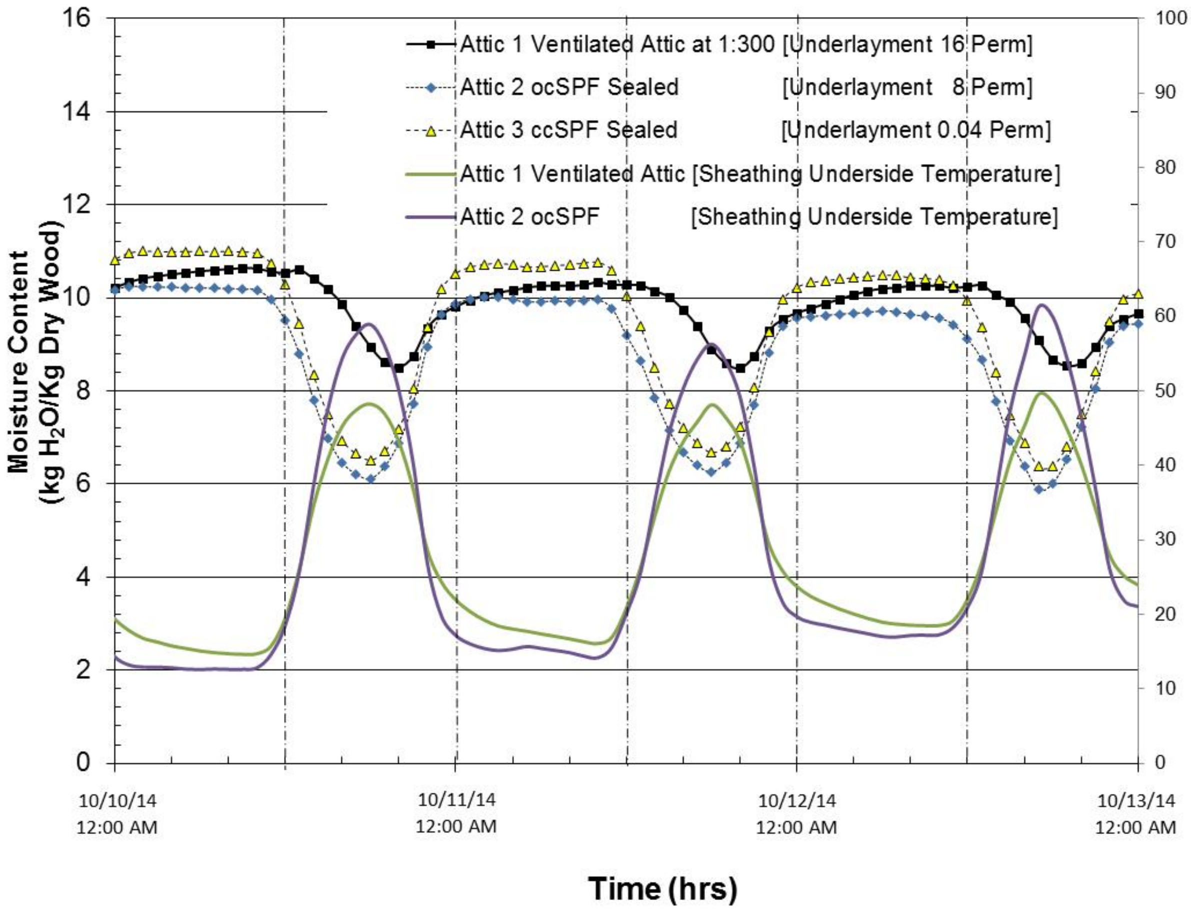

Fig. 9. The moisture content of the roof deck sheathing measured on the attics sealed with spray foam insulation (R-22 insulation adhered to sheathing) and on the attic with 1:300 ventilation (R-38 on attic floor).

Sealed Attic — Ceiling Heat Flows

Contractors sealing and insulating attics in ASHRAE Climate Zones 1 through 4 often apply spray polyurethane foam (SPF) insulation to a thickness of R-20 [Holladay, 2010; Dillon, 2013] and argue that there are "diminishing returns" for adding more insulation which increases material costs and limitations due to fire code compliance. This level of insulation does not meet the IECC 2015 prescriptive code levels for attics. Building America recommends that sealed attic R-value should follow table N1102 of the 2012 International Residential Code (IRC).

Field results from the NET facility reveal an interesting trend regarding the true behavior of attics with both open cell and closed cell SPF, as well as code levels of attic floor insulation, Figure 10. The heat fluxes crossing the attic floor of the two different sealed attics insulated with R-22 of spray foam were measured using heat flux transducers; see section on Instrumentation. The flux in both sealed attics is literally double the flux of a ventilated attic having IECC 2015 code levels of insulation on the attic floor. Twice as much heat would be entering the home through the attic due to radiation heat transfer from the decks to the bare gypsum board floor.

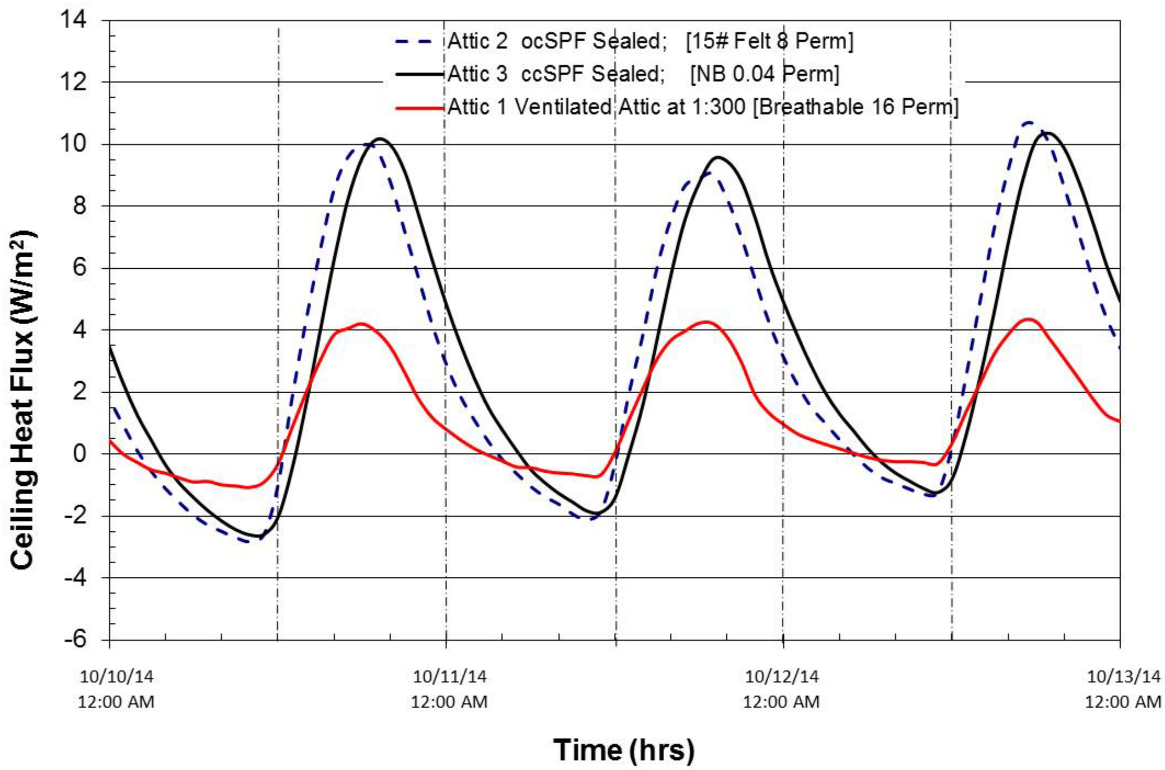

Fig. 10. The heat flux crossing the attic floor of the sealed attic (no insulation on the floor) and the conventionally ventilated attic having R-38 insulation lying on the floor.

The attic air temperatures in the sealed attics were less than that of the ventilated attic; they being only about 2 to 3°C warmer that the outdoor air. However, ceiling drywall has a low thermal resistance, about (≅R-0.45), and is susceptible to the higher heat flows despite the lower attic air temperatures in the sealed attics as compared to the ventilated attic with R-38 insulation on the attic floor. Parker (2005) conducted field tests of ventilated and sealed attics on FSEC Flexible Roof Facility (FRF). He tested a ventilated attic having R-19 on the attic floor against a sealed attic with 6-inches of ocSPF (R-22) in the roof rafters. His results were similar to the results by ORNL with exception of the magnitude in difference. The peak day flux of the sealed attic at the FRF was 60% higher than that of the R-19 ventilated attic. In comparison the NET showed fluxes 150% higher than the ventilated attic with R-38 insulation. The results should be investigated analytically for the tradeoff between cost effectiveness and energy savings to show what the optimal level of insulation should be for sealed attic systems.

CONCLUSIONS

Field experiments were conducted on a building located in the hot, humid climate of Charleston SC. Several attic systems were tested for two full years under a well-controlled indoor environment to observe the thermal and hygrothermal effects of a hot and humid climate. Three major findings were observed for attics sealed with open cell spray polyurethane foam and closed cell spray polyurethane foam as compared to a conventionally ventilated attic with R-38 insulation on the attic floor.

- The attic sealed with ocSPF showed higher moisture movement during the warmer months of the year than observed in the colder months. The attic with ccSPF showed similar trends but the moisture transfer crossing the ccSPF was much less than that observed for the ocSPF because ccSPF is less permeable than ocSPF.
- Moisture was physically observed along the 2 by 6 rafters of the attic sealed with ocSPF. Water damage was observed about 1.6 meters up from the soffit. Checks made at the completion of the field study did not show evidence of moisture near the ridge, rather water marks were observed along the rafters about mid span of the roof.
- Sealed attic insulated with spray polyurethane foam that is less than code levels of insulation will have significantly higher heat flows crossing the attic floor because the difference in thermal resistances of bare drywall as compared to an insulated ceiling predominates over the benefit of the reduced attic air temperature.

REMOMMENDATIONS

There is limited information on the flexural properties (bending stress and modulus of elasticity) of plywood and OSB. Green et al. (1999) and Ayrilmis, Buyuksari and As (2010) demonstrated that the mechanical properties of plywood and OSB decrease as the temperature of the wood increases. The repetitive drying and wetting of plywood and OSB roof sheathing should be studied to document the wood's fatigue life when subjected to the stress and strain of roof loads while exposed to the diurnal temperature and humidity levels occurring in hot and humid climates. It is clear that sealed attics have many advantages for high-performance, low-load homes. It is not clear how to achieve this end with a high-R, moisture-managed solution that is acceptable to production builders. Rose (1998) recommended an air gap be provided between the sheathing and the top of the insulation in unvented attics to allow ventilation to carry the moisture out of the roof system. Lstiburek (2015) has successfully demonstrated a vapor diffusion ridge vent that is water tight but vapor open to expel moisture from the sealed attic. His results show all the moisture migrates toward the ridge. It is the author's belief that both an inclined cavity and the vapor diffusion ridge vent are needed to solve this problem which is technologically complex, requiring consideration of both thermal and hygrothermal behavior in natural conditions, as well as requiring complex integration into builders' and trade subcontractors operations.

NOMENCLATURE

ccSPF = closed cell spray polyurethane foam

ocSPF = open cell spray polyurethane foam

RH = *Relative Humidity (%)*

Pa = *Pascal unit of pressure*

m = *meter*

MC = *moisture content of wood*

NB = *non breathable membrane*

ng = *10^{-9} grams*

R-38 = thermal resistance to heat transfer [38·(hr·ft^{2}·°F)/Btu]:IP units

= thermal resistance to heat transfer [6.7 (m^{2}·K)/Watt]: SI units

s = *seconds*

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APPENDIX A
MISCELLANEOUS INSTRUMENTATION

Weather Station

Weather data collected on the roof of the NET facility include wind speed and direction, solar irradiance, night-sky radiation, rainfall, and outdoor ambient temperature, relative humidity, and barometric pressure. These data are logged by the DAS and written to the same attic data files on a weekly basis. The outdoor air temperature was measured using a shielded thermistor accurate to +/- 0.2°C from 0 to 70^{o}C. Total global solar irradiance was also measured on the pitched roofs (one pyranometer for each roof slope). Night-sky radiation was measured using a pyrgeometer. Spectral range of the pyrgeometer is 4,500 to 42,000 nm with a non-linearity less than 1% of measure over the range -250 to 250 W/m^2.

Moisture Pins

The moisture content of wood is directly relatable to the electrical resistance of the wood, which in turn, can be related to the moisture content of the wood. The resistance of wood is typically so high that it usually cannot be measured directly without specialized equipment. Moisture pins, circuits and conversions of resistance to moisture content were developed by ORNL. A circuit for measuring the very high resistance typical of wood with a standard DAS or hand-held multi-meter is shown schematically in Figure 1a, as reported by Straube, Onysko and Schumacher (2002).

Rw is the resistance of the wood; Rp is the protection resistor (in the event that pins are short circuited by moisture on the wood surface); the triangle is an optional diode which protects the data acquisition equipment by ‘‘clamping’’ the voltage to a specific maximum if the pins are shorted; Rs is the sensing resistor; and E is the supply voltage. Typically Rp=Rs=100 kΩ and E=12V combined with a 16-bit analog-to-digital converter, Straube, Onysko and Schumacher (2002).

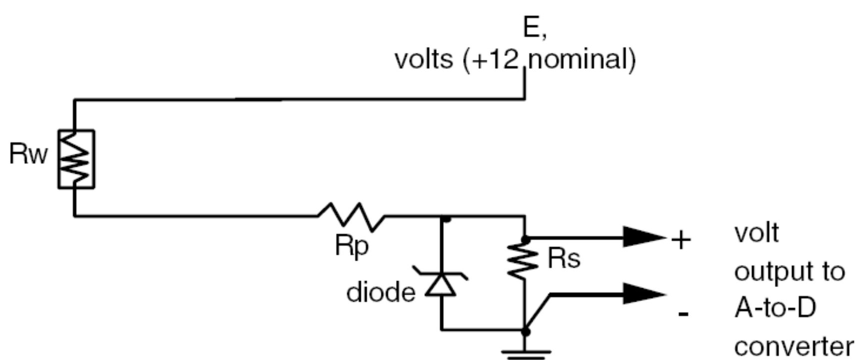

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Figure 1a. Circuit to measure resistance of wood with DAS.

Using Ohm's Law we can say that:

$$I = E / (R_W + R_P + R_S) \tag{1}$$

and

$$V = I * R_S \text{ and } I = V / R_S \qquad (2)$$

For the same current (I), equating equations (1) and (2) we have:

$$\frac{V}{E} = \frac{R_S}{(R_W + R_P + R_S)} \qquad (3)$$

Therefore, in terms of the resistance of the wood in ohms:

$$R_W = R_S\left(\frac{E}{V}\right) - R_P - R_S \qquad (4)$$

An empirical fit of moisture content to electrical resistance with and without temperature effects was formulated from literature data gleaned from ASTM D4444-13 (2013) and James (1988) and compared to data from Garrahan (1989), Carli, TenWolde and Munson (2007) and Huber Engineering (2013). The formulation of the ORNL equation takes the form:

$$MC_u = 10^{[a + b \cdot Log_{10}\{Log_{10}\{R_W\}\}]} \qquad (5)$$

where the a and b coefficients of Equation 5 are derived from linear fits to data from James (1988) and ASTM D4444-13 for 20 different species of wood, including oriented strand board data gleaned from Huber Engineering (2013). Figure 2a shows the consistency of the correlation against literature data.

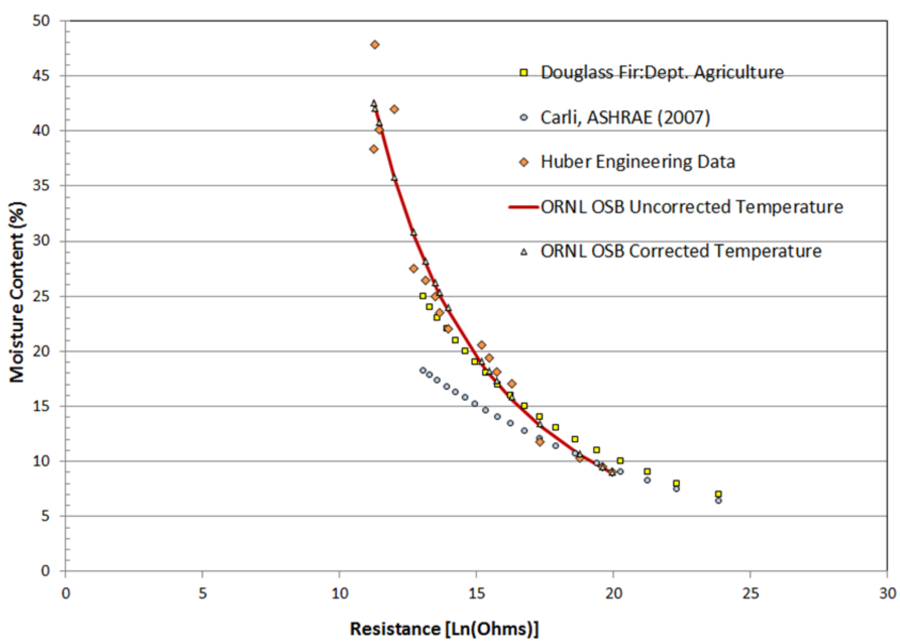

Figure 2a. Empirical fits of moisture content of Douglas fir and oriented strand board (OSB) plotted from data gleaned from the open literature. Wood measurements made at about at 20°C.

The results in Figure 2a are for a wood temperature of about 20°C. The ORNL correlation was made more robust by using data from James (1988) and Garrahan (1989) to account for temperature effects in the range of roof deck temperatures experienced on the NET facility. Note that information by James omits derivation of his correction for temperature compensation. The correction to temperature takes the form:

$$MC_{cor} = \frac{a + bx + cx^2 + dx^3 + ey}{1 + fx + gx^2 + hx^3 + iy}$$

where

x = wood temperature (°F) as measured by a thermistor adjacent each pair of pins

y = MC_u the uncorrected moisture content from Equation 5

Garrahan (1989) conducted an extensive series of moisture measures for Douglas-fir and provided correction tables usable in field and laboratory measurements. Garrrahan's results as reported by Straube, Onysko and Schumacher (2002) yielded an average error in the order of 0.5%MC for an identified species, although individual readings may be as much as 2%MC different from the oven-dry values as reported by Straube, Onysko and Schumacher. Results of the ORNL correlation based on James (1988) and ASTM D4444-13 (2013) is shown against Garrahan (1989) for wood temperatures of -5, 22.8 and 80°C, Figure 3a.

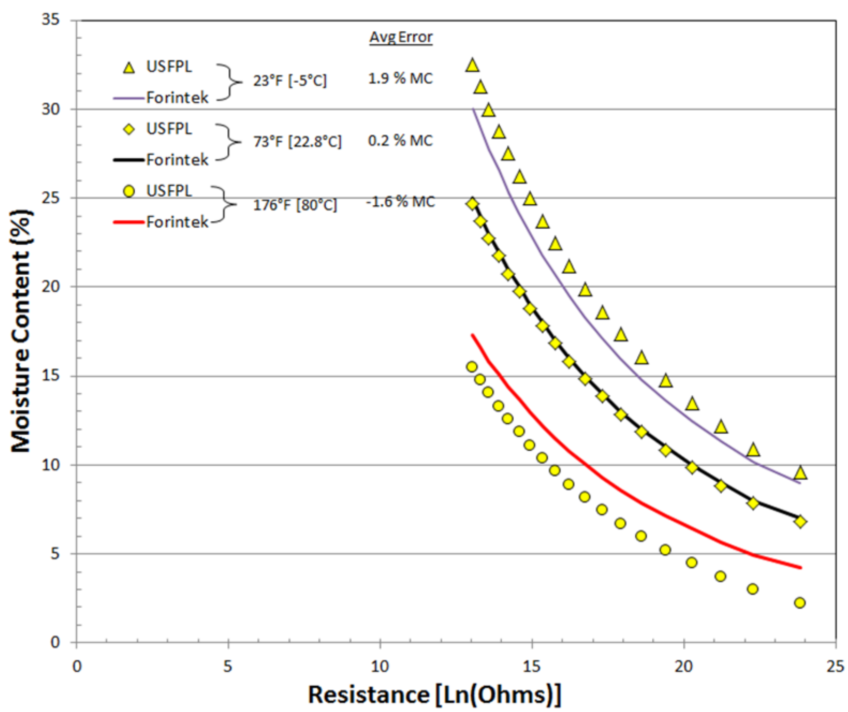

Figure 3a. ORNL fit of moisture content for Douglas fir plotted from data gleaned from the open literature (symbols are for fit to USFPL data) compared Garrrahan's results (solid lines are Forintek data).

The average absolute error at the 3 temperature levels are +1.8% difference at 80°C wood temperature; 0.2% difference at 22.8°C wood temperature and -1.6% difference at -5°C.