# Thermal and Hygrothermal Performance of Ventilated Attics With and Without Breathable Underlayments

**Sudhir Railkar, Ph.D.**[A]
*GAF, Member ASHRAE*

**Adem Chich**
*GAF*

**Ming Shiaio, Ph.D.**
*GAF,Member ASHRAE*

**Andre Desjarlais**[B]
*ORNL, Member ASHRAE*

**William Miller, Ph.D.**
*ORNL, Member ASHRAE*

## ABSTRACT

*The primary purpose of passive ventilation is to manage attic moisture and lower attic air temperature. This paper details results collected from a full year of field-testing at a facility constructed with 7 roof/attic configurations including both sealed and ventilated designs with breathable and non-breathable underlayments. The Natural Exposure Testing (NET) facility was built in Charleston, South Carolina to study the impact of a hot, humid climate on the hygrothermal performance of roof and attics. Two attics were configured identical except one was fitted with breathable and other with a non-breathable underlayment to compare effect of breathability on hygrothermal performance. Both attics were ventilated with identical 1:300 soffit-ridge ventilation system. A third attic with non-breathable underlayment and 1:150 ventilation was also constructed to evaluate the ventilation effect. Humidifiers introduced identical moisture loads in the attics to simulate moisture loads emanating from the conditioned space due to occupancy habits. The average moisture load was estimated from previously collected data by ORNL on various attics in Southern climates. Attics in the study were fitted with temperature, humidity and heat-flux sensors at identical locations. Results from the analysis of field data indicate that breathable membranes and ventilating attics in hot, humid climates provide effective temperature and moisture control.*

## INTRODUCTION

The effect of natural ventilation in a residential attic cavity has been studied extensively since the 1930's (Rowley et al., 1939). It was found that the main purpose of ventilating an attic space was to manage moisture in cold climates. The studies performed by Frank Rowley et al (Rowley, Algren, & Lund, 1939) have concluded that natural ventilation openings are required in cold climates for the circulation of air in the attic space to prevent surface condensation on the underside of the roof sheathing. Following Rowley's work, the National Housing Agency published "Property Standards and Minimum Construction Requirements for Dwellings" for the Federal Housing Association (FHA) in 1942. This document contains the first record of the 1:300 specifications. (FHA, 1942).

Although attics have dramatically changed since the days of Rowley, his recommendations remain well adopted and have been extended to other climates. As new technologies and building practices continue to evolve, the thermal performance of the attic is known to depend on many construction components, such as breathable or non-breathable underlayments, use of a radiant barrier, size of ventilation area (1:150, 1:300), and above sheathing ventilation (William Miller et al., 2007). The recent introduction of sealed attics and the movement of the insulation from the attic floor to the

Author A is the R & D Manager for Steep Slope at GAF, Author B is the Group Leader, Building Envelopes Group at ORNL

rafters also can impact attic performance.

In this paper, the effects of breathability of an underlayment on attic performance are studied. Breathability is defined by the permeance of the underlayment. A material with perm rating below 0.1 perm is vapor impermeable and is considered a non-breathable underlayment. A material exceeding 10 perm is classified as vapor permeable and breathable. Underlayment materials with water vapor permeances ranging from near 0 to 100 perms are currently available in the marketplace. In the present research, standard 15lb paper, and breathable and non-breathable underlayment were tested on ventilated and unvented attics. The purpose of this research is to compare and contrast the hygro-thermal performance of breathable and non-breathable underlayment materials on vented and sealed attic assemblies in a hot and humid climate.

## THE FACILITY AND THE EXPERIMENTS

An existing test facility in South Carolina known as Natural Exposure Test (NET) facility was modified to accept a family of 7 different attics, as shown in Figure 1. These attics were monitored for a period of two years and the test data was used to compare the hygro-thermal performance.

*Figure 1: The southern exposure of the NET Facility in Charleston SC.*

The attic of the NET test building was subdivided into seven separate attic modules by using barrier walls thermally insulated to about R-15. The barriers were air sealed using calk and spray foam sealants. These subdivided attics were then configured with various combinations of attic ventilation, permeable and impermeable underlayment, above sheathing ventilation, and solar reflectance of the shingle roof covering to study their effect on attic performance. A schematic of the attic assemblies is shown in Figure 2. Relevant features of the attics are listed in Table 1.

## THE ATTIC CONSTRUCTIONS

The Attic 1 (Table 1) has 1:300 soffit and ridge ventilation with a permeable underlayment (16 perms) and it is covered in dark colored asphalt shingles having solar reflectance of 0.03. The soffit and ridge openings are of equal area. Attic 7 has 1:150 soffit and ridge ventilation with the soffit vent designed into the fascia. An impermeable, peel and stick type underlayment (0.1 perms) serves as the underlayment. Attic 7 has dark colored shingles. Attic 2 has 6 inch of open cell foam attached to the underside of the roof sheathing. The underlayment is 15 lb. felt paper (8 perms) that is covered by traditional dark colored shingles. This attic has no insulation on the attic floor. All other attics have R-38 attic floor insulation. Attic 3 is ventilated at 1:300 ratio with a non-breathable underlayment (0.04 perms) and traditional dark colored shingles. Attic 4 is identical to Attic 3 except it has cool shingles (solar reflectance 0.28). Attic 5 is equipped with above sheathing ventilation (1-3/4 inch air gap) with 15 lb. felt paper (8 perms) and dark colored shingles. Attic 6 is ventilated at 1:300 ratio. A radiant barrier is on the underside of the sheathing. The underlayment is 15 lb. felt paper (8 perms).

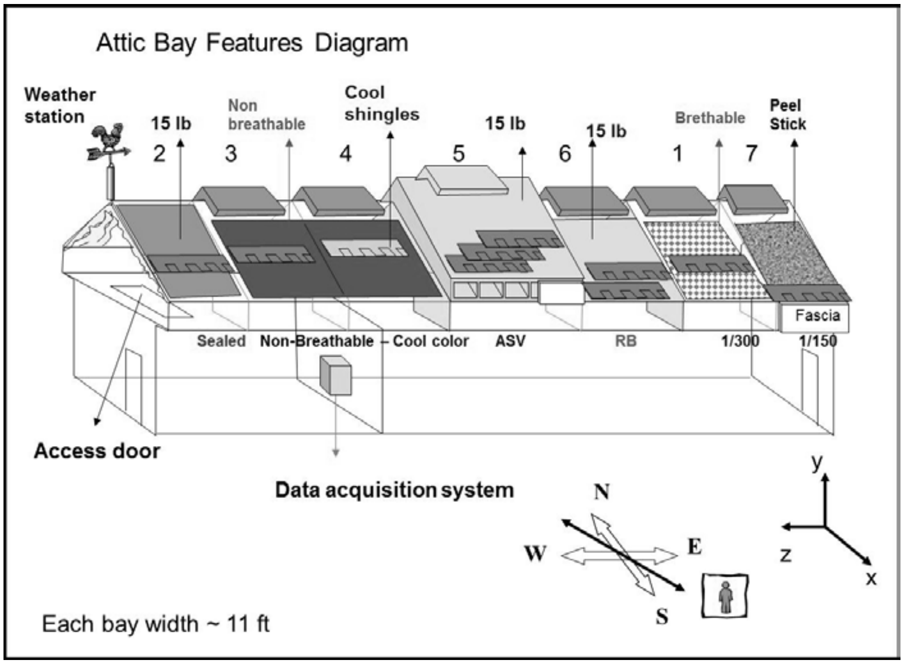


*Figure 2: Test attic assembly layout on NET Facility in Charleston SC.*

Table 1: Attic configuration summary

| Attic No. | Attic Insulation | Ventilation | Underlayment | Radiant Barrier | shingle solar reflectance |
|---|---|---|---|---|---|
| 1 | R38 on attic floor | 1/300 soffit-ridge | Synthetic breathable film (16 perm) | none | SR=0.03 |
| 2 | 5.5" open cell spray foam on roof sheathing | sealed attic | 15lb felt (8 perm) | none | SR=0.03 |
| 3 | R38 on attic floor | 1/300 soffit-ridge | Synthetic non-breathable (0.04 perm) | none | SR=0.03 |
| 4 | R38 on attic floor | 1/300 soffit-ridge | Synthetic non-breathable (0.04 perm) | none | SR=0.28 |
| 5 | R38 on attic floor | 1/300 soffit-ridge & 1-3/4 inch air gap above sheathing | 15lb felt (8 perm) | none | SR=0.03 |
| 6 | R38 on attic floor | 1/300 soffit-ridge | 15lb felt (8 perm) | under sheathing | SR=0.03 |
| 7 | R38 on attic floor | 1/150 intake-ridge ventilation | non-breathable (0.1 perm peel & stick) | none | SR=0.03 |

## THE INSTRUMENTATION

Temperature sensors, relative humidity (RH) sensors, and heat flux transducers were attached at pertinent locations to analyze the in situ performance of the individual attic bays. The sensors were placed in an identical pattern for each attic cavity as shown in Figure 3 to standardize the comparison of results, see Appendix A for the types and calibrations of the instruments.

To simulate moisture generation from occupied home conditions, moisture was added to the ventilated attic spaces by installing a humidifier. The sealed attic was not ventilated and the intent was to observe the effects of the outdoor ambient when the attic was not ventilated. The amount of moisture introduced into the ventilated attics was determined using simulation data for interior hygrothermal loading of residential homes conducted by Arena, Karagiozis and Mantha (2009).

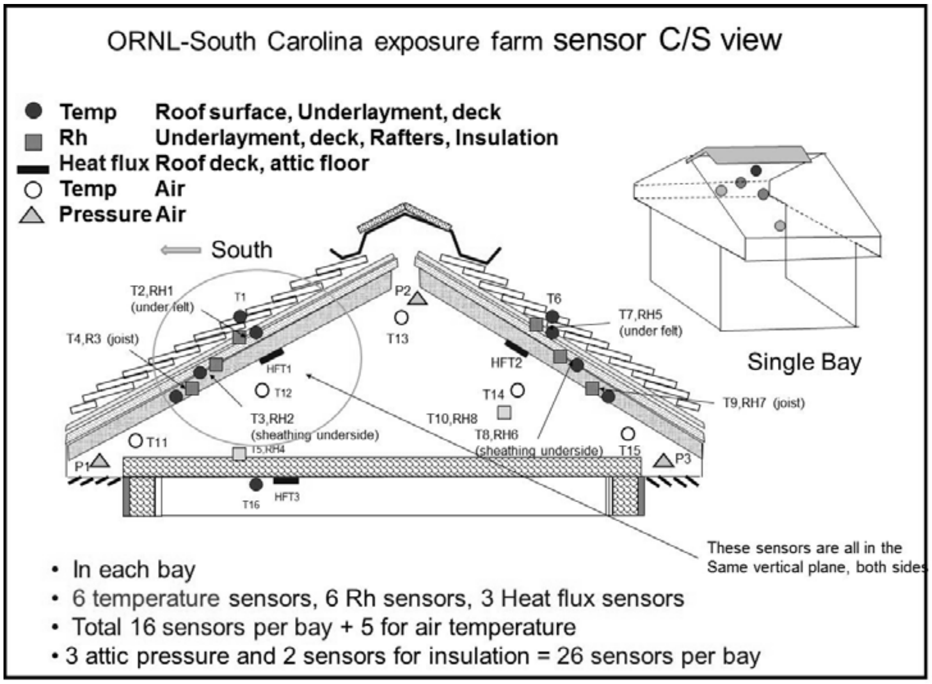


*Figure 3: Instrumentation layout for each attic assembly*

### THE EXPERIMENTAL RESULTS

The temperature, moisture, and heat-flux data were analyzed and used for evaluating comparative performance of various attics. In this paper, only those data from attics with breathable and non-breathable underlayments are presented and discussed.

#### Moisture in Underlayments

The moisture level measured between the sheathing and underlayment in Attic #1 with a breathable underlayment (16 perm), Attic #3 having a non-breathable underlayment (0.04 perm) and Attic #7 with peel and stick underlayment are shown in Figure 4 for the winter and summer of calendar year 2011. Figure 4 shows the partial pressure of water vapor averaged over the respective month for all 3 attics.

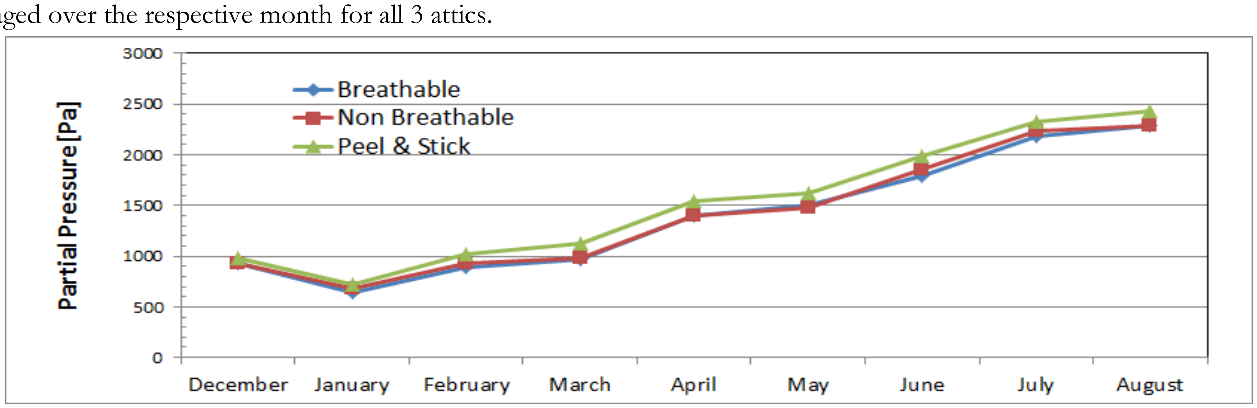


*Figure 4: Underlayment moisture level for Attic #1, #3, and #7 on the north facing side from Jan-to-Dec.*

Moisture content increases between the underlayment and the roof deck for all 3 attics as the season warms from December through August. There is almost no difference in the overall moisture level for the breathable underlayment on Attic 1 and the non-breathable underlayment on Attic 3. Both attics have the same soffit-to-ridge ventilation ratio of 1:300. However, the peel and stick underlayment on Attic 7 equipped with 1:150 fascia and ridge ventilation shows the deck's moisture content to be consistently higher with the largest differences observed during the warmer summer months. The result is consistent with measures of relative humidity and specific humidity collected in the 3 attics. Attic 7 with its higher ventilation flow area had the highest levels of attic air specific humidity during the period of review.

### Effect of underlayment breathability on RH levels in deck

Since the attics and the roof system with both breathable and non-breathable underlayments used in this study were constructed identically, we can further investigate the relationships between the moisture level at the underlayment and the moisture migrations in other parts of the roofing system. It is important to understand the effects of breathability on roof-deck moisture level, as lowering moisture level is desirable for reducing condensate potential. The moisture levels are represented in Fig. 5 by monthly averages of the partial pressure of water vapor measured in the roof-deck for both the winter and summer of calendar year 2011. Attic #1, #3, and #7 under study at the NET facility are displayed as solid lines for partial pressures measured between the underlayment and the roof deck. Dashed lines in Fig. 5 represent partial pressures at the underside of the sheathing (facing the attic). Both the specific humidity and relative humidity are functions of the partial pressure, and it is therefore a good indicator of moisture content of the roof.

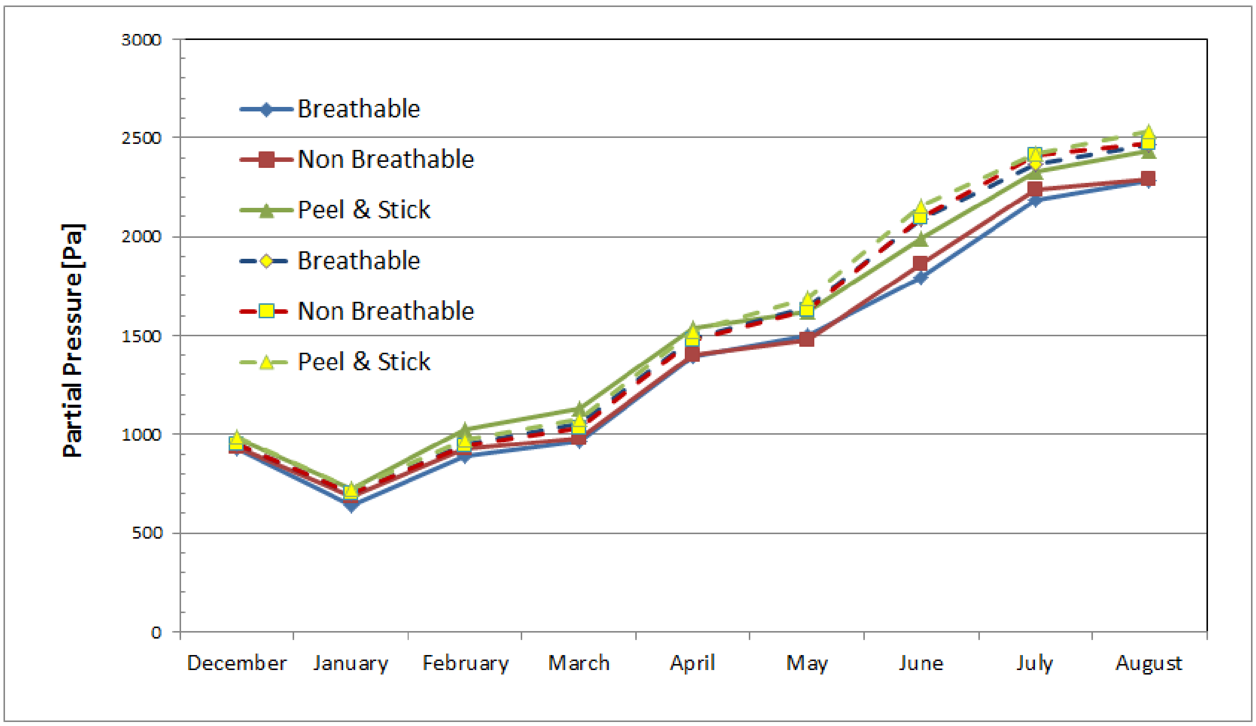


Figure 5: Roof-deck and underlayment moisture represented by the partial pressure of the water vapor computed from temperature and relative humidity measures made at the top-side and underside of the sheathing.

Results show over the season a higher partial pressure occurring at the underside of the sheathing rather than on top of the sheathing. The reason is attributed to the attic ventilation which introduces hot and humid outdoor air into the attics. There is again observed little difference in the partial pressure at the underside of the sheathing (dashed lines, Fig. 5) for the attic with breathable underlayment (Attic #1) as compared to Attic#3 with the non-breathable underlayment. Again the peel and stick shows the highest moisture levels especially during the warmer summer months.

The roof deck is coldest during the early morning hours from about 4 AM till 8 Am and it is at this time that the sheathing is most susceptible to condensation. For Attic #7 with peel and stick type of underlayment (0.1 perm), the roof deck moisture level was found to be the highest of the 3 attics; however, it has a higher rate of attic ventilation which may serve to further protect the deck for condensation.

### Effect of breathability on attic air RH levels

Figure 6 reveals the attic air specific humidity measurements for Attic #1, #3, and #7. We observed that the attics all had about the same specific humidity for 3 contiguous days of field testing in January and also in August. Therefore it is expected that all 3 attics will have about the same susceptibility to moisture condensation. Hence from data in Figures 4-6, it can be seen that the attic with breathable underlayment (Attic#1) maintains about the same moisture level as observed for the peel and stick (Attic#7) and the non-breathable underlayment (Attic #3).

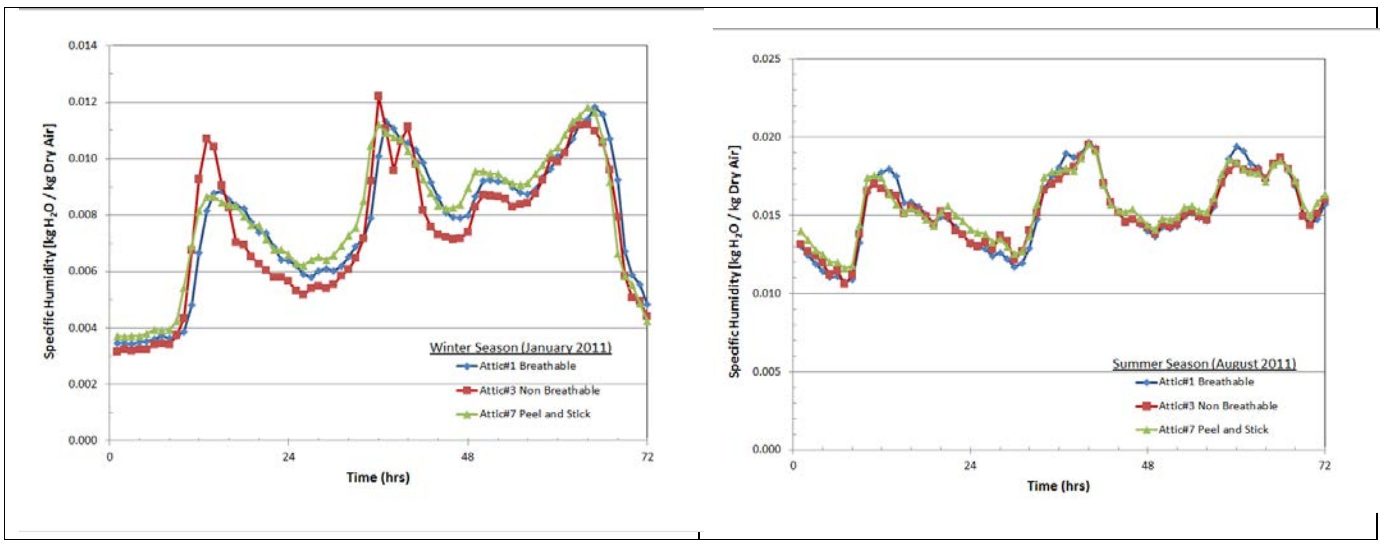


*Figure 6. Moisture in attic air for a typical week in winter and summer under study at NET facility.*

### Winter moisture control in attics

In attics, accumulation of moisture in the moisture-sensitive components is a concern especially when the moisture would be driven from the conditioned space into the attic. For NET test facility in SC, this period is from December through March. To study such risk, the temperatures of OSB and the underlayment in each attic were examined to determine the potential for surface condensation based upon surface temperature depression below the air dew point temperature. The attic air dew point temperature was calculated using equation 1 and compared to the field data on an hourly basis. Condensate occurs when the dry bulb temperature ($T_{db}$) of a surface is depressed below the dew point temperature of the surrounding attic air. A simple estimation shown in Equation 1 is used to calculate the dew point temperature ($T_{dp}$). Note that Equation 1 is based on a psychometric state point with known air temperature and relative humidity, where the coefficient “a” is 17.27, and coefficient “b” is 237.7 (Simmons, 2008).

$$T_{dp} = \frac{b\left(Ln(RH)+\frac{aT_{db}}{b+T_{db}}\right)}{a-Ln(RH)-\frac{aT_{db}}{b+T_{db}}} \qquad (1)$$

The results are shown in Table 1, where the total number of times when the surface temperatures of the wood joist or OSB dropped below the dew point temperature of the attic. Hours showing the potential for condensation were logged and calculated as a percentage of the total time of data collection.

**Table 1. Surface Condensation Potential**

| Attic | Feature | Hours Tsheath<$T_{dp}$ | % Time for Condensation on Sheathing | Hours Tjoist<$T_{dp}$ | % Time for Condensation on Joist |
|---|---|---|---|---|---|
| 01 | Breathable | 102 | 5.1% | 48 | 2.4% |
| 03 | Non-breathable | 110 | 5.5% | 72 | 3.6% |
| 07 | Peel and Stick | 75 | 3.72% | 32 | 1.6% |

According to reduced field data listed in Table 1, Attic #1 and Attic #3 both show the same potential risk for condensation during the winter months. There was no observable potential for condensation during the summer months in the hot and humid climate of Charleston SC. Note that both attics are identical and have 1:300 soffit-ridge vents. All 3 attics appear similar in thermal and hygrothermal performance. The reduced hours observed for the peel and stick in Table 1 is due more to uncertainty and is not deemed significant but does possibly reveal the benefit 1:150 fascia vents.

## CONCLUSIONS

The field data from experiments conducted in Charleston SC show that the potential for condensation occurs primarily during the winter months with almost not potential observed in the hot and humid summer months. In terms of moisture management, the peel and stick was observed to have higher partial pressures on the underside and top-side of the sheathing; however, the attic’s larger ventilation openings helped reduce the potential for condensation. The demonstrates that there is no major concerns regarding condensation of attics ventilated at 1:300 or 1:150 with breathable or non-breathable underlayment.

## ACKNOWLEDGEMENTS

The authors would like to thank Mark LaFracnce DOE, Michelle Betz GAF, and Walter Zarate, GAF, for their assistance and significant support during this research project. The comments from Ming Shiao are also greatly appreciated.

NOMENCLATURE

a = constant in Magnus-Tetens equation

b = constant in Magnus-Tetens equation

T = temperature, deg. C

## Subscripts

db = Dry bulb

dp = Dew point

## REFERENCES


Arena, L.B., Karagiozis, A. and Mantha, P. 2009. "Monitoring of Internal Moisture Loads in Residential Buildings-Research findings in Three Different climate Zones," in Thermal Performance of the Exterior Envelopes of Buildings, X, proceedings of ASHRAE THERM X, Clearwater, FL., Dec. 2009.

ASHRAE Handbook - Fundamentals (I-P Edition). (2009). American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

ASTM Standard C1340. (2004). Standard Practice Estimation of Heat Gain or Loss Through Ceilings Under Attics Containing Radiant Barriers by Use of a Computer Program. Annual Book of ASTM Standards (Vol. 4.06), West Conshohocken, PA: American Society for Testing and Materials.

Burch, D. M., & Treado, S. J. (1979). Ventilating residences and attics for energy conservation - An experimental study. In M. H. Reppart (Ed.), Summer Attic and Whole-House Ventilation. Washington D.C.: National Bureao of Standards.

Federal Housing Administration. (1942). Property standards and minimum construction requirements for dwellings. Washington D.D.: Federal Housing Administration.

Fricklas, Richard, (Sept. 21-22, 1995), Underlayments for Steep-slope roof construction. Proceedings of the 11th conference on roofing technology

Rowley, F. B., Algren, A. B., & Lund, C. E. (1939). Condensation of moisture and its relation to building construction and operation. ASHVE Transactions, 44(1115).

Rudd, A. F., & Lstiburek, J. (1998). Vented and Sealed Attics in Hot Climates. ASHRAE Transactions.

Simmons, R. E. (2008, May 1). Estimating Dew Point Temperature for Water Cooling Applications. Retrieved November 10, 2011, from Electronics Cooling: http://www.electronics-cooling.com/2008/05/estimating-dew-point-temperature-for-water-cooling-applications.

Wilkes, K. E. (1991a). Analysis of Annual Thermal and Moisture Performance of Radiant Barrier Systems. Oak Ridge, TN: Oak Ridge National Laboratory.

Wilkes, K. E. (1991b). Thermal Model of Attic Systems with Radiant Barrier Systems. Oak Ridge: Oak Ridge National Laboratories.

Wilkes, K. E., & Rucker, J. L. (1983). Thermal Performance of Residential Attic Insulation. Energy and Buildings, 5, 263-277.

Miller, W. A., Childs, P. W., Desjarlais, A.O., Haun, L., Jacobs, J., Karagiozis, A. N., Kosny, J., Petrie, T. W., Syed, A. M., Wilson, J., Yarbrough, D. W., and Youngquist, A., "Next Generation Roofs and Attics for Homes" ACEEE Summer Conference, Pacific Grove, CA, Aug. 2008.

Miller, W. A., Keyhani, M., Stovall, T. and Youngquist, A. 2007. "Natural Convection Heat Transfer in Roofs with Above-Sheathing Ventilation," in Thermal Performance of the Exterior Envelopes of Buildings, X, proceedings of ASHRAE THERM X, Clearwater, FL., Dec. 2007.

# Appendix A
# Instruments and Calibrations

The data logger and instrumentation used at the Natural Exposure Test (NET) facility is discussed for documentation of the instrumentation. Relative humidity and thermistor sensors were purchased in bulk and fabricated in-house and tested and calibrated at the ORNL Metrology Laboratory. The response of several thermistor sensors was measured at the following nominal conditions; 15.8, 18.5, 21.2, 23.9 and 26.6 °C. The manufactures specification for the temperature response is +/- 0.2°C; all probes met this requirement. 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.

### Data Logger

Campbell Scientific Model CR1000 micro-loggers are used for remote acquisition and recording of field data. The loggers are equipped with 4 MB of memory, a 25-channel multiplexer for thermocouples, a rechargeable battery, a 115 Vac-to-24 Vdc transformer, a modem, a modem surge protector, a weatherproof enclosure and associated cables. The data loggers scan every 15 seconds and reduce analog signals to engineering units. Averages of the reduced data are 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.

### Temperatures

Attic air, return air and the outdoor air temperatures will be measured using thermistors, which are a semiconductor device that changes resistance with temperature. Accuracy is about 10 times better than that of thermocouples. The model 192-103-LET-A01 HONEYWELL S&C / FENWALL thermistors are used to measure air and surface temperatures. It is rated at 10,000 Ohm resistance, tolerance of ±0.2 °C [0.36 °F]; 25/85 BETA = 3974.

- http://www.newark.com/jsp/displayProduct.jsp?sku=10M5346&CMP=KNC-G10000680&HBX_OU=50&HBX_PK=192-103LET-A01

### Relative Humidity (RH)

The HIH-4000 Series Humidity Sensors by Honeywell is used for all envelope and indoor air measures of RH. The sensor has a current draw of only 200 μA. The HIH-4000 Series sensor is a laser trimmed, thermoset polymer capacitive sensing element with on-chip integrated signal conditioning; stated accuracy is ±3½% of reading.

- http://www.phanderson.com/hih-4000.pdf

### Pressure

A 0 to 0.1 in differential air pressure sensor by Aschroft model CXLdp will measure bi-directional differential pressure across the ceiling. Two other CXLdp will measure pressure drop from the attic to the north- and south-facing sides of the home. The sensor outputs 4 to 20 ma or 0 to 10 Vdc in proportion to a 0 to 0.1 in of water column. The transducer requires excitation of 12 to 36 Vdc. Accuracy is stated as ±0.8% of span.

- http://www.instrumart.com/assets/Ashcroft-CXLdp-Data-Sheet.pdf

### Solar Irradiance

Total global solar irradiance is measured on the pitched roofs (one pyranometer for each roof slope). The pyranometers selected for the study are the Li-C or LI-200SZ silicon photo-detectors. Night-sky radiation is also measured using a pyrgeometer from Kipp; & Zonen..

### Moisture Pins

Measuring the moisture content of wood is often used as a fundamental measure of performance, since it is often the mold and decay of the wood components that is the performance problem of interest. Wood has the useful characteristic that it allows moisture content to be measured by measuring resistance and subsequently translating this electrical resistance into moisture content. 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 will be provided 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 4.

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 A-to-D converter.

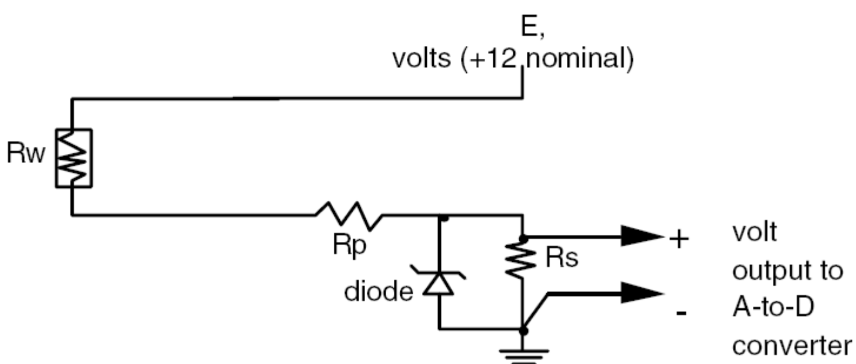


Figure 4. Circuit to measure resistance of wood with DAS.

Using Ohm’s Law we can say that:

$$I = E \big/ \left(R_W + R_P + R_S\right) \qquad (1)$$

and

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

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

$$\frac{V}{E} = \frac{R_S}{\left(R_W + R_P + R_S\right)}$$

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

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

An empirical fit with temperature is used to convert the wood's resistance measure into moisture content of the wood between the two pins. The empirical fit will differ from one type of wood to another.

### Heat Flux Transducer (HFT)

A HFT consists of a sensitive thermopile composed of many fine-gauge thermocouples connected in series on opposite sides of a flat material of know and stable thermal resistance. This thermal resistance creates a temperature difference across the flat material in the presence of heat flux. The temperature difference is detected by the thermocouple junctions, and the voltage generated across the thermopile is proportional to the heat flux through the HFT. The sensitivity of the HFT (mV·.m$^2$ per W) is proportional to the number of thermocouple junctions in series and to the thermal resistance of the flat material.

The calibration of heat flux sensors was contracted to R&D Services. R&D conducted the calibrations in a Fox heat flow metering apparatus using the protocol ASTM C 518-10, "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus." Each HFT was inserted into a guard made of the same materials that the sensor would be attached to in the field. Calibration temperatures were set based on measured deiling and roof deck temperatures measured in the field.

### Thermal Conductivity of Fiberglass Batt

R&D Services also conducted calibrations to measure the thermal resistance of fiberglass batt insulation. A unique Fox heat flow metering apparatus having footprint of 30-in by 30-in was used to measure the thermal resistance of the un-faced fiberglass batt insulation. The ASTM C 518-10 protocol was observed for the calibrations. In the field, the HFTs were taped to the gypsum board facing into the attic. A thermistor was taped to the gypsum board adjacent the HFT and the calibrated batt was placed on top. A thermistor was inserted jus into the fiberglass batt so to shield it from radiation. The setup enabled a convenient check of the HFT as compared to the flux computed from the two thermistors measuring the temperature difference across the batt insulation and the calibrated conductivity of the batt.