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General Aniline and Film Report 2012: Analytical and Field Study of the Effects of Ventilation on Thermal Performance and Moisture Control in Residential Attics

January 2013

Prepared by

William Miller, Ph.D.
Kaushik Biswas, Ph.D.
Manfred Kehrer
Andre Desjarlais
Stanley Atherton, University of Tennessee Graduate Student

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Energy and Transportation Division

GENERAL ANILINE AND FILM REPORT 2012: ANALYTICAL AND FIELD STUDY OF THE EFFECTS OF VENTILATION ON THERMAL PERFORMANCE AND MOISTURE CONTROL IN RESIDENTIAL ATTICS

William Miller, Ph.D.
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OAK RIDGE NATIONAL LABORATORY
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EXECUTIVE SUMMARY

The attic bay of the Natural Exposure Test (NET) facility in Charleston, South Carolina, was subdivided into seven uniquely different attic assemblies for measuring the thermal and hygrothermal performance of different roof constructions with breathable and nonbreathable underlayment. Salient features of the roofs and attics are shown in the following table, which includes an abbreviated name for each roof and attic test cell.

Attic number	Notation	Ceiling insulation[a]	Roof deck insulation	Underlayment	Ventilation	Roof solar reflectance
01	Control (CTRL)	R_{US}-45.6 batt insulation		16 perm breathable	1:300 soffit/ridge	0.03
02	Sealed (SLD)		R_{US}-22 open cell spray foam	8 perm felt paper	Sealed	0.03
03	Nonbreathable (NB)	R_{US}-45.6 batt insulation		0.04 perm nonbreathable	1:300 soffit/ridge	0.03
04	Cool Color (CC)	R_{US}-45.6 batt insulation		0.04 perm nonbreathable	1:300 soffit/ridge	0.28
05	Above-sheathing ventilation (ASV)	R_{US}-45.6 batt insulation		8 perm felt paper	1:300 soffit/ridge	0.03
06	Radiant barrier (RB)	R_{US}-45.6 batt insulation		8 perm felt paper	1:300 soffit/ridge	0.03
07	Fascia flow (FF)	R_{US}-45.6 batt insulation		0.10 perm nonbreathable	1:150 soffit/ridge	0.03

[a] R_{US} has units of [h·ft^2·°F]/ Btu

The roofs were fitted with asphalt shingles having 0.033-solar reflectance, with the exception of the cool color shingle roof, which has a solar reflectance of 0.28. All attics were equipped with 1:300 vents except for the attic with fascia flow; it has a 1:150 vent area ratio of ridge plus soffit vents to attic footprint. Ceiling insulation was installed on all attic floors except in the sealed attic, which features R_{US}-22 open-cell spray foam insulation applied to the underside of the roof deck. Cool color shingles, a radiant barrier, above-sheathing ventilation, and fascia flow rated at 1:150 vent area were features showcased on four of the attics. An additional two attics were equipped with 1:300 soffit-ridge ventilation, 0.033 solar reflectance shingles, and R_{US}-45.6 floor insulation. A breathable underlayment was used to protect the sheathing of one attic (called the CTRL attic), and a nonbreathable underlayment was selected for the other, the NB attic.

Attic air temperatures and heat flux measures were reduced using time-of-day BIN averages to illustrate a "typical" diurnal period for the winter (January–March) and summer (April–September). The control attic reaches the hottest BIN average summer temperature of 43°C (109.4°F) during summer, closely followed by the NB and FF attics. The SLD attic shows the least variation in temperature throughout the diurnal cycle. Among the vented attics, the ASV attic had the lowest attic temperature fluctuations. The ASV and RB attics share a similar attic air temperature curve, having a 7°C (12.6°F) lower peak temperature than

the CTRL attic. It is of keen interest that the SLD attic had the lowest average attic air temperature; however, because the ceiling was not insulated, SLD had the highest ceiling heat gains and losses of all field-tested attics. Its primary benefit is to reduce the impact of leaky ducts on the space-conditioning energy consumption. At the NET facility, the ducts were very leak-tight.

A parametric analysis was conducted to study the effect that modifying the ventilation area ratio has on heat and moisture control in an attic cavity. Modifying the standard of 1:300 shows little benefit in moisture control and heat flux reduction through the ceiling for a wide range of ventilation ratios.

An analysis of the surface condensation potential in each attic cavity reveals almost no potential for condensation during the summer and only a small potential for condensation during the winter season. The ASV attic had the lowest potential for condensation on the oriented strand board deck; only 1.0% of the total time of winter data collection. In comparison, the CTRL attic showed a 5.1%, the RB a 4.1%, and the CC a 5.1% potential. The potential for condensation on a percentage-of-total-time basis is the highest for the NB attic, which has a 1:300 ventilation ratio and a nonbreathable underlayment rated at 0.04 perm.

Field data did, however, reveal a surprising result for moisture management in the SLD attic. All attics except SLD revealed decreases in relative humidity as irradiance increased the stack effect. Yet the opposite was true of SLD, because its relative humidity rose during the heat of the day. Solar energy drove moisture out of storage in the open spray foam and actually caused the relative humidity to increase in the attic during the hottest portion of the day. On some particularly hot days, relative humidity was at or near full saturation (i.e., 100%). At this condition, water vapor is in equilibrium with liquid water and all interior attic surfaces are wet! Without a leaky duct, the SLD approach actually exacerbates humidity in attics exposed to hot, humid climates. The inclusion of an impermeable underlayment does not appear to resolve the problem, as reported in parallel work by Carlos (2011), who used open cell spray foam and an impermeable underlayment in the roof and attic of a home located in South Florida.

1. INTRODUCTION

The benefit of natural ventilation in a residential attic cavity has been the topic of many debates and scholarly reports since the 1930s. The purpose of ventilating an attic cavity is to prevent the collection of condensate on the structural surfaces and to create a thermal buffer between the conditioned space and the ambient air. The current standards are not specific to climate zone, despite the fact that each climate zone may require ventilation for very different reasons.

To address the issue of ventilation effects in a hot and humid climate, a Natural Exposure Testing (NET) facility was constructed in Charleston, South Carolina, in 2008. This multi-cavity in situ facility is equipped with seven separate attic bays, featuring unique construction materials for performance comparison. Yearly performance comparison data have been examined for key observations on the effect of ventilation.

Furthermore, an industry-standard attic performance prediction tool was benchmarked to the field data and was shown to be accurate for predicting the diurnal performance of the NET facility. A battery of simulations were run for diurnal air exchange rates, the results of which are compared with gas tracer analysis tests performed during the summer of 2011.

A parametric study involving various attic ventilation area ratios was performed using the benchmarked prediction tool to show the effect of varying ventilation-area ratios on the thermal and moisture-control capabilities of attics with standard construction, above-sheathing ventilation (ASV), and radiant barrier (RB) systems.

1.1 JUSTIFICATION

In some climates, proper natural ventilation of residential attic spaces is a strategic method for maintaining a sustainable residence. Ventilation removes unwanted moisture by advection through intentionally constructed vents and through air gaps in the structure of the cavity caused by inevitable construction flaws. The traditional purpose of permitting this controlled infiltration of outdoor air is to protect the durability of attic materials through heat and moisture control using airflow driven by wind and stack effects. However, the effectiveness of natural ventilation in minimizing characteristic heat gains in an attic cavity, mainly through the attic floor to the conditioned space, continues to be a topic of debate.

The amount of necessary natural ventilation is dictated by a number of compounding variables and can therefore vary extensively, depending on the climate zone, level of insulation, and airtightness of the structure. The 1:300 rule was established based on experiments made on flat roofs under steady state conditions (Rose, 1995), which does not correlate well to in situ performance on a typical structure. The purpose of this study is to report on the effects of attic ventilation on the thermal and moisture dynamics of the NET facility in Charleston, South Carolina. The data from this facility are a prime representation of warm, moist climates where the effectiveness of attic ventilation for moisture management has been called into question.

1.2 PREVIOUS WORK

Traditional residential construction, even in primitive societies, makes use of ventilation to create a preferable thermal environment and remove unwanted airborne materials. The modern residential roof and attic system is essentially a basic shelter framework, the purpose of which is to protect the contained living space for a long period of time from unwanted elements.

The institution and modification of natural and forced attic ventilation is typically considered "green" engineering, a methodology of sustainable design that decreases both the energy consumption of a residence and its environmental footprint. Previous studies have investigated the advantages or disadvantages of attic ventilation by observing its impact on decreasing the amount of solar heat gain through the attic space and preventing condensation on the interior attic surfaces.

1.2.1 Rowley and the FHA

In 1939, the Federal Housing Administration (FHA) set a natural ventilation area ratio standard as a means of minimizing condensation on the underside of the roof sheathing. This requirement was the result of the research performed by Frank Rowley, professor at the University of Minnesota, and published in ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) *Transactions* (Rowley, Algren, & Lund, 1939). Rowley concluded that natural ventilation openings are required for the circulation of air in the attic space to prevent surface condensation on the underlayment of the roof. Following Rowley's work, the National Housing Agency published *Property Standards and Minimum Construction Requirements for Dwellings* for the FHA in 1942. This document contains the first record of the 1:300 specifications. (FHA, 1942)

This ratio remains a construction standard to the present day, despite Rowley's own revision to the ratio in favor of a quarter square inch of vent area per square foot of attic footprint, or a 1:576 ratio. It should also be noted that Rowley's proposed 1:300 ratio has no numerical modifiers for application with separate climate zones, specific roof deck inclinations, duct specifications, or insulation types and amount, all of which are critical variables in determining the performance of natural ventilation systems.

1.2.2 Jordan and the HHFA

After the Second World War, the Housing and Home Finance Agency (formerly the FHA) performed laboratory tests concerning the appearance of condensate in attic systems (Housing and Home Finance Agency, 1948). The result of this experiment was the observed formation of frost along the unvented apparatus and a lack of frost on the ventilated apparatus. It must be noted that this investigation took place in a cold climate in which the naturally ventilated air was not moisture-rich. Further experiments indicated that the amount of ventilation necessary to prevent the buildup of condensate must increase if more insulation is added to the attic floor. In other words, the 1:300 ratio would not provide enough ventilation if more insulation were placed on the attic floor.

1.2.3 National Bureau of Standards

In July 1979, the National Bureau of Standards (now referred to as the National Institute of Science and Technology) published a collection of research titled *Summer Attic and Whole-House Ventilation* (Burch & Treado, 1979). Featured in this publication was a study performed by Burch and Treado, entitled *Ventilating Residences and Their Attics for Energy Conservation*. Although the scope of the study was the benefits of whole-house ventilation compared with the use of a comparable air-conditioning system, part of the research focused on the possible energy savings and cost benefits of adding additional ventilation types to an attic system that featured primarily soffit-to-soffit ventilation. The conclusion of the ventilation comparison was that additional area for natural ventilation was not an effective method of energy conservation, specifically in attics with 4 and 6.5 inches of ceiling insulation.

According to their data, introducing additional attic ventilation resulted in a 25% decrease in ceiling heat gain and a 16% decrease in duct heat gain. However, Burch and Treado concluded that the overall whole house cooling load decreased only 6%, because the heat gains through the ducts and ceiling represented a small portion of the overall cooling load on the test homes (Burch & Treado, 1979).

An integral part of Burch and Treado's analysis of these test homes was their estimation of attic ventilation rates, based on a sulfur-hexafluoride tracer gas technique. The tracer gas was released into the attic space and the air was sampled at various locations to determine the dilution of the gas. From the dilution measurement, the ventilation rates were determined.

1.2.4 Prediction of Ventilation, Heat Transfer and Moisture Transport in Attics

Walker (1993) developed an attic simulation model that considers both heat and moisture transfer through an attic cavity. The model was validated to measured data from the Alberta Home Heating Research Facility and then used in a parametric study to examine strategies for moisture control. The results of this study showed that increasing ventilation rates from standard amounts was not always the best strategy for moisture control. It also showed that ventilation strategy should depend on climate zone and attic construction (Walker, 1993).

1.2.5 Vented and Sealed Attics in Hot Climates

Rudd and Lstiburek (1998) addressed the need for solutions related to the entry of moisture-rich air in hot, humid climates and the need to obtain an effective barrier to infiltration at the tops of residences to reduce energy consumption. Rudd and Lstiburek took the one-dimensional finite-element model developed by Vieira (2003) and made empirical modifications to provide a more exact benchmark against field data. The results of this experiment showed that a sealed attic with an air and thermal barrier on the sloped roof deck can be built without an associated energy penalty in hot climates, compared with traditional ventilated constructions (Rudd & Lstiburek, Vented and Sealed Attics in Hot Climates, 1998).

1.2.6 Issues related to Venting of Attics and Cathedral Ceilings

TenWolde and Rose investigated the merits of conventional ventilation relative to alternative designs with respect to attic temperatures, ice damming, and shingle durability. Their paper is primarily a comparative study on previous research of other authors. The conclusions reached in the paper were based on work published by Rowley, Beal, Chandra, Burch, Treado, and others. TenWolde and Rose conclude that ventilation is a recommended practice in cold climates. However, they recommend that conventional ventilation be only an optional design choice for warm, humid climates (Tenwolde & Rose, 1999).

1.2.7 A Preliminary Experimental Assessment of the Comparative Thermal Performance of Attics and Cathedral Ceilings in a Cold Climate

A multiple-test-bay residential research facility was built in Cloquet, Minnesota, to investigate the relative energy and moisture performance of various building envelope components and systems. Insulation types on the attic floors in the test bays varied among R-38 batts, blown cellulose, loose Fiberglass, and R-13 batts. The thermal performance of a ventilated attic and a cathedral ceiling were analyzed using heat and mass transfer correlations during a 6 month period in the spring of 1998. Reduction of the data from the facility showed that vented attics maintained a colder average attic air temperature. From a purely thermal perspective, a cathedralized, ventilated roof deck has the highest energy penalty compared with a ventilated attic cavity and an unvented cathedralized deck (Goldberg, Huelman, & Bridges, 1999).

1.2.8 Comparative Evaluation of the Impact of Roofing Systems on Residential Cooling Energy Demand in Florida

In 2000, the Florida Power and Light Company and the Florida Solar Energy Center instrumented six adjacent Habitat for Humanity homes for unoccupied observation in Ft. Myers, Florida. The data collected from this facility were compared with simulations performed using the DOE-2.1E simulation

engine with new subroutines that explicitly estimate the performance of attics with duct interaction. The results revealed that roof decks covered with white, highly reflective materials provided an 18–26% reduction in annual cooling energy use, whereas a sealed attic cavity provided only a 6–11% reduction when insulation on the attic floor was R-19. The authors concluded that roof decks with high solar reflectance properties offer the most significant energy savings compared with alternative ventilation strategies, terra cotta tiles, and alternative shingle designs (Parker, Sonne, Sherwin, & Moyer, 2000).

1.2.9 Comparison of Sealed and Deck-Insulated (Cathedralized) Attics with Conventional Attics: Where and When Do Cathedralized Attics Save Energy?

A study compared cathedralized and conventional attics to determine where and when cathedralized (sealed and deck-insulated) attics offer cost savings against conventional attic construction. The AtticSim tool was validated for six separate climate zones, and the output was used to construct a comparison of annual cooling loads for the cathedralized attic and various configurations of conventional attics. The modifications to AtticSim for this project featured a new capacity to model ducts in the attic cavity (Petrie, Stovall, Wilkes, & Desjarlais, 2004).

2. FACILITY

Each attic in the NET facility was designed to highlight a specific material or system for an analytical comparison of moisture and heat control. Specific significance is placed on the stand-alone performance of these different systems, so that a proper design standard can be detailed for hot and humid climates. Successful benchmarking of the data collected from this facility will also lead to conclusions for other climate zones. Certain materials are common to certain attics, such as a roofing membrane or a ventilation scheme. For a diagram of these features, see Fig. 1.

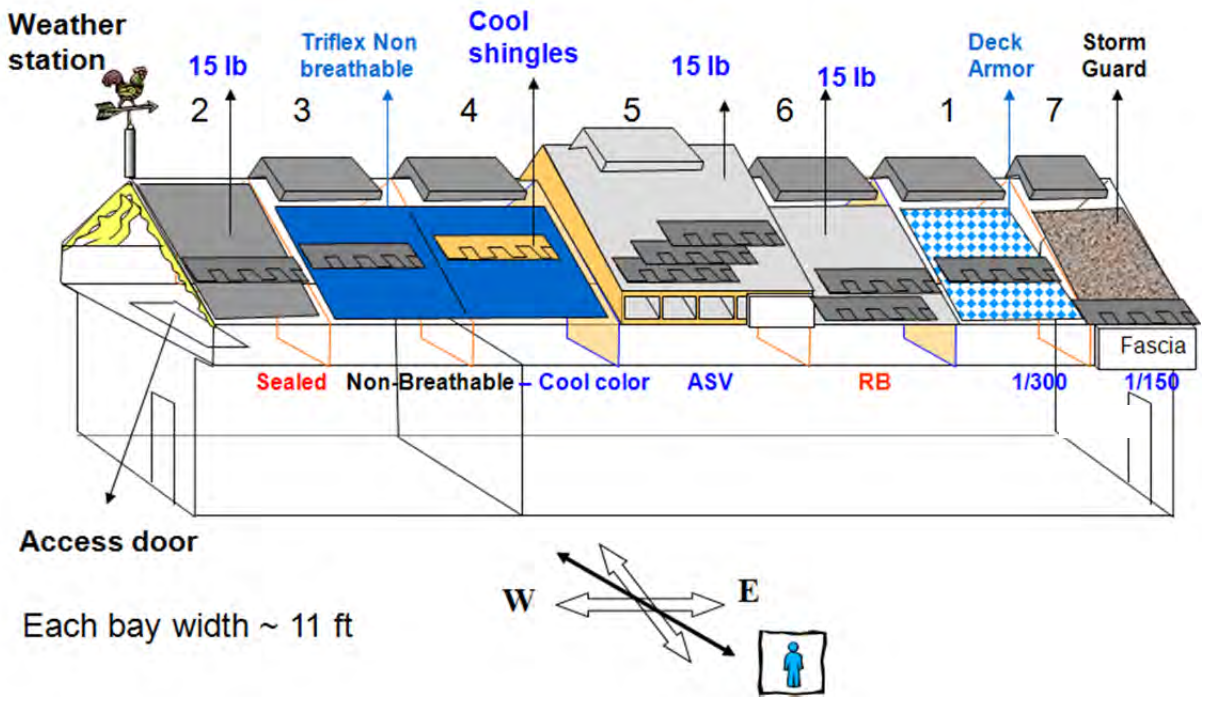


Fig. 1. Charleston NET facility attic features.

2.1 ATTIC FEATURES

The NET has seven separate attic bays featuring a sealed attic, an attic fitted with 1:150 ventilation, and others with 1:300 ventilation areas. Breathable and nonbreathable roof membranes were installed to observe their effects on thermal and moisture movement in the attics. All roofs feature asphalt shingles. One asphalt shingle contained cool color pigments; the others had conventional pigment coloring. An attic was fitted with ASV and another was fitted with a perforated foil-faced sheathing, which served as an RB. Table 1 provides a brief description of the different attics and their respective features.

The breathability of an underlayment is defined by the International Residential Code (ICC 2009) to have a vapor permeability within one of four given categories:

- Vapor impermeable: membrane with permeance < 0.01 perm
- Vapor semi-impermeable: membrane with permeance between 0.1 and 1.0 perm
- Vapor semi-permeable: membrane with permeance between 1.0 and 10.0 perm
- Vapor permeable: membrane with permeance > 10 perm

Table 1. Attic Features

Attic number	Notation	Ceiling insulation[a]	Roof deck insulation	Underlayment	Ventilation	Roof solar reflectance
01	Control (CTRL)	R_{US}-45.6 batt insulation		16 perm breathable	1:300 soffit/ridge	0.03
02	Sealed (SLD)		R_{US}-22 open cell spray foam	8 perm felt paper	Sealed	0.03
03	Nonbreathable (NB)	R_{US}-45.6 batt insulation		0.04 perm nonbreathable	1:300 soffit/ridge	0.03
04	Cool color (CC)	R_{US}-45.6 batt insulation		0.04 perm nonbreathable	1:300 soffit/ridge	0.28
05	Above sheathing ventilation (ASV)	R_{US}-45.6 batt insulation		8 perm felt paper	1:300 soffit/ridge	0.03
06	Radiant barrier (RB)	R_{US}-45.6 batt insulation		8 perm felt paper	1:300 soffit/ridge	0.03
07	Fascia flow (FF)	R_{US}-45.6 batt insulation		0.10 perm nonbreathable	1:150 soffit/ridge	0.03

[a] R_{US} has units of [h·ft^2·°F]/ Btu

2.2 INSTRUMENTATION AND DATA REDUCTION PROTOCOL

During the construction of the NET facility, thermistors, humidity probes, heat flux transducers (HFTs), and pressure taps were installed at locations consistent from attic to attic to analyze the in situ performance of each attic bay. The sensors were placed in an identical pattern for each attic cavity to allow fair comparisons of one attic with another.

2.2.1 Temperature and Relative Humidity Sensors

Thermistor temperature sensors were combined with relative humidity (RH) sensors by placing the two sensors in a permeable sack made of Tyvek®, the result of which is referred to as a “combo probe.” Thermistor temperature sensors are also used for sensing shingle underside temperature, as well as the temperature where the Fiberglass insulation lies on the gypsum of the attic floor. The stratification of attic air temperature is sensed through five thermistors, which are evenly spaced from soffit to soffit. Figure 2 is a diagram of the sensor locations inside the cavity and Table 2 details the location of each sensor.

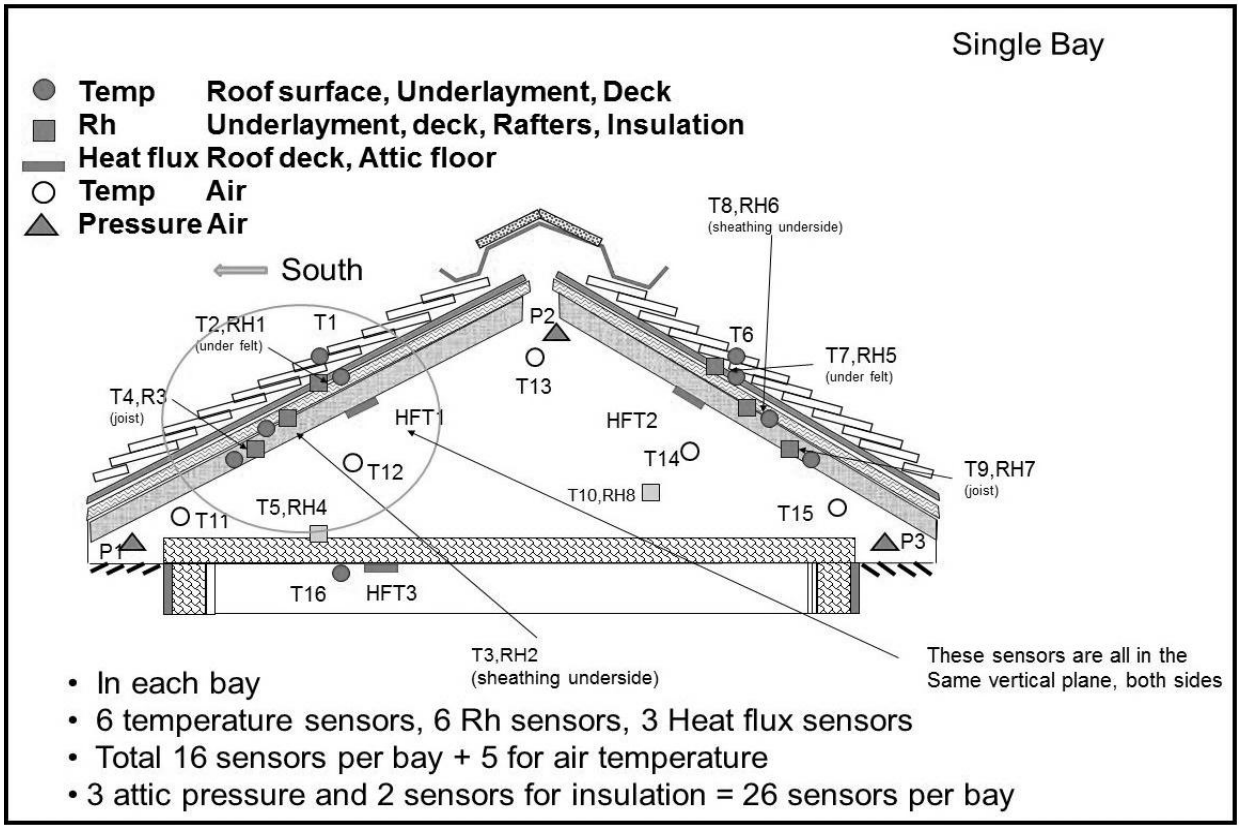


Fig. 2. Sensor location diagram.

Table 2. Sensor locations

Sensor identification	Location (north and south)	Sensor type
T11-T15	Air stratification at soffits	Thermistor
T1,T6	Shingle underside	Thermistor
T2,RH1 and T7,RH5	Deck underlayment	Thermistor and RH probe
T4,RH3 and T9,RH7	Joist	Thermistor and RH probe
T5,RH4	On top of insulation	Thermistor and RH probe
T10,RH8	Hanging mid-plane air	Thermistor and RH probe
T3,RH2,HFT1 and T8,RH6,HFT2	Interior of oriented strand board deck	Thermistor and RH probe and Flux Transducer
T16,HFT3	Interior ceiling	Thermistor and RH probe and flux transducer

2.2.2 Heat Flux Transducers

HFTs were attached to the undersides of the inclined roof decks, as well as on the interior surfaces of the gypsum board on the attic floors, as shown in Fig. 3. These pre-calibrated devices generate an electrical signal proportional to the total heat rate applied to the surface of contact and allow collection of conductive heat flux data through the inclined roof decks and the attic floors. The roof deck HFTs were calibrated in a surface-applied configuration and the attic floor HFTs were calibrated between gypsum board and Fiberglass insulation using a Fox heat flow apparatus to correct for two-dimensional heat flow effects.

Fig. 3. Heat flux transducer and combo probe located under insulation.

2.2.3 Weather Station

Weather data collected on the roof of the NET facility include wind speed and direction, solar irradiance, rainfall, ambient temperature, RH, and barometric pressure. These data are logged in the same data acquisition system (DAS) files and are similarly collected on a weekly basis.

2.3 DATA REDUCTION

Field data were transmitted via modem on a weekly basis from the Charleston NET facility to the Oak Ridge National Laboratory (ORNL) campus. The data were received and automatically sorted into data files upon weekly collection. Not all of the data transmitted from the facility were pertinent to this study, because the DAS also recorded data from the wall panel assemblies. Therefore, an automated compilation routine was necessary for easy performance tracking and comparison. This sequence of programs was created using Microsoft Visual Basic macros in Excel. The total data reduction routine has four distinct portions to allow for easy conversions to other applications and projects.

2.3.1 Routine 1: Clean_Convert

Clean_Convert is a separate routine to import the field data files and perform the necessary conversion from comma-separated .RPT files to easily accessible Excel spreadsheets. This routine also separates the data into specific folders labeled by acquisition system and date of collection. This standalone macro was necessary because several instances of power failure or data loss occurred throughout this study. Each

instance would slightly change the date logging system in the field data files, which required that the user be able to manually input the timestamp for the correct data.

2.3.2 Routine 2: Raw_Compiler

The Raw_Compiler macro opens and moves the required data values from each individual DAS file and compiles them into a single weekly report. This macro involves pasting data from the facility sensors and weather station into a premade template that automatically generates weekly comparison graphs of important performance data for easy observation. Before the compiler could function, each data column location had to be catalogued in an array, which is used by the macro in a copy and paste loop. For added ease of use, this macro can be run for multiple weeks at one time, which allows quick recompiling of past data when new comparative performance data need to be observed. For a single week of field data, this is the only macro that the user must run to see comparative trends in the data.

2.3.3 Routine 3: BoundaryCondition_Creator

The AtticSim program requires a very specific format for boundary condition and weather input files. The macro BoundaryCondition_Creator further compiles the report files output from Raw_Compiler into separate files for weather data and temperature boundary conditions. Successful use of this routine requires that a corresponding weekly report file be created before execution.

2.3.4 Routine 3: AtticSim_Execute

Correctly setting up and executing an AtticSim simulation is a tedious task, especially when multiple runs are required. To save time when running simulation batches, we created a Windows batch (.bat) file that runs a variation of AtticSim that only requires the user to specify a file path and date stamp. This modified AtticSim file also writes out the surface radiation and combined convection heat flux coefficients for analysis.

2.3.5 Routine 4: AtticSim_Output

This final standalone macro compiles the output of a specific AtticSim run or series of runs based on date stamp and attic bay. Similar to the Raw_Compiler macro, the template of AtticSim_Output automatically generates charts for quick observation. The output charts can be easily modified, or modifications can be made to the template file so that specific weeks of data can be recompiled to investigate different simulation results.

3. RAW DATA ANALYSIS

The bulk of the data presented as raw or field data in this report were collected during 2011 and separated into summer and winter seasons. Winter corresponds to January to April, and the summer period is considered to be May to September. The data were not contiguous because of unforeseeable incidents at the NET facility, including a lightning strike and multiple incidents when construction crews broke communication lines.

The data in this section have been reduced using the scheme discussed in the previous section and further complied in a batch form to detail the performance of the individual attic bays for a 4 month period. The data that follow have been time-step averaged over the entire operational period (BIN-type averaging scheme), to show "typical" 24-hour performance for the season. This method of presentation is commonly used in climate-comparison reports for residential performance.

Benchmarking of the field data for the seven attics (Appendix D) revealed a discrepancy in the HFT measures for the south-facing roof deck of the CTRL attic. Heat flux measures computed from thermometry measurements made across the deck and near the same location as the HFT yielded heat flux measures more consistent with both computer simulation and field data for the CTRL, FF, and NB attics. The measured HFT data for the roof deck of the CTRL and NB attics indicated a higher latent load for the NB deck, which is not physically correct and is inconsistent with results computed by WUFI (Appendix A). WUFI computed a higher latent load for the CTRL having a breathable underlayment compared with the NB attic with its impermeable underlayment. Hence thermometry measurements were included for comparing the heat flux through the roof decks of the CTRL, FF, and NB attics. Integrated heat flows through the roof decks used the NB attic as a control. However, ceiling heat flux used the CTRL as a base.

3.1 ROOF DECK HEAT FLUX COMPARISON

HFTs were placed on the undersides of the north- and south-facing roof decks to measure the heat transfer to and from the attic. BIN-averaged winter and summer measures are shown in Figs. 4a and 5a for the south-facing deck. Positive heat flux is heat flow into the attic, and heat flow out of the attic is negative. Error bars are displayed in Fig. 5a and are based on the manufacturer's specifications.

The winter and summer heat flows entering the SLD attic are the lowest of all the tested attic systems simply because of the R_{US}-22 spray foam used to seal the attic. Its performance is followed by the ASV, RB, and CC attics. The SLD, ASV, RB, and CC attics reduce the heat gained during the day; but during the winter nights, the SLD, ASV, and RB attics also limit losses compared with the CTRL attic (Fig. 4a). Reductions in heat transfer can imply a heating or cooling penalty, depending on the weather conditions. For example, during winter, the daytime heat gain through the roof may be beneficial in reducing the heating load of the building, and the nighttime heat losses in summer may alleviate the cooling loads.

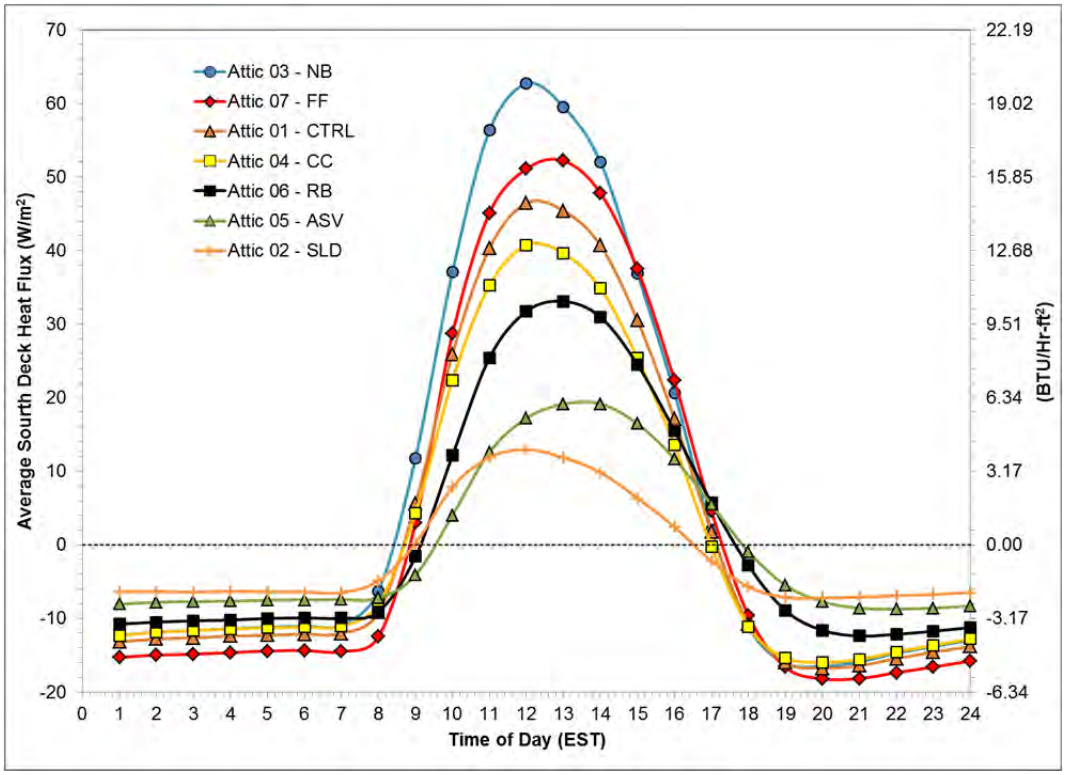


Fig. 4a. Average winter south deck heat flux.

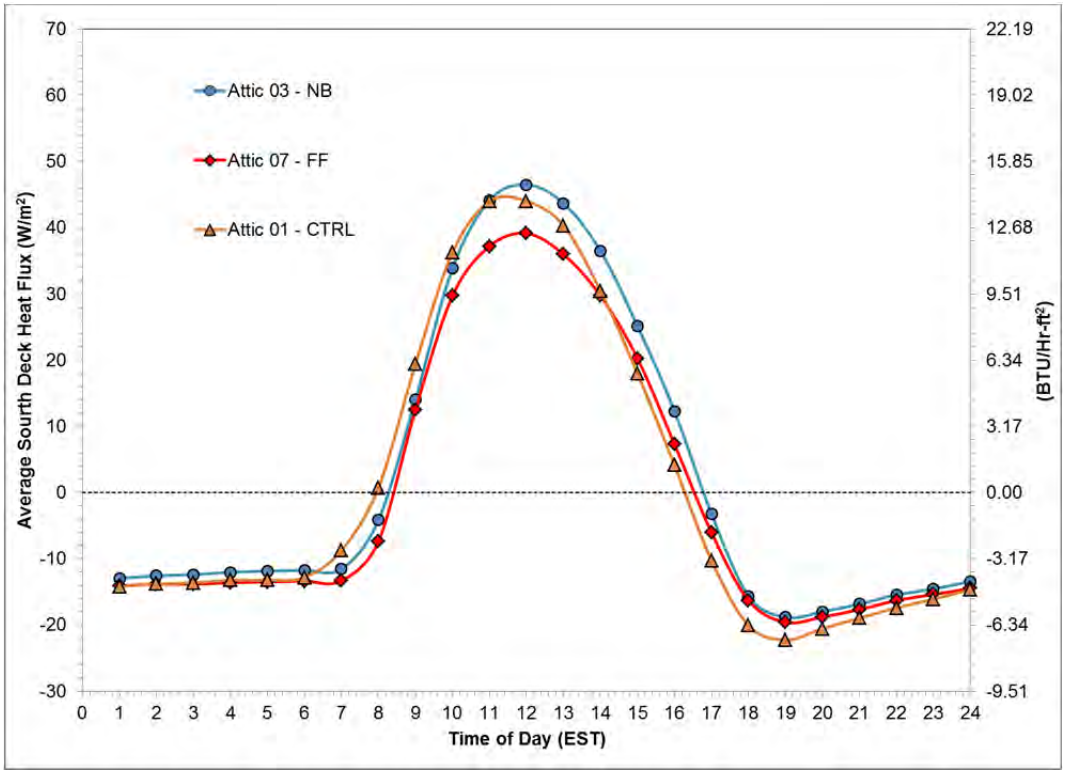


Fig. 4b. Average winter south deck heat flux using thermometric calculations (ΔT/R).

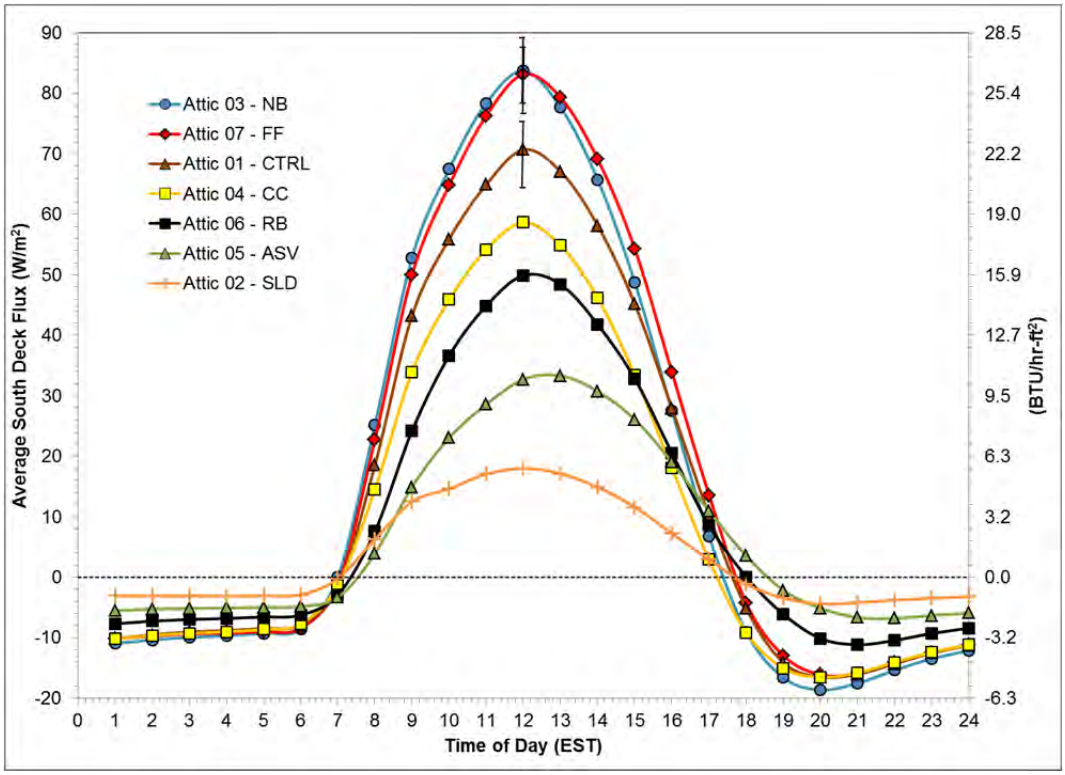


Fig. 5a. Average summer south deck heat flux.

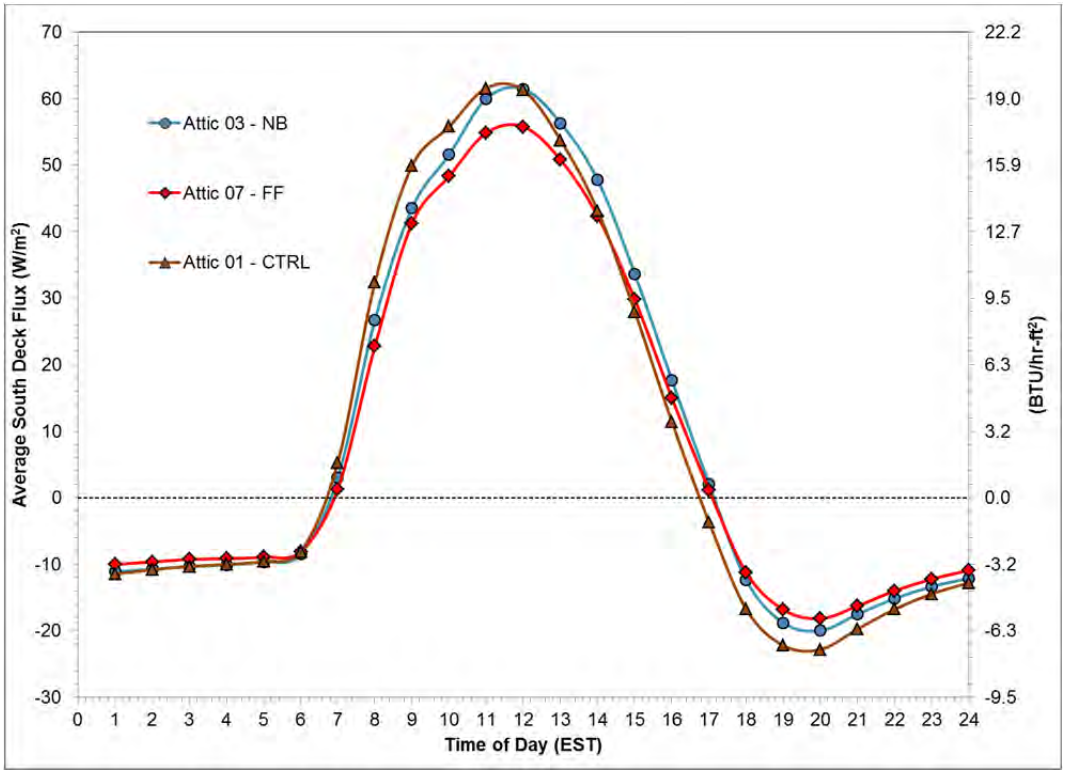


Fig. 5b. Average summer south deck heat flux using thermometric calculations (ΔT/R).

The NB, CTRL, and FF attics are equipped with underlayments of differing breathability. The underlayment for the NB attic is impermeable, and the one used on the FF attic is semi-impermeable. The CTRL attic has a vapor-permeable underlayment (see Table 1). The HFT field data for these three attics show the CTRL as having the lowest winter (Fig. 4a) and summer (Fig. 5a) heat flows crossing the south-facing roof deck. However, the results appear inconsistent compared with the FF attic, which has more attic ventilation area (1:150) than does the CTRL (1:300). Thermometry (Fig. 2) and thermal conductivity measures were therefore used to compute heat flux for winter and summer data (Figs. 4b and 5b). Samples of the oriented strand board (OSB) deck material were retrieved from the NET facility and tested for thermal conductivity using a Fox heat flow apparatus.

With the thermometric calculations, the BIN-averaged data (based on temperature difference across the roof deck) show very similar performance between the NB and CTRL attics, whose assemblies are identical except for their nonbreathable and breathable underlayments. The FF attic shows a lower heat flux crossing the roof deck, which makes better physical sense because it has a larger ventilation area for increased attic ventilation (Fig. 4b).

The summer heat flows entering the CTRL, NB, and FF attics also appear more consistent with the thermometric calculations, showing the FF attic as having a lower heat flux than the NB and CTRL attics, which have similar heat flux measures to each other. Lestiburek, Karagiozis and Gassman (2011) conducted computer simulations that show little difference in computed water vapor transport between impermeable and permeable underlayments. The results in Figs. 4b and 5b are more consistent with the findings by Lestiburek, Karagiozis and Gassman (2011). WUFI simulations computed the latent heat flux crossing the south-facing roof deck of the CTRL and NB (Appendix A). WUFI results showed that the CTRL with a breathable membrane had a 10% higher heat flow than the NB deck with the impermeable membrane (Table A.2, Appendix A). That result is contradictory to the HFT data shown in Fig. 5a. Therefore, we believe the HFT placed on the roof deck of the CTRL is in error and that Figs. 4b and 5b present a better characterization of the heat flow through the deck of the CTRL attic.

To further investigate the impact of the roof thermal characteristics, the heat flux data were integrated over the entire winter and summer periods to determine the total heat gains and losses through the roofs. The integration was performed by a simple application of the trapezoidal rule:

$$Total\ Integrated\ Flux\ [hr * \frac{W}{m^2}] = \sum_{n=0}^{m} .5 * \Delta X_n * (Y_n + Y_{n+1}) \quad (1)$$

where

Y_n and Y_{n+1}	correspond to the current and future time step
ΔX_n	is the time step (one hour in this case)
m	is the subscript denoting the final point in the series, which varies depending on the summer or winter data sets.

Keep in mind that this integration represents a summation of the area under the curve of the heat flux. The positive and negative heat fluxes were integrated separately to determine the heat gains and losses for each attic. The integrated heat gains and losses and the net heat transfer are shown in Table 3. The net heat transfer for each period is calculated as the sum of the heat gain and heat loss. Also shown in Table 3 are the percentage reductions with respect to the NB attic rather than the reference CTRL attic. The results of Figs. 4a and 5a show the HFT measurements for the CRTL attic as being suspect, and Figs. 4b and 5b show that NB has performance similar to that of CTRL.

Table 3. Integrated heat transfer through the south deck (both seasons)

Attic	Feature	Integrated heat gain [$\frac{kJ}{m^2}$]	Reduction from NB (%)	Integrated heat loss [$\frac{kJ}{m^2}$]	Reduction from NB (%)	Net heat transfer [$\frac{kJ}{m^2}$]	Reduction from NB (%)
				Winter			
03	NB	103,618	0.0	−57,793	0	45,825	0.0
07	FF	90,719	12.4	−71,594	−23.9	19,125	58.3
01	CTRL	78,095	NA	−62,230	NA	15,865	NA
04	CC	66,892	35.4	−58,520	−1.3	8,371	81.7
06	RB	55,452	46.5	−47,799	17.3	7,653	83.3
05	ASV	33,188	68.0	−35,622	38.4	−2,434	105.3
02	SLD	20,497	80.2	−31,439	45.6	−10,941	123.9
				Summer			
2	SLD	55875	76.9	-19554	73.3	36321	78.5
5	ASV	102835	57.6	-30320	58.6	72515	57.1
4	CC	165355	31.8	-68783	6.1	96571	42.9
6	RB	143470	40.8	-45670	37.7	97800	42.1
1	CTRL	209420	13.6	-65810	10.2	143610	15.0
3	NB	242284	0.0	-73252	0.0	169032	0.0
7	FF	248722	-2.7	-65955	10.0	182767	-8.1

In winter, the FF, CC, RB, ASV, and SLD attics all allowed lower net heat gains than the NB; in fact, the SLD and ASV attics showed net losses through the south roof. This implies that, during winter, there are potential heating penalties associated with the FF, CC, RB, ASV, and SLD roofs compared with the NB roof. During summer, however, the SLD, ASV, CC, and RB attics reduced the heat gains compared with the NB attic, which is beneficial in terms of cooling loads. The FF attic with 1:150 vent area allowed higher heat gains compared with the NB attic during the summer. The FF attic also incorporated a nonbreathable semi-impermeable underlayment over the roof deck. Therefore the FF attic as computed from the HFTs had less heat gain in the winter (penalty) and more heat gain in the summer (added penalty) than the NB attic. However the thermometric calculations in Fig 5b are not consistent with the HFT measures because the differences are within uncertainty of measurement.

3.2 WINTER CEILING HEAT FLUX COMPARISON

Heat flux through the attic floor into the conditioned space is the primary indicator of an attic's burden on the heating, ventilation, and air-conditioning system of a residence. Each attic in the facility was outfitted with an HFT to measure the amount of heat entering (or leaving) the conditioned space. Data during the summer and winter months of 2011 were analyzed in BIN averages as well as on the basis of an overall integrated value for comparison. BIN-averaged winter ceiling heat fluxes are shown in Fig. 6 (with error bars of ±7.5 % for the CTRL attic).

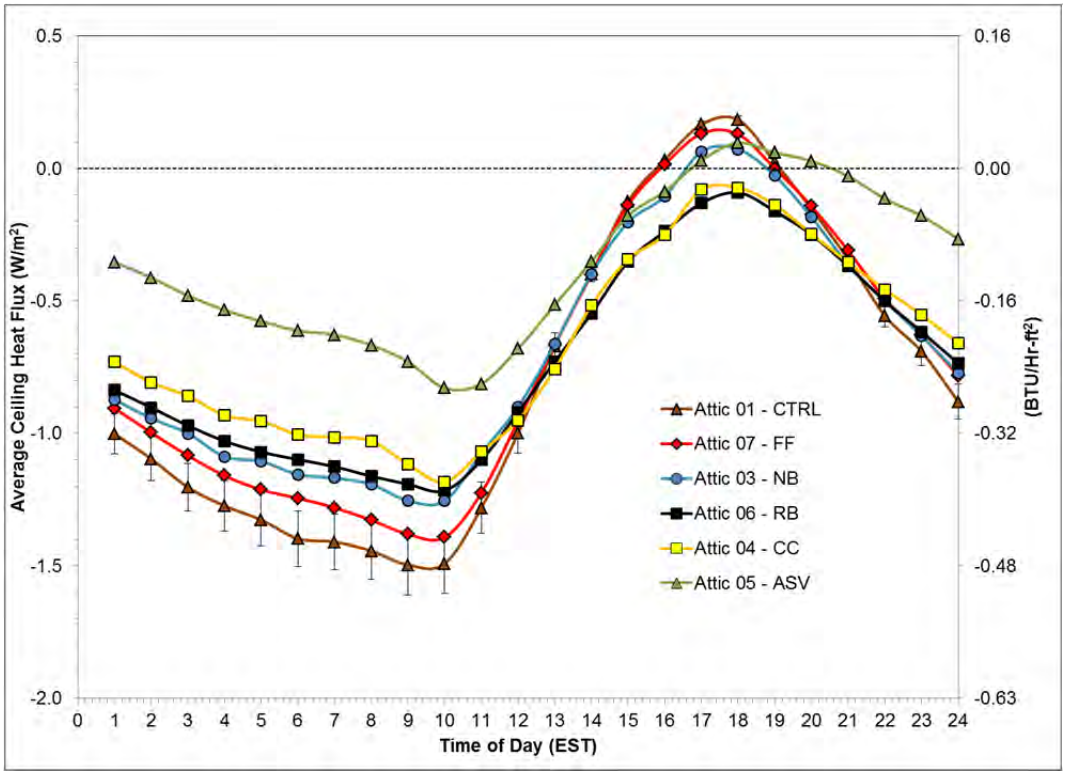


Fig. 6. Average winter ceiling heat flux.

The sign convention of the ceiling HFTs is positive for heat flowing from the attic into the conditioned space. As expected, the heat flow is mainly in the negative direction (indicating an attic space that is cooler than the conditioned space). The data suggest that the CC and RB attics remain cold enough that, on average, the direction of heat flow never reverses. The result implies that roof and attics in cold climates should not be equipped with cool color shingles or RBs.

The ASV attic, attic 05 in Fig. 6, has the lowest average diurnal variation (amplitude of oscillation across the zero line). It also shows the least amount of heat lost from the conditioned space during the early morning (1:00– 6:00 a.m.). The FF, NB, and CTRL attics all incur heat losses during the early morning hours and all have small heat gains during periods of peak winter irradiance compared with the ASV attic. Therefore, the air space in the ASV helps alleviate the winter penalty and should be viewed as a good practice to include in future advanced attic designs.

Open cell spray foam was applied to the roof deck and gable ends of the SLD attic. Once cured, the foam fully covered the 2 by 6 rafters, and its R-value was computed at about R_{US}-22. No insulation was placed on the floor of the SLD attic; therefore, a direct comparison of ceiling flux is biased toward the other attics having R_{US}-45.6 ceiling insulation. It is interesting that, because the SLD attic has no insulation on the attic floor, its flux values are much higher and vary more than the other adjacent attics that have R_{US}-45.6 batt ceiling insulation. Figure 7 illustrates the large difference in ceiling flux for the SLD attic compared with the CTRL and ASV attics. If the duct in the SLD attic leaked tempered supply air, then the SLD attic would incur less heat transfer across the ceiling because the space would be conditioned (see the section “Simulated Sealed Attic Performance with Leaky Ducts”).

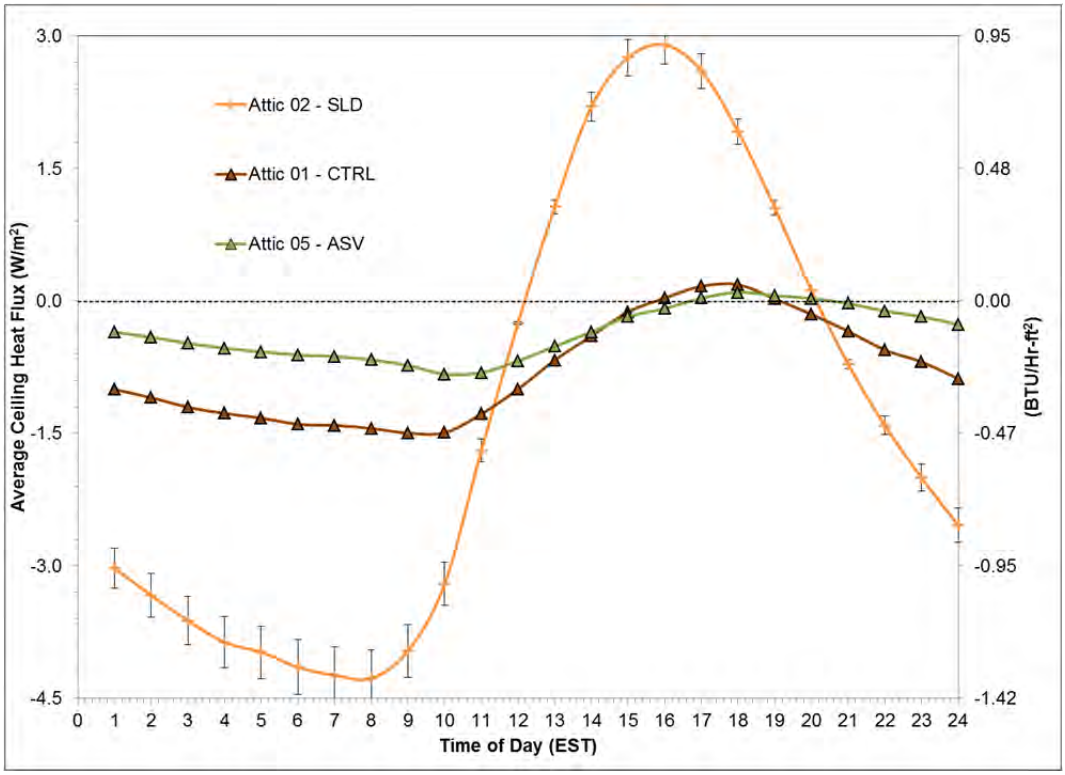


Fig. 7. Sealed attic ceiling winter heat flux.

The integrated heat transfer through the ceiling during winter was also calculated; the results for the different attics are provided in Table 4. The positive (heat flux gain) and negative (heat flux loss) transfer were integrated separately and then summed to determine the net heat transfer. The heat flow through all attic ceilings was primarily out of the conditioned space, as evidenced by the substantially higher integrated heat loss compared with the heat gain. This is to be expected during winter conditions.

Table 4. Integrated ceiling heat transfer (winter 2011)

Attic	Feature	Integrated heat gain [—	Reduction from CTRL (%)	Integrated heat loss [—	Reduction from CTRL (%)	Net heat transfer [—	Reduction from CTRL (%)
05	ASV	715	28.3	−3415	49.3	−2701	53.0
04	CC	535	46.3	−5431	19.4	−4896	14.8
03	NB	732	26.5	−5832	13.5	−5100	11.2
06	RB	478	52.0	−5765	14.5	−5287	8.0
07	FF	952	4.4	−6278	6.9	−5326	7.3
01	CTRL	996	0.0	−6742	0.0	−5746	0.0
02	SLD	6736	−576.1	−16471	−144.3	−9735	−69.4

Overall, the ASV attic reduced the net heat loss through the attic floor by 53% compared with the CTRL attic. CC and RB attics showed comparable reductions of 14.8% and 11.2% respectively, despite the fact that neither had positive heat gains throughout the winter (Fig. 6). Another important observation is that

the doubling of the ventilation area in the FF attic accounted for only a 7.3% reduction in the ceiling heat transfer. With no ceiling insulation, the heat loss through the ceiling of the SLD attic was 69.4% higher than the loss through the CTRL attic.

3.3 SUMMER CEILING HEAT FLUX COMPARISON

During the summer, the temperature of the attic can exceed 50°C (122°F) for exposures in Charleston's hot, humid climate. The temperature potential drives the heat transfer from the attic into the conditioned space at a generally larger magnitude than in the winter. The BIN-averaged summer heat fluxes through the attic floor are shown in Fig. 8a. All attics, with the exception of the ASV case, have a window of time from 3:00 to 9:00 a.m. during which the heat flux is slightly negative. During this period, the temperatures in the attic cavities are, on average, less than the temperature in the conditioned space because of night-sky radiation from the roof decks. The ASV, CC, and RB attics demonstrate relatively similar levels of ceiling flux, with an average peak flux ranging from 0.9 to 0.98 W/m^2 compared with a peak heat flux of 1.61 W/m^2 through the ceiling of the CTRL attic. The addition of the low-permeance membrane to the NB attic appears to decrease the peak heat flux of the NB attic by 0.34 W/m^2 compared with the CTRL attic. The data also imply that the larger ventilation area of the FF attic (1:150) did reduce the ceiling flux compared with the CTRL attic with a 1:300 vent area. The FF and NB attics both have nonbreathable underlayment; here, added attic ventilation did not reduce ceiling heat flux. The heat flux from the NB attic peaks at 1.27 W/m^2 compared with a 1.44 W/m^2 peak for the FF attic, a 0.17 W/m^2 difference in flux that is within the measurement uncertainty for the HFTs.[1] Therefore, the most definitive conclusion about the ceiling fluxes will be reserved for the upcoming section describing the integrated summer gains and losses in Table 5.

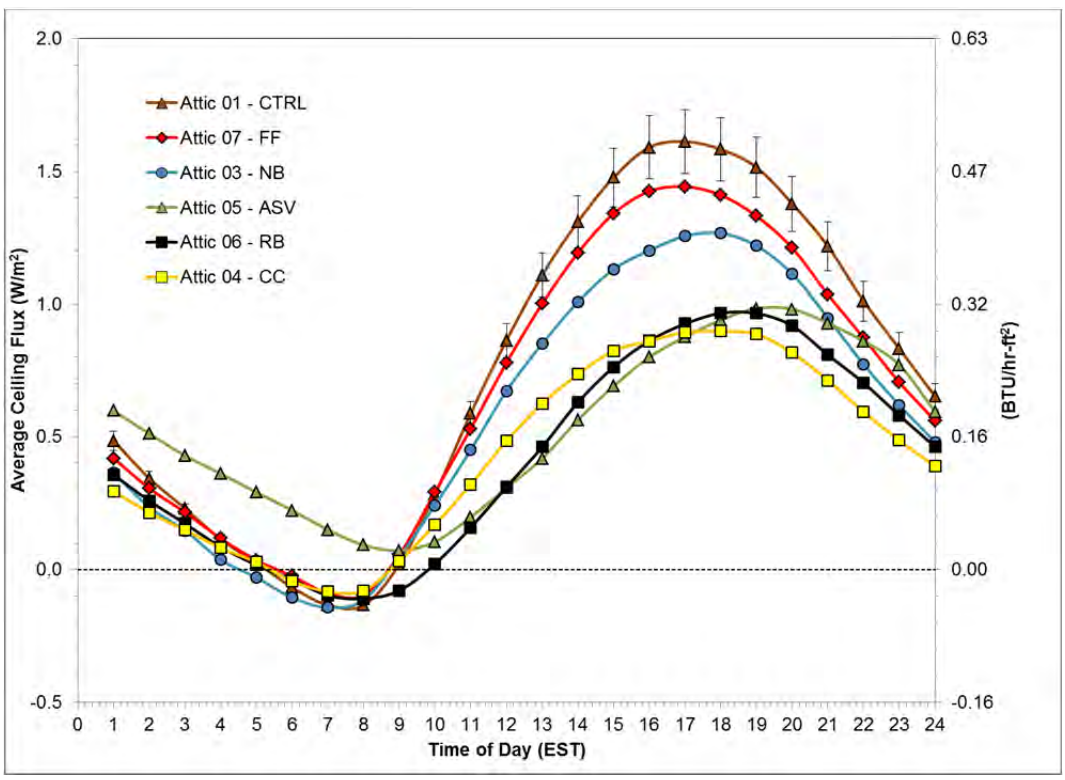


Fig. 8a. Average summer ceiling heat flux.

[1] Uncertainty is ±7.5% of the reading, as stated by the manufacturer.

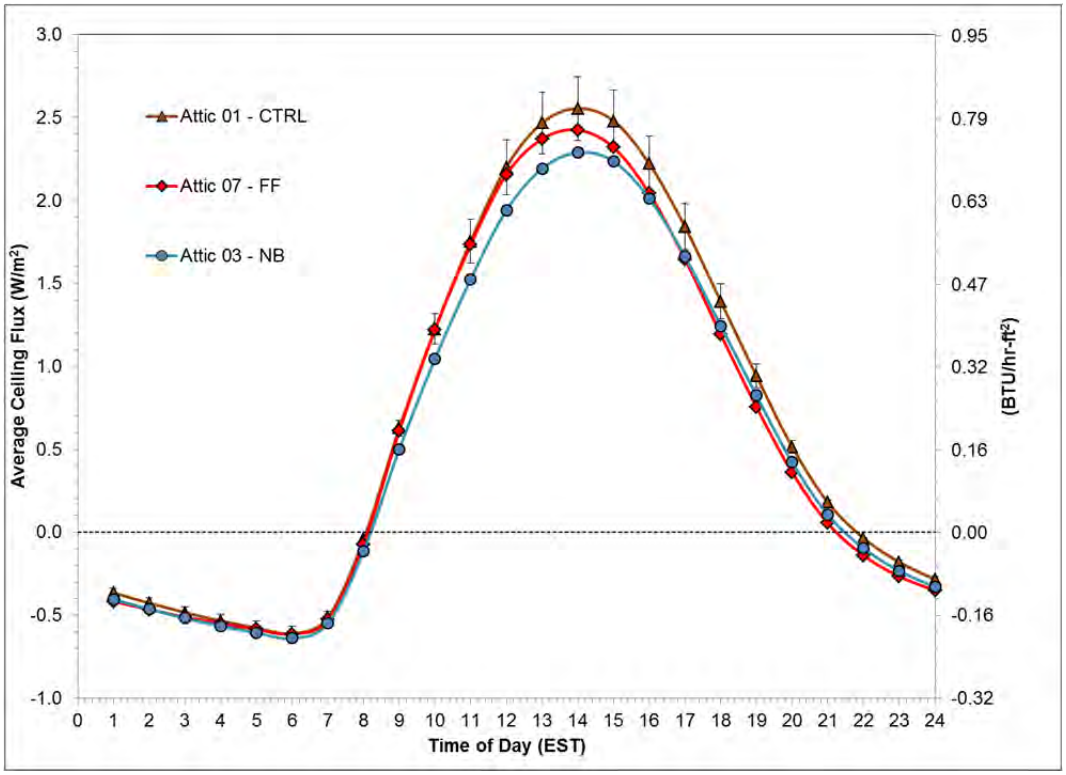


Fig. 8b. Average summer ceiling heat flux using thermometric calculations (ΔT/R).

Table 5. Integrated ceiling heat transfer (summer 2011)

Attic	Feature	Integrated heat gain [—	Reduction from CTRL (%)	Integrated heat loss [—	Reduction from CTRL (%)	Net heat transfer [—	Reduction from CTRL (%)
06	RB	5616	39.2	−1034	7.9	4582	43.6
04	CC	5545	40.0	−879	21.7	4667	42.5
05	ASV	6425	30.5	−645	42.5	5780	28.8
03	NB	7232	21.8	−1031	8.1	6201	23.7
07	FF	8193	11.4	−905	19.4	7288	10.3
01	CTRL	9244	0.0	−1122	0.0	8122	0.0
02	SLD	41453	−348.4	−4441	−295.9	37012	−355.7

An additional check was made of the deck flux crossing the CTRL, FF, and NB attics. Thermometry data measured across the roof deck were used with measured thermal conductivity data for the OSB to compute the heat flux crossing the south-facing roof decks (Fig. 8b). The BIN-averaged data show the same trends as reduced from the HFTs (Fig. 8). However, there are differences in the magnitude of the reduced data between the HFT measures and the thermometry measures. Results in Fig. 8b show the CTRL with the highest peak load of the three systems included. Again, the differences between the CTRL and FF attics are within the measurement uncertainty. However, the NB attic shows a drop of about 10% in deck flux compared with the CTRL, which has a breathable membrane. The WUFI tool (Appendix A) was used to compare the two systems and revealed a 10% drop in latent load due to the vapor flow

through the breathable underlayment on the CTRL. Therefore, because of the consistency in results between WUFI computations and reduced thermometry measures, the drop in roof deck flux from the CTRL to the NB attics (Fig. 8b) is attributed in part to the drop in water vapor flow across the impermeable underlayment on the NB attic.

Figure 9 compares the BIN-averaged SLD ceiling heat flux with that in the CTRL and ASV attics. The SLD ceiling peak heat flux was 9.93 W/m^2, much higher than the CTRL attic peak ceiling flux. These data show the need to include insulation on the attic floor of the SLD attic if the duct system is airtight or not in the attic. Reducing the impact of duct losses on building energy use is key to the SLD attic's performance. The section "Simulated Sealed Attic Performance with Leaky Ducts" later in this report better illustrates the effect of SLD attic on space conditioning loads if leaky ducts are present in the attic.

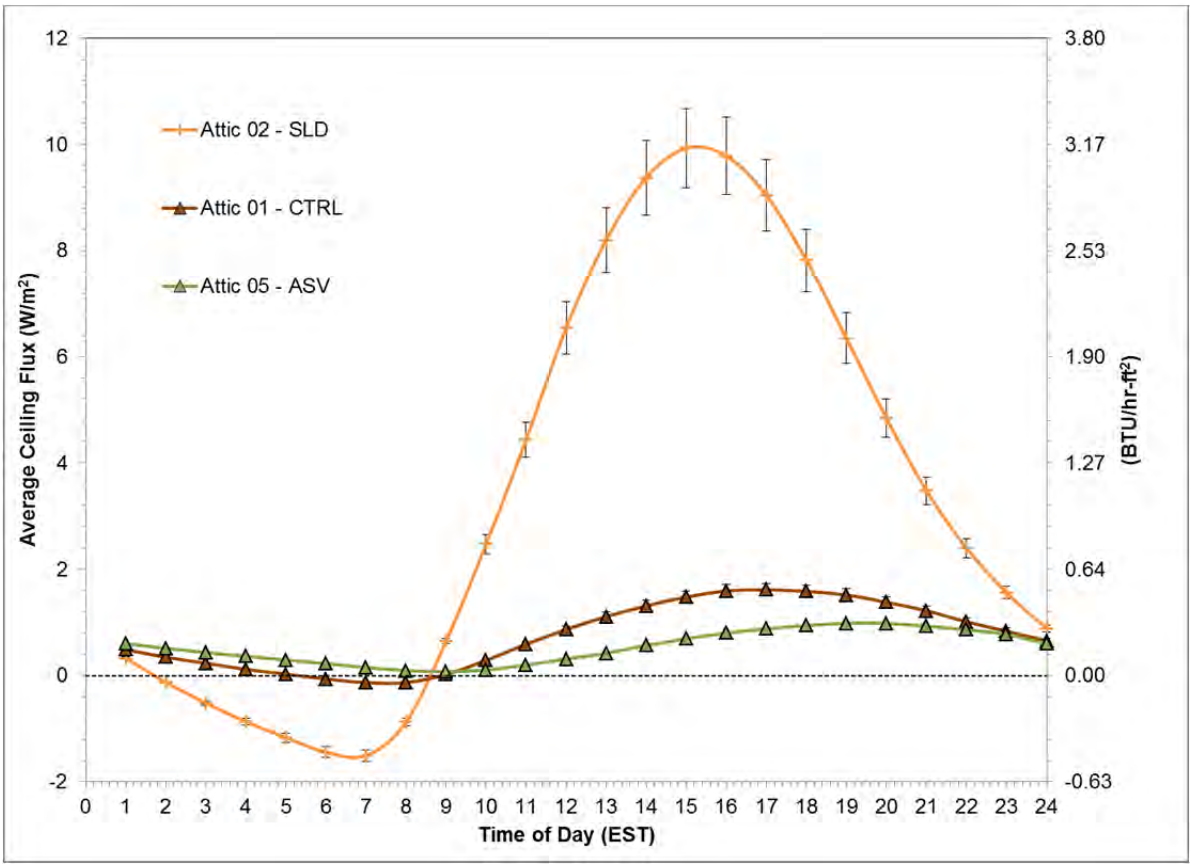


Fig. 9. Sealed attic ceiling summer heat flux.

Table 5 provides the summertime integrated heat transfer through the ceiling for the different attics. The RB and CC attics showed the greatest benefit in minimizing heat flow through the attic floor. As expected, the heat gains through the ceiling were much larger than the heat losses. Compared with the CTRL attic, the RB attic demonstrated a 43.6% reduction and the CC a 42.5% reduction in the net ceiling heat gain. This pattern is logical because the increased reflectivity of the CC shingles and the long-wave radiation shielding of the RB offer protection against incident solar radiation, the dominant mode of summer heat transfer in an attic cavity.

ASV results in a 28.8% reduction compared with the CTRL attic, followed closely by the use of a low-permeability membrane (NB) at 23.7%. As was also the case for the winter data, the 100% increase in the ventilation area of the FF (compared with the CTRL) attic resulted in a 10.3% reduction in the net ceiling heat transfer.

3.4 AIRFLOW—GAS TRACER ANALYSIS

Tracer gas testing was performed on several attics during a trip to the NET facility in June 2011. It was decided that the optimal configuration of dosing and sampling lines for each attic bay was to have a single dosing line located at an axially central location in the attic bay at approximately half the total height of the respective bay (around 2.5 ft above the insulation). The two sampling lines were hung from existing connections approximately 2 ft above the insulation and 4 ft from the centerline of the cavity.

Sampling tubes were measured to a proper length (determined previously inside the attic cavity) and cut. Each attic bay was equipped with electrical conduits for running sensor wires to the DAS. Sampling and dosing tubes were also run through the conduit. Data were collected at different times for each attic, because the gas dosing and sampling filters are sequentially staged by the dosing instrument. A summary of the data collected and calculated air change per hour (ACH) values is provided in Table 6. Exponential decay curves for runs 1, 3, and 4 are shown in Figs. 10, 11, and 12. The exchange rate calculation for ACHs is based on a tracer gas exponential decay method (ASTM, 2006).

Table 6. Gas tracer analysis results

Run	Attic	Date	Start time	Stop time	Outdoor temperature (°C)	Attic temperature (°C)	Wind speed (MPH)	Wind direction (N=0°)	ACH
1	01	6/30/2011	2220	2246	29.30	40.0	3.37	40.9	2.71
2	01	6/30/2011	2350	0019	31.50	43.0	3.57	99.9	2.04
3	03	6/30/2011	1637	1708	27.10	36.6	1.31	207.3	3.68
4	07	6/30/2011	2225	2246	29.30	40.1	3.37	40.9	3.21
5	07	6/30/2011	2354	0019	31.50	43.2	3.57	99.9	2.73

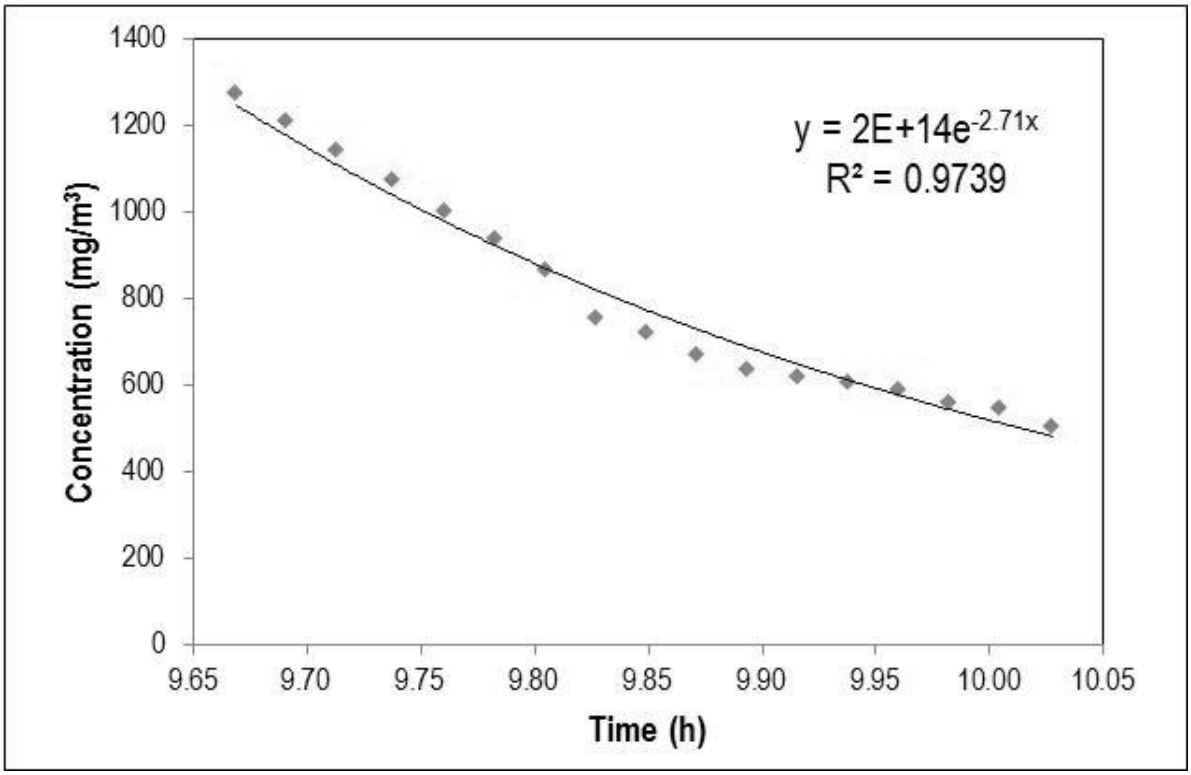


Fig. 10. Attic 01 gas tracer decay curve.

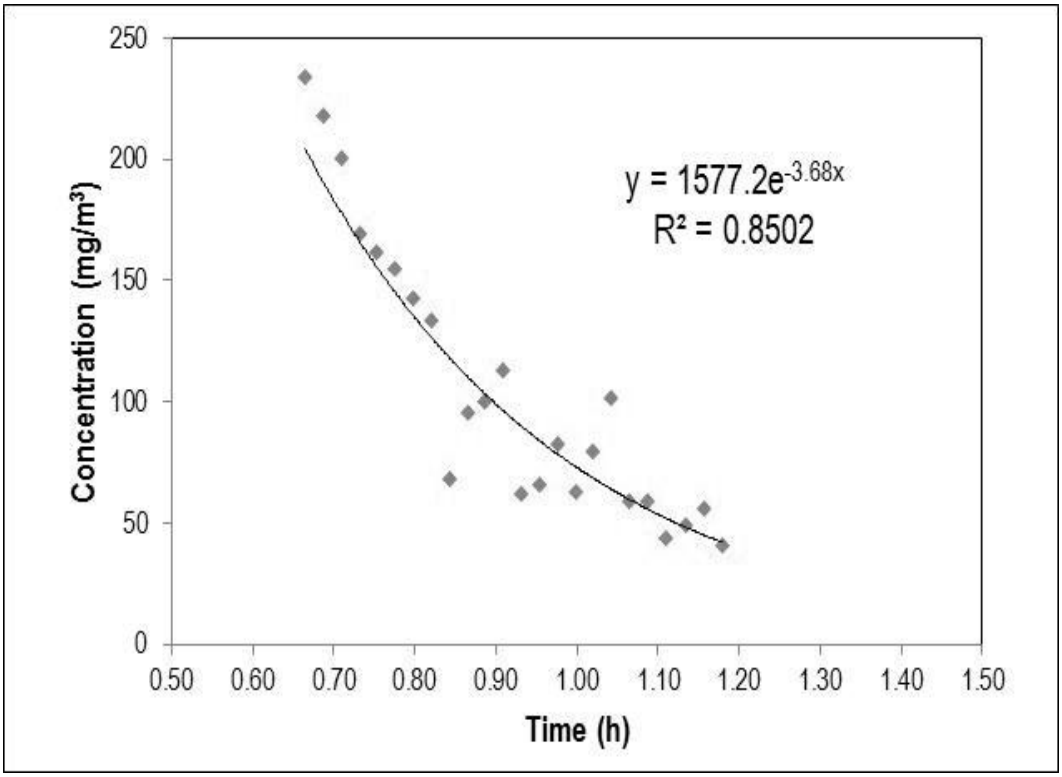


Fig. 11. Attic 03 gas tracer decay curve.

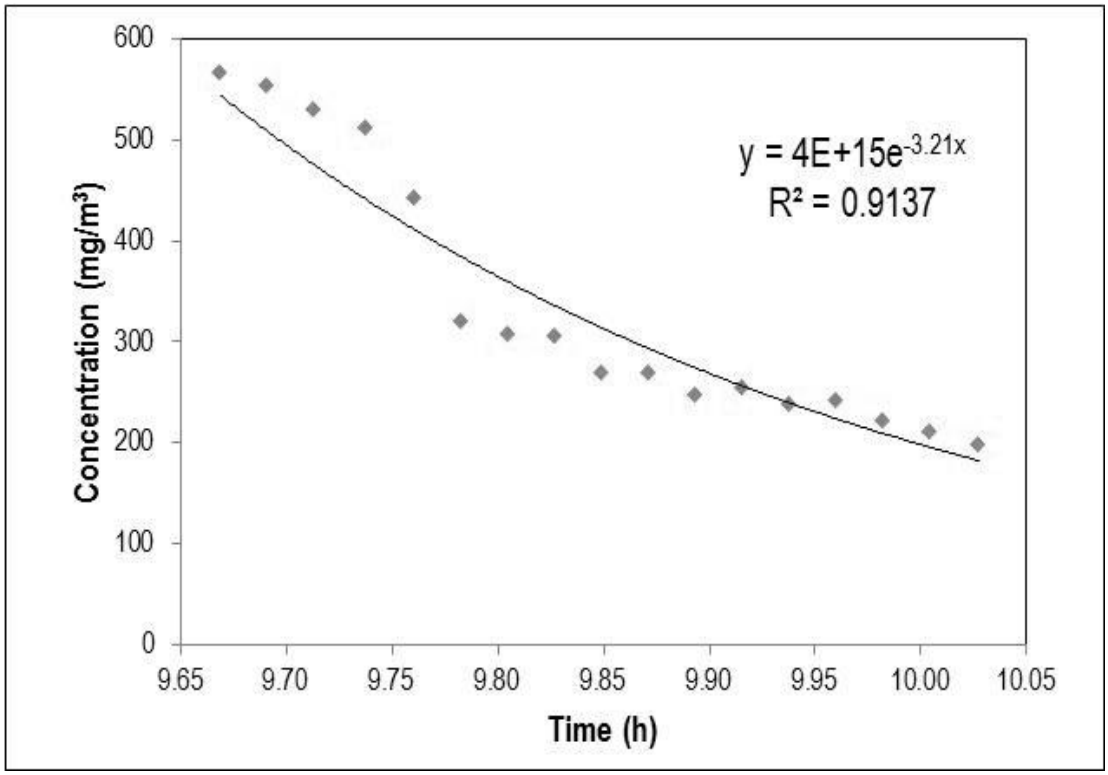


Fig. 12. Attic 07 gas decay curve.

3.5 SEASONAL COMPARISON OF ATTIC STRATEGIES

Even without a detailed analysis, it is clear that ASV has an advantage over the other attic systems because its roof deck has additional thermal resistance. It has already been shown that the ASV attic had the best performance during winter and reduced the net ceiling heat transfer in summer by 28.8% compared with the CTRL attic. The CC and RB attics showed larger ceiling heat transfer reductions in summer but did not perform as well as the ASV attic during winter.

Figure 13 shows the BIN-averaged daily attic temperatures during winter and the BIN-averaged temperatures in the interior conditioned space. The CTRL attic reached the warmest temperature of 24.7°C (76.5°F) during winter; and the SLD attic showed the least variation in temperatures throughout the diurnal cycle (Fig. 13), followed by the ASV and RB attics. Of particular interest are the time shifts between the temperature profiles of the SLD and ASV attics compared with the other attic profiles. They illustrate the effect of increased thermal capacitance and resistance to heat transfer through the roof deck due to the additional ASV materials and the foam insulation under the SLD roof. Of course, in the absence of any ceiling insulation, even with the lowest temperature fluctuations, the SLD attic allowed the highest heat flow through the ceiling. Data from the CTRL and FF attics suggest that during winter, increasing the area of flow (and therefore logically the rate of flow) does not significantly change the average attic air temperature during daytime heating.

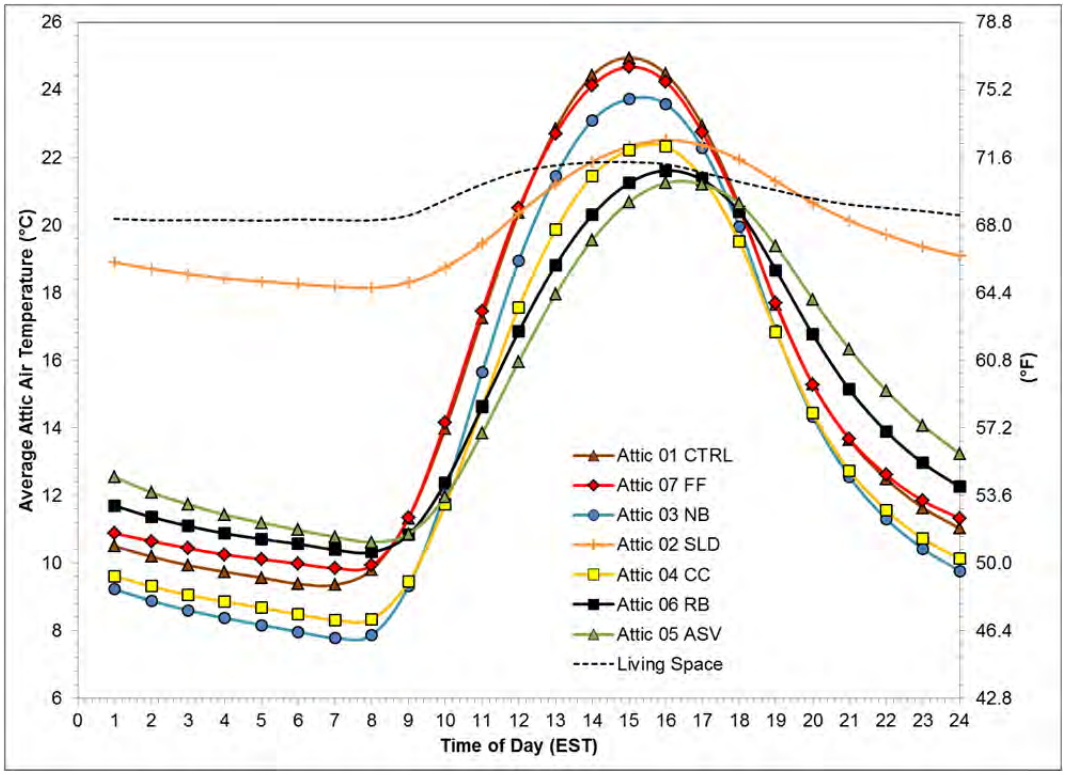


Fig. 13. Winter comparative average attic air temperatures.

Figure 14 shows a similar graph of summer BIN-averaged attic air temperatures. During summer, the ASV and RB attics had very similar performances, sharing an approximately 7°C (12.6°F) lower peak temperature than the CTRL attic. According to Fig. 14, increasing the ventilation area ratio from 1:300 to 1:150 in the summer decreases the peak attic air temperature only by approximately 2°C (3.6°F). The peak CC attic temperature was about 4°C (7.2°F) lower than the peak of the CTRL attic. Again, the SLD attic showed the lowest temperature fluctuations compared with the other attics.

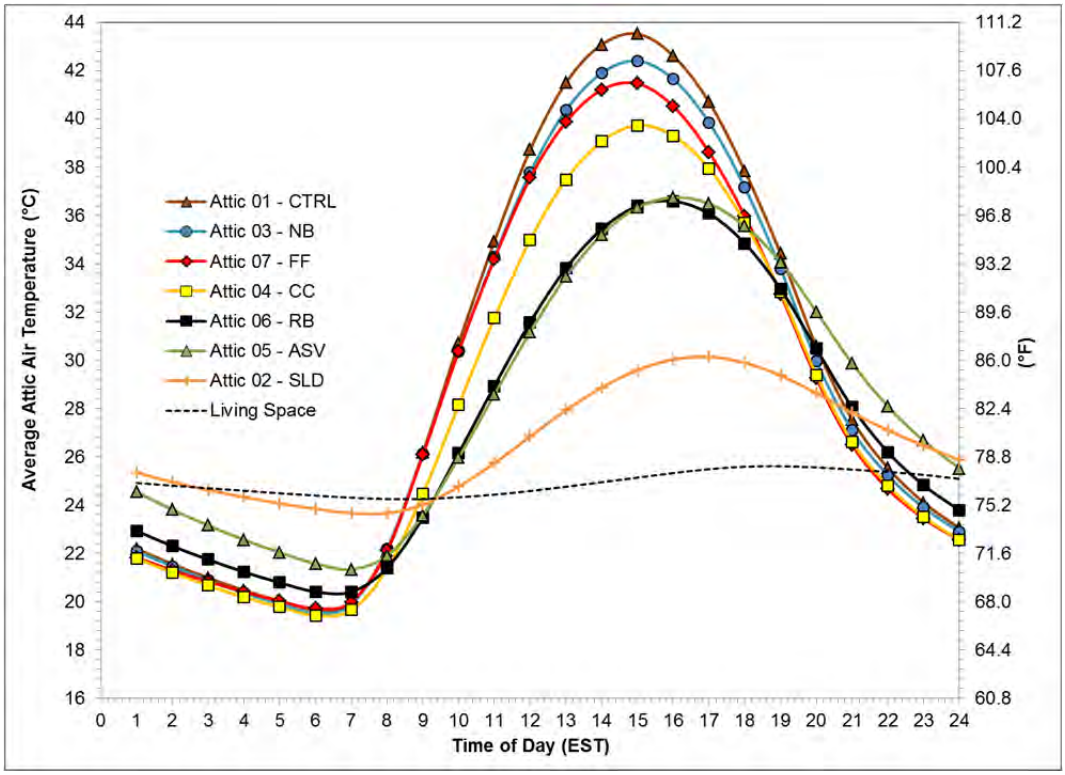


Fig. 14. Summer comparative average attic air temperatures.

3.6 MOISTURE AND HUMIDITY CONTROL

Thus far, the major trend seen in ASV performance is the low magnitude of natural oscillation in both temperature and flux. This damped diurnal oscillation is preferred because it limits the opportunity for the surfaces of the attic, specifically the OSB underlayment, to fall below the dew point temperature of the attic, which leads to condensation of water vapor. Atherton (2011) investigated the temperatures of the OSB underlayment in each attic to determine if there was potential for surface condensation based on surface temperature depression below the dew point temperature of the air. Attic air dew point temperature was calculated using a standard ASHRAE routine and compared with the field data on an hour-by-hour basis. Condensate occurs when the dry bulb temperature of a surface is depressed below the dew point temperature of the surrounding air, which in this case is the air inside the attic cavity. The method chosen to calculate the dew point temperature (T_{dp}) for this report is a simple estimation based on a psychometric state point determined by a known air temperature and RH. Note that Eq. (2) is specifically for Celsius temperature. Coefficient *a* in Eq. (2) is 17.27, and coefficient *b* is 237.7 (Simmons, 2008).

(2)

The total number of times that the surface temperatures of the wood joist or the OSB sheathing dropped below the dew point temperature of the attic was logged and compared with the total time of data collection as a percentage (Table 7). According to Table 7, the ASV attic had the best surface condensation moisture control, with the possibility of condensation at only 0.99% of the recorded time.

Table 7. Surface condensation potential

Attic	Feature	Hours Tsheath<Tdp (3023 total)	% time for condensation on sheathing	Hours Tjoist < Tdp (3023 total)	% time for condensation on joist
			Summer		
03	NB	0	0.00%	0	0.00%
04	CC	0	0.00%	0	0.00%
01	CTRL	0	0.00%	0	0.00%
06	RB	0	0.00%	0	0.00%
05	ASV	0	0.00%	0	0.00%
07	FF	0	0.00%	0	0.00%
Attic	**Feature**	**Hours Tsheath < Tdp (2015 total)**	**% time for condensation on sheathing**	**Hours Tjoist < Tdp (2015 total)**	**% time for condensation on joist**
			Winter		
05	ASV	20	0.99%	10	0.50%
07	FF	75	3.72%	32	1.59%
06	RB	83	4.12%	26	1.29%
01	CTRL	102	5.06%	48	2.38%
04	CC	103	5.11%	62	3.08%
03	NB	110	5.46%	72	3.57%

The increased ventilation in the FF attic provided better dew point control than was seen in the NB attic, with a 1.74% decrease for the sheathing and a 1.98% decrease for the joist. The ASV attic showed the best performance in surface condensation prevention in the winter months.

In the hot, humid climate of Charleston, results show the FF (equipped with the largest ventilation area of all the attics) has attic RH levels higher than the CTRL and NB attics fitted with 1:300 vent areas. The higher the outdoor RH and the larger the vent area of the attic, the higher will be the humidity in the attic, especially during the summer when there is more moisture in the ambient air than in the winter. Among the vented attics, the ASV attic maintained lower peak RH and showed the minimum oscillation between the peak and lowest RH. The CC had the highest peak RH during winter in the early morning hours; during summer, the CC and RB attics showed the highest peak RH in the early morning hours.

Of keen interest in Figs. 15 and 16 is the BIN-averaged RH in the SLD attic compared with the other ventilated attics. The RH behavior in the SLD attic is substantially different from that in the other attics. Its peak averaged RH occurred in the afternoons, when the RH was the lowest in the other attics; this phenomenon is more pronounced during summer but is also observed in winter. Stack effects are largest around solar noon, and the ventilated attics properly lose water vapor then.

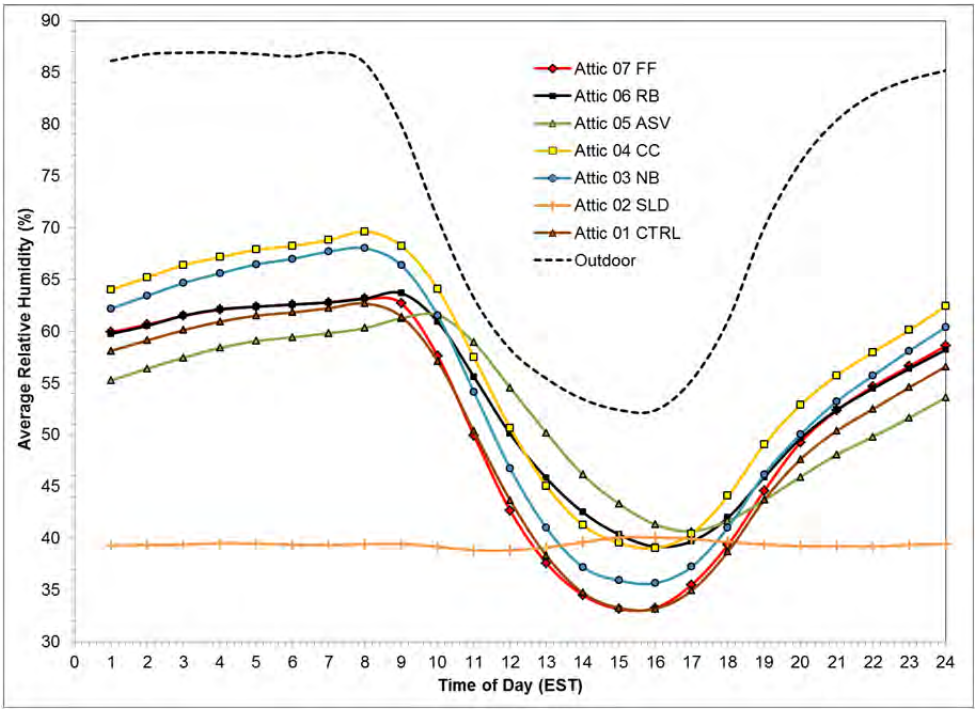


Fig. 15. BIN-averaged hourly attic relative humidity during winter.

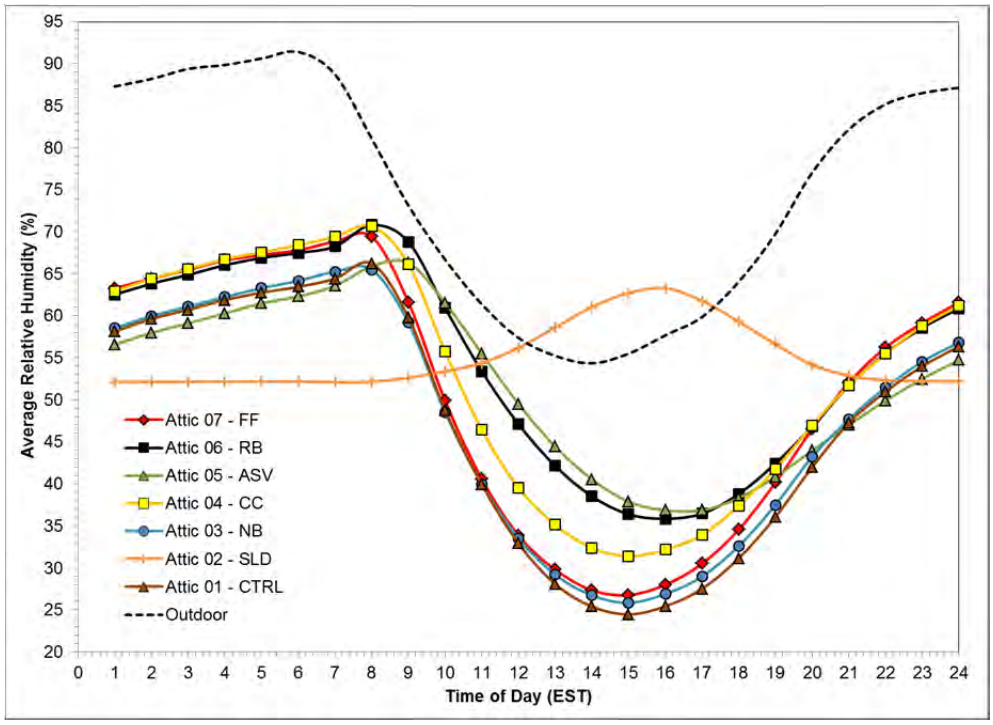


Fig. 16. BIN-averaged hourly attic relative humidity during summer.

However, the SLD attic was not able to do so (Fig. 16). For the RH in the SLD attic to increase when the outdoor RH dropped in the afternoon hours, the open cell spray foam would have to be storing water. To better understand the phenomenon, we held a portable hygrometer to the spray foam. We observed, during an October afternoon with a clear sky, a continued rise in the RH at the face of the open cell foam.

Therefore, the open cell foam was storing moisture, which the afternoon sun drove into the attic air, raising the RH. Colon (2011) made similar measurements on a home field-tested in Florida. However, in the Florida home, a nonbreathable underlayment was used, whereas in Charleston, 15# felt paper with 8 perm breathability was used to protect the OSB deck.

3.7 SIMULATED SEALED ATTIC PERFORMANCE WITH LEAKY DUCTS

The key reason for sealing an attic is to capture lost energy from a leaky duct and use it to make the attic part of the conditioned space. If the attic air is relatively close to the air temperature in the conditioned space, then the ceiling flux will be negligible. Concerns associated with the sealed attic arise because the retrofit increases the volume of the conditioned space, forcing the heat pump to run longer to satisfy load compared with a vented attic with a well-insulated, leak-tight duct. Simulations were conducted using AtticSim to compute the attic air temperature for the CTRL attic with and without a 10% leaky duct and for the SLD attic (Fig. 17) with a duct leaking 10% of its supply air into the attic. The simulations for three contiguous hot and humid days in July revealed that the SLD attic had attic air temperatures about 85°C cooler than those in the CTRL attic. Therefore, the SLD attic could have less ceiling heat loss compared with the CTRL over the diurnal cycle because the duct leaks would temper the air in the attic. However, the added run time of the heat pump would cause the home with the SLD attic to use about $100 more electricity[2] annually to condition the residence, compared with the home with no duct in the attic.

Figure 18 shows a comparison of the ceiling loads due to a sealed attic and to a control direct-to-deck shingle attic, similar to the SLD and CTRL attics presented in this study. Both attics are assumed to contain ducts with 20% leakage. AtticSim simulations were done to calculate the ceiling loads for a range of ceiling and roof R-values in Austin, TX, which lies in climate zone 2A. Similar to the present study, the shingle attic was assumed to contain ceiling insulation, and the sealed attic contained insulation at the roof deck. With the same insulation levels as the Charleston study—R-38 ceiling insulation in the shingle attic and R-21 roof insulation in the sealed attic—the ceiling load due to the sealed attic is about 57% lower than that of the shingle attic. These results show the importance of considering duct losses when evaluating the performance of sealed attics.

[2] The cost of electricity for a longer run time was estimated using Energy Plus.

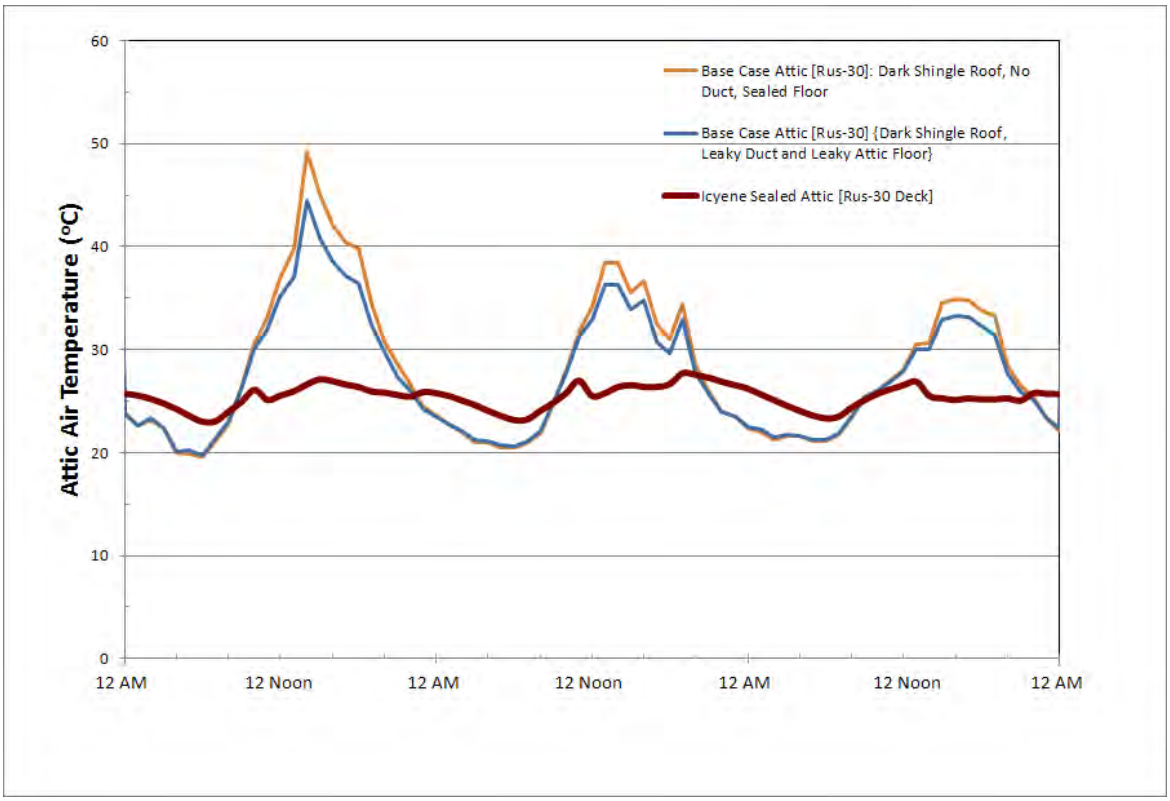


Fig. 17. AtticSim winter simulations for the SLD attic and the CNTRL attic. A 10% leaky duct is assumed in the SLD attic.

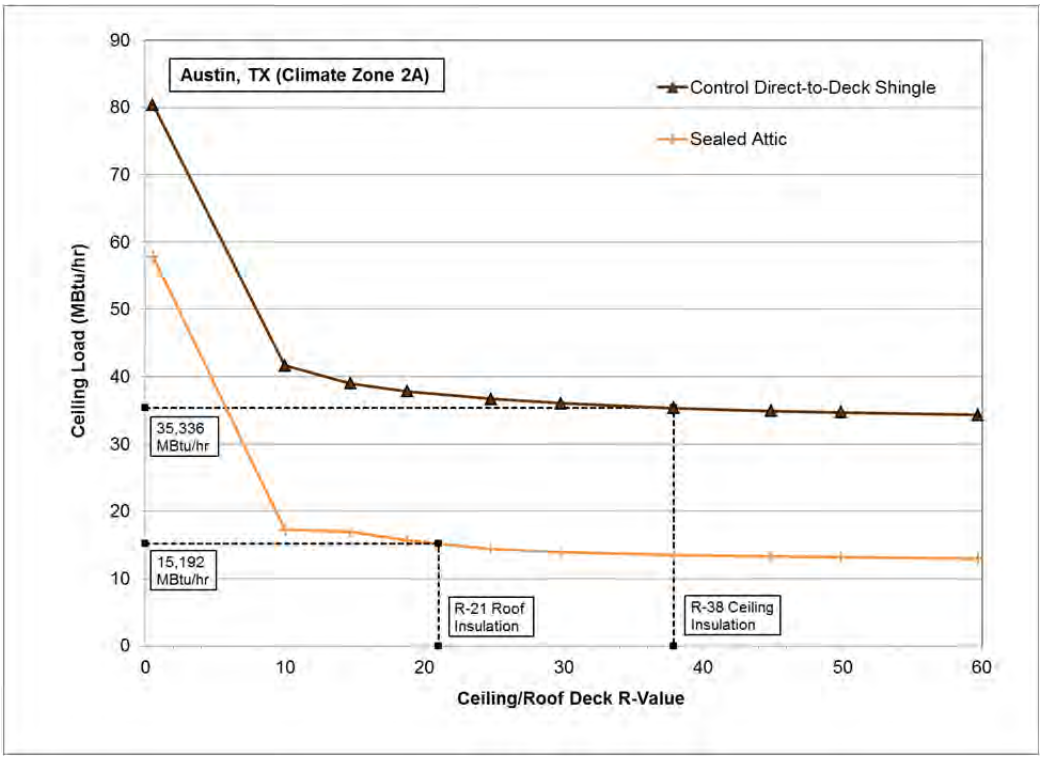


Fig. 18. Comparison of ceiling load with 20% leaky ducts in attic.

3.8 RADIANT BARRIER AND COOL COLOR SHINGLES—RADIATION CONTROL IN ATTIC CAVITIES

The RB foil competes effectively with the ASV attic in terms of maintaining a moderate attic air temperature in both seasons. Its performance is virtually indistinguishable from that of the ASV attic during the summer months. RB foils block the flow of heat from the roof deck to the ceiling, causing a decrease in heat flux (Fig. 19). Compared with the CTRL attic, the RB attic drops the BIN-averaged flux on the south roof deck by about 21 W/m^2 attic during peak irradiance. Computations for the CTRL attic show a radiation heat transfer coefficient of about 4.7 W/(m^2·K) compared with the ceiling's convection coefficient of about 1 W/(m^2·K). Therefore, the heat transfer from deck to ceiling is radiation-dominant. However, adding the foil to the underside of the deck causes the radiation coefficient from roof deck to ceiling to drop to about 0.05 W/(m^2·K).

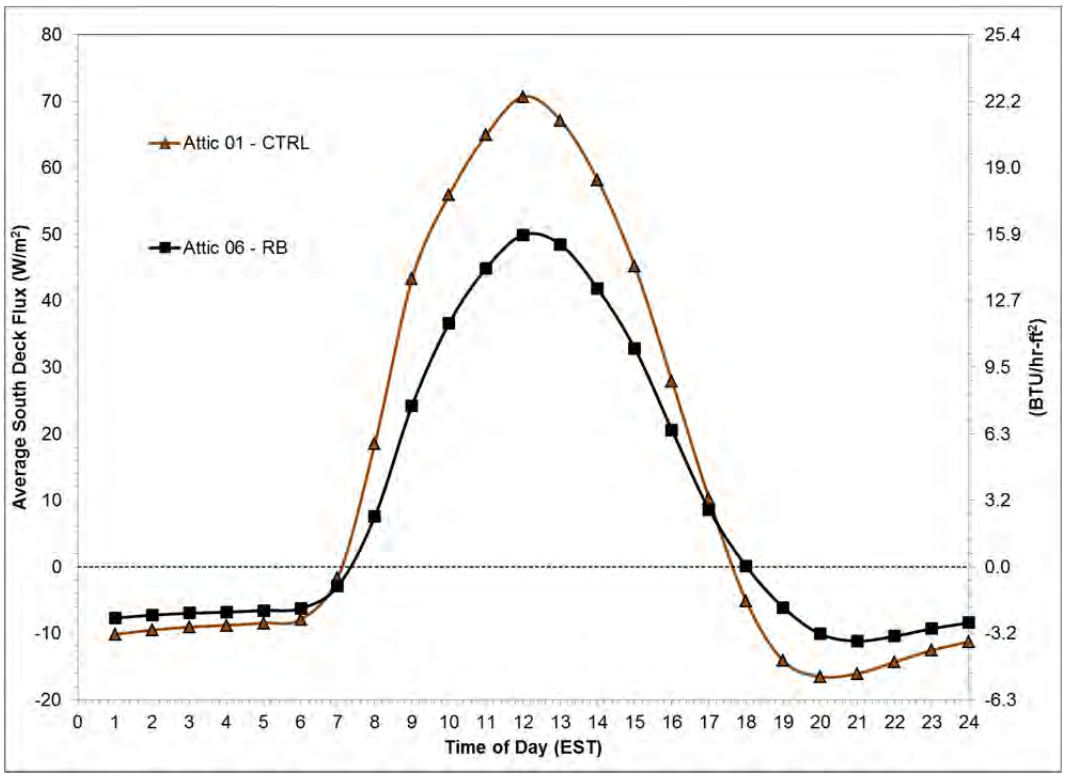


Fig. 19. Summer radiant barrier effect on average south deck flux.

The highly reflective pigmentation of the CC shingles performed similarly to the RB during the summer months, especially in reducing heat flow through the roof deck. As seen previously in Fig. 5, the average heat flux through the deck was very close to the RB curve and roughly peaked at 7 W/m^2 higher than the RB.

In comparison, the RB foil maintained lower daytime attic air temperatures than the CC shingles in the summer months and warmer evening attic air temperatures during the winter months (Figs. 13 and 14). The CC and RB profiles for heat flux through the ceiling are almost identical for both seasons.

3.9 BENCHMARKING—INSULATION THICKNESS AND HFT DATA CONFIDENCE

Insulation thickness measurements were taken for each attic cavity to determine the actual density, thermal conductivity, and R-value of the Fiberglass batts. Samples were taken from the facility and

brought back to ORNL for material property analysis. Including the investigation into the thermodynamic properties of the insulation is necessary to best understand the degree of confidence in the data related to the performance analysis of each attic. The insulation thickness test results are shown in Table 8.

Table 8. Insulation thickness test results

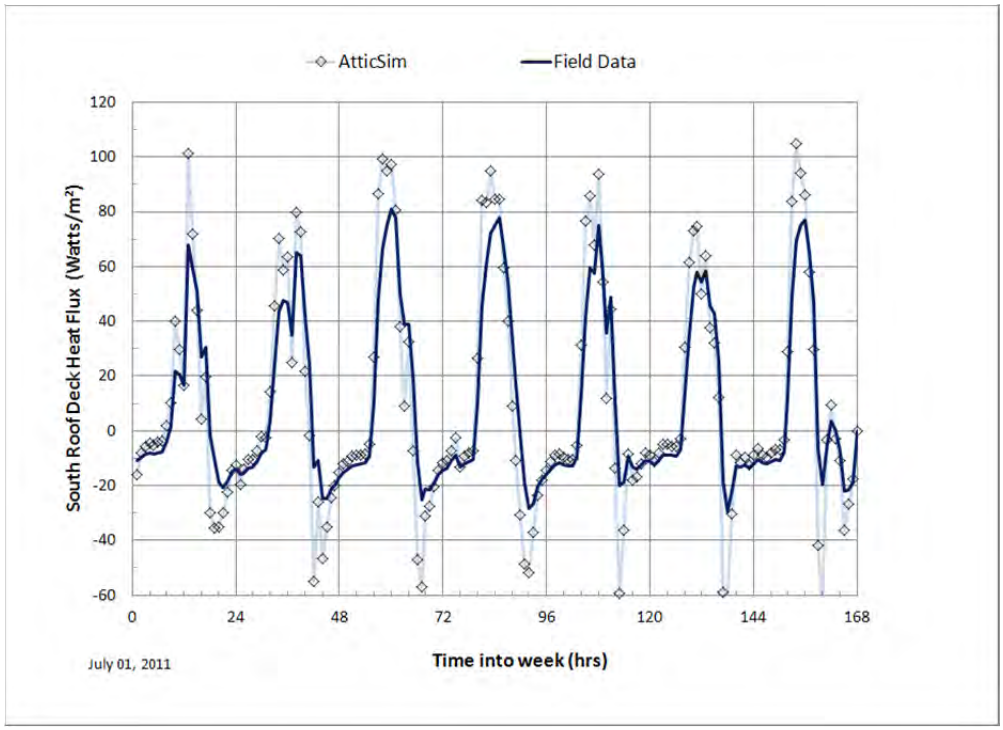
	John Manville Fiberglass (FBG) insulation		Fiberglass sample measurements	
Attic	**Paper-backed FBG touching HFT[a] (in.)**	**FBG placed on top of rafters[b] (in.)**	**Paper-backed FBG touching HFT (in.)**	**FBG placed on top of rafters (in.)**
1	6.5	6.5	9.0	5.0
2	0.0	0.0	N/A	N/A
3	6.5	6.5	9.0	6.0
4	6.5	6.5	7.0	6.0
5	6.5	6.5	7.0	6.0
6	6.5	6.5	7.0	6.0
7	6.5	6.5	7.0	7.0

[a] Kraft-faced batts, R-19, have manufacturer-specified thickness of 6½ in.
[b] Unfaced batts, R-19, have manufacturer-specified thickness of 6½ in.

3.10 BENCHMARKING—ROOF DECK AND CEILING HEAT FLUX

AtticSim was used to estimate the heat flux into the roof sheathing and through the ceiling. Figure 20 shows benchmarks of AtticSim against the south deck heat flux and against the ceiling heat flux for the CTRL attic. The computed south roof deck heat fluxes (bold line) agree well with the measured data, as does the computed ceiling heat flux. Simulations at peak irradiance show AtticSim over predicts the roof deck heat flux (Fig. 20a) but predicts the ceiling flux well (Fig. 20 a and b). The inconsistency is believed to be due to the prediction of airflow inside the attic and the uncertainty in the R-value of the fibrous insulation, which is typically within ±5% of the label value used for the analysis. Figure 21 shows similar benchmarks for the FF attic with 1:150 fascia flow. AtticSim again overshoots the measured data collected at around solar noon but predicts well the data during the evening hours. During peak irradiance, stack effects are the strongest, and recent tracer gas testing shows AtticSim to underpredict the stack effect inside the attic.

a: Benchmarked attic 01 (CTRL) south roof deck heat flux



b: Benchmarked attic 01 (CTRL) ceiling heat flux

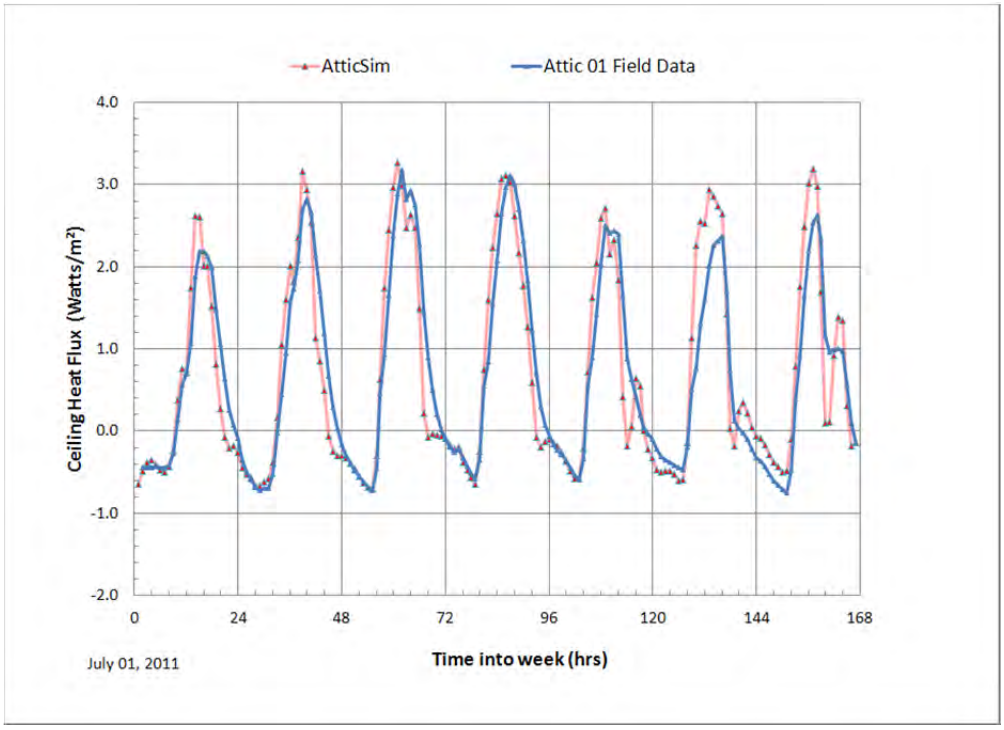
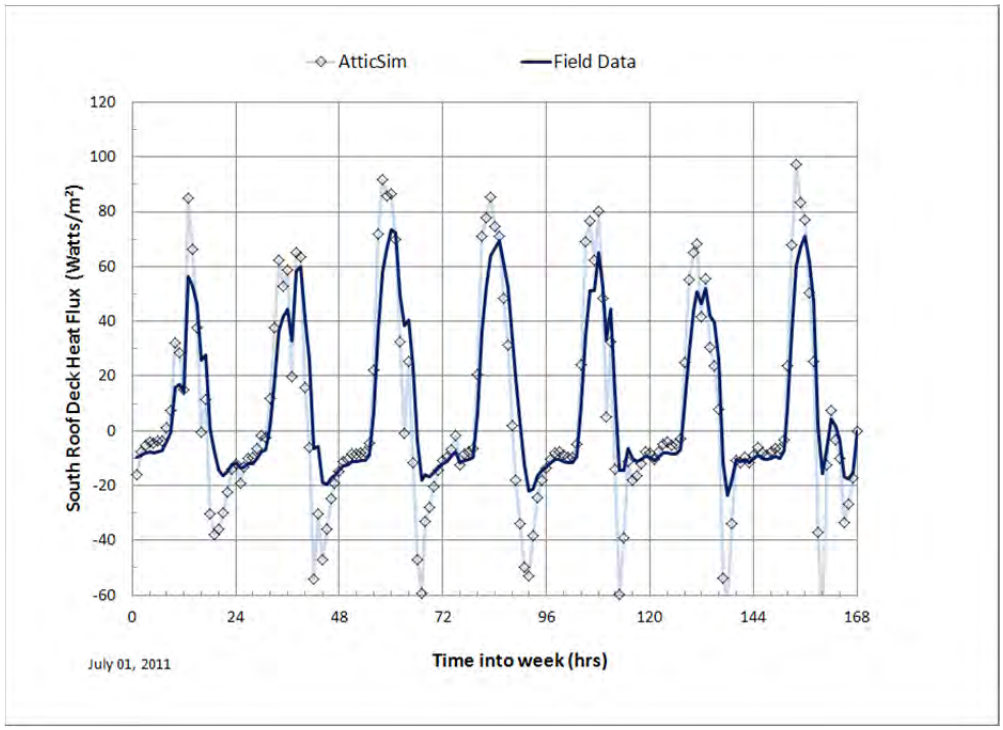


Fig. 20. AtticSim benchmark against field data: (a) roof deck heat flux and (b) attic floor heat flux for the CTRL attic with 1:300 vent area (attic 01).

a: Benchmarked attic 07 (FF) south roof deck heat flux



b: Benchmarked attic 07 (FF) ceiling heat flux

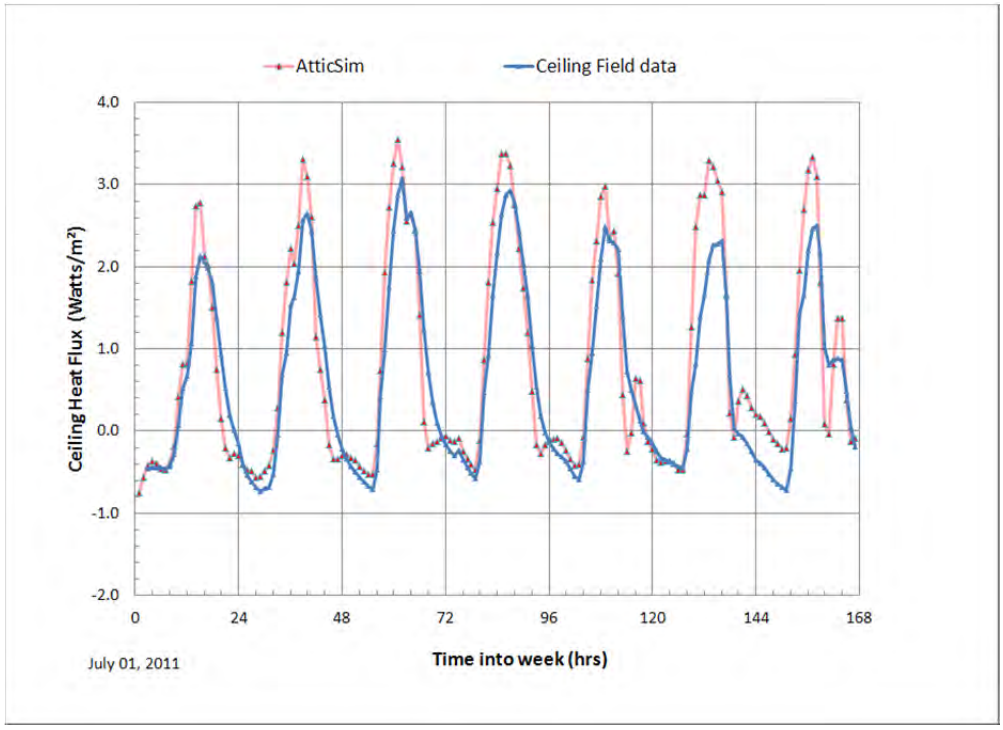


Fig. 21. AtticSim benchmark against field data: (a) roof deck heat flux and (b) attic floor heat flux for the attic with fascia flow (1:150 vent area) assembly (attic 07).

3.11 VENTILATION EFFECTS ON MOISTURE AND HEAT CONTROL—A PARAMETRIC STUDY

A parametric study was conducted on the CTRL, RB, and ASV attics by varying in equal parts the soffit and ridge ventilation areas. Ventilation-to-footprint area ratios of 1:25, 1:50, 1:150, 1:300, and 1:500 were simulated using TMY2 (Typical Meteorological Year) data. The average diurnal ACH values in the CTRL attic are presented for the winter and summer seasons in Figs. 22 and 23. Increasing the ventilation ratio increases the flow rate and causes an increase in the amplitude of the maximum ventilation, from 30 ACH at 1:500 to about 300 ACH at 1:50. The trend follows the diurnal cycle closely because much of the attic ventilation is caused by stack effects driven by irradiance.

There is an obvious limit to how much air flow can be achieved by increasing the ventilation area of the soffits and ridge vents. If the attic were constructed with a 1:50 ventilation ratio, the net ventilation area would be 2000/50 = 40 ft^2, which is not practical. But in order to observe trends, we conducted simulations up to the limit of 1:25.

As the air exchange rate increases, there should be less potential for condensation in the attics. We computed the condensation potential on the OSB sheathing for the entire year by comparing the predicted sheathing temperature with the predicted dew point temperature of the attic air. The percentage of total time for condensate potential is shown in Table 9 for the results shown graphically in Figs. 24 and 25.

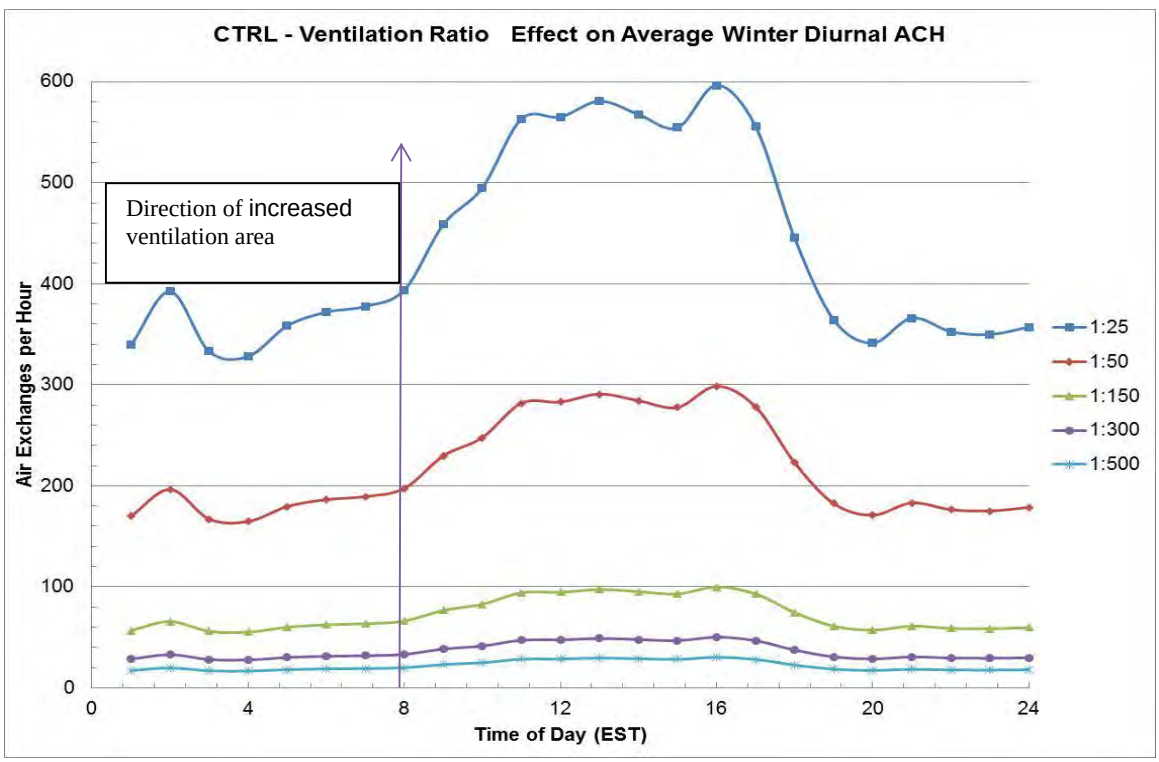


Fig. 22. Ventilation rate effect on average winter diurnal ACH.

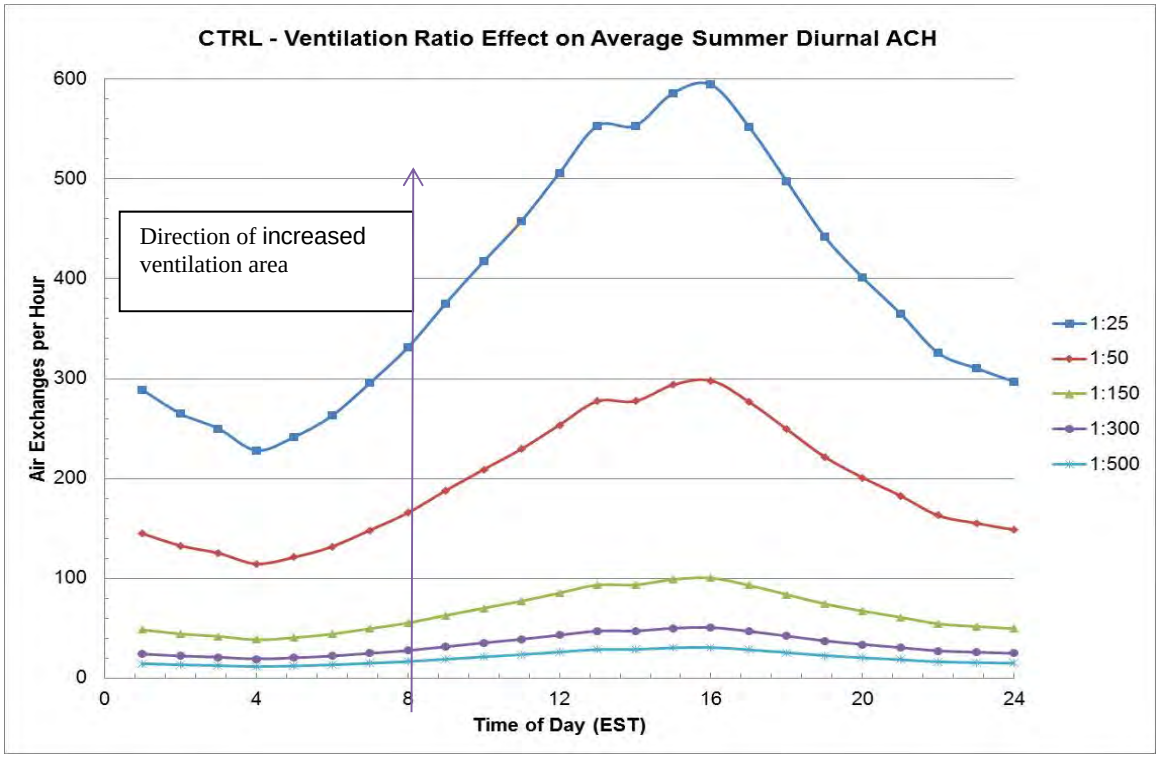


Fig. 23. Ventilation ratio effect on average summer diurnal ACH.

Table 9. TMY2 results of underlayment condensate potential

	Percentage of total time in which $T_{sheathing} < T_{dp}$				
Attic type	**1:25**	**1:50**	**1:150**	**1:300**	**1:500**
RB	15.38%	15.87%	16.44%	16.98%	17.15%
CTRL	11.35%	11.78%	12.46%	12.68%	12.6%
ASV	2.79%	2.83%	2.84%	2.88%	2.73%

The simulation results show that the potential for condensation on the OSB sheathing decreases consistently with an increase in ventilation area (e.g., from 1:300 to 1:150). However, the magnitude of the effect is relatively small compared with the differences seen from changing the attic construction. For example, the result of increasing the ventilation area in a CTRL attic from the standard 1:300 to 1:150 is a decrease in potential for condensation of only 0.22%. If the CTRL attic is retrofitted with an ASV system, however, the percentage potential for sheathing condensation is 2.88%, a 12.2% drop.

The addition of an RB to the attic sheathing has the effect of keeping the surface cooler during the night, especially during the winter months. This occurs because the RB reduces the emission of long-wave radiation into the attic from the roof deck during the daylight hours; then at night, it reflects the heat from the conditioned space, reducing the temperature of the OSB. Since the early morning hours are the most likely time for condensation potential, the cooler surface of the OSB would lead to a higher likelihood that condensation would occur. To properly illustrate this point, the data from Table 9 are graphed in Fig. 24.

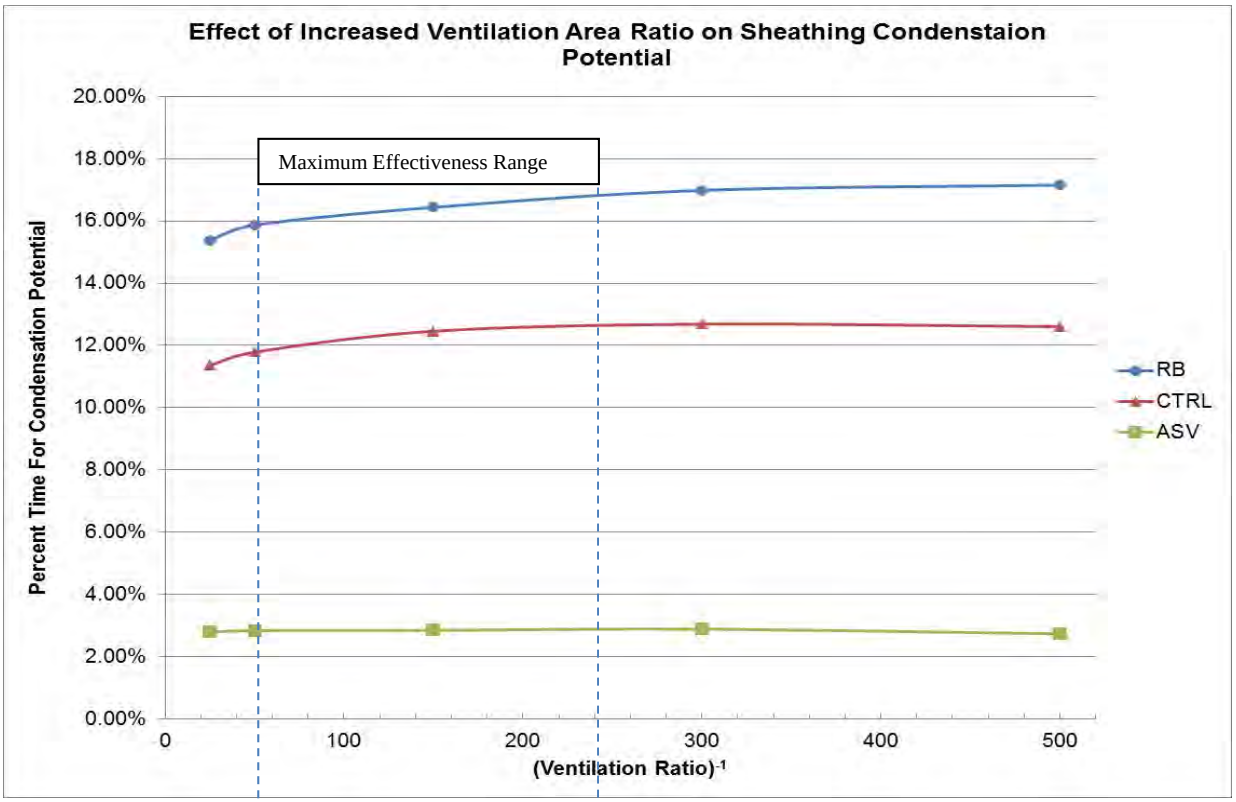


Fig. 24. Effect of increased ventilation ratio on sheathing condensation potential.

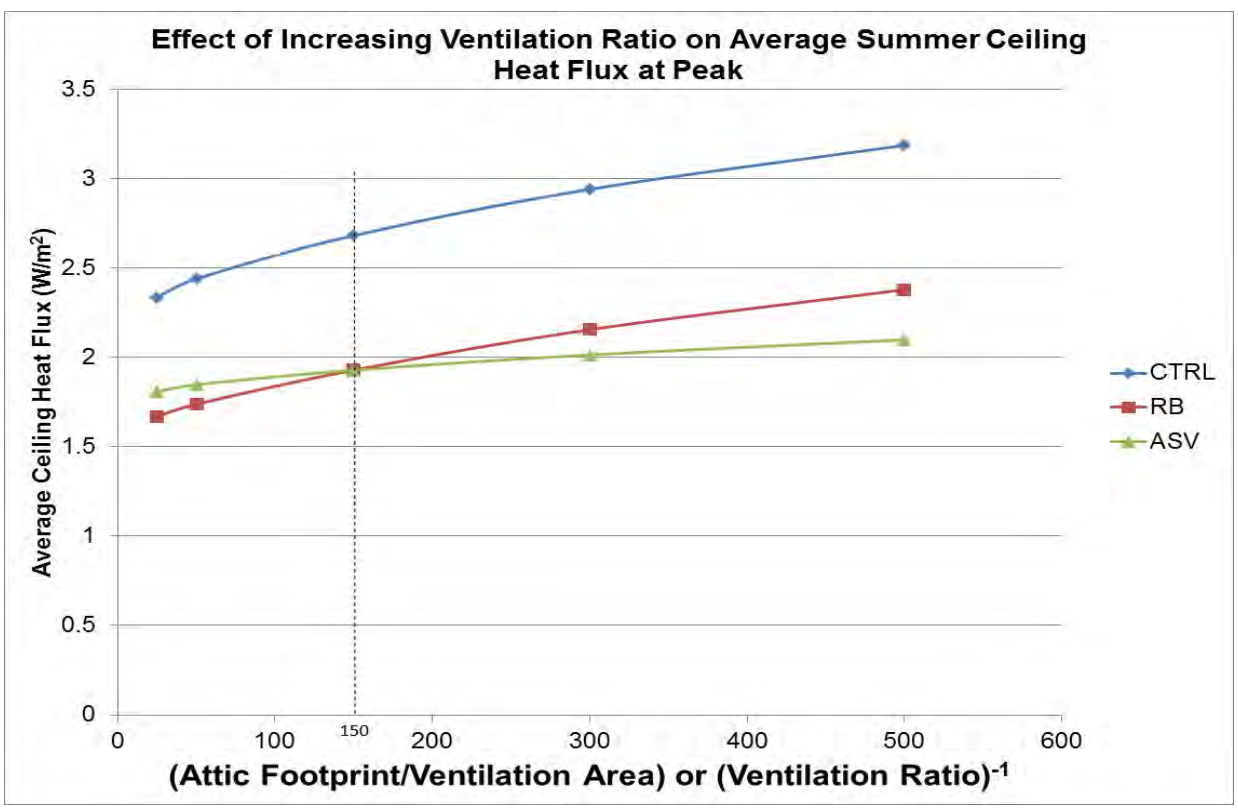


Fig. 25. Effect of ventilation ratio on peak day ceiling heat flux—simulation results.

As seen in Fig. 24, the condensation prevention induced by increasing the ventilation ratio from 1:300 to 1:100 is 2% for the CTRL attic, whereas there is no change in condensation prevention for the attic with ASV. The conclusion to be gleaned is that the potential for condensation is not strongly dependent on the soffit-ridge ventilation ratio, especially when considered against the benefit of ASV.

Simulations were also run to compare ventilation effects on the ceiling heat flux (Fig. 25) and are presented for time-of-day BIN averages to mirror the presentation style of the field data. Ceiling heat flux values at peak heating are directly affected by the construction type of each of the attics simulated. The RB attic has long-wave radiation control, whereas the ASV attic has an additional roof deck and an air gap to retard the flow of heat through the deck. The most important observation in Fig. 25 is that heat flux in the region of common practice is only slightly sensitive to variations in the ventilation ratio. The maximum difference in the average heat flux between any of the data points for each attic is about 0.2 W/m^2.

At the design condition of 1:150, the average ceiling heat flux is approximately equal for the RB and ASV cases. From a heat transfer point of view, this is very interesting because the result implies that merely adding a foil coating to the underside of the OSB sheathing can provide the same level of heat flow control through the ceiling plane as an ASV system, assuming that the insulation levels are equal.

4. CONCLUSIONS

4.1 CEILING HEAT FLOW

The CTRL, FF, and NB attics—with, respectively, permeable, semi-impermeable, and impermeable underlayments—yielded the largest seasonal ceiling heat flows of all attic assemblies. The largest differences were observed during the summer. Of the three systems, the impermeable underlayment caused the NB attic to have the lowest ceiling heat flow. Ceiling flux computed from the temperature gradients across the ceiling insulation and gypsum board showed similar trends consistent with HFT measurements. The summertime seasonal heat flux for the NB attic dropped 23% of the flux penetrating the ceiling of the CTRL attic; the drop is believed to be attributable in part to the drop in latent flux across the 16-perm breathable membrane for the CTRL compared with the 0.04-perm impermeable underlayment on the NB attic. The WUFI code predicted a 10% drop in flux (Appendix A) as the underlayment changes from breathable to nonbreathable. Therefore, the results are consistent with theory, and the NB underlayment shows slightly better summer performance as a result of a drop in latent load compared with the CTRL with breathable underlayment.

The ASV, CC, and RB attics demonstrate relatively similar reductions in summer ceiling flux; however, over the winter season, the attic fitted with ASV had the least diurnal variation in ceiling heat flux of all seven attics, especially during the early morning (1:00–6:00 a.m.). Integration of the total heat flux over the winter season shows that the ASV attic reduces the net heat loss through the attic floor by 53% compared with the conventional CTRL attic.

Integration of the summer data showed that, compared with the CTRL standard, the RB attic demonstrated a 43.6% reduction and the CC showed a 42.5% reduction in the net heat gain through the ceiling.

As a result of the lack of ceiling insulation and because the duct was leak-tight, the SLD attic allowed the highest heat fluxes through the ceiling. The sealed attic approach must make the attic a semi-conditioned space by exploiting the losses from a leaky duct system.

4.2 ATTIC VENTILATION

Ceiling heat flux at peak day irradiance is directly affected by the construction type of each of the test attics. For example, the RB attic has long-wave radiation control, whereas the ASV attic has an additional roof deck and air gap to retard the flow of heat through the deck. However, increasing the ventilation area ratio does not show significant improvement in the thermal performance of an attic system. For conventional attic ventilation practice, the heat flux is only slightly sensitive to variations in ventilation ratio. Therefore, ventilation is required more for moisture control than for thermal control.

4.3 HYGROTHERMAL CONTROL

Data reduction revealed almost no potential for condensation of water vapor onto the sheathing during the summer season in the hot, humid climate of Charleston, SC, for any of the attic constructions at the NET facility. In the winter season, there are periods of time when the OSB sheathing temperature drops below the dew point of the attic air. The potential for condensation on the basis of a percentage of total time is the highest for the attic with the smallest ventilation area (1:300 ventilation ratio) and fitted with a nonbreathable underlayment. Increasing the ventilation ratio decreases the condensation potential from 5.1% to 3.7% during the winter months, whereas the ASV attic reduces the potential to a mere 1.0% of total time.

4.4 SEALED ATTIC ISSUES

Building America advocates that homeowners seal attics to keep out outdoor ambient humidity in hot and humid climates (Baechler and Love, 2004). However, all ventilated attics with the exception of the SLD attic revealed drops in RH as irradiance increased stack effects. The opposite was true in the SLD attic, in which solar energy drove moisture out of storage in the open cell spray foam and actually caused the RH to increase in the attic. On some particularly hot days, RH was at full saturation (i.e., 100%). At this condition, water vapor is in equilibrium with liquid water and therefore all interior attic surfaces are wet! Without a leaky duct, the SLD attic approach actually exacerbates humidity control in attics under exposure in hot, humid climates. However, presence of leaky ducts does not necessarily provide adequate mitigation of the attic moisture issue.

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APPENDIX A. LATENT FLUX PREDICTION AS AFFECTED BY THE BREATHABILITY OF UNDERLAYMENT

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Latent heat effects can contribute to the overall heat flux in a roof assembly. International Energy Agency Annex 24 concluded that latent heat effects can contribute to about 5% of the heat flux for active masonry walls in cold climates. For the flux to be a higher contribution, it is necessary that moisture go through a phase change within the roof assembly, which can occur through liquid to vapor or from vapor to liquid transfers.

Liquid to vapor transfer requires that liquid water be absorbed and then leave the assembly as vapor. The exterior shingles have no capillary activity for liquid uptake; however, driving rains can make the shingle system wet. Solar irradiance can then drive the water through a permeable underlayment, into and through the wood of the roof deck and into the attic.

Two WUFI simulations were conducted for the roofs (Fig. A.1) using the WUFI tool for calculating hygrothermal behavior. One simulation assumed a low-permeability underlayment, the other a high-permeability membrane. The results confirmed the physics mentioned above for the NET test roofs. WUFI used measured field data as boundary conditions (Table A.1) and computed moisture content in the OSB to judge whether moisture effects are responsible for the different measured thermal results for the two different roof assemblies.

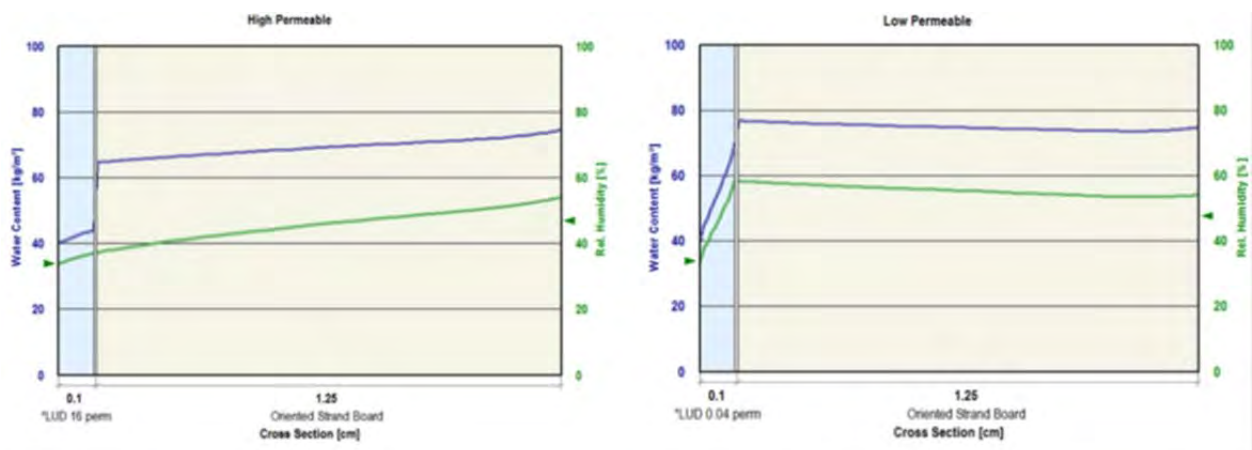

Fig. A.1. Profile of moisture content and relative humidity within the two studied roof assemblies averaged over the calculated time period 03/25/2010 and 07/29/2010.

Table A.1. WUFI simulations were conducted on the CTRL and NB roof and attic assemblies

Name	High permeability	Low permeability
Exterior boundary condition	Measured	Measured
Exterior surface transfer resistance	0	0
Underlayment	16 perm	0.04 perm
Sheathing (OSB)	1.25 cm (½ ’’)	1.25 cm (½ ’’)
Interior surface transfer resistance	0.1 m^2K/W (0.569 $ft^2 \cdot h \cdot °F/Btu$)	0.1 m^2K/W (0.569 $ft^2 \cdot h \cdot °F/Btu$)
Interior boundary condition	Measured	Measured

The only difference between the two roof assemblies is the permeance of the underlayment; the CTRL has a breathable underlayment (16 perms) and the NB a nonbreathable membrane (0.04 perms). WUFI used its material property database and modeled a moisture-dependent thermal conductivity of 1.5 % per mass percentage of moisture in the OSB sheathing.

Results for the high-permeability and the low-permeability roof assembly show a significant difference in the moisture content at the joint between underlayment and OSB. The highly permeable roof assembly has lower moisture content because the breathable membrane lets accumulated moisture easily dry to the exterior. Results for the two roofs and attics are tabulated in Table A.2 to judge the effect of the moisture on the energy fluxes of the OSB decks.

Table A.2. Averaged moisture content, heat conductivity of the OSB and thermal boundary condition over the calculated time period as well as the integrated heat flux (energy flux)

	High permeability	Low permeability	Difference
Moisture content, OSB	69.3 kg/m^3 (4.33 lb/ft^3)	74.9 kg/m^3 (4.74 lb/ft^3)	
Moisture content, OSB [M.-%]	11.6	12.6	
Thermal conductivity, OSB, at average moisture content	0.153 W/mK (0.0884 Btu/h·ft°·F)	0.155 W/mK (0.0900 Btu/h·ft·°F)	−1.2 %
Interior temperature	29.5 °C (85.1 °F)	29.0 °C (84.2 °F)	
Exterior temperature	22.9 °C (73.2 °F)	23.0 °C (73.4 °F)	
Temperature difference, int. – ext.	6.7 K (10.8 °F)	6.0 K (12.1 °F)	10 %
Calculated energy flux	105 kWh/m^2	94.3 kWh/m^2	10 %

It is seen in Table A.2 that the moisture content of the OSB causes only a 1.2 % difference in the moisture-dependent thermal conductivity and can therefore not explain the measured or the calculated difference of 10% in the heat flux between Attic 01 (CTRL, 16 perm underlayment) and Attic 03 (NB, 0.04 perm underlayment). Furthermore, the higher thermal conductivity of the OSB combined with the highly permeable underlayment should yield a higher heat flux, not a lower flux as suggested by the field data (see Fig. 5).

Therefore, the anomaly in deck heat flux for the CTRL attic (16 perm underlayment) and the NB attic (0.04 perm underlayment) is not explained by latent heat flows due to diffusion of moisture through the roof deck. Further investigation is needed to review the impact of moisture transfer on both durability and heat and mass transport for roofs with and without low-permeability membranes.

APPENDIX B. MATERIAL PROPERTY DATA

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	Attic 1	Attic 2	Attic 3	Attic 4	Attic 5	Attic 6	Attic 7
Shingle							
Thickness (mm)	7.2644	7.2644	7.2644	7.2644	7.2644	7.2644	7.2644
k (W /m K)	0.0937	0.0937	0.0937	0.0937	0.0937	0.0937	0.0937
Cp (J/kg K)	1757.3	1757.3	1757.3	1757.3	1757.3	1757.3	1757.3
ρ (kg/m^3)	1121.3	1121.3	1121.3	1121.3	1121.3	1121.3	1121.3
Underlayment							
Thickness (mm)	0.7621	0.7621	0.7621	0.7621	0.7621	0.7621	1.397
k (W /m K)	1.175	0.0129	1.175	1.175	0.0129	0.0129	0.0129
Cp (J/kg K)	1000.0	1260.0	1000.0	1000.0	1260.0	1260.0	1260.0
ρ (kg/m^3)	240	800	170	170	800	800	800
Sheathing							
Thickness (mm)	11.113	11.113	11.113	11.113	11.113	11.113	11.113
k (W /m K)	0.0999	0.0999	0.0999	0.0999	0.0999	0.0999	0.0999
Cp (J/kg K)	1878.4	1878.4	1878.4	1878.4	1878.4	1878.4	1878.4
ρ (kg/m^3)	649.99	649.99	649.99	649.99	649.99	649.99	649.99
Douglass Fir							
Thickness (mm)	50.8 by 101.6	50.8 by 101.6	50.8 by 101.6	50.8 by 101.6	50.8 by 101.6	50.8 by 101.6	50.8 by 101.6
k (W /m K)	0.1528	0.1528	0.1528	0.1528	0.1528	0.1528	0.1528
Cp (J/kg K)	1631.8	1631.8	1631.8	1631.8	1631.8	1631.8	1631.8
ρ (kg/m^3)	615.11	615.11	615.11	615.11	615.11	615.11	615.11
Ceil insulation							
Thickness (mm)	442.34		442.34	442.34	442.34	442.34	442.34
k (W /m K)	0.0661	N/A	0.0661	0.0661	0.0661	0.0661	0.0661
Cp (J/kg K)	711.28		711.28	711.28	711.28	711.28	711.28
ρ (kg/m^3)	32.034		32.034	32.034	32.034	32.034	32.034
Gypsum board							
Thickness (mm)	12.7	12.7	12.7	12.7	12.7	12.7	12.7
k (W /m K)	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Cp (J/kg K)	1087.84	1087.84	1087.84	1087.84	1087.84	1087.84	1087.84
ρ (kg/m^3)	800.923	800.923	800.923	800.923	800.923	800.923	800.923

APPENDIX C. PERMEANCE DATA

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	Material	Approximate thickness (in)	Permeance (Perms)
Underlayment	Breathable UDL used in Attic 01	0.03	16.0
	Low permeance UDL used in Attic 03 and Attic 04	0.03	0.04
	Low permeance UDL used in Attic 07	0.03	0.10
Building materials	Standard 15-lb felt	0.03	8.0
	Douglass fir 2×4	3.5	0.05
	Gypsum board	0.5	50.0
	OSB	0.43752	3.00
	Hardy Board	0.50004	11.0

APPENDIX D. ATTIC BENCHMARKS

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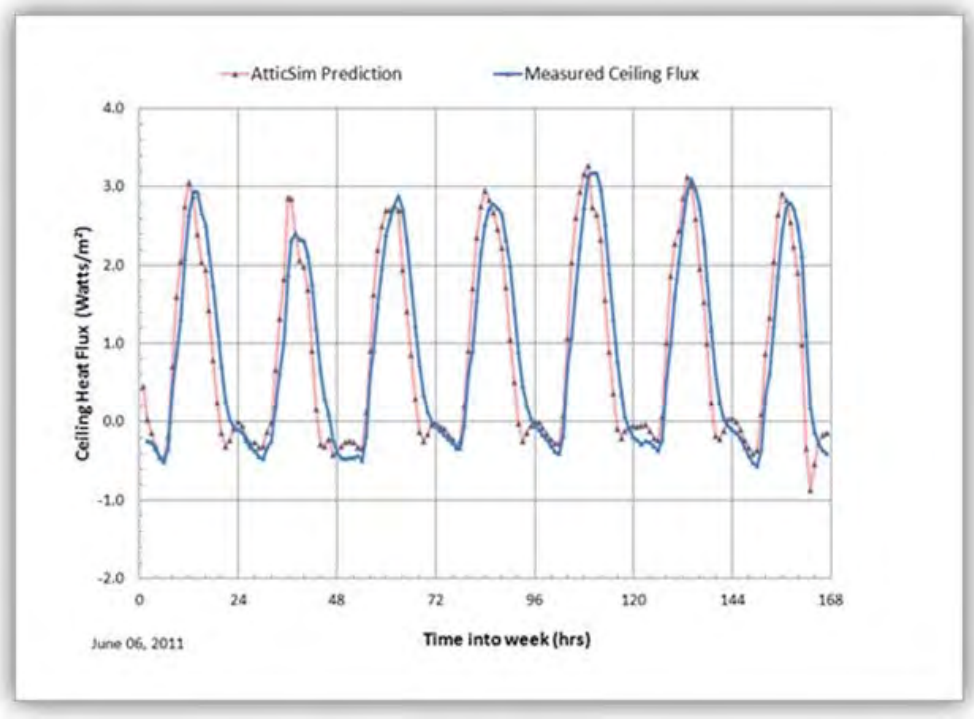
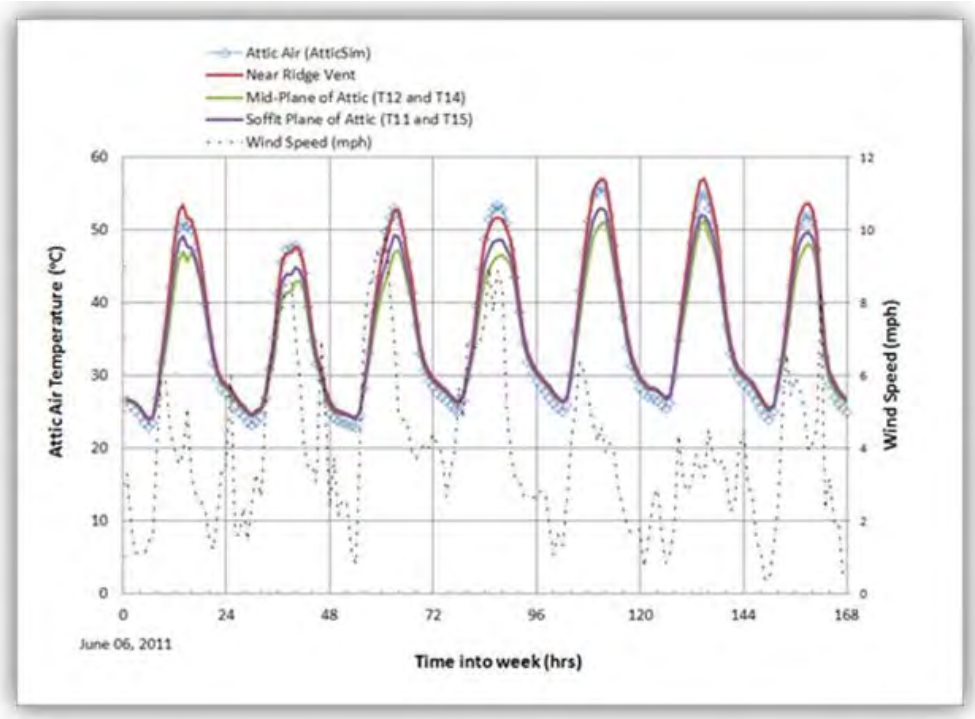
ATTIC 01 BENCHMARK

Ceiling Heat Flux

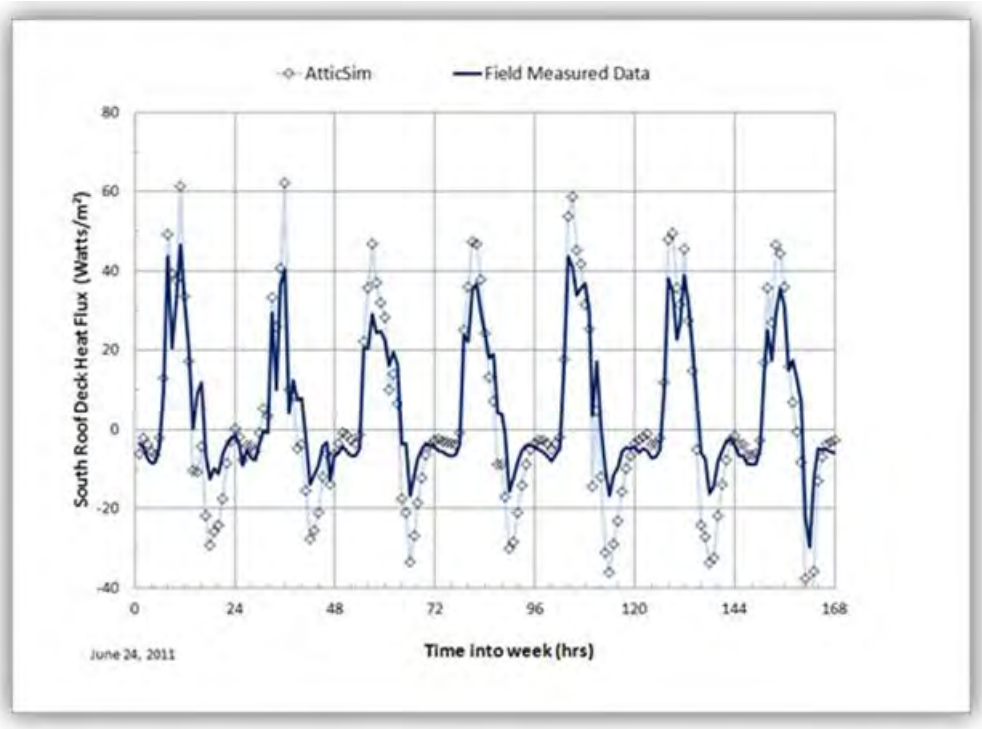


Attic 1: Computed and measured attic air temperature.

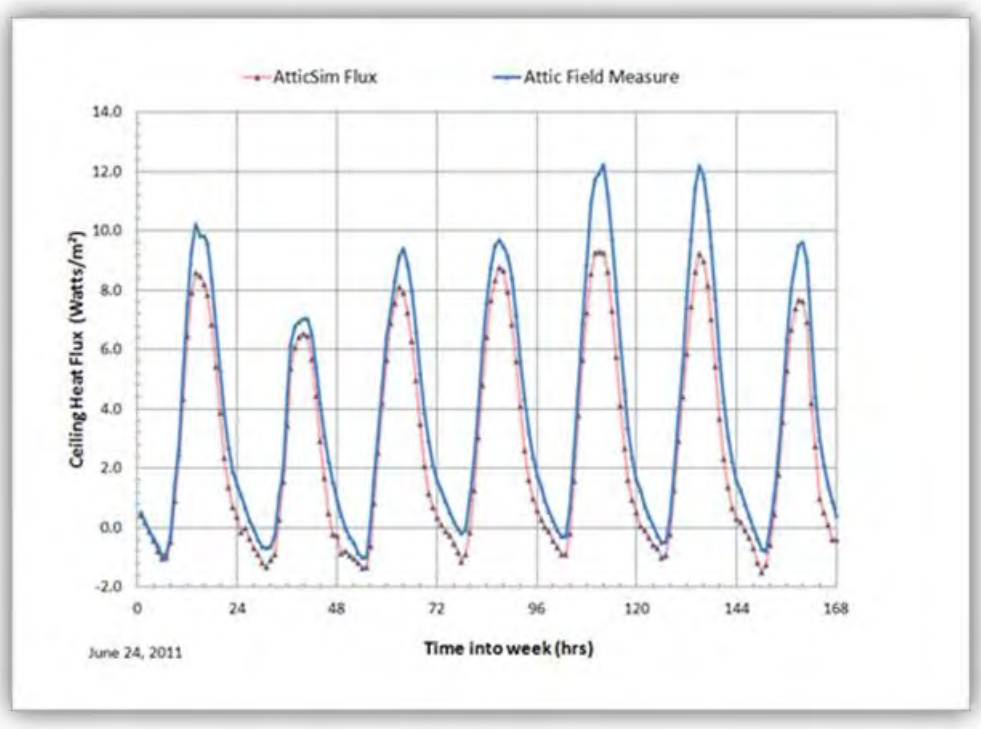


ATTIC 02 BENCHMARK: SEALED ATTIC (OPEN CELL FOAM R-22)

Computed and measured heat flux across open cell foam in south roof deck

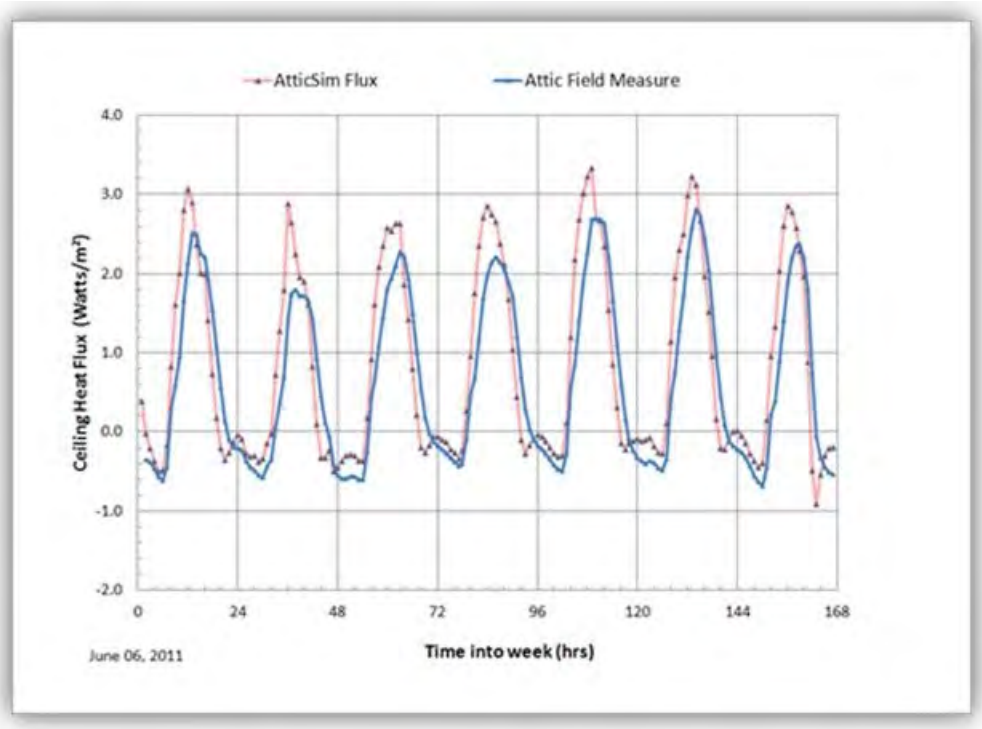


Computed and measured ceiling heat flux across R-0.5 gypsum board

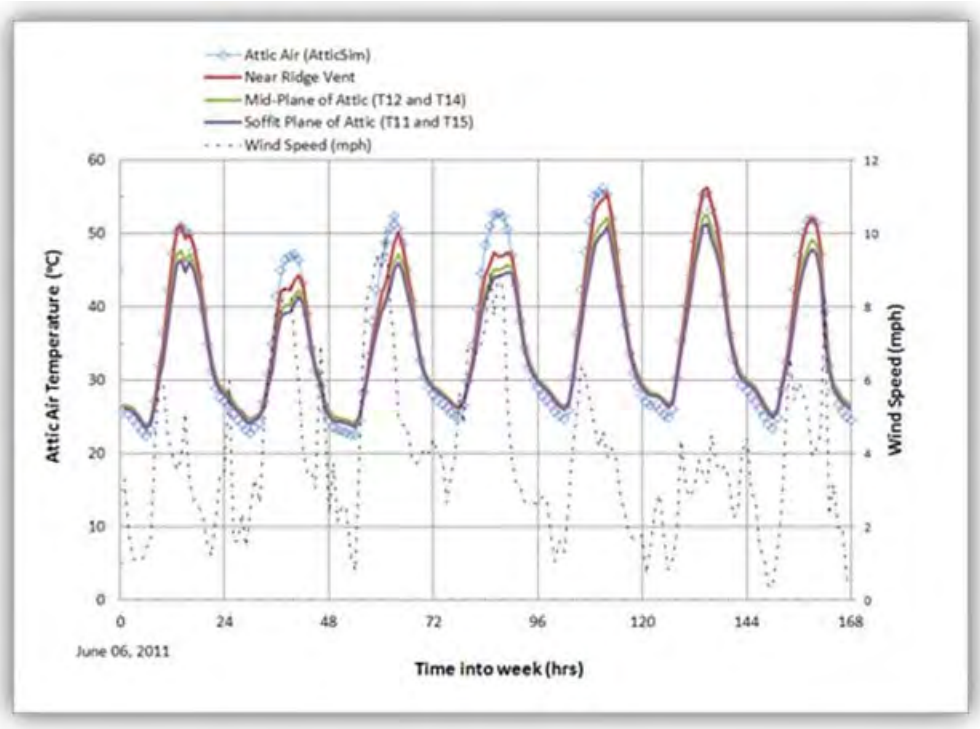


ATTIC 03 BENCHMARK: NONBREATHABLE UNDERLAYMENT

Computed and measured ceiling heat flux across R-45.6 batt insulation

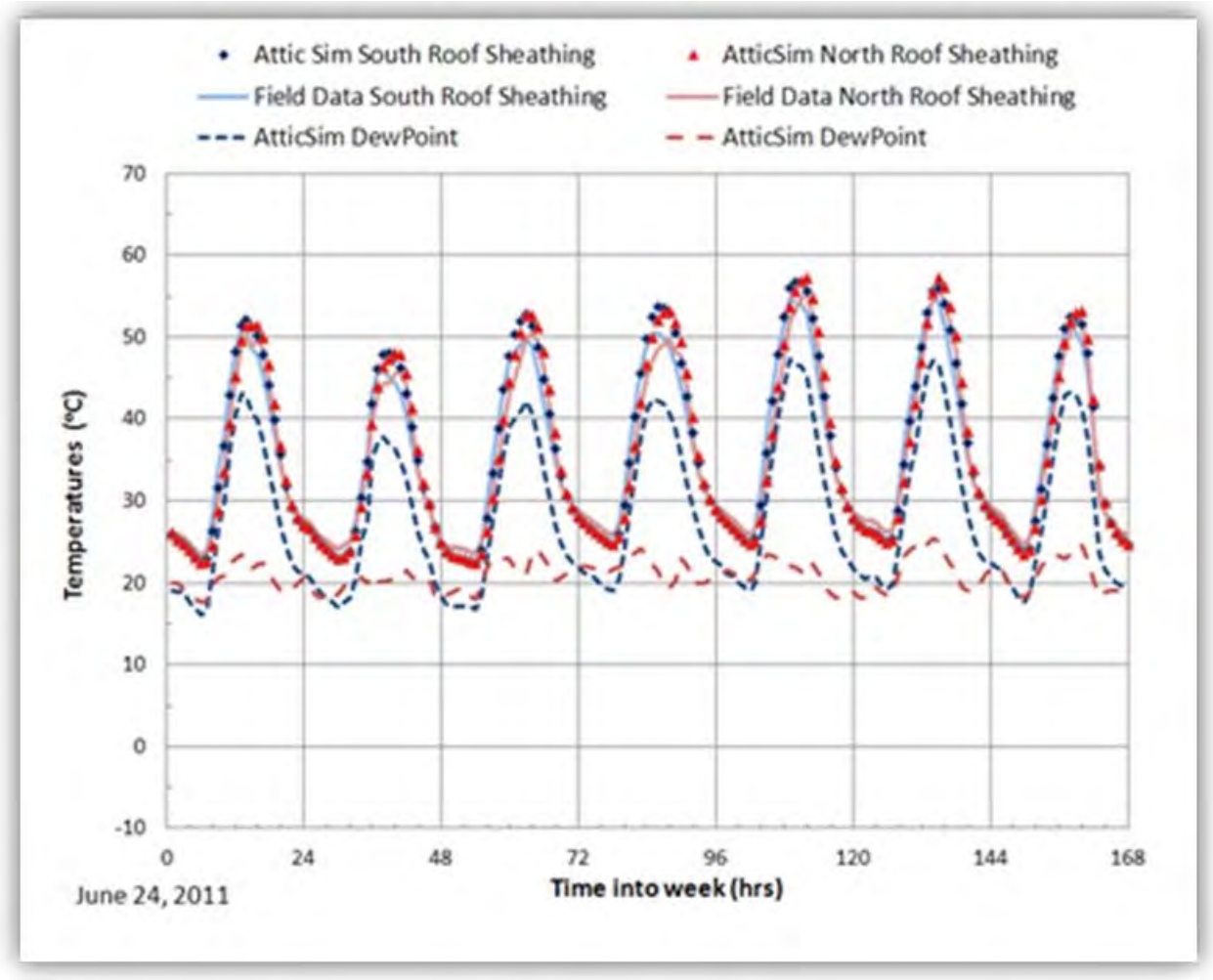


Computed and measured attic air temperature



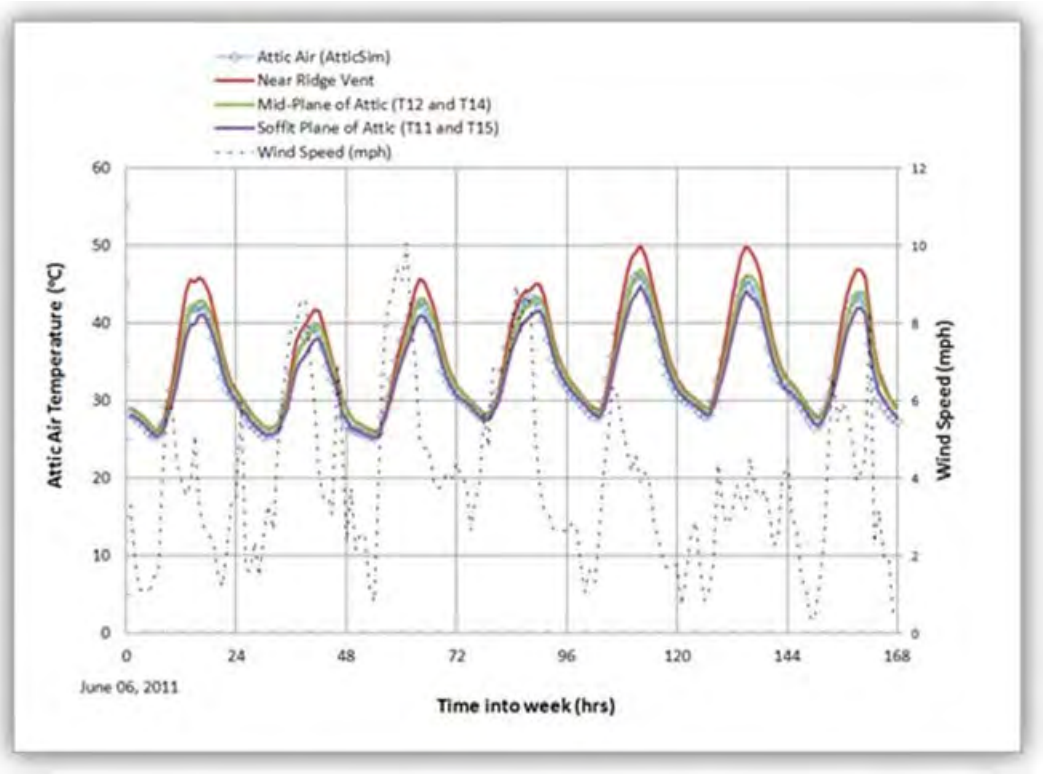
ATTIC 04 BENCHMARK: COOL COLOR SHINGLE

Computed and measured sheathing temperature; measure made on side facing attic



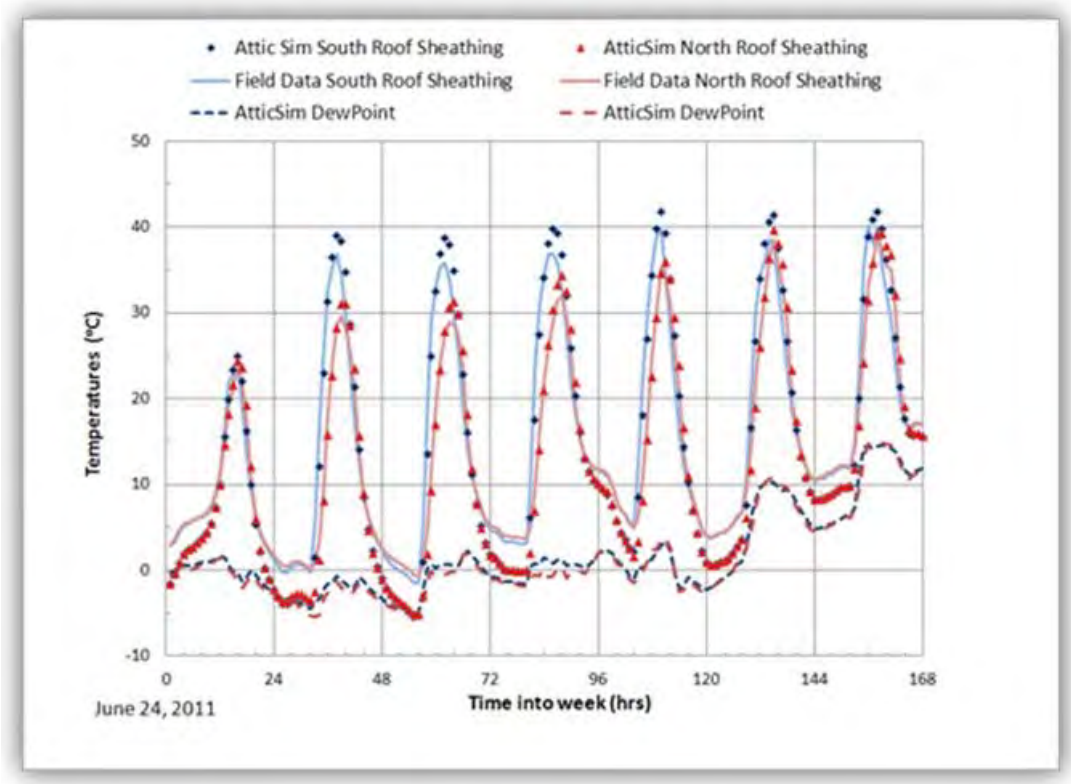
ATTIC 05 BENCHMARK: ABOVE-SHEATHING VENTILATION

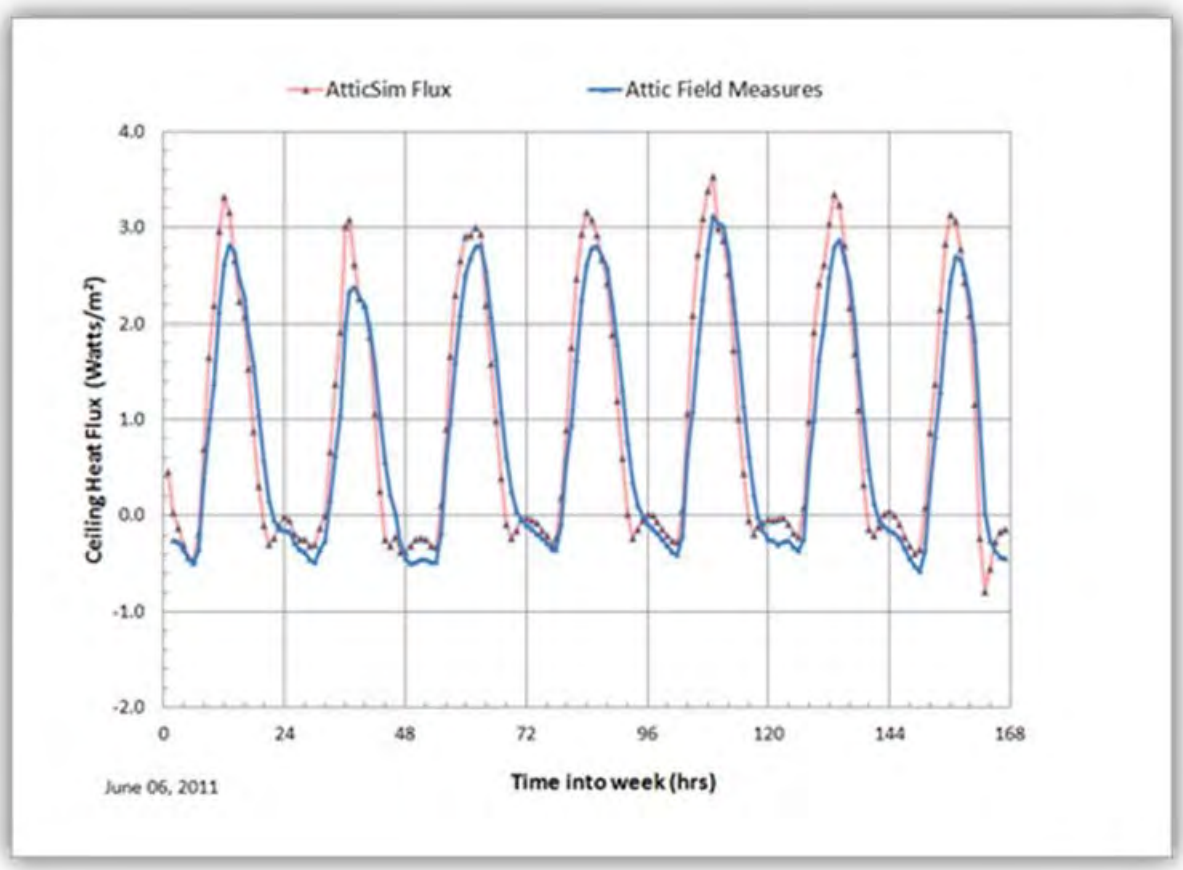
Computed and measured attic air temperature



ATTIC 06 BENCHMARK: RADIANT BARRIER

Computed and measured sheathing temperature; measure made on side facing attic



ATTIC 07 BENCHMARK: FASCIA FLOW 1:150

Computed and measured ceiling heat flux across R-38 batt insulation