

Residential Attic Ventilation In A Hot And Humid Climate:
Effects Of Increased Ventilation On Thermal Performance
And Moisture Control

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Stanley Arthur Atherton
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DEDICATION

This thesis is dedicated to my mother and father, who gave me the gift of love and quality time: thank you for teaching me that even the most imposing task can be accomplished if taken a step at a time. It is also dedicated to my loving wife Melissa, with whom I boldly embrace the challenges and rewards of a long life to come.

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ABSTRACT

The reality of the effect of natural ventilation in a residential attic cavity has been the topic of many debates and scholarly reports since the 1930's. The purpose of ventilating an attic cavity is to prevent 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 facility was constructed in Charleston, South Carolina in 2008. This multi-cavity in-situ facility is equipped with seven separate attic bays, featuring a wide variety of construction materials for performance comparison. Yearly performance comparison data has been examined for key observations on the effect of ventilation, which comprises approximately half of this report.

Furthermore, an industry-standard attic performance prediction tool was benchmarked to the field data and is shown to be accurate for predicting diurnal performance of the NET facility. A battery of simulations were run for diurnal air exchange rates, the results of which are compared to 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, and Radiant Barrier systems.

The results of this study are based on the analysis of field data, benchmarked simulations, and parametric study on ventilation ratio effectiveness. Ventilation variation is shown to have only a minor effect on the moisture control and thermal performance of residential attic cavities. In comparison, attics equipped with radiant barrier foil or above sheathing ventilation provide a greater range of control over thermal and moisture infiltration.

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LIST OF SYMBOLS

A	Area
A_i	Inside Area
A_o	Outside Area
A_{min}	Minimum Area
β	Volume Expansion Coefficient
C_p	Specific Heat
C_w	Wind Speed Correction Factor
ε	Thermal Emissivity
G_{rc}	Grashof number Based on Roof Pitch
G_r	Grashof Number
h_{fc}	Forced Convection Heat Transfer Coefficient
h_{nc}	Natural Convection Heat Transfer Coefficient
h_r	Radiation Heat Transfer Coefficient
h	Combined Convection Heat Transfer Coefficient
H_{io}	Height of Attic Cavity
H_{NPL}	Height of the Neutral Pressure Plane
k	Thermal Conductivity
$\bar{\mu}$	Average Permeance
μ	Dynamic Viscosity
L_c	Characteristic Length
$\dot{m}_{stack}$	Mass Flow Rate of Air from Stack Effect
$\dot{m}_{vent}$	Combined Mass Flow Rate
$\dot{m}_{wind}$	Mass Flow Rate of Air from Wind Effect
Nu	Nusselt Number
$N_{u,f}$	Nusselt Number in Forced Convection
φ	Percent Relative Humidity
ρ_a	Density of Air
Pr	Prandtl Number
P_{ws}	Partial Pressure of Saturated Water Vapor
P_w	Partial Pressure of Water Vapor
Q_{stack}	Stack Effect Volumetric Flow Rate
Q_{vent}	Wind Effect Air Flow Rate
Q_{wind}	Combined Volumetric Flow Rate
q_v	One Dimensional Vapor Flux

Ra	.....	Rayleigh Number
Re	.....	Reynolds Number
T	.....	Temperature
σ	.....	Stefan-Boltzmann Constant
T_A	.....	Air Temperature
T_V	.....	Outdoor/Vent Temperature
T_{dp}	.....	Dew-Point Temperature
t	.....	Thickness
θ	.....	Angle of Roof Pitch
$V_{w,c}$	.....	Corrected Wind Speed
ν	.....	Kinematic Viscosity
w_x	.....	Specific Moisture Content

LIST OF ATTACHMENTS

File 1	Field Data Cleaner	Clean_Convert.bas
File 2	Field Data Compiler	Raw_Compiler.bas
File 3	Boundary Condition Compiler	BoundaryCondition_Creator.bas
File 4	AtticSim Execution Batch File	AtticSim_Execute.bat
File 5	AtticSim Fortran Source Code	AtticSim_ASV_VersionIV_DPMACRO.for
File 6	AtticSim Output Compiler	AtticSim_Output.bas
File 7	Combo Probe Calibration Results	T_RH_Calibration.pdf

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Attic ventilation remains a controversial issue for homes. As early as 1942, the Federal Housing Administration set a 1:300 requirement (i.e., vent opening to attic footprint) as a means of minimizing condensation on the underside of the roof sheathing. Many believe ventilation significantly reduces the summer load and thereby improves durability of the roof because of the reduced roof temperature at peak sunlight. Others have concluded that attic ventilation is not an effective energy conservation procedure, and does not play a major role in extending the service life of a roof and attic system. Typical residential attic systems experience extreme temperature variations over the diurnal cycle in comparison to the conditioned space, which can lead to the buildup of moisture on the interior structure and duct surfaces in the attic. The moisture typically enters as a latent load from the conditioned space and from the outdoor ambient via leaks in the roof construction. The issue of condensate buildup is of special importance to climates that experience naturally high levels of relative humidity. The data collected for this Master's Thesis was collected from a facility in Charleston, South Carolina, which was constructed for the purposes of comparing new building materials in adjacent isolated attic cavities while maintaining identical spatial and weather boundary conditions. Data gleaned from this facility is invaluable, for it allows direct comparison of *in situ* performance. This method of study also eliminates uncertainties involved with comparing data from separate residences. References to specific manufacturers and products have been omitted, in an effort to preserve the integrity of this study.

1.1 Justification of Study

In some climates, proper natural ventilation of residential attic spaces is a strategic method of maintaining a sustainable residence. Ventilation removes unwanted moisture by advection through intentionally-constructed vents and also 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, and provide some level of stack-effect air flow to ensure air quality in the conditioned space. The effectiveness of natural ventilation in minimizing characteristic heat

gains in an attic cavity, namely through the attic floor to the conditioned space and duct losses, has been a topic of fierce debate.

The amount of necessary natural ventilation is dictated by a number of compounding variables, and can therefore vary extensively depending on climate zone, insulation amounts, airtightness of the structure, and other factors. The 1:300 standard 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 is a prime representation of warm, moist climates where the effectiveness of attic ventilation has been called into question most frequently.

1.2 Previous Work

The debate on the benefits and detriments of residential attic ventilation in America has been a highly contested subject since the early decades of the 20th century. 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 from unwanted elements of heat and moisture transfer.

The institution and modification of natural and forced attic ventilation is typically considered “Green” engineering, a methodology of sustainable design that decrease both of the energy consumption of a residence as well as the environmental footprint of the structure. 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 condensation prevention on the interior attic surfaces. Such research has sparked fierce debate on the effectiveness, as well as the actual cost-savings potential of ventilation.

1.2.1 Rowley and the FHA “ASHVE Transactions”

In 1939, the Federal Housing Administration 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 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 one-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 in separate climate zones, specific roof deck inclinations, duct specifications, or insulation type and amount; all of which are critical variables in determining the performance of natural ventilation systems.

1.2.2 Jordan and the HHFA "HHFA Technical Bulletins"

After the Second World War, Jordan and 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 an observed formation of frost along the unvented apparatus, and a lack of this 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 (which is the case in southern climates). Further experiments indicated that the amount of ventilation necessary to prevent the buildup of condensate would increase with the increased amount of installed attic insulation. In other words, that the 1:300 ratio would not provide a sufficient amount of ventilation if large quantities of insulation were installed.

1.2.3 National Bureau of Standards "Summer Attic and Whole-House Ventilation"

In July 1979, the National Bureau of Standards (now referred to as NIST) published a collection of research titled *Summer Attic and Whole-House Ventilation*. Featured in this publication was a study performed by Burch and Treado, entitled *Ventilating Residences and Their Attics for Energy Conservation*. While the scope of the study was on the benefits of whole-house ventilation compared to 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 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 the data presented, introduction of 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 cooling load was only decreased by 6%, because the heat gains through the ducts and ceiling only represented a small percentage of the overall cooling load on the test homes (Burch & Treado, 1979).

An integral portion 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. The results of the ventilation rate calculations are featured in the AtticSim program used in this thesis, see Section 5.1.1.

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

In his Doctoral Thesis, Walker develops 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. Also, that ventilation strategy should depend on climate zone and attic construction (Walker, 1993).

1.2.5 Vented and Sealed Attics in Hot Climates

The rationale behind this 1998 study was to address the need for solutions related to the entry of moisture-rich air in hot and humid climates and the need to obtain an effective barrier to infiltration at the top of residences for reduction in energy consumption. Rudd and Lstiburek took the one-dimensional finite-element model developed by Parker in 1991 and made empirical modifications to provide a more exact benchmark against data from previous roof test facilities. The result of this experiment showed that sealed attics with an air and thermal barrier on the sloped roof deck can be built without associated energy penalty in hot climates, as compared to 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

This paper investigates the relative merits of conventional ventilation to alternative designs with respect to attic temperatures, ice damming, and shingle durability. This paper is primarily a comparative study on previous research of other authors. The conclusions reached in this 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 should only be 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 from 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 six 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 in comparison to 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 was compared to simulations performed using the DOE-2.1E simulation engine with new subroutines that explicitly estimates the performance of attics with duct interaction. Results revealed that roof decks with white, highly reflective materials provided an 18-26% reduction in annual cooling energy, while a sealed attic cavity provided only 6-11% when insulation on the attic floor is R-19. The authors conclude that roof decks with high solar reflectance properties offer the most significant energy savings in comparison to alternative ventilation strategies, terra cotta tiles, and alternative shingle design (Parker, Sonne, Sherwin, & Moyer, 2000).

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

The purpose of this report was to determine where and when cathedralized (sealed and deck-insulated) attics offer cost savings against conventional attic constructions. 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 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).

1.3 Factors That Affect Thermal Transfer and Collection of Condensate in Attic Cavities

1.3.1 Climate Zone

The standard for ventilation has no modifier for climate zone. Addressing this deficiency is the most important topic of this investigation. Distinct climate zones in the U.S. have been defined by Building America by annual precipitation and characteristic temperature.

The primary purpose of attic ventilation in cold climates is to prevent ice damming caused by snow melt, with additional consideration to elimination of the moist air transported from the conditioned space. Ice dams are an issue mainly in houses with insufficient insulation, such that the roof deck is heated from heat lost through attic floor. Increasing the roof deck temperature melts the contacting snow, leading to a buildup of ice on the colder surface of the overhang or gutter. Ventilation prevents ice damming by maintaining a cooler roof deck surface temperature, which prevents melting on the underside of collected snow banks. However, ice damming and moisture collection can also be prevented in attic designs with no ventilation (Lstiburek, 2005).

Residential attics in hot and humid climates, like the climate in Charleston, require very different ventilation schemes than cold climates. Maintaining moderate surface temperatures is not the solution for preventing moisture issues in these climates. In fact, improper ventilation can allow excessive infiltration of warm and moisture-laden air to the cavity (Rudd & Lstiburek, Vented and Sealed Attics in Hot Climates, 1998).

1.3.2 Vapor Diffusion through Roof Deck Structure

Diffusion of water vapor through a surface is driven by difference in partial pressures of water vapor in the air on opposite sides of the surface. The general diffusion mass flow is based on Fick's Law (shown below in one-dimensional form):

$$\frac{dw_x}{d\theta} = -\bar{\mu} * A * \frac{dP_w}{dx} \quad (1)$$

Note that the negative sign denotes the fact that water vapor flow from high vapor pressures to low vapor pressures, similar to the phenomena of Fourier's Law of conduction heat transfer from high to low temperatures. Therefore, vapor flux in one dimension per unit area [nanograms/in²s] is proportional to the product of vapor pressure difference and vapor Permeance, which is merely the permeability divided by the thickness of the material. The partial pressure of water vapor for each surface is calculated via psychometrics. Note that Permeance values of certain building materials are attached as Appendix B.

$$q_v = \bar{\mu} * (P_{w,1} - P_{w,2}) \quad (2)$$

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 relative humidity. Note that the following Equation 3 is specifically for Temperature units of Celsius. Coefficient "a" in Equation 3 is 17.27, and coefficient "b" is 237.7 (Simmons, 2008).

$$T_{dp} = \frac{b \left(\ln(RH) + \frac{aT_{db}}{b + T_{db}} \right)}{a - \ln(RH) - \frac{aT_{db}}{b + T_{db}}} \quad (3)$$

1.3.3 Influx of Moist Air on Condensate-Prone Surfaces

In the situation where hot and humid air has infiltrated the cavity, the surfaces of certain un-insulated HVAC ducts in the attic cavity can easily reach the dew point temperature of the surrounding air and condensate will form. This is also true for solid surfaces near the ducts. Additional condensate issues can be compounded by air leaking from the supply ducts (Rudd, Lstiburek, & Moyer, Measurement of Attics Temperatures and Cooling Energy Use in Vented and Sealed Attics in Las Vegas, Nevada, 1998).

1.3.4 Water Vapor Permeability

Permeability (denoted by $\bar{\mu}$) is a material property that indicates the quantity of vapor flow for a unit area and unit thickness due to a unit vapor pressure difference. Values of Permeability are determined by Wet- and Dry-Cup testing, with typical averages found in the ASTM standard E96 (ASTM Standard E96, 1989). To address the transfer of moisture through the roof deck, vapor retardant materials have been substituted for the traditional felt paper underlayment in certain instances.

CHAPTER 2

EXPERIMENTAL DATA COLLECTION

The NET (Natural Exposure Testing) Facility is located at Bethel Hill Road in the city of Hollywood, approximately twenty miles from the center of Charleston, South Carolina. This facility has been operational in different modes since 2006, and features seven separate attic cavities as well as the capability of testing wall panels of different composition. ORNL partnered with a leading roofing materials manufacturer in the use of this facility to study the benefits and effects of several different emerging technologies and building products on the heat gained through the attic cavity, surface temperature control through application of radiant barrier technology and cool-color shingles, as well as moisture control through varying ventilation techniques.

The NET facility structure was assembled in an axial east-west orientation, such that each attic cavity has a North and South side. The conditioned space underneath the attic systems is separated into two rooms, which are kept at a constant temperature. To mimic the latent load of an occupied structure, each separate attic cavity is equipped with a constant set output humidification system, with the exception of the Polyicynene sealed Attic 2. Details of the moisture output testing of these humidifiers will be covered in a separate section.

2.1 General Construction

Each attic bay has a general footprint of 24' by 12', with a roof pitch of 3:12. Construction included 2' x 4' rafter construction (2' x 6' in the case of the Polyicynene sealed attic), OSB sheathing atop the rafters, and shingles attached to the exterior surface, see Figure 1. The conditioned space below is separated into two rooms by a separately conditioned control room that stores the DAS system and acts as a central hub for data processing and communication. Soffit and Ridge vents are continuous for the entire facility, but are rendered inoperable in the sealed attic via application of open cell Polyicynene foam.



Figure 1: Attic Bay Construction

General construction of each roof and attic system involves the structural components as seen below in Figure 2. OSB sheathing is laid over the rafters, followed by the underlayment and then the asphalt shingles. Ventilation is provided by perforated vents running along the ridgeline and soffit undersides. The ceiling is insulated with a multilayered stack of fiberglass batts, or no insulation in the case of Attic 2, on top of the gypsum board ceiling.

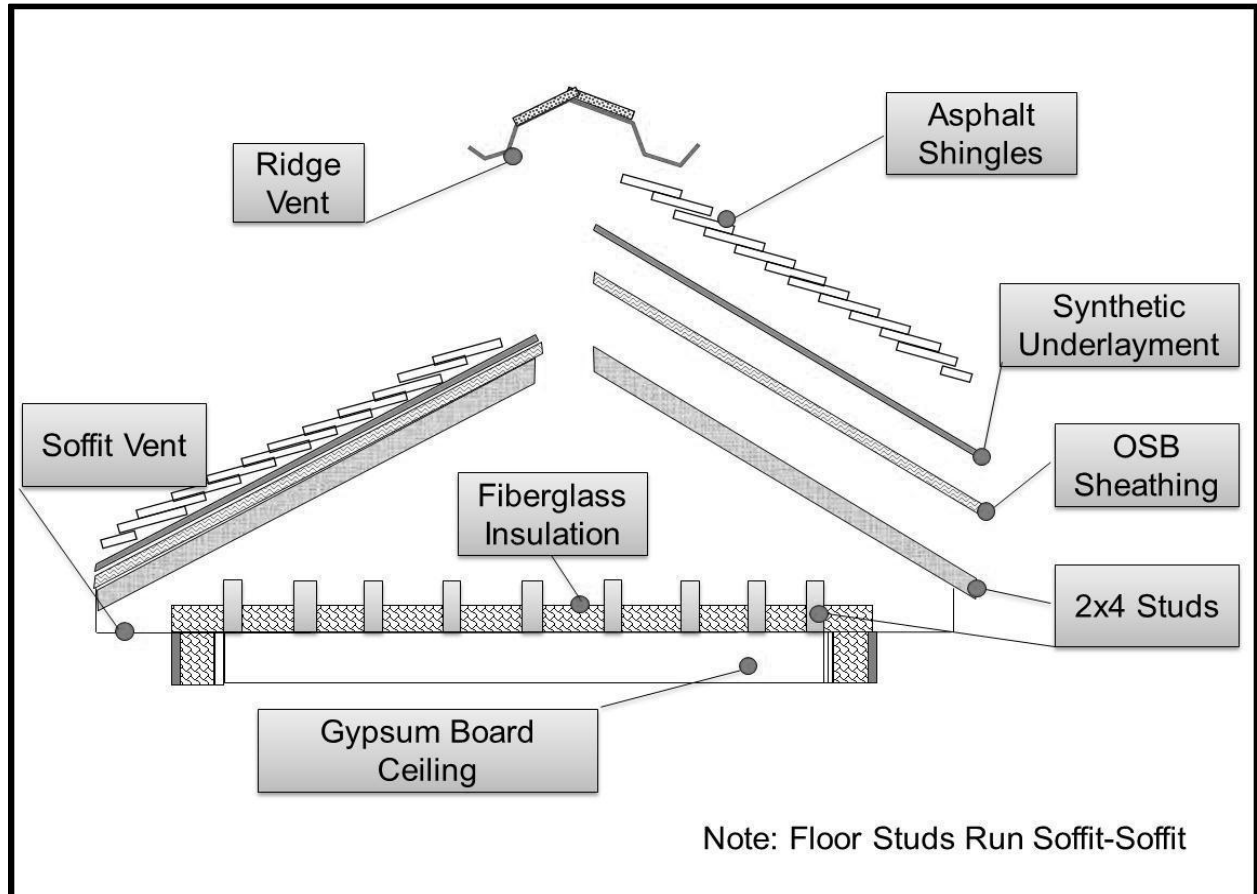


Figure 2: Cross-Section of Attic Cavity

Entrance to the attic space is through an extending staircase on the interior west end of the facility into Attic 02, see Figure 3. Each of the seven attic bays were constructed to operate independently from each other through thick rigid foam insulation and sealed OSB separator doors, such that the axial (interior gable surfaces east-west) heat transfer is not completely eradicated, but is small enough that any heat loss or gain through the interior walls as a direct result of the performance of neighboring cavities would not play a significant role in the analysis.

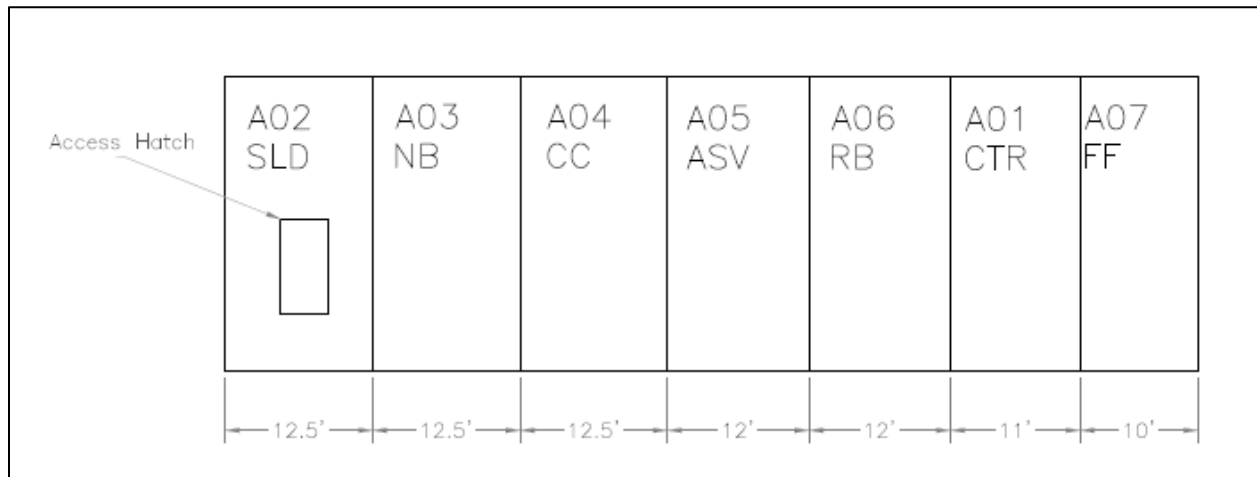


Figure 3: NET Facility Floor Plan (Attic Bay Overlay)

2.2 Attic Cavity Design

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, such 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 as well. Certain materials are common to certain attics, such as roofing membrane or ventilation scheme. For a diagram of these features, see Figure 4.

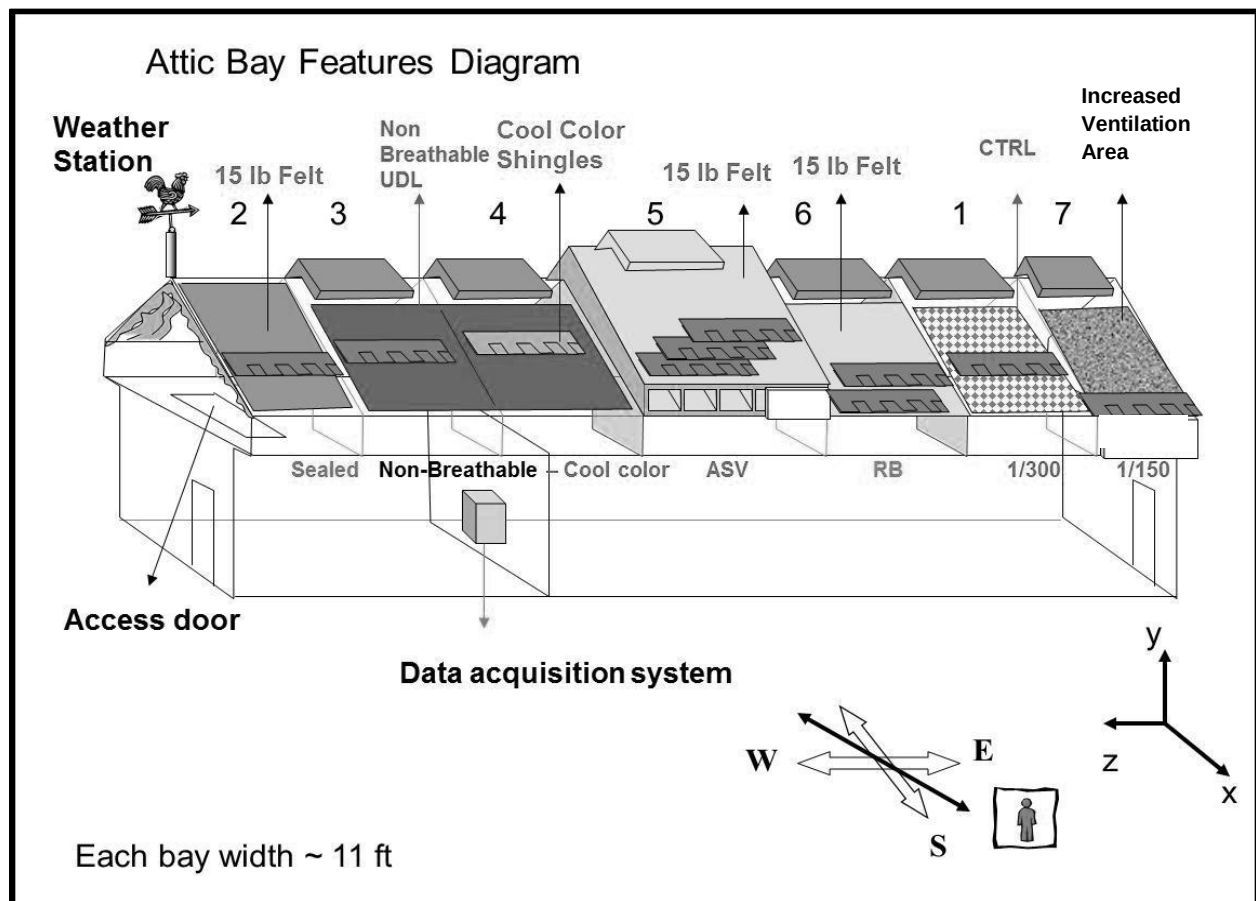


Figure 4: Cavity Features

The featured comparison materials or systems for each attic are given in Table 1. For scope of this study, more focus is placed on a comparison of Attics 01, 03 and 07 because of the controlled increase in ventilation area ratio. Note that similar analyses were performed on each cavity, and certain results pertaining to schemes other than ventilation will be featured in this report.

Table 1: Attic Bay Comparison Attributes

Attic Cavity	Acronym	Insulation	Ventilation Scheme	Shingle Reflectance	Membrane Permeability	Attic Length
Attic 01	CTRL	R-38 Fiberglass	1:300	.033	Low	12.5'
Attic 02	SLD	R-21 Polyicynene	Sealed No Ventilation	.033	Nominal	12.5'
Attic 03	NB	R-38 Fiberglass	1:300	.033	Low	12.5'
Attic 04	CC	R-38 Fiberglass	1:300	.274	Low	12'
Attic 05	ASV	R-38 Fiberglass	1:300 Plus ASV	.033	Nominal	12'
Attic 06	RB	R-38 Fiberglass	1:300	.033	Nominal	11'
Attic 07	FF	R-38 Fiberglass	1:150	.033	Low	10'

2.2.1 Attic 01 – Conventional Control

The materials for this attic bay were selected to best represent a conventional residential attic to act as a standard baseline of performance. This attic features R-38 fiberglass batt insulation on the attic floor between 16" on-center 2' by 4' rafters and standard asphalt shingles over 15-pound felt paper underlayment. Soffit and ridge vents were modified prior to installation to fit the 1:300 ventilation standards.

2.2.2 Attic 02 – Polyicynene Sealed

In order to support the increased load associated with spray foam application on the interior deck surfaces, Attic 02 was constructed with 16" on-center 2" by 6" rafters then sealed

with approximately 5" of expanding Polyisocyanurate spray foam directly on the underside of the OSB roof sheathing, see Figure 5. Application of foam insulation across the inclined roof deck planes creates a quasi-conditioned space in the attic cavity, such that the solar effect heat gain is decreased. Typical expanding spray foams eliminate air movement, preventing the infiltration of moist outdoor air associated with warm coastal climates (Parker D. , 2005). Possible benefits of the sealed foam design include a logically obvious decrease in heat flow through the roof deck (due to increased R-value of the roof deck), a decrease in duct heat losses, and lower levels of relative humidity.

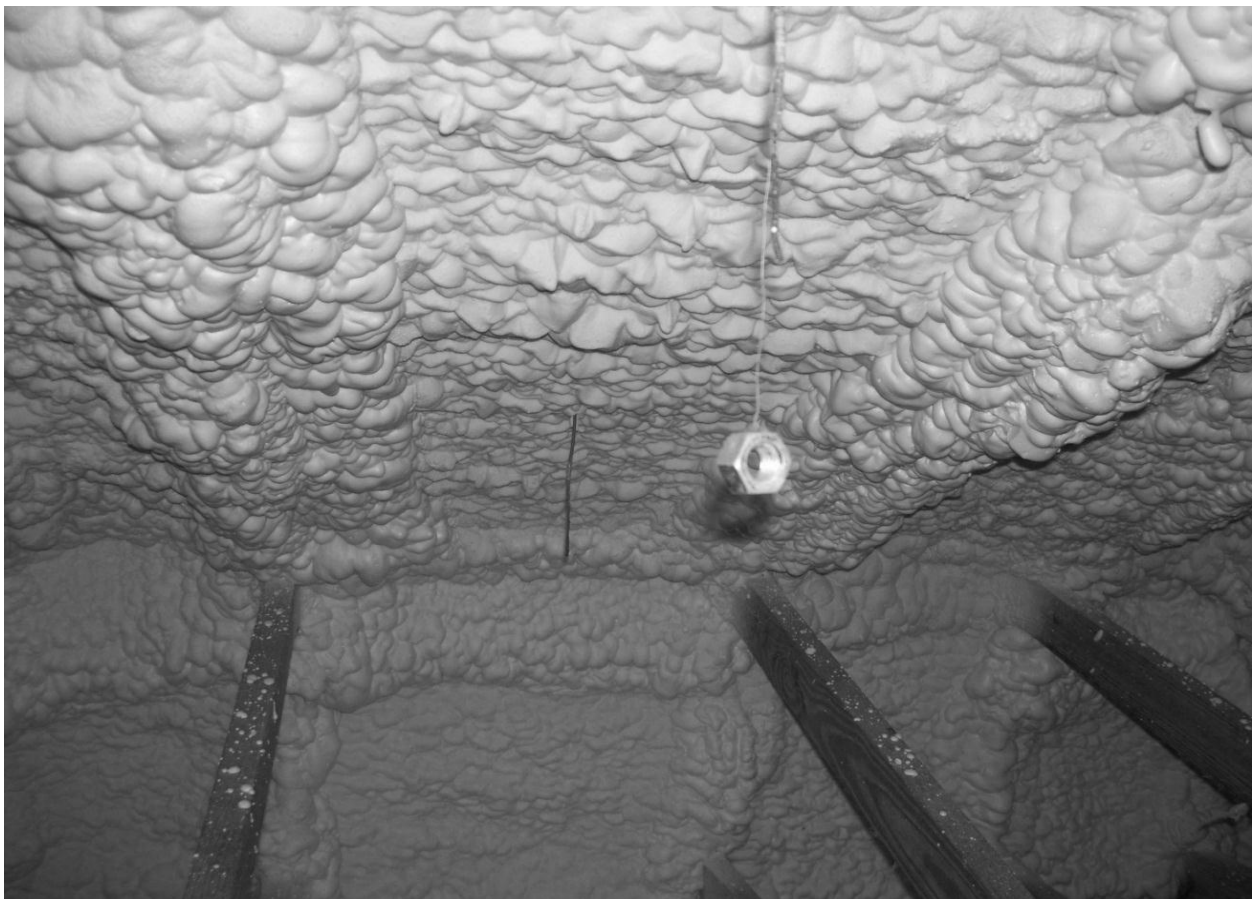


Figure 5: Polyisocyanurate Foam Application

While there are some possible benefits to this design, when sealing an attic with no duct system, the lack of a vapor barrier and insulation on the attic floor may have twofold negative effects on the performance of the attic in terms of energy savings and moisture control. Specifically, that despite quasi-conditioned space in the attic cavity, there will always be a

temperature difference across the attic floor and the low thermal resistance of the zero-insulation surface will allow for heat flow. Additionally, barring the usage of a vapor retarder on the attic floor surface, normal occupancy leads to latent moisture infiltration that could become trapped in the attic and accumulate on wood and duct surfaces.

2.2.3 Attic 03 – Non-Breathable Underlayment

Roofing underlayment is an organic or synthetic membrane applied on the roof deck under the shingles. Typical underlayment membranes are, by nature, a secondary line of defense against moisture penetration through the roof deck. Permeance and weight are the standards by which membranes are compared. The term “Non-Breathable” refers to the low permeability of the membrane applied to the roof deck. The ventilation scheme of this Attic is identical to the standard Attic 01. Attic 06 was constructed with a similar underlayment, so Attic 03 provides a solid performance baseline by which to measure the possible benefits of increased ventilation. The Permeance value for the “Low-Perm” underlayment in Attic 07 is 0.1, and alternately 0.04 for Attics 03 and 04.

2.2.4 Attic 04 – Cool Color Shingles

The phrase “Cool Color” refers to the increased solar reflectance of the shingle surface granules. The solar reflectance of the “Cool Color” shingles is .274, as compared to .033 for all other roof constructions on this facility. The benefit of a shingle surface with a high reflectance is a decreased surface temperature during peak heating. Surface temperatures of shingle roofs are usually quite high in southern climates during the spring and summer seasons. High shingle temperatures are a direct consequence of solar heat gain.

2.2.5 Attic 05 – Above Sheathing Ventilation

The purpose of the Above Sheathing Ventilation design is to create an air cavity under the shingle construction to decrease the heat load to the roof and further prevent moisture condensation on the sheathing surfaces. The airflow through the ASV cavity is driven primarily by thermal buoyancy (stack effect) and by wind-driven effects when wind is present. This air gap is usually constructed on a batten or double-batten system, creating a gap of 1” to 2”. This ventilation method is used in combination with standard soffit and ridge ventilation.

2.2.6 Attic 06 – Foil Face Radiant Barrier

A radiant barrier is essentially a foil-faced sheathing designed to reflect radiation heat transfer from the hot inner surface of the roof deck and reflects penetration of infrared solar

radiation. Later in this report, the relative importance of radiation and convection will be discussed.

2.2.7 Attic 07 – No-Breathe Underlayment with Increased Ventilation (1:150)

The ridge and soffit vents of Attic 07 were modified to fit a modified 1:150 ventilation ratio standard, which allows a two-fold increase in ventilation area from the CTRL. Construction is similar to the CTRL, except for the addition of a low-Permeance underlayment and an attic length of 10' instead of 12'. To eliminate possible performance effects of the low-Permeance underlayment, the proper method to determine the effectiveness of increased ventilation is to compare the performance of attics 07 and 03. Note that the construction of attic 3 differs only in ventilation ratio and attic length.

2.3 Instrumentation and Data Reduction Protocol

During the construction of the NET facility, sensors 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, for accuracy of comparison results.

2.3.1 Temperature and Relative Humidity Sensors

The primary temperature sensors were manually combined with relative humidity probes, the result of which is referred to as a “combo probe”. Secondary thermistor temperature sensors are used for the sensing shingle underside and temperature as well as the temperature where the fiberglass insulation lays on the gypsum of the attic floor. The stratification of attic air temperature is sensed through five combo probes, which are suspended from the OSB sheathing. Full product details and specifications can be found on Honeywell’s website (Honeywell). Figure 6 is a diagram of the sensor locations inside the cavity and Table 2 details the standard location of each sensor.

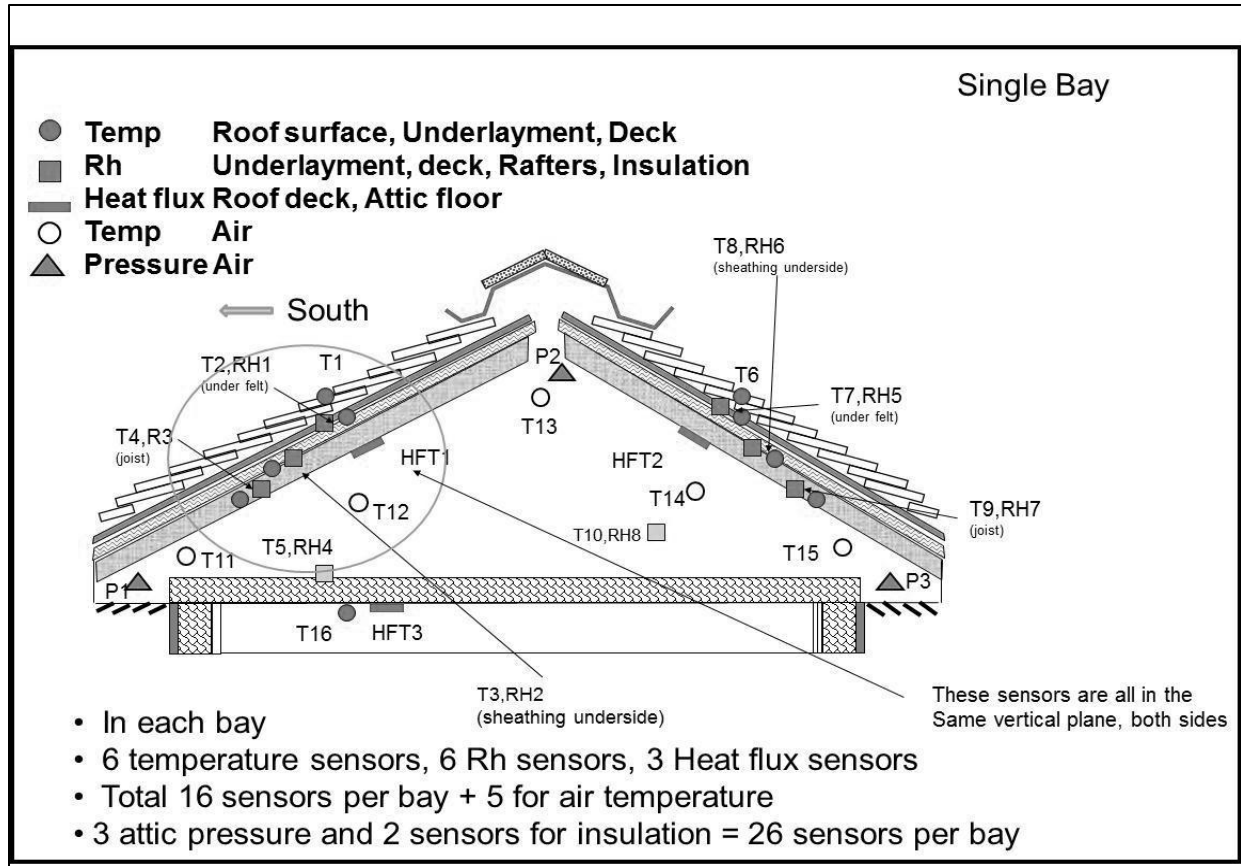


Figure 6: Sensor Locations Diagram

Table 2: Sensor Locations

Sensor Identification	Location (North and South)	Sensor Type
T11-T15	Air Stratification at Soffits	Temp. Only
T1,T6	Shingle Underside	Temp. Only
T2,RH1 and T7,RH5	Deck Underlayment	Temp.+%RH
T4,RH3 and T9,RH7	Joist	Temp.+%RH
T5,RH4	On Top of Insulation	Temp.+%RH
T10,RH8	Hanging Mid-Plane Air	Temp.+%RH
T3,RH2,HFT1 and T8,RH6,HFT2	Interior of OSB Deck	Temp.+%RH and Flux Transducer
T16,HFT3	Interior Ceiling	Temp. and Flux Transducer

2.3.2 Heat Flux Transducers

Heat Flux Transducers (HFTs) were attached to the OSB underside of the inclined roof decks, as well as on the interior surface of the gypsum board on the attic floor, see Figure 7. 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 floor. The HFTs must be calibrated in the configuration that they will be operating in. Therefore the roof deck HFTs were calibrated in a surface-applied configuration and the Attic Floor HFTs were calibrated in between gypsum board and fiberglass insulation using a Fox Heat Flow Apparatus.



Figure 7: Heat Flux Transducer and Combo Probe Located Under Insulation

2.3.3 Weather Station

Weather data collected on the roof of the NET facility include wind speed and direction, solar irradiance, rainfall, and ambient temperature, relative humidity, and pressure. These data values are logged in the same DAS files and are similarly collected on a weekly basis.

2.3.4 Calibrations

Insulation thickness measurements were taken for each attic cavity during a NET facility visit on 9/29/2011, for the purpose of determining 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, which was performed by Mrs. Theresa Stovall. Inclusion of the investigation into the actual thermodynamic properties of the insulation is necessary to best understand my degree of confidence in the data related to the performance analysis of each attic. The results of the insulation thickness tests are shown in Table 3.

Table 3: Insulation Thickness Test Results

	John Manville FBG Insulation		FBG Sample Measurements	
	¹ Paper-backed FBG Touching HFT	² FBG Placed On Top Of Rafters	Paper-backed FBG Touching HFT	FBG Placed On Top Of Rafters
Attic	(in)	(in)	(in)	(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

¹ Kraft-Faced Batt, R-19 have manufacturer specified thickness of 6½ in.

² Unfaced Batt, R-19 have manufacturer specified thickness of 6½ in.

Before installation, all sensors for use in the NET facility were calibrated at the Oak Ridge National Laboratory. Calibration results for the combination humidity/temperature probe are attached to this document in File 7: T_RH_Calibration.pdf.

2.4 Data Reduction

Field data was transmitted via modem on a weekly basis from the Charleston NET facility to the ORNL campus. The data was received and automatically sorted into data files upon weekly collection. Not all of the data transmitted from the facility was pertinent to this study, because the DAS system 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. These files (Files 1-6) have been provided as attachments to this report for future application.

2.4.1 Routine 1: Clean_Convert

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 the user to have the ability to manually input the timestamp for the correct data.

2.4.2 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 for quick re-compiling of past data when new comparative performance data needs 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.

2.4.3 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 prior to execution.

2.4.4 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, I 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.

2.4.5 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.

2.4.6 Routine 5: Charleston_Full

In certain instances, it is preferable to run a specific week or weeks of data from the very beginning, and executing all four Macros independently would be redundant. Therefore, I have essentially written a Macro script specifically designed to run Routines 1-4 from start to finish. This overhead macro carries the script variables from one routine to the next to assure accurate execution.

CHAPTER 3

DATA ANALYSIS

3.1 Winter 2011 (January to April)

Several unfortunate incidents occurred during the data collection in 2010; including lightning strikes, HVAC malfunction and telephone disconnection. Data, while still logged and reduced, showed discontinuities and inconsistencies. Therefore, the data to be presented for this report begins on January 1, 2011 and runs to April 30, 2011. The data in this section has been reduced using the scheme discussed in section 2.4, and further compiled in a batch form to detail the performance of the individual attic bays for a four-month period. The data that follows has been time-step averaged over the entire operational period (BIN-type averaging scheme), to show “standard” 24-hour performance for the season. This method of presentation is commonly used in climate-comparison reports for residential performance, see Parker, 2005.

3.1.1 Winter Temperature Data

As discussed in Chapter 3, surface and air temperatures in the attic cavity increase with height from the attic floor. The average stratification of south-facing surface temperatures inside of the control attic is shown in Figure 8. The effects of capacitance (ability of a body to store thermal energy) of each component of the upper attic construction can also be observed in Figure 8; the surfaces that have more density and therefore a higher capacitance (i.e. the wood joists and the OSB sheathing) retain heat longer after the peak heating zone than less dense materials like the underlayment. Also, the effect of night-sky radiation cooling is seen in the depression of the shingle temperature in the evening. Observation of the winter 2011 data exposed a potential for surface condensation on the sheathing and joist surfaces inside the attic cavities. Using a psychometric routine, the dew point temperature of the attic air was computed and compared against the surface temperatures of the OSB sheathing and the 2” by 4” joists (ASHRAE Handbook - Fundamentals (I-P Edition), 2009). During the early morning hours, there are occasional times when the surface temperatures are depressed below the attic air dew point temperature. During these time periods, the surfaces experience condensation potential, the results of which are shown later in this report on a hour-by hour basis.

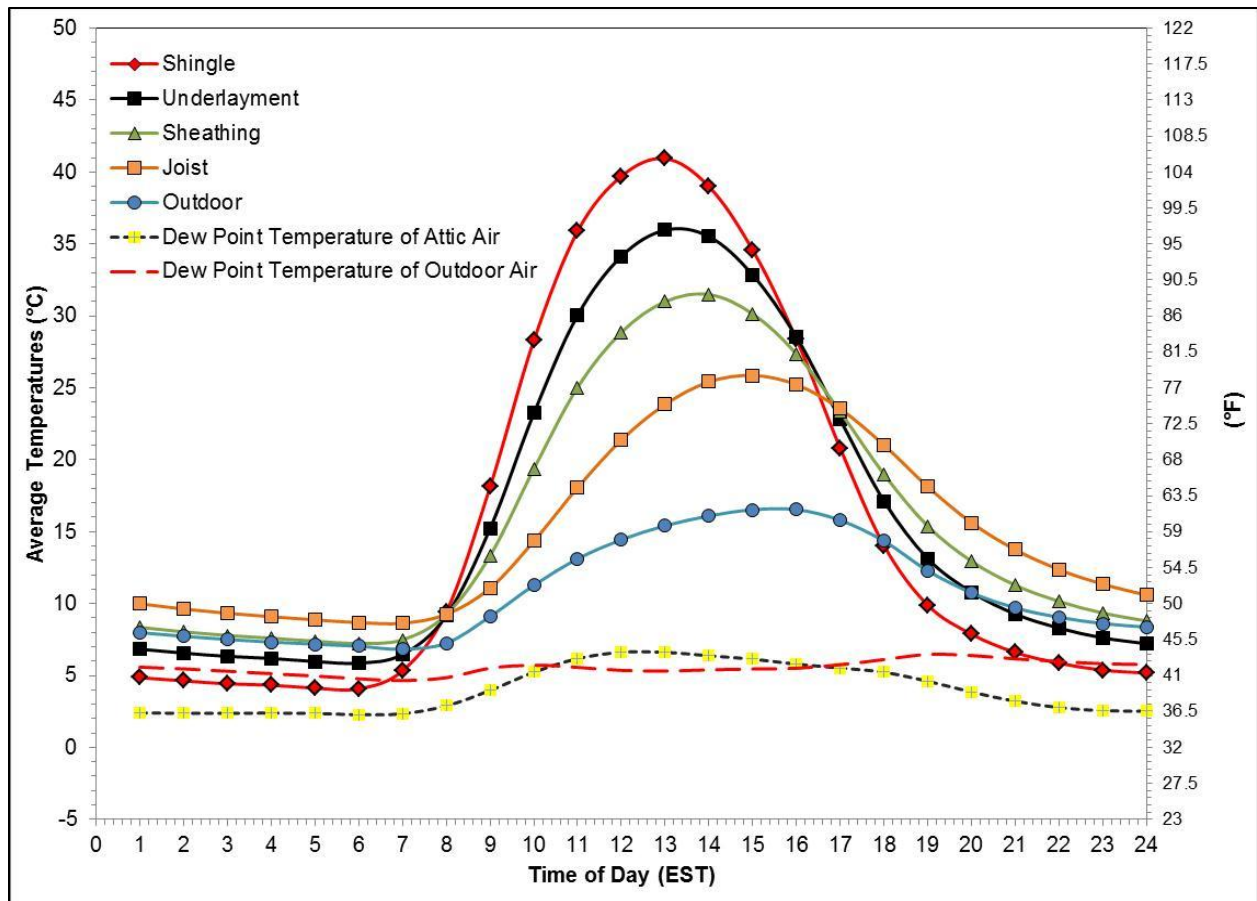


Figure 8: Winter Diurnal Attic Surface Temperatures

Stratification of temperatures is also observed in the temperatures of the attic air at different height values inside the cavity, Figure 9. It is logical to assert that the height-related temperature difference is a function of solar heating on the top of the roof, a relationship which is verified by Figure 9 in which the maximum difference in soffit air temperature to ridge temperature is at a maximum of 3°C (5°F) at approximately 3 P.M.

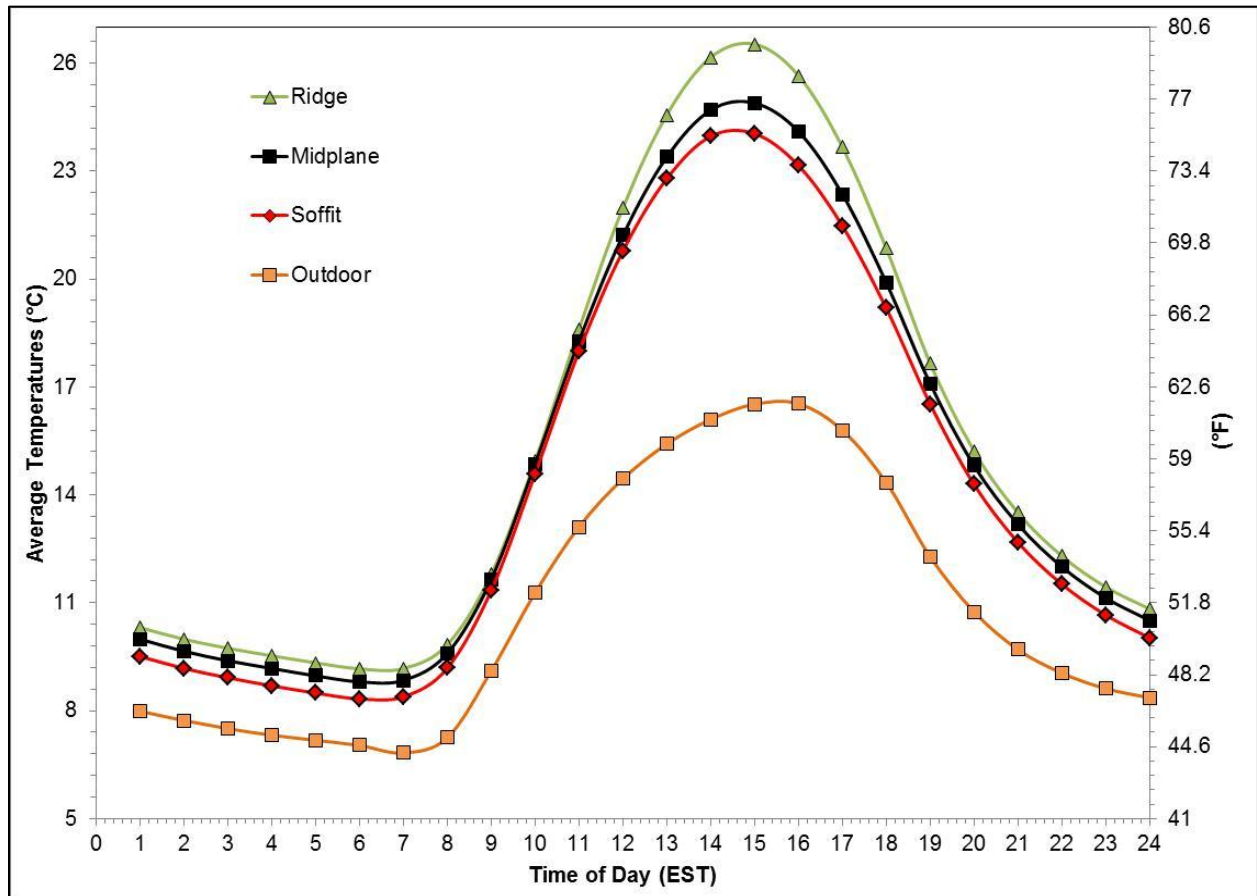


Figure 9: Winter Stratification of Attic Air Temperatures

Comparative attic air temperatures are shown below in Figure 10. The control attic reaches the warmest temperature of 24.7°C (76.5°F) during the peak heating zone, while the attic with ASV shows the least variation throughout the diurnal cycle. Of particular interest is the little difference between the attic air temperatures of the CTRL (ventilation 1:300) and the FF (ventilation 1:150). The data suggests that during the winter months, increasing the area of flow (and therefore logically the rate of flow) does not change the average attic air temperature during daytime heating. Another point of note is the performance of the Cool Color shingle attic; which does not gain heat during the day due to higher reflectivity, but also drops to the second lowest valley temperature of 8.3°C (46.9°F).

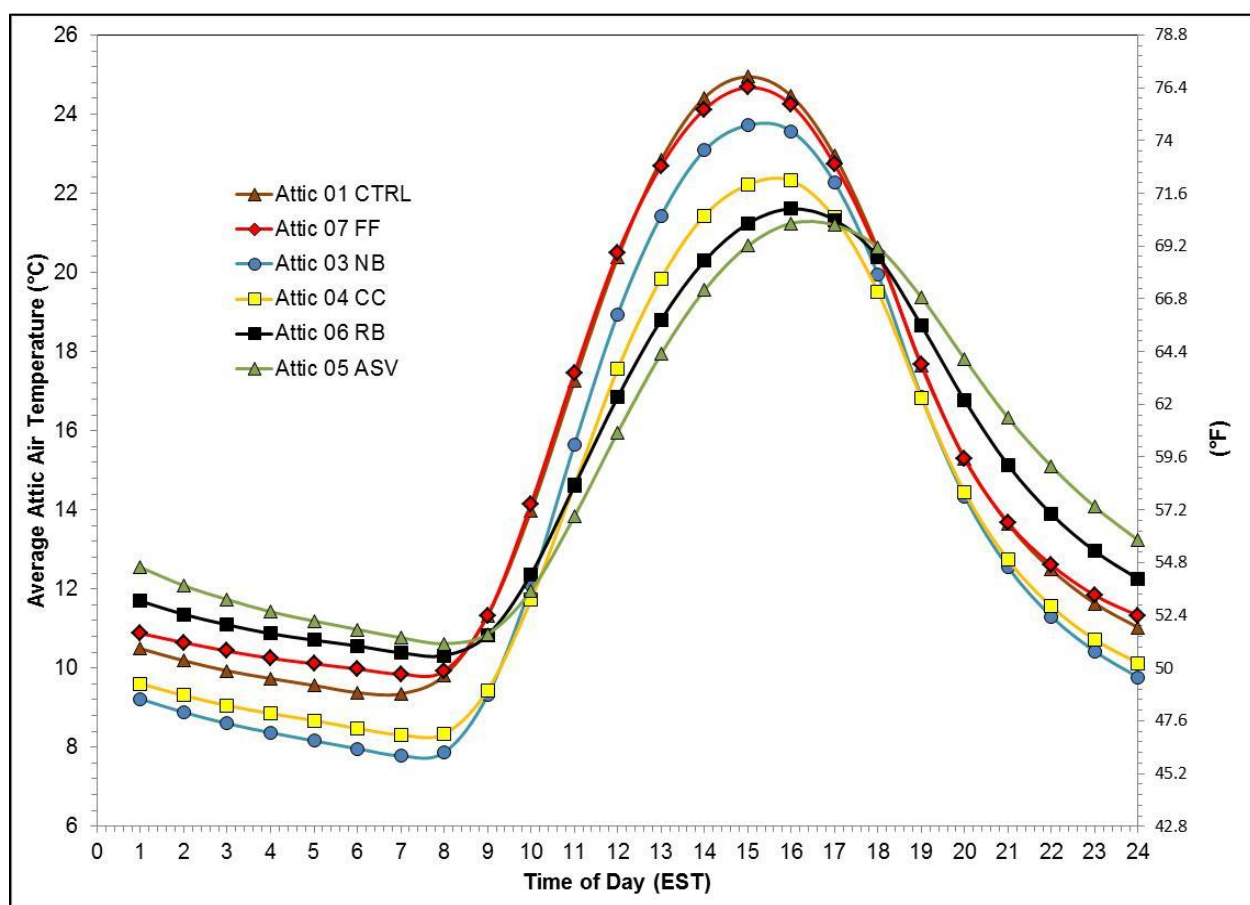


Figure 10: Winter Comparative Average Attic Air Temperature

The average shingle temperatures of the control attic versus the Cool Color (CC) shingle area shown in Figure 11. The CTRL shingle temperature peaks at 40.7°C (105.3°F) while the CC shingle peak temperature is only 33.7°C (92.66°F), a depression of 7°C (13.6°F). The collected data also shows that the north-side temperature CC shingle dropped below the dew point temperature of the ambient air 538 out of the total 2015 hours (on a 15 minute average), approximately 26.7% of the total time. Condensation that remains on the shingle plane can be transported via diffusion through the shingle construction during the heating cycle, but unless there are defects in the placements of the shingles, the system is generally considered to be watertight (Miller & Kehrer, 2011).

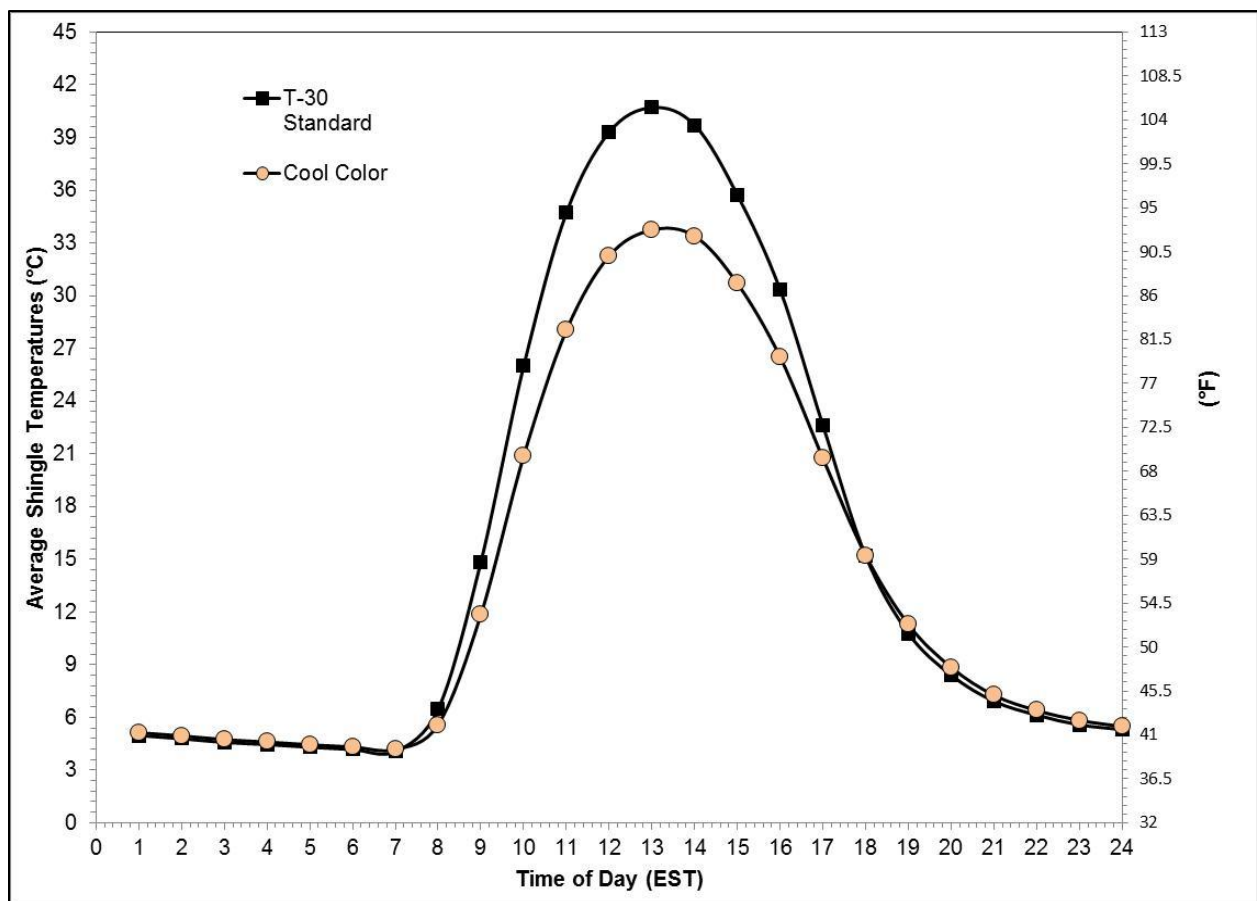


Figure 11: Average Winter Shingle Temperatures: CTRL vs. CC

3.1.2 Winter Heat Flux Data

A comparison of North deck heat fluxes are shown in Figure 12. According to the data, the attic with the highest deck heat flux is Attic 03, which is approximately 5 W/m^2 higher than the CTRL at peak day heating. This result does not seem logical, as the only difference between the CTRL and the NB attics is the addition of a heavier, low-permeance underlayment. The addition of such a layer should theoretically decrease the heat flux through the roof deck, because the low-permeance membrane would block any moisture-related heat flow from crossing the boundary.

The ASV has the least peak day heat flux, at 24.5 W/m^2 lower than the CTRL attic. This is related directly to the increase in amount of materials used in the construction of the two roof decks. The ASV roof has a second roof deck and an additional air gap for heat removal, therefore the North deck flux is much less than the standard at peak. The CC and RB roofs do a fair job of decreasing the flux through the North deck, with a decrease of 14 W/m^2 and 10 W/m^2 , respectively. The heat flux transducers have an accuracy range of 5-10% according to the manufacturers which allows for a small amount of uncertainty in the measurements.

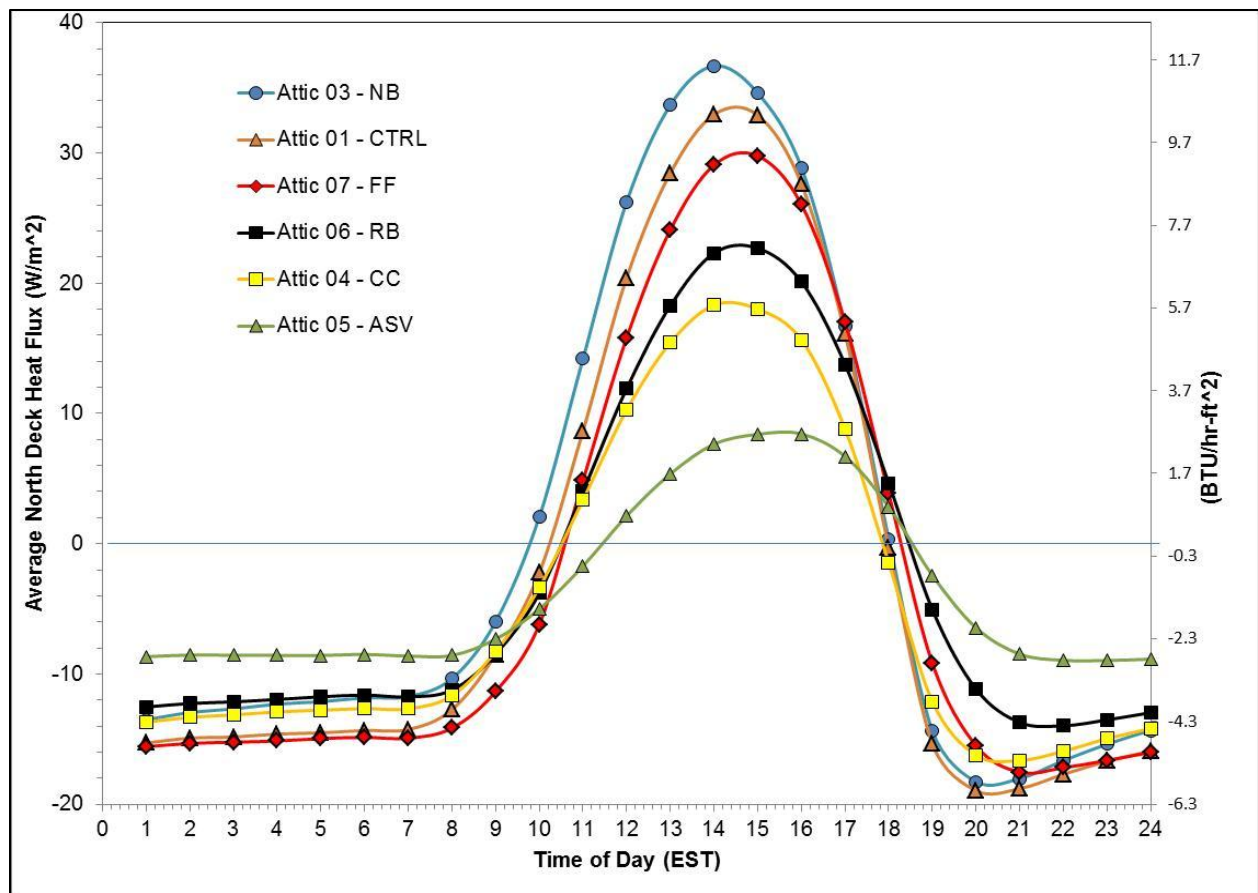


Figure 12: Average Winter Comparative North Deck Heat Flux

Average South deck heat flux values for the winter cycle are shown below in Figure 13. The South deck is exposed to higher levels of solar radiation in both the summer and winter months, and therefore the average heat flux through the South deck is higher than the North. The South deck heat flux measurements show the same trends as the North deck; however the effect of increasing the ventilation area from the NB to the FF attic is a greater magnitude on the North deck. The sequence of observing the trends in ventilation is that to identify the process by which ventilation and composition changes in the CTRL, NB, and FF attics.

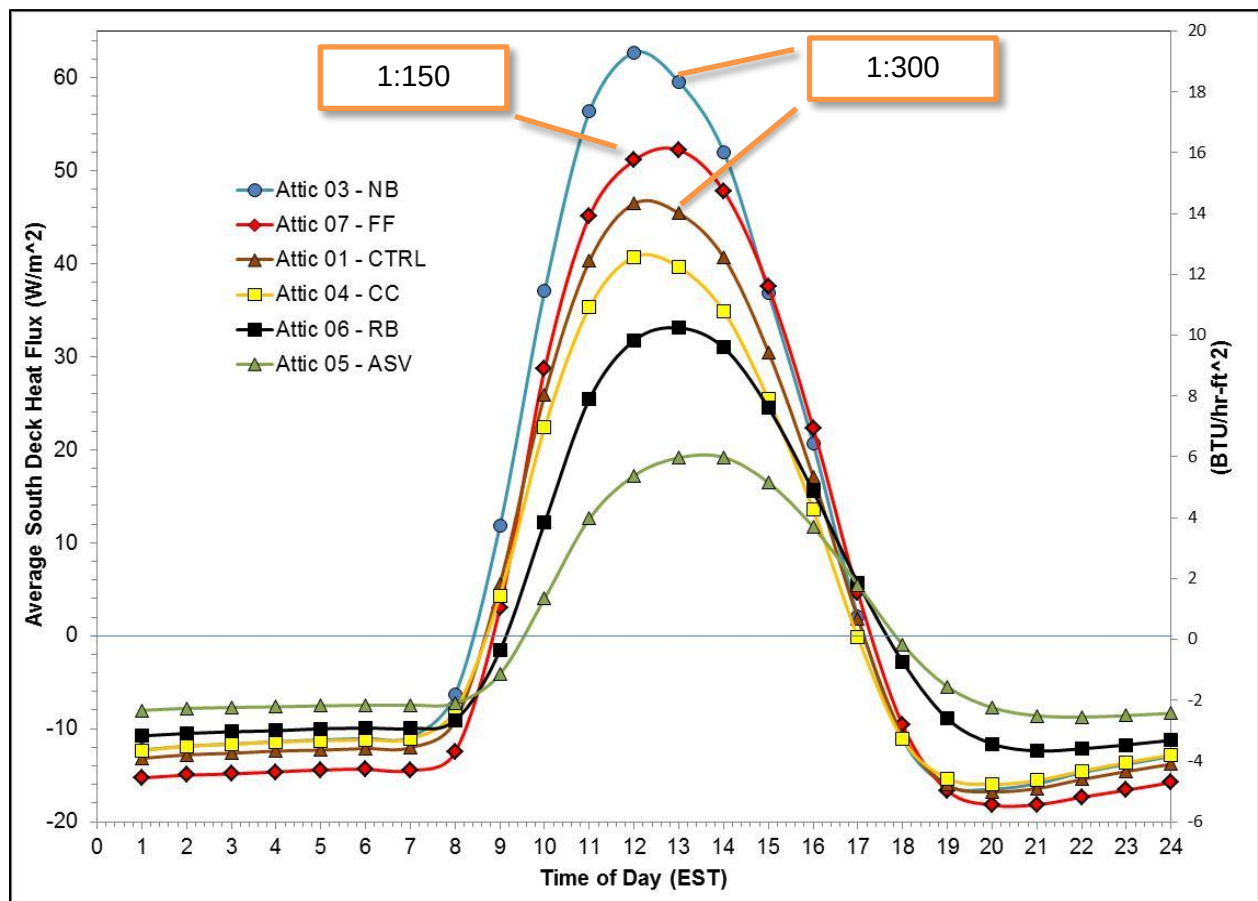


Figure 13: Average Winter Comparative South Deck Heat Flux

The aforementioned process is shown in Figure 14. The standard CTRL attic has a 15-lb felt paper permeable membrane, a 1:300 ventilation ratio, and is represented by the brown triangles. The NB attic is identical to the CTRL attic, except the membrane is exchanged with a low-permeable underlayment. This change constitutes an increase in South roof deck flux of 10 W/m^2 , and is represented in Figure 14 by the blue circles. The FF attic, presented as red diamonds, then varies from the NB only by increasing the area ratio of ventilation from 1:300 to 1:150. Therefore, to observe the effects of ventilation increase, we must observe the difference in heat flux between the NB and the FF attics, which according to the collected data is a reduction by 16.1 W/m^2 . Error bars have been added to Figure 14 to show the 5-10% uncertainty in the measurements. The error bars overlap, and therefore the variation in deck heat flux between the attics with differing flow areas and membrane permeability values fall within the uncertainty of measurement.

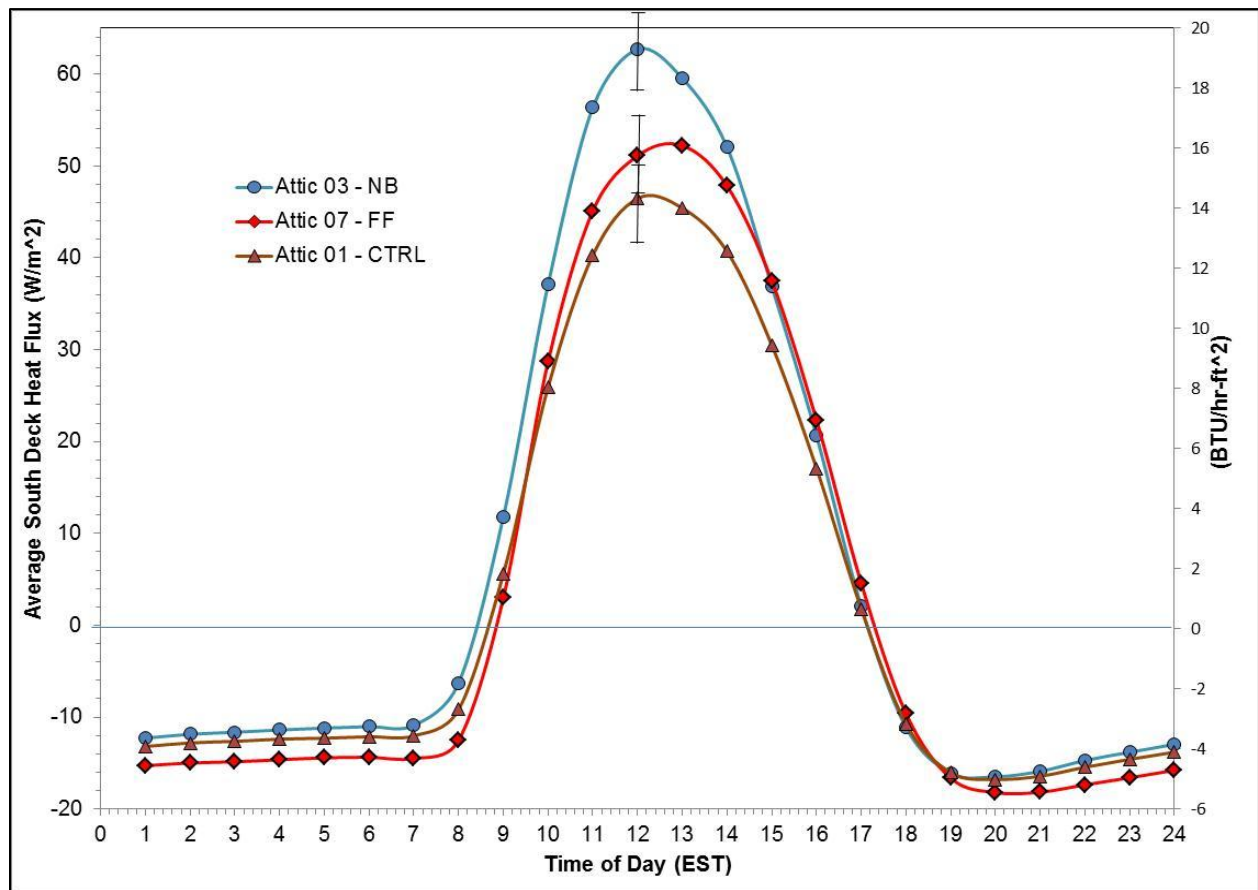


Figure 14: Winter Comparison of CTRL, NB, FF Attic Ventilation on South Deck Heat Flux

Another observation from the South roof heat flux is the decrease in flux as a result of application of a perforated radiant barrier foil on the underside of the OSB sheathing, see Figure 15. The RB attic shows a 15 W/m^2 flux decrease from the CTRL at peak heating.

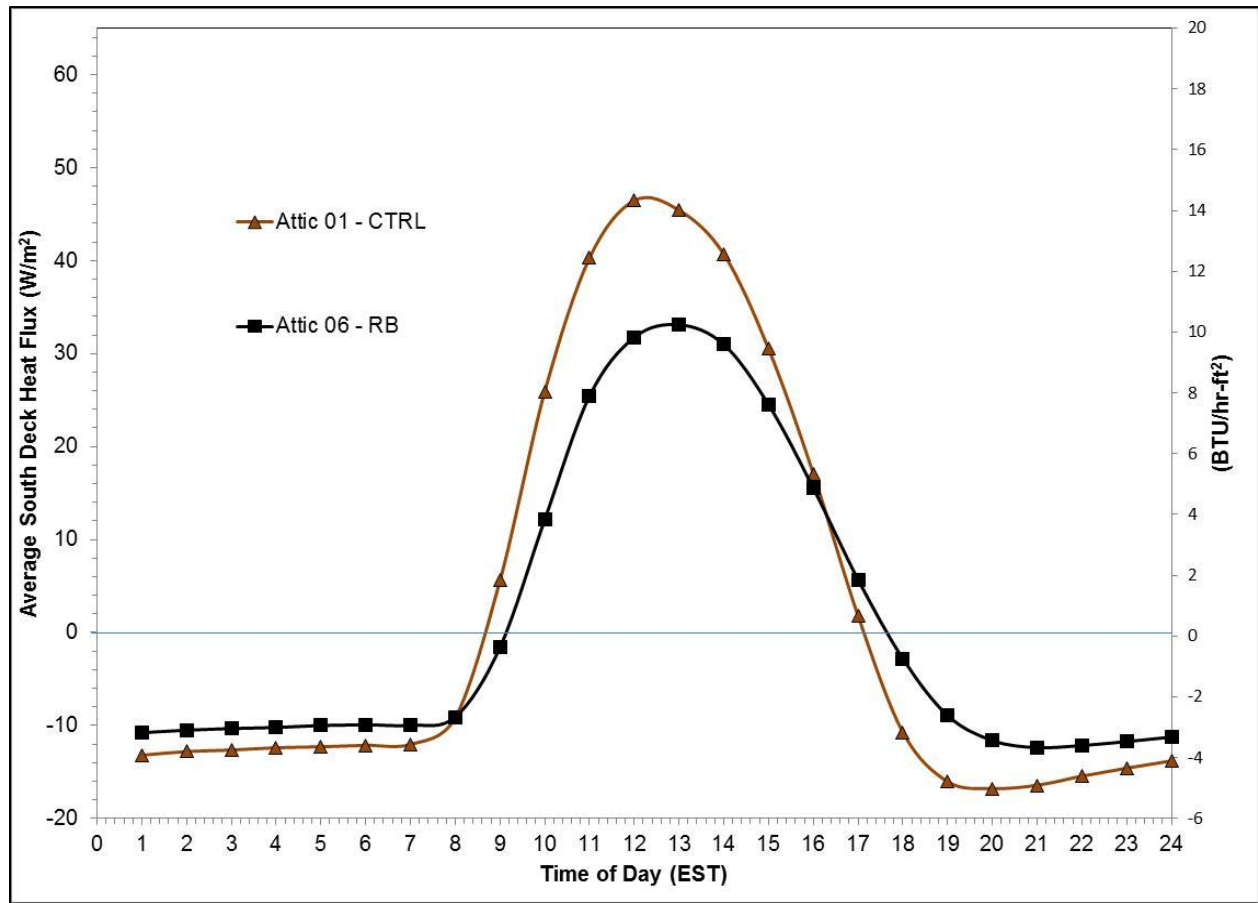


Figure 15: Winter Radiant Barrier Effect on Average South Deck Flux

The comparative heating or cooling load from each attic construction on the conditioned space and HVAC system can be better understood by observing the heat flux through the attic floor surface. The heat flux transducers in this instance are located in between the insulation (assumed uniformly distributed and packed) and the gypsum board that separates the conditioned space from the attic, refer to previous Figure 7 for a photo of the HFT in place. The collected flux data for all attics is within the range of -1.6 and 0.5 W/m^2 . This narrow range adds to uncertainty in the validity of the measurements. The HFT operated by measuring a temperature difference across a known medium using a thermopile. Therefore, as the difference in temperature across the medium decreases, the sensitivity of the instrument decreases. This phenomenon can be observed in Figure 16.

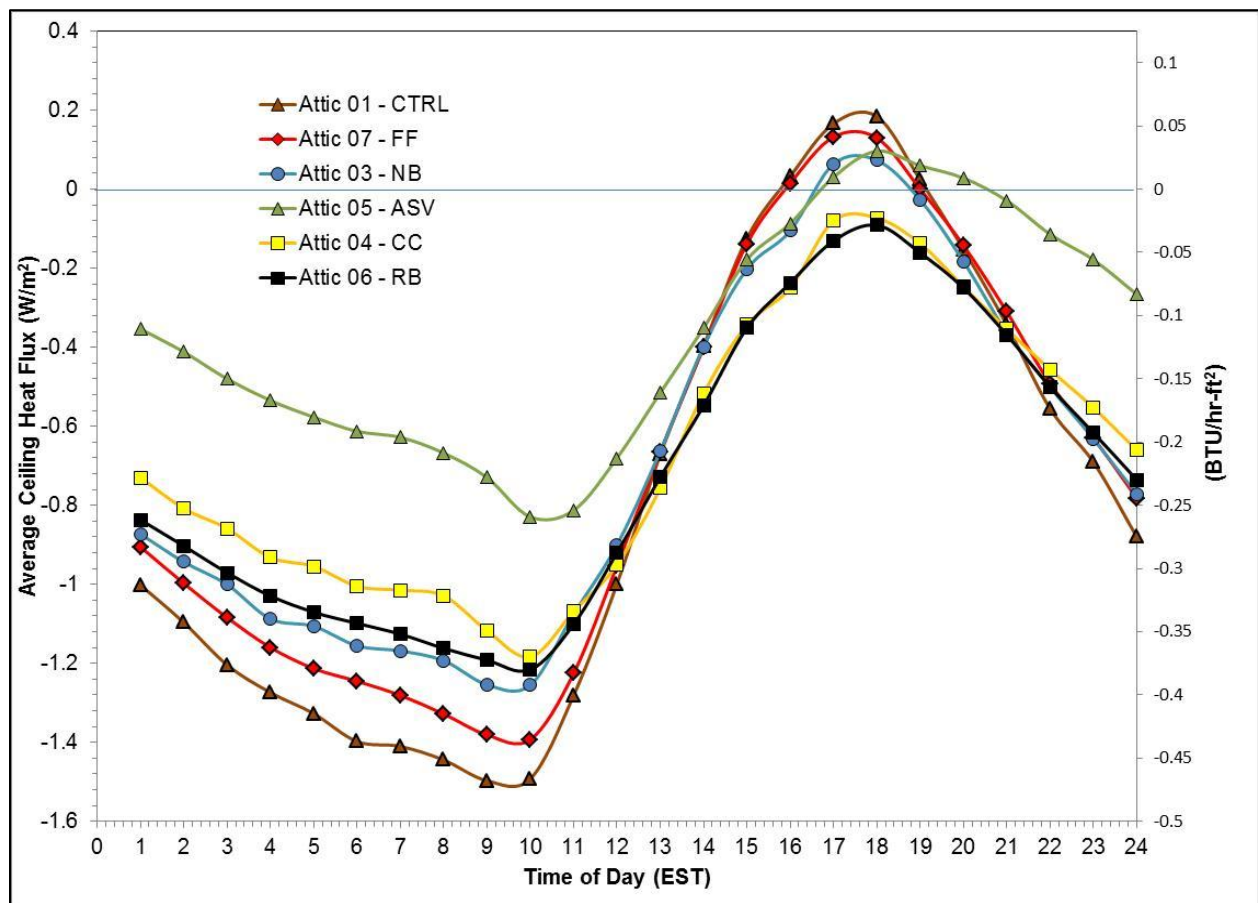


Figure 16: Average Winter Comparative Ceiling Heat Flux

The sign convention of the ceiling HFTs is positive for heat flowing from the attic into the conditioned space. The data suggests that the CC and RB attics remain cold enough that on average, the direction of heat flow never reverses. As before, the ASV attic has the least average diurnal variation and the least amount of heat lost from the conditioned space during the early morning, with a value of 0.668 W/m^2 higher than the CTRL at 10 A.M.

3.1.3 Winter Moisture Calculations

To determine the possibility of condensation on surfaces inside the attic cavity, the temperatures of the wood joist and OSB sheathing have been compared to the attic air dew point for each cavity. Due to the sporadic nature of this data, it is not presented in time-averaged format. Instead, the data is presented as a percentage of time that the surface temperature was depressed below the dew point temperature calculated using Equation 6 and presented in Table 4.

Table 4: Winter Moisture Calculations

Attic	Hours $T_{\text{sheath}} < T_{\text{dp}}$ (2015 total)	% Time for Condensation on Sheathing	Hours $T_{\text{joist}} < T_{\text{dp}}$ (2015 total)	% Time for Condensation on Joist
03 - NB	110	5.46%	72	3.57%
04 - CC	103	5.11%	62	3.08%
01 - CTRL	102	5.06%	48	2.38%
06 - RB	83	4.12%	26	1.29%
07 - FF	75	3.72%	32	1.59%
05 - ASV	20	0.99%	10	0.50%

According to Table 4, the ASV attic has the best surface condensation moisture control, with the possibility of condensation at only 0.99% of the recorded time. The increased ventilation FF attic does provide better dew point control than the NB attic, with a 1.74% decrease for the sheathing and a 1.98% decrease for the joist.

3.2 Summer 2011 (May to September)

Data collection for May through September of 2011 was the longest span of data taken without significant loss of data connection or confidence in data values. During this range of time, a team of researchers made trips to the facility to perform various experiments and correct issues with the HVAC system. Experimentation included sampling the fiberglass insulation for further material analysis at ORNL, and tracer gas ventilation rate testing to determine *in situ* ventilation values.

3.2.1 Summer Temperature Data

Like the winter 2011 data, the summer data has been time-step averaged over the entire operational period, to show “standard” 24-hour performance for the season. Figure 17 and Figure 18 show the stratification of average surface and air temperatures inside the CTRL attic during the summer collection period. Shingle temperatures can be incredibly high in the summer months. Note that the sensors for shingle temperature are actually on the underside of the shingle, so the actual temperature on the shingle exterior can be slightly hotter than reported.

The diurnal heat profile shown in Figure 17 and 18 illustrate how the solar heat gain affects the temperatures of each of the construction materials as well as the attic air stratification. During the early morning, the shingle temperature drops below that of the other materials due to the effect of night sky radiation, which is the shingle surface transferring heat to the cold ambient sky temperature. Dew point temperatures of the outdoor and attic air are shown in Figure 17, but when observed in the bin average method, the possibility of surfaces dropping below the dew point temperature seems unlikely. The bin average method essentially overrides the few times during the sample period that the attic surfaces are depressed below the dew point temperature of the attic air. Therefore, the dew point condensation potential is observed on an hour-to-hour basis later in this report.

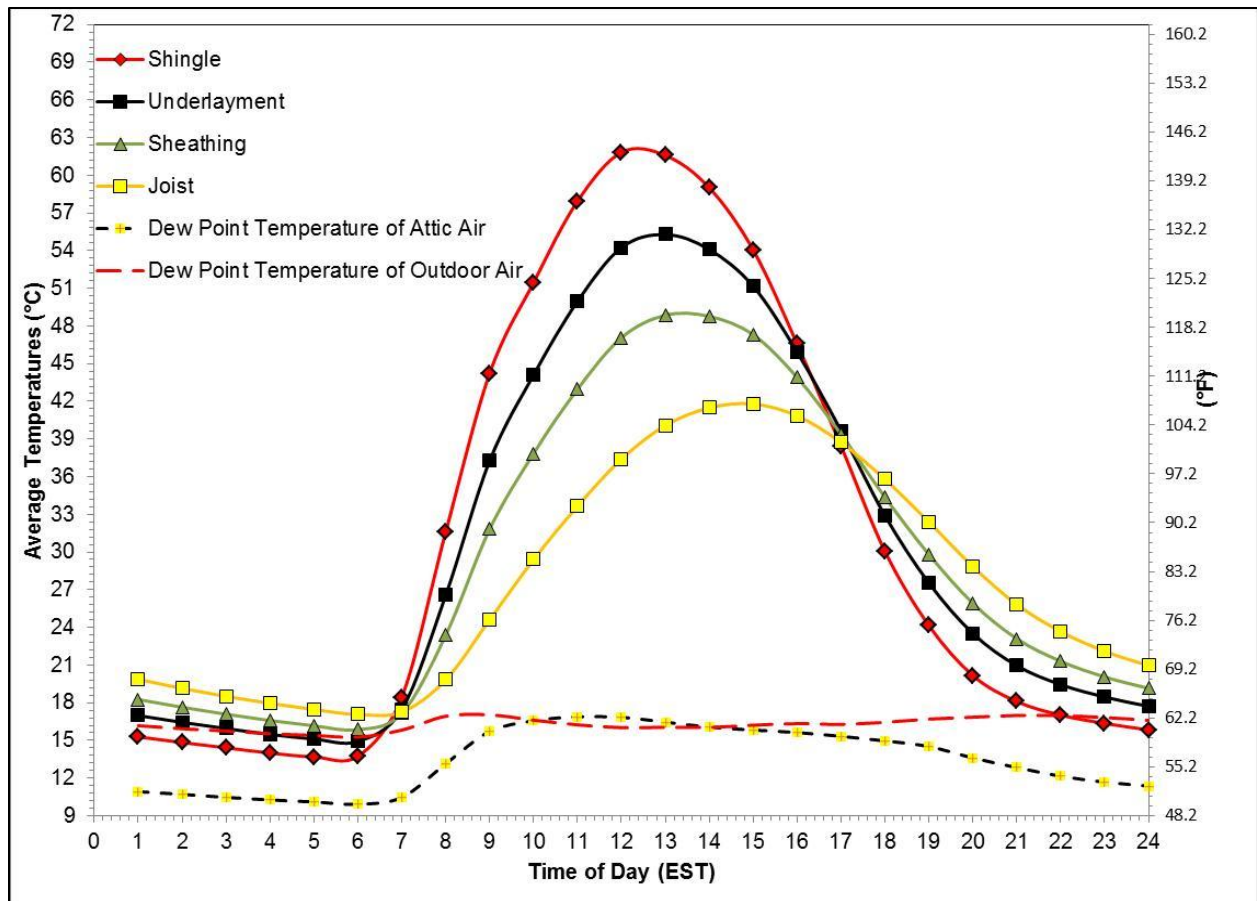


Figure 17: Summer Diurnal Attic Surface Temperatures

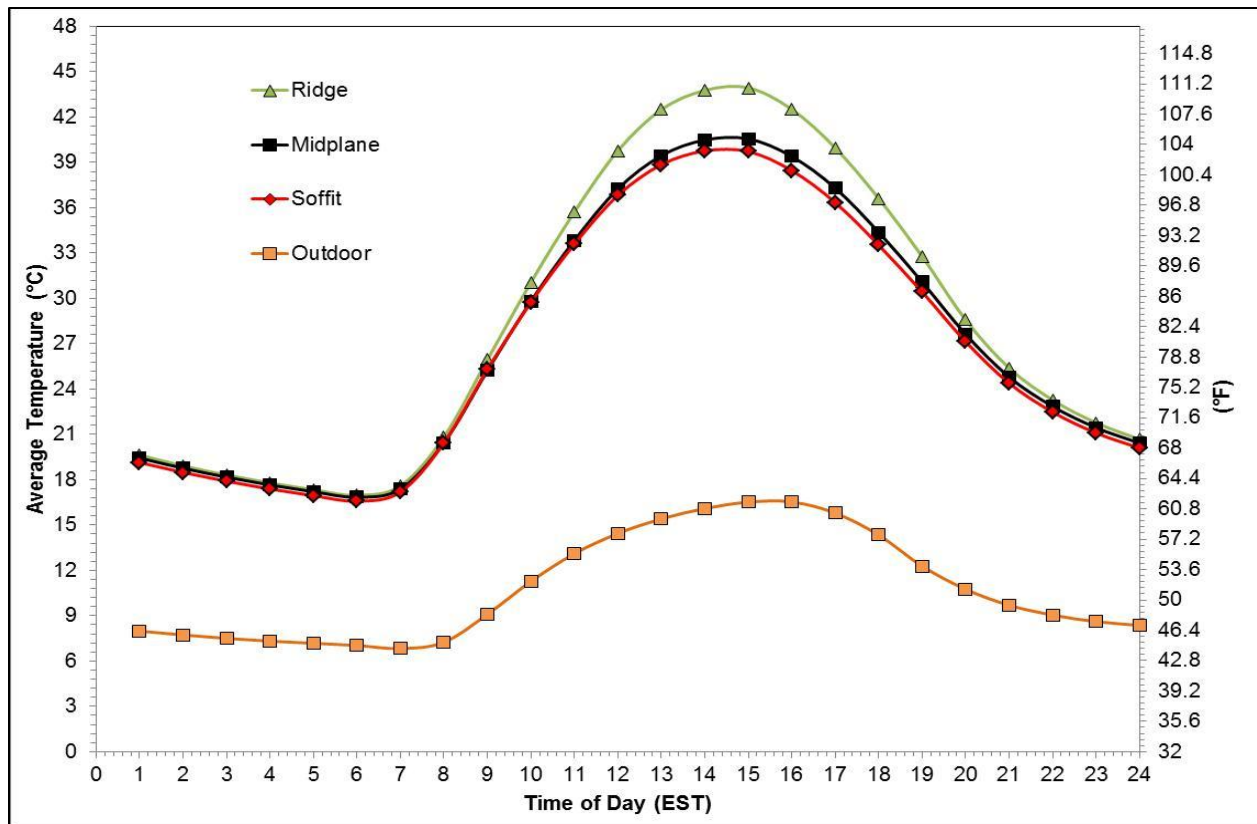


Figure 18: Summer Stratification of Attic Air Temperatures

Comparative summer attic temperatures are shown below in Figure 19. For the summer period, the ASV and **Error! Reference source not found.** RB attics have very similar performance, sharing a 7°C (12.6°F) lower peak temperature than the CTRL attic. According to Figure 19, increasing the ventilation area ratio from 1:300 to 1:150 in the summer only decreases the peak attic air temperature by approximately 1°C (1.8°F). The CC attic operates at 4°C (7.2°F) lower than the peak of the CTRL attic.

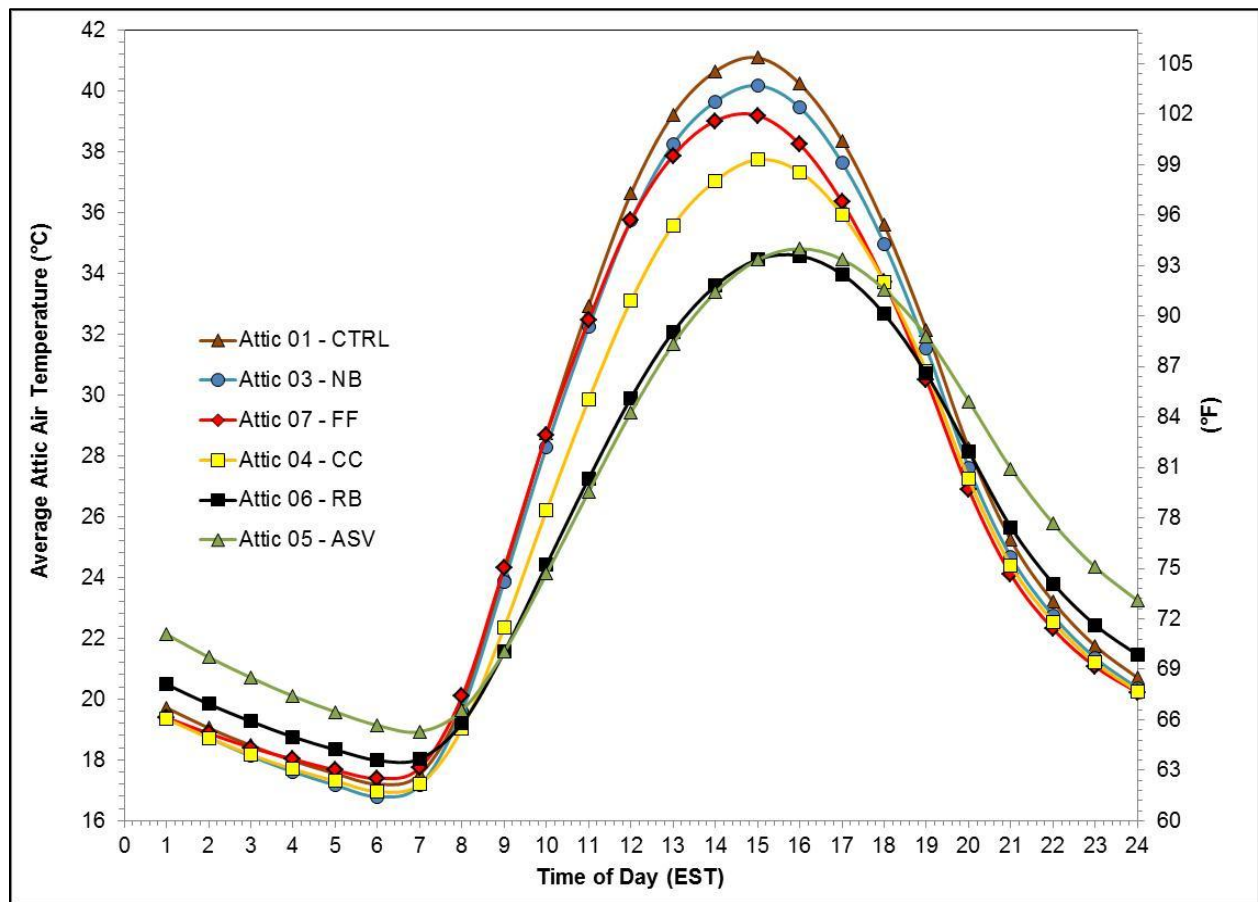


Figure 19: Summer Comparative Average Attic Air Temperature

The low-reflectance CC shingles have an average peak at 52.6°C (126.7°F) as seen in Figure 20. This value compares favorably with the T-30 shingles on the CTRL attic, which peak at 60.9°C (141.6°F). The difference is 8.3°C (14.9°F), which is comparable to the difference in the winter, which was 7°C (13.6°F).

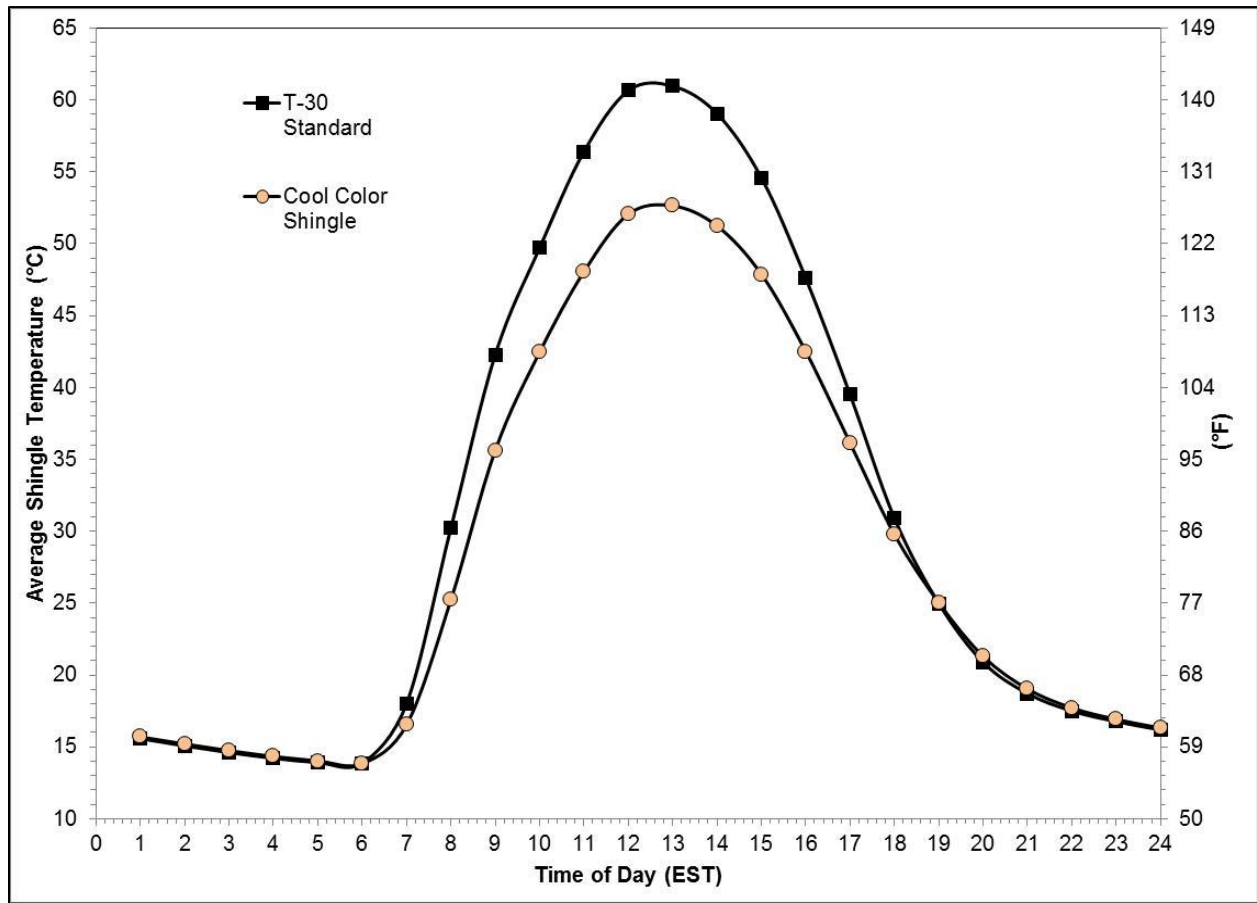


Figure 20: Average Summer Shingle Temperatures: CTRL vs. CC

3.2.2 Summer Heat Flux Data

A comparison of summer average North deck heat flux is shown in Figure 21. According to the collected data, the ASV attic allows the least amount of heat flux through the North deck, peaking at only 23.45 W/m², compared to the CTRL which peaks at 64.5 W/m². Similar to the case with attic air temperature, the RB and CC attics share almost identical performance, peaking in the 42-45 W/m² range during the heating period. NB attic shows an increase in heat flux of 5.5 W/m² in comparison to the CTRL. Increasing the ventilation ratio from the NB to the FF attic shows a decrease in peak flux of 8.4 W/m².

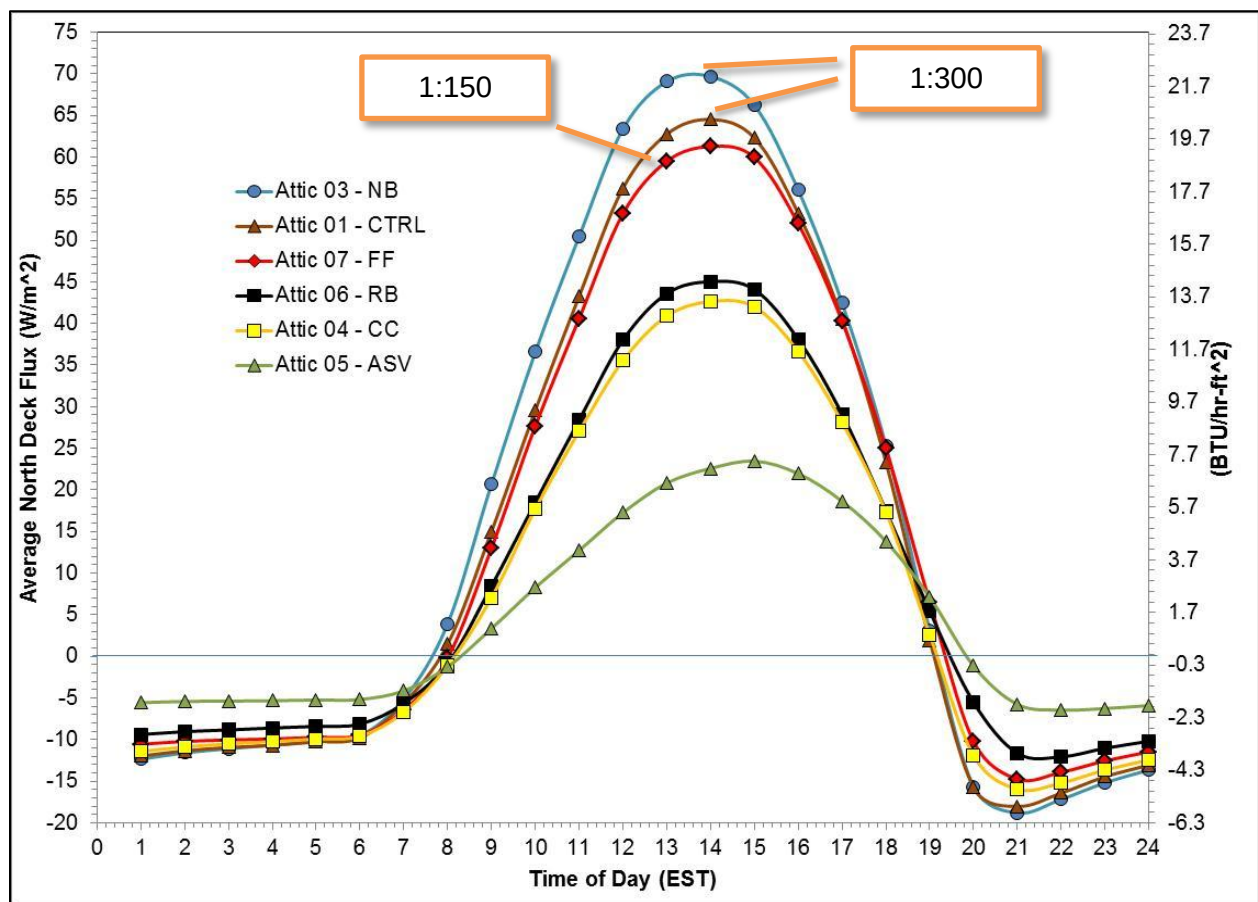


Figure 21: Average Summer Comparative North Deck Heat Flux

During the summer season, the South roof deck experiences more incident solar radiation than the North deck, therefore the heat flux through the South is expected to be greater than that passing through the North deck. South deck heat flux measurements show the same general trends as the North deck; however the effect of increasing the ventilation area from the NB to the FF attic is a greater magnitude on the North deck similar to the winter data. The ASV attic again shows the best performance in inhibiting the heat flow through the roof deck, followed by the RB and CC attics, see Figure 22. Error bars are again included on the CTRL curve to show the 5-10% accuracy of the sensors. The difference observed between the CTRL attic and the NB attic fall within the uncertainty of the measurements, therefore conclusions based on the effect of membrane permeability on roof deck heat flow cannot be made.

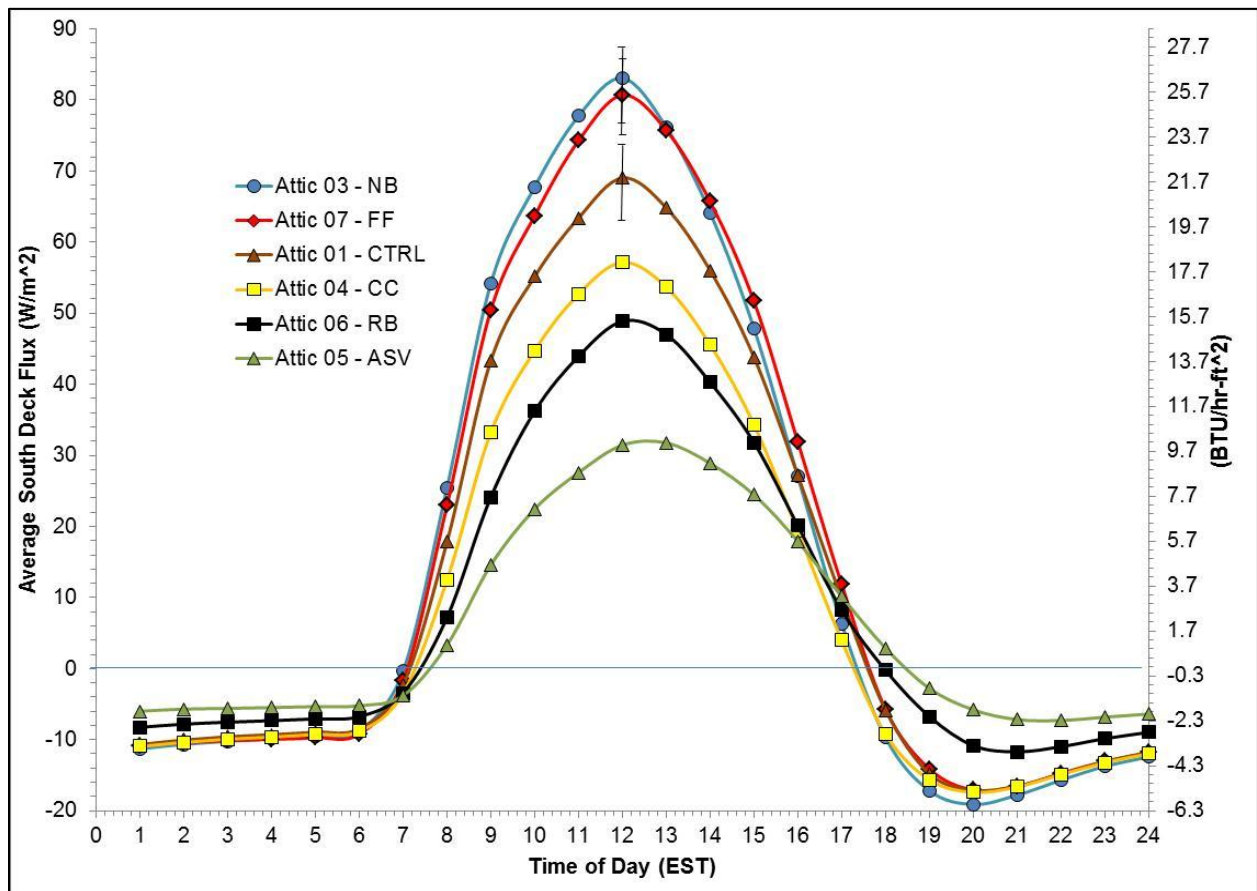


Figure 22: Average Summer Comparative South Deck Flux

Of particular interest in this data set is the inhibiting effect that the radiant barrier foil has on the flow of heat through the South roof deck. The radiant barrier reflects penetration of infrared solar radiation, and should therefore show a significant decrease in heat flux through the sun-side South deck. Figure 23 shows the average south roof deck flux for the CTRL and the RB attics. The radiant barrier foil in decreases the heat flux 20.96 W/m² from the CTRL attic. The RB attic also maintains a higher temperature during the evening hours.

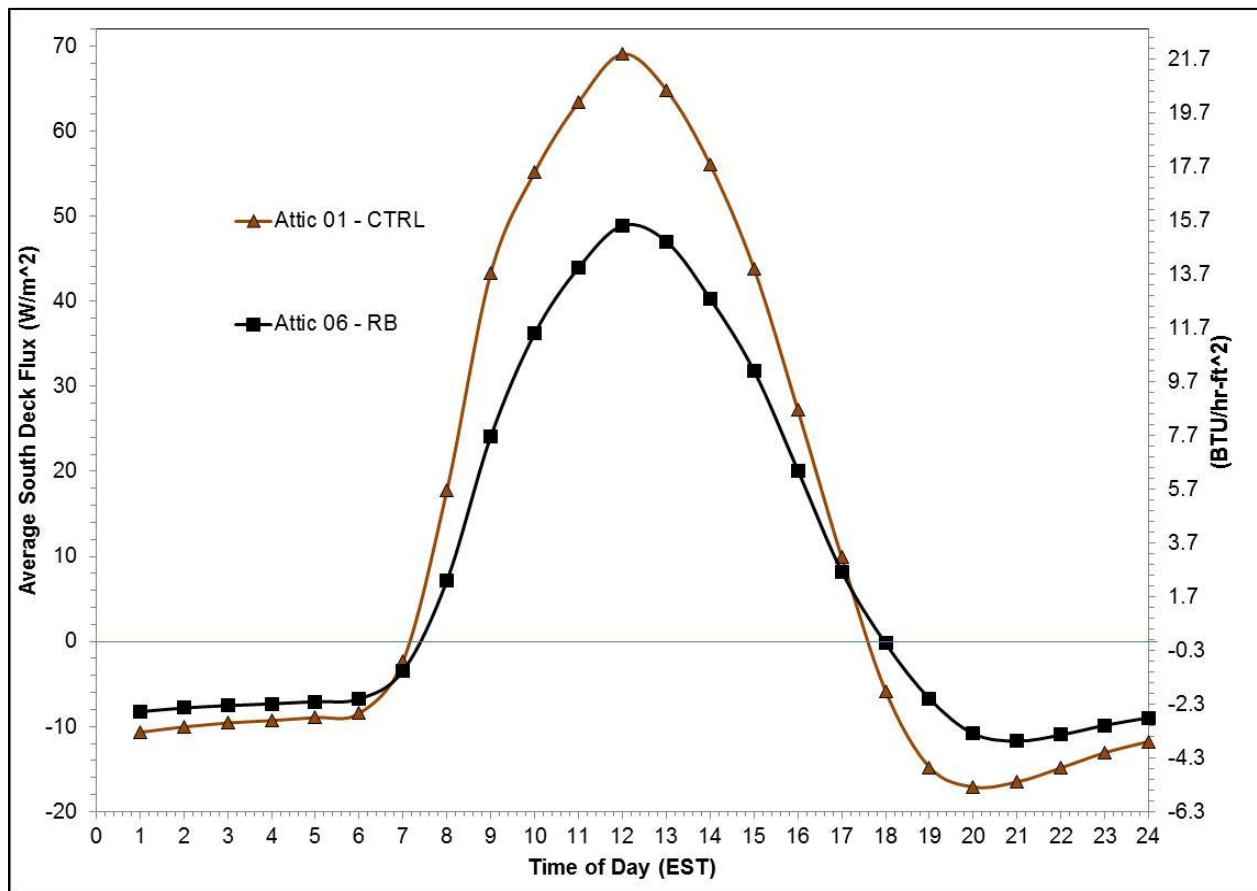


Figure 23: Summer Radiant Barrier Effect on Average South Deck Flux

Observing heat flux through the attic floor is especially important during the summer months, because the temperature of the attic can reach upwards of 43.3°C (110°F) and that temperature difference drives the heat from the attic into the conditioned space at a generally larger magnitude than in the winter for the Charleston, SC climate. The average heat flux through attic floor is shown below in Figure 24. All attics, with the exception of the ASV case, have a window of time from 3:00 A.M. to 9:00 A.M. where the heat flux is negative. For this period, the temperature in the attic cavities is actually less than the conditioned space.

Attics ASV, CC, and RB demonstrate relatively the same performance for the case of ceiling flux with an average peak flux value of 0.86 W/m², which is 0.67 W/m² less than the CTRL. Adding the low-Permeance membrane appears to decrease the heat flux by 0.35 W/m². Increasing the ventilation area from the NB at 1:300 to the FF at 1:150 increases the heat flux from the NB peak of 1.16 W/m² to the FF peak of 1.36 W/m², which is an increase of 0.2 W/m². Once again, the apparent restricted amplitude of the HFT due to the high R value of the fiberglass insulation causes some uncertainty into the sensitivity of these measurements.

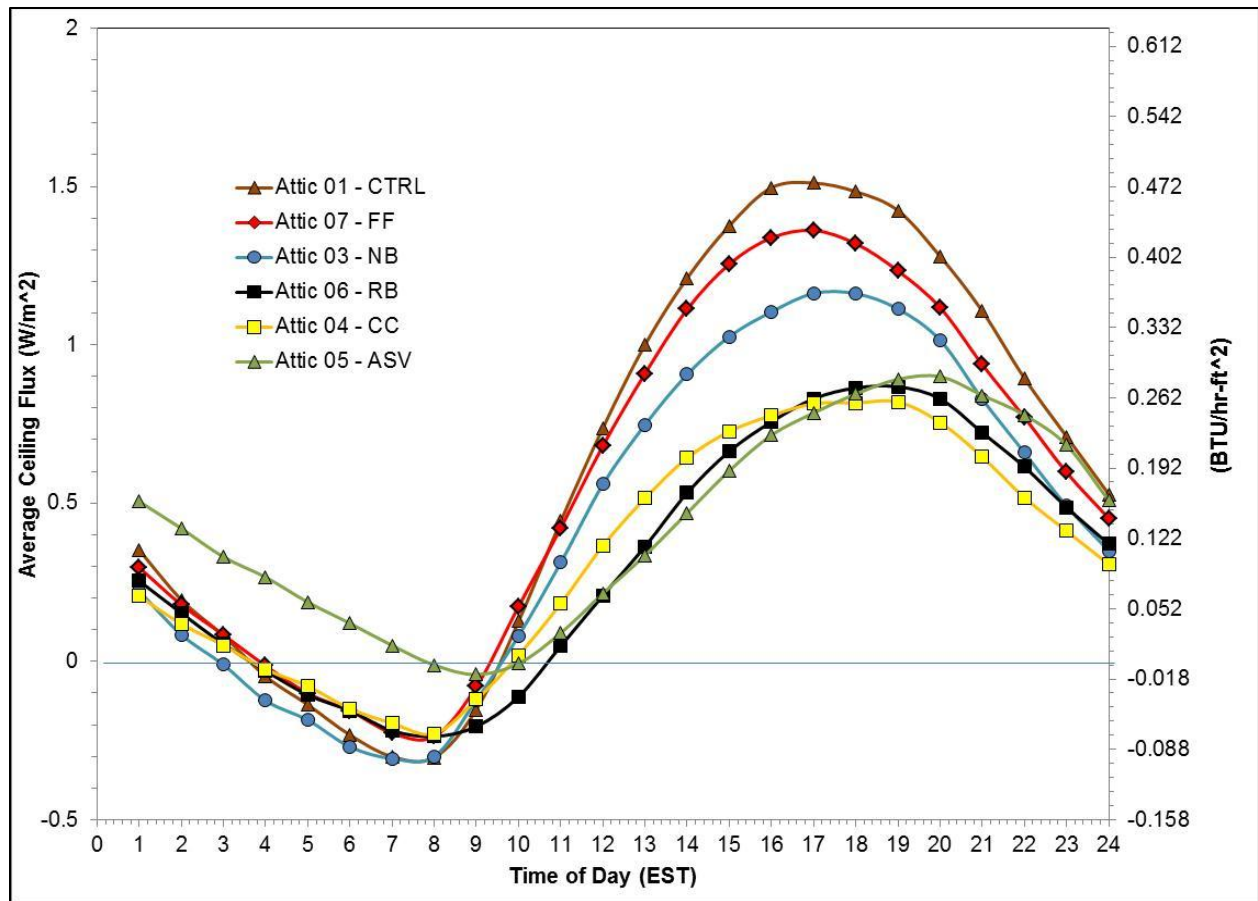


Figure 24: Average Summer Comparative Ceiling Heat Flux

3.3 Airflow – Gas Tracer Analysis

Tracer gas testing was performed on each attic during a trip to the NET facility in June 2011. Diana Hun, a fellow researcher at ORNL 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 feet above insulation). The two sampling lines were hung from existing connections approximately 2 feet above insulation, and four feet from the centerline of the cavity.

Once the Sampling tubes were measured out to correct length (measured previously inside the attic cavity), and cut. Each attic bay features insulated-stuffed outlets for the DAS lines, which proved to be perfect locations for inserting the sampling and dosing tubes into each respective cavity. Data was collected at different time for each attic, because the gas dosing and sampling filters would lose data resolution if more than two attics were being analyzed during a single session. A summary of the data collected and calculated air change per hour values are shown below in Table 5.

Table 5: 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	40.00	3.37	40.9	2.71
2	01	6/30/2011	2350	0019	31.50	43.00	3.57	99.9	2.04
3	03	6/30/2011	1637	1708	27.10	36.60	1.31	207.3	3.68
4	07	6/30/2011	2225	2246	29.30	40.14	3.37	40.9	3.21
5	07	6/30/2011	2354	0019	31.50	43.17	3.57	99.9	2.73

Exponential decay curves for runs 1, 3, and 4 are shown below in Figures 25-27. The exchange rate calculation for ACH is based on a tracer gas exponential decay method (E741, 2006)

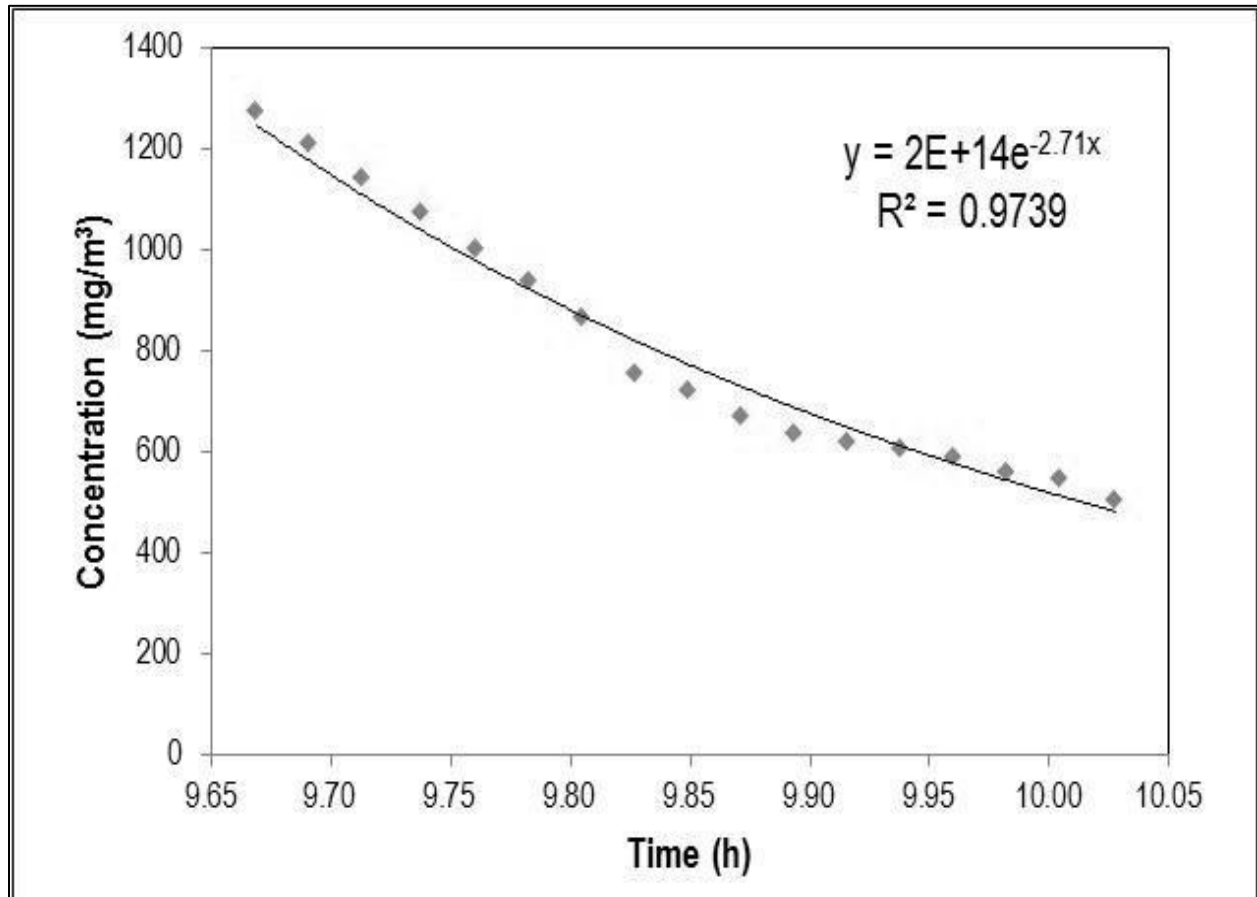


Figure 25: Attic 01 Gas Tracer Decay Curve

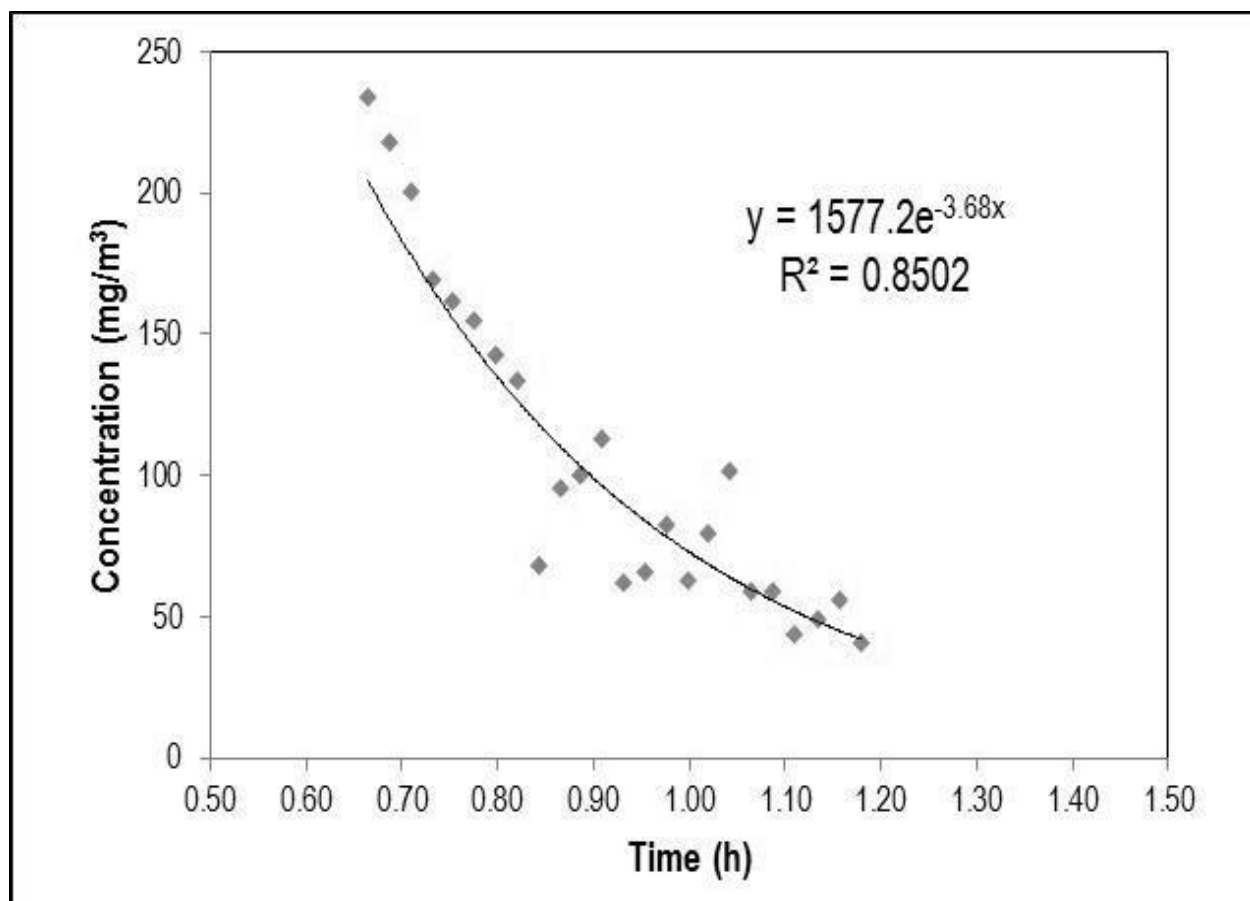


Figure 26: Attic 03 Gas Tracer Decay Curve

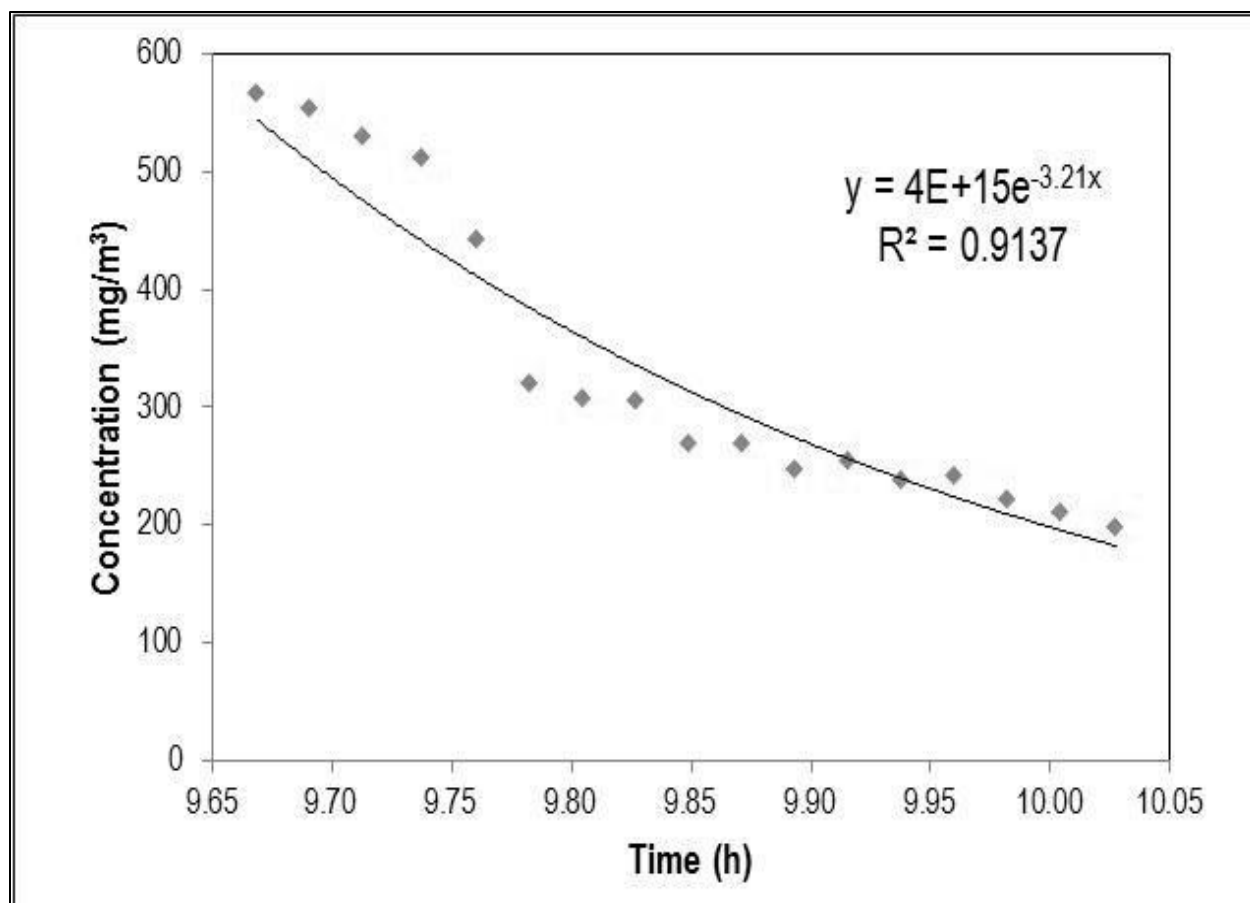


Figure 27: Attic 07 Gas Tracer Decay Curve

CHAPTER 4

SIMULATION BENCHMARK

4.1 Conceptual Fluid Dynamics

The purpose of this report is to investigate the effect of varied ventilation area on heat flow reduction and prevention of moisture condensation on attics surfaces. Therefore, the most pertinent conceptual derivation is that of the flow rate of ambient air into the attic as a factor of ventilation inlet/outlet area. Note that the following derivations are based on work done by Wilkes in 1991. The ventilation inside of the attic cavity is driven by pressure differences across the building envelope caused by wind and air density differences due to the temperature difference between the outdoor and indoor air. The latter is known as the stack effect. The pressure at any point is dependent on the magnitude of these two effects and the characteristics of each ventilation opening (Wilkes, Modeling of Residential Attics, 1981).

4.1.1 Flow Due to Stack Effect

The stack effect occurs when the air density differs between the interior and exterior of the building. The pressure at a given elevation results from the mass of air column above that elevation which is a function of the density of the air. When the indoor and outdoor air temperatures differ, the air densities, and thus the column masses and pressures, will be different (ASHRAE Handbook - Fundamentals (I-P Edition), 2009). The height at which the exterior and interior pressures are equal is called the neutral pressure plane. Determining the pressure difference caused by the stack effect first requires calculation of the neutral pressure plane inside the attic cavity (Wilkes, Analysis of Annual Thermal and Moisture Performance of Radiant Barrier Systems, 1991). The following calculations assume that the ventilation areas for soffit and ridge vents are equal. If this is not the case, the equation is modified using the minimum area (A_{min}) between soffit and ridge vents, as see in Equation 12. If the temperature of the air in the attic cavity is greater or less than the outdoor temperature, than the neutral pressure plane height is calculated by:

$$H_{NPL} = \begin{cases} \frac{H_{io}}{\left[1 + \left(\frac{A_i^2}{A_o^2} \right) * \left(\frac{T_{A,abs}}{T_{V,abs}} \right) \right]} & \text{for } T_A > T_V \\ \frac{H_{io}}{\left[1 + \left(\frac{A_i^2}{A_o^2} \right) * \left(\frac{T_{V,abs}}{T_{A,abs}} \right) \right]} & \text{for } T_A < T_V \end{cases} \quad (4)$$

Therefore, the flow due to stack effect in CFM is:

$$\dot{Q}_{stack} = \begin{cases} .65 * A_{min} * \sqrt{64.348 * (3600)^2 * H_{NPL} * \frac{T_{A,abs} - T_{V,abs}}{T_{A,abs}}} & \text{for } T_A > T_V \\ .65 * A_{min} * \sqrt{64.348 * (3600)^2 * H_{NPL} * \frac{T_{V,abs} - T_{A,abs}}{T_{V,abs}}} & \text{for } T_V > T_A \end{cases} \quad (5)$$

The mass flow rate of air is therefore,

$$\dot{m}_{stack} = \dot{Q}_{stack} * \rho_{air} \quad (6)$$

4.1.2 Flow Due to Wind Pressure Effect

Airflow in the attic cavity from incident wind entering through the windward soffit vents causes a positive pressure and a negative pressure on the leeward side of buildings. To equalize pressure, air will enter the windward soffit vents and be exhausted from the ridge vent and the leeward soffit vents. This flow depends directly on the speed and direction of the incident wind and the flow area and type of vents.

For the purposes of this report, only the case of soffit and ridge vents are considered for natural ventilation into the attic cavity. The directional effect on calculation of wind speed at the vent is dependent on the argument, denoted by the term “ C_w ” of the following expression:

$$C_w = |\sin((\theta_w + 90) * 3.1415 [radians]/180[degrees])| \quad (7)$$

The corrected wind speed is therefore:

$$V_{w,c} = \begin{cases} 0.087 * V_w & \text{if } C_w = 0 \\ .45 * V_w * (0.087 + 0.13 * C_w^{2.5}) & \text{if } C_w \neq 0 \end{cases} \quad (8)$$

Calculating the air flow due to wind pressure requires a modification to account for ventilation type. This modification is based on a flow coefficient that varies depending on the type of ventilation used in the structure. Values corresponding to various ventilation methods have been calculated based on effectiveness coefficients developed by Burch and Treado. The airflow due to wind in an attic cavity is therefore:

$$\dot{Q}_{wind} = \frac{5280.0 * A_{min} * V_{w,c}}{C_f} \quad (9)$$

Where C_f is the flow coefficient developed based on Burch and Treado, which is 0.38 for the ventilation strategy in the Charleston facility. The mass flow rate of the flow due to wind pressure is therefore (Burch & Treado, 1979):

$$\dot{m}_{wind} = \dot{Q}_{wind} * \rho_{air,i} \quad (10)$$

4.1.3 Combined Stack and Wind-Driven Flows

According to ASHRAE Fundamentals, combining the mass flow rates associated with stack effect and wind accomplished with a simple sum of the squares method:

$$\dot{m}_{vent} = \sqrt{(\dot{m}_{stack})^2 + (\dot{m}_{wind})^2} \quad (11)$$

Therefore, the combined volumetric flow rate is the mass flow rate divided by the density of air.

$$\dot{Q}_{vent} = \dot{m}_{vent} / \rho_{air,i} \quad (12)$$

4.2 Conceptual Heat Transfer

This section is a discussion on the equations used for the coefficients of heat transfer for each interior and exterior surface of the attic cavity. The AtticSim tool has been modified to print out the heat transfer coefficients for every surface per time step, for investigation into the dominant effects of the separate modes of heat transfer on the separate surfaces. Understanding the significance of these coefficients is crucial in designing heat control systems.

For simplified analysis, each interior and exterior surface of the attic cavity is considered to be a flat plate, experiencing radiation and mixed forced-natural convection. Conduction heat transfer is calculated according to the application of calculated conduction transfer functions (Wilkes, Thermal Model of Attic Systems with Radiant Barrier Systems, 1991).

4.2.1 Natural Convection

Natural convection heat transfer coefficients for interior and exterior surfaces of the attic are calculated based on the theory of isothermal flat plates with a correction for the tilted angle of the roof deck (Holman, 1981). The temperature difference between the surface temperature and the surroundings is given as:

$$\Delta T = T_{Surface} - T_{Surrounding Air} \quad (13)$$

Further calculations require properties of the air for flat-plate analysis, which require the film temperature to be calculated. The film temperature near the surface of the flat plates is given by:

$$T_{film} = \frac{T_S + T_A}{2} \quad (14)$$

In which “S” and “A” subscripts refer to the surface and ambient air, respectively (Wilkes, Thermal Model of Attic Systems with Radiant Barrier Systems, 1991). Based on this calculation of film temperature, the specific properties of air listed in Table 6 can be determined in preparation for calculating the dimensionless variables associated with fluid dynamics and heat transfer. Note that the ideal gas assumption was used in these calculations.

Table 6: Calculated Air Properties

Property of Air	Symbol	Units
Thermal Conductivity	k	Btu/(hr·ft·°F)
Dynamic Viscosity	μ	lb/(hr·ft)
Thermal Expansion Coefficient	β	1/°F (Ideal gas assumption)
Density	ρ_a	lb/ft ³
Specific Heat	C_p	Btu/(lb·°F)
Kinematic Viscosity	ν	ft ² /hr

The Rayleigh number is, therefore, calculated by the following equation:

$$R_a = (4.16975 * 10^8) * \beta \rho_a C_p |\Delta T| * \frac{L_c^3}{\nu/k} = G_r Pr \quad (15)$$

Pitch of the roof deck changes the method in which the Grashof number (and therefore the Rayleigh number) is calculated. The NET facility in Charleston has a pitch of 3:12, or 14.04°. Note that all mentions of the variable theta (θ) in the following equations are assumed to be in units of degrees, and the equations include a conversion to radians. Therefore, the equation for

Nusselt number is as follows. If ΔT negative, or when the surface is hotter than the surroundings, than

$$N_u = .56 * (R_a * \cos(90 - \theta) * (\pi/180))^{.25} \quad (16)$$

However, if the surrounding air is hotter than the surface, another logic sequence is required. The slope of the surface must again be taken into account. First a comparison Grashof number must be calculated based solely on the roof pitch.

$$G_{rc} = 10^{\frac{\theta}{(1.1870 + 0.0870 * \theta)}} \quad (17)$$

Then the Grashof number, which is an approximate ratio of the buoyancy to viscous forces on a fluid, is calculated:

$$G_r = R_a / Pr \quad (18)$$

If G_{rc} is less than G_r :

$$N_u = .56 * (R_a * \cos((90 - \theta) * \pi/180))^{.25} \quad (19)$$

However, if G_{rc} is greater than G_r :

$$N_u = .14 * \left(R_a^{\frac{1}{3}} - (G_{rc} * Pr)^{\frac{1}{3}} \right) + 0.56 * \left(G_{rc} * Pr * \cos((90 - \theta) * \pi/180) \right)^{.25} \quad (20)$$

From the value of the Nusselt number, the natural convection heat transfer coefficient is calculated by the Nusselt number time the thermal conductivity over the characteristic length.

$$h_{nc} = N_u * k / L_c \quad (21)$$

4.2.2 Forced Convection

The heat transfer coefficient for forced convection on an inclined or horizontal flat plate is taken from Holman 5th edition (Holman, 1981). This calculation requires the kinematic viscosity determined in the calculation of the natural convection heat transfer coefficient, as well as the velocity of the air over the surface.

For each surface in the attic cavity, the Reynolds number must be calculated with the air velocity, characteristic length of the surface, and the previously calculated kinematic viscosity.

$$R_e = V * L_c / \nu \quad (22)$$

If the flow is laminar, the correlation for Nusselt number is:

$$N_{u,f} = 0.664 * \left(P_r^{\frac{1}{3}}\right) * \left(R_e^{\frac{1}{2}}\right) \quad (23)$$

If the flow is turbulent, than the Nusselt correlation is:

$$N_{u,f} = \left(P_r^{\frac{1}{3}}\right) * (0.037 * R_e^{0.8} - A_{factor}) \quad (24)$$

Where the variable A_{factor} is solved by the equation:

$$A_{factor} = 0.037 * (R_{e,crit}^{0.8}) - 0.664 * \left(R_{e,crit}^{\frac{1}{2}}\right) \quad (25)$$

The forced convection heat transfer coefficient is therefore:

$$h_{fc} = NUS_f * \frac{k}{L_c} \quad (26)$$

4.2.3 Combined Forced and Natural Convection Coefficient

Combination of forced and natural flows is performed according to Churchill's correlation, with the assumption that all surfaces are experiencing assisting flow (Wilkes, Thermal Model of Attic Systems with Radiant Barrier Systems, 1991).

$$h_c = (h_{fc}^3 + h_{nc}^3) \quad (27)$$

A summary of the correlations used in this model is shown below in Table 7.

Table 7: Summary of Mean Natural and Forced Convection Coefficients

Mode	Surface Type	Correlation	Condition
Natural Convection	Horizontal surface, heat flow up	$Nu = 0.54 * Ra^{1/4}$	for $Ra < 8 \times 10^6$
		$Nu = 0.15 * Ra^{1/3}$	for $Ra > 8 \times 10^6$
	Horizontal surface, heat flow down	$Nu = 0.58 * Ra^{1/4}$	for all Ra
	Vertical surface	$Nu = 0.59 * Ra^{1/4}$	for $Ra < 1 \times 10^9$
		$Nu = 0.10 * Ra^{1/3}$	for $Ra > 1 \times 10^9$
	Angled surface ($\theta < 2^\circ$) heat flow down	$Nu = 0.58 * Ra^{1/4}$	for all Ra
	Angled surface ($\theta > 2^\circ$) heat flow down	$Nu = 0.56 * (Ra \sin \theta)^{1/4}$	for all Ra
	Angled surface, heat flow up	$Nu = 0.56 * (Ra \sin \theta)^{1/4}$	for $(Ra/Pr) < Gr_c$
		$Nu = 0.14 * \left(Ra^{1/3} - (Gr_c * Pr)^{1/3} \right) + 0.56(Gr_c Pr * \sin \theta)^{1/4}$	for $(Ra/Pr) > Gr_c$
		$Gr_c = 10^6$	for $\theta < 15^\circ$
		$Gr_c = 10^{(\theta/(1.1870+0.0870*\theta))}$	for $15^\circ < \theta < 75^\circ$
		$Gr_c = 5 * 10^9$	for $\theta > 75^\circ$
Forced Convection	All surfaces	$Nu = 0.664 * Pr^{1/3} Re^{1/2}$	for $Re < 5 \times 10^5$
		$Nu = Pr^{1/3} * (0.037 * Re^{0.8} - 850)$	for $Re > 5 \times 10^5$

4.2.4 Radiation View Factors

The view factors associated with the radiation interaction inside the attic cavity were calculated by Ken Wilkes for the computer tool AtticSim based on a principle text by E.M. Sparrow and R.D. Cess in 1966. Calculation details for the radiation view factors are rather arduous; therefore I will refer the reader to a full description of the AtticSim protocol featured in the ASHRAE report 717 (Ober & Wilkes, 1997). The AtticSim protocol is an ASTM standard and has been repeatedly benchmarked against collected data from several sources (Petrie, Stovall, Wilkes, & Desjarlais, 2004).

4.2.5 Radiation Heat Transfer Coefficients

Surface to surface radiation heat transfer and calculation of radiation heat transfer coefficients inside of the attic cavity are calculated, like the radiation view factors, according to the enclosure method as described by Sparrow and Cess. This method assumes that each planar surface is grey, isothermal, opaque, a diffuse emitter, a diffuse reflector, and has uniform

radiant flux. For a detailed derivation of the surface heat transfer coefficient inside the cavity, refer to ASHRAE RP717 (Ober & Wilkes, 1997). In short, radiation heat transfer is given by the equation:

$$Q_{r,ij} = h_{r,ij}(T_i - T_j) \quad (28)$$

Where $h_{r,ij}$ is the radiation heat transfer coefficient:

$$h_{r,ij} = \sigma \varepsilon (T_i + T_j)(T_i^2 + T_j^2) \quad (29)$$

Using this method of calculating the h_r coefficient models the radiation mode of heat transfer similar to the convection mode. Additionally, presenting the coefficient in this form technically linearizes radiation heat transfer, such that it is proportional to a first-order temperature difference instead of proportional to a difference of temperatures that are raised to the fourth power (Incropera & DeWitt, 2007). Comparison analysis of the combined forced/natural convection and the radiation heat transfer coefficients is a practical way to draw conclusions on the dominating heat transfer mode on the known isothermal surfaces. These coefficients will be calculated using the AtticSim tool in a later section for analysis.

4.3 AtticSim Description

The ASTM C1340 protocol referred to as “AtticSim” was used in this study to model the thermal and moisture performance for roof and attic systems in residential homes. AtticSim was first developed by Pevie in 1980 and revised by Ken Wilkes in 1989, and has been revised again by Dr. William A. Miller to include calculation options for increasingly complex attic constructions. AtticSim calculates heat and moisture transfer through a seven- or nine-surface attic cavity with available calculation options to include ducts and truss systems. Please refer to Figure 28, which is a diagram of the cavity surfaces.

The AtticSim tool models the transient performance of a typical residential attic cavity, and is sensitive to thermal capacitance effects and variations in solar irradiance (Petrie, Stovall, Wilkes, & Desjarlais, 2004). The ability to model duct and truss systems was included in augmentations of the code during revisions made by Wilkes in 1998. However, since the ducts in the Charleston NET facility attic are well sealed, the duct and truss calculation routines have been disabled for benchmarking to decrease the time of calculation.

AtticSim is, by nature, a series of energy balances on the interior and exterior surfaces on an attic cavity. Conduction transfer functions for each interior and exterior surface, based on

“usage of the thermal response factor method to account for transient heat transfer and thermal energy storage phenomena” (Petrie, Stovall, Wilkes, & Desjarlais, 2004). These transfer functions, which are calculated by a separate routine and included in the AtticSim input file, are the coefficients necessary for computation by the simultaneous solver that AtticSim uses for calculating temperatures on each surface. This method of surface heat transfer calculations is based on one-dimensional flow through a composite wall, where each layer of the composite has temperature independent properties, and where temperature values vary linearly with time on a per-hour basis.

The model can account for different insulation R-values on the seven surfaces of the attic. It has an algorithm for predicting the effect of air-conditioning ducts placed in the attic, as reported by Ken Wilkes in 1991 and described in (ASTM, 2004). The code was also the subject of an ASHRAE research project and was validated against field data from seven different field sites. Validations for predicting the ceiling heat flows for all of the data from the seven sites, resulted in an average difference between the predicted and measured values of 3.6% for summer data and 1.2% for winter data (Ober & Wilkes, 1997). The ability to simulate above-sheathing ventilation was formulated and validated against the field data for tile, stone-coated metal, standing-seam metal, and asphalt shingle roofs with and without ASV and with and without Cool Color roofs. AtticSim yielded predictions within $\pm 3^{\circ}\text{F}$ (1.7°C) of field measures for surface temperatures and integrated ceiling and deck heat fluxes within $\pm 10\%$ of field measures when exercised for the case of ASV (Miller, Keyhani, Stovall, & Youngquist, 2007).

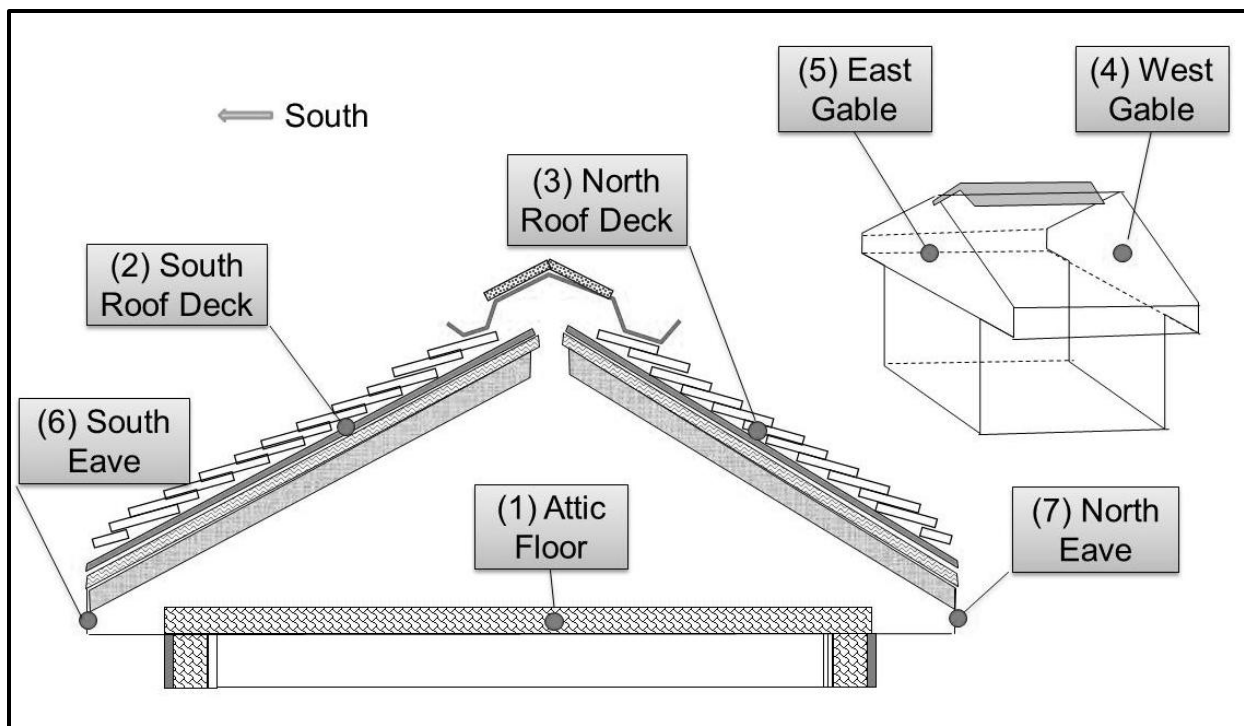


Figure 28: AtticSim Cavity Node Locations

4.4 AtticSim Benchmark to Charleston NET Facility

Summer and winter data for Attics 01, 03 and 07 were benchmarked using AtticSim on 10/18/2011. The NET facility lacks an instrument to measure solar heat gain; AtticSim was run with the boundary conditions set as the temperatures of each shingle, and the indoor air temperature. Runs were also executed with the ceiling underside specified as a boundary condition to view the code's ability to predict the heat transfer across the ceiling insulation. Accurate use of AtticSim required cataloging the material and thermodynamic properties of the construction materials, a portion of which are included in Appendix A. To best show the prediction accuracy of AtticSim, the results of the first week of data in Attic 01 is shown for each graphical presentation.

A graph of the actual summer OSB sheathing temperature for the first week of collection is shown below in Figure 29, overlaid with the AtticSim prediction. AtticSim performs very well in predicting the surface temperature of the underside of the OSB sheathing, with a maximum deviation of approximately 1 °C from the collected data.

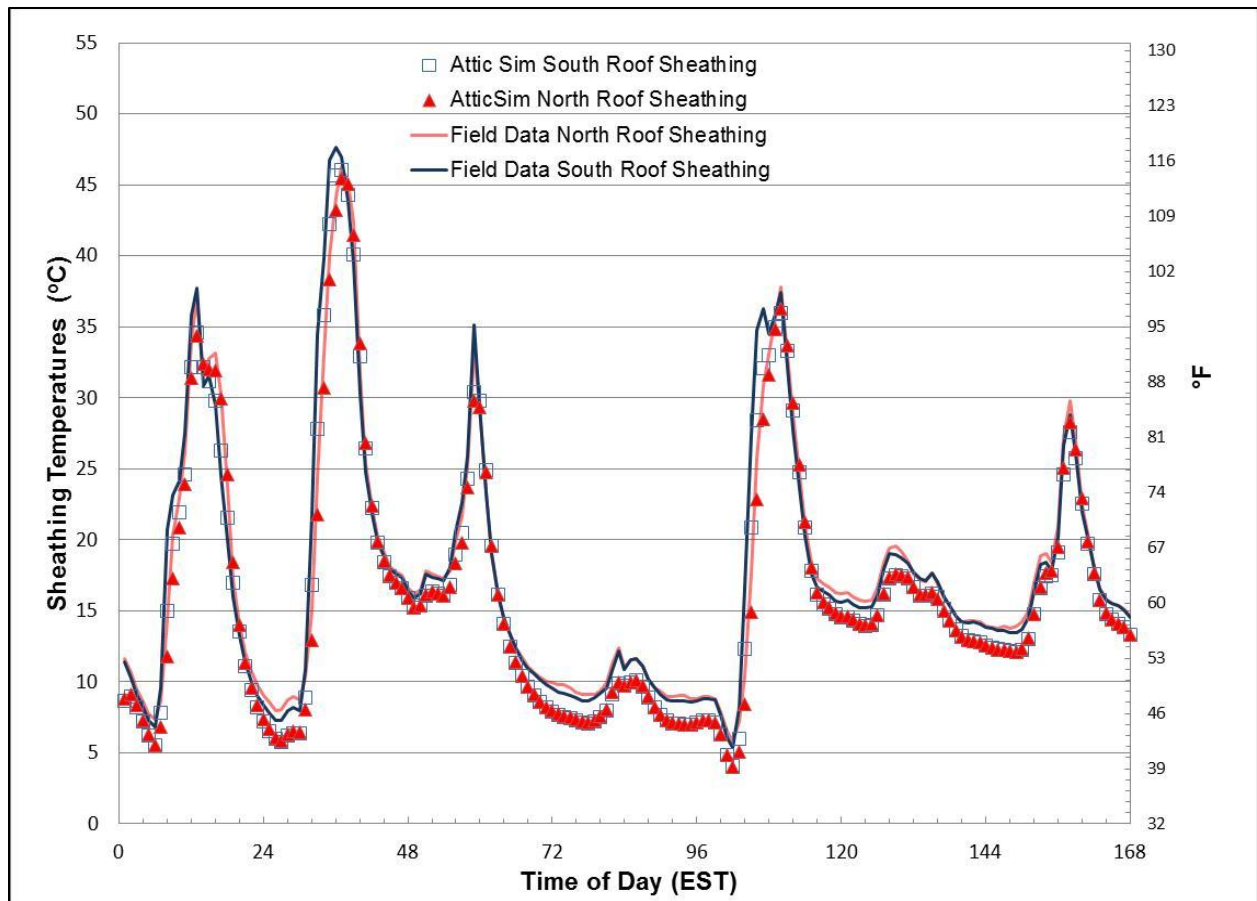


Figure 29: AtticSim Summer Prediction of Underside Temperature of OSB Sheathing

Winter sheathing temperatures are shown in Figure 30. AtticSim predicts the winter sheathing temperatures within a maximum difference of 5 °C for the first week.

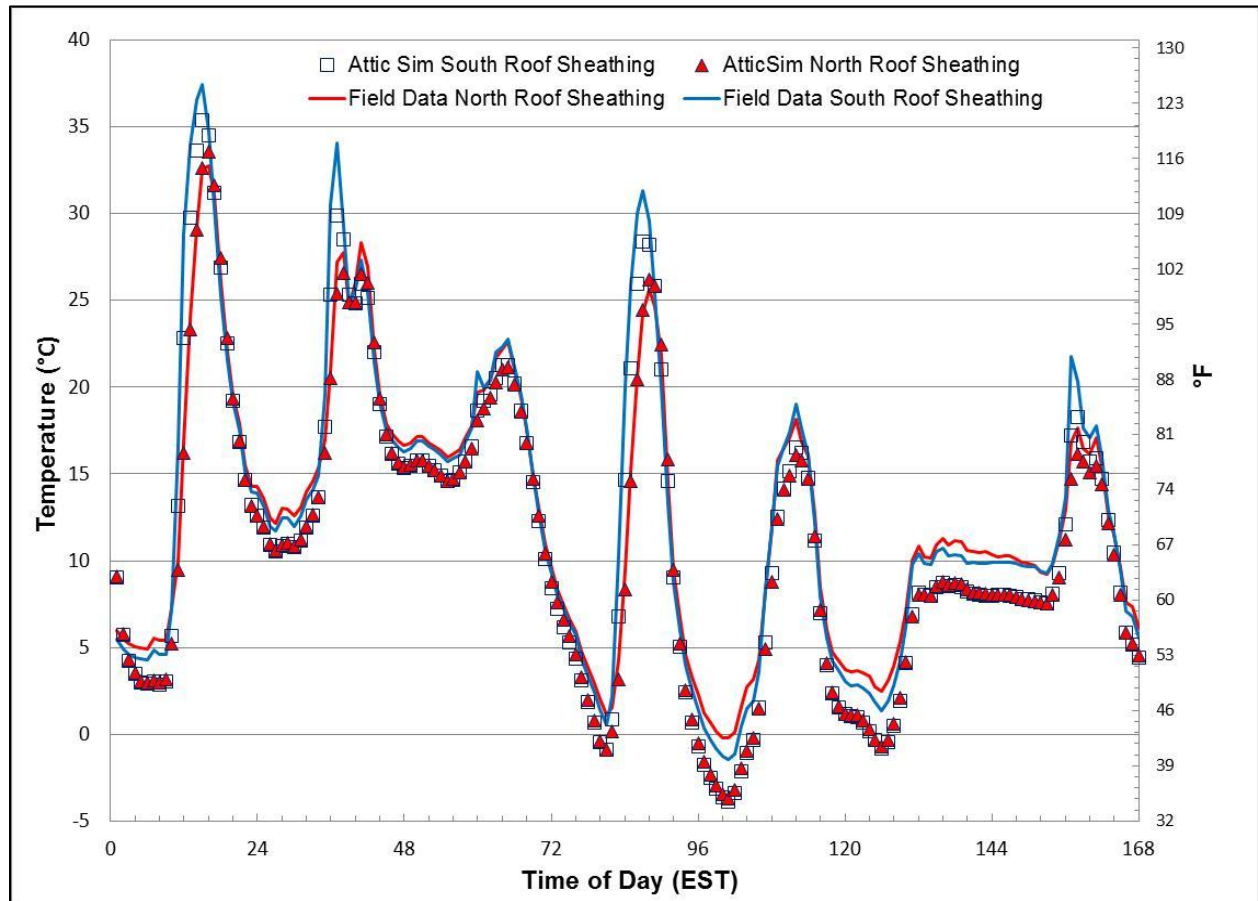


Figure 30: AtticSim Winter Prediction of Underside Temperature of OSB Sheathing.

Figure 31 shows the first week of summer ceiling heat flux data overlaid with the prediction from AtticSim. As seen in the previous discussion of the field data in chapter four, the apparent restricted amplitude of the HFT due to the high R value of the fiberglass insulation causes some uncertainty into the sensitivity of these measurements. This trend is highlighted by the AtticSim prediction, which tends to over-predict the flux during the day and under-predict during the night. The confidence of this prediction is tested in the following section, which shows the variation of the prediction with small differences in insulation properties to account for spatial nonhomogeneity. Winter predictions are also shown in Figure 32, and show the same trends in prediction.

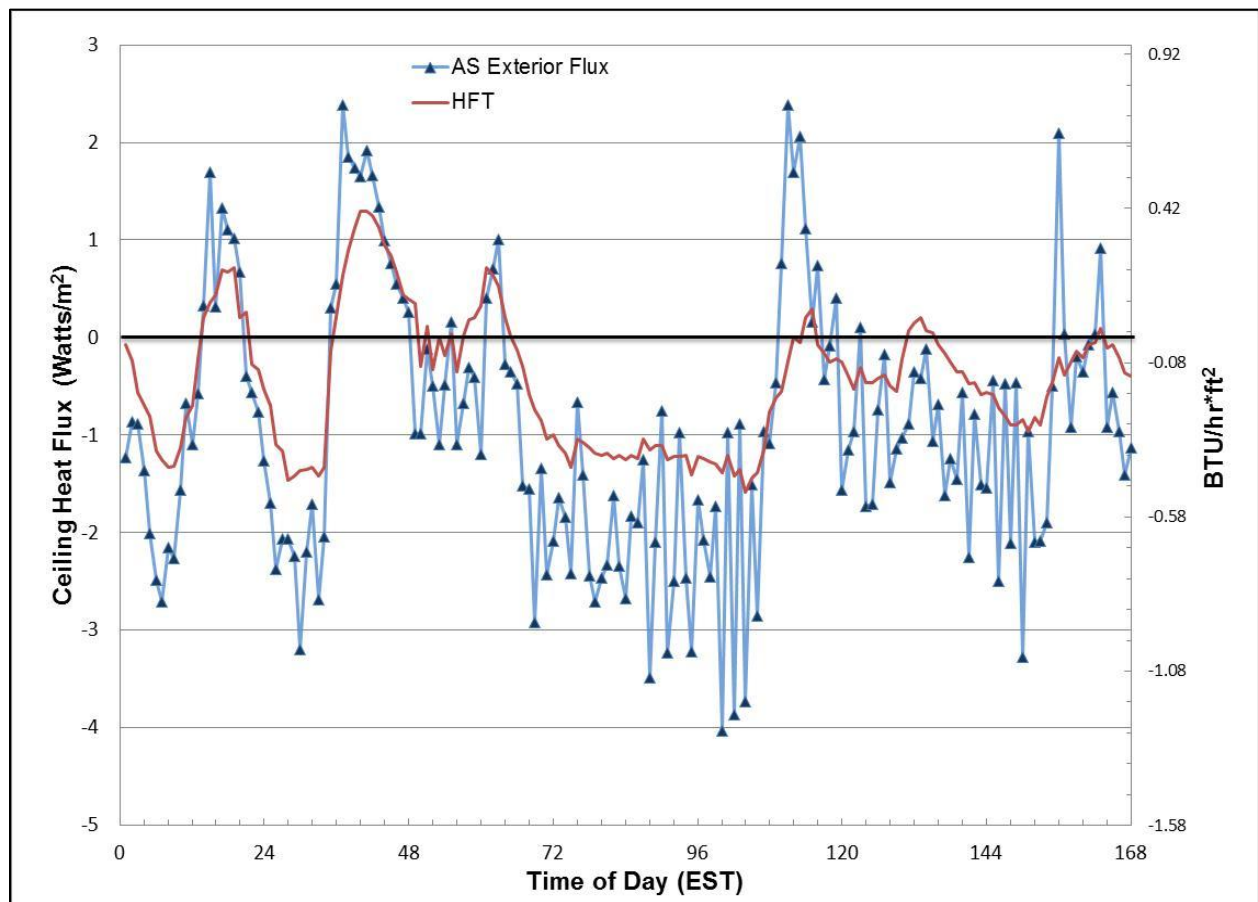


Figure 31: AtticSim Summer Ceiling Heat Flux Prediction

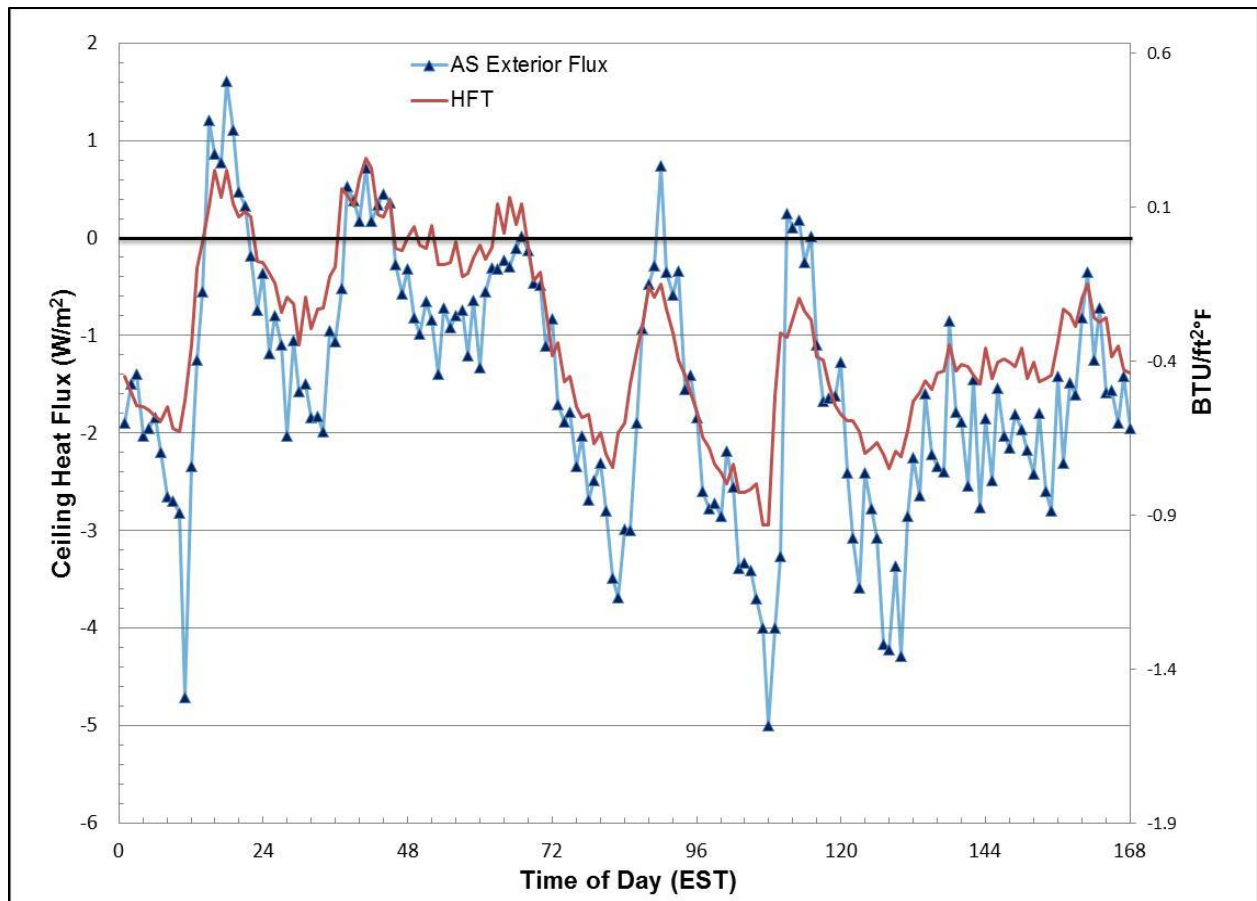


Figure 32: AtticSim Winter Ceiling Heat Flux Prediction

The heat flux through the South deck during the first week of summer data collection is shown below in Figure 33, with the same trends of over-prediction in the region of severe slope change. The maximum over-prediction is 60 W/m² at peak solar irradiance.

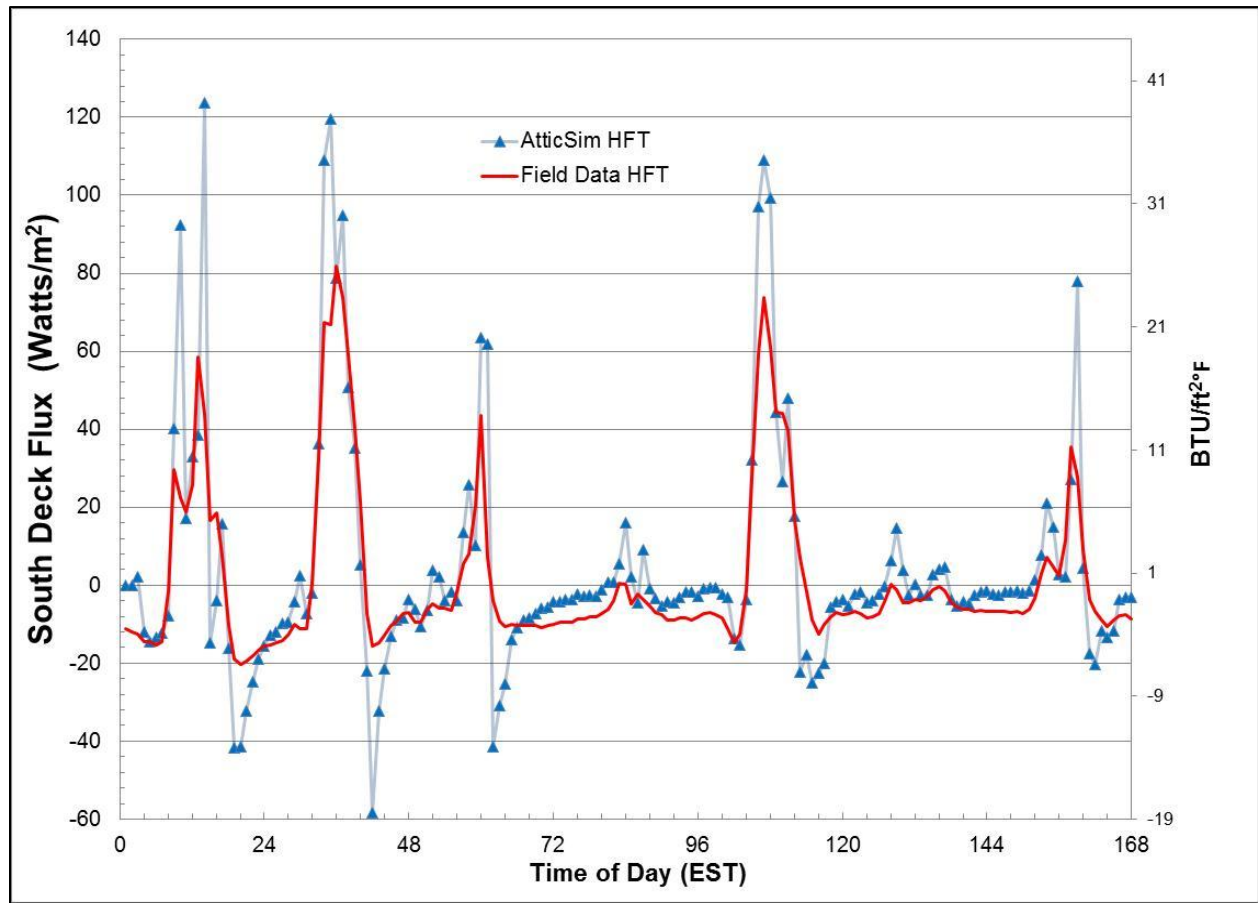


Figure 33: AtticSim Summer South Deck Heat Flux Prediction

Heat through the North roof deck is shown in Figure 34 for the first week of the winter data with the predicted values overlaid. Generally, the AtticSim prediction is accurate, except at points of slope sign change. The heat flux is calculated based on the prescribed conduction transfer functions that take into account the time history to predict temperature for any one time calculation.

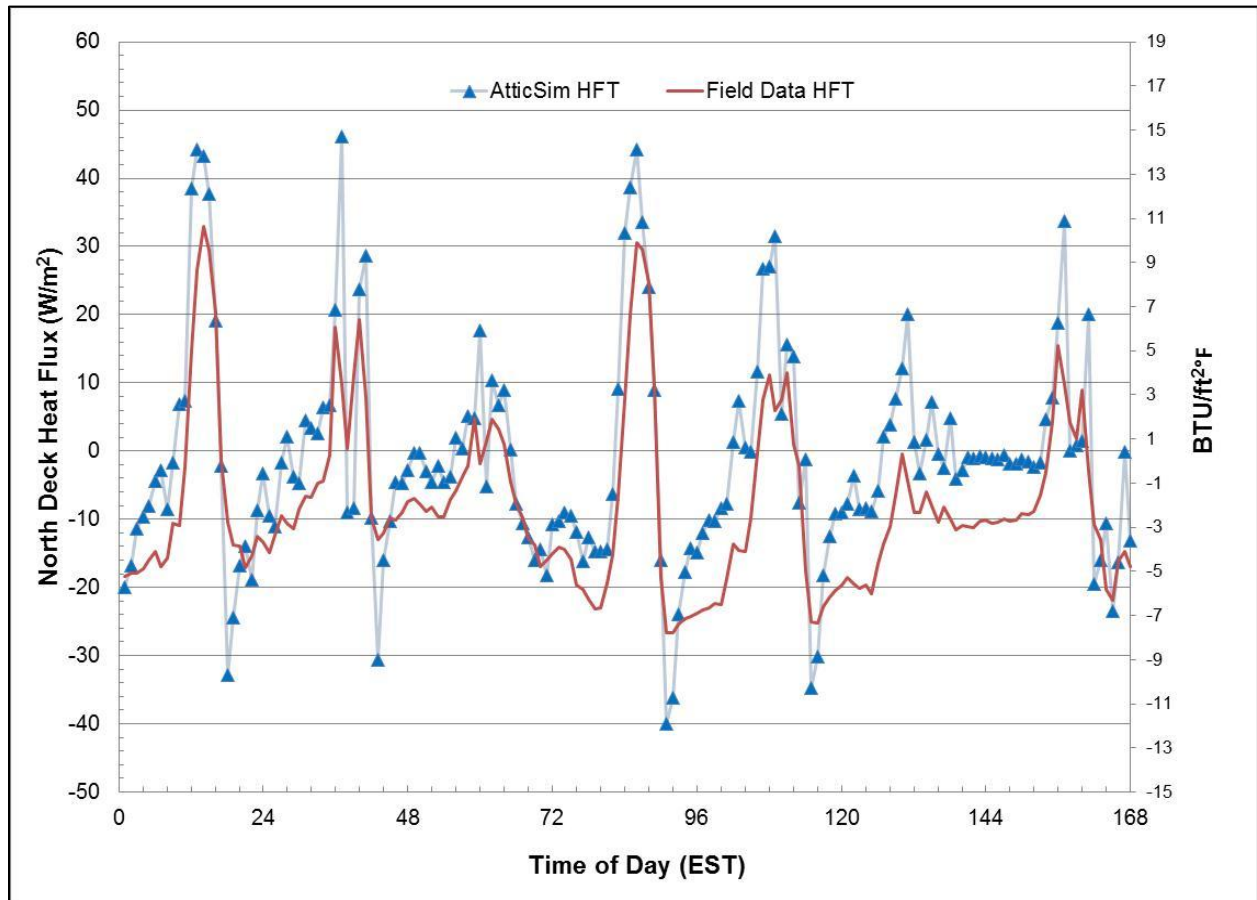


Figure 34: AtticSim Winter North Deck Heat Flux Prediction

The accuracy of the AtticSim prediction captures the diurnal trends observed in the field data. However, the prediction calculations are based on material properties which are assumed to be homogeneous. This is not a logical assumption for a field study, especially in the case of the fiberglass batt insulation. An investigation into the actual thickness of the insulation in each attic bay in section 4.4 revealed that the thickness of the insulation in the separate attic bays was not homogeneous, neither was it exactly the thickness given by the supplier. The crew who installed the insulation stacked one insulation batt over another in an attempt to increase the R-value of the whole system. This practice actually lowers the R-value, since fiberglass insulation works by trapping and warming the air in the honeycomb of spaces among the spun materials (Johns Manville Insulation).

A major assumption in using the AtticSim prediction tool is the calculation accuracy of the air changes per hour in the attic cavity based on the correlation developed by Burch and Treado for soffit-ridge attic ventilation. To address this concern, simulations were run for Attics 1, 3, and 7 during the period of time that the ORNL research team was performing gas tracer analysis. The main body of the testing for these attics was performed overnight during unmanned periodical dosing and sampling. This method only takes into account the flow rates during the early morning. Unfortunately, the effects of solar-induced natural convection cannot be observed during this time period. Future testing should involve diurnal periodical dosing and sampling. Result of the AtticSim simulation of the CTRL attic is shown against the data collected on 6/30/11 in Figure 35. The AtticSim calculation method is sufficiently effective at predicting the ACH rates during late evening hours.

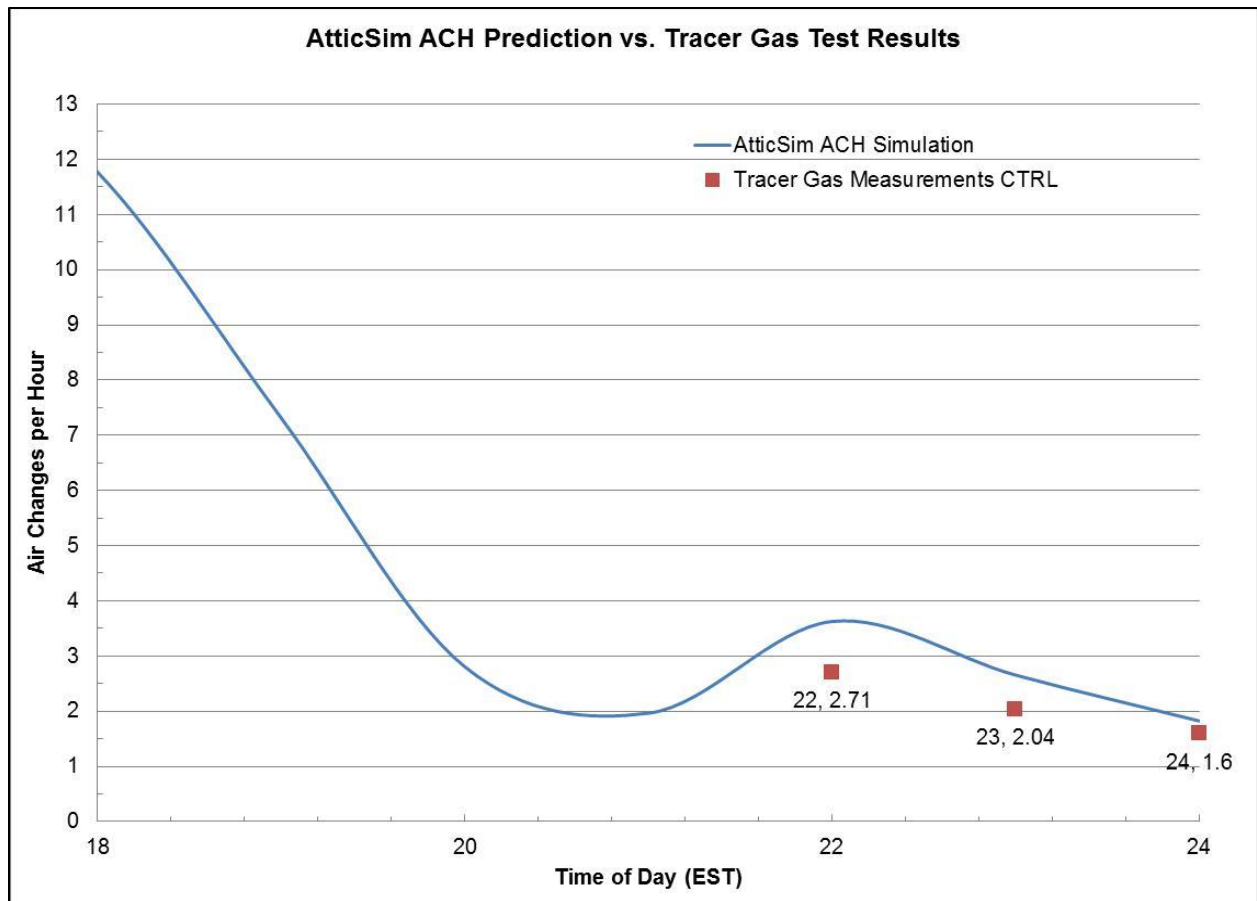


Figure 35: AtticSim ACH Benchmark

4.5 Insulation Data Confidence

In the initial benchmark of AtticSim to the NET facility, material properties were collected from standards to create conduction transfer functions. The results of the benchmark have already been shown to be acceptable. However, for a rigorous analysis, measures should be taken to validate the accuracy of the simulation. To address the effect of possible variation in the material properties of the fiberglass insulation, a material property analysis was performed on samples taken from the facility. Table 8 shows the comparison of the material properties used in the initial analysis and the results of the analysis of the insulation samples.

Table 8: Results of Material Properties Investigation

	Thermal Conductivity [Btu/(ft-°F-hr)]	Density [lb/ft³]	Specific Heat [BTU/lb-°F]	R-Value [US]
Initial Values	0.0250	2.0	0.17	38.00
Test Results	0.0267	1.63	0.17	37.06

The new material properties, which vary only minimally from the initial value, were incorporated in creating new conduction transfer functions and input files which were used in running new simulations. The results of the new simulations did not show a significant increase in accuracy or a significant deviation from the initial simulations, therefore I can conclude that the initial results of the simulation accurately predict the results of the field data reduction within reason.

4.6 Heat Transfer Coefficients Analysis

AtticSim features the capability of printing out the calculated convection and radiation heat transfer coefficients for analysis. Observing the comparative magnitudes of the convection and radiation heat transfer coefficients on any surface can be a rough indicator of which heat transfer mode dominates that surface. According to the simulation, the average radiation heat transfer coefficients inside the cavity are greater than the average combined natural and forced convection coefficient. Therefore, it can be surmised that radiation is the dominant mode of heat gain inside the attic cavity. This result is confirmed by the findings in the previously shown Figure 15. The average heat transfer coefficients for the summer data on Attic 01 are shown below in Figure 36.

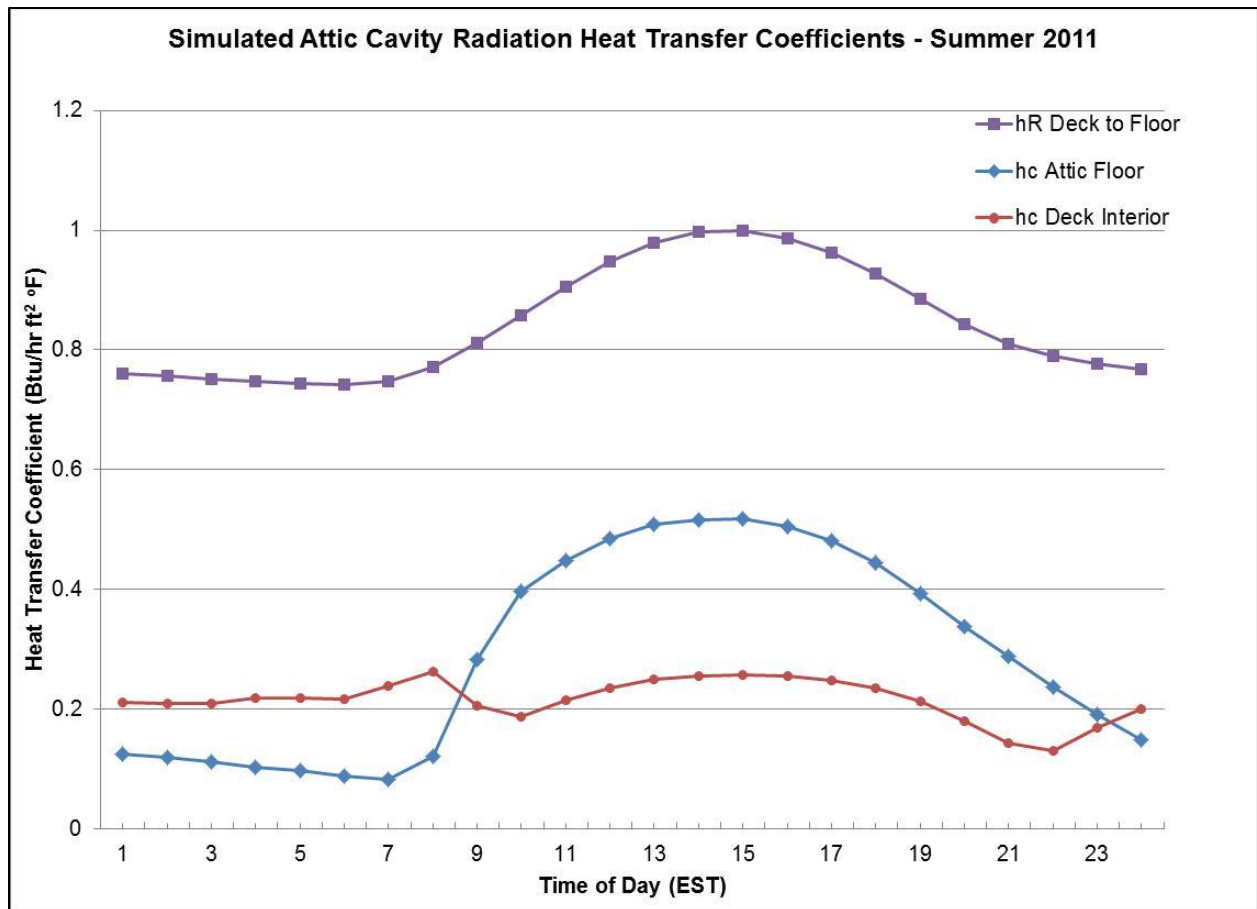


Figure 36: Average Heat Transfer Coefficients Attic 01 - AtticSim Prediction

The peak-day trend of incident solar radiation is clearly seen in the deck-to-floor radiation heat transfer coefficient, which increases to a maximum at approximately 3 P.M. The same trend of peak-day heating is seen in the combined convection heat transfer coefficient for the decks and attic floor, but at lower overall amplitudes. Because the linearized surface-to-surface radiation heat transfer coefficient is greater in magnitude than the combined convection coefficients, it can be surmised that radiation is the dominant mode of heat transfer in the attic cavity.

4.7 Ventilation Prediction

The AtticSim program has been shown to successfully predict the thermal and fluid performance of each attic cavity at the NET facility, including the difference in the ventilation schemes of Attics 01, 03 and 07. Using a standard year of TMY (Typical Meteorological Year) data, the year-long performance of the NET facility has now been modeled, with a particular focus on the variation of ventilation. The effect of varying the ventilation area is observed by

taking three of the base attics (CTRL, RB, and ASV) and performing a parametric study on varying ventilation rates.

Equal part soffit and ridge ventilation areas were varied in each attic at footprint-to-ventilation area ratios of 1:25, 1:50, 1:150, 1:300, and 1:500 for a total of 15 year-long data simulations to show an overall effect of modifying the ventilation area for moisture control and heat transfer buffering to the conditioned space. Results of these simulations are shown for the ASV, RB, and CTRL cases with varying ventilation area ratios.

Increasing the ventilation area ratios increases the actual orifice area through which wind-driven flow passes through. As discussed previously, AtticSim calculates the air changes per hour (ACH) values at each hour based on an empirical routine developed for soffit and ridge vent systems (Burch & Treado, 1979). This ACH computation has been benchmarked to the NET facility via tracer gas analysis in a previous section of this report. Average diurnal ACH values in the CTRL attic are presented for the winter and summer seasons in Figure 37 and Figure 38 to show the effect of increasing ventilation ratio on the flow rate.

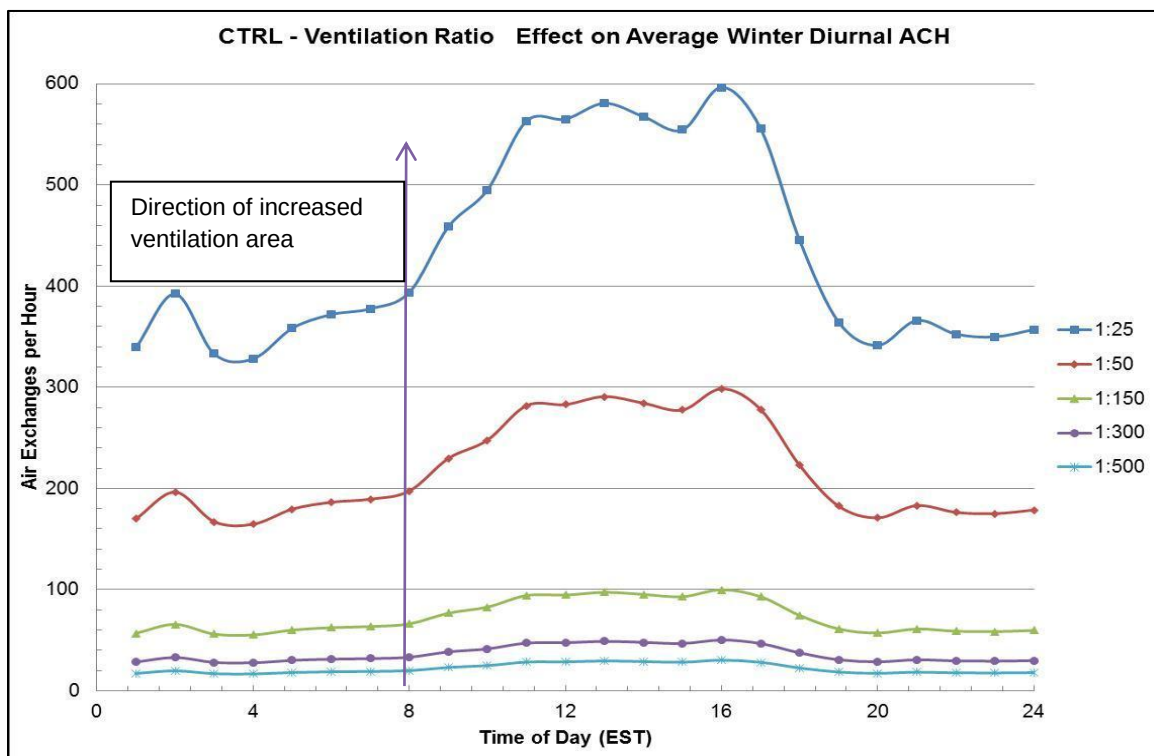


Figure 37: Ventilation Rate Effect of Average Winter Diurnal ACH

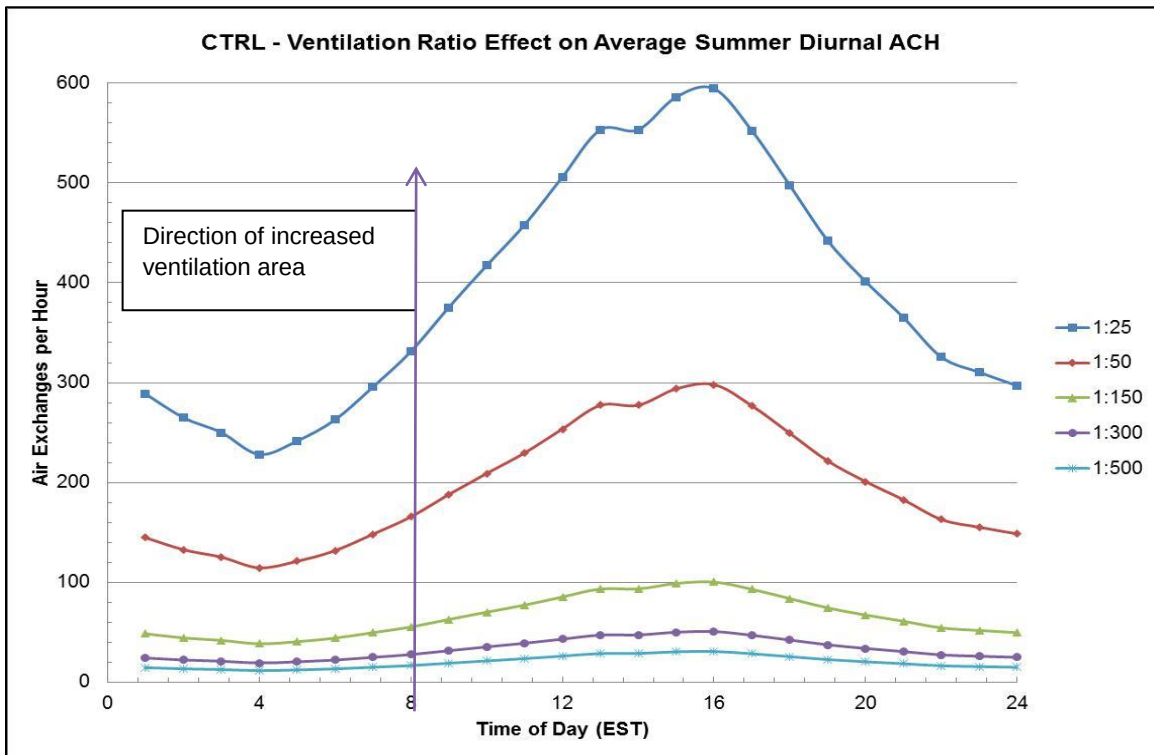


Figure 38: Ventilation Ratio Effect on Average Summer Diurnal ACH

The effect of increased ventilation ratio is an increase in flow rate over the entire diurnal cycle, but also in the amplitude of the maximum ventilation at the peak, from 30 ACH at 1:500 to 594 ACH at 1:25. Maximum ventilation takes place at approximately 5 P.M., with minimum ventilation occurring at 4 A.M.

Increasing the ventilation area for the attic cavity would logically increase the air flow rate up to a certain point where the model would approach the situation of a system of flat plates suspended in an open airstream. Therefore, there is an obvious limit to how much air flow one can achieve by increasing the ventilation area. This limit is shown in the following, in which the effects of increasing the ventilation ratio are shown on the maximum and minimum ACH values on both winter (Figure 39) and summer (Figure 40) seasons.

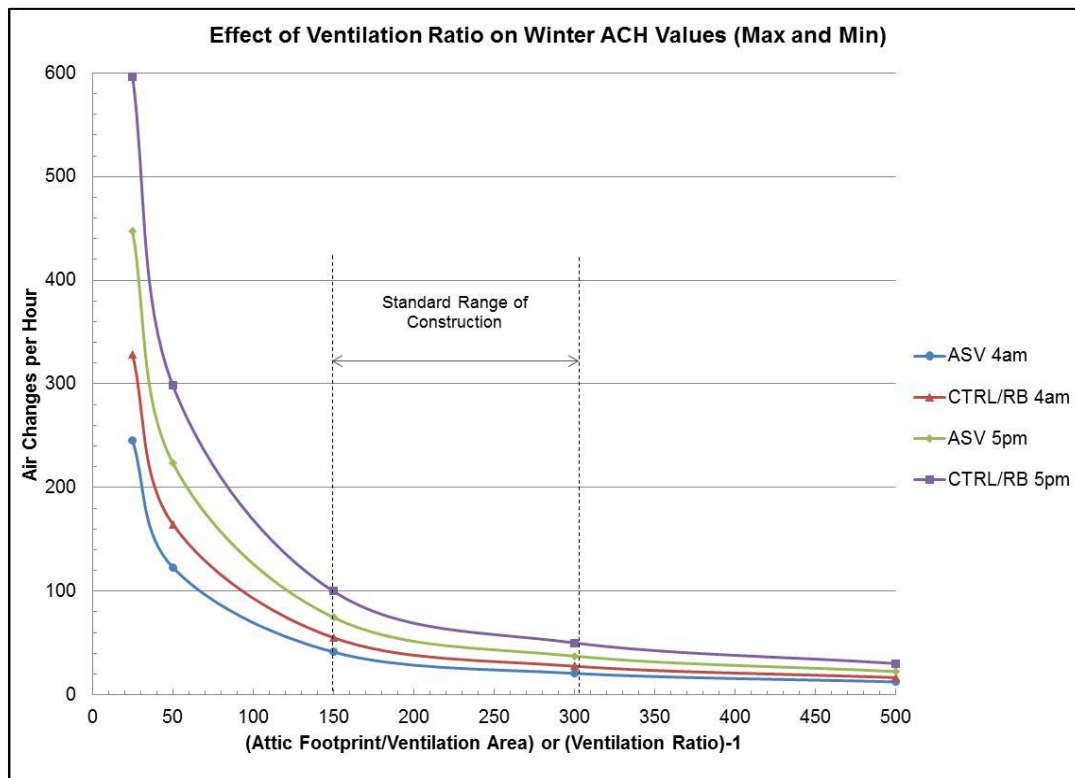


Figure 39: Effect of Ventilation Ratio on Maximum and Minimum Winter ACH Values

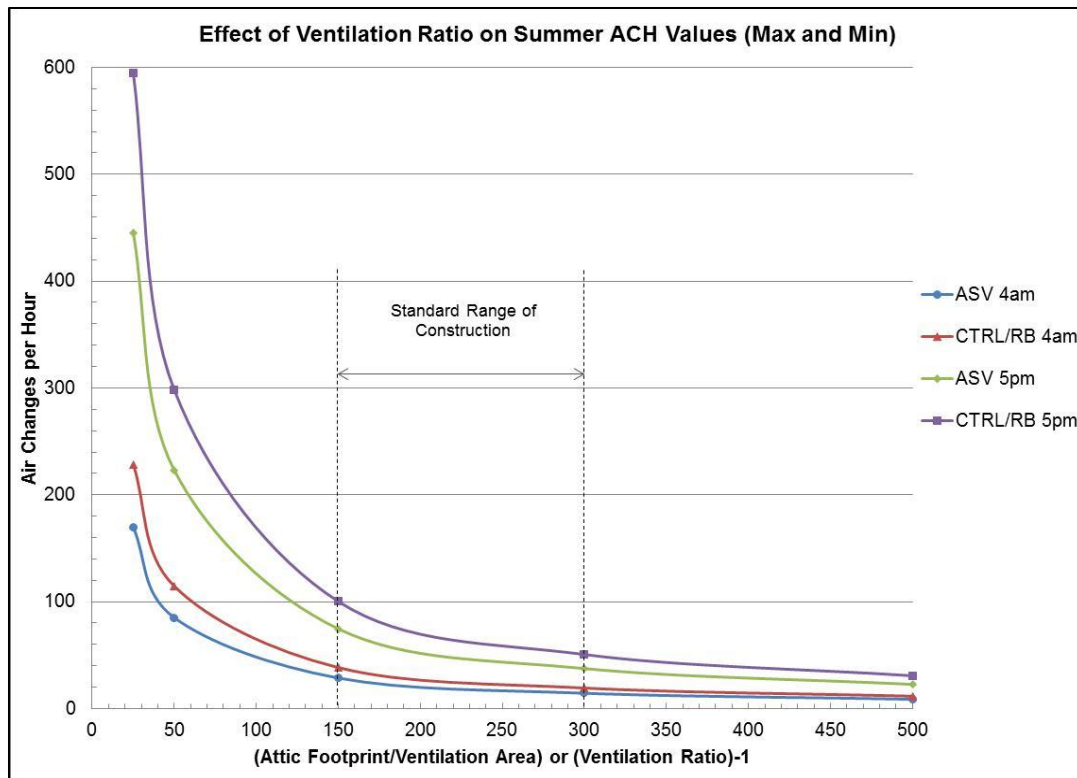


Figure 40: Effect of Ventilation Ratio on Maximum and Minimum Summer ACH Values

As seen in the figures above, increasing the ventilation ratio has a greater effect on the air changes per hour calculation during the summer months, and only during the early morning. As the scale of data approaches 1:50, the ACH prediction increases exponentially. The reality, however, is that an attic will never be constructed with a ventilation ratio close to 1:50. For example, if a residence has an attic footprint of 2,000 square feet. If the attic was constructed with a 1:50 ventilation ratio, the net ventilation area would be $2000/50 = 40$ square feet. At this point, the attic is no longer operating as an effective barrier against inclement weather conditions. For purposes of this report, the ventilation ratio reasonability limit is 1:50, although the ratio limit would be closer to 1:100 in practice.

Furthermore, the benefit in ACH is between the ratio values of 1:500 and 1:300 at peak solar heating is only 20 ACH for the CTRL and 15 ACH for the ASV, whereas the rate of benefit is significantly higher when the ratio is increased past 1:150. The range in which increasing ventilation ratio most effectively increases the ACH values (without approaching the limit of reasonable ventilation) is within the range of 1:250 to 1:100.

Even more important than the effective increase of the ventilation rate is the prevention of condensation on the surfaces of the attic. Condensation potential on the OSB sheathing was calculated for the entire year by simulating the dew point temperature of the attic air and comparing the predicted sheathing temperature against it. The percentage of total time for condensate potential is shown below in Table 9 such that the results will emulate the results of the field data analysis previously shown in Table 4.

Table 9: TMY2 Results of Underlayment Condensate Potential

Attic Type	Percent of total time in which $T_{\text{sheathing}} < T_{\text{dp}}$				
	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 with an increase in ventilation area (an example of an increase in area would be from 1:300 to 1:150) consistently decreases the potential for condensation on the OSB sheathing. However, the magnitude of the effect is relatively small in comparison to the difference seen by changing the attic type. For example, the result of increasing the ventilation area in a CTRL attic from the standard 1:300 to 1:50 is a decrease 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% decrease.

The addition of the radiant barrier to the attic sheathing has the effect of keeping the surface cooler during the night, especially during the winter months. This is explained by the simple fact that the radiant barrier halts the long-wave radiation down through the roof deck during the daylight hours, and then performs the same way with the heat from the conditioned space during the night and early morning hours, which would depress the temperature of the OSB. Since the early morning hours are the most likely time frame 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 is graphed below in Figure 41.

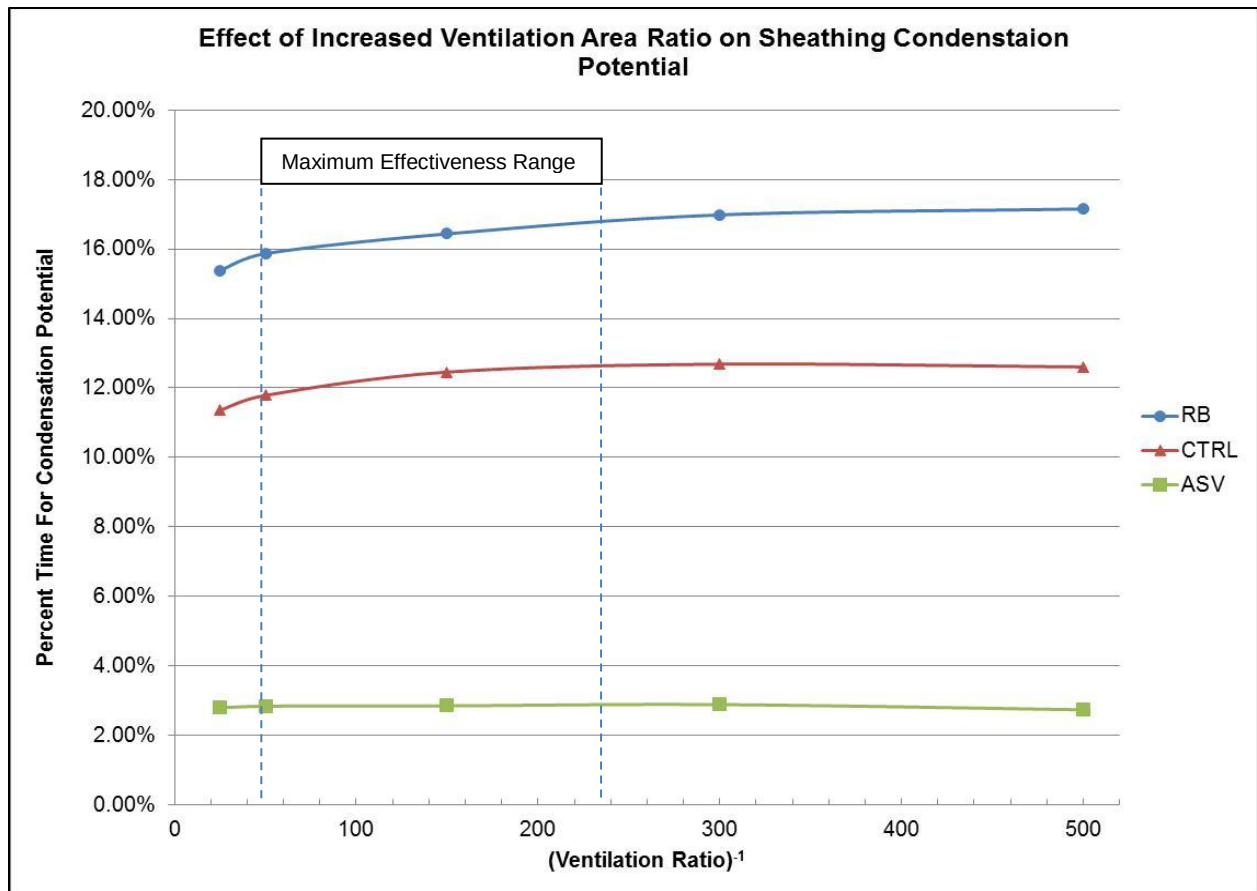


Figure 41: Effect of Increased Ventilation Ratio on Sheathing Condensation Potential

As seen in the figure above, the condensation prevention induced by increasing the ventilation ratio from 1:300 to 1:100 is 2% for the CTRL attic whereas the change in condensation prevention change is approximately 0% for the attic with above sheathing ventilation. The conclusion to be gleaned from Figure 41 is that the potential for condensation is not strongly dependent on soffit-ridge ventilation ratio, especially when considered against the benefit of above sheathing ventilation.

Simulations were run for the comparison of ventilation effect on the ceiling heat flux, which is a common indicator of the influence the attic cavity has on the HVAC system of a residence. The data presented for simulation of flux are shown on time-of-day bin averages, to mirror the presentation style of the field data. Summer simulation shows that the average peak ceiling heat flux in the CTRL attic occurs at approximately 5 P.M., at which point the maximum stratification of ventilation effect is observed, Figure 42. The results of the ASV and RB simulations agree.

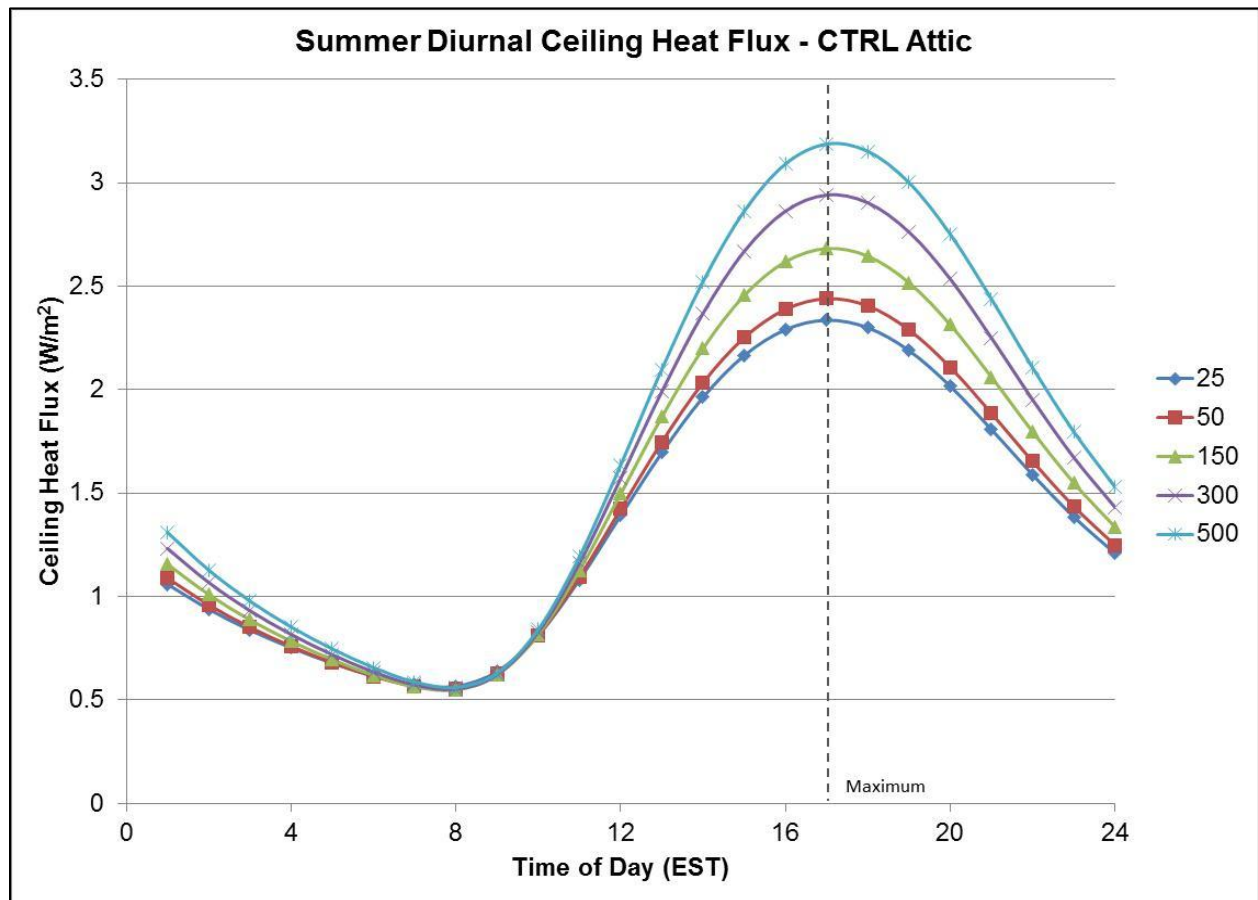


Figure 42: Average Result of Summer Diurnal Ceiling Heat Flow Flux Simulations

Ceiling heat flux values at peak heating is directly affected by the construction type of each of the attics simulated. The RB attic has long wave radiation control, while the ASV attic has an additional roof deck and air gap to retard the flow of heat through the deck. Peak heating ceiling fluxes are shown for each simulated attic construction in Figure 43 below. The most important observation in Figure 43 is that heat flux in the region of common practice is only slightly sensitive to variations in ventilation ratio. The maximum difference in the average heat flux between any of the data points for each attic is 0.2 W/m^2 . When one takes into account that the accuracy of the standard heat flux transducer used is 5%, the flux difference could be so minute that a measurement system in the field would not register a significant measurement.

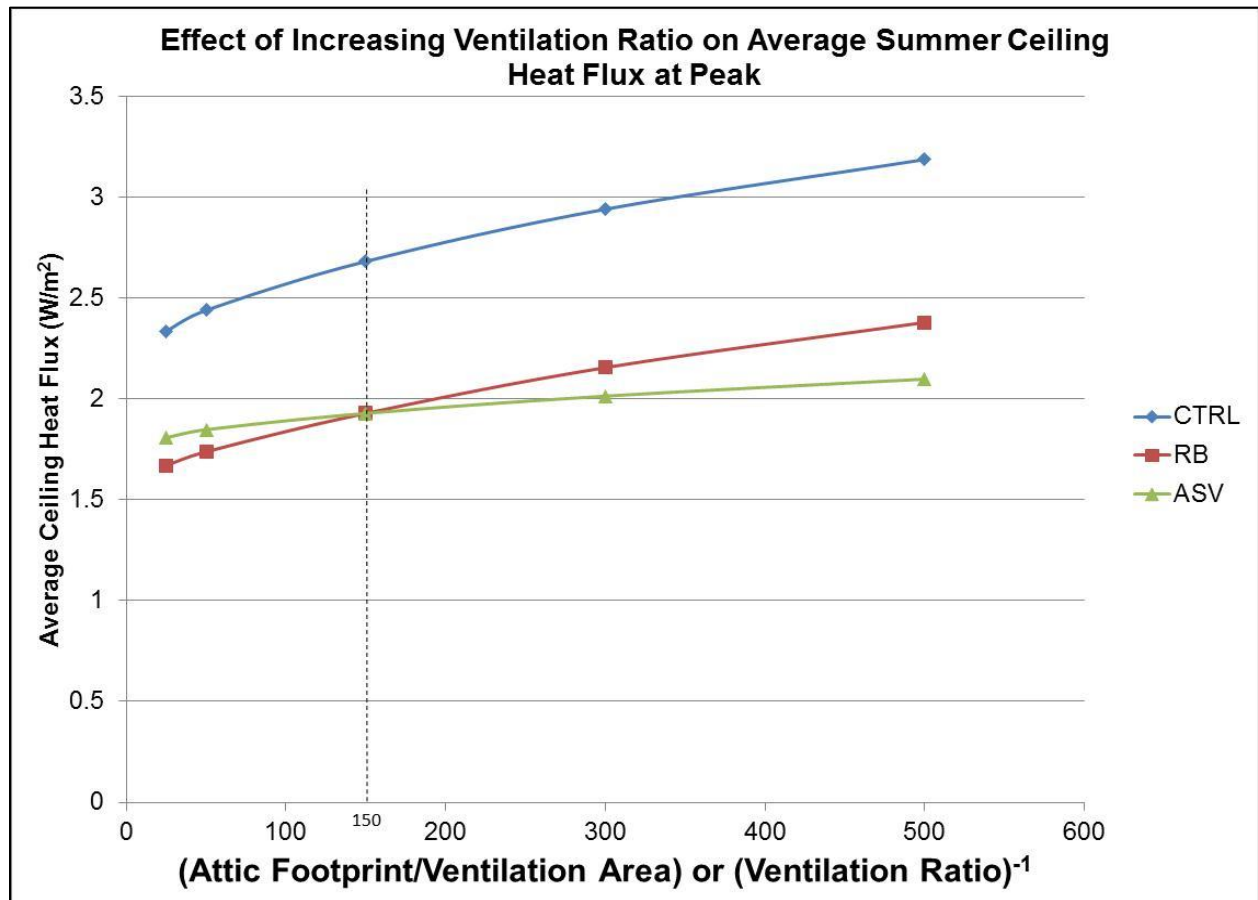


Figure 43: Effect of Ventilation Ratio on Peak Day Ceiling Heat Flux - Simulation Results

As noted in Figure 43, 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 a bold statement. Previous in this report is an investigation into the heat transfer coefficients on the inner surfaces of the attic cavity. The result of which was the determination that radiation is the dominant mode of heat transfer in the attic cavity. Figure 43 shows that mere addition of 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.

CHAPTER 5

CONCLUSIONS AND RECCOMENDATIONS

The effect of natural ventilation on the performance of an array of *in situ* attic bays has been shown through analysis of field data from the NET facility, an accurate benchmark of the field data to a commercially used computer simulation tool, and subsequent simulations of typical year-long climate data. Analysis of the field data showed that increasing the ventilation area ratio from 1:300 to 1:150 resulted in a reduction of peak heat flux through the South roof deck of 16.1 W/m^2 on average during January-May 2011 and a 2-5 W/m^2 peak during May-September. This is not a significant reduction when compared to the reduction from radiation control using a low-reflectance shingle or a radiant barrier system. Above Sheathing Ventilation provides the greatest reduction in summer heat flux through the roof deck, and maintains the least fluctuation in attic air temperature in both seasons. Therefore, according to the analysis of the field data, increasing the ventilation area ratio does not show significant improvement to the thermal performance of an attic system. Peak heat flux to the conditioned space was decreased by a mere $.15 \text{ W/m}^2$ in the summer and actually increased by $.2 \text{ W/m}^2$ in the winter.

Calculations based on the field data have shown that sheathing condensation potential is not an issue for the summer season in Charleston, SC for any of the attic constructions at the NET facility. In the winter season, however, there are periods of time when the OSB sheathing temperature drops below the dew point of the attic air. The potential for condensation on a percent of total time basis is the highest for the attic with a 1:300 ventilation ratio and a non-breathable underlayment. I believe that this result of the humidifiers running at constant output throughout the diurnal time frame, exposing the underside of the sheathing to an unnatural amount of moisture, which is subsequently trapped in the OSB by the low permeability underlayment.

Increasing the ventilation ratio decreases the condensation potential from 5.06% to 3.72% during the winter months, whereas the ASV attic reduces the potential to a mere 0.99% of total time. The major caveat to this result is the fact that there were no moisture sensors on the surface of the duct system running through the attic cavities. The addition of such instrumentation could provide useful information about condensation on the duct surface.

Several batteries of on-site testing were required for development of an accurate simulation profile. Gas tracer analysis performed on the attic cavities dealing with ventilation strategies were performed to collect data for benchmarking the AtticSim simulation tool to the ventilation profiles of the attics in the NET facility. Exponential decay rate analysis resulted in the collection several ACH values for the RB, ASV, and CTRL attic. Unfortunately due to scheduling issues, the tests were performed during the late evening, during which time the effect of thermal-induced natural convection is less of a factor in ventilation. Fiberglass insulation samples were taken from each attic cavity and run through a full thermal material property analysis. Conduction transfer functions and input files were created based on that analysis and benchmarking of the AtticSim simulation tool was performed.

AtticSim was successfully benchmarked to each of the attic cavities using the shingle temperatures as boundary conditions in lieu of solar irradiance data. The simulations showed accurate results in predicting the surface temperature inside the attic cavity, deviating only 5°C at maximum from the measured OSB sheathing temperatures from the field data. The benchmarked data for heat flux through the attic floor was shown to be less accurate. Given that the amplitude of variation of heat flux over the diurnal is minimal, and that the flux is calculated with conduction transfer functions, the variation is deemed acceptable. The data collected from the gas tracer analysis was compared to the benchmarked simulation results, and showed a maximum variation of 2 ACH from the field data.

Radiation heat transfer was shown to dominate combined forced and free convection inside the attic cavity by means of an investigation of heat transfer coefficients. This is a rough indication that controlling radiation through the attic cavity should take precedence over controlling the airflow, from a purely heat transfer point of view. This point is confirmed by the field data analysis of the heat flux through the attic floor, in which the addition of a radiant barrier or high-reflectance shingles show significant reductions in heat flux as compared to the increase of ventilation area ratio. The attic with highly reflective shingles showed an average decrease of 15 W/m² through the entire sampling period in the roof deck heat flux against a standard construction, as well as comparable performance against the radiant barrier system for summer ceiling heat flux control.

Once AtticSim was successfully benchmarked, parametric analyses were performed for typical yearly meteorological data for Charleston over a range of attic ventilation ratios from 1:25 to 1:500 to determine the effectiveness of varying the ventilation ratio on air exchange rates,

moisture control, and heat flux through the attic floor into the conditioned space. Simulations were presented for the average effect on diurnal air exchange rates in a CTRL-type attic, in which increasing the ventilation area ratio shows an amplification of ACH values over the diurnal period. Times of maximum and minimum airflow were determined to be 5 P.M. and 4 A.M. respectively. Analysis of these time frames showed that the ACH rate has a general insensitivity to variations within the range of reasonable operation.

Analysis of condensation potential was performed in the same fashion as with the field data, observing the percentage of total time that the sheathing underside temperature was depressed below the dew point temperature of the attic air. The results of that analysis showed that the benefit seen by increasing the ventilation ratio was minimal for every attic analyzed, nor was the potential for condensation strongly dependent on soffit-ridge ventilation ratio, especially compared to the benefit of the addition of above sheathing ventilation.

Heat flux through the attic floor and ceiling, which is a strong indicator of the heating or cooling load imposed on the HVAC system by the attic, was analyzed over the range of soffit-ridge ventilation ratios. Because of the limited range of the heat flux through the attic floor, the effectiveness of varying the ventilation showed very minimal benefit within the range of reasonable operation. It was also observed that the average ceiling heat flux for the ASV and RB attics is approximately equal at a soffit-ridge ventilation ratio of 1:150. This observation shows the tradeoffs between radiation control and moisture control in the attic cavity.

In conclusion: based on the analysis of field data and benchmarked simulations, thermal and moisture control in the attic cavity are insensitive to variations in ventilation area ratio, within the scope of reasonable application. It is beyond question that a certain amount of natural ventilation is required for proper thermal and moisture control of an attic with code-level insulation, but varying the ventilation area from the current standard will not yield the benefit of moisture elimination with above sheathing ventilation or the heat buffer capability of a radiant barrier system.

My recommendations for similar projects and future work on the subject are as follows. As cold duct returns are a main location of condensation formation in the attic cavity, additional sensors should be fitted to the exterior of the ductwork and surfaces near possible leak sites. These additional sensors could be factored in to an analysis for a greater degree of accuracy when comparing the simulation of the potential for condensation to actual condensation values.

When conducting gas tracer analysis an effort to determine flow rates out of an attic system, a test should be run on a periodic dosing scheme throughout a 24-hour period if possible. This method of analysis would allow analysis of ACH over the diurnal period, which has been shown to be highly variable depending on time of day and wind speed.

At the Charleston facility, latent loads were simulated by humidifiers in each attic bay. These humidifiers were not self-powered and through the duration of this study lost functionality for a variety of reasons. If this experiment were to be duplicated, I would recommend a different method of latent simulation. The latent load should come from the conditioned space itself, therefore attempting to calculate any moisture diffusion through the ceiling plane would not provide correct results.

Insulation inhomogeneity has been a topic of continual frustration throughout this study. As stated previously, the effect of stacking batts of insulation on top of each other has the potential of actually decreasing the R values of the overall insulation, and causes “smash-down” irregularities. While this issue is mostly unavoidable when dealing with commercial insulation installation crews in residential application, care should be taken in maintaining homogeneity of insulation levels when dealing with comparing the thermal performances of separate attic bays.

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APPENDIX A:

Material Properties

	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	0.7621
k (W /m K)	0.0129	0.0129	0.0129	0.0129	0.0129	0.0129	0.0129
Cp (J/kg K)	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0
ρ (kg/m ³)	1101.3	1101.3	1101.3	1101.3	1101.3	1101.3	1101.3
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
Douglas 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	N/A	442.34	442.34	442.34	442.34	442.34
k (W /m K)	0.0661		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 B:

Permeance Data

	Material	Approximate Thickness (in)	Permeance (Perms)
Underlayment	Low Permeance UDL	0.03	0.04
	Standard 15-lb Felt	0.03	8.0
Building Materials	Douglass Fir 2x4	3.5	0.05
	Gypsum Board	0.5	50.0
	OSB	0.44	3.0
	Hardyboard	0.5	11.0

VITA

Stanley Arthur Atherton was born in Knoxville, TN to Jeffrey Sr. and Angela Atherton on April 26, 1987. He spent his childhood in Chattanooga, TN, where he attended Family Christian Academy for primary and Chattanooga State Technical Community College for high school. He returned to Knoxville in 2005 to pursue a B.S. in Mechanical Engineering at the University of Tennessee at Knoxville, and graduated in May 2010. He was offered a graduate research position at Oak Ridge National Laboratory and an opportunity to pursue a M.S. in Mechanical Engineering, which he completed following the submission of this thesis on December 4th, 2011. Stanley and his wife Melissa were married on June 5th, 2010.