MOISTURE TRANSPORT IN VENTILATED ATTIC SPACES FOR HOT-HUMID CLIMATES

By

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To my loving wife

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASHRAE	American Society of Heating Refrigeration and Air Conditioning Engineers
AtticSIM	Attic Simulation Software by Oak Ridge National Laboratory
CarrierHAP	Carrier Hourly Analysis Program
HVAC	Heating Ventilation and Air Conditioning
UF	University of Florida
US	United States

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Ventilated spaces in the built environment create unique and beneficial microclimates. While the current trends in building physics suggest sealing attics and crawlspaces, comprehensive research still supports the benefits of the ventilated microclimate. Data collected at the University of Florida Energy Park show the attic environment of asphalt shingled roofs to be typically hotter than the outdoor conditions, but when properly ventilated, sustains a much lower relative humidity. The hot, humid regions of the United States can utilize this internally convective air mass to provide stable moisture levels within attic spaces. Positioning the buildings primary boundary at the ceiling deck allows for utilization of a buffer climate to minimize moisture trapping in insulation and maximize the insulation's thermal benefits. This investigation concludes that the conditions in a ventilated attic are stable through seasonal changes and promote cost effective, energy efficient climate control of unconditioned spaces in hot, humid regions.

Hot and humid climates present a challenge to limit moisture entrainment and condensation within the building envelope. Ventilated attics perform the function of purging intruding moisture. Ventilated attics change with the seasons to make the best

use of ceiling insulation and maintain building health. Soffit and ridge vent configurations suppress excessive ventilation during mornings hours limiting the dense, moist air coming in contact with a cool duct surface.

Using computer simulation and a mathematical model, the data collected at the University of Florida Energy Park was used to investigate the interaction of mechanical ventilation ductwork placed in residential attics. Output data from this model show moisture can condense at the duct surface under certain conditions. Proper installation reduces the duct leakage and mitigates the effects of condensation. Thus the data indicate crimped or damaged ductwork can sufficiently cool the surface to lead to condensation.

CHAPTER 1
INTRODUCTION

The microclimatic conditions surrounding a building have a direct impact on the energy consumption necessary to provide indoor comfort. The hot, humid climate of Florida provides unique challenges for energy efficient building design. Silberstein and Hens show that insulation of the building envelope is greatly hindered by the intrusion and stagnation of absorbed moisture. With correctly ventilated spaces and properly positioned insulation, excessive moisture should not accumulate [1]. Their study investigates the benefits of removing moisture continuously through ventilation. The ventilated attic structure serves the purpose of creating a climatic barrier enhancing the performance of the insulation. When a ventilated attic does not cool significantly over night, in colder regions, a high rate of moisture removal has been reported [2]. Their results indicated a reduction of soffit ice dams and increased insulation efficiency of the ceiling space. Although the previous research does not discuss all aspects of attic microclimates, their conclusions warrant further investigation of the effectiveness of ventilated attics in warmer regions with increased nighttime temperatures.

Alternatively, moisture can be transported by pressure differences moving vapor from a conditioned space to an unconditioned space which can lead to potential moisture problems, such as mold and mildew growth. Lstiburek, et. al. describes the necessity to properly seal building cavities between conditioned and unconditioned spaces to prevent condensation of water vapor that is communicated between these adjacent spaces [3]. This research illustrates that ventilation can create pressure differences leading to moisture transport between spaces. The previous research did not investigate a particular attic for a full twelve month period. Thus, during certain

months, pressure differences across adjacent spaces may fluctuate yielding a beneficial self-regulating system of moisture movement. Research presented indicates ventilation of an attic space in hot, humid regions serves to purge hot, moist air providing an air mass with a lower humidity ratio to sit directly above the indoor conditioned space. This is a beneficial cycle that directly controls unwanted condensation and inhibits the growth of mold and mildew within attic insulation and on roof truss members.

Therefore, the ventilated attic should not represent the effective building envelope, but instead be defined as a primary boundary to control the impact of weather on the interior of a building and the mechanical support systems. The conditioned space below the attic, a separated and insulated space, functions as the true building envelope where all other systems are operating to support the environmental conditions within that space. Humidity, temperature, and ventilation rates are important factors in the heat and moisture transport of both conditioned and unconditioned spaces that affect indoor comfort, energy efficiency, and air quality.

A yearlong investigation exploring each factor of the climate through all seasons and taking into account varying outdoor conditions is necessary to quantify the benefits of a ventilated attic microclimate requires. However, previous research has failed to present data over a yearlong period in a hot, humid region to evaluate the benefits of passive ventilation and its effects on moisture transport.

For this study, yearlong measurements were taken during 2005 and 2006 at the University of Florida Energy Park. The data presented in this paper provide a complete illustration of the climate developing within the unconditioned attic spaces of residential and light commercial construction. As weather patterns shift in different regions the attic

conditions are altered accordingly through temperature swings and wind speed. The attic conditions also vary based on roofing type and vent location.

Building codes vary by state, but it is generally accepted by the building science community that residential construction should promote a minimum attic ventilation and position opposing vents at the soffits and ridge in standard residential construction. Different climatic regions across the United States (US) require different building strategies. A detailed overview of seasonal and temporal interactions between the building envelope and the climate is required to fully understand the system.

Attic ventilation serves to “prevent condensation and wood decay” [4]. Mathematical models have been developed by many researchers to predict attic ventilation rates and humidity levels required to prevent condensation on roofing surfaces. These models have identified key environmental characteristics effecting temperature and moisture movement in the building envelope. Assessing these complex elements requires detailed datasets to analyze and validate simulation results in the changing seasons.

In humid regions, attic ventilation is an area of strong focus. Various physical and modeling experiments have investigated the benefits of attic ventilation, including mitigating high temperatures, improving insulation performance, and energy efficient building envelopes. Moisture removal is not adequately addressed in many modeling experiments. Thermal attic models require an analysis of heat transfer mechanisms and moisture balances in roofing structures. Stratified air transient models such as the one illustrated by Parker et. al. (1991) and Burch et. al. (1979) predict changes in attic temperature and explore the impact on condensation and air conditioning energy

consumption and performance. While these models have achieved success in prediction of appropriate ventilation rates and temperature conditions, validation datasets are not sufficiently large enough to validate diurnal moisture fluctuations and explore seasonal differences in attic environments.

The data presented were collected using a variety of sensors over a two year period, and the data describe changes in attic humidity as a function of external and internal measured elements. The data clearly illustrate predictive seasonal shifts. Data collected and analyzed as part of this doctoral research show humidity fluctuations are regular oscillations and promote a healthy building envelope. Attic ventilation is also a seasonally beneficial element of the building envelope. Evaluation of the building envelope and understanding seasonal microclimates is essential to achieving energy efficiency, and this data will aid in evaluating the impact of mechanical ductwork impact on condensation.

Investigating the microclimate of attics in the southeast also requires analysis of heating ventilation and air conditioning (HVAC) duct work. Common construction practice places the ductwork and air handler in unconditioned attic spaces. The test attics built at the University of Florida (UF) Energy Park did not contain ductwork, so analysis of the data required the use of a computer-based simulation to examine the effects of conditioned ductwork. The digital simulation focuses on common installation procedures that could lead to condensation. Problems include crimping, compressing, and bending of flexible ducts that can create interstitial points of reduced insulation. The model developed for this research adds to the thermal attic models published in the

literature and leverages the data collected from the UF Energy Park between 2005 and 2006.

CHAPTER 2
LITERATURE REVIEW

Mechanical ventilation and refrigerated air conditioning, in the hot and humid southeastern US, produce challenges to the building envelope. Conditioned air must remain thermally disconnected from the humid environment to prevent condensation and moisture problems, such as potentially hazardous mold and mildew growth. Additionally the structural integrity of a building can be challenged under circumstances of significant saturation of building materials. Research efforts in the last thirty years have sought to investigate the corresponding phenomena.

Building codes used in the southern US come primarily from previous building experience in colder latitudes. These codes are often adapted to particular needs of the south, such as high humidity. Ventilated attics as a construction technique originated in northern climates, primarily as a method for reducing ice dam formation at the eves.

Samuelson, a Norwegian researcher, concluded that ventilation serves little purpose during the winter when there is not a significant temperature gradient to allow the moving air to accumulate moisture. Alternatively, ventilation in the summer environment is beneficial because it transports moisture. In the Norwegian climate night-time ventilation allows for condensation, and it is only during the summer months when there is adequate heat generation in the air space to purge the attic of stored moisture [2].

Samuelson’s research provides a useful understanding of ventilated attics applicable to the hot, humid regions similar to Florida. Florida has very few cold days and generally dry winter conditions can maintain a high rate of moisture removal. The air flow of a hot, humid region can transport more moisture thereby increasing the

effectiveness of adequate ventilation. This research describes the development of a microclimate model useful in predicting and interpreting changes to ventilated attic structures. Samuelson's model investigates the variability in vented spaces to provide an optimal minimum cavity size and to explore the use of increased insulation along the ceiling deck. These conclusions, while expected to return significantly different values, are exploring the same areas of building science that influence residential energy efficient construction in the southeastern US.

Blom draws similar conclusions in that moisture movement requires ventilation. The author addresses the ventilated attic climate in cold and moderate regions. It was concluded that ventilation in attic spaces should not be overlooked for modern roof construction. The ventilation gaps store enough heat to prevent significant ice formation, and remove sufficient moisture to protect insulation and building materials [5].

There is applicability in the conclusions of Blom's research for hot, humid climates. The ridge vents produce little benefit given that ice formation is only a concern at the eves of Norway's buildings; however their use is desirable for buildings in Florida where high heat moves more moisture through a thermal gradient. This venting creates air flow and moisture removal which serves as a barrier to the elements. Therefore the thermal barrier should be placed where the conditioned spaces meet the unconditioned spaces. While increased temperatures, which create snow melt in the north, are likely in vented spaces it is this heat gain coupled with moving air that reduces the humidity levels of the attic spaces. The focus should be placed on insulating between unconditioned spaces and the interior. Research from the northern climates and the problems in the hot, humid climates illustrate a need for reducing air intrusion. Lstiburek,

et. al. found that building pressures created by mechanical ventilation retards air intrusion and can influence air flow, which as a result carries moisture.

Case studies present evidence that pressurization within building cavities can retard environmental intrusion and improve energy efficiency of mechanical equipment. Assessing the building envelope as a pressure boundary provides a unique view of environmental interactions influencing the microclimate created within conditioned and unconditioned spaces. Lstiburek, et. al. utilize this difference to support claims of forced ventilation for crawlspaces and sealed attics. The cases presented give insight into the remediation of problem buildings, but fail to illustrate other, simpler remediation techniques. Additionally, the authors' approach was not based on economic feasibility or cost of remediation measures [3].

Lstiburek, et. al. presents a clear picture of a microclimate formation within a building envelope between conditioned and unconditioned spaces. Pressure differences cannot be ignored and necessitate preventative measures to ensure energy efficiency, structural stability, and environmental quality. A pressure boundary exists for the conditioned space and improves the indoor air quality for the occupied space. Following this method for the unconditioned spaces will waste energy to improve efficiency for the mechanical systems. The semi-conditioned space created from pressurization will move moisture, but will also cost the building operator money to condition a space that will not be used by occupants.

Previous research concludes that ventilation and pressurization limits air infiltration and reduces moisture in attics and crawlspaces. However, the conclusion also works for other building envelope construction techniques including above

sheathing ventilation. Miller et. al. simulated and tested comparisons between roofing materials and the benefits of the ventilation with respect to solar reflective materials. The simulation included a Computational Fluid Dynamics scheme, which laid the ground work for the development of the code package AtticSim. The study verified results on measured data taken from test attics constructed to minimize extraneous parameters, such as leakage of conditioned air.

The previous study illustrates the benefits of ventilation to reduce heat effects and transport infiltrated moisture. Under normal conditions, a roof with a tile or shake layer retains a thermal mass, trapping heat that would enter the attic space with other roofing materials. In combination with ventilation beneath the roofing element, a thermally buoyant, mixed convective region is created. Coupling these two elements reduces the heat flux through the roof decking. Additionally, when shake roofing of different reflection values was used, a reduction in heat flux was observed. It was concluded that darker roofing material produces more thermal buoyancy in the ventilated cavity, offsetting the effects of the increased heat gain. Therefore, the benefits of ventilation produce a more significant reduction in heat flux [6].

The study by Miller, et al. illustrated the benefits of ventilation below sheathing in hot, humid regions. Heating of a surface above a ventilated region creates a naturally regulated air flow. Based on their conclusion, air movement reduces heat flux, but also removes excess moisture.

Walker and Forest conducted research to investigate the changes in the attic environment with changes in ventilation rates. While the research focuses on ventilation as a heat mitigation technique, data are needed to understand ventilation rates to

optimize moisture removal. Also, cold nights and wet winters of Alberta, Canada present a challenge for ventilation to remove moisture. This experiment investigated, ventilation rates measured through a tracer gas applied to the building envelope and attic space intrusion from both outdoor and interior areas. Additional moisture content on the roof sheathing was examined to determine a correlation between moisture and ventilation. The primary conclusion presented was a strong linear relationship between wind speed and attic ventilation. Air changes in the attic increase with increasing wind speed allowing for more effective ventilation. Air changes increased from 2 per hour to 10 per hour when the attic space changed from sealed to vented. No conclusions were drawn linking moisture content of wood members to ventilation rates. All ventilated spaces reported no significant moisture content [7].

Research by Walker and Forest illustrates a need for linking the moisture removal in the attic with appropriate building code requirements that benefit the whole building envelope. Creating a solar heated and ventilated air space above the conditioned region heats the air allowing it to store more moisture desorbed from the building products. Buoyant and mixed convection will subsequently remove the moisture with constant air changes. This phenomenon was not proven by Walker and Forest, but provides a strong case for the research undertaken at the University of Florida.

The air movement in an unconditioned space relies on weather conditions outside of the structure. It has been shown to rely heavily on solar radiation, wind speed, wind direction, and surrounding obstructions. These factors make the modeling of the attic moisture-temperature interaction highly non-linear, and the transient problem is identified using a microclimate approach.

Medina and Young identified several factors complicating the use of insulation at the roof decking to limit heat gain to an attic space. Their research uses computer simulations to test the benefits of a radiant barrier system for the hottest three months of the year for all climatic regions of the continental United States. A net benefit in the reduction of peak hour heat flux exists in all climate zones. This investigation did not see an advantage for the winter periods, so produced no data for those months [8]. The model was a heat and mass transfer model taking into account the effects of solar radiation, re-radiation of roof decking, convective heat transfer, and ventilated moisture intrusion. This model describes the microclimatic effects of buoyant and mixed convective flows and highlights no overall benefit due directly to air movement. Heat flux reduction was the primary indicator of successful use for the radiant barrier. It was determined that ventilation was not a heat flux reduction component, and varying the amount of ventilation had no effects. The greatest heat flux savings and best performing simulation for a hot, humid climate occurred in a sealed attic space. The model as constructed provides for an analysis of soffit/ridge vent combination and produces a larger heat flux savings over soffit/soffit or soffit/gable combinations due to the air stratification.

Medina and Young give little explanation for how the model handles moisture in wooden attic members and the effect of heat flux on moisture retention. Driving the internal climate of the attic is the solar load in combination with the moisture infiltration and removal. The research justifies the evaporation of moisture in the attic, a cooling element particularly for the attic members themselves. The moisture removal was not considered as a necessary element to maintain air quality of the space or structural

integrity. This model illustrates the need to investigate the moisture component and solve for equilibrium between the benefits of moisture removal and heat flux reduction.

Shashua-Bar, et. al. present research in the *International Journal of Climatology* describing a similar microclimate focusing on building orientation, proximity to other buildings, and albedo of surfaces. The simulations illustrate deviations of the built environmental climate from meteorologically expected data by a maximum of 6 degrees Kelvin. The conclusions state that a clustered building group with narrow spacing, decreases the surrounding temperature due to significant solar shading. This data illustrates the changes in the climate created by built structures, and predicting these effects will allow community planners to better engineer the urban landscape for energy efficiency and thermal comfort [9]. The application of this research extends to the elements of the building that are enclosed but unconditioned. These areas are most affected by changes to the immediate external microclimate. A structure's proximity and orientation affect the thermal performance on internal boundary layers and should be considered when investigating the microclimate of the built environment. The expected thermal effect of building positions will change the interaction of ventilated attics and moisture condensation conditions, especially in hot, humid regions. As previously determined by Walker, et al., the element driving ventilation in an attic is wind incident on a building structure [10]. Thermal effects of building proximity may disrupt temperature gradients necessary to move air in channels of heavily populated areas. The net effect of building microclimates both internally and externally must be evaluated together to assess the building impact on the climate and residents.

Moisture intrusion in hot, humid climates creates a unique design challenge for building envelopes. The literature illustrates the temperature-moisture interaction must be investigated as a transient system. The structural integrity of a building can be challenged under circumstances of significant saturation, so envelope design should focus on building health. Refrigerated air conditioning adds complexity to the systems, but should be designed to cooperate with the existing attic conditions. Research efforts as part of this dissertation are meant to model and analyze the interaction between the attic microclimate and refrigerated air ductwork.

CHAPTER 3
METHODS AND EQUIPMENT

Data Collection

The research took place at the Building Products Test Facility on the University of Florida campus in Gainesville, Florida. The building was completed in 1998 and was wired to provide data related to the internal microclimate of structures, both ventilated and sealed in hot, humid regions. Data have been collected at that facility since 2001.

For this study, data collected during 2005 and 2006 were analyzed. Figure 3-1 illustrates the floor plan; the building used had 12 bays. Bay 9 was chosen for this analysis due to the construction of a ventilated crawlspace and attic using wood framing members typical of Florida residential construction. The bay is also centrally located shielding the instruments from edge effects. The conditioned space has dimensions of 10.5 ft (3.2 m) wide and 20.0 ft (6.1 m) long with ceiling heights of 7.9 ft (2.4 m). Above the conditioned space is a standard attic with floor dimensions of 9.8 ft (3.0 m) long and 10.5 ft (3.2 m) wide with a roof slope of 5:12. The attic also had a ventilation area of 1.91 ft^2 (0.18 m^2) for every 200.2 ft^2 (18.6 m^2) of attic floor space, or a ventilation ratio of 1:105.

The building is oriented with the long axis running East-West. The pitched roof deck surfaces face North and South and are constructed with asphalt shingle roofing. The soffits and ridge were vented with materials from AirVent, Inc. The soffit vent provided a ventilation area of 9 in^2/ft (190.5 cm^2/m) and the ridge vent provided 18 in^2/ft (381 cm^2/m). Ceiling deck insulation to R-30 was applied alternating fiberglass and cellulose insulation. The interior space was conditioned with a single Packaged-

Through-the-wall Air Conditioner (PTAC), and the space was kept at 76°F +/-1°F (24.4°C +/- 0.5°C) in the summer and 68F +/-1°F (20°C +/- 0.5°C) in the winter.

In addition to the building, a weather monitoring station from Campbell Scientific, Inc. was used and positioned 24.9 ft (7.6 m) northwest of the building at a height of 9.8 ft (3.0 m). This monitoring station measured the external conditions of temperature, relative humidity, barometric pressure, wind speed, and wind direction. Weather conditions were compared to measurements taken inside the building, constructing a relationship between the external conditions and the resulting internal attic climate.

Sensors were placed throughout the attic to measure movement of air, temperature, and moisture. Combined temperature and relative humidity sensors were located in the center of the attic, ridge vent, and soffit vents. Additionally, thermocouples were attached to various roof joists at the lower and middle positions on both roof deck surfaces, and between the plywood sheathing and shingles. Air flow was measured by bidirectional anemometers which were positioned in both soffits, in multiple positions at the ridge vent, and three other locations along the roof decking of the attic. Figure 3-2 illustrates the placement of various sensors within the test facility.

Data were recorded every 15 minutes for the two year period. During the collection period, the system consistently collected data for 34,891 data points per year out of a possible 35,040 points for an accurate description of 99.6% of the year. The data were recorded and organized according to a digital timestamp. Times were consistently Eastern Standard Time without including changes for Daylight Savings Time. An accurate conclusion was drawn from the collected data of both the average and instantaneous microclimatic conditions of ventilated attics.

Model Development

The attic microclimate data were incorporated into the model to predict refrigerated air duct surface temperature for ductwork placed in an attic in Florida. Focusing on duct surface temperature was important for this study to assess condensation events. No data was collected for an HVAC duct placed in attics, so the computer simulates a cylindrical flex duct positioned parallel to the ridge line on the ceiling deck and centered in the attic.

The model inputs can be manipulated to analyze many configurations of ducts and installation qualities. Variable parameters include duct inner and outer diameters, insulation level, and leakage, which allow the user to analyze the two years of 15 minute data sets collected for Gainesville, Florida and examine leaking or poorly installed ductwork. Analysis of the duct work in attics presented in this study examines a standard flex duct at optimal construction as per Residential Construction Manual D [11].

Simulation models were completed using an iterative energy balance method with MATLAB© software. Appendix A contains the MATLAB© script used for the analysis. The model solves the energy balance in three steps. Conduction heat transfer from the conditioned air through the insulation is solved using a finite difference method. Nodes are placed on the inner and outer surface of the duct. The air temperature inside the duct was considered well mixed as a simplifying assumption. Thermal storage of the duct insulation was calculated using Equation 3-1.

$$Q_{stored} = \rho * V * C_p * (T_t - T_{t-1}) \quad \textbf{(3-1)}$$

Where ρ = Material density

C_p = Specific heat or Heat capacity of material

V = Material volume

T_n = Surface temperature

Heat transfer on the exterior of the duct is dominated by convection and radiation. Energy balance for convection was calculated by the standard algorithm in Equation 3-2. The convection coefficient was calculated at each time step and was based on the attic configuration, forced air flow, natural air flow, and temperature. Equation 3-3 was used to compute the convection coefficient. This method is outlined in ASHRAE Fundamentals [4].

$$Q_{convection} = A * h * (T_{duct} - T_{attic}) \tag{3-2}$$

$$h_{forced} = 0.664 * Pr^{1/3} * \sqrt{\mathrm{Re}}$$
$$h_{natural} = 0.56 * \sqrt{(Ra * \cos(90 - Roof\ Pitch))} \tag{3-3}$$
$$h = \sqrt[3]{(h_{forced}^3 + h_{natural}^3)}$$

Where Ra = Raleigh number

h = Convective heat transfer coefficient

Re = Reynolds number

Pr = Prandtl number

The radiative algorithm is calculated for each surface in the attic in 15 minute intervals. For each surface in the calculation the temperature difference was considered using a fourth degree polynomial. This radiative component was calculated for all three participating surfaces: north roof deck, south roof deck, ceiling deck, and duct surface. Equation 3-4 illustrates the algorithm adapted from the text by Modest [12].

(3-4)

$$Q_1^{radiative} = \Psi_1 * \sigma * A_1 * (\varepsilon(T_1^4 - T_2^4) + \sum_{n=1}^{6} \frac{T_n^4 - T_{n+1}^4}{\left(\frac{1}{\varepsilon_n}\right) + F_{(n)(n+1)} * \left(\frac{1}{\varepsilon_n}\right) - 1})$$

Where Ψ_1 = Fraction of radiation attenuated in moist air

σ = Boltzmann's constant

A_1 = Surface area

ε_n = Surface emissivity

T_n = Surface temperature

F_{nm} = Surface to surface view factor

Air between the roof decks and the duct work was considered a participating medium. Relative humidity of the attic was used to calculate air moistures' interactive effects. This calculation was simplified using lookup tables [12].

Conditions inside the ductwork came from parametric simulation of the heating and cooling demand of a conditioned space below the attic. The demand parameters were taken from CarrierHAP© software simulations for this segment of the building. Data tables are presented in Appendix B. Since the collected data set did not record the on and off cycling of the package terminal air conditioning unit, the CarrierHAP© simulation was used to correlate the duct air flow rate to outside air temperature. Comparison of the data and the y-intercept of the regression indicate that at an outdoor air temperature of less than 62°F (16.67°C) the space requires some heating demand and if greater than 72°F (22.22°C) some cooling is required.

The model uses the outdoor signature to initiate airflow through the duct and air temperature within the duct. Since the attic microclimate data is only calculated at a resolution of 15 minutes, the initial mixing of air within the duct and maximum length of cycling was neglected. Internal duct temperatures of 85°F (29.44°C) were used for

heating and 55°F (12.78°C) for cooling. These values reflect the simulation analysis from Carrier Hourly Analysis Program (CarrierHAP©). This program is often used in the industry for energy and HVAC analysis on residential and commercial buildings.

Duct surface temperature data with varying the thickness of duct insulation and absorption coefficient of the duct surface were calculated for each month. While every month was investigated, the seasonal changes and the summer months are most applicable to the investigation of condensation.

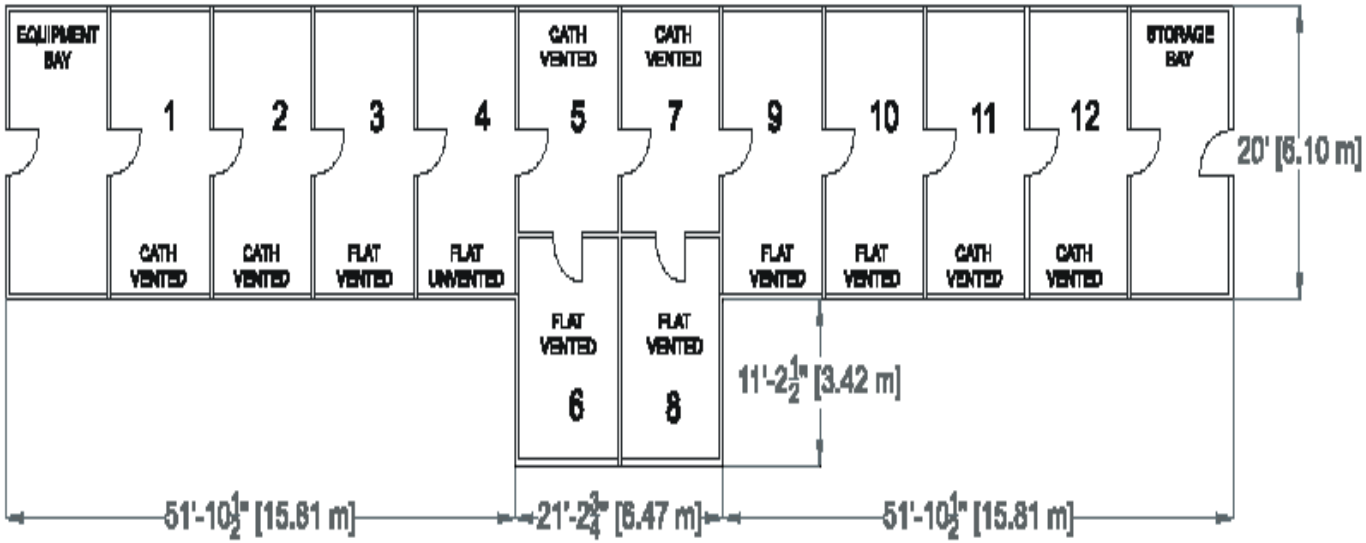

Figure 3-1. Plan-view of test facility

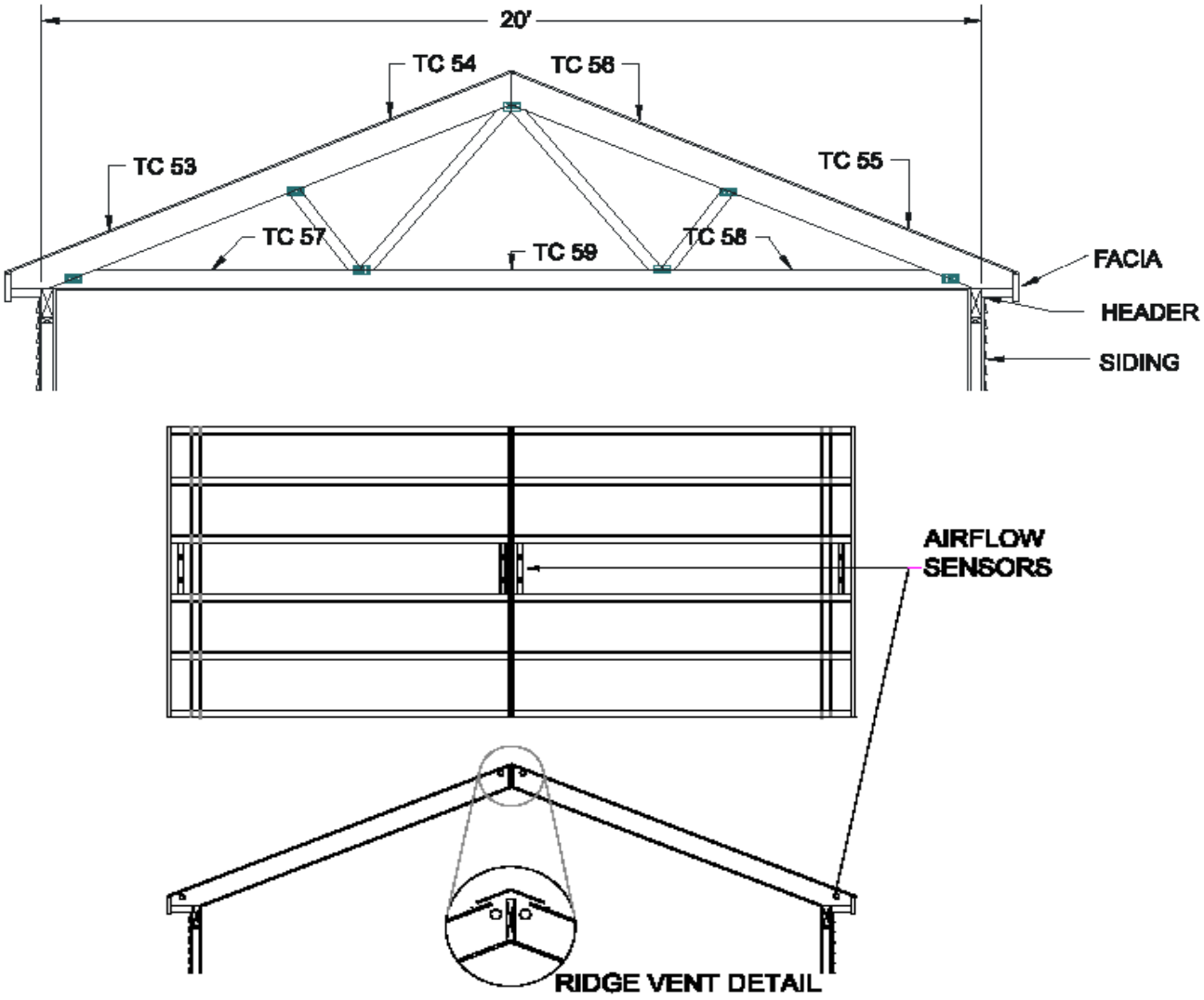

Figure 3-2. Illustration of sensor positions in test facility attic space

CHAPTER 4
RESULTS AND ANALYSIS OF DATA

Internal Microclimate

Applying this data uniformly requires analysis of averages for hours, days, and months. The data collected in this study were characterized for 2005 and 2006 to develop an accurate average for the simulation model.

Monthly averages define an operating and consistent climate for the building envelope within the attic. On the exterior, the shingles heat up and store heat, which is conducted to the roof's decking and reradiated to the attic space. During the month of August, the shingle surface temperature peaks at 177°F (80.6°C) and 163°F (72.8°C), for the southern and northern facing roofs, respectively. These extreme temperatures are the primary driving forces that provide energy to create the attic microclimate. While the extreme data points are important to consider, it is the duration of these extreme temperatures that is significant. During May through August the shingles spend over 250 hours a month above 100°F (37.8°C), and in July through August over 80 hours a month above 150°F (65.6°C). Figure 4-1 displays the time spent above 150°F (65.6°C) for the shingles on both the northern and southern roof faces.

The sustained high temperatures of asphalt shingles contribute to a hot attic environment. Temperature differences between north and south facing roof decks create convective currents of air inside the attic. The internal temperature of the attic space can peak as high as 121°F (49.4°C) during the month of July, and spend over 200 hours above 100°F (37.8°C) for the month of August. Figure 4-2 illustrates the temporal range for extended periods of high temperatures.

Relative humidity measurements were taken throughout the attic and coupled with air flow measurements to calculate the moisture transport through the attic vents. In addition, wooden roof members were wired with thermocouples to assess the likelihood of condensation on attic members and absorption by the wood framing. Figure 4-3 displays the monthly relative humidity at inlets and outlets for air flow with respect to the attic interior and outdoor conditions. The data collected in this study offer a complete view of the average microclimatic conditions that can form within a ventilated attic under a variety of external conditions throughout all seasons.

A ventilated attic possesses many advantages for a hot, humid climate. While peak attic temperatures are high during summers, the relative humidity remains well below that of the external environment. Relative humidity is of specific interest in this study because the overall health of the attic depends on the temperature and moisture gradient around the wood framing members. Attic humidity ratios could be derived from the data collected; however, this study's primary focus was on with absorption and desorption of moisture. The exchange of moisture between the porous wood surfaces and the attic air is a function of relative humidity.

As shown in Figure 4-3, the monthly average relative humidity for the attic is consistently lower than the exterior. This relationship is also true for the instantaneous data recorded at 15 minute intervals. Figure 4-4 and Figure 4-5 illustrate the temporally averaged daily conditions for January and July.

The moist air entering the attic through the soffits gains heat and rises a vertical distance of 5.2 ft (1.6 m) before exiting the ridge vent. Figure 4-6 illustrates the temperature rise as air travels from soffit to ridge averaged over the course of each

month. As the temperature rises, the air can hold more moisture lowering the relative humidity, decreasing the chance of condensation, and reabsorbing any moisture that precipitates onto the insulation or attic members.

This moist air is maintained at high temperatures well above the dew point which limits the instances where condensation can occur. Figure 4-7 displays the monthly average temperatures for the attic interior, roof joist surface, and dew point calculated according to the ASHRAE method. The roof joist member remains slightly higher in temperature than the attic interior air measurement due to absorbed energy from the radiated heat of the roof deck. From this figure, it can be concluded that condensation onto roofing members is rare and adequate ventilation does not cause accumulated moisture by inhibiting the radiative heat gain. Additionally, the radiation of heat from the roof decking is an important element in the heat balance of the attic space.

Figure 4-8 compares the temperature of roofing materials and the attic temperatures with the outdoor conditions. Heat flux due to solar radiation drives the internal microclimate. Both Figure 4-3 and Figure 4-8 illustrate this hotter, drier microclimate with respect to outdoor conditions. A key element to this shift in microclimate is the effect on stored moisture. For each 15 minute increment the mass flow rate of moisture through the soffit and ridge was calculated using Equations 4-1 and 4-2.

$$\dot{m} = A * \vec{v} * \frac{1}{\vartheta(T,P)} * (1 + \frac{W_{ma}}{W_{da}}) \quad \textbf{(4-1)}$$

$$\vartheta(T,P) = R_{da} * T * \frac{(1+1.6078*\frac{W_{ma}}{W_{da}})}{p} \quad \textbf{(4-2)}$$

Where $\dot{m}$ = Mass flow rate

$\vec{v}$ = Air velocity

A = Free area of ventilation

$\vartheta(T, P)$ =S volume of air

$\frac{W_{ma}}{W_{da}}$ = Moisture content in the air corrected for partial pressure

T = Air temperature

P = Atmospheric pressure

R_{da} = Gas constant for dry air based on the carbon-12 scale

The moisture flow rate data were time averaged for each month creating an average day. Figure 4-9 through Figure 4-12 display 4 out of 12 months. This illustrates seasonal differences in attic moisture properties. These averages represent inflow at the soffits and outflow at the ridge. Diurnal cycling creates an attic that “breathes” by taking in air and moisture at certain times and then releasing it later. The system cannot negate the storage of moisture both within the attic space and the wooden attic members; therefore, there is no observed equilibrium. A forward lagging of the system is evidence of the slight rise of moisture in the attic as it responds to incoming humid air. The overall trend in the graphs displays a consistent system, which is primarily attributed to a ventilated attic.

Looking closely at the data it is clear that the air flow consistently enters the attic through the soffits. The cross-sectional area of the soffit is smaller than the ridge vents. Thus, the ridge vent has a higher volumetric flow rate than the soffit vents and provides the only successful pathway to remove moisture. Therefore, moisture flow is governed by the ridge vent.

Seasonal Humidity Switch

The data were categorized and averaged to remove outliers by creating hourly averages from the collected 15 minute intervals. The observation of seasonal trends was analyzed by using a monthly average day approach. Data collected at a given hour were then averaged daily during that month to construct a representative day. The representative day illustrates typical attic conditions during the given month. Performing this data transformation allows for the interpretation of seasonal and monthly data relationships in the hot, humid southeast.

The primary focus of this analysis will focus on data collected by sensors to measure mixed attic conditions as a result of seasonal climatic changes, including temperature, absolute humidity, and environmental characteristics. Comparison of collected data to the ASHRAE design conditions illustrates that the data ranges collected are normal for Gainesville, Florida and the hot, humid south. Additionally, the utilization of humidity ratios, air change rates, and average day analyses provide for a more detailed view of seasonal processes and microclimate interactions than limited data sets using single value average monthly conditions. Analyses of collected data illustrate seasonal variety in the accumulated moisture of a ventilated attic. The data confirm that ventilated attics retain more moisture during the summer months where the days are warmer and the outside humidity levels are high, but as the seasons shift, the moisture level is naturally removed. Figure 4-13 and Figure 4-14 illustrate the seasonal changes in a box plot where the monthly average days are combined into a single box, and the monthly changes describe a consistent seasonal variation annually. Measured data show that air changes per hour fluctuate diurnally and seasonal fluctuations match

the changes in humidity ratio throughout the year. Figure 4-13 and Figure 4-14 illustrate changing attic humidity ratio over time.

Daily fluctuations in the attic humidity ratio are a function of hot, humid air entering the attic through intended and untended penetrations in construction. The construction sealed the ceiling surface in conditioned space to eliminate movement of air through the ceiling plane. The airflow through soffit and ridge penetrations was measured and converted to air changes per hour. Air changes were calculated using Equation 4-3.

$$\text{ACH}=\frac{\left[AF_{\text{ridge}} * A_{\text{ridge}} * L_{\text{ridge}} - AF_{\text{soffit}} * A_{\text{soffit}} * L_{\text{soffit}}\right]}{\text{V}} \quad \textbf{(4-3)}$$

Where AF_n = Air flow

A_n = Area

L_n = Length

V = Volume of attic

In Figure 4-15, a time series plot illustrates air change rates for the attic for each collection year. Figure 4-16 displays the stratification in relative humidity as measured at various attic locations. The figures show movement of moisture vertically with each air change. Data confirm the air stratification moves moisture from soffit to ridge. All data collected illustrate a useful picture of transient attic conditions through a variety of seasonal conditions.

Duct Model

Microclimate characterization data were organized for input into the duct model. While the model calculates the energy balance for the attic, the duct surface temperature was the output analyzed for this study. The surface temperature was analyzed for each month for given set of input conditions.

Two key variables were changed in the model runs to explore the controlling influence over duct condensation: the reflective or absorptive coefficient and the thickness of the duct insulation. The duct surface temperature changes in response to changes in the insulation thickness.

Figure 4-17 data come from input conditions with a reflective surface typical of most residential flexible ductwork. Surface absorbtivity coefficient of the duct modeled by Figure 4-17 was 0.1. To compare the results, a surface absorbtivity of 0.86 was compared in Figure 4-18. This value was chosen for a ductwork that might be painted or manufactured in a darker color to prevent condensation. For convergence of the radiation equation, the duct surface must be of equal or lower absorbtivity coefficient with the roof deck. The two absorbtivity coefficients chosen for this study, 0.1 and 0.86, illustrate the system currently assembled in many residential attics in Florida and a possible change to those systems to reduce building health issues, respectively.

Figure 4-17 illustrates a much cooler duct surface than Figure 4-18. As duct surface temperature decreases, the likelihood of condensation increases. Figure 4-18 shows higher temperatures which increase the heat gained by conditioned air travelling to the living space. Either duct design can succeed during the summer months in hot, humid climates, but both designs require proper installation. Crimping the duct or

compressing the installation by more than fifty percent significantly lowers the surface temperature allowing more heat transfer to conditioned air.

Seasonal changes to temperature and humidity of the outside will affect the likelihood of condensation and any inconsistencies in installation will further exacerbate condensation problems. Figure 4-19 and Figure 4-20 illustrate the same duct surface resulting from average monthly conditions in October. The cooler attic in October shows that duct surface condensation is dependent on the temperature of the air inside the duct. Conditions were tested for several years, and Table 4-1 displays data for July 2005 and 2006.

Discussion

Data collected were used to analyze averages for months and seasons. The microclimate analysis points out problematic times and seasons where ductwork temperatures reach conditions of saturation on their surface as a result of moisture intrusion. Capillary movement of moisture through porous roofing materials and ceiling surfaces creates many potential intrusion points. Although this research discusses only shingled roofing, the most common roofing material in Florida, similar principles could be used to draw conclusions about various other roofing materials. Research conducted for this project investigated the mechanisms that move moisture once inside unconditioned spaces. Previously presented literature suggested sealing the space to prevent intrusion, but in hot, humid climatic zones sealing all intrusion points requires more thorough and precise methods.

Research presented by Wendell Porter of the University of Florida showed how moisture travelled through a well shingled roof [13]. Data presented as part of this

research show that transient attic conditions provide a natural convective cycle. Within the attic, diurnal cycles of heating cause thermal buoyancy to move air from the soffits to the ridge. Air change in the attic is naturally controlled by available solar radiation to heat the roof's surface, the size, and position of the attic penetrations. The air changes per hour of unconditioned space fluctuate in a consistent pattern that increases throughout the day. Minimum air exchange rates occur in the early morning during cooler months. Air exchange rates decrease at the times when the humidity ratio of ambient air is highest, thus reducing the likelihood of moisture intrusion. The resulting microclimate maintains a resistance to saturation providing a solid barrier to the elements, and serves to remove moisture at a rate consistent with the prevention of mold and mildew growth.

Under these circumstances the building envelope boundary of hot, humid regions should be considered conditioned space and be insulated accordingly. Overall this data supports increased insulation and materials with high thermal resistances to be positioned at the ceiling deck thus reducing the heat flux into conditioned spaces. Sealing the attic spaces entirely and insulating the structure would reduce the thermal heat transfer from an attic. However, this would provide no outlet for moisture transported through porous roofing materials and the ceiling plane.

When air enters the attic, the model shows natural convective system moving moisture from soffit to ridge along the thermal gradient. In the event of moisture intrusion, this movement alleviates damage to insulation and prevents seepage into the conditioned space.

Figure 4-16 shows the stratification in humidity through various points in the attic. Natural convection purges moisture through fresh air input from soffit to remove moisture through the ridge, and similarly to a switch can turn on and off depending on the time of day or season. Without proper positioning of vents the thermal stratification will not allow for the removal of moisture.

Looking closely at the data it is clear that air flow consistently enters attics through the soffits. The ridge vent, with a higher volumetric flow rate than the soffit vents, provides the bulk air flow out of the attic creating the only successful pathway to remove moisture. Therefore, moisture flow is governed by the ridge vent.

The building position plays a significant role in the stratification because, although heating of the roof surface drives the system, strong wind entering the soffits causes mixing in the unconditioned space. Since weather fluctuations in the hot, humid South do not create a consistent wind direction and most conventional construction has obstructions like trees and/or other buildings, thermal stratification is the only air flow mechanism capable of providing consistent air movement. Roofing surface temperatures will create different gradients based on solar angle position; however, if incident solar radiation is available after a moisture entrainment event the internal convection will still stratify the air and remove moisture.

Condensation issues in Florida occur on HVAC supply ductwork and insulation when the surface temperature of a less insulated duct reaches the dew point. Problems persist in early morning hours when space cooling demand may cause short cycles of HVAC units and the dew point of moist morning air is still high. Fluctuations in time series data presented in Figure 4-15 illustrate how early morning ventilation is reduced,

restricting moist outside air from entering the attic, but subsequently increases during the hotter parts of the day, thus purging excess moisture.

Ventilation rates illustrate that fluctuations vary seasonally and diurnally while maintaining active airflow. Under conditions described in this study, the mean effectiveness of this ventilation methodology is 0.13, based on Equation 4-4 [14].

$$Q = E * A * V \tag{4-4}$$

Where, Q = Air flow rate ($\frac{m^3}{s}$)

E = Effectiveness of ventilation

A = Free area of ventilation (m^2)

V = Wind Velocity ($\frac{m}{s}$)

Wind driven ventilation's effectiveness is 0.24 for a soffit-only configuration and 0.095 for a ridge-only configuration. All measures of effectiveness were calculated using free outlet area. This variation on ventilation effectiveness is necessary to illustrate removal hot, moist air.

Walker describes typical ventilation effectiveness to range between 0.25 – 0.35 for diagonal winds and 0.5 - 0.6 for perpendicular winds. These values are derived from empirical data collected by Barre and Sammett (1950) for farm structures. Values in this study indicate a lower average effectiveness resulting from variation in exterior pressure patterns on the roof, and a lack of predominant wind direction at the data collection site. Although positioned in an open suburban area, buildings and trees around the site also affect the wind driven effectiveness factor.

The relative effectiveness between the soffit and ridge agree with the distribution of pressure along the roof and indicate a lower pressure at the ridge than at the soffit.

This also illustrates the necessity for multiple roof penetrations at multiple locations. Without the variation in effectiveness and pressure under varying wind conditions the moist air would not have a gradient to follow and the moisture movement would not follow the path of greatest effectiveness in a transient system.

Figure 4-21 illustrates the change of ventilation effectiveness with wind speed. Ventilation effectiveness decreases quickly then remains fairly consistent overall for the majority of wind speeds. Under the proposed ventilation conditions, soffit and ridge openings provide a balanced air movement configuration maintaining a steady flow of air through the attic.

Understanding the effectiveness of the ventilation openings (Figure 4-21), Figure 4-22 illustrates the need for providing both ridge and soffit ventilation. The total air flow attributed to wind and thermal forces are outlined in Equations 4-4 and 4-5, respectively [14].

$$Q_{thermal} = A * \theta(2gH * \left(\frac{T_i - T_o}{T_i}\right))^{0.5} \quad \textbf{(4-5)}$$

Where, A = Free area of ventilation (m^2)

Θ = 0.40 + 0.0025|Ti – To|

H = Height difference between inlet and outlet (m)

Ti = Attic Air Temperature (°C)

To = Outside Air Temperature (°C)

The volumetric flow rate of air leaving the attic space through the net free area of installed openings is controlled by both thermal and wind forces. It is the interaction of these forces which minimizes ventilation during cool, moist mornings when condensation on ductwork is most likely to occur.

The duct model analyzed the surface temperature of the duct. Convective heat transfer from the roof decking moves air through the attic, and radiative heat transfer drives temperature changes of the duct surface. Insulation is intended to limit the energy transferred through the duct to the conditioned air. Manufactures produce ducts with a reflective surface to distribute the incident radiation away from the surfaces allowing the duct to maintain a lower surface temperature.

Most attics in the hot, humid South contain at least a few feet of flexible duct. The round duct is installed in a variety of ways often hanging from rafters, draped over trusses, or bent to the boot. These installation procedures can lead to crimped, bent, or compressed insulation. As the insulation is compressed more heat is gained by the conditioned air. Additionally, these locations are the most likely for condensation. As cool conditioned air reaches a junction of compressed insulation the surface temperature drops. The model presented in through this research investigates this transient condition with an iterative solution methodology solving for convergence between the two boundary conditions at the surface of the duct.

Decreasing the thickness of insulation decreases the temperature of the surface. Using average monthly conditions constructed for characterizing the ventilated microclimate, the highest likelihood of condensation occurs during the swing months of the year. This is supported by October's output data. Model outputs are presented in Figure 4-19 and Figure 4-20. Months where cycling of the HVAC system in the cool, early morning pose the highest risk of condensation, even if the HVAC system is cycling for a short period of time.

Duct surface absorbtivity can increase the amount of heat gained from roof deck radiation and decrease the risk of condensation. The model analyzed flexible ducts under normal reflective conditions with an absorbtive coefficient of 0.1 and under a painted condition with an absorbtive coefficient of 0.86. Data presented for an average day in July illustrate the rise in surface temperature. A duct design with reflective or absorbtive surfaces can provide conditioned air during the summer months in hot, humid climates, but both designs require proper installation.

Installation procedures for residential attic duct work are described in Manual D of the residential code [15]. Duct layout and handling are a central focus, and if done properly will mitigate the building health issues associated with moisture intrusion caused by condensation. Moisture in the attic only condenses before being ventilated if the duct surface is sufficiently cooled. Improperly stretched or bent ductwork creates compression areas which also limits the amount of insulation contacting the duct surface. Crimping the duct or compressing the installation by more than fifty percent significantly lowers the surface temperature when the HVAC system is running.

Another influential component is surface air mixing caused by duct leakage. Gaps in the flexible duct due to poor joins or with improper sealing of the air handler will decrease film temperature at the duct surface in the vicinity of the leak. The model data represents a system with a five percent duct leakage, typical of residential installations. Leakage fractions are included in the initial Carrier HAP© inputs and the Matlab© model. The surface mixing was considered uniform for simplicity of the transient solution. Under average conditions, a 5% average leakage did not significantly increase condensation rates in the digital simulation.

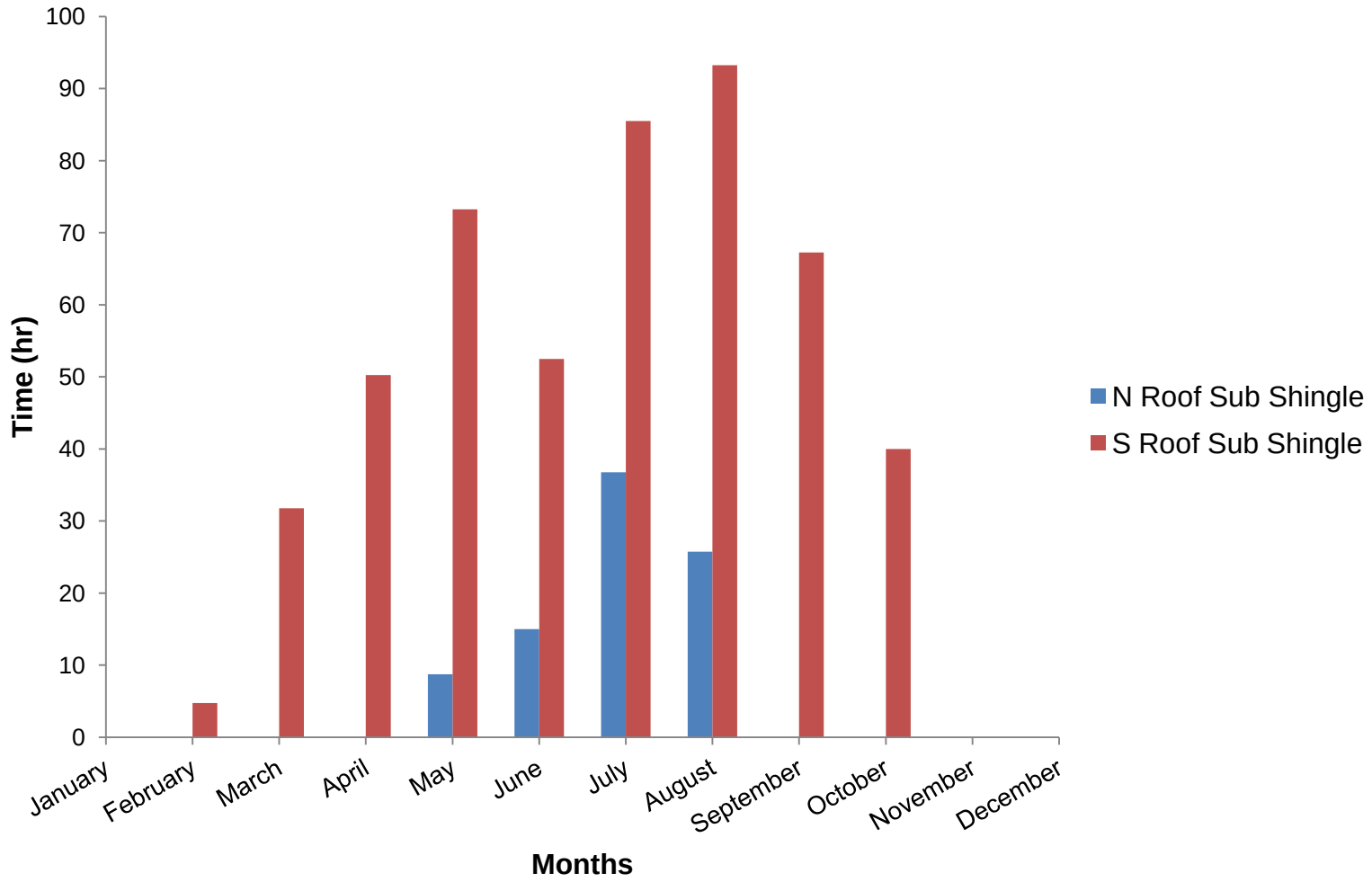

Figure 4-1. Time spent above 150°F (65.6°C) for both north and south facing shingles

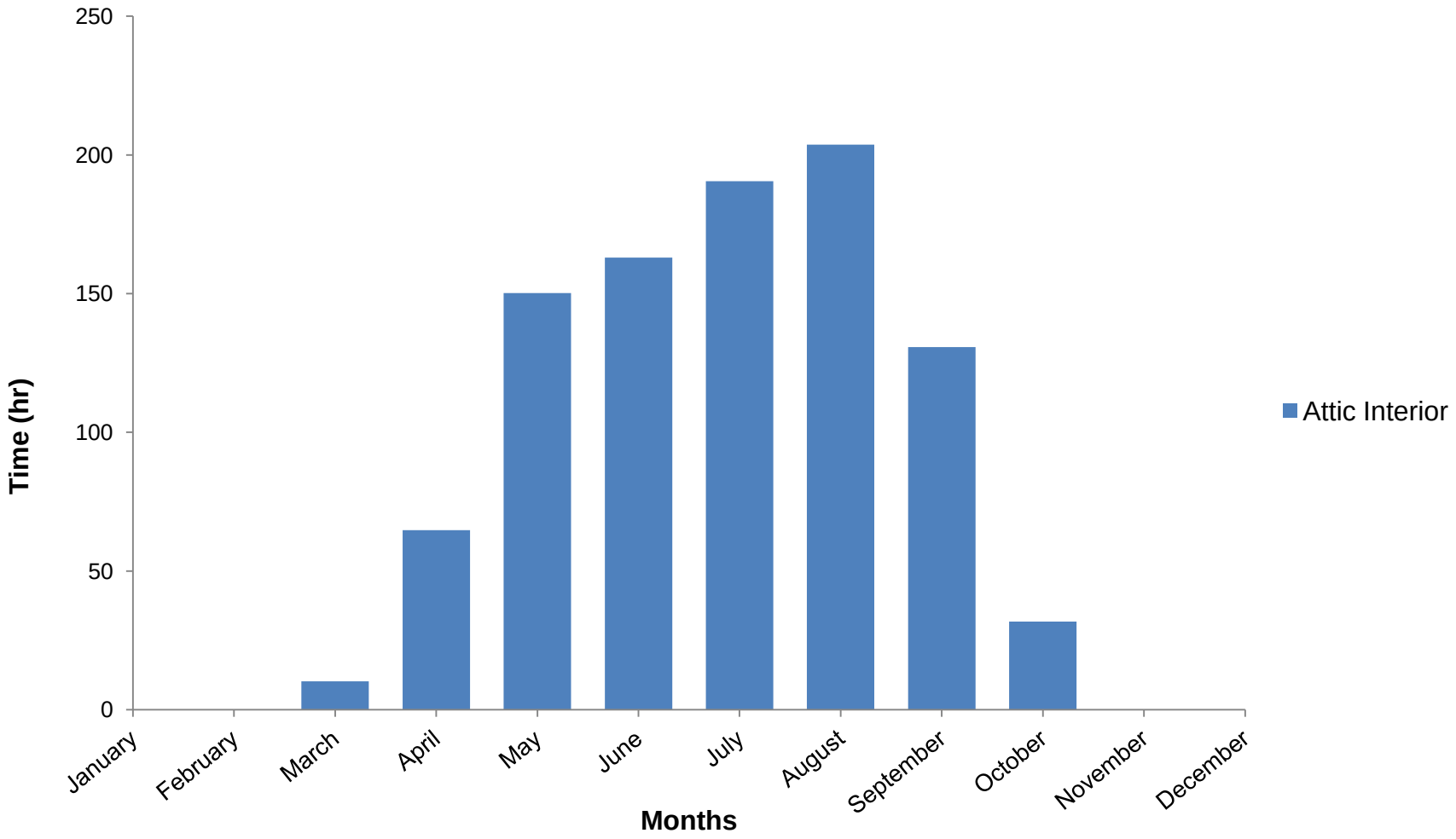

Figure 4-2. Time spent above 100°F (37.8°C) for attic space

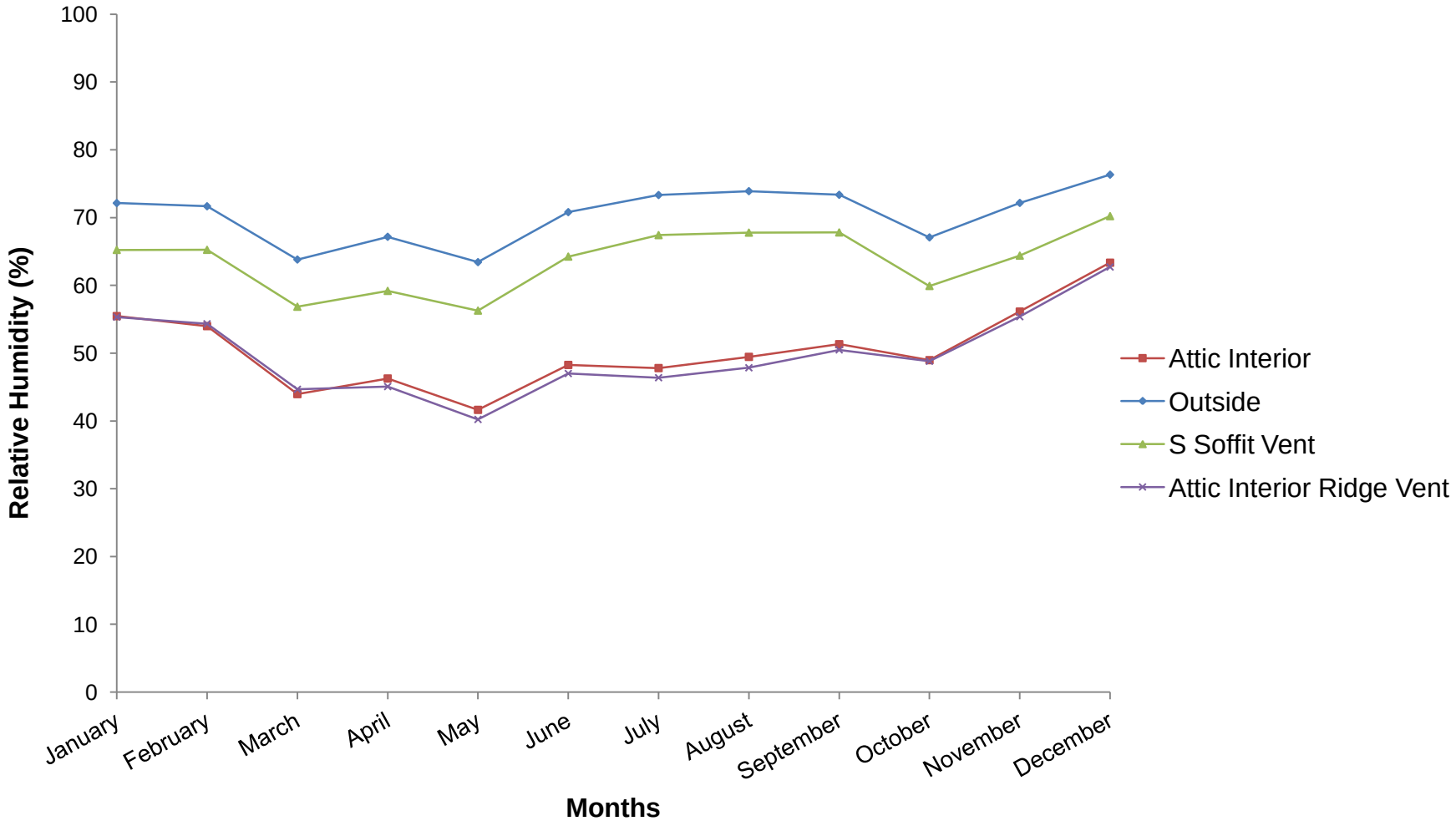

Figure 4-3. Monthly averages of relative humidity at various points

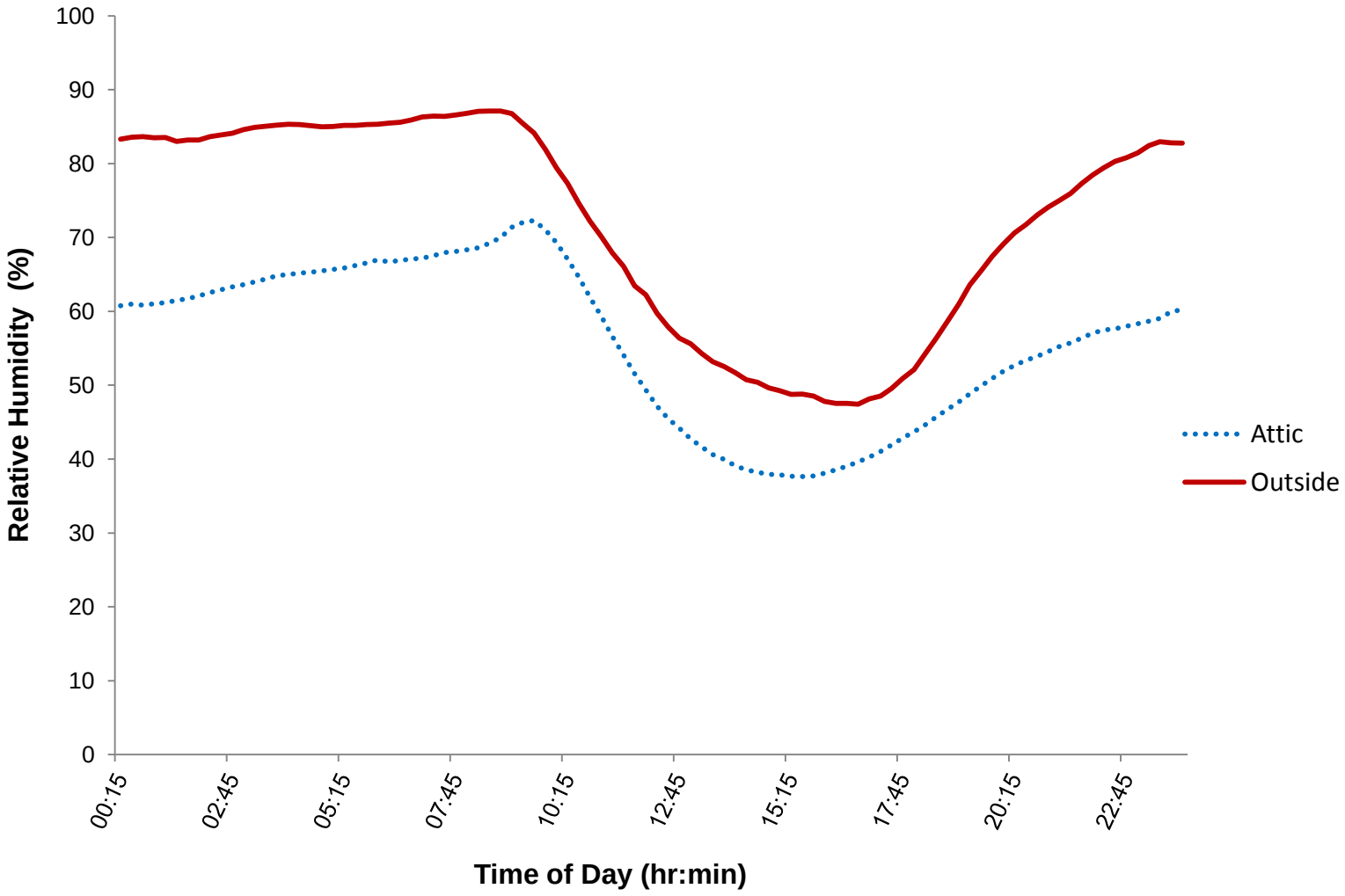

Figure 4-4. Time averaged daily relative humidity conditions for the average day in January

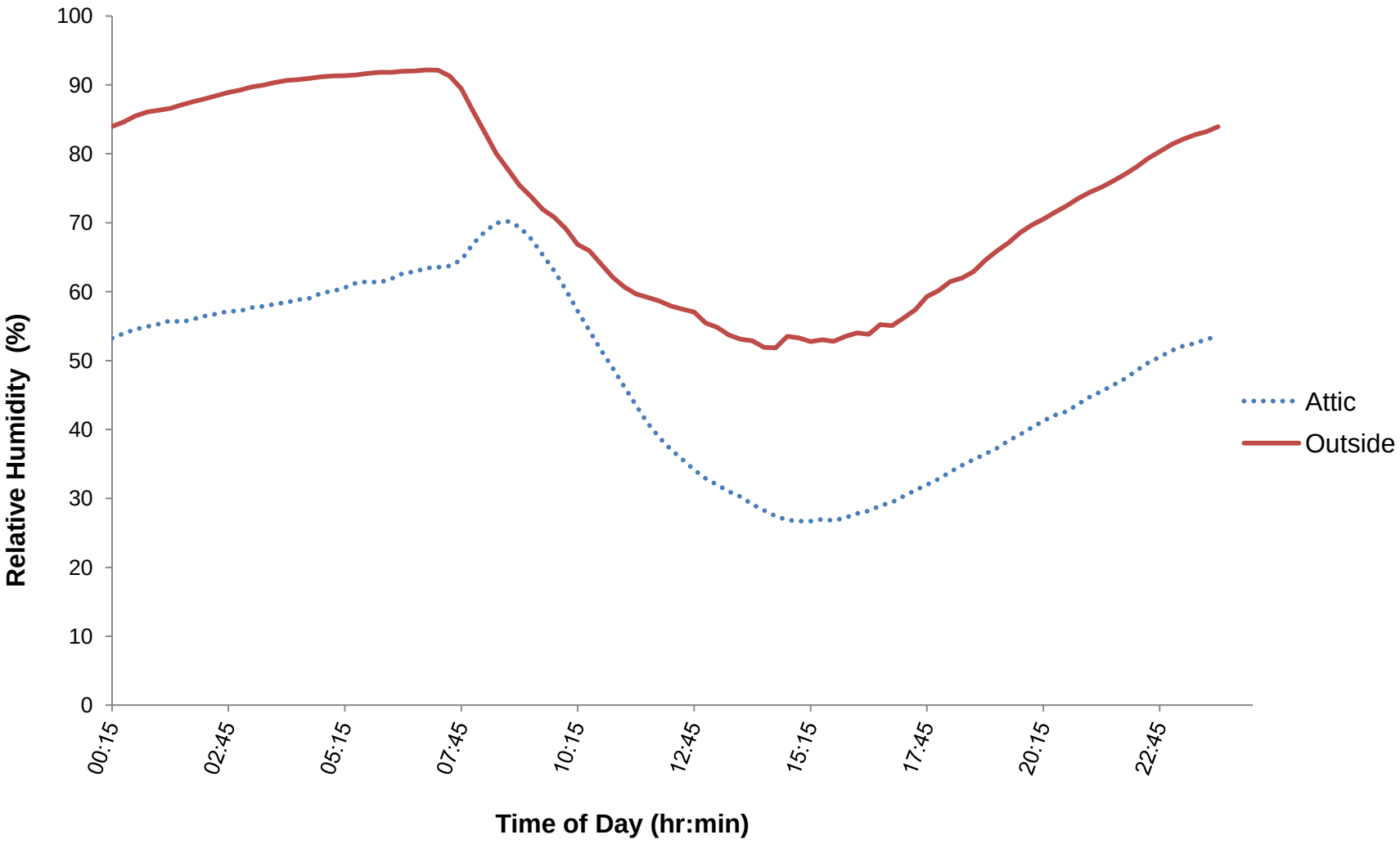

Figure 4-5. Time averaged daily relative humidity conditions for the average day in July

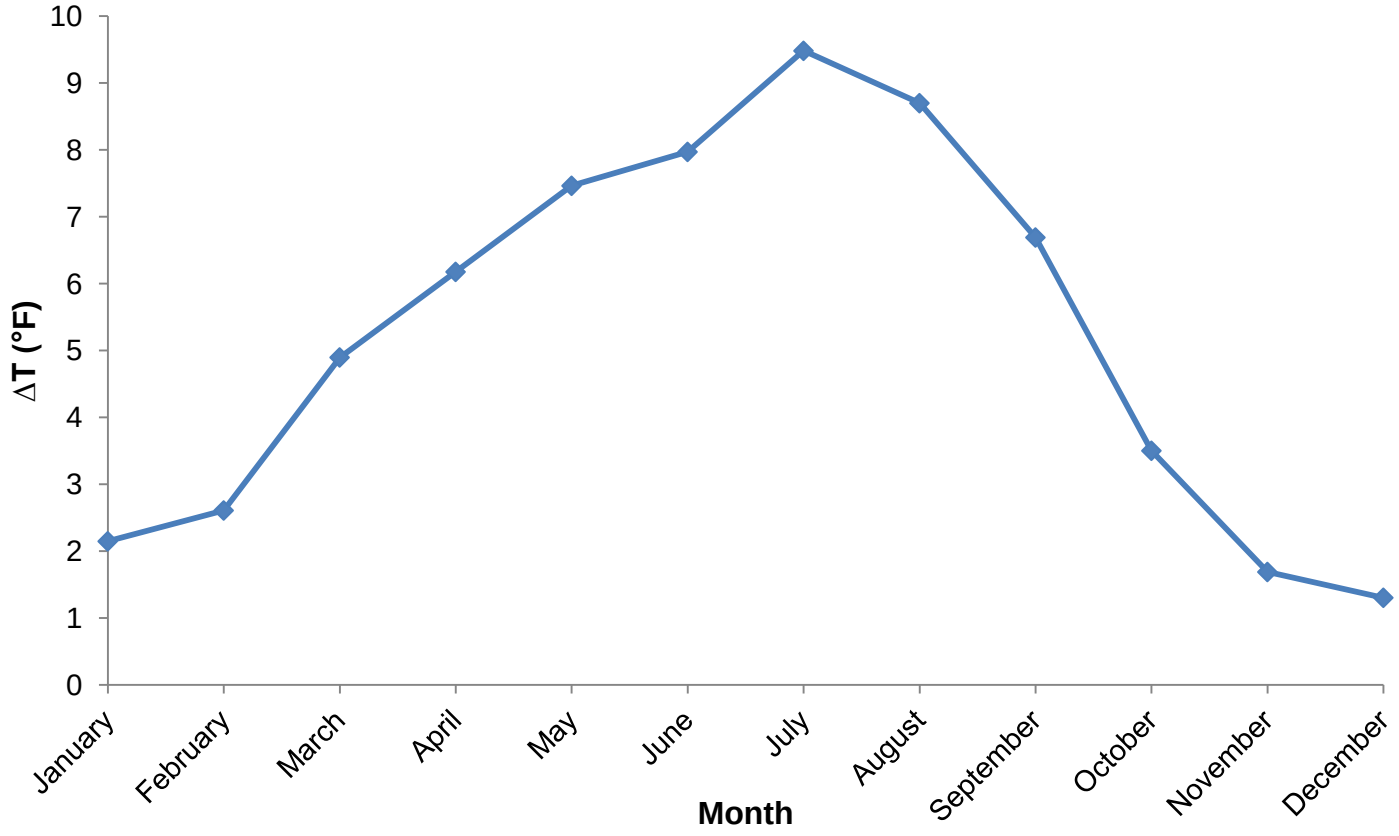

Figure 4-6. Average temperature difference of air travelling from soffit to ridge

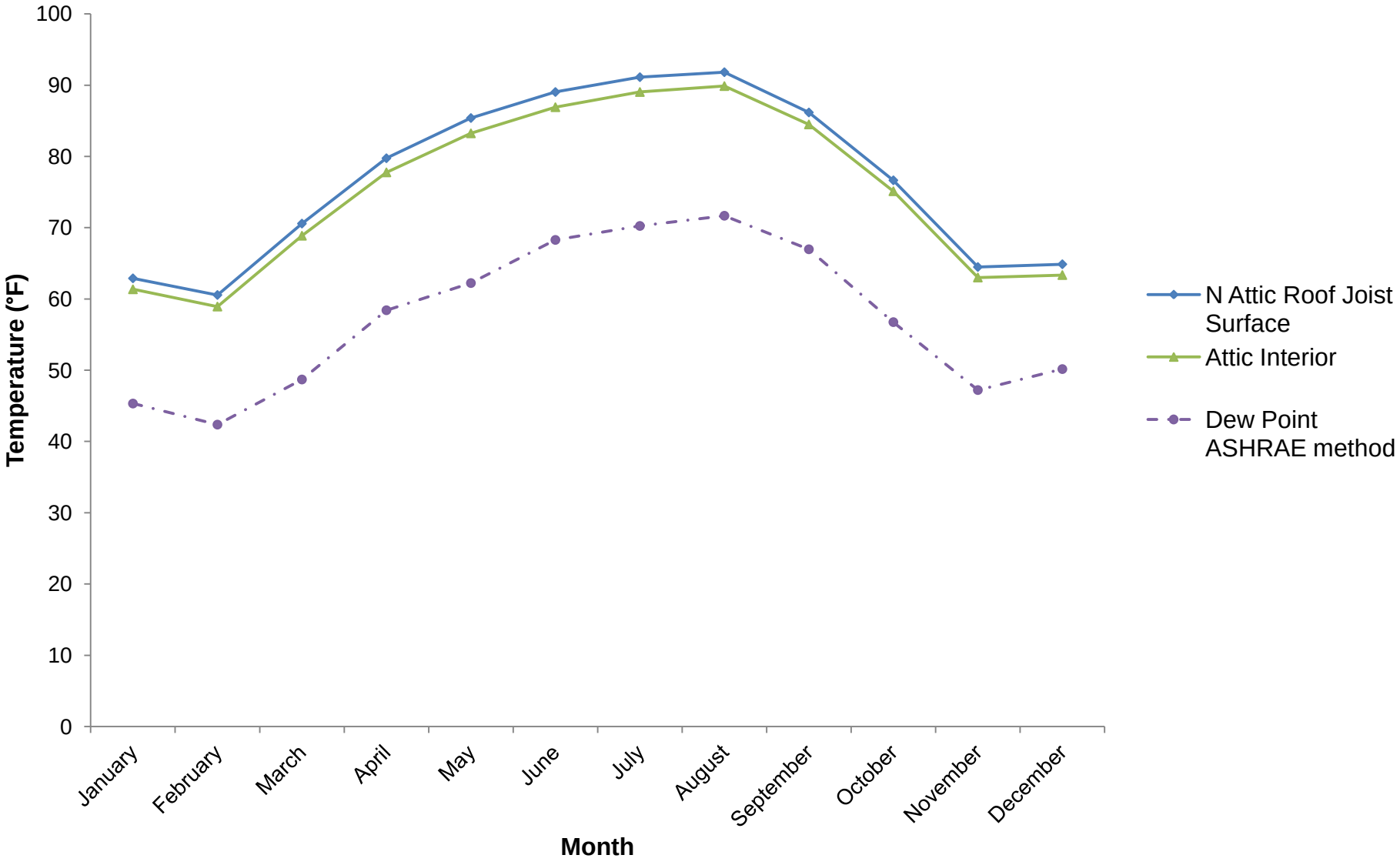

Figure 4-7. Monthly average temperature comparison for attic materials

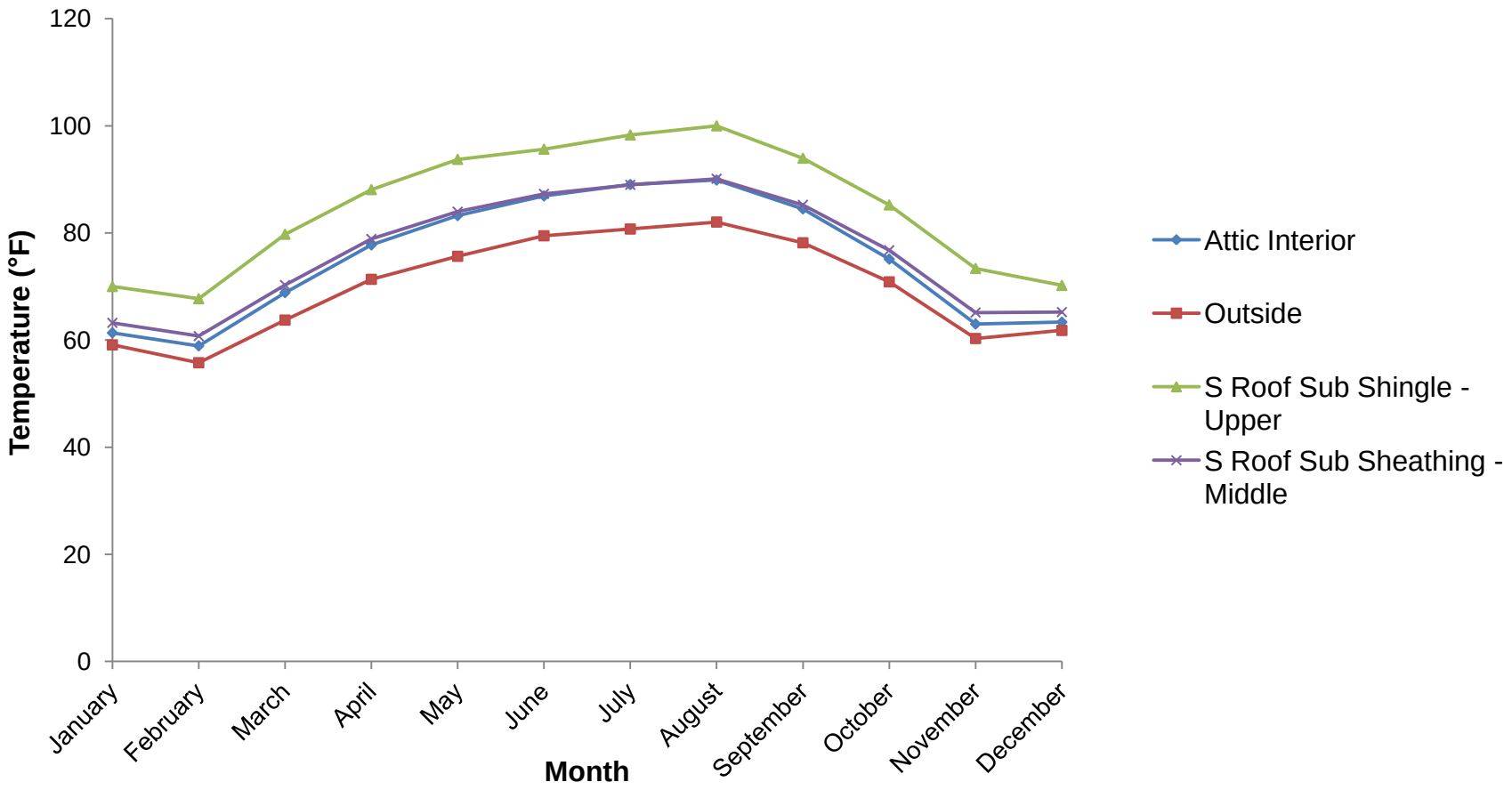

Figure 4-8. Temperature comparison of attic elements to environmental conditions

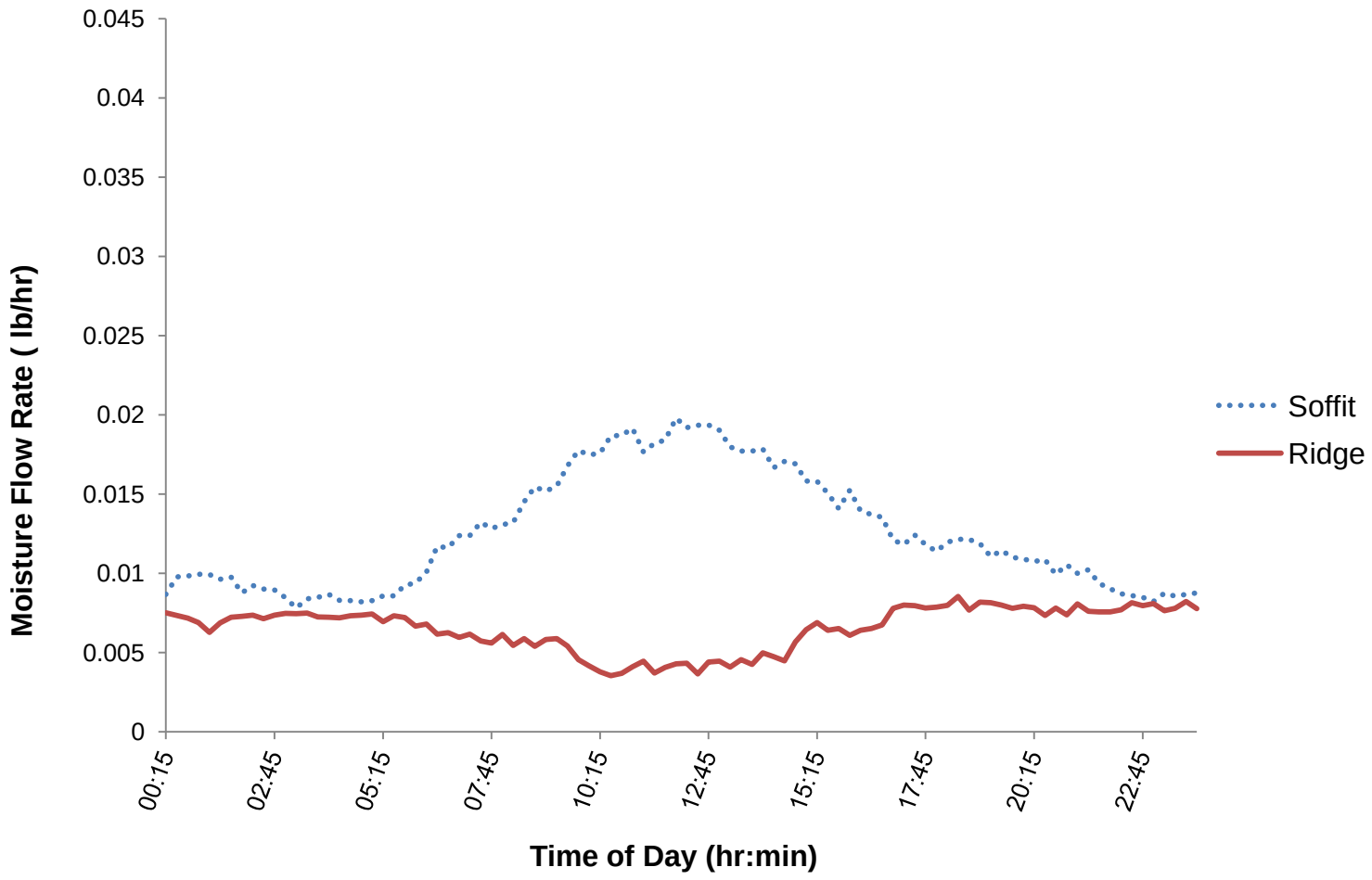

Figure 4-9. January moisture flux for the attic environment

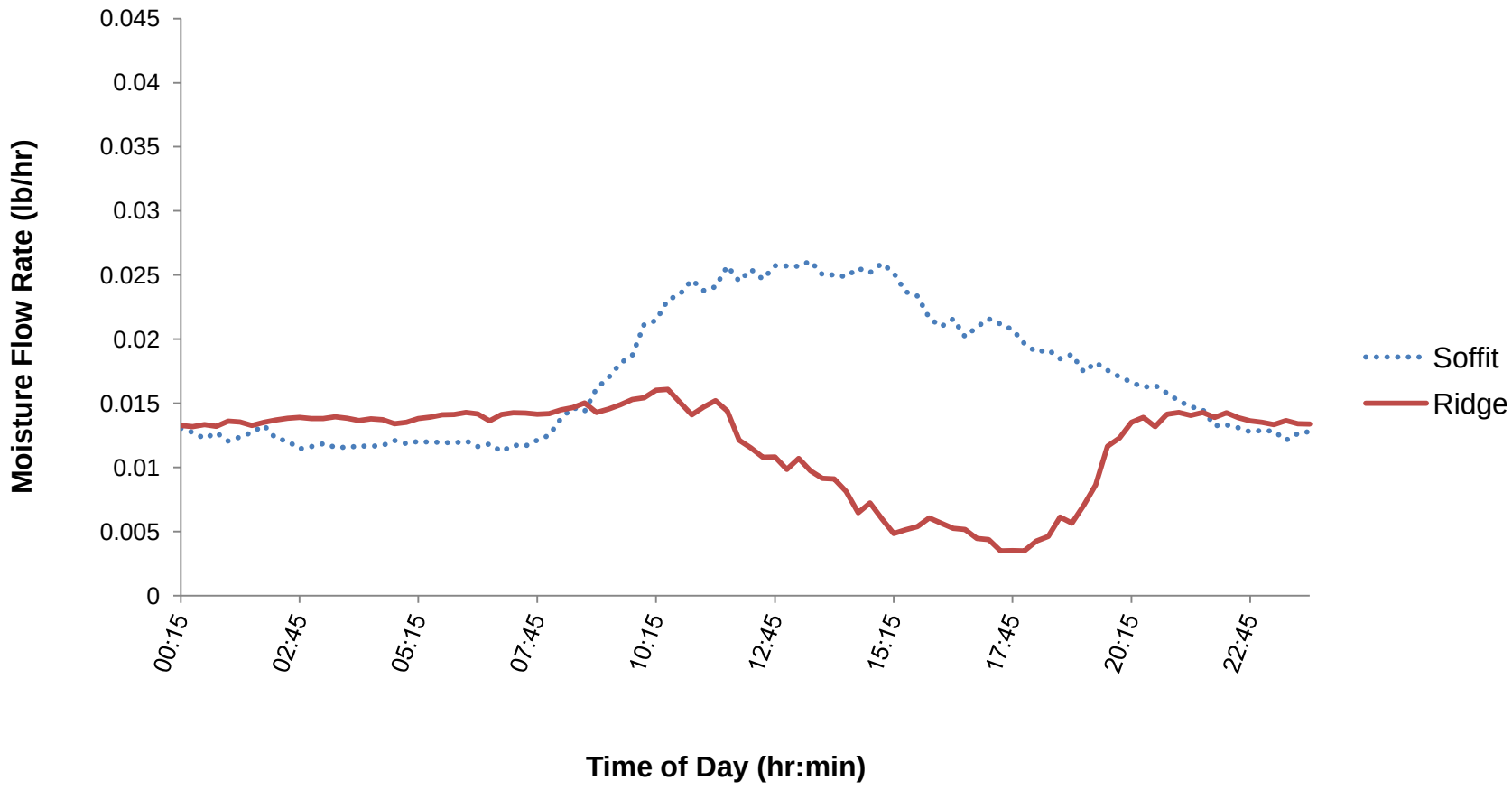

Figure 4-10. April moisture flux for the attic environment

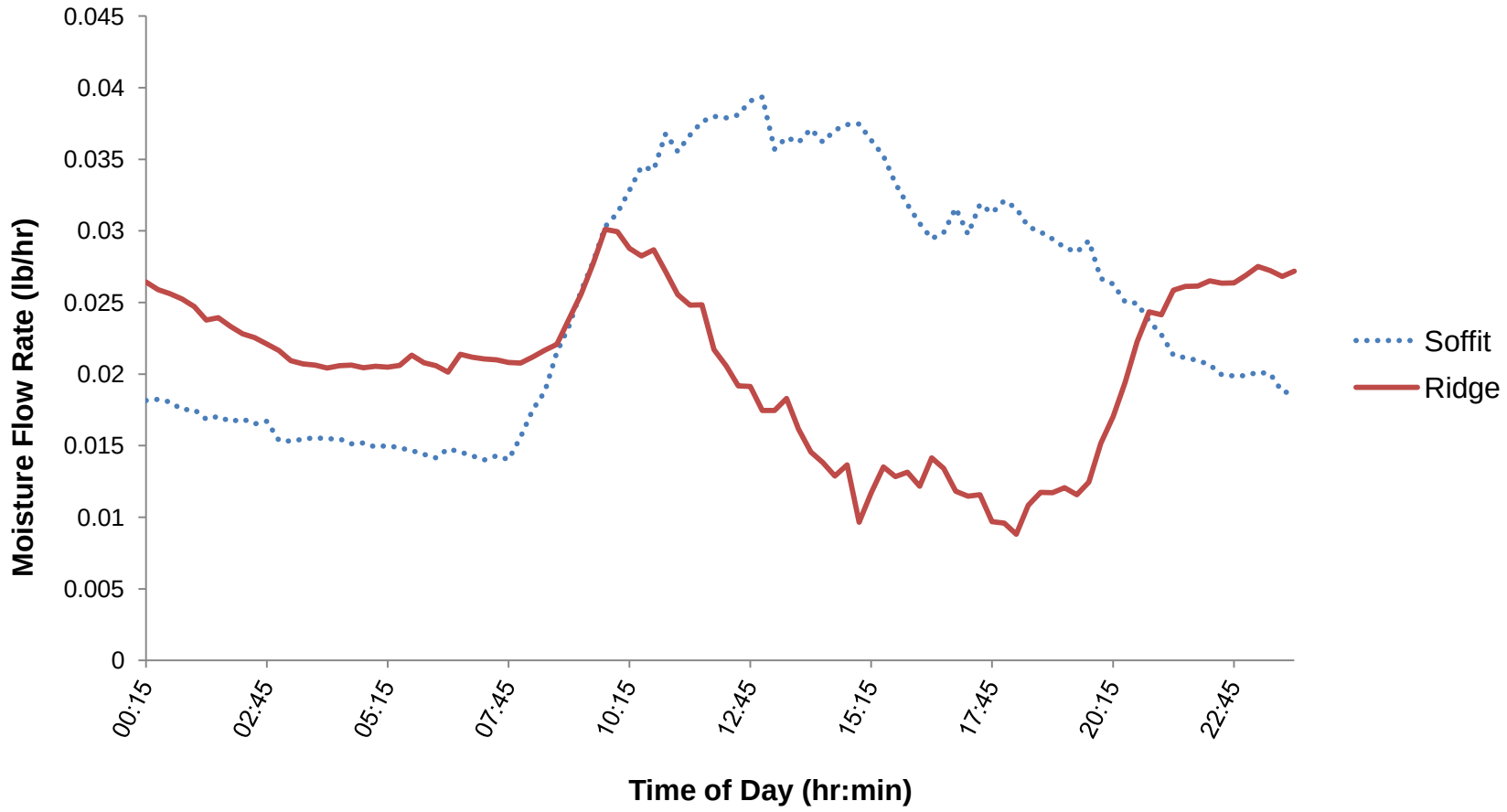

Figure 4-11. July moisture flux for the attic environment

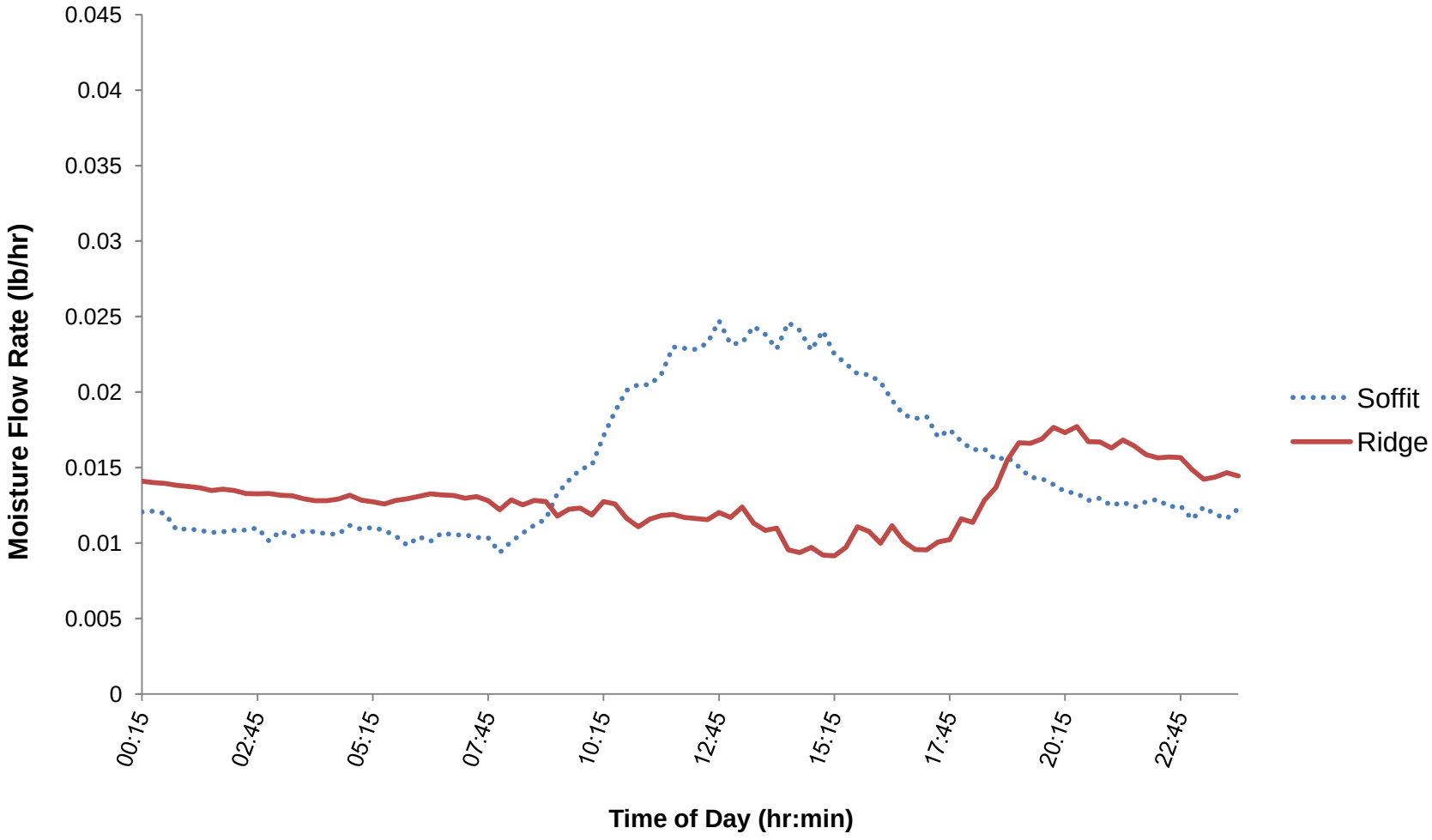

Figure 4-12. October moisture flux for the attic environment

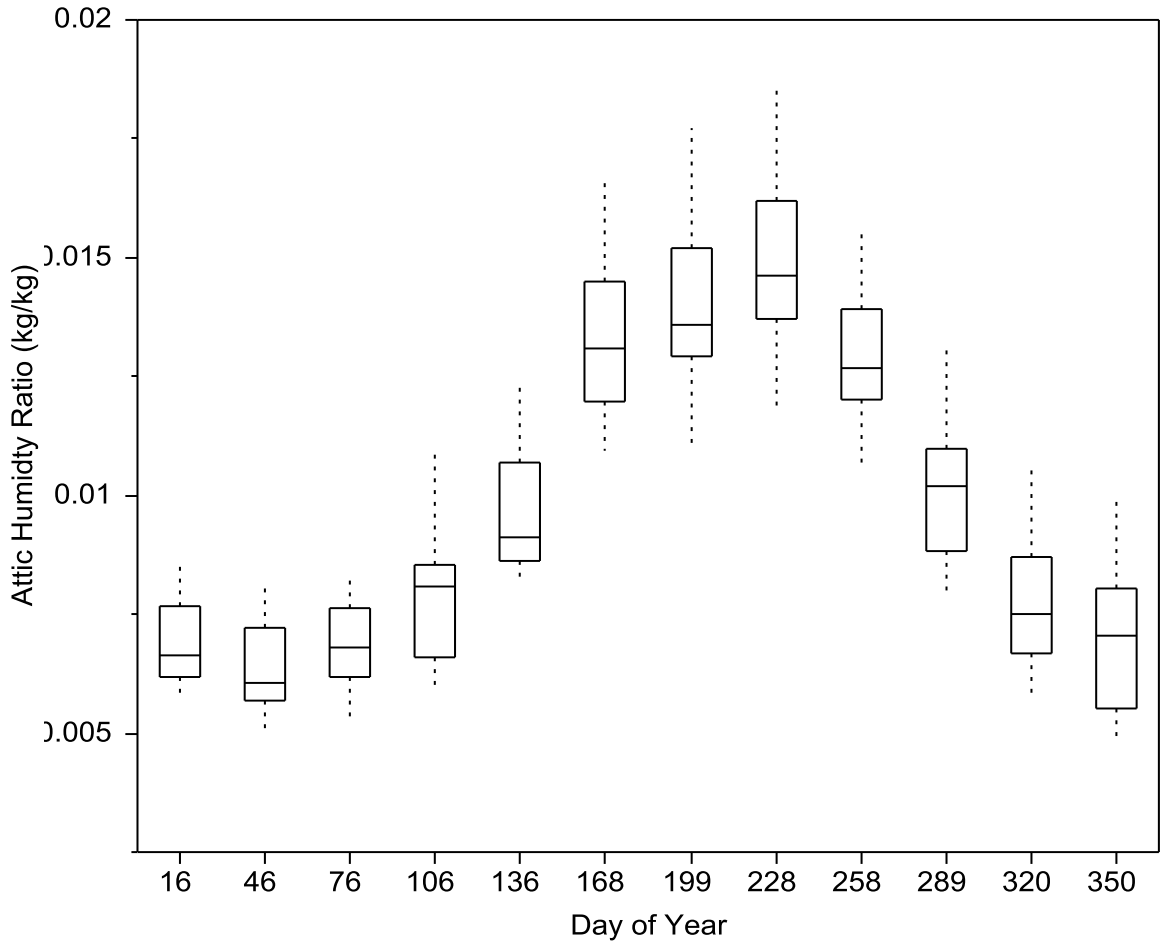

Figure 4-13. Monthly averaged seasonal values for the attic humidity ratio over 2005 and 2006 (1kg/kg = 1 lb/lb)

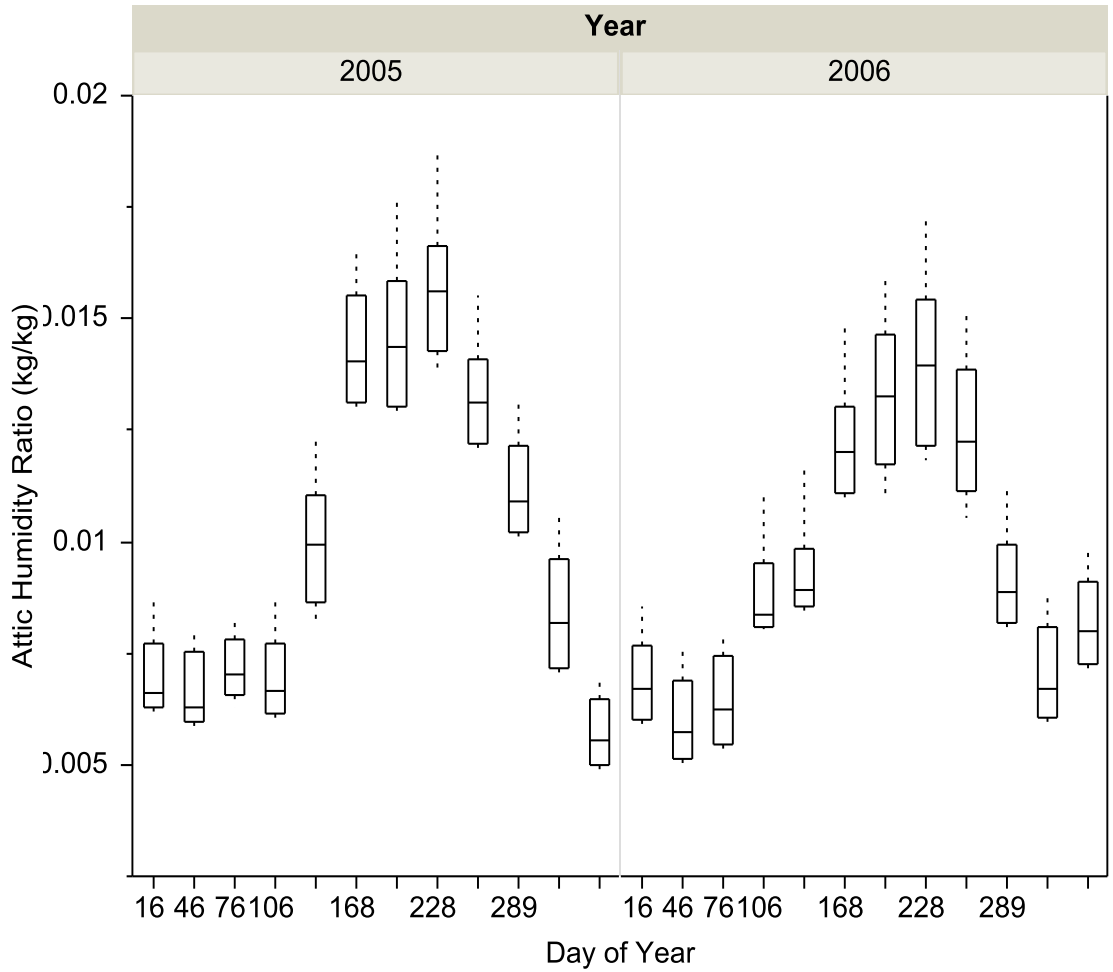

Figure 4-14. Monthly averaged seasonal values for the attic humidity ratio comparing the two year data set (1kg/kg = 1 lb/lb)

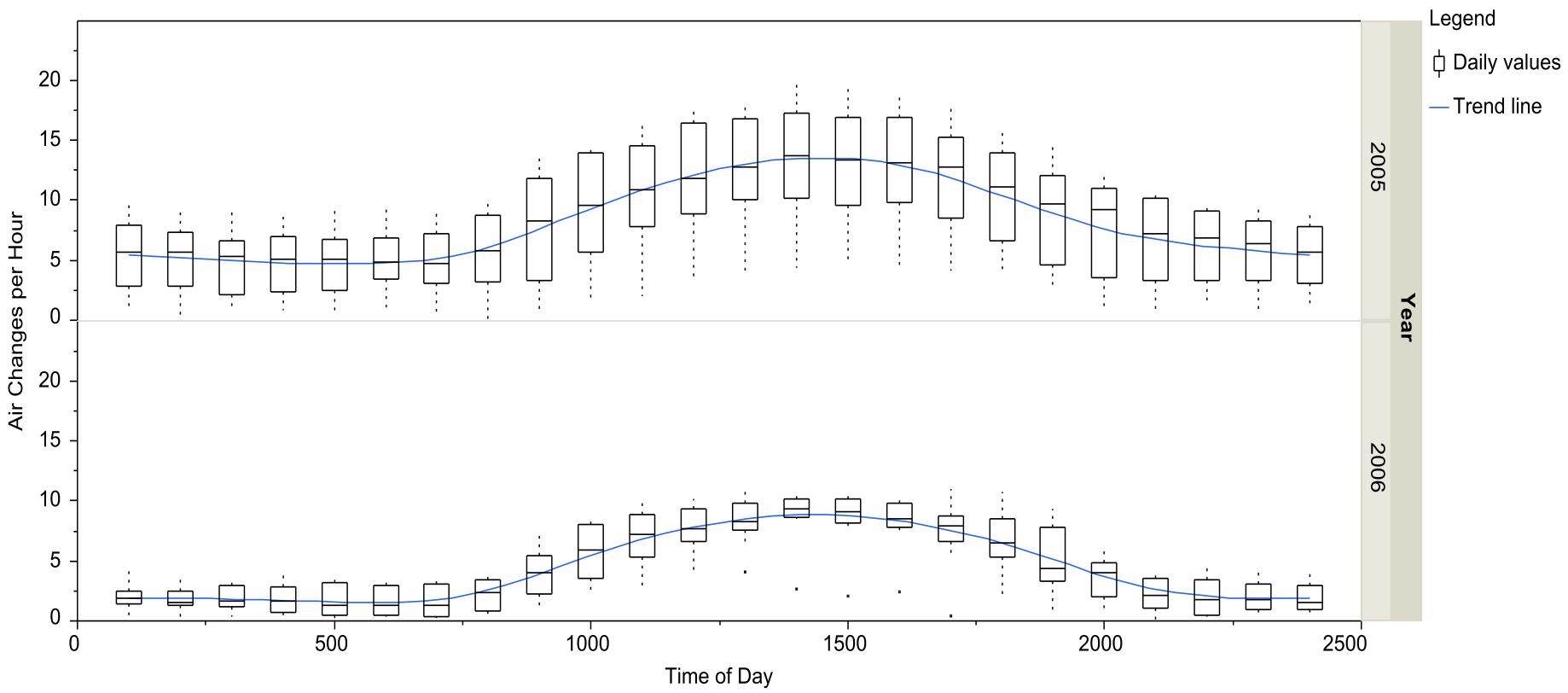

Figure 4-15. Time series variation in attic air changes per hour for 2005 and 2006

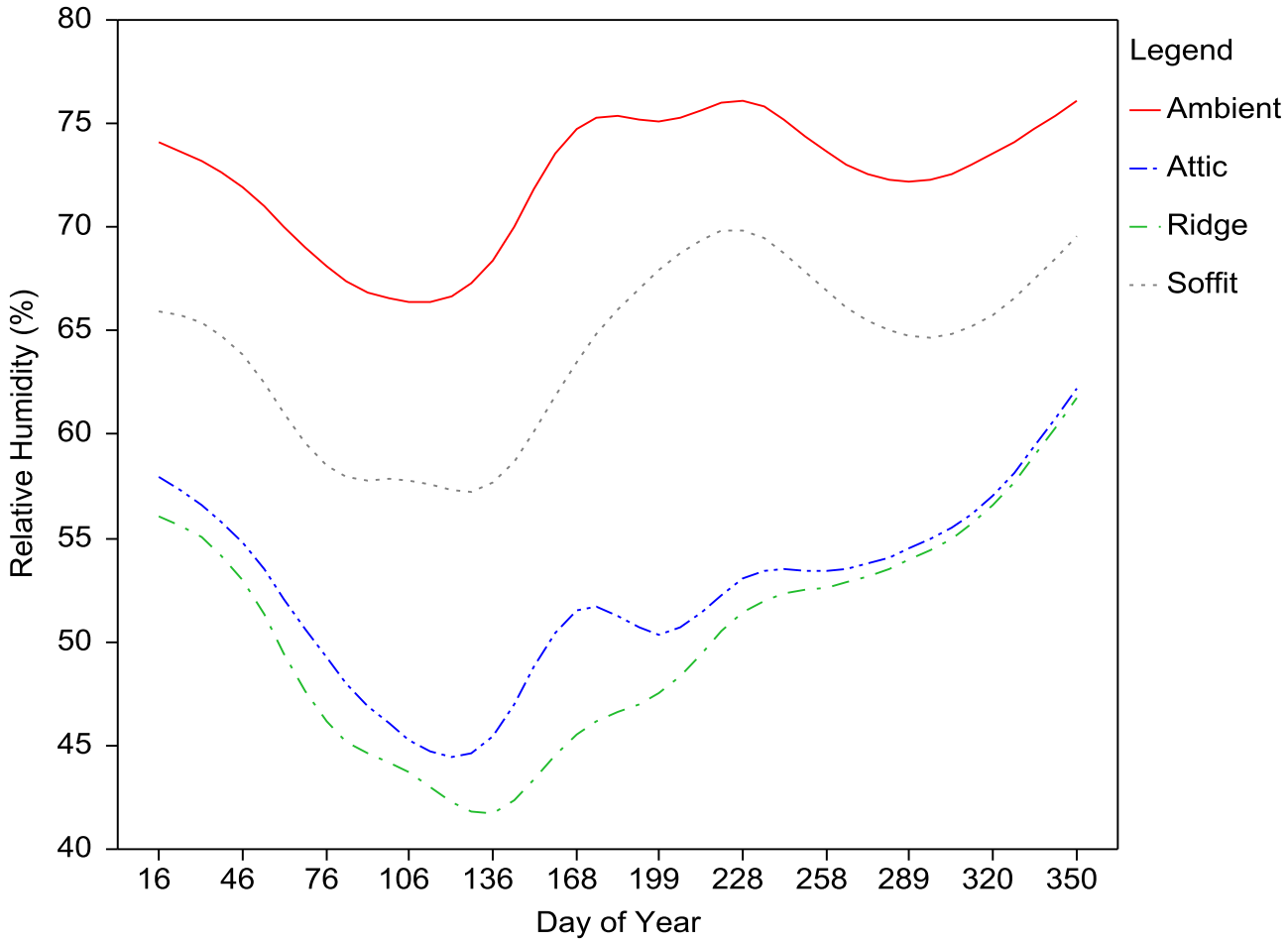

Figure 4-16. Fluctuations in relative humidity at various attic locations

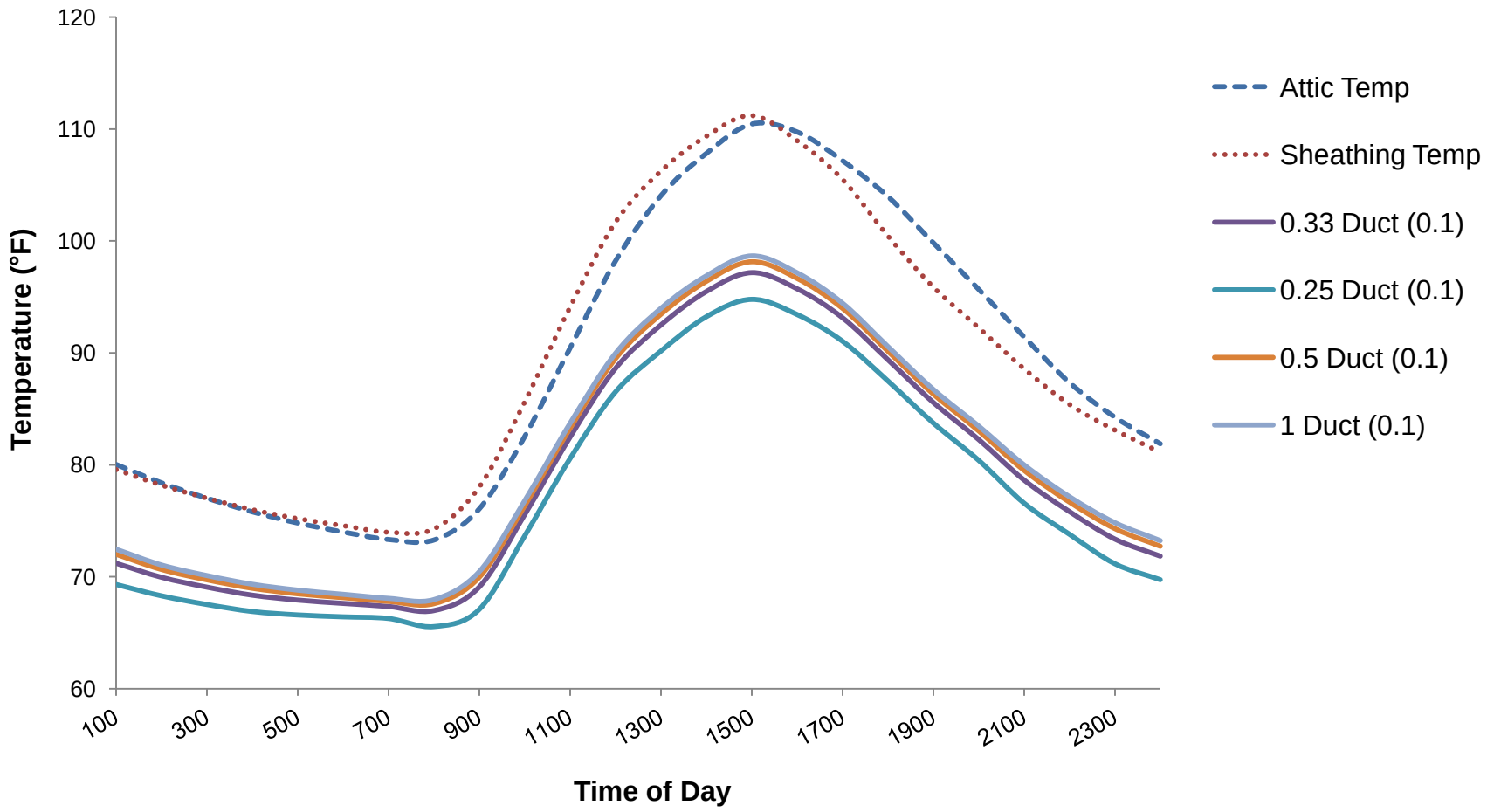

Figure 4-17. Temperature comparison of various thicknesses with duct absorptivity of 0.1 in July

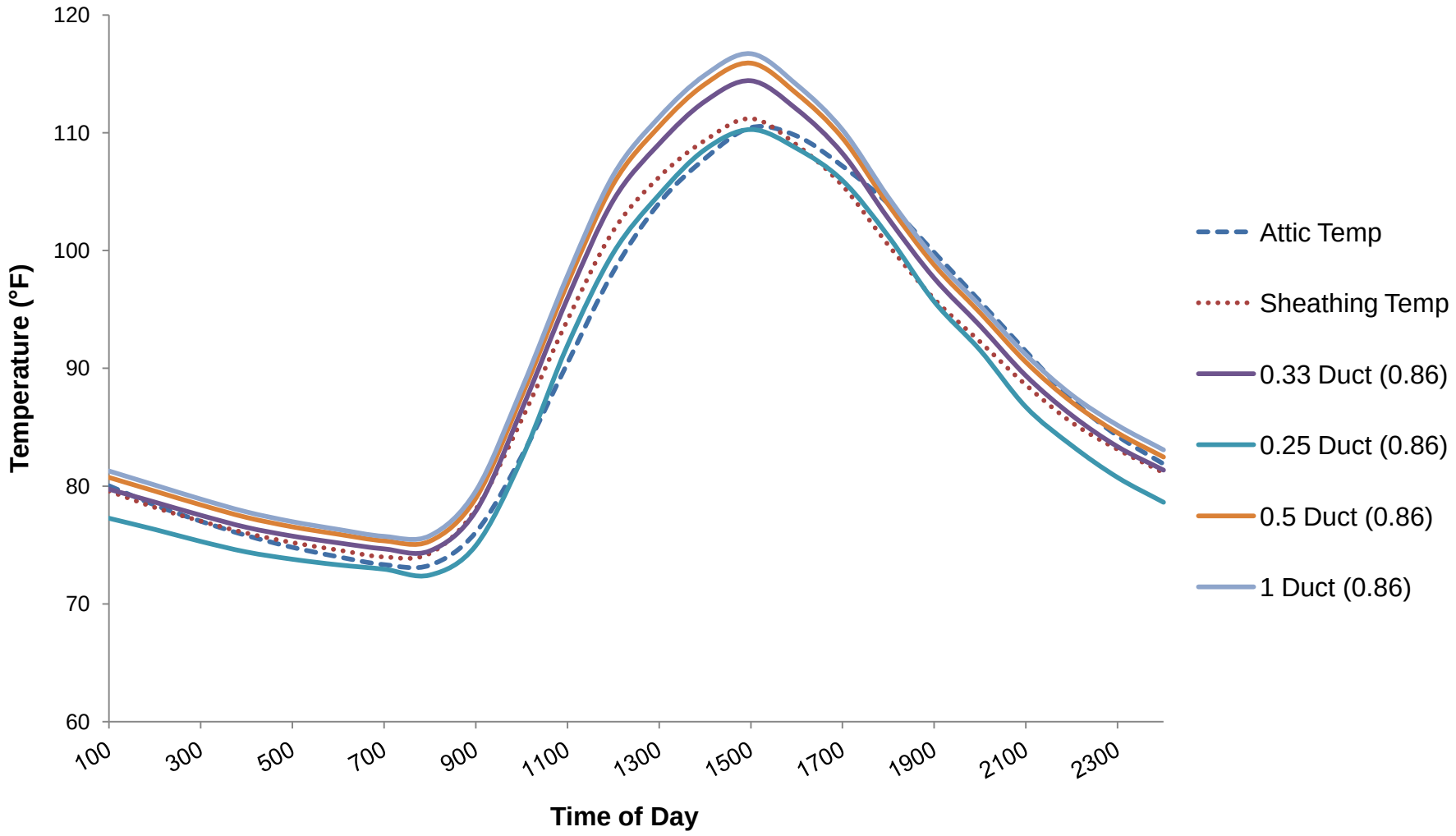

Figure 4-18. Temperature comparison of various thicknesses with duct absorptivity of 0.86 in July

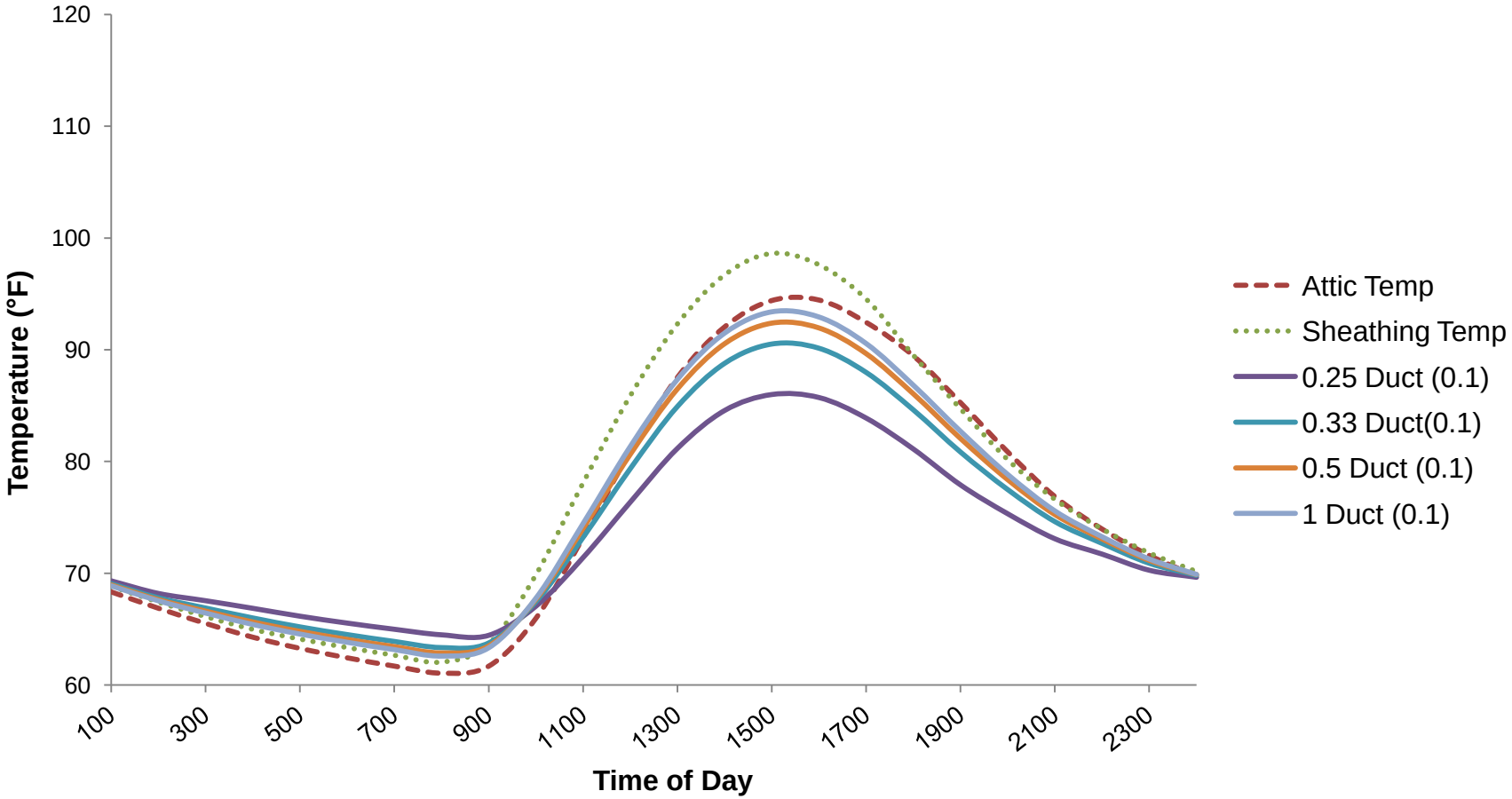

Figure 4-19. Temperature comparison of various thicknesses with duct absorptivity of 0.86 In October

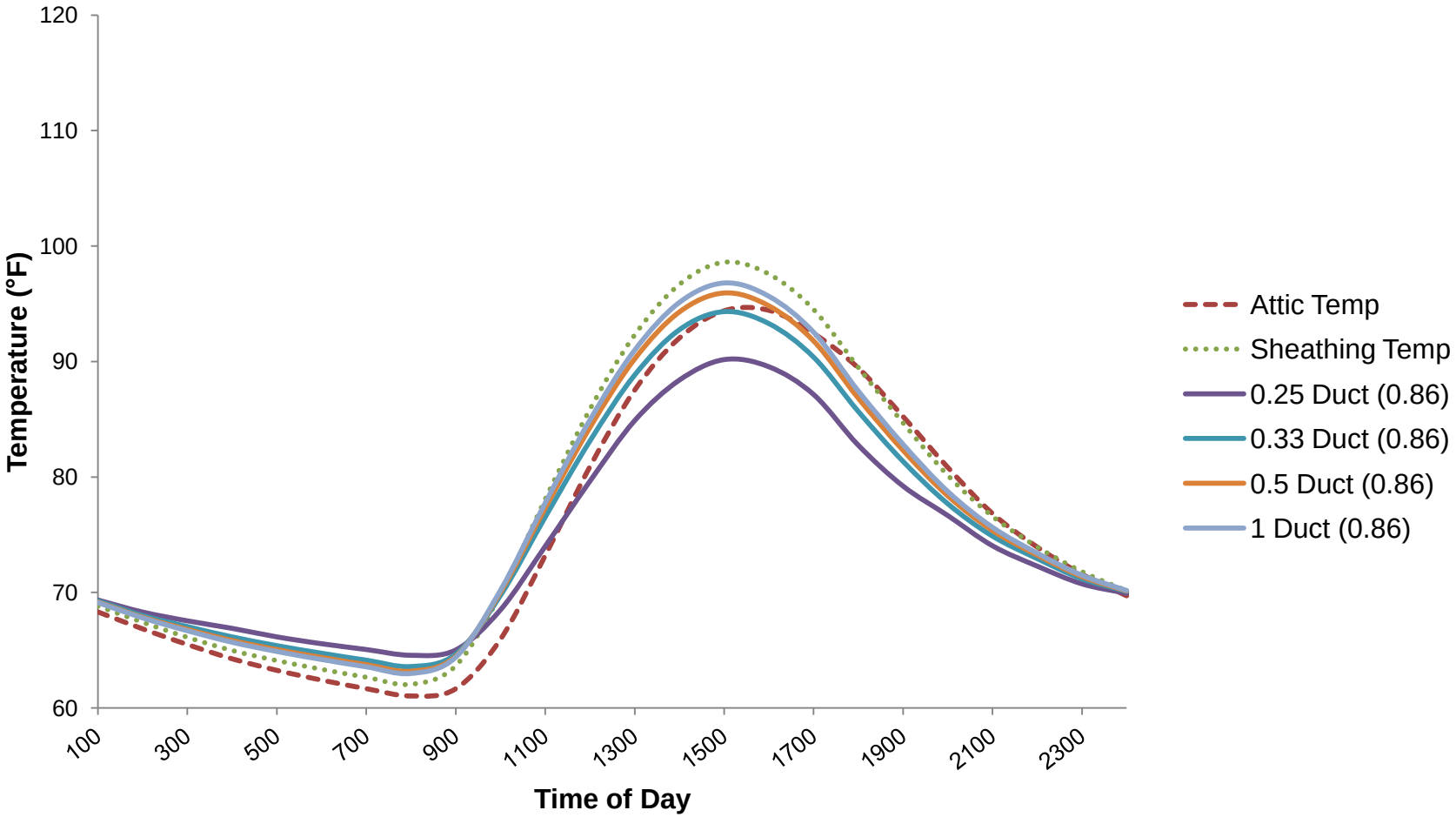

Figure 4-20. Temperature comparison of various thicknesses with duct absorptivity of 0.1 in October

Table 4-1. Comparison of raw temperature data between 2005 and 2006 in °F

Time of Day	July 2005				July 2006			
	0.25	0.33	0.5	1	0.25	0.33	0.5	1
100	74.07	75.97	76.76	77.18	77.26	79.73	80.74	81.29
200	73.22	74.91	75.62	76.01	76.31	78.63	79.58	80.09
300	72.62	74.15	74.84	75.21	75.29	77.52	78.42	78.90
400	71.93	73.52	74.17	74.53	74.40	76.49	77.35	77.81
500	71.40	72.94	73.58	73.92	73.78	75.75	76.55	76.98
600	70.93	72.53	73.18	73.53	73.30	75.17	75.92	76.32
700	70.79	72.27	72.89	73.22	72.94	74.66	75.36	75.73
800	70.37	72.08	72.77	73.15	72.44	74.49	75.33	75.79
900	73.12	75.39	76.25	76.72	74.93	77.87	78.97	79.57
1000	78.35	81.61	82.74	83.34	82.30	86.47	87.62	88.24
1100	85.13	88.64	90.04	90.79	91.94	95.93	97.19	97.87
1200	89.62	94.10	95.64	96.46	99.80	104.26	105.65	106.40
1300	92.31	96.72	98.40	99.30	104.75	109.06	110.54	111.33
1400	94.19	99.36	101.12	102.06	108.59	112.68	114.13	114.91
1500	94.89	99.47	101.32	102.25	110.28	114.42	115.92	116.72
1600	93.69	97.96	99.61	100.49	108.68	112.00	113.33	114.09
1700	91.88	94.73	96.24	97.05	105.95	108.24	109.55	110.25
1800	86.47	89.10	90.37	91.05	101.21	102.71	103.89	104.52
1900	83.51	86.17	87.38	88.03	95.66	97.65	98.78	99.38
2000	81.23	84.10	85.25	85.87	91.54	93.61	94.72	95.32
2100	79.66	81.60	82.66	83.23	86.70	89.36	90.53	91.15
2200	77.49	79.47	80.46	80.99	83.43	86.01	87.13	87.74
2300	75.79	78.00	78.94	79.45	80.72	83.34	84.53	85.17
2400	74.75	76.83	77.74	78.22	78.62	81.35	82.48	83.08

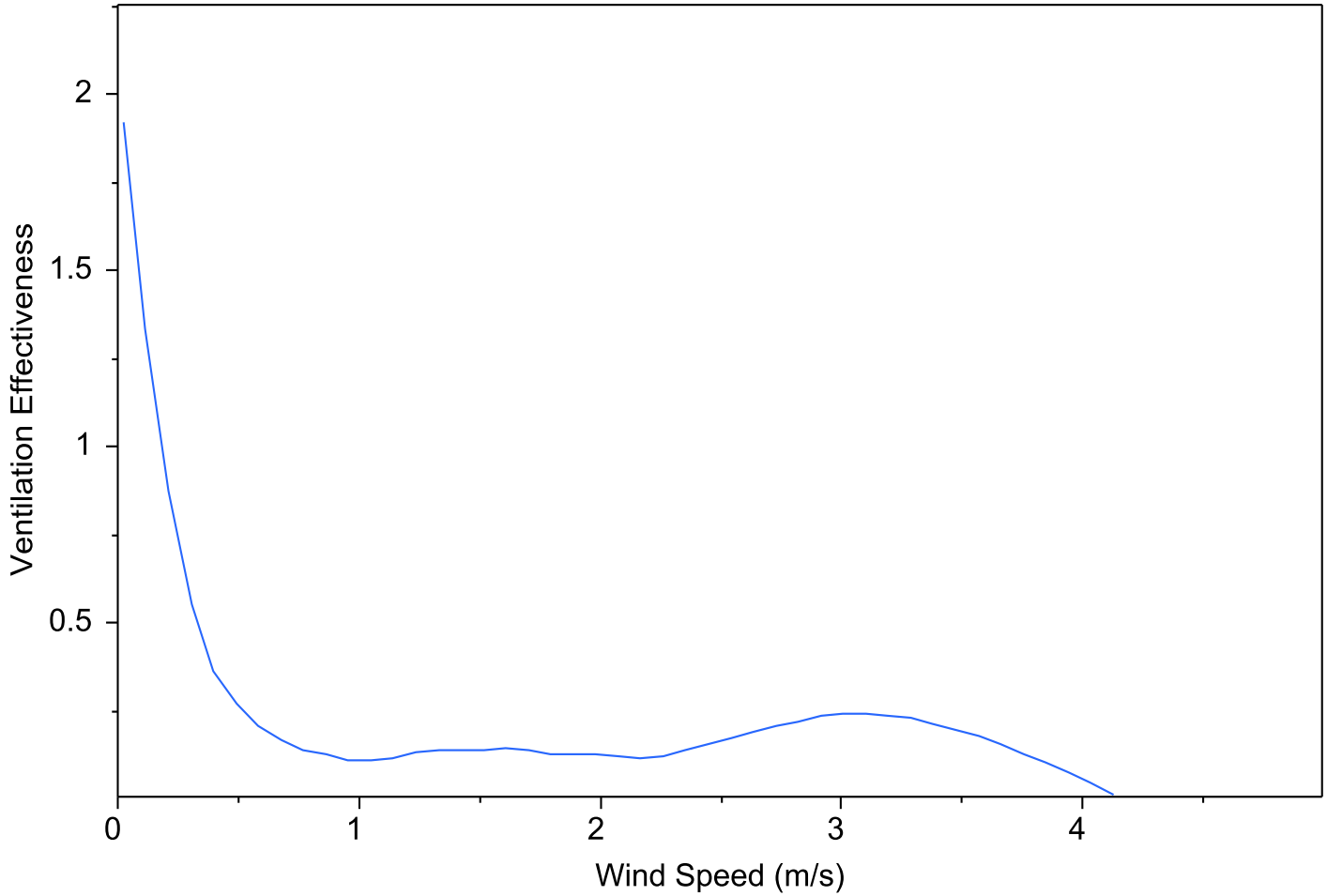

Figure 4-21. Empirical ventilation effectiveness profile with respect to wind speed

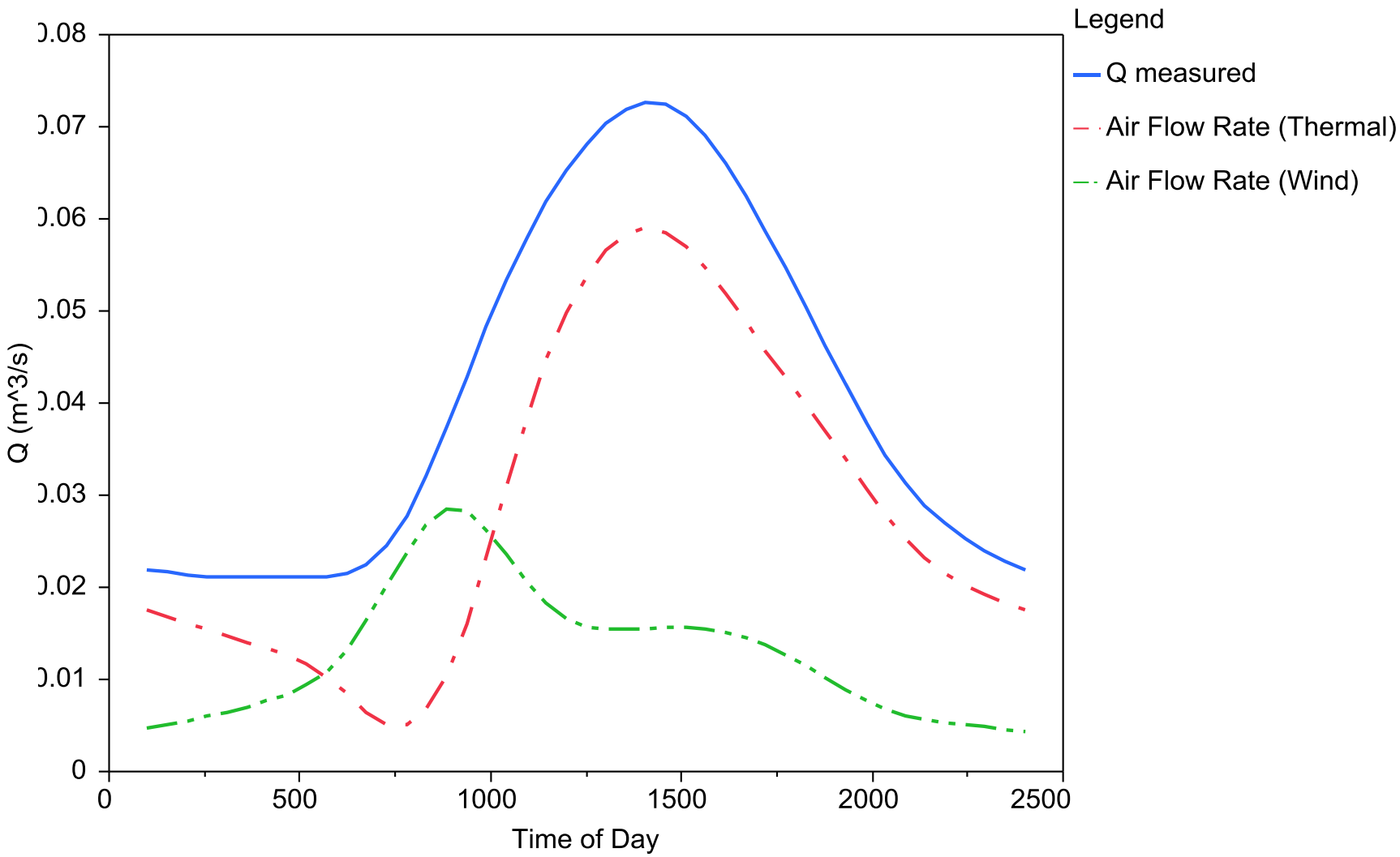

Figure 4-22. Volumetric flow rate in the attic with respect to time of day averaged over years

CHAPTER 5
CONCLUSION

Passively cooling attic spaces in hot, humid climates must be achieved in conjunction with ventilation rates that sustain moisture removal. Moisture movement through building materials will occur in hot, humid regions. Capillary movement of moisture through shingles, siding, and venting penetrations will force water into plenum spaces. Sealing these spaces with an impermeable membrane will force the plywood sheathing and truss members to store more moisture increasing mold and mildew problems. Moving this moisture requires air movement. It is possible that sealing the attic spaces entirely and insulating the structure would reduce the thermal heat transfer from an attic, but this would provide no outlet for moisture transported through porous roofing materials or past the ceiling plane.

The air movement in the attic serves to maintain a microclimate that is consistently dryer than the outdoor environment. Bulk air movement out of the ridge vent, contingent on radiated heat to the roof, is the result of natural thermal buoyancy and illustrates the necessity of ridge venting for proper microclimate development. Designing for a hot, humid climate must balance undesirable heat storage while maintaining a moving air mass that can carry moisture through the ridge.

A ventilated attic possesses many advantages for a hot, humid climate. While peak attic temperatures are high during summers, the relative humidity remains well below that of the external environment. Relative humidity is of specific interest in this study because the overall health of the attic depends on the temperature and moisture

gradient around the wood framing members. The exchange of moisture between the porous wood surfaces and the attic air is a function of relative humidity.

The resulting attic climate provides high temperature gradients between the attic and the conditioned spaces below. Under these circumstances the building envelope boundary of hot, humid regions should be considered conditioned space and insulated accordingly. Overall, these data support increased insulation and materials with high thermal resistances positioned at the ceiling deck to reduce the heat flux into conditioned space. A dry attic climate creates efficient insulation and a healthy building.

The built environment is served by ventilated attics that surround the air conditioning ductwork. While traditional building codes allow for installation of this equipment in attic spaces, many cannot be effectively sealed and thereby lose energy in the transmission of conditioned air. Best practices for building design would place ductwork in conditioned spaces. Since much of the existing housing still contains ductwork in attics and cannot easily be retrofitted, ventilation and proper installation are necessary to gain efficiency and to reduce incidences of condensation.

The model created for this research uses data collected for attic parameters and creates a transient attic microclimate. Output data from this model show that the movement of moisture entering attics is removed by the ventilation from natural convection. If moisture becomes entrapped in the attic, it will become stagnant and condense at the duct surface or within ceiling insulation. Proper installation reduces the duct leakage and mitigates the effects of condensation. These data indicate that ductwork with crimped or damaged parts, present locations where conditioned air can

sufficiently cool the surface and lead to condensation, especially during swing months when air conditioning may cycle during cool moist mornings.

The methodology presented in this paper shows that ventilation will remove trapped moisture, mitigating the problems of poorly installed ductwork. Adding the necessary inputs for a sealed attic and closing off the vents provides insight into the likelihood of condensation. Further analysis and long-term studies on the effect of entrained moisture are necessary to draw conclusions needed to make policy updates to the state building codes. This model can be used for future studies looking for insight into the mechanics of heat and moisture transfer in ventilated and un-ventilated spaces.

APPENDIX A
MODEL SOURCE CODE

```
%Attic physical Characterisitics (all in feet)
R = 1.5; %Outer Radius of the duct
r = 0.75; %Inner Radius of the duct
atticWidth = 6.1/.3048;
atticHeight = 1.6/.3048;
atticLength = 3.162/.3048;
sheathingLength = sqrt((atticWidth/2)^2+atticHeight^2);
roofPitchDeg = atand(atticHeight/(atticWidth/2));
roofPitchRad = atan(atticHeight/(atticWidth/2));
charLength = atticWidth/2;   %characterisitic length for sheathing surfaces
A = sheathingLength*atticLength;
A1 = A;
A2 = A1;
A3 = 20;
A4 =1;
A345 = 22;
a2 = sind(53.973)*(8-R);
ductLength=1;
Ad = 2*pi()*R*ductLength; %% Surface Area
[Data,Variables] = xlsread('E:/Research/Attic 9 Data and Weather/Sep
2006.xls','Sheet1');
numrows = size(Data,1);

[radData,radVariables] = xlsread('E:/Research/Attic 9 Data and
Weather/ViewFactors.xls','Sheet1');
   F12 = radData(1);
   F13= radData(2);
   F15= radData(3);
   F14= radData(4);
   F1345= radData(5);
   F1d= radData(6);
   F21= radData(7);
   F2345= radData(8);
   F2d= radData(9);
   F31= radData(10);
   F3451= radData(11);
   F32= radData(12);
   F3452= radData(13);
   F3d= radData(14);
   Fd1= radData(15);
   Fd2= radData(16);
   Fd3= radData(17);
   Fd4= radData(18);
```

```
   Fd5= radData(19);
   F23= radData(20);
   F25= radData(21);
   F24= radData(22);
sigma = 0.1714E-8;
epsr = 0.86;
epsd = 0.1;
rho = 1-epsd;
RH = [10,50,75,100];
epsg =[0.1,0.19,0.22,0.47];
delta = [0,0.1,0.2,0.3,0.4,0.5,0.6,0.8,1.0,1.5,2,2.5,3,5];
Psi =
[1,0.9157,0.8491,0.7934,0.7458,0.704,0.6672,0.6042,0.5532,0.4572,0.39,0.3401,0.301
6,0.2077];

%Guesses for iteration of duct surface temp
Tduct = zeros(numrows,10);
Troof1 = zeros(numrows,1);
Troof1K = zeros(numrows,1);
Troof2 = zeros(numrows,1);
Troof2K = zeros(numrows,1);
Tceil = zeros(numrows,1);
To = zeros(numrows,1);
TceilK = zeros(numrows,1);
ToK = zeros(numrows,1);
aRH = zeros(numrows,1);
atticTemp = zeros(numrows,1);
airVelocity = zeros(numrows,1);
exteriorTemp= zeros(numrows,1);
bayTemp= zeros(numrows,1);
time = zeros(numrows,1);
tolerance  = zeros(numrows,10);

%Initial guess for exterior duct temp
for h=1:10
   for i=1:numrows
      Tduct(1,h) = Data(1,5);
      tolerance(i,h) = 1;
   end
end
%Tduct(1,1) = Data(2,5);
%[radData,radVariables] = xlsread5('F:/Research/Attic 9 Data and
Weather/ViewFactors.xls','Sheet1');
for h=1:1
   epsd = 0.1*h;
   rho = 1-epsd;
```

```
    for i=2:numrows
        Tduct(i,h) = Data(i,5)+30;
        atticTemp(i,1) = Data(i,9);
        airVelocity(i,1)= abs(Data(i,14));
        exteriorTemp(i,1) = Data(i,28);
        bayTemp(i,1) = Data(i,8);
        time(i,1) = Data(i,2);

        % Calculation of interior boundary conditions
        if atticTemp(i)>85
            ductTemp = 55;
            ductAirVelocity = 2;
        elseif atticTemp(i)<62
            ductTemp = 85;
            ductAirVelocity = 2;
        else
            ductTemp = bayTemp(i,1);
            ductAirVelocity = 1;
        end

        filmTemp = ductTemp;
        ductAirTK = (ductTemp+459.67)/1.8;
        ductAirK = (0.6325E-5*sqrt(ductAirTK)/((1+245.4*10^(-
12/ductAirTK))/ductAirTK))*241.77;  %thermal conductivity of Air (in english units I think)
        ductAirCp = (3.4763+(1.066E-4)*ductAirTK)*0.068559;
        ductAirMu = (145.8*ductAirTK*sqrt(ductAirTK)/(ductAirTK+110.4))*241.9E-7;
        ductAirRho = 22.0493/ductAirTK;
        ductAirKinVis = ductAirMu/ductAirRho;

        ductBeta= 1/(filmTemp+459.67);
        ductPr = 0.7880-2.63E-4*ductAirTK;
        ductRa =
4.16975E8*ductBeta*ductAirRho*ductAirCp*ductTemp*charLength^3/ductAirKinVis/duct
AirK;
        ductRe = ductAirVelocity*charLength/ductAirKinVis;
        if ductRe<5E5
            ductforNu = 0.664*ductPr^(1/3)*sqrt(ductRe);
        else
            ductforNu = ductPr^(1/3)*(.037*ductRe^0.8-850);
        end

        %Calculate Convective Coefficients Interior
        forConCoeff = ductforNu*ductAirK/charLength;
        ductConvCoeff = forConCoeff;
```

```
% Calculation of Boundary Conditions for Convective transfer
atticT = atticTemp(i,1);
filmTemp = atticT;
atticAirVelocity = airVelocity(i,1)/60;
atticAirTK = (atticT+459.67)/1.8;
atticAirK = (0.6325E-5*sqrt(atticAirTK)/((1+245.4*10^(-
12/atticAirTK))/atticAirTK))*241.77;  %thermal conductivity of Air (in english units I think)
atticAirCp = (3.4763+1.066E-4*atticAirTK)*0.068559;
atticAirMu = (145.8*atticAirTK*sqrt(atticAirTK)/(atticAirTK+110.4))*241.9E-7;
atticAirRho = 22.0493/atticAirTK;
atticAirKinVis = atticAirMu/atticAirRho;

atticBeta= 1/(filmTemp+459.67);
atticPr = 0.7880-(2.63E-4)*atticAirTK;
atticRa =
4.16975E8*atticBeta*atticAirRho*atticAirCp*atticT*charLength^3/atticAirKinVis/atticAirK;
atticRe = atticAirVelocity*charLength/atticAirKinVis;
atticnatNu = 0.56*(atticRa*cosd(90-roofPitchDeg))^0.25;
if  atticRe<5E5
   atticforNu = 0.664*atticPr^(1/3)*sqrt(atticRe);
else
   atticforNu = atticPr^(1/3)*(.037*atticRe^0.8-850);
end

%Calculate Exterior Convective Coefficients
atticForConCoeff = atticforNu*atticAirK/charLength;
atticNatConCoeff = atticnatNu*atticAirK/charLength;
atticConvCoeff = nthroot(atticForConCoeff^3+atticNatConCoeff^3,3);

% Defining Cyclindrical Mesh, Concentric circles R and Theta
   %deltaR=R-r;    % duct insulation thickness in ft.
   insTH = (R-r)/12;   % insulation thickness in inches.
   insK = 1/5;     % Duct insulation value R-5 per inch

 Troof1(i,1) = Data(i,5);
 Tceil(i,1) = Data(i,16);
 To(i,1) = Data(i,28);
 aRH(i,1) = Data(i,11);
 Troof2(i,1) = Troof1(i,1);
% Actually values in Rankine (all Kelvin temperature are Rankine) for
% units consistancy
Troof1K(i,1) = Troof1(i,1)+459.67;%*0.555556 + 255.37;
Troof2K(i,1) = Troof2(i,1)+459.67;%*0.555556 + 255.37;
TceilK(i,1) = Tceil(i,1)+459.67;%*0.555556 + 255.37;
ToK(i,1) = To(i,1)+459.67;%*0.555556 + 255.37;
Length = ductLength*atticLength; %length of duct in ft
```

```
    Aduct = 2*pi()*r*Length + 2*pi()*R*Length + 2*(pi()*R^2 - pi()*r^2);
%2*pi()*R*Length; % area of duct in feet^2
    AductSurface = 2*pi()*R*Length; %Surface of duct area
    Vduct = pi()*Length*(R^2 - r^2); %pi()*(deltaR)^2*Length;
    CpDuct = 0.23;%Btu/lbF
    rhoDuctSurface = 4.0; %lb/ft^3
    j=0;
    while abs(tolerance(i,h))>0.7
        j = j+1;
        % Conductive Heat Transfer
        Qcond = Aduct*insK*insTH*(ductTemp-Tduct(i,h));

        % Convective Heat Transfer
        Qconv = AductSurface*atticConvCoeff*(Tduct(i,h)-atticTemp(i,1));

        % Mass Capacitance of duct surface
        Qstored = rhoDuctSurface*Vduct*CpDuct*(Tduct(i,h)-Tduct(i-1,h));

        % Radiative Heat Transfer
        beta = interp1(RH,epsg,aRH(i));
        deltaR = beta*a2;
        deltaCeil = beta*2*pi()*R;

        Psibr = interp1(delta,Psi,deltaR);
        Psibc = interp1(delta,Psi,deltaCeil);
        Q1S = Psibr*sigma*A1*(((Troof1K(i,1)^4 -
Troof2K(i,1)^4)/((1/epsr)+F1d*Fd2*rho*((1/epsr)-1))) + (Troof1K(i,1)^4 -
TceilK(i,1)^4)/((1/epsr)+F1d*Fd3*rho*((1/epsr)-1)));
        Q2S = Psibr*sigma*A2*((Troof2K(i,1)^4 -
Troof1K(i,1)^4)/((1/epsr)+F2d*Fd1*rho*((1/epsr)-1)) + (Troof2K(i,1)^4 -
TceilK(i,1)^4)/((1/epsr)+F2d*Fd3*rho*((1/epsr)-1)));
        Q3S = Psibc*sigma*A3*((TceilK(i,1)^4 -
Troof1K(i,1)^4)/((1/epsr)+F3d*Fd1*rho*((1/epsr)-1)) + (TceilK(i,1)^4 -
Troof2K(i,1)^4)/((1/epsr)+F3d*Fd2*rho*((1/epsr)-1)));
        TductK  = Tduct(i,h)+459.67;%*0.555556 + 255.37;

        Q1g = Psibr*sigma*A1*(epsr*(Troof1K(i,1)^4 - ToK(i,1)^4) + ((Troof1K(i,1)^4 -
Troof2K(i,1)^4)/((1/epsr)+F12*((1/epsr)-1))) + (Troof1K(i,1)^4 -
TceilK(i,1)^4)/((1/epsr)+F13*((1/epsr)-1)) + epsr*(Troof1K(i,1)^4 - ToK(i,1)^4)*F14 +
epsr*(Troof1K(i,1)^4 - ToK(i,1)^4)*F15 + (Troof1K(i,1)^4 -
TductK^4)/((1/epsr)+F1d*((1/epsd)-1)));
        Q2g = Psibr*sigma*A2*(epsr*(Troof2K(i,1)^4 - ToK(i,1)^4) + (Troof2K(i,1)^4 -
Troof1K(i,1)^4)/((1/epsr)+F21*((1/epsr)-1)) + (Troof2K(i,1)^4 -
TceilK(i,1)^4)/((1/epsr)+F23*((1/epsr)-1)) + epsr*(Troof2K(i,1)^4 - ToK(i,1)^4)*F24 +
epsr*(Troof2K(i,1)^4 - ToK(i,1)^4)*F25 + (Troof2K(i,1)^4 -
TductK^4)/((1/epsr)+F2d*((1/epsd)-1)));
```

```
        Q3g = Psibc*sigma*A3*((TceilK(i,1)^4 - Troof1K(i,1)^4)/((1/epsr)+F31*((1/epsr)-
1)) + (TceilK(i,1)^4 - Troof2K(i,1)^4)/((1/epsr)+F32*((1/epsr)-1)) + (TceilK(i,1)^4 -
TductK^4)/((1/epsr)+F3d*((1/epsd)-1)));
        Qd = sigma*AductSurface*((TductK^4 - Troof1K(i,1)^4)/((1/epsd)+Fd1*((1/epsr)-
1)) + (TductK^4 - Troof2K(i,1)^4)/((1/epsd)+Fd2*((1/epsr)-1)) + (TductK^4-
TceilK(i,1)^4)/((1/epsd)+Fd3*((1/epsr)-1)) + epsd*(TductK^4-ToK(i,1)^4)*Fd4 +
epsd*(TductK^4-ToK(i,1)^4)*Fd5);

        Q1 = Q1S + Q1g;
        Q2 = Q2S + Q2g;
        Q3 = Q3S + Q3g;
        Qradiative = (Q1 + Q2 + Q3 + Qd);
        tolerance(i,h) = Qstored - (Qcond + Qconv + Qd);
        Tduct(i,h) = Tduct(i,h) - 0.01;
        if j>10000
            Tduct(i,h) = Tduct(i-1,h);
            tolerance(i,h)=0.5;
        end
    end
    Tduct(i,h)
  end
end
```

APPENDIX B
HEATING AND AIR CONDITIONING PARAMETERS

Design Cooling Day

Table B-1. System Data

Component	Location	Dry-Bulb Temp (°F)	Specific Humidity (lb/lb)	Airflow (CFM)	CO2 Level (ppm)	Sensible Heat (BTU/hr)	Latent Heat (BTU/hr)
Ventilation Air	Inlet	92.1	0.01618	36	400	535	1367
Vent - Return Mixing	Outlet	78.7	0.00836	1022	795	-	-
Supply Fan	Outlet	79.4	0.00836	1022	795	757	-
Central Cooling Coil	Outlet	54	0.00805	1022	795	27838	1486
Central Heating Coil	Outlet	54	0.00805	1022	795	0	-
Cold Supply Duct	Outlet	55	0.00805	971	795	-	-
Zone Air	-	79.5	0.00808	971	810	25511	120
Return Plenum	Outlet	79.5	0.00808	971	810	0	-
Duct Leakage Air	Outlet	54	0.00806	51	795	-	-
Return Duct	Outlet	78.2	0.00808	1360	809	-	-

Air Density x Heat Capacity x Conversion Factor: At sea level = 1.080; At site altitude = 1.074 BTU/(hr-CFM-F)
Air Density x Heat of Vaporization x Conversion Factor: At sea level = 4746.6; At site altitude = 4720.8 BTU/(hr-CFM)
Site Altitude = 151.0 ft

Table B-2. Zone Data

Zone Name	Zone Sensible Load (BTU/hr)	T-stat Mode	Zone Cond (BTU/hr)	Zone Temp (°F)	Zone Airflow (CFM)	CO2 Level (ppm)	Terminal Heating Coil (BTU/hr)	Zone Heating Unit (BTU/hr)
Zone 1	27544	Cooling	25511	79.5	971	810	0	0

Design Heating Day

Table B-3. System Data

Component	Location	Dry-Bulb Temp (°F)	Specific Humidity (lb/lb)	Airflow (CFM)	CO2 Level (ppm)	Sensible Heat (BTU/hr)	Latent Heat (BTU/hr)
Ventilation Air	Inlet	30	0.00173	41	400	-1697	0
Vent - Return Mixing	Outlet	66.1	0.00173	658	543	-	-
Supply Fan	Outlet	66.8	0.00173	658	543	488	-
Central Cooling Coil	Outlet	66.8	0.00173	658	543	0	0
Central Heating Coil	Outlet	95.7	0.00173	658	543	20435	-
Cold Supply Duct	Outlet	95	0.00173	625	543	-	-
Zone Air	-	67.1	0.00173	625	552	-18761	0
Return Plenum	Outlet	67.1	0.00173	625	552	0	-
Duct Leakage Air	Outlet	95.7	0.00173	33	543	-	-
Return Duct	Outlet	68.5	0.00173	1360	552	-	-

Air Density x Heat Capacity x Conversion Factor: At sea level = 1.080; At site altitude = 1.074 BTU/(hr-CFM-F)
Air Density x Heat of Vaporization x Conversion Factor: At sea level = 4746.6; At site altitude = 4720.8 BTU/(hr-CFM)
Site Altitude = 151.0 ft

Table B-4. Zone Data

Zone Name	Zone Sensible Load (BTU/hr)	T-stat Mode	Zone Cond (BTU/hr)	Zone Temp (°F)	Zone Airflow (CFM)	CO2 Level (ppm)	Terminal Heating Coil (BTU/hr)	Zone Heating Unit (BTU/hr)
Zone 1	-19211	Heating	-18761	67.1	625	552	0	0

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BIOGRAPHICAL SKETCH

Barrett Mooney is interested in energy efficiency and in the residential and agricultural sectors. He began his studies as an undergraduate at the University of Florida in Nuclear Engineering where he earned his Bachelor of Science degree. While pursuing his degree, he was inducted to the American Nuclear Honor Society, Alpha Nu Sigma, and graduated Cum Laude. After graduation, Barrett worked with the United States Nuclear Regulatory Commission inspecting mechanical systems for regulatory compliance. He returned to graduate school apply his background in physics to the study of temperature and moisture movement in agricultural structures. While at the Department of Agricultural and Biological Engineering, Barrett earned his Master of Engineering and worked on several non-thesis projects including greenhouse modeling and animal housing designs. He studied weather modeling and moisture transport in pursuit of his doctorate, and was inducted into the Honor Society of Agriculture, Gamma Sigma Delta, and became an active member of the American Society of Agricultural and Biological Engineers. After graduation Barrett would like to publish his research and advance the field of transient thermal and moisture modeling in various systems including crop dynamics, animal housing, and greenhouse operations.