JACKSONVILLE BUILDING SCIENCE, LLC

# Sensor Data Analysis

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# Executive Summary

The residence located at XXXX XXXXX XXXX has experienced moisture related issues each summer for quite some time. These issues manifested themselves last season in an area of limited airflow adjacent to the attic scuttle at the north end of the second floor.

In an effort to monitor the temperature and humidity as the hot, humid season was approaching, four sensors were installed to collect the appropriate data and determine if a recurrence of the previous summer's issues were taking place. Further, the collected data could provide valuable insight into the conditions prevalent in the attic and the proper course of action to mitigate the recurring issues. The report that follows is an analysis of three months of data collected by the sensors on an hourly basis.

The collected data and subsequent analysis provide some insight into the conditions in the attic, however this is hampered by the lack of baseline conditions for comparison. Further, the breadth of information gathered was limited by the small number of sensors placed in the attic. With only two attic sensors, the conditions observed by those sensors could be influenced by localized conditions in proximity to those sensors. Taking this into consideration, few conclusions can be drawn with certainty. However, the data does give some insight into general conditions experienced by tile roof attics, allowing hypotheses of the proper ventilation techniques for tile roof attics. One certainty has arisen from the gathered data: the relative humidity present around the scuttle access approaches the maximum allowable interior value, an indication that moisture problems persist.

The report attempts to find the source of the elevated indoor humidity, specifically focusing on the attic conditions and ventilation. Assuming the absence of any localized conditions surrounding the sensors, the data was analyzed and scoured for any indication of the source of the problem. To reiterate, there is a significant amount of uncertainty associated with these recommendations due to the limited number of sensors and lack of a baseline comparison.

The analysis showed that the additional vents installed in the two roof sections have not prevented the indoor humidity levels, in proximity to the scuttle access, from increasing. The installation of a gasket at the scuttle and a small supply in the immediate area also seem to have had little effect. Considering past research performed on tile roof attics, this report speculates that attic ventilation may be causing the conditions that are leading to high indoor humidity levels.

The ventilation in the residence is completely in agreement with the Florida Building Code, actually exceeding the standard. However, the building code may have overlooked the unique conditions experienced in tile roof attics that do not necessitate ventilation and perhaps are harmed by the Florida Building Code Ventilation Requirement. The collected data appears to show that the temperature experienced within tile roof attics is very low in comparison to other attic configurations. This low temperature causes the ventilation to be limited, all but eliminating the beneficial effects of ventilation on load reduction. Further, the ventilation is exposing the attics to ambient moisture and offering little help in evaporating such moisture. The ventilation is likely the cause of the elevated humidity experienced in proximity to the scuttle.

Based on the test results and other scientific inquiries into this subject, it is recommended that the best possible course of action is to temporarily seal the attic from the outside environment and monitor the results with sensors. This can be accomplished by sealing the soffit, off ridge vents and any other opening to the outside.

Alternatively, every attic penetration in the vicinity of the north attic alcove should be sealed to prevent vapor migration and every duct connection inspected for leakage to prevent surfaces from reaching dew point temperatures. Also, the scuttle could be relocated to a location that is distant from ventilation and surfaces that could reach dew point.

## 1.0 Introduction

The Florida building code explicitly requires ventilation in all Florida attics unless an air impermeable insulation system is applied directly to the underside of the roof sheathing. Two possible rationales exist behind the building code ventilation requirement: to reduce attic temperatures and control moisture. A number of studies have revealed the merits of such requirements on attic temperature. A study done by the Florida Solar Energy Center (Beal et al, 1995) depicts the effects of ventilation on attic temperature and ceiling heat flux. The study also showed that levels of ventilation much higher than the building code requirement are far more effective in reducing attic temperature.

In the October 2002 issue of the *ASHRAE* journal, Rose and Tenwold explain the moisture justification behind the building code ventilation requirement. This article states that the ventilation requirement of 1:300 was originally determined to prevent condensation within attics in cold climates as well as preventing ice dams in those attics. The article suggests that there is no merit for providing ventilation in hot humid climates, as ventilation actually increases attic humidity levels.

In requiring ventilation in hot humid climates serious moisture issues can develop, as the attic is exposed to the humid ambient air. Very high levels of humidity are experienced throughout the day in Florida, peaking during the morning hours. As a result of ventilation this humidity and moisture are introduced to the attic, which has a number of dry surfaces and materials available to absorb this moisture. Attic environments, without adequate opportunity to evaporate moisture, are very sensitive to the introduction of moisture and are prime habitats for microbial growth.

In conventional asphalt shingle attics, moisture does not appear to be an issue. This is likely due to high attic temperatures convectively forcing air out of the ridge vents, creating a chimney effect. Attics with tile roofs and other high performance roof coverings achieve much lower attic temperatures, due to the reflection of a large portion of solar radiation and interstitial air spaces around each tile. This lower attic temperature reduces the ventilation, while still exposing the attic to the high humidity ambient air.

The unique characteristics of tile roof attics require a different approach to ventilation. The lower temperatures question the need for ventilation at all, as ventilation only exposes them to moisture. Further investigation will reveal the conditions in tile roof attics and the proper ventilation requirement.

## 2.0 Objective

The residence has a terra cotta colored barrel tile roof and has been experiencing moisture related issues for quite some time. The proximity of all moisture issues to ceiling penetrations, particularly the scuttle access, suggests that the attic environment is the primary cause of the issues and has spawned this investigation into the conditions experienced within tile roof attics. The scope of this study is to determine the conditions in the attic, the cause of high humidity levels in the home, and ultimately the conditions that result in reoccurring summer moisture issues.

## 3.0 Background

### 3.1 Attic and Moisture Issues

High attic humidity levels can have serious repercussions in Florida homes. High humidity air contains a lot of moisture that readily condenses out of the air due to the high dew point. This condensation will occur in the attic on any surface below the relatively warm dew point. With conditioned homes it is easy to generate cool surfaces in the attic, in spite of proper sealing of the conditioned space. This can be attributed to thermally conductive metals that get cooled by the conditioned space or the 58 °F air stream that passes through the ducts and grills. Proper insulation helps prevent the transfer of energy from the conditioned space to the attic, limiting cold surfaces in contact with the humid air. However it is impossible to entirely prevent the attic air from coming in contact with cool surfaces and air that result from the conditioned space below. With humid attic air, any minute communication between the attic air and conditioned space will cause condensation.

The other effect of high attic humidity levels is vapor flow into the home. The gradient created by the vapor pressure of the high humidity attic causes vapor to be pulled into the dry air within the home. This vapor flows through any gap, hole, or semi permeable surface, creating moist materials along the ceiling and high humidity levels within the home.

Lastly the materials within the attic can absorb significant amounts of moisture in the presence of humid air with abundant moisture. Beal and Chandra, site studies that determine a wood moisture content of 30% will generate microbial growth. Another study by the Florida Solar Energy Center (Fairey et al, 1988) documented the cycle of absorption and evaporation of moisture by attic materials. The study revealed that during the hot part of the day the ventilation airflow picks up moisture from the attic materials, likely due to the increasing temperature of those materials. However, during the cool evening period, the attic absorbs moisture from the ambient air. This suggests a daily inhaling and exhaling of moisture by attic materials. Under certain conditions, this cycle can cause the attic materials to reach critical values for the propagation of microbial cultures.

### 3.2 Florida Building Code Ventilation Requirement

The Florida Building Code R806.2 requires ventilation in the form of off-ridge and eave/cornice ventilation, totaling 1/150$^{th}$ of the total area of the attic. If the off-ridge vents, located 3 feet above the eave, account for 50 to 80 percent of the ventilation area, the ventilation area can be reduced to 1/300$^{th}$ of the attic area. Also, if a vapor barrier is installed on the attic side of the ceiling, the ventilation can be reduced to 1/300$^{th}$.

In conventional asphalt shingle attics, this ventilation requirement creates a flow of outside air through the attic, replacing the high temperature attic air with cooler outside air. It may actually prevent a buildup of moisture in the attic, limiting stagnation and creep of air into the insulation and gaps. This is a result of the high attic temperature convectively forcing air out of the ridge vents and creating a stack effect. This situation likely was not intentional, since it only exists in the extremely hot asphalt shingle attic. With other roof configurations, the ventilation is much more limited and can have very adverse effects due to the introduction of moisture to the attic.

## 3.3 Roof Performance

The tile roof attic experiences unique conditions due to the reduced load that results from the good thermal performance of the tile. A 2002 study done by Danny Parker at FSEC compares various roof materials, as well as a sealed attic with foam insulation, and summarizes their effect on building cooling load. The study found that compared to dark asphalt shingles, white flat tiles reduced HVAC energy use by 17%. White s-tile roof material reduced energy use by 20%. A sealed attic with foam insulation on the underside of the roof deck and asphalt shingles reduced the HVAC energy use by 9%. The largest cooling load reduction was experienced by a white metal roof, with a 23% reduction. All cases had R-19 insulation on the attic floor, except the foam insulation case. All cases also had Florida building code minimum ventilation. Obviously, this report proves that tile roof materials can cause significant reductions in attic temperatures and the heat flux into the home. The 1995 study by Beal and Chandra corroborates this finding, measuring a 40 to 50% reduction in ceiling heat flux as a result of tile roofing.

The most important factor contributing to roof heat load reduction is reflectivity. Reflectivity represents the fraction of solar radiation incident on the surface that will be reflected and therefore not absorbed or transmitted by the material. Danny Parker's study also measured the reflectivity of the various roof materials, finding an 8% reflectivity associated with asphalt shingles. This is in stark contrast to the 37% reflectivity achieved by terra cotta barrel tile, 74% by white barrel tile, and 77% by white flat tile. All of the energy that is reflected by a tile is lost and therefore not conducted and radiated to the attic and conditioned space below. This highlights the effect of reflectivity on roof performance. Tile roofs also have the benefit of air space surrounding the tiles, allowing for ventilation (although the bottom opening is usually sealed to prevent small animals from damaging the tiles thus preventing a ventilation air stream) as well as acting as insulation between the tile and the roof deck.

## 4.0 Procedure

The residence has two separate attics: the North Attic and the South Attic. Both attics have ventilation in excess of the building code requirement, which was installed in response to microbial issues that reoccur every summer.

Three sensors were originally installed, one in each attic and one outside, measuring relative humidity and temperature at one hour intervals. This yielded a detailed daily picture of the conditions in the attic environment compared to the outside conditions. These three initial sensors began logging data April 2, 2008. A fourth sensor was added June 11, 2008 within the interior of the home, near the scuttle access, where most of the prior microbial issues occurred.

The attic sensors in the North Attic and South Attic offer different perspectives of the attic environment. Both sensors were placed near the scuttle accesses, the apparent source of the moisture issues. However, the North Attic sensor was in close proximity to the additional attic ventilation, where as the South Attic sensor was placed on the opposite side of the attic to the additional vents. This offers a perspective of the effect of the ventilation on the entire attic environment.

The sensor utilized was the Onset HOBO U10 Temp/RH Data Logger. This sensor has an accuracy of ± 3.5% RH and ± 0.72 °F.

*Table 1: Sensor Specs*

| Sensor | Location | Attachment |
|---|---|---|
| 1 | North Attic | Suspended from 2x6 roof supports |
| 2 | South Attic | Suspended from 2x6 roof supports |
| 3 | Outside | Alcove adjacent to Garage |
| 4 | Interior | Suspended from ceiling adjacent to North Attic scuttle |

  

## 5.0 Technical Approach

The only data interpretation required was the humidity ratio calculation:

(1) $$w = \frac{P_v}{P_{tot} - P_v}$$

(2) $$w = \frac{\varphi P_g}{P_{tot} - \varphi P_g}$$

Where:

| | | | |
|---|---|---|---|
| Where: | $w$ | = | Humidity Ratio |
| | $P_{tot}$ | = | Total Pressure of Air |
| | $P_v$ | = | Partial Pressure of Water Vapor |
| | $\varphi$ | = | Relative Humidity |
| | $P_g$ | = | Saturated Vapor Pressure of Water (temperature dependent) |

$P_g$ was calculated from the specific volume of saturated water vapor at each temperature. This required extrapolation from a table and utilization of the ideal gas law. The total pressure was assumed to be a constant 1 atm or 101.325 kPa.

# 6.0 Results

## 6.1 Attic Temperature

### *6.1.1 Overall Comparison of Attic Sensor with Outdoor Sensor*

*Figure GK-1* presents the temperature profiles over the 15 week study period. Over the course of the study, the daily attic temperatures ranged from 50 to 105°F. During the final few weeks of the study, when the conditions were more typical of Florida summers, the maximum daily temperatures ranged from 85 to 105°F. In conventional asphalt shingled attics, the temperatures can achieve 140°F on a typical Florida summer day.

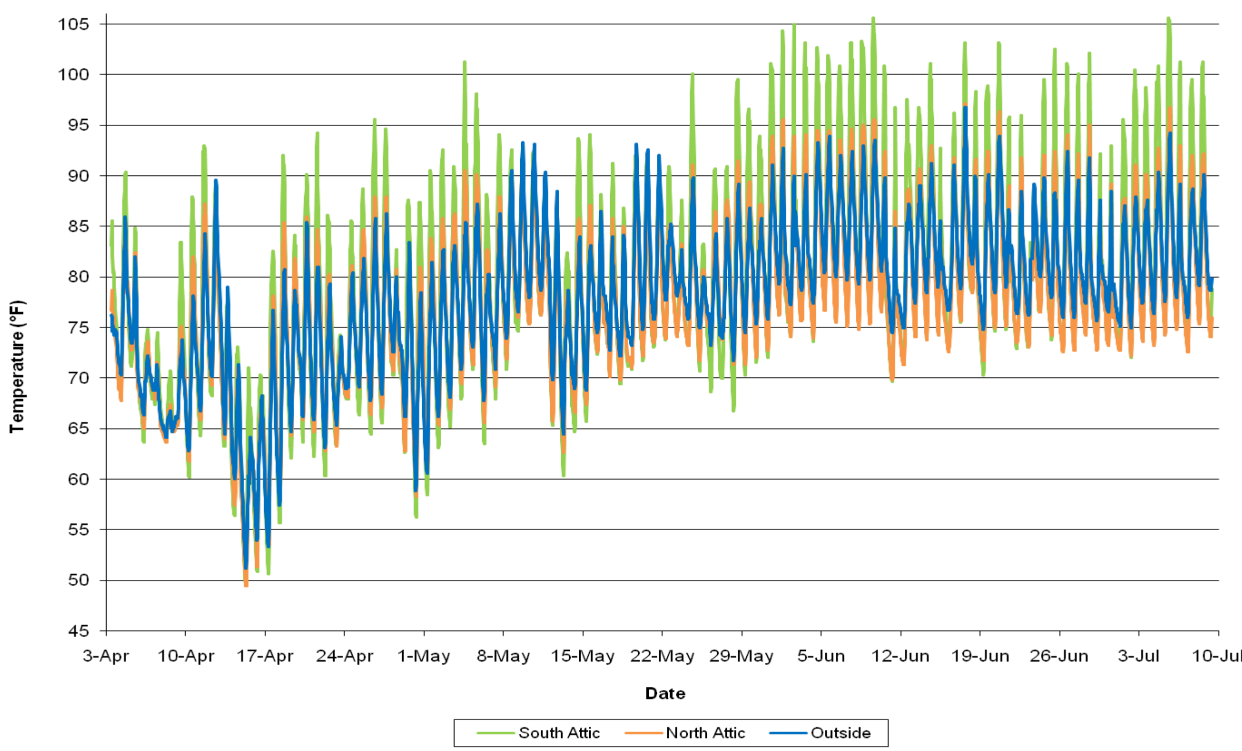


*Figure GK-1: 15 Week Temperature Readings*

*6.1.2 The South Attic experiences much higher temperatures than the North Attic.*

Over the 15 week study period the South Attic consistently peaked at 10 to 20 degrees greater than the outside temperature and 5 to 10 degrees greater than the North Attic. The higher temperatures can be attributed to the location of the sensor, since there should be no difference in attic temperature. Both sensors were placed in close proximity to the scuttle access, for convenience. The North Attic scuttle is very close to additional ventilation, while the South Attic scuttle is not. Thus, the North Attic sensor is influenced by the relatively cool ventilation air, while the South Attic sensor is exposed to more typical attic conditions.

*6.1.3 The North Attic experiences near ambient temperatures.*

As a result of the proximity to the additional ventilation, the North Attic was within 5 degrees of the outside temperature during the entire 15 week period. The ventilation appears to have only a minimal effect on the entire attic, due to the high South Attic temperature readings. *Figure GK-2* illustrates the proximity of the North Attic temperature to ambient, plotting the difference in attic temperature from outside during the 15 week study period.

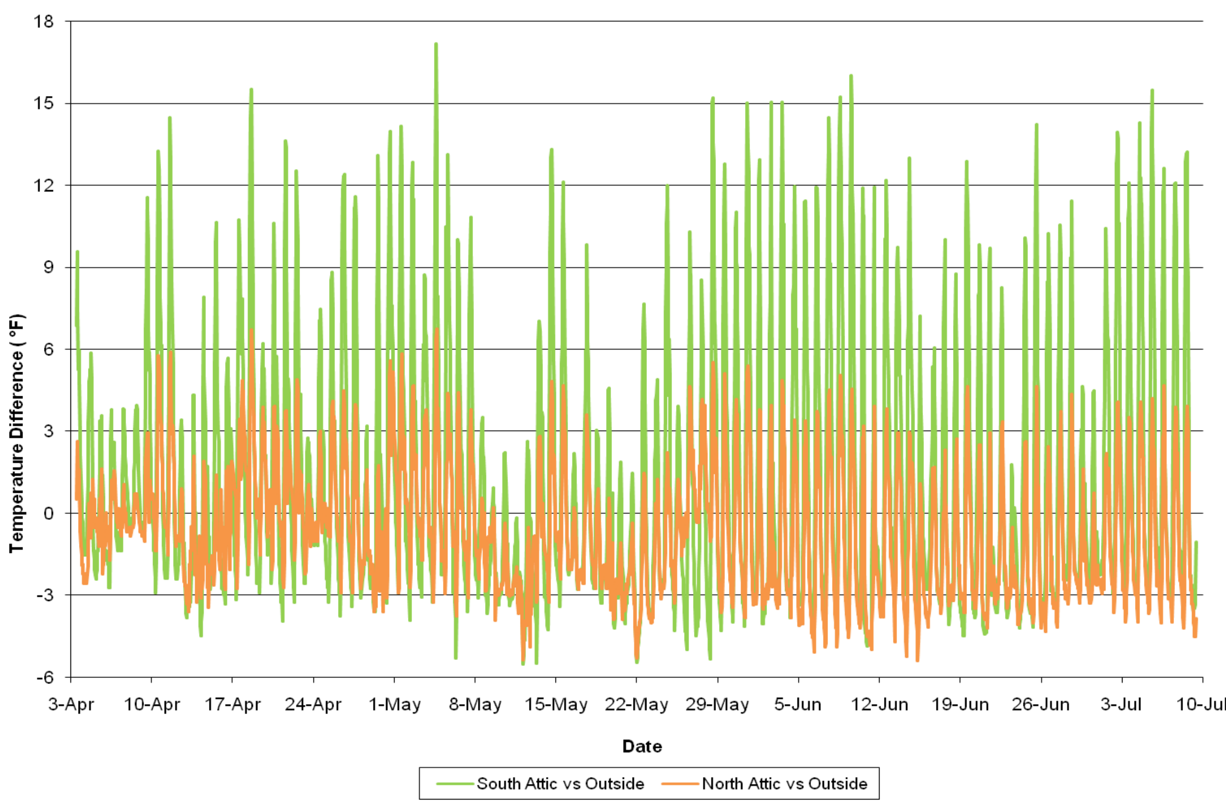


*Figure GK-2: 15 Week Attic Temperature Difference from Ambient*

*6.1.4 Both attics tracked the outside temperature cycle closely.*

*Figure GK-3* illustrates the daily cycle of the attic and ambient temperatures. Though the temperatures differed, there is almost no difference in the shape of the profile. The changes in attic temperature closely mimic the changes in ambient temperature, however with more exaggeration. This indicates that the solar radiation is the determining factor in both attic and ambient temperatures. The only noticeable difference in the profile occurred in the morning and evening. In the morning, the attic temperatures began to rise slightly after the ambient temperatures. In the evening the attic temperatures began to fall before the ambient temperature. This phenomenon is a result of the roof reflecting a large percentage of the low angle solar radiation, a result of the more reflective, smooth surface of roof tiles.

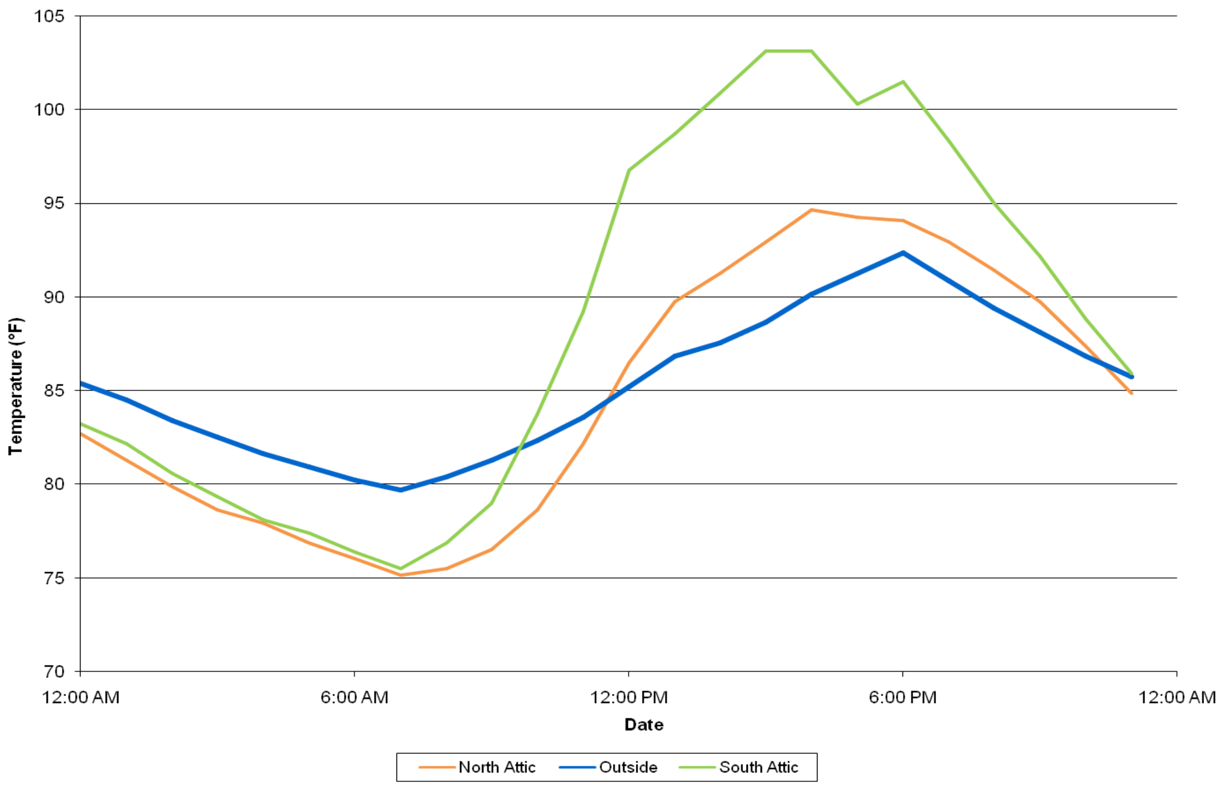


*Figure GK-3: Daily Temperature Profile (6/7)*

## 6.2 Relative Humidity

*6.2.1 The humidity experienced in the attics is very high, due to the exposure to outside air.*

Relative humidity is a ratio of the amount of moisture in the air to the total amount of moisture that the air is capable of holding. The moisture capacity of the air is dependent on temperature: warmer air can hold more water vapor than cold air. High relative humidity will prevent evaporation since the air is near capacity and can hardly take on more water. Further, humid air will condense at a higher temperature (has a higher dew point). The relative humidity in the attic during the latter part of the study period, when the attic began experienced typical summer conditions, approached critical values.

*Figure GK-4* plots two weeks of relative humidity readings, when the attic experienced typical summer conditions. At times, the attic relative humidity exceeded the ambient relative humidity. Further, the attics consistently achieved a relative humidity in excess of **70%** and occasionally reached **85%**. A relative humidity of this value induces condensation and prevents evaporation.

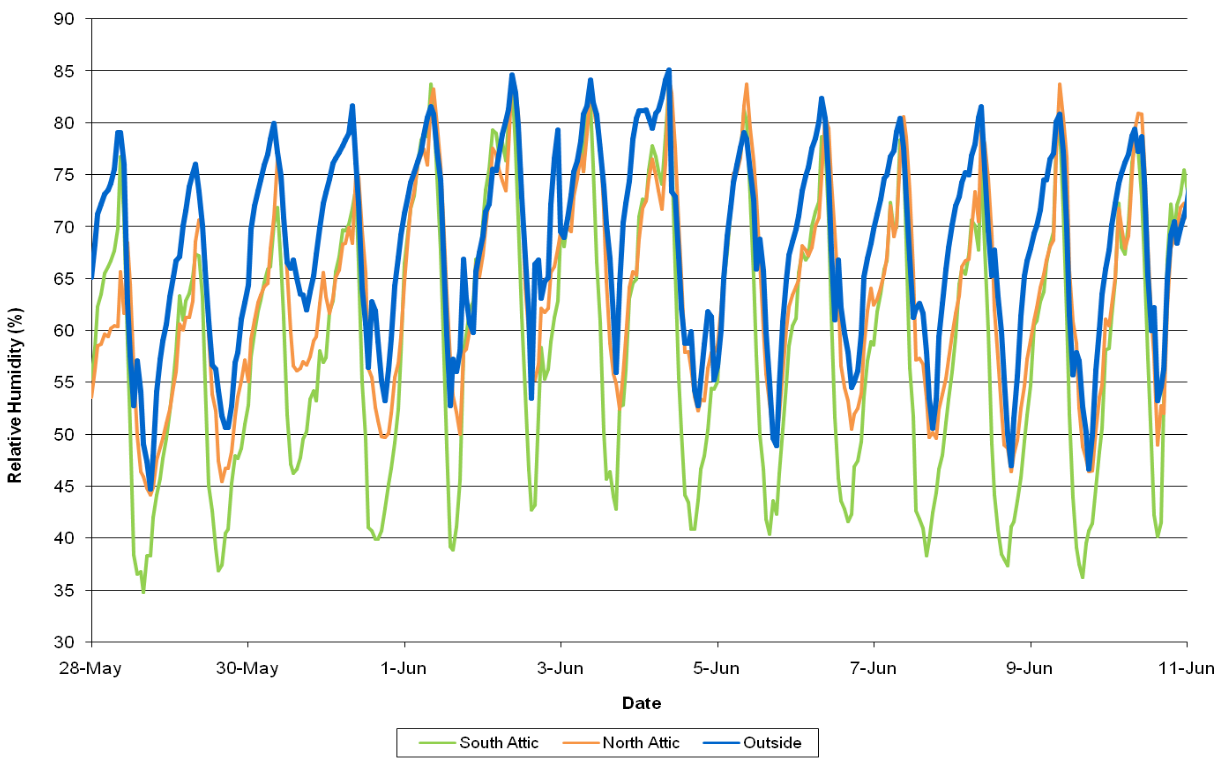


*Figure GK-4: 2 Week Relative Humidity Readings*

  

*6.2.2 The attics experienced periods of very low relative humidity due to the high temperature.*

The daily relative humidity low was experienced during the afternoon, when the temperature in the attics was excessively high. The daily humidity profile is shown in *Figure GK-5.* As explained, high temperature air can hold more water, thus the relative humidity dropped during the day even though the amount of moisture in the air may have increased. During the evening and morning hours, the relative humidity increased due to the dropping temperatures. The humidity ratio, which is **not** temperature dependent, may be a better indicator and is discussed at length in the next section.

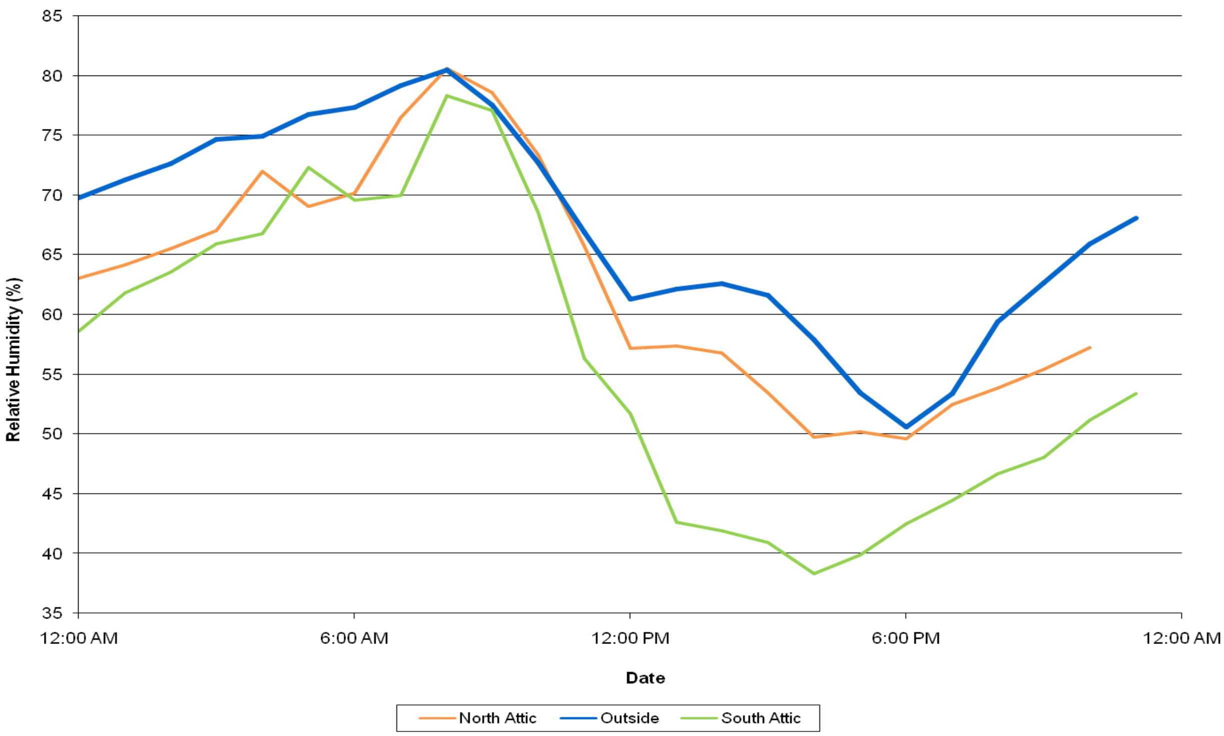


*Figure GK-5: 24 Hour Relative Humidity Profile (06/07)*

*6.2.3 The North Attic experiences a higher Relative Humidity than the South Attic.*

The North Attic consistently experiences a higher relative humidity than the South Attic, a result of two factors. First, the North Attic sensor is exposed to cooler ventilation air, thus with equal amounts of moisture in the air, the North Attic will have a higher relative humidity than the South Attic. The other factor is the exposure to ambient humidity from the additional ventilation. During the late morning when the sun rises and the relative humidity is still very high, the rising attic temperature will cause a small but increasing amount of ventilation. Due to the additional ventilation area, the North Attic sensor will be exposed to more ventilation air than South Attic sensor in the morning. The North Attic sensor is exposed to this high humidity airstream that is infiltrating the attic. The South Attic sensor also reads an uptake in morning moisture indicated by its late morning RH spike, but it is not as significant due to its distance from the additional ventilation and higher temperature.

However, this does highlight the fact that both attics are taking in outside moisture as a result of the ventilation, regardless of the amount of ventilation.

## 6.3 Humidity Ratio

*6.3.1* Humidity ratio is the ratio of the mass of water vapor to the mass of dry air in a parcel or volume of air. During the summer months, the attics maintain a high humidity ratio, causing the moisture to be absorbed into surfaces, creep into the conditioned space and preventing any evaporation.

*Figure GK-7* illustrates the different conditions experienced during the spring and summer months. The final 5 weeks of the study (summer conditions) maintained humidity ratio values far greater than the values experienced during the first 9 weeks of the study (spring conditions). The humidity ratio during the entire four week summer period averages greater than 0.016, whereas the first 9 weeks only achieved a few peaks in that humidity ratio range. Further, the humidity ratio did not dip below 0.012 during the final five weeks, compared to the initial 9 week period where there were frequent drops as low as 0.004. This illustrates the constant high humidity ratio experienced by the attic during the summer months.

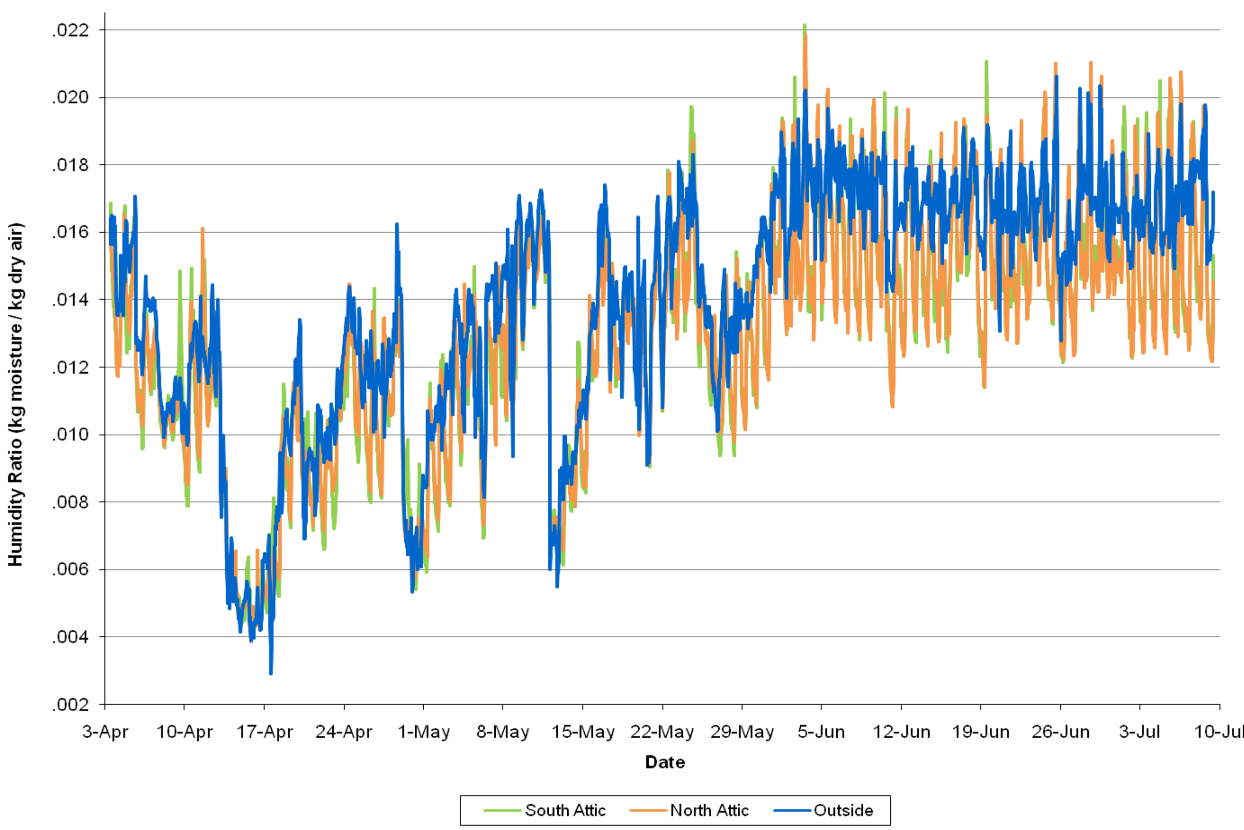


*Figure GK-6: 15 Week Humidity Ratio*

*6.3.2 The humidity ratio cycle illustrates the daily uptake of moisture into the attic.*

The humidity ratio is defined as the mass of the moisture contained in the air per mass of dry air. This is an indicator of the amount of moisture in the air and is not dependent on the temperature of the air. Plotted in *Figure GK-6* is the daily humidity ratio profile in the attics compared to ambient. The ambient humidity ratio remains relatively constant, dropping slightly during the middle of the day. However, the attics experience a rapid increase in the humidity ratio during the early morning. This moisture is contained in the attic throughout the day and only drops in the evening. The morning spike indicates the morning uptake of ambient moisture by the attics.

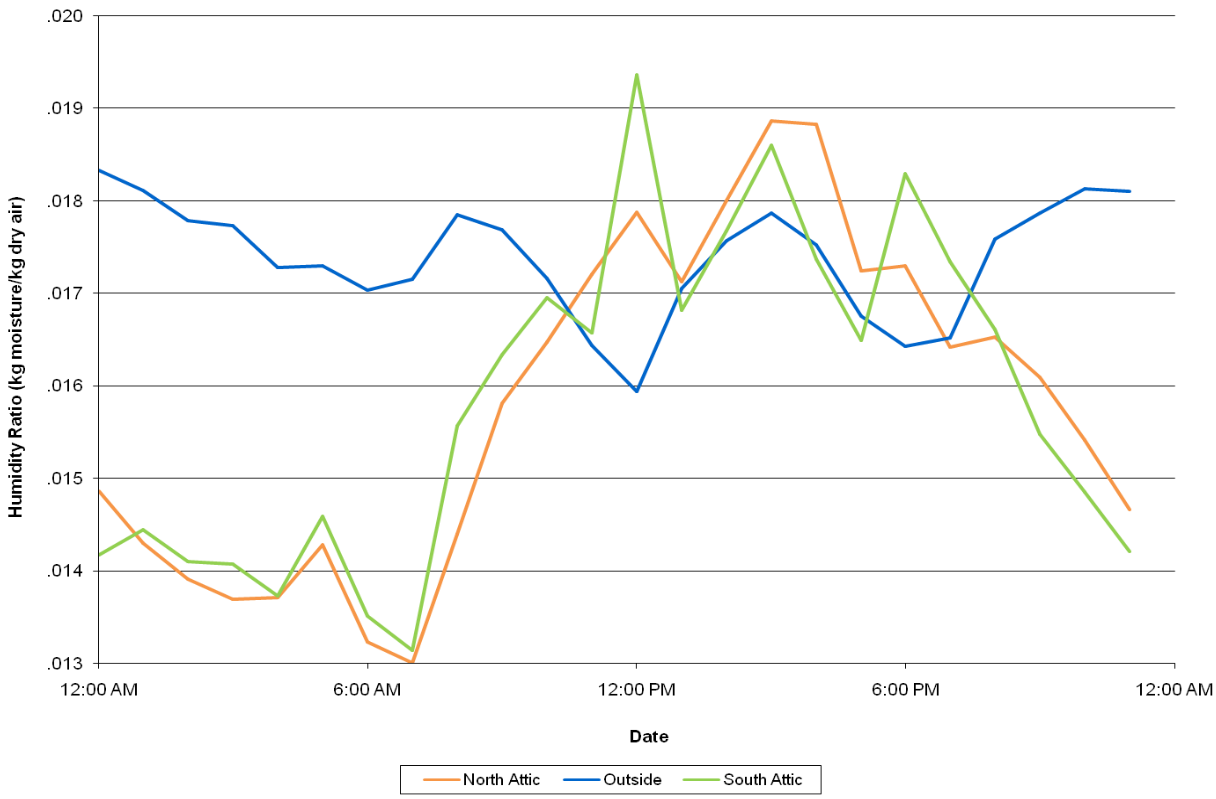


*Figure GK-7: 24 Hour Humidity Ratio Profile (06/07)*

## 6.4 Dew Point

*6.4.1 The attics come very close to the dew point.*

*Figure GK-8* shows a comparison of the attic temperature to the dew point. The dew point is the temperature below which condensation will occur. Usually this only occurs on surfaces that drop below the dew point. If the entire air mass drops below the dew point, then fog will occur. The dew point is dependent on the amount of moisture in the air. The closer the air is to saturation, the easier it is to get the moisture out of the air. This results in a higher dew point temperature.

Neither attic dropped below the dew point over the entire 15 weeks; however both attics are consistently within a few degrees of the dew point in the early morning. This may create surfaces that are below the dew point, generating condensation. The close proximity to the dew point is a result of the high humidity of the air.

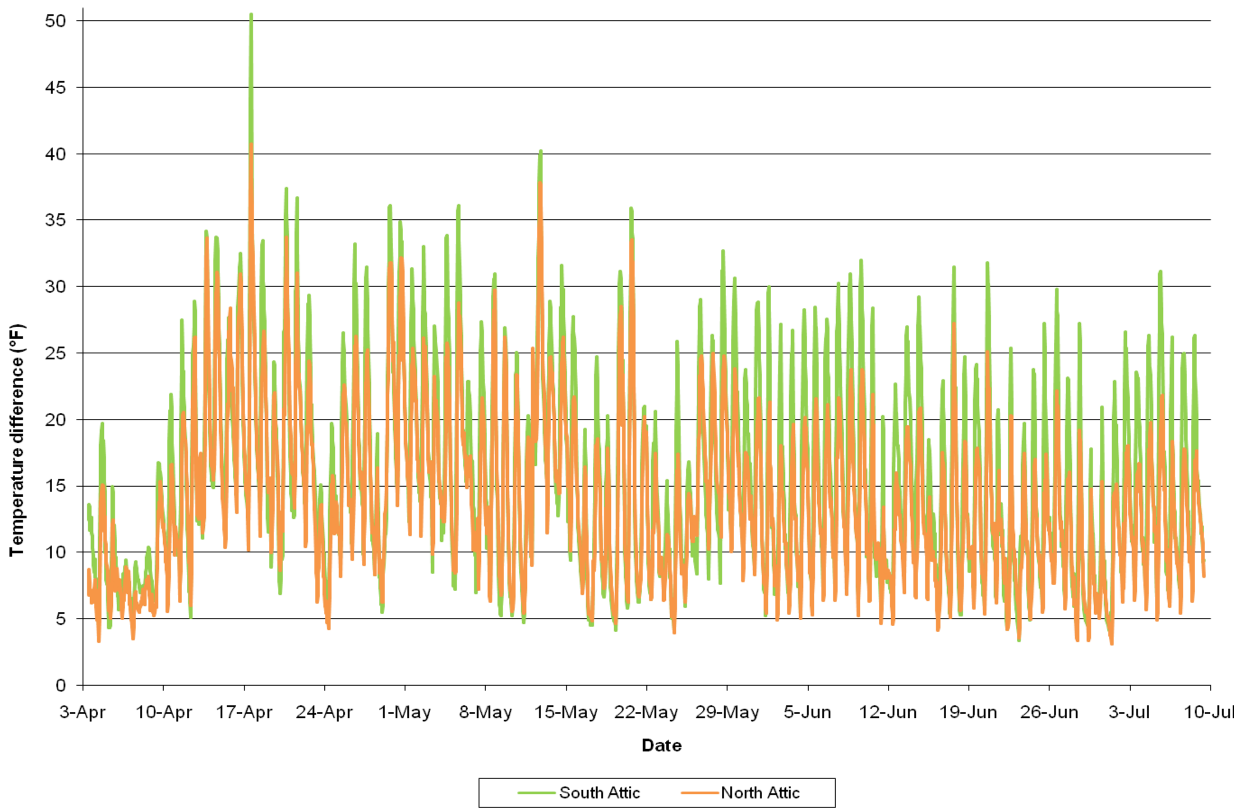


*Figure GK-8: 15 Week Attic Temperature Difference from Dew Point*

## 6.5 Interior Conditions near Scuttle Access

On June 11th, 2008 a fourth sensor was added to the interior of the home to track conditions around the North Attic scuttle access. The sensor was installed in response to high relative humidities sensed by a portable RH meter.

*6.5.1 The relative humidity nears allowable limit for residential conditions according to ASHRAE.*

*Figure GK-9* plots the relative humidity and temperature experienced near the North Attic scuttle access inside the home. Also potted is the North Attic relative humidity for comparison. The relative humidity experienced inside the house ranges from 50 to 65 % RH. 55% RH is considered the maximum allowable in the Building Science community and ASHRAE considers 60% to be the maximum before moisture related issues take place. Achieving 65% RH puts the home at risk of moisture issues.

*6.5.2 The conditions around the scuttle access may be affected by the attic conditions.*

Comparing the profile of the North Attic RH and interior RH suggests that the interior RH may be affected by the attic RH. There is a slight lag between the two profiles, however most of the interior RH peaks were experienced at the same time as the attic peaks. The largest humidity peak occurred when the temperature in the house increased sharply June 16th. This likely was the result of an increase in the thermostat set point turning of the air conditioner for an extended period, preventing any dehumidification of the air for that period of time.

It is logical to correlate the attic and interior relative humidities, considering the proximity of the sensor to the North Attic scuttle access, which creates an interruption in the ceiling barrier and insulation. A seal was installed to help mitigate the flow of vapor into the home through the scuttle hole, however the seal is imperfect. The attic conditions are too extreme for the seal to completely prevent communication. Further, the North Attic scuttle is very close to the additional ventilation, thereby exposing the scuttle to even worse conditions than are experienced in other parts of the attic. Also there are numerous attic penetrations that could also provide a water vapor pathway. These may be contributing to the moisture issues associated with the North Attic scuttle.

  

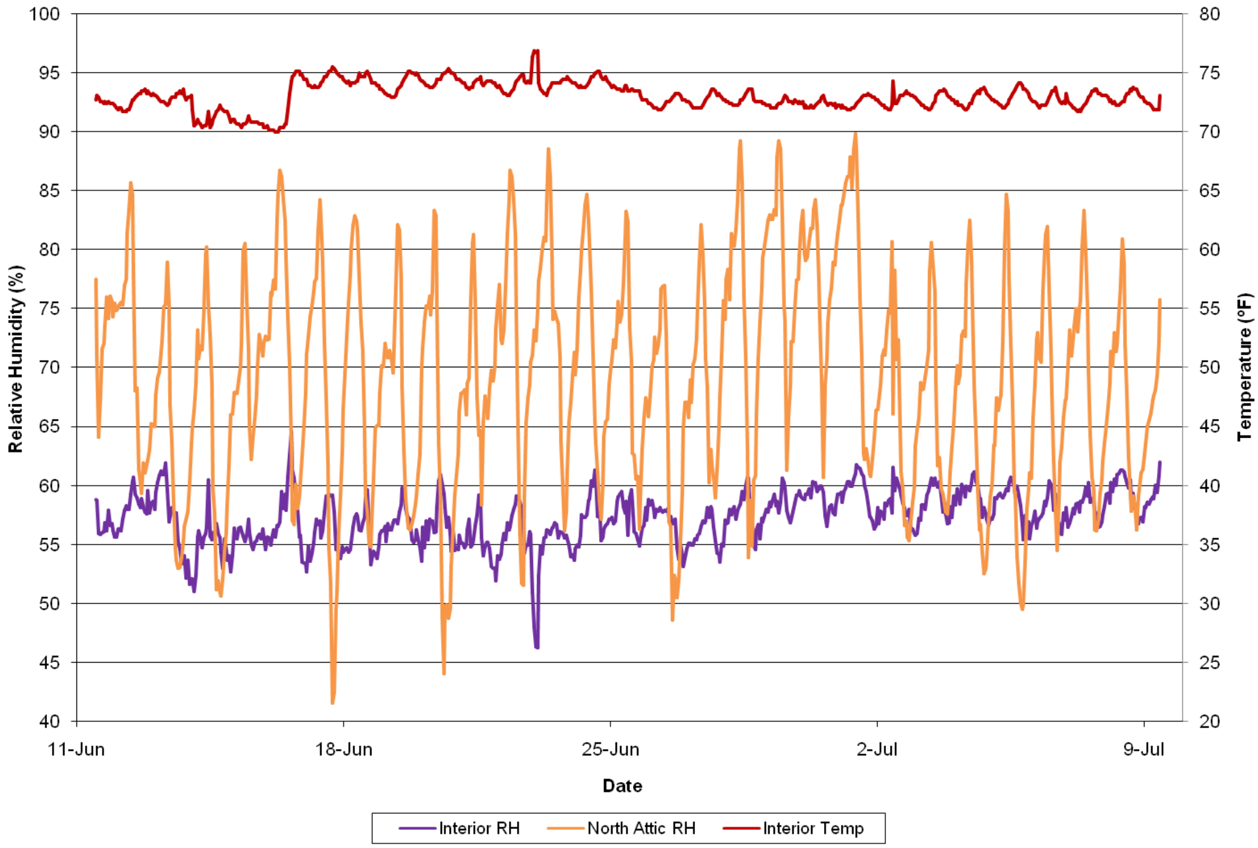


*Figure GK-9: 4 Week Interior Conditions Compared to North Attic*

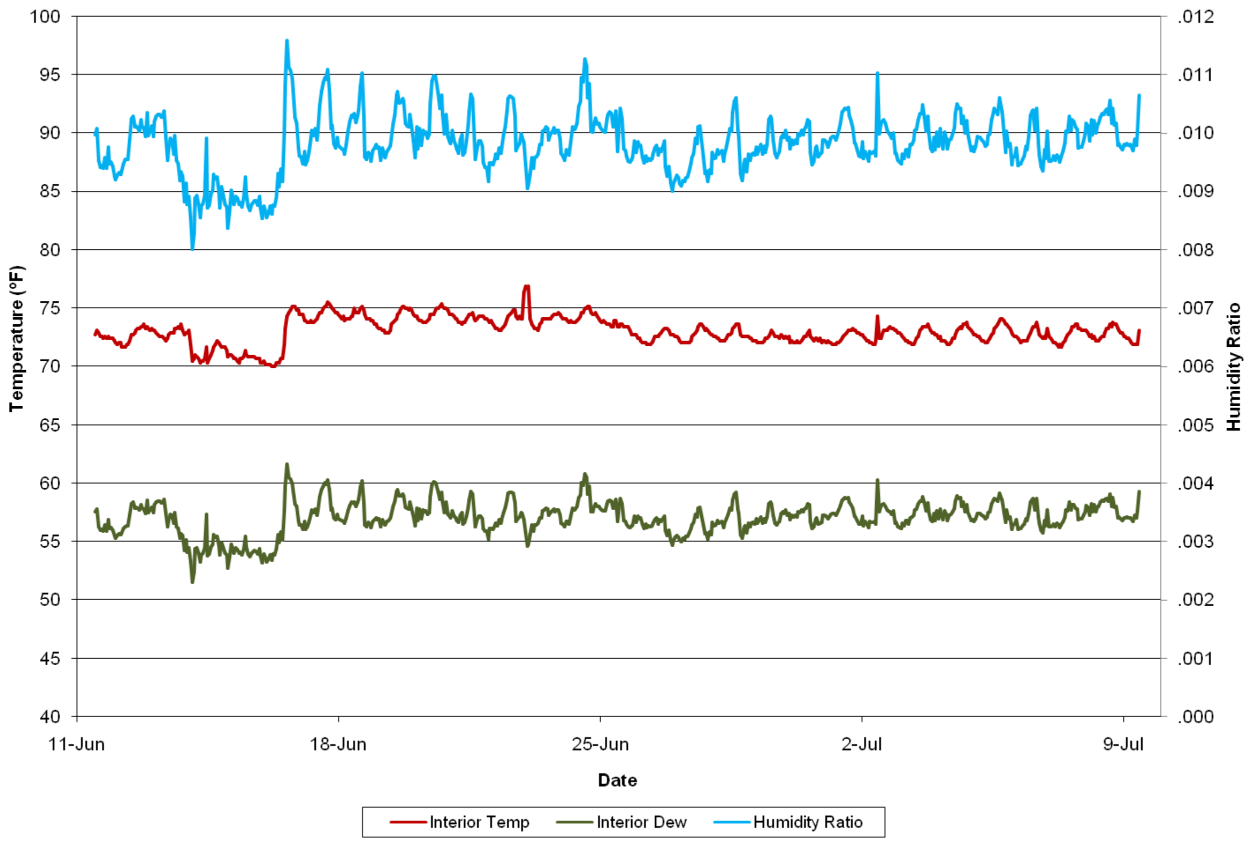


*Figure GK-10: 4 Week Interior Conditions*

## 7.0 Summary

- The attics are very cool in comparison to traditional shingled roof attics.
- The ventilation in the attics is very limited primarily as a result of the low temperature.
- Without the excessively hot attic temperatures, tile roof attics do not need ventilation for temperature reduction.
- The minimal nature of ventilation prevents any beneficial moisture control.
- Ventilation in tile roof attics only exposes the attic environment to ambient moisture.
- The low temperature of the attics combined with the high relative humidity, brings the attics very close to the dew point in the evenings and early mornings.
- The attics retain a lot of moisture during the summer season.
- The humidity in the home near the North Attic scuttle access is very high, indicating vapor flow from the attic into the home.
- The North Attic scuttle is very close to the soffit ventilation, which exposes the scuttle to more humidity than is experienced in other parts of the attic. This may be the cause of the moisture issues associated with the North Attic scuttle.

## 8.0 Conclusions

The high humidities and other moisture issues experienced in the attics are a direct result of the ventilation. Asphalt shingle attics benefit from high attic temperature, which causes significant convective force and therefore ventilation. The ventilation helps control attic moisture in these attics. In tile roof attics, the low temperature limits the convective force and thus the ventilation. The ventilation only exposes the attics to ambient moisture. This is highlighted by the North Attic sensor experiencing higher humidity than the South Attic sensor, possible due to its proximity to the soffit ventilation. Further, the North Attic scuttle, which is very close to the ventilation, experiences moisture issues each summer. The ventilation may be the source of the moisture issues surrounding the scuttle .

Tile roof attics do not need ventilation for heat load reduction as they are already very cool. The logical solution is to eliminate ventilation entirely.

## References

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Beal, D., Chandra, S., "The Measured Summer Performance of Tile Roof Systems and Attic Ventilation Strategies in Hot, Humid Climates", Proceedings of the Thermal Performance of the Exterior Envelopes of Buildings VI. Oak Ridge National Laboratory/U.S. Department of Energy, 1995. Clearwater, FL.

Fairey, P., Swami, M., Beal, D., “RBS Technology: Task 3 Report”, Sponsored by Florida Power and Light Company/US Department of Energy. 1988.

Parker, D., Sonne, J., Sherwin, J., “Comparative Evaluation of the Impact of Roofing Systems on Residential Cooling Energy Demand in Florida”, Proceedings of ACEEE 2002 Summer Study. American Council for an Energy Efficient Economy, Washington, DC. 2002.

# Appendix A: Calculations

| Raw Data | | | | | Dew Point Diff | Humidity Ratio Calculation | | | Comparison to Outside | |
|---|---|---|---|---|---|---|---|---|---|---|
| Plot Title: 1277242 | | | | | | | | | Difference | |
| # | Time, GMT-04:00 | Temp, °F | RH, % | DewPt, °F | | vg | Pg | w | Temp, °F | RH, % |
| 1 | 4/3/2008 12:00 | 76.703 | 79.58 | 69.96 | 6.743 | 43.8355 | 3137.1849 | 0.0157 | 0.522 | -5.08 |
| 2 | 4/3/2008 13:00 | 78.624 | 74.67 | 69.95 | 8.674 | 41.4708 | 3327.9504 | 0.0156 | 2.618 | -6.65 |
| 3 | 4/3/2008 14:00 | 76.876 | 77.21 | 69.24 | 7.636 | 43.5581 | 3158.1812 | 0.0153 | 2.257 | -12.63 |
| 4 | 4/3/2008 15:00 | 76.354 | 79.27 | 69.51 | 6.844 | 44.3951 | 3095.6266 | 0.0154 | 1.215 | -9.24 |
| 5 | 4/3/2008 16:00 | 76.181 | 79.28 | 69.34 | 6.841 | 44.6725 | 3075.4121 | 0.0153 | 1.39 | -8.6 |
| 6 | 4/3/2008 17:00 | 75.832 | 78.38 | 68.67 | 7.162 | 45.2320 | 3035.3870 | 0.0150 | 1.561 | -8.34 |
| 7 | 4/3/2008 18:00 | 75.139 | 78.71 | 68.12 | 7.019 | 46.3432 | 2958.7755 | 0.0146 | 0.868 | -9.17 |
| 8 | 4/3/2008 19:00 | 74.446 | 81 | 68.28 | 6.166 | 47.4543 | 2885.7518 | 0.0147 | -0.173 | -8.84 |
| 9 | 4/3/2008 20:00 | 74.098 | 79.67 | 67.46 | 6.638 | 48.0123 | 2850.3566 | 0.0143 | -0.693 | -7.05 |
| 10 | 4/3/2008 21:00 | 73.407 | 80.69 | 67.15 | 6.257 | 49.1202 | 2782.4585 | 0.0141 | -1.212 | -7.81 |
| 11 | 4/3/2008 22:00 | 72.891 | 80.7 | 66.65 | 6.241 | 49.9476 | 2733.7205 | 0.0138 | -1.555 | -6.02 |
| 12 | 4/3/2008 23:00 | 72.028 | 78.26 | 64.93 | 7.098 | 51.3313 | 2655.7183 | 0.0130 | -1.898 | -2.41 |
| 13 | 4/4/2008 0:00 | 71.168 | 77.75 | 63.91 | 7.258 | 52.7102 | 2582.0613 | 0.0126 | -1.894 | -3.65 |
| 14 | 4/4/2008 1:00 | 70.137 | 75.84 | 62.2 | 7.937 | 54.3633 | 2498.6834 | 0.0119 | -2.235 | -5.22 |

## A.1 Raw Data

Obtained from sensors

## A.2 Dew Point Diff

Difference between temperature and dew point

*(a-1)* $\Delta DP = T - DP$

Therefore,

*(a-2)* $Col.6 = Col.3 - Col.5$

## A.3 Humidity Ratio Calculation

The humidity ratio was calculated using *Equation 2*. Restated below:

*(a-3)* $w = \frac{\varphi P_g}{P_{tot} - \varphi P_g}$

Where:
- $w$ = Humidity Ratio
- $P_{tot}$ = Total Pressure of Air
- $\varphi$ = Relative Humidity
- $P_g$ = Saturated Vapor Pressure of Water (temperature dependent)

For *Equation 2*, $\varphi$ was obtained by the sensors and $P_{tot}$ is assumed to be standard atmospheric pressure, 101.325 kPa. The remaining variable, $P_g$, was calculated from the specific volume of saturated water vapor, $v_g$, which varies over temperature.

  

## Saturated Water Specific Volume, $v_g$

To determine the value of the saturated vapor pressure of water at a specific temperature, an extrapolation formula was generated from a table of properties of water shown in *Table A-1*.

*(a-4)* $col.\ 7 = \text{IF}(\text{col.}3 < 41, ((vg\_41 - vg\_32)/9 * (\text{col.}3 - \_32) + \text{vg\_32}),$
$(\text{IF}(\text{col.}3 < 50, ((\text{vg\_50} - \text{vg\_41})/9 * (\text{col.}3 - \_41) + \text{vg\_41}),$
$(\text{IF}(\text{col.}3 < 59, ((vg\_59 - vg\_50)/9 * (col.3 - \_50) + vg\_50),$
$(\text{IF}(\text{col.}3 < 68, ((vg\_68 - vg\_59)/9 * (col.3 - \_59) + \text{vg\_59}),$
$(\text{IF}(\text{col.}3 < 77, ((vg\_77 - vg\_68)/9 * (col.3 - \_68) + \text{vg\_68}),$
$(\text{IF}(\text{col.}3 < 86, ((vg\_86 - vg\_77)/9 * (col.3 - \_77) + \text{vg\_77}),$
$(\text{IF}(\text{col.}3 < 95, ((vg\_95 - vg\_86)/9 * (col.3 - \_6) + \text{vg\_86}),$
$(\text{IF}(\text{col.}3 < 104, ((vg\_104 - vg\_95)/9 * (col.3 - \_95) + \text{vg\_95}),$
$(\text{IF}(\text{col.}3 < 113, ((vg\_113 - vg\_104)/9 * (col.3 - \_104) + \text{vg\_104}),$
$(1)))))))))))))))))$

*Table A-1: Saturation Properties of Water*

| | T | vg | vf |
|---|---|---|---|
| 0.1 | 32 | 0.001000 | 206.132 |
| 5 | 41 | 0.001000 | 147.118 |
| 10 | 50 | 0.001000 | 106.377 |
| 15 | 59 | 0.001001 | 77.925 |
| 20 | 68 | 0.001002 | 57.7897 |
| 25 | 77 | 0.001003 | 43.3593 |
| 30 | 86 | 0.001004 | 32.8932 |
| 35 | 95 | 0.001006 | 25.2158 |
| 40 | 104 | 0.001008 | 19.5229 |
| 45 | 113 | 0.001010 | 15.2581 |
| 50 | 122 | 0.001012 | 12.0318 |
| 55 | 131 | 0.001015 | 9.56734 |
| 60 | 140 | 0.001017 | 7.67071 |
| 65 | 149 | 0.001020 | 6.19656 |
| 70 | 158 | 0.001023 | 5.04217 |
| 75 | 167 | 0.001026 | 4.13123 |
| 80 | 176 | 0.001029 | 3.40715 |
| 85 | 185 | 0.001032 | 2.82757 |
| 90 | 194 | 0.001036 | 2.36056 |
| 95 | 203 | 0.001040 | 1.98186 |
| 100 | 212 | 0.001044 | 1.6729 |
| 105 | 221 | 0.001047 | 1.41936 |
| 110 | 230 | 0.001052 | 1.21014 |
| 115 | 239 | 0.001056 | 1.03658 |

**Saturated Vapor Pressure of Water, $P_g$**

$P_g$ was then calculated using the ideal gas law.

*(a-5)* $PV = mRT$

$$P = \frac{mRT}{V}$$

$$P = \rho RT$$

*(a-6)* $P = \frac{RT}{v}$

Where,

*(a-7)* $v = \frac{1}{\rho}$

Thus,

*(a-8)* $P_g = \frac{RT}{v_g}$

*(a-9)* $col.\ 8 = \frac{(461.5*(col.3\ -32)*\frac{5}{9}+273.15)}{col.7}$

**Humidity Ratio, *w***

Plug the value obtained for $P_g$ along with $\varphi$ and $P_{tot}$ into *Equation a-3.*

*(a-10)* $col.10 = 0.622 * \left(col.\frac{4}{100}\right) * col.8/(101325 - (col.8 * col.4/100))$

A.4 Comparison to Outside

Simply the value minus the outside value.

## Appendix B: Glossary

*ASHRAE* **-** American Society of Heating Refrigeration and Air Conditioning Engineers

*Dry Bulb Temperature* **-** The temperature of air as indicated by an ordinary thermometer

*Dew Point Temperature* – temperature at which water vapor has reached the saturation point(100% relative humidity) Condensation begins to occur once the temperature falls below the dew point temperature

*Humidity ratio* – the ratio of the mass of water vapor to the mass of dry air in a parcel of air

*Relative Humidity* – ratio of the partial pressure or density of water vapor to the saturation pressure or density

*Water Vapor* – water in the vapor or gaseous stage