Thermal Properties of Biological Skins

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Objective:

The objective of this project was to study the thermal properties of biological skins. Three experimental roof set-ups were constructed including a black roof, a cool roof, and a green roof. Experimental equipment was used to measure and compare the thermal properties of these three roofs.

Overview of Work:

The term biological skin refers to a vegetation layer on the outermost surface of a building. Common examples of biological skins include living walls and green roofs. Biological skins are advantageous in that they provide many benefits to the building inhabitants and their surrounding community. The work this semester was focused on assessing the thermal benefits of biological skins through the analysis of a green roof. Three experimental roof modules were constructed on the roof of the Baker Building to test the thermal properties of green roofs. Each module was constructed using standard residential roofing techniques. Each module was constructed using one 4' X 8' piece of plywood, four 2"X4"X8' studs, roofing tar paper, charcoal black asphalt roofing shingle, and stainless steel roofing nails. Each of the three experimental roof modules measured 4'X8' with a total surface area of 32 sq. ft. One of the roof modules was painted with a 0.01" coating of SuperTherm and SuperBase. This low-emissivity coating is commonly applied to what is known as "cool roofs". The high albedo of this cool roof coating is designed to reflect a large majority of the incident solar radiation. The second test roof included green roof modules on the surface of the roof. The final test roof was left as a standard black roof, which is the common roof that is found on most residential homes. Therefore, the three different experimental roof modules provide comparisons to be made between a standard black roof, a cool roof, and a green roof.

The data acquisition equipment consisted of two Hukseflux HFP01 heat flux sensors, numerous K-type Omega Engineering thermocouples, and one Graphtec GL220 midi Logger. The thermocouples were used to make temperature measurements, while the heat flux sensor was used to make heat flux measurements.

Initial Work:

Initially, it was decided that the thermal R-value would be a useful metric of measure to compare the three different roofing systems with. In order to characterize the thermal R-value of each roof three parameters were needed including (1) the exterior surface temperature, (2) the interior surface temperature, and (3) the heat flux passing through the roof. Thermocouples were placed at each necessary surface to measure the exterior and interior surface temperatures. The heat flux sensors were attached to the underside of two of the roof modules to measure the heat flux passing through the experimental roofs. Under steady-state conditions, the thermal R-value was calculated using Equation (1):

$$R = \Delta T / Q \qquad (1)$$

Where R is the thermal resistance, ΔT is the difference between the exterior and interior surface temperature, and Q is the measured heat flux. The use of Equation (1) assumes that the test apparatus is under steady-state conditions, which requires that both ΔT and Q remain constant.

Unfortunately, the green roof supplies were not available for testing while the weather was still warm. Therefore, measurements were made on the cool roof and black roof in order to characterize the remaining systems. Figures (1) and (2) below present preliminary measurements made on the cool roof and black roof experimental roof modules, respectively. The outer temperature, inner temperature, and heat flux were all measured quantities. The resulting R-value was calculated from these three variables using Equation (1).

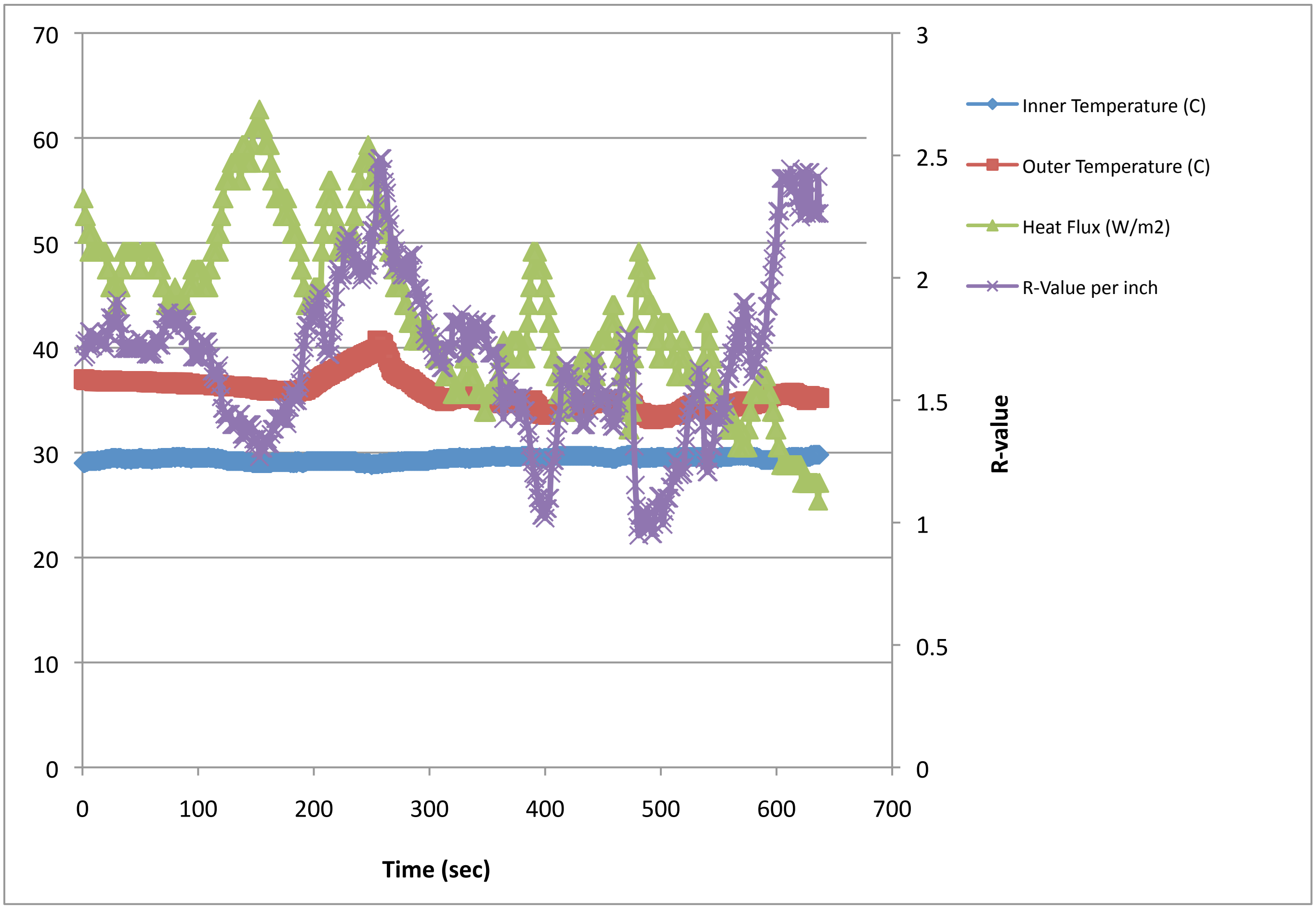

Figure 1: Cool Roof Data 10/19/2010

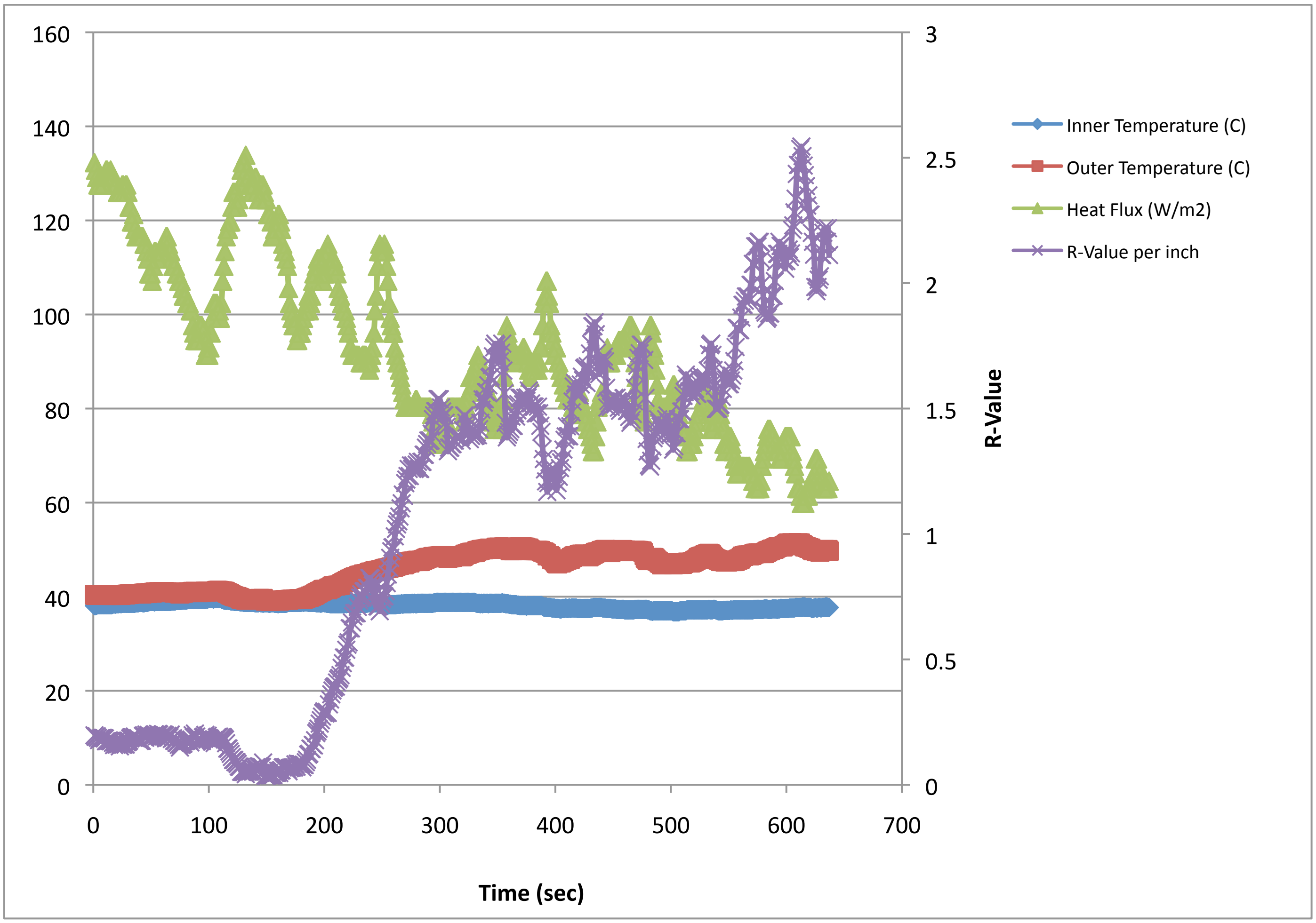

Figure 2: Black Roof Data 10/19/2010

Figures (1) and (2) illustrate the highly fluctuating nature of the recorded data. The small deviations in both the temperature and heat flux measurements can be attributed to the environment of the experimental set-up. For instance, presence of a light breeze acted to instantaneously cool the exterior surface temperature through convection. Furthermore, a cloud passing overhead effectively blocked the sun and consequently effected the incident solar radiation, which in turn affected the exterior surface temperature and the resultant heat flux. Figure (2) illustrates that the exterior surface temperature of the black roof steadily increases over time, while the exterior surface temperature of the cool roof does not exhibit an increasing trend. Comparisons of Figures (1) and (2) reveal that the cool roof has a reduced exterior surface temperature, a reduced interior surface temperature, and a reduced heat flux. The highly fluctuating R-value trend lines reveal that the use of Equation (1) is insufficient, as the system is not operating under steady state conditions.

To further test the steady-state assumption, data was recorded on a perfectly clear day without a cloud in the sky. The hope was that the constant incident solar radiation would create a steady state operating condition. Figures (3) and (4) present the measurements made on the cool roof and black roof experimental roof modules, respectively:

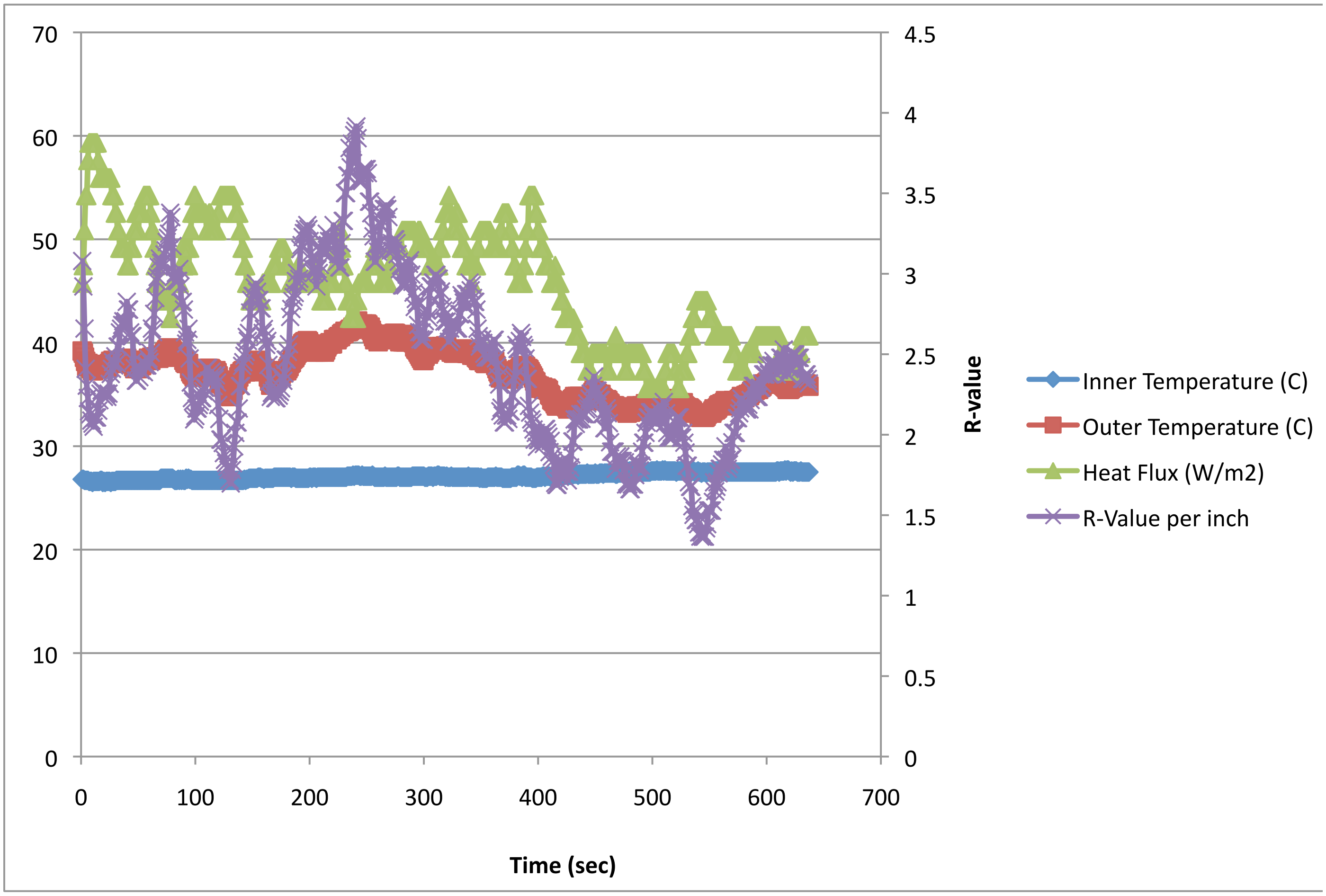

Figure 3: Cool Roof Data 10/22/2010

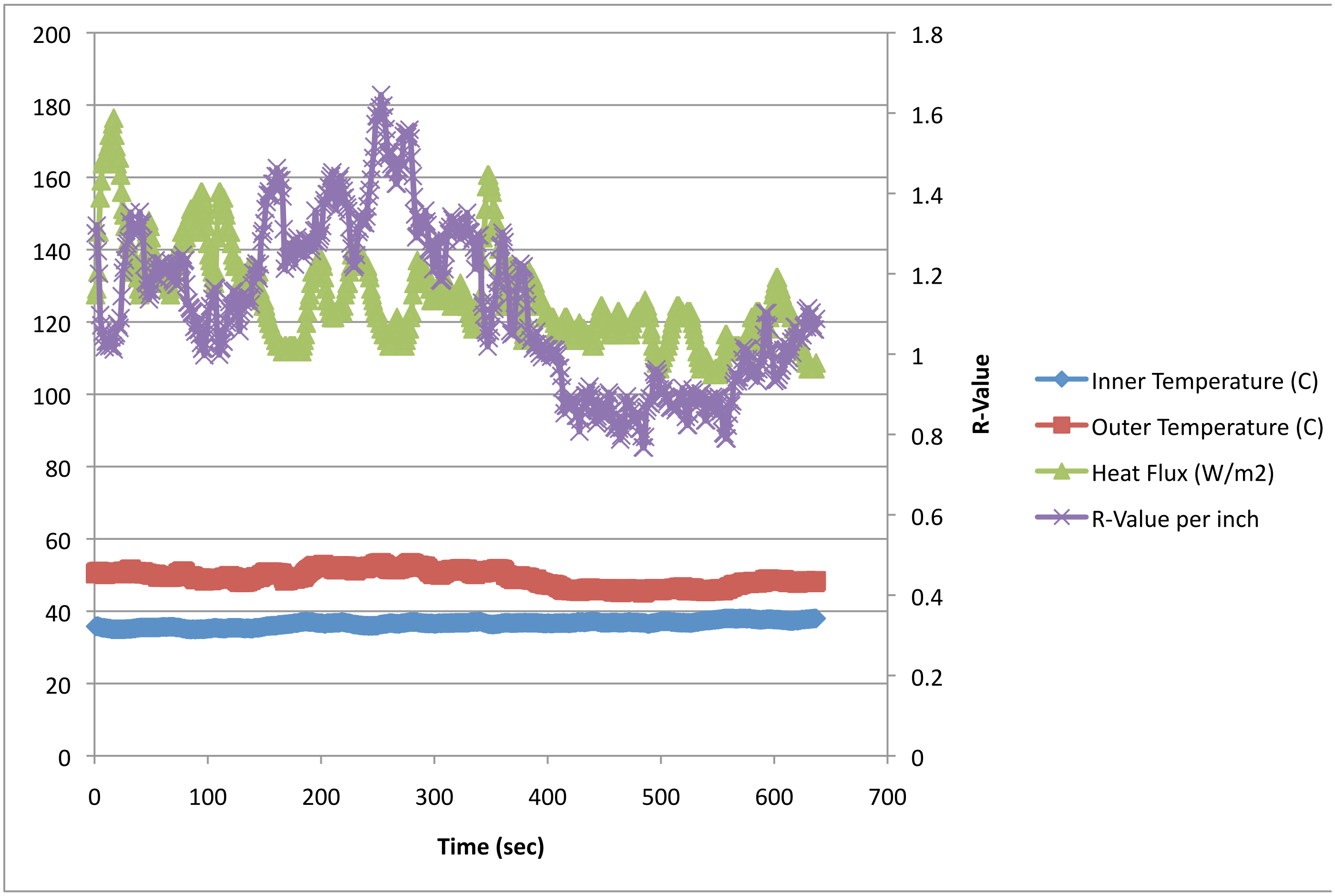

Figure 4: Black Roof Data 10/22/2010

Figures (3) and (4) reveal that even with a steady and uniform exposure to solar radiation, steady state conditions were not met. While the interior surface temperature remained fairly constant, the outer surface temperature and heat flux fluctuated. An analysis of the experimental set-up reveals why the system cannot be assumed to be operating under steady state conditions. Each of the materials used to construct the roof modules possess both a unique specific heat capacity and a unique density. Therefore each material behaves as a thermal mass, introducing thermal inertia to the system. Consequently, each material stores and releases heat at a different rate. The system is therefore time dependent due to its thermal inertia. The use of Equation (1) calculates the instantaneous R-value of the system which is not representative of the true R-value. For instance, when a cloud passes overhead the exterior surface temperature of the roof changes instantaneously. However, the resultant heat flux through the system and interior surface temperature does not change instantaneously due to the thermal inertia of the system. This leads to an incorrect calculation of the thermal R-value.

Both a 3 minute and a 5 minute time-averaged analysis of the system were completed, but the calculated R-value still illustrated significant fluctuations. Ultimately, the system behaved in a transient manner. The analysis of a transient system is significantly more complex than the analysis of a steady state system. To aid in the analysis, Dr. James Brown was consulted. Dr. James Brown holds a PhD in Building Physics from Georgia Tech, and is extremely knowledgeable in the thermal properties of building materials.

Revised Work:

After meeting with Dr. Jason Brown several important conclusions were made regarding the thermal properties of roof systems. An outdoor roof exposed to solar radiation is effected by all three modes of heat transfer: convection, conduction, and radiation. Furthermore, a green roof undergoes additional cooling due to the evapotranspiration from the plants on the surface of the module. Initially, it was assumed that the R-value could be an all-encompassing unit of measure to assess the thermal properties of each roof. However, this assumption is flawed due to the fact that the R-value only accounts for the thermal resistance of the roof to conduction. Convection and radiation are not accounted for by the R-value metric. The R-value is a material property which can be calculated by knowing the thermal conductivity of each material within the roof, and can not be changed by either convection or radiation effects.

As explained earlier, the only difference between the cool roof and the black roof is a thin 10-mil coating of SuperTherm that has been applied to the cool roof. Ultimately, this thin coating does not change the thermal conductivity of the cool roof. The cool roof and the black roof resist conduction equally, leading them to have comparable R-values. However the boundary conditions of each roof are different, leading each roof to have a different thermal response. The high albedo coefficient of the cool roof allows the cool roof to reflect a large percent of the incident solar radiation. As shown in Figures 3 and 4 the heat flux passing through the cool roof is less than the heat flux passing through the black roof. This reduction in heat flux is due to the reflected solar radiation, and not to a difference in the thermal R-value of the two roofs. Furthermore, the convection effects on the cool roof and black roof can assumed to be the same. The forced convection on each roof can be assumed to be the same, as both roofs are exposed to the same atmospheric conditions. Due to the reduced operating temperatures of the cool roof, the natural convection on the cool roof will be slightly different than that of the black roof. Ultimately, the difference in thermal characteristics between the cool roof and black roof is mainly due to each roof's response to incident solar radiation. Furthermore Figures 3 and 4 above illustrate that when the system is not operating under steady state conditions, the thermal R-value is extremely difficult to measure.

When comparing the thermal characteristics of a green roof with either a black roof or a white roof, the thermal mass of each roof must be considered. The planting medium of the green roof adds a significant volume of thermal mass to the green roof system, causing it to perform differently than the roof systems with lower thermal masses. The characteristics of a system with a high thermal mass greatly complicates the analysis. Two systems can have similar thermal R-values but different thermal masses, and the two systems will behave extremely differently. Systems with high thermal mass add thermal inertia to the analysis. Thermal inertia adds a time delayed response to the system. In a roof application, this can be seen by the delayed response of the roof's inner surface temperature to a change in its outer surface temperature. Ultimately, thermal mass significantly changes the thermal characteristics of a system. Due to these differences, a mass-weighted thermal R-value can be calculated. However, the magnitude of the mass weighted thermal R-value is dependent on the location of the system and so cannot be universally compared to the standard thermal R-value. This further illustrates why the thermal R-value is not a useful metric of measure to compare roofing systems.

When comparing the thermal performance of a black roof, a cool roof, and a green roof the corresponding R-value is not a useful metric to use. Furthermore, calculating the thermal R-value is extremely difficult unless the system is operating under steady state conditions. Therefore, it was decided to analyze a different metric of measure. It was decided that the total amount of heat energy that enters each roof over a certain period of time through its roof is the important metric of comparison. This total amount of energy cannot be instantaneously measured by a heat flux sensor, but instead can be calculated with instantaneous heat flux measurements over a specific period of time. By measuring the total amount of energy that passes through the roof over a certain period of time the effects of thermal mass are included in the analysis. During the cooling season, it is desirable to minimize the amount of heat entering a building through its roof, and during the heating season it is desirable to maximize the amount of heat that enters the building through its roof.

Unfortunately, the green roof module supplies were not delivered in time to complete measurements on the green roof during warm weather. Previous measurements made on the cool roof and black were used to analyze the total amount of energy passing through each roof during a simulated cooling season. The data was recorded on October 22, 2010 for a total time of 16 minutes. Figure 5 below presents the corresponding results:

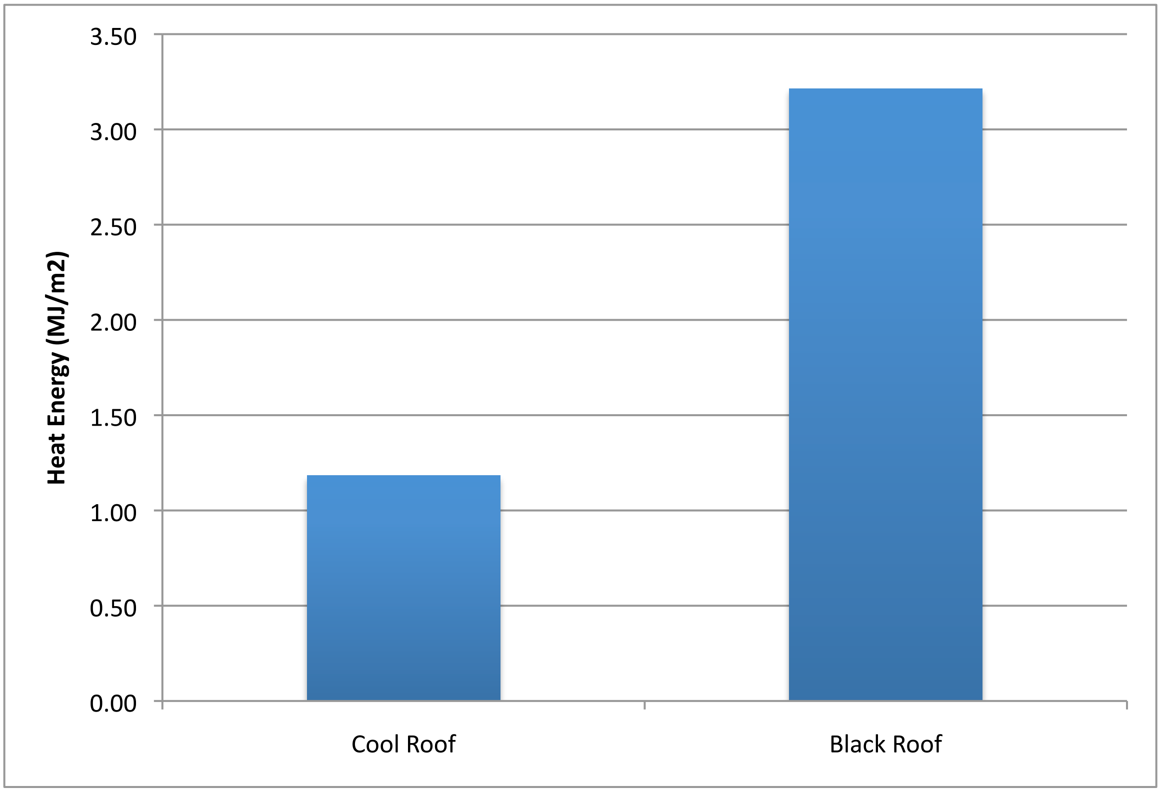

Figure 5: Roof Comparison, 10/22/2010 Data

Figure 5 illustrates that 1.2 MJ/m^2 of heat energy passed through the cool roof and 3.2 MJ/m^2 of heat energy passed through the black roof. The black roof let in 2.7 times more heat energy per square meter, as compared to the cool roof. With an ambient temperature of 86°F, the outdoor temperature is above the interior set-point temperature of a standard building. Therefore, the cool roof illustrates superior performance, as it allows a smaller amount of heat energy to pass through the roof system.

In early December, 33 ft^2 of green roof module supplies arrived. A specific planting pattern was implemented, as illustrated in Figure 6 below:

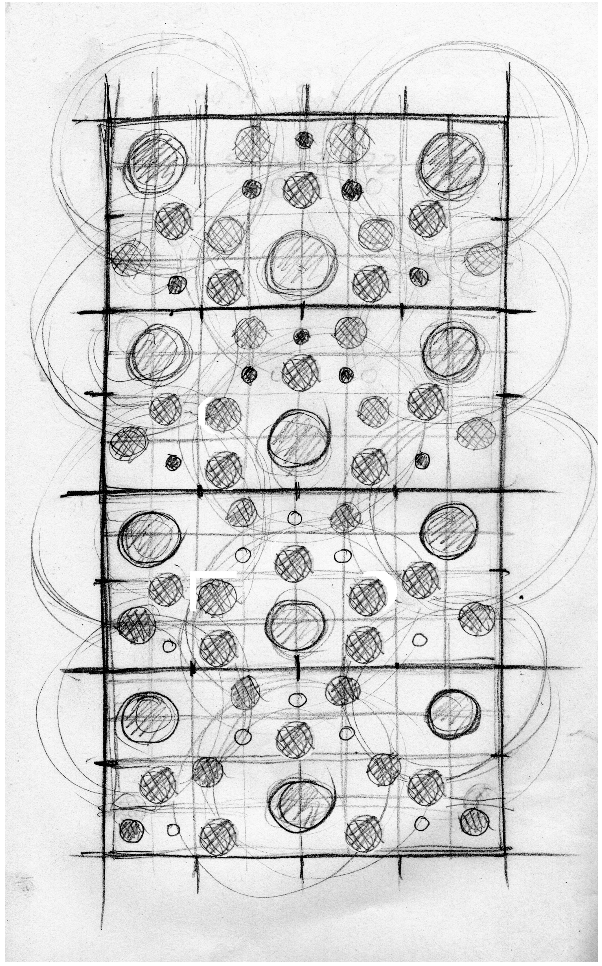

Figure 6: Green Roof Planting Diagram

Where the species *Muhlenbergia capillaris* is represented by the largest dots, the species *Eragrostis spectabilis* is represented by the medium sized dots, and the species *Carex pensylvanica* is represented by the smallest sized dots. This specific planting pattern was chosen to provide uniform plant coverage once the plants are fully developed.

On December 3rd, 2010 test measurements were made on both the green roof and cool roof. The ambient temperature of the testing environment was 47°F. Due to the low ambient temperature, the outdoor temperature of the experimental setup was lower than the interior set-point temperature of a standard building. Therefore this experiment simulates a building operating during its heating season. Figure 7 and 8 below present the recorded data:

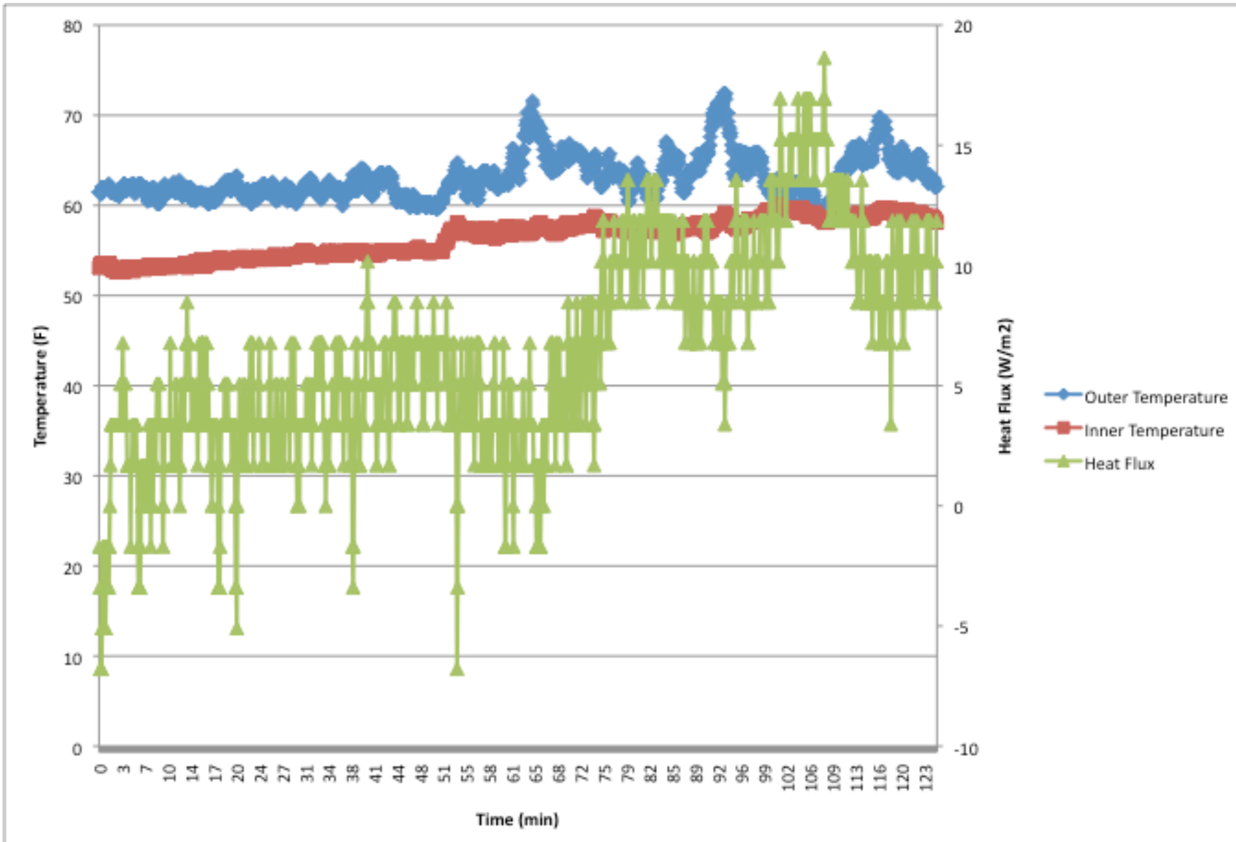

Figure 7: Coof Roof Data 12/03/2010

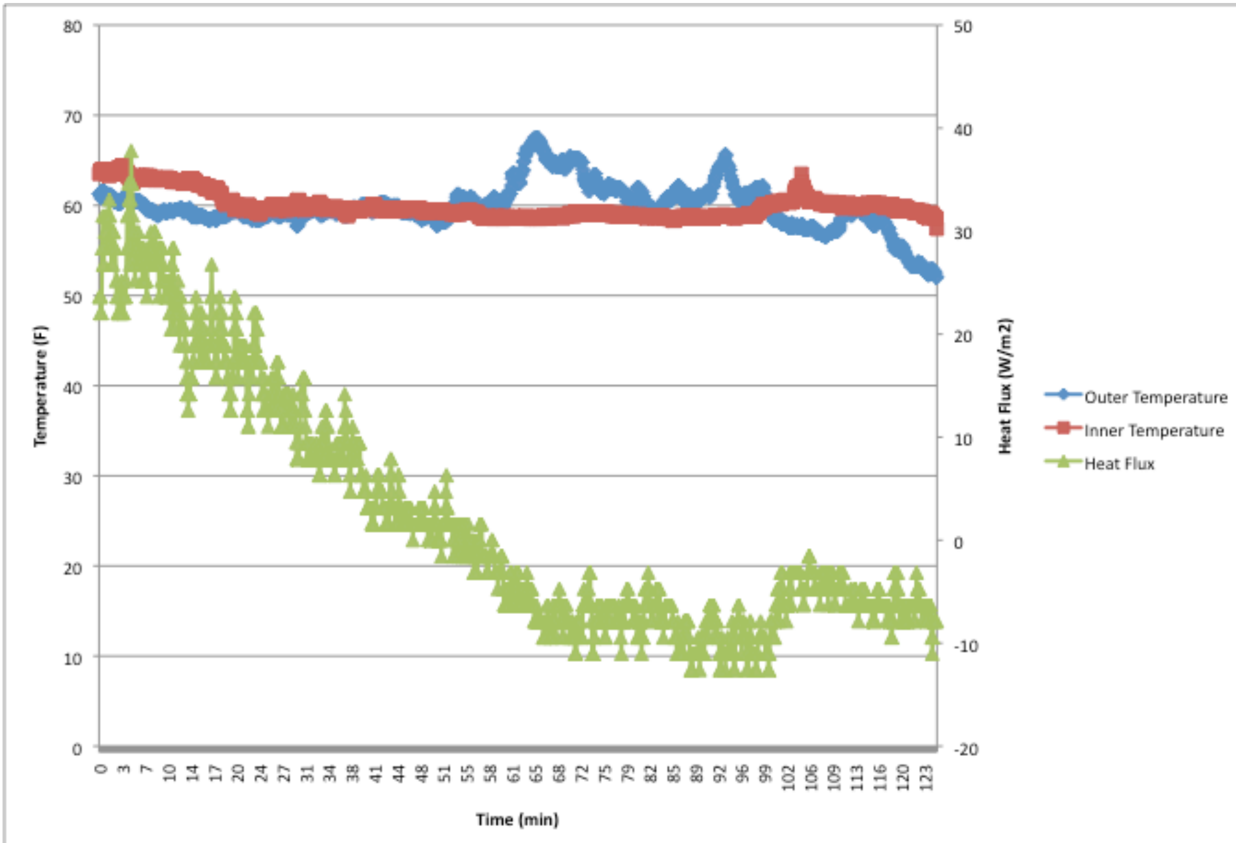

Figure 8: Green Roof Data 12/03/2010

Comparisons of Figure 7 and 8 reveals that the outer temperatures of both roofs are similar in magnitude over the course of the experiment. However, the interior temperature of the green roof is significantly higher than the interior temperature of the cool roof. The increased temperature of the interior environment of the green roof is favorable when compared to the cool roof, due to the fact that a simulated building would be operating in its heating season and would be heating its interior environment. Furthermore, the thermal mass properties of the green roof can be seen by comparing Figures 7 and 8. In Figure 7, the heat flux measurement follows the outer temperature measurement with a lag of around 20 minutes. For instance, in Figure 7 a local maximum outer temperature occurs at 65 minutes, while the corresponding local maximum heat flux measurement occurs at 82 minutes. However, Figure 8 illustrates that the trends for the outer temperature and corresponding heat flux of the green roof cannot be easily correlated. This can be attributed to the high thermal mass of the green roof, in which the time lag is greater than the total time of the experiment. Unfortunately, the battery life of the data logger limited the length of the experiment. In future experiments, a power line has been arranged to be provided to allow the data logger to operate for an extended period of time. In order to fully assess the thermal mass properties of the green roof, the optimal experiment should occur over a period of 24 hours. Figure 8 reveals that the interior temperature of the green roof remained fairly constant, while Figure 7 reveals that the interior temperature of the cool roof was more variable. The constant interior temperature of the green roof can be attributed to its thermal mass, which provides thermal inertia to dampen out minor temperature fluctuations. Figure 9 below presents the total heat energy flow of each system:

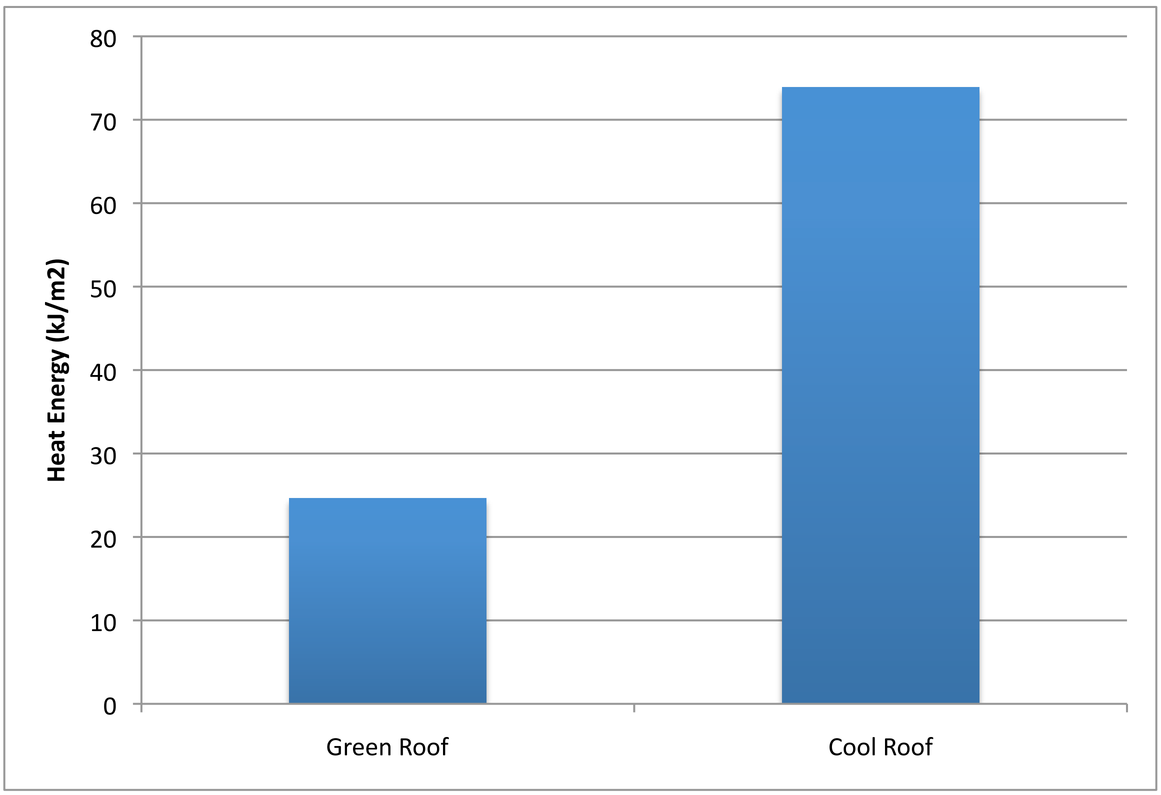

Figure 9: Roof Comparison, 12/03/2010

Figure 9 illustrates that 25 MJ/m^2 of heat energy passed through the green roof and 74 MJ/m^2 of heat energy passed through the cool roof. Therefore, the cool roof let in 3 times more heat energy per square meter, as compared to the green roof. Due to the cold ambient conditions of the experiment, it is favorable for a roof system to let in the most amount of heat energy possible. However further analysis reveals that even though the cool roof let in more energy during the experiment, the green roof illustrated more favorable characteristics. The green roof exhibited a nearly constant interior temperature that was on average 4°F warmer than the interior temperature of the cool roof. During segments of the experiment, the interior temperature of the green roof was as much as 10°F warmer than the interior temperature of the cool roof. Even though the cool roof let in more heat energy than the green roof, the green roof was able to maintain a higher interior temperature due to the stored heat energy in its thermal mass. Therefore as stated earlier, to fully characterize the performance of each roof system it is necessary to perform the experiment over a period of 24 hours.

Conclusion:

The objective of this project was to study the thermal properties of biological skins. The experimental setup included three different roof modules including a black roof, a cool roof, and a green roof. Initially, it was desired to compare the thermal R-value of each roof. However further investigation revealed that the thermal R-value was not a useful metric to compare the three different roof systems due to the differences in reflected radiation and thermal mass. Therefore, it was decided that the total heat energy passing through each roof system over a period of time would be a useful indication of the desired performance of each roof. However this metric alone is not enough to compare the three different roofing systems, as the interior temperature of each roof is of also of great importance. Ultimately it was demonstrated that the cool roof allowed 2.7 times less heat energy to pass into the interior of the roof when compared with the black roof during a buildings cooling season. Furthermore, it was demonstrated that the green roof's thermal mass increased its desired performance during winter testing. Despite the fact that the cool roof allowed 3 times more heat energy to enter into the interior of the roof module, the green roof was able to maintain a constant interior temperature that was consistently higher than the interior temperature of the cool roof.

The acquisition of a newly planted 1000 square foot green roof on the roof of the Baker Building will greatly facilitate further research. This large test bed will provide ample opportunity to test different plant combinations, plant environments, and operating conditions. Furthermore, an electrical outlet near the newly installed green roof will be provided. This will allow the data logger to record experimental measurements over extended periods of time. Without an electrical outlet, the data logger must run on a battery. The short battery life of the data logger greatly limited the length of each experiment. With the ability to perform experimental measurements over days, instead of hours, the thermal mass characteristics of the green roof can further analyzed. Ultimately, this new green roof will provide researchers with the necessary experimental setup to analyze the characteristics of living skins.

Acknowledgments:

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