Thermal Performance of Vegetative Roofing Systems

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ABSTRACT

Vegetative roofing, otherwise known as green or garden roofing, has seen tremendous growth in the last decade in the United States. The numerous benefits that green roofs provide have helped to fuel their resurgence in industrial and urban settings. There are many environmental and economical benefits that can be realized by incorporating a vegetative roof into the design of a building. These include storm-water retention, energy conservation, reduction in the urban heat island effect, increased longevity of the roofing membrane, the ability of plants to create biodiversity and filter air contaminants, and beautification of the surroundings by incorporating green space.

The vegetative roof research project at Oak Ridge National Laboratory (ORNL) was initiated to quantify the thermal performance of various vegetative roofing systems relative to black and white roofs. Single Ply Roofing Institute (SPRI) continued its long-term commitment to cooperative research with ORNL in this project. Low-slope roof systems for this study were constructed and instrumented for continuous monitoring in the mixed climate of East Tennessee. This report summarizes the results of the annual cooling and heating loads per unit area of three vegetative roofing systems with side-by-side comparison to black and white roofing systems as well as a test section with just the growing media without plants.

Results showed vegetative roofs reduced heat gain (reduced cooling loads) compared to the white control system due to the thermal mass, extra insulation, and evapo-transpiration associated with the vegetative roofing systems. The 4" and tray systems reduced the heat gain by approximately 61%, while the reduction with the 8" vegetative roof was found to be approximately 67%. The vegetative roofing systems were more effective in reducing heat gain than in reducing heat losses (heating loads). The reduction in heat losses for the 4" and tray systems were found to be approximately 40% in the mixed climate of East Tennessee. It should be noted that these values are climate dependent.

Vegetative roofs also reduced the temperature (heat exposure) and temperature fluctuations (thermal stress) experienced by the membrane. In the cooling season of East Tennessee, the average peak temperature of the 4" and tray systems was found to be approximately 94°F cooler than the control black roofing system. The average temperature fluctuations at the membrane for the 4" and tray systems were found to be approximately 10°F compared to 125°F for black and 64°F for white systems. As expected, the 8" vegetative roof had the lowest fluctuations at approximately 2°F.

Future work will include modeling of the energy performance of vegetative roof panels in the test climate of East Tennessee. The validated model then will be used to predict energy use in roofs with different insulation levels and in climates different from the test climate.

INTRODUCTION

Vegetative roofs provide many environmental and economic benefits to the design of a building, including storm water retention, energy conservation, sound attenuation, reduction in the urban heat island effect, increased longevity of the roofing membrane, the ability of plants to create biodiversity, filter air contaminants and sequester carbon, and aesthetic benefits (Christian and Petrie 1996, Eumorfopoulou and Aravantinos 1998, Liu and Baskaran 2005, Wong et al. 2003). Vegetative roofs have been in existence for centuries. They have been used for winter insulation and summer cooling. Research

and development work in Germany in 1960-1970 resulted in the present lightweight vegetative roofs (Peck 2009). Various field studies have been conducted by researchers such as Sonne (2006) and DeNardo (2005). Predictive models have been developed by various investigators such as Kumar and Kaushik (2005), Palomo Del Barrio (1998), Theodosiou (2003), and Sailor (2008). It should be noted that the model developed by Sailor (2008) has been integrated into the EnergyPlus building energy simulation program (Crawley et al. 2004) to allow energy modelers to investigate vegetative roof design options.

Vegetative roofs are typically classified as "extensive" or "intensive" systems. Extensive vegetative roofs use a shallow substrate layer (up to 4 in); low growing plants such as drought tolerant sedum and grasses; and require minimal maintenance. In contrast, intensive vegetative roofs require deeper substrate layer; use a wide variety of plants such as trees and shrubs; and require high maintenance and irrigation system.

Lightweight vegetative roofing systems are often compared to cool roofing such as white roofs. To date, research across the United States and internationally has looked at the heat flow and temperatures of various vegetative roof designs. There is increasing need for a comprehensive energy analysis that is successful at modeling vegetative and white roof technology while taking into account the yearly climatic conditions across the United States and the building envelope. Well-characterized test data from side-by-side comparison of vegetative and conventional low-slope roofs are essential to a successful model.

The vegetative roof research project at Oak Ridge National Laboratory (ORNL) was initiated in June 2008 to quantify the thermal performance of various vegetative roofing systems relative to black and white roofs. SPRI continued its long-term commitment to cooperative research with ORNL in this project. Low-slope roof systems for this study were constructed and instrumented for continuous monitoring in the mixed climate of East Tennessee. Two 4 ft × 8 ft test panels on the Roof Thermal Research Apparatus (RTRA) were used to construct 4 ft x 4 ft test sections for the vegetative roofs. Another 4 ft × 8 ft test panel on the RTRA was used for an exposed black ethylene propylene diene monomer (EPDM) membrane (4 ft x 4 ft test section) and an exposed white thermoplastic polyolefin (TPO) membrane (4 ft x 4 ft test section). These are the control systems. The vegetative roofing systems include a commercially available modular vegetative roofing system (nominal 4" tray system), a nominal 4" typical roof vegetative system, and a nominal 8" intensive depth vegetative roofing system. In addition, a nominal 4" typical soil (no plant) with erosion mat was installed for side-by-side comparison with the roof vegetative systems.

This report summarizes the results of the annual cooling and heating loads of these panels in East Tennessee climate. The thermal performance is collected in sufficient detail and for long enough periods (52 weeks) to validate the model of system behavior.

EXPERIMENTAL

Figure 1 shows the vegetative roofing systems constructed for this project, which consist of the plant layer, growing media, drainage layer, root barrier, protection layer, and membrane. The same black EPDM membrane was used under the vegetative roof test sections. All the test sections have similar insulations under the membrane (layer wise and type) with identical instrumentations. To monitor thermal performance, thermocouples and heat flux transducers were used in all systems. Pairs of thermocouples

were located under all membranes, between the pieces of wood fiberboard insulation and on top of the deck. The fiberboard provided thermal resistance of R-3.8. For each vegetative roofing system, one thermocouple was located near the surface and a second thermocouple was situated in the middle of the growing media. A heat flux transducer was located between the pieces of fiberboard in the center of each test section (Figure 1). In addition, moisture content was measured with dielectric sensors that were located in the middle of the growing media in all the vegetative roofing systems including the test section with no plants. The moisture probe measures the dielectric constant of the soil in order to determine its volumetric water content. Local weather data such as temperature, relative humidity, rainfall and solar radiation were also monitored continuously by a weather station located on the rooftop of the RTRA facility.

The 4" standard vegetative system and the growing media (no plants) shared one 4 ft by 8 ft panel with each system occupying half (4 ft by 4 ft section). The 8" vegetative system and the tray system shared another 4 ft by 8 ft panel. The exposed white-TPO and black-EPDM membrane systems (control systems) shared a third panel. Computer simulation verified that the two systems sharing the same panel did not thermally impact each other. A data acquisition system (DAS) did continuous monitoring of the thermocouples, heat flux transducers, moisture sensor, and weather data from the weather station. The experimental data were recorded 24/7 at 15 minute intervals. Week 1 started June 13, 2008. This report summarizes the annual data collected (ending June 12, 2009).

Properties of Vegetative Roofing Systems

Table 1 shows the loading (weight per unit area) of the vegetative roof test sections. The lightest loading is the tray system (modular vegetative roofing system) and the heaviest loading is the 8" vegetative roofing system. The loading of the 4" vegetative roof is between the heaviest and lightest and is similar to the loading of the growing media without plants.

An effort will be made to model the internal heat flows of the vegetative roofing systems using Simplified Transient Analysis of Roofs (STAR). STAR is a one-dimensional finite difference model for heat conduction (Wilkes 1989). STAR requires a layer–by-layer description of the physical and thermal properties of the roofing system such as density, thermal conductivity, and specific heat.

Solar reflectance of the exposed smooth surfaces (white and black membranes) was measured in accordance to ASTM C1549-04. Table 2 shows the solar reflectance of these two surfaces after one year of exposure and after cleaning. Table 3 shows the solar reflectance values for the vegetative roofing systems that were made in accordance to ASTM E1918-06.

The thermal conductivity and specific heat of the black and white membranes and the fiberboard will be obtained from the literature, including measurements conducted at ORNL. For the vegetative systems, an attempt will be made to measure the thermal conductivity properties at different moisture contents, which will be included in the STAR computer model.

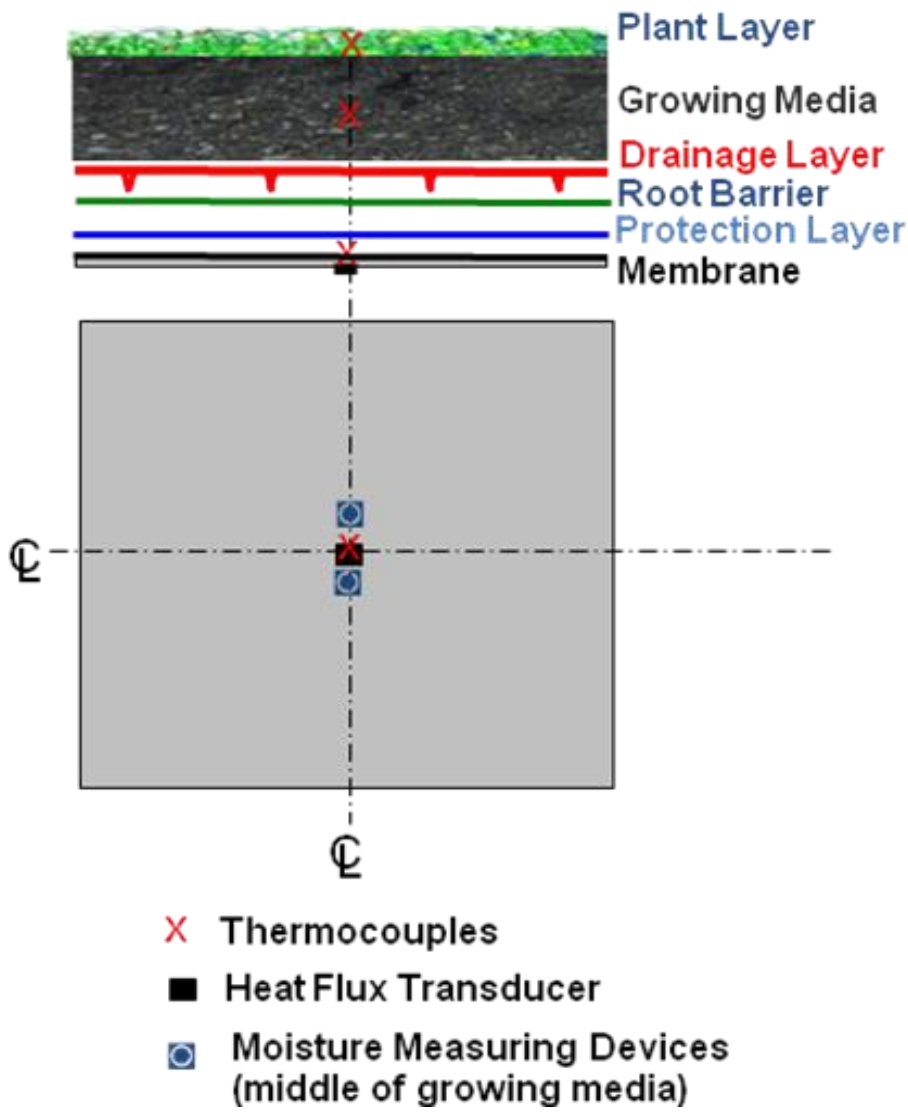

Figure 1. Layers of a Typical Vegetative Roofing System

Table 1. Loading (weight/area) of Vegetative Roofing Systems

Test Section	Covering or Loading	Thickness (in)
Black Control	Bare EPDM	0.045
White Control	Bare TPO	0.050
Growing Media (No Plants)	17 lb/ft^2 on EPDM	4.5
4" Standard Vegetative Roof	15 lb/ft^2 on EPDM	4.5
8" Vegetative Roof	31.6 lb/ft^2 on EPDM	8.5
4" Tray System	9 lb/ft^2 on EPDM	4.5

Table 2. Solar Reflectance of White-TPO and Black-EPDM Control Systems

Test Section	Solar Reflectance (%)
Black Control (weathered- after one year of exposure)	5.6
White Control (weathered- after one year of exposure)	68.2
Black Control (cleaned)	4.9
White Control (cleaned)	74.9

Table 3. Solar Reflectance of Vegetative Roofing Systems

Test Section	Solar Reflectance (%)
4" Standard Vegetative Roof	11.7
8" Vegetative Roof	13.5
4" Tray System	12.0
Growing Media (with Erosion Mat)	9.7

RESULTS AND DISCUSSIONS

Moisture Content

As mentioned previously, moisture content was measured with dielectric sensors located in the middle of the growing media in all the vegetative roofing systems including the test section with no plants. The sensor measures the dielectric constant of the soil in order to determine its volumetric water content.

Heavy watering was initiated during the initial installation of the vegetative roofs. During the first several months (June 13, 2008 to October 2, 2008), the vegetative roofs were watered twice a week for approximately 10 minutes. This allowed the plants (various species of sedum) to be established in the test climate of East Tennessee. Figure 2 shows the moisture content of the 4" vegetative roof during one of the watering schedules (June 27 to July 3, 2008). The watering is shown by sharp increase in the moisture content (Figure 2). Figure 3 shows the plant coverage around this time period (June 26, 2008). The plant coverage seems to be around 65% of the total area of the 4" vegetative roof.

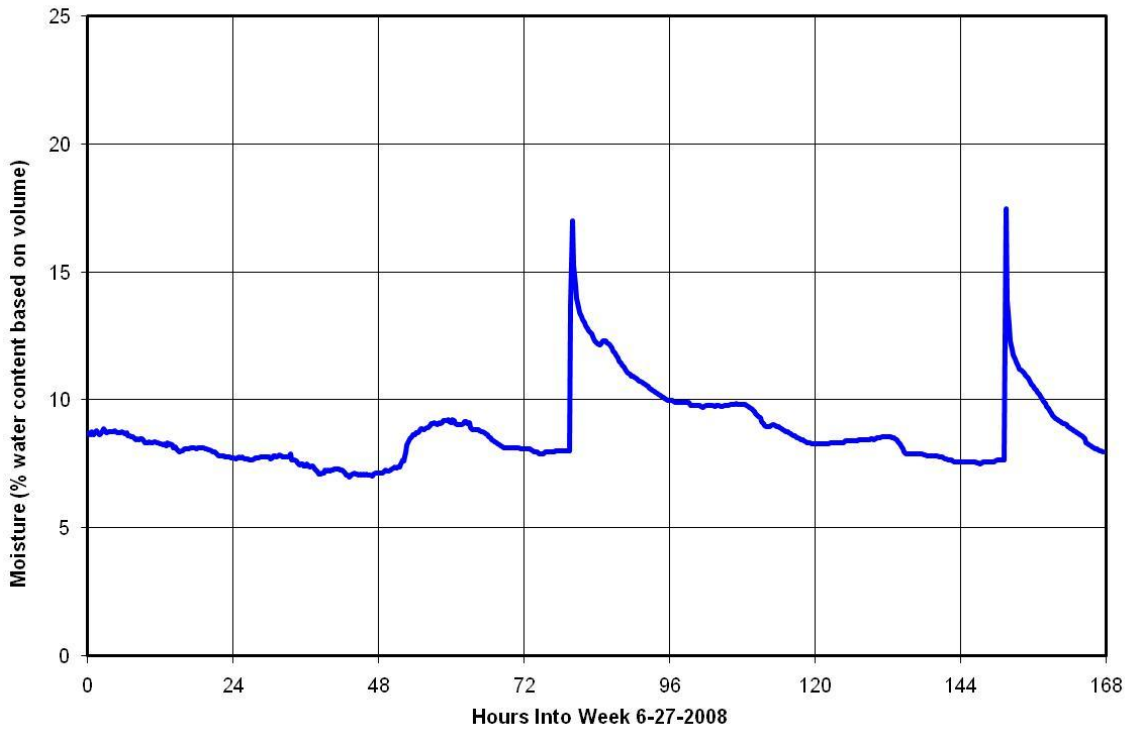

Figure 2. Moisture content of 4" vegetative roofing system during the heavy watering schedule

Figure 3. Plant coverage of 4" vegetative roofing system (picture taken on June 26, 2008)

Figure 4 shows the moisture content of the 4" vegetative roofing system during one of the rain events (rainfall of 1.04") on February 18, 2009. Figure 5 shows the plant coverage around this time period (February 6, 2009). This shows full plant coverage of the surface.

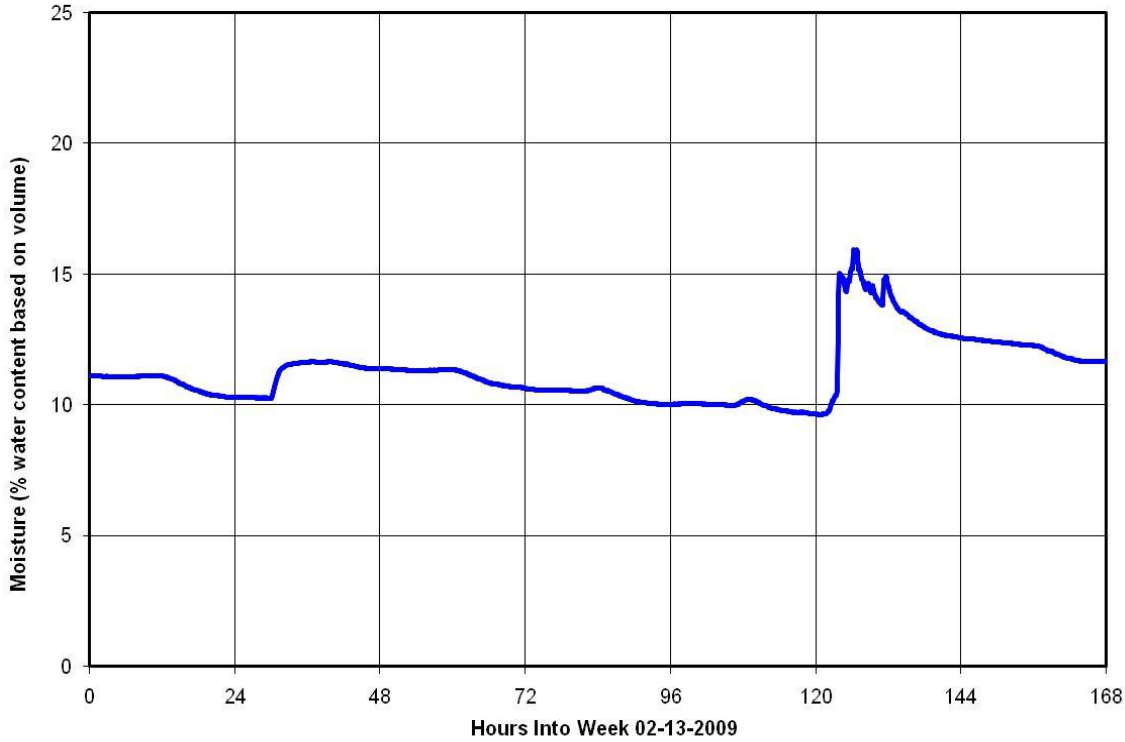

Figure 4. Moisture content of 4" vegetative roofing system during a rain event (February 18, 2009)

Figure 5. Plant coverage of 4" vegetative roofing system (picture taken on February 6, 2009)

Comparison of Thermal Performance

The thermal performance data were analyzed using a dead band in outdoor temperature between 75°F and 60°F when the building does not require heating or cooling. Therefore, the following definitions were

applied to the heat fluxes through the fiberboard insulation. The heating loads (heat losses) were defined as the summation of all the negative heat fluxes when outdoor air temperature is less than 60°F and the cooling loads (heat gain) were defined as the summation of all the positive heat fluxes when the outdoor air temperature is greater than 75°F.

Figure 6 shows the weekly cooling load comparison between the growing media and the 4" vegetative roofing system in the mixed climate of East Tennessee. As expected, the majority of the cooling loads occurred from the second week of April to the second week of October. The average cooling load of the growing media was found to be approximately 38% greater than the average cooling load of the 4" vegetative roofing system.

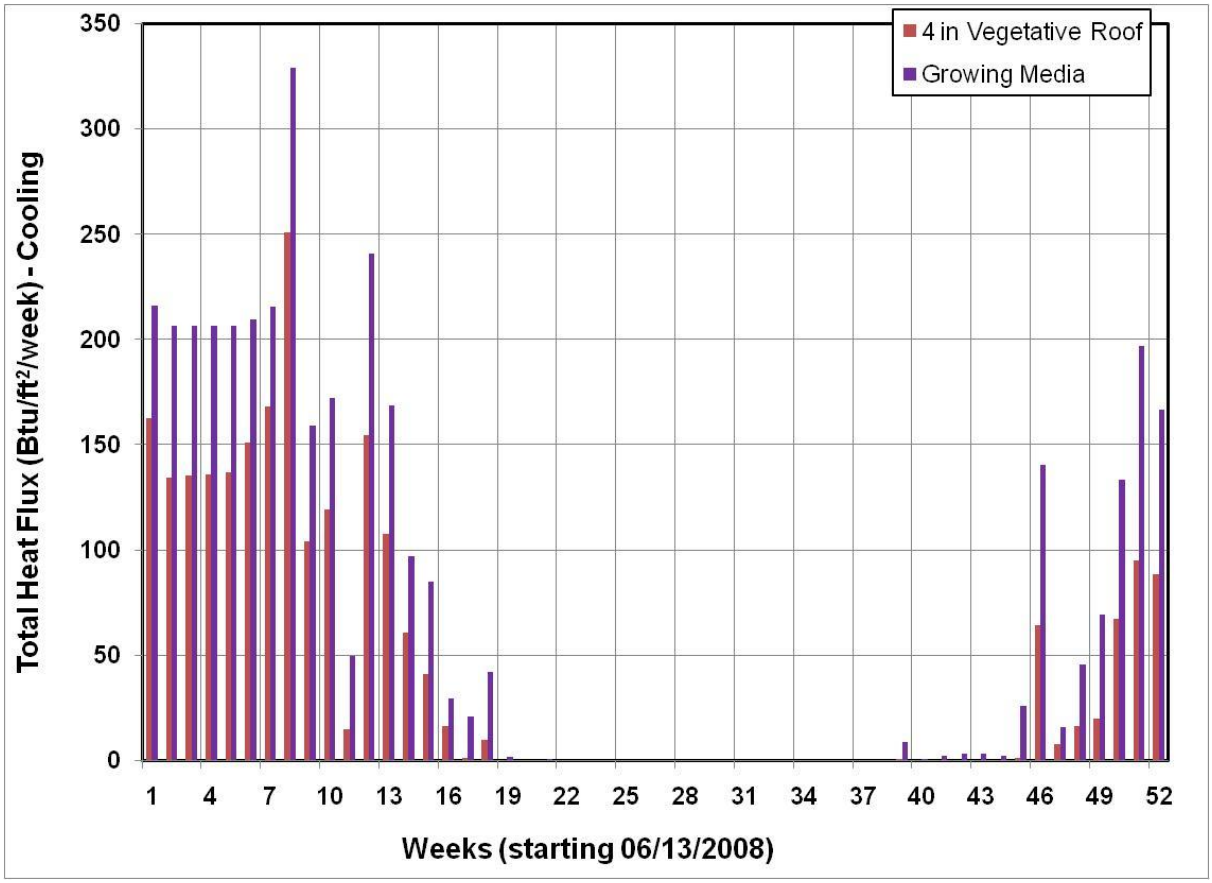

Figure 6. Comparison of cooling loads between growing media and 4" vegetative roofing system

Figure 7 shows the weekly heating load comparison between the growing media and the 4" vegetative roofing system. As expected, the majority of the heating loads occurred from the end of October to the first week of April. The average heating load of the growing media was found to be slightly lower (~9%) than the average heating load of the 4" vegetative roofing system.

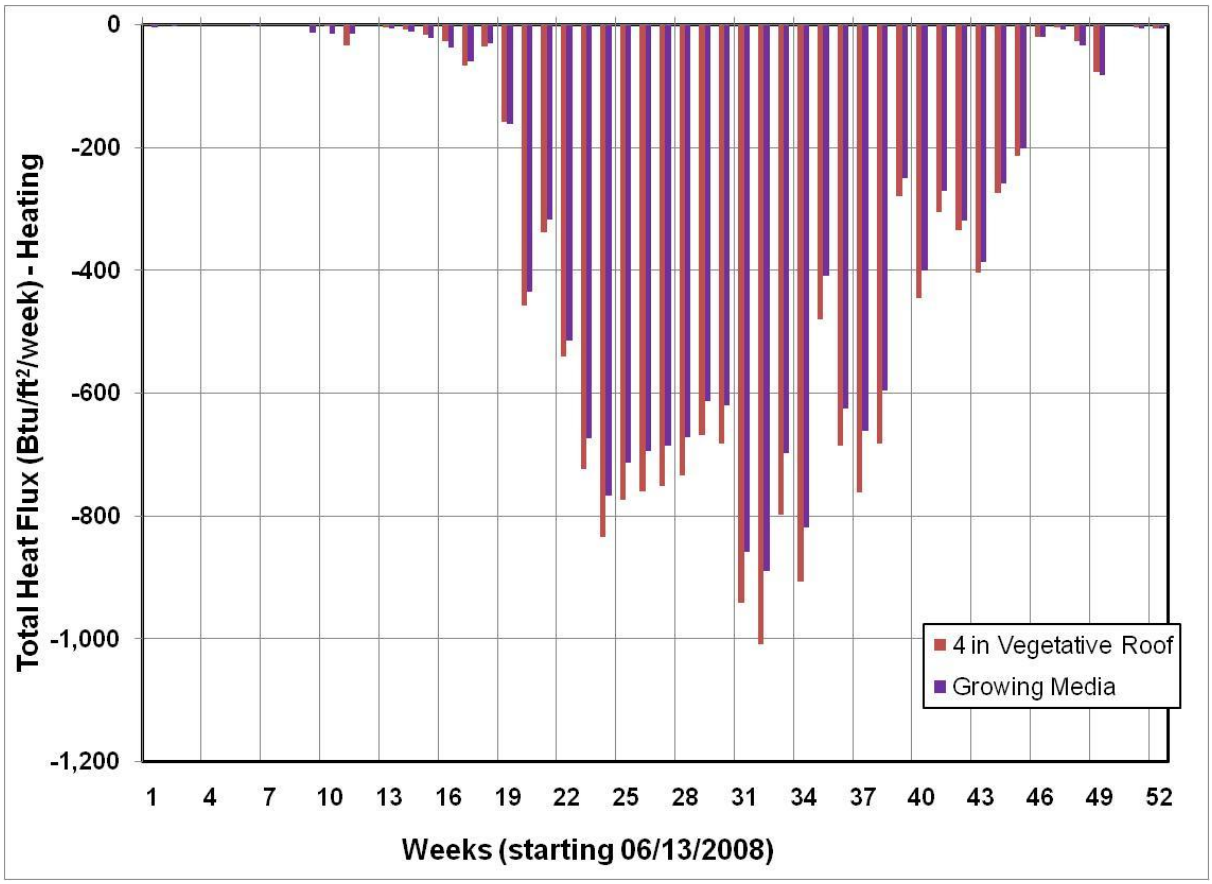

Figure 7. Comparison of heating loads between growing media and 4" vegetative roofing system

The analysis continued with a more detailed comparison of the thermal performance of the black and the vegetative roofing systems to the white system. Figure 8 compares the cooling load between the vegetative roofing systems (including growing media without plants and the black membrane) to the white roofing system. This was accomplished by subtracting the cooling load for the white membrane from the corresponding cooling load for each vegetative roofing system. Positive values for this difference represent more cooling requirement for the subject system than the white. As expected, the black system showed the largest cooling load (largest heat gain) compared to the white system. The thermal mass, extra insulation, and evapo-transpiration associated with the vegetative roofing systems made their cooling performance more effective than the white control roofing system in the East Tennessee climate. The cooling loads of 4" vegetative and tray systems were found to be similar, with a reduction in heat gain of approximately 61% compared to the white control system. The reduction in heat gain for the 8" vegetative roofing was slightly higher (approximately 67%). This is due to the additional thermal mass and extra insulation provided by the additional growing media for the 8" vegetative roofing system.

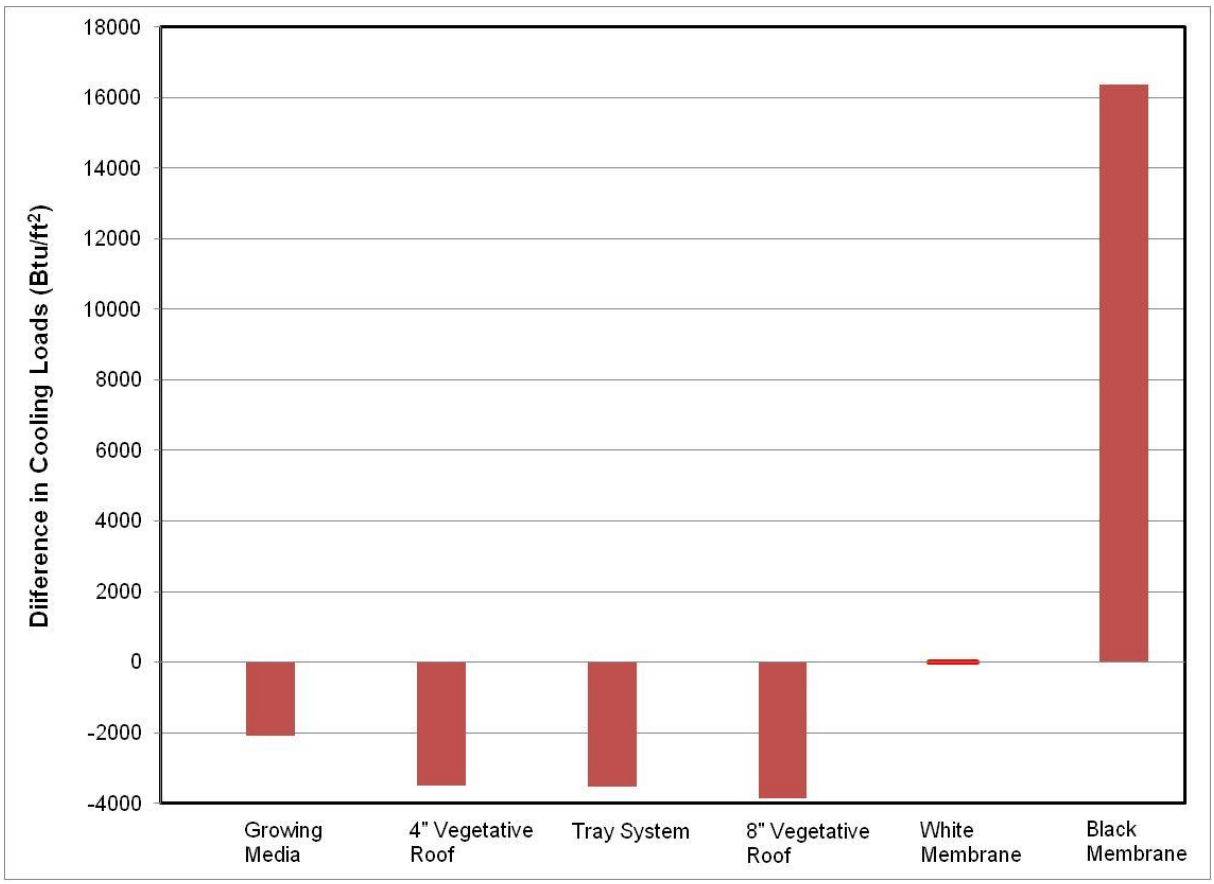

Figure 8. Cooling loads of vegetative and black roof sections indexed to the white section cooling load

Figure 9 compares the heating load between the vegetative roofing systems (including growing media without plants and the black membrane) to the white roofing system. This was accomplished by subtracting the heating load for each vegetative roofing system from the corresponding heating load for the white roofing system. Negative values for this difference represent less heating load requirement for the subject system than the white. As expected, the black system showed less heating load than the white roofing system. The heating loads for all the vegetative roofing systems including the growing media without plants resulted in reduced heating loads (reduced heat losses) compared to the black control roofing system due to the effect of thermal mass and extra insulation. The reduction in heat losses for the 4” and tray systems were found to be approximately 40% compared to the white control system. The reduction in heat losses for the 8” vegetative roofing was slightly higher at approximately 55%. This is again due to the additional thermal mass and extra insulation provided by the additional growing media for the 8” vegetative roofing system.

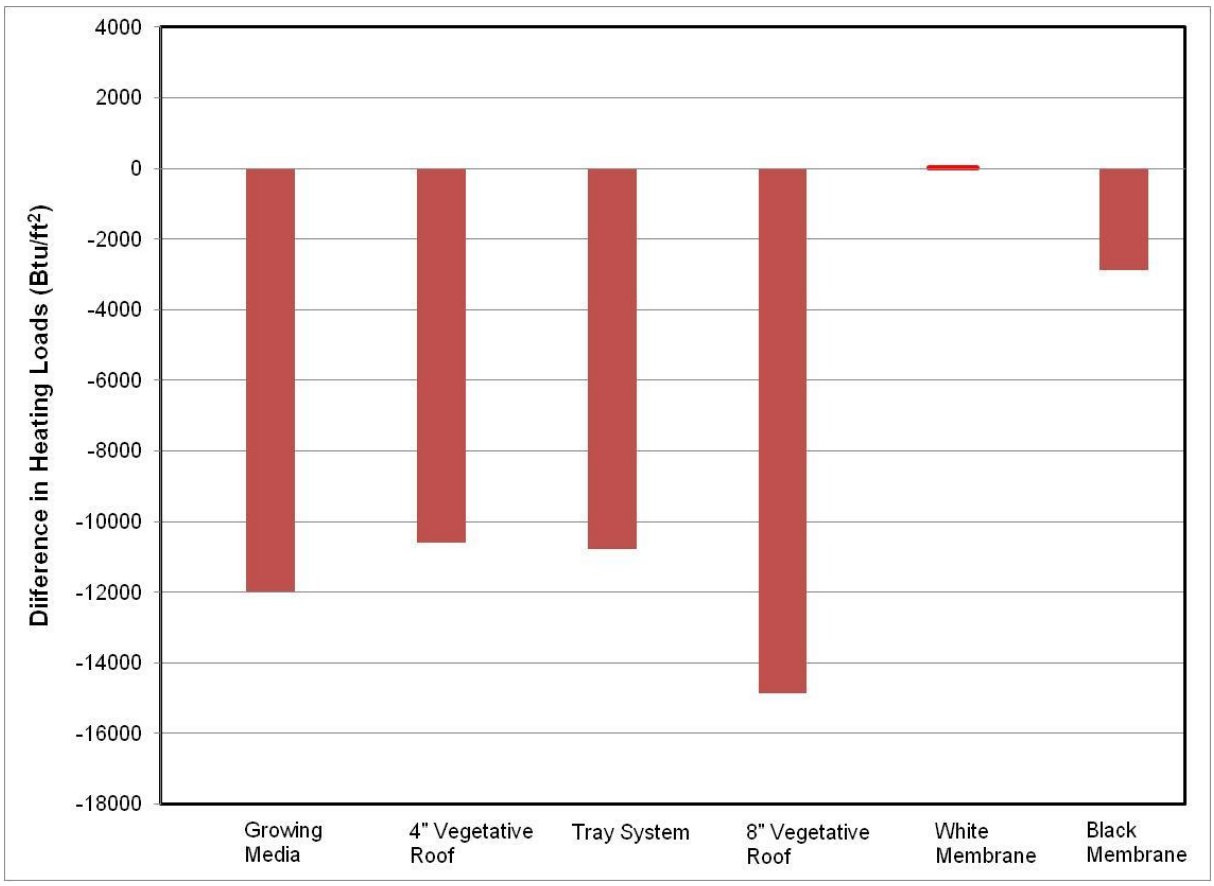

Figure 9. Heating loads of vegetative and black roof sections indexed to the white section heating load

Diurnal Behavior of Heat Flux and Temperature Measurements

<u>Cooling Dominated Period</u>

Figure 10 is a sample of the diurnal behavior of the heat flux measurements during the cooling dominated period of this project (April 24-29, 2009). The peak values of heat fluxes and their corresponding time are affected by the thermal mass, extra insulation, and evapo-transpiration of the vegetative roofing systems. The peak times are important parameters for the operation of the building. The vegetative roofing systems show consistent delays relative to both black and white roofing systems. During the cooling dominated period of East Tennessee, the average times for peak heat fluxes (average times for 15 clear or almost clear days during the period April 24 – June 3, 2009) for the vegetative roofs relative to the black system were found to be approximately 6 hours (tray system 5.9 h, 4" vegetative roof 6.2 h, and growing media 5.8 h). As expected, the heat flux of the 8" vegetative roof showed very small fluctuations with no obvious peak heat flux (Figure 10). The average peak times for the black and white systems were found to be within 0.3 hours.

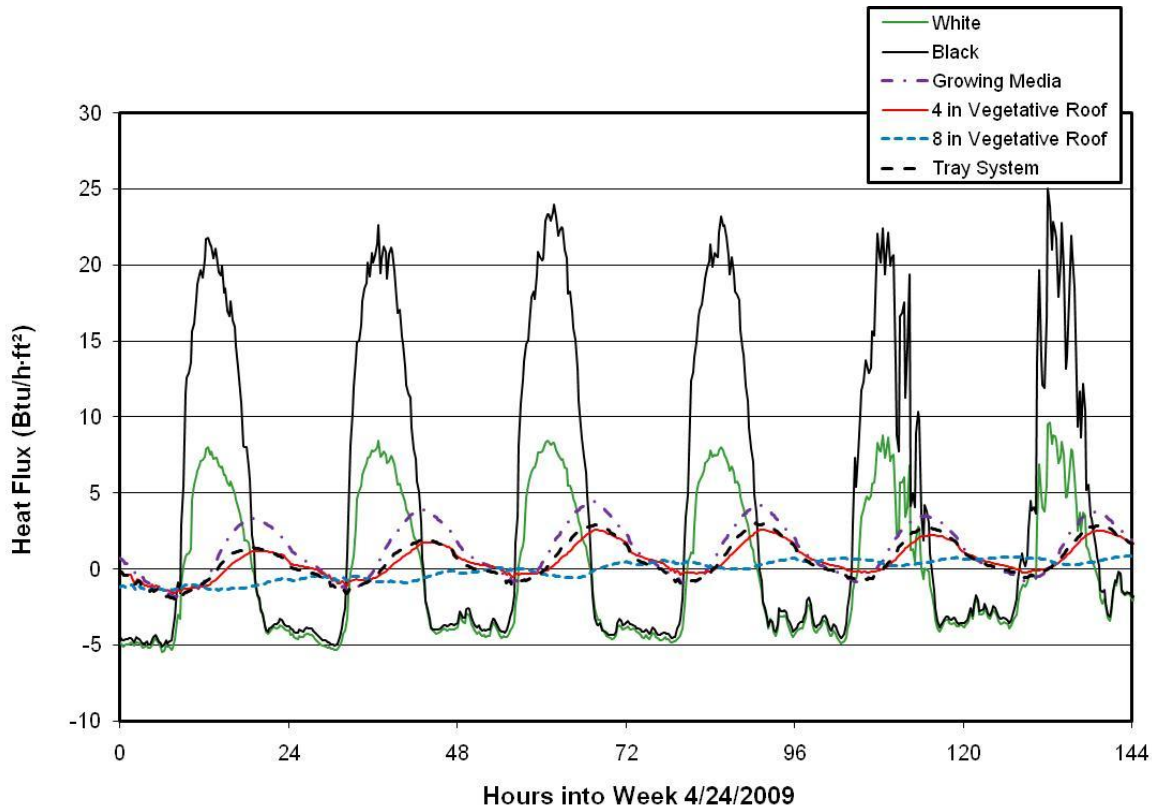

Figure 10. Diurnal behavior of heat flux measurements (April 24-29, 2009)

Figure 11 shows the diurnal behavior of membrane temperatures during April 24-29, 2009. The membranes of the control roofing system (black and white) experienced much higher temperatures and larger temperature fluctuations than the vegetative roofing systems. During the cooling dominated period of East Tennessee, average peak membrane temperatures of the white roofing system remained approximately 61°F cooler than the black membrane. The 4" and the tray systems were found to be approximately 94°F cooler than the black control system while the 8" was found to be approximately 100°F cooler. The growing media was found to be approximately 83°F cooler than the black system.

The temperature fluctuations experienced by the vegetative roofs were found to be much lower than the black and white control systems (Figure 11). The average temperature fluctuations at the membrane for the 4" and tray systems were found to be approximately 10°F compared to 125°F for black and 64°F for white control systems. The average temperature fluctuation in the growing media was found to be larger than the 4" and tray system at approximately 24°F. As expected, the 8" vegetative had the lowest fluctuations at approximately 2°F.

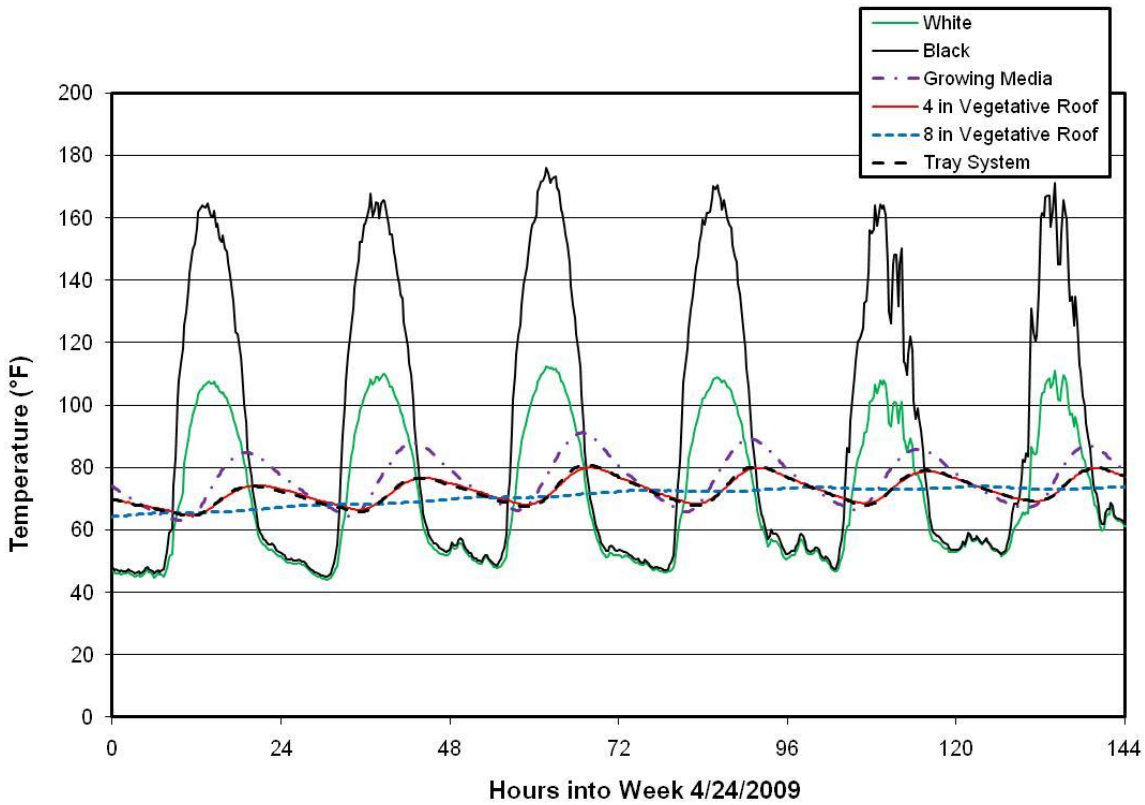

Figure 11. Diurnal behavior of membrane temperatures (April 24-29, 2009)

Heating Dominated Period

Figure 12 is a sample of the diurnal behavior of the heat flux measurements during heating dominated period of this project (March 2-5, 2009). The average peak times (average times of data for 15 clear or almost clear days during the period January 1 – March 30, 2009) for the black and white were found to be within 4 minutes. The delays in average peak times were similar to the time delays observed in the cooling dominated period (approximately 6 hours).

Figure 13 shows the diurnal behavior of membrane temperatures during March 2-5, 2009. The vegetative roofing systems experienced much lower temperature fluctuations than the black and white roofing control systems. During the heating dominated period of East Tennessee, average peak membrane temperature of the white roofing system remained approximately 56°F cooler than the black membrane. The 4”, 8”, and the tray systems were found to be approximately 70°F cooler than the black. The growing media was found to be approximately 65°F cooler than the black system. The average temperature fluctuations at the membrane for the 4” and tray systems were found to be approximately 8°F compared to 109°F for black and 55°F for white control systems. The average temperature fluctuation in the growing media was found to be slightly larger than the 4” and tray systems at approximately 12°F. The 8” vegetative again had the lowest fluctuations at approximately 2°F.

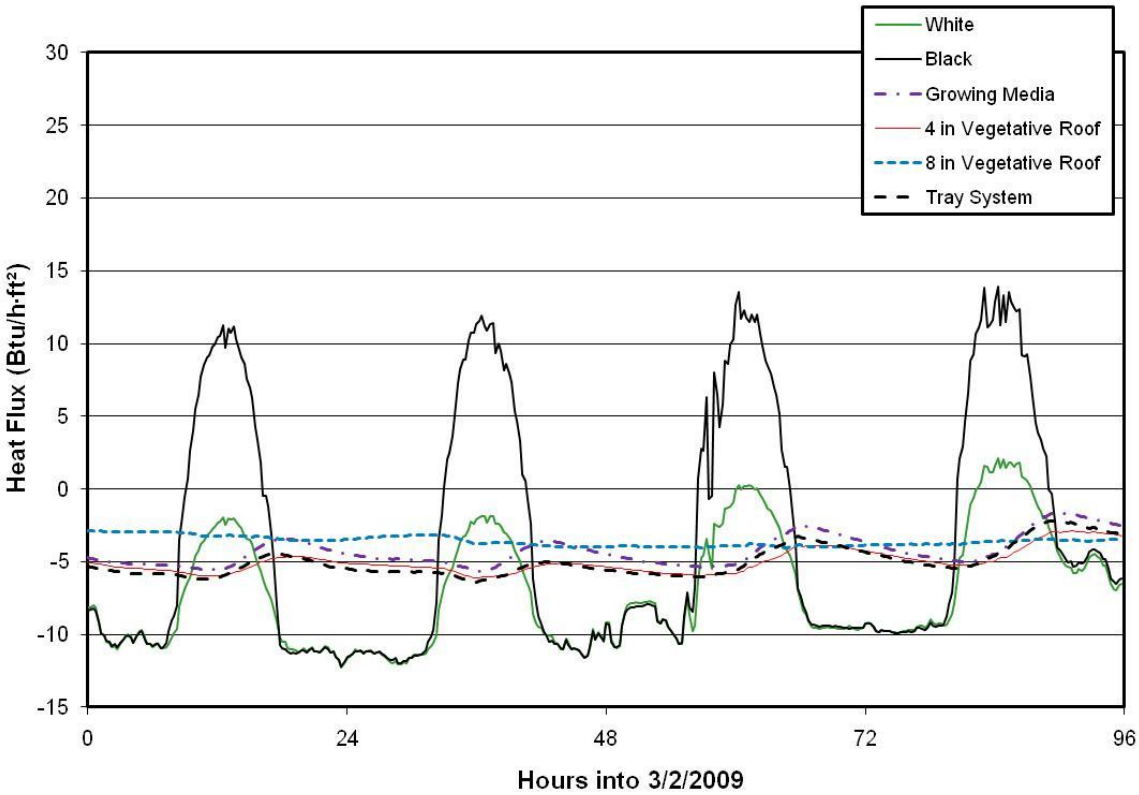

Figure 12. Diurnal behavior of heat flux measurements (March 2-5, 2009)

SUMMARY AND FUTURE WORK

Summary of the annual cooling and heating loads obtained from the RTRA facility demonstrated that vegetative roofs help to reduce heat gain in the cooling dominated periods and heat losses in the heating dominated periods in the mixed climate of East Tennessee. This would result in lower heating and cooling demands for the conditioned space and offers energy savings. It should be noted that the energy savings are climate dependent. It also depends on the heating/cooling equipment used and their efficiencies.

Results also showed lower temperatures and temperature fluctuations experienced by the roofing membrane than the control black-EPDM and white-TPO roofing systems. In the cooling dominated period of East Tennessee, the membrane temperatures of 4” and the tray systems were found to be approximately 94°F cooler than the black. In the heating dominated period, the membrane temperatures of 4”, 8”, and the tray systems were found to be approximately 70°F cooler than the black. In the heating dominated period of East Tennessee, the average temperature fluctuations at the membrane for the 4” and tray systems were found to be approximately 8°F compared to 109°F for black and 55°F for white control systems. As expected, the 8” vegetative system had the lowest fluctuations at approximately 2°F.

Future work will include an effort to model the internal heat flow for the vegetative roofing systems with the STAR computer model in the test climate of East Tennessee. STAR is a transient one-dimensional finite difference model for heat conduction. The model simulates heat flow in multilayer roofing systems.

This will require materials with known properties such as thermal conductivities and specific heats. STAR has been successfully used to model systems in previous projects. The validated STAR computer model will be used to predict energy use in roofs with different insulation levels and in climates different from the test climate. Future work will also include evaluation of R-value trade-off in these systems.

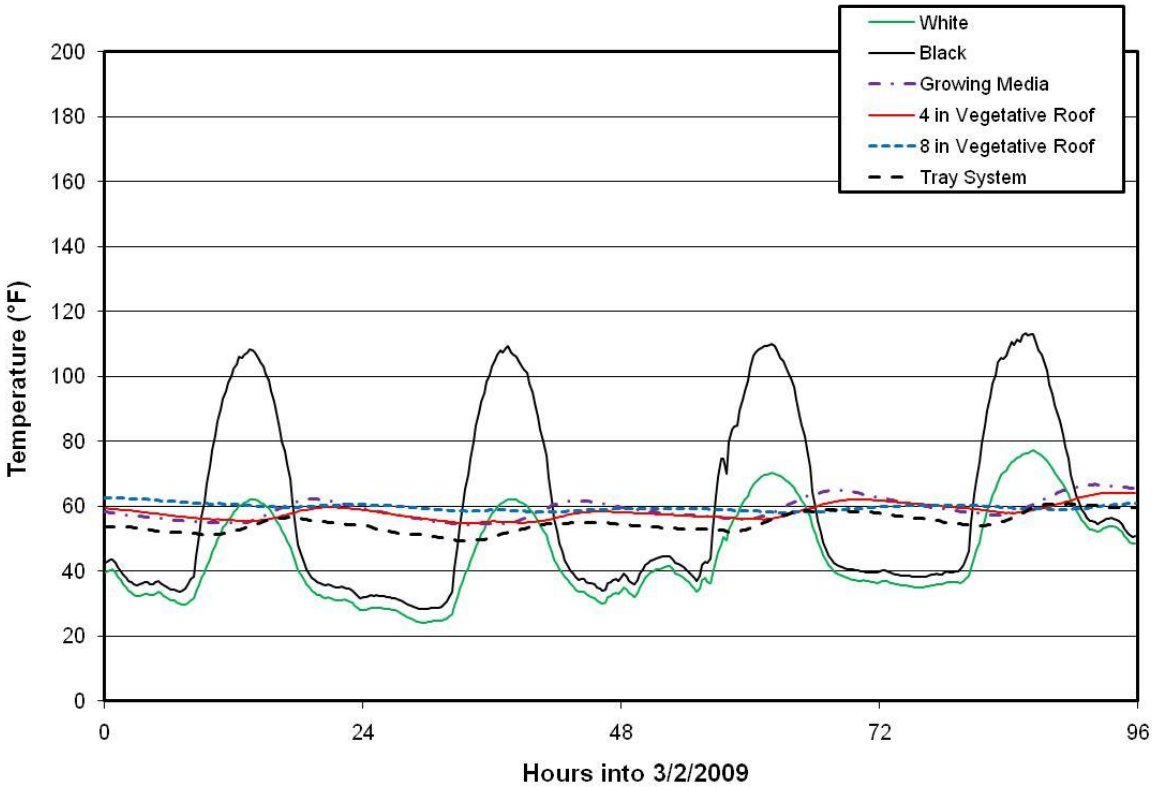

Figure 13. Diurnal behavior of membrane temperatures (March 2-5, 2009)

ACKNOWLEDGMENTS

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