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Energy Savings Resulting from Installation of an Extensive Vegetated Roof System on a Campus Building in the Southeastern United States

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1. Introduction

Green building design, as defined by the United States Environmental Protection Agency (USEPA), is “the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from design, to construction, operation, maintenance, renovation and ultimately deconstruction” [1]. However, according to the United States Green Building Council (USGBC), commercial buildings in the US alone account for:

- 65% of electricity consumption,
- 30% of greenhouse gas emissions,
- 30% of raw materials use,
- 30% of waste output (136 million tons annually), and
- 12% of potable water consumption [2].

The building infrastructure (Residential, Commercial, Institutional, and Industrial) in the United States (US) consumes over two-thirds of the nation’s electricity demand and accounts for one-third of all domestic energy consumption [3]. Regrettably, conventional forms of energy production have an adverse impact on natural ecosystems. Collectively, our buildings contribute to 38.9% of the nation’s total greenhouse gas emissions. Faced with rising energy costs, diminishing fuel resources and emerging environmental concerns, scientific research has begun to address these challenges by adopting sustainable or green building alternatives.

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2. Common roofing systems

The choice and type of urban roofing system is dependent on environmental concerns such as sun exposure and meteorological factors such as temperature, wind and rain. Some roofs may have covenants to determine their usage. Different systems have been developed and designed to perform at its most effective configuration given the exposure conditions of the building location. As a result, many roofing systems exist and are commonly used by the construction community.

There are many roofing systems used today that depend on the building type, whether is for residential or for commercial applications. The most common systems are listed as follows [4]:

- Built-up,
- Preformed metal, and
- Shingles.

A brief description of the three roofing system is provided involving advantages, disadvantages and durability characteristics of each.

2.1. Built-up

Built-up roofing systems are most common for flat roof applications. They consist of several layers of material built-up from the internal structural frame of the building. They are most commonly made of alternating layers of plywood, felt, asphalt, tar and gravel [4]. The major advantage of this system is its waterproofing characteristics, and out of all roofing systems, built-up roofs are considered to have the highest degree of waterproofing. However, the system has poor fire resistance, generally requires a professional to install, and is difficult to locate roof leaks. The system typically lasts for 22.5 years [5]; [6].

2.2. Preformed metal

Another common roofing system is made of preformed metal panels. The panels are generally made from aluminum, steel and copper [4]. They are most commonly found with contemporary designs. They come in flat, ridged, ribbed or corrugated forms. These systems are easy to install and repair, and can be painted any color. They are considered fire resistant. The panels are easily damaged by wind, falling trees and tree limbs, or any other type of contact. They generally last for 25 years [5]; [6].

2.3. Shingles

Shingle roofs come in many forms. Shingles are commonly made of asphalt, slate, wood and clay tiles [4]. Asphalt shingles are the most popular, especially for residential construction. They are available in a variety of sizes, weights, and colors. They require little maintenance and are easy to install. However, they are considered to have poor fire resistive qualities. Asphalt shingles generally last for 16–17 years with proper maintenance [5]. Slate and ceramic tiles are highly expensive due to their aesthetic and durability properties. They are fire resistant and have attractive appearances. Yet, they are extremely heavy and require strong structural support. They are also very brittle, and require increased amount of time to install which often entails specialized tools. Repairs are in most cases difficult. Slate and ceramic tiles are considered the most durable, lasting for 20–100 years with proper maintenance. Wood shingles and shakes are also attractive options. They are easy to install and are a natural insulator. However, they are highly flammable and require treatments for weather and insect protections. They generally last for 10 to 20 years with proper maintenance [5]; [6].

3. Urban heat–island reduction and building energy conservation

For millions of Americans living in and around cities, heat islands are of growing concern. This phenomenon describes urban and suburban temperatures that are 2 to 10°F (1 to 6°C) hotter than nearby rural areas. Elevated temperatures can impact communities by increasing peak energy demand, air conditioning costs, air pollution levels, and heat-related illness and mortality. The Environmental Protection Agency (EPA) recommends installing cool or vegetative green roofs, planting trees and vegetation and switching to cool paving materials as a way of reducing the negative effects of urban heat islands. The EPA says green roofs, if installed widely in a city, can contribute to heat island reduction by replacing heat-absorbing surfaces with plants, shrubs, and small trees. The vegetation cools the air through evapotranspiration (or evaporation of water from leaves). Planted rooftops remain significantly cooler than a rooftop constructed from traditional heat-absorbing materials. Further, green roofs reduce summertime air conditioning demand by lowering heat gain to the building.

Energy modeling (i.e., energy simulation) is a method for predicting the energy consumption of an occupied structure. Building energy analysis must consider numerous thermal characteristics including: wall and roof materials, the size and orientation of the building, how the building is occupied and operated, as well as influences from the local climate.

The surface temperature of a roof exposed to solar radiation, the resulting heat flow into the building, along with associated indoor temperatures and cooling needs depend on the effect of solar radiation, surface absorptivity, ambient air temperature and wind speeds adjacent to the surface [7]. When vegetative roofs are considered, because of added thermal mass, it is also important to take into account hourly heat transfer when determining energy consumption, as the heat flux through a vegetated roof can be quite different from conventional roofing.

R-values and *U*-values have been used for many years as a measurement of a building envelope's thermal performance. However, these attributes do not fully take into account the effects of thermal mass, and by themselves, are inadequate in describing the heat transfer properties of construction assemblies with significant amounts of thermal mass [8]. Vegetated roofs are more dependent on the interaction between the roofing systems' unit weight, density, thermal conductivity, moisture content, vegetal coverage and specific heat. Therefore, it is often necessary to utilize computer software, which incorporates these elements into the analysis of high thermal mass roof structures and associated energy consumption. The steadystate *R*-values traditionally used to measure energy performance will not accurately capture the complex, dynamic thermal behavior of vegetated roof systems.

4. Vegetated (green) roof systems

Green roofs are engineered ecosystems that rely on vegetation to provide benefits such as reduction of roof temperatures and stormwater retention [9]. Green roofs offer benefits of reducing stormwater runoff, improving air and water quality, and providing habitat and biodiversity for urban centers [10]. Hydrologic modeling has demonstrated that widespread green roof implementation can significantly reduce peak runoff rates, particularly for small storm events [11]. By combining the Green-Ampt method with evapotranspiration of green roofs, Roehr and Kong [12] estimated the potential runoff reduction achieved by green roofs is 20%. Green roofs provide an excellent option to improve stormwater runoff [13]. Green roofs are primarily valued based on their increased roof longevity, reduced stormwater runoff, and decreased building energy consumption [14]. Carter and Jackson [11] noted that research studies have primarily been focused on roof-scale processes such as individual roof stormwater retention, plant growth, or growing medium composition. Few studies have examined the impact that widespread green roof application could have on the hydrology of a real-world watershed [11]. A major barrier to increasing the prevalence of green roofs is the lack of scientific data available to evaluate their applicability to local conditions [15].

Green roofs are typically classified as being either an intensive or extensive roof [16]. Intensive green roofs are often used on commercial buildings in order to have large green areas that incorporate all sizes and types of plants. These roofs use grasses, ground covers, flowers, shrubs and even trees. They often include paths and walkways that travel between different architectural features to provide space where people can interact with the natural surroundings. Intensive green roofs, sometimes termed “rooftop gardens”, utilize planting mediums that have greater depth than extensive green roofs; the deeper soil allows intensive roofs to accommodate large plants and various plant groupings. Intensive green roofs require more maintenance than extensive green roofs because of the plant varieties they will support.

Extensive green roofs have a planting medium that ranges from 1.6 to 6 inches deep. Typically, drought-tolerant sedums (succulent plants) and grasses are used since they are shallow-rooted and use little water. Plant diversity on these roofs is kept low to simplify care and to be sure all plants have similar moisture requirements.

Extensive green roofs can significantly reduce both the timing and magnitude of stormwater runoff relative to a typical impervious roof [17]. They note, however, that regional climatic conditions such as seasonality in rainfall and potential evapotranspiration can strongly alter the stormwater performance of vegetated roofs. Factors such as type of green roof and its geometrical properties (slope), soil moisture characteristics, season, weather and rainfall characteristics, age of the vegetated roof, and vegetation affect the runoff dynamics from green roofs [18]. Fioretti *et al.* [19] noted that green roofs significantly mitigate storm water runoff generation, as well reducing the daily energy demand. Aitkenhead-Peterson *et al.* [20] note that most studies on runoff quality from green roofs have been conducted in cooler northern climates. Villarreal and Bengtsson [21] recommended the use of a combination of best management practices; additionally, they observed that green roofs are effective at lowering the total runoff from Augestenborg (Sweden) and that detention ponds should successfully attenuate storm peal flows. Niu *et al*. [22] noted that over the lifetime of a green roof (~40 years), the net present value is ~30% to 40% less for a green roofs as compared with conventional roofs (not including green roof maintenance costs). Kirby *et al*. [23] note that extensive vegetated roof systems offer at least 16% enhancement in reducing stormwater runoff as compared to conventional roofs. Clark *et al*. [14] further note that the additional upfront investment of a green roof is recovered at the time when a conventional roof would be replaced. Rosatto *et al*. [24] concluded that green roofs contribute positively in reducing runoff, with greater retention with vegetated plots and thicker substrate.

Vegetated roof systems have a number of advantages over that of conventional roof systems. Benefits associated with green roof systems include [25]:

- Urban greening has long been promoted as an easy and effective strategy for beautifying the built environment and increasing investment opportunity.
- With green roofs, water is stored by the substrate and then taken up by the plants from where it is returned to the atmosphere through transpiration and evaporation.
- Depending on the plants and depth of growing medium, during the summer, green roofs retain 70% to 90% of the precipitation that falls on them; in winter they retain between 25% to 40%.
- Green roofs not only retain stormwater, but also moderate the temperature of the water and act as natural filters for any of the water that runs off.
- Green roofs reduce the amount of stormwater runoff and delay the time at which runoff occurs, resulting in decreased stress on sewer systems at peak flow periods.
- Through the daily dew and evaporation cycle, plants on vertical and horizontal surfaces can cool cities during hot summer months and reduce the Urban Heat Island (UHI) effect. The UHI is also mitigated by the covering some of the hottest surfaces in the urban environment, such as black rooftops.
- Green roofs can also help reduce the amount of dust and particulate matter throughout the city, as well as the production of smog. This plays a role in reducing greenhouse gas emissions and adapting urban areas to a future climate with warmer summers.
- Green roofs help to achieve the principles of smart growth and positively affect the urban environment by increasing amenity and green space.
- The greater insulation offered by green roofs can reduce the amount of energy needed to moderate the temperature of a building, as roofs provide the greatest heat loss in the winter and the hottest temperatures in the summer.
- The presence of a green roof decreases the exposure of waterproofing membranes to large temperature fluctuations, which can cause micro-tearing, and ultraviolet radiation.

- Green roofs have excellent noise attenuation, especially for low frequency sounds. An extensive green roof can reduce sound from outside by 40 decibels, while an intensive one can reduce sound by 46-50 decibels.
- Green roofs can sustain a variety of plants and invertebrates, and provide a habitat for various bird species.

Historically, studies on green roofs have explored their energy performance compared with traditional roofs. Thermal performance indicated a significant reduction (~40%) of a building cooling load during the summer period [26]. Similar results were achieved for a nursery school, with reductions ranging from 6% to 49%, and reduction ranging from 12% to 87% on the last floor of the nursery school [27]. Wong *et al.* [28] note that green roofs tend to experience lower surface temperatures than the original exposed roof, especially in areas well covered by vegetation. When green roofs are well covered by vegetation, the resulting substrate moisture will tend to keep substrate temperature lower than the original exposed bare roof. These studies determined that over 60% of the heat gain was mitigated by vegetated roof systems. Summertime data have indicated significant lower peak roof surface temperature and higher nighttime surface temperature for green roofs as compared to conventional roofs [29]. The maximum average daily temperature seen for the conventional roof surface was 54.4^{o}C (129.9^{o}F) in his study, while the maximum average day green roof surface temperature was 32.8^{o}C (~21.7^{o}C lower than the conventional roof). Green roofs offer cooling potential (~3.02 kWh/day) to maintain an average room air temperature of 25.7^{o}C (78.3^{o}F) [30]. Green roofs help minimize environmental burdens, conserve energy, and extend the life span of the roofing system in overall sustainability [31]. Up to 30% of total rooftop cooling is due to plant transpiration [32]. Bell and Spolek [33] compared different types of plants for use in increasing the thermal resistance (*R*-value) of green roofs, and found that ryegrass delivered the highest effective *R*-value compared with bare soil, *Vinca major, Trifolium repens*, and *Sedum hispanicum.* Also, though increasing the depth of bare soil from 5 to 14 cm (2.0 to 5.5 inches) increased the *R*-value, no difference was found for different depths of planted soil. This implies that the bulk of benefit toward *R*-value is from evapotranspiration and leaf shading, rather than the moist soil [33].

There are several detailed building simulation programs (BSPs) that take into consideration the complete interaction between all thermal-based elements. The most popular BSPs are A Simplified Energy Analysis Method (ASEAM), Building Design Advisor (BDA), Building Load Analysis and Systems Thermodynamics (BLAST), Builder Guide, Bus^{++}, Dynamic Energy Response of Buildings (DEROB), DOE-2, Energy-10, Energy Plus, ENERPASS, ENER-Win, ESP, FEDs, Home Energy Saver, Hot 2000, TRNSYS, and VisualDOE ([34]; [35]; [36]).

UAB has utilized Visual DOE in the past with great success in the analysis of innovative structures designed for energy efficiency. VisualDOE uses the DOE 2 calculating core and provides output in both numerical and graphical forms. This software is a preferred calculation method due to its cost, previous verification/validation success, ease of use, database support and reasonable input/output requirements. We envision that this computer simulation tool will be able to effective capture the differences in roof types being explored in the purposed research.

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5. Results and discussion

5.1. Thermal performance of mini-roof structures

5.1.1. Mini-roofs

During this study, 15 mini-roof combinations were observed for trends in internal temperatures. The various 15 mini-roof combinations are summarized in Table 1. Several of the mini-roof structures are depicted in Figure 1. This photo shows the layout of the 15 mini-roofs, and a vegetated roof from which surface temperatures of the mini-roofs were measured periodically using an infrared thermometer (see Figure 1).

(a) (b)

Figure 1. a) Layout of the 15 mini-roods; (b) vegetated mini-roof (surface temperatures were measured using an IR thermometer.

The roofing materials used are all standard commercial flat roof materials. Flat roof materials were only looked at during the study, since the primary application for the roofing combinations will be on a commercial flat roof top, and not a slanted roof structure. Each mini-roof is 2.4-m (8.0-ft) long x 1.2-m (4.0-ft) wide x 1.2-m (4.0-ft) deep (see Figure 1). A number of different roofing systems are being examined for their energy performance. All roofs are insulated with 5.1 cm (2.0-in) of extruded polystyrene. Then the particular roofing combination being investigated is applied over the insulation and sealed. The roofs also include a proper drainage spout, to ensure correct water evacuation, such as on a real roof.

The roofing systems being studied using the 15 mini-roofs are listed in Table 1.

Mini-Roof No.	Mini-Roof Description
1 (Sensor B)	White TPO/PVC/ Elvaloy fully adhered, FiberTite Membrane.
2 (Sensor C)	Black 60-mil EPDM fully adhered/coated/white urethane, Mule Hide Membrane.
3 (Sensor D)	Black 60-mil EPDM fully adhered, Mule Hide Membrane.
4 (Sensor E)	Beige TPO/PVC/Elvaloy fully adhered, FiberTite Membrane.
5 (Sensor F)	White granular modified, Firestone SBS Modified Membrane.
6 (Sensor G)	Black granular modified, Firestone SBS Modified Membrane.
7 (Sensor H)	Black granular modified coated/white urethane, Firestone SBS Modified Membrane.
8 (Sensor I)	Bituthene IRMA with lightweight "T Clear" pavers.
9 (Sensor J)	Bituthene IRMA with river rock ballast.
10 (Sensor K)	Bituthene IRMA with vegetative green roof, ½-in. drain mat, 350-lbs dry soil.
11 (Sensor L)	Bituthene IRMA with vegetative green roof, 1-in. drain mat, 350-lbs dry soil.
12 (Sensor M)	Black 60-mil EPDM loose, ballasted with river rock, Mule Hide Membrane.
13 (Sensor N)	Black 60-mil EPDM loose, ballasted with #300 marble chips, Mule Hide Membrane.
14 (Sensor O)	White TPO/PVC/Elvaroy loose laid, ballasted with river rock, FiberTite Membrane.
15 (Sensor P)	Bituthene IRMA with vegetative green roof, ½-in. drain mat, 350-lbs dry soil.
Sensor S	Sensor inside mini-roof No.10 (inside the soil of the green roof).
Sensor T	Sensor under the white TPO/PVC/Elvaloy loose laid, ballasted with river rock.

Notation – TPO: thermoplastic polyolefin; SBS: styrene-butadiene-styrene; PVC: polyvinyl chloride; EPDM: ethylene propylene diene monomer; IRMA: inverted roof membrane assembly.

Table 1. Mini-roof descriptions.

To investigate the thermal properties of the roofing structures an ambient temperature probe was placed inside of each roof (see Figures 2 and 3) recording temperature data every 10 minutes of each day, for more than 3 years. This data was then automatically sent to a data logger and placed into an Excel file for review later. The temperature probe reports the temperature to the nearest hundredth of a degree Centigrade.

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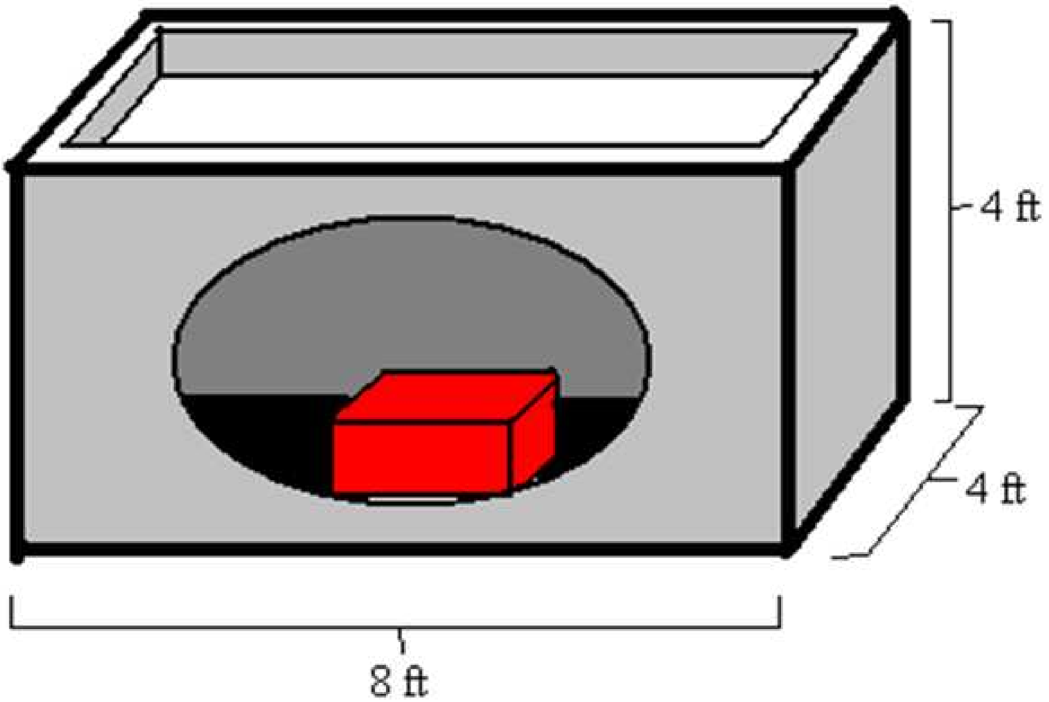

Figure 2. Depiction of a Typical Mini-Roof System.

Figure 3. Mini-roof system showing temperature sensor installed inside a mini-roof.

Figure 4 presents some typical temperature profiles on several different days.

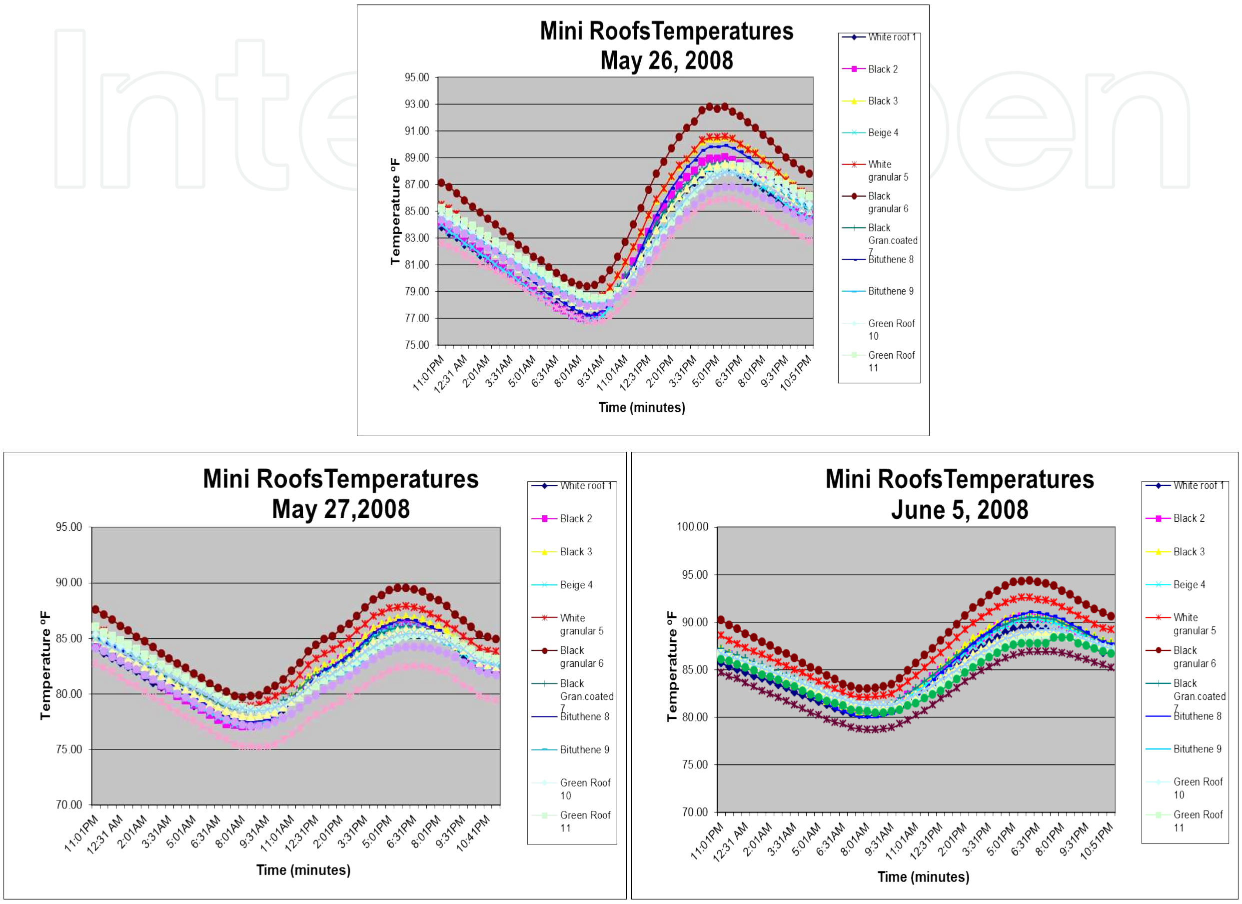

Figure 4. a. Temperature profile inside the various mini-roofs on May 26, 2008. b. Temperature profile inside the various mini-roofs on May 27, 2008 [37]. c. Temperature profile inside the various mini-roofs on June 5, 2008.

The results from these mini-roof structures have shown the following trends [37]:

- Clean white roofs resulted in consistently lower temperatures inside the mini roof than the other roofing materials.
- Black roofs resulted in the highest temperature readings.
- Green roofs resulted in temperatures typically ~1.1-1.7°C (2-3°F) higher than the white roofs; however, they will dampen the drainage of rainfall during a rain storm through the retention of water onto the soil.
- Bituthane (river rock) performs only slightly better than black roofing materials.
- White granular roofing behaved similarly to black granular roofing materials.

- Over time, the reflective (white) roofs become dirty, losing some of their reflectivity, resulting in the roof being less energy efficient.
- White marble chips behaved slightly worse than green roofing materials, but considerably better than black roofing and granular roofing materials.
- While it is too early to come to a definitive conclusion, preliminary evaluations indicate that the "white" and "green" roofs both significantly reduce the roofs surface temperature and therefore, the air temperatures above and around the roof.

Surface temperature measurements during the months of June and July on the various roofing materials used with our mini-roof systems were collected. During this time period, roofing surface temperatures ranging from 20.6°F to 82.2°C were observed. The lower surface temperature values, 20.6°C to 48.3°C, are found in a loose rock or stone roof combination. The higher temperature values occurred on the roofing combinations primarily made of a coating or membrane; these roofs exhibited temperatures roughly between 25.6°C to 82.2°C. The vegetative mini-roofs exhibited surface temperatures ranging between 21.7°C to 52.2°C, while their large counterpart, the pilot roof on top of the University of Alabama at Birmingham (UAB) Hulsey Center, exhibited higher temperatures ranging from 31.7°C to 61.1°C. When looking at the specific roofs contained in each subset of Table 1, it was observed that generally, the lighter colorization of the roof resulted in cooler temperatures. For example, the white Firestone SBS is cooler than the black Firestone SBS on any given day. This thermal property is observed due to the reflectivity of the roof. The darker colored roofs absorb more incoming light radiation than the light colored roofs causing the dark roofs to become hotter. (Since the roofs temperatures observed are taken during the late spring and early summer, it can be inferred that overall roof temperature will increase during late summer).

Photographs of several of these mini-roofs are presented in Figures 5 through 9. Figure 10 presents a typical temperature profile of the 15 mini-roofs during the course of a typical summer week. Series 1 through 5 denoted in the figure refer to the fifteen mini-roofs listed in Table 1. This figure shows a cyclical nature of the temperature readings over each day, generally showing a sinusoidal behavior of temperature; the temperature is cool in the morning, warms up, and is at its hottest during mid-afternoon, and then cools down during evening hours.

Trends seen in statistical comparisons of internal temperatures of similar roofs (using the null hypotheses: $\mu_1 \geq \mu_2$) are summarized below [38]:

- Between the two river rock roofs, Roof 9 will most likely always be hotter or equal to roof 12.
- Between the 3 vegetative roofs, all the roofs are statistically equal to each other in thermal properties.
- Both SBS Firestone roofs are statistically the same, but roof 6 is usually hotter.
- The TPO/PVC/Elvaloy Roofs are statistically the same.
- The 60-mil EPDM roofs are also statistically the same.

Figure 5. Black mini-roof.

Figure 6. White (reflective) mini-roof.

Figure 7. Mini-roof equipped with river rocks.

Figure 8. Mini-roof equipped with crushed marble chips.

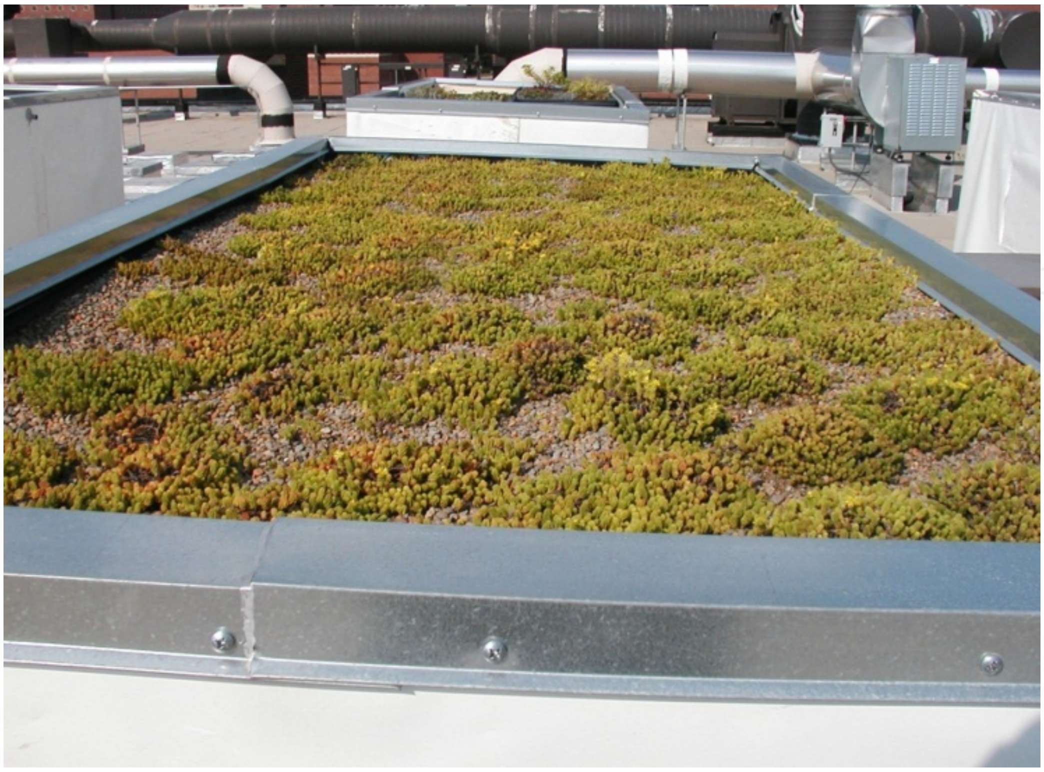

Figure 9. Vegetative mini-roof equipped with sedum plants.

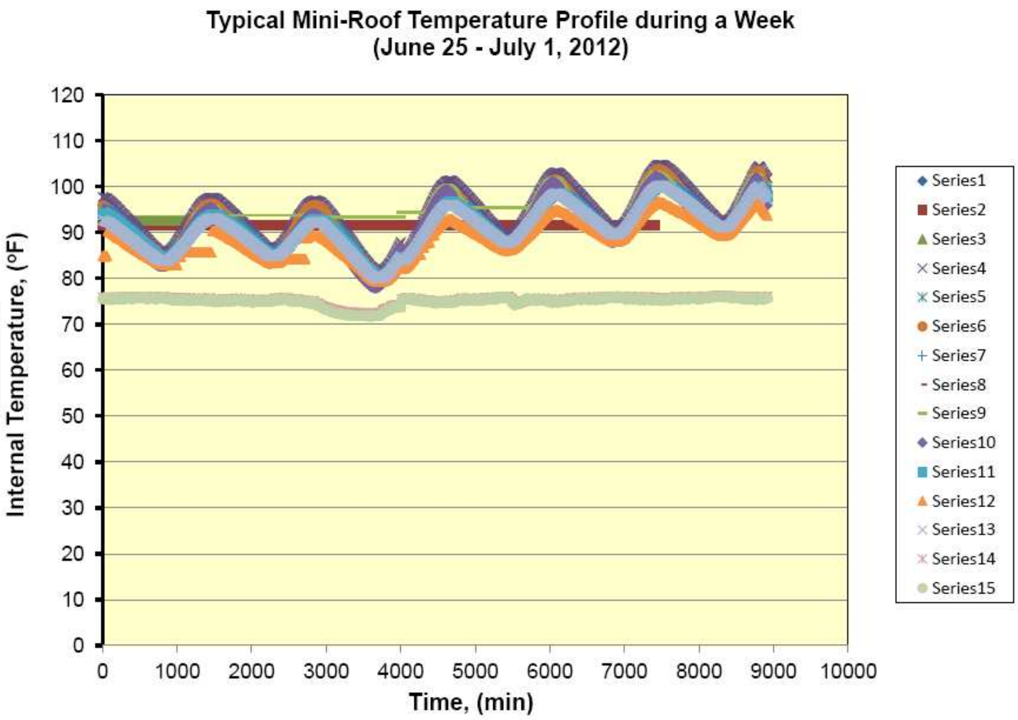

Figure 10. Typical internal mini-roof temperatures during the course of a week.

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After acquiring the necessary raw data from the mini-roof sensors, Microsoft Excel (version 2010) was used to plot the data to discover trends in the temperature readings. Subsequent to discovering the trend, a mathematical model was fit to the data. It was noticed that the temperatures cycled in a sinusoidal fashion on yearly and daily time frames, and therefore a general form sine function was utilized as a potential model. Fourier transforms were utilized in order to determine the oscillation frequency of the temperature (ω_0 from the general form $x = A \sin(\omega_0 t + \phi) + C$) by transforming the time domain of the collected raw data into a frequency domain. Two major peaks were discovered from the spectrum: one representing the yearly frequency and the other representing the daily oscillations. After calculating the frequencies, the phase angle (ϕ) and the amplitude (A) of the general form were determined through a regression analysis.

The modeling procedure was applied for all 15 mini-roofs in the study. The developed sine-wave functions indicated that most roofs were statistically different from one another from an amplitude aspect but the phase angles were statistically the same. It was also discovered that almost all roofs had significantly different average mean roof temperatures, but the significance was mostly prevalent in the summer months. During other times of the year, the roofs behaved in a similar fashion (see Tables 2 and 3 for statistics and means of roofs). The fitted sine wave functionalities for the 15 mini-roofs are listed in Table 4.

Statistics of Phase Angles	
Mean	4.0303
Standard Error	0.00343
Median	4.0276
Mode	4.0242
Standard Deviation	0.01329
Sample Variance	0.000177
Kurtosis	12.0174
Skewness	3.3228
Range	0.05512
Minimum	4.0211
Maximum	4.0762
Sum	60.4541
Number (count)	15

Table 2. Summary of statistics for the phase angles from curve fitting.

Statistics of Means	
Mean	66.67
Standard Error	0.18
Median	66.62
Mode	N/A
Standard Deviation	0.68
Sample Variance	0.46
Kurtosis	3.11
Skewness	1.11
Range	3.06
Minimum	65.42
Maximum	68.47
Sum	1000.12
Number (count)	15

Table 3. Summary of statistics for the means from curve fitting.

Roof	Final Equation	Amplitude from sinefind.exe	Phase Angle	r^2	Mean
1	$T = 20.1632*\sin((2*\pi*3.17894\ e^{-8}\ x\ t) +4.021975)+66.68283$	20.163	4.022	0.696	66.683
2	$T = 20.5499*\sin((2*\pi*3.18\ e^{-8}\ x\ t) +4.02272)+66.63564$	20.550	4.023	0.701	66.636
3	$T = 20.392*\sin((2*\pi*3.18\ e^{-8}\ x\ t) +4.07624)+66.47947$	20.392	4.076	0.712	66.479
4	$T = 20.482*\sin((2*\pi*3.18\ e^{-8}\ x\ t) +4.021125)+66.35505$	20.482	4.021	0.698	66.355
5	$T = 20.4891*\sin((2*\pi*3.18\ e^{-8}\ x\ t) +4.03214)+67.54093$	20.349	4.032	0.701	67.541
6	$T = 20.7812*\sin((2*\pi*3.18\ e^{-8}\ x\ t) +4.03142)+68.46883$	20.781	4.031	0.699	68.469
7	$T = 20.2886*\sin((2*\pi*3.18\ e^{-8}\ x\ t) +4.02415)+67.08382$	20.289	4.024	0.701	67.084
8	$T = 20.7812*\sin((2*\pi*3.18\ e^{-8}\ x\ t) +4.02415)+66.18969$	20.781	4.024	0.695	66.190
9	$T = 20.3285*\sin((2*\pi*3.18\ e^{-8}\ x\ t) +4.024975)+66.91944$	20.329	4.025	0.701	66.919
10	$T = 19.8608*\sin((2*\pi*3.18\ e^{-8}\ x\ t) +4.02758)+66.6981$	19.861	4.028	0.697	66.698
11	$T = 20.0128*\sin((2*\pi*3.18\ e^{-8}\ x\ t) +4.026215)+66.62328$	20.013	4.026	0.697	66.623
12	$T = 20.0479*\sin((2*\pi*3.18\ e^{-8}\ x\ t) +4.027853)+66.27383$	20.048	4.028	0.694	66.274
13	$T = 19.9914*\sin((2*\pi*3.18\ e^{-8}\ x\ t) +4.0325)+66.47272$	19.991	4.033	0.696	66.473
14	$T = 20.0661*\sin((2*\pi*3.18\ e^{-8}\ x\ t) +4.032494)+65.42343$	20.066	4.032	0.689	65.423
15	$T = 19.4628*\sin((2*\pi*3.18\ e^{-8}\ x\ t) +4.028672)+66.27177$	19.463	4.029	0.692	66.272

Table 4. Fitted sine-wave functionalities describing the internal temperatures in the mini-roofs.

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These results of this study were in agreement with research conducted by Watson [39] addressing the urban heat island effect for the City of Birmingham, Alabama. By studying the effect from different building facades, building materials and seasonal traits. The data indicates amplitudes (A) ranging from 19.5 to 20.7 degrees and phases angles roughly 4.2 to 4.3 radians. The r^2 values ranged from 0.69 to 0.71showing the data modeling was applicable to understanding the trends. The best model developed was for roof 3 (see Figure 11), having the highest correlation coefficient of all 15 mini-roofs.

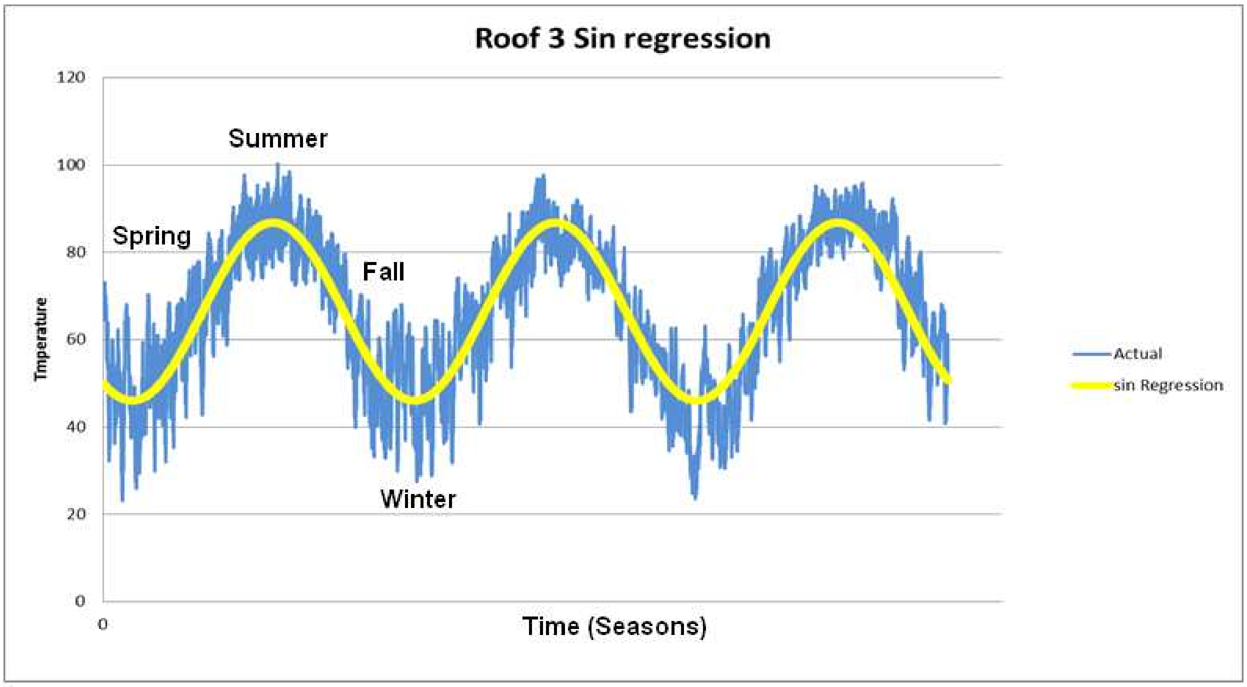

Figure 11. Fitted sine wave regression for a mini-roof system.

Based on the information collected on these mini-roof systems, the UAB Facilities Management Department decided to install an extensive vegetated roof on top of Hulsey Center as a roofing retrofit. UAB wants to obtain more fundamental information and knowledge for establishing green roofs in the southeastern U.S. In the Birmingham, Alabama area, fairly high rainfalls [approximately 132.1 cm/year (52 inches/year) on average] are obtained. However, during the summer months, it is common to have periods of drought with minimal rainfall and very hot and humid days [with temperatures in the 32.2^{+o}C (90+^{o}F range]. Such climatic conditions require plants that can withstand both significant rainfall events and drought conditions.

Photographs of the construction of the pilot green roof system on Hulsey Center are shown in Figures 12 to 14. Photographs of the system taken in June 2009 are shown in Figures 15 to 17.

Figure 12. Construction phase for installing a pilot vegetative roof on top of Hulsey Center.

Figure 13. Construction phase for installing a pilot vegetative roof on top of Hulsey Center.

Figure 14. Initial vegetative roof immediately after installation on top of Hulsey Center.

Figure 15. Vegetative roof on top of Hulsey Center (June 2009).

Figure 16. Vegetative roof on top of Hulsey Center (June 2009).

Figure 17. Close-up of vegetative roof on top of Hulsey Center (June 2009).

Of the roofing area of 1709.4 m ^{2} (18,400 ft ^{2}) for Hulsey Center, an extensive pilot green roof has been installed on ~1388.0 m ^{2} (14,940 ft ^{2}), i.e., occupying ~81.2% of the roofing area, or approximately 1375.9 m ^{2} (0.34 acres). [Prior to installing the pilot green roof, the UAB civil engineering senior design class investigated the loading of a wet vegetative roof on top of Hulsey Center, and found that the current building infrastructure could withstand the loading associated with the vegetative roof. Hulsey Center was originally designed to have two additional floors in the building]. This pilot green roof contains more than 20,000 sedum plants (*Sedum hispanicum*). In the construction of this vegetated roof, the existing roof was removed down to the structural concrete deck. A waterproof roofing membrane was installed directly to the concrete deck. A layer of 7.6-cm (3-inches) of extruded polystyrene roofing insulation was then applied, to which a 226.8-gm (8-oz) non-woven geo-textile scrim sheet was applied. Then, 0.6-m (2-ft) x 0.6-m (2-ft) x 5.1-cm (2-in) prestressed pavers or brick pavers were installed for design, decoration, and access to the vegetative roof. Then, 8.9-cm (3.5-inches) of light weight engineered soil were applied. Sedum plants were planted at the rate of 1615 plants per 100 m ^{2} (150 plants per 100-ft ^{2}). The cost of retrofitting the roof and installing a pilot green roof on top of Hulsey Center was ~$150,000 (USD).

The current pilot green roof on top of Hulsey Center was installed in July 2008. Research conducted at Penn State University shows that green roofs planted with sedum plants reduce the building energy costs [40]. UAB's Facilities Management Department maintains records of the utilities bills (e.g., natural gas, water, and electricity) for each building on campus. The costs of utilities prior to and after implementation of the pilot green roof are shown in Figures 18 through 20 for natural gas, water, and electricity. Since 2006, the costs of natural gas, water, and electricity have increased by 47%, 28%, and 145%, respectively. Due to the increasing rates of these utilities, a more accurate determination is shown with the usage of these utilities, shown in Figures 21 through 23. In the graph symbols, those indicated with a red interior color depict the cost or usage after installation and implementation of the vegetative roof system. The other symbol colors depict the cost or usage prior to installation and implementation of the vegetative roof system. Generally, the usage of natural gas, water, and electricity are lower than that compared to the utility usage prior to installation of the green roof on top of Hulsey Center.

The current pilot green roof on top of Hulsey Center was installed in July 2008. Research previously conducted at Penn State University indicated that green roofs planted with sedum plants reduce the building energy costs [41]. The Facilities Management Department at UAB maintains records of the utilities bills (e.g., natural gas, water, and electricity) for each building on campus. The quantities and costs of utilities prior to (5 years) and after implementation (~3 years) of the pilot green roof have resulted in building energy reductions of 20% to 25%.

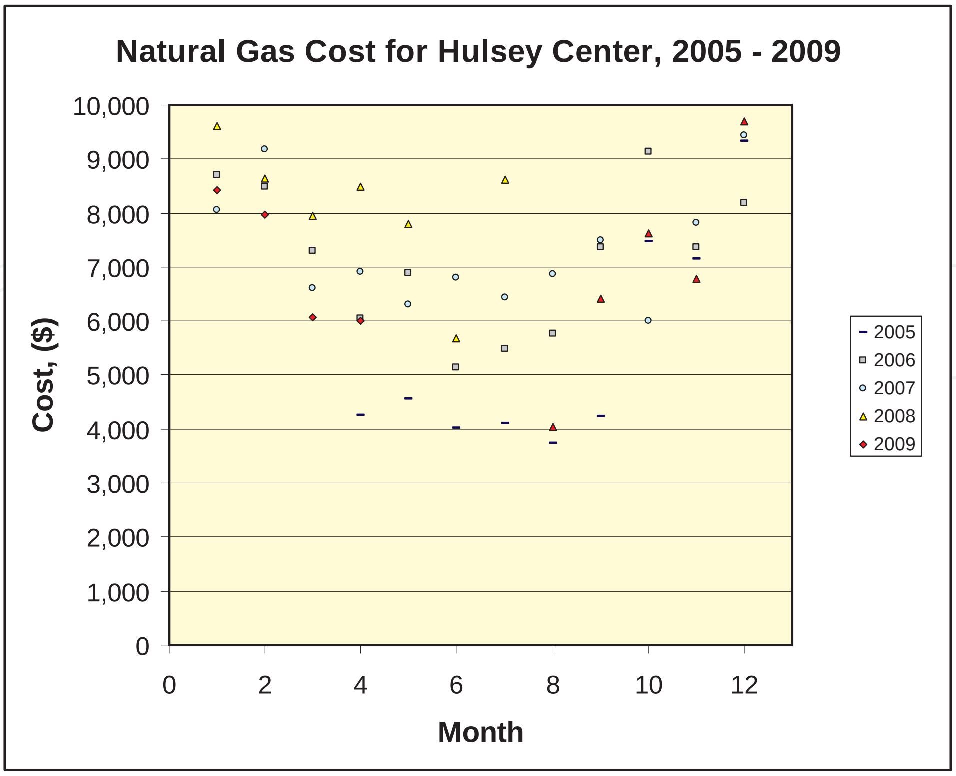

Figure 18. Cost of natural gas for operation of Hulsey Center, 2005 – 2009.

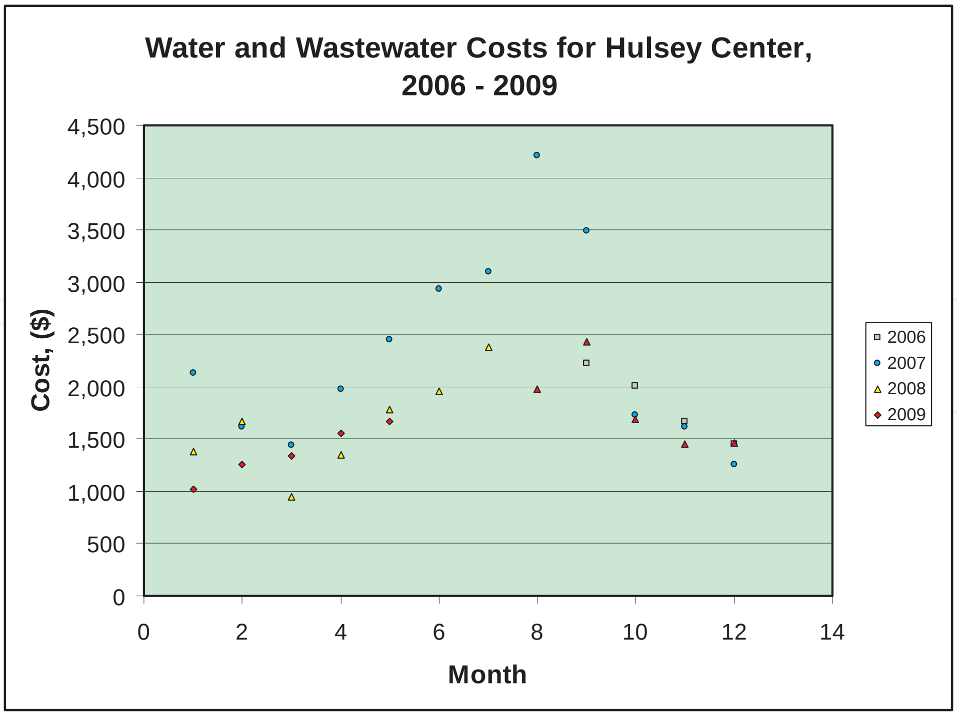

Figure 19. Cost of water/wastewater for operation of Hulsey Center, 2006 – 2009.

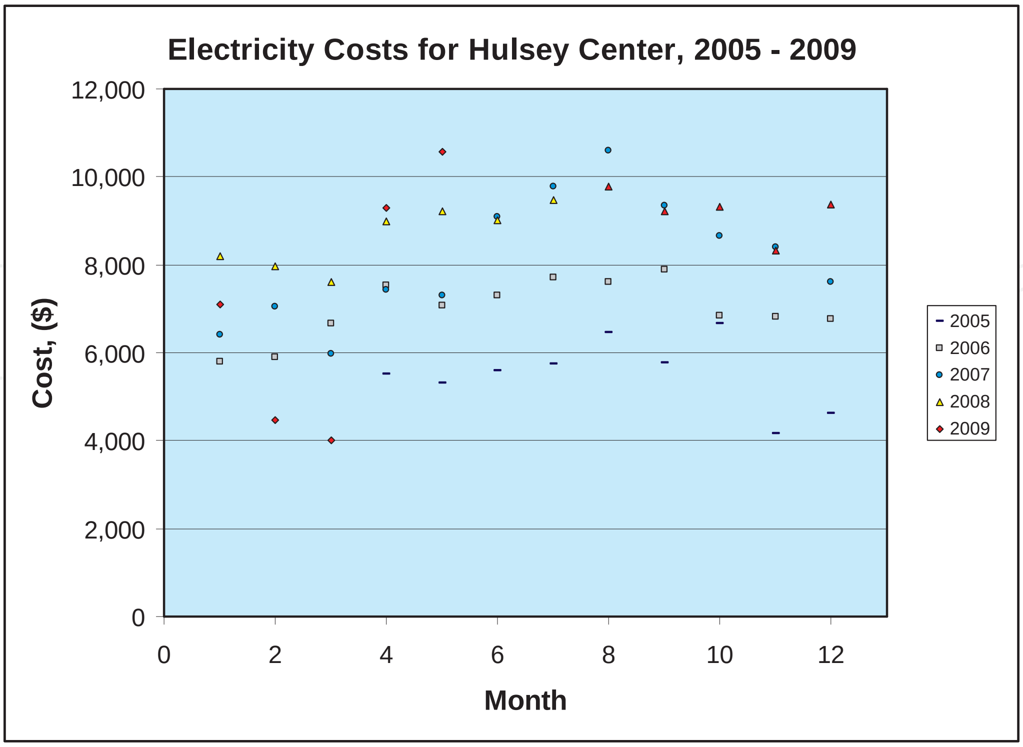

Figure 20. Cost of electricity for operation of Hulsey Center, 2005 – 2009.

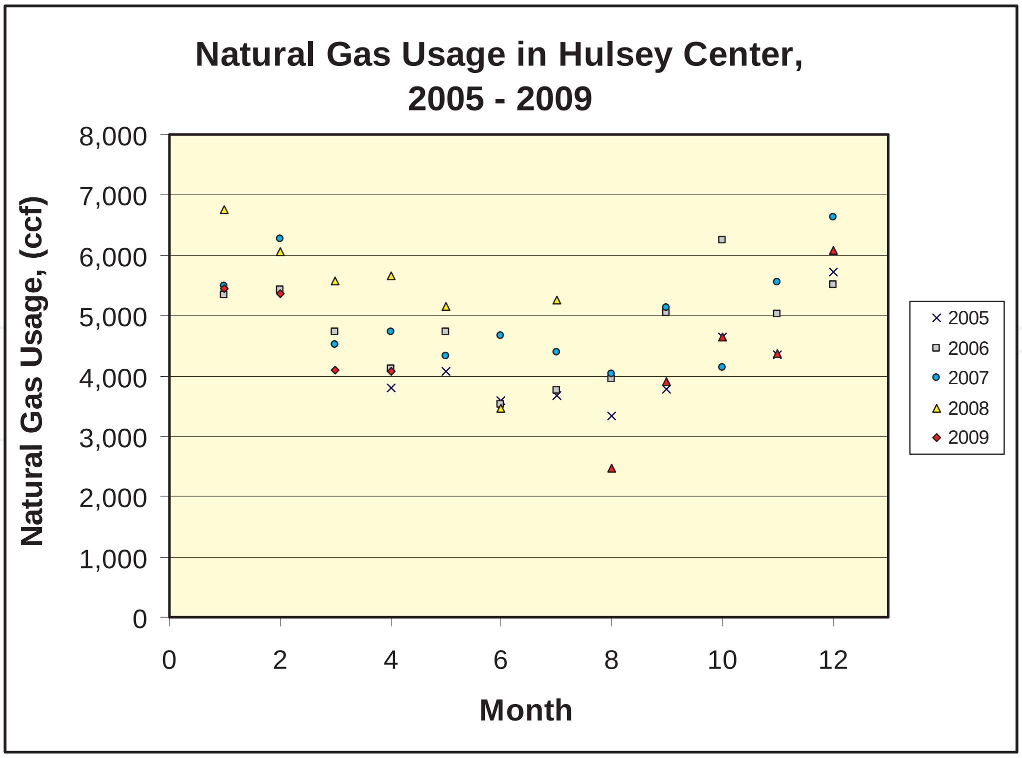

Figure 21. Natural gas usage for operation of Hulsey Center, 2005 – 2009.

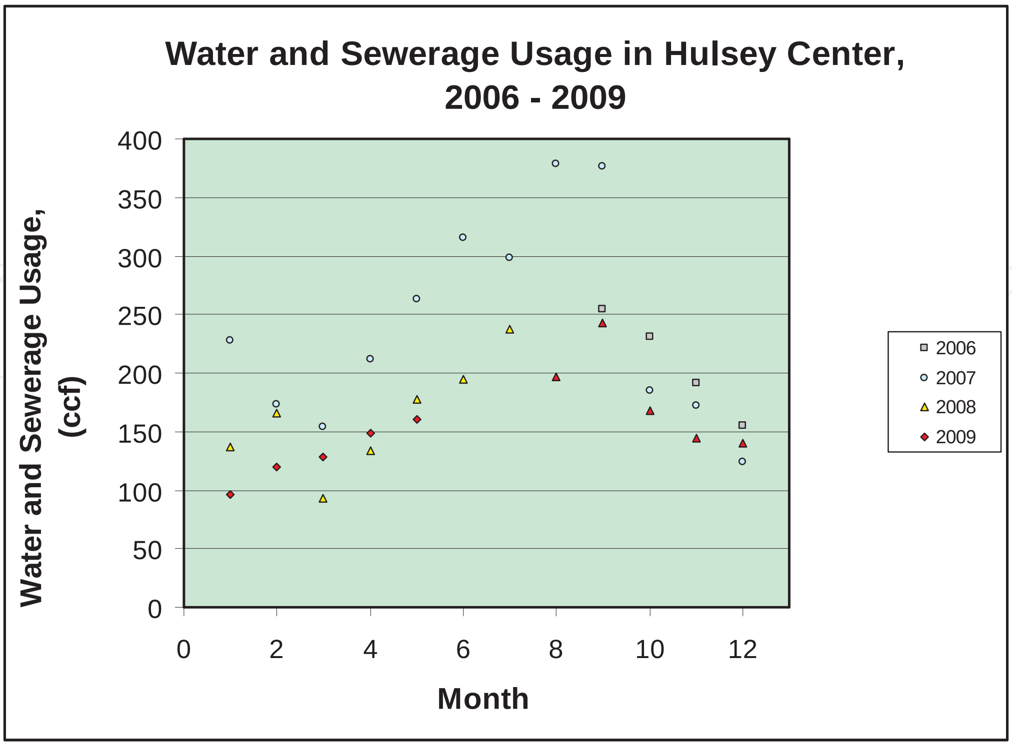

Figure 22. Water/wastewater usage for operation of Hulsey Center, 2006 – 2009.

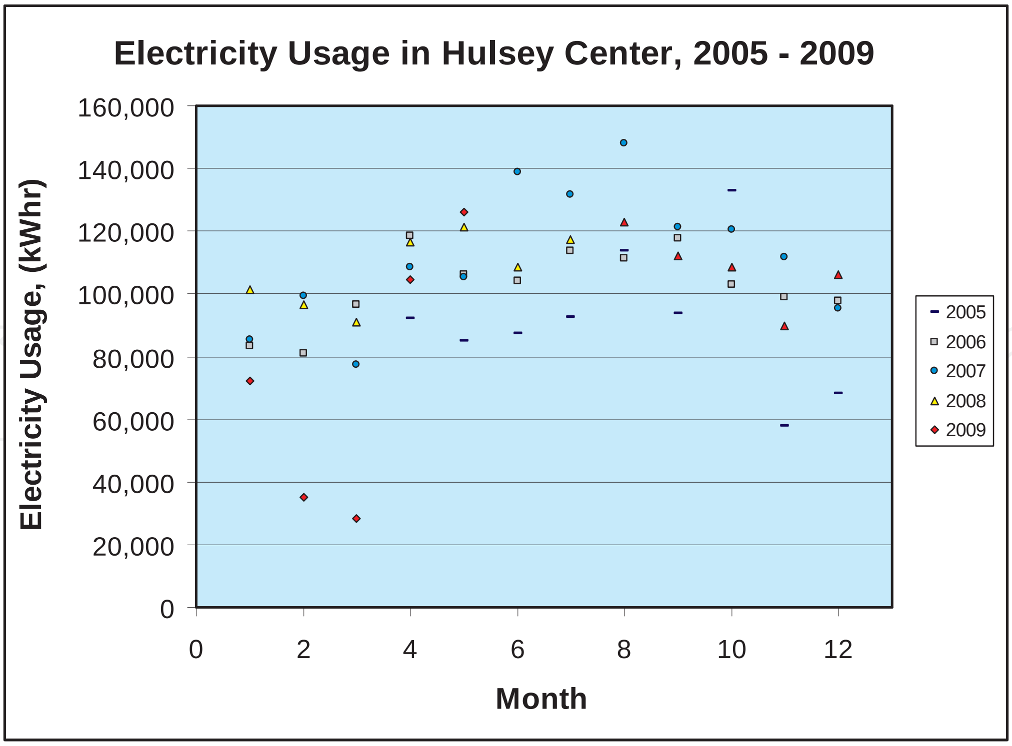

Figure 23. Electricity usage for operation of Hulsey Center, 2005 – 2009.

6. Summary and conclusions

The behavior of different roofing materials affects the heating loads placed upon the buildings and their heating, ventilation, and air conditioning (HVAC) systems. Black roofs resulted in the highest temperature readings. Black roofing materials and bituthane (river rock) perform the poorest of the roofing materials tested, resulting in the highest heating load being placed on the building infrastructure. White granular roofing behaved similarly to black granular roofing materials. Clean white roofs resulted in consistently lower temperatures inside the mini-roof than the other roofing materials; however, over time, the reflective (white) roofs become dirty, losing some of their reflectivity, resulting in the roof being less energy efficient. Green (vegetated) roofs are fairly efficient in terms of energy performance due to evapotranspiration effects. Green roofs resulted in temperatures typically ~1.1-1.7^{o}C (2-3^{o}F) higher than the white roofs; however, they will dampen the drainage of rainfall during a rain storm through the retention of water onto the soil, and thereby lessen the discharge into stormdrains. Green roofs can significantly reduce stormwater runoff, reduce peak flow quantities, and lengthen the time of concentration from roofing structure [23]. “White” and “green” roofs both significantly reduce the roofs surface temperature and therefore, the air temperatures above and around the roof.

Hypothesis testing indicated that, between the 3 vegetative mini-roofs, all the min-roofs are statistically equal to each other in thermal properties. Both SBS Firestone mini-roofs are statistically the same, but mini-roof 6 is usually hotter. The TPO/PVC/Elvaloy mini-roofs are statistically the same. The 60-mil EPDM mini-roofs are also statistically the same.

The temperature varies in a sinusoidal fashion both during the course of the day and on an annual basis. For the various mini-roof structures, the phase angle (ϕ) and the amplitude (A) of the general form were determined through a regression analysis. The developed sine-wave functions indicated that most roofs were statistically different from one another from an amplitude aspect but the phase angles were statistically the same. It was also observed that almost all roofs had significantly different average mean roof temperatures, but the significance was mostly prevalent in the summer months. During other times of the year, the roofs behaved in a similar fashion.

Based on the information collected on these mini-roof systems, the UAB Facilities Management Department installed a vegetated roof on top of Hulsey Center as a roofing retrofit. The vegetated roof is ~1388.0 m^2 (14,940 ft^2) in area, and contains approximately 20,000 sedum plants. Utility bill information both prior to and after implementation of the green roof were gathered for electricity, natural gas, and chilled water were collected. The costs of utilities prior to and after implementation of the pilot green roof indicated utility bill (energy) savings of ~20% to 25% (compared to the case prior to implementation of the vegetated roof system).

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