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# Thermal Comfort Assessment of a Green Roof at the College of Architecture and Landscape Architecture in Tucson, Arizona

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*Abstract: This paper describes a method for thermal comfort assessment of green roofs in the urban environment of hot-arid regions. The dual goals of this study are to emphasize green roof technology and to create thermally comfortable outdoor spaces. Method of investigation for this project started with an experiment, which included building a test cell of 4'x4'x4'with data acquisition system that accommodated four different roof types. This test cell was then used to record the four environmental variables that helped predict thermal comfort. These were: Surface Temperature, Dry bulb Temperature, Globe Temperature, and Relative Humidity. Average air velocity was used. The premise behind conducting this experiment was to establish the thermal benefits of green roof technology over other roof types studied for hot arid surrounding. The project applied to a proposed green roof at the College of Architecture and Landscape Architecture in Tucson, Arizona. Distinct locations were chosen on the proposed roof for performing thermal comfort analysis. Fish eye lens photography along with other data acquisition systems were used to simulate the conditions using OUTDOOR © program. The results indicated uncomfortable conditions on the proposed roof which were improvised through design modifications and conducting simulation to create thermally comfortable outdoor spaces.*

Keywords: Green Roof, Thermal Comfort, Outdoor Software

## Introduction

**UNTIL THE NINETEENTH** century, less than 5% of the world's population lived in cities, and by 1950 a third of the world's population had urbanized. This trend did not slow down, even in the post industrial economies, which has led to today's urban population reaching almost 50%, or 3 billion people. This number is projected to grow to 6 of 9 billion, or swing to an urban ratio of two to one (Tibaijuka. A.K., Maseland J., and Moor J., 2005). To meet the demands of habitation, commerce and transportation for this ever increasing populace, virgin lands are fast replaced by urban forms. Physical properties of preferred materials like concrete, asphalt and glass used to construct these urban elements in turn contributes significantly towards local warming. This primary cause of Urban Heat Island Effect further aggravates the harsh climate found in desert regions like Tucson, Arizona.

Tucson, Arizona is located in the Sonoran Desert of the United States. The regional climate is classified as dry subtropical. The temperature in summer rises above 100°F (37.8°C) the diurnal swing can be up to 30°F (around 15°C). The winter nighttime temperatures drop below 40°F (4.5°C). The average annual rainfall is about 11 inches (279.4 mm) primarily

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received in the form of winter rains and summer thunderstorms during the monsoon months of July and August. The city enjoys over 300 days of sunshine and is favored for outdoor activities and enjoyment.

However, an analysis of 30–yr temporal trends in urban and non-urban minimum temperatures across the region conducted at the University of Arizona indicated -Tucson's Urban Heat Island was ~3°C over the last century, with >2°C of this warming in the last 30 years (Comrie. A. C., 2000). So if this trend continues it not only threatens the energy performance but also the outdoor lifestyle once enjoyed by the community.

Today ecological designers in their endeavor to alleviate the myriad impacts of urbanization employ several sustainable design elements. Green roof technology is one such design component that holds the potential to mitigate Urban Heat Island effect. This green building strategy presents an opportunity to replace impervious roof surface with permeable living plant surfaces.

The College of Architecture and Landscape Architecture at University of Arizona are planning a green roof on the new expansion building. This study assists the initiative taken by the college to increase awareness of the myriad benefits of incorporating green roof technology in a desert environment by:

- Investigating the performance of green roof in comparison to other roof types commonly found in the hot-arid region of Tucson through a Test Cell Experiment.
- Performing Thermal Comfort Evaluation using the OUTDOOR©[1] software on the proposed green roof design to accommodate outdoor living.

Additionally, this task is undertaken with a broader perspective of developing a methodology to analyze and design thermally comfortable outdoor spaces throughout the city.

## Test Cell Experiment

To compare the performance of different roof surfaces a test cell of 4'w x 4'd x 4'h with four separate roof types; 1) Asphalt shingle, 2) Corrugated metal, 3) Saturated (after watering or rain) green (vegetated) roof and 4) Dry green (vegetated) roof were constructed (See Figure 1 for the different construction components). Appropriate instruments comprising of a radiation shield, data logger, globe thermometer and thermocouple were mounted 1' above and below the top (roof) surface of the test cell. This test cell was then used to record the four environmental variables: Surface Temperature, Dry Bulb Temperature, Globe Temperature, and Relative Humidity. Average air velocity was used and not measured (Data derived from TMY2 – Typical Meteorological Year). The data was recorded from April 29'07 to May 3'07 with one day dedicated for each roof type. Following were the weather conditions during the course of the experiment: Average daytime temperatures - 90.2°F (32.3°C) with an average RH of 22% and Average nighttime temperatures – 62.6°F (17°C) with an average RH of 30%.

The premises behind conducting this experiment were:

[1] OUTDOOR© program is developed by Dr. Chalfoun at the University of Arizona, College of Architecture and Landscape Architecture for assessment of outdoor thermal comfort conditions in a particular location if the thermal and geometrical conditions are identified.

- To validate the thermal benefit of green roof over other roof types for hot-arid surrounding.
- Record weather data for comparison with data derived from MRT[2] program for similar day and roof surface so as to validate the data acquisition system used for assessing thermal comfort over the chosen case study.

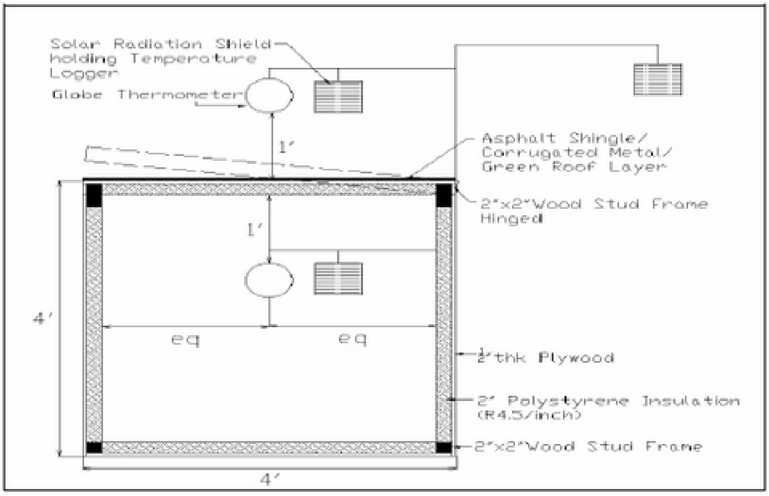


Figure 1: Section through Test Cell –Construction Components and Location of Instruments

Figure 2: Four Roof Types: Asphalt Shingle, Corrugated Metal, Saturated Green (Vegetated) Roof and Dry Green (Vegetated) Roof

## Result Analysis for Test Cell Experiments

Graphical and analytical comparison of the recorded surface and globe temperatures bring forth the thermal benefit of green roof technology as follows:

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[2] MRT is a computer program written by Dr. Chalfoun and can be used to predict surface temperatures based on TMY (Typical Meteorological Year) data.

### *Comparison of Average Surface Temperatures for All Roof Types*

As seen in Figure 3 (below) the average surface temperatures for both saturated and dry green roof are the lowest and most consistent between day and night due to shading and evapotranspiration provided by the vegetation. Between the two types of green roofs; saturated green roof maintains lower surface temperature during the course of day as the presence of moisture aids in the evaporative heat loss through the system (However the average surface temperature for this roof type adds up to be higher due to transition period between 9am-10am when the previous metal roof type was changed to green roof type). The other advantage observed of green roof is its thermal mass property due to which the inside surface temperature rises after a time delay (Figure 3 - below).

### *Comparison of Average Globe Temperatures for All Roof Types*

Globe temperature is a composite temperature that can be used to estimate the effect of temperature, humidity and solar radiation on humans. As noticed in Figure 4 (below) the average globe temperatures for all roof types are high which indicates extremely uncomfortable thermal conditions for human occupant. However comparatively lower globe temperatures lasting for shorter period of time were recorded for both types of green roof due to their lower surface temperatures. This presents greater potential for achieving thermal comfort by altering other prevailing conditions in that space through design modification.

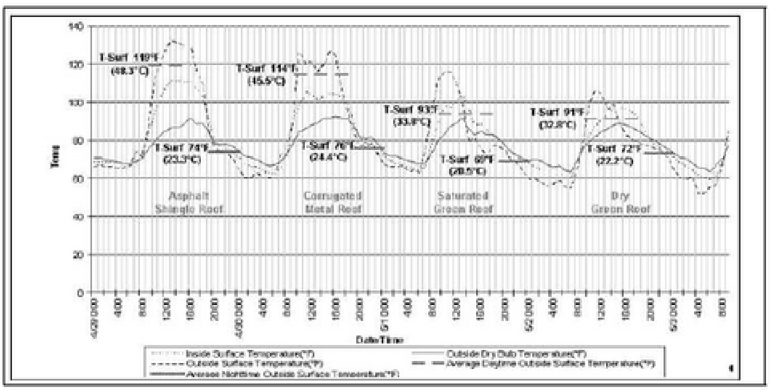


Figure 3: Graphical Comparisons of Average Surface Temperature for All Roof Types

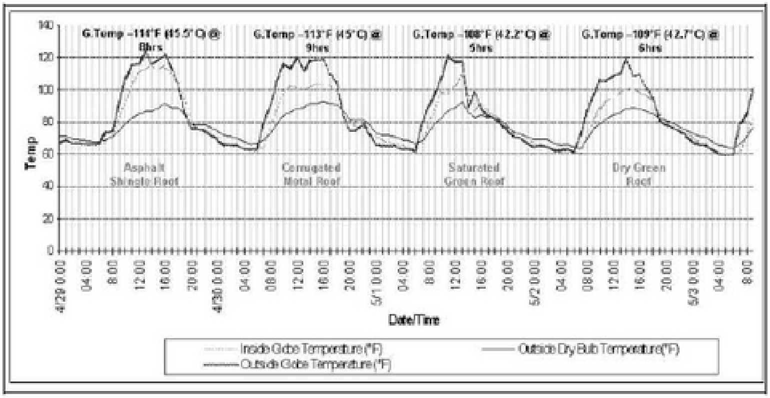


Figure 4: Graphical Comparison of Average Globe Temperature for All Roof Types

## *Validation of the Data Acquisition System to be Used for Assessing Thermal Comfort Over the Chosen Case Study*

The data gathered for green roof on May 1 by performing test cell experiment was then compared with data derived from MRT program for the same day and similar roof surface. Figure 5 (below) shows graphical comparison of results achieved by performing simulation using these two data acquiring system in OUTDOOR© program. The approximate difference found between the results was 2 to 3°F. These findings validate the method of deriving weather data by using MRT program for inputting in OUTDOOR© program to perform thermal comfort analysis on the chosen case study.

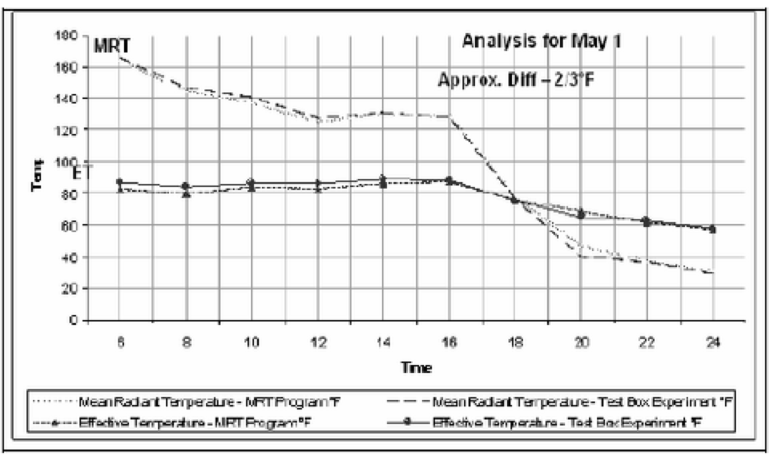


Figure 5: Graphical Comparison of Simulation Result; Derived by using Separate Data Acquisition Systems

## Conclusion for the Test Cell Experiments

The test cell experiment results verify the initial premise by bringing forth the superior thermal performance of green roof type over the other two roof types for hot-arid climate. Based on the experiment it can be concluded that the lower surface temperatures recorded in the green roof will assist in maintaining low ambient temperatures in turn contributing towards mitigating the Urban Heat Island effect. This inference then provides a foundation for the following study of including green roof technology as a primary strategy towards achieving thermal comfort on the chosen case study. Thus aiding in achieving the ultimate goal of developing a methodology to analyze and design thermally comfortable outdoor spaces.

## Thermal Comfort Evaluation using the Outdoor© Software

Thermal comfort is defined as: “that condition of mind which expresses satisfaction with the thermal environment”. This section describes the methodology and results of the thermal comfort assessment for the proposed green roof at the College of Architecture and Landscape Architecture in Tucson, Arizona. To start with, three distinct locations were chosen on the roof for analysis using the OUTDOOR© program. To demonstrate the methodology the simulations are conducted for extreme climate months: June 21 (summer solstice) and December 21 (winter solstice) which then accommodates the comparatively milder conditions prevailing during the rest of the year. The simulation results at the chosen locations were found to be thermally uncomfortable. Hence an approach was undertaken to enhance the thermal conditions through an iterative process of applying design strategies and performing simulation using the OUTDOOR© program. It was anticipated that analysis of these design modifications and the role they played in achieving thermal comfort could then form a guideline for designing and achieving thermal comfort at other locations on the roof.

## Project Description

The proposed green roof (See Figure 6) for the College of Architecture and Landscape Architecture covers 50% of the roof area the remaining is covered with concrete pavers. The green roof mainly comprises of vegetated beds with mass plantings of succulents and a few cacti. Trees (10′ diameter X 12′ height) are planned on the north side of the terrace. A vegetated facade (exposed metal mesh and vines) abuts and extends 10’ in height on the south side of the building.


Figure 6: Birds Eye View of the Proposed Green Roof for College of Architecture and Landscape Architecture

## Determining Thermal Comfort

The experiment involved two major steps:

- Estimating a person's view factor at each location using fish eye lens photography.
- Predicting effects of surrounding elements and landscaping materials on microclimatic conditions using the OUTDOOR© program.

### *Estimating Person's View Factors using Fish Eye Lens Photographs*

The fish-eye lens photography technique represents a person's view factor in a radiating field (I.D.Watson and G.T.Johnson, 1998). It enables a designer to determine surfaces whose long wave radiation affect human thermal comfort. A person's view-factor is defined as the fraction of the radiant flux that strikes a person from a particular surface to that which would be received from the entire environment radiating uniformly.

To determine view factors, a physical model of the proposed green roof on a scale of 1" = 6' was constructed. Then a CI–110 Digital Plant Canopy Imager was used to capture fish-eye lens photographs. Since a person's radiating environment is represented as a sphere, photos were taken for both hemispheres by looking either north-south or east-west. A polar grid whose annuli and radii correspond to a specific fraction of a person's view factor was then superimposed upon each fish-eye photograph to calculate relative quantities of myriad surface. Calculating the cells taken by each radiating element then provided the View Factor for that particular location.

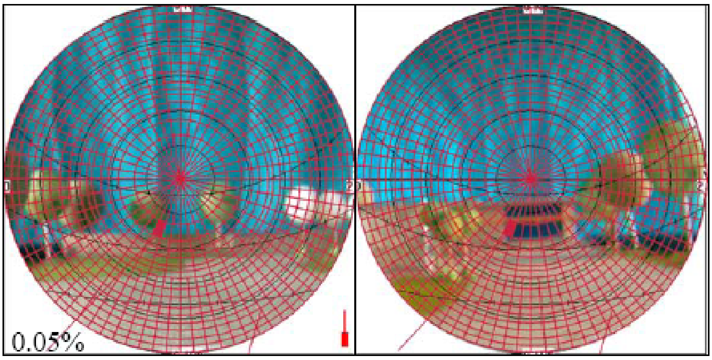


Figure 7: Example of Polar Grid Superimposed on Fish Eye Photographs Looking East-West

## *Outdoor© Program*

Developed by Dr.Chalfoun at the University of Arizona, the OUTDOORS© program is used for predicting and evaluating thermal conditions of outdoor spaces. The program analyzes effects of certain physical characteristics such as temperatures, solar radiation, convective forces, air moisture, metabolic rate, clothing insulation value, reflectivity, absorptivity, and the emissivity of surrounding natural and manmade surfaces. These parameters are analyzed by the program to predict the Mean Radiant Temperature[3] (MRT) and the Effective Temperature[4] (ET) acting on the human body and affecting the thermal comfort sensation. This analytical tool provides opportunities for understanding the impact of design decisions on microclimatic condition. Informed designs that account for the above mentioned parameters then can contribute towards improving thermal comfort and energy efficiency at the city level. The Predicted Mean Vote[5] (PMV) index was also calculated to represent human thermal comfort on a scale from -5 to +5. A range between -2 (cool) to +2 (warm) was considered to be comfortable as it accounts for 60% people being satisfied based on the Predicted Percentage of Dissatisfied[6] (PPD) scale. As environments are perceived differently by each individual this range accommodates reasonable percentage of satisfied people at that particular location.

[3] Mean Radiant Temperature (MRT) – It is that uniform temperature of an imaginary enclosure in which radiant heat transfer from human body equals the radiant heat transfer in the actual non-uniform enclosure.

[4] Effective Temperature (ET) - This index combines both temperature and humidity into a single index, so two environments with the same ET evoke the same thermal response even though they have different temperature and humidity, but have the same air velocity.

[5] Predicted Mean Vote (PMV) – Fanger (1970) devised this thermal index that predicts the average thermal sensation that a group of occupants may experience at a given place. For complex outdoor environments Gagge, Foblets, and Berglund (1986) introduced a modified PMV that can be applied to a broader range of humidities and temperatures. The resulting PMV scale is an 11-point scale ranging from +5 (intolerably hot) through 0 (neutral) to –5 (intolerably cold)

[6] PPD is the predicted percentage of dissatisfied people at each PMV. As PMV changes away from zero in either the positive or negative direction, PPD increases.

## Result Analysis of Proposed Green Roof Design

### *Description of Locations Chosen for Performing Thermal Comfort Analysis*

The criterion behind selecting these locations was mutually exclusive yet together represent the physical conditions commonly found on the remaining proposed green roof (See Figure 6 - above).

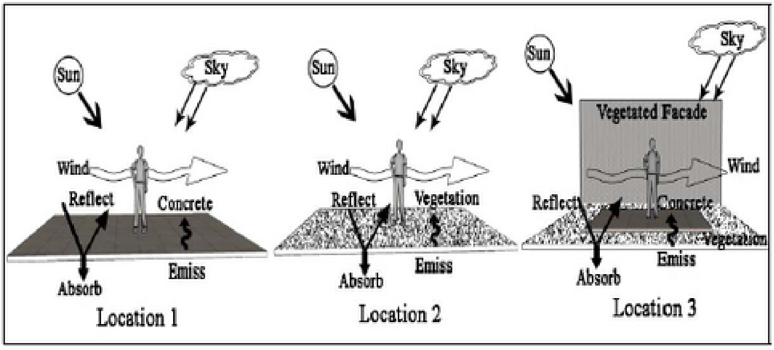


Figure 8: Sketch of All Three Locations

*Location 1* - This location is considered as the base case for the study, with a person standing on the terrace without any shading and thus receiving full direct solar radiation, ground reflected shortwave radiation, and the long wave radiation from the concrete pavers.
*Location 2* - This is one of the most important locations since it addresses green roof strategy. The thermal comfort of a person standing at this location would not only be influenced by the shortwave and the long wave radiation from the soil and vegetation but also from their evaporation and evapotranspiration properties.
*Location 3* - The third location is unique in the terms that it combines features from both of the above location i.e. green roof with central concrete paved area. In addition to which a vegetated façade comprising of a metal mesh and vines is present along the south side of this location.

### *Comparison of Thermal Comfort Performance at the Three Locations*

Fish eye lens photography along with the earlier established data acquisition system (derived using MRT program) were used to simulate conditions at the above mentioned locations using the OUTDOOR© program. The simulation runs performed for June 21 and December 21 at the three locations were compared. The June 21 analysis results seen in Figure 9 (below) indicate high Mean Radiant Temperatures for all three locations, due to which the Effective Temperature exceeds the comfort range presumed between 68°F-80°F (20°C-26.6°C). However, in comparison the Effective Temperature at location 2 (green roof) was found to be 6°F (3.3°C) less than location 1 (base case) due to the presence of ground cover (soil & vegetation) that cool the surfaces with evaporation and shading. Overall the overheating problem at all locations lasts for about 10 hours throughout the day during which the use of roof is vastly impacted.

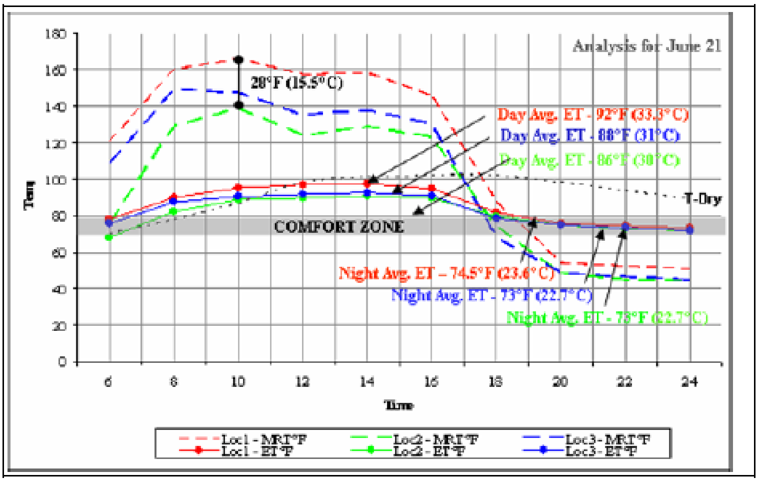


Figure 9: Comparison of Thermal Comfort Performance at the Three Locations for June 21

The December 21 analysis results indicated in Figure 10 (below) revealed high Mean Radiant Temperature between 8am-2pm, which aids in bringing the Effective Temperature within comfort range. This implies that unlike summer the maximum exposure of the terrace to direct solar radiation is favorable for winter months along with the thermal mass properties provided by material like concrete and green roof. The nighttime results indicated excessive cooling of surfaces (Avg. Mean Radiant Temperature - 15°F (-9°C) at 6pm) as the heat is rapidly lost to the clear open desert skies. Additionally, the performance result for location 3 disclosed uncomfortable conditions existing at that location throughout the day. This condition exists due to the undesirable shading present due to the vegetated façade, which blocks southern solar radiation.

Overall the simulation results for June 21 and December 21 indicate thermally uncomfortable conditions at all three locations of the proposed roof. To counteract these conditions, design modifications were suggested and simulated in OUTDOOR© program following the above explained methodology. To demonstrate the application of this process, location 2 with its comparatively superior performance, was chosen for conducting thermal comfort analysis.

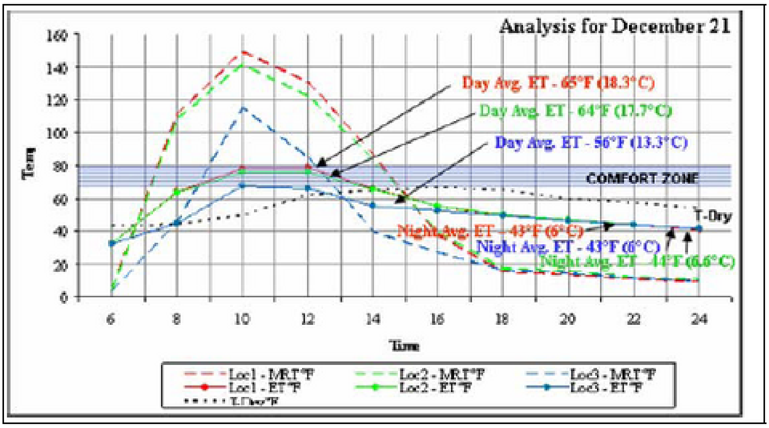


Figure 10: Comparison of Thermal Comfort Performance at the Three Locations for June 21

## Result Analysis of Design Modifications Suggested at Location 2

### *Methodology Followed for Application of Design Modifications at Location 2*

Multiple design strategies were suggested and simulated at location 2 to improve thermal comfort conditions at that location. However for this paper the final probable design strategies applied are presented. The process included simulating each strategy in addition to the previous strategy simulated, which finally together impact the thermal performance at location 2. Graphical results presented below clearly explain the role and impact each design strategy had towards achieving thermal comfort.

The design modifications were suggested with the aim of altering the geometry of the space - in terms of building and landscape materials, shading conditions and humidity levels present. However, design modifications suggested retained consistency with the building architecture so as to preserve its character.

### *Thermal Comfort Analysis After Application of Design Strategies at Location 2*

*Strategy 1 – Paving Material*

Location 2 was redesigned as an accessible space for passive activities. Similar spaces on the remainder roof use concrete pavers, alternatively metal grating resting 3” above planting surfaces was proposed and simulated.

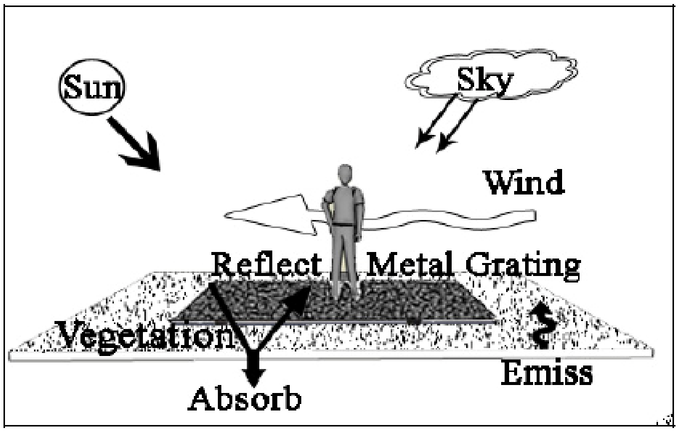


Figure 11: Location 2 – Strategy 1

The simulation results indicated a marginal rise in temperatures for June 21 due to the introduction of paving material where initially there was only vegetated roof. The double layer property of the new paving maintains lower summer daytime temperatures due to evapotranspiration effect of green roof and low nighttime temperatures due to low emissivity of metal which cools down faster. The much desired rise in temperature observed for December 21 is due to the high thermal mass provided by the green roof system.

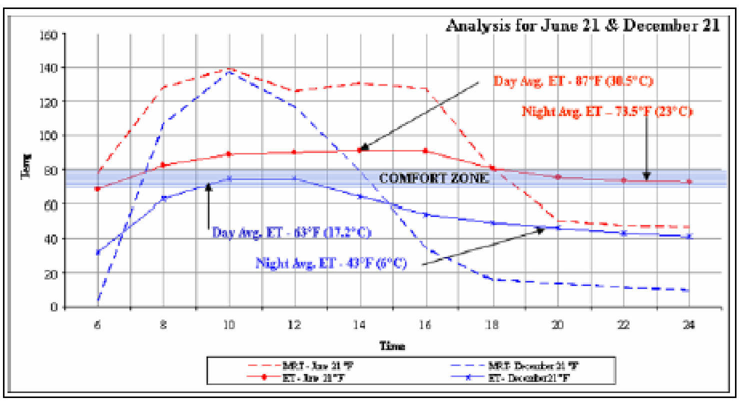


Figure 12: Thermal Comfort Performance of Strategy 1

*Strategy 2 – Shading Device*

The shading structure comprised of an open PV Panel System for the roof and Vertical Screen for the west facade. Figure 14 (below) shows the combined results for this and the earlier strategy.

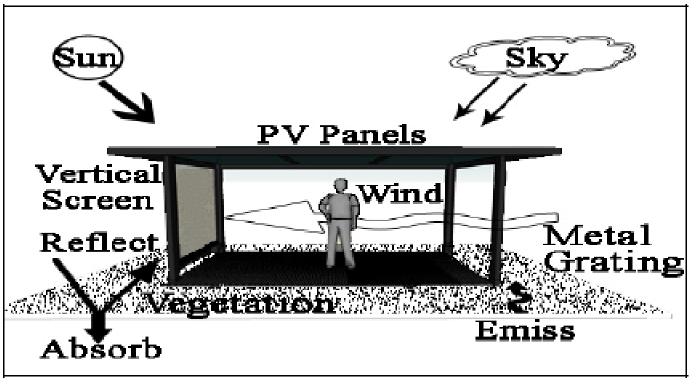


Figure 13: Location 2 – Strategy 2

*Open PV Panel* - The provision of shading structure vastly improves the thermal comfort as it protects human occupant from direct solar radiation along with reducing the surface temperatures of material in shade. Additionally, the openings present in the PV system help release the trapped radiation inside the structure into the surrounding thus further cooling summer temperatures. Whereas the low solar angles of winter penetrate the shading device thus, warming the temperatures inside the structure. However the risk of loss of radiation through the open PV system during winter months was eliminated by providing operable PV system which can be closed to trap nighttime long wave radiation to increase temperatures.

*Vertical Screen* - It was observed that the screen blocked the solar radiation during June 21 analysis thus reducing temperatures. Conversely, at night the screen traps radiant heat and hinders the cooling process. During winter months when solar heating is required the screen blocks solar rays thus further dropping daytime temperatures. However at night it assists in trapping long wave radiation which then helps in warming the space. Based on this study it seems suitable to provide adjustable screens, which could be retracted as required.

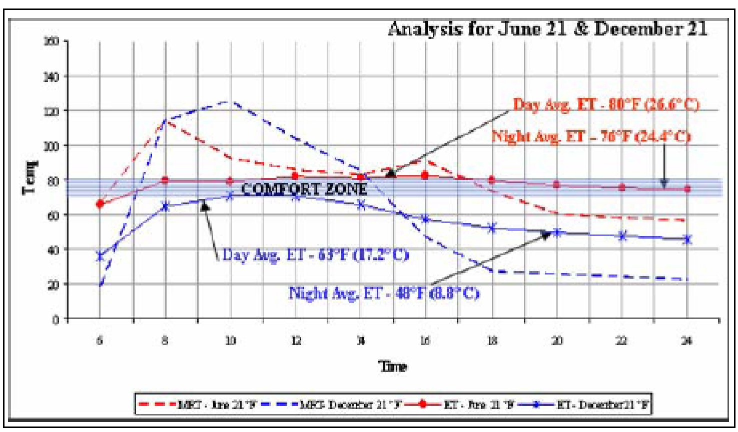


Figure 14: Thermal Comfort Performance of Strategy 3

*Strategy 3 – Water Feature (Evaporative Cooling)*

The water feature type simulated was misters (60%RH). Evaporative cooling works when the temperature is high and the air is dry. Hence this strategy was simulated only for summer. Addition of water to surrounding increases relative humidity which drops the dry bulb temperature thus bringing the ET within comfort zone.

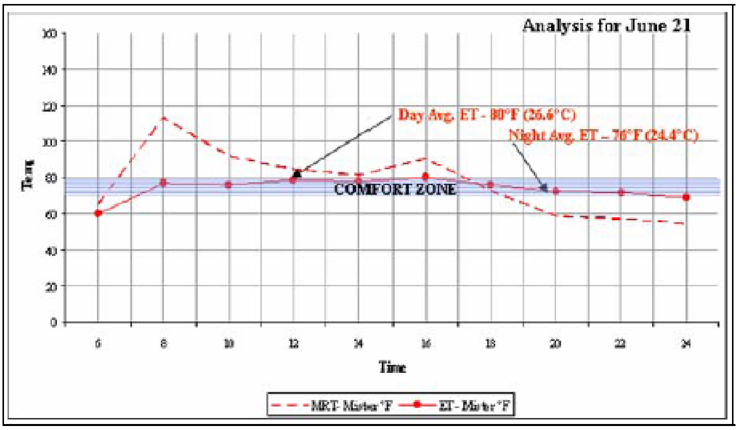


Figure 15: Thermal Comfort Performance of Strategy 4

## Conclusion for Thermal Comfort Analysis

Figure16 (below) compares base case and the final case. The June 21 results indicate drastic drop up to 77°F (42°C) at 2pm in the Mean Radiant Temperature which then reduces the Effective Temperature from 92°F (33.3°C) to 77°F (25°C) during the day and from 75°F (23.8°C) to 70°F (21°C) during the night. The improved ET reduces the uncomfortable conditions existing on the roof from 10hrs during the day to 5hrs of moderate discomfort.

The new temperatures for December 21 as seen in Figure 17 (below) imply that comfort period on the roof has increased from the previous 5hrs to about 10hrs. The PMV (Figure 18 below) results signify overall increase in people satisfaction with the new temperatures.

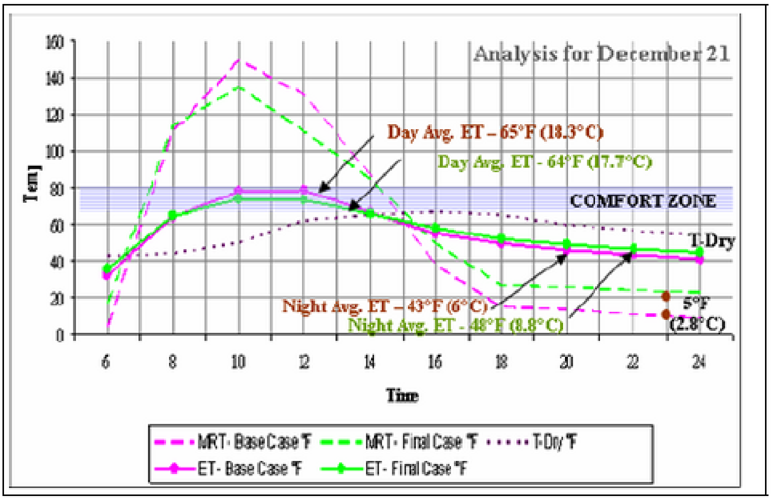


Figure 16: Comparison of Thermal Comfort Performance for Base Case and Final Case (June 21)

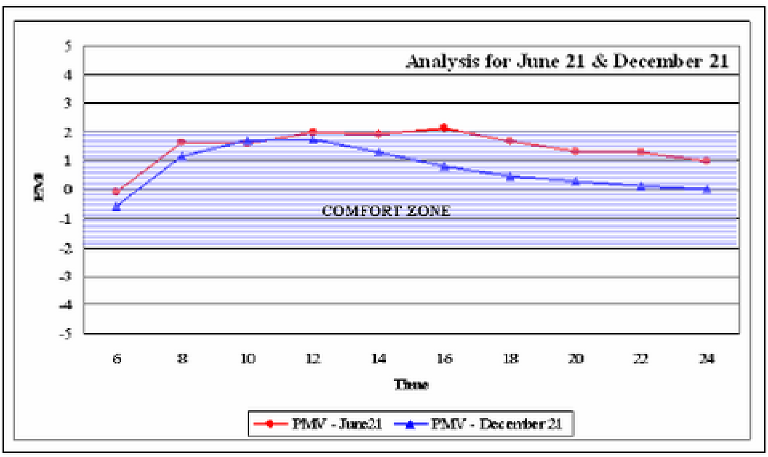


Figure 17: Comparison of Thermal Comfort Performance for Base Case and Final Case (December21)

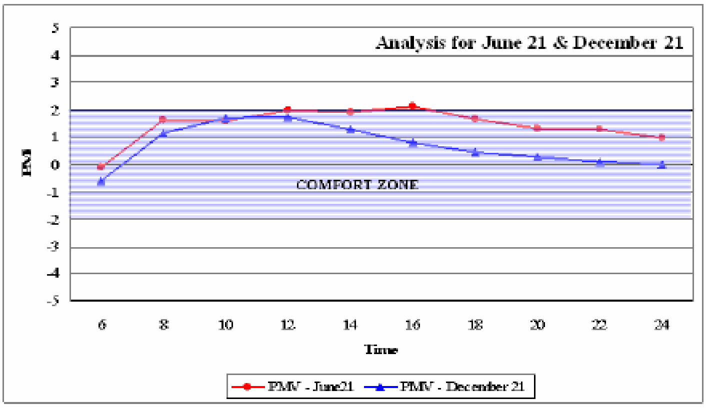


Figure 18: Predicted Mean Vote Values for Final Case

## Conclusion

This study depicts the benefits of replacing impervious roof surfaces with permeable living plant surfaces as achieved through the test cell experiment. The results elucidate the numerous benefits of employing green technology in hot-arid climates especially towards mitigating Urban Heat Island Effect and achieving Energy Efficiency.

The scope further extends to include a thermally comfortable green roof that supports outdoor activities. The use of OUTDOOR© program to predict and modify the microclimatic conditions brought forth the importance of integrating computer simulation at design stage to accomplish a climate responsive solution. Though this methodology was developed to assist the execution of the proposed green roof on Architecture building, this technique could be applied to other projects of similar nature. This method then could be a tool for ecological designers to test different design solutions so as to make an informed decision towards creating thermally comfortable outdoor spaces.

The College of Architecture and Landscape Architecture by creating thermally comfortable spaces on their green roof not only benefit from its myriad environmental benefits but also multiply their usable spaces. Such spaces then contribute towards improving the urban environment and mitigating the Urban Heat Island effect. Also, increased use of outdoor space could reduce use of indoor space for performing certain activities thus promoting outdoor living and in turn conserving energy.

## Acknowledgment

I would like to thank Dr. Nader Chalfoun for his help and support and for the implementation of the methodology and permission to use the Outdoors© software for this research.

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