# A SIMULATION TOOL FOR THE STUDY OF URBAN HEAT ISLAND MITIGATION

Harvey Bryan, Ph.D.
Vidhi Agarwal
Porus Sam Antia
School of Architecture,
Arizona State University, PO Box 871605;
Tempe, AZ 85287-1605

## ABSTRACT

This paper explores the possibilities of mitigating the urban heat island effect by generating climate-responsive urban design guidelines for a hot arid climate. Many of the outdoor urban surfaces such as streets, sidewalks and building elements use low albedo materials that also have high thermal capacity. Field measurements indicate that it is not uncommon to have on a summer day surface Sol-air temperature of 150ºF (65ºC). The aggregation of such high surface temperatures is the prime cause of the urban heat island. Our understanding of this phenomenon has been hampered because the physics of radiant heat exchange are so complex it can only be modeled accurately at the urban scale by computer simulation. The paper illustrates the potential of a simulation program called RadTherm as a design tool to mitigate outdoor surface temperatures. The study models a typical urban streetscape in RadTherm to optimize the interaction between building materials, surface properties, adjacencies (view factors) and resultant surface temperatures. The performance of distinct parts of the urban streetscape are planned to demonstrate the possible application of the program for developing urban design guidelines to mitigate the urban heat island.

## INTRODUCTION

The summer temperature in urban areas are typically 2 to 8$^{o}$F higher than their adjoining rural surroundings, this phenomenon is called the urban heat island (UHI). Higher temperatures result in increased energy usage to support air conditioning. Increased energy production increases emissions of greenhouse gases, which contribute to global climate change. This cycle serves to increase the frequency and duration of extreme temperatures. The UHI can also cause the increased formation of harmful smog, as ozone precursors such as nitrous oxides (NOx) and volatile organic components (VOCs) combine photochemically to produce ground-level ozone. Researchers have discovered that the primary reasons for this phenomenon in urban areas are the climate, topography, weather patterns, surface properties and vegetation. The last two factors constitute the majority of heat accumulation that is attributable to human activities. Urban design guidelines often neglect this aspect.

The adverse effects of the UHI can be minimized by designing an external environment that minimizes the excess heat gains to the urban environment. Increasing the albedo of the urban streetscape surfaces and reducing the insolation striking buildings can contribute to mitigating the UHI effect.

The thermal properties of surface materials, self-shading, shading by adjoining buildings and foliage, all form the setting for the study of the urban heat island. This requires an understanding of the physics of radiant heat exchange which involves the direct solar, long wave re-radiation from building materials and the heat capacity of the material. All these, along with building layouts and street orientations form a complex interaction that can only be accurately captured by computer simulation. One simulation program that potentially can accomplish this is called RadTherm, which was developed by ThermoAnalytics Inc[1].

RadTherm was developed for the defense and automotive industry to aid in the analysis of the thermal behavior of their designs. It is a windows-based cross-platform thermal modeling tool, which can be used to model objects with complex surface geometry. RadTherm models 3D conduction, convection and multi-bounce radiation. The output from RadTherm generates user-friendly graphic temperature map of the object's surface temperatures.

## THE SIMULATION TOOL

RadTherm has an optional building module option built into it, which allows it to be used for performing building simulations. It requires a surface mesh of the geometry that can be built within the interface or can be imported from common data formats like Autocad (dxf). The thickness of each layer of the surface mesh, the boundary conditions and material properties are assigned in the user interface. Natural environment can be modeled as a terrain with an option for specifying foliage and moisture settings. Comprehensive environmental data from a weather file can be put in a program specific format and utilized to capture thermal effects of natural environments such as wind vector, sky temperature, and solar radiation (direct and diffuse). Solar band multi-bounce radiation calculations are performed to capture effects of part-to-part and part-to-terrain reflectance.

**Model Inputs and Calculations**

The geometry parts in RadTherm are based on the shell mesh. The properties of materials are assigned in the user interface through a 3-layer input option for a single layer mesh geometry. The thickness of each layer of the assembly forming the building envelope can be input along with the material properties, specified convection and imposed heat loads. RadTherm solves the energy balance equation simultaneously for convection, conduction and radiation. All temperature and heat load data are input as constants or as functions of time at user discretion.

**Radiation Exchange in RadTherm**

Radtherm uses the net-radiation equation based on emissivity, surface area, view factors and surface temperatures for computing radiation exchange. The net-radiation solution is integrated into the thermal and radiometric solutions, thus accounting for time or temperature varying surface conditions.

**Conduction in RadTherm**

Radtherm computes both planar conduction between elements and conduction through the thickness of elements. Conduction through an element (from the front surface node to the back surface node) is based on the element surface area, thickness and thermal conductivity. Internal temperatures for buildings can be set to account for 3-dimensional conductivity. Material thicknesses and conductivities are user inputs. Thermal conductivity of materials for composite assemblies can be defined by the user in the material library of the program.

**Convection in RadTherm**

For building simulation purposes, where natural environments play a role in analysis, RadTherm can utilize weather data for wind speed, direction, solar and other data, and automatically calculate convection values based on the planar orientation of each element. Natural convection can be combined with forced convection for analysis.

## THE CASE STUDY

**Model Setup**

The simulation model used for the study is representative of a typical urban streetscape. The model consists of four buildings in the Phoenix metropolitan area that were clustered together for the purpose of representing a typical urban streetscape in a hot arid climate. The building geometry was imported from Autocad and further additions were made using the RadTherm interface. Surface material properties and thickness for elements were assigned as close as possible to the actual buildings used for the study.

The weather data was taken from the TMY2 file for Phoenix and converted to a prism format that is compatible with RadTherm. The sky data was modeled using RadTherms sky modeling routines to calculate long wave infrared radiation based on geographic location. The solar data is structured to take inputs for total Solar and direct solar radiation values from the weather file. Convection was calculated for all outside surfaces by using wind data from the weather file. The solution time was set up every 60 minutes.

**Initialization**

The model was run for 20 days for initialization so that the steady state solution was reached for August 21$^{st}$. The default value of part initial temperature of 68ºF was set as a boundary condition during model set up to accelerate convergence of the model. This is used as the numerical seed value when solving the steady state solution. The temperature entered as the initial temperature may not be the temperature of the part when the model is converged.

**Convergence**

The solution tolerance method was used to determine when the iterative solution has converged. The maximum change in temperature for an element between two consecutive iterations was set to a default value of 0.01ºF. Initially a maximum of 100 iterations for each time step, which were further increased to 500 for the model to converge.

## RESULTS

The surface temperatures of the urban streetscape were obtained as a function of every solution time step. The results for August 21$^{st}$ were analyzed for the purpose of the study. The surface temperature maps of the streetscape modeled were compared with the shading analysis done in 3-D modeling software called Autodesk VIZ 3.0 for every hour of the day. Figures 1 to 8 illustrate the variance in surface temperatures as a function of thermal and optical properties of materials in accordance with the sun angle over a period of time.

The shading analysis complemented the RadTherm results. The spot measurements were taken in the shaded and unshaded areas for several materials (Tables 1 to 4) by clicking on the cell or grid. More detailed results for temperatures for the whole geometry can be generated as tables and graphs using the RadTherm interface. The re-radiation effect and thermal storage capacity of materials emerged as a significant factor for the high surface temperatures.

The surface temperatures obtained from the simulation model compares well with the field measurements taken with a Raytek infrared thermometer for building materials with similar properties (color and heat capacity)[2]. Further accuracy for results can be obtained by increasing the meshing in the model.

## IMPLICATIONS

The study explores the potential of an application and is not a definitive methodology for evaluation of UHI effect. The next step for this work would be to validate our RadTherm results with measurements of actual buildings. ASU's UHI Initiative is planning to soon purchase a high-end thermal imaging camera. Since the buildings we analyzed for this study do exist in the metropolitan area, we plan to take thermal images of these buildings and overlay them to our RadTherm simulations for further validation.

There also exist several urban climatological simulators that we also would like to investigate, particularly how well they model radiant surface temperatures. One climatological simulator that we are very excited about is ENVI-met[3]. It is a non-hydro-static model for simulation of surface-plant-air interactions, especially inside urban environments. The model calculation includes shortwave and longwave radiation fluxes with respect to shading, reflection and re-radiation from building systems and the vegetation. It gives surface and wall temperature for each grid point. It has a typical time frame of 24 to 48 hours with a time step of 10 sec at maximum. It also includes calculation of biometeorological parameters like Mean Radiant Temperature and Fanger's Predicted Mean Vote (PMV). Linking the detailed surface temperature calculations of RadTherm with the accurate environmental predictions of ENVI-met would be a more accurate methodology for future UHI studies.

Another step in formulating urban design criteria for a hot-arid climate would be to integrate outdoor comfort issues and the predicted mean vote (PMV) model for thermal comfort with the surface temperature maps. The radiant interactions of properties of material are a prime driver of pedestrian thermal comfort.

## CONCLUSION

Preliminary investigations demonstrate the potential of RadTherm as a design tool for mitigating the urban heat island effect. The simulation model can be made more discrete by including the effect of foliage, vegetation and anthropogenic heat sources.

Variances in urban streetscape surface materials, their properties, shading, layouts and orientation can be tested with computer simulation to generate urban guidelines for mitigating the urban heat island effect. RadTherm gives an integrated picture of the surface temperature map with time and movement of the sun. The interface is user-friendly and the output graphics are comprehensive to analyze problems of this nature.

Further validation with field measurements and thermal images can be used to generate a better picture of the existing heat island scenarios in urban areas. Also, alternative materials, orientations and layouts can be investigated with this tool to generate climate-responsive urban design guidelines for a hot arid climate.

## ACKNOWLEDGMENT

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## REFERENCES

1. www.thermoanalytics.com

2. Bryan, H. J. , Cook, J., Cool Architectural Materials and Assemblies, A Report to the Valley Metro Rail, Arizona State University, 2003, Tempe, AZ.

3. www.geographie.rub.de/agklima/envimet/

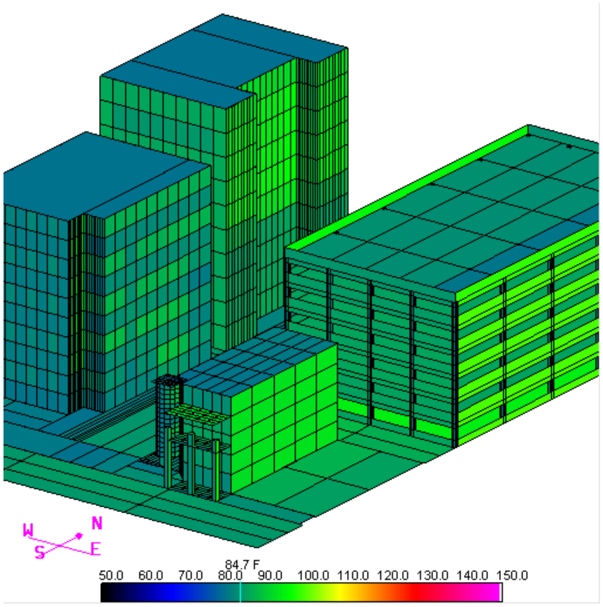


*Figure 1 Surface Temperatures of the urban streetscape at 9:00am, 21st August*

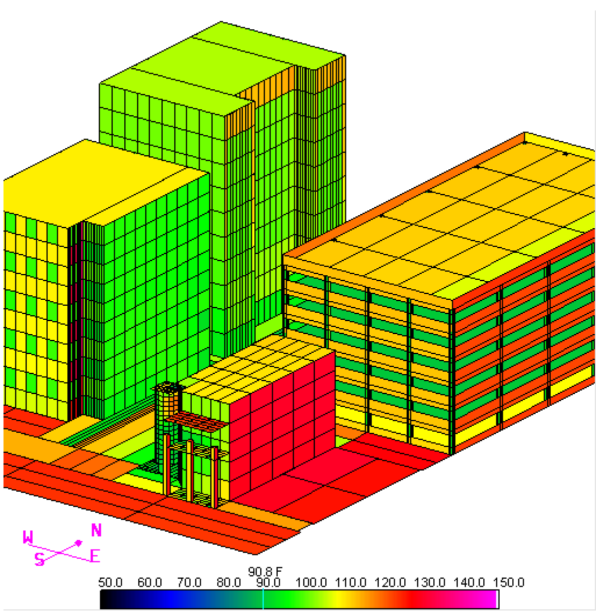


*Figure 3 Surface Temperatures of the urban streetscape at 12:00 noon, 21st August*

*Table 1 Surface Temperature in ºF at 9:00am*

| MATERIAL | SHADED | UNSHADED |
|---|---|---|
| Concrete Roof | 79.1 | 83.1 |
| Black Asphalt | 81.3 | 88.7 |
| Concrete Sidewalk | 78.5 | 83.7 |
| Brick Wall, Red | 78.5 | 85.6 |
| Glass, Reflective | 82.6 | 86.2 |

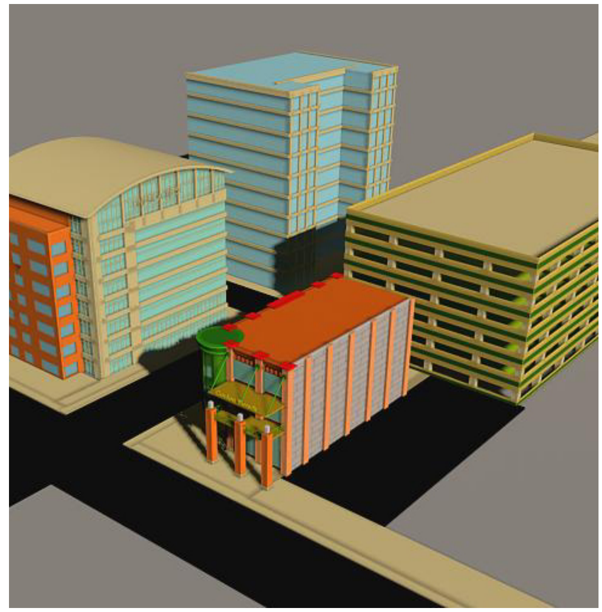

*Figure 2 Shading Analysis of the urban streetscape at 9:00am, 21st August*

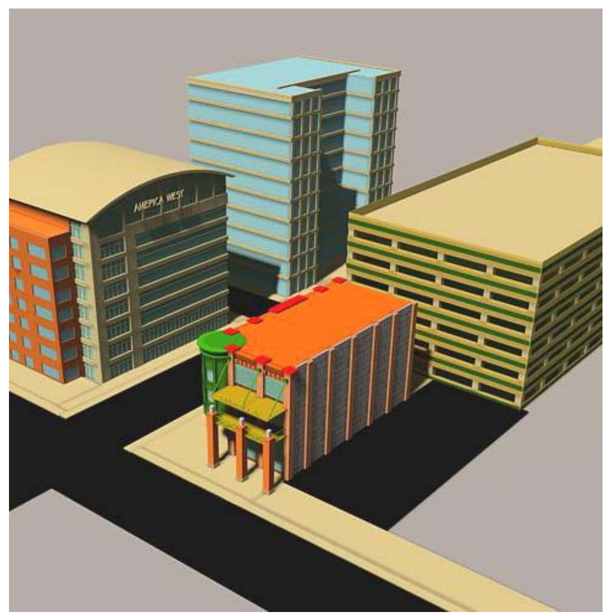

*Figure 4 Shading Analysis of the urban streetscape at 12:00 noon, 21st August*

*Table 2 Surface Temperature in ºF at 12:00 noon*

| MATERIAL | SHADED | UNSHADED |
|---|---|---|
| Concrete Roof | 107.2 | 111.6 |
| Black Asphalt | 92.7 | 123.8 |
| Concrete Sidewalk | 87.4 | 115.6 |
| Brick Wall, Red | 97.1 | 109.3 |
| Glass, Reflective | 93.4 | 97.6 |

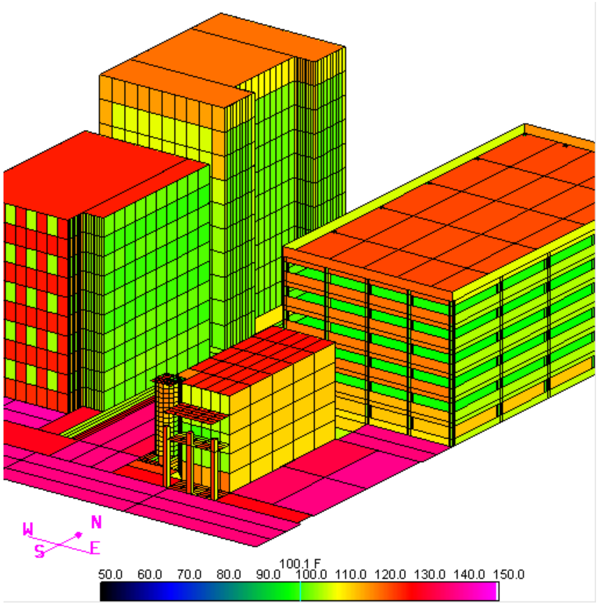


*Figure 5. Surface Temperatures of the urban streetscape at 3:00pm, 21st August*

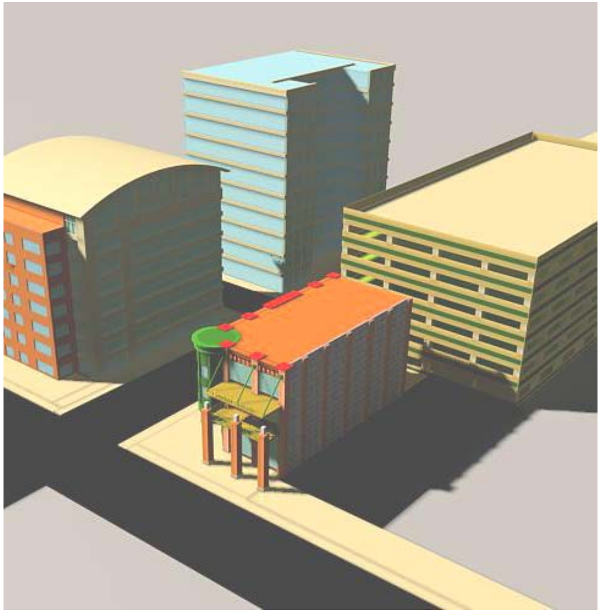

*Figure 6. Shading Analysis of the urban streetscape at 3:00pm, 21st August*

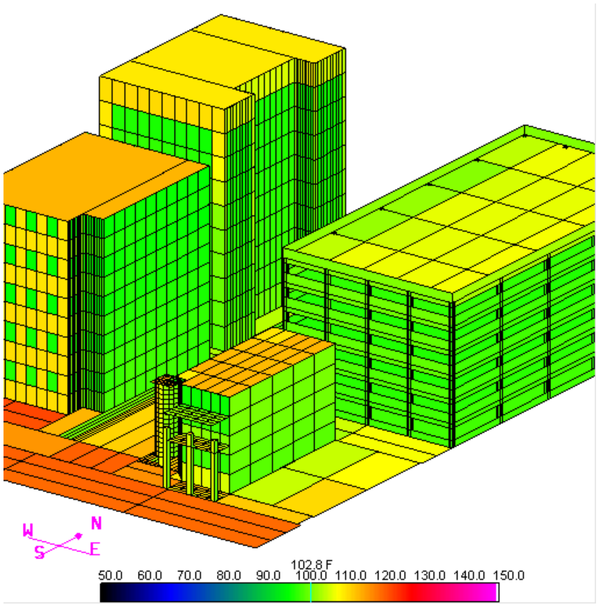


*Figure 7. Surface Temperatures of the urban streetscape at 6:00pm, 21st August*

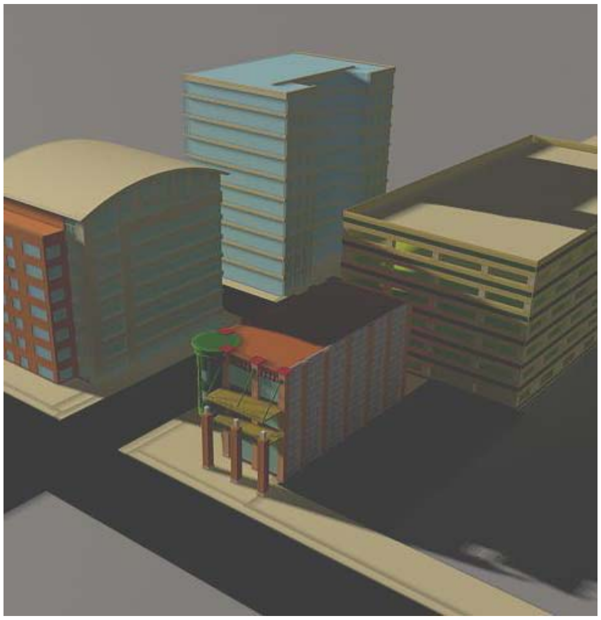

*Figure 8. Shading Analysis of the urban streetscape at 6:00pm, 21st August*

*Table 3. Surface Temperature in ºF at 3:00pm*

| MATERIAL | SHADED | UNSHADED |
|---|---|---|
| Concrete Roof | 123.1 | 127.2 |
| Black Asphalt | 126.5 | 139.3 |
| Concrete Sidewalk | 124.2 | 130.7 |
| Brick Wall, Red | 100.1 | 127.3 |
| Glass, Reflective | 100.9 | 104.9 |

*Table 4. Surface Temperature in ºF at 6:00pm*

| MATERIAL | SHADED | UNSHADED |
|---|---|---|
| Concrete Roof | 104.7 | 115.1 |
| Black Asphalt | 106.5 | 122.5 |
| Concrete Sidewalk | 101.8 | 113.7 |
| Brick Wall, Red | 100.1 | 112.2 |
| Glass, Reflective | 99.3 | 98.9 |