# EFFECTS OF THREE LANDSCAPE TREATMENTS ON BUILDING MICROCLIMATES, AND ENERGY AND WATER USE

by

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## APPROVAL BY THESIS DIRECTOR

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E. Gregory McPherson — April 19, 1990

E. Gregory McPherson — Date
Professor of Landscape Architecture

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## ABSTRACT

Vegetation near structures may reduce cooling loads in warm desert regions. This study was conducted to measure vegetation effects on warm-season energy use of three structures surrounded by different landscapes: 1) decomposed granite (rock), 2) shrubs and decomposed granite (shade), and 3) a bermudagrass lawn (grass). Surface and air temperatures, relative humidity, cooling energy and irrigation water use were measured. Actual energy use was compared to use predicted by microcomputer program MICROPAS. Vegetation resulted in cooler surfaces on most test dates. The grass treatment had lowest air temperatures for all dates. Grass and shade treatments had higher relative humidity and lower actual and predicted electrical use than the rock treatment. The shade treatment had the lowest predicted electrical use for all dates and lower utility costs (water and electricity) than grass (all dates) and rock treatments (two of three dates). Vegetation adjacent to structures had a significant effect on building energy use.

# INTRODUCTION

Historic increases in building cooling costs has heightened consumer interest in practices that may ultimately reduce their utility costs such as altering residential building construction and microclimates. The amount of energy used for structural cooling is influenced largely by building characteristics, occupant behavior, and climate. The amount of impermeable surfaces and characteristics of vegetation installed around a structure may also influence energy consumption by altering building microclimates. For example, in hot, arid climates, an urban landscape containing a lawn and shade trees will have a very different microclimate and effect on building energy use than one emphasizing water conservation through the use of drought tolerant plants or minimal vegetation (Bajza et al. 1977). Previous research in this area has considered surface energy balances of specific urban microclimates or energy use of structures, but many questions still remain regarding the relationships between these factors.

## Scientific Background:

Researchers have measured various components of urban and rural microclimates such as surface energy balances, air and surface temperatures, and relative humidity, and described how these components are influenced by various microclimatic surfaces or materials (Oke 1979; Suckling 1980; Jones and Suckling 1983). Comparisons of energy balances have been made between rural and urban areas (which differ greatly in the amount of vegetated surfaces) in a similar geographic region. This was done in an attempt to define their energy transfer differences as related to varying amounts of vegetation (Yap and Oke, 1974a). Previously, it has been assumed that urban areas have evapotranspiration rates lower than rural areas due to higher amounts of non-evaporating surfaces. However, irrigated urban areas, such as lawns and parks, often have a latent heat flux great enough that it exceeds the net available radiation value (Yap and Oke, 1974a).

Other studies have suggested that vegetation may reduce structural cooling loads through evapotranspirational cooling from the plants and shading outside surfaces of structures. Savings in building cooling costs have been demonstrated after strategic placement of vegetation for structural shading purposes (Huang et al. 1987; McPherson et al. 1988). Estimates of cooling costs have also been made using computer programs that develop a model of a structure, vary the shading patterns around exterior walls, and use empirical formulas to determine cooling loads of the modeled structure (McPherson and Rowntree, 1986).

Many questions remain unanswered in the field of urban climatology, especially in the description of energy balances of differing microclimates and their possible effects on building energy performance. For example, few studies have described and compared energy balances and energy use of similar structures with different microclimates, such as a site surrounded by landscape plants as compared to one with no vegetation. Also, little research has considered repeated comparison of computer-predicted and field measurements of energy use of existing structures as a means to evaluate the accuracy of computer modeling in predicting energy consumption of a building.

Purpose:

This research was initiated to further investigate microclimatic effects on residential energy use for cooling by measuring energy balance components and energy use of three similar structures, each surrounded by a different landscape. In addition, water use was measured to determine if a significant reduction in energy use of a structure was counterbalanced by an increase in water use for the landscape surrounding the structure. The study was accomplished in three phases:

1) Surface temperatures, outside air temperature, relative humidity, and electrical use were measured and statistically analyzed to determine if significant differences existed

among the structures.

2) Actual energy use was measured and compared to modeled results of the three structures using the microcomputer program MICROPAS.

3) Irrigation water costs were combined with building energy costs to provide a more complete cost analysis of the three different landscapes.

Hypotheses:

I hypothesized that there were significant microclimatic differences among the three landscapes, such as surface temperatures and relative humidity, and these microclimatic differences would have significant effects on energy used for structural cooling during warm weather. Furthermore, it was hypothesized that structures surrounded by vegetation that shaded exterior walls and provided evapotranspirational cooling would have a greater reduction in cooling loads than those surrounded by decomposed granite. Additionally, the structure surrounded by grass would have a much greater cost for irrigation water than the structure surrounded by shrubs. Therefore, total costs of electricity and irrigation water during warm seasons would be lower for landscapes providing structural shading than for landscapes with no vegetation or grass.

Scope and Limitations of the Study:

Three one-quarter scale (1:4) structures representing recently constructed residences were built on plots with similar site conditions, each with a different landscape treatment. Energy use for each structure was predicted using the microcomputer program Micropas. Results of this study will be related only to the structures and no inferences to full-scale residences will be made. Landscape treatments were not replicated.

Definition of Terms:

Treatments will be referred to as: 1) "rock", for the structure surrounded with decomposed granite; 2) "shrub", for the structure surrounded by shrubs and decomposed granite; and 3) "grass", for the structure surrounded by a Bermudagrass lawn.

Organization of Thesis:

Following the introduction, Chapter Two reviews the literature relating to the thesis topic and is divided into three sections: 1) energy fluxes of urban microclimates, 2) computer modeling of building energy fluxes, and 3) effects of existing urban landscapes on energy use. Chapter Three is a description of the materials and methods used in this research. Chapter Four contains results and summaries regarding the hypothesis tested. This is followed by a conclusion of the study which includes suggestions for further research and a discussion of the usefulness of the research.

# LITERATURE REVIEW

Three areas of research are reviewed in this chapter, with the first area focusing on studies measuring various urban surface energy balances. In such studies, researchers have described microclimatic effects on energy balances, but little research has directly compared balances among microclimates within one geographic region. This section is followed by a review of computer modeling of building energy fluxes. Exterior conditions such as temperature, wind speed and vegetation are included in models to predict the effect of these factors on building energy fluxes. The last section reviews research evaluating possible energy costs and savings of various established residential landscapes. Some research dealt with the evaluation of the costs of landscape installation and maintenance, while other studies examined changes in building energy use due to introduction of vegetation around a site.

## Energy Fluxes of Urban Microclimates

Changes in building density and vegetation have resulted in fluctuations of surface energy balances in urban environments (Balling and Brazel, 1987a, 1987b, 1987c; Kirby and Sellers, 1987). For example, increases in the proportion of land dedicated to urban parks and residential landscaping can greatly affect the latent heat flux of an area (Yap and Oke, 1974a; Oke, 1978). In addition, urbanization has been associated with increases in local temperature and wind speed and decreases in relative humidity. Urbanization affects the values of surface energy components, such as latent and sensible heat fluxes (Balling and Brazel 1987a, 1987c). Comparisons have also been made among energy balances and temperatures of various urban surfaces, such as exterior walls and landscape features, in an attempt to describe bioclimatic variations possibly correlated with fluctuations in building density or vegetation (Oke 1979, 1988; Suckling, 1980).

### Measuring the urban energy balance

Urban energy balances are difficult to accurately measure due to the effects of varying environmental and site factors, such as weather, adjacent structures, building construction and occupancy. Researchers have attempted to limit these factors by measuring energy balances of relatively isolated urban sites, such as in the center of a grass lawn, an "urban canyon" (formed by the walls and ground between two adjacent buildings), or a residential home.

The instrumentation used to measure components of the energy balance is similar for many studies; net radiation ($Q^*$) is measured with a net radiometer, soil energy storage

(Qg) with soil heat flux plates or soil temperature sensors, and latent heat (Qe) with a lysimeter or using micrometeorological techniques. Sensible heat flux can also be measured using the eddy correlation technique that uses a yaw-sphere thermometer (Yap and Oke, 1974b). The surface energy balance equation is:

Net Radiation (Q*) + Latent Heat (Qe) + Sensible Heat (Qh) + Soil Energy Storage (Qg) + Respiration + Photosynthesis = 0.

In the case of urban energy balances, values for photosynthesis and respiration are very small and are usually excluded.

<u>Studies of various urban energy fluxes</u>

One of the earliest studies of energy fluxes of an urban surface was conducted by Oke (1979) and involved measurements of a suburban lawn in Vancouver, B.C. during four summer days. His results demonstrated that latent heat transfer was the dominant sink for surface radiative heat surplus with Qe exceeding Q* for most of the afternoon. Suckling (1980) performed a similar study and measured energy fluxes of a suburban lawn in Brandon, Manitoba, over four three-day periods in the summer. Again, Qe was the dominant sink accounting for 55.4 and 78.3% of Q* in the morning and afternoon, respectively. Latent heat was higher in Oke's (1979) study than in Suckling's study, possibly because the Vancouver lawn had complete water availability and was near sources of horizontal sensible heat advection. The close proximity of advective heat sources, such as exterior walls, may greatly alter energy fluxes and make comparison difficult among similar urban surfaces located at different sites.

Oke (1979) also evaluated the energy balance of a typical suburban area from a tower 15 m above the ground. In addition to measuring Q*, reversing differential psychrometer and yaw sphere-thermometer eddy correlation systems were used to measure the Bowen ratio (Qh/Qe) value and Qh. This study demonstrated that Qe of the Vancouver suburban lawn was approximately twice that of the surrounding suburban area even though Q* of the lawn was considerably less. Higher Q* of the surrounding area was due to large sensible heat gains from large, dry impervious surfaces such as parking lots and buildings.

One limitation of these studies was lack of comparison among surface fluxes within a site. Nixon et al. (1980) compared temperatures of several surfaces (such as a lawn, trees, and residence walls) of a residential landscape, but measured fewer components of the energy balance than had Oke (1979) and Suckling (1980). They measured surface temperatures of landscape features with a radiation thermometer and downward and reflected solar radiation measured with a pyranometer. Their results indicated that midday incoming radiation from solar and atmospheric sources was balanced by emitted radiation from features of the landscapes, evapotranspiration from vegetation, and albedo from the driveway. In addition, they concluded that shaded surfaces of the residence contributed from 30 to 50 % less heat to the home than sunlit surfaces.

Jones and Suckling (1983) went beyond previous studies and compared energy balance components of a rooftop lawn and a tar and gravel roof located on the same building, thereby reducing effects of varying site factors such as relative humidity and sensible heat advection from nearby surfaces. Measurement of energy fluxes were compiled into 5-day averages and exhibited seasonal patterns that corresponded closely to surface moisture. During winter and rainy summer periods net radiation was mainly expended for evapotranspiration and differences between the two treatments were minimal. During drier periods evapotranspiration cooled the lawn surface while the tar and gravel surfaces had greater emitted long-wave radiation and increased surfaces temperatures. Jones and Suckling (1983) stated that latent heat of the lawn dominated the energy balance throughout all periods while sensible heat and latent heat of the tar and gravel roof dominated measurements during dry periods and wet periods, respectively. Similar conclusions have been reached for comparable studies of urban energy balances (Yap and Oke, 1974a; Kalanda et al., 1980). Researchers have noted that the diversion of available energy to sensible and latent heat flux is partially determined by available humidity. If actual evapotranspiration is less than potential, sensible heat flux increases and, in some cases, may be the dominant term of an energy balance (Wilmers, 1988).

Energy fluxes of an urban canyon, typically located in inner city areas, can exert localized climatic control. Frequently these canyons are linked with urban heat islands. Nunez and Oke (1977) examined the energy exchange occurring within an urban canyon, including the canyon air volume, which is the air contained within this canyon structure and bounded at the top by an imaginary "lid" approximately at roof level. They noted that the line of demarcation between the urban canopy layer and urban boundary layer (a transitional layer between the disturbed flow near the ground surface and smooth flow of the atmosphere) was approximately at the level of the roofs. A line of demarcation is used in most theoretical urban atmosphere models where the surface layer is assumed to be horizontal and homogeneous. Nunez and Oke (1977) measured all components of the energy balance except Qh which was obtained as a residual. Their results indicated that 50 to

60% of Q* was dissipated by turbulent transfer during the day, 25 to 30% was stored in canyon materials such as concrete walls and sidewalks, and 10% was used by evaporation from the canyon floor. In general, the energy balances of the walls and floor are strongly influenced by the canyon geometry, orientation of the radiation exchanges, and the materials of the walls and floor. This is supported by findings of a study conducted by Tuller (1973), where canyon geometry was the determining factor in amount of net radiation received on a canyon surface.

Summary

One obstacle to development of consistent descriptions of surface energy balances is the difficulty encountered in comparing results from different studies given the wide variation in site conditions and insufficient replication and statistical analysis of measurements. Jones and Suckling (1983) attempted to reverse this trend by measuring energy fluxes of two surfaces (lawn and tar-gravel roof) with similar site conditions and intercalibrating instruments before measurements were taken. Height of instrumentation above surfaces also varies considerably among studies. This affects the magnitude of the energy flux measured. In addition, there has been some concern over spatial variability of heat fluxes within a site. Yap and Oke (1974) tested for spatial variability by comparing measurements of sensible heat flux recorded 5 m apart, using yaw sphere thermometers. Their results indicated similarity between these measurements. These potential differences between location should be evaluated prior to comparison of measurements between study sites.

Given the various methods used, it is interesting to note that several of the studies reported Qe to be the dominant term when irrigation is practiced and positively correlated with evapotranspiration rates. It is also the one component of the energy balance that previously has been underestimated in urban areas, possibly due to underestimation of the amounts of urban vegetative cover (Marotz and Coiner, 1973). In addition, it is difficult to quantify the climatic effect of vegetated areas outside the immediate vicinity due to convection of air reducing and suppressing wider effects of vegetation (Wilmers, 1988). Given these results, it appears that urban vegetation affects microclimatic conditions to a much greater extent than researchers have previously noted. Research that describes the energy balance variations among different urban microclimates may provide a more accurate indication of the total effect of these microclimates on a urban area. With more accurate measurements of urban energy balances, researchers will be able to more effectively predict the effects of microclimatic changes on other urban energy fluxes, such as energy performance of buildings.

## Computer Modeling of Building Energy Fluxes

Several researchers have already attempted to describe the effects of microclimatic changes on residential energy use through the application of computer modeling of varying building and climatic conditions. Computer modeling is a valuable tool for predicting energy fluxes of sites that cannot be not easily measured, such as an inhabited residence, and testing the effects of factors such as irradiance, wind speed, and shading due to vegetation on building energy costs. Some researchers have developed their own computer programs while others have altered existing programs to model the effects of these factors on building energy use.

### Determining building energy performance using computer modeling

Rauhala (1984) developed a model to predict the effect of outside air temperature, wind, and solar access to buildings on energy consumption for heating of 3400 buildings at 24 sites in Finland. Characteristics of the building thermal properties were calculated using empirical formulas. Transmission losses were calculated according to total conductance of the building and heating degree days. Ventilation was estimated based on air pressure differences across various parts of the building. Internal energy gains were attributed to building occupants, warm water supply, lighting and other electrical devices, and solar gain from windows and walls. Solar gain was calculated by applying the transmission coefficient of the windows combined with the varying angles of solar incidence and air temperature. Incidence of solar radiation on the building was determined by developing monthly radiation maps of the sky and assigning radiation amounts based on building orientation.

Results from these studies suggested that energy consumption for heating was dependent primarily on the number of heating degree days. The most favorable structure for reduced heat consumption was one freely subjected to solar access, situated on a relatively warm site and sheltered from winds (Rauhala, 1984). The greatest limitation of this study may be oversimplification of the model, such as exclusion of reflected radiation and more specific construction details. Such omissions may lead to erroneous predictions of heating loads.

Comparison of actual energy balance measurements with computer-predicted values may provide more accurate explanations of urban climatological phenomena. Burch et al. (1975) used the National Bureau of Standards Load Determination Program (NBSLD) to compare measured heating and cooling loads with corresponding computer-predicted values. NBSLD utilizes American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE, 1985) algorithms that calculate either time-varying heating and cooling loads or variations in indoor temperature. The program requires outdoor weather data and construction details of the building. In this study by Burch et al. (1975), hourly weather data from Michigan and Georgia were used.

The structure was a 1200 sq. ft., four-bedroom townhouse exposed to simulated winter and summer temperatures inside a large environmental chamber. Activities of a six-person family were simulated; electric light bulbs represented body heat, and doors were periodically opened and closed. Inside temperature was maintained at 24°C, and appliances and furniture were present. Gas, electricity, and water were supplied to the test house and metered. Ambient air and surface temperatures, and air velocity were measured. Hourly heating and cooling input energies were measured and compared with corresponding computer-predicted values. Their results typically indicated that the NBSLD program predicted maximum loads 3.2% higher and energy requirements 1.5% lower than actual measured values. For summer cooling, predicted maximum loads were within a fraction of a percent of actual use and predicted energy requirements were 8.2% lower than measured values, possibly due to unrealistically high heat gains from the refrigeration compressor and condenser unit located in the kitchen (Burch et al., 1975).

In comparison to Rauhula's model, Burch et al.'s study was more successful in limiting site interactions by conducting the research in a environmental chamber. Also, building characteristics and conditions were more accurately simulated and measured. Results of Burch et al. show the difficulty in quantifying exterior conditions and providing accurate predictions of energy use through computer modeling. Without accurate measurements of input variables, computer modeling is not a reliable tool for researchers and may lead to erroneous predictions of building energy performance.

Modeling the effects of vegetation on building energy use

Huang et al. (1987) developed a model that quantified microclimatic changes due to the addition of urban vegetation using existing agricultural and meteorological data from various locations. This microclimate model was combined with a DOE-2.1 building energy simulation program (1980) to predict effects of microclimatic changes on cooling energy-use for a typical one-story house.

In this study, weather and building description files were modified to create a shading option in the program. Potential evapotranspiration was predicted using an empirical model originally developed for estimating water loss in crops. The model, developed by Jensen and Haise (1963), uses dry bulb temperature and solar radiation measurements. It was noted that evapotranspiration rates were more closely related to net solar radiation than to air temperature or humidity. Construction details of the simulated house were based on standard U.S. building practices and the operating and infiltration conditions were obtained from statistical surveys of current homes in warm climates. Geometry and transmissivity of trees were determined and included in the program. Two experimental conditions were considered: 1) a uniform increase in tree canopy around all sides of the house and 2) trees placed for shading only on the west and south sides of the house.

The model developed by Huang et al. (1987) predicted that a 25% increase of vegetation around the house could save between 25 and 40% of annual cooling energy use for houses in Sacramento, CA and Phoenix, AZ, respectively. Savings were attributed mostly to the effects of increased evapotranspiration with only 10 to 30% of savings attributed to shading, but the authors stated that by using a calculation for potential rather than actual evapotranspiration, predicted savings from evapotranspiration were based on maximum calculated limits. Shading from vegetation reduced irradiance on windows, walls, and roofs causing a reduction in warm air convection and infiltration.

McPherson et al. (1988) used computer simulation to study the effects of irradiance and wind reductions due to vegetation on energy performance of four residences located in Madison, WI, Salt Lake City, UT, Tucson, AZ, and Miami, FL. The building prototype was a one-story ranch home with windows representing 12% of the floor area. Data for inside and outside temperature differences, wind speed and empirical constants were used in MICROPAS (1985), a microcomputer energy analysis program, to calculate hourly infiltration. Building constants were based on coefficients selected for structures of similar construction. Irradiance reductions were modeled using a combination of MICROPAS (1985) and SPS (Shadow Pattern Simulator) (McPherson et al., 1985), a computer program that simulates shade cast from plants on buildings.

Results demonstrated that space cooling was most affected by roof and west wall shading whereas heating costs were mostly affected by south and east wall shading. In hot climates, dense shade reduced annual space-cooling costs by 53 to 61%, but increased heating costs in cold climates. A reduction in wind also affected energy costs. A 50% wind reduction lowered annual heating costs by 11% in Madison and 9% in Salt Lake City, but increased annual cooling costs by 23 and 17% in Tucson and Miami.

## Summary

Through the use of computer modeling, researchers have been able to predict energy performance of a building and demonstrate changes in energy fluxes due to addition of vegetation around a structure. In warmer climates, shading and evapotranspiration from trees have a significant effect on structural space cooling, while in colder climates vegetative windbreaks may provide significant savings in heating costs.

One of the more difficult tasks in computer modeling is accurately describing thermal properties of the building that is being modeled. Building specifications may be clearly defined whereas the calculations used to define thermal properties of the building may vary greatly among studies. Some researchers have compared predicted and measured values of building performances and reported differences between their results, but were not able to provide an explanation for these differences (Burch et al., 1985; Huang et al., 1987). Further research in this area may provide more accurate description of thermal properties of a modeled building and possibly reduce differences between predicted and measured results.

## Effects of Existing Urban Landscapes on Energy Use

Introducing vegetation into an urban site can provide several positive benefits such as reduction in urban heat islands and air pollution, and increased relative humidity, fresh air supply, and noise absorption (Bernatzky, 1982; Zangvil, 1982). One obvious economic effect of vegetation is reduction of building cooling costs by increasing evapotranspirational cooling and reducing outside air temperatures, irradiance on exterior walls, and air infiltration rates. Researchers have studied and compared the effects of various existing landscapes on these factors in different climates, enabling prediction of possible energy savings and costs from these landscapes.

### Field studies

Several researchers have analyzed the effects of vegetation around residential sites and reported that strategic placement of landscaping around a building can reduce cooling requirements by: blocking solar radiation from the building, foundation, and ground; cooling microclimates near the residence through evapotranspiration; and channeling or blocking warming air flows through and around the residence ( DeWalle, 1983; Parker, 1983; Parker, 1987). In most cases, shading of east and west walls by deciduous trees provides the greatest savings in summer cooling costs but still allows irradiance to walls and windows in the winter. In addition, benefits of shading may be optimized by placement of trees and shrubs reasonably close to the residence.

The effects of vegetation on wind has been documented. Whether or not windbreaks are beneficial in reducing energy costs is partially dependent on the climate of the area. In cold climates, wind reduction next to exterior walls can reduce infiltration of cold air into the residence causing a decrease in heating costs. For example, vegetative windbreaks in the Central U.S. may reduce heating requirements 23 to 34% (Flemer III, 1976). In warmer climates, a vegetative windbreak may cause an increase in summer air temperatures by decreasing circulation near exterior walls, causing warm air to stagnate and increase wall temperatures, and thereby increasing cooling loads. Windbreaks that shade buildings and allow air to circulate next to structures may reduce cooling costs due to lower wall temperatures and decreased warm air convection (Hoyano 1988; Hutchison et al., 1983; Parker, 1981-1982; Parker, 1983).

In humid climates, increased vegetation may raise latent cooling loads of buildings from additional outside moisture, and reduce ventilation due to lowered wind speed and nighttime radiative cooling (Huang et al. 1987, Hutchison et al. 1983). This research has shown that climatic conditions for urban sites are highly variable and should be studied carefully prior to installation of vegetation, thereby allowing for more accurate predictions of possible energy savings, or losses, from the proposed landscape.

Prediction of residential landscape and energy costs

Prediction of energy savings attributable to the introduction of urban vegetation should also consider the costs of landscape installation and maintenance. For example, a landscape maintenance may require more resources than are saved in cooling and heating loads. Depending on the type of vegetation installed, the amount and costs of maintenance can vary considerably. Parker (1981-1982) conducted an energy analysis procedure of three alternative residential landscapes. The three landscapes analyzed were: 1) a grass lawn, 2) an "energy conservation" landscape containing low-maintenance and disease-resistant plants, and 3) an "urban forest" that produced extensive structural shading. Results indicated that a lawn was less energy intensive in terms of maintenance requirements than either a shrub or a five-year-old tree on an area basis, but an extensive lawn would not block incidence of solar radiation on a residence. This may increase structural cooling loads compared to a structure that would be shaded by shrubs and trees. Therefore grass may have greater landscape and structural cooling costs as compared to the energy conservation and urban forest landscape. In addition, maintenance of lawns may contribute significant pollutants such as exhaust and noise pollution to the local environment. The energy conservation landscape minimized consumption of resources as well as negative impacts on the environment. The benefits of this landscape was maximized with vegetation planted close to the residence for shading and by using native plant species. The urban forest landscape used minimal amounts of fossil fuels for maintenance and led to reductions in energy used for air conditioning.

<u>Summary</u>

An increase of vegetation in urban areas can affect both building cooling and heating costs by altering the microclimate and solar gain on exterior walls and windows. Optimal reduction in cooling costs are usually obtained by shading east and west walls and placing vegetation near structures. Wind reduction from windbreaks are most successful in reducing air infiltration during the winter, thereby reducing heating costs. In some cases, reduction of air speed in warmer climates may actually increase cooling costs. By considering all of these factors, along with an analysis of landscape costs, a planner could more accurately assess the possible economic benefits of urban vegetation. One of the ultimate aims in studies of urban climatology is the development of a model that will enable planners and builders to accurately predict the microclimatic effect of proposed vegetation around a future site.

# MATERIALS AND METHODS

## Building Construction

Three one-fourth scale structures with building specifications similar to those of new home construction were built at the Campus Agricultural Center, Tucson, AZ (Figure 1). Each structure was built in the center of a 15.3 m x 15.3 m graded, level area. Structures were 3.1 x 3.7 x .61 m, with 3.7 m-long walls facing approximately north and south and the 3.1 m-long walls facing approximately east and west. Orientation was 344°, 74°, 164°, and 254° for the north, east, south, and west walls, respectively.

Structures were erected on 10.2 cm concrete slabs with the slab edge having an overall thermal transmittance value (U-value) of 0.7 (ASHRAE). Interior framing consisted of 5.1 x 10.2 cm studs, 61 cm on center (Figure 2). Walls were constructed of 1.9 cm plywood siding on the exterior, followed by sheathing, fiberglass batt insulation, and dry wall on the interior, with a U-value of 0.49 W $m^{-2}$ $K^{-1}$. Exterior walls and overhangs were painted with light gray latex paint with measured absorptivity of 0.75.

Pitched roofs (12°) consisted of 1.3 cm plywood covered with roofing paper and asphalt shingles and had a composite

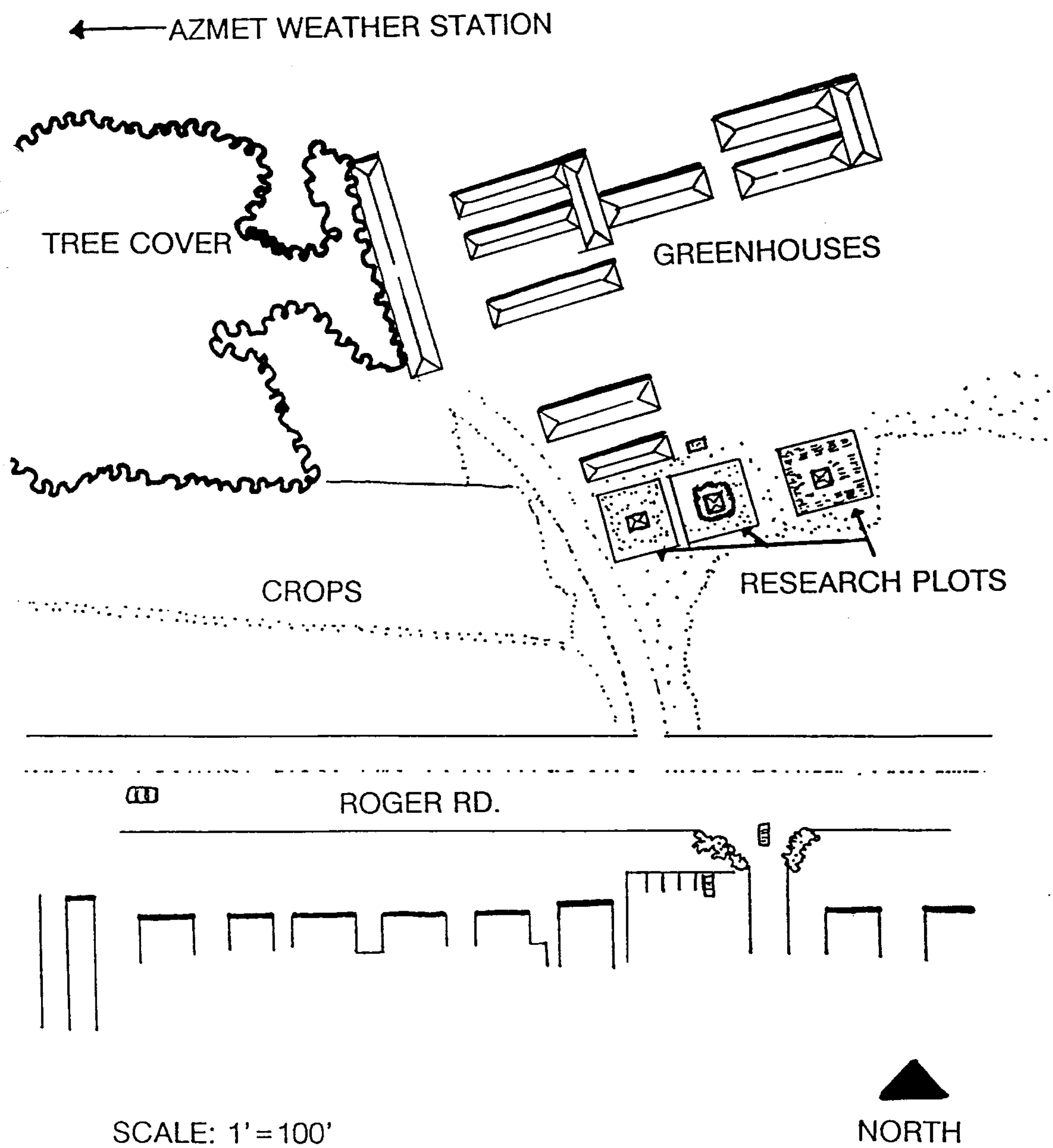
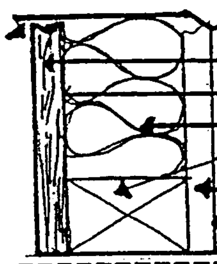


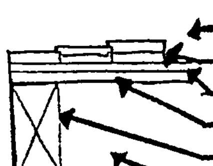

Figure 1. Site plan of research plots, Campus Agricultural Center, Tucson, AZ.

## WOOD FRAME WALL (R-11)*



| No Stud Section (75%) | | Stud Section (SW) (25%) |
|---|---|---|
| 0.97* | Outside Air Film | 0.97 |
| 4.37 | 5/8" TI-11 | 4.37 |
| .34 | 15 lb. Roofing Felt | .34 |
| 62.46 | R-11 Insulation | - |
| - | 2 x 4 16" O.C. | 24.81 |
| 2.56 | 1/2" Drywall | 2.56 |
| 3.86 | Inside Air Film | 3.86 |
| 55.93 | Total Resistance | 9.20 |
| | Composite Resistance | 65.13 |
| | Composite U-Value | 0.49 |

## ROOF AND ATTIC

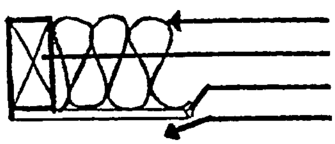


| No Joist Section (90%) | | Joist Section (JC) (10%) |
|---|---|---|
| 0.97 | Outside Air Film | 0.97 |
| 2.50 | 1/4" Asphalt Shingle | 2.50 |
| 0.34 | 15 lb. Roofing Felt | - |
| 3.52 | 1/2" Plywood | 3.52 |
| - | 2 x 4" Rafters 24 O.C. | 24.70 |
| 8.2 | Attic | 8.29 |
| 14.05 | Total Resistance | 3.97 |
| | Composite Resistance | 18.09 |
| | Composite U-Value | .49 |

* = SI units

Figure 2. Building construction detail (continued on next page).

## CEILING R-30



| No Joist Section (90%) | | Joist Section (JC) (10%) |
|---|---|---|
| 170.0 | R-30 Insulation | - |
| - | 2 x 4" Joists 24" O.C. | 24.70 |
| 2.56 | 1/2" Drywall | 2.56 |
| 4.37 | Inside Air Film | 4.37 |
| 159.55 | Total Resistance | 2.91 |
| | Composite Resistance | 28.60 |
| | Composite U-Value | .20 |

## SLAB - ON GRADE

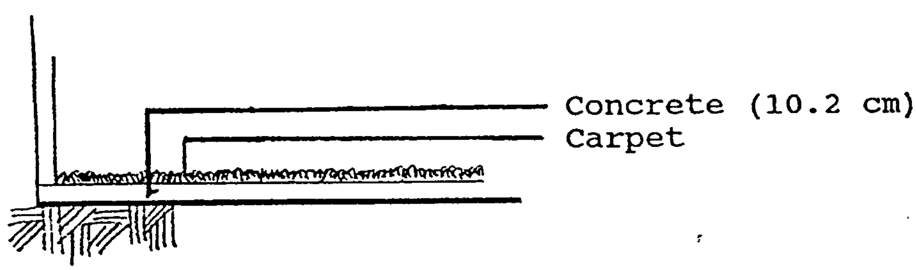



Figure 2. Building construction detail.

U-value of 1.78 W $m^{-2}K^{-1}$ and measured absorptivity of 0.70 (Figure 2). Ceilings were constructed of one layer of dry wall and two layers of fiberglass batting and had a calculated composite U-value of 0.02 W $m^{-2}$ $K^{-1}$. Single-pane windows, each .31 x 1.22 m including the aluminum frame, were centered in the south, east and west walls. The 0.23 $m^2$ glazing areas had calculated U-values of 9 W $m^{-2}$ $K^{-1}$. Access into each model was through a 0.37 x 0.49 m, 1.3 cm plywood door located in the north wall, with a U-value of 1.6 W $m^{-2}$ $K^{-1}$ and measured absorptivity of 0.75.

## Building Operating Conditions

Prior to installation of air conditioners and lighting, temperature comparisons among structures were conducted to verify site and structure similarity. Room air conditioners (Emerson Model 8LJ9H) with rated energy efficiency ratios of 7.2 and a cooling capacity of 8.4 x $10^6$ J (115 volts, 9 amps) were positioned in the center of the north wall of each structure. Thermostats were set at 25.5 °C and daily indoor temperatures were recorded for three days and statistically analyzed for verification of similar operating conditions among structures prior to treatment installation. The windows remained closed during the study.

A single 300 W bulb was installed in the center of the ceiling of each model to simulate internal heat gain from occupants, appliances, and lighting. Four occupants for the structure was assumed. In addition, carpet was installed in each model to represent thermal properties of a typical residence floor. After preliminary testing, the 300 W bulb was replaced with a 100 watt bulb due to overcompensation of internal heat gains for the structure size.

Interior mass for the structures was determined by estimating the mass of materials typically found in a full-size home and using a fraction (1\16; 1\4 x1\4) of the total amount of interior mass. Specific heat capacity was then calculated for the interior mass of the structures and fifty, 3.79 L plastic milk containers filled with water were used to represent the calculated heat capacity.

## Landscape Treatments

### Installation

Treatments were installed during June 1987 after adjusting the inside air temperatures of the three structures, with air conditioners operating, to 25.5℃. The three treatments were: 1) a seeded Bermudagrass lawn, 2) ten, 18.9 L shrubs planted 0.5 m from the east and west exterior walls and eight, 56.8 L shrubs; three planted 0.5 m from the north exterior wall and five planted 0.5 m from the south exterior wall, and 0.05 m of dark red decomposed granite covering the remaining exposed ground, and 3) the entire area covered with 0.05 m of dark red decomposed granite (232 $m^2$).

Irrigation

Irrigation of shrubs and the lawn were automated. A drip system was installed with twenty-six, 3.79 L per hour emitters with one emitter for 18.9 L shrubs and two emitters for 56.8 L shrubs. Initially, the shrubs remained in containers with approximately 1.52 cm of the container was above ground. During this period irrigation water was applied 3 hours per day (one during the day and two at night). The shrubs were removed from containers and transplanted into the ground in September and irrigation was decreased to one hour per day in November, 1987. Twelve pop-up sprinklers Toro 570 Series were installed prior to seeding of the lawn. During the summer months, irrigation was scheduled from 0300 to 0400 to achieve an irrigation rate of 0.01 m/day.

Maintenance

Maintenance included bi-monthly fertilization (Turf Royale; 21-7-4) and bi-weekly mowing and of the lawn and fertilization (9-month time release Osmocote; 20-20-20 N-P-K) and pruning of the shrubs during the warm seasons.

Shade coefficients

The amount of shade on the structure was determined by photographing and producing a slide of each wall, projecting these slides on paper, outlining and measuring unshaded areas, and dividing this measurement by the total square footage for that wall on May 24, 1988 at 10 a.m. and 2 p.m. The mean shaded fractions for the four walls were:

1. South: 0.92
2. East: 0.78
3. North: 0.25
4. West: 0.86

## Data Collection

### Temperature and energy balance components

After installation of the three landscape treatments, six days (five clear and one cloudy) were selected for data collection: June 3, July 7, August 7, October 2, 1987 and May 25 and September 18, 1988. Weather data was recorded at the site and compared to data recorded by a AZMET weather station located 360 m west of the site. Total solar radiation was measured with a Star pyranometer, wind direction with a Met-One Model 024A sensor, and net radiation with a Micromet Systems Model Q3. These measurements were automatically stored on a Campbell Scientific CR21X datalogger. Indoor and outdoor temperatures were measured every 60 minutes (except for June, 1987; temperatures were measured every 15 minutes) with Campbell Scientific Model 107 temperature probes and stored on a Campbell Scientific CR21 data logger. Stored data was transferred periodically to a cassette tape and eventually a floppy diskette for analysis. One temperature probe was suspended from the center of each structure ceiling and outdoor temperature probes were suspended underneath each northwest exterior overhang. Surface temperatures of the walls, north and south side of the roofs, and soil 5 m north and south of the structure were recorded manually with a hand-held infrared thermometer (IRT) each hour from 0600 to 2100. The IRT was checked prior to each set of hourly measurements for accuracy with an IRT calibrator. Outside air temperature and relative humidity were also recorded manually each hour with a hand-held Coreci temperature and relative humidity probe for October 2, 1987 and May 25 and September 18, 1988.

Electricity consumption

Electrical use of each structure (for air conditioner and light bulb) was recorded on a calibrated Westinghouse recording watt-hour meter provided by Tucson Electric Power Co. Data from these meters was stored on magnetic tape, transferred to a floppy diskette, and translated for analysis.

Water consumption

Lawn water use was calculated from measurements of water depth applied. Ten containers were placed similar distances apart throughout the lawn and the sprinkler system operated for 15 min. The depth of water in each container was recorded and a mean calculated. Water use for the shrub treatment was measured by operating the drip system for 15 min. and measuring the total amount of water emitted. These measurements were replicated three times and overall means calculated.

## MICROPAS Analysis

A microcomputer program developed for building design analysis, MICROPAS (Enercomp 1985), was used to predict electricity consumption of the three structures. These predictions were based on descriptive data entered by the user such as building size and construction and simplified assumptions of certain values in the program such as constant exterior film coefficients. The main calculation performed by MICROPAS is hourly calculation of building energy use based on building orientation, thermal characteristics, occupant behavior, and specific weather data. The MICROPAS weather data consists of: dry-bulb temperature, wind speed, wind direction, direct-beam radiation and diffuse radiation. Typically these data are obtained from a government weather station near the site and data for one year is summarized into seven days representing each season. For this study, hourly data were used from measurements taken for October 2, 1987, May 25, 1988, and

September 18,1988 at the study site and nearby AZMET station.

MICROPAS input data

Values for some of the building thermal characteristics are listed in the MICROPAS User Manual, while others are calculated based on model dimensions. For example, infiltration is described in the manual as tight, medium, or loose, and fractions relating to a base value for infiltration and wind and temperature infiltration are given for each category. Our models fit the description of loose infiltration and the corresponding fractions (.1, .013, .03) were entered. Areas of a structure with different thermal characteristics were defined as "zones". In our study, each structure was divided into three zones: house, attic, and soil. Descriptive data for each zone were entered into MICROPAS (see Appendix A for example of data input file).

## Statistical Analysis

Paired t-test analysis was performed on data collected for six dates: June 3, July 7, August 7, October 10, 1987, May 25, and September 18, 1988. Measurements for structure surface temperatures of six dates and measurements of outdoor temperatures, relative humidity, and electricity consumption for cooling for three dates were compared to determine if there were significant differences between treatments. In addition, comparisons were made between MICROPAS modeled and actual electricity consumption to determine if similar results were found across the three dates recorded.

# RESULTS AND DISCUSSION

## IRT Measurements

Comparison of infrared thermometer (IRT) measurements using paired t-test analysis indicated significant mean temperature differences between treatments for several surfaces. Number of temperature differences between treatments often varied across the six dates analyzed (any differences noted in the text were statistically tested).

### June 3, 1987

Measurements recorded on June 3, 1987 indicated very few differences between mean surface temperatures of the three treatments (Tables 1 and 2). This may have been due to minimal microclimatic differences around treatments since landscape (treatment) installation was completed the previous day. Comparisons between grass and shade and grass and rock treatments indicated that the grass treatment had warmer north and south soil temperatures. The immaturity of the grass for this date would explain these results; the high amount of exposed, dark soil would have greater radiation absorption properties than decomposed granite surrounding the other treatments. The rock treatment had higher mean temperatures for west and north walls, and a cooler south soil temperature compared with the shade

Table 1. Minimum, maximum, and mean temperatures of east wall, south wall and roof, west wall, north wall, roof, and soil, and south soil recorded hourly 0600 a.m. to 2200 p.m., June 3, 1987 (℃)

| Surface /Treatment | Temperature (℃) Minimum | Maximum | Mean | SD |
|---|---|---|---|---|
| East wall | | | | |
| Grass | 25.30 | 62.90 | 43.35 | 11.94 |
| Shade | 26.50 | 63.10 | 44.08 | 11.97 |
| Rock | 26.60 | 63.50 | 44.35 | 12.55 |
| South wall | | | | |
| Grass | 19.50 | 49.30 | 36.99 | 9.42 |
| Shade | 18.30 | 49.50 | 37.26 | 9.49 |
| Rock | 18.20 | 50.70 | 36.94 | 9.58 |
| South roof | | | | |
| Grass | 13.40 | 65.10 | 42.62 | 17.88 |
| Shade | 12.20 | 66.80 | 42.72 | 18.10 |
| Rock | 12.00 | 66.60 | 42.31 | 18.07 |
| West wall | | | | |
| Grass | 17.30 | 69.00 | 41.06 | 16.61 |
| Shade | 17.20 | 67.50 | 41.25 | 16.74 |
| Rock | 16.70 | 70.30 | 42.52 | 17.82 |
| North wall | | | | |
| Grass | 15.20 | 52.50 | 37.42 | 10.82 |
| Shade | 19.20 | 51.20 | 37.32 | 9.98 |
| Rock | 18.80 | 55.00 | 38.38 | 11.15 |
| North roof | | | | |
| Grass | 13.50 | 62.10 | 41.63 | 16.86 |
| Shade | 12.70 | 65.10 | 41.84 | 17.56 |
| Rock | 11.90 | 62.60 | 41.82 | 17.40 |
| North soil | | | | |
| Grass | 18.00 | 60.70 | 41.37 | 14.44 |
| Shade | 19.10 | 56.80 | 38.44 | 11.18 |
| Rock | 16.90 | 54.80 | 38.85 | 12.11 |
| South soil | | | | |
| Grass | 18.10 | 58.60 | 41.09 | 14.23 |
| Shade | 17.70 | 52.60 | 37.82 | 11.30 |
| Rock | 17.90 | 51.20 | 37.34 | 10.89 |

Table 2. T-test values for treatment comparisons of east wall, south wall and roof, west wall, north wall, roof, and soil, and south soil temperatures recorded June 3, 1987.

| | Treatment Compared | | |
|---|---|---|---|
| Surface | Grass-Shade | Grass-Rock | Shade-Rock |
| East wall | $-1.54^{z}$ | -2.00 | -0.76 |
| South wall | -1.17 | 0.12 | 0.87 |
| South roof | -0.27 | 0.74 | 1.44 |
| West wall | -0.39 | -1.83 | $-3.08^{**y}$ |
| North wall | -0.85 | -1.73 | -2.17* |
| North roof | -0.33 | -0.40 | 0.04 |
| North soil | 3.07** | 3.22** | -0.89 |
| South soil | 3.42** | 3.55** | 2.76* |

z = (-) indicates a lower mean for first treatment of t-test comparison.

y = t-test for mean differences between treatments, significant at the 5% (*) and 1% (**) levels, respectively.

treatment. Overall, shade and rock treatments had the greatest number of mean temperature differences between them for this date. This was probably due to vegetation shading the structure and reducing surface temperatures of the shade treatment.

July 6, 1987

There were several differences between mean surface temperatures on this day (Tables 3 and 4). This was possibly due to maturation of vegetation around grass and shade treatments thereby increasing evapotranspirational cooling and shading by vegetation. In addition, higher solar radiation (Appendix B) than the previous date caused increased surface warming and may have led to increased differences between treatments. The shade treatment was warmer than the grass treatment for all surfaces except the north roof and wall. Evapotranspiration from the lawn apparently provided more cooling than evapotranspiration and shade provided by shrubs around the shade treatment. In addition, ground reflectivity around the grass treatment was higher than in June due to the mature, dense lawn thereby reducing soil surface temperatures, but increasing solar heat gain on building walls. The grass treatment was warmer than and similar to the shade treatment for the north roof and wall, respectively. The rock treatment was warmer than

Table 3. Minimum, maximum, and mean temperatures of east attic and wall, south wall, roof, and soil, west wall and attic, north soil, wall, and roof recorded hourly 0600 a.m. to 2100 p.m., July 6, 1987 (℃).

| Surface /Treatment | Temperature (℃) Minimum | Maximum | Mean | SD |
|---|---|---|---|---|
| East attic | | | | |
| Grass | 10.10 | 56.90 | 37.31 | 12.63 |
| Shade | 14.20 | 63.10 | 40.31 | 14.34 |
| Rock | 13.70 | 66.70 | 43.68 | 15.38 |
| East wall | | | | |
| Grass | 9.60 | 58.60 | 36.58 | 13.77 |
| Shade (Sun)* | 13.70 | 65.80 | 40.26 | 14.53 |
| Shade (Shaded) | 13.90 | 45.60 | 34.31 | 8.83 |
| Rock | 13.70 | 68.00 | 42.08 | 15.84 |
| South wall | | | | |
| Grass | 11.50 | 40.50 | 29.64 | 9.20 |
| Shade | 16.90 | 42.90 | 33.08 | 8.56 |
| Rock | 14.70 | 49.00 | 34.97 | 11.56 |
| South roof | | | | |
| Grass | 4.40 | 67.40 | 39.18 | 21.53 |
| Shade | 3.30 | 72.20 | 40.87 | 23.70 |
| Rock | 5.40 | 67.30 | 38.61 | 21.32 |
| South soil | | | | |
| Grass | 10.90 | 36.90 | 25.49 | 7.80 |
| Shade | 14.00 | 62.20 | 40.58 | 16.23 |
| Rock | 13.70 | 61.00 | 40.04 | 15.67 |
| West wall | | | | |
| Grass | 10.20 | 67.60 | 35.88 | 18.72 |
| Shade (Sun) | 13.10 | 71.50 | 39.23 | 19.62 |
| Shade (Shaded) | 13.70 | 52.50 | 34.70 | 12.78 |
| Rock | 13.20 | 74.40 | 41.43 | 20.64 |
| West attic | | | | |
| Grass | 11.20 | 66.90 | 35.89 | 18.23 |
| Shade | 11.90 | 72.10 | 39.10 | 19.84 |
| Rock | 12.60 | 71.00 | 41.47 | 20.12 |
| North soil | | | | |
| Grass | 11.20 | 34.40 | 25.72 | 7.42 |
| Shade | 14.90 | 64.40 | 41.61 | 16.67 |
| Rock | 13.70 | 60.10 | 40.28 | 16.08 |
| North wall | | | | |
| Grass | 13.00 | 52.80 | 32.43 | 10.80 |
| Shade | 15.10 | 44.20 | 34.33 | 9.11 |
| Rock | 15.40 | 56.50 | 36.96 | 12.37 |

(Table continued on next page)

Table 3, continued

| Surface /Treatment | Temperature (℃) Minimum | Maximum | Mean | SD |
|---|---|---|---|---|
| <u>North roof</u> | | | | |
| Grass | 5.00 | 66.20 | 39.59 | 20.97 |
| Shade | 5.10 | 68.90 | 40.28 | 21.40 |
| Rock | 6.00 | 64.20 | 39.03 | 20.49 |

* = Measurements of unshaded and shaded areas of the east and west wall were recorded separately for the shade treatment.

Table 4. T-test values for treatment comparisons of east attic and wall, south wall, roof, and soil, west wall and attic, north soil, wall, and roof temperatures recorded July 6, 1987.

| Surface | Treatments Compared Grass-Shade | Grass-Rock | Shade-Rock |
|---|---|---|---|
| East Attic | -4.19**[zy] | -7.80** | -5.32** |
| East wall | -8.18** | -8.37** | -4.44** |
| South wall | -7.34** | -8.61** | -1.95 |
| South roof | -2.83* | 1.20 | 3.46** |
| South soil | -7.32** | -7.50** | 2.90* |
| West wall | -6.47** | -9.60** | -3.25** |
| West attic | -5.55** | -8.19** | -3.54** |
| North soil | -6.94** | -6.88** | 1.67 |
| North wall | -1.87 | -6.91** | -2.25* |
| North roof | -1.76 | 1.48 | 3.28** |

z = (-) indicates a lower mean for first treatment of t-test comparison.
y = t-test for mean differences between treatments, significant at the 5% (*) and 1% (**) levels, respectively.

the grass treatment for all surfaces except for south and north sides of the roof which were similar between treatments. The rock treatment was also warmer than the shade treatment for all surfaces except the south wall and north soil which had similar mean temperatures.

The shaded east and west wall surfaces of the shade treatment were compared with the unshaded east and west walls of other treatments. This was done to determine the significance of partial structural shading of walls by vegetation in reducing surface temperatures. There were differences between rock and shaded surfaces of the shade treatment only. For this date mean temperature differences occurred between eight of the ten surfaces compared between treatments.

August 6, 1987

There were fewer significant differences between the grass and shade treatments for August 6, 1987 than July 6 measurements, perhaps due to the presence of clouds during the afternoon that reduced incoming radiation (Tables 5 and 6). Reduction of radiation on treatment surfaces reduced surface temperatures and possibly influenced differences between surface mean temperatures of the treatments. The grass treatment was warmer for south wall measurements and cooler for soil and roof measurements relative to the shade

Table 5. Minimum, maximum, and mean temperatures of east attic and wall, south wall, roof, and soil, west wall and attic, north soil, wall, and roof recorded hourly 0600 a.m. to 2100 p.m., Aug. 6, 1987 (℃).

| Surface /Treatment | Temperature (℃) Minimum | Maximum | Mean | SD |
|---|---|---|---|---|
| East attic | | | | |
| Grass | 27.90 | 63.70 | 43.46 | 10.95 |
| Shade | 25.90 | 61.30 | 41.95 | 9.38 |
| Rock | 28.80 | 68.00 | 47.89 | 12.39 |
| East wall | | | | |
| Grass | 27.20 | 66.00 | 43.82 | 11.97 |
| Shade (Sun)* | 27.90 | 65.60 | 43.41 | 11.45 |
| Shade (Shaded) | 25.40 | 43.20 | 36.56 | 5.80 |
| Rock | 28.10 | 67.50 | 47.11 | 13.23 |
| South wall | | | | |
| Grass | 24.20 | 43.50 | 35.94 | 6.15 |
| Shade | 25.00 | 38.30 | 32.96 | 4.33 |
| Rock | 20.80 | 49.40 | 39.48 | 8.88 |
| South roof | | | | |
| Grass | 21.00 | 69.80 | 46.85 | 17.40 |
| Shade | 19.80 | 73.10 | 48.15 | 18.72 |
| Roof | 20.00 | 70.10 | 46.09 | 16.79 |
| South soil | | | | |
| Grass | 23.00 | 38.70 | 31.54 | 5.28 |
| Shade | 24.50 | 61.00 | 44.05 | 12.08 |
| Rock | 24.40 | 60.30 | 43.80 | 11.62 |
| West wall | | | | |
| Grass | 23.00 | 62.00 | 40.06 | 13.39 |
| Shade (Sun) | 24.20 | 55.70 | 38.83 | 11.06 |
| Shade (Shaded) | 24.20 | 45.80 | 35.24 | 6.65 |
| Rock | 24.10 | 64.70 | 43.38 | 14.61 |
| West attic | | | | |
| Grass | 22.40 | 61.60 | 39.74 | 13.17 |
| Shade | 22.90 | 61.40 | 40.00 | 12.70 |
| Rock | 23.90 | 65.50 | 44.21 | 14.51 |
| North soil | | | | |
| Grass | 22.40 | 39.50 | 30.99 | 5.02 |
| Shade | 24.80 | 60.50 | 44.16 | 11.89 |
| Rock | 23.50 | 61.50 | 44.15 | 12.68 |
| North wall | | | | |
| Grass | 24.30 | 44.40 | 35.52 | 6.27 |
| Shade | 25.40 | 43.00 | 35.79 | 5.54 |
| Rock | 20.30 | 46.80 | 37.63 | 7.98 |

(Table continued on next page)

Table 5, continued

| Surface /Treatment | Temperature (℃) Minimum | Maximum | Mean | SD |
|---|---|---|---|---|
| <u>North roof</u> | | | | |
| Grass | 20.80 | 70.00 | 45.73 | 16.47 |
| Shade | 20.50 | 70.20 | 46.81 | 16.92 |
| Rock | 24.20 | 67.00 | 45.18 | 15.66 |

* = Measurements of unshaded and shaded areas of the east and west wall were recorded separately for the shade treatment.

Table 6. T-test values for treatment comparisons of east attic and wall, south wall, roof, and soil, west wall and attic, north soil, wall, and roof temperatures recorded Aug. 6, 1987.

| Surface | Treatments Compared Grass-Shade | Grass-Rock | Shade-Rock |
|---|---|---|---|
| East Attic | 1.03 | -7.01**[z] | -3.80** |
| East wall | 0.76 | -4.83** | -4.28** |
| South wall | 3.52** | -4.57** | -4.85** |
| South roof | -2.50* | 1.37 | 3.66** |
| South soil | -7.12** | -7.44** | 0.73 |
| West wall | 1.44 | -4.91** | -4.47** |
| West attic | -0.89 | -6.19** | -5.09** |
| North soil | -7.23** | -6.52** | 0.03 |
| North wall | 0.75 | -3.77** | -2.55* |
| North roof | -2.43* | 0.88 | 2.40* |

z = (-) indicates a lower mean for first treatment of t-test comparison.

y = t-test for mean differences between treatments, significant at the 5%(*) and 1%(**) levels, respectively.

treatment on this date. Compared to the rock treatment, the grass treatment was cooler for all surfaces except the north and south roof surfaces. Similar findings were observed for July measurements. The rock treatment was warmer than the shade treatment for all east and west surfaces, and south and north walls. Interestingly, the shade treatment had warmer south and north roof temperatures. This may have been caused by vegetation of the shade treatment reducing air circulation near the surface, allowing warm air to stagnate, and thereby increasing roof surface temperatures. This process is often referred to as "heat trapping". The greatest number of differences were between grass and rock and shade and rock treatments. Results for this date indicated that the presence of vegetation, either as a lawn or as shrubs and trees, reduced the majority of mean surface temperatures enough to be significantly less than a treatment with no adjacent vegetation.

October 2, 1987

For October 2, 1987 measurements the grass treatment had warmer mean temperatures than the shade treatment for east wall, south soil, and all north surfaces (Tables 7 and 8). Warmer temperatures for the south wall of the grass treatment was probably because of no shading from

Table 7. Minimum, maximum, and mean temperatures of east attic and wall, south wall, roof, and soil, west wall and attic, north soil, wall, and roof recorded hourly 0600 a.m. to 2100 p.m., Oct. 2, 1987 (℃).

| Surface /Treatment | Temperature (℃) Minimum | Maximum | Mean | SD |
|---|---|---|---|---|
| East attic | | | | |
| Grass | 14.60 | 56.10 | 32.15 | 10.92 |
| Shade | 15.90 | 39.80 | 30.18 | 9.73 |
| Rock | 15.10 | 56.20 | 33.64 | 11.16 |
| East wall | | | | |
| Grass | 15.10 | 51.10 | 31.81 | 9.91 |
| Shade (Sun)* | 16.90 | 52.40 | 32.45 | 9.55 |
| Shade (Shaded) | 16.80 | 35.40 | 29.20 | 5.73 |
| Rock | 15.30 | 58.70 | 33.49 | 11.61 |
| South wall | | | | |
| Grass | 15.00 | 57.40 | 35.63 | 13.15 |
| Shade | 18.00 | 34.10 | 28.65 | 5.36 |
| Rock | 16.70 | 57.80 | 35.07 | 11.61 |
| South roof | | | | |
| Grass | 9.80 | 50.50 | 32.91 | 13.80 |
| Shade | 9.90 | 52.00 | 30.49 | 14.12 |
| Roof | 9.50 | 49.30 | 33.01 | 13.72 |
| South soil | | | | |
| Grass | 12.60 | 31.20 | 24.74 | 5.91 |
| Shade | 16.40 | 45.50 | 32.37 | 10.27 |
| Rock | 15.60 | 45.00 | 31.57 | 10.17 |
| West wall | | | | |
| Grass | 13.90 | 61.00 | 34.62 | 16.14 |
| Shade (Sun) | 17.10 | 53.40 | 32.76 | 11.81 |
| Shade (Shaded) | 16.60 | 46.50 | 31.18 | 9.83 |
| Rock | 15.50 | 66.60 | 37.24 | 17.26 |
| West attic | | | | |
| Grass | 13.90 | 57.50 | 34.51 | 15.55 |
| Shade | 16.00 | 62.50 | 35.02 | 15.41 |
| Rock | 14.90 | 63.30 | 36.90 | 17.13 |
| North soil | | | | |
| Grass | 11.80 | 31.50 | 24.93 | 5.84 |
| Shade | 17.40 | 43.30 | 30.40 | 8.86 |
| Rock | 15.30 | 44.80 | 31.84 | 10.23 |
| North wall | | | | |
| Grass | 15.00 | 34.60 | 27.12 | 6.07 |
| Shade | 17.20 | 35.00 | 28.38 | 5.69 |
| Rock | 16.00 | 36.90 | 29.02 | 6.70 |

(Table continued on next page)

Table 7, continued

| Surface /Treatment | Temperature (℃) Minimum | Maximum | Mean | SD |
|---|---|---|---|---|
| <u>North roof</u> | | | | |
| Grass | 10.00 | 47.90 | 30.31 | 12.05 |
| Shade | 9.70 | 48.60 | 31.46 | 13.15 |
| Rock | 9.60 | 45.60 | 30.26 | 12.15 |

* = Measurements of unshaded and shaded areas of the east and west wall were recorded separately for the shade treatment.

Table 8. T-test values for treatments comparisons of east attic and wall, south wall, roof, and soil, west wall and attic, north soil, wall, and roof temperatures recorded Oct. 2, 1987.

| Surface | Treatments Compared Grass-Shade | Grass-Rock | Shade-Rock |
|---|---|---|---|
| East Attic | -1.13 | 3.75**[z] | 2.14* |
| East wall | -2.71* | 3.33** | 1.79 |
| South wall | -2.48* | -0.46 | 2.56* |
| South roof | -1.44 | 0.41 | 1.60 |
| South soil | -6.29** | 5.87** | -1.86 |
| West wall | 1.26 | -6.86** | 2.75* |
| West attic | 0.53 | 5.17** | 1.86 |
| North soil | -4.85** | 5.61** | 1.73 |
| North wall | -5.39** | 8.05** | -2.36* |
| North roof | -3.15** | 0.18 | 3.12** |

z = (-) indicates a lower mean for first treatment of t-test comparison.

y = t-test for mean differences between treatments, significant at the 5%(*) and 1%(**) levels, respectively.

vegetation. The grass treatment was also cooler than several rock treatment surfaces; east and west walls and attics, south and north soil, and north wall. Roof temperatures between grass and rock treatments were similar as was the case for the two previous dates. The shade treatment had cooler east attic, south wall, west and north wall temperatures than the rock treatment. The greatest number of differences in mean surface temperatures were observed between grass and rock treatments. Shade and rock treatments had the fewest number of differences in mean surface temperatures.

May 25, 1988

The shade treatment had warmer east attic, south roof and soil, and north soil temperatures than the grass treatment on May 25, 1988 (Tables 9 and 10). South wall measurements were similar for the grass and shade treatments, which seemed unusual since data for the three previous dates showed lower mean temperatures for the south wall of the shade treatment. This may have been a result of: 1) higher early morning temperatures around the shade treatment resulting from warm air trapped near the wall, in combination with 2) small temperature differences between treatments for this day (Table 10). These factors may have offset the effect of cooler daytime temperatures of the

Table 9. Minimum, maximum, and mean temperatures of east attic and wall, south wall, roof, and soil, west wall and attic, north soil, wall, and roof recorded hourly 0500 a.m. to 2100 p.m., May 25, 1988 (℃).

| Surface /Treatment | Temperature (℃) Minimum | Maximum | Mean | SD |
|---|---|---|---|---|
| East Attic | | | | |
| Grass | 13.00 | 56.30 | 37.41 | 11.95 |
| Shade | 15.70 | 64.50 | 41.17 | 13.78 |
| Rock | 15.90 | 64.80 | 43.14 | 13.81 |
| East Wall | | | | |
| Grass | 12.60 | 60.10 | 37.38 | 13.80 |
| Shade (Sun)* | 15.70 | 64.00 | 39.30 | 14.86 |
| Shade (Shaded) | 17.00 | 41.50 | 32.35 | 7.47 |
| Rock | 16.70 | 65.40 | 42.22 | 14.86 |
| South Wall | | | | |
| Grass | 13.30 | 38.90 | 30.26 | 8.68 |
| Shade | 18.90 | 38.40 | 31.21 | 6.61 |
| Rock | 16.70 | 46.60 | 35.46 | 10.06 |
| South Roof | | | | |
| Grass | 9.40 | 63.60 | 40.62 | 19.46 |
| Shade | 9.20 | 71.30 | 43.26 | 21.94 |
| Roof | 9.90 | 64.00 | 40.41 | 19.01 |
| South Soil | | | | |
| Grass | 12.30 | 37.00 | 27.28 | 7.96 |
| Shade | 17.10 | 58.20 | 40.74 | 14.09 |
| Rock | 17.60 | 59.40 | 39.91 | 13.82 |
| West Wall | | | | |
| Grass | 13.30 | 66.20 | 37.33 | 17.08 |
| Shade (Sun) | 16.70 | 62.60 | 37.11 | 15.59 |
| Shade (Shaded) | 16.90 | 47.80 | 32.28 | 9.20 |
| Rock | 16.40 | 70.20 | 40.55 | 17.79 |
| West Attic | | | | |
| Grass | 13.30 | 66.50 | 38.00 | 16.81 |
| Shade | 15.80 | 57.20 | 35.69 | 12.44 |
| Rock | 15.90 | 71.20 | 40.87 | 17.82 |
| North Soil | | | | |
| Grass | 12.20 | 37.10 | 27.07 | 8.15 |
| Shade | 18.10 | 54.90 | 39.58 | 12.73 |
| Rock | 18.70 | 56.10 | 38.93 | 12.48 |
| North Wall | | | | |
| Grass | 14.60 | 46.90 | 32.96 | 9.27 |
| Shade | 17.60 | 41.80 | 34.16 | 7.75 |
| Rock | 16.60 | 49.90 | 35.90 | 10.07 |

(Table continued on next page)

Table 9, continued

| Surface /Treatment | Temperature (°C) Minimum | Maximum | Mean | SD |
|---|---|---|---|---|
| <u>North Roof</u> | | | | |
| Grass | 9.50 | 64.30 | 41.04 | 18.61 |
| Shade | 10.10 | 68.50 | 41.79 | 20.03 |
| Rock | 9.90 | 61.60 | 40.31 | 18.30 |

* = Measurements of unshaded and shaded areas of the east and west walls were recorded separately for the shade treatment.

Table 10. T-test values for treatment comparisons of east attic and wall, south wall, roof, and soil, west wall and attic, north soil, wall, and roof temperatures recorded May 25, 1988.

| Surface | Treatments Compared Grass-Shade | Grass-Rock | Shade-Rock |
|---|---|---|---|
| East Attic | -4.91** | -10.22**[z] | -3.74** |
| East wall | 4.20** | -11.90** | -6.22** |
| South wall | 1.09 | -11.05** | -3.61** |
| South roof | -3.99** | 0.63 | 3.55** |
| South soil | -8.56** | -8.31** | 2.12* |
| West Wall | 0.26 | -7.87** | -3.18** |
| West Attic | 1.66 | -6.72** | -3.09** |
| North Soil | -10.74** | -8.62** | 0.61 |
| North Wall | -1.46 | -7.24** | -2.03 |
| North Roof | -1.42 | 1.73 | 2.16* |

z = (-) indicates a lower mean for first treatment of t-test comparison.
y = t-test for mean differences between treatments, significant at the 5%(*) and 1%(**) levels.

shaded south wall, explaining a mean temperature similar to the grass treatment. The rock treatment was warmer than the grass treatment for all surfaces except the south and north roofs. Similar results for roof temperatures were also observed on July 6, August 6, and October 2. Compared to the shade treatment, the rock treatment had warmer east and west surfaces and south wall, but had cooler south and north roof temperatures. Cooler roof temperatures were also observed for July and August. Heat trapping may have been the cause of the warmer roof temperatures of the shade treatment. The number of mean temperature differences was greatest for grass-rock and shade-rock treatment comparisons and smallest for grass-shade treatment comparisons.

<u>September 18, 1988</u>

On September 18, 1988 the grass treatment had cooler north wall, north roof, and south and north soil temperatures than the shade treatment (Tables 11 and 12). There was no difference between south wall temperatures of the shade and grass treatments. These results suggest that cooling effects from evapotranspiration and shading of the shrubs were similar to the cooling effect of evapotranspiration from the grass. In comparison to the rock treatment, the grass treatment was cooler for all surfaces except the south and north roof, as was the case

Table 11. Minimum, maximum, and mean temperatures of east attic and wall, south wall, roof, and soil, west wall and attic, north soil, wall, and roof recorded hourly 0600 a.m. to 2300 p.m., Sept. 18, 1988 (℃).

| Surface /Treatment | Temperature (℃) Minimum | Maximum | Mean | SD |
|---|---|---|---|---|
| East attic | | | | |
| Grass | 10.50 | 50.40 | 31.68 | 11.67 |
| Shade | 12.90 | 45.30 | 30.59 | 9.41 |
| Rock | 11.20 | 66.40 | 39.02 | 14.11 |
| East wall | | | | |
| Grass | 10.90 | 51.60 | 31.24 | 12.33 |
| Shade | 13.90 | 36.40 | 27.85 | 7.17 |
| Rock | 12.30 | 55.80 | 35.79 | 13.95 |
| South wall | | | | |
| Grass | 12.60 | 44.20 | 30.17 | 10.51 |
| Shade | 15.40 | 37.20 | 28.96 | 7.45 |
| Rock | 12.50 | 54.90 | 36.25 | 13.33 |
| South roof | | | | |
| Grass | 5.30 | 58.40 | 32.82 | 18.77 |
| Shade | 3.00 | 69.50 | 33.01 | 28.24 |
| Roof | 4.50 | 62.60 | 33.35 | 19.92 |
| South soil | | | | |
| Grass | 10.90 | 33.20 | 23.29 | 8.72 |
| Shade | 13.80 | 51.60 | 33.57 | 12.58 |
| Rock | 13.20 | 52.10 | 33.15 | 13.07 |
| West wall | | | | |
| Grass | 11.20 | 62.00 | 32.68 | 18.01 |
| Shade | 14.90 | 45.60 | 28.85 | 8.86 |
| Rock | 11.60 | 65.50 | 36.78 | 19.27 |
| West attic | | | | |
| Grass | 10.70 | 61.80 | 32.53 | 17.95 |
| Shade | 11.80 | 40.00 | 29.15 | 9.49 |
| Rock | 10.40 | 67.00 | 36.58 | 19.11 |
| North soil | | | | |
| Grass | 10.50 | 34.70 | 23.16 | 9.07 |
| Shade | 17.70 | 49.20 | 33.15 | 11.65 |
| Rock | 14.40 | 50.60 | 32.71 | 11.98 |
| North wall | | | | |
| Grass | 11.90 | 36.50 | 26.40 | 8.67 |
| Shade | 14.10 | 38.00 | 28.67 | 7.73 |
| Rock | 12.30 | 39.00 | 29.16 | 9.19 |
| North roof | | | | |
| Grass | 5.00 | 55.00 | 31.10 | 17.84 |

(Table continued on next page)

Table 11, continued

| Surface /Treatment | Temperature (℃) Minimum | Maximum | Mean | SD |
|---|---|---|---|---|
| North roof | | | | |
| Shade | 3.30 | 62.00 | 33.92 | 20.71 |
| Rock | 4.90 | 55.60 | 30.76 | 17.60 |

Table 12. T-test values for treatment comparisons of east attic and wall, south wall, roof, and soil, west wall and attic, north soil, wall, and roof temperatures recorded Sept. 18, 1988.

| Surface | Treatments Compared Grass-Shade | Grass-Rock | Shade-Rock |
|---|---|---|---|
| East attic | 0.52 | -2.57* | -2.46* |
| East wall | 1.37 | -8.48** | -2.79* |
| South wall | 0.86 | -7.72** | -3.49** |
| South roof | -0.07 | -0.76 | -0.13 |
| South soil | -8.71** | -7.59** | 1.52 |
| West wall | 1.45 | -3.83** | -2.76* |
| West attic | 1.34 | -4.40** | -2.74* |
| North soil | 2.28* | -9.02** | 1.02 |
| North wall | -6.10** | -6.44** | -1.13 |
| North roof | -3.66** | 0.78 | 3.58** |

z = (-) indicates a lower mean for first treatment in comparison.

y = t-test for mean differences between treatments, significant at the 1% (**) and 5% (*) levels.

for the four previous dates. The rock treatment was warmer than the shade treatment for all surfaces except for the south roof, north wall and soil temperatures. North and south soils of the rock and shade treatments were similar, as was the case in the four previous dates. The grass and rock treatments had the greatest number of differences between them overall whereas grass and shade treatments had the fewest number of differences between them (Table 12).

Summary

From these results, it can be concluded that some surface differences between treatments occurred on the majority of the six dates measured. For example, the north and south soils were cooler for the grass treatment than other treatments on all dates except June 3, 1987. This exception was probably due to increased radiation absorption of exposed soil resulting from lack of sufficient grass cover.

The shade treatment had cooler south wall temperatures than one or both of the other treatments on four of the six dates as a result of shading from dense vegetation. For five of the six dates the grass and shade treatments had cooler east, west, and north wall temperatures than the rock treatment. The shade treatment had cooler east walls than the grass treatment for May and October measurements. The grass treatment had cooler east and west walls for July measurements.

Roof temperatures were similar between grass and rock treatments for all dates, probably since no roof shading was present on these treatments. In addition, evapotranspirational cooling from the lawn apparently did not greatly reduce roof temperatures of the grass treatment. In comparison to the shade treatment, rock and grass treatment roofs were cooler for several dates. These results may be explained by a phenomena caused by vegetation near treatment surfaces. Vegetation behaves like a screen and reduces air circulation near the surfaces thereby trapping warm air near surfaces. This lengthens the time of increased air and surface temperatures.

The most important findings from these measurements is that the presence of shrubs or a grass lawn around a treatment had a significant cooling effect on several treatment surfaces compared with a treatment with no adjacent vegetation. It also appears that the maturity of vegetation and climatic conditions influence the amount of difference between treatment surface temperatures. For example, the number of differences between treatments increased as vegetation became denser and taller. Also, measurements taken on a cloudy day (August 6) did not have as many significant differences between treatments as compared to measurements taken on a clear day during the same season.

## Measurements of Relative Humidity and Outside Air Temperature

Measurements of outside air temperature and relative humidity around each treatment indicated differences between treatments on October 2, 1987, May 25 and September 18, 1988. Measurements recorded on October 2 were all significantly different between treatments (Tables 13 and 14). The grass model had the highest mean for relative humidity (13.7%) and lowest mean for outside temperature (25.2 ℃) whereas the rock treatment had the lowest relative humidity (11.2%) and the highest outside air temperature (26.4℃). Similar differences in relative humidity between treatments were observed for May 25, 1988 (Tables 15 and 16). Mean outside temperature was lowest for grass whereas rock and shade treatments had similar outside temperatures. The vegetation was denser in May than October which may have caused increased heat trapping and higher outside air temperatures.

The grass treatment had the highest daily mean for relative humidity on May 25, 1988 (20.6%) whereas the rock

Table 13. Minimum, maximum, and mean values of relative humidity and outside temperature for each treatment recorded hourly 0600 a.m. to 2100 p.m. Oct. 2, 1987.

| | Treatments | | |
|---|---|---|---|
| Variable | Grass | Shade | Rock |
| <u>Relative humidity</u> (%) | | | |
| Minimum | 13.70 | 12.10 | 11.20 |
| Maximum | 41.40 | 32.40 | 30.70 |
| Mean | 19.39 | 17.35 | 15.30 |
| <u>Outside temperature</u> (℃) | | | |
| Minimum | 25.20 | 26.20 | 26.40 |
| Maximum | 33.80 | 34.70 | 35.50 |
| Mean | 30.68 | 30.98 | 31.40 |

Table 14. T-test values for treatment comparisons of relative humidity and outside temperature recorded Oct. 2, 1987.

| Treatments Compared | Relative Humidity | Outside Temperature |
|---|---|---|
| Grass-Shade | 3.39**[z] | -2.33* |
| Grass-Rock | 6.26** | -2.97** |
| Shade-Rock | 6.53** | -2.71* |

z = t-test for mean differences between treatments, significant at the 5% (*) and 1% (**) levels, respectively.

Table 15. Minimum, maximum, and mean values of relative humidity and outside temperature for each treatment recorded hourly 0500 a.m. to 2100 p.m., May 25, 1988.

| Variable | Treatment | | |
| --- | --- | --- | --- |
| | Grass | Shade | Rock |
| Relative humidity (%) | | | |
| Minimum | 11.10 | 10.10 | 9.60 |
| Maximum | 42.50 | 40.30 | 37.50 |
| Mean | 20.64 | 18.35 | 16.84 |
| SD | 9.39 | 8.84 | 8.32 |
| Outside temperature(℃) | | | |
| Minimum | 17.70 | 18.60 | 18.90 |
| Maximum | 39.20 | 39.40 | 38.60 |
| Mean | 32.41 | 32.42 | 32.54 |
| SD | 6.00 | 6.16 | 6.16 |

Table 16. T-test values for treatment comparisons of relative humidity and outside temperature recorded May 25, 1988.

| Treatments compared | Relative humidity | Outside temperature |
| --- | --- | --- |
| Grass-Shade | 3.17**[z] | -0.05 |
| Grass-Rock | 5.54** | -0.45 |
| Shade-Rock | 5.23** | -0.71 |

z = t-test for mean differences between treatments, significant at the 5%(*) and 1% (**)levels, respectively.

treatment had the lowest (16.8%). Outside air temperatures were surprisingly similar for all treatments for this date, ranging between 32.41 to 32.54℃. Relative humidity measurements were similar between the grass and shade treatments for September 18, 1988 and both of these treatments had higher relative humidity than the rock treatment (Tables 17 and 18). The grass treatment had a lower outside air temperature than shade and rock treatments whereas the shade treatment had a higher outside temperature than the rock treatment. Again, higher temperatures around the shade treatment may have been due to heat trapping from the dense vegetation.

Summary

Results from these three dates indicated that there were more significant differences between relative humidity than outside temperature measurements between treatments. In addition, relative humidity was higher for treatments surrounded by vegetation compared to the treatment without vegetation for all dates. This was probably due to evapotranspirational cooling by plant material. The grass treatment had the greatest levels of relative humidity and probably evapotranspiration because of greater leaf area and irrigation levels than the shade treatment. Higher temperatures due to the lack of evaporative cooling in the rock treatment may have been exacerbated by advection of

Table 17. Minimum, maximum, and mean values of relative humidity and outside temperature for each treatment recorded hourly 0600 a.m. to 2300 p.m., Sept. 18, 1988.

| Variable | Treatment | | |
|---|---|---|---|
| | Grass | Shade | Rock |
| <u>Relative humidity</u> (%) | | | |
| Minimum | 7.50 | 6.40 | 4.50 |
| Maximum | 57.00 | 41.70 | 39.00 |
| Mean | 18.94 | 17.72 | 14.45 |
| SD | 13.50 | 11.33 | 10.95 |
| <u>Outside temperature</u> (°C) | | | |
| Minimum | 14.00 | 14.20 | 14.80 |
| Maximum | 38.30 | 40.10 | 38.50 |
| Mean | 28.82 | 29.59 | 29.36 |
| SD | 7.81 | 8.76 | 8.07 |

Table 18. T-test values for treatment comparisons of relative humidity and outside temperature recorded Sept. 18, 1988.

| Treatments Compared | Relative humidity | Outside temperature |
|---|---|---|
| Grass-Shade | 1.09 | -2.19* |
| Grass-Rock | 4.28**[z] | -1.49 |
| Shade-Rock | 6.40** | 0.68 |

z = t-test for mean differences between treatments, significant at the 5% (*) and 1% (**) levels, respectively.

sensible heat from drier surfaces nearby (greenhouses, bare soil). The treatments surrounded by vegetation had relative humidities that were similar on September 18, 1988. For the two remaining dates (October and May) the grass treatment had higher relative humidities.

Outside temperature was only significantly different for four of the nine comparisons between treatments. On two of the dates the shade treatment had warmer outside temperatures than the grass treatment. Interestingly, the rock treatment was only warmer than the grass or shade treatments on one of the dates. This may be due to cooler night temperatures around the rock treatment causing the mean outside temperature to be lower and therefore similar to that of other treatments. It has been noted in several studies (Suckling, 1980; Wilmers, 1988; Yap and Oke, 1974a) that evapotranspiration from plants causes a reduction in outside air temperatures. In our study plant evapotranspiration had a more significant effect on relative humidity levels than outside air temperatures near structures. Plant architecture may have the most significant effect on outside air temperatures near structures by reducing air flow around structures and blocking re-radiation of building heat gain during the night.

Measurements of Structure Electrical Consumption

Significant differences were observed between treatments for the three dates electrical consumption was recorded (Tables 19 and 20). On October 2, 1987 grass and shade treatments used a similar amount of electricity for cooling and used less than the rock treatment. On the second date, May 25, 1988, the grass treatment used significantly less electricity than other treatments and the shade treatment used less electricity than the rock treatment. On September 18, 1988 the shade treatment used less electricity than grass and rock treatments and the grass treatment used less than the rock treatment.

Differences between outside air temperatures around treatments did not relate to differences between their electrical use. For example, compared to the shade treatment, the grass treatment had a lower outside temperatures for October and September measurements, but had lower electrical consumption than the shade treatment for May measurements only. On this date outside temperatures of the shade and grass treatments were not significantly different. AZMET weather data for these three dates may offer an explanation for these findings (Appendix B). May 25 had the greatest value for evapotranspiration for the

Table 19. Minimum, maximum and mean electrical use recorded on Oct. 2, 1987 and May 25 and Sept. 18, 1988 (wh).

| | Date | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | October 2 | | | May 25 | | | September 18 | | |
| Treatment | Min | Max | Mean | Min | Max | Mean | Min | Max | Mean |
| Grass | 9 | 273 | 144 | 4 | 244 | 112 | 4 | 354 | 122 |
| Shade | 33 | 268 | 143 | 9 | 268 | 133 | 9 | 258 | 105 |
| Rock | 71 | 359 | 201 | 10 | 360 | 175 | 10 | 427 | 177 |

Table 20. T-test values of comparisons between recorded electrical use for three treatments on Oct. 2,1987, and May 25 and Sept. 18, 1988.

| Treatments Compared | Date: October 2 | May 25 | September 18 |
|---|---|---|---|
| Grass & Shade | .38 | -6.70** | 2.13* |
| Grass & Rock | -12.05**[z] | -8.30** | -9.33** |
| Shade & Rock | -10.42** | -7.68** | -6.21** |

z = t-test for mean differences between treatments, significant at the 5% (*) and 1% (**) levels, respectively.

three dates; evapotranspirational cooling from the lawn may have been large enough to significantly lower electrical consumption. For September measurements the shade treatment used less electricity than the grass treatment. Potential evapotranspiration for September 18 was lower than the other two dates (Appendix A). Therefore evapotranspirational cooling from the lawn may have been substantially reduced. Consequently, surface shading from vegetation may have had a relatively greater effect than evapotranspirational cooling on reducing electrical consumption for this date.

## Modeling Electrical Consumption Using MICROPAS

Comparison of computer-predicted energy use indicated differences between treatments for October 2, 1987 and May 25 and September 18, 1988 (Tables 21 and 22). For all dates, the shade treatment had lower predicted consumption than grass and rock treatments and the grass treatment had lower consumption than the rock treatment (Table 22). In addition, comparison between modeled and measured electrical use of each treatment showed significant differences for six of the nine comparisons (Table 23). These differences may be a result of factors such as long-wave radiation and evapotranspiration not being accurately quantified and included in MICROPAS calculations. Comparisons between

Table 21. Minimum, maximum, mean values of predicted electrical use for Oct. 2, 1987, and May 25 and Sept. 18, 1988 based on modeled energy performance by MICROPAS (wh).

| | Date | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | October 2 | | | May 25 | | | September 18 | | |
| Treatment | Min | Max | Mean | Min | Max | Mean | Min | Max | Mean |
| Grass | 82 | 273 | 179 | 0 | 246 | 123 | 0 | 211 | 83 |
| Shade | 86 | 224 | 154 | 2 | 173 | 90 | 0 | 162 | 59 |
| Rock | 89 | 288 | 187 | 7 | 251 | 131 | 0 | 225 | 95 |

Table 22. T-test values of comparisons between MICROPAS predicted electrical use for three treatments on Oct. 2, 1987, and May 25 and Sept. 18, 1988.

| Comparison | October 2 | May 25 | September 18 |
|---|---|---|---|
| Grass-Shade | 5.09** | 4.53** | .25** |
| Grass-Rock | 9.40** | 10.44** | 5.37** |
| Shade-rock | 6.23** | 6.17** | 5.23** |

z = t-test for mean differences between treatments, significant at the 1% (**) level.

Table 23. T-test values of comparisons between actual and MICROPAS predicted electrical use for three treatments on Oct. 2, 1987, and May 25 and Sept. 18, 1988.

| | Date | | |
|---|---|---|---|
| Treatments | October 2 | May 25 | September 18 |
| Grass | 5.57**[z] | 0.89 | 3.79** |
| Shade | 1.63 | 4.72** | 6.69** |
| Rock | 1.47 | 4.79** | 6.29** |

z = t-test for mean differences between treatments, significant at the 1% (**) level.

modeled and measured electrical use of shade and rock treatments for October 2, 1987 and the grass treatment for May 25, 1988 were similar. For all comparisons predicted results were less than the actual results (Table 23).

Summary

Modeled and actual electrical consumption was less for treatments surrounded by vegetation. Modeled electrical use was less for the shade treatment than other treatments for all three dates. Actual electrical use of the shade treatment was less than the grass treatment for only one date. It was also observed that measured electrical use had more fluctuations between hourly measurements compared to predicted electrical use. This may indicate that actual measurements reflected greater sensitivity to climatic conditions than did modeled MICROPAS measurements. For example, the measured electrical use indicated that different landscapes such as shrubs with decomposed granite and a grass lawn may have similar effects on reduction of electrical consumption. MICROPAS does not include long-wave radiation in the calculation of energy use. Possibly if actual values for this energy component were included there may be a smaller predicted difference between the grass and shade treatments. Another possible explanation of the inconsistency between predicted and actual electrical use is unpredictable interactions between daily climatic conditions such as relative humidity, outside air temperature, and wind speed around structures. They may cause one landscape to have a more significant effect on electrical use for structural cooling compared to the other landscape.

## Cost Determination

Costs of electricity for air conditioning and irrigation water were calculated for each treatment for three dates (Table 24). On October 2, 1987 irrigation for shrubs was approximately four times greater than typical irrigation levels. This was because the shrubs were containerized and required additional water. Therefore, the rock treatment had the lowest total costs for this date only. For May and September measurements the shade treatment had the lowest total costs. On these dates the shrubs were irrigated at moderate levels since they were removed from containers and transplanted the previous November. Irrigation for the shade treatment was 45%, 19%, and 26% of total costs for the three dates. Air conditioning cost for the shade treatment was 31%, 26%, and 41% lower than the rock treatment for the three dates. The grass treatment had the highest total costs for all three dates (Table 24). Irrigation cost was 84%, 87%, and 86% of total costs for the grass treatment for these three dates. For air conditioning cost the grass treatment was 28%, 38%, and 32% lower than the rock treatment for the three dates (Table 24).

Table 24. Estimated air conditioning and water costs for rock, shade, and grass treatments for Oct. 2, 1987, and May 25 and Sept. 18, 1988.

| Date | Treatments | AC Cost[x] | Water cost[y] | Total |
|---|---|---|---|---|
| | | ($/day) | | |
| October 2 | Grass | 0.28 | 1.45 | 1.73 |
| | Shade | 0.27 | 0.22 | 0.49 |
| | Rock | 0.39 | 0 | 0.39 |
| May 25 | | | | |
| | Grass | 0.21 | 1.45 | 1.66 |
| | Shade | 0.25 | 0.06 | 0.31 |
| | Rock | 0.34 | 0 | 0.34 |
| September 18 | | | | |
| | Grass | 0.23 | 1.45 | 1.68 |
| | Shade | 0.20 | 0.07 | 0.27 |
| | Rock | 0.34 | 0 | 0.34 |

x = Based on $0.08/kwh
y = Based on $1.47/1000 cubic ft.

## CONCLUSIONS

This study indicated that altering landscapes adjacent to buildings may have a significant effect on energy use of these buildings in a warm desert region. Results showed that the treatments surrounded by vegetation experienced significant reduction in their electrical consumption compared to the treatment without vegetation. It has been noted previously by other researchers that the presence of plants may modify variables such as relative humidity, solar heat gain, long-wave radiation gain, and heat loss by convection (Hutchison, 1983, Jones and Suckling, 1983; and Oke, 1978). These microclimatic modifications may directly influence the energy performance of a building. This study confirmed that relative humidity and outside air temperatures around treatments and treatment surface temperatures are modified by microclimatic changes attributable to landscaping around each treatment.

Several researchers have also noted the important effects of evapotranspiration on urban climates, especially under irrigated conditions (Kalanda et al., 1980; Yap and Oke, 1974). The shade treatment in this study experienced evapotranspirational cooling from shrubs but this did not appear to have as great of an effect on increasing relative humidity as did the grass lawn. The lower level of evapotranspiration around the shrub-dominated shade treatment was probably due to lower irrigation rates and transpiring surface area compared to the grass treatment.

Significant surface temperature differences were observed between treatments due to different landscape elements of the treatment microclimates. Nixon et al. (1980) noted marked differences in surface temperatures of various landscape elements such as driveway, asphalt, and vegetation. Recording the number of surface temperature differences between treatments may be useful for predicting possible reductions in electrical consumption for structural cooling. For example, in this study the rock treatment had the greatest number of warmer surfaces and used the greatest amount of electricity for cooling for all three dates compared to the treatments with vegetation. Use of this technique for predicting differences in electrical use should be tested further with replication of surface temperature and electrical use measurements of treatments in various sites over several dates.

Some of the differences between the shade and grass treatments were due to increased temperatures on shaded surfaces of the shade treatment. This may be explained by the location of shrubs. Close proximity of vegetation to a treatment has been shown to cause an increase of surface temperatures due to poor air circulation and eventually stagnated warm air during the day ( "heat trapping"). By planting vegetation a greater distance from the treatment there may be more air circulation and consequently, lower surface temperatures.

Even after considering these differences in the variables measured there was not a consistent difference in electrical use between grass and shade treatments. Similar electrical use of these treatments indicates the effectiveness of shading over evapotranspirational cooling in reducing cooling costs, considering that the lawn had a much greater leaf surface area (with a leaf area index above 1.0) than the shrubs. Furthermore, usefulness of evapotranspiration cooling in lowering electrical consumption may be greatly reduced during high humidity conditions. Calculation of irrigation water costs for grass also indicated the ineffectiveness of this large area of lawn for reducing total energy use. A typical Tucson residence would not have such a large ratio of lawn area to building floor area. It is possible that a treatment with shrubs and a lawn one-quarter of the area used in this study would have lower total costs compared to the rock treatment. Furthermore, it may be possible to more accurately estimate total costs of irrigation water and electricity by examining types and ratios of landscape elements surrounding treatments. By calculation of cost per sq. ft. of particular vegetation it may be possible to combine observed treatment surface temperatures with calculated irrigation costs to predict electrical and water costs for various existing residences.

Finally, evaluation of a landscape surrounding a structure should consider the landscape uses. For example, consideration of non-tangible values such as aesthetics and human comfort are given high priority in many landscape plans. As indicated in our results, the rock treatment had lower total costs than the grass treatment, but it may be considered a less pleasing environment for outdoor users. The shade treatment had the lowest total costs, provided aesthetic value and shade for outdoor use thereby furnishing several desirable qualities. Identification of user needs combined with predicted energy and water costs of a landscape may provide a reliable method for designing energy-efficient and attractive urban landscapes.

# APPENDIX A

## INPUT DATA FOR MICROPAS

```
CONTROL DATA
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RUN DATA

1> RUN TITLE (25 char) ..................ROCK MODEL SEPT 18
2> PROJECT TITLE (25 char) ..................CAMPBELL FARM
3> OWNER'S NAME (25 char) .................. GREG MCPHERSON
4> SITE LOCATION (25 char) ......................... TUCSON
5> BUILDING TYPE (SINGLE,CLUSTER,DESIGN,NONE) ...... SINGLE

SITE AND WEATHER DATA

 1> BUILDING LATITUDE (decimal deg) ................. 32.2
 2> BUILDING ROTATION (deg,0=S,90=W,-90=E,180=N) .... 0
 3> NUMBER OF WARMUP DAYS (10 maximum) .............. 5
 4> WEATHER DATA FILE NAME (CZ12,etc) ............... SPM3
 5> WIND CORRECTION FACTOR (fraction) ............... .6
 6> HEATING MODE GROUND REFLECTIVITY (fraction) ..... .22
 7> COOLING MODE GROUND REFLECTIVITY (fraction) ..... .22
 8> GROUND TEMP DAILY FACTOR (fraction) ............. .8
 9> GROUND TEMP MONTHLY FACTOR (fraction) ........... .15
 10> GROUND TEMP ANNUAL FACTOR (fraction) ........... .05
 11> HVAC SIZING: LOCATION (25 char) ................ TUCSON

SIMULATION CONTROL DATA

 #> NUMBER OF SIMULATION SEASONS (8 only) ........... 8
     SEASON        SIMU-
     NAME          LATE
                   SEASON
     ------1------ ---2----
 1>  WINTER        NO
 2>  WINTER/SPRING NO
 3>  SPRING/SUMMER NO
 4>  SUMMER        53
 5>  SUMMER/FALL   NO
 6>  FALL/WINTER   NO
 7>  PEAK HEATING  NO
 8>  PEAK COOLING  NO

GENERAL OUTPUT SPECIFICATIONS

 1> COPY OF INPUT DATA (YES,NO,FORMAT) .............. FORMAT
 2> SUMMARY (YES,NO) ................................ YES
```

```
 3> FORM 2 (YES,NO) ................................. NO
 4> HVAC SIZING: CALCULATIONS (YES,NO) .............. NO
HOURLY OUTPUT SPECIFICATIONS

 #> HOURLY OUTPUT DESIRED (YES,NO) .................. YES
```

| SEASON NAME | AMB-IENT SUM | ZONE LOADS | ZONE CON-SUMP | ZONE HEAT FLOWS | MASS SUM-MARY | TEMP SUM-MARY | TEMP GRAPH | HOURLY OUTPUT DAYS |
|---|---|---|---|---|---|---|---|---|
| --1------ | --2-- | --3-- | --4-- | --5-- | --6-- | --7-- | --8-- | ---9---- |
| 1>WINTER | NO | NO | NO | NO | NO | NO | NO | TYPICAL |
| 2>WTR/SPG | NO | NO | NO | NO | NO | NO | NO | TYPICAL |
| 3>SPRG/SUM | NO | NO | NO | NO | NO | NO | NO | TYPICAL |
| 4>SUMMER | YES | YES | YES | YES | YES | YES | YES | 7 |
| 5>SUM/FALL | NO | NO | NO | NO | NO | NO | NO | TYPICAL |
| 6>FALL/WTR | NO | NO | NO | NO | NO | NO | NO | TYPICAL |
| 7>PK HEAT | NO | NO | NO | NO | NO | NO | NO | TYPICAL |
| 8>PK COOL | NO | NO | NO | NO | NO | NO | NO | TYPICAL |

```
ZONE DATA
=========

 #> NUMBER OF ZONES (5 maximum) ..................... 3

ZONE 'HOUSE'

 1> NAME (HOUSE,SUNSPACE,etc) ....................... HOUSE
 2> FLOOR AREA (sqft) ............................... 120
 3> VOLUME (cuft) ................................... 240
 4> HEAT CAPACITY (Btu/F) ........................... 180
 5> INTERNAL GAIN (Btu/day) ......................... 15560
 6> INTERNAL GAIN SCHEDULE (INTERNAL,NONE,etc) ... INTERNAL
 7> INFILTRATION BASE ACH (ac/hr) ................... .1
 8> INFILTRATION TEMPERATURE ACH (ac/hr-F) .......... .013
 9> INFILTRATION WIND ACH (ac/hr-mph) ............... .03
 10> HEAT EXCHANGER SYSTEM NAME (HEATEX,NONE,etc) ... NONE
 11> HEATING SYSTEM NAME (FURNACE,NONE,etc) ....... HEATSTP
 12> COOLING SYSTEM NAME (HEATPUMP,NONE,etc) ........ AC
 13> VENTILATION SYSTEM NAME (NATURAL,NONE,etc) ..... NONE
 14> HEATING MODE THERMOSTAT NAME (HEATCNST,etc)... HEATCNST
 15> COOLING MODE THERMOSTAT NAME (COOLCNST,etc)... COOLCNST
 16> HVAC SIZING: NUMBER OF PEOPLE .................. 4
 17> HVAC SIZING: APPLIANCE GAIN (Btu) .............. 1200
 18> HVAC SIZING: INFILTRATION (TIGHT,MEDIUM,LOOSE) . LOOSE

ZONE 'ATTIC'

 1> NAME (HOUSE,SUNSPACE,etc) ....................... ATTIC
 2> FLOOR AREA (sqft) ............................... 120
 3> VOLUME (cuft) ................................... 69
```

```
 4> HEAT CAPACITY (Btu/F) ........................... 20
 5> INTERNAL GAIN (Btu/day) ......................... 0
 6> INTERNAL GAIN SCHEDULE (INTERNAL,NONE,etc) ...... NONE
 7> INFILTRATION BASE ACH (ac/hr) ................... .1
 8> INFILTRATION TEMPERATURE ACH (ac/hr-F) .......... .013
 9> INFILTRATION WIND ACH (ac/hr-mph) ............... .03
 10> HEAT EXCHANGER SYSTEM NAME (HEATEX,NONE,etc) ... NONE
 11> HEATING SYSTEM NAME (FURNACE,NONE,etc) ......... NONE
 12> COOLING SYSTEM NAME (HEATPUMP,NONE,etc) ........ NONE
 13> VENTILATION SYSTEM NAME (NATURAL,NONE,etc) ..... NONE
 14> HEATING MODE THERMOSTAT NAME (HEATCNST,etc) .... NONE
 15> COOLING MODE THERMOSTAT NAME (COOLCNST,etc) .... NONE
 16> HVAC SIZING: NUMBER OF PEOPLE .................. 0
 17> HVAC SIZING: APPLIANCE GAIN (Btu) .............. 0
 18> HVAC SIZING: INFILTRATION (TIGHT,MEDIUM,LOOSE) . NONE

ZONE 'SOIL'

 1> NAME (HOUSE,SUNSPACE,etc) ....................... SOIL
 2> FLOOR AREA (sqft) ............................... 120
 3> VOLUME (cuft) ................................... 1200
 4> HEAT CAPACITY (Btu/F) ........................... 50000
 5> INTERNAL GAIN (Btu/day) ......................... 0
 6> INTERNAL GAIN SCHEDULE (INTERNAL,NONE,etc) ...... NONE
 7> INFILTRATION BASE ACH (ac/hr) ................... 0
 8> INFILTRATION TEMPERATURE ACH (ac/hr-F) .......... 0
 9> INFILTRATION WIND ACH (ac/hr-mph) ............... 0
 10> HEAT EXCHANGER SYSTEM NAME (HEATEX,NONE,etc) ... NONE
 11> HEATING SYSTEM NAME (FURNACE,NONE,etc) ......... NONE
 12> COOLING SYSTEM NAME (HEATPUMP,NONE,etc) ........ NONE
 13> VENTILATION SYSTEM NAME (NATURAL,NONE,etc) ..... NONE
 14> HEATING MODE THERMOSTAT NAME (HEATCNST,etc) .. SOILHEAT
 15> COOLING MODE THERMOSTAT NAME (COOLCNST,etc) .. SOILCOOL
 16> HVAC SIZING: NUMBER OF PEOPLE .................. 0
 17> HVAC SIZING: APPLIANCE GAIN (Btu) .............. 0
 18> HVAC SIZING: INFILTRATION (TIGHT,MEDIUM,LOOSE) . NONE

OPAQUE SURFACE DATA
===================

 #> NUMBER OF SURFACES .............................. 8
NAME      AREA     U-VALUE  AZIMUTH  TILT     ABSORP-  ZONE
          (sqft)   (Btu/hr  (deg)    (deg)    TIVITY   NAME
                    -sf-F)                     (frac)
--1---- ---2---- ---3---- ---4---- ---5---- ---6---- ---7--
1>SWALL    21.6    .087      -16     90       .8       HOUSE
2>WWALL    17.6    .087       74     90       .8       HOUSE
3>NWALL    22.3    .087      164     90       .8       HOUSE
4>EWALL    17.6    .087     -106     90       .8       HOUSE
```

| | | | | | | |
|---|---|---|---|---|---|---|
| 5>SROOF | 72.4 | .314 | -16 | 18 | .68 | ATTIC |
| 6>NROOF | 72.4 | .314 | 164 | 18 | .68 | ATTIC |
| 7>SLABEDGE | 44 | 0 | 0 | 0 | 0 | HOUSE |
| 8>DOOR | 2 | 1.07 | 164 | 90 | .8 | HOUSE |

GLAZING SURFACE DATA
====================

GLAZING SURFACES

#> NUMBER OF SURFACES .............................. 3

| NAME | AREA (sqft) | U-VALUE (Btu/hr -sf-F) | AZIMUTH (deg) | TILT (deg) | NUM OF PANES | ZONE NAME | TREAT-MENT NAME |
|---|---|---|---|---|---|---|---|
| -1-- | --2--- | ---3---- | ---4--- | --5--- | --6--- | ---7---- | ---8- |
| 1>SGLS | 2.65 | 1.04 | -16 | 90 | 1 | HOUSE | OVER1 |
| 2>WGLS | 2.65 | 1.04 | 74 | 90 | 1 | HOUSE | OVER2 |
| 3>EGLS | 2.65 | 1.04 | -106 | 90 | 1 | HOUSE | OVER2 |

GLAZING TREATMENTS

#> NUMBER OF TREATMENTS ............................ 2

| NAME | GLAZ HEI-GHT | OVER-HANG LENG | OVER-HANG HIGH | HEAT SHAD FACT | COOL SHAD FACT | SHADING SCHED NAME | SHUT U-VAL. | SHUT TRAN FACT | SHUTTER SCHED. NAME |
|---|---|---|---|---|---|---|---|---|---|
| --1--- | -2-- | --3-- | --4-- | --5-- | --6-- | --7--- | -8----- | -9----- | -10- |
| 1>OVER1 | .9 | .63 | .375 | 1 | .9 | NONE | 0 | 0 | NONE |
| 2>OVER2 | .9 | .125 | 1.6 | 1 | .9 | NONE | 0 | 0 | NONE |

ABSORBED INSOLATION FRACTIONS

#> NUMBER OF FRACTIONS ............................. 6

| | GLAZING SURFACE NAME | ZONE OR MASS SIDE | HEATING FRACTION | COOLING FRACTION |
|---|---|---|---|---|
| | ---1---- | ---2---- | ---3---- | ---4---- |
| 1> | SGLASS | SLABTOP | .4 | .4 |
| 2> | WGLASS | SLABTOP | .4 | .4 |
| 3> | EGLASS | SLABTOP | .4 | .4 |
| 4> | SGLASS | JUGSIDE | .4 | .4 |
| 5> | WGLASS | JUGSIDE | .4 | .4 |
| 6> | EGLASS | JUGSIDE | .4 | .4 |

INTER-ZONE DATA
===============

INTERIOR SURFACES BETWEEN ZONES

#> NUMBER OF SURFACES .............................. 1

| | NAME | AREA (sqft) | U-VALUE (Btu/hr -sf-F) | ZONE OR MASS SIDE #1 | ZONE OR MASS SIDE #2 |
|---|---|---|---|---|---|
| | ---1---- | ---2---- | ---3---- | ---4---- | ---5---- |
| 1> | CEILING | 120 | .035 | HOUSE | ATTIC |

MASS DATA
=========

```
 #> NUMBER OF MASSES (10 maximum) ................... 2
```

MASS 'SLAB'

```
 1> NAME (SLAB,MASSWALL,WATER,etc) .................. SLAB
 2> TYPE (NODAL,ISOTHERM,ENERPHASE) ................. NODAL
 3> SURFACE AREA (sqft) ............................. 120
 4> THICKNESS (inches) .............................. 3
 5> VOLUMETRIC HEAT CAPACITY (Btu/cuft-F) ........... 32
 6> CONDUCTIVITY (Btu-ft/hr-sqft-F) ................. 1.83
 7> SIDE #1 MASS SURFACE NAME (SLABTOP,etc) .........
SLABTOP
 8> SIDE #1 AIR FILM CONDUCTANCE (Btu/hr-sqft-F) .... .6
 9> SIDE #1 ZONE NAME (HOUSE,AMBIENT,etc) ........... HOUSE
 10> SIDE #2 MASS SURFACE NAME (SLABBOT,NONE,etc) .SLABBOT
 11> SIDE #2 AIR FILM CONDUCTANCE (Btu/hr-sqft-F) ... 8
 12> SIDE #2 ZONE NAME (AMBIENT,GROUND,NONE,etc) .... SOIL
```

MASS 'JUG'

```
 1> NAME (SLAB,MASSWALL,WATER,etc) .................. JUG
 2> TYPE (NODAL,ISOTHERM,ENERPHASE) ................. NODAL
 3> SURFACE AREA (sqft) ............................. 27
 4> THICKNESS (inches) .............................. 3
 5> VOLUMETRIC HEAT CAPACITY (Btu/cuft-F) ........... 62.3
 6> CONDUCTIVITY (Btu-ft/hr-sqft-F) ................. .35
 7> SIDE #1 MASS SURFACE NAME (SLABTOP,etc) .........
JUGSIDE
 8> SIDE #1 AIR FILM CONDUCTANCE (Btu/hr-sqft-F) .... 3
 9> SIDE #1 ZONE NAME (HOUSE,AMBIENT,etc) ........... HOUSE
 10> SIDE #2 MASS SURFACE NAME (SLABBOT,NONE,etc) ... NONE
 11> SIDE #2 AIR FILM CONDUCTANCE (Btu/hr-sqft-F) ... 0
 12> SIDE #2 ZONE NAME (AMBIENT,GROUND,NONE,etc) .... NONE
```

SYSTEMS DATA
============

ENERGY COSTS

```
 1> FUEL COST (dollars/therm) ...................... .5
 2> ELECTRICITY COST (dollars/kWh) ................. 0.08

HEATING SYSTEMS

 #> NUMBER OF HEATING SYSTEMS ...................... 1
 NAME     HEATING  SEASONAL HEATING   DUCT     SIZING:
          FUEL     EFF OR   CAPACITY  LOSS     DUCT
          NAME     COP      (Btu/hr)  FRACTION LOCATION
---1--- ---2---- ---3---- ----4---- ---5---- -----6-----
1>HEATSTP  ELECTRIC .89      UNLIMITED 0        ATTIC

COOLING SYSTEMS

 #> NUMBER OF COOLING SYSTEMS ...................... 1
NAME SEASONAL COOLING   LATENT   DUCT     SIZING:  SIZING:
     EER      CAPACITY  LOAD     GAIN     LATENT   DUCT
     (Btu/Wh) (Btu/hr)  FRACTION FRACTION LOAD     LOCATION
--1-----2---- ----3---- ---4---- ---5---- ---6--------7----
1>AC  7.2      UNLIMITED .03       0       .03      ATTIC

VENTILATION SYSTEMS

#> NUMBER OF VENTILATION SYSTEMS .................. 1
NAME FAN  FAN   TEMP INLET OUTLET HIGH  INLET   STACK  WIND
     FLOW POWER DIFF AREA  AREA   DIFF AZIMUTH EFFIC- EFFIC-
    (cfm)(W/cfm) (F)(sqft) (sqft) (ft)  (deg)  IENCY  IENCY
-1----2-- ---3----4---5-----6--- --7-- ---8--- --9--- --10--
1>NAT. 0     0    0   0     0      0     164     1.0    1.0

THERMOSTAT SYSTEMS

 #> NUMBER OF THERMOSTAT SYSTEMS ................... 4
NAME    HEATING COOLING VENTING HEATING COOLING VENTING HOURLY
        TEMP    TEMP    TEMP    SETBACK SETBACK SETBACK SCHED
        (F)     (F)     (F)     TEMP(F) TEMP(F) TEMP(F) NAME
--1----2--- ---3--- ---4--- ---5--- ---6--- ---7--- ---8----
1>HEATCNST 70   78      78      0       0       0       NONE
2>COOLCNST 70   78      70      0       0       0       NONE
3>SOILHEAT 68   73      0       0       0       0       NONE
4>SOILCOOL 68   73      0       0       0       0       NONE

SCHEDULE DATA
=============

 #> NUMBER OF HOURLY SCHEDULES (10 maximum) ......... 1

HOURLY SCHEDULE 'INTERNAL'
```

```
1> NAME (INTERNAL,SETBACK,etc) ..................INTERNAL
2> HEATING MODE (ON,OFF,AUTO,OPEN,CLOSED,UP,BACK,fraction)
1.   .042      2.   .042           3.   .042           4.   .042
5.   .042      6.   .042           7.   .042           8.   .042
9.   .042     10.   .042          11.  .042           12.  .042
13.  .042     14.   .042          15.  .042           16.  .042
17.  .042     18.   .042          19.  .042           20.  .042
21.  .042     22.   .042          23.  .042           24.  .042
3> COOLING MODE (ON,OFF,AUTO,OPEN,CLOSED,UP,BACK,fraction)
1.   .042      2.   .042           3.   .042           4.   .042
5.   .042      6.   .042           7.   .042           8.   .042
9.   .042      10.  .042          11.  .042           12.  .042
13.  .042      14.  .042          15.  .042           16.  .042
17.  .042      18.  .042          19.  .042           20.  .042
21.  .042      22.  .042          23.  .042           24.  .042
```

# APPENDIX B

## SUMMARIZED AZMET WEATHER DATA

Table 1. Summarized AZMET weather data for June 3, 1987.

| | MAX. | MIN. | MEAN | TOTAL | UNITS |
|---|---|---|---|---|---|
| TEMPERATURE | 39.9 | 15.1 | 29.1 | | DegC |
| RELATIVE HUMIDITY | 28.4 | 6.8 | 13.6 | | % |
| VAPOR PRESS. DEF. | | | 3.9 | | KPas |
| SOLAR RADIATION | | | | 29.8 | MJ/Sq M |
| PRECIPITATION | | | | 0.00 | MM |
| SOIL TEMP. 2 IN | 29.7 | 16.4 | 23.0 | | DegC |
| SOIL TEMP. 4 IN | 27.0 | 17.3 | 22.1 | | DegC |
| WIND SPEED | 7.4 | | 2.1 | | M/S |
| WIND VECTOR DIR. | | | 98 | | Degrees |
| REF. EVAPOTRANSPIRATION | | | | 9.10 | MM |

Table 2. Summarized AZMET weather data for July 6, 1987.

| | MAX. | MIN. | MEAN | TOTAL | UNITS |
|---|---|---|---|---|---|
| TEMPERATURE | 40.6 | 14.0 | 28.3 | | DegC |
| RELATIVE HUMIDITY | 16.9 | 6.5 | 11.1 | | % |
| SOLAR RADIATION | | | | 31.1 | MJ/Sq M |
| PRECIPITATION | | | | 0.00 | MM |
| SOIL TEMP. 2 IN | 31.5 | 17.9 | 24.5 | | DegC |
| SOIL TEMP. 4 IN | 29.2 | 19.1 | 24.1 | | DegC |
| WIND SPEED | 5.3 | | 1.7 | | M/S |
| WIND VECTOR DIR. | | | 102 | | Degrees |
| REF. EVAPOTRANSPIRATION | | | | 9.20 | MM |

Table 3. Summarized AZMET weather data for August 6, 1987.

| | MAX. | MIN. | MEAN | TOTAL | UNITS |
|---|---|---|---|---|---|
| TEMPERATURE | 37.1 | 24.4 | 30.2 | | DegC |
| RELATIVE HUMIDITY | 90.5 | 17.9 | 51.4 | | % |
| VAPOR PRESS. DEF. | | | 2.4 | | KPas |
| SOLAR RADIATION | | | | 26.4 | MJ/Sq M |
| PRECIPITATION | | | | 0.00 | MM |
| SOIL TEMP. 2 IN | 37.6 | 25.0 | 30.3 | | DegC |
| SOIL TEMP. 4 IN | 35.5 | 25.6 | 29.9 | | DegC |
| WIND SPEED | 6.5 | | 1.8 | | M/S |
| WIND VECTOR DIR. | | | 128 | | Degrees |
| REF. EVAPOTRANSPIRATION | | | | 7.20 | MM |

Table 4. Summarized AZMET weather data for October 2, 1987.

| | MAX. | MIN. | MEAN | TOTAL | UNITS |
|---|---|---|---|---|---|
| TEMPERATURE | 33.9 | 15.7 | 26.3 | | DegC |
| RELATIVE HUMIDITY | 88.0 | 9.1 | 29.5 | | % |
| VAPOR PRESS. DEF. | | | 2.8 | | KPas |
| SOLAR RADIATION | | | | 20.6 | MJ/Sq M |
| PRECIPITATION | | | | 0.00 | MM |
| SOIL TEMP. 2 IN | 26.5 | 17.7 | 21.1 | | DegC |
| SOIL TEMP. 4 IN | 25.3 | 18.9 | 21.7 | | DegC |
| WIND SPEED | 8.7 | | 3.5 | | M/S |
| WIND VECTOR DIR. | | | 108 | | Degrees |
| REF. EVAPOTRANSPIRATION | | | | 7.60 | MM |

Table 5. Summarized AZMET weather data for May 25, 1988.

| | MAX. | MIN. | MEAN | TOTAL | UNITS |
|---|---|---|---|---|---|
| TEMPERATURE | 37.6 | 16.9 | 28.1 | | DegC |
| RELATIVE HUMIDITY | 37.2 | 8.0 | 16.1 | | % |
| VAPOR PRESS. DEF. | | | 3.4 | | KPas |
| SOLAR RADIATION | | | | 28.9 | MJ/Sq M |
| PRECIPITATION | | | | 0.00 | MM |
| SOIL TEMP. 2 IN | 35.9 | 17.4 | 24.3 | | DegC |
| SOIL TEMP. 4 IN | 32.0 | 19.2 | 24.6 | | DegC |
| WIND SPEED | 5.0 | | 1.8 | | M/S |
| WIND VECTOR DIR. | | | 311 | | Degrees |
| REF. EVAPOTRANSPIRATION | | | | 8.50 | MM |

Table 6. Summarized AZMET weather data for September 18, 1988.

| | MAX. | MIN. | MEAN | TOTAL | UNITS |
|---|---|---|---|---|---|
| TEMPERATURE | 35.6 | 12.4 | 24.0 | | DegC |
| RELATIVE HUMIDITY | 44.2 | 8.6 | 22.8 | | % |
| VAPOR PRESS. DEF. | | | 2.7 | | KPas |
| SOLAR RADIATION | | | | 24.5 | MJ/Sq M |
| PRECIPITATION | | | | 0.00 | MM |
| SOIL TEMP. 2 IN | 31.8 | 15.9 | 23.0 | | DegC |
| SOIL TEMP. 4 IN | 29.2 | 18.7 | 23.6 | | DegC |
| WIND SPEED | 7.1 | | 1.9 | | M/S |
| WIND VECTOR DIR. | | | 186 | | Degrees |
| REF. EVAPOTRANSPIRATION | | | | 7.30 | MM |

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