# SonoranSystems: Building Simulation Modeling Using a Crassulacean Acid Metabolism Analogy

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## ABSTRACT

Biomimicry is one source of inspiration for innovation in the passive thermal design of buildings and of strategies that decrease the need for auxiliary heating and cooling systems. Although one could design a building to visually resemble a natural model (i.e., a house that looks like a cactus), it is more advantageous in many cases to design a built system so that it behaves like the model (i.e., a house that reduces heat gain and water loss through a layered wall design). This paper explores the potential for using analogies drawn from Crassulacean acid metabolism (CAM) to create a software program that simulates selected building materials to predict temporal building temperature variations.

When we draw a connection between the chemical system of the CAM species and the thermal system of a built environment, we are able to construct a conceptual conversion factor that relates the natural model to the artificial product via the respective dynamic processes. The conceptual nature of this conversion does not equate a specific biological component to a specific building component. It only allows us to compare the chemical behavior of the biological model to the subsequent building system and its thermodynamic behavior. In this analogy, a building envelope comprised of a layered thermal mass provides the thermodynamic equivalent to the CAM pathway within the cell. A computer program, SonoranSystems, was developed by one of the authors (Wiebe) in order to analyze the thermodynamics of a building envelope that is the result of a biomimetic translation of the CAM.



## 1 INTRODUCTION

Climate responsiveness in architecture is a crucial goal in the pursuit of new building strategies to increase the efficiency of the built thermal environment. One method of determining potential strategies is to look towards nature for inspiration. Biomimetics is the field of study in which nature serves as “model, mentor, or measure,” as described by the Biomimicry Institute (2009). The natural model can range in the purpose it serves and in the way that it is viewed. For example, succulent cactus species of the Sonoran Desert can be discussed in terms of ecological (relationship to other plants and animals), morphological (size, shape), anatomical (internal architecture), and physiological (photosynthesis, CAM) adaptations. After investigation of each of these categories of characteristics, we selected the physiological aspect for further investigation and translation to a building metaphor. Specifically, we used Crassulacean acid metabolism (CAM), a remarkable climate adaptation found in some of the succulent cacti in the Sonoran Desert, as the basis for this project.

Existing software (that we are aware of) does not have the ability to model thermodynamically the material assemblies under consideration nor to produce output data in the form of temperature profiles, which are necessary steps in the subsequent comparison of the building's thermodynamic behavior to the metabolic functioning of the CAM plant. One of the authors (Wiebe) created a Windows-based application, SonoranSystems, in order to test the building systems that are the product of this biomimetic investigation. Using the conversion factor, stomata are translated to thermochromic laminated glazing (TLG), cytoplasm and vacuole to thermal mass, and chemical differentials to heat differentials. The application uses hourly TMY3 climate data for thirteen cities in the Sonoran Desert and, ultimately, outputs indoor temperatures for a designed case and a reference case. The program simulates a series of material assemblies comprised of TLG, water, concrete, and methlymethacrylate (mmc). This program allows the comparison of diurnal metabolic functions with the diurnal heat transfer and temperature profiles of a south-facing wall assembly. In order to compare the chemical behavior of CAM and the thermal behavior of a wall assembly, output will be in the form of temperature profiles.

## 2 THE DESERT AND THE CRASSULACEAN ACID METABOLISM

The hot, arid climate type is characterized by a large temperature range (very low nighttime temperature and very high daytime temperatures), little humidity, and intense solar radiation (Watson 1993). As the psychometric chart shows (fig. 1), a number of building strategies that decrease the need for auxiliary HVAC systems already exist. This project investigates new design methods and strategies for thermal control in a particular place; however, this type of analysis could be extended to other climates and their respective biological adaptations.

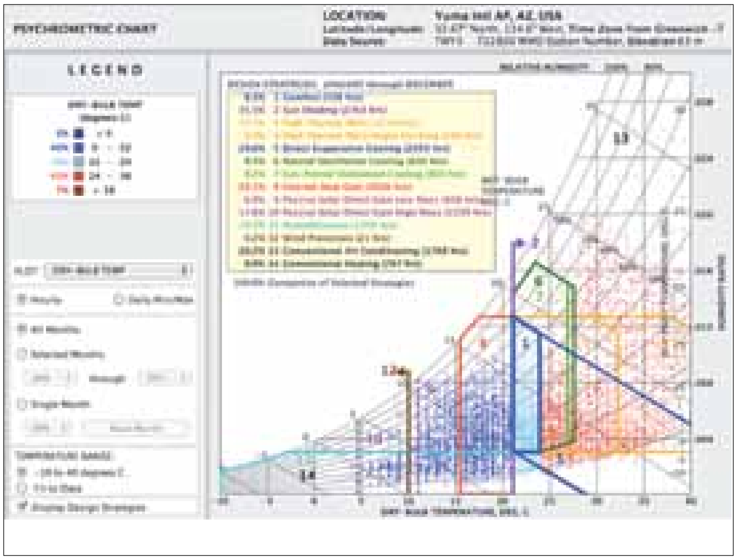


**Figure 1** Psychometric chart for Yuma, Arizona from Climate Consultant

Optimal rates of photosynthesis are dependent on the availability of sunlight, water, and carbon dioxide. The retention of water and carbon dioxide has an important inverse relationship: the conservation of one may have a detrimental effect on the level of the other. This becomes a substantial issue in climates with low humidity and high temperatures: when stomata are open to take in carbon dioxide, they transpire large amounts of water, leaving the plant dehydrated. It is the necessity to both take in carbon dioxide and prevent water loss that motivates the development of the Crassulacean acid metabolism (Davies et al. 1961).

CAM is an adapted photosynthetic system that mitigates this CO2/H2O collection dilemma. Instead of gathering CO2 during the daytime, plants with the CAM system open their stomata only at nighttime when incident solar radiation and outdoor temperature are at their minimum. The CO2 gathered at nighttime is stored as malic acid in the cell vacuole, and then during daytime hours when sunlight is available, the malic acid is converted to polysaccharides or hexose sugars (Kluge and Ting 1978).

The CAM is used primarily to conserve water. This adaptation is contingent on two main features: 1) the stomatal rhythms and 2) the ability to store carbon dioxide as malic acid for use later in photosynthesis. The diurnal functioning of these two mechanisms is highly rhythmic, and there exists a certain level of hysteresis in their daily fluctuations.

## 3 SIMULATING BIOLOGY

CAM is viewed primarily as a system of chemical reactions, as the daily undulating of concentrations of certain chemical compounds, and as the spatial arrangement of the cell, making these reactions possible. It is modeled as three reactant pools (internal carbon dioxide concentration, malic acid concentration in the cytoplasm, and malic acid concentration in the vacuole) and three transfer functions, which describe the changes in those concentrations (fig. 2).

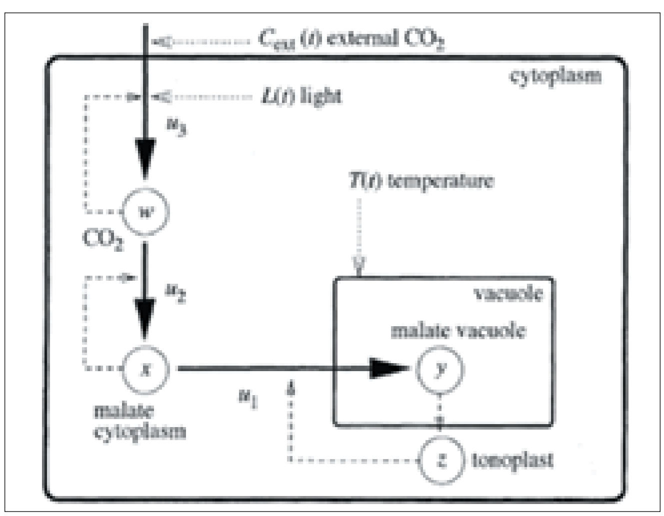
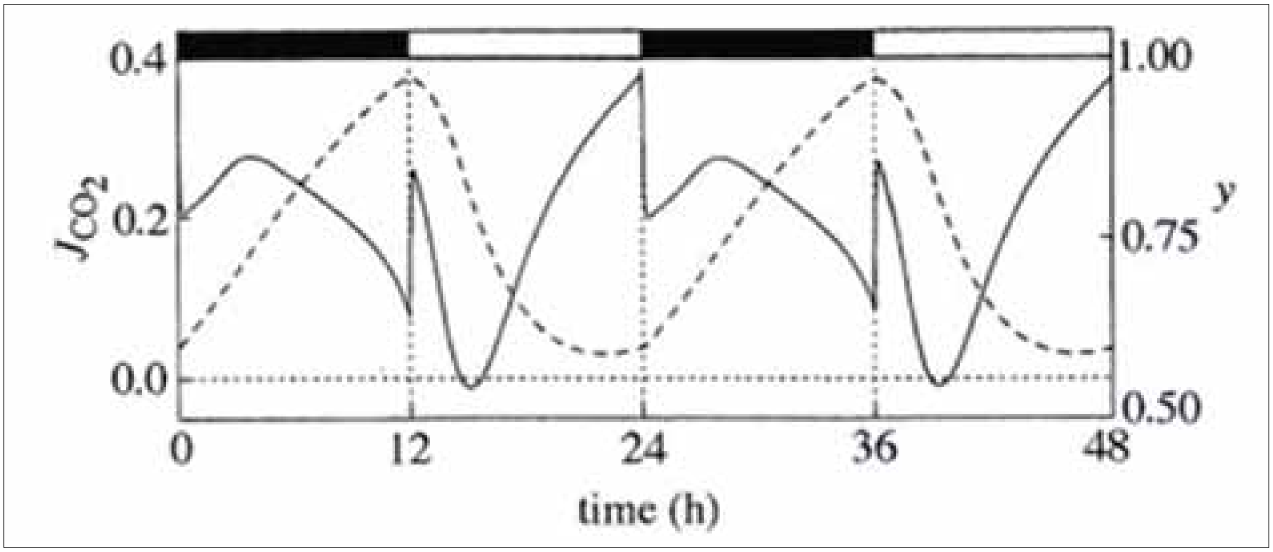



**Figure 2** Simulation model of Crassulacean acid metabolism

Using this simplified model from Blasius et al. (1999), we can plot metabolic functioning as a function of temperature, of light, and of external carbon dioxide levels. The variables w, x, y, and z represent the concentration of carbon dioxide in the cytoplasm, the malate concentration in the cytoplasm, the malate concentration in the vacuole, and the tonoplast order, respectively. The tonoplast is the membrane of the vacuole, and the tonoplast order is a value that describes the permeability of the membrane at time t. The set of equations that defines this system can be found in the source document. Using numerical algorithms presented in an earlier paper by Neff et al. (1998), we solved these equations and generated the following profiles (figs. 3, 4):

**Figure 3** Concentration of carbon dioxide in the cytoplasm (solid line) and concentration of malate in the vacuole (dashed line)




This computer simulation of CAM presented by Blasius et al. (1999) is an important characterization of this metabolic adaptation for two reasons:

1) it represents CAM as the simplest set of pools of compounds, and their respective differences, that accurately models a much more complex system, and

2) the simulated system of reactions induced by differential concentrations can be related to the simulation of heat transfer between temperature nodes via the principle of differentials.

Empirical data presented by Kluge and Ting (1978) support and supplement these theoretical graphs (figs. 5, 6).

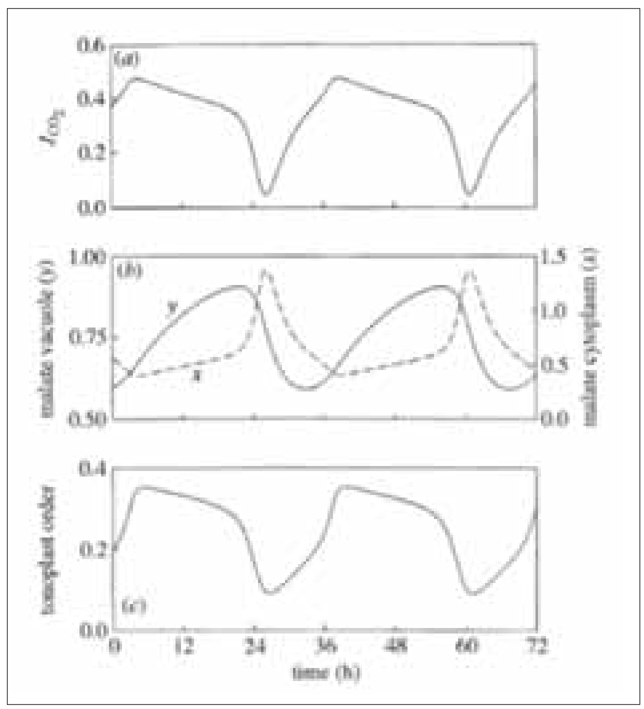



**Figure 4** 72-hour metabolic profile

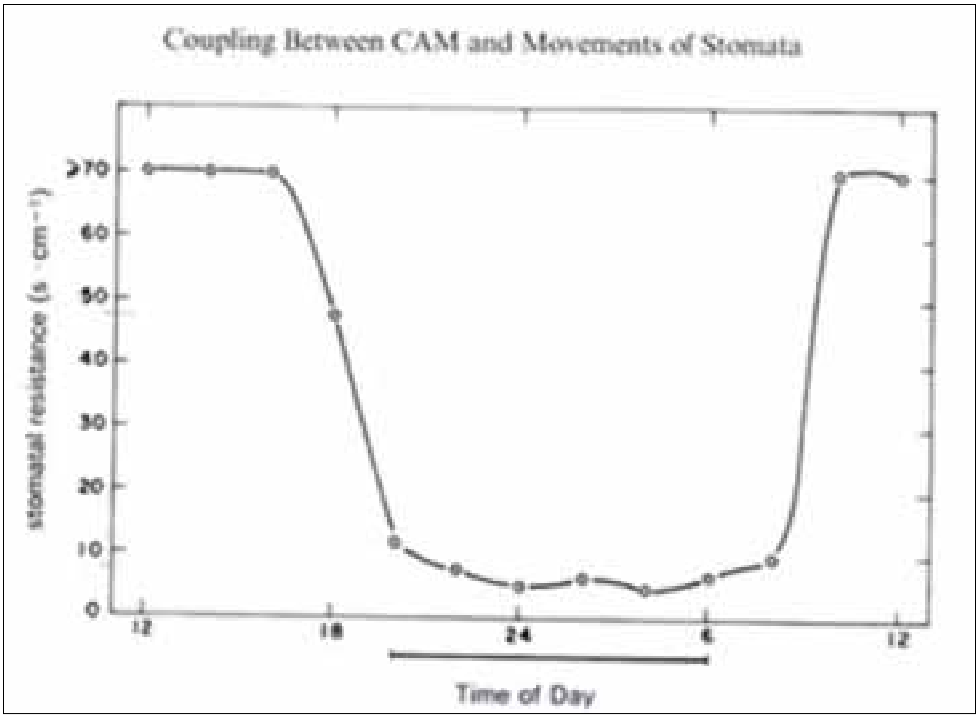
## 4 MIMICKING MATERIALS AND PROCESSES

We subjected the pieces of this simulation-based model of CAM to a biomimetic transformation process. The conceptual nature of this conversion does not allow us to equate “this biological component” to “that building component.” It only allows us to compare the chemical behavior of the biological model to the subsequent building system and its thermodynamic behavior.

Stomata are translated to thermochromic laminated glazing (TLG) cytoplasm and vacuole to thermal mass, and chemical differentials to heat differentials. A building envelope comprised of layered thermal mass with a variable barrier layer (thermochromic glazing) provides the thermodynamic equivalent to the CAM pathway within the cell (fig. 7).

The materials, with their different thicknesses and thermal properties, generate temperature profiles that are out of phase with each other, while responding to adjacent material temperatures. The thermal mass materials used are water, concrete, and methylmethacrylate (mmc). Water has been included in this project predominantly for its biomimetic correspondence to the CAM pathway, but also for the larger role it plays in all scales of the biological system. Concrete has been included because it is a ubiquitous building material that allows for complex forms, tough structures, and

**Figure 5** Daily fluctuation of stomatal resistance of Opuntia basilaris



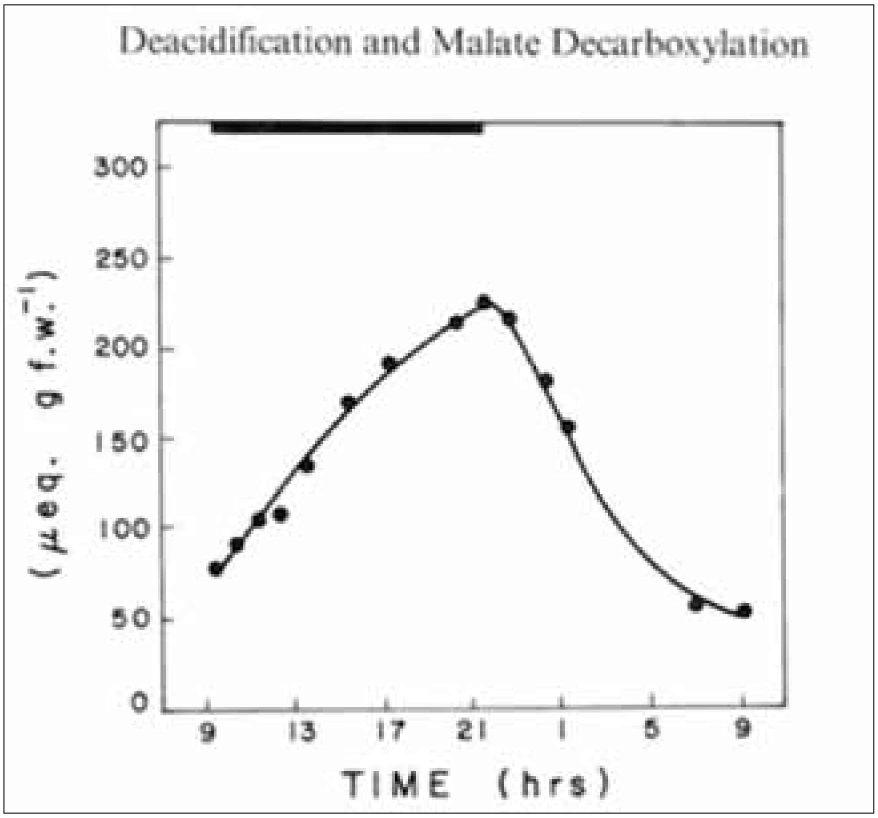




**Figure 6** Malic acid concentration in the vacuole of Kalanchoe tubiflora

substantial thermal mass. MMC was integrated into the project as an example of a material with a more substantial thermal resistance, and allows for the investigation of the consequences of the placement of thermal resistance in relation to thermal mass.

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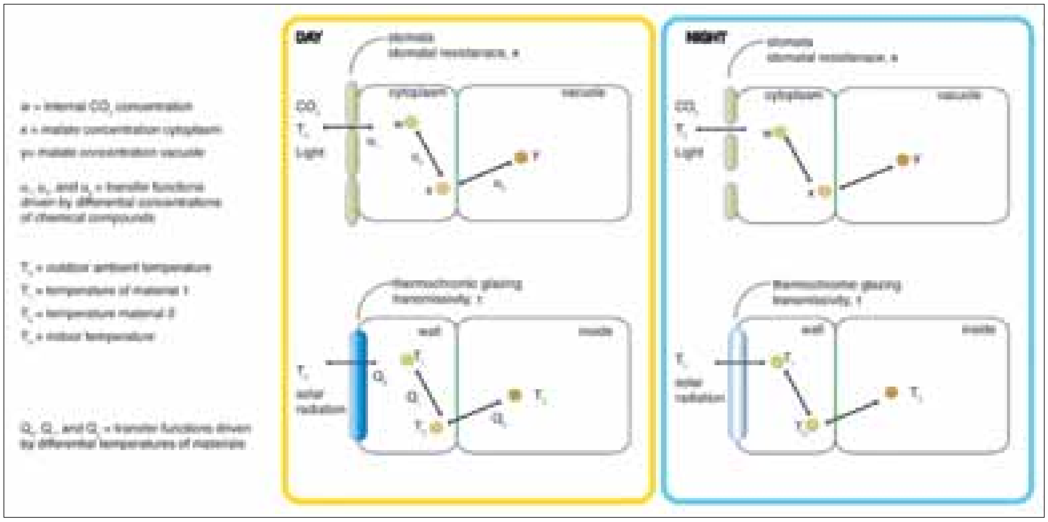



Figure 7
Biomimetic analogy

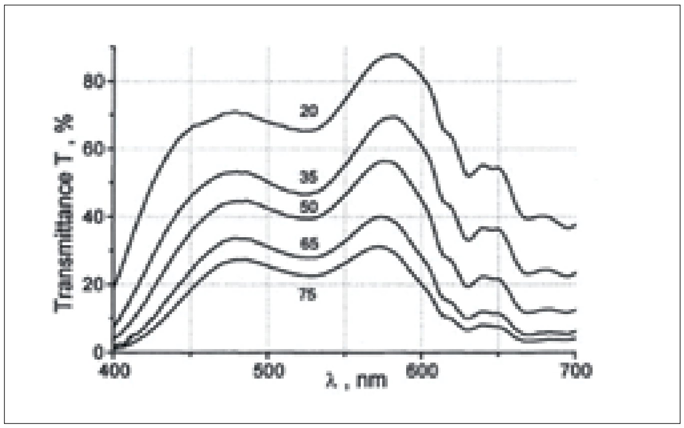



**Figure 8** Transmissivity of thermochromic glazing with wavelength and temperature

The data employed here to model the behavior of the thermochromic glazing comes from the paper Smart thermochromic glazing (Arutjunjan et. al., 2005), in which the authors outline the energy savings of a thermochromic laminated glazing (TLG). They present the spectral transmittance of the TLG for a range of temperatures (fig. 8). This graph is interpolated and extrapolated and, with computational methods and values from ASTM E 971-88 and G 173-03, the data is used in SonoranSystems.

Values for water are taken from Dincer and Rosen (2002):

Although there are many varieties of concrete mixtures that have somewhat different physical properties, the following values are used for this project, taken from Dincer and Rosen (2002):

As described in Transwall Versus Trombe Wall (Nayak 1986), a transwall is comprised of two layers of water, separated by a piece of semi-transparent material, which, in this case, is methylmethacrylate (mmc) (fig. 9).

MMC material properties from Nayak (1986):

$$c_{p,mmc} = 1.46\ kJkg^{-1}K^{-1}$$
$$\rho_{mmc} = 1204\ kgm^{-3}$$
$$k_{mmc} = 1.729\ Wm^{-1}K^{-1}$$

## 5 SONORANSYSTEMS: THERMAL MODEL

In order to calculate temperature profiles, we must first calculate the perpendicular component of the incoming direct, normal radiation. Solar angles are calculated for every hour by using equations taken from the ASHRAE Handbook of Fundamentals 2005.

Using material properties and a combination of conduction, convection, and radiation equations, we assembled the following algorithms and used them in SonoranSystems. These equations are for a three-layer wall, but the number of wall layers and temperature nodes can be adjusted (fig. 10).

Two buildings are modeled: the design case (where the parameters of the south wall assembly can be changed) and the reference building. The design building is modeled to have glazing on the south façade equal to 5 percent of the façade area, with standard double-pane (not thermochromic) glazing. For the north, east, and west walls, the roof, and one standard-glazed south-facing window, the following thermodynamic values are used:

Finally, indoor temperature is calculated as the sum of the heat flows into the space from the walls and the roof:

Hourly indoor temperature is plotted against the ambient outdoor dry-bulb temperature, the temperature of each material

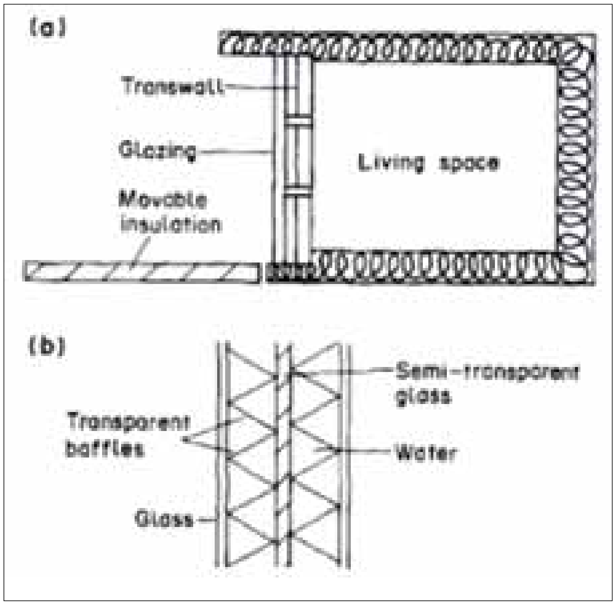



**Figure 9** Transwall

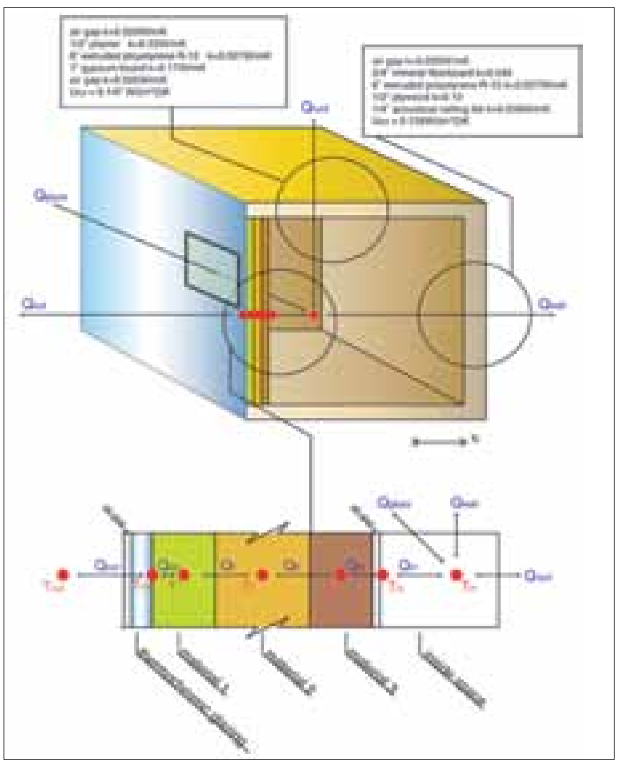


**Figure 10** Thermodynamic model

layer, and the indoor temperature of a reference case.

$$U_{wall} = 0.147\ Wm^{-2}K^{-1}$$
$$U_{roof} = 0.139\ Wm^{-2}K^{-1}$$
$$U_{glaze} = 3.92\ Wm^{-2}K^{-1}$$

The reference case has all the same dimensions and climate conditions as the designed case. The main difference is that all walls, including the south wall, have the same thermodynamic properties as the north, east, and west walls in the design case. The roof conditions are identical in both cases, and like the design case, there is a window on the south wall equal to 5 percent of the south façade area.

$$U_{glaze} = 3.92\ Wm^{-2}K^{-1}$$

The indoor temperature of this reference case will provide a baseline in determining relative thermal performance of the designed case.

## 6 SONORANSYSTEMS: INPUTS AND OUTPUTS

The available input variables for SonoranSystems are:

1) Time period (i.e., July)
2) Location (i.e., Yuma, Arizona)
3) Building dimensions (length and width in meters)
4) Wall assembly (1–3 layers)

For the "time period," the user can select a month or input a custom time period in hours of the year. To assemble a wall section, the user inputs a thickness, highlights a material, and clicks the orange "add layer" button. Material layers must be added sequentially, beginning with the outermost layer. The user can clear the assembly by clicking the brown "clear" button. If tabular data is required in addition to a temperature plot, the user must select the type of assembly from the list of material combinations. Once all variables are specified, hitting the red "next" button will generate the outputs both in the table on the input screen and in temperature profiles on an output screen (fig. 11).

In addition to temperature, SonoranSystems uses a metric similar to a heating or cooling degree-day, using indoor temperatures and a comfort zone instead of weather data and a reference temperature. This metric is called the heating zone area and the cooling zone area (units are [degrees Celsius-days]) (fig. 12). In the simulation, the comfort zone is set to 20–25 degrees Celsius, but this range can be adjusted if necessary.

To generate a temperature profile, the user inputs the information regarding location, building dimensions, and wall construction. The program will produce a graph of temperature profiles for the time period specified by the user (figures 13 and 14). For this example the length and width of the building are set to 5m and 3m, respectively, the height of the building is 3m, and the location of the building is set at Yuma, Arizona.

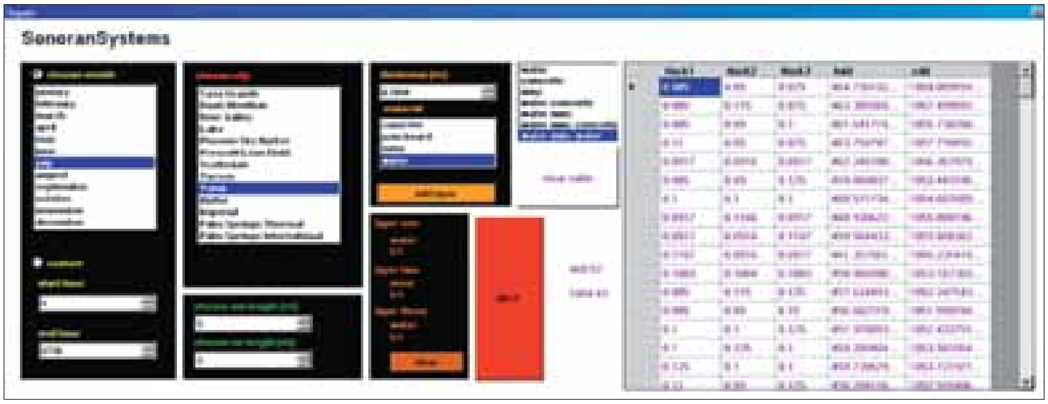


Figure 11 Input screen with table filled with output data

This graph includes ambient outdoor temperatures (blue), temperatures at each layer of the wall (green, orange), indoor air temperature (red), and the indoor air temperature of the reference case (salmon), all in Celsius. At the top of the output screen the user inputs are listed along with the heating and cooling zone area values and a diagram of the type of wall section being simulated.

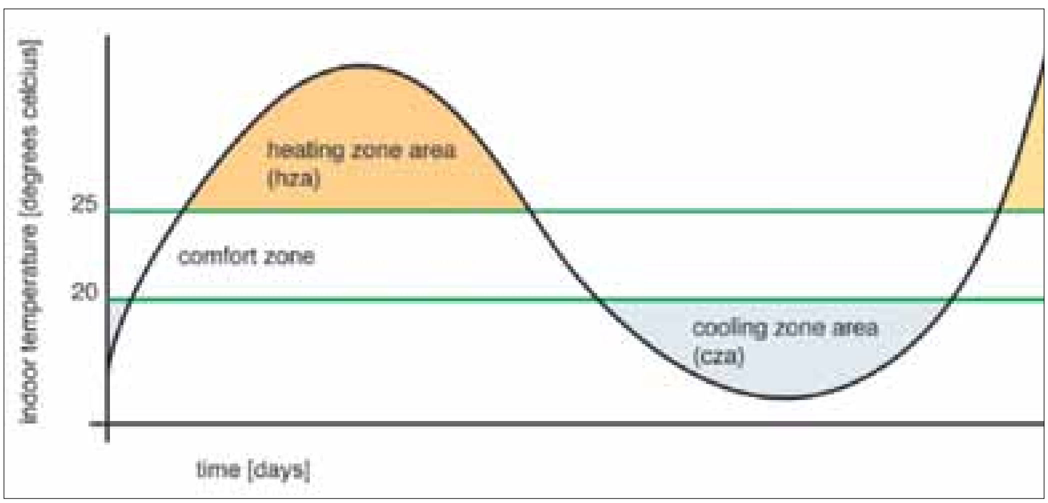



Figure 12 Heating and cooling zone areas

In order to test a large amount of samples at once and quantitatively compare their thermal efficiencies, the program also outputs a table of heating and cooling zone area values for a set of predefined assemblies (21 different one-layer assemblies, 66 two-layer assemblies, and 231 three-layer assemblies). These values are displayed on the table on the right side of the input screen (fig. 11).

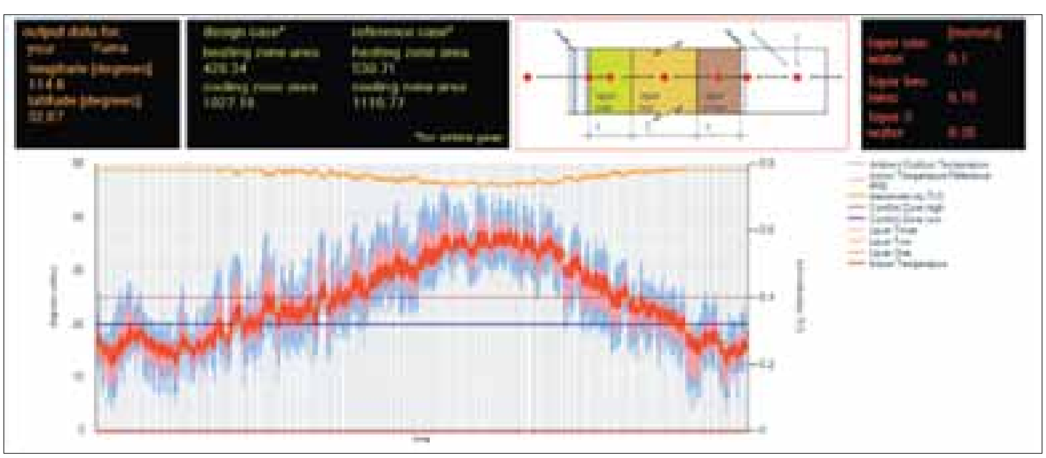


Figure 13 Output screen, time period: year

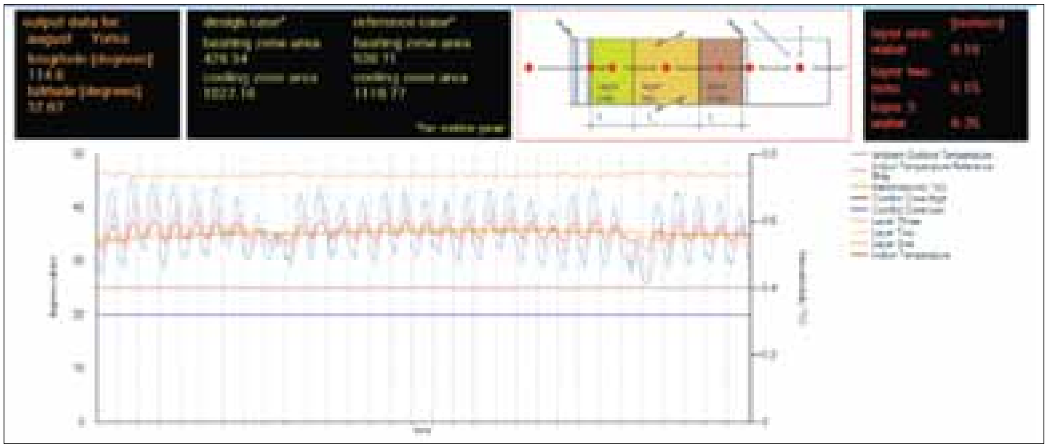


**Figure 14** Output screen, time period: August

## 7 ANALYSIS

The tabular data can be exported to MS Excel for supplementary analysis of thermal efficiency in relation to the design of the wall assembly. For the water-mmc-water wall construction, the location of the water had a greater effect on efficiency than the total water content or total thermal mass of the wall (fig. 15).

The 10cm water-15cm mmc-35cm water wall assembly does not have the highest thermal mass (60cm water wall does) nor does it have the lowest thermal conductivity (60cm mmc does). However, simulation results showed that it has the lowest heating and cooling zone area values of all the assemblies tested. Compared to the reference case, the heating zone area was reduced by 19% and the cooling zone area was reduced by 8%, making this assembly, like most others tested, more useful for cooling purposes, which is important for the Sonoran desert. It is the integration of the thermal mass of water and conductivity of mmc that precipitates the most efficient assembly.

It is known that thermal mass (water) inside of an insulating layer (mmc) is an effective strategy for thermal control in desert regions. The fact that it was a conclusion of this project both further proves the effectiveness of that strategy and supports the validity of the simulations in this project.

For each type of wall assembly 24 hours of data was looked at to observe any diurnal behaviors (or biological resemblance) of the system for a typical cold day and hot day.

The temperature profiles generated allow for the comparison of the diurnal temperature fluctuation of the indoor space and wall to the metabolic functioning of CAM more than existing energy simulation programs. However, the oscillatory behavior of the wall assemblies was minimal (due to thermal mass effects) and thus difficult to compare to the behavior of the natural model.

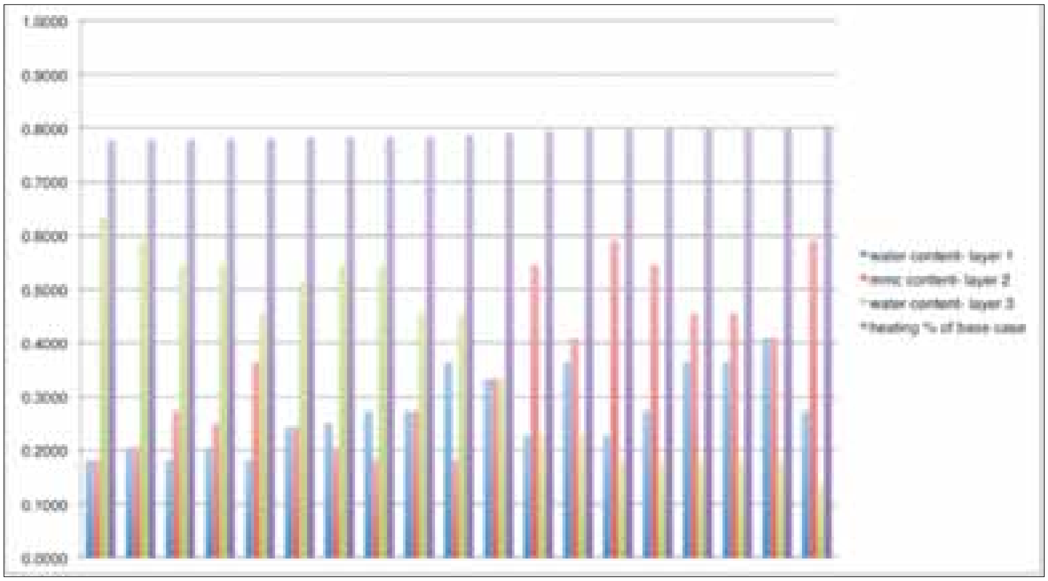
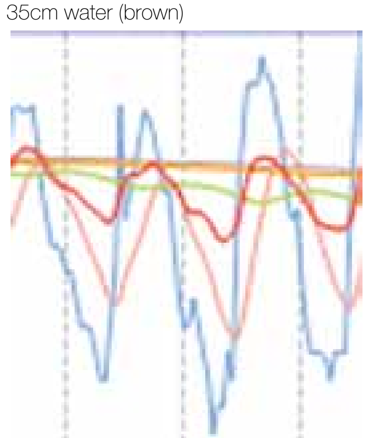
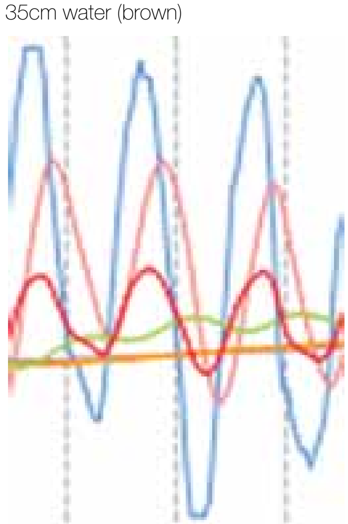


**Figure 15** Assessment of heating zone area of a water-mmc-water wall in relation to the distribution of water and mmc: water content in outer layer (blue), mmc content (red), water content in inner layer (green), and heating zone area as a percentage of the base case (purple)

**Table 1.** 2 day analysis of water-mmc-water wall on typical hot day and typical cold day

| Water-mmc-water | |
|---|---|
| **Heating**<br>February 12–13 | 10cm water (green)- 15cm mmc (orange)- 35cm water (brown)<br> |
| **Cooling**<br>August 3–4 | 10cm water (green)- 15cm mmc (orange)- 35cm water (brown)<br> |

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## CONCLUSION

Complexity is an important aspect of natural systems, and the three-layer wall system was the most complex type of assembly tested in this project Furthermore, the fact that the water-mmc-water wall has a clear correlation between the arrangement of the layers and the effectiveness of the wall evokes the spatial conditions of the biological system where proximity and specific architecture is a necessary aspect of the chemical system. It is the three-layer wall system in which efficiency correlates with a certain degree of diurnal temperature oscillation for the entire year.

The temperature profiles (and transmissivity profile) make it possible to begin to observe and compare the behavior of the built thermodynamic system in relation to the behavior of the natural model. However, the ability to make quantitative analyses of the natural and built oscillations was not built into the program. The algorithms outlined in Blasius et al. (1999) would have provided an important quantitative description of the natural model. However, the numerical methods required for those calculations were outside the scope of this project. The successful integration of these equations into SonoranSystems would allow the program to actually compute the degree of biological resemblance of a given wall assembly in terms of quantitative wave-function analyses. Additional validation studies should be made to ascertain the results of this program including construction and testing of a prototype. In addition, improvements (i.e. user interface) could be made to make SonoranSystems useful for others to use. However, this project has shown that it is possible to create a software program where the chemical behavior of a biological model can be compared to the subsequent building system and its thermodynamic behavior as a method of exploring multi-layer wall systems.

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## NOMENCLATURE

$c_p$ = *heat capacity* $[kJkg^{-1}K^{-1}]$

$k$ = *thermal conductivity* $[Wm^{-1}K^{-1}]$

$\rho$ = *density* $[kgm^{-3}]$

$t$ = *thickness* $[m]$

$A$ = *area* $[m^2]$

$V$ = *volume* $[m^3]$

$\tau$ = *transmissivity*

$\alpha$ = *absorptivity*

$\varepsilon$ = *emissivity*

$h$ = *convection coefficient*

$w$ = *width of building* $[m]$

$l$ = *length of building* $[m]$

$T$ = *temperature* $[^\circ C]$

$Q$ = *conduction heat flow* $[W]$

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