# A Bi-Directional Thermal Rectifying Facade ~ for a Hot-Arid Climate

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Designers of the built environment accept the responsibility to understand our local ecosystems to integrate architecture within a specific context of its site. We possess the ability to destroy or survive with our environment—built environment-within-ecosystem—as the two boundaries enter a direct/indirect immersion with each other. This level of responsibility can be achieved on all scales perceived by the conscious condition. On a micro-level, considerations include energy flow and economy of natural resources. On a meso-level, sustainable systems and subsystems determine the human thermal comfort level of a habitable volume. Lastly, on a macro-level, socio-political agendas can be addressed.

A biomimetic, performance-based design solution, inspired by the local flora and fauna, is proposed with consideration of twin ecologies; "'Mind' immanent in the large biological system—the ecosystem" (Bateson 1972, 466). The resulting design solution is a prototype of a south oriented, non-load bearing wall system proposed for the Sonoran Desert, North America. With a proposed site near the United States-Mexican border town of Nogales, Sonora, this wall system will aid in the thermoregulation of a new medical clinic to serve recently deported Mexican migrants from the United States.

## TWIN ECOLOGIES ~ ECO-LOGICS

> 'Ecology' (greek): study of the interaction of living organisms with their inanimate (climate, soil) and their animate environment, as well as the study of resource and energy management in the biosphere and its subcategories. (Daniels 1997, 6).

The built environment presents the preceding definition of ecology. It describes perceivable, measurable boundaries. A theory of *twin ecologies* offers an encompassing concept.

> Bioenergetics—the economics of energy and materials within a coral reef, a redwood forest, or a city—and second, an economics of information, of entropy, negentropy, etc. (Bateson 1972, 466).

Bioenergetics represents the hard sciences with identifying measurable boundaries at specific thresholds.

> …units bounded at the cell membrane, or at the skin; or of units composed of sets of conspecific individuals. These boundaries are then the frontiers at which measurements can be made to determine the assistive-subtractive budget of energy for the given unit. (Bateson 1972, 466).

In contrast, the science of the Mind represents an informational or entropic ecology through a more computational processing system. This

> …deals with the budgeting of pathways and of probability. The resulting budgets are fractioning (not subtractive). The boundaries must enclose, not cut, the relevant pathways (Bateson 1972, 467).

The differences/causes of the bioenergetics ecology give impetus to the informational, entropic ecology. Our sensory manifold perceives these external pathways and processes them through the internal pathways of the Mind. Reason, as a result of processing, allows us to make decisions that influence the built environment. Logic is the fundament of reason—*eco-logics*.

## CLIMATIC EXTREMES ~ DESERTIFICATION

> ...smooth space is constantly being translated, transverse into a striated space; striated space is constantly being reversed, returned to a smooth space. In the first case, one organizes even the desert; in the second, the desert gains and grows; and the two can happen simultaneously. (Deleuze and Guattari 1987, 474-475).

In the built environment, the greatest impacts are atmospheric pressures (local climate). By observing the thermodynamics of the global climate you begin to understand how the flow of energy behaves in relation to the Sun's direct radiation along the curvature of the Earth. "Air movements in the atmosphere are a result of solar irradiation driven by pressure differences." (Daniels 1997, 51). The natural convection loop of the Earth has its greatest impact along the horse latitudes running parallel to the equator at 30° north and south latitudes. Along this equatorial swath, air is heated by the Sun's direct radiation. Cooler temperatures exist along the Earth's curvature further away from the equator due to less exposure to solar radiation. As the two air masses compete to reach a state of equilibrium, the less dense warmer air rises and is replaced by the cooler air inducing a natural convection loop through thermal buoyancy (pressure difference).

> As the air sinks it warms by compression, and because there is no source of evaporating water, it becomes drier with increasing temperature. Not only can sinking air not produce rain, but when it reaches the ground it absorbs water from the soil and vegetation, creating even more arid conditions. (Phillips and Comus 2000, 10).

This thermodynamic behavior causes hot-arid climates along the horse latitudes. Characteristics of this climate zone include a surplus of solar radiation exposure and extreme seasonal and diurnal air temperature differences.

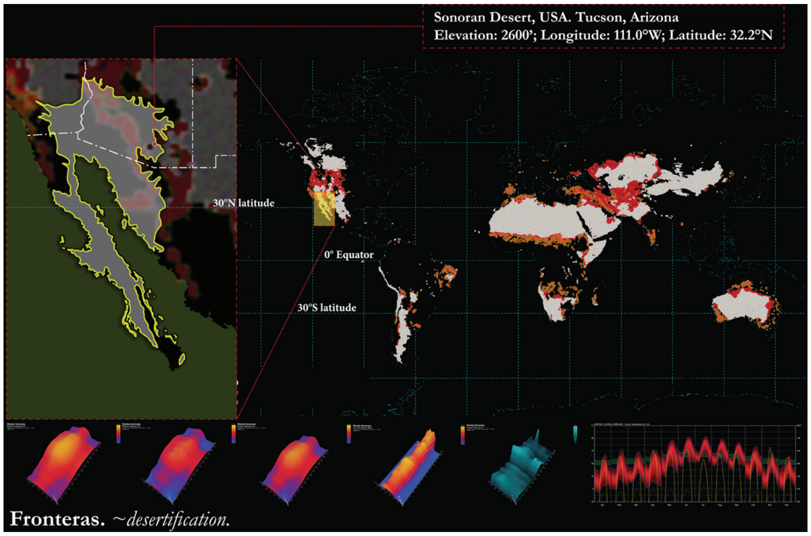

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Figure 1: Global Desertification (White = Current Desert; Red = High Vulnerability; Orange = Very High Vulnerability) + Local Climate Data generated from the Weather Tool in Ectotect (bottom of image).

Generally speaking, the thermal enclosure of a habitable volume does not perform efficiently enough to maintain a self-sufficient human thermal comfort level. To adapt to the extreme temperature difference, mechanical systems are implemented to condition the space. The burning of fossil fuels as a result of these systems' extraneous use and unsustainable growth in these areas resulting in the urban heat island effect have been linked to an increase in greenhouse gas emissions and the deterioration of the ozone layer. As a result, the intensity of the Sun's radiation will exaggerate the convection loop causing more hot-arid conditions, *desertification*. Desertification describes the difference of this growth, which blurs the boundaries of arid lands as it expands and adapts with adjacent ecosystems (Figure 1).

The Sonoran desert is a region along the northern horse latitude. Temperature extremes in the hot-arid lands vary both seasonally and diurnally.

> The dry, transparent air, and cloudless skies transmit maximal solar energy to the ground where much of it is absorbed and converted to heat; the temperature rises dramatically. At night the same conditions permit most of this heat to be radiated to the sky, and the temperature plummets. (Water vapor, either as humidity or cloud cover, reflects infra-red heat and slows heat loss.) Daily temperature variation can be more than 50°F (28°C). The same conditions create great seasonal fluctuation. High-elevation deserts that have 100°F (38°C) days in summer can experience nights below 0°F (-18°C) in winter. (Phillips and Comus 2000, 12)

In the Sonoran Desert city of Tucson, Arizona (Elevation: 2600 ft; Longitude: 111.0° W; Latitude: 32.2° N), desert conditions are more extreme. Tucson is affected by a rain shadow desert effect from the surrounding mountain ranges and prevailing winds. An approaching weather system will drop its moisture on the windward slope and descend on the leeward slope where it warms and dries. Additionally, unsustainable urban growth in this area exacerbates these drier conditions. Desertification swells.

## BIOMIMETICS ~ ADAPTATIONS

> The flexible environment must also be included along with the flexible organism because; the organism which destroys its environment destroys itself. The unit of survival is a flexible organism-in-its-environment. (Bateson 1972, 457).

A study of local natural ecologies and their behavior in extreme climatic conditions is analyzed to offer insight to a biomimetic, performance-based design solution. The native flora and fauna offer insight to design techniques/strategies that can inspire building practices to have a more cohesive exchange/interchange within its ecosystem.

Equipped with motor skills, the local fauna seek shelter to create habitat, moving into shaded areas or microclimates and even burrowing as a thermoregulation technique. Additionally, the fauna hunt and gather at opportunistic times of day in extreme heat, early morning, evening and during the night to minimize excessive heat gain for survival.

The local flora does not have the capability of free movement. The morphology compensates with inherent passive and active *eco-logic* design strategies. The passive strategies include smaller leaf profiles (some with spines—a modified leaf profile), which achieve minimal surface to reduce transpiration and water loss as well as limit direct solar radiation, water conservation/harvesting and self-shading techniques. Active systems include the CAM process of photosynthesis, where the stomata opens at night to avoid excessive daily heat gain in order to perform the gas exchange necessary for photosynthesis.

Since the habitable built environment has physical boundaries of mostly permanent/immobile systems, as with the flora, the following observations were locally observed.

In the analysis of a Barrel Cactus, the ribs are more frequent at the south and south-west orientations; the areas of the most solar radiation/heat gain. The cylindrical, undulating surface design also manipulates the convective currents within the thermal boundary layer for self-thermoregulation. Additionally, the spines and thorns serve as a self-shading strategy and host the location of the stomata as a component of the CAM process. The presence of chlorophyll in the Palo Verde tree’s green trunk assists with photosynthesis. The species is also drought deciduous and have a very small leaf profile.

Agave plants open their leaves to capture and divert rainwater to their roots during winter rains. The Prickly Pear Cactus is characterized by their large pads called cladodes which have a more direct surface exposure to extreme radiation. The cladodes have spines and glochids which help diffuse direct solar radiation and minimize heat gain. The growth of the cladode array enables self-shading for the entire plant while diverting rainwater to its roots.

### PROBLEM STATEMENT

In cities with hot-arid climates like Tucson, Arizona, modulating the diurnal average temperature difference of 27.8°F (15.3°C) is the critical problem in maintaining consistent interior human comfort level for each season. How can the thermal boundary layer be optimized to mediate the temperature value extremes?

### HYPOTHESIS

Flexibly controlling the heat flow through the thermal boundary layer of a conditioned volume may yield a consistent indoor temperature value. To create a more integrated environmental response, the phenomenon of thermal rectification is implemented to modulate the diurnal temperature differences for each season. This is realized through the prototype development of a responsive, non-load bearing wall system with a southern orientation for the Sonoran Desert, North America.

### METHOD

The prototype of the wall system addresses ecology on the micro-meso-levels and the architectural application of this system can be perceived the macro scale. To coexist within the local ecology, the built environment should possess the same or modified *eco-logic* strategies. This includes passive and active systems to enable a sustainable human thermal comfort level.

### MICRO-LEVEL: ENERGY FLOW ~ HEAT TRANSFER

> Climate' is a subtle thing, and includes a sort of micro-meteorology. A sheltered corner has a climate of its own; one side of the garden wall has a different climate to the other; and deep in the undergrowth of a wood celandine and anemone enjoy a climate many degrees warmer than what is registered on the screen. (Thompson 1942, 217).

Thermal energy is the manifestation of the vibration of atoms. Heat can be perceived as tiny packets of vibrations called phonons. Phonons are a quantum mechanical version of a special type of vibration motion in which each part of a lattice oscillates with the same frequency. Molecular diffusion describes this random movement of particles through a medium which flow from a region of a higher concentration (of temperature or pressure) to a region of a lower concentration. When heat by the way of thermal energy is introduced into a system, or through a medium, heated molecules become excited and will flow to a region of less excited molecules across a temperature gradient. The particles will continue to flow with the intention of equalizing the two temperatures, achieving a steady state of equilibrium. Because molecular diffusion is a random movement of particles it is challenging to control the heat flow in a system.

A thermodynamic system is a set of material variables—temperature, pressure, density and internal energy—that are different from their immediate surroundings. The boundaries between the energies consist of non-visible phenomena. The difference between these energies takes form in what is known as the thermal boundary layer. Consisting of multilayered zones of activity, energy exchange and mostly non-visible phenomena, the thermal boundary layer taken as a whole introduces a concept of boundary as a behavior. “This where energy transfers and exchanges form and where work acts upon the environment.” (Addington and Schodek 2005, 51-52) Only heat and work can cross this invisible boundary. This threshold operates as the transition mediating the exchange between one or more sets of variables. In the built environment, the boundary layer exists where a conditioned volume (the interior of a building) meets an environment of different variables and conditions. This typically occurs at the enclosure boundary of a building (wall, floor and roof systems). Managing the energy exchange through this physical boundary will control the difference between the two given volumes.

Is it possible to control the random movement of phonons (heat) through this physical~thermal boundary layer?

Thermal rectification is a phenomenon observed in thermodynamics which allow phonons to flow in one direction at a time with the use of a rectifying system. A thermal rectifier, or diode, works similar to an electric diode allowing unidirectional flow of electrically charged molecules. However, the flow of energy behaves in a more direct polarized flow. Enabling flexibility of heat transfer through the rectifier (wall system) may help modulate seasonal and diurnal temperature extremes to achieve and maintain an acceptable human thermal comfort level.

Heating and cooling degree days were evaluated to determine the heating and cooling season for the specific climate. The corresponding sun angles for each month were studied to determine how radiation could aid in the regulation of the internal thermal environment to moderate the extreme climatic conditions.

The goal of the wall system is to block solar gain and heat transfer to the interior, insulated space during the cooling season and retain solar gain through thermal mass in the heating season and cooler night temperatures. To achieve this goal a careful optimization of the three modes of heat transfer (conduction, convection and radiation) needs to be implemented to control the diffusion of these phonons.

Passively, conduction and convection could be used in the cooling season to diffuse heat transfer from solar radiation. Conduction retards daily heat gain through the material properties and thickness of the enclosure system. Convection enables night flushing of excess heat gain into the interior.

In the heating season, radiation and conduction strategies could be implemented to harness interior daily heat gain. Radiation adds heat to the habitable space for daily solar gain. Conduction, through thermal mass that is charged by radiation, can retard the heat flow through the enclosure across the temperature gradient to the cooler exterior air mass. Blocking natural convection through the thermal boundary (to the exterior) will disrupt the loop preventing escaping heat; instead, retaining it to condition the interior volume.

The heat transfer concepts previously noted are mostly passive heating and cooling solutions. Due to the limits of these passive strategies, active strategies may be implemented in extreme climatic conditions. As previously mentioned heat and work can cross the thermal boundary layer. Heat can be converted into work through a responsive, active component within the system. Because a rectifying system can only transfer heat in one direction at a time, a bi-directional thermal rectifying component incorporated in an enclosure system could serve as the active strategy. This will allow a flexible oscillation between heating and cooling modes to enable a direct exchange with the surrounding thermal environment. This would better assist thermoregulation of the interior to coexist with extreme diurnal and seasonal temperature differences.

### MESO-LEVEL: PROTOTYPE DESIGN ~ EXECUTION

The meso-level accumulates the effects of the components operating at the micro-level into a more comprehensive system. This comprehensive system represents the built environment. A biomimetic approach was executed to commence the design for the working prototype in an attempt to integrate the design into the local climate and natural ecosystem, its site.

Two passive and one active biomimetic elements are observed and implemented into the design. First is the morphology of the cladodes of the Prickly Pear cactus. Depending on the orientation, cladodes have a large amount of surface area exposed to direct and indirect solar radiation. To reduce solar gain two passive shading strategies are employed for each individual pad: the spines and glochids and surface deformation. The active strategy is the movement of the stomata during the CAM process.

Thermoregulation in extreme temperatures challenges the performance of the enclosure of an interior volume. An analysis of the effects on the thermal environment was evaluated to develop a strategy to optimize the relationship between the two volumes; a conditioned interior space and the exterior environment.

In passive heat transfer design the wall system will allow for direct daily solar gain during the heating season and block direct daily solar gain during the cooling season through natural convection and conduction.

The active element of the wall system will attempt to create bi-directional thermal rectification by controlling convection, the fastest and most easily controlled mode of heat transfer. The opening and closing of a thermally actuated damper will have the ability to retain the heat for nighttime heating and allow nighttime flushing of excess heat gain by modulating the natural convection loop. The damper offers the bi-directional effect of heat transfer in order to control the random lattice movement of phonons. The active element in the damper will be composed of a bi-plastic material; thermo-responsive. This concept works on the logic of different coefficients of linear expansion. Actuated at a specific temperature threshold, heat will then be converted to mechanical work, allowing for a porous exchange between environments to assist in bi-directional thermal rectification.

In developing the morphology of the prototype module, geometrically derived minimal surfaces are implemented to mimic the surface deformation

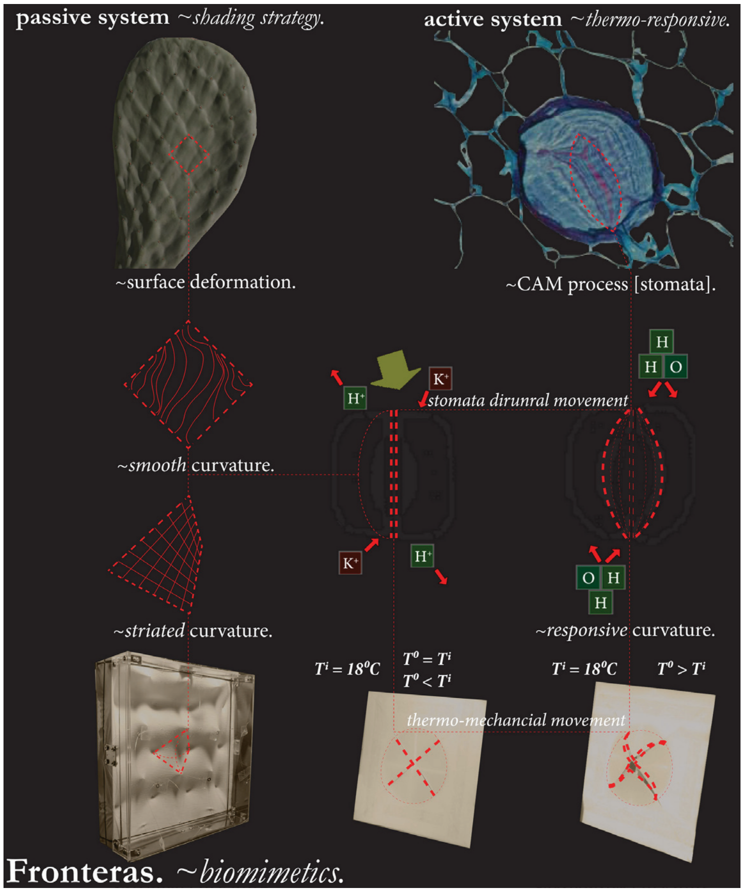

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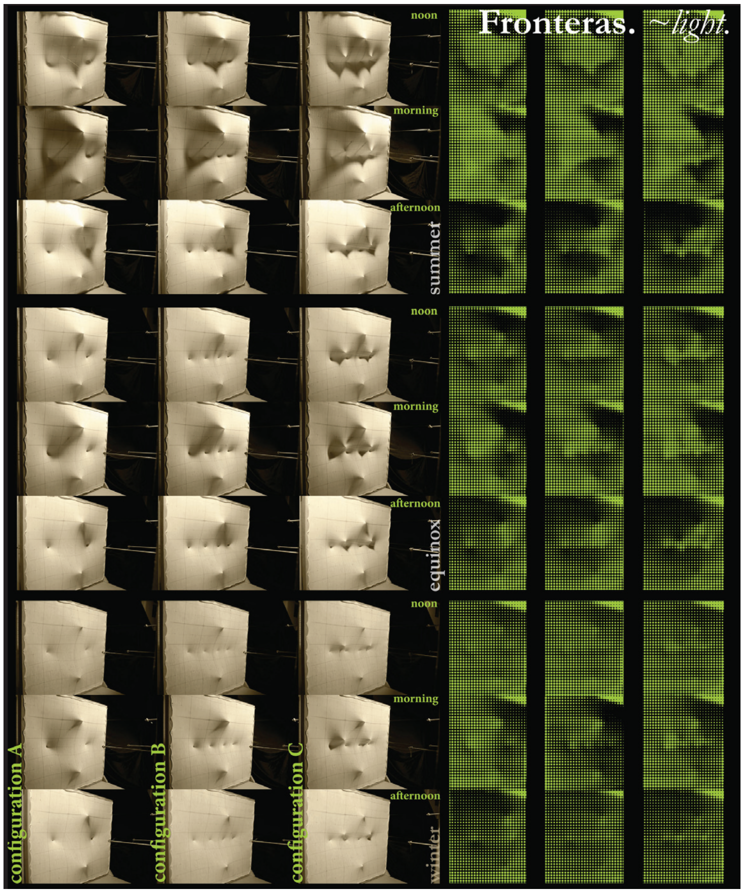
Figure 2: Biomimetics/logics

shading strategies of the Prickly Pear cactus. The India Fig Cactus, *Opuntia ficus-indica*, was chosen because of its smaller spines and greater surface deformation.

Minimal surfaces in the built environment are geometrically derived by a ruled surface (curvature created by constructing a series of straight lines connecting points along two lines of different, yet corresponding coordinates in a Euclidean grid).

The hyperbolic-paraboloid is a ruled surface geometry which mimics the surface deformation shading strategy of a Prickly Pear cladode (Figure 2: top left). The generation of this geometry is easily constructed by connecting points with lines on two parallel, skewed lines. A field of these forms can create an undulating surface to serve as self-shading. Additionally, minimal surface geometries result in an economy of materials, using only what is needed to achieve the essence of the form.

Form-finding logic commenced with a pre-tensioned fabric-form using two opposing grids to dictate the prototype's achievement of hyperbolic-paraboloid geometries. The pre-tensioned fabric maintains the minimal surface construction method of an abstracted representation of a series of straight lines, on a smaller scale. An acrylic jig (14"x14"x5") with a pre-tensioned fabric



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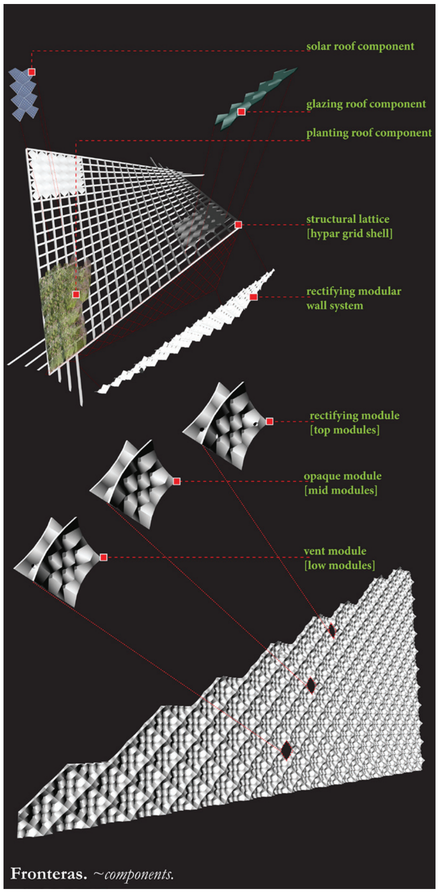

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stretched across the center was constructed and evaluated with a set of light studies to analyze the proposed shading strategy (Figure 2: lower left).

A second jig (24"x24"x42") was constructed to better define and control the points within a three-dimensional environment (Figure 4: top). This consisted of two wood frames with threaded rods suspended within acrylic panels (attached to the wood frames). In the center were two frames with pre-tensioned fabric. Nylon wire (fishing line) was stitched into the fabric and fastened to the rods. As the rods moved horizontally, points along the fabric are altered, realizing different minimal surface synclastic and anticlastic curvatures.

With a series of simulated Sun studies, an aperture is designed in response to the local sun angles to allow or block the solar radiation for each season. This process is used to better define the module, which will be stacked to form a series of hyperbolic-paraboloid modules to create an overall wall system (Figure 3: left). Light intensities were graphed and evaluated to establish the final fabric form model (Figure 3: right).

Once the morphology of the module was defined through the form-finding logic it was solidified with several coats of polyester resin (Figure 4: middle-top). These physical models will assist in mold making for the final module and allow for more precise digital fabrication.

Figure 3: Light/Sun angle studies with graph of light intensities.

Figure 4: Form-Finding and Prototype Fabrication Process

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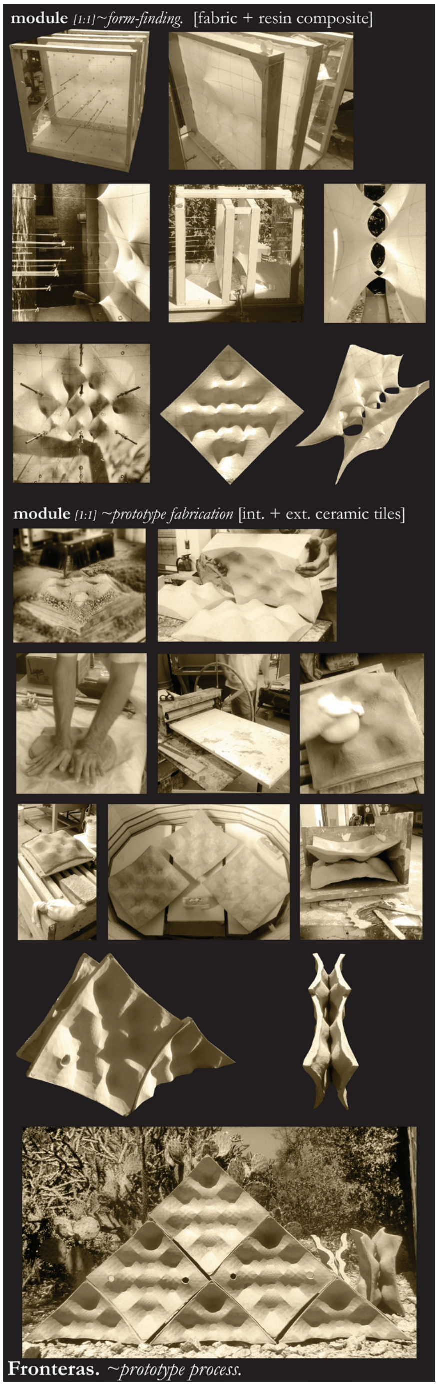

Figure 5: Medical Clinic Components + Wall System.

The geometry of the models was then digitized into a wood mother-mold generated from a three-axis CNC machine. Several plaster molds were poured from the mother-mold for optimization.

For a better structural and thermo-regulative solution, a cone 5 stoneware (Calico from= Laguna Clay) was proposed. To mimic the form of the fabric-resin composite models (with an interior air cavity), two pressed ceramic tiles (interior/exterior) would replace the composite material. The clay was pressed into the molds then fired with a Bailey's Oval Kiln in the Materials Laboratory at the University of Arizona College of Architecture and Landscape Architecture (figure 4: lower half). The two tiles were adhered together with PC-7, an industrial adhesive.

Three types of modules are constructed (Figure 5: bottom). The rectifying modules at the top have two apertures on both the interior and exterior face. The thermally actuated dampers will be installed on both faces. The middle modules will be solid-opaque on each face to allow airflow/heat transfer within the cavity. This will induce a thermal buoyancy effect similar to the logic of a trombe wall. The bottom modules will have a solid exterior face and an open aperture on the inside to allow the cooler air to vent into and through the interior cavity.

The active element (damper) proposed is a thermally actuated material called 'c)) motion' developed by Greg Blonder of Talus Furniture (Figure 2: bottom right). These will be installed in the apertures of the rectifying modules and undergo thermal testing and evaluation.

## MACRO-LEVEL: APPLICATION ~ SOCIO-POLITICAL

> "...matter is slow space and space is fast matter...matter and spirit are the same, they follow the same direction...Could spirit be such infinitely fast matter that to our eyes it disappears as matter?" (Ugarte 2000)

The implementation of this wall system into the context of the built environment addresses ecology on the macro-level (socio-political). As proposed, this will be installed as part of the enclosure system of a thermally self-regulating medical clinic.

The geography of the Sonoran desert includes a controversial border between two allied countries. In the United States, national security measures and the government's handling of illegal immigration have questioned basic human rights of deported migrants. The concerns not presented in the national media are the health hazards that arise as a result of this process. To offer a solution, these will be proposed along the United States-Mexican border to serve as a medical clinic for the recently deported. The proposed site will be near the border entry check-point in Nogales, Sonora, Mexico.

Continuing the minimal surface geometry concept, the clinic will be designed as a shell structure in the form of the hyperbolic parabaloid. The nature of creating curvature by connecting a series of straight lines will ease construction techniques to achieve the essence of the design on each scale.

The clinic will be oriented with the thermal rectifying façade facing the south. The grid shell offers framework for a kit-of-roof components to allow flexibility of different roof surfaces. Areas of the roof with a north orientation will contain glazing units and provide ambient daylighting. Roof areas with a southern exposure will contain solar roof components. All other roof components will be planting units. (Figure 5: top).

The doubly curved hyperbolic grid shell will allow for a resolution of structural forces (doubly curved surface ~ compression = tension), rainwater harvesting (allowing the water to gather at the points of contact with the ground) and thermal regulation (allowing the heat to rise within the natural convection loop to actuate the dampers as well as thermal mass from the planting units). The implemented biomimetic design strategies will allow the dwelling to be integrated into the local ecosystem through an enhanced thermodynamic exchange.

## CONCLUSION ~ NEXT STEPS

The dampers will be implemented into the rectifying modules. The modules will be mortared into a mock-up wall and the working prototype will undergo digital and empirical thermal testing to evaluate the performance of the heat transfer concept. Modifications to the module will be proposed once the results have been analyzed.

The final step will be implementing parametric design using a CAD design plug-in, Grasshopper. This will digitally dictate points along the form of the module to correspond to local sun angles and climate data; allowing for a quicker design and fabrication process in other locations specific local climates.

With the addition of parametric design, local data observed and implemented into the design through an algorithmic process, the informational/entropic ecology will become more striated, better informing the bioenergetics ecology—an *eco-logic~twin ecologies*. ◆

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