High Performance Building Envelopes:

Principles from Natural Homologues and Analogues

by Jed Laver
08 December. 2008

A Master's Report Submitted to the Faculty of the School of Architecture. In Partial Fulfillment of the Requirements For the Degree of Master of Architecture in the Graduate College of The University of Arizona.

Emerging Material Technologies
University of Arizona
School of Architecture
Fall 2008

High Performance Building Envelopes:

Principles from Natural Homologues and Analogues

By Jed Laver

A Master's Report Submitted to the Faculty of the Department of Architecture. In Partial Fulfillment of the Requirements For the Degree of Master of Architecture in the Graduate College of The University of Arizona.

Approval by Master's Report Thesis Committee Members:

Dale Clifford, Chair Date
Assistant Professor

Alvaro Malo, Date
Professor of Architecture

Dr. Pamela B. Vandiver Date
Professor of Material Science

Jason Vollen Date
Professor of Architecture Rensselaer Polytechnic Institute

Emerging Material Technologies
University of Arizona
School of Architecture
Fall 2008

The University of Arizona Electronic Theses and Dissertations

Reproduction and Distribution Rights Form

Name (Last, First, Middle) (please print) **Jed Laver**	
Degree (Ph.D., ED.D., MS, MA, etc: **MArch II**	
Major: **Architecture**	
Date you defended: **December 08 2008**	
Title of Dissertation (please print) **High Performance Building Envelopes: Principles from Natural Homologues and Analogues**	
The University of Arizona Library Release	*I hereby grant to the University of Arizona Library the nonexclusive worldwide right to reproduce and distribute my dissertation or thesis and abstract (herein, the "licensed materials"), in whole or in part, in any and all media of distribution and in any format in existence now or developed in the future. I represent and warrant to the University of Arizona that the licensed materials are my original work, that I am the sole owner of all rights in and to the licensed materials, and that none of the licensed materials infringe or violate the rights of others. I further represent that I have obtained all necessary rights to permit the University of Arizona Library to reproduce and distribute any nonpublic third party software necessary to access, display, run or print my dissertation or thesis. I acknowledge that University of Arizona Library may elect not to distribute my dissertation or thesis in digital format if, in its reasonable judgment, it believes all such rights have not been secured.* *Signed:*________________________________ *Date:* __________________________________

Last updated: Feb 15, 2005

Table of Contents

Acknowledgments

We gratefully acknowledge the following people and companies, whose support and services enabled us to reach the current status of the project.

Institutional Support:

University of Arizona: Vice President of Research Office Faculty Initiation Grant

Boston Society of Architects: Research Grants in Architecture

University of Arizona, school of architecture

University of Arizona: Professor Aurore Chabot, ceramics laboratory in the College of Art

Industry Support:

Glaz-Tech Industries Inc.

Architectural Glass and Glazing

Catalina China

Grant Road Lumber

Marjon Ceramics INC.

Solid Concepts

Technical Support:

Dr. William Bickel: UA department. of Physics

Peter Testa Principal in Charge of Design of TESTA Architecture & Design and founding director of the Emergent Design

Paulus Musters: UA College of Architecture & Landscape Architecture, laboratory coordinator

Matt Gindlsburger, technical and analytical support using the CNC laboratory

Brent Vanderworth, providing day to day critics

David Stone Material experimentalist

Dana Smith for the use of her kilns

EcoCeramic Credit

This thesis relies extensively on the EcoCeramic Research project as a medium for proof of concept. EcoCeramic Research is a grant funded research project with Jason Vollen as the Principles Investigator. The author collaborated with Kelly Winn as the principle graduate designers. EcoCeramic is a material driven investigation into ceramics and composites in architecture. Kelly Winn integrated his research of digital fabrication, simulation, and rapid prototyping into the EcoCeramic research process. The author developed a thermal performance building envelope system based off of natural homologues and analogues also integrating his research in EcoCeramic. Each graduate researcher collaborated in the creation of EcoCeramic as a proof of concept for their respected research topics.

Photographs, illustrations and drawings created during the EcoCeramic phase of this project were often created jointly by both the author and Kelly Winn. The author gratefully acknowledges Kelly Winn as the principle photographer during EcoCeramic research. Without whom the project, as designed, would not have been possible. The author further expresses gratitude to his advisors, Dale Clifford, Jason Vollen, Álvaro Malo and Dr. Pamela Vandiver for their extensive input and intellectual contribution to this thesis..

Introduction

Abstract

Design derived from natural homologues and analogues began with the primitive hut and has continued throughout history. Nature in relation to performance driven architecture, however, is a recent and developing field of study. The principles that allow flora and fauna to survive in the arid climate of the Sonoran Desert are investigated for thermal design strategies, specifically that of the barrel cacti and termite mounds.

The design principles are studied, tested, and integrated into a masonry wall system, EcoCeramic. EcoCeramic is grant funded research project charged with investigating composite materials in ceramic architecture. The project moves through prototyping, fabrication and assembly of the wall system. By integrating natural homologues and analogues into EcoCeramic research the designers intend to decrease the summer thermal gains, and increase the solar gains in winter months.

The masonry wall will test and demonstrate the design potential of ceramics and the effectiveness of passive design strategies. Testing is accomplished through the use of data loggers, guarded hot box and control tests for smaller experiments. This project is a detailed report of the fabrication, testing, and optimization of materials and full scale units, as well as the integration of the recorded design data into a performance profile.

Introduction

Located in the upper Sonoran Desert, Tucson Arizona is a growing city with construction practise primarily utilizing stick frame construction (Energy Information Administration EIA). While visitors often remark on the 'greenness' of the desert, Tucson citizens utilize intensive climate control. Although the local vegetation is well suited for long days of intensive solar exposure it too cannot survive without its own climate modification methods.


Fig. 1. US Map

Project Parameters

This thesis applies the relationship between thermal and structural principles found in natural homologues and analogues to the field of architecture. The investigation is primarily centered on the application of thermal principles found in nature into a ceramic masonry wall system.

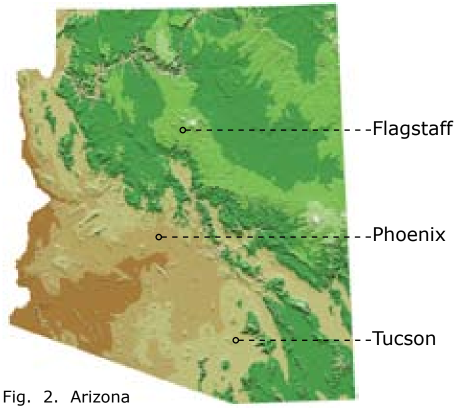


Fig. 2. Arizona

Research Objectives

The intent of this research is to demonstrate principles found in natural homologous and abstracted into an architectural application fulfill the following requirements.

- Directly influence the thermal performance (thermal transfer) of a building
- Cost effective building methodology
- Streamlined manufacturing techniques
- Standardized assembly methods
- Adaptive design technique to local climate characteristics

Methods

The primary mode of investigation is research based design. Geometric forms and materials will be designed and tested to scale. Technology transfer and application will complement the primary research. The research is concerned with both the implementation of thermal principles into the building envelope and the feasibility of mass producing a new building block for a given location. Testing methods include both the use of Hobo data loggers, EcoTect, and Flow wizard.

Regional Weather Trends

To some, global climate change remains a scientific uncertainty; however, empirical evidence is clear: regions of the earth are experiencing abnormal and severe weather patterns (NOAA comparative climate data). In the arid region of Southern Arizona, the average temperature has increased 2.5 degrees in the last 50 years, while the number of cloudy days and the inches of annual rainfall have decreased (Arid Land Institue) (NOAA Tucson Historic Temperatures). This increasingly hot and arid climate necessitates a unique and bio-climatic response in order to effectively dwell in the region.

50 year average Temperature & Precipitation

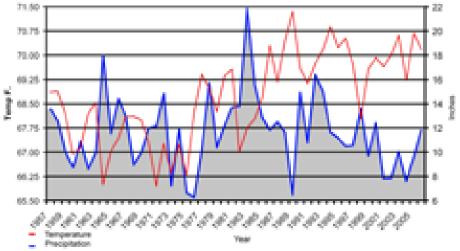


Fig. 3. Average precipitation and Temperature

2008 Arid Lands Institute University of Arizona

Regional Building Culture

In an age of economy and mass production, many building projects use international building techniques and assemblies regardless of place. Regional architecture is often relegated to a boutique style or dismissed off-handedly as traditional. Of the homes in Phoenix, Frank Loyd Wright reports: "...three fourths of the dwellings here are of wood and brick brought from great distances and worked up into patterns originated, east, and thirty years ago. The houses are quite as indigenous as a cocked hat and almost as deciduous; one half of the cost of the whole-freight." (Wright p141).

Fig. 4. Stick & Frame Construction

In southern Arizona, the arid climate necessitates an understanding of the properties of building materials and the principles of thermodynamic performance. Contractors, architects, and builders are aware of the high thermal conditions of the Sonoran desert. The most common response to the heat is a standard formula to mitigate the environmental forces; this includes the use of higher R-value wall sections, reduced fenestration, and more "efficient" air conditioning units. In 2001, the Department of Energy (DOE) reported that the implementation of these strategies is marginally effective: buildings were only maintaining the interior micro climate in the range of 60% efficiency (DOE 2001 Residential Energy Consumption survey).

In contrast to these more "modern" architectural techniques, the traditional rammed earth architecture of the Southwest region has relied on the principles of thermal mass. Construction of a high thermal mass home is labor intensive and consequently perceived as cost-prohibitive. Typical estimates for rammed earth construction can range from 50 to 100 dollars more per square foot than stick framing. The designers can postulate that the primary reason for a lack of thermal mass appropriation is an inadequate understanding of the thermal environment and a lack of familiarity with the vernacular construction.

Fig. 5. Rammed earth Construction
Photograph from flicker.com

Energy Impact

The Laws of Thermodynamics state that when two systems come into contact with each other, there will be a net exchange until the two are in thermal equilibrium. The greater the thermal difference is, the more rapid the thermal exchange. Thus, in the standard Tucson home, on a 37°C day, with radiant temperatures approaching 48°C, an air conditioning unit must run constantly to maintain the standard 23°C interior temperature. The 9°C difference in radiation thermal gain is what sets the Sonoran desert region apart as unique. The national impact of AC translates to 1,000 *kgs* of CO_2 per person per year, or 300 billion metric tons of CO_2 per the United State population per year for cooling alone. (EIA DOE) In southern Arizona, the average person consumes 1,500 *kgs* of CO_2 per person per year (DOE)

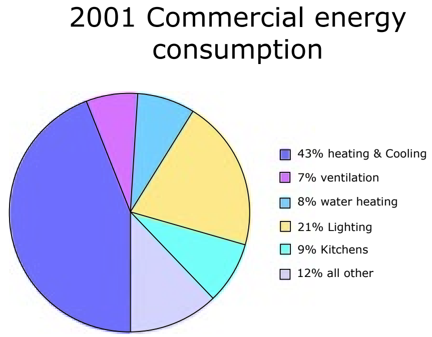


Fig. 6. Commercial energy consumption
2001 Average residential energy consumption

The energy cost of mechanical cooling is significant as the average Tuscon citizen spends nearly 797 dollars annually for cooling alone (2001 DOE). Escalating energy costs further the financial and environmental impact of living in accustomed comfort levels. With over 17 billion dollars spent annually on residential cooling per year, even the smallest increase in energy costs has significant economic bearing.

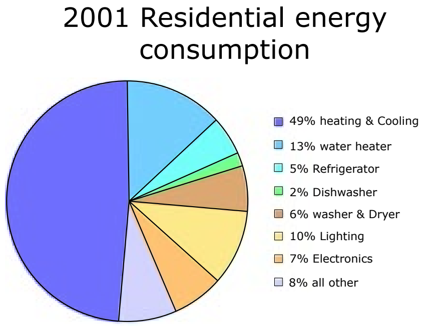


Fig. 7. Residential energy consumption.
Residential Energy Consumption Survey 2001

While innovative construction may be more expensive up front, the real savings is in long term energy savings. When occupants of both residential and commercial pay more than 40 percent of their energy bill on climate control the energy saving potential is substantial.

This thesis report attempts to solve a problem found in the inadequacy of current building skins for the Tucson climate. Furthermore it aims to inspire the art of ceramics in the building industry as a potential fully integrated building skin. This report details the research, design, prototyping, and fabrication necessary to introduce a new typology of building technology.

Homologues and Analogues

Barrel Cacti

Barrel cacti were investigated due to their obvious ribs and valleys and their ability to self shade. Investigation revealed the following:

The researcher observed that

- Cacti thorns change color by elevation.
- Cacti thorns change color from base to tip.
- Cacti change in geometric and tissue density.
- Cacti lose more water in winter than summer due to aperture openings.
- Cacti modify micro climate in radiation absorption and convection.
- Sources: Lewis & Nobal, Watson, Gibbs, Smith

Applying these findings to architecture, the following possibilities emerge

- If a wall system used localized density and intentional conductivity, it could maneuver thermal loads to the ground or the air.
- If a wall system had a gradient density in material and geometry, the top and bottom of the wall would respond differently (to heat/thermal energy).
- If the skin worked primarily to shade and reduce radiation on horizontal surfaces the interiors could maintain comfort levels for longer durations.
- If the geometry prohibited or limited solar access during the hottest periods, perhaps the cooling load would change.
- The system could transfer heat to the ground via the foundation, the root system.


Fig. 8. Barrel Cacti rib


Fig. 9. Barrel Cacti

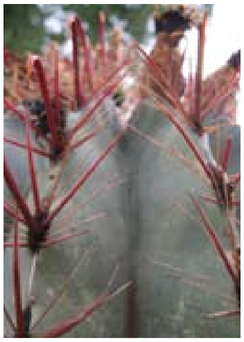


Fig. 10. Ribs


Fig. 11. Winter, apex


Fig. 12. Summer apex

Termite Mounds

Termites and termite mounds were investigated due to their well known thermal and ventilation properties. Furthermore, termites were investigated due to their inspiration of East gate Harare.

The researcher observed that

- Termite mounds respond to solar exposure.
- Termite mounds ventilate in response to solar angles and climate.
- Termite mounds have increased surface area to volume in response to the greater the solar exposure.
- Termites build to a cooler temperature than desired.
- Termites have a very strict thermal and humidity tolerance levels.
- Sources: Korb, J. et all, Skaife,

Applying these findings to architecture, the following possibilities emerge

- Stack and horizontal ventilation should respond to ambient temperatures, creating micro climate winds.
- Thermal mass and thin shell construction could be re-thought with ventilation and stable core temperatures in mind.
- If ventilation played a more major role in future construction, energy cost could be greatly reduced.
- If architecture responds to solar exposure, solar intensity, and minor climate passive systems, it can become more effective.
- If an insect with a 2 degree tolerance can survive in a climate of 20 degree thermal swings, mankind may be able to abstract ventilation and orientation principles for a higher degree of thermal comfort by utilizing passive systems.

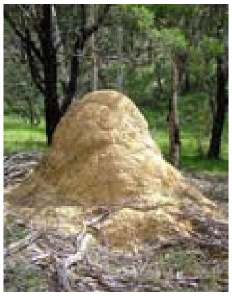


Fig. 13. Dome mound

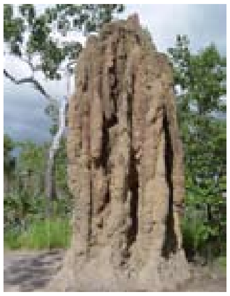


Fig. 14. Cathedral

Photographs from flicker.com

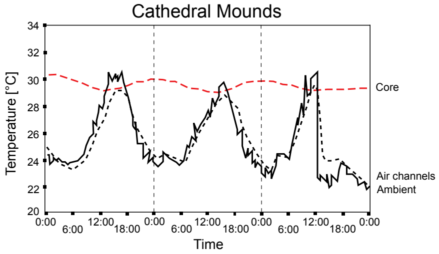


Fig. 15. 3 day thermal cycle (Korb, J)

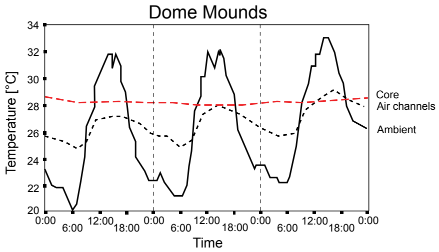


Fig. 16. 3 day thermal cycle (Korb, J)

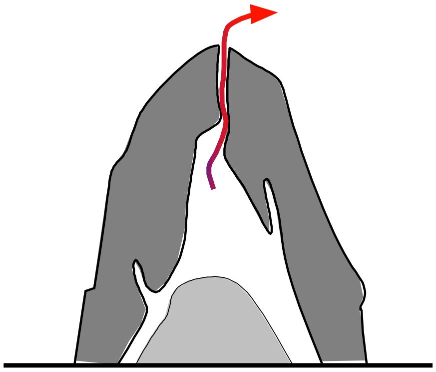


Fig. 17. Dome mound

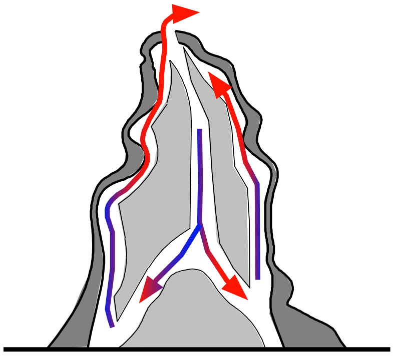


Fig. 18. Cathedral mound daytime

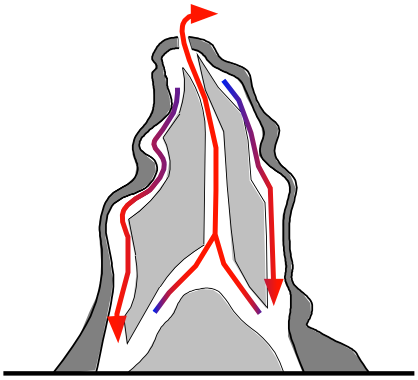


Fig. 19. Cathedral mound nighttime

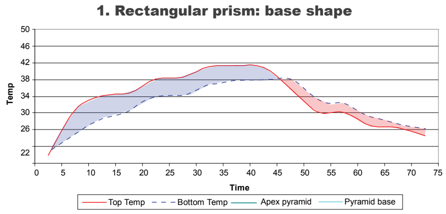
Thermal Experimentation

Since the surface of an object impacts the thermal loss potential, could a surface impact the radiant thermal gain as well? These experiments use aluminum because the thermal transfer occurs at a faster rate than concrete, easier to form precise shapes, and the pure material section. Tests were conducted using a control form, omega thermocouples, and sample sizes 10 cm by 10 cm with variations in height depending on the surface topography.

Several forms were investigated, including variations on convex/concave, rectangular groves, and lastly pyramids. For these tests, the mode of investigation involved the more precise omega thermal couples, control volume, and the same mass.

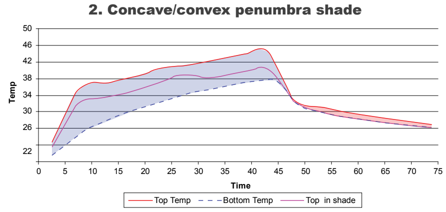
Octahedral pyramids had the highest surface area to mass ratio, and best mitigated surface radiation. Introducing octahedral pyramids to the exposed surface decreased the thermal penetration by 9°C. While maintaining the exact same net surface temperature as the base case.

Placing the octahedral pyramids on the underside surface and maintaining a flat exposed surface, I found that the exposed surface heated 2°C over the base case, while the underside surface increased 3°C. The thermal inversion in relationship to the surface topography indicates that the surface area of both sides directly impacts thermal flow through the material; However, the surface exposed to radiant heating has the most impact on thermal transfer through the material.



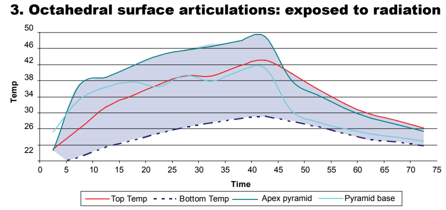
Exposed surface: 48°C
Underside surface: 42°C

Fig. 20.



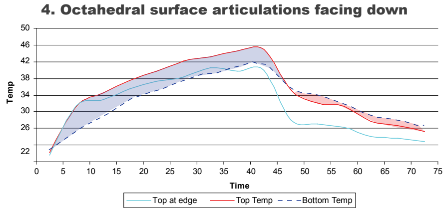
Exposed surface: 47°C
Underside surface: 42°C

Fig. 21.



Exposed surface: 47°C
Underside surface: 33°C

Fig. 22.



Exposed surface: 49°C
Underside surface: 45°C

Fig. 23.

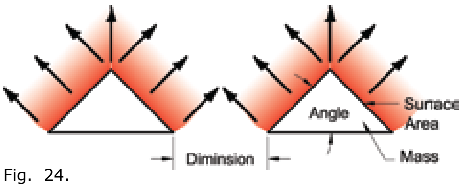


Fig. 24.

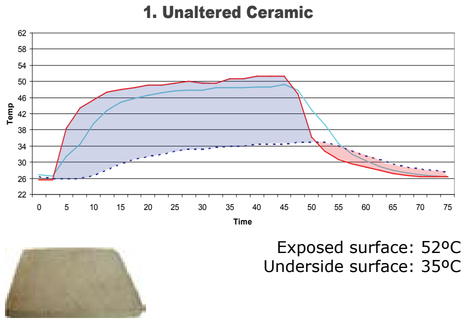
Optimization of surface area to mass in section

Ceramic Experimentation II

This series of graphs is a continuation on the experiments with aluminum. Specifically these tests are about the addition of color, ventilation, and evaporation as strategies for cooling or heating a surface. Using a control volume and control sample, these tests were conducted with the hobo data loggers, terra-cotta clay samples 9 cm by 9 cm by 1 cm.

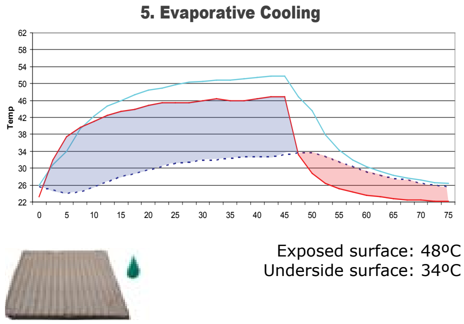
Evaporative cooling was conducted after the ceramic body was saturated, containing 6% water by weight, and then exposed to radiant thermal gain. Saturation of the ceramic proved to cool the unit by 4°C. Ventilation cooled the surface by 10°C. Combining both evaporation and ventilation cooled the surface by 15°C.

In addition to testing cooling, the designers sought to find out the effect of color change on thermal gain. The designers found that a dark blue stain would allows for a 7°C increase in total absorbed radiation. This technique, similar to barrel cacti could be utilized in areas exposed to winter sun only.



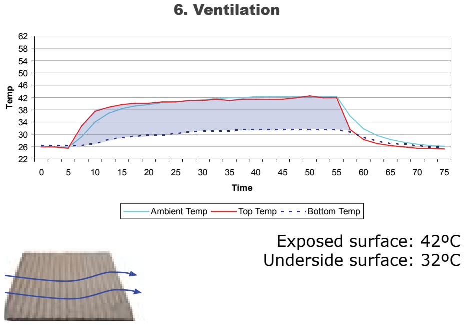
Exposed surface: 52ºC
Underside surface: 35ºC

Fig. 26.



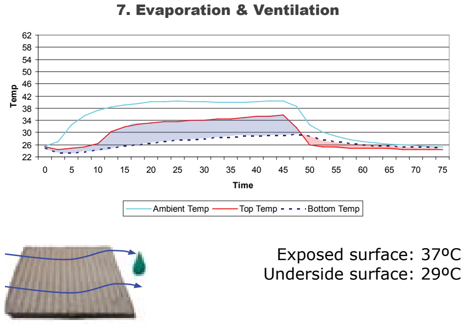
Exposed surface: 48ºC
Underside surface: 34ºC

Fig. 27.



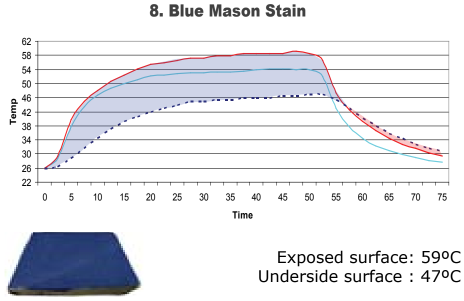
Exposed surface: 42ºC
Underside surface: 32ºC

Fig. 28.



Exposed surface: 37ºC
Underside surface: 29ºC

Fig. 29.



Exposed surface: 59ºC
Underside surface : 47ºC

Fig. 30.

Potential application of experimentation

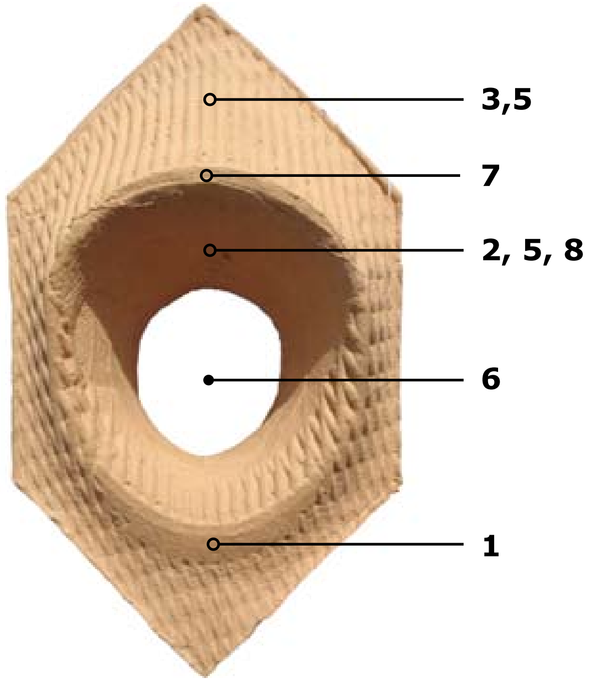


Fig. 25.

Design strategies

Typical construction standards for both cold climates and hot climates use insulation as the primary thermal strategy. Many believe that the greater R value will decrease or eliminate thermal gain. The R value impacts thermal transfer, but conduction is only a single mode of transfer, and not necessarily the most significant for all regions of the world. In order to better understand thermal transfer, one must abstract several principles:

Thermal exchange

Heat always moves from hot to cold, the greater the temperature difference, the faster the flow. In this way it is similar to electricity, which moves from a positive to a negative charge. Like electricity the greater the difference between two extremes the less the medium of transfer matters (excepting total insulators).

Thermal radiation

Radiation behaves in the same wavelengths as light, being reflected to the same magnitude and emitted at similar magnitudes. Materials that reflect well tend to radiate well.

Thermal path (conduction)

Once again similar to electricity, heat moves through the material with the least resistance and easily transverses great distances to avoid exchanges through resister material, insulation. Conduction is the most significant means of thermal transfer through a material.

Convection

Any thermal transfer through liquids or gasses is convection. Convection is second most common method of cooling in humans, air, and in conditioning applications.

Laws of thermodynamics

From the first law of thermodynamics the energy input into a wall or roof surface must equal the energy output. Without a means to direct the energy it will follow the course of the second law of thermodynamics. The thermal differences between two environments, interior and exterior, will reach equilibrium. The greater the thermal difference the faster the thermal transfer. The thermal transfer equals change of temperature over change in time.

Applications

In hot and arid climates a home with a high R value offers little protection to occupants against thermal gains. Desert climates are particularly affected by radiant thermal gains as opposed to convection and conduction thermal gains experienced in northern climates.

Radiation applied

Design strategy 2:
The EcoCeramic wall system has an articulated surface to provide summer shade, penumbra, and allows winter solar thermal gain. The penumbra shaded region maintains a 4°C (7°F) thermal difference compared with a surface directly exposed to solar radiation. Even with 50 percent shading, the interior temperature can still fluctuate, 24-42°C, similar to a non-shaded system. Shade delays the heating cycle and lowers the intensity of thermal gain.

Design strategy 3:
Radiant thermal gains with pyramid surfaces decreased the thermal transfer through the sample up to 10°C (18°F) compared to a smooth surface. By applying the CNC tool path to the solar exposed surfaces the designers hope to decrease the net thermal transfer through the system.

Design strategy 8:
The application of a dark stain to the ceramic body influences solar absorption/reflection. During the most intense solar periods, white reflects up to 50 percent of incoming radiation, while the winter the black absorbs up to 96 percent of incoming radiation (Parmer). Experimentation showed that the application of mason stain increased the amount of heat transferred through the material by 12°C (21.6°F). Thus the face tile has dark mason stain applied to the cone which receives winter sun, allowing the tile to warm the surrounding air.

Convection applied

Design strategy 1:
Similar to the thermal regulation strategies of the termite mounds, the overall geometry and the surface articulations generates a non-laminar air film moderating convection gain and loss. The cone contains a smooth surface and employs principles of air pressure.

Design strategy 5: Evaporative cooling is an effective means of tempering interior thermal conditions in arid regions decreasing the overall energy demand from air conditioning (Berman). The masonry wall system utilizes the evaporative cooling as the under fired ceramic will be exposed to water. For example, on a 38°C (100°F) day, with 15-35 percent relative humidity (RH), evaporative cooling will lower the wall surface temperature and immediate surrounding air temperatures by 8-14°C (14-25ºF) (NOAA). When RH rises above 50 percent, evaporative cooling becomes ineffective. In southern Arizona, the RH consistently remains at levels below 40 percent during daylight hours most of the year (Berman).

Design strategy 6: Separating the face tile from the structural brick enables air flow upwards through the wall system driven by draft and thermal differences between the top and the bottom wall temperature. Constant vertical air movement during from April to October evacuates the thermal load from the wall system.

Design strategy 7: Combining principles 5 and 6 cools the air and moves it increasing the net effectiveness of either strategy.

Conduction applied

Design strategy 9: By suspending the face tiles from the structure, the designers hope to decrease the thermal conduction through the wall at the surface, and encourage natural convective cooling inside the wall section.

Design strategy 10: The interior portion of the system contains expandable foam insulation with an R value of 4 per inch and 3 inches thick. The last layer of defence prevents undesirable lateral air movement.

Design strategy 11: The wall system uses thin tiles varying from 1-3 cm in thickness depending upon location. Similar to the cathedral mounds, tile portions exposed to summer sun are thin, 1 cm, enabling the masonry to absorb and release heat quickly. In the dome mounds, the tile's cone is thicker and serves as a heat sink.

Thermal Principles

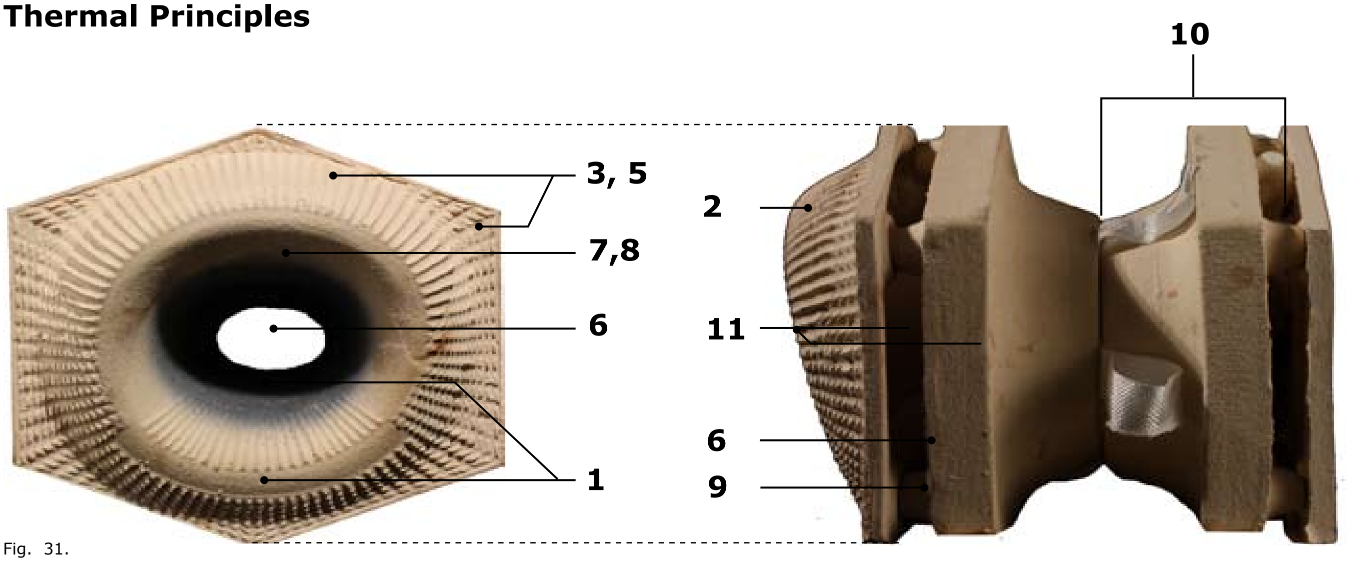


Fig. 31.

Fig. 32.

EcoCeramic Research

EcoCeramic Research

EcoCeramic Research is a funded research project charged with investigating ceramics as an alternative building material. Funds were granted from the University of Arizona faculty initiated research, and the Boston Society of Architecture. Two segments from the grant application are worth noting bellow.

Problem statment

This grant will fund the fabrication, testing and optimization of materials and full-scale panels, the correlation of the generated design data into a desired end-product performance-profile, and the fabrication of ceramic composite building panels that will be assembled into a permanent shade structure on the U of A campus. Specifically, the initial phase of the project involves making several molds for the slip casting of the ceramic testing shells, assembling the heated lamination press, producing multiple iterations of composite test panels with varying degrees of multidimensional complexity, and performing initial strength tests to gather data on design-performance criteria of the building products. The refined building products will be assembled collaboratively on campus, as a newsworthy demonstration of the new technology.

Expected results

The final building panel prototype is expected to be plastic in form, exhibit increased tensile properties, added resilience and a high degree of durability, while maintaining compressive strength. The data collected during the testing phase will be compared with that of control shells produced without Kevlar and glass-fiber reinforcement and used to seek outside industry funding.

EcoCeramic research was investigated in the above parameters, with the addition of using the project as a testing ground for the thermal principles found in natural homologues and analogues. The following section describes the EcoCeramic, and the results.

Form

Typical masonry or brick construction utilizes the rectangular prism as the standard tiling mode. The triangle, rectangular prism, and the hexagon are the only forms that tile efficiently across a single surface without the need for a second condition. In a surface area to perimeter ration a triangle is only 76% efficient to the 100% rectangular prism. While the hexagon is the most efficient, 115% . The designers opted to work with the hexagon. The hexagon has the advantage of a more efficient surface area to perimeter ratio.

The Penrose tiling system, non-periodic tiling, both rotational symmetry, and mirror symmetry influenced the ultimate design of the packing system. The Penrose tile system contains opportunities for multiple tiling patterns and packing densities.

After unpacking the basic Penrose the designers selected one of two hexagon forms that emerged. The designers then explored the single hexagon's tiling potential. Finding the first, smaller hexagon inadequate for ceramic casting, The designers elected to utilize the larger hexagon for the following two reasons: two acute angles created a natural stress point in a cast ceramic block, and the two long sides are, proportionally, to close together to optimize the available surface area.

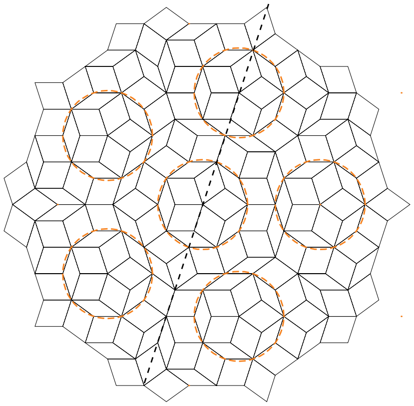


Fig. 33. Symmetrical penrose tiling pattern

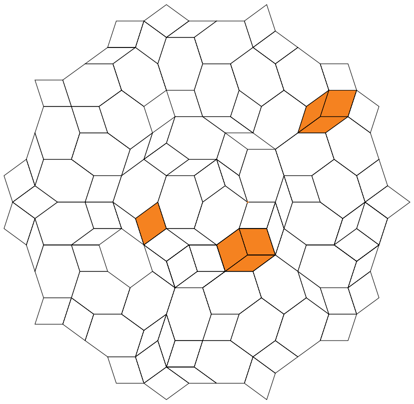


Fig. 34. Hexagon penrose tiles

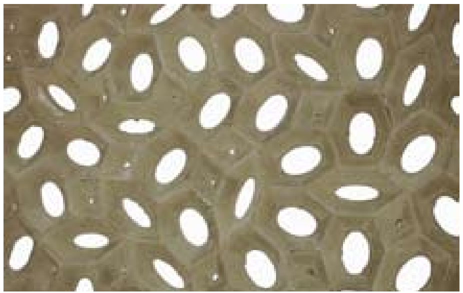


Fig. 35. Penrose wall system

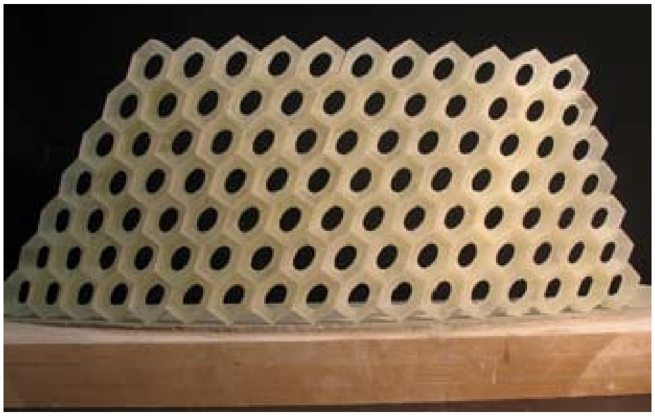


Fig. 36. Prototype IIIa tiling patterns

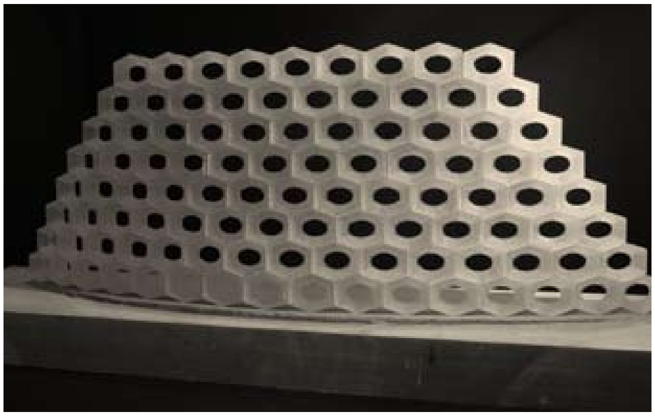


Fig. 37. Prototype IIb tiling patterns

Fig. 38.

Prototypes

This prototype attempted to address increased surface area in a hexagonal tile pattern. Using Maya as a modeling platform, the skin was deformed to provide shading similarly to what is found in the barrel cacti. The designers took the digital file into MasterCAM and were able to CNC out the positive mold. The designers then took a rubber casting of both positive molds to create the negative production mold. The rubber allowed the production of both plastic and plaster prototypes. The plastic allowed for experimentation with color and less material for a tilling pattern. The plaster provided a wall surface that the designers could test light qualities and tiling patterns.

The designers also experimented with centrifugal cast rubber as a possible breathing wall. In this case expansion would decrease the surface area during the winter, and contraction would increase the surface area during the summer.

Through the process of creating this prototype the author was able to synthesize the design sequence into stages of digital creation, mold creation and production sequence. Latex rubber proved to be a quality production mold for both plaster and plastic casting.

Fig. 39. Two part rubber mold

Fig. 41. Cast Plater Paris light study

Fig. 40. Cast Plastic tiles

Fig. 42. Hollow wall membrane, able to expand and contract

Prototype II

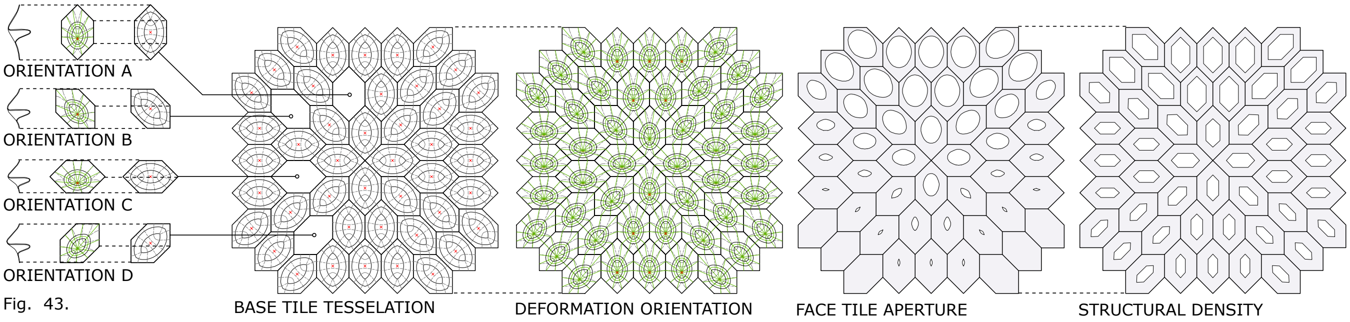


Fig. 43.

Self shading section and tile tesselation

Structure

The second generation incorporated a structural unit coupled with a skin element. The designers separated the functions of the tile system into one part that performed surface cooling and the second part preforms as a structural unit to apply the surface to. The structure as an independent unit allows the skin to be removed and replaced with new prototypes.

Skin

The production of the skin experimented with plaster press molding. The face unit was conceived as a simple shape using the Computer Numerically Controlled mill, CNC, tool path to add surface area where needed.

Fig. 44. Structural brick

Fig. 45. Male and Female Press molds, first

Shading analyses

Tucson AZ:
Latitude 32.12
Longitude 110.93

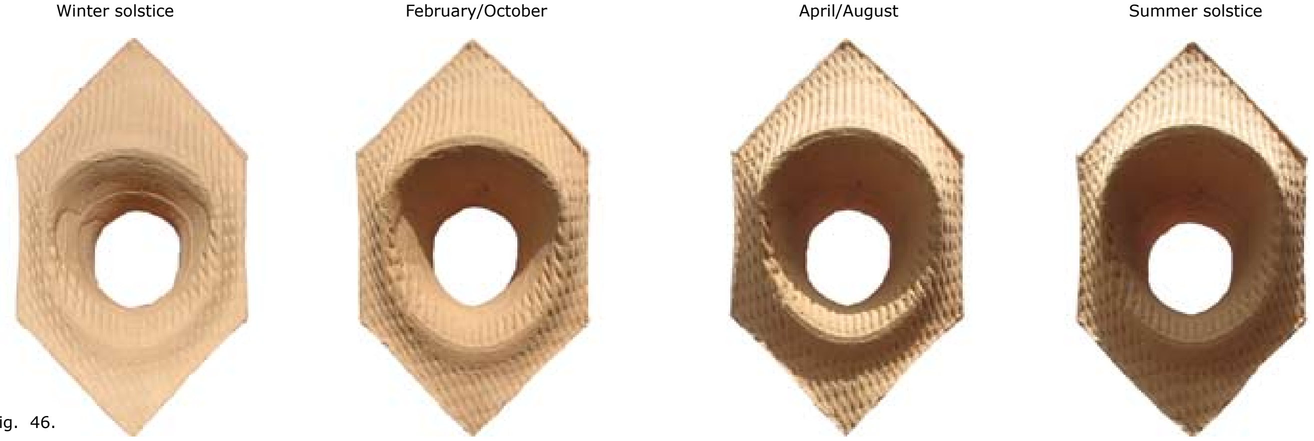


Fig. 46.

Prototype II glass

Glass is a specialized ceramic, considered a liquid with infinite viscosity. The amorphous non-crystalline structure allows the transfusion of light (Beveridge, Philippa). Glass is used to creates a transparent unit with a similar formal logic to the ceramic skin. Glass mold making, however, required the designers to develop a new system of mold making.

Typical glass slumping relies on low heat (650-705°C) and longer kiln times; however, to create a three dimensional glass unit in which the glass would flow up as well as down before solidifying, the designers were compelled to create a unique kiln schedule and optimize an existing plaster formula for higher temperate casting of 980°C.

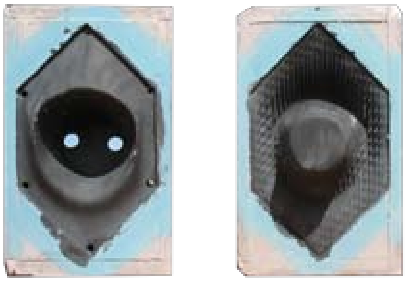


Fig. 47. Two part glass molds

Fig. 48. First glass prototype

Fig. 49.

Ceramics

Terra-cotta has fallen out of the main stream construction pallet as a conventional building material. Some reasons may be the complexity of molds, non structural (in typical applications) and it fails when exposed to water for long durations of time. Due to the flexibility of ceramics, however, a ceramic body can be structural, easily formed, and exposed to moisture.

The designers began experimenting in clay by taking a standard terra-cotta formula and created a series of samples to test. The designers found that the clay body expanded rather than contracted at temperatures above 1166°C. The expansion was due to a chemical reaction with Talc. Previous research had determined, to handle water, the clay body needed to shrink approximately 12 percent and have a porosity of 7 percent or greater. Through an iterative process of revision and baking ceramic bodies the designers were able to optimize the ingredients and clay body.

Batch 4

60%	Lincoln fire clay
30%	Green Ball
10%	30 mesh Sand
1/3	Water by weight

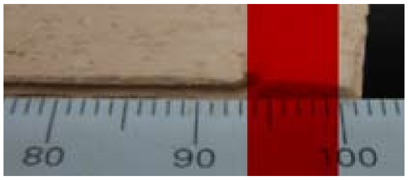


Fig. 50.

Cone 06	
Porosity	18.9%
Shrinkage	6%
Wick Rate	7 s

Fig. 51.

Cone 04	
Porosity	18.5%
Shrinkage	7%
Wick Rate	8 s

Fig. 52.

Cone 2	
Porosity	7.8%
Shrinkage	10%
Wick Rate	13 s

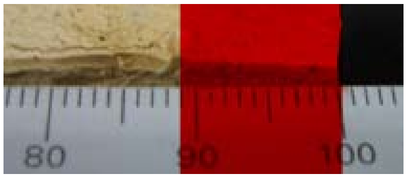


Fig. 53.

Cone 4	
Porosity	9%
Shrinkage	11%
Wick Rate	25 s

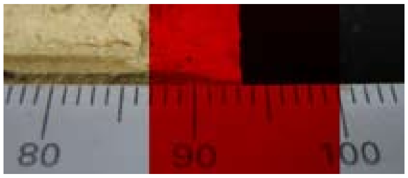


Fig. 54.

Cone 6	
Porosity	6.7%
Shrinkage	13%
Wick Rate	45 s

Batch 5

Ivory paper clay prepared by LagunaClay.

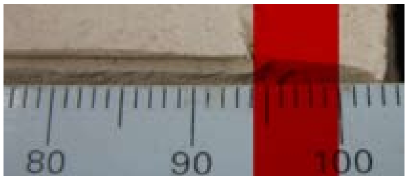


Fig. 55.

Cone 06	
Porosity	20.8%
Shrinkage	6%
Wick Rate	5 s

Fig. 56.

Cone 04	
Porosity	20%
Shrinkage	7.5%
Wick Rate	6 s

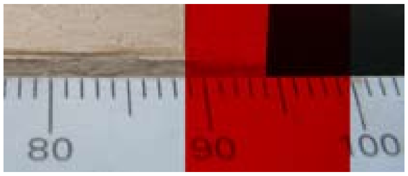


Fig. 57.

Cone 2	
Porosity	11.1%
Shrinkage	11%
Wick Rate	7 s

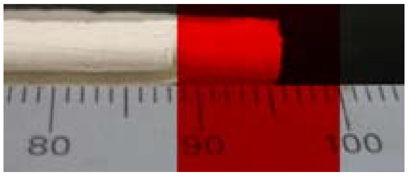


Fig. 58.

Cone 4	
Porosity	12.2%
Shrinkage	11.5%
Wick Rate	30 s

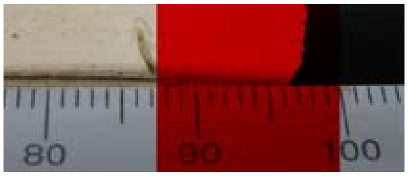


Fig. 59.

Cone 6	
Porosity	9.5%
Shrinkage	12.5%
Wick Rate	45 s

Properties

After moving through several clay bodies we found a formula that would work well for the desired application. After talking to Laguna clay about producing our clay we found they offered a similar clay body. The differences between our clay body and Laguna's clay body was insufficient to order a custom batch of clay. This is especially true after Laguna Clay offered to subsidize our purchase if the designers used "off the shelf clay bodies."

Soldate-30

75%	Lincoln fire clay
25%	Green Ball
5%	30 mesh Sand
1/3	Water by weight

The addition of glass fiber composite reinforcement significantly altered both the tensile and the compressive strength of the clay body. Using the Instron 3869 material tester the author found that tensile strength doubled and compression strengths tripled. Further tests by setting the maximum force to 2000 LBF found that the a sample could withstand up to 5 repeated loading tests before failure.

Cone 6_EcoCeramic exterior unit		
porosity	10%	
Shrinkage	14%	
Wick Rate	12 seconds	
3 Point bending	100 lbf	300 lbf w/glass fiber
Compression	1,000 lbf	3,000 lbf w/glass fiber

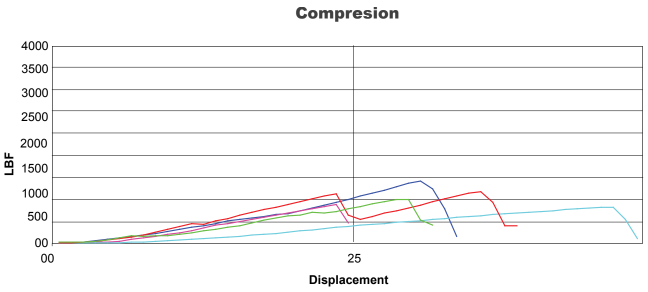


Fig. 62.

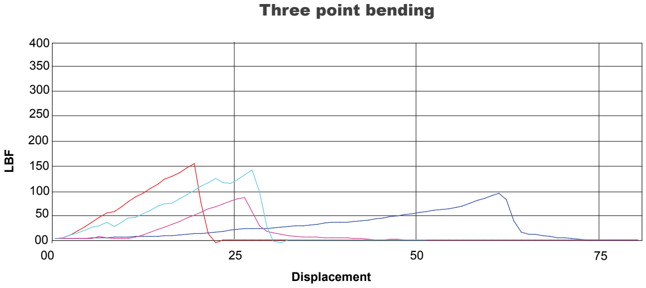


Fig. 60. 8.

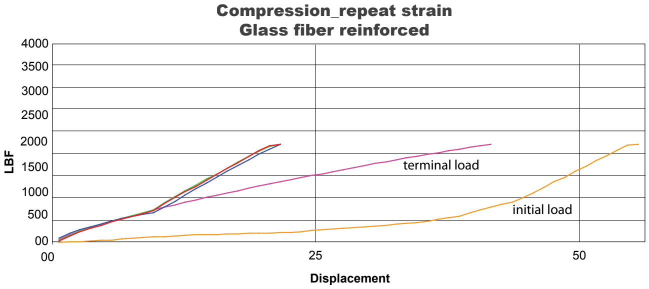


Fig. 63.

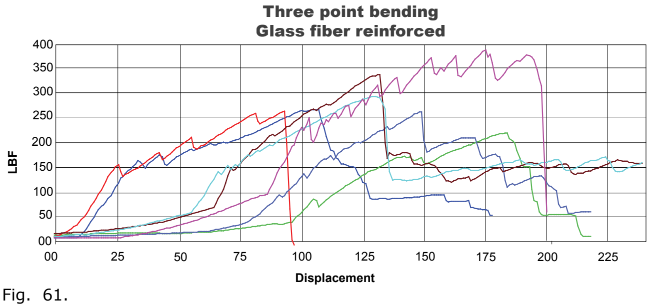


Fig. 61.

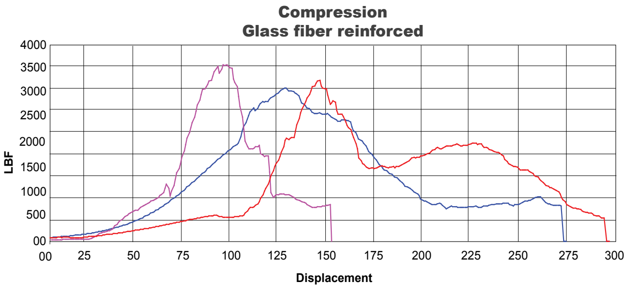


Fig. 64.

Assembly

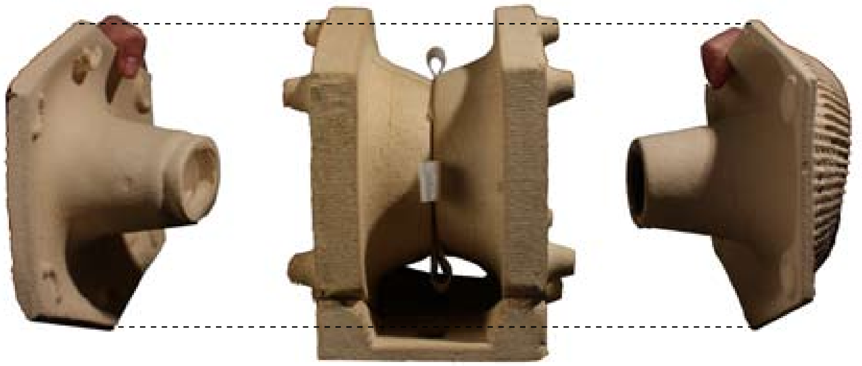


Fig. 65. Components

Fig. 66.

Fig. 67.

Fig. 68.

Fig. 69.

Fig. 70.

Fig. 71.

Fig. 72.

Fig. 73.

Fig. 74.

Fig. 75.

Composites

One problem in ceramic building assemblies is the lack of inherent tensile strength. In a brick or concrete masonry unit, CMU, wall assembly the masonry unit is in compression while the mortar, also in compression, acts as a self-leveling surface. Without any force to resist tension, the wall fails under lateral force (strong wind), seismic events, or any other lateral force. To stabilize the masonry wall system steel is added. Replacing steel reinforcing, EcoCeramic blocks incorporate fiberglass and composite materials for post-tensioning between each block such that the entire system is net worked into one cohesive unit.

Composite materials also allow for the joining of the individual units. Due the mode of fabrication, each structural ceramic unit (SCU) is one half of a complete SCU. Typical modes of joining would include slip joining, a method most commonly used to attach a coffee mug to its handle. This joint, unfortunately, is non-structural and shears on impact forces. The second joining method uses a glaze slip and high fired. This method is strong, resist tension, but uses cone 11 firing temperatures when the clay is fired to cone 6.

Through applying composite bonding with fiberglass and high strength epoxy, the fired halves can be easily joined in a permanent structural application. The composite creates a joint capable of withstanding shear and tensile forces. Typical joints resist three points bending with ~70 LbF, while a fiber reinforced ceramic joint fails at greater than 200 LbF. Furthermore, testing with the Instron 3369 showed that failure was non-catastrophic.

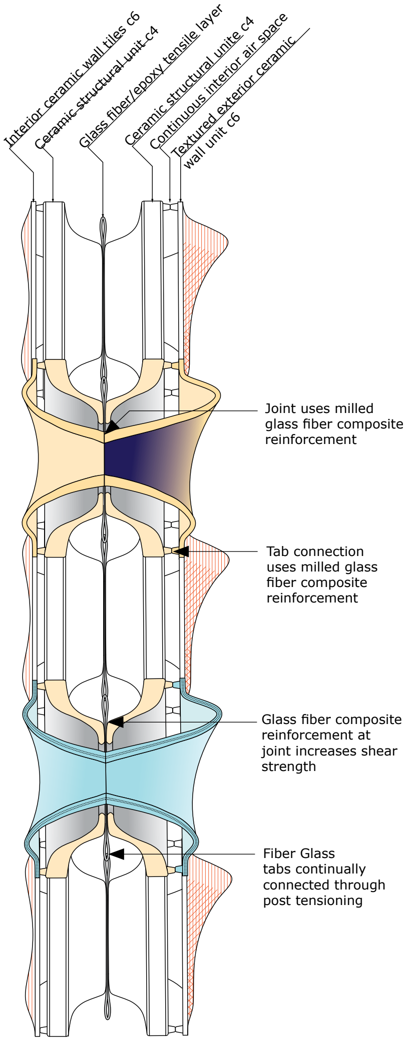


Fig. 76.

Glass and tile assemblies

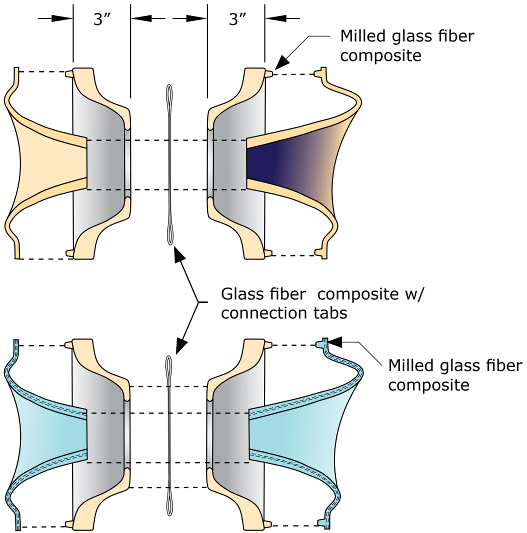


Fig. 77.

Typical brick module plan and elevation

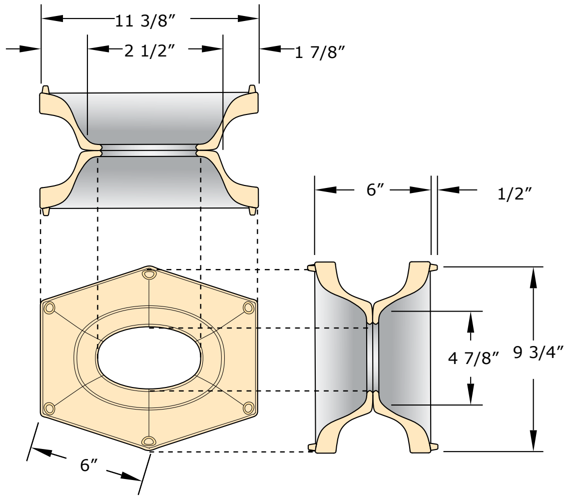


Fig. 78.

Forming logic

Ceramics, like any material, has a set number of known fabrication techniques. Clay bodies are typically extruded, jiggered, slab formed, slip cast, or pressed. With each mode of fabrication comes limits, and benefits.

- Extrusion is used to create liner elliments.
- Jiggered or spinning is used to create symmetrical deep shapes.
- Slab formation is used primarily for planer units.
- Slip casting is primaraly for asymmetrical hollow units or units.
- Pressing is used to create three dimensional objects with material high density or structural objects.

Due to the complexity of the form and the quantity needed, pressing is the only viable option. Slip casting, the other known method, would shrink around the cone, preventing a smooth release and compromising the integrity of the unit.

Working with Catalina China Inc., the designers devised a method of mold making and a strategy for pressing the CSU and face tile. Essentially, both are a complicated plate, a single surface with three dimensional geometry in the xyz axis.


Fig. 79. Jiggering


Fig. 80.


Fig. 81. Slip casting molds


Fig. 82. Extrusion


Fig. 83. RAMpress molds


Fig. 84. Pinch edge

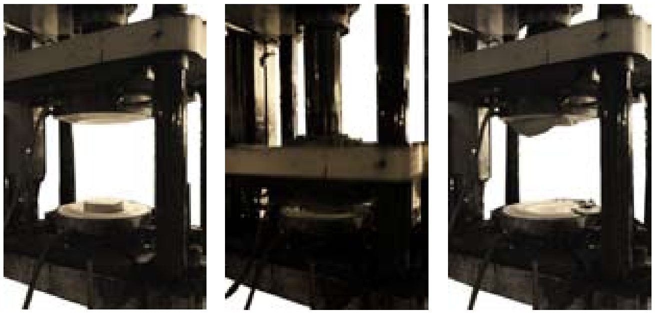


Fig. 85. RAM Press


Fig. 86. RAMpress


Fig. 87. Drying racks

Alternative designs

The methods of production often inform the formal logic of the final form. Using a pressing method the designers are able to create Tile A. However if the designers utilized a slip casting methodology the designers could not make a cone, but were enabled to create hollow forms, tiles B & C. If neither of these production options are available one can slab from a fin and use a design strategies analogous to tile D. While each forming process has it's limitation each also has its own advantage.

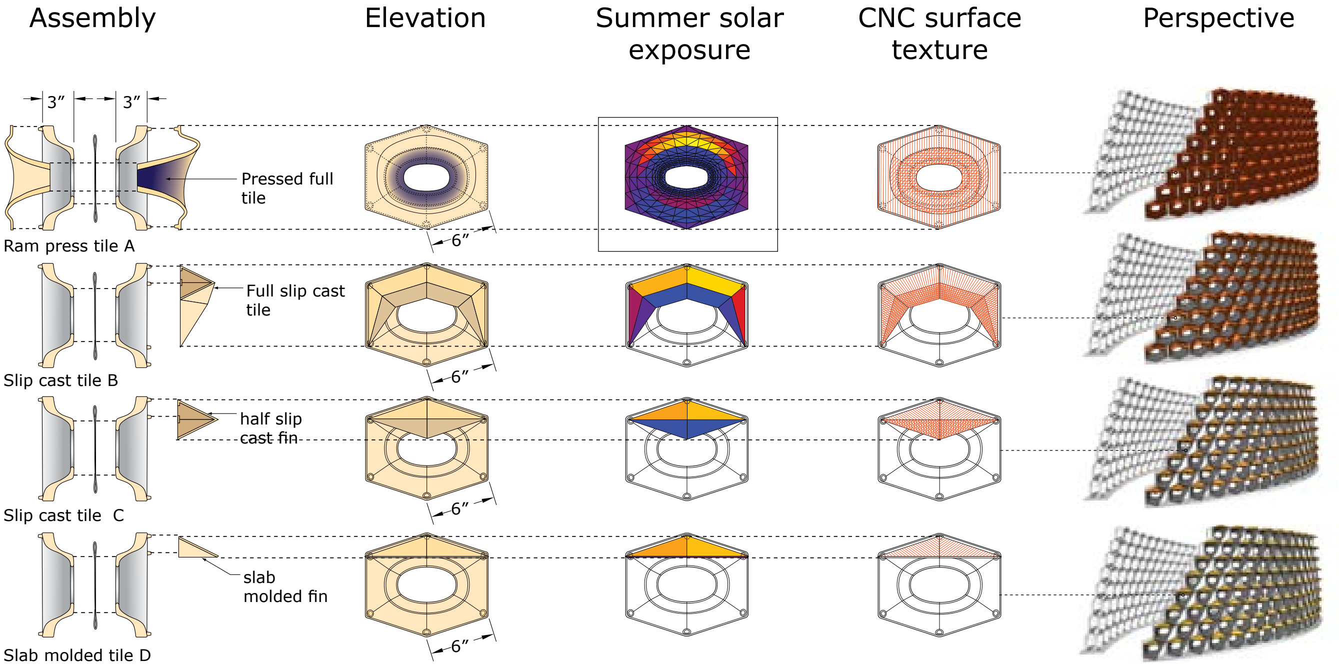


Fig. 88. Design alternatives

Fabrication

Beginning with a digital model, the process of fabrication quickly moves through the following process:

Molds

- Use digital modeling tools create a digital master molds.
- Usie Master cam or similar software to prepare the digital model for the CNC three axis mill.
- CNC an MDF mold, male and female with pinch points and gutters creating master mold.
- Coat MDF with polyurethane (four coats sand with 220 (200 whats) in between each coat).
- Apply a single coat of hard wax (trewax) to the MDF mold.
- Place a wire cage one inch above master mold, following the contour of the mold as closely as possible. Using wire hooks to suspend the cage from the die sides, and steel rods to hold in place during the plaster pour.
- Tie the MOLDUCT to wire cage and connect MOLDUCT to air fitting on steel die.
- Pour CERAMICAL into mold.
- Flip mold upside down; (working die is now on top).
- Initiate the purge according to schedule given when plaster obtains 37ºC.
- Remove master mold from working die by gently separating the two surfaces.
- Set working dies on its side and continue to purge, sponging water off the surface frequently.
- If the working die is properly made, it should be completely dry and serviceable within 2 hours after initial pour.
- When completely purged, scrape the back of the die flat with a straight edge.
- Repeat process for opposing working mold.


Fig. 89. MDF


Fig. 90. CNC positive


Fig. 91. Steel Die


Fig. 92. Detail steel die


Fig. 93. Mold duct


Fig. 94. Mold duct in Steel Die

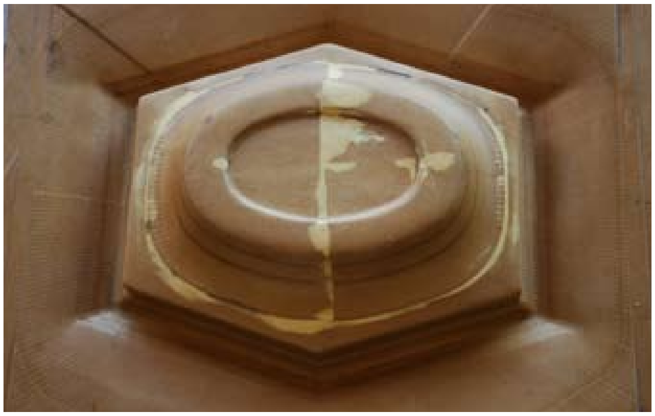


Fig. 97. MDF mold, with polyurethane finish


Fig. 95. Mold ready to cast


Fig. 96. Plaster cast


Fig. 98. Pressurizing plaster mold


Fig. 99. Negative plaster

Purging

Purging a plaster mold allows for greater strength, faster drying time and an on demand release of a clay unit. CeramiCAL was designed for both impact strength and to facilitate a purging process. Essentially the air pressure forces all water that is not bonded to the plaster out of the mold. Thus the placement of MolDuct in relation to the master mold is essential for a clean release of the ceramic unit.

Production plaster cast

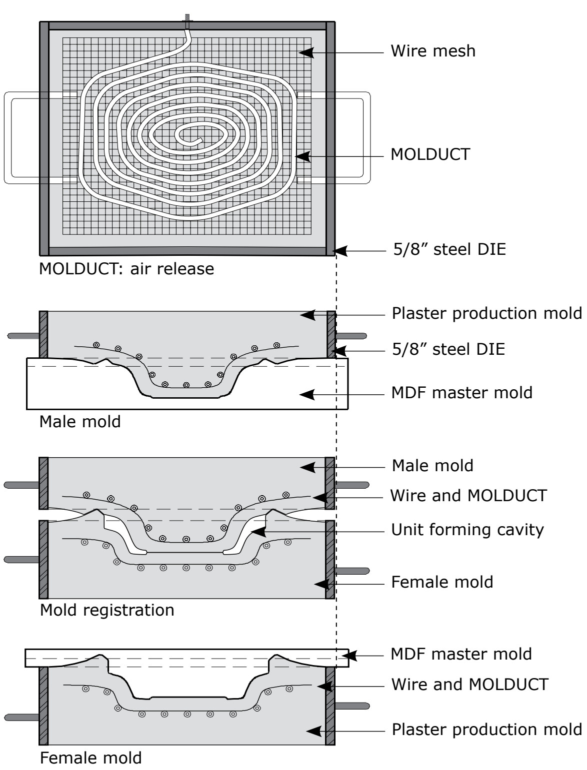


Fig. 100. Production sequence

Fig. 101. Pressurizing negative working mold

Pressing

- Pre-determined clay charge made from extruded blank is placed on the lower die.
- Press is activated, bringing the two dies into registration, dispersing the clay charge into the cavity of the unit.
- Air is applied to the lower die, releasing the clay from the lower die.
- The dies are separated leaving the clay unit in the top die.
- The operator removes any flash from the gutter in the top die.
- The operator applies air to the upper die, releasing the clay unit from the upper die. The unit then drops onto a board, or the operator's hand.
- The operator places the unit in a drying rack, and then removes any excess water from the die.
- Repeat process

Fig. 102. Male and female dies

Fig. 103.

RAM Press Process

Fig. 104. Clay charge ready

Fig. 105. Pressing clay

Fig. 106. Unit formed

EcoCeramic Structural Unit (CSU)

In the Emerging Material Technologies Ceramics Laboratory, one person can press 40 CSUs in an 8 hour day. If one had the facilities available at Catalina China Inc., a solitary worker would be capable of production 600 or 300 CSUs in a single day.

Production issues

Problems included warpege and deformation of the tiles edges. This caused an excess of manual labor. Solutions included firing the CSUs upside down to "even out" the warpege.

Issues with the firing process included a non-uniform ramp up and ramp down in the firing process. Further problems included a lack of air flow to evenly distribute the heat throughout the kiln. These problems manifested themselves in cracking, uneven firing, uneaven shrinkage, and explosions.

Solutions included altering the kiln rate from 148.9ºC per hour to 65.6ºC. This change limited nearly all cracking and warpage due to the firing process. The designers were not able to use forced convection, as none of the available kilns were built for production ceramic firing schedules.

EcoCeramic exterior unit (CEU)

Utilizing the Emerging Material Technologies Ceramics Laboratory, one person can press 50 CEUs in an 8 hour day while in a production facility a solitary worker is capable of producing 550 units in a day.

Production issues

Issues in the drying included warpege and deformation of the tiles edges; drying edges would slump and take a non-planer final form.

Due to the uneven edges, each exterior face unit would only touch three of the six knobs on which to fasten to the structural unit. The consistent issue of a single raised corner indicates that part of the problem occurred before drying and firing in the removal of the CEU from the RAMPress. A even distribution air is needed in the male mold such that the unit and does not require prying the unit off by hand.


Fig. 107. Drying units


Fig. 108. kiln


Fig. 109. Produced units


Fig. 110. application of mason stain

Demonstration project

One purpose of EconCeramic was to build a pavilion as a demonstration of principles. Using form and geometry language of Eladio Dieste, and Richard Serra the ceramic wall follows a simple curve leaning in on itself as it rises up (Apendix A). The form is intended to assist in the stabilization of a single wall as well as to provide a greater spacial experience

Fig. 111.

Structure and Form

Rather than rely on mortar to create a tilting wall the designers opted to slope the foundation. Each unit is then place perpendicular to the foundation and as the foundation changes slope the changes are reflected in the structure.

Structural stabilization through deformation

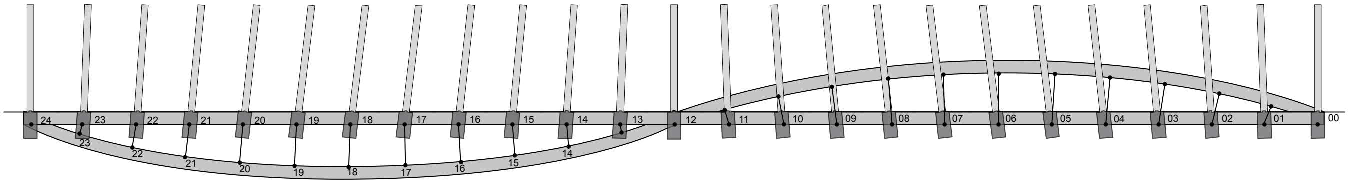


Fig. 112. Plan overlaid on section

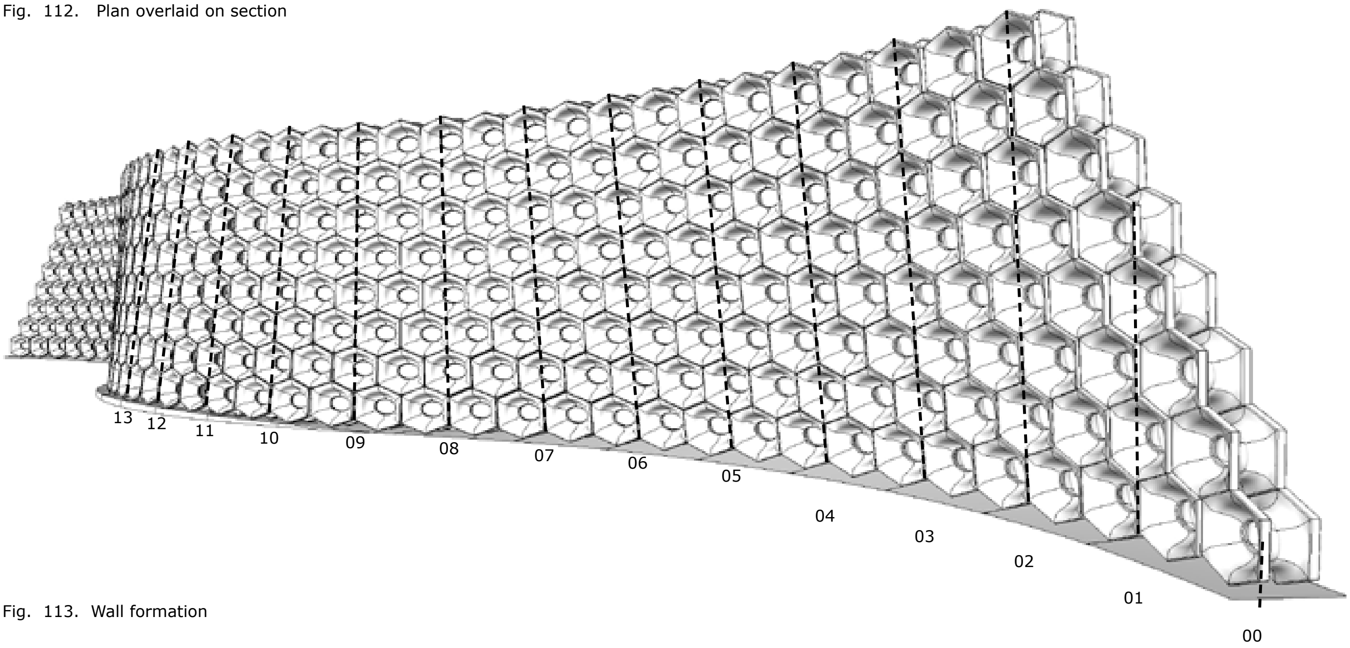


Fig. 113. Wall formation

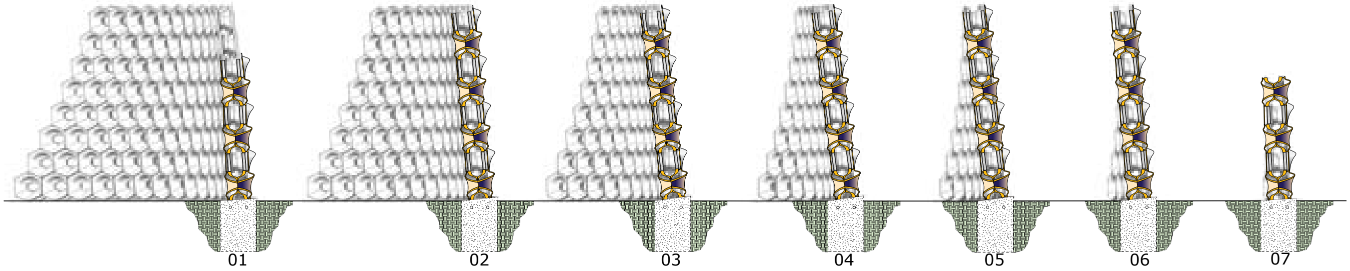
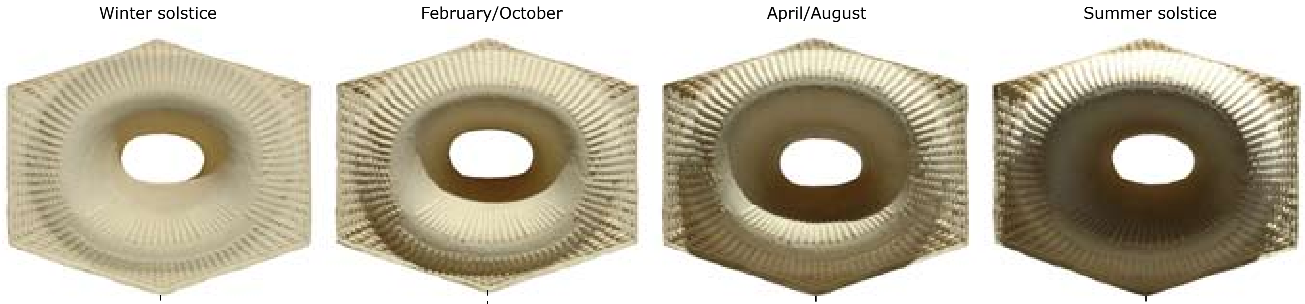


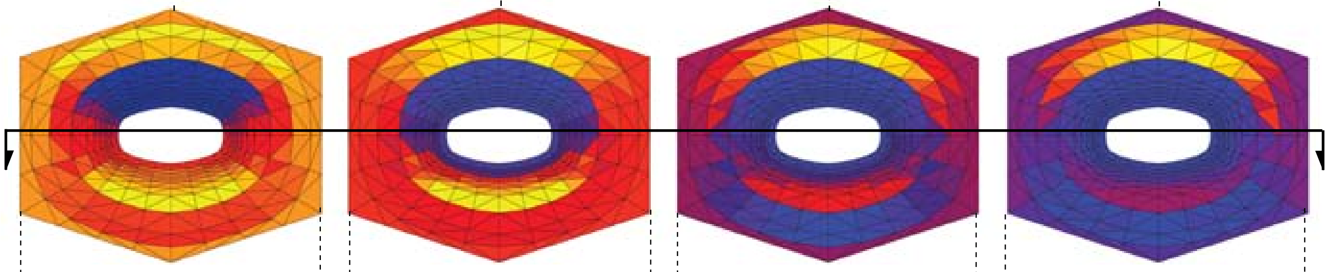
Fig. 114. Section sequence

Tucson AZ:
Latitude 32.12
Longitude 110.93

Shading analyses



Solar incidence



Solar section

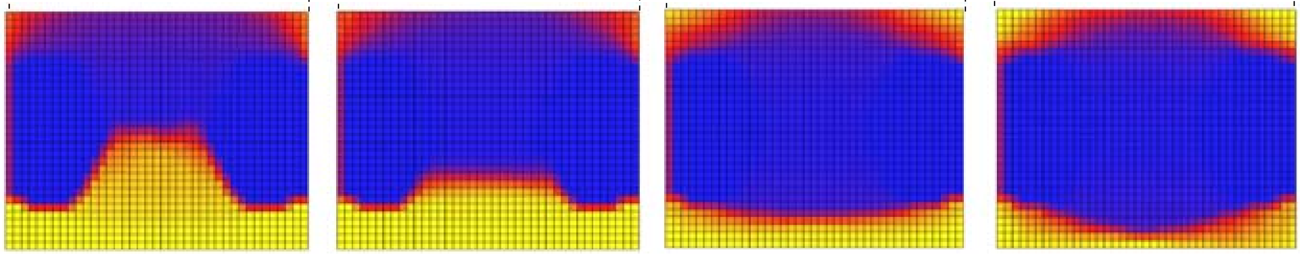
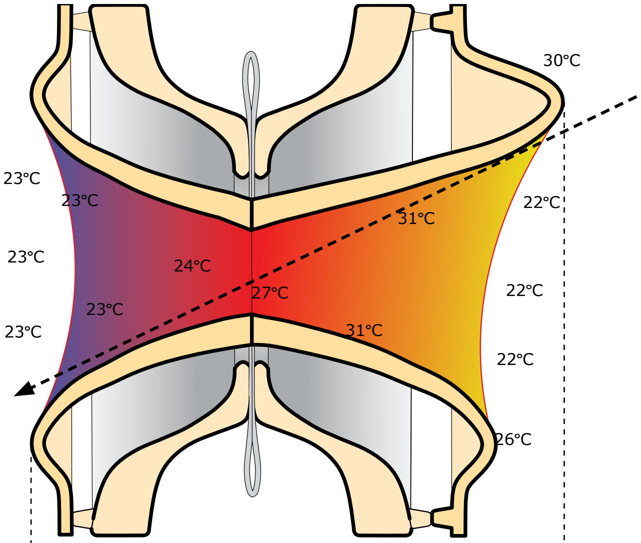


Fig. 115. Solar analyses sequence

Thermal section

Winter solstice



Comparative thermal analysis

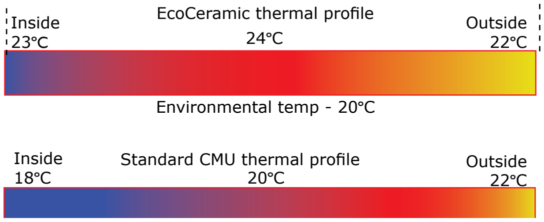
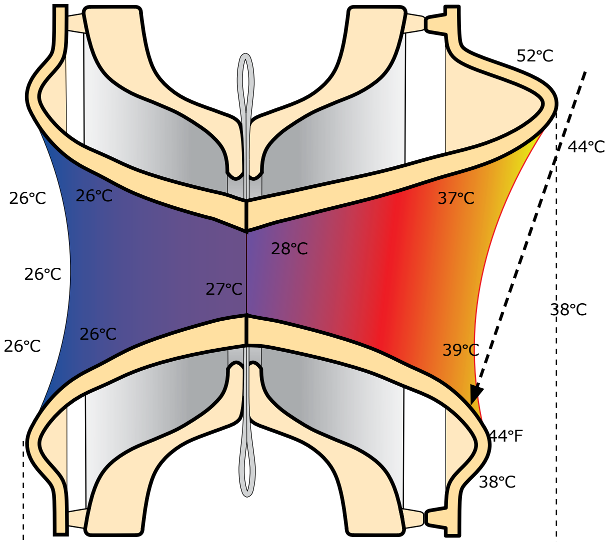


Fig. 116. Thermal section

Summer solstice



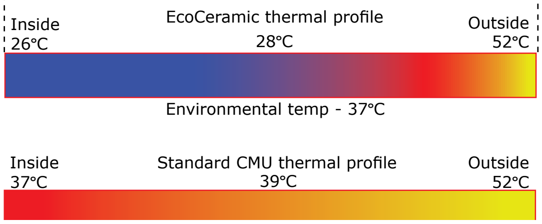


Fig. 117. Thermal section

Thermal plan

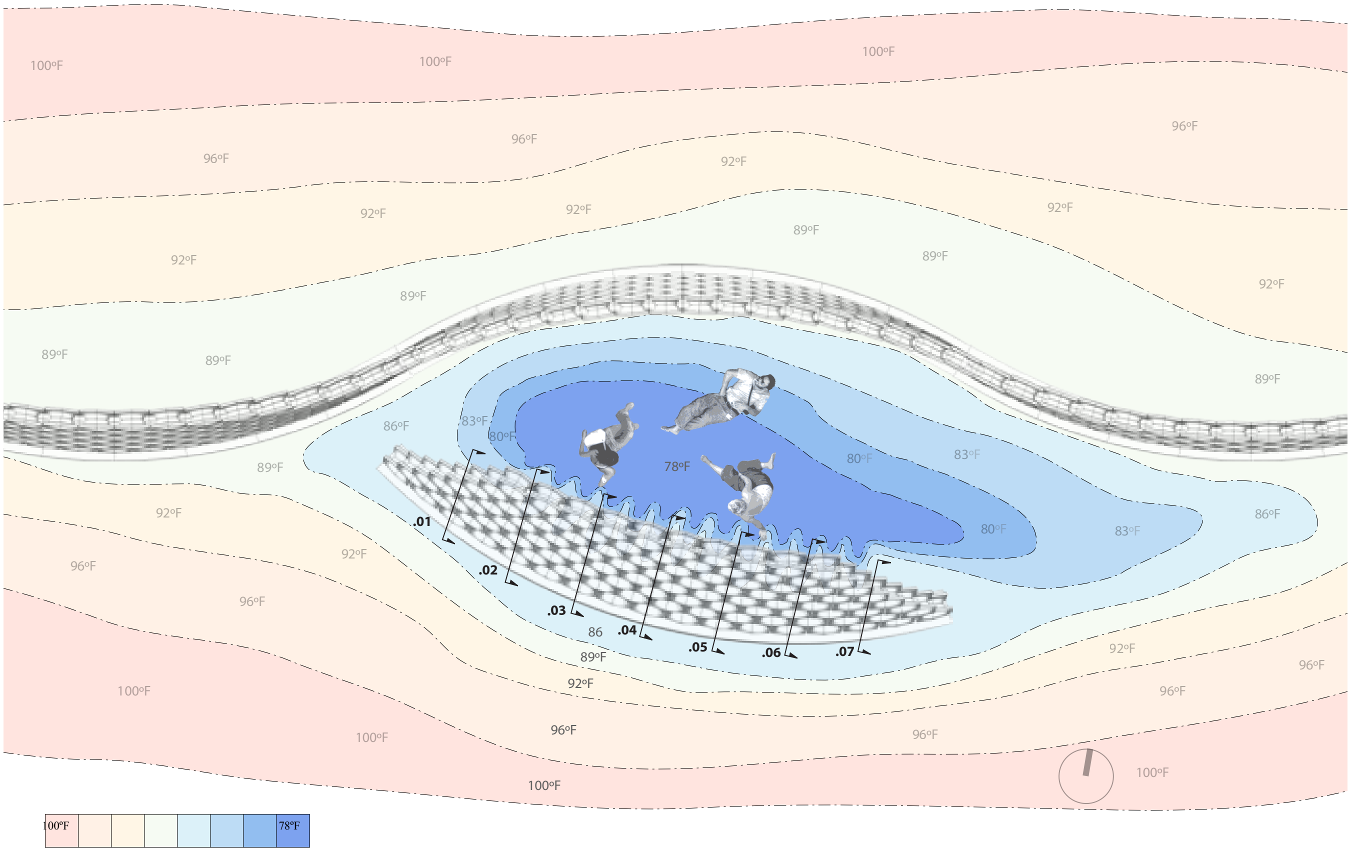


Fig. 118. Thermal plan

Thermal Tests

Thermal Principles

Principles found in nature; surface area, material thickness, color, shade and ventilation are abstracted and applied to a series of ceramic units to create a wall system capable of passively tempering the Sonoran Desert climate to within habitable temperatures, 23-30°C.

Based on thermal experimentation the following principles are applied:

- 1) Smooth surface area for neutral thermal gain/loss.
- 2) The surface of the tile is shaped in conjunction with solar angles to maximize shading in the summer months and increase solar gain during the winter months.
- 3) Increasing the surface area through the CNC tool path allows for radiant gain to dissipate back into the environment.
- 4) Increased surface area facing towards the wall on interior surface, directs gains back into wall cavity.
- 5) Water soaks the tiles during the night for evaporative day time cooling.
- 6) Tabs allow an air flow between the tile and the structure.
- 7) Select tiles allow air to flow through the wall, transporting moist and cool air inside.
- 8a) The tile (exposed to summer sun) is left without glazing so that the light color may reflect most of the summer sun.
- 8b) The cone, which receives only winter sunlight, is colored dark blue with mason stain warming the wall system.
- 9) Tabs also limit conduction thermal transfer to the structural unit.
- 10) The hollow section can be filled with fiber insulation.
- 11) The tile is thinnest in areas most affected by summer sun, and thickest for regions most affected by winter sunlight.

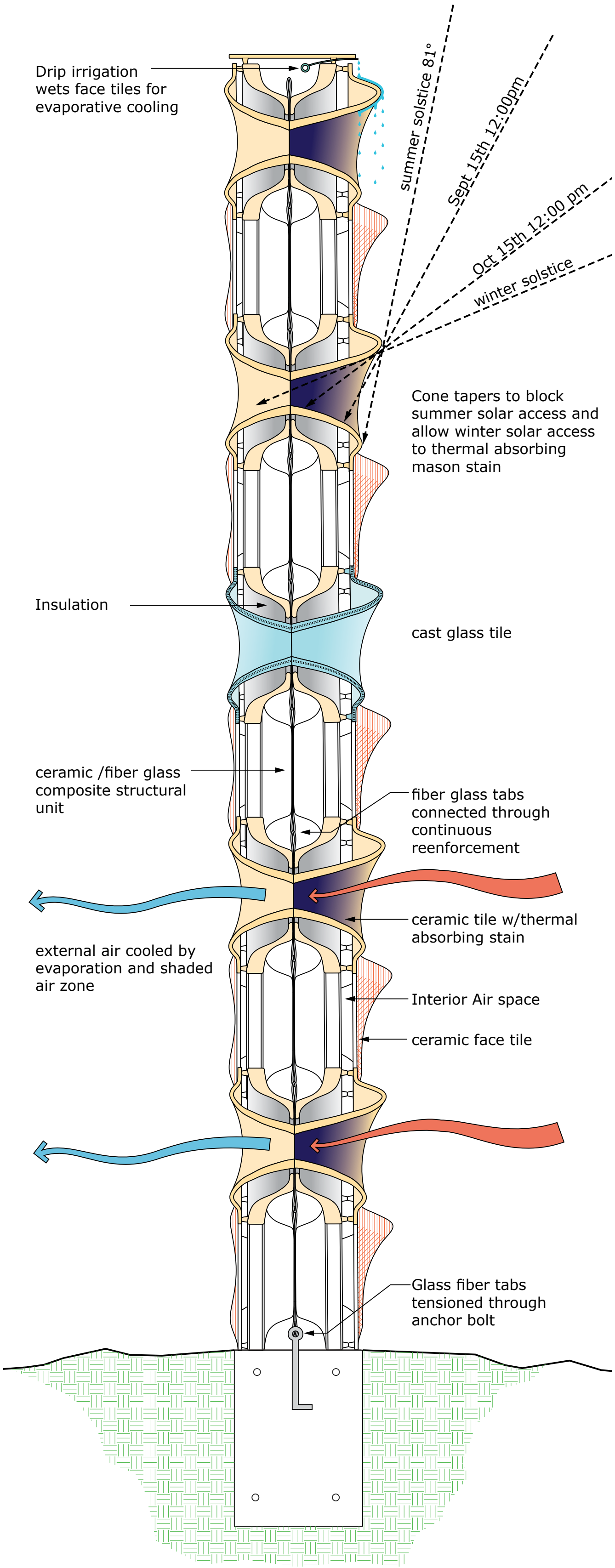


Fig. 119. Diagrammatic section

Expected results

The designers expected the cone to attract and retain heat into the night, delaying the cooling of the wall. The wall system receives greater solar exposure, than summer months, further maximizing potential winter radiant thermal gains. In addition a layer of expandable insulating foam is added into half of the unit, eliminating horizontal air movement, and providing limited conduction barrier. Finally a continuous vertical ventilation between the skin and the structural units acts as a convective thermal barrier. With these strategies the designer hopes to offset the cool winter nights, and retain the thermal swings to within 23-30°C.

Thermal section

November 2008
Solar noon
Latitude 32.12
Longitude 110.93

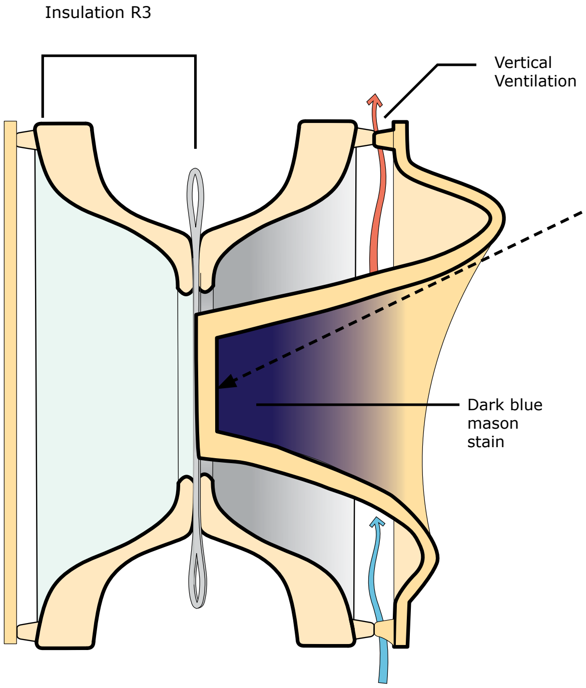


Fig. 120. Thermal strategies

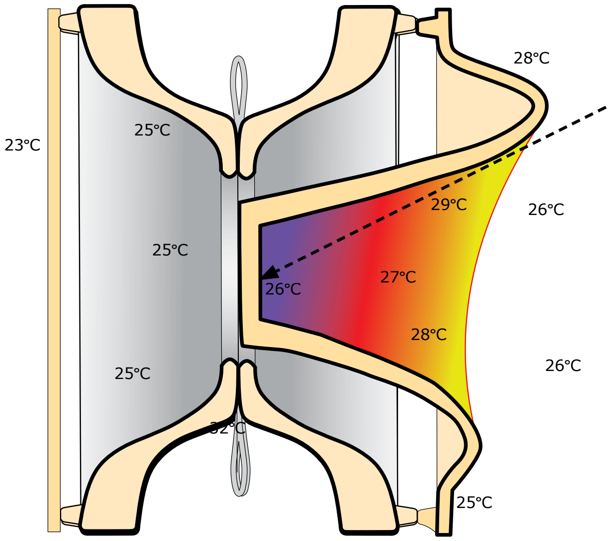


Fig. 121. Expected results

Methodology

The American Society for Testing and Materials International, ASTM, does not have a standard radiation thermal gain test procedure, rather one adapts the ASTM C1363, guarded hot box, by exposing the test surface to solar radiation. Unlike other tests, which wait for thermal equilibrium, this experiment requires a three day cycle, similar to field experimentation. In order to reduce weather related errors, the test series alternated between wall surface assemblies.

- The testing chamber is one cubic meter in volume or 35.3 cubic feet.
- Floor dimensions are 1.3 meters wide by 1 meter deep. (~4’ x 3’)
- Five of the 6 sides are sheathed in 7.62 cm (3 inches) of homogenous polystyrene insulation with an R-value of 12.
- The combined material R-Value is 13.4 on five sides of the cube with a wall thickness of 12 cm (4.75 inches).
- Nine thermocouple data loggers record environmental, wall, and interior temperatures.

Fig. 122.

Guarded Hot Box: test 01

- The interior maintained a 2ºC (4ºF) thermal difference at the warmest point in the day with a thermal delay of 2 hours.
- From approximately 15:00 to 9:00 the following day the interior maintained a warmer temperature compared to the exterior.
- The surface temperature consistently remained above the ambient temperature.
- The internal ambient temperature is closely linked to the external environmental temperatures separated only through the thermal lag.
- The test was conducted during cloudy and cold days, consequently should be re-conducted for verification.

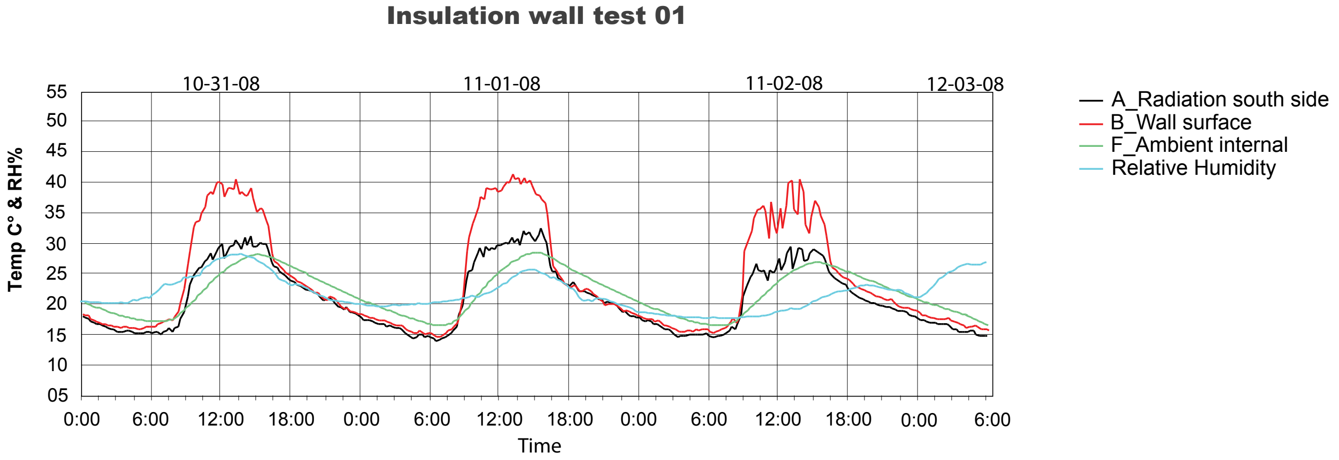


Fig. 123. Guarded Hot Box

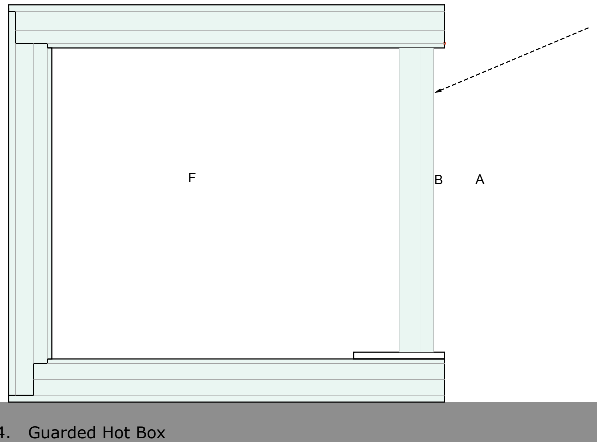


Fig. 125. Guarded Hot Box

Fig. 124. Guarded Hot Box

EcoCeramic Wall: test 02

- The interior maintained a 5°C (8°F) thermal difference at the warmest point in the day with a thermal delay of two hours.
- From approximately 14:00 to 9:00 the following day the interior maintained a warmer temperature then the exterior.
- The cone absorbed and retained heat through the night until 6:00.
- The cone was less dependent on temporal thermal fluxes compared to the eyebrow, and vertical surface.
- The eyebrow and the articulated surface of the ceramic quickly cool off to below ambient temperatures (nighttime).
- The eyebrow warmed above ambient temperature consistently and cooled to environmental temperatures with sunset.
- The vertical surface, near perpendicular solar exposure, warmed greater than the eyebrow in nearly every test.
- Internal temperature is co-dependent on the wall cavity temperature, cone temperature and ambient temperature.

Sensor locations

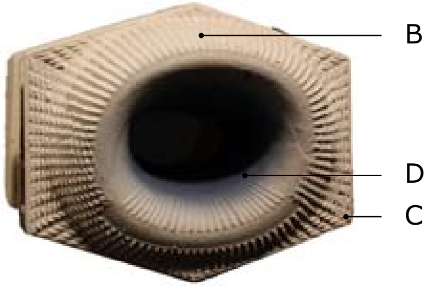


Fig. 126.

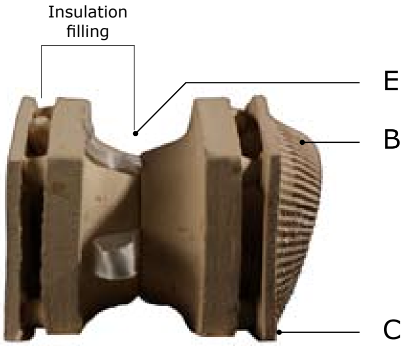


Fig. 127.

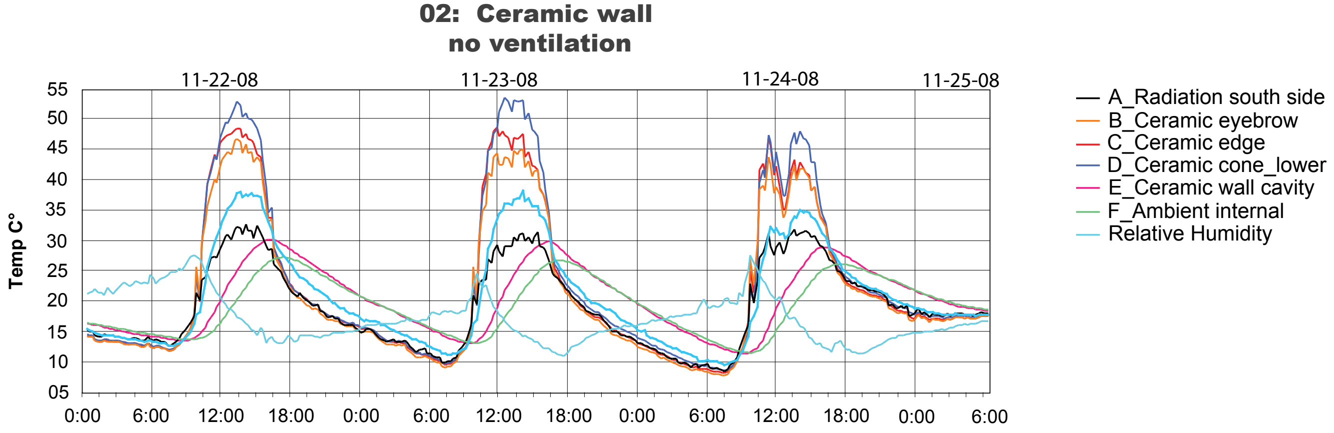
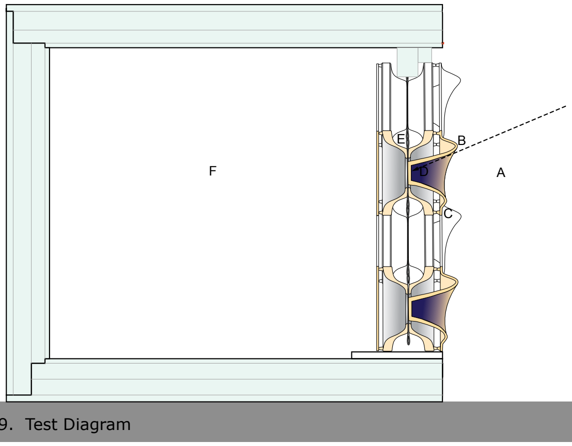


Fig. 128. Test 01 results



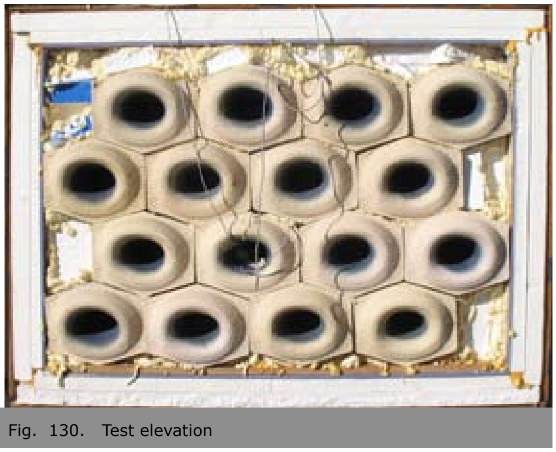


Fig. 129. Test Diagram

Fig. 130. Test elevation

CMU Wall: test 03

- The interior maintained a 2.2°C (3.6°F) thermal difference at the warmest point in the day with a thermal delay of two hours.
- From approximately 15:00 to 10:30 the following day the interior maintained a warmer temperature then the exterior.
- The CMU wall absorbed heat through radiation as expected and lost the heat at a reduced rate compared to the ceramic wall.
- The CMU wall, external surface, remained warmer than the ambient temperature.
- The test was conducted at very high humidity levels, and needs to be re conducted to verify results as humidity affects the thermal loss.
- Internal temperature is closely linked to cavity and surface temperatures.

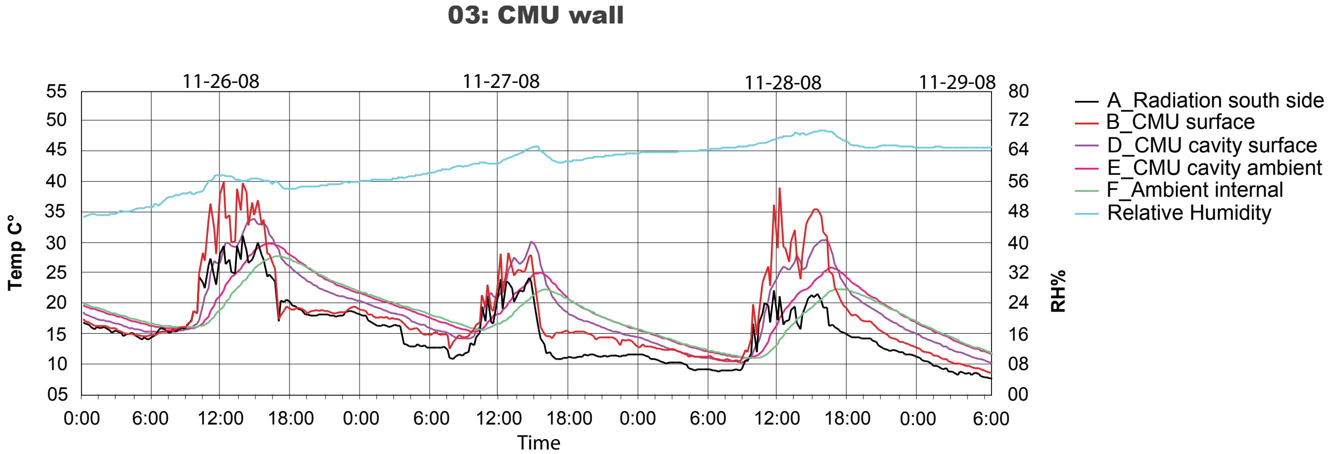


Fig. 131. CMU test

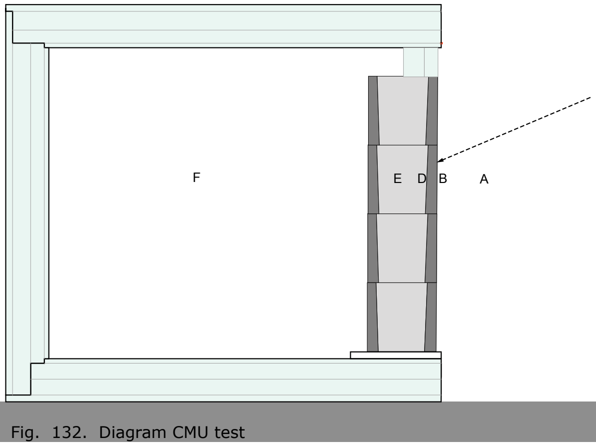


Fig. 132. Diagram CMU test

Fig. 133. Elevation CMU test

EcoCeramic Wall: test 04

- The interior maintained a 3.4°C (6°F) thermal difference at the warmest point in the day with a thermal delay of two hours.
- The wall cavity remained warmer than the internal temperature until 0:00.
- The cavity and internal temperature remains warmer than environmental temperatures from 16:30 to 9:30.
- Between the environmental temperature and the internal peak temperature there is a 3 hour lag.
- Both the high and the low internal temperatures maintain a 4°C thermal difference.
- The cone absorbs 1-2°C more thermal energy than the vertical ceramic surface in a humid environment, but fails to gain the expected temperature in on a typical day.
- The eyebrow and the articulated surface of the ceramic quickly cool off to below ambient temperatures (nighttime).
- The cone is directly linked to solar radiation for warming, but mediates the environmental and internal ambient thermal flux between 18:00 and 9:00 the following day.

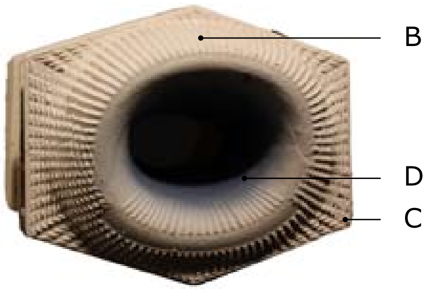


Fig. 125.

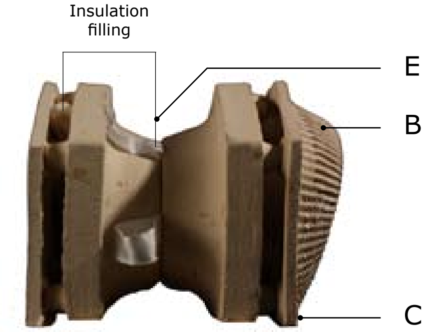


Fig. 126.

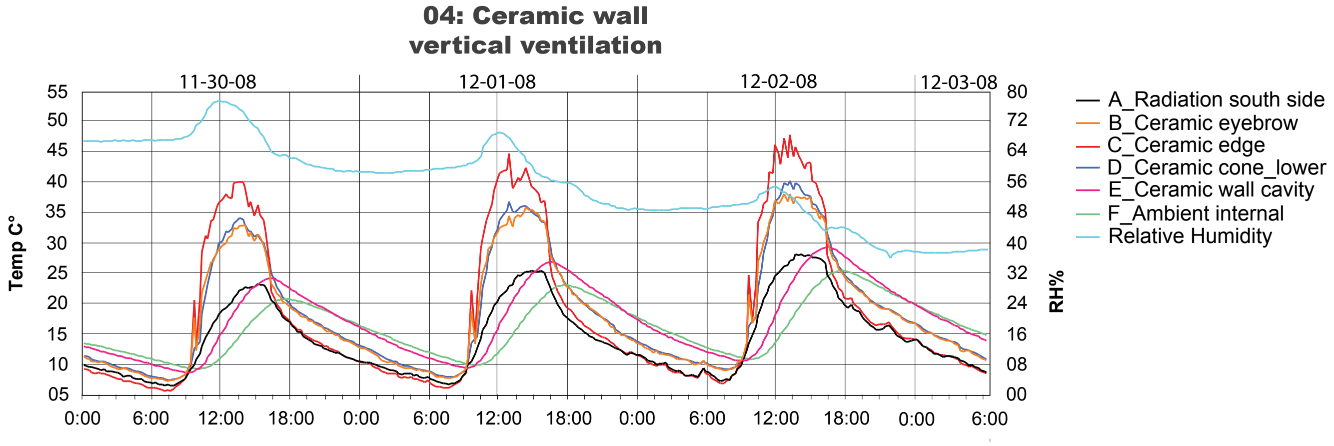


Fig. 134.

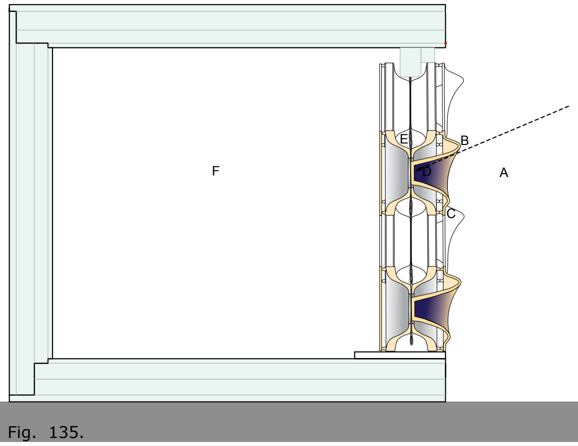


Fig. 135.

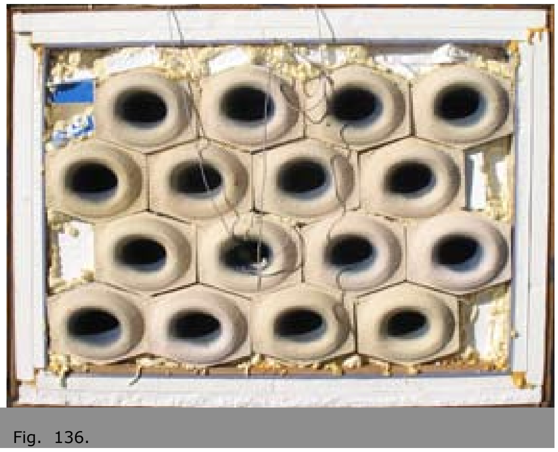


Fig. 136.

CMU Wall: test 05

- Expecting results on Sunday morning

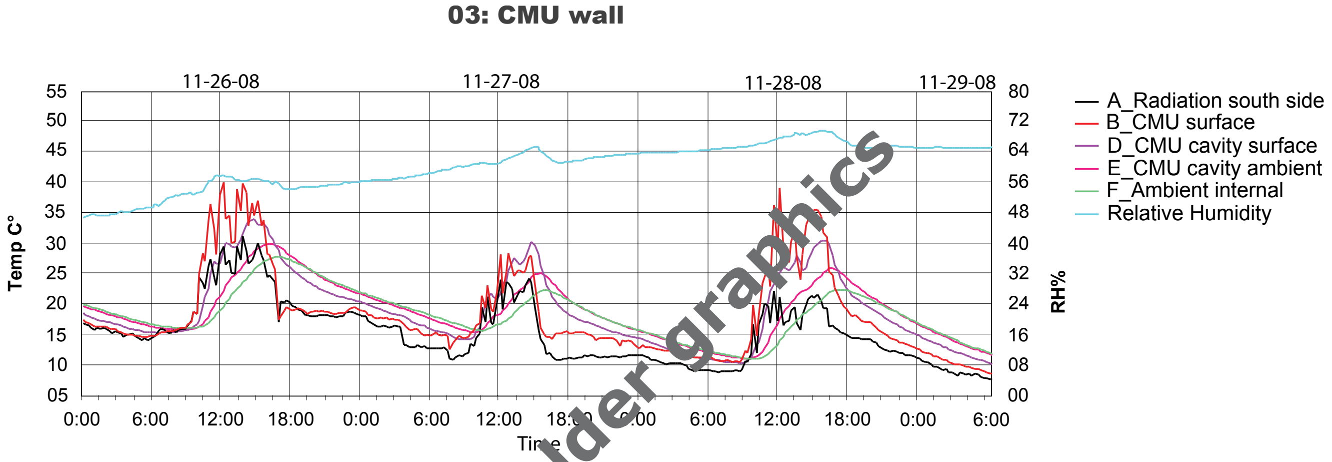


Fig. 137. CMU test

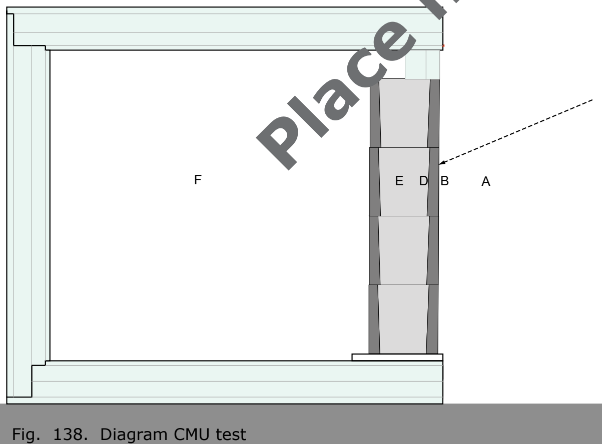


Fig. 138. Diagram CMU test

Fig. 139. Elevation CMU test

Thermal findings

- The EcoCeramic external surface consistently warmed above ambient temperatures, with the highest recorded temperatures on the surfaces nearly perpendicular to the solar path.
- The articulations, CNC tool path, allow the surface to quickly cool off to bellow ambient temperatures with the loss of direct solar exposure.
- The EcoCeramic wall system was able to reduce thermal swings by up to 5°C (8°F) compared to the CMU wall which was only able to mitigate thermal swings by 2.2°C (3.6°F).
- Variations in solar exposure delayed conduction through the EcoCeramic wall system.
- At 9:30 each day a spike of 8°C occurred over 15 minutes, it is not known what causes this thermal spike. The thermal spike was seen in three separate data loggers, and several points were not exposed to solar radiation.
- Articulations seem to delay conductive thermal transfer through the wall system.
- If the cavity was filled with insulation a reduction in thermal transfer, and greater retention of heat would be expected.
- A vertical ventilation system that is operable, open for summer and closed in the winter, would further help retain and release thermal gains.

Comparative thermal analysis

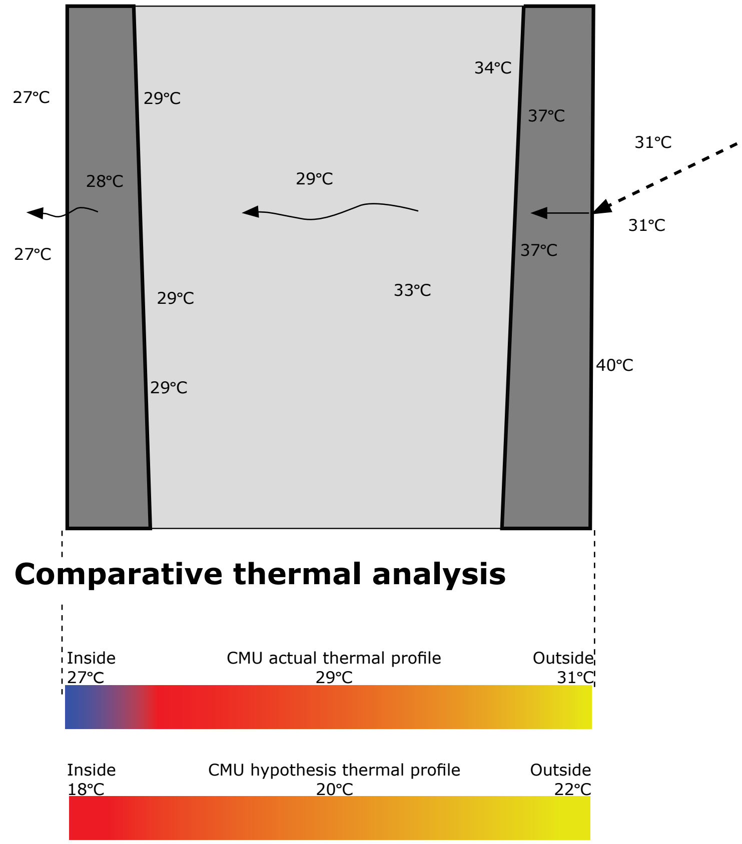


Fig. 140. Data from test 03 at 15:00 hours

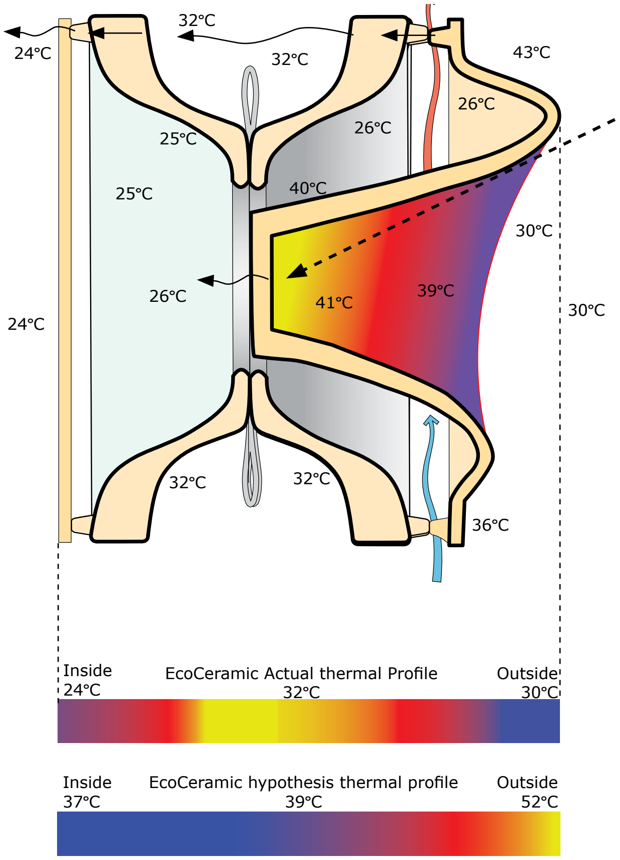


Fig. 141. Data from test 04 at 15:00 hours

Expected summer results

Through observing the thermal performance of the EcoCeramic wall system in the winter months the author purposes a revised summer performance hypothesis:

- The wall system should perform better than expected when evaporative cooling is utilized during the early morning through afternoon.
- As the degree of heating is directly linked to solar exposure, the self shading will eliminate radiant thermal gains throughout the summer months.
- Throughout May and June the wall system should be able to cool near wall conditions up to 15°C.
- Strategic ventilation caries built up heat away allowing the skin to radiate thermal gains back in to the environment and not towards the interior portions.
- The nature of traditonal wall systems, flat planes, allows an even build up of heat that moves through conduction to the internal surface. EcoCeramic creates large variations in thermal gains across the skin surface enable conduction to function laterally opposed to only directed towards the interior.

Revised thermal section

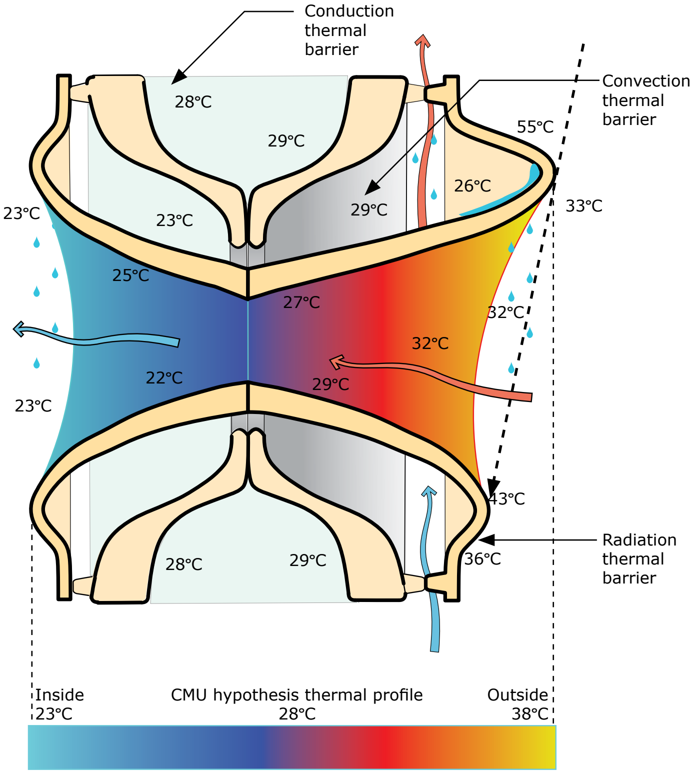


Fig. 142. Ambient 38°C

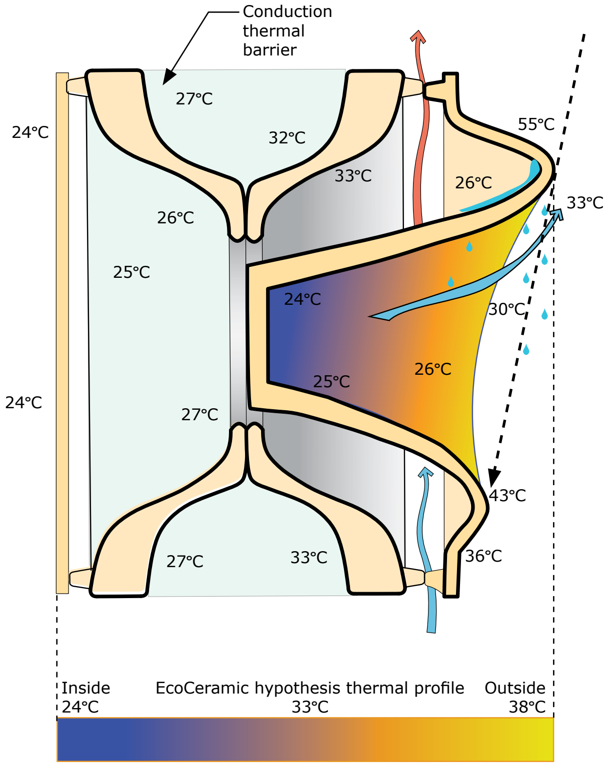


Fig. 143. Ambient 38°C

Applications

Using existing technology, coupled with emerging fabrication techniques each production mold set cost between fifty and seventy five dollars to fabricate in materials, with the addition of time a new generation of molds could be as low as $750.00. The low cost, coupled with the fast turnaround, enables architects and designers to act intelligently. Unhindered by off the shelf products a responsive unique building skin can be fabricated uniquely for a project or climate. As seen in Koppen's Climate map of the wold this climate hot and air encompasses much of the wold's landmass.

Climate & Principles

The climate and geographical location are the primary factors that influence these design strategies. A change in climate, and or a different geographical region would alter these design strategies. To break down the problem simply let us first assume uniform geography and changing climate conditions.

In a hot and humid climate:

- Increase the ventilation perpendicular and parallel to wall surface to cool.
- Increase shading near the wall surface.
- Use under fired or non-fired ceramics to absorb moisture.

In a cold and arid climate:

- Increase in concave surface area to absorb and retain heat.
- Increase dark colors for solar absorption.
- Use surface topography to decrease surface convection loss.
- Select a nonporous ceramic body and fire to a cone 11.

In a cold and humid climate:

- Implement dark colors to absorb heat.
- Concave surface typography to retain heat.
- Increase seasonal ventilation based off humidity cycles.
- Use under fired or non-fired ceramics to absorb moisture.

Each region in the world brings with it unique geographical, cultural, and climate characteristics.

Project analysis

While a structural module was design concurrently with the exterior unit the exterior unit does most of the thermal control. As such the designers hypothesize that one could simply apply the external unit to an existing building system or integrate it into new construction. As the immediate application of a post built process the design would alter in the length of the cone, and the perimeter of the hexagon. One could also exchange the hexagon unit for a rectangular unit that was in the same proportional language as the building.

Local post tensioning with glass fibers and epoxy is an ineffective method of joining from the standpoint of labor intensive. The author prepossess a search for alternative tension methods, such as a tape system wrapping units together, or taping the edges.

Due to the ease of rapid prototyping CMU proportions could be adapted and utilized by many in the construction industry.

Future studies

- This research was primarily focused on the aspects of passive geometry controlling and directing thermal flows. Future iterations would study the desired and healthy thermal ranges and investigate if passive methods could achieve these thermal tolerances.
- Variations of this research may include prototyping and investigating varying forms of fabrication and formal responses to the thermal environment
- Prototype a "typical" brick module based off the 8 by 8 by 16 CMU with principles based off of natural Homologues and Analogues
- The next step in this line of research lies in active building skins. As the hornet is capable of exchanging heat for electricity and back again so could a building skin.

Conclusions

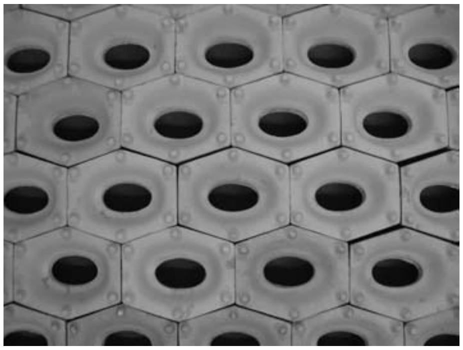
The author found the following:

01. Radiation is the primary source of thermal gain in each tested wall system.
02. The EcoCeramic wall system actively reduces surface temperatures (through radiation) throughout the day and night.
03. Geometry of the object, and geometry of the surface impact radiant thermal gains/losses.
04. Shaded vertical wall surface reduces radiant thermal gains.
05. A wall system can be optimized for orientation and climate conditions.
06. Passive architectural systems can temper the Sonoran environmental temperatures
07. The strategic application of color, mason stain, coupled with concave forms helps retain heat tempering the winter environmental temperature.
08. A wall system based on natural analogues and homologous can alter environmental temperatures.

- The EcoCeramic wall system was able to reduce winter thermal swings when compared to the CMU wall.

09. Protection against thermal gains in Southern Arizona is best when radiation, convection and lastly conductive thermal transfer are integrated into a wall system.
10. Separating the face tile from the structural unit allows vertical ventilation to cool exterior surface reducing the thermal gain.
11. Evaporative cooling integrated into the ceramic is effective at retaining a cool surface.
12. Use of Ecotect and similar programs can describe the thermal environment.
13. Rapid prototyping methods are easily adapted into the design of unique, computer generated ceramic molds.
14. Using existing production techniques allows for a rapid production process.
15. Using earthenware clay bodies and rapid production methods, production RAMpress, is an cost effective manufacturing process that is easily re-tooled for variable conditions.
16. Ventilation through wall cool cools interior.

Photographs will take place over the weekend or not at all



Photographs will take place over the weekend or not at all

Bibliography

"Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, by State." *Energy Information Administration*, www.eia.doe.gov, retrieved July 2008

Berman, A., Extending the Potential of *Evaporative Cooling for Heat-Stress Relief.* Journal of Dairy Science., 89, pp. 3817-3825, 2006.

Brebbia C.A. Design and Nature IV: Comparing Design in Nature with Science and Engineering. *High Performance Masonry Wall systems: principles derived from natural analogue,* by Jed Laver and others. UK: Wessex Institute of Technology, 2008.

"Comparative Climatic Data;" *U.S., National Climatic Data Center,* NOAA, 2001. www.ncdc.noaa.gov/oa/climate, Accessed September 2008.

Conrad, John W. *Studio Ceramic Dictionary.* San Diego: Falcon Company, Publishers, 1990.

Dieste, Eladio, Innovation in Structural Art. New York: Princeton Architectural Press, 2004.

Gibbs JG, DT Patten. "Plant temperatures and heat flux in a Sonoran desert Ecosystem". Oecologia., 5, pp. 65-84, 1970.

Heinrich, B, and American Society of Zoologists. *Insect thermoregulation.* New York: Wiley, 1981.

Ishay, Jacob S., Sverdlov, Anna, Pertsis, Vitaly, Gavrilov, Yulia, & Steinberg, David,. "Light Modulates Electric Phenomena in Hornet Cuticle." *Photochemistry and Photobiology,* 2004, 80: pg. 115–118.

Ishay, Jacob S., Goldstein, Orna., Rosenzweig, Eyal., Kalicharan, Dharamdajal., and Jongebloed, Willem L. "Hornets Yellow Cuticle Microstructure: A Photovoltaic System." *Physiological Chemistry and Physics and Medical NMR*. v 29. 1997. pg. 71-93.

Korb, J. "Thermoregulation and ventilation of termite mounds." *Naturwissenschaften*, 90(5), pp. 212-19, 2003.

Korb, J., and Linsenmair, K. E. "The effects of temperature on the architecture and distribution of Macrotermes bellicosus (Isoptera, Macrotermitinae) mounds in different habitats of a West African Guinea savanna,." *Insectes Sociaux*, 45, pp. 51-65, 1998.

Korb, J., and Linsenmair, K. E. "Ventilation of termite mounds: new results require a new model." *Behavior Ecology*, 11(5), pp. 486-94, 2000.

Korb, J., and Linsenmair, K. E. "Thermoregulation of termite mounds: what role does ambient tempera¬ture and metabolism of the colony play?" *Insectes Sociaux* 47(4), pp. 357-63, 2000.

Korb, J., and Linsenmair, K. E. "Ventilation of termite mounds: new results require a new model." *Behavior Ecolog*y 11(5), pp. 486-94, 2000.

Comparative Climatic Data; U.S., National Climatic Data Center, NOAA, 2001. www.ncdc.noaa.gov/oa/climate Accessed July 2008.

Lewis, D. A., & Nobel, P. S. "Thermal energy exchange model and water loss of a barrel cactus, ferocactus acanthodes." *Plant Physiology*., (60), pp. 609-16, 1977.

Laugier, Marc-Antoine. *Essai sur l'architecture: Essays on Architecture*. Translated by and Anni Herrmann. Los Angeles: Hennessey & Ingalls, 1977. 305pp

Malcolm Jr. Jones., *History of Air Conditioning*. Air Conditioning. Newsweek. Winter 1997 v130 n24-A p42(2). Retrieved February 2008. Accessed July 2008.

Moffett, Marian. *A World History of Architecture.* Boston: McGraw-Hill Companies, 4. Pgs. 431-2, 448-9

Nobel P. S., "Water relations and photosynthesis of a barrel cactus, ferocactus acanthodes, in the Colo¬rado Desert." *Oecologia*., 27, pp. 117-33, 1977.

O'Gorman, James F. *The Architecture of Frank Furness.* Philadelphia: The Falcon Press, 1973.

Olgyay, Victor., *Design with Climate: Bioclimatic approach to architectural regionalism.* New Jersy: Princeton University Press, 1973.

Parmer, Cole "Emissivity of Specific Materials; U.S." Chicago IL. www.coleparmer.com, Accessed September 2007.

"Potassium feldspar." *Encyclopædia Britannica*. 2008. Encyclopædia Britannica Online. www.britannica.com Retrieved 01 Sep. 2008.

"Residential Energy Consumption Survey 2001" *Department of Energy,* www.eia.doe.gov/emeu/recs retrieved on October 20th 2008

Seeley, T., & Heinrich, B. "Regulation of temperature in the nests of social insects." *Journal of Compara¬tive Physiology* A: Neuroethology, Sensory, Neural & Behavioral Physiology., 193(11) 159, 1981.

Skaife, S.H. *African insect life*. London: Country life books, 1979.

Smith, Stanley D., & Didden-Zopfy, Brigitte, & Nobel, Park S. "High-temperature responses of North Ameri¬can cacti." *Ecology*., 65(2) pp. 643-51, 1984.

Solomon, N.B., "New Building systems Mimic Nature and return to a biocentric approach to design." *Architectural Record,* 190(9) pp 173, 2002.

"Southern Arizona Temperature and Precipitation." *Arid Land Institute.* University of Arizona

Sullivan, H. Louis,. Autobiography of an Idea. New York: American Institute of Architects, 1949. pg 188-97.

Tsui, E., *Evolutionary architecture*. *Natures as a basis for design,* New York: John wiley & Sons, 1999.

"Tucson Arizona Historic Temperatures." *National Oceanic Atmospheric Administration*, www.nws.noaa.gov, retrieved April 2007.

Vitruvius, Marcus., *The Ten Books on Architecture.* Translated by Morris Hicky Morgan. New York: Dover Publications INC., 1960.

Watson, AN. "Preliminary study of the relation between thermal emissivity and plant temperatures." O*hio Journal Science.*, 33, pp. 435-50, 1933.

Wright, Frank Lloyd. *The Essential Frank Lloyd Wright: Critical Writings on Architecture.* Canada: Princeton University Press, 2008.

Glossary

1 law of Thermodynamics	Conservation of energy; the change in the internal energy of a closed thermodynamic system is equal to the sum of the amount of heat energy supplied to the system and the work done on the system.
2 law of Thermodynamics	Entropy; the total entropy of any isolated thermodynamic system tends to increase over time, approaching a maximum value.
Annealing point:	Also known as the tempering point, the point at which the internal strains in the glass are eliminated by stabilizing the material over a period of time, 480-425ºC (900-800ºF.)
ASTM:	
Clay body porosity:	Weigh dry fired clay unit in grams then submerge fired unit in boiling water, for one hour and let the unit sit for 8 hours. Then perform second measurement of unit weight. Porosity is calculated using the following equation: (Weight dry / weight saturated) *100 = Porosity
ASTM: compression:	These tests should be conducted using the Instron 3369. Each sample should be exactly the same size, 1” by 1” diameter cylinders.
ASTM: Shrinkage:	Use a mold and press uniform blocks of clay, scribe a 10 cm line in the surface, and allow the clay to fully dry. Length un-fired - Length fired = Shrinkage
ASTM: tension:	Also known as three point bending, these tests are conducted using the Instron 3369 using the same sample size.
ASTM: Testing Environmental thermal exchange:	Use half of the guarded hot box, ASTM C1363, and expose the wall section to the environment. To offset the loss of variables of environmental exposure the test must occur over a three day period.
ASTM: Wick rate:	Time how long it takes the ceramic to absorb a single drop of moisture on the surface: Time initial - Time final=Wick rate
Clay Batt:	The clay from which the unit is pressed. The batt must have sufficient excess to form the unit and the pinch points.
Conduction	The most significant means of heat transfer in a solid. On a microscopic scale, conduction occurs as hot, rapidly moving atoms and molecules interact, transferring some of their energy (heat) to these neighboring atoms.
Thermoelectricity	The relationship between electrons, heat fluxes and electrical currents generating electricity through a material thermal difference.
Convection	Generally the dominant form of heat transfer in liquids and gases (air).
Die casing:	The metal frame enclosing the plaster body of each die member. Die casings may be any shape or cast and can be welded or bolted together.
Diversification:	The formation of crystalline structure in glass (cloudy glass) caused by holding the glass at long and high temperatures. It can be avoided by cooling faster.
Excess clay:	That portion of the initial clay batt over and above the actual amount required to fill the ware forming cavity and form the pressed piece.
Fire polishing	A thermal polish to the surface of glass occurring at approximately 675ºF
Flash:	The portion of clay batt outside of the ware forming cavity after pressing.
Glass molds:	Typically plaster or ceramic mold that forms a cavity for the glass.
Initial heating:	The initial and rapid warming of the kiln achieving the soak temperature. The temperature must be higher than the strain point.

Kiln drying:	Rapid drying of a mold inside the kiln. Most benefit arises when drying is added to the kiln schedule.
Gutters:	The slope away from the pinch point
Liquidus	Point at which a material is moves from solid to liquid
Master Die:	The original die produced, by which all subsequent RAM die molds are made from requiring both a male and female member.
Parting line:	A line on the plaster model determined by the modeler which separates the die into male and female members.
Permeability:	The portion of plaster which permits the flow of air through the plaster die to release ware from the face.
Pinch point:	The raised portions of the gutter area which act to restrict the flow of clay from the ware forming area.
Purging:	The term used to describe the treatment given plaster dies shortly after they are cast, whereby all excess water and solvable ingredients harmful to the permeability are expelled from the plaster dies by air pressure.
Quartz inversion:	A thermal range that quartz inverts, expanding 2 percent and then contracts 2 percent. To avoid cracking, this cool down stage (575-600°C) should be moved through very slowly.
R value	The inverse of U. R value is measured in watts per meter squared in degrees kelvin. W/(m^2 K)
Radiation	The only form of heat transfer that can occur in the absence of a medium; thus, it is the only means of heat transfer through a vacuum.
RAM die:	Two pressing elements. Each die is composed of two members: a male member and a female member. Each of these members consists of a plaster body with a metal die casing formed under air pressure.
Rapid cooling:	The initial cool down from the working temperatures to the quartz inversion range.
Slip joining	Union of two non-fired ceramic pieces through the application of wet slip and pressing the pieces together.
Soak:	A temperature hold that allows the glass to settle reducing the amount of air entrapment.
Softening point:	The temperature at which the glass quickly and visibly distorts under its own weight.
Sprew	Device for pouring glass through mold into negative cavity
Strain point:	From 800-500oF the glass passes through the strain point. Bellow 500oF the glass has no stress. You don't really define what it is
Thermal shock:	Caused by rapid change of temperature in a short time period.
Ware releasing unit:	A permeable tubing which follows the contour of and just beneath the die face which allows the admittance of air to the die face.
Ware forming cavity:	A cavity between the two opposing die members contoured for the formation of pressed ware.
Working temperatures:	The thermal range at which glass begins to flow. Glass is a correlation between time and temperature; increase either and the glass will become more fluid.
U value	Measures the rate of heat transfer through a building element over a given area, under standardized conditions, 24 °C, at 50% humidity with no wind.

Material glossary

CERAMI-CAL®	A low-consistency form of HYDROCAL Gypsum Cement formulated to produce a dense, smooth-wearing die material for pressing clay-ware; 100 parts dry to 40 parts wet.
Diatomaceous Earth	A strengthening agent
Edgar plastic kaolin (EPK):	: Release agent mixed in small amounts into a plaster mold.
Graphite powder:	An additive to squeegee oil as the primary release agent in fusing and annealing glass.
HYDROCAL®:	A gypsum product offering higher strengths than typical plaster products. HYDROCAL® is especially designed for thin sections, which require high green (early) strength to minimize breakage during removal from intricate latex molds. Dry strength 5,000 psi, dry impact strength 1,750 psi; 100 parts dry to 38 parts wet
HYDROPERM:	Gypsum Cement used to produce permeable plaster molds for casting of many non-ferrous metals and alloys; 100 parts dry to 70 parts wet
HYDRO-STONE® :	One of the hardest and strongest of all gypsum products, it is recommended for producing high-quality novelty and statuary castings requiring extremely hard surfaces. Dry strength 10,000 psi, dry impact strength 1,320 psi; 100 parts dry to 32 parts wet
Kiln wash:	A water soluble release agent, applied in multiple coats to create a smooth, easy to release surface even at temperatures up to 1095 °C
Medium Density Fiberboard (MDF):	A composite wood product similar to particleboard made from wood waste fibers glued together with resin, heat, and pressure
MolDuct Ties:	Used to attach the Molduct tubing to wire frame
MolDuct Tubing:	Special woven cotton tubing used in pressing dies for air passageways. Air, forced through the tubing, forces the release of the pressed piece from the dies
Pottery plaster:	USG® Pottery Plaster is industry-wide known for working reliability, productivity and highly successful results. USG® Pottery Plaster is for all types of ceramic slip casting applications. Dry Strength - 2,400 psi; 100 parts dry to 70 parts wet.
Squeegee oil:	Release agent; squeegee or pine oil mixed with graphite powder works well for fusing and annealing but does not perform at temperatures greater than 900oF. The graphite powder should be suspended in the solution.
ULTRACAL:	Super-strength gypsum product recommended where extreme accuracy and greater surface hardness are required, as in duplicator models. ULTRACAL 30 has the lowest expansion of any rapid-setting gypsum cement available. Dry Strength - 6,000; 100 parts dry to 45 parts wet
wire mesh:	Used to hold the Molduct off the mold

Figure list

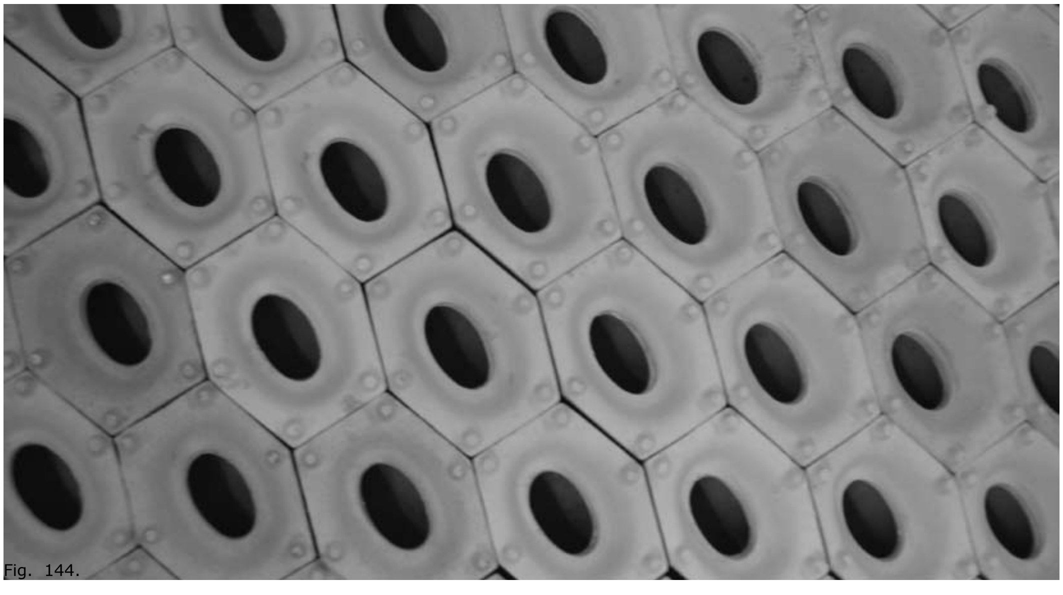


Fig. 144.

Appendices

Appendix A

Hornets and Hive Structure

Hornets were investigated through a literature review due to their unique ability to survive in nearly any climate while maintaining a constant body and hive temperature year around. The hive was looked at due to the packing efficiency of the hexagon unit, and the relationship between the hornet and the hive.

Fig. 145. Hornet comb (Seeley)

The researcher observed that

- The gaster contains type p and type n semiconductors carrying a constant electric charge throughout the hornet.
- Several hornet species are capable of exchanging built up electric charge to a thermal response.
- The hornet could move between heat and electricity generation as needed.
- The silk in the hornets nest provides storage for electrical and thermal energy and is capable of transferring heat to electricity and visa versa.
- The gaster due to the material can only absorb light 90º
- The hornet’s system acts as a battery, storing electricity and converting it to heat, or when too hot converting heat to electricity, the system can generate between 20-40ºC.
- The hexagon packing is the most energy efficient packing structure.
- The hive is capable of tempering environmental temperatures and storing electricity.

Sources: Heinrich, Ishay, seeley

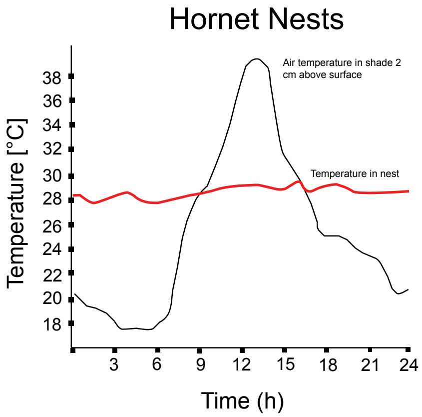


Fig. 146. Hornet temperature swings (Ishay)

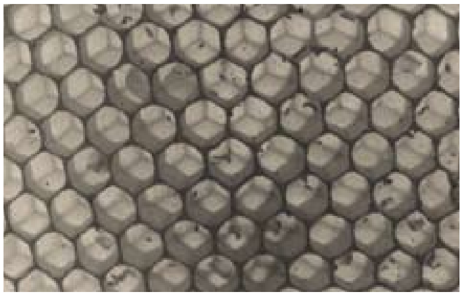


Fig. 147. Bee’s honey comb

Applying these findings to architecture, the following possibilities emerge

- Wall systems could exchange heat into electricity, and back again.
- A light weight structural skin could eliminate the need for conventual insulation.
- A wall systems could perform as a storage of both heat and power for the occupants.

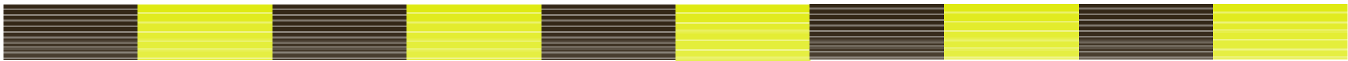


Fig. 148. P-N Junction causes continual flow of electricity

Homo Sapiens

Humans are investigated for the stringent thermal conditions for optimal performance. The second reason is human comfort. What is comfort, how is it achieved, is it constant or dependent on exterior factors?

The researcher observed that

- Humans use radiation for sixty percent of their thermal exchange. Convection accounts for twenty five percent and conduction for fifteen percent.
- Blood vessels regulate thermal flow to extremities, stabilizing the core by nearly 600 percent contraction and expansion.
- Secretion of sweat and hair regulate conduction and convection.
- Comfort often depends on climate, with direct and indirect radiation the largest contributors to the sensation of comfort.
- No single method is sufficient to optimize comfort levels to modern standards.
- Comfort levels depend on the individual and location but generally range from 23-30°C.
- Sources: Berman, Olgyay

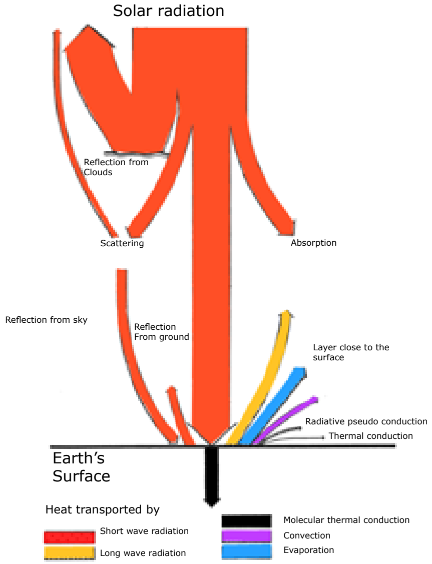


Fig. 149. (Oglay)

Applying these findings to architecture, the following strategies emerge

- Controlling and directing radiation is paramount to personal comfort.
- Utilization of shade to diffuse direct solar radiation tempers the highest solar thermal gains.
- A peripheral ventilation system capable of expansion and contraction could mitigate convection thermal gain and loss.
- Conduction should be considered as the last line of defence in the building skin.

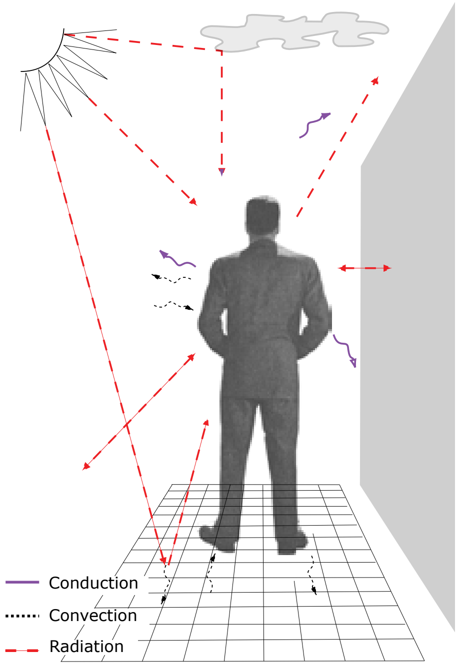


Fig. 150. Thermal flux around humans (Oglay)

Architectural case studies

Primitive Hut

Shelter architecture, found in nature, is the most basic form of construction. The front piece to Marc-Antoine Laugier's Essays on Architecture brought this architectural theory back into mainstream in 1755 AD. When Laugier referred to simplicity in architecture, he meant "the inherent quality of nature" (Laugier).

Marcus Vitruvius also wrote, " All machinery is derived from nature... when our ancestors had seen that this was so, they took their models from nature, and by *imitating* them were led on by divine facts, until they perfected the contrivances which are serviceable to our life" (Vitruvius).

The primitive hut is the result of mankind's desire to have shelter from heat, protection from rain, and avoiding dark subterranean locations. It is the basic relationship between man and the environment. In this way, architecture has roots in imitating nature for shelter.

Vitruvius further, delineated of the relationship between ornamentation, proportion and nature. Doric columns were derived from the foot print of a man, height and breast of a man, while Ionic columns were derived similarly from a woman's body; the capitol of the Corinthian order came from the acanthus plant (Vitruvius). In Greek and Roman times, architecture was no longer simply about the imitation of nature, but proportionality and ornamentation found in nature.

Fig. 151. Primitive Hut (photo from essays on architecture

Fig. 152. Corinthian column, Saint John's Basilica Rome

Antoio Gaudi

Antoio Gaudi re-examined the classical notions of proportion in nature and added the layer of structure. The column structure in his Sagrada Família imitates tree branching, while each column is buttressed like a tree trunk to optimize its strength. Gaudi also developed the parabolic arch in architecture, a system found everywhere in nature.

Fig. 153. Sagrada Família

Mick Pearce

The Eastgate Shopping Center in Harare Zimbabwe gained recent international attention due to its bio-climatic design strategies (Tsui, Solomon). Pearce found in local termite populations inspiration for the building's thermal strategies. Unlike his predecessors, Pearce is one of the few recent architects to implement design principles found in nature.

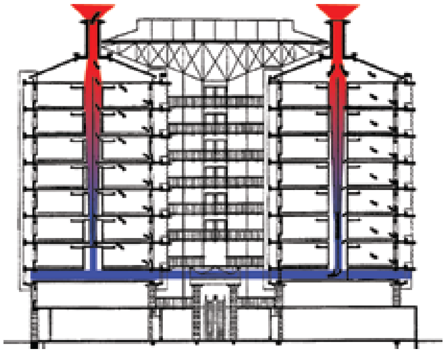


Fig. 154. EastGate Center section diagram (Solomon)

Eladio Dieste

The Church of Christ the Worker in Alantida, Uruguay, is a prime example of Dieste's devotion to brick and form. Eladio once wrote, "I work with brick because it is cheap, the forms I chose allow me to maximize the material's potential and save on building costs" (Dieste). Projects by Eladio prove that form with a purpose is both economical and efficient. Furthermore, Eladio was able to span great distances with a single thickness of brick due to the form. Thus, the form and the material are co-dependent on each other.

Fig. 155. Church of Christ the worker (Dieste)

Richard Serra

Serra's work with sheet steel forms a natural alliance with the curving forms of Dieste's work in masonry. They both worked with their material and geometric curves to achieve an artistic and structural result, Olson in 1986, Intersection I & II in 1992 through 93, Sidewinder in 1999 and Te Tuhirangi Contour in 2000-02.

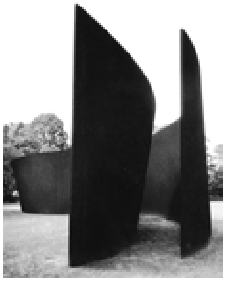


Fig. 156. Sidewinder 1999 (Serra)

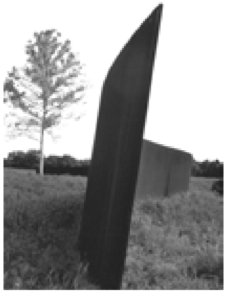


Fig. 157. Contour 290 2004 (Serra)

Frank Lloyd Wright

Frank Lloyd Wright often created complex concrete units for Florida Southern College, and utopian homes across America. His work strived for the fewest possible unique units, rapid production, and standard assembly techniques. Often he would incorporate custom cast glass into the concrete units to create a unique apertures.

Fig. 158. Usonian Automatic cast modules

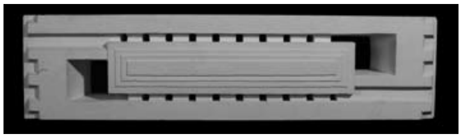


Fig. 159. Florida Southern College cast module

Appendix B

Ram Press procedure for creating Master Mold to Working Die.

01. Step procedure for creating Master Mold to Working Die.
02. Use digital modeling tools to create the digital master molds.
03. CNC an MDF mold, male and female with pinch points and gutters creating master mold.
04. Coat MDF with polyurethane (four coats sand with 220 in between each coat).
05. Apply a single coat of hard wax (trewax).
06. Place wire cage 1” above master mold, following the contour of the mold as closely as possible. Use wire hooks to suspend the cage from the die sides, and steel rods to hold in place during the plaster pour.
07. Tie the MOLDUCT to wire cage and connect MOLDUCT to air fitting.
08. Measure CERAMICAL and water slake plaster into water, (100g CERAMICAL to 40g water).
09. Let sit for 7 minutes then mix with a mechanical mixer for 10 minutes.
10. Pour CERAMICAL into mold.
11. Frequently tap the sides of the die, removing air pockets, and remove the steel rods, and wire hooks so that the cage is held in place by the plaster alone (~3 minutes after pour).
12. Screet plaster level, adding more as needed (~3-5min after initial pour).
13. Check plaster for initial set (~100oF or 7min after initial pour).
14. Flip mold upside down; (master mold is now on top).
15. Initiate the purge according to schedule given when plaster obtains 100ºF.
16. Remove master mold from working die by gently separating the two surfaces.
17. Set working dies on side and continue to purge, sponging water off the surface frequently.
18. If the working die is properly made, it s*hould be completely dry and serviceable within 2 hours after initial pour.*
19. *When completely purged support the working dies and carefully and accurately scrapes the back of the die flat with a straight edge as the back will continue t*o expand due to the plaster.

Purge schedule:

When the temperature of the ceramical rises to 37.8°C, initiate purge at 10 psi. Increase the pressure by 10 psi every minute until air pressure between 90 and 110 psi is obtained. Continue the purge at 90-110 psi until the mold is dry, about three hours

Note:
Around 30 psi, position mold on edge so that the water may run off without hindrance. Draining the purged water ensures clean passage of air, and an expedited drying time.

Step procedure for pressing and releasing clay units

01. Pre-determined clay charge made from extruded blank is placed on the lower die.
02. Press is activated, bringing the two dies into registration, spreading the clay charge into the unit cavity.
03. Air is applied to the lower die, releasing the clay from the lower die
04. The dies are separated leaving the clay unit in the top die.
05. The operator removes any flash from the gutter in the top die.
06. The operator applies air to the upper die, releasing the clay unit from the upper die, unit drops onto a board or into the operator’s hand.
07. The operator places the unit in a drying rack, and then wipes down both dies with a sponge removing any excess water.

Repeat process

Step procedure for creating slip cast molds.

08. Use digital modeling tools to create the digital master molds.

09. CNC the mold into MDF.
10. Coat the MDF master mold with 4 coats of polyurethane sanding in between each coat.
11. Wax mold using a hard wax, release agent.
12. Construct a box around the mold fully enclosing the master mold (also coated with polyurethane).
13. Measure 4 parts pottery plaster to 3 parts water.
14. Slake plaster into the water, let sit for 4 minutes.
15. Mix the plaster and water using a rotary mixer for 4-6 minutes depending on environmental temperature. (Hot environments require a decreased mixing time).
16. Pour plaster into mold, tamping the air bubbles out.
17. After 5-24 hours (depending on the geometry), remove the master mold.
18. Let the plaster dry for 3-4 days before moving to next step.

Step procedure for casting with slip cast

01. If using a two part mold, fasten both parts together with tie down cables.
02. Check that the mold has sufficient ventilation for pouring slip.
03. Fill mold cavity with slip and let sit for 20-30 minutes (actual time is dependent on plaster thickness and surface area to be covered).
04. Flip mold upside down and drain excess slip out..
05. Leave mold upside down for 24 hours
06. Remove ceramic unit from mold.
07. Clean mold and re-apply release agent.
08. Repeat process.

Slumping glass molds.

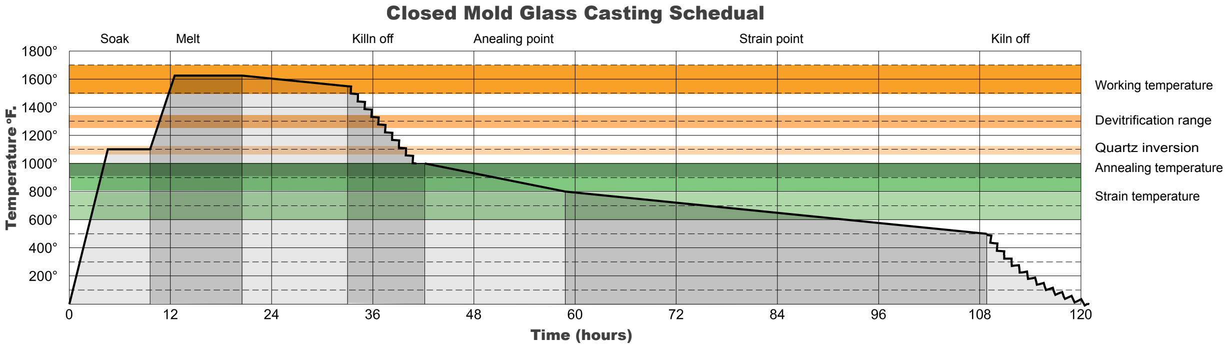
01. Step procedure for Glass molds.
02. Use digital modeling tools to create the digital master molds.
03. CNC the mold into MDF.
04. Coat the MDF master mold with 4 coats of polyurethane sanding in between each coat.
05. Wax mold using a hard wax.
06. Construct a box around the mold fully enclosing the master mold (also coated with polyurethane).
07. Measure 80% HYDROPERM 15% Diatomaceous Earth 5% EPK.
08. Measure 70% of the dry weight in water.
09. Slake plaster into the water, let sit for 4 minutes.
10. Mix the plaster and water using a rotary mixer for 4-6 minutes depending on environmental temperature. Be careful not to move the mixer in and out of the mix. (Hot environments require a decreased mixing time.)
11. Pour plaster into mold, tamping the air bubbles out.
12. After 5-24 hours (depending on the geometry and mold material) remove the master mold.
13. Let the plaster dry for 3-4 days before going onto the next step.
14. Apply three coats of kiln wash to plaster with 20 minutes drying time between each coat.
15. Kiln dry molds to 288°C for one hour, then turn off kiln and let molds return to room temperature (six hours).
16. Place washed and dry glass in mold
17. Initiate the kiln sequence.
18. Remove glass/mold only after kiln is within 30° F. degrees of ambient temperature. (Thicker two part molds with 1” walls require a stabilization time of 24 hours after achieving room temperature before removing from kiln.)
19. Remove glass, wash plaster off.
20. Sand with wet sander as required.

Two part glass molds:

01. Follow slumping glass molds steps 01-05 with the exception of for both the male and female mold with registration points.
02. Place wax sprews and wax air vents on mold sprews/vents are placed to eliminate air entrapment in the cast
03. Follow steps 06-20

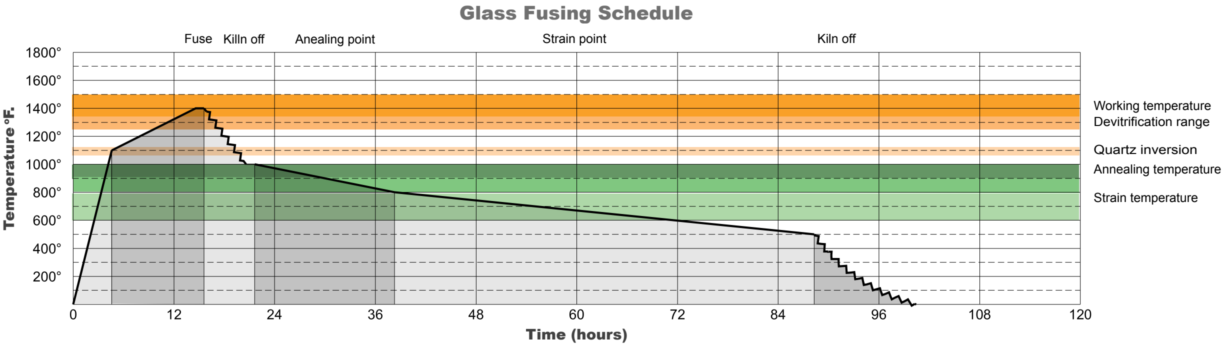
Notes:

4000 grams of dry plaster mix will fill a volume of 110 cubic inches. All plaster should be slaked, and soak for 3-4 minutes before mixing mechanically for 5-7 minutes.



Rapid heating
R1: 4 0F. p/m
T1: 1100 0F.
H1: 300 min.
Melt
R2: 3 0F. p/m
T2: 1625 0F.
H2: 420 min.
Slow cooling
R3: 0.1 0F. p/m
T3:1550 0F.
H3: 1 min.
Rapid cooling
R4: 0.0 0F. p/m
T4: 1000 0F.
H4: 60 min.
Annealing
R4: 0.2 0F. p/m
T4: 800 0F.
H4: 1 min.
Strain
R5: 0.1 0F. p/m
T5: 500 0F.
H5: 1 min.
Rapid cooling
R6: 0 ^{0}F. p/m
T6: 80 ^{0}F.
H6: 1 min.
Program end
R7: -1 ^{0}F. p/m
T7: 80 ^{0}F.
H7: 0 min.

Fig. 160. Closed glass casting schedule



Rapid heating
R1: 4 ^{0}F. p/m
T1: 1100 ^{0}F.
H1: 300 min.
Softening
R2: 0.5 ^{0}F. p/m
T2: 1400 ^{0}F.
H2: 1-90 min.
Rapid cooling
R3: 0.0 ^{0}F. p/m
T3:1000 ^{0}F.
H3: 60 min.
Annealing
R4: 0.2 ^{0}F. p/m
T4: 800 ^{0}F.
H4: 1 min.
Strain
R4: 0.1 ^{0}F. p/m
T4: 500 ^{0}F.
H4: 1 min.
Rapid cooling
R5: 0 ^{0}F. p/m
T5: 80 ^{0}F.
H5: 1 min.
Program end
R6: -1 ^{0}F. p/m
T6: 80 ^{0}F.
H6: 0 min.

Fig. 161. Fusing glass schedule

Glass slumping

The liquidus temperature of glass is directly dependent on the composition of the glass. Due to the wide range of available material matrixes of glass it mealts between 760° and 1370°C. Most glass will begin to soften at or around 650°C. Knowing the softening point enables the designer to design proper molds and proper kiln schedules for the casting.

Notes:

- Duration of working temperature is dependent on glass thickness, size, and proximity to the heating elements.
- If one is unsure of working times, check on the glass every 15 minutes. (When kiln temperature is above 1200° F, wear proper eye protection.) Do not let the temperature fall below 1150oF while checking.
- After fusing the unit together, follow typical cool down schedule.

Slumping schedule
Rapid heating
R1: 4 ^{0}F. p/m
T1: 1100 ^{0}F.
H1: 120 min.
Softening
R2: 0.5 ^{0}F. p/m
T2: 1200 ^{0}F.
H2: 1-90 min.
Rapid cooling
R3: 0.0 ^{0}F. p/m
T3:1000 ^{0}F.
H3: 60 min.
Annealing
R4: 0.6 ^{0}F. p/m
T4: 800 ^{0}F.
H4: 1 min.
Strain
R4: 0.3 ^{0}F. p/m
T4: 500 ^{0}F.
H4: 1 min.
Rapid cooling
R5: 0 ^{0}F. p/m
T5: 80 ^{0}F.
H5: 1 min.
Program end
R6: -1 ^{0}F. p/m
T6: 80 ^{0}F.
H6: 0 min.

Appendix C

ORTON STANDARD PYROMETRIC CONES				
"From the Edward Orton, Jr. Ceramic Foundation, Columbus, Ohio"				
Ramp rate 65.5° C (150° F) per hour				
Cone	Celsius	Fahrenheit	Color	Changes in claybody
022	600	1112	Dull Red	Diversification
021	614	1137		
020	635	1175		
019	683	1261		
018	717	1322		Glass slumps
017	747	1376		
016	792	1457		
015	804	1479		
014	838	1540		
013	852	1565		
012	884	1623	Cherry Red	
011	894	1641		Glass fuses
010	900	1652		Earthware
09	923	1693		
08	955	1751	Orange	
07	984	1803		
06	999	1830		
05	1046	1914		
04	1060	1940		
03.5	1080	1976		
03	1101	2014		
02	1120	2048		Higher fire earthware
01	1137	2079		
1	1154	2109	Yellow	
2	1162	2124		Soft stoneware
3	1168	2134		
4	1186	2167		
5	1196	2185		
6	1222	2232		
7	1240	2264		
8	1263	2305		Stoneware clay matures
9	1280	2336		
10	1305	2381	White	Hard stoneware
11	1315	2399		
12	1326	2419		
13	1346	2455		Porcelin matures
14	1366	2491		
15	1431	2608		

Fig. 162. Orton cone standerds

Appendix D

Mold Costs						
Master Mold						
Material/time	Brick	Face Tile	Inside tile	Wedge	Inside (w/ pattern)	Inside (smooth)
MDF	$65.59	$81.99	$32.80	$8.20	$32.80	$32.80
Glue	$1.31	$1.31	$2.63	$0.99	$1.58	$1.31
CNC time ($70 p/h)	$700	$630	$52.50	$4.38	$52.50	$52.50
MasterCAM time	120 min	120 min	120 min	45 min	120 min	120 min
Finish time	120 min	120 min	120 min	45 min	120 min	120 min
Labor	$179.20	$179.20	$179.20	$67.20	$179.20	$179.20
Cost	$946.11	$892.51	$267.13	$80.76	$266.07	$265.81
Working Mold						
Material/time	Brick	Face Tile	Inside tile	Wedge	Inside (w/ pattern	Inside ((smooth)
Mold Duct	$3.94	$3.94	$3.94	$3.94	$3.94	$3.94
MoldDuct ties	$1.81	$1.81	$1.81	$1.81	$1.81	$1.81
Wire Mesh	$2.80	$2.80	$2.80	$2.80	$2.80	$2.80
Plaster	$75.27	$75.27	$75.27	$4.69	$37.64	$37.64
Perp Time	90 min	90 min	90 min	20 min	60 min	60 min
Cast time	180 min	180 min	180 min	30 min	120 min	120 min
Labor	$201.60	$201.60	$201.60	$37.33	$134.40	$134.40
Cost	$285.42	$285.42	$285.42	$50.58	$180.59	$180.59
Glass Molds						
Material/time	Rubber Glass Mold	Material/Time	Plaster Glass Mold			
MDF	$49.19	Hydroperm	$100.97			
Glue	$1.31	EPK	$7.20			
Rubber	$78.36	DEarth	$48.39			
CNC time	$157.50	Labor (casting	150 min			
Mastercam time	120 min	Labor (prepare)	70 min			
Finishing time	120 min	Labor (total)	$164.27			
Labor	$179.20	Quantity	10			
Bucket (use cost)		Life cycle	8			
MDF box	$5.47	Glass units	80			
Working time	90 min					
Labor	$67.20					
Cost each	$538.23		$4.11			

Fig. 163. Material costs

Ceramic Unit Price List							
Product	Material ($)	Labor (time)	Cost (per unit)	Produced (#)	Weight (lb)	Wall (lb)	Total cost
Brick	$1.79	$8.35	$10.14	120	13	1560	1001.64
Exterior	$1.50	$9.74	$11.25	75	5	375	730.72
Interior	$1.11	$14.96	$16.07	40	5	200	598.40
Flat	$0.93	$9.04	$9.96	25	5	125	225.95
Articulated	$0.93	$8.88	$9.80	25	5	125	221.87
Glass exterior	$25.39	$13.69	$39.08	45	4	180	616.24
Glass Hexagon	n/a	$5.00	$5.00	30	4	120	150.00
Glass cone	n/a	$2.00	$2.00	25	1	25	50.00
Structure				120		1560	
Exterior				120		555	
Interior				120		570	
					Total weight	2710 lbs	$3594.85

Fig. 164. Fabrication costs