Biomimetic House in Tabuk, Saudi Arabia

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Engs 44 Sustainable Design 15S

Project Report

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Introduction

Nature continuously adapts to the environment - despite any harsh conditions, nature finds its way to prosper. As a result, when humans similarly want to overcome extreme climate, it is advantageous to base the designs off nature's adaptations. For the Engs 44 sustainable design project, our team chose to target a hot and dry climate that has characteristic diurnal temperature extremes. Saudi Arabia, a desert country known for its abundance of oil, attracted our attention because its climate and needs fit our interests well. Specifically, we focused on the city of Tabuk, in the northwestern region of Saudi Arabia. We studied the local flora and fauna in the local area as well as in places with similar climate to understand their adaptations to the environment. Our goal was to apply as many biomimetic features to our house designs as possible, while still maintaining good engineering practices and implementing state of the art technologies. After our midterm presentation, we pared back our design and focused on the human centered aspect in order to optimize the house for a comfortable living experience. Furthermore, thorough engineering analyses were performed for the different aspects of the structure in order to test the viability of our design. Finally, the engineering analyses provided valuable suggestions on how to refine the design to truly adapt to the local environment to strive for a net-zero-energy residence building.

Characterization of Site

Tabuk, Saudi Arabia is located at 28˚23'50" N, 36˚34'44" E. It is the capital city of the Tabuk province and is a moderate sized city with a population of roughly 500,000 people. It has a steady growth rate of 13,000 people per year, meaning that it is a healthy and growing population that will continue to sustain the city in the coming years.[1]

Saudi Arabia is an islamic state, which means that the Islamic religion is the primary governance of the administration and legal system. The national language is Arabic, but English is also spoken widely in the cities. Their government is a monarchy which is headed by the king, who also acts as their head of military and is advised by the Council of Ministers and the Consultative Council.[2] Saudi Arabia has an economy that is heavily dependent on oil, as the country is the world's leading producer and exporter of oil.[3] Because of this, the cost of energy in the country is very low and there is not a particularly environmentally-minded culture in place. However, the threat of depleting its oil sources is starting to encourage a shift towards greener and more sustainable technologies.[4]

Climatologically, there are multiple important factors to consider for comfortable living in Tabuk. The relative humidity swings by 40% each day, and 30% annually. For example the humidity in June swings from 10% to 40% from day to night, whereas in January the high is around 77% in the day and drops to 32% at night. The temperature also swings both daily and yearly, getting as high as 110°F in the summer and as low as 40°F in the winter. There is very little precipitation, total to only 5 cm per year. However, the area does have prevalent levels of groundwater. There is not a copious amount of wind, however the wind that is present comes mostly from the north, northwesterly directions - with 17% coming from the northwest, 16%

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[1] Mackey, Sandra. The Saudis: Inside the Desert Kingdom. Updated Edition ed. New York: W.W. Norton, 2002. 234. Print.
[2] "Government." Royal Embassy of Saudi Arabia, Washington DC. Web. 7 June 2015.
[3] "Economy and Global Trade." Royal Embassy of Saudi Arabia, Washington DC. Web. 8 June 2015.
[4] Patel, Sonal. "Shifting Sands: The Middle East's Thrust for Sustainability." *Power Magazine*, 1 July 2014. Web. 9 June, 2015. <http://www.powermag.com/shifting-sands-the-middle-easts-thrust-for-sustainability/>

coming from the north, and 13% coming from the west. The average wind speed ranges from 0 to 15 mph, and the wind rarely exceeds 28 mph. There is very little cloud coverage, with only 15% cloud coverage at the cloudiest time of the year. The total cooling degree days for the area are 2,370, while the total heating degree days are 1,140.[5]

Objectives

Our main objective in designing our biomimetic building is to create a comfortable living area in Tabuk, Saudi Arabia by using aspects of nature and its adaptations to the desert environment. We want to reduce total energy and water usage, using the average energy and water consumption of a household in Tabuk as a comparison. The reduced total energy of our design will come from a combination of passive and renewable energy; and the reduced water consumption will be supplied by harvesting rainwater and capturing atmospheric moisture.

Specifications & Constraints

Specifications

To achieve these objectives, we set ourselves some specifications and constraints regarding how we will incorporate more sustainable design practices into our house. In order to maintain a "comfortable" living area, the temperature must range from 68°F to 78°F and the relative humidity range from 20% to 60% in the summer and up to 80% in the winter.[6] We planned on achieving this without the help of an HVAC system. Specifically, about 70% of heating, ventilating, and air-conditioning needs were aimed to be taken care of through passive heating and cooling. For comfortable ventilation, we aimed to maintain an air exchange rate of twice every three hours. In addition, we would supply all of our building's electricity needs with

[5] "WeatherSpark Beta." Average Weather For Tabuk, Saudi Arabia. Web. 7 June 2015.
[6] "In Search of Comfort." ES 44 Lecture Slides 7-8, Benoit Cushman-Roisin, Dartmouth College

solar photovoltaic panels. In regards to water, we would implement a water heating and cooling system that eliminates the need for fossil fuel powered water heater or cooler, and a greywater recycling system that would reduce total water consumption and supplement the water demand through rainwater and dew collection technologies. Our house was designed for a family of four, which is typical in Saudi Arabia. However, further research on Saudi Arabian culture showed that the local people are family oriented therefore the feature of extra guest bedrooms should be implemented. Further information on the cultural aspect is discussed in the Cultural Constraints section below.

Geographical Constraints

The constraints of siting our building in Tabuk, Saudi Arabia include the relatively dramatic temperature swing of 20-30°F daily and up to 60°F seasonally, as well as the relative humidity swing of 40% each day and 30% seasonally. There is fairly intense solar radiation at an average of around 4.5 sun hours on average daily. Again given that Tabuk is located in a desert, on average there is only about 5 cm of precipitation per year. There are limited winds, at a yearly average of 15 mph. Additional constraints include the siting of the structure (further discussion in the Siting of Structure section) and the cost of the house. All these constraints are important to keep in mind because they not only tell us what the geographical limits are but also help refine our overall design.

Cultural Constraints

In addition to our previous specifications, during the second iteration of our design process we wanted to be sure that our design was not only environmentally feasible, but also culturally sensitive. So we added additional specifications to consider important cultural aspects.

Research showed that as of 2012, about 80% of Saudis live in urban metropolitan areas, meaning in order to reach the largest market, our building needs to be built in and adaptable to an urban area.[7] For this important reason we sited our structure at an urban area (please refer to the Siting of Structure section) to meet this specification. In terms of traditional building techniques and constraints, our group discovered that an important structural constraint was the height of the minarets in the area. Every Islamic mosque has towers called minarets, as shown in Figure 1 below[8]. Traditionally, during the 5 prayer times each day, a member of the mosque would read out a call prayer from the top of the minaret so it could be heard throughout the city. Because of this, minarets are customarily supposed to be the tallest structures within the city, meaning our structure needs to be below the height of the minaret in Tabuk.[9] Unfortunately there wasn't height data to be found on Tabuk's minaret, instead we found the height of 7 different minarets and averaged them to come up with a limiting height of 237.9 *ft*. We also decided to include a courtyard to mimic the courtyard or Sehan that is often seen in traditional architecture. The Sehan not only provides a cooler outdoor space with

Figure 1. Picture of minarets in Saudi Arabia.

[7] House, Karen Elliott. On Saudi Arabia: Its People, Past, Religion, Fault Lines--and Future. New York: Alfred A. Knopf, 2012. 69. Print.
[8] Picture taken from http://blogs.ei.columbia.edu/wp-content/uploads/2011/09/minarets.jpg
[9] "Architecture." Royal Embassy of Saudi Arabia, Washington DC. Web. 7 June 2015.

fountains and shade, it also is a space where the women of the house need not be covered in the hijab clothing traditionally necessary in public.[10] Lastly we turned to the basic layout of the house using the knowledge that Saudi Arabia is based upon a family oriented culture. Only 30-40%of the working age population actually holds a job, thus much time is spent visiting the family.[11] Commonly the extended family even live in a large compound together.[12] Because of this, we made sure that there is enough bedroom space to allow for a larger family unit to live within our structure, and aimed to implement integral family spaces that can be used for relaxing and spending time with visitors.

Siting of Structure

Because of the size and wind collection mechanism, the siting of our structure was limited to certain areas of the city. The building had to be located on the outskirts of the city where it had minimal surrounding structures to block the wind. Ideally the site should be oriented south to north to maximize solar utilization and wind harnessing. The south and southeast sides of the city are not viable because of the need for unobstructed access to the wind. In our original design the size footprint of the house was about ~ 1400 ft^2 per floor, which is around the size of a average home. However our final design had a final square footage of 11,529.82 ft^2 and a footprint of 2839.09 ft^2. The cone structure surrounding the house plus a courtyard demanded a larger footprint, meaning that we needed a fairly large plot in which to build our structure. With all these specifications related to optimizing our design, the ideal locations to site our structure were shown below in Figure 2.

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[10] "Islamic Architecture – Sehan." Web. 7 June 2015. http://www.itilsurvival.com/islamic-architecture-sehan.html.
[11] McDowall, Angus. "Saudi Arabia Doubles Private Sector Jobs in 30-month Period." Al Arabiya News. Web. 7 June 2015.
[12] Long, David E. Culture and Customs of Saudi Arabia. Westport, Conn.: Greenwood, 2005. 37-39. Print.

Figure 2. Schematic figure showing ideal locations to site our structure.

Flora, Fauna and Biomimicry

Saudi Arabia contains one of the world's largest continuous bodies of sand[13], though the desert is punctuated in the Tabuk region by shrublands and more fertile gullies, or *wadis*[14]. The harsh environment means that there is limited biodiversity, but the plants and animals that do exist have been finely adapted to survive in the area.

Plants in Tabuk are sparse, mostly sedges or small annual flowers[15], interspersed with shrubs and trees. One of the most iconic trees found in Tabuk is the umbrella thorn tree, which combines a deep taproot and a large canopy to maximize its water absorption[16]. Its canopy shades the ground below it to minimize evaporative losses, allowing the roots to gain as much

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[13] Hogan, C Michael. "Arabian Desert and East Sahero-Arabian Xeric Shrublands." The Encyclopedia of Earth. Ed. Mark McGinley. World Wildlife Fund, 16 May 2014. Web. 21 Apr. 2015.
[14] Hogan, C Michael. "Red Sea Nubo-Sindian Tropical Desert and Semi-desert." The Encyclopedia of Earth. Ed. Mark McGinley. World Wildlife Fund, 16 May 2014. Web. 21 Apr. 2015.
[15] Thomas, Jacob. "Vegetation of Northern Province." Plant Diversity of Saudi Arabia. Kind Saud University, Riyadh, 26 Feb. 2011. Web. 23 Apr. 2015.
[16] "Tree Structure Reduces Water Loss: Umbrella Thorn Trees." Ask Nature. The Biomimicry Institute, 2015. Web. 19 Apr. 2015.

water as possible. Meanwhile, the taproot reaches deep underground to get water from aquifers. The Arabian Desert is also home to several thorny varieties of trees, such as the Red Thorn or the Christ's Thorn Jujube, which protect themselves from water loss due to being eaten or damaged by animals. Other trees have spines or hairs on their trunks and branches to provide some shade and to protect from drying winds[17]. Many of the shrubs found in Tabuk have very small leaves to minimize the surface area; while elsewhere in the world, large leaves are beneficial to capture maximum sunlight, in the Arabian Desert, it is more beneficial to reduce the evaporative surface area. Some plants even have thick, waxy coatings on their leaves and stems to further prevent evaporation. Finally, many species of plants in the Tabuk region are annuals. They grow and reproduce for a short time after rainfall, then lie dormant until conditions become favorable again.

Animals have even more varied adaptations to the region. The camel, an iconic desert dweller, stores the majority of its fat in its hump, where its insulating effect on the body is minimized. It also has long hair to absorb the sun's heat away from its body and long legs to elevate itself off the sand, which can have temperatures up to 50˚F higher than the air. Large mammals such as the ibex, gazelle, or Arabian Oryx have large horns which radiate heat away from their brain, allowing them to function even when their body temperature rises above its equilibrium[18]. Similarly, the Cape Hare and the caracal have large ears, which serve the same purpose[19]. The Hyrax, Sand cat, fox, and many other desert animals are nocturnal, or at least are less active during the heat of the day. Many of these species, as well as the honey badger, and

[17] Follman, Ilene, L. *Life in the Desert*. Dayton, Ohio: Milliken Publishing Company, 1995.
[18] "Carotid Rete Cools Brain: Thomson's Gazelle." Ask Nature. The Biomimicry Institute, 2015. Web. 21 Apr. 2015.
[19] Goodwin, Peter. *How Everyday Things Work: 60 Descriptions and Activities*. Portland, ME: J. Weston Walch Publisher. 1992.

rock hyrax, live in burrows or caves to avoid the hot sun. Additionally, most desert animals have light coloring to help reflect sunlight and camouflage with surroundings.

Invertebrates as well have adapted ways to survive the desert. The White Desert Snail is native to the Tabuk region and uses its shell to protect it from the heat. Not only do the shape and white color reflect the vast majority of the sun's rays, but the shell helps shade the ground below the snail to prevent its getting heat. Finally, the snail can retract into the whorls of its shell and use chambers of air to insulate itself from the ground and air. Termites, which live in many arid regions, build large mounds with openings at the base to catch wind and create air currents through the structure, forming their own natural ventilation and cooling system. Finally, in other even more arid deserts of the world, the Namibian Fogstand Beetle has a uniquely textured shell, whose increased surface area helps the beetle to condense fog and humidity onto its back. The shell also has channels which direct the water into the beetle's mouth, ensuring that none of the collected water is wasted.

In our design, we tried to incorporate many of these features: a structure to catch the wind and create natural ventilation, as with the termite mound; a shell to mimic the desert snail, or a canopy to mimic the umbrella thorn tree to shade the house and protect it from the sun; deep basements after the burrowing animals to take advantage of the earth's constant temperatures below ground; stilted legs to elevate our structure off the sand, as with the camel; light coloring to minimize sun absorption; and, finally, the crux of all life on earth, capturing the sun's energy for solar electricity and lighting.

Initial Design

For our initial design, we tried to incorporate as many aspects of biomimicry as possible to maximize sustainability and symbiosis with the environment. The preliminary design included the following features:

<u>Dew water collection roof system</u>

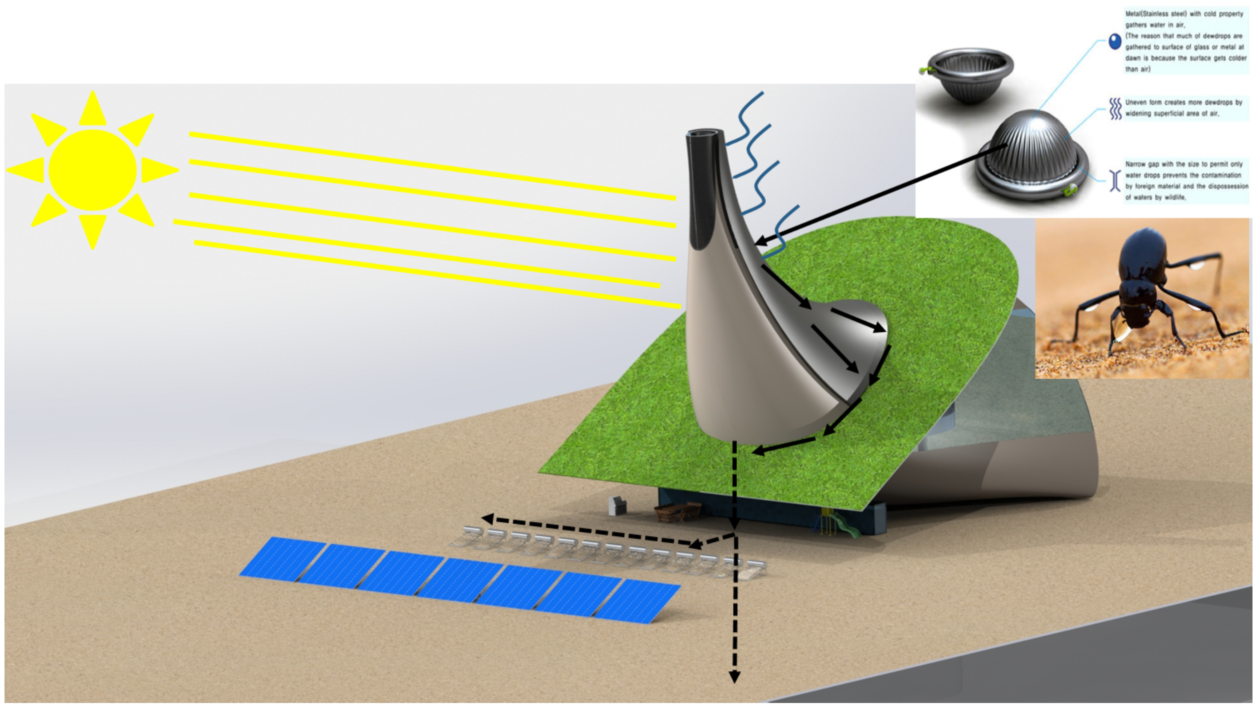


Figure 3. Picture showing the top surface of the cone-shaped structure that is designed to collect moisture from the air, adapting the beetle water collection system.

The dew water collection roof system of our house was based off the Namibian beetle. We designed the roof to have a stainless steel textured surface that mimics the Namibian beetle's shell, which maximizes surface area to collect condensation from the high relative humidity in the air. Despite the fact that our house isn't located in Namibia, Tabuk offers a very similar climate that allows us to capitalize on the beetle's water collection method. As you can see from Figure 3, the water is collected on the back side of the cone, where it is in the shade and allows the textured stainless steel to remain cooler than the air, promoting condensation of the high relative humidity air. When the water droplets form on the surface, they are then guided by gravity and channels on the roof into gutters that collect the water to be stored in tanks, with some of the water distributed to the living roof. One holding tank is on the ground floor at the back of the house. This holding tank is meant to be used as a thermal mass which would only heat up in the winter when the temperature falls below comfortable levels, due to an overhang which blocks all but the low angle sunlight in the winter. The thermal mass would then radiate into the house to keep it warm. The next part of the water would flow into the solar water heaters which would provide hot water for the house, while the rest would travel underground where it would be stored and cooled to ground temperature in a large holding tank. This water would be used for drinking, flushing the toilet, showering, and fulfill all the other household requirements. This water would also act as a thermal mass to help cool the air that we would pass through it, which we will talk about in later sections.

Living roof

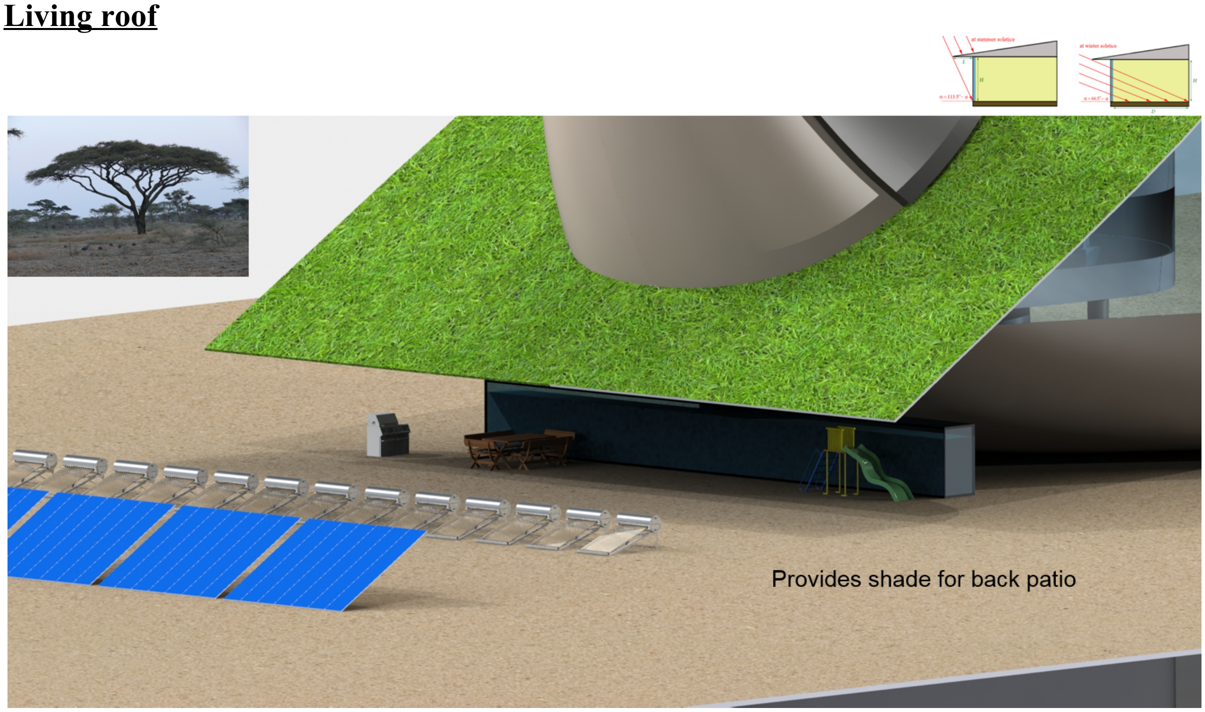


Figure 4. Living roof angled toward the south, provides more shading for the structure.

The living roof is based off the umbrella thorn tree, with the hopes that it would also provide shade to the house underneath it, like the trees canopy provides side to the soil and roots beneath it. It would also extend off the back of the house and provide shade to a back patio.

Solar Chimney

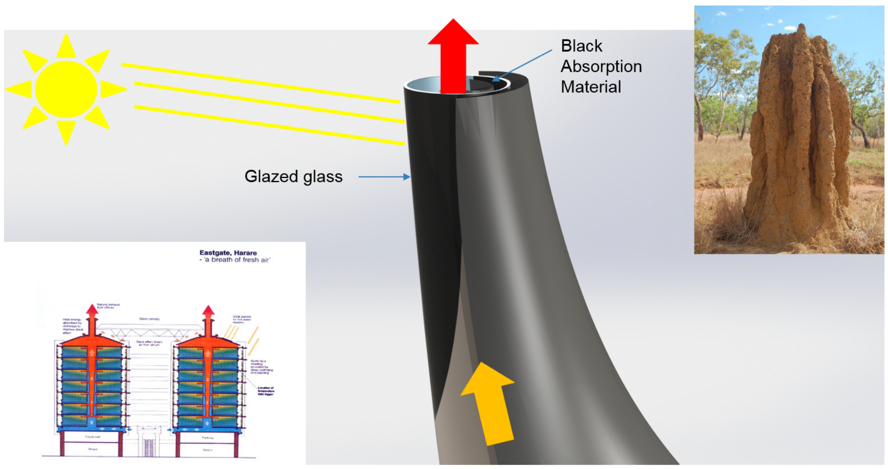


Figure 5. Solar chimney, which is part of the cone structure, is adapted from the termite mound.

Since Tabuk is in the desert and has a very hot climate, we decided that a passive cooling system was needed. In order to facilitate this, we decided to add a solar chimney to the structure based off the termite mounds in Zimbabwe. The solar chimney has a window at the top what allows sunlight to penetrate and get absorbed on the backside of the solar chimney which was a black absorbent material that absorbs the heat and solar radiation from the sun. The material heats up the air at the top of the chimney causing it to rise which creates a negative pressure to pull out hot air from the rest of the house, replacing it with cool air from underground. The solar chimney is oriented on the back side of the house and faces South to maximize sun exposure.

Wind collection shell

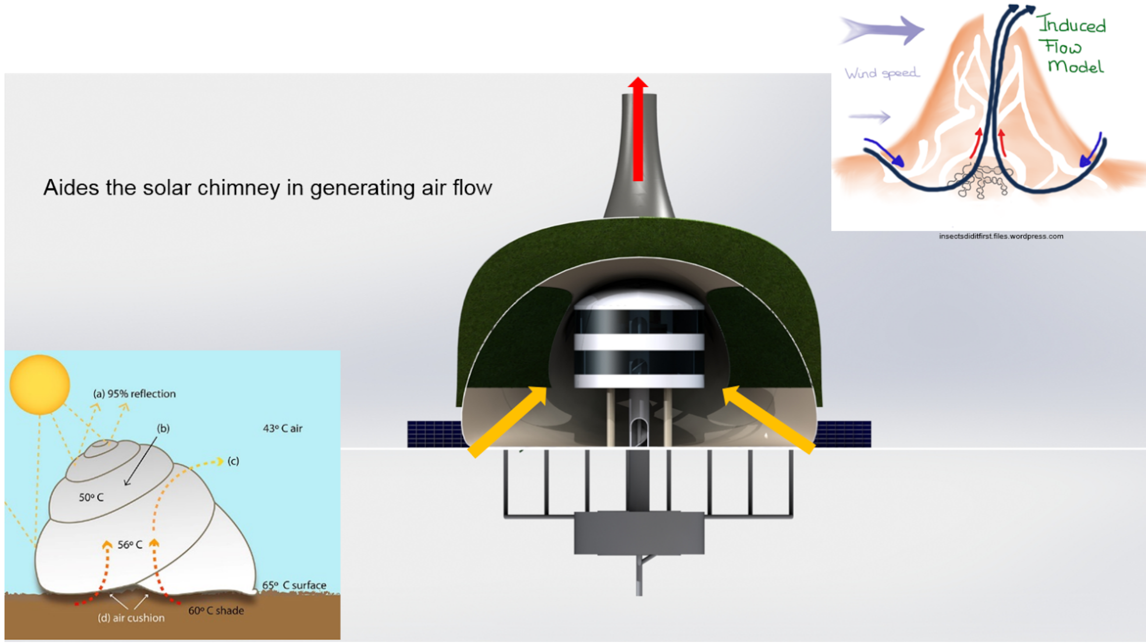


Figure 6. The cone structure with large opening to the north captures wind efficiently with the aid of buoyancy of air flow generated by solar chimney.

To aid the air flow generation from the solar chimney, we added in a wind collection shell to harness Tabuk's average 15 mph wind speeds. The wind collection shell is also based off the termite mounds of Zimbabwe, which have air inlets down on the ground level, which allow wind to enter and flow through the structure and cool the rest of the structure before leaving out the top. Our wind collection shell also resembles the desert snail shell, as it also functions as a shield from the sun to our inside house, and its twirling nature resembles the inside of a snail. The shell's main purpose is to collect wind and accelerate that wind as it moves into the structure. Leveraging Bernoulli's principle, we hope to generate draft out of the house from the airflow generated from the wind collection in addition to the solar chimney.

Elevated house and underground basement

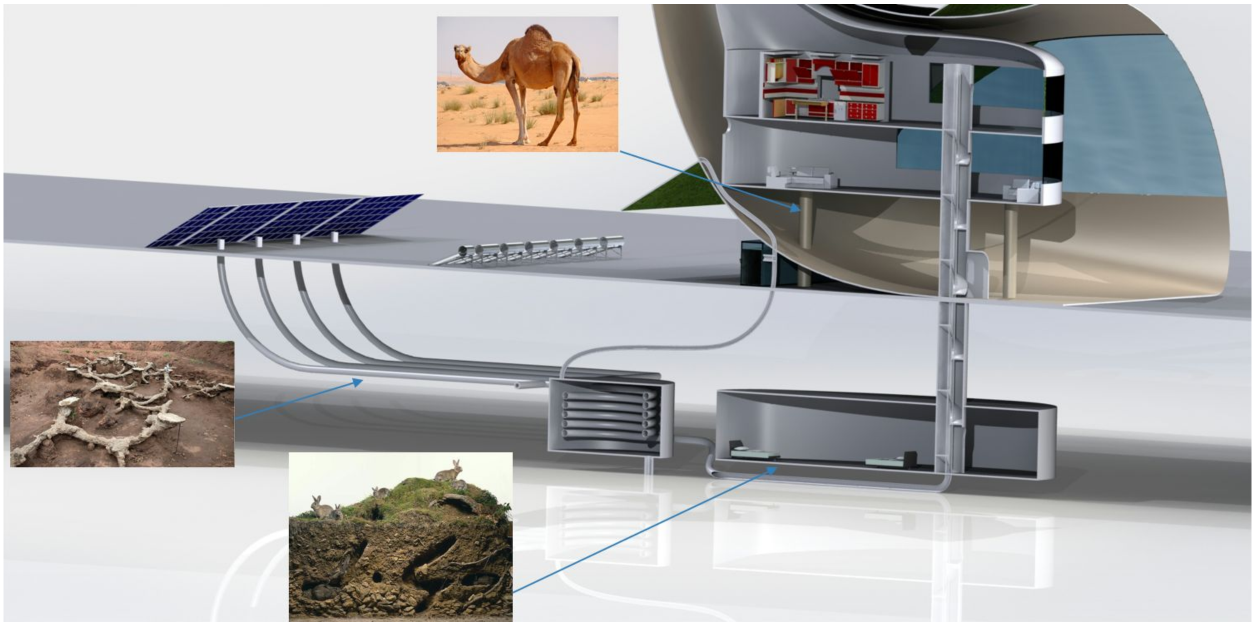


Figure 7. Elevated house and underground living areas help residents keep cool.

The house is elevated off the ground, mimicking the long legs of a camel. We thought that by elevating our house, we would reduce the average temperature of the house as compared to the ground and therefore reduce the amount of cooling required. We also built a deep basement in our house. The basement was 30 feet underground and mimics the dessert rabbit's tendency to burrow into the ground to escape the harsh temperatures from the sun outside. The basement is also where the bedrooms are, and therefore would make for a very cool sleeping environment even if it was hot upstairs. Similarly, the pipes that bring air underground for the geothermal cooling, would be spread-out in a network of underground pipes to facilitate a dispersion of heating from the hot air coming underground, so that the heating load would be dispersed and allow the ground to remain cool. This also mimics the termites mound and the burrowing dessert animal's network of tunnels.

House layout

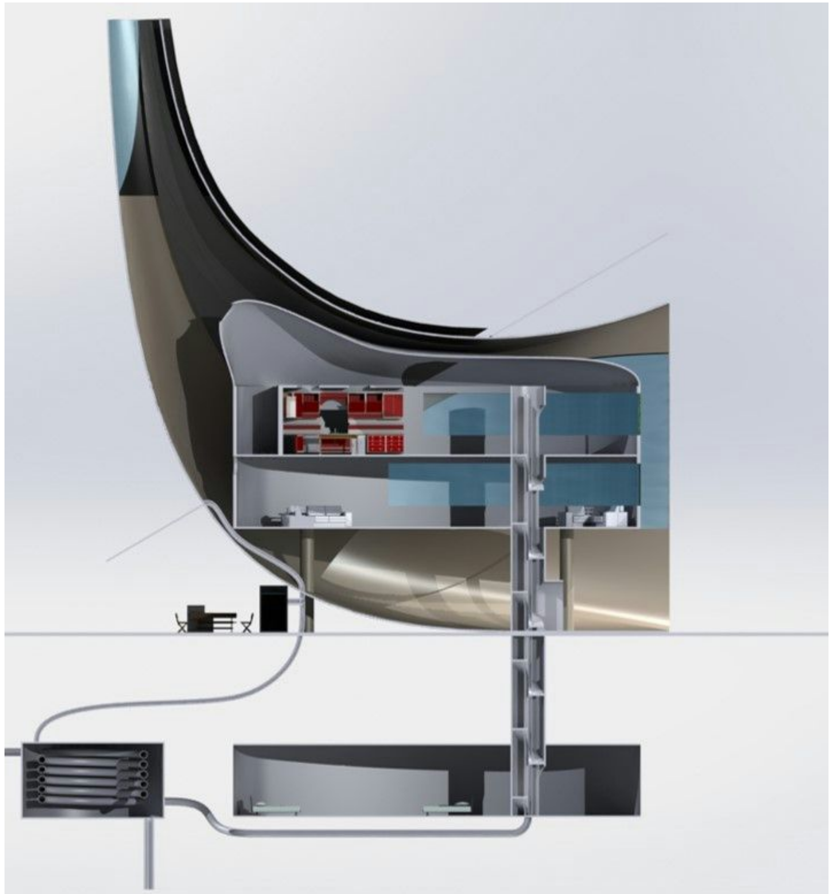


Figure 8. Layout of house that helps isolate heat and keep the rest of the house cool.

The house has its kitchen and laundry upstairs so that the heat from those activities will rise and exit the house through the ports in the roof, instead of heating up the rest of the house above them if they were on the first floor. The back patio also has a grill to promote outdoor cooking which would also prevent the house from heating up. The main living space was designed to be on the first floor so that it would be cooler and more inhabitable. The basement, like it was mentioned earlier, would be were the family would sleep since it would be the coolest area of the house.

Geothermal cooling

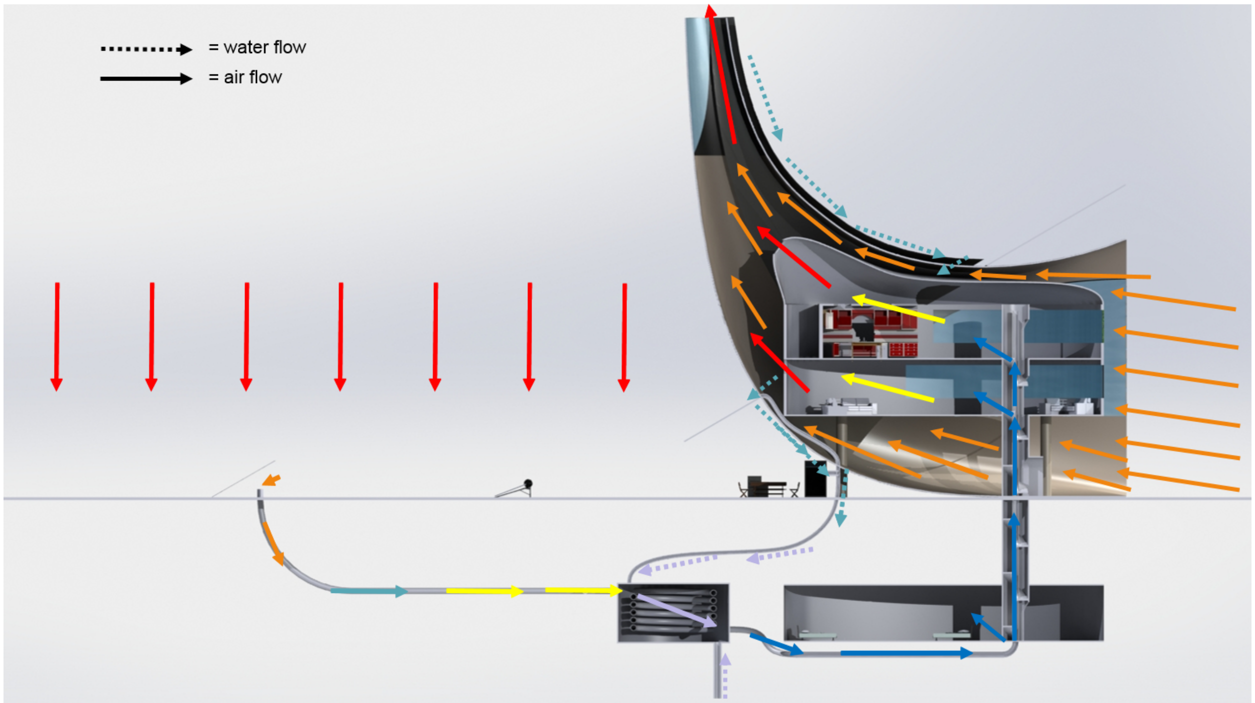


Figure 9. Air and water flow.

As you can see from the full system design above, the water is collected from the roof and flows down into the cistern underground where it cools to ground temperature and acts as a thermal mass. The air then flows into the inlet tubes, which are strategically placed under the solar panels so that they are shaded and thus kept cooler than the rest of the outside air. The air then proceeds into the network of tunnels and gets cooled down to ground temperature without elevating the ground temperature too much. The air temperature is further reduced when it enters into the water cistern through the heat exchange coil. After passing through the heat exchange coil, the air proceeds to enter the house from the basement. The air is drawn through the network of tubes and into the house due the airflow generated passively through two mechanisms: the solar chimney and the wind collection shell. As you can see from the diagram, the cool air is drawn up into the house and proceeds through a ventilation tube that outlets at bottom of each floor. The cold air is then circulated throughout the floors and as it heats up it rises and is drawn out the outlet ports in the ceilings of each floor by the airflow generated by the wind collection shell and the solar chimney.

<u>Materials and lighting</u>

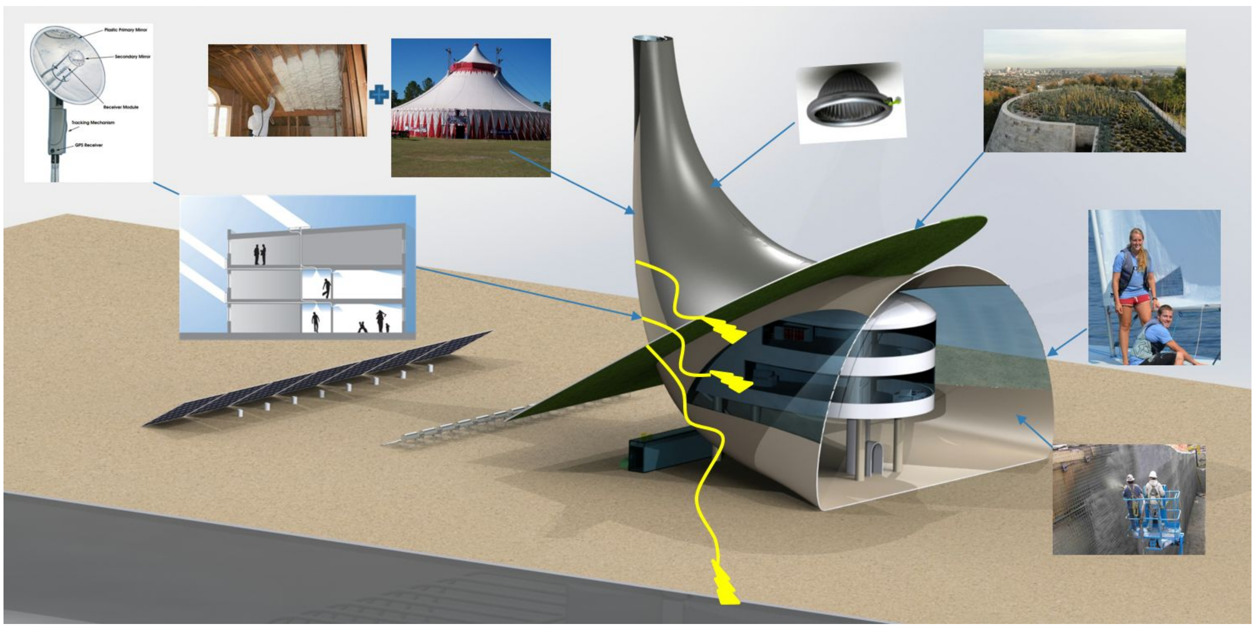


Figure 10. Design incorporating passive lighting and materials.

Since the back of the house is completely shielded by the wind collection shell, and since the basement has no windows either, we decided to implement a solar optic lighting system to passively light the back rooms and basement during the day. The materials of the shell structure would either be a stretched canvas over a metal frame, like a circus tent, with foam insulation sprayed on it for a better R-value. Or the whole structure could be framed in rebar and sprayed with shotcrete if more rigidity is required.

Basic Dimensions

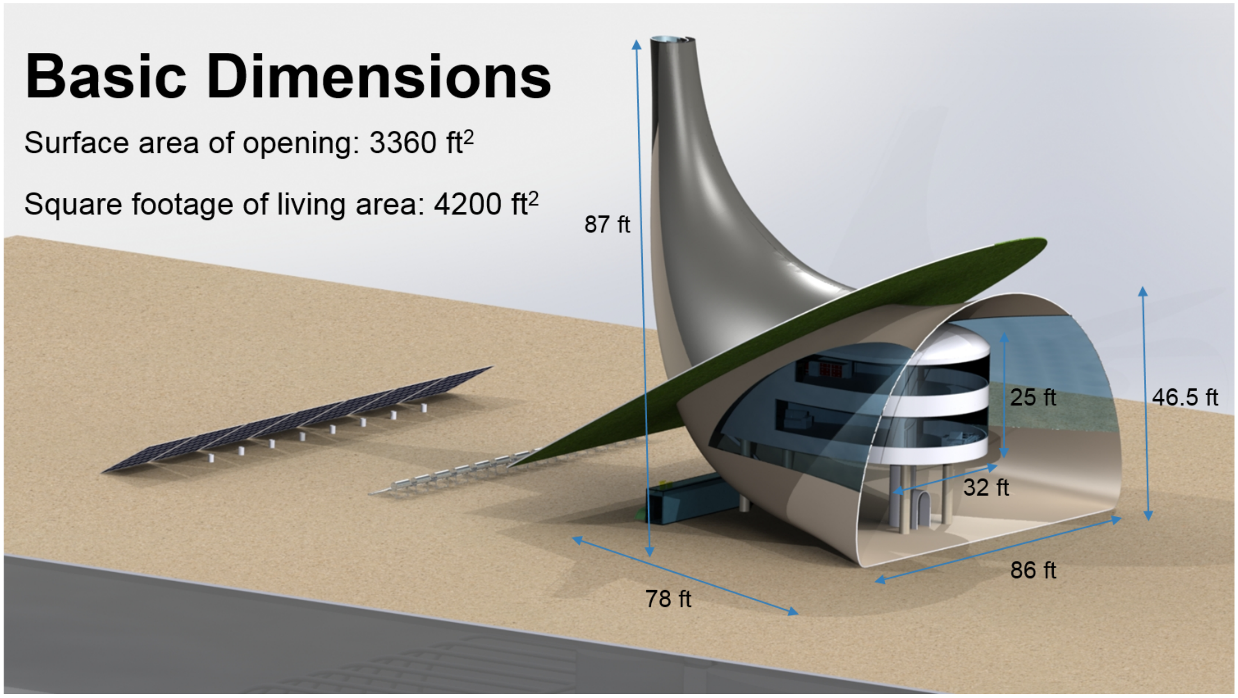


Figure 11. The basic dimensions of the design.

Engineering Analysis

Thermal Analysis

Tabuk has hot and dry summer and mildly chilly winter. To prevent the house from gaining and losing too much heat to the environment, we decided to equip the walls, roof, and windows with high level of insulation. In addition to insulation, thermal analysis for the house is done by using the highest daytime and nighttime temperatures in the summer (110 and 75 °F) - the goal is to make sure the thermal system is capable of cooling the house in the summer and heating in the winter to a comfortable range of temperature ((68+78)/2 = 73 °F). To do so, a layer of thermal mass is added to the interior side of all walls with insulation on the exterior side. The reason for putting the thermal mass on the inside is that in an extremely hot climate like Tabuk, even thermal mass, which requires a lot of input energy to raise its temperature, can get overheated. The thick layer of insulation works to prevent the thermal mass from getting too hot and releasing the heat into the house during the day. Thermal mass, correctly used, moderates internal temperatures by averaging out diurnal extremes. This increases comfort and reduces energy costs. To complement insulation and thermal mass, a geothermal system is used to account for the rest of the temperature difference to bring the final indoor temperature to 73 °F.

Insulation

The R-values of the walls, roof, and windows are 36, 50, and 5.89 $ft^2 \bullet °F \bullet hr/BTU$, respectively. The specific insulation materials that are used for the listed R-values are further discussed in the materials section of this report. With these R-values, the Heat-Loss (heat exchange with the environment) is calculated to be 500 $BTU/°F \bullet hr$. At Tabuk, the cooling degree-days is 2,370 and the heating degree-days is 1,140, which is about half of the cooling degree-days. Combining the calculated Heat-Loss with the degree-days, our system would need to remove 28 MBTU of heat in the summer and add 13.7 MBTU of heat in the winter according to Equation (1).

$$\text{Heat Load} = \text{Heat-Loss}*(\text{degree-days}) \qquad \text{Equation (1)}$$

Where Heat-Loss is calculated using Equation (2).

$$\text{Heat-Loss} = A_{wall}/R_{wall} + A_{roof}/R_{roof} + A_{window}/R_{window} \qquad \text{Equation (2)}$$

Thermal Mass Calculation

The value of Heat-Loss is required for the next step of the thermal analysis because we need to know how much heat is lost to the environment through conduction in relation with the amount of heat that will be lost through convection at the thermal mass. In the process of figuring out how much thermal mass is needed, we use an exponential function to approximate the temperature increase during the days and temperature decrease during the nights. Since the function of the thermal mass is to even out the diurnal temperature extremes, we assume the thermal mass keeps the indoor temperature at the average of the two extremes, 92.5 °F. The design variable, thermal inertia *k* is obtained so that the thermal mass is sufficient to slow down the indoor temperature from simulating with the outdoor temperature by allowing the indoor temperature to rise or drop by only ⅓ of the temperature difference (110 - 75 = 35 °F), as shown below by Equation (3).

$$e^{-kt} = 1/3 \qquad \text{Equation (3)}$$

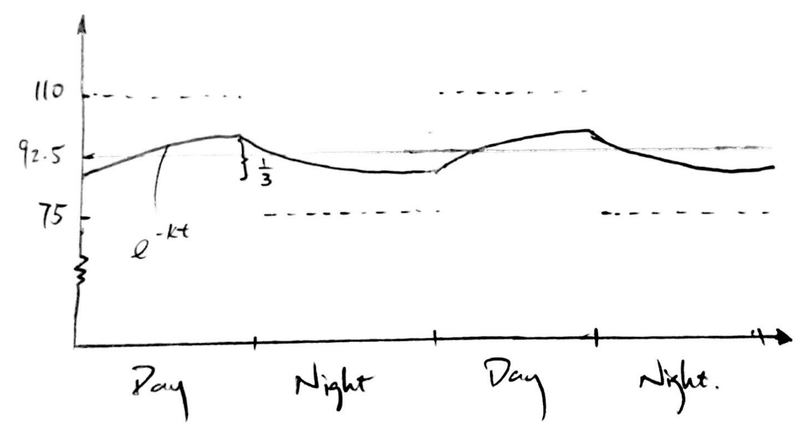


Figure 12. Diurnal temperature change as an exponential function due to thermal mass.

With this in mind, *k* is a unitless constant equal to 0.092, and is equal to Equation (4), which compares Heat-Loss to the environment and U ($0.84\,BTU/ft^3{\bullet}°F{\bullet}hr$), the heat exchange due to convection of warm air that is created next the walls and convects through the room. We chose concrete as the material for thermal mass because it is recyclable and has high specific heat. Thus the volumetric specific heat, H, is equal to 30.1 $BTU/ft^3{\bullet}°F$. With all these information, the volume of thermal mass is obtained using the following equation and is equal to $153 ft^3$.

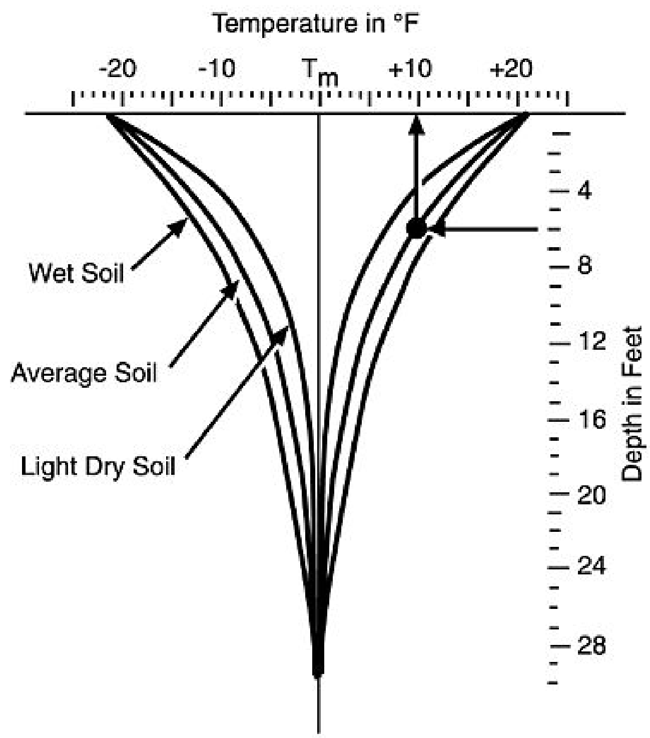
$$k = \frac{A*U*HL}{A*U+HL}\frac{1}{H*V_{mass}} \qquad \text{Equation (4)}$$

Again, since we want to put thermal mass on all the walls, the thickness of the thermal mass is therefore 0.57 inch by dividing the total volume over the total area of walls.

As a result, thermal mass stabilizes and reduces indoor temperature by 110 - 92.5 = 17.5 °F. As we can see that the the indoor temperature is still too high so in order to allow the people who live in the house to feel thermal comfort, temperature is further reduced to 73 °F by geothermal cooling.

Geothermal system

Finally we use a geothermal system to account for the rest of the temperature difference from 73°F. According to Figure 13, we know that at 30 feet into the ground, the temperature remains constant throughout the year, which is the mean earth temperature. At Tabuk the mean earth temperature is approximately 65°F. We have pipes that take ambient air down to the water tank at 30 *ft*. As air passes through the pipes in the water tank, the water bring the temperature of the air to an equilibrium at 65°F. The air is then directed into the house.



In the summer, 4,411 BTU/hr is removed by the cool air, and in the winter, 4,863 BTU/hr is added to the house by the warm air and the passive solar heating through the windows on the south side of the house. Notice that in the summer we hope to use the air at 65°F to cool the house to 73°F, but in the winter the only using air isn't sufficient to warm up the house. As a result, we installed windows on the southern side of the house with overhangs that allow direct solar gain in the winter and prevent it in the summer by using annual solar angles. The flow rate of the air from the geotherm system is obtained from the analysis on the wind harnessing feature of the shell structure in the wind section.

Wind, Solar Chimney, and Geothermal Analysis[20]:

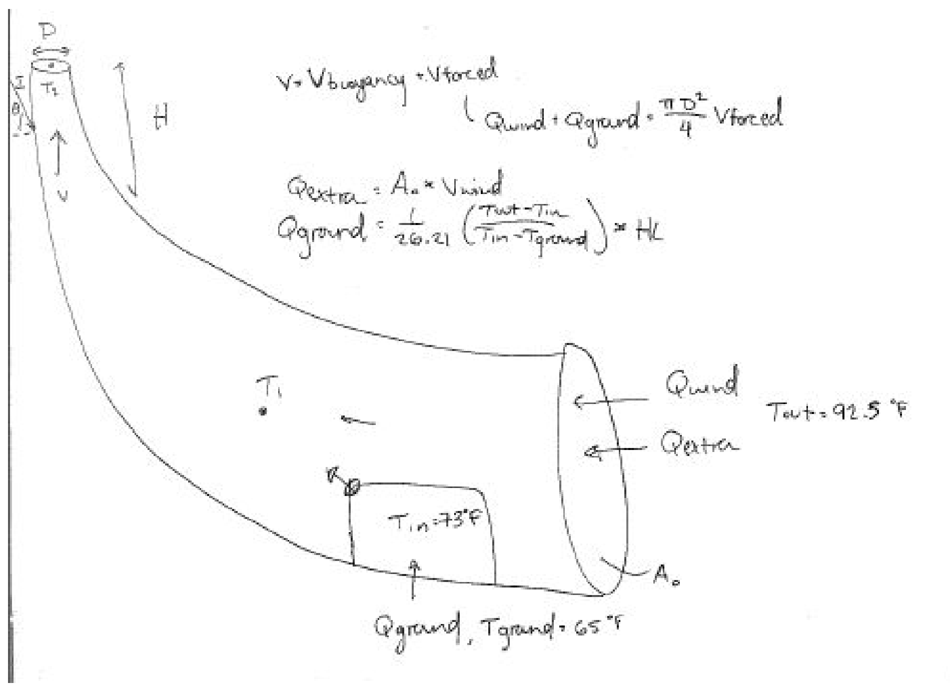


Figure 14.

Because of the complicated airflow created by the shell structure of our design, we couldn't physically separate the geothermal and solar chimney cooling system from wind analysis, and instead had to consider them as one complicated function when completing the mathematical analysis. There were 6 variables we considered important to understanding the

[20] All of these calculations were done using code that can be seen in appendix B.

function of our house, the volumetric flow rate caused by the wind, the buoyancy, and the ground(Q_{wind}, Q_{ground}, Q_{extra}), the temperature inside the shell(T_1), and the velocity caused by the wind and the buoyancy (V_{forced}, $V_{buoyancy}$). In order to calculate these values we assumed a mitigated air temperature of 92.5 degrees Fahrenheit (because of the previously mentioned thermal mass), a ground air temperature of 65 degrees Fahrenheit, and an inside house temperature of 73 degrees Fahrenheit.

Of these variables, the velocity caused by the wind, and the volumetric flow rate caused by the wind, and the ground were easy to find using physical relationships. We used the definition of volumetric flow rate to find Q_{wind}:

$$Q_{wind} = A_0 \times v \quad \text{(Eq 1)}$$

Where A_0 is the area of the shell opening and v is the known velocity of the wind outside of the shell. Here we used the yearly average of 15 mph. We used the relationship between HL and forced infiltration to create an equation for Q_{ground}. The equation iteration can be seen below:

$$HL \times \Delta T = I \times \Delta T \quad \text{(Eq 2)}$$

$$I = (26.21)Q_{ground} \quad \text{(Eq 3)}$$

$$HL = \sum \frac{1}{R} A \quad \text{(Eq 4)}$$

$$Q_{ground} = \frac{1}{26.21} \times \frac{T_{out} - T_{in}}{T_{in} - T_{ground}} \times HL \quad \text{(Eq 5)}$$

Where 26.21 is the known quantity H_{air}, 0.0182, multiplied by a unit conversion, T_{in} is the desired temperature inside the house, T_{out} is the outside temperature mitigated by the thermal mass, and T_{ground} is the temperature of the air coming from the geothermal system.

Finally we calculated V_{forced} by considering the relationship it has with Q_{wind} and Q_{ground}, as well as the area of the solar chimney opening to come up with the following equation:

$$V_{wind} = \frac{Q_{ground} + Q_{wind}}{\frac{\pi D^2}{4}} \qquad \text{(Eq 6)}$$

Where D is the diameter of the solar chimney opening.

However, for the velocity and volumetric flow rate caused by buoyancy and the temperature inside the shell, we were required to do an iterative coding process to uncover how the shell functions. Because we had three unknowns we needed three equations, so we used the relationships shown below:

Flow in = Flow out: $$Q_{extra} = \frac{\pi D^2}{4} V_{buoyancy} \qquad \text{(Eq 7)}$$

Heat Budget: $$T_1 = \frac{T_{out}(Q_{wind} + Q_{extra}) + T_{in}(Q_{ground})}{Q_{wind} + Q_{extra} + Q_{ground}} \qquad \text{(Eq 8)}$$

Solar Chimney: $$(V_{buoyancy} + V_{forced})(V_{buoyancy}{}^2 + 2V_{buoyancy}V_{forced}) = \frac{8gH^2 I \cos\theta}{\pi \rho C_p T_1 D} \qquad \text{(Eq 9)}$$

We began the integration process by randomly choosing the values T_1 = 300 K and $V_{buoyancy}$= 1000 ft/min. We then inserted these values into the above equations to calculate a value for Q_{extra}, and new values for T_1 and $V_{buoyancy}$. We then took those new values and repeated the calculation. This process was repeated until the old and new values for T_1 and $V_{buoyancy}$ converged to a common value, unveiling the actual physical values for our structure.

There were some important discoveries that came from our calculations that uncovered some changes that need to be made. The largest change was the reduction of our cone's opening from 3348 ft^2 to 1004.7 ft^2. While originally we were concerned with being able to catch enough wind to make this design viable, it turns out that, using the 15 mph yearly wind speed average, we were catching enough wind to create around 600 mph gusts within the shell. We researched safe wind speeds and eventually set 100 m/s as the desired wind speed limit within the shell, which led to the size reduction[21]. We also expanded the solar chimney to a 10 ft diameter to help mitigate this problem. Our calculations also indicated a volumetric flow rate through the house of 1267.4 ft^3/min, which is right within our spec range, because with a total house volume of 120228 ft^3, the flushing rate becomes once every 1.6 hours. However because of high level of friction caused by the piping necessary to cool the air, it's required to implement a small fan to keep this rate consistent. The energy needed to maintain this will be negligible however and easily managed, either with our solar panels, or a small turbine at the top of the solar chimney.

The other important discovery that the calculations uncovered was how the shell and the solar chimney work together in the presence and absence of wind. If you look at the table below at the scenario with wind, you can see that shell is working very well, with high Q_{wind} and V_{forced} values. What happens however is that the wind is moving so quickly that the solar chimney barely has a chance to heat the air before it passes through the shell, meaning that the cooling here is fueled primarily by the wind, with very little help from the solar chimney. However when examining scenarios with negligible wind speeds we see the opposite happen. Obviously the wind levels are doing practically no work, but the solar chimney kicks in. Inherently the velocity levels it creates are much lower than those created by the wind, but they still do sufficient work to keep the house at a comfortable 73 degrees.

[21] The upper limit of the viable shell opening area was calculated using code that can be seen in appendix C.

Variable	With wind (15 mph)	Without wind (negligible wind speeds)
Q_{wind}	1325939 ft^3/min	0 ft^3/min
Q_{ground}	1267.4 ft^3/min	1267.4 ft^3/min
Q_{extra}	.1 ft^3/min	2659.6 ft^3/min
V_{forced}	16898.5 ft/min	81.6 ft/min
$V_{buoyancy}$	.001 ft/min	33.8 ft/min
T_1	T1 = 92.5 ℉	89.8 ℉

Table 1. Calculations with and without wind.

Water System, Collection, and Storage

In compliance with our objectives, our house design incorporates a greywater recycling system to significantly decrease the total water consumption by using greywater from sinks and showers to flush the toilets. By doing this, the 16.7% of total domestic water consumption used for toilets is recycled from outputs that otherwise would have been considered waste regardless. We found a variety of estimated total domestic water consumption per capita in Saudi Arabia, since the data on this is not the most reliable. We took this into account and very conservatively (meaning that the actual domestic water usage is most likely less than our estimate) estimated that the domestic water consumption is around 45,000 gallons per person per year. We wanted to err on the safe side of too much water so that it could handle any fluctuations in water consumption, and there would be no chance of running out of water. We multiplied the per capita estimate by four to get around 182,500 gallons of water per year for our entire household.

Subtracting the amount saved with the greywater recycling system, we calculated that our house should collect a total of 152,000 gallons to be completely off the grid in terms of water. Our on-site water collection comes from both rainwater harvesting and capture of atmospheric moisture, and we found that we would actually have a surplus of water each year. We also estimated the desired size of our water cistern using monthly precipitation and relative humidity patterns to ensure a continuous supply of water.

Rainwater Harvesting

We plan to collect as much of the limited precipitation as possible, and we estimated how much using the roof area, average precipitation in the area, and a 60% efficiency that is standard in rainwater harvesting in this equation:

$$Rainwater\ collection\ (gallons) = Roof\ area\ (m^2) * \frac{precipitation\ (mm)}{1000\ (mm/m)} * 0.60 * \frac{264.172\ gal}{1\ m^3}$$

The annual estimate, using 6.4 cm of precipitation and a roof collection area of 686.7 m^2, is 6970 gallons per year. The monthly breakdown of rainwater harvesting is shown further below in Table 2 to calculate cistern size.

Atmospheric Moisture Capture

The equation we used to determine how much water the biomimetic material would capture is based on an estimation from the co-founder of NBD Nano, a company designing a self-filling water bottle also inspired by the Namibian desert beetle. Their technology has the potential to harvest “three liters per square meter per hour in an area with 75% humidity”.[22]

[22] “Nanotech Water Bottle Harvest Water from the Air.” Web. 26 November 2012. http://www.nextnature.net/2012/11/nanotech-water-bottle-harvests-water-from-the-air/

Using this estimate, a biomimetic collection area of 225 m^2, and a conservative efficiency of 25% (given that this technology isn't fully developed yet), we came up with the following equation:

$$Volume\ collected = \frac{3\ liters}{m^2 * hr} * Area\ (m^2) * \frac{\%RH}{75\%} * 25\% * \frac{24\ hours}{1\ day} * \frac{365\ days}{1\ year}$$

We calculated that we could collect 208,050 gallons each year with an average of 40% relative humidity. In total, considering the greywater recycling system and both collection technologies, we estimate a yearly surplus of water of around 57,600 gallons of water. This would take care of any fluctuations in water consumption, including visits from extended family or friends. Again, we broke this down and looked at monthly swings in relative humidity in the next section to calculate the cistern size.

Water Storage - Cistern Size

After creating a table for each month's average precipitation and relative humidity, we decided that a 10,000 gallon water tank would be sufficient in storing water throughout the drier months with plenty of room for fluctuations in water consumption.

	# of days	RH (%)	precip (mm)	Dew (gallons)	Rainwater	Total Collected	Surplus/Deficit
January	31	50	5	24568.0	544.2	25112.2	9903.9
February	28	51	5	22634.3	544.2	23178.5	7970.2
March	31	48	4	23585.3	435.4	24020.7	8812.4
April	30	38	3	18069.4	326.5	18395.9	3187.6
May	31	35	1	17197.6	108.8	17306.5	2098.2
June	30	30	3	14265.3	326.5	14591.8	-616.5
July	31	26	5	12775.4	544.2	13319.6	-1888.7
August	31	32	7	15723.5	761.9	16485.4	1277.1
September	30	40	31	19020.4	3374.2	22394.6	7186.3
October	31	45	0	22111.2	0.0	22111.2	6902.9
November	30	47	0	22349.0	0.0	22349.0	7140.7
December	31	50	0	24568.0	0.0	24568.0	9359.7
					totals:	243833.4	61333.8
CONSTANTS	Dew	Rainwater		Monthly water usage (gal)			
Area	250	686.7		15208.3			
Efficiency	0.25	0.6					

Table 2. This table shows a typical year in Tabuk, with an annual precipitation of 6.8 cm and an average relative humidity of 41%.

As depicted in the figure above, the expected water deficit lasts only from June to July. This two-month period is easily covered by the surplus in the prior two months. Unlike the calculation in class, we did not assume the total water usage would come before the total water collected each month because the dew harvesting, which is the bulk of the total water collected, will capture the atmospheric moisture every single day. Even with the low of 10% relative humidity, the biomimetic material will capture at the very least 158.5 gallons each day using the equation mentioned in the previous section on atmospheric moisture capture.

Refined Design

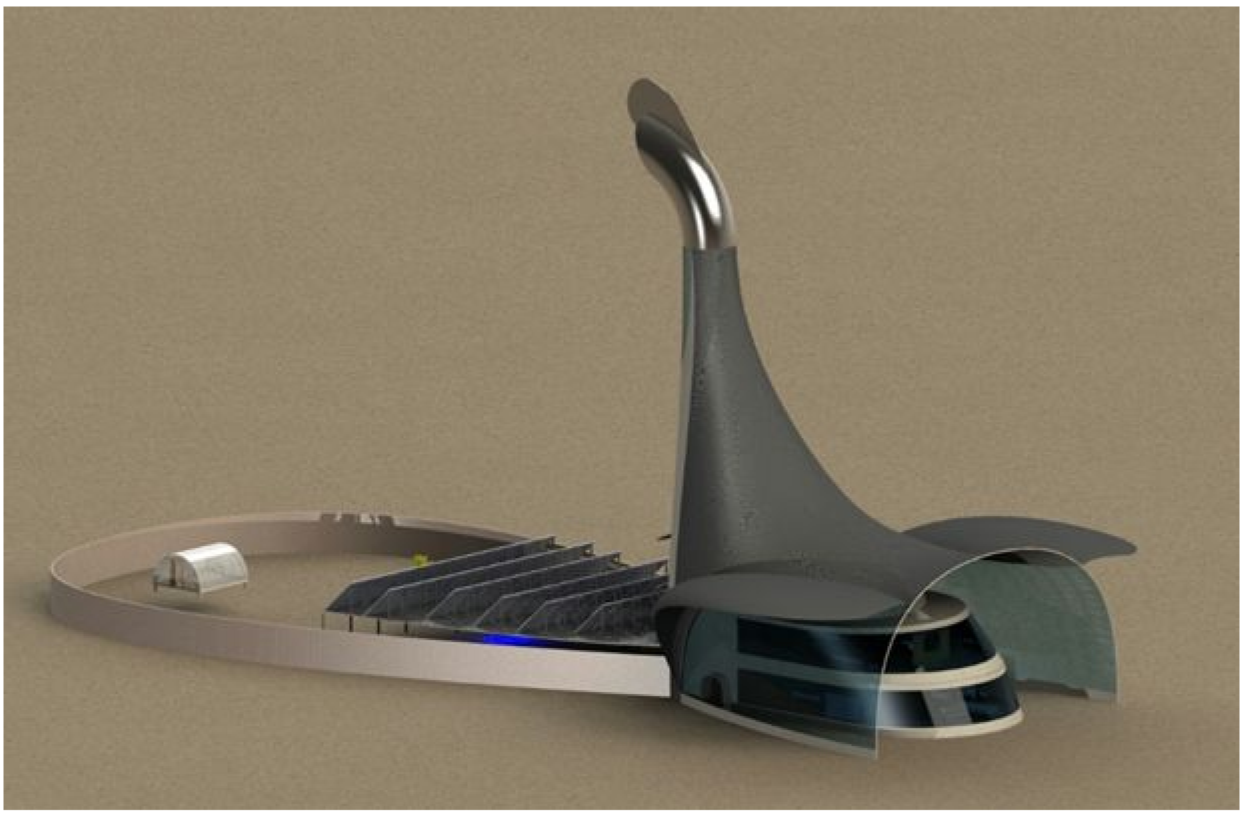


Figure 15: Front side angle view of house.

After the midterm presentation we got some insightful feedback from peers and Professor Cushman-Roisin addressing some human centered design concepts that we had held off on refining as we were first trying to accomplish our biomimetic features. For our final design, we turned our focus on refining our engineering analysis of the biomimetic features, as well as the comfort and convenience of the inhabitants.

<u>Layout Changes</u>

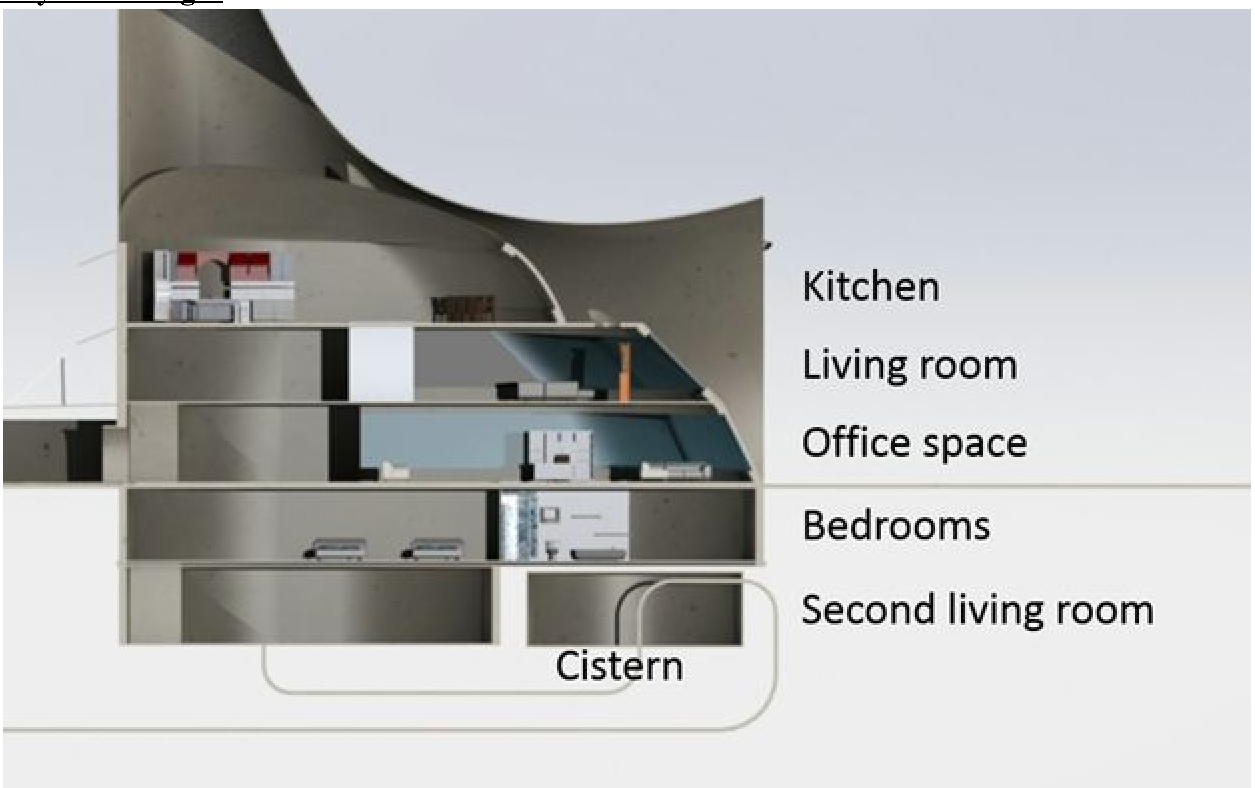


Figure 16. New house layout plans.

One large criticism of the design, was that the top and bottom of the house were not connected, except for by a steep spiral staircase. The concern was that the owners would not like walking down 3 flights of stairs just to get to their bedrooms, even if this meant that their bedrooms stayed cool. After careful consideration, we decided to remove the stilts that supported our structure so that the house could rest on the ground. We decided that this was acceptable because our house is shaded by the outer shell and the ground inside will stay cool, therefore making the stilts less important than we originally thought.

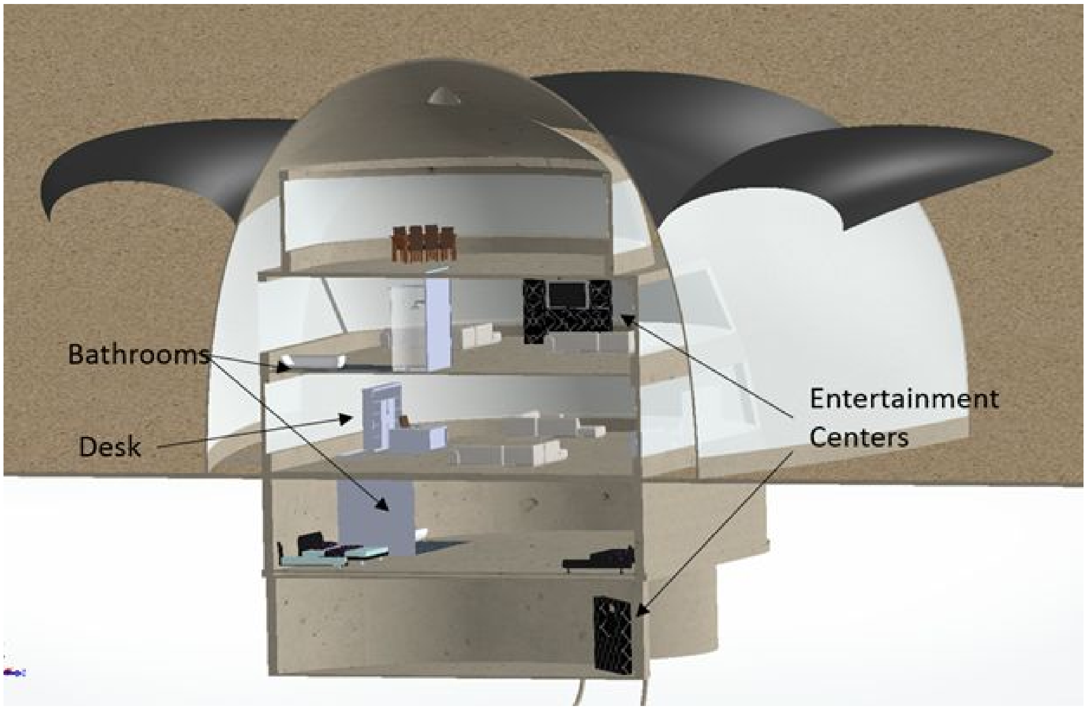


Figure 17. Refined house layout.

In addition to removing the stilts, we also raised the bedrooms up to the first basement level instead of having them submerged two floors below ground, which prevents the inhabitants from having to trek down as many flights of stairs to get to bed. We also increase the number of beds on the bedroom floor in case the extended family visits.

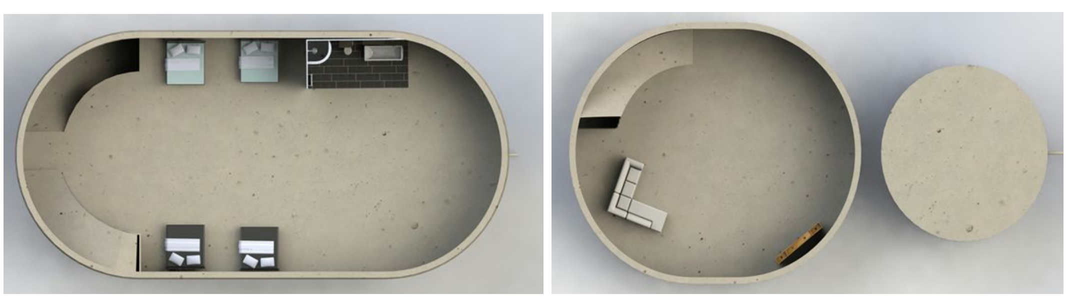


Figure 18 & 19: First and second basement levels, respectively.

We did keep the second basement floor but significantly reduced its size and purpose. It now serves as a secondary living room in case the upstairs living room gets too hot. Just like the burrowing desert animals, the inhabitants will be able to burrow down into the second basement level to escape the heat. This hopefully shouldn't be a problem however, since our passive geothermal cooling system should suffice. Additionally, the water cistern has increased in size to accommodate the extra water we will be collecting from our dew collection roof. It is also placed under the rest of the house so that it is shielded from the sun. In addition, we replaced the narrow spiral staircase with multiple curved staircases on each floor as these are preferable especially if you have young children who could fall down them.

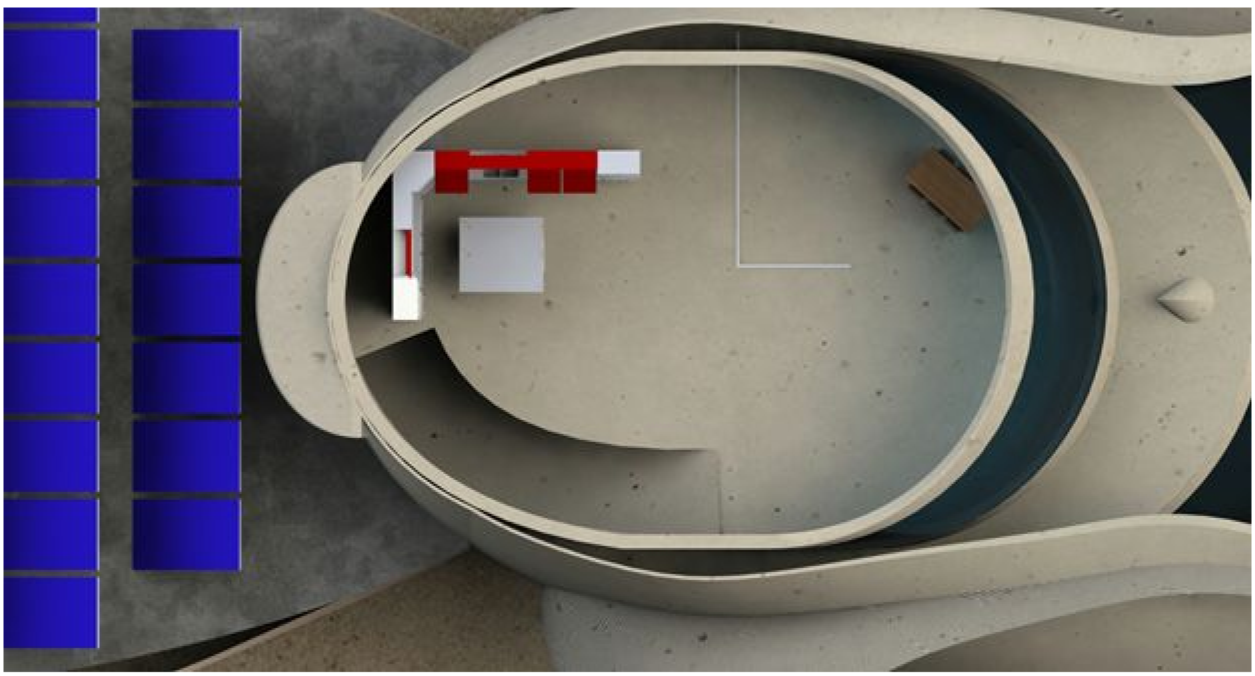


Figure 20. First floor.

As you can see, the kitchen and laundry are still on the top floor so that the heat produced can rise out of the house and avoid heating up the surrounding floors.

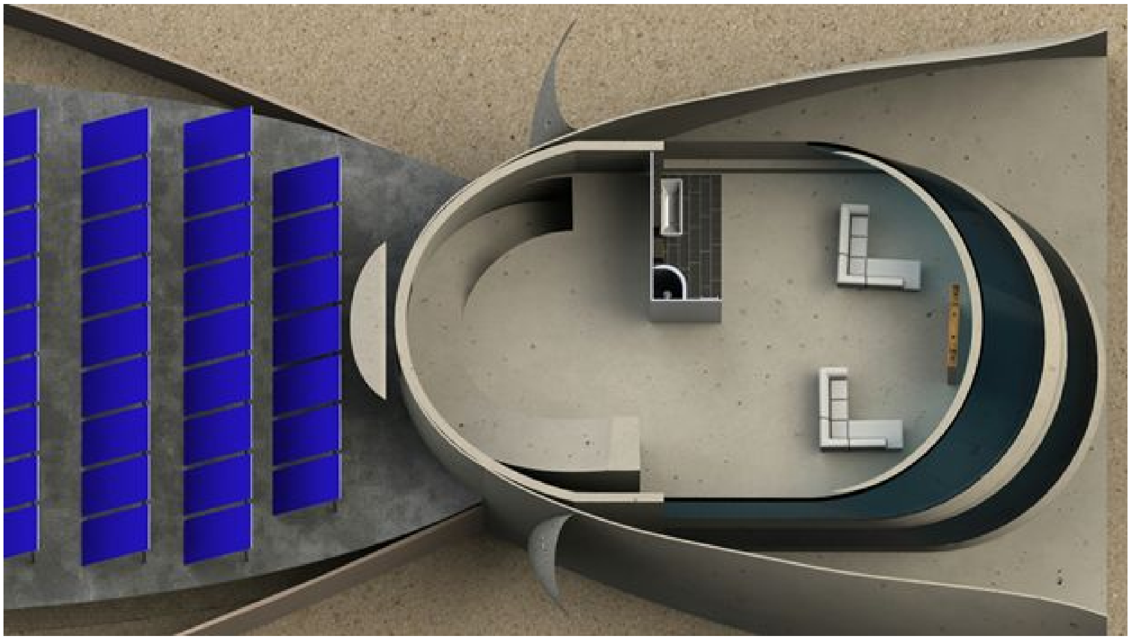


Figure 21. Second floor.

The living room area is now on the second floor and has increased in size. The overall house has also increased in size in order to accommodate visitors and extended family that might be congregating in the house at any one time.

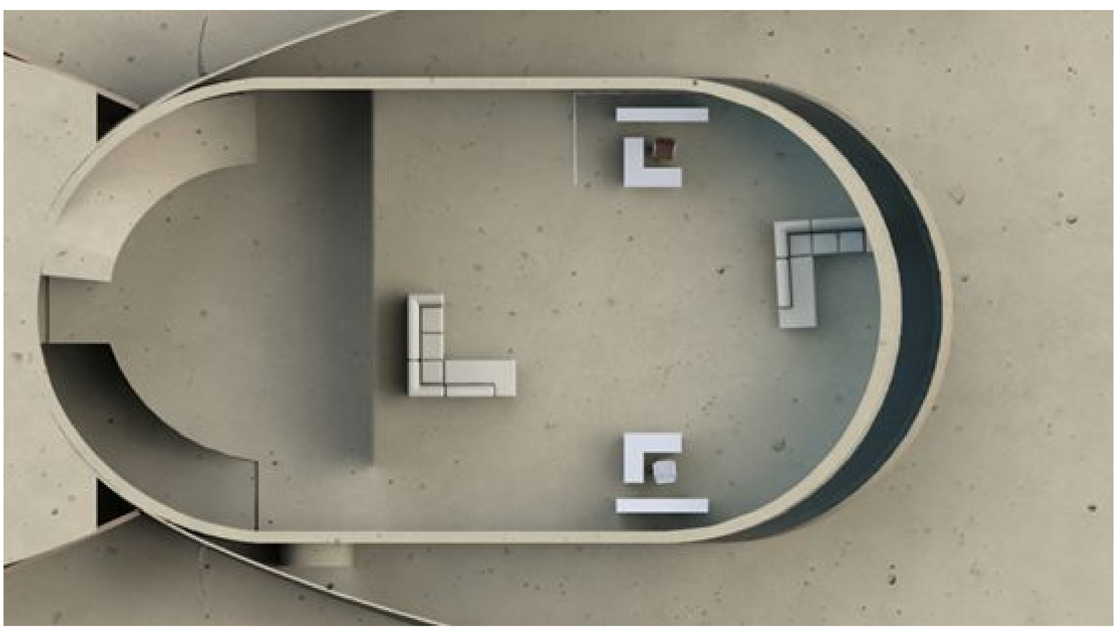


Figure 22. Third floor.

Another modification to the house layout was to put in an office on the first floor of the house. Again, the cultural research found that work was not as important as family time, and therefore we thought that the inhabitants would like to work from home. This is a concept adapted from the Beddington Zero Energy Development, which also has commercial workspace on the first floor. This will similarly help in reducing the carbon footprint of the inhabitants as they then won’t be required to travel into the office for work.

Front opening

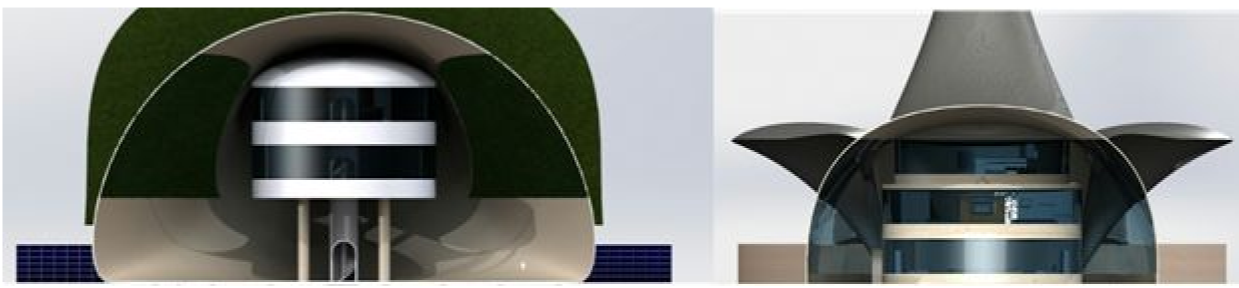
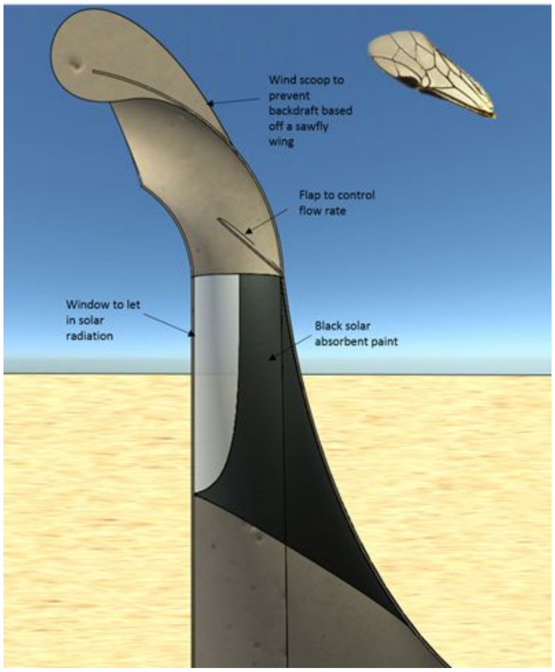


Figure 23. Initial (left) and refined design (right).

The wind collection opening size was dramatically reduced to prevent as much air flow into the shell, as the initial calculations informed us that the original design would result in supersonic winds speeds inside the shell. In addition to reducing the opening size, we also decided to build the shell out of shotcrete to ensure it was strong enough to withstand the force of the wind.

Solar Chimney and Wind Scoops



The solar chimney was adjusted to have a larger opening so that air could flow through it easier, preventing supersonic wind speed inside our shell. The wind scoop was also added to prevent backdraft from flowing down the solar chimney. The wind scoop is on a rotating bearing, and the fin on the top is based off a sawfly wing which catches in the wind and directs the wind scoop in the direction of the wind.

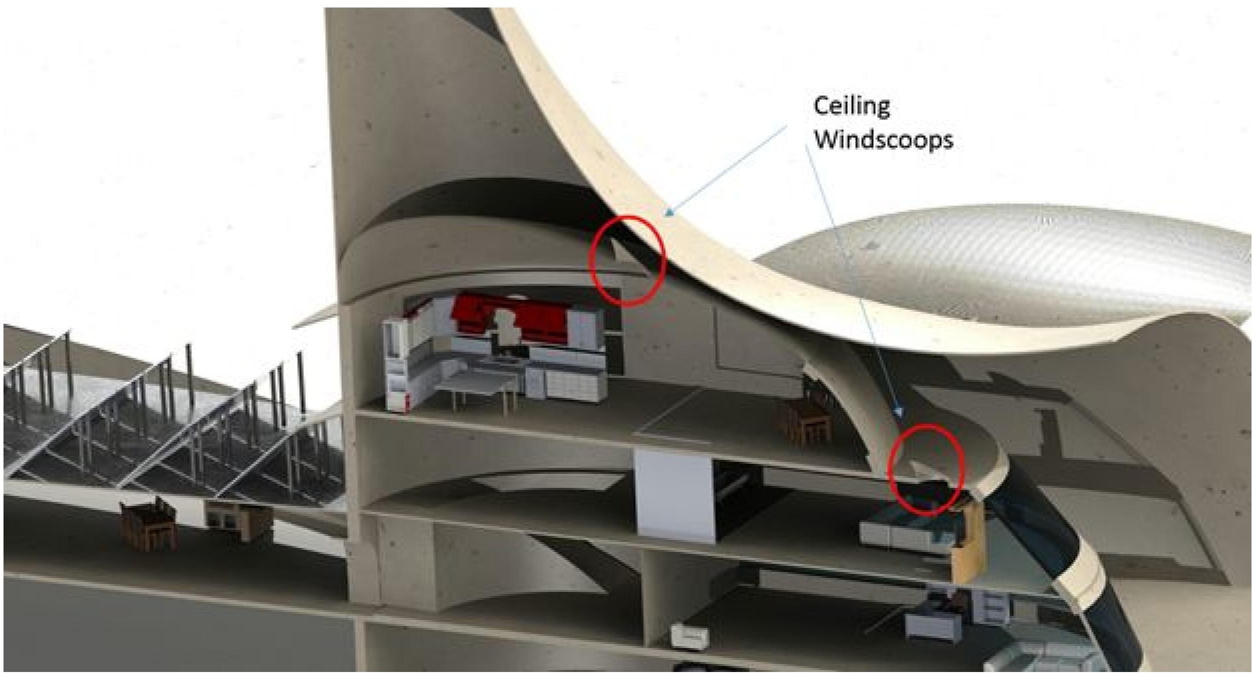


Figure 24. Depiction of wind scoops.

Wind scoops were also added to the ceiling ports to prevent back draft and sand from entering the house.

Back Patio Changes

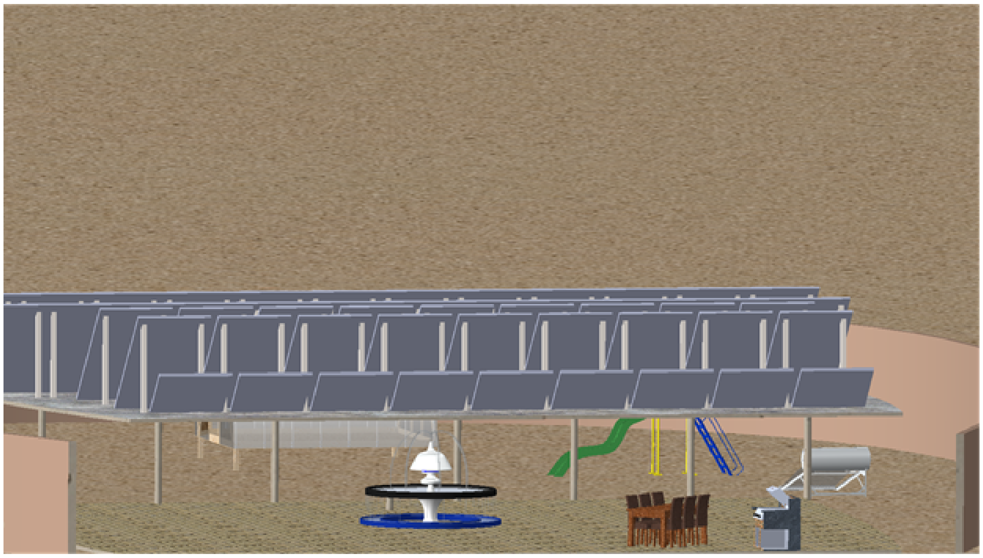


Figure 25. Image of back patio and possible additions.

We decided to add a water fountain to the back patio to incentivize people spending time outside, and cooking outside, which prevents the house from heating up. The water fountain will help to cool the surrounding area, and is also aesthetically beautiful. Since we are collecting excess water with the dew collection roof, we thought that adding the water fountain would be a nice added touch. Another option would be to add a greenhouse in the back yard, which would allow the inhabitants to grow their own food further reducing their carbon footprint as they wouldn't be buying vegetables that had to be trucked in from far away. Similar to the old design, the back patio has an outside grill and kitchen, as well as a jungle gym set for children to play on.

An important change was putting up a wall around the backyard to create a courtyard. This was due to our cultural research that found that the women are not allowed to go outside without their traditional attire on that covers themselves, unless other people can't see them. By putting up an 8 foot wall around the back yard, the women are then able to relax outside without their traditional attire on.

Solar panels

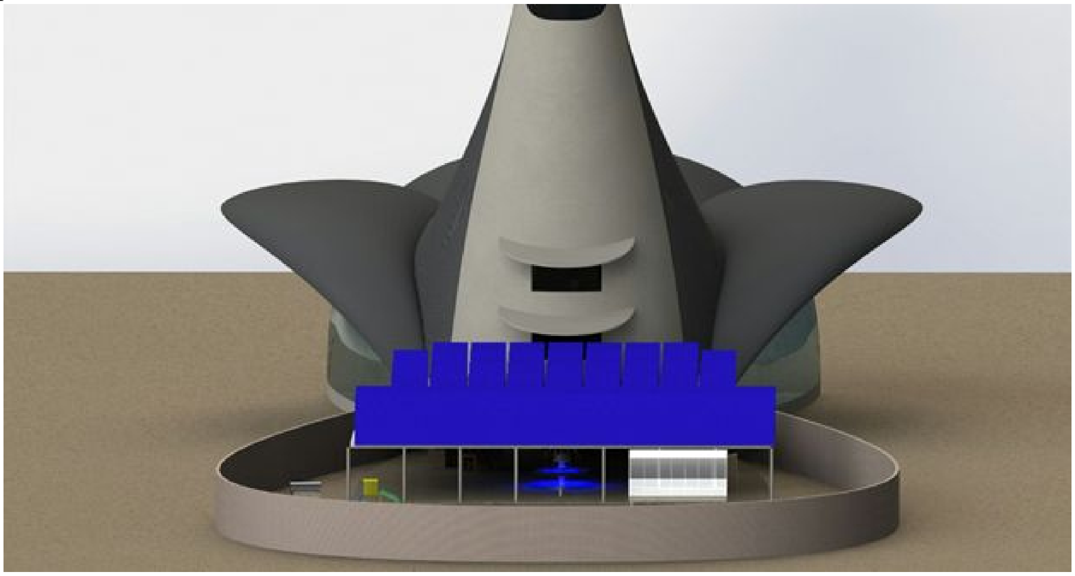


Figure 26. Back view of refined design.

Instead of having the solar panels in the backyard, the patio rooftop was added so that it was large enough to encompass the solar panels required for the house. The roof therefore has 58 50 ft^2 solar panels on it at an angle of 60 degrees to get the most solar radiation and also prevent sand from building up on them. The solar thermal water panels for passive water heating only needed to be 50 ft^2, and we placed it on the ground to allow the hot water to passively circulate upstairs to the kitchen, laundry room, and upstairs bathroom.

Back side windows

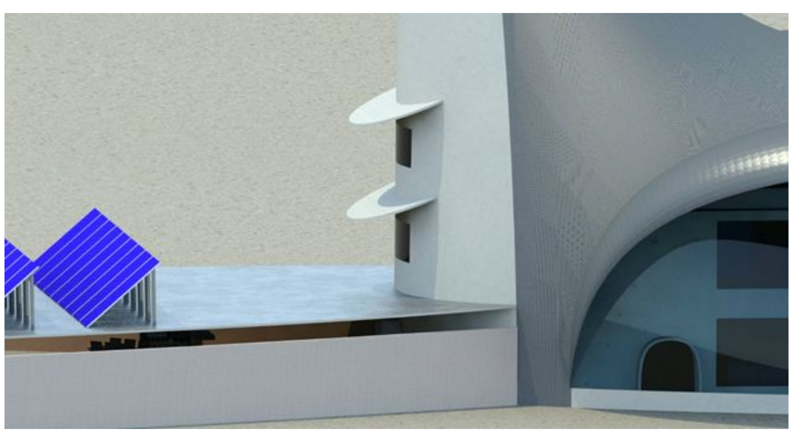
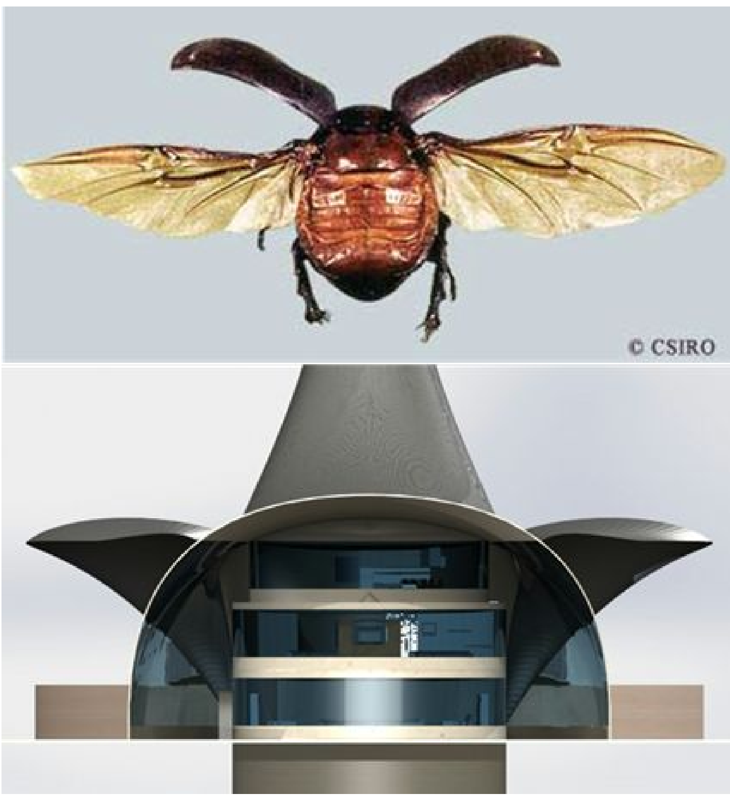


Figure 26. Close-up view of window overhangs, with realistic depiction of sun angle.

Since the house is no longer on stilts and abuts against the shell on the back side, we decided to include two windows so that we would not require active heating during the winter or active lights during the day. The length of the overhangs are 3.5 feet (calculations found in Appendix D) to provide shade in the summer and allow sunlight in during the winter months.

Replacing Living Roof with Canopy



After initial calculations informed us that the inside of the shell was going to be subject to supersonic winds if its original design was kept, we reduced the opening of the wind collection shell and opened up the top of the thermal chimney. We were still concerned with the living roof design, as its purpose of shading the house was redundant because the shell was already doing that, and its function as a garden would be tricky to facilitate without access to the roof. We also realized that the shading of the back patio could be accomplished using a standalone roof, which led us to remove the living roof entirely. Then the only concern was how to continue to shield the inner house from the solar radiation that would come through the windows in the shell. We decided to design a canopy to cover the shell windows instead of the large living roof. The canopy is based off the elytra of a beetle, as a key concern was creating too much lift from the use of the living roof, which would cause the living roof to rip off the structure. By mimicking the beetle's elytra, we were able to minimize this concern. The purpose beetle's elytra is to protect the fragile wings of the beetle, while still allowing the beetle to fly. Therefore their design is aerodynamic enough to reduce drag, but does not add any significant amount of lift (less than 1% of their body weight).[23]

Therefore this biomimetic design allows the canopy to both shield the house from solar radiation, while simultaneously preventing the canopy from needing to be made incredibly strong to prevent it from breaking off the house due to strong winds. Additionally the design allows the shell to have windows in it without heating the house too much.

<u>Comparison of old and new design</u>

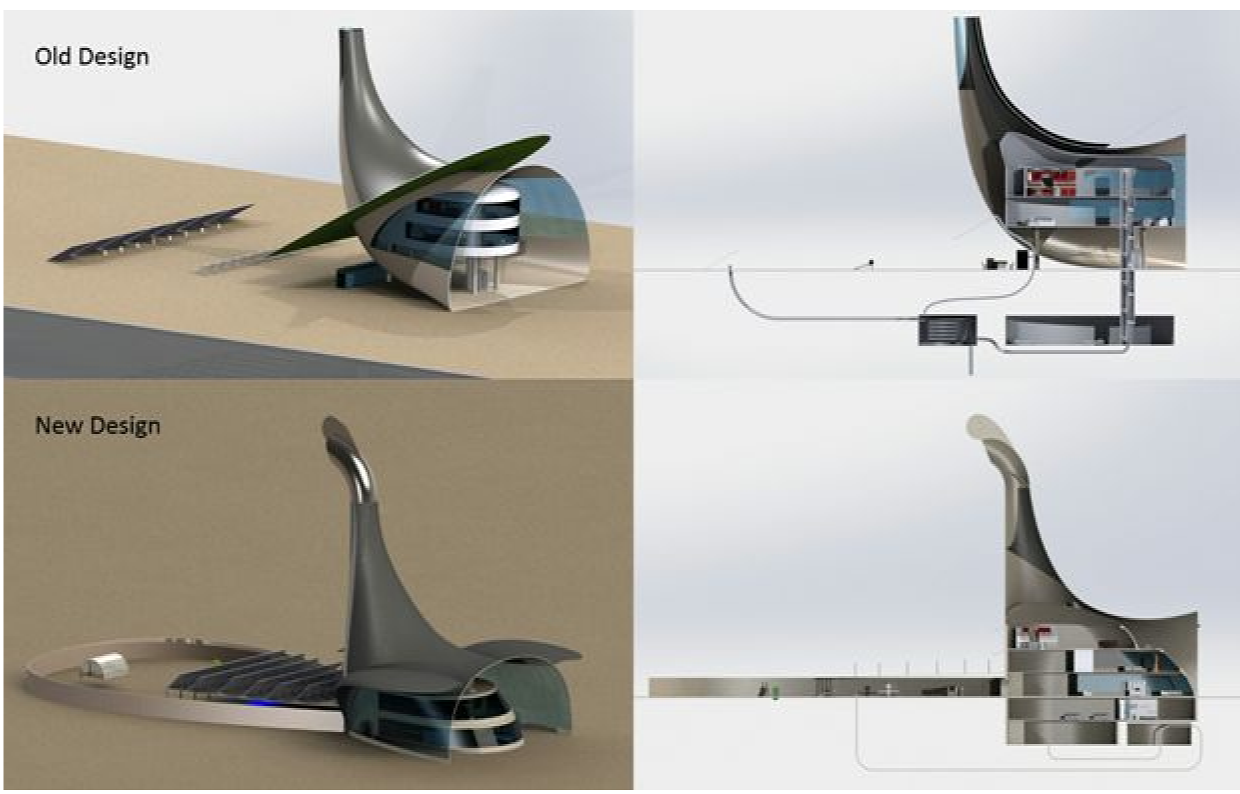


Figure 27. Comparison of the old and new design. Larger versions in Appendix A.

[23] Sitorus, Patar Ebenezer, Hoon Cheol Park, Doyoung Byun, Nam Seo Goo, and Cheol Heui Han. "The Role of Elytra in Beetle Flight: I. Generation of Quasi-Static Aerodynamic Forces." Journal of Bionic Engineering: 354-63.

Materials

For the shell structure, we planned to use shotcrete sprayed onto canvas and rebar. The large windows would be ADC (allyl diglycol carbonate) plastic, a highly transparent, lightweight glass alternative often used for optical lenses. The biomimetic "beetle" material would be made from textured stainless steel, and the "wing" canopies would be canvas.

For the inner structure, we selected high R values for the walls (R=36) and roof (R=50), achieved through polyiso foam insulation, as well as triple-glazed windows (R=5.89). We also accounted for 0.3 inches of concrete around the entire structure to act as a thermal mass. The patio and wall around the backyard will be constructed from local sandstone to be as sustainable as possible.

Environmental Impacts & Benefits

An important aspect when considering the environmental impacts and benefits of our building is the current behavior towards sustainability. In the oil-based economy of Saudi Arabia, there has not been a lot of thought or action towards environmentally friendly practices. Therefore, simply encouraging more passive, efficient, and renewable design aspects and technologies is a huge step forward in terms of environmental benefit.

The impacts of our house are fairly typical of any large building construction, meaning that the materials and physical impacts of our house make up the most of our footprint. The materials, however, are mostly made of the same materials as other traditional Saudi Arabian houses so the only comparative impact is the larger volume of materials necessary for constructing a larger house. The construction of the outside shell with shotcrete does have the benefit of being more environmentally friendly because the concrete is formed on site, thus reducing the transportation costs of shipping huge blocks of concrete to the foundation site.

In addition, our house has many environmental benefits, given that it is entirely off the grid for water and electricity. The house design provides all 182,500 gallons of water that the household consumes, saving that amount from being taken from the limited aquifer that the rest of the city relies on. Our house is also net-zero in terms of energy, as it produces its electricity needs through solar panels. Just from these energy savings of 32,000 kWh per year, our carbon footprint is reduced by 22.1 metric tons of carbon emissions every single year.

Symbiosis with surroundings

Our building is symbiotic with its surroundings not only by its mimicry of local flora and fauna, but in its utilization of the region's high relative humidity and incident solar radiation, as well as its harnessing wind and the high thermal mass of the earth. Additionally, the house generates its own water and electricity, so it does not need to deplete natural resources such as the local aquifer or fossil fuels.

Energy Analysis

To estimate a baseline energy usage for our household, we multiplied the Saudi Arabian average per capita energy use - 8161 kWh/year[24] - by four, our expected number of occupants, to give us a total of 32,644 kWh/year. Though we could not find a breakdown of energy consumption by end use for Tabuk, we found a breakdown for Arizona, a similar climate. We estimated that 25% (8161 kWh/year) of energy is used for air conditioning[25], 15% (4897

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[24] "Electric Power Consumption." World Bank Data. International Energy Agency, 2014. Web. 28 May 2015.
[25] "Household Energy Use in Arizona." *Residential Energy Consumption Survey*. US Energy Information Administration, 2009.

kWh/year) for space heating, 20% (6529 kWh/year) for hot water, and 15% for lighting[26]. We hoped to reduce all four of these main usages with our design.

We calculated previously that we could maintain interior temperatures through our passive solar chimney and wind collecting design, creating a zero-energy climate control. This reduces energy consumption by a total of 40%, allowing inhabitants to conserve 13,058 kWh/year. We also hoped to implement solar optic lighting in our structure, which would provide passive lighting throughout the day. If we estimate that 50% of light use is during sunlight hours, then the family could reduce energy consumption by an additional 7.5%, or 2448 kWh/year. In Tabuk's climate, heating water through solar thermal energy is ideal, since it is so hot and sunny for the majority of the year. We wanted to meet the entire 6529 kWh/year (17.887 kWh/day) demand using solar thermal energy. With an average solar radiation of 6.3 kWh/m^2/day in Tabuk[27], and estimating 60% efficiency, we calculated that the house would require (17.887 kWh/day)/(6.3 kWh/m^2/day)*(.6) = 4.7 m^2 (50 ft^2) of solar thermal panels.

The remaining energy demand is only 32.5% of the original value, or 10609 kWh/year (29.1 kWh/day). We hoped to meet this demand with solar energy through photovoltaic cells. We calculated that we would need (29.1 kWh/day)/(6.3 sunhours)*(1000 W/kW)/(5 W/ft^2) = 1000 ft^2 of solar panels. Accounting for a large inefficiency in storing the energy in batteries when the sun is not shining, as well as accounting for large fluctuations when occupants may have guests or additional family, we estimated we would need an array of 270 m^2 to supply this energy.

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[26] "Frequently Asked Questions." Electricity Use in the United States. US Energy Information Administration, 2014. Web. 28 May 2015.
[27] "Solar Data Tools." Renewable Resource Atlas of Saudi Arabia. Saudi Arabia Solar Industry Association, 2013. Web. 29 MAy 2015.

Economic Analysis

To do a brief economic analysis of our project, we first calculated the energy savings a typical Saudi family living in our home could expect. Based on local electricity prices of 1.3¢ for the first 2000 kWh per month and 6.9¢ for each additional kWh/month, our family using 2720 kWh per month would save $75.70 each month, or $908.45 each year. While this may seem a small savings, it is important to point out how low these prices are. In the United States, electricity costs on average 12¢/kWh; a savings of 32644 kWh per year would result in a monetary savings of $3917 per year.

We also calculated the savings due to water collection. Because the rain and dew collection systems account for the family's entire water usage, they would be saving approximately 182500 gallons of water/year. With local water costs of 3¢/m^3, or 0.011¢/gallon (2), this would equate to an annual savings of $21.90. Again, to compare to the United States, where water prices average $1.50/$m^3$, this would equate to an annual savings of $1036.93/year.

To estimate the total cost of the house, we used the following:

Material	Cost/unit	Total Cost
Concrete (shell)[28]	$90/$yd^3$	$19034
Canvas[29]	$5/yd	$4117
Steel[30]	$2/$ft^2$	$2691
ADC plastic[31]	$1/$ft^2$	$3564

[28] "Concrete Cost Calculations." L&M Construction Chemicals. Laticrete International, Inc. Web. 205
[29] https://www.fashionfabricsclub.com/c83_apparel-fabric-canvas-fabric

[30] http://www.metalsdepot.com/
[31] http://www.edmundoptics.com/optics/windows-diffusers/visible-windows/clear-optical-cast-plastic-windows/1916

House[32]	Walls: $170/m^2 Windows: $360/m^2 Roof: $150/m^2	$51000 $72000 $24000
Solar Thermal Panels[33]	$200/m^2	$1000
PV cells[34]	$175/m^2	$47250
Solar Optic System[35]		$4000
Total Material Cost		$228,000

Table 3: Cost estimates.

Factoring in the cost of labor to be approximately ⅓ the cost of the total house, and $50,000 for excavation due to the expansive basement, the total cost of the house would be approximately $360,000. At a sizeable 11,000 square feet, this is a cost per square foot of approximately $32.73. Given that the average price of a house in Tabuk is around $160,000, our biomimetic house would cost a family $200,000 more than purchasing an average house. With the annual savings of $930 calculated before, this leads to a payback period of 215 years. Again, to compare this to the United States, where the average house costs $208,000, the biomimetic house would be an added expense of $152,000. With an annual savings of $4954, this leads to a payback period of approximately 30 years. It is also important to note that the house's square footage is much larger than an average house in either country, meaning that a family purchasing this home would likely be comparing it to homes of higher-than-average value, and the payback period would be shortened.

[32] http://www.greenbuildingadvisor.com/blogs/dept/musings/study-shows-expensive-windows-yield-meager-energy-returns, http://www.improvenet.com/r/costs-and-prices/roofing-cost-estimator
[33] http://www.solarthermalworld.org/sites/gstec/files/story/2015-04-06/course_solar_taylor_thermal.pdf
[34] https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-SOLAR_PV.pdf
[35] http://www.brightenyourhome.net/Home-Automated-System.html, http://www.solatube.com/residential/residential-pricing

Measure of Success & Conclusion

To measure our success, we looked to see if we had accomplished our objectives: we maintained an interior temperature of 73˚F year-round with 100% passive technologies, and generated all electricity through solar power. Our air exchange rate is twice every 3.2 hours, compared to our goal of twice every 3. We can house a family of four as well as some of their extended relatives. We collect more water than we consume and generate all of our hot water needs through solar thermal panels.

The only goal that we did not meet was the 25-year payback period, however, it is difficult to compare our four-story, 11,000 square foot home with an extensive outdoor patio to an "average" home. Additionally, in regions where resources are more expensive, we calculated a payback period of 30 years, which nearly meets our original goal.

In conclusion, in Tabuk, our design would be far more successful as a house meant to increase sustainability and environmental awareness than as a house designed to save money via electricity and water costs. While it could be affordable for a wealthy family, it would be unlikely to save them money in the long run. Even the house is not economically viable in the Tabuk province, it could be more successfully implemented in other regions of the world, where utilities are more expensive. Arizona, for example, has a similarly hot and dry climate, and much greater costs of living, and therefore might make more economic sense as a location for this structure.

Ultimately, our house successfully incorporated several of nature's desert adaptations and achieved off-the-grid water and net-zero energy. This was made possible with the help of design changes like greywater recycling and utilization of passive heating and cooling. By simply taking advantage of the environment's already existing resources, namely the atmosphere's relative humidity and the intense solar radiation, our environmental impact was greatly reduced. While our exact design may not be the most economically feasible, many of these design features could easily be translated to many types of buildings in a region similar to Tabuk, Saudi Arabia. Our design combines a multitude of the variety of possibilities that could help further the field of sustainable design at a time and place where it's most needed.

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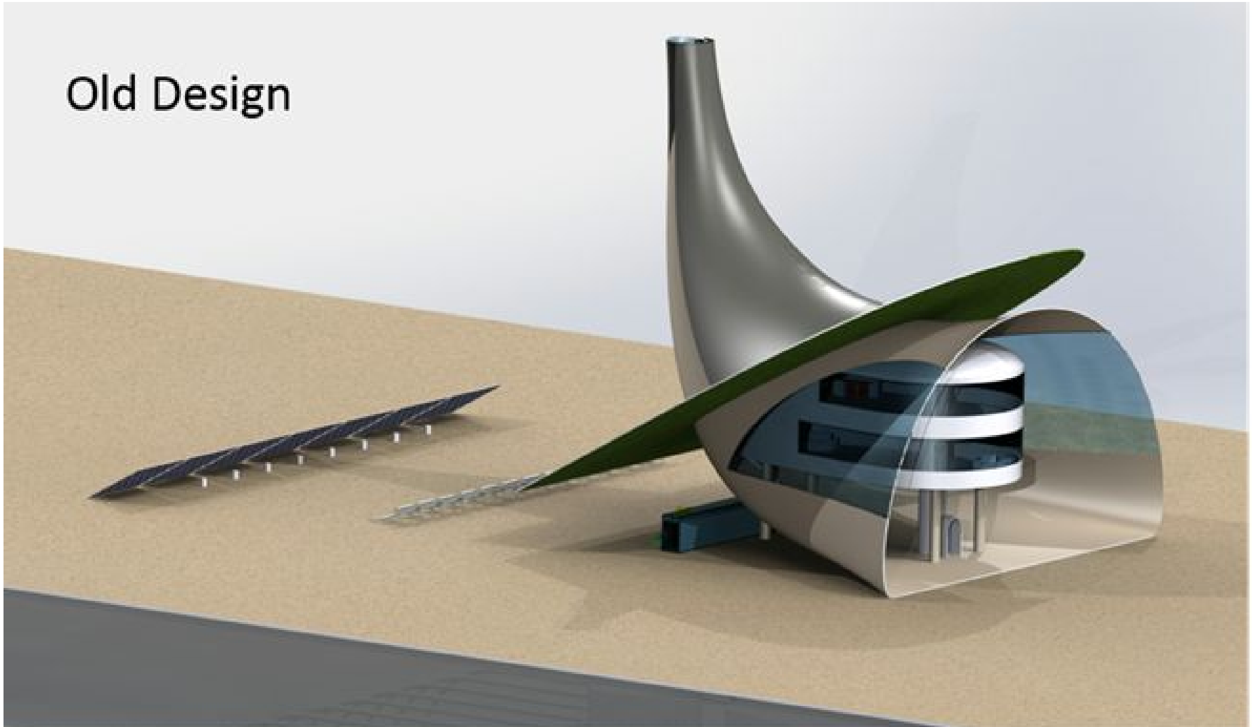
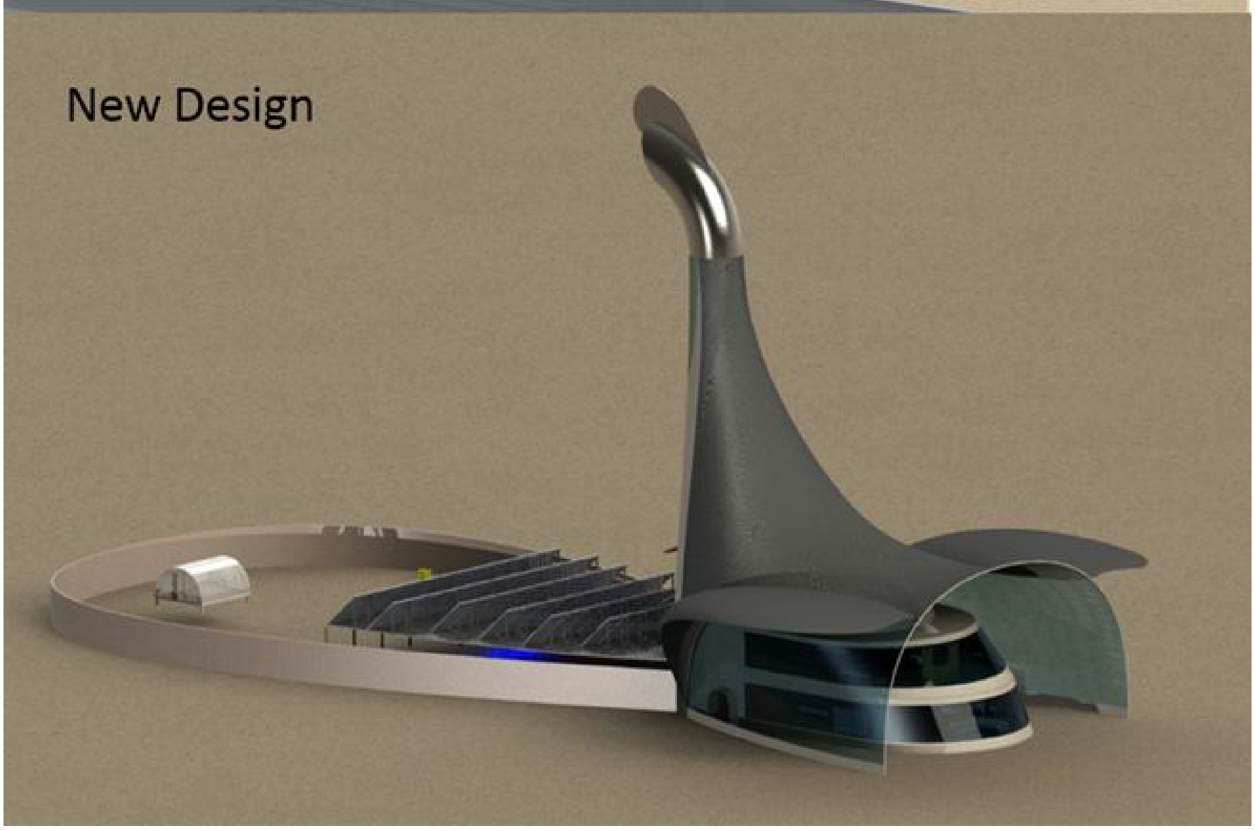
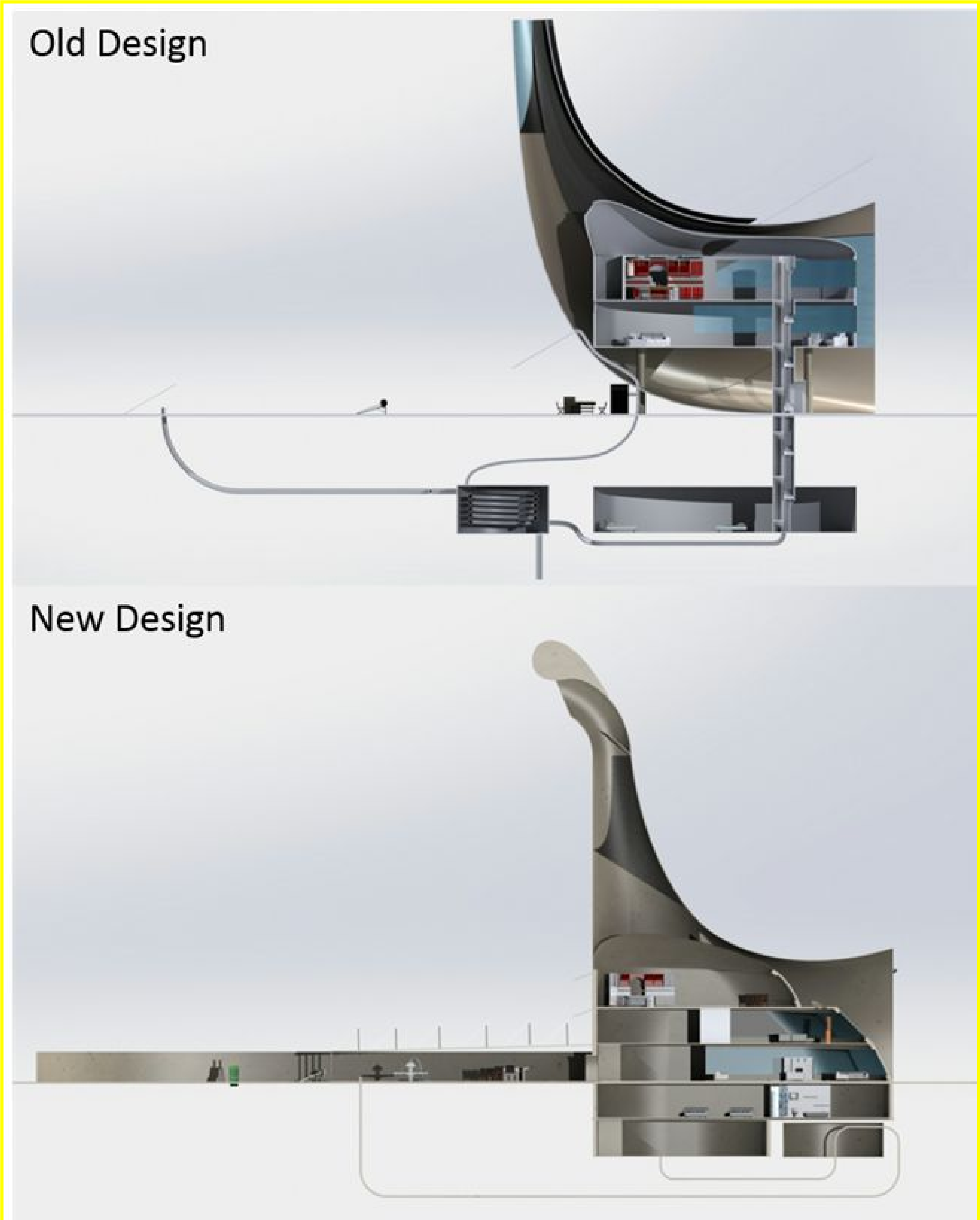
Appendix A - Additional Figures






Old Design
New Design

Appendix B - Program Code

```
%Callan George
%Engs 44
%Thermal/wind analysis

clear
close
clc

%Caluclation of volumetric flow rate of the wind. Here we are assuming just northerly wind to
%simplify the problem
Vwind = 6.7056; %wind speed (m/s)
Ao= 1004.5; %Area of opening (ft^2)
Ao = .092903*Ao; %Area of opening (m^2)
theta = 0; %angle of the wind from perpendicular
Anew = Ao*cos(theta); %Area of wind caught (m^2)
Qwindm = Anew*Vwind; %volumetric flow rate (m^3/s)
Qwind = 2118.880003*Qwindm; % volumetric flow rate (ft^3/min)

%Calcualtion of volumetric flow rate from the ground
Rroof = 50; %r value roof
Rwindows = 5; %r value windows
Rwall = 36; %r value walls
Aroof = 1709.9-81.28; % area roof (ft^2)
Awindows = 2136.7+81.28; %area windows (ft^2)
Awall = 3300; % area wall (ft^2)
HL = Aroof/Rroof + Awindows/Rwindows + Awall/Rwall; % HL for house (BTUS/(Hour*degF)
HL = HL * 24; % HL for house (BTUS/(Day*degF)
Tout = 92.5; %temperature outside mitigated by thermal mass (degF)
Tin = 73; %ideal inside temperature (degF)
Tground = 65; %temperature of air coming from the ground (degF)
Qground = (1/26.21)*((Tout-Tin)/(Tin-Tground))* HL; %volumetric flow rate (ft^3/min)
```

```matlab
%Calculation for forced wind velocity
D = 10; %diameter of solar chimney (ft)
%velocity of forced wind (ft/min) (needs to be less than 19 685.0394 ft/min)
Vforced = (Qground + Qwind) / (pi*(D^2)/4);

%Loop for finding the value of  Vbouancy, T1, and Qextra
Vbuoyancy = 1000; %starting guess for Vbouancy to start the iteration process (ft/min)
T1abs = 300; %starting guess for temperature to start the iteration process (K)
check = 1;
Dm = D*0.3048; %diameter in meters
Vforcedm = 0.00508*Vforced; %Vforce in m/s
g = 9.81; %m/s^2
H = 7.62; %height of the solar part of the chimney (m)
I = 1.0614580417578958*1000; %Irradiance on July 1st (W/m^2)
theta = 85; %angle of the sun hitting the chimney in the summer (degrees)
den = 1.15; %air density (kg/m^3)
Cp = 1005; %Heat capacity of air (J/kg.K)

while check >= .00001
    Vbuoyancym = 0.00508*Vbuoyancy; %Vbouancy in m/s
    %breaking up the Vb calculation to simplify changes.
    RHS = ((8*g*(H^2)*I*cosd(theta))/(pi*den*Cp*T1abs*Dm));
    %Calculation of New Vbuoancy (m/s) using guess Vbuoancy and guessed T1
    Vbuoyancynew = RHS/((Vbuoyancym+Vforcedm)*(Vbuoyancym+2*Vforcedm));
    %Vbuoyancynew = RHS *(1/(Vbuoyancym*(Vbuoyancym+Vforcedm)))-2*Vforcedm;
    %Vbuoyancynew = RHS *(1/(Vbuoyancym*(Vbuoyancym+2*Vforcedm)))-Vforcedm;
    Vbuoyancynew = 196.850394*Vbuoyancynew; %Changing Vbuoancynew to ft/min
    %calculating Qextra using the new calculation of Vbuoancy (ft^3/min)
    Qextra = ((pi*D^2)/4)*Vbuoyancynew;
    T1 = (Tout*(Qwind+Qextra)+(Tin*Qground))/(Qwind+Qextra+Qground); %calculating a new T1 (degF)
    T1abs = (T1-32)*(9/5)+273.15; %Changing T1 To Kelvin
    %calculating the convergence of the Vbuoancy values
    check = abs((Vbuoyancynew-Vbuoyancy)/Vbuoyancy);
    Vbuoyancy = Vbuoyancynew;
end

T1 = (T1abs - 273.15)* (5/9) + 32.00; %Changing T1 to degF

fprintf('Qwind = %d ft^3/min\n',Qwind)
fprintf('Qground = %d ft^3/min\n',Qground)
fprintf('Qextra = %d ft^3/min\n', Qextra)
fprintf('Vforced = %d ft/min\n', Vforced)
fprintf('Vbuoyancy = %d ft/min\n', Vbuoyancy)
fprintf('T1 = %d degF\n', T1)
```

Appendix C

```
%Callan George
%ENGS 44
%area opening caculation

%Caluclation of volumetric flow rate of the wind to determine area opening we need. Here we are assuming just northerly wind to
%simplify the problem
Vwind = 15; %wind speed (m/s)
Ao=0:.1:311.93; %Area of opening (m^2)
theta = 0; %angle of the wind from perpendicular
Anew = Ao*cos(theta); %Area of wind caught (m^2)
Qwind = Anew*Vwind; %volumetric flow rate (m^3/s)
Qwind = 2118.880003*Qwind; % volumetric flow rate (ft^3/min)
Anew = Anew*10.7639; %ft^2
n=length(Qwind);

%Calcualtion of volumetric flow rate from the ground
Rroof = 50; %r value roof
Rwindows = 5; %r value windows
Rwall = 36; %r value walls
Aroof = 1928.79; % area roof (ft^2)
Awindows = 791.88; %area windows (ft^2)
Awall = 1914.84; % area wall (ft^2)
HL = Aroof/Rroof + Awindows/Rwindows + Awall/Rwall; % HL for house (BTUS/(Hour*degF)
HL = HL * 24; % HL for house (BTUS/(Day*degF)
Tout = 92.5; %temperature outside mitigated by thermal mass (degF)
Tin = 73; %ideal inside temperature (degF)
Tground = 65; %temperature of air coming from the ground (degF)
Qground = (1/26.21)*((Tout-Tin)/(Tin-Tground))* HL; %volumetric flow rate (ft^3/min)
Qground = Qground*ones(1,n);


%Calculation for forced wind velocity
D = 10; %diameter of solar chimney (ft)
Vforced = (Qground + Qwind) / (pi*(D^2)/4); %velocity of forced wind (ft/min)

Ideal = 100*196.850394; %the limit of how large Qwind should be (ft/min)
X = Ideal*ones(1,n);

plot(Anew,Vforced,Anew,X)
```

Appendix D - Overhang Calculations