# Low-Cost Scheffler Solar Concentrator for the Developing World

A Senior Project

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Bachelor of Science, Mechanical Engineering

by

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## 1. ABSTRACT

This report will outline an approach to design, test, and build a low-cost Scheffler solar concentrator to be used for safer, sustainable and cost effective cooking in the developing world. The function of Scheffler concentrators and a proposed method to create one in an economic, environmentally conscious manner is summarized. If successful, the design will be presented in a way that is readily and freely available to anyone in the world. The authors have examined existing technology and researched the availability and cost of different materials. Analysis was performed in order to verify the feasibility of the different design ideas and narrow the ideas to one final design. The final design is outlined, with accompanying descriptions and support in the appendices of the report.

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## 5. INTRODUCTION

According to the World Health Organization, more than 3 billion people depend on solid fuels in order to cook food, boil water, and heat their homes [11]. Many people spend nearly as much money and time collecting the fuel to cook their food as they do for the food itself. More often than not, the ventilation in homes that are burning solid fuels is poor or non-existent, which can lead to lung disease, eye problems and house fires. Each year, indoor pollution related to burning these solid fuels can be linked to more than 1.5 million deaths worldwide [11]. Cooking is a human necessity that should be safe and accessible to everyone.

Solar energy is an abundant, renewable and non-polluting resource [4]. A solar cooker uses the energy from sunlight to heat, cook and pasteurize food or drink. Parabolic concentrators are forms of solar devices that work by collecting the sunlight of an area, redirecting, and concentrating it to a smaller area, creating a source of heat at the focal point. A traditional parabolic collector is based off of the bottom of a paraboloid. This means that the focal point is positioned between the sun and the reflector during cooking, and lies along the axis of symmetry of the collector dish. Moreover, traditional parabolic collectors require precise and frequent two-axis tracking of the sun's position to maintain focus [9].

Scheffler solar concentrators are a special type of parabolic solar concentrator based off of the lateral section of a paraboloid (see Figure 1 below). Due to its construction, a Scheffler concentrator only requires one axis tracking, and the fixed focus is away from the incident beam radiation and away from the dish itself. Seasonal adjustments are made simple by flexing the dish [10].

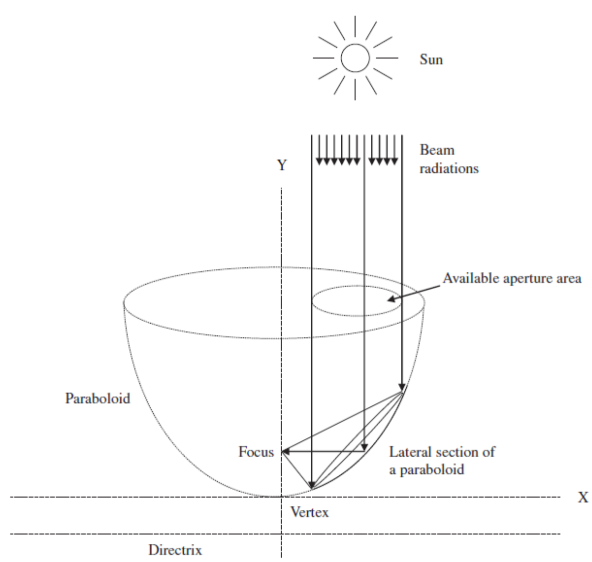



**Figure 1 - Section of a Scheffler reflector in a paraboloid**

A Scheffler collector has already been developed at Cal Poly (see Appendix A) based on project plans directly from the inventor's website, but the completed collector lies outside a reasonable price range for many people. The frame for the current Scheffler dish is made of machined aluminum, while the dish itself is made of thin sheets of highly polished aluminum [10]. At slightly less than two thousand dollars, the current design is too expensive for widespread implementation and the manufacturing process requires special tools that are not widely available. This project team will develop an alternative concentrator, based on the solar principles of Wolfgang Scheffler that is easily and cheaply manufactured for developing countries.

### 5.1 OBJECTIVE

The objective for the Senior Project team is to create a low-cost Scheffler dish, preferably out of sustainable, locally sourced and easily obtainable materials, while maintaining adequate performance and ease of manufacturing. The sponsor has established a quantitative measure of performance, and the engineering specifications have been set. The final Scheffler concentrator must:

- Cost less than $100
- Have the ability to be manufactured on-site
- Produce a focal area with 90% of the radiation in an area of less than 15 X 15 cm
- Have seasonal adjustment capability

In order to achieve project objectives, certain tasks will be fulfilled throughout the design process. Brainstorming, conceptualization, and prototyping will be carried out through the duration of the project. Also, research, communication, and creation of analytical techniques for design evaluation will be required. The team hopes to build a large number of working prototypes that can be tested against quantitative goals and requirements in order to progress for the duration of the project.

Studies for experimental power output may be required to characterize prototypes. Analysis of surface imperfections, material reflectivity, focal point concentrations, and structural integrity need be addressed. The group will be developing test procedures to evaluate prototypes and analyze how they will meet the requirements for final design. Some optional techniques that may be considered include composites analysis, economy of various manufacturing processes, and safety analysis.

The essential materials required for this project will be prototype components for construction, and a steady light source (such as the sun). In addition (and for more complete analysis) the team also foresees the potential use of testing lamps, solar power testing equipment, a 3D scanner for surface modeling, machine shop tools, solid modeling software, and plenty of food to cook on test days. The senior design team hopes to also meet with various faculty members and solar industry specialists to discuss detailed analysis, design methods, and general recommendations or advice.

The three students involved will generally be equally responsible for different aspects of the project, but can draw on their individual specialties when appropriate. Among the students' specialized skills are experience in project economics, design and implementation of manufacturing processes, and advanced CAD and mechanical design. All group members are capable of performing any of the facets of the project. A management plan has been established in Section 9 of this report.

## 6. BACKGROUND

Currently, there is a Scheffler collector at Cal Poly that was made several years ago by students in the Physics department (see appendix A) [10]. The collector works well, but cost several thousand dollars to manufacture, and required close to one thousand hours of labor to assemble [1]. The collector was built by following an instruction manual that was acquired online from the inventor. The senior project team has access to the existing collector, as well as several contacts that were involved with the original project [10].

In order for the team to produce a viable collector, they must gain an understanding of how a Scheffler collector works, and the shape required for optimum cooking. Simo Alberti, a Cal Poly graduate student, is researching the theoretical possibilities for a Scheffler Concentrator, as well as calculating the acceptable level of error for the surface of the dish that will still allow the user to effectively cook.

Some Scheffler collectors are large enough and precise enough to be used in Crematoriums and Smelters [10]. In theory, these devices can achieve radiation intensity 45,000 times higher than the radiation intensity of the sun [2]. However, the senior project team is primarily concerned with dishes that are smaller and used for cooking. The relatively low power requirements of solar cookers allows for more surface imperfections and less stringent tolerances.

Many of the brainstorming discussions for the Scheffler reflector have been focused on material requirements. The team is approaching the design with material sustainability in mind and has researched many options for locally available and affordable materials. Some of these options include reused materials taken from trash, natural composites, or structural materials that were grown in local areas (bamboo, wood, etc.). Regardless of the actual material used, the optimal approach is to design using materials that are economical to the user in a particular area. For this reason, the team may design with very general global materials in mind, or create a list of acceptable materials that meet construction requirements.

Existing parabolic solar concentrators can function well for cooking applications, but are expensive to buy or make. For example, the Cantina West Solar Power Cooker - a standard parabolic solar concentrating cooker - costs $170.00 on the company’s website [8]. A standard and comparable model for this project is a $17 parabolic solar cooker developed by students at MIT [6]. Their design used mylar-coated canvas with a bamboo rib structure. This is considered to be the state of the art by the design team, although it is not a Scheffler-type reflector but a parabolic reflector. While our explicit requirement is to design a Scheffler system more economical than the current Cal Poly design, the aforementioned products will also be used to gage the success of the senior project team’s final design.

## 7. DESIGN DEVELOPMENT

In order to achieve project objectives, certain tasks will be fulfilled throughout the design process. Initial brainstorming and conceptualization have now been completed, and detailed design and prototyping will be carried out through the remainder of the project. The team would like to build several working prototypes that can be tested against quantitative goals and requirements in order to progress during the project process.

### 7.1 ANALYSIS

In order to design a Scheffler concentrator that meets all of the design goals and requirements, the senior project team first had to gain a working understanding of the current Scheffler concentrator, as well as theoretical limits and constraints. Simo Alberti, a Cal Poly graduate student, has been analyzing the theoretical limits of a Scheffler concentrator. Through his analysis, he will be able to determine what level of imperfection is acceptable on the surface of the dish, giving the team a measurable goal [1]. Samples of his analysis can be found in Appendix B of this report. A three dimensional scanner may also be used to find and model imperfections on the surface of the current collector, allowing the team to locate potential problem areas for future prototypes.

In order to analyze the performance of various prototypes, the team will develop various tests to evaluate surface imperfections, solar power output, reflectivity, and/or absorbance of the reflective surfaces. These types of tests are common for solar engineering practices and may be beneficial for prototype analysis [2].

The team has several methods of analyzing the concentrator, ranging from qualitative and relatively simple to very theoretical and complex. The team's first study of Scheffler operation was in the form of cooking lunch. Since the whole point of the Scheffler concentrator is to cook, this was arguably the best analysis tool available to the team. After cooking lunch, the team was able to develop a mental list of things that could be improved or changed. The team found that the concentrator was over-designed, as the level of manufacturing cost and complexity was unnecessary for the relatively low-precision application of cooking.

During the cooking process, it was noticed that the focal diameter was hard to measure, simply because of how bright it was. Even with the use of dark sunglasses or a welding mask, the team was not able to document the actual size of the focal area. The focal area is a valuable parameter to know, as one can calculate the concentration ratio that the dish is achieving. In order to measure the focal area, the team had to wait for a full moon, which luckily occurred on a clear night. The moonlight could then be safely focused, and then the focal area was measured. This is shown below in Figure 2.

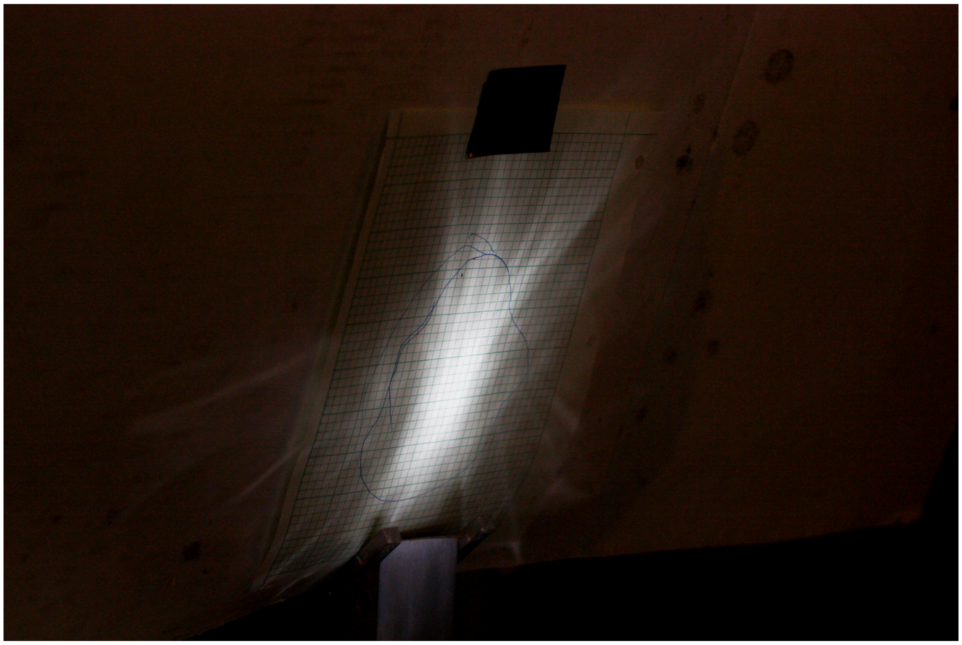


**Figure 2 - Moonlight being focused on a piece of engineering paper**

As a preliminary study of optical and thermal performance, an evaluation model was developed to test the Scheffler dish for the ME 450 (Solar Power Systems) course. A length of pipe was centered at the focal point of the dish and used to heat running water to test the thermal performance of the dish. A computer model was written to estimate theoretical values of output temperatures, and compared with measured results. The test procedure was relatively crude because of the time allotted for the experiment, but was successful in measuring an increase in water temperature. This indicates that the dish and procedure do work and that the experimental set up can be further refined to test later prototypes. The theoretical model, while not as complete as Simo Alberti's research (Appendix B), also showed promise in characterizing the thermal performance of the solar concentrator.

## 8. SELECTED CONCEPT DESIGNS

Initially, many different methods for achieving the shape of the dish were explored. Options included vacuum forming to a mold, press forming to a mold, cutting with a template, or tensioning fabric to the specified shape. Once several viable concepts were established, different materials and manufacturing processes were studied in detail, in order to get the right combination of performance and cost, with the emphasis on low cost.

After brainstorming, rough concepts were sketched without consideration of engineering feasibility. These first concepts were primarily to serve as a way to put any and all ideas out in the open for the team to develop further. After initial concept sketching, the team came together to see which of the sketches or which combination of sketches could be realistically accomplished.

The team created a list of all ideas and concepts, including structural and reflective material possibilities. Some designs were eliminated based on Go/No-Go specifications. The ideation and brainstorming session can be found in Appendix C.

The results from ideation sessions were then put into weighted decision matrices that were created by the team based on the design categories that were believed to be the most important. Three decision matrices were created: one for overall concept, one for structural material selection and one for reflective material selection. The decision matrices can be found in Appendix D.

The background research and brainstorming sessions that was completed in the first ten weeks of design have led to several promising conceptual designs. The team plans to develop each of the top concepts concurrently and to conduct more research before settling on the best one.

### 8.1 SHEET METAL DISH

Sheet metal offers a great combination of strength and workability. It was found early in the design process that sheet metal can be readily formed into a complex shape while still retaining strength. In early prototyping, an ordinary piece of sheet metal could be easily formed to approximate the bottom section of a paraboloid with the use of an English Wheel. The English Wheel consists of two hardened steel rollers that pinch the sheet metal, and spread the material to form an even, extended surface. One of the rollers is flat, while the other is curved. By rolling the sheet metal through the English Wheel, the metal is forced into a curve. By rolling the material through the tool in two different directions, the fabricator can achieve a section of a sphere or a paraboloid.

The team member who explored this concept found that the learning curve for sheet metal forming was steep. Having had no prior experience forming sheet metal, he was able to produce an approximation of the bottom section of a paraboloid in little more than half of an hour. It was found that the shape of the metal could be easily formed, and that sheet metal could also eliminate the need for a secondary reflective surface, which other concepts would require. By polishing the sheet, one could potentially create a surface that is reflective enough to cook.

**Figure 3 - A sheet metal approximation of a paraboloid, with aluminum coated mylar.**

After the promise of the first crude prototype, a second larger one was created with more care and thoughtfulness. The team wants to design the dish in a way that can be easily manufactured by someone with limited resources. The second sheet metal prototype was fabricated with this in mind. Since the prototype was intended to approximate the bottom section of a paraboloid, the focal point would be located directly above the center of the prototype. For manufacturing purposes, the team decided that the location of this focal point (determined by how steep of a curve is put into the metal) should be approximately arms length. This way, the fabricator can qualitatively measure the shape of the dish without any special measurement tools. If there is a light source approximately behind the the fabricators head, and the sheet is held at arms length away, then all points on the sheet should be reflecting light directly into the fabricators eyes (it should be noted here that the light source should be a dim one, so that the manufacturer is not at risk of blinding themselves).  Any point that does not reflect light is not accurately approximating the paraboloid, and should be worked further.

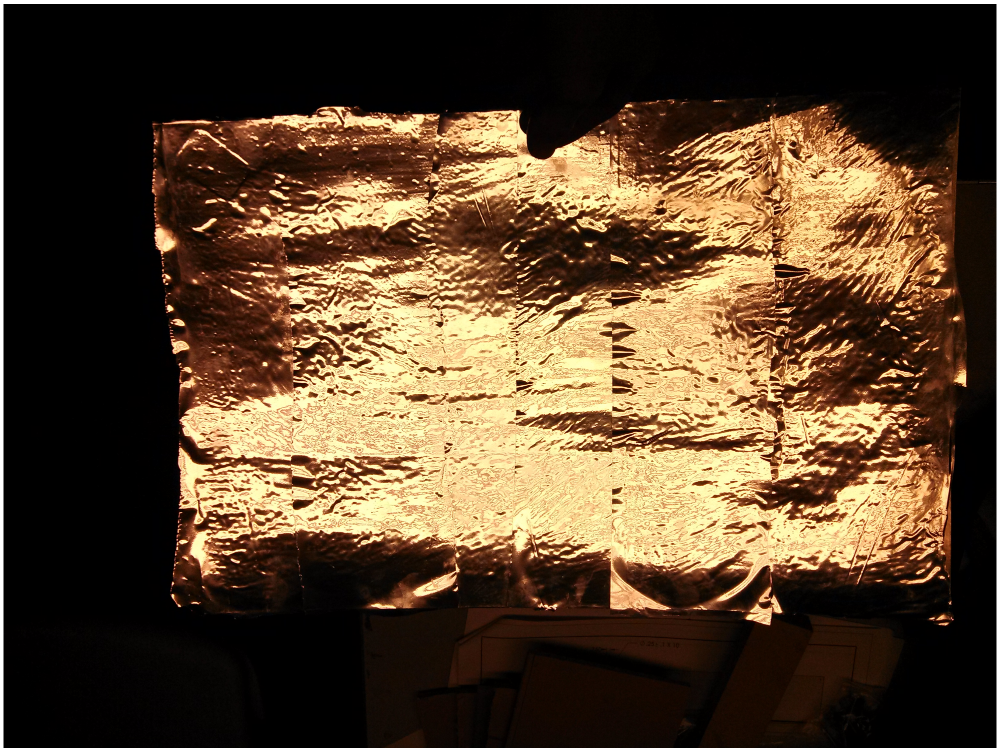


**Figure 4 - Picture of sheet metal approximation. The photograph was taken close to the focal point of the dish. All the illuminated portions of the sheet are successfully focusing light, whereas the dark areas are not.**

When the shaping was complete, strips of aluminum mylar were adhered to the surface to increase reflectivity. When taken into the sun, it was found that the prototype was very effective when compared to the relatively short manufacturing time, yielding a focal area roughly 10x10cm.

Although initially promising, a formed sheet metal design would have to be further refined. It is unlikely that many people have access to an English Wheel, which was crucial to forming the prototype. The team will explore if similar results can be achieved by a more skilled metal worker with less specialized tools, such as a hammer and anvil. The method of holding the dish at arms length to assess accuracy would also have to be adjusted for the Scheffler shape, due to the location of the focal point not being directly above the center of the dish.

The team will also have to design the dish with the ability to adjust for different seasons. The team feels that adjustment can be accomplished in two ways. Either the dish can be designed with the ability to flex, or the team could design several rigid dishes with the intention of using different ones at different times of year. A decision will be made when an in-depth cost analysis has been completed

## 8.2 STRETCHED FABRIC DISH

Working towards the idea of globally available and usable materials, fabric continually came to mind. People from all parts of the world use fabric, and all parts of the world have people who know how to form fabric. The shape of a Scheffler solar concentrator can be formed by fabric in a way similar to how a tent or umbrella holds a three-dimensional shape. Also, methods of folding, cutting, and joining fabric can yield complex shapes. Examples of this can be seen in origami arts, and the complex art of sail making. A design embodying the low cost of fabric, and a relatively simple fabric manufacturing process was envisioned.

Almost immediately, a very simple concept was drawn for how to achieve the collector geometry. After discussing the plan with sail-makers at SLO Sail and Canvas, some major points of concern were identified. The initial idea was to pull the fabric in order to create enough planes to approximate a Scheffler paraboloid. The outline of the shape would be affixed to a rigid, elliptical rim, and the third dimension achieved by pulling individual points on the fabric. Fabric does, however, hold undesired curvatures when pulled at a point, so this initial idea introduces difficulties if not enough pull points are chosen to adequately approximate the correct shape. The ultimate solution using this method of forming fabric involves stretching a fabric ring around an elliptical hoop. The fabric would be pulled at either localized point, another lower concentric hoop, or a combination of the two. The top side of the canvas will be coated in reflective material, giving an approximated Scheffler dish.

Another solution to the forming of fabric into a working solar concentrator involves cutting and sewing it into the correct shape. A gore is a section of fabric that is cut in a specific shape, so that when it is joined to another section of fabric a more complex shape is achieved. This method may also be used to create complex three-dimensional shapes. For a paraboloidal concentrator, segments are cut in curved isosceles wedges and sewed together side by side. Variations in the length of wedges will create the different section of an elliptical aperture, and the curvature of the wedge will create the specified deflection of the finalized dish. This method creates a more even surface for a specified shape but may also have issues when stretched to account for declination adjustments throughout the year.

The frame for a fabric Scheffler dish can be made out of any structural materials this group specified, but in practice was developed using bamboo for the first crude prototype. Bamboo is easy to form and join by hand using a gas torch (for heat bending) and twine. It is also surprisingly flexible for its strength. The group purchased a bundle of bamboo from a nursery in Paso Robles (Paso Bamboo). Three culms of bamboo were bent to shape and joined with twine to form an approximate elliptical rim of a Scheffler dish. The method is depicted below:

**Figure 5 - Hoop approximately 3 feet in diameter, bent with a blowtorch and twine.**

Another option for the frame is to use natural composites, currently being researched by Dr. Eltahry Elghandour at Cal Poly. In the interest of using locally sourced and sustainable materials, the possibility of using structural, natural composites has been explored. Composite materials are a combination of two or more materials in the interest of utilizing their respective benefits [9]. Usually, composites consist of two materials, a matrix structure and reinforcing fibers. Natural composites work similarly by using organic materials as the fibrous reinforcing structure [12].

Under the guidance of Dr. Elghandour, the group began preliminary research into the practical use of natural composites. Dr. Elghandour expressed that natural composites can be made in a very cost-effective and simple manner [3]. He stated that structural materials can be fabricated to perform with the required strength and flexibility, and with locally sourced materials. Practical research into methods of manufacturing natural composites began with an attempt to create a mat of palm fronds gathered on the Cal Poly campus. Unfortunately this effort was set back by rain but will continued in the following quarter.

**Figure 6 - Initial layout of plant leaves to make a composite lattice.**

The basic idea of creating appropriate Scheffler concentrator structures with natural composites involves flexibility. Composites are generally rigid materials that are not made to flex, although can be designed to if necessary [3]. Flexible elements of the dish can probably be made by designing thin strips of natural composites that contain fibers oriented longitudinally along the member. Rigid members of the dish can be made thicker and with randomly oriented fibers [9].

### 8.3 COB/CONCRETE DISH

Cob is an ancient composite building material consisting of clay, sand and straw. Cob has been used for thousands of years to build structures such as houses and even ovens. To make cob soil (clay and sand), water and straw are mixed and kneaded into a “dough”. The dough can then be shaped to create a structure.

Using the dough and a mold of a Scheffler dish, the team would compress the cob onto a male mold or shape the cob by hand, using a mold to check for accuracy. The low-cost and high availability of this material make it an extremely desirable candidate for the Scheffler dish.

Another similar possibility, if cob were not available, is to use concrete. Concrete is one of the most widely used and inexpensive building material in the world. It is extremely durable and relatively easy to work with.

The major drawback is that the dish would not be flexible and thus would not allow for seasonal adjustments. The team has considered the possibility of making multiple dishes that each approximate the shape of the Scheffler dish for different seasons. The team needs to analyze how many approximations it would take to maintain the focal diameter that is necessary to cook for every day of the year. A small model is currently being developed, using a satellite TV dish as a simple mold.

## 9. SELECTED DETAIL DESIGN

### 9.1 CONCEPT DESIGN SELECTION

The senior project team decided to go ahead with the stretched fabric design, which is outlined in section 8.2. It was decided that the best way to accomplish this was to first build a mold, consisting of a series of flat pieces that approximated the shape of the Scheffler dish. The dimensions of the cross sections were determined using Simo Alberti's MATLAB code. After the team had begun to design the concept further, it was decided that fabric, although readily available, had complications associated with manufacturing.

After research into fabric shaping methods, it was discovered that fabric is not as easy to work with as was originally imagined. The team found that it would be difficult to form the fabric in a reliable and predictable way. Originally, the concept relied on the ability to make planar sections of fabric that would approximate the correct shape of the Scheffler dish. Complications arose when the team discovered fabric will produce a negative sloping curvature between planar sections. The concept then developed into laying out the fabric to drape over a dish mold and then spraying it with an epoxy or other hardener so that it could be formed into a more robust shape. As the epoxy dried, the shape of the dish could be further reworked.

While the mold for the stretched fabric was being designed, it was noted that the mold looked similar to the skeletons that are used during wooden boat building. It was then that the team decided thin strips of wood, such as fencing slats, could easily be pressed into the skeleton mold for fabrication. A picture of a boat being built with a similar method can be seen in Figure 7 below.

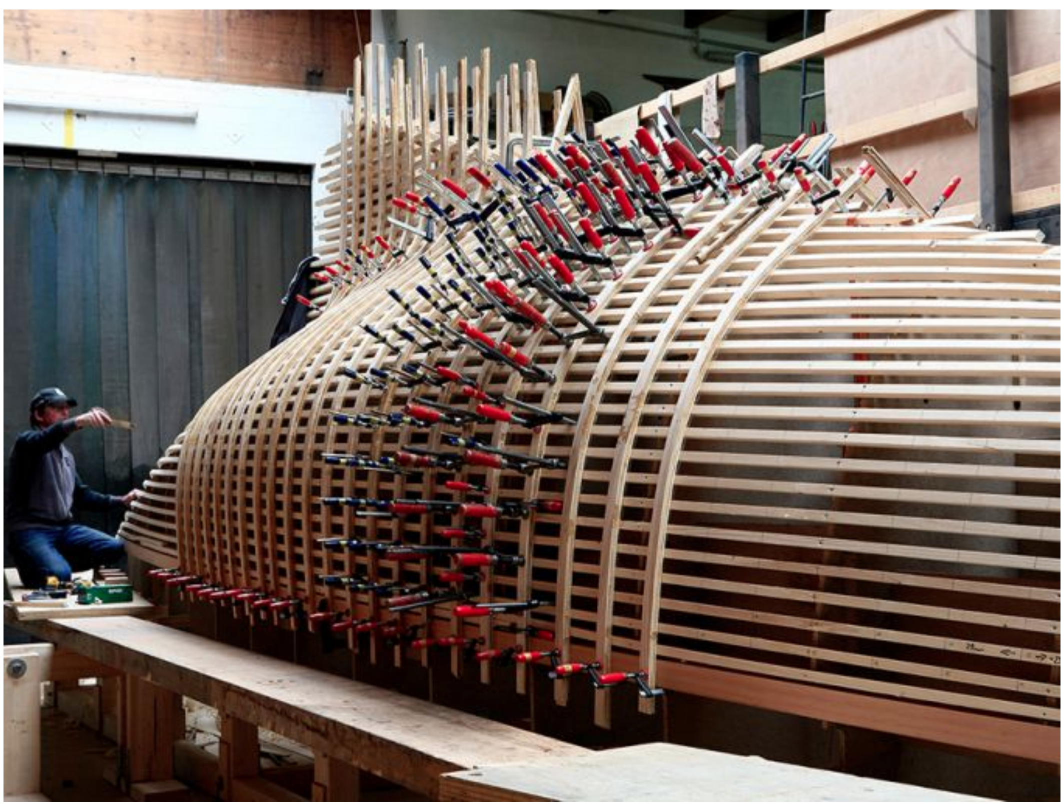


**Figure 7 - A typical manufacturing method of wooden boat hulls**

## 9.2 DETAIL DESIGN DESCRIPTION

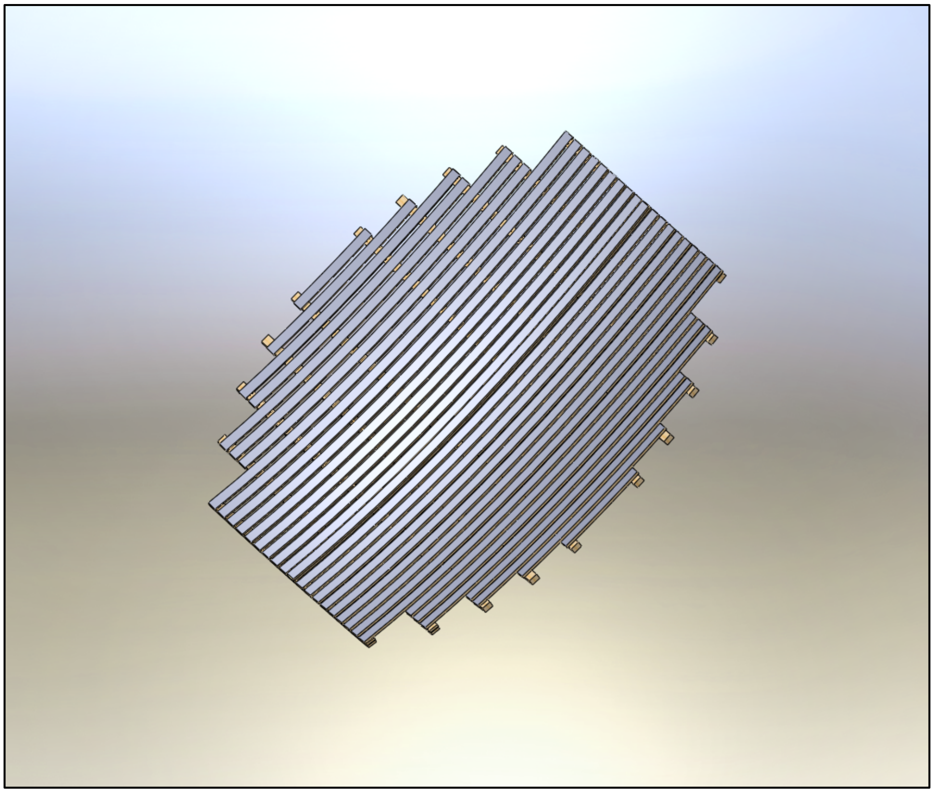


**Figure 8 - A rendering of the Scheffler dish**

The ribs of the new Scheffler solar concentrating dish are to be made from laminated, curved wood sections. Thin strips of wood material, such as balsa or douglas fir, will provide the appropriate flexural rigidity and satisfy the low-cost nature of the project objectives. These eleven curved members are achieved by gluing two sections of thin wooden slats along their length, bending them to the correct geometry, and clamping them in place so that they dry holding shape. When the clamps are released, any tendencies of one slat to return to original shape are resisted by the other slat, and vice versa.

The dish backing is made from the same material as the ribs, only arranged without spaces between members. The common fabrication method allows for low-variability in operation types, and also for materials to be bought in higher bulk. There will be 34 wood-composite dish slats and 10 wood-composite structural ribs.

The mold structure is constructed with ⅛-in thick plywood sections, which define the radii for each lateral rib. The sections are aligned and spaced along three M8 threaded steel rods and secured with hex nuts. The entire mold assembly is comprised of common, inexpensive materials. All operations are well-defined, simple steps, which do not involve uncommon tooling or specialized practices. Eleven plywood sections were used to define the 2 $m^2$ dish and associated rib geometry.

The reflective surface of the dish will be made of aluminum-coated mylar strips. The strips are adhered to the dish backing so that no folding or wrinkling occurs. Aluminum-coated mylar has excellent reflectivity properties and is extremely low-cost for commercial use. A basic epoxy adhesive can be used to adhere mylar segments to the laminate wood dish structure.

A full description of the assembly is outlined with pictures in Appendix G, and fully dimensioned drawings are given in Appendix H.

### 9.3 MATERIAL SELECTION

Material and component selection has been largely based on research of what is widely available. The senior project team chose basic construction materials for the majority of the design. The entire structure of the dish is designed using wood, however, manufacturing of the dish must be based on readily and locally available materials. The intention of the final design is not meant to be the only solution to the problem, but rather a suggestion. The senior project team wants the design of the dish to be simple enough that it can be easily adapted to materials that are available to the end users.

The Cal Poly Scheffler team also intends to refine material selection throughout the remainder of ME 429/430 in order to produce more efficiently priced iterations. Using a uniform dish surface such as fiberglass may prove to be more cost-effective and these options should be left open to the selection of final users.

Sizing of the Scheffler solar concentrator enables end-users to select a more or less powerful device. A 2 $m^2$ dish has been selected as a good option for cooking in personal homes, but larger communities may wish to cook with large-scale concentrators. Fortunately, scaling for the Scheffler dish is linear, and dimensions may be augmented with a multiplier to create plans for higher output instruments. Guidelines for this process will be outlined in further detail in the Final Report at the completion of ME 430.

### 9.4 SAFETY

Thus far, the senior project team has not identified any major sources of danger that would be encountered during the end use of the Scheffler dish. However, it is worth noting that the dish is designed to concentrate sunlight, which can be dangerous if one is exposed for long periods of time. Risk of sunburn and damage to eyesight are significantly increased during the use of the Scheffler dish. However, these risks can be easily avoided by wearing dark sunglasses, or some other form of eye protection, as well as long sleeves and gloves, and potentially sunscreen.

During manufacture of the Scheffler device, care should be taken to use all tooling properly and safely. While power tools are not mandatory for any portion of assembly, they may be used and appropriate care should therein be observed. Layup of curved wood composite structures will require heavy application of adhesives that may introduce contact or respiratory risks. Protective outerwear such as gloves, safety glasses, and facemasks may be used for these steps.

All manufacturing processes involve common tooling and practices, and none require particularly hazardous materials. Care should be taken at all times, and operators should practice good sense and judgment throughout fabricating, building, assembly, and operating procedures.

## 10. MANAGEMENT PLAN

The Cal Poly Scheffler Concentrator team developed a management plan in order to effectively achieve project goals. A general timeline was created to increase awareness of milestones, and each group member was given responsibilities based on their availability and skill-sets.

### 10.1 SCHEDULING

A Gantt chart was developed in order to organize tasks for the duration of the senior. In many cases, absolute dates and tasks were difficult to determine but the group made estimates for all work required to finish the Scheffler solar concentrator. The Gantt chart will be continually updated as tasks and dates change. Also, the group website will reflect the most recent schedule of tasks so that all who are interested can follow the teams progress. The Gantt chart can be found in Appendix E.

### 10.2 TEAM MEMBER RESPONSIBILITIES

Each team member was assigned a specific role for the completion of the project. While all team members will participate and be involved in each task and sub-task, each specific team member will be responsible for meeting the final deliverable of their role. Therefore, each team member will gain valuable experience as a team manager during some part of the process while the workloads remain equal. Jason will lead the manufacturing process. His hands-on building experience as a carpenter's apprentice makes him most qualified for this role. Nick has two years of manufacturing engineering experience and will be responsible for the modeling and ensuring that the team stays within the allotted budget. Darren's focus on quality and analytical approaches makes him most qualified to lead the testing of components and system to ensure that they meet the engineering specifications.

### 10.3 BUDGET ANALYSIS

Although the cost of the final design has been discussed (< $100), the team is still waiting to hear from CP Connect in regards to the status of the funding proposal that was submitted. Until the status of that funding is known, the team cannot establish a final project budget.

There are several items that will be purchased for prototyping and the final build: structural materials for the dish and support stand (i.e. sheet metal, canvas, bamboo, epoxy, fasteners, twine, etc.), reflective materials (i.e. aluminum mylar, aluminum foil, acrylic mirrors), and perhaps some testing equipment.

Because the emphasis of the senior project is to keep material and manufacturing costs low, the team may have the option to build and test several different detailed designs, as the budget allows. The final ten weeks will be focused on selecting and redesigning the best prototype in order to meet the project goals and objectives. The team has created a cost spreadsheet in order to keep track of all purchases.

## 11. MANUFACTURING AND ASSEMBLY

During the manufacturing process the team attempted to use tools and materials that are readily available around the world. All steps were designed to be completed with common construction practices and tools, and require little technical experience. The exact process for construction and assembly of the low-cost Scheffler dish is a suggestion, and by no means the only way to achieve the end goal. Process alterations can be made at any step to further simplify or expedite manufacturing.

Before the dish could be assembled, it was necessary to construct an accurate mold to drive the shape of the completed dish. The team used a negative mold so that the structure of the dish could be pressed into the mold while curing and to prevent sliding out of position.

### 11.1 THE PLYWOOD MOLD

Two 4'X8' sheets of 7/16" oriented-strand board (OSB) were used for the main structure of the mold. Eleven rectangular pieces (0.2 m X 1.5 m) were cut from the two 4'X8' sheets of OSB using a table saw:

**Figure 9 - Jason using a table saw to cut support slats for the Scheffler dish.**

A 10 ft. piece of 2X6 was cut in half using a jig-saw. The two pieces of 2X6 were used as the end pieces of the mold to provide stiffness in order to keep the OSB profiles aligned. The 8 mm holes for the threaded rod were then drilled in the eleven OSB profiles and the two pieces of 2X6 using a drill press (alternative: power drill):

**Figure 10 - Jason drilling pilot holes for the alignment thread rod.**

In order to draw the curves in the OSB profiles, the team constructed a large drafting compass using a long 2X4, a nail for the pivot point and a carpenter's pencil. The curves were then carefully cut using a jigsaw (alternative: thin hand saw). Imperfections (i.e. raised sections) of the curves were sanded smooth using coarse sandpaper.

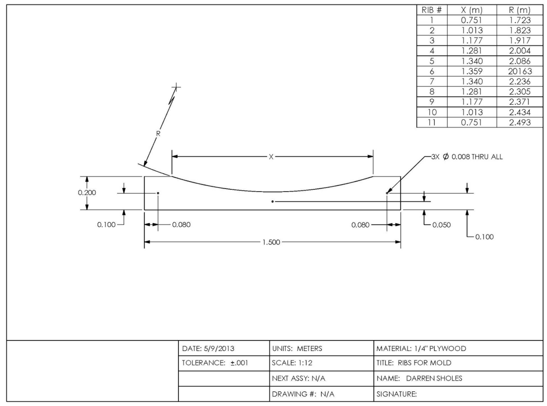



**Figure 11 - Solidworks drawing for the eleven mold segments.**

The three threaded rods were carefully pushed into the predrilled holes of the 2X6 held in place with hex nuts on either side of the 2X6. The OSB profiles were then slid onto the rod, one profile at a time, with hex nuts on either side used to hold the profile in the desired location along the threaded rod (three threaded rod with a hex nut on either side of the profile leads to 6 hex nuts per profile).

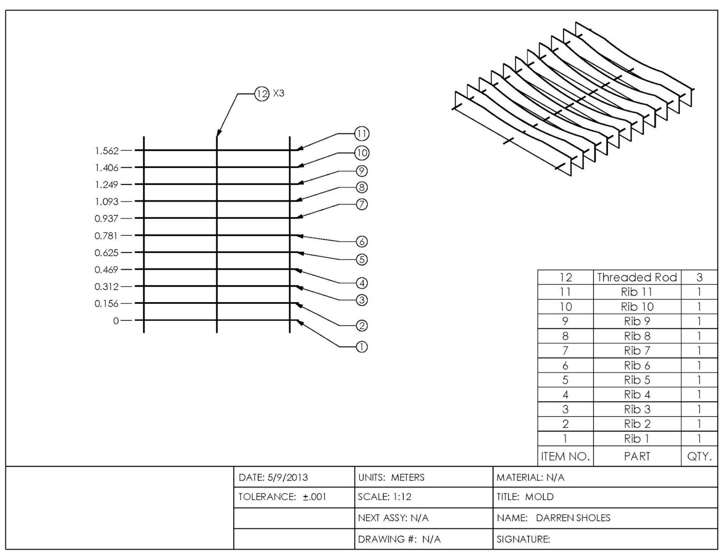



**Figure 12 - Solidworks assembly showing the complete mold for the Scheffler dish.**

The final 2X6 is positioned last in the same manner as the first 2X6. There will be excess threaded rod after the profiles are all positioned. The manufacturer can cut the excess rod using a hacksaw. This process is time intensive, but it gives users the ability to make fine adjustments to the positions of the profiles during the assembly process.

Once the mold is fully assembled, the manufacturer can begin the construction of the dish.

## 11.2 THE DISH

The wood slats used to create the wood laminate were cut from two 4'X8' sheets of 2.7mm plywood utility panel using a table saw. Each wood slat was cut to 1.5" wide by 8' long. One layer of wood slats was laid into the mold, each slat cut to the appropriate length based on the mold dimensions. A thin handsaw was used to make the cuts. A second layer was laid and cut in the same manner as the first. The second layer was then removed and set aside in an organized manner.

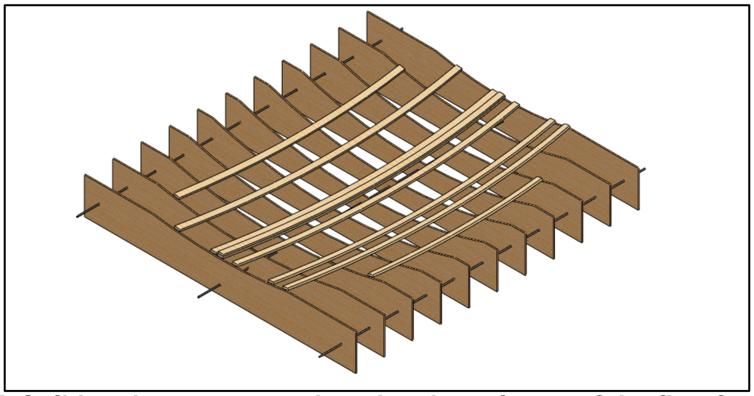


**Figure 13 - A Solidworks representation showing a layup of the first few dish slats.**

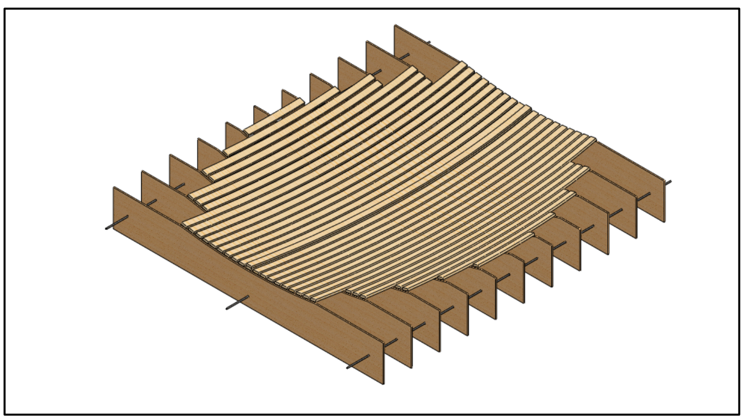


**Figure 14 - A Solidworks representation showing the total layup of the dish slats.**

At this point, the manufacturer should be prepared with a large plastic tarp and a large amount of sand or dirt (~75 lb). Using paint brushes, a generous amount of wood glue was applied to the top of the first layer of wood slats. The second layer was then carefully laid on top of the first. The plastic tarp was laid on top of the second layer. A large amount of sand was poured onto the assembly. It is important to distribute the weight of the sand equally across the entire mold. The weight of the sand pushes the slats into the mold, forming the shape of the dish. The dish was then left to cure for 24 hours.

The sand and the plastic tarp were removed. The wood laminate was fully cured, forming the surface of the dish. It was noticed that some excess wood glue had seeped through the spaces between the wood slats and dried on the surface of the dish. A power sander, with medium grade sandpaper, was used to remove as much of the dried glue as possible. Some surface roughness remained, adding to the surface imperfections. The next step was to construct the backing ribs.

In order to save time, the team purchased pre-cut wood lattice for the backing ribs instead of cutting ribs from a sheet of plywood. Note that the cost of the dish could be decreased significantly if the manufacturer is willing to cut the wood slats for the ribs from a sheet of plywood. The ribs were pre-formed using the OSB profiles of the mold as guides. The ribs were layered and left to cure in the same manner as the wood laminate for the surface of the dish.

The ribs were then adhered to the back of the dish using wood glue. This process was time intensive. Two ribs were adhered at a time. Each pre-formed rib was carefully laid into the curve of the corresponding OSB profile. Wood glue was spread onto the ribs. The dish was then carefully laid onto the ribs. The plastic tarp and large amount of sand were placed back onto the assembly and the wood glue was left to dry. The process was repeated, two ribs at a time, until all eleven ribs were adhered to the back of the dish in the proper location.

Next the reflective material was adhered to the surface of the dish. The team chose to use aluminum tape, commonly used in duct repair, because it is inexpensive and already contains an adhesive, making it easy to apply to the surface of the dish. Other reflective options include aluminum mylar, small pieces of cut or broken mirror, or polished aluminum strips. A single strip of tape was applied to each wood slat. The tape was slightly wide for the wood slats, so a sharp knife was used to carefully trim the excess tape:

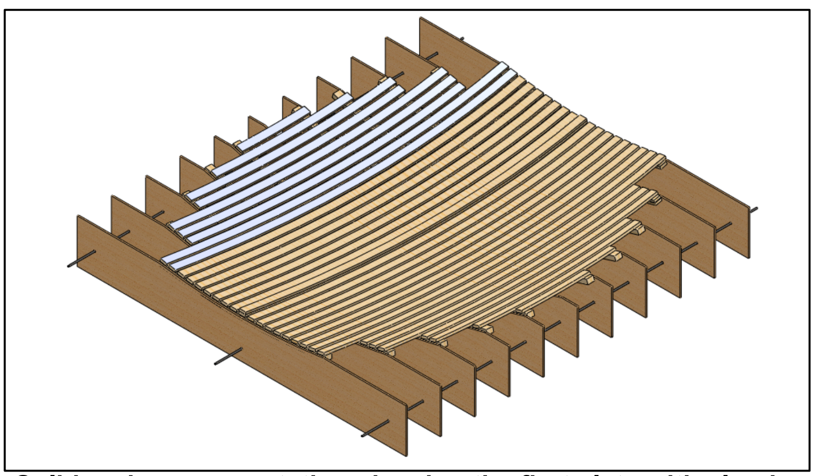


**Figure 15 - A Solidworks representation showing the first slats with aluminum duct tape.**

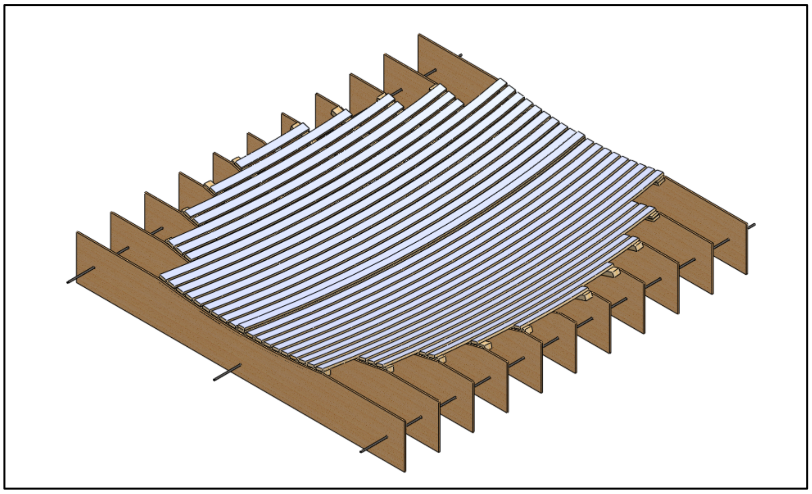


**Figure 16 - Solidworks representation showing the completed dish in the mold.**

At this point, hooks, steel wire and turnbuckles can be added enable the user to flex the dish. Clearance holes were drilled at each end of the dish, through the dish surface and backing ribs. Hooks were inserted and held in place with hex nuts. Washers should be used in order to distribute the load and avoid damaging the wood. Steel wire and crimping loop sleeves were used to connect the hooks to each other along the back of the dish. The dish could then be “opened up” for winter adjustments by twisting the hooks and tightening the steel wire, similar to tuning a guitar. To add summer adjustment capability, reverse the orientation of the hooks and add turnbuckles located in the center of the dish. The turnbuckles can be tightened to flex the dish. The dish should now be fully functional. A full description of the assembly is outlined with pictures in Appendix G, and fully dimensioned drawings are given in Appendix H.

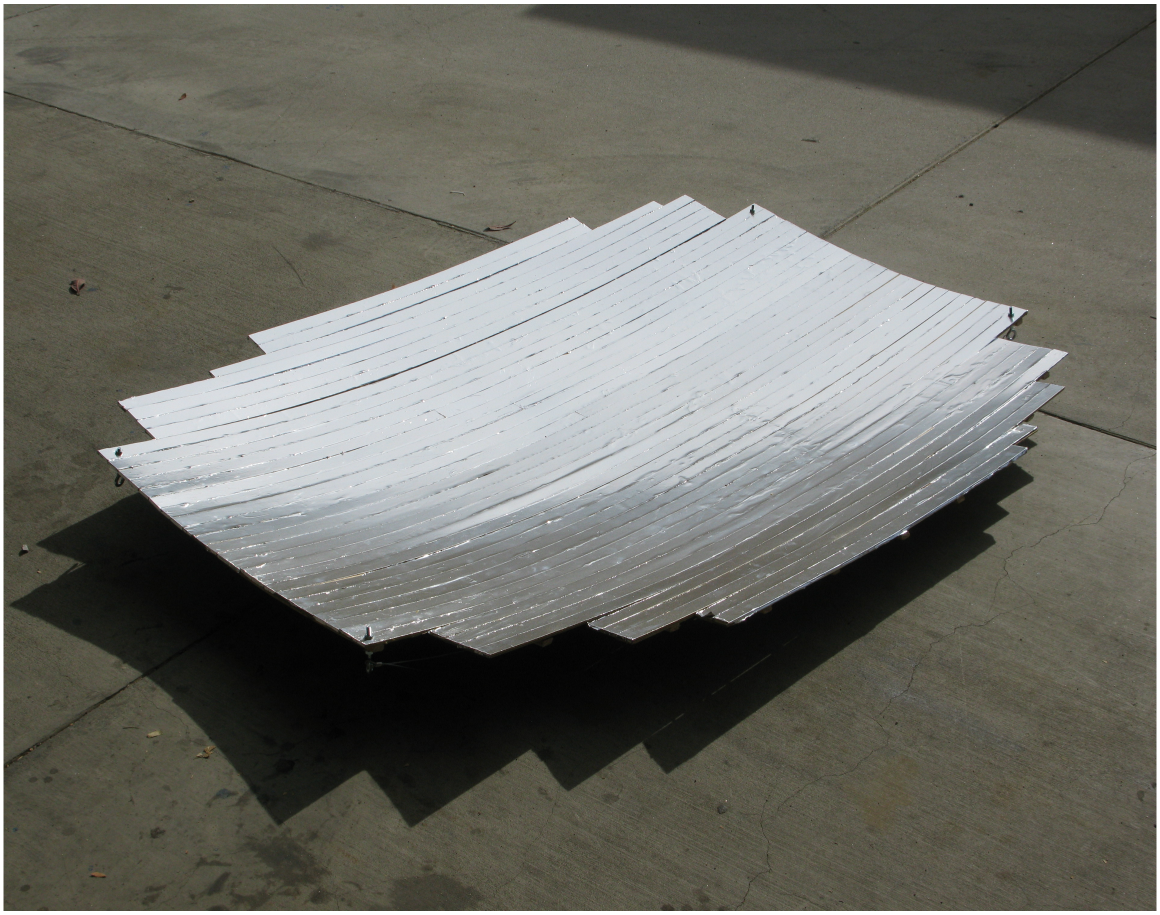


**Figure 17 - The Low-Cost Scheffler solar concentrating dish.**

## 12. DESIGN VERIFICATION AND TESTING

A simple boiling test was performed in order to verify the success of the final design. The test was performed at solar noon avoiding the need for an accurate stand/tracking system for dish. The team attempted to boil .5 liters of water in a small black kettle. The goal was a boiling time of ten minutes. The temperature of the water was initially measured to be 65 F. The black kettle was hung from a hook at the focal point of the dish. After ten minutes, the temperature of the water was measured to be 155 F. The temperature of the surface of the kettle at the focal point was measured to be 350 F. However, the focal point was located on the side of the kettle. Creating a proper stand, which would direct the light to the bottom of the kettle, would most likely decrease the boiling time.

The team created an EES program in order to calculate the concentration factor of the dish based on the test results. The optical efficiency and concentration ratio of the team's dish were calculated to be 10.1% and 4.816, respectively. These values were calculated using the initial and final temperature of the 0.5 liters of water based on the ten-minute test.

The team also calculated the theoretical minumum optical efficiency and concentration ratio necessary to raise the temperature of 0.5 liters of water from 65 F to 212 F in ten minutes. The theoretical minimum values are 11.8% optical efficiency and a concentration ratio of 5.614. This EES code can be used to compare past and future iterations of the Scheffler dish built at Cal Poly. The formatted equations and solutions from the EES code can be found in Sections I and J of the appendix.

The stated goals of the senior project (outlined in section 5.1) were revisited upon completion of testing.

The final cost of the dish was $141.38. The goal of building the dish for $100 or less was not met, but the senior project team has provided suggestions for manufacturing that will drive the cost of the dish below $100. A list of these suggestions is provided in Section 13.

The dish can easily be manufactured on site, assuming the persons building the dish have access to some common and inexpensive tools, and have an avenue to acquire some pre-manufactured hardware, such as nuts and bolts. Specific tools and materials are discussed in the manufacturing plan (Section 11) and listed in Section F of the appendix.

Having 90% of the focused sunlight directed into a 225cm2 area is largely dependant on how carefully the entire assembly process is carried out. Small imperfections in the mold or the surface slats can quickly lead to an increase in focal area. The dish that the senior project team made had 90% of the focused sunlight directed into an area approximately 400cm2. This focal area was largely the effect of surface imperfections caused by excess wood glue, which seeped onto the reflective surface of the dish. The shape of the focal area led the group to believe that the sides of the dish must be flexed inwards, towards each other, further in order to tighten the focal area. Turnbuckles were added and the sides were flexed, which produced a slightly tighter focal area. The dish should be mounted to a proper tracking stand for future tests.

Seasonal adjustments can be made by tensioning or de-tensioning the steel cables across the surface of the dish. Due to the short time frame of the senior project, long-term performance of the dish is unknown. The durability and performance of the dish throughout the seasons will largely depend on the care taken during the assembly process, as well as maintenance performed on the completed dish. Further tests should be performed throughout the different seasons in order to calculate an average concentration factor for the year. Further suggestions for lengthening the life of the dish are given in Section 13.

## 13. CONCLUSIONS AND RECOMMENDATIONS

Throughout the construction of the dish, the senior project team envisioned alternative methods of construction, as well as alternative materials that would have brought down cost, eased construction, or added to the overall quality of the dish. The senior project team is sure that many alternatives exist, depending on tools and materials available, time available, and desired level of functionality desired. Following is a list of recommendations and suggestions, as well as the potential for cost reduction for future manufacturers:

- Use more (or less) cross-sectional approximations of the paraboloid when constructing the mold. More cross-sections would increase the accuracy of the final dish. If more cross-sections are used, the senior project team suggests cutting them from thinner plywood. If less are used, use thicker plywood.

- Thread-rod is not mandatory for spacing the cross-sections. Future manufacturers could use pieces of wood as spacers, or pipe, or really anything that is readily available. Thread rod gives the manufacturers the ability to fine-tune the spacing of the cross-sections. Rigidity between members is important and should be considered.

- The cross-sectional approximations do not need to be made out of plywood. Anything that is relatively rigid, durable, and easy to cut precisely could be used. Plexiglass, sheet metal, or wood are all options.

- If a jig-saw is not available, all of the cutting could be done carefully with a thin handsaw.

- The mold could be constructed as negative, or positive mold. The main advantage of a negative mold is that the manufacturers can continue to use the mold as support while working on the surface of the dish, whereas the positive mold would require the manufacturers to remove the dish from the supporting mold to work on the surface. The main advantage of the positive mold is a more accurate dish surface (the thickness of the wood laminate is not accounted for and affects the accuracy when using the negative mold).

- If the manufacturer posses the time, the senior project team suggests cutting the surface slats, as well as the supporting ribs out of plywood. A tablesaw with a good, square fence will make this step much easier. To save time, one could buy pre-fabricated lattice slats for the surface and support ribs. The latter option is considerably more expensive.

- The surface slats and the supporting ribs could also be made from something other than plywood. The manufacturer will want to use a material that is both flexible and stiff. Certain types of plastic or metal are viable options. Conduit piping could be used for the supporting ribs.

- The surface slat composites could be adhered with something other than wood glue. Using screws is a possibility, but depending on the material used for the slats, could introduce undesirable stress concentrations and inconsistent flexing.

- The reflective tape could be replaced with pieces of mirror, polished pieces of metal, or aluminum coated mylar. Manufacturers may be tempted to use a reflective paint, but the senior project team would strongly caution against this option, as paint will have many small surface imperfections that will decrease the efficiency of the dish.

- The flexing of the dish throughout the seasons could be accomplished by integrating pulleys and cables to a mounting stand, or extendable rods also mounted to a stand. The senior project dish flexes without the support of a stand, but has the disadvantage of partially shading the surface of the dish with the turnbuckles.

- The senior project team suggests that any persons who build a Scheffler dish for long-term use keep the surface clean, which can be accomplished with a damp rag. Weatherproofing of the wood, lubrication of the metal parts, and occasional maintenance will add to the longevity of the dish.

- Construction of more than one Scheffler dish at a time would reduce costs, as there is less waste material, and specialized tasks could be split up between several small teams. The cost of the mold becomes insignificant with the production of many Scheffler dishes. Detailed cost information can be found in Section F of the appendix.

## 14. REFERENCES


1 Alberti, Simo. *Evaluation of a Scheffler Solar Concentrator*. California Polytechnic State University, n.d.

2 Duffie, John A., and William A. Beckman. *Solar Engineering of Thermal Processes*. New York U.a.: Wiley & Sons, 2012. Print.

3 Elghandour, Eltahry, Dr. "Research into Locally-Sourced Natural Composites." Personal interview. 25 Feb. 2013.

4 Gelman, Rachel. "2011 Renewable Energy Data Book." *Energy Efficiency and Renewable Energy*. National Renewable Energy Laboratory, n.d. Web.

5 Madrigal, Alexis. "MIT Students Create $17 Solar Cooker." *Wired.com*. Conde Nast Digital, 23 July 2008. Web. 07 Feb. 2013.

6 "MIT Energy Initiative." *MIT Students Create Low-cost Solar Cooker/heater*. Massachusetts Institute of Technology, n.d. Web. 15 Mar. 2013

7 Munir, A., O. Hensel, and W. Scheffler. "Design Principle and Calculations of a Scheffler Fixed Focus Concentrator for Medium Temperature Applications." *Solar Energy* 84 (2010): n. pag. Web.

8 "Parabolic Solar Cooker: Cantinawest's "Solar Burner"" *Parabolic Solar Cooker: Cantinawest's "Solar Burner"* N.p., n.d. Web. 15 Mar. 2013.

9 "Putting It Together - The Science and Technology of Composite Materials." *Science in the News*. NOVA, n.d. Web. 15 Mar. 2013.

10 Rapp, Jason. *Construction and Improvement of a Scheffler Reflector and Thermal Storage Device*. *Digitalcommons.calpoly.edu*. Dr. Peter Schwartz, Nov. 2010. Web.

11 Rehfuess, Eva. *Fuel for Life: Household Energy and Health*. Rep. N.p.: World Health Organization, 2006. Print.\

12 Saxena, Mohini, Asokan Pappu, Anusha Sharma, Rahi Haque, and Sonal Wankhede.*Composite Materials from Natural Resources: Recent Trends and Future Potentials*. Tech. CSIR- Advanced Materials and Processes Research Institute, Council of Scientific & Industrial Research, n.d. Web.

13 Scheffler, Solare Brücke, http://www.solare-bruecke.org/index.htm

14 *Wooden Boat Layout*. N.d. Photograph. *Wooden Boat Builds*. Classic Boat Magazine. Web.

15 Duffie, John A., and William A. Beckman. *Solar Engineering of Thermal Processes*. Hoboken, NJ: Wiley, 2006. Print.

## 15. APPENDICES

### A. ORIGINAL CAL POLY SCHEFFLER COLLECTOR

**Figure 18 - The original Cal Poly Scheffler collector.**

## B. SIMO ALBERTI'S ANALYSIS

The senior project team has access to a Matlab program created by Simo Alberti. The Matlab program is extremely versatile and will allow the team to better understand theoretical models of the Scheffler concentrator, as well as analyze models of actual prototypes and final products.

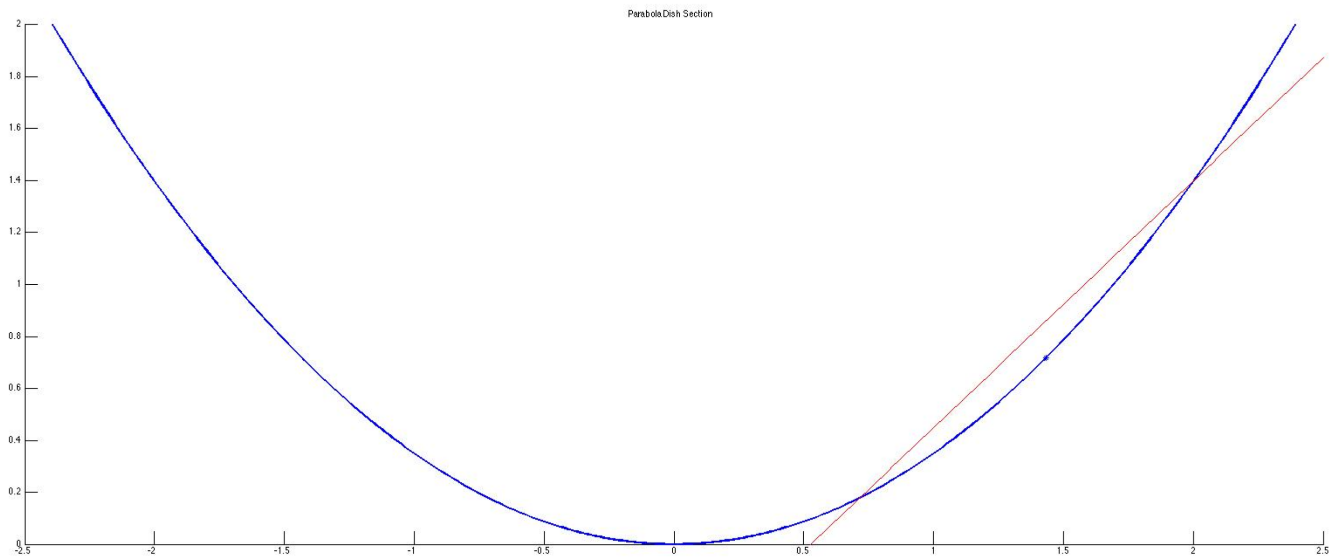



**Figure 19 - Section of Paraboloid that is used for a Scheffler Concentrator**

The surface of the Scheffler dish is based off the side of a three dimensional paraboloid. A cross section of a paraboloid, which has a focal point of x=0, and y=1 (dimensionless) is shown in Figure 19 above. The red line represents the section of the paraboloid that is used for a Scheffler concentrator. Using the side of the parabola allows for easier tracking.

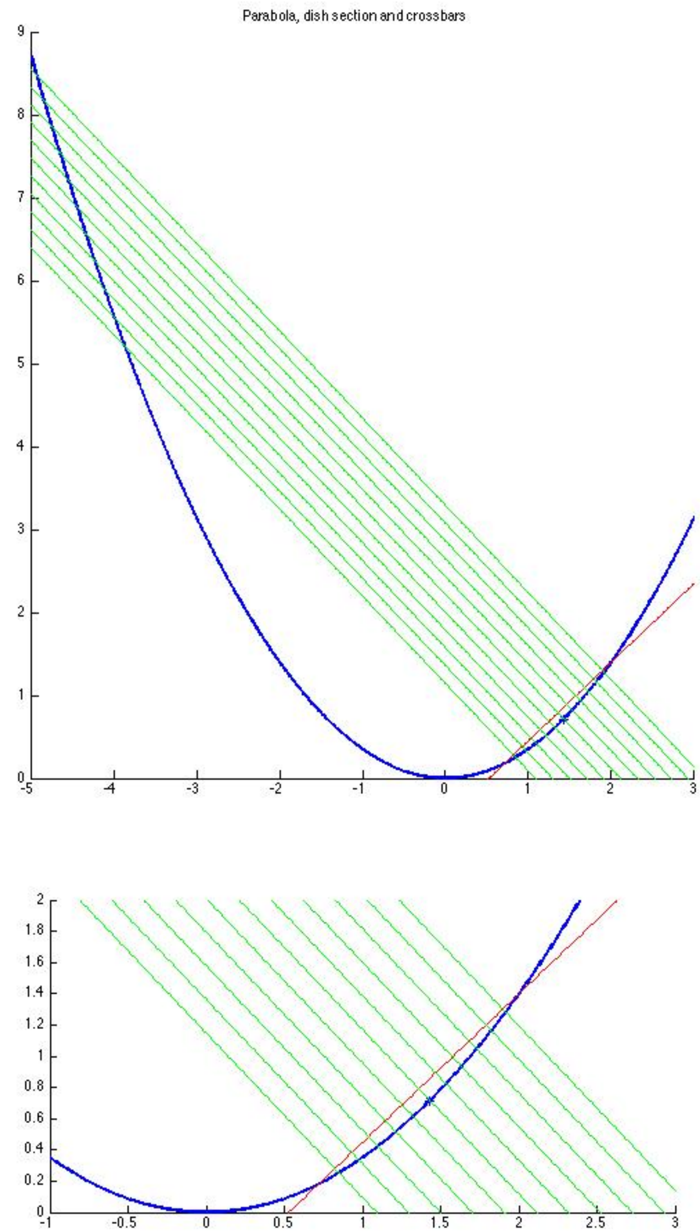



**Figure 20 - Crossbars as they are distributed on the Scheffler Concentrator**

In Figure 20, the supporting crossbars underneath of the Scheffler concentrator are shown as being projected to the other side of the parabola. Where the projection meets the other side will give the curvature of each crossbar.

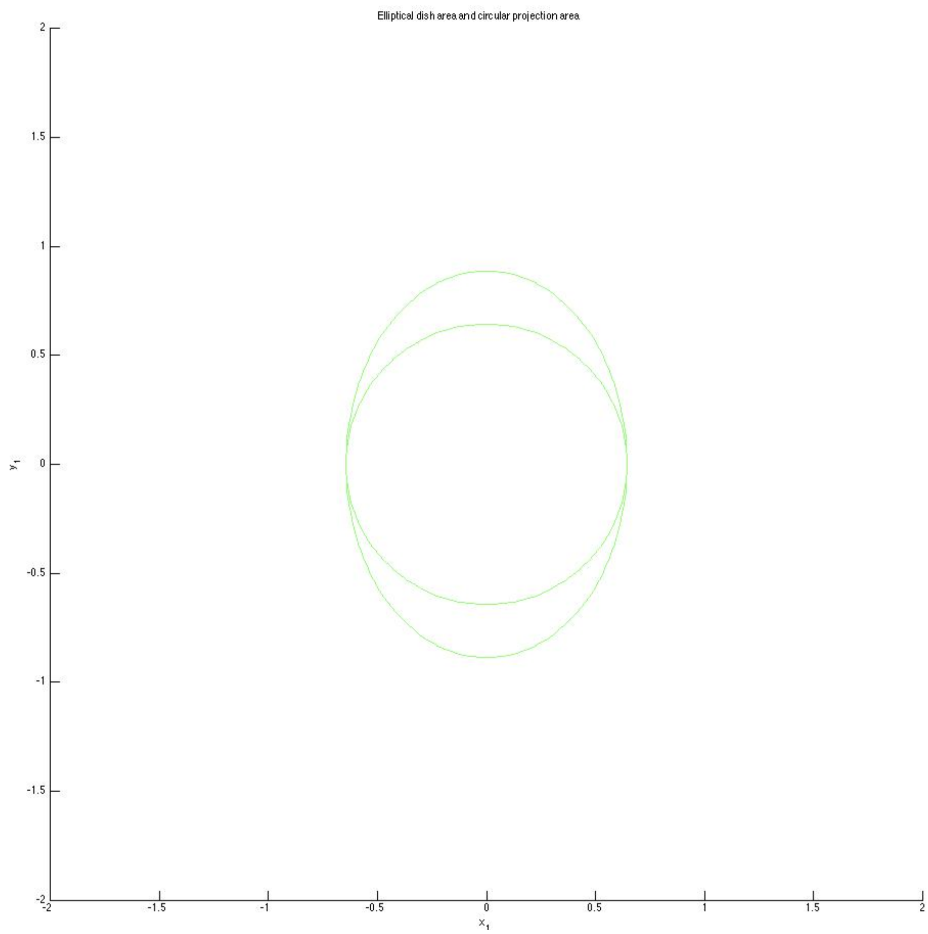



**Figure 21 - Elliptical area of dish, and projection area (aperture area) that the sun "sees"**

The aperture area that the sun sees is a circle, with a diameter equal to the minor diameter of the elliptical Scheffler dish. This is due to how the Scheffler dish is oriented during operation.

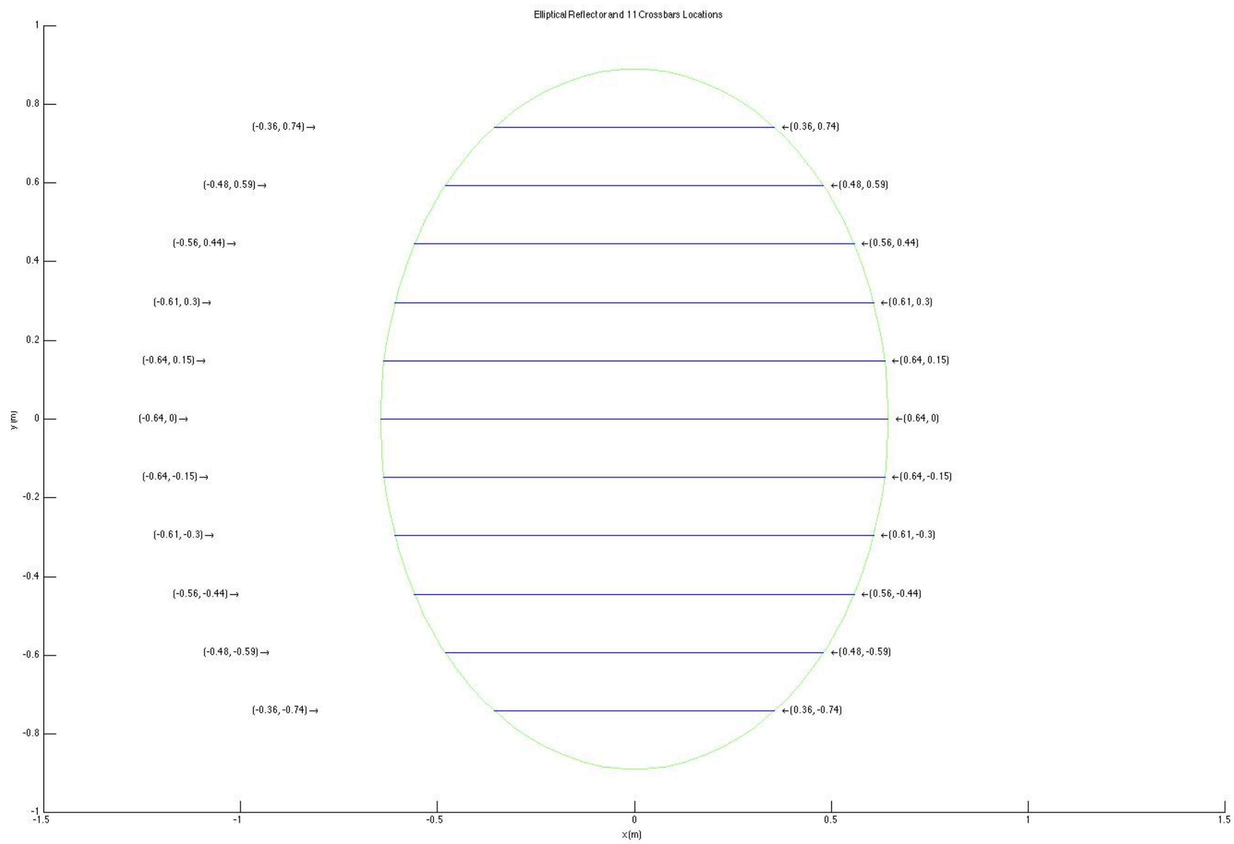



**Figure 22 - Location of crossbars**

Based off of the desired focal point location, one can find the equation of the ellipse that is formed by taking a section of the paraboloid. Based off of the size of this paraboloid, the lengths of the crossbars can be easily determined.

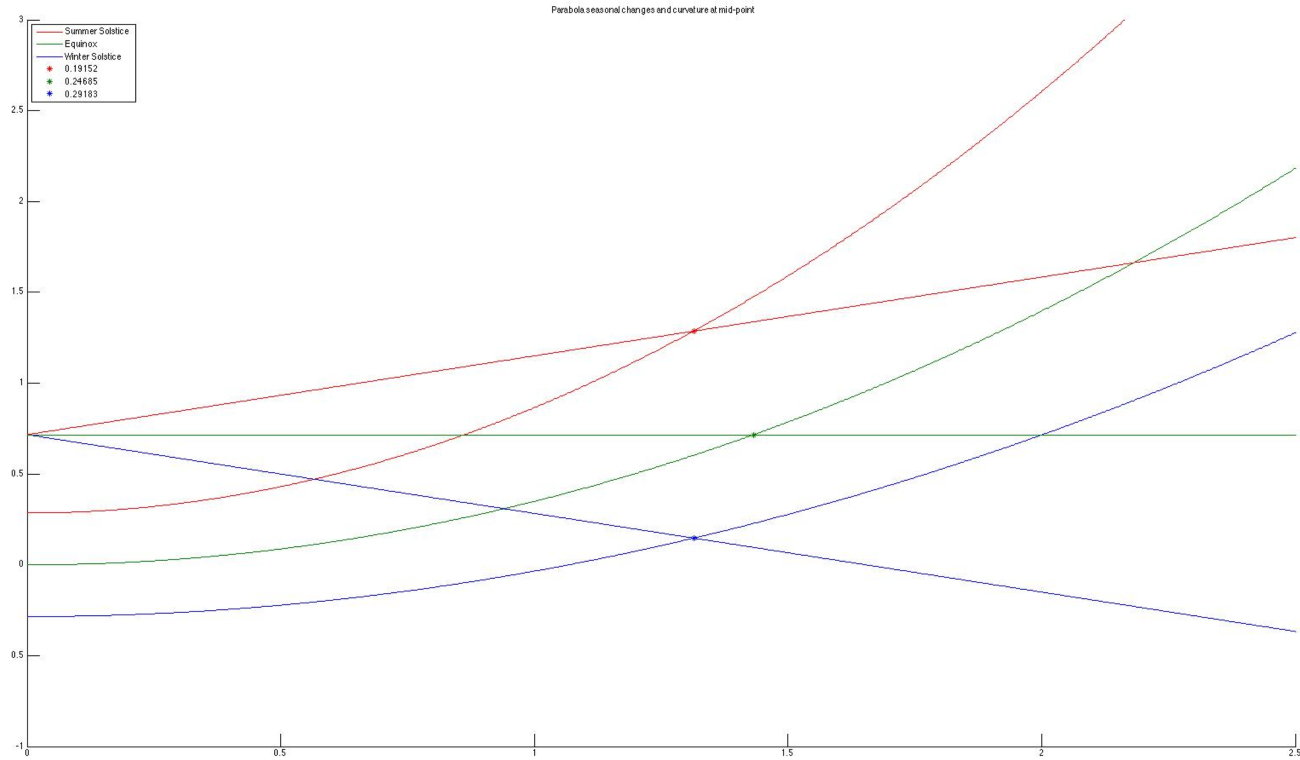



**Figure 23 - Seasonal changes of parabola cross-sections and midpoint**

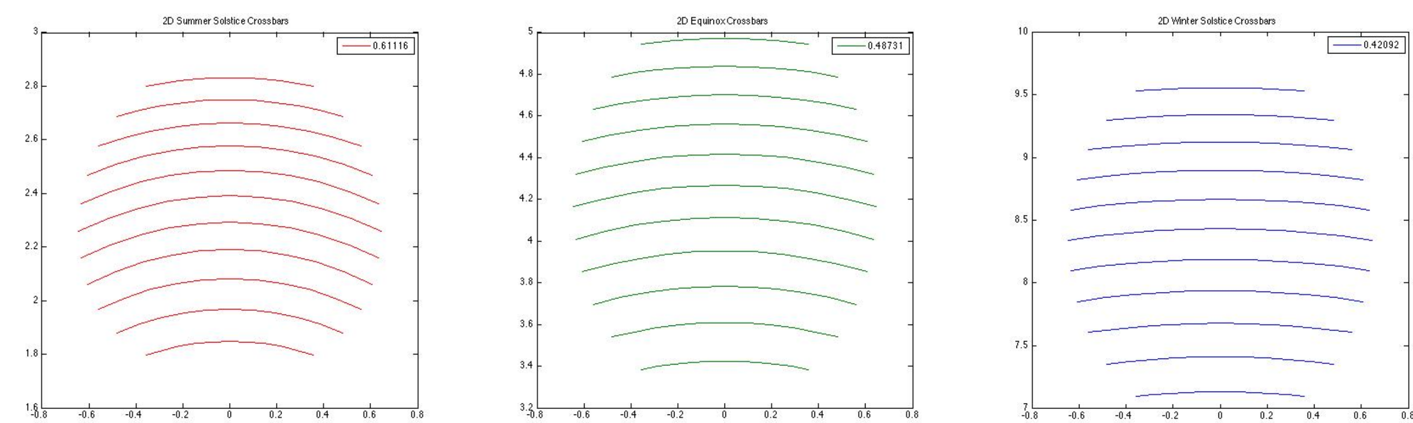



**Figure 24 - Curvature of crossbars for different seasons**

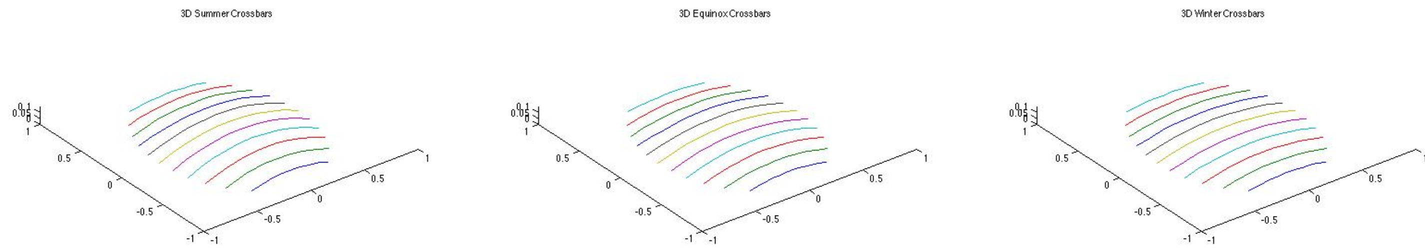



**Figure 25 - Three-dimensional crossbars for different seasons**

The crossbars that are supporting the underside of the Scheffler concentrator must approximate the steeper or shallower parabolas required for each season. The varying degree of steepness and crossbar depth is shown in Figure 23, Figure 24, and Figure 25.

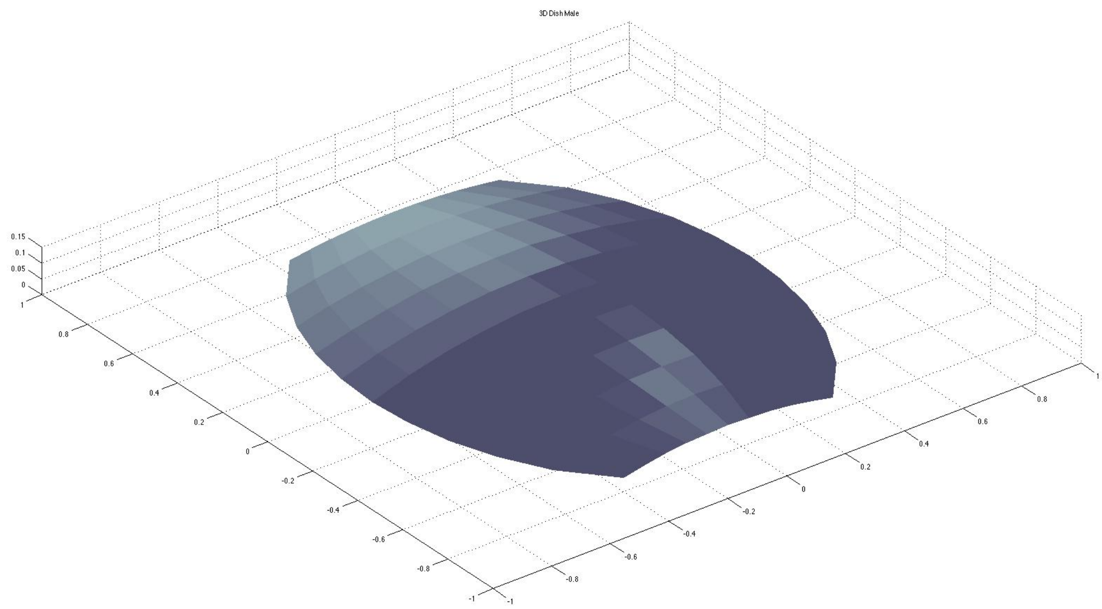


**Figure 26 - Three Dimensional representation of concentrator surface**

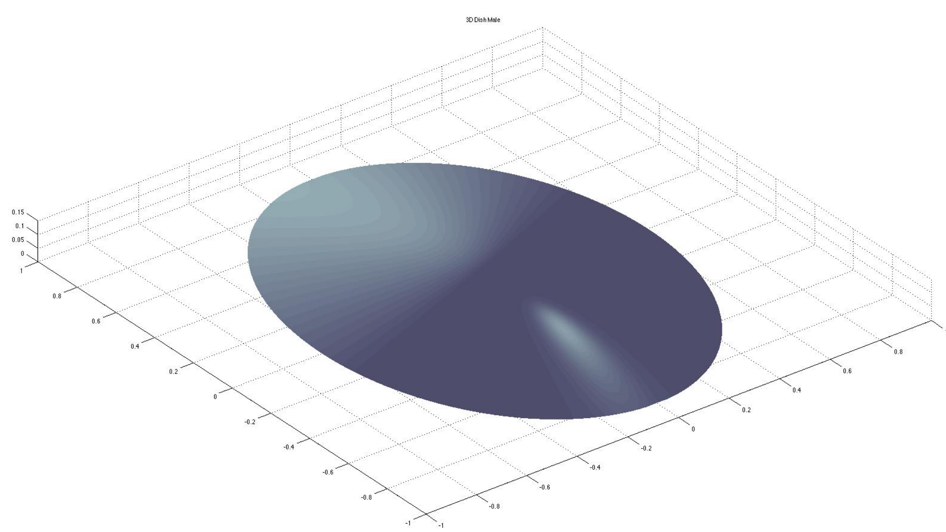


**Figure 27 - Three-dimensional representation of a higher resolution concentrator surface**

By modeling the desired number of crossbars, one can see the varying degree of surface perfection. Figure 26 shows a surface that has been approximated with 11 flat sections. Figure 27 shows a surface that has been approximated with 1001 flat sections. A higher degree of resolution on the surface of the Scheffler dish would provide a smaller, more intense focal point.

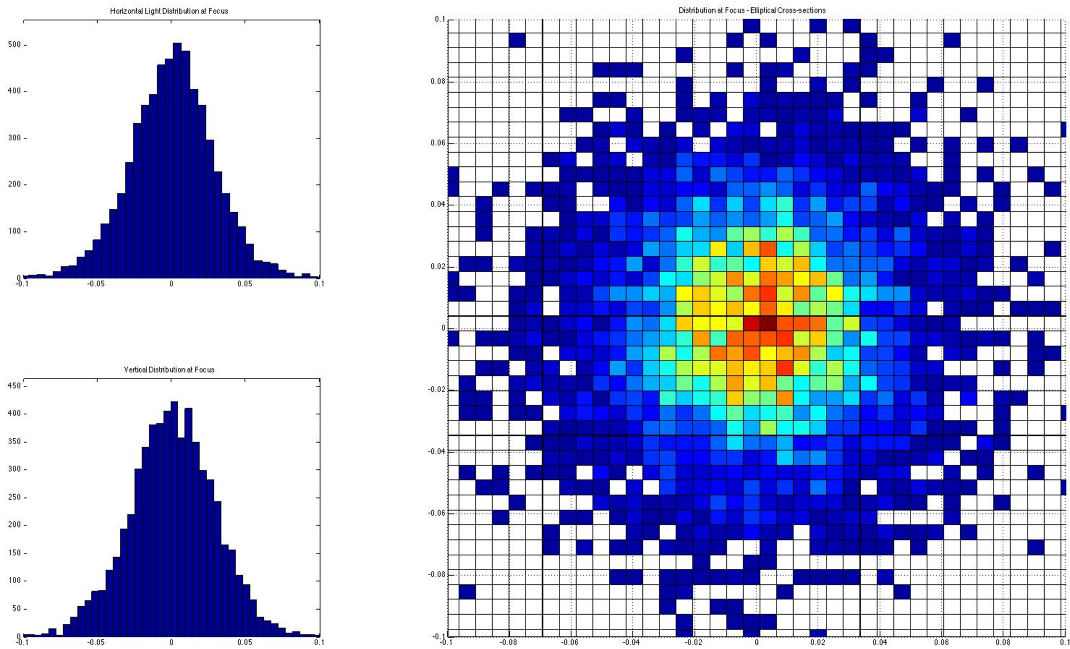



**Figure 28 - Irradiation intensity vs. distance from focal point. Error modeled as 1% with a Gaussian distribution.**

The Matlab program that we were provided with allows us to model different levels of error on the surface of the Scheffler concentrator and analyze the theoretical amount of power at and around the focal point. For practical purposes, we want most (80% or more) of the focused radiation to be within a 15x15cm area around the location of the focal point.

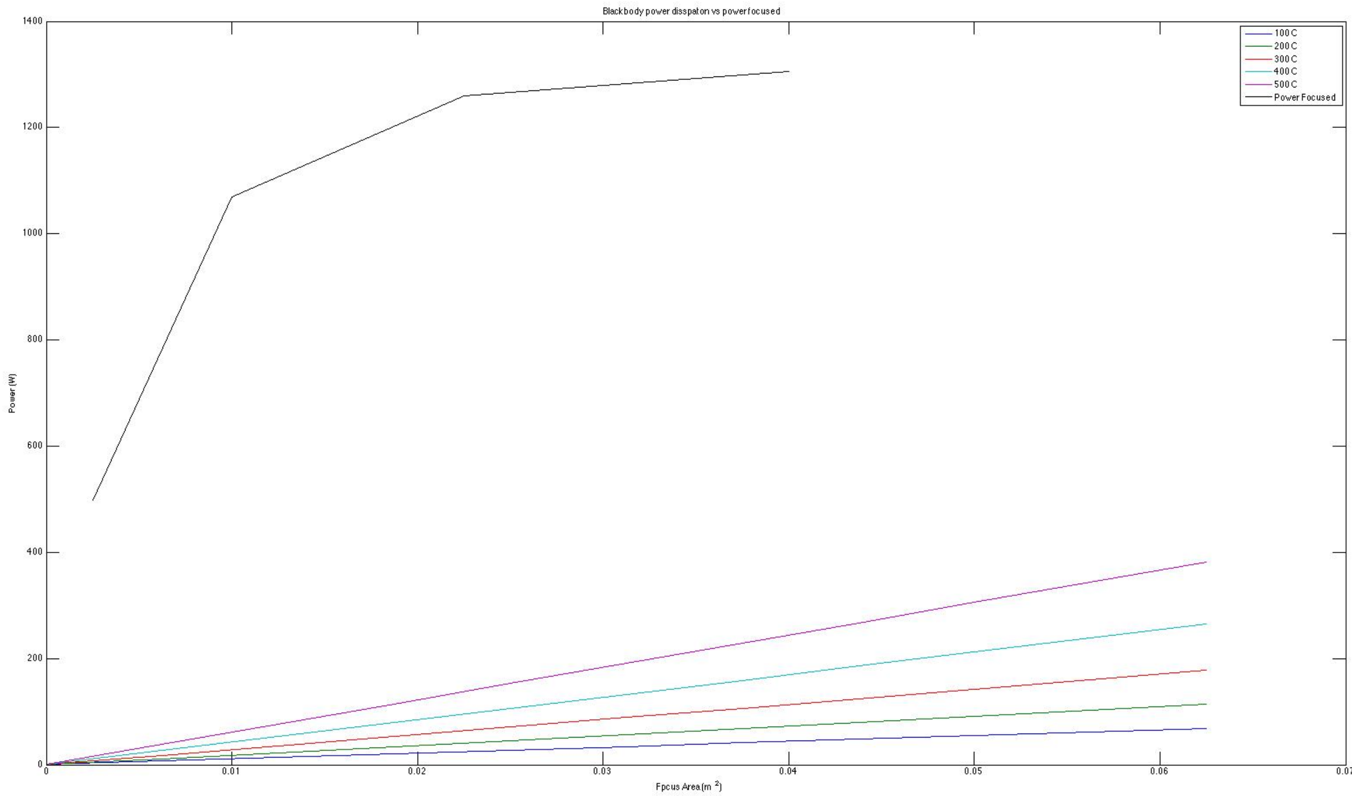



**Figure 29 - Power focused vs. Incoming power, modeled for different operating temperatures.**

As the surface of the concentrator heats up, there are more losses due to the concentrator radiating heat to the atmosphere. Figure 29 shows incoming power from the sun, as well as the amount of outgoing radiation for different surface temperatures. The difference between the top curve and the lower straight curves represents the concentration ratio. The theoretical maximum concentration ratio for a Scheffler concentrator is approximately 45,000, which is far higher than what is required to cook.

## C. IDEATION/BRAINSTORMING

Concept development began with a series of brainstorming and ideation sessions. This collaboration produced a large number of concept ideas on all levels of the project design. The following two figures show the result of the leading ideas produced by ideation, redlined on a pass/fail basis. This assessment was a preliminary step to choose a reasonable number of ideas to evaluate with a weighted decision matrix.

Ideation/Brainstorming

System Concepts:

- ~~Basket Weave out of local plants~~
- ~~Use the rib cage and hide of deceased local animals~~
- Make different approximations of Scheffler for different seasons (that do not flex) out of:
    - Cob, Adobe, or Mud Brick
    - Cardboard
    - Inflatable
- Use similar design to current Scheffler but use ______ for the ribs:
    - "natural" composites
    - Wood
    - PVC Pipe
    - Bamboo
    - Kenaf
    - Fiberglass coated cardboard composite
    - Aluminum Poles
    - Bone/Ribs
- ~~Weave old bike tubes around ribs to form dish.~~
- Segmented "puzzle" concept
    - Attached or hinged pieces create a polygonal approximation of elliptical Scheffler shape.
- Tent Design
    - Stretch canvas around outer rim and use hooks and string at different lengths and locations to approximate scheffler shape
    - Use poles as "ribs" and run them through slots in canvas or tent-like material to approximate the shape of the dish.
- ~~Umbrella Design~~
    - Similar to tent but source off taut surface is central
    - Dish folds together for easy storage
- Sheet Metal
    - Bend/Hammer one large piece of sheet metal into the shape of the Scheffler and check against mold.
    - Bend smaller pieces of sheet metal and attach them to form the shape of the dish.
- Cardboard/Paper Folding
    - Similar to "fancy" paper airplane kits. In the immortal words of Jason Morgan: "Cut, Fold, Duct Tape. Scheffler."
- ~~Pin Impression Board~~
- Pipe (Heliostat Array)

**Figure 30 - Redlined ideation for design concepts**

Structural Materials:

- Cob, adobe, mud brick
- ~~Brick~~
- Cardboard
- Concrete
- Aluminum
- "Natural" Composites
- Bamboo
- Sheet Metal
- Conduit
- PVC/ABS
- Wood
- Chicken Wire
- Steel Tubing
- Canvas
- Kenaf
- Fiberglass-Coated Cardboard Composite
- Aluminum Poles
- ~~Bike Tubes~~
- ~~Cow Ribs~~
- ~~Bone~~
- ~~Sand~~

Reflective Material:

- Highly-Polished Aluminum Strips
- Sheet Metal
- Aluminum –Coated Mylar
- Space Blankets
- Aluminum Foil
- Mirror
- Mirror Pieces
- Glass
- Broken Glass
- Aluminum Cans
- Potato Chip Bags
- ~~White Paper~~
- White Paint
- Corrugated Steel

- Reflective Paint
- ~~Water~~
- ~~Sunscreen~~
- CDs
- ~~Reflective Coating on Road Signs~~

**Figure 31 - Redlined ideation of design concepts**

## D. DECISION MATRICES

In order to arrive at a couple top concept ideas, a series of decision matrices were used for the structural materials, reflective materials, and overall concepts. For material selections, cost, availability, and safety were large consideration factors. The two materials decision matrices are shown in Table 2 and Table 3. The top resulting structural materials were canvas, chicken wire, and PVC. The top resulting reflective surfaces were space blankets, aluminum mylar, and reflective paint. All of these selections ranked high for being low-cost and easy to use, which agrees with our project design philosophy.

After deciding on a couple of top materials, we created a decision matrix for conceptual designs (Table 1). The concepts were appropriately sourced from our leading material selections, and again chosen with emphasis on cost, availability, and safety. The lead designs chosen are briefly described here:

**Tent Design – 97 points**
The Scheffler tent design works to embody a simplified structure, which is hopefully as easy to assemble as a basic tent. It would consist of a fabric material stretched taut in the shape of a Scheffler-defined, elliptical section of a paraboloid. The fabric would be coated with a reflective material. The entire structure may be designed for rapid set up and break down, and also for small storage volume.

**Cob/Concrete Approximation – 83.75 points**
The approximation design was envisioned as a way to reduce the complication of having a flexible reflective surface. A low-cost method of developing a series of reflective surfaces would be created to approximate the correct Scheffler shapes for various parts of the year. Cob or concrete are readily available in all parts of the world, are easy to work with, and are extremely low cost. With a well-designed molding method, it would not be necessary to use a reflective surface that is designed to deflect in order to capture changes in solar declination angle. A MATLAB simulation will be used to analyze how many surfaces would be necessary based on the geometric inaccuracy.

**Cardboard/Paper Folding**
To avoid using costly structural materials, a concept using notched and adjoined sheets was developed. A coated cardboard or paper structure could be arranged that would create a Scheffler dish shape. A reflective material would be placed onto the approximated surface to complete the device.

**Sheet Metal**
During a crude prototyping work session, it was found that simple sheet metal can be formed with curves in two separate planes. The sample curve that was developed focused sunlight surprising well after only 45 minutes of work. If a large enough sheet can be formed into the

proper dish shape, the resulting device would be very cheap, easy to construct, and would not require the same level of structural support.

**Table 1 - Decision matrix for top concept designs**

| | Weight | Cob/Concrete Approx. | Segmented "Puzzle" | Tent Design | Sheet Metal | Cardboard/Paper Folding | Pipe Array (Heliostat) | Standard |
|---|---|---|---|---|---|---|---|---|
| Cost | 10 | 5 | 2 | 3.75 | 2.5 | 5 | 2 | 0 |
| Availability of Materials | 8 | 5 | 2 | 4.5 | 3.5 | 3 | 1 | 0 |
| Ease of Manufacturing/Assembly | 4 | 2.5 | 2.5 | 2.75 | 1 | 3 | 2.5 | 0 |
| Ease of Use | 5 | -3 | 0 | 3.5 | 0 | -0.25 | 1.5 | 0 |
| Sustainability of Materials | 2 | 5 | 3 | 5 | 1 | 3 | 0 | 0 |
| Durability | 5 | -2.25 | -3 | -3 | 3 | -3 | -0.5 | 0 |
| Safety | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Score: | 83.75 | 37 | 97 | 74 | 75.75 | 43 | 0 |

**Table 2 - Decision matrix for reflective surface material selection**

| | Weight | Sheet Metal | Al Mylar | Space Blankets | Al Foil | Mirror | Broken Glass | Recycled Al | Reflective Paint | CDs | Standard |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cost | 10 | 1 | 4 | 5 | 3 | -3 | 0 | 1 | 3 | -1 | 0 |
| Availability | 8 | 1 | 0 | 0 | 2 | 0 | 4 | 4 | 0 | 2 | 0 |
| Sustainability | 2 | 1 | -1 | -1 | 1 | -1 | 5 | 5 | -5 | 5 | 0 |
| Durability | 5 | 0 | -2 | -2 | -3 | -4 | 1 | -1 | 0 | -2 | 0 |
| Safety | 8 | 0 | 2 | 2 | 1 | -2 | -3 | 0 | -1 | 0 | 0 |
| Reflectivity | 8 | 0 | 1 | 2 | -2 | 2 | 0 | -1 | 2 | 0 | 0 |
| Ease of Use/Handling | 5 | 0 | 2 | 3 | 1 | -3 | -4 | -1 | 2 | 3 | 0 |
| | Score: | 20 | 62 | 85 | 30 | -67 | 3 | 34 | 38 | 21 | 0 |

**Table 3 - Decision matrix for structural material selection**

| | Weight | Sheet Metal | Cob/Adobe | Cardboard | Concrete | Nat. Composites | Bamboo | Conduit | PVC/ABS | Wood | Chicken Wire | Steel Tubing | Canvas | Cardboard Composite | Standard |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cost | 10 | 2 | 5 | 4 | 5 | -1 | 3 | 2 | 3 | -1 | 4 | -2 | 4 | 3 | 0 |
| Availability | 8 | 2 | 5 | 2 | 5 | 5 | 2 | 1 | 2 | 2 | 4 | 1 | 5 | -1 | 0 |
| Sustainability | 2 | 1 | 5 | 3 | 5 | 1 | 3 | 1 | -1 | 1 | 1 | 1 | 5 | 0 | 0 |
| Durability | 5 | 5 | 2 | -5 | 4 | 3 | 3 | 4 | 4 | 4 | -2 | 5 | -1 | -1 | 0 |
| Safety | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Flexibility | 8 | 1 | -5 | 1 | -4 | 1 | 1 | 2 | 2 | -1 | 5 | -1 | 5 | 1 | 0 |
| Ease of Use/Handling | 5 | 0 | 3 | 5 | -1 | -2 | 0 | 2 | 3 | -4 | -1 | -3 | 5 | -2 | 0 |
| | Score: | 71 | 85 | 70 | 83 | 45 | 75 | 76 | 95 | 0 | 99 | -8 | 150 | 15 | 0 |

## E. GANTT CHART

A Gantt chart was developed in order to efficiently move through the remaining tasks for senior design. In manner cases, absolute dates and tasks were difficult to determine but the group made estimates for all work required to finish the Scheffler solar concentrator. The Gantt chart will be continually updated as tasks and dates change. Also, the group website will reflect the most recent schedule of tasks so that all who are interested will be up-to-date. Below is the current Gantt chart for group 15.

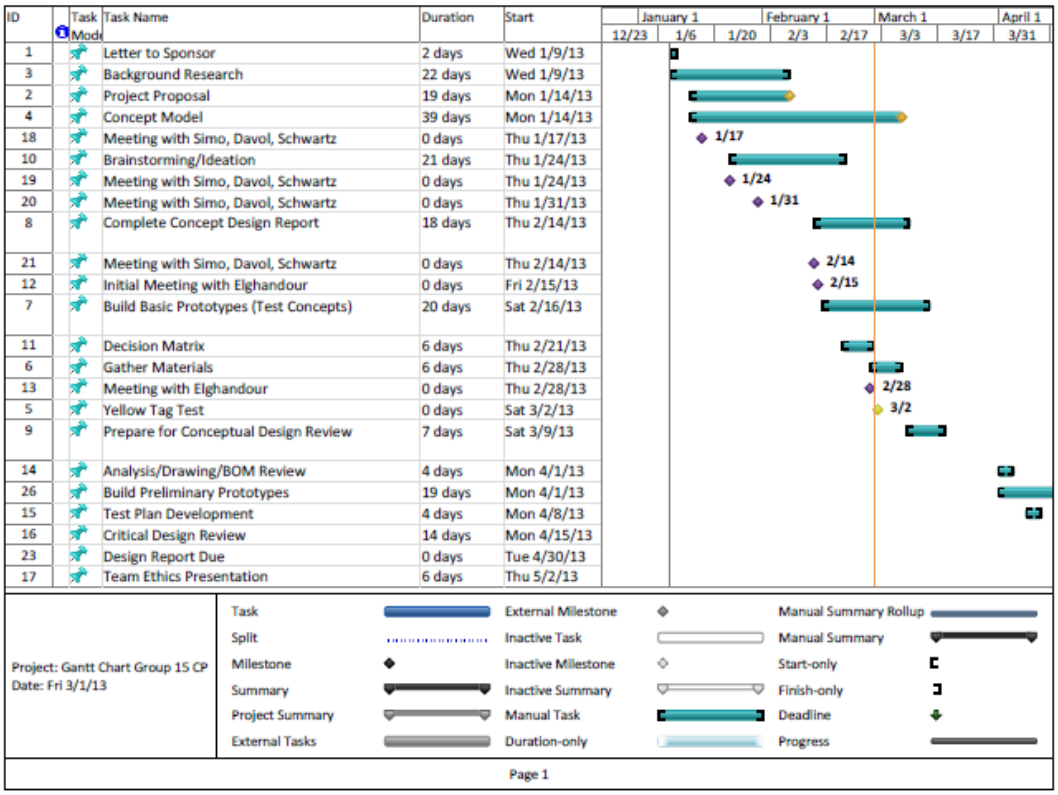



**Figure 32 - Gantt chart of tasks and activities for senior design group 15: Design of a Low-Cost Scheffler Solar Concentrator**

## F. TOOLS AND MATERIALS

**Table 4: Bill of Materials and cost breakdown for mold.**

| Item | Qty. | Unit Cost | Total Cost |
|---|---|---|---|
| 2X6 | 1 | $5.65 | $5.65 |
| 7/16" 4'X8' OSB sheets for mold profiles | 2 | $10.24 | $20.47 |
| Coupler Nuts | 3 | $1.60 | $4.80 |
| Thread Rod - 1 m | 6 | $4.17 | $25.00 |
| Hex Nuts - 100 pc. | 1 | $13.00 | $13.00 |
| **Grand Total** | | | **$68.92** |

**Table 5: Bill of Materials and cost breakdown for final dish.**

| Item | Qty. | Unit Cost | Total Cost |
|---|---|---|---|
| 2.7mm 4'X8' Plywood Sheet for Wood Slats | 2 | $13.67 | $27.33 |
| Wood Glue - 1 Gal. | 1 | $15.97 | $15.97 |
| Wood Lattice - Ribs | 22 | $3.42 | $75.24 |
| Aluminum Tape - 1 Roll. | 2 | $7.88 | $15.76 |
| Steel Wire - 1 ft. | 12 | $0.59 | $7.08 |
| **Grand Total** | | | **$141.38** |

## LIST OF TOOLS USED FOR MANUFACTURING AND ASSEMBLY

Two or three people will make the manufacturing process easy. If more than one dish were being made at a time, a larger group that splits up tasks may be appropriate. All materials and tools listed below were used by the senior project group. Substitutions can be made, at the discretion of the manufacturer, based on local availability:

**For Mold:**
- Pencil
- Table Saw
- Drill Press
- Tape Measure (Metric)
- Straight Edge/Level
- 8 mm drill bit
- Tape Compass OR
- 2X4 (Compass for drawing curves)
- Nail (Compass for drawing curves)
- Hammer
- Jig Saw (Cut curves and cut 10 ft. 2X6 in half)
- Sand paper

**For Dish:**
- Pencil
- Drill
- 3/16” drill bit (holes for hooks for flexing dish)

- Table saw
- Hand saw
- Knife (or box cutter for cutting aluminum tape)
- Sand paper
- Power Sander
- Mask (when sanding)
- Clamp set
- Large amount of sand (~75 lb)
- Paint brush (for spreading wood glue)
- Wire cutters (to cut steel wire for flexing dish)

## G. DETAILED LAYOUT OF FINAL DESIGN

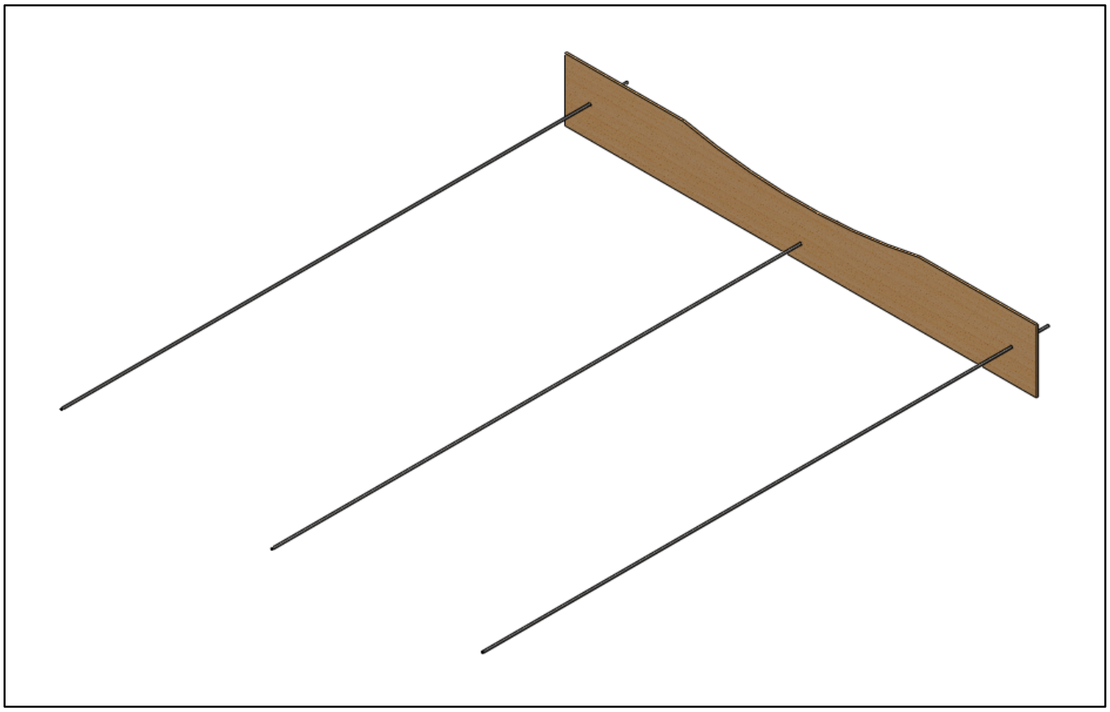


Figure 33 - Step 1 of assembling the mold

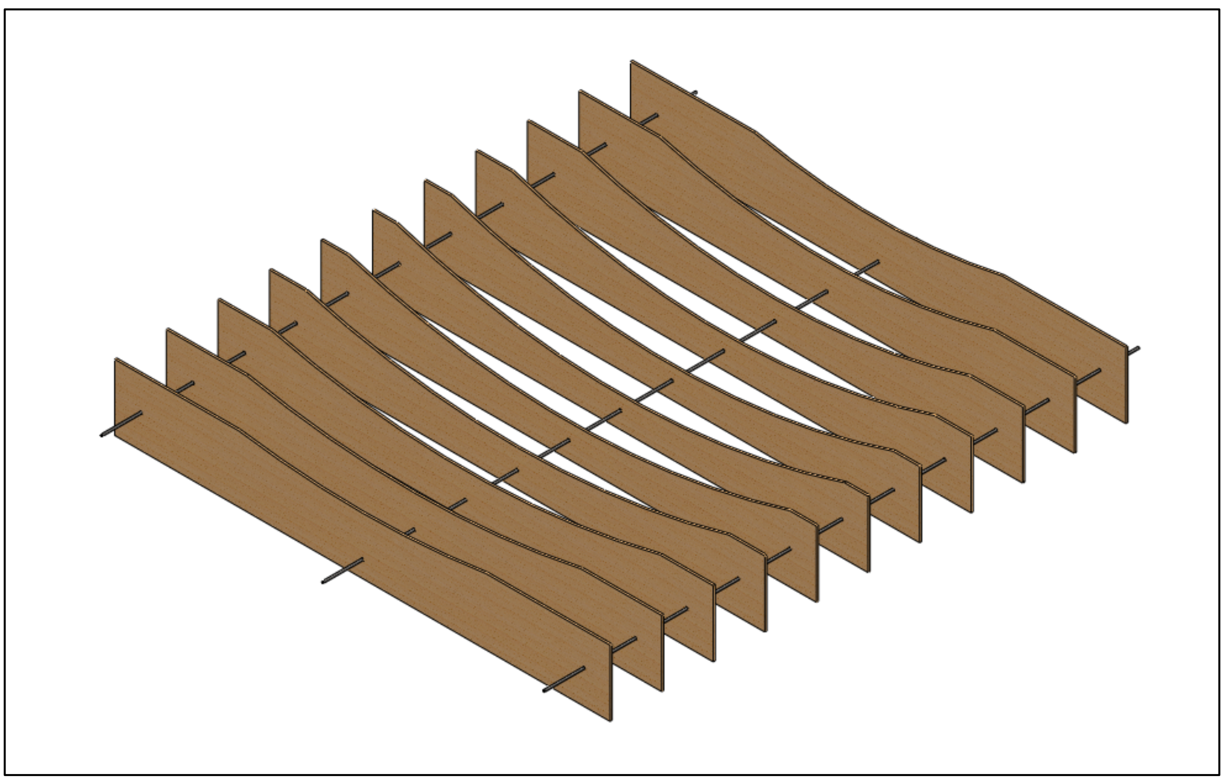


Figure 34 - Completed mold

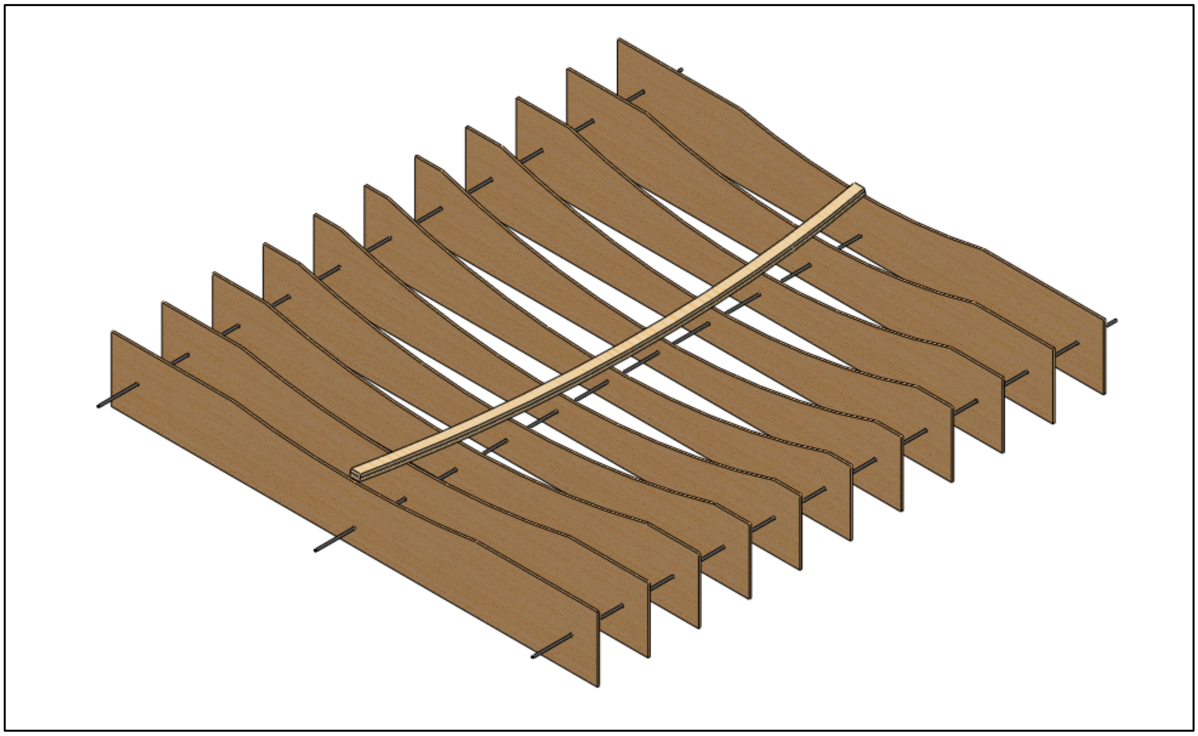


**Figure 35 - Fitting the spine to the mold**

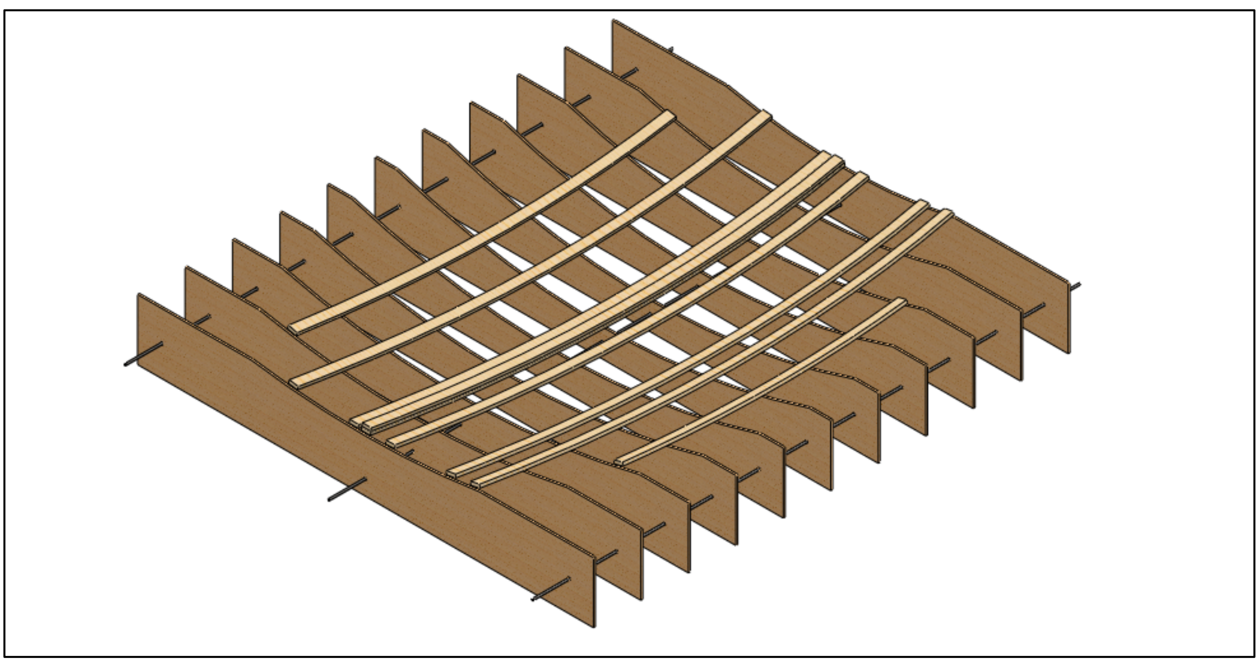


**Figure 36 - Layout of wooden slats onto mold**

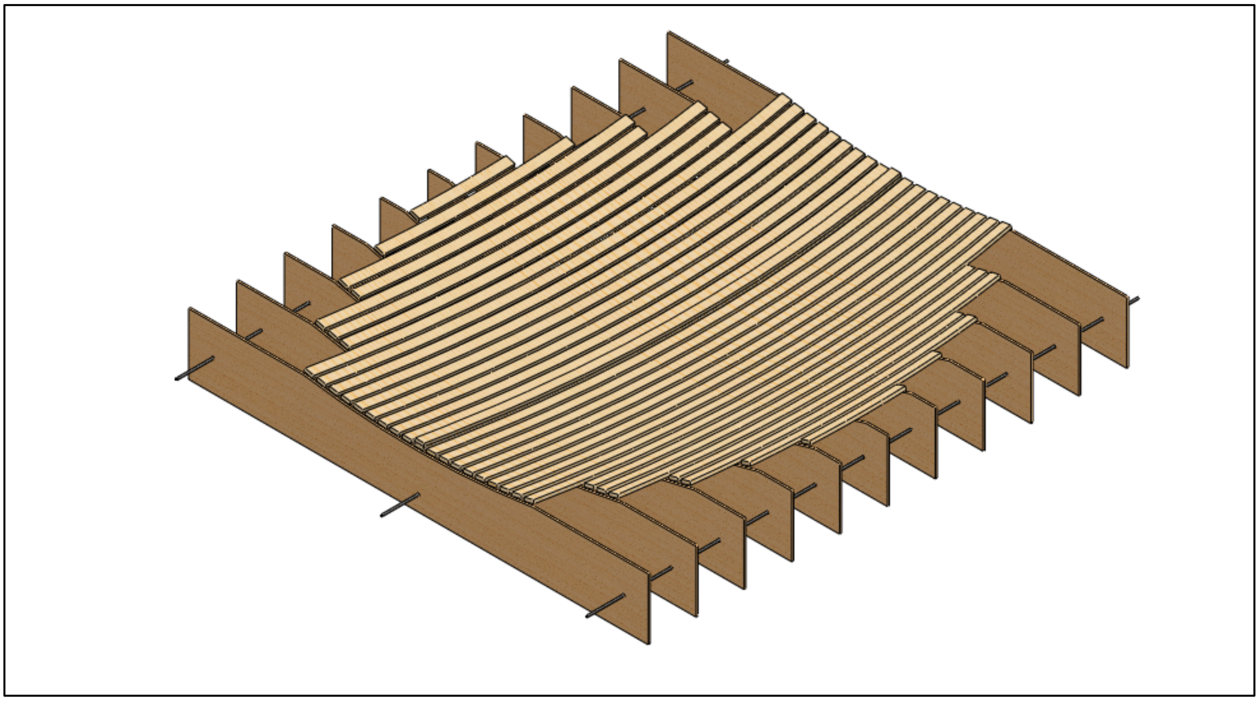


Figure 37 - All wooden slats laid onto mold

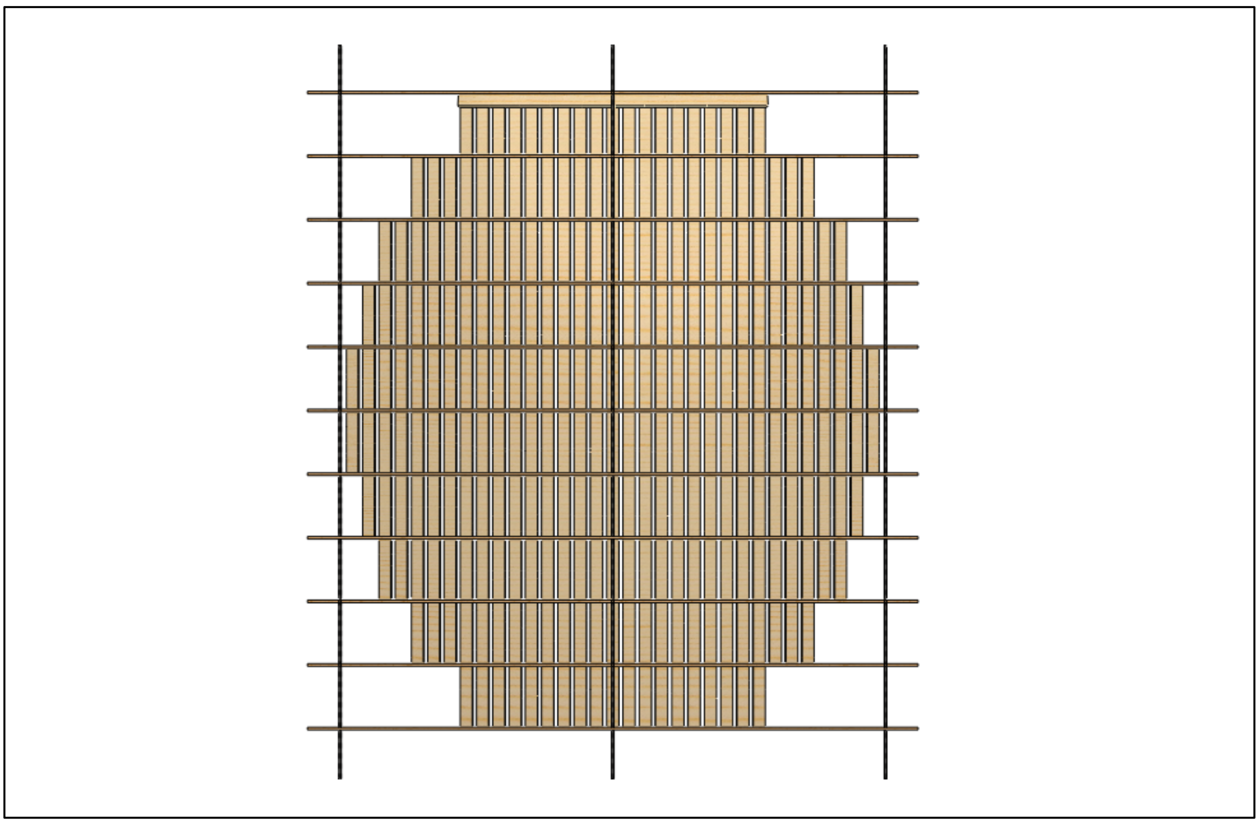


Figure 38 - Backside of the mold with slats laid out, in preparation for laying structural ribs

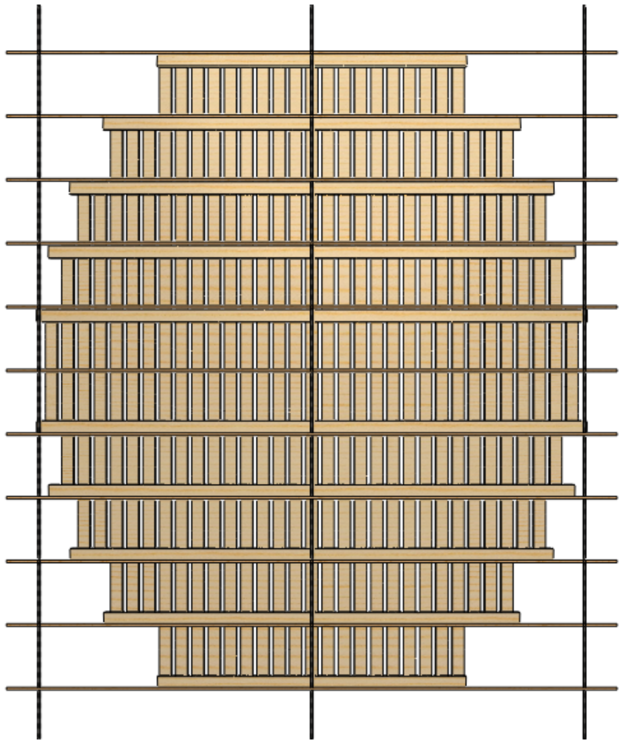


**Figure 39 - Backside of mold, with structural ribs adhered**

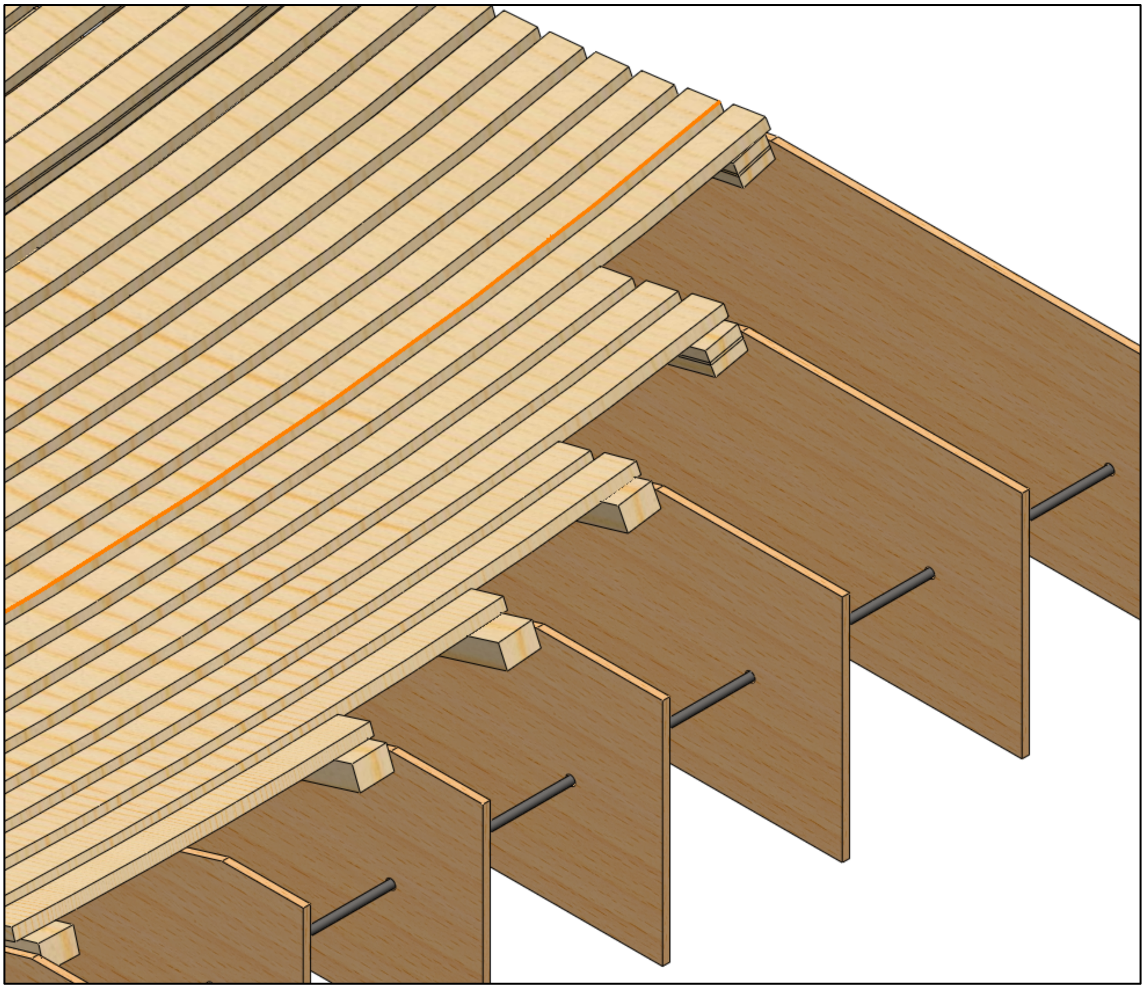


**Figure 40 - Close up of wooden slats and structural ribs sitting in mold**

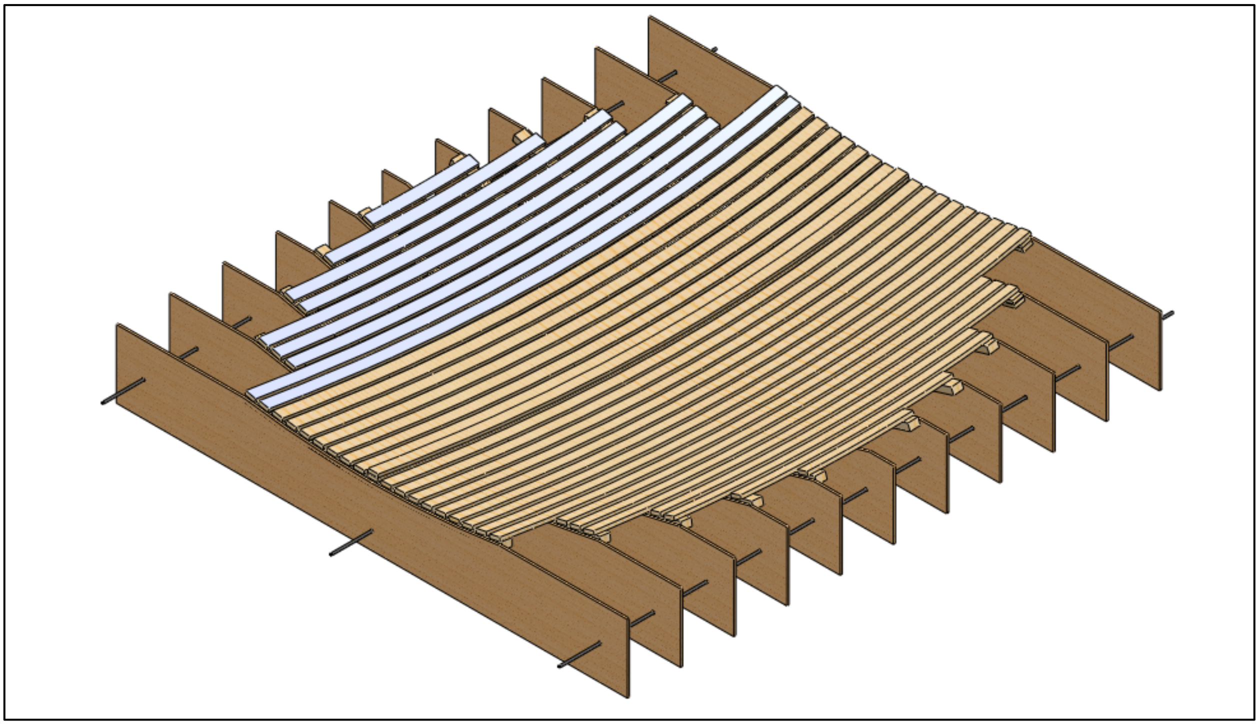


Figure 41 - Adhere metalized plastic onto surface of wood slats

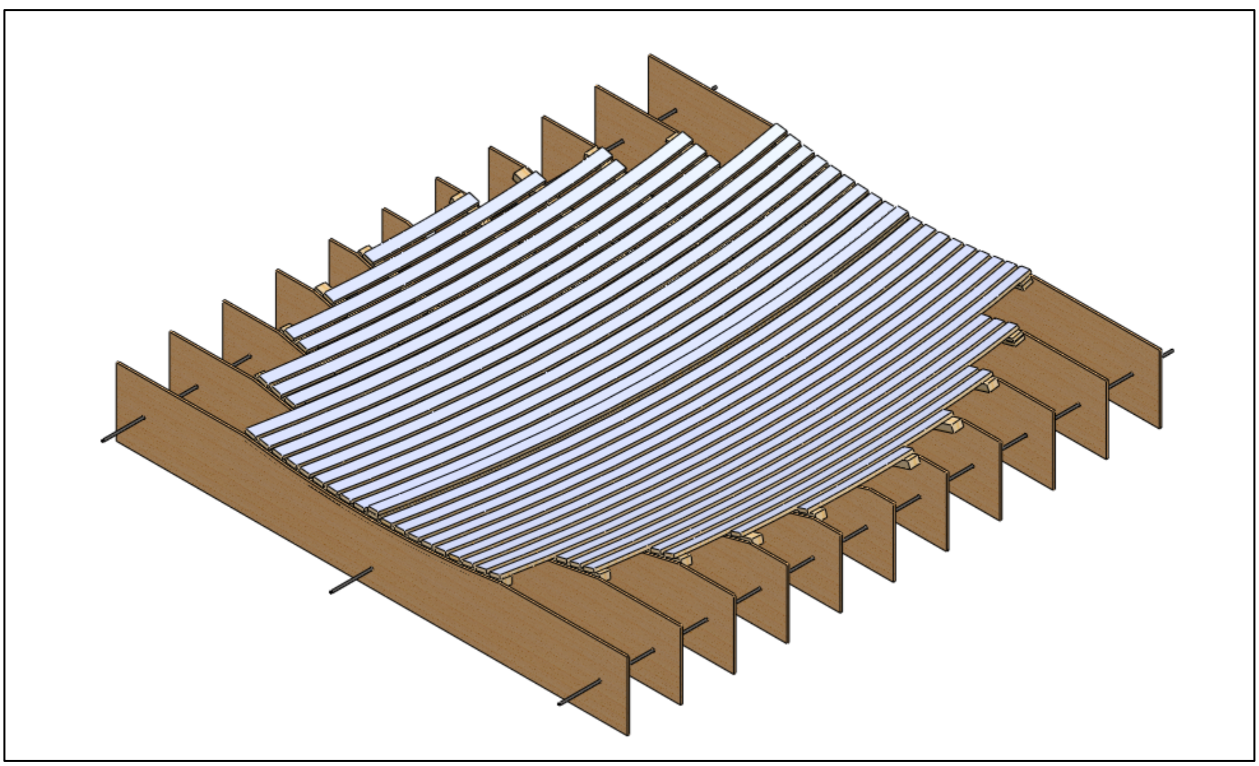


Figure 42 - Completed dish in mold

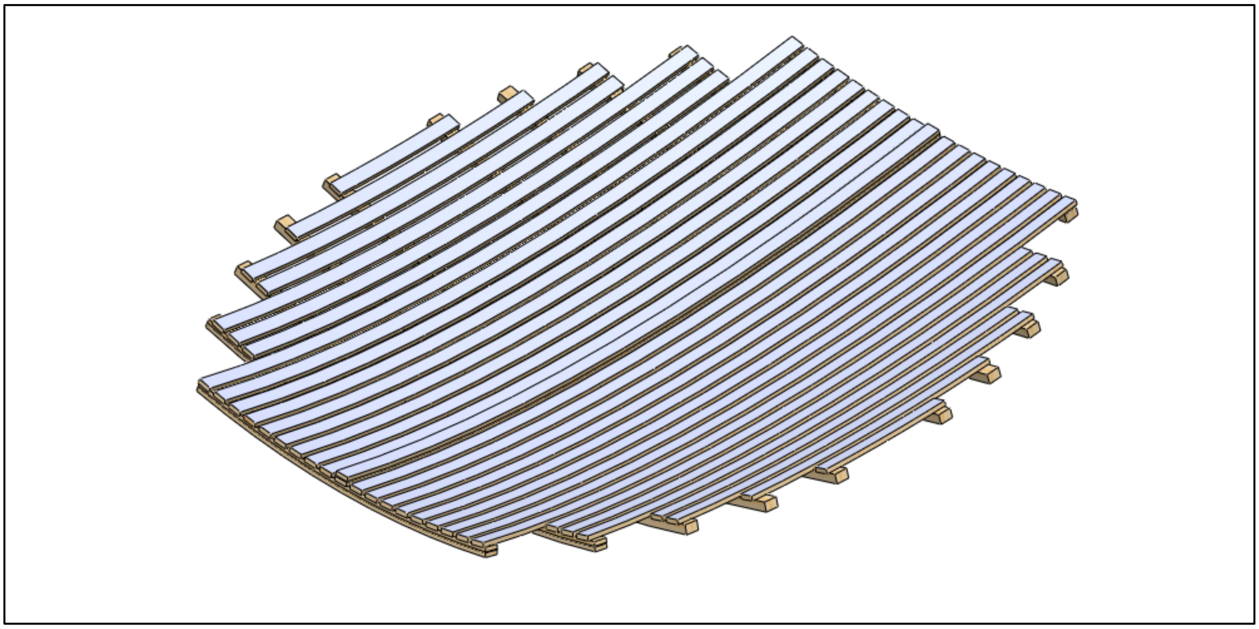


**Figure 43 - Completed dish lifted out of mold**

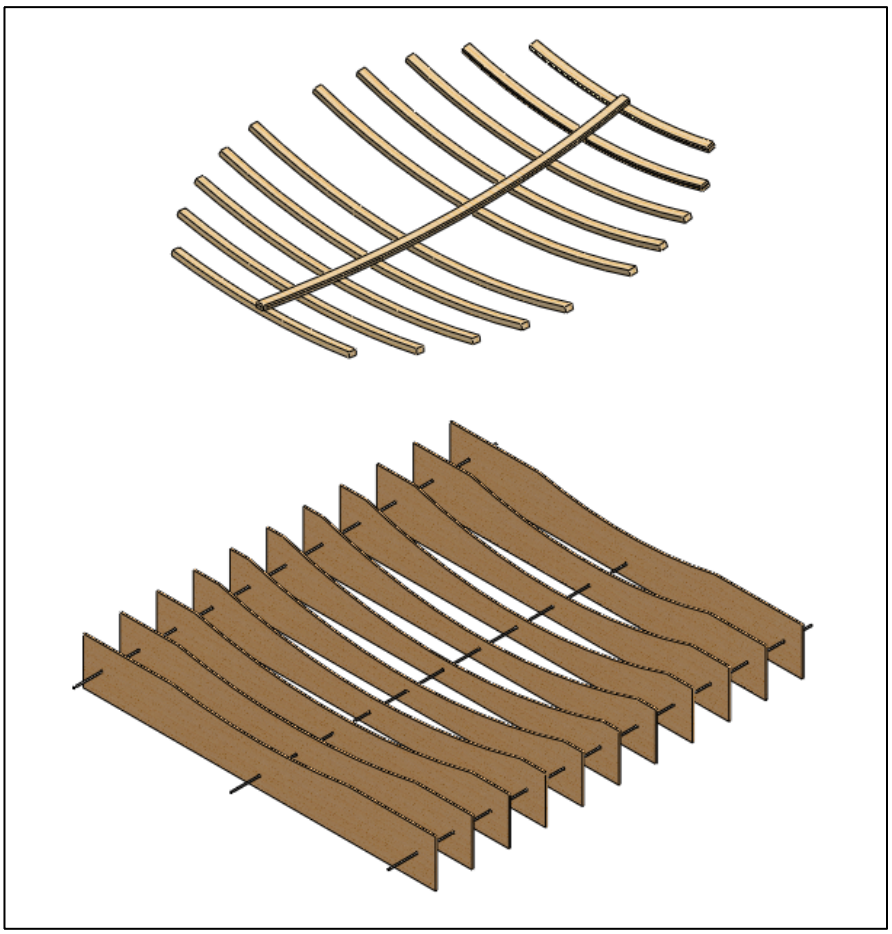
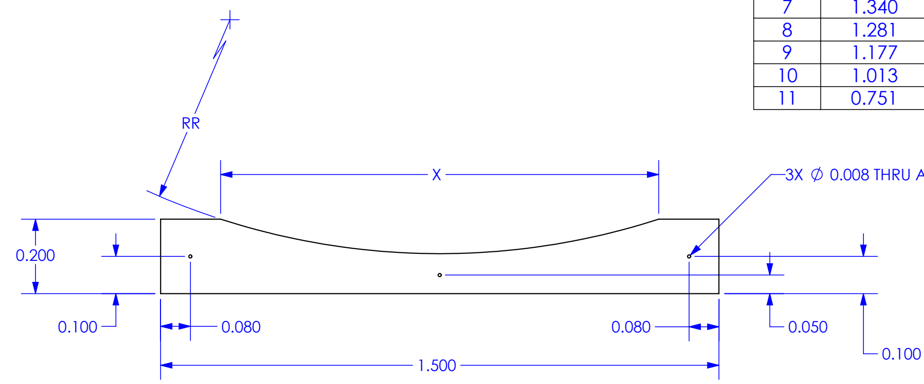


**Figure 44 - Depiction of structural ribs and mold**

## H. DIMENSIONED DRAWINGS

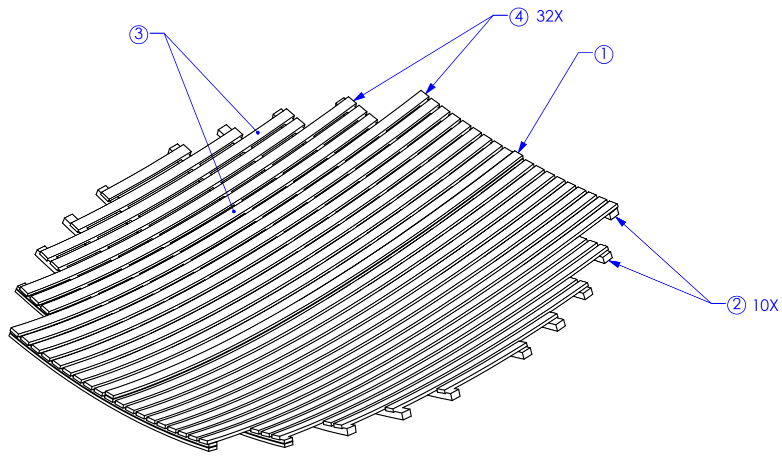
Following are two dimensioned drawings. The first is of the plywood ribs that will be used to form the mold. The second is of the completed dish.

| RIB # | X (m) | R (m) |
|---|---|---|
| 1 | 0.751 | 1.723 |
| 2 | 1.013 | 1.823 |
| 3 | 1.177 | 1.917 |
| 4 | 1.281 | 2.004 |
| 5 | 1.340 | 2.086 |
| 6 | 1.359 | 20163 |
| 7 | 1.340 | 2.236 |
| 8 | 1.281 | 2.305 |
| 9 | 1.177 | 2.371 |
| 10 | 1.013 | 2.434 |
| 11 | 0.751 | 2.493 |




| | | | |
|---|---|---|---|
| | DATE: 5/9/2013 | UNITS: METERS | MATERIAL: 1/4" PLYWOOD |
| | TOLERANCE: ±.001 | SCALE: 1:12 | TITLE: RIBS FOR MOLD |
| | | NEXT ASSY: N/A | NAME: DARREN SHOLES |
| | | DRAWING #: N/A | SIGNATURE: |

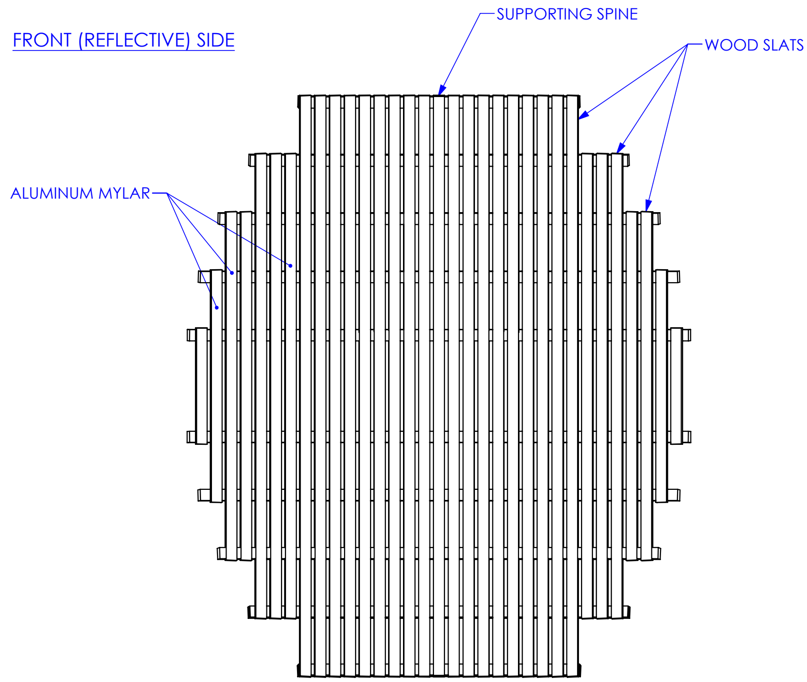
**Figure 45 - Dimensioned drawing of one rib of mold**




| ITEM NO. | PART | DESCRIPTION | QTY |
|---|---|---|---|
| 4 | WOOD SLATS | 3 X 1 cm CROSS SECTION, CUT LENGTH TO FIT MOLD | 34 |
| 3 | ALUMINUM MYLAR | CUT STRIPS AND GLUE TO WOOD SLATS | 2 m^2 |
| 2 | SUPPORTING RIB | COMPOSITE OF STACKED WOOD SLATS AND GLUE | 10 |
| 1 | SPINE | COMPOSITE OF STACKED WOOD SLATS AND GLUE | 1 |

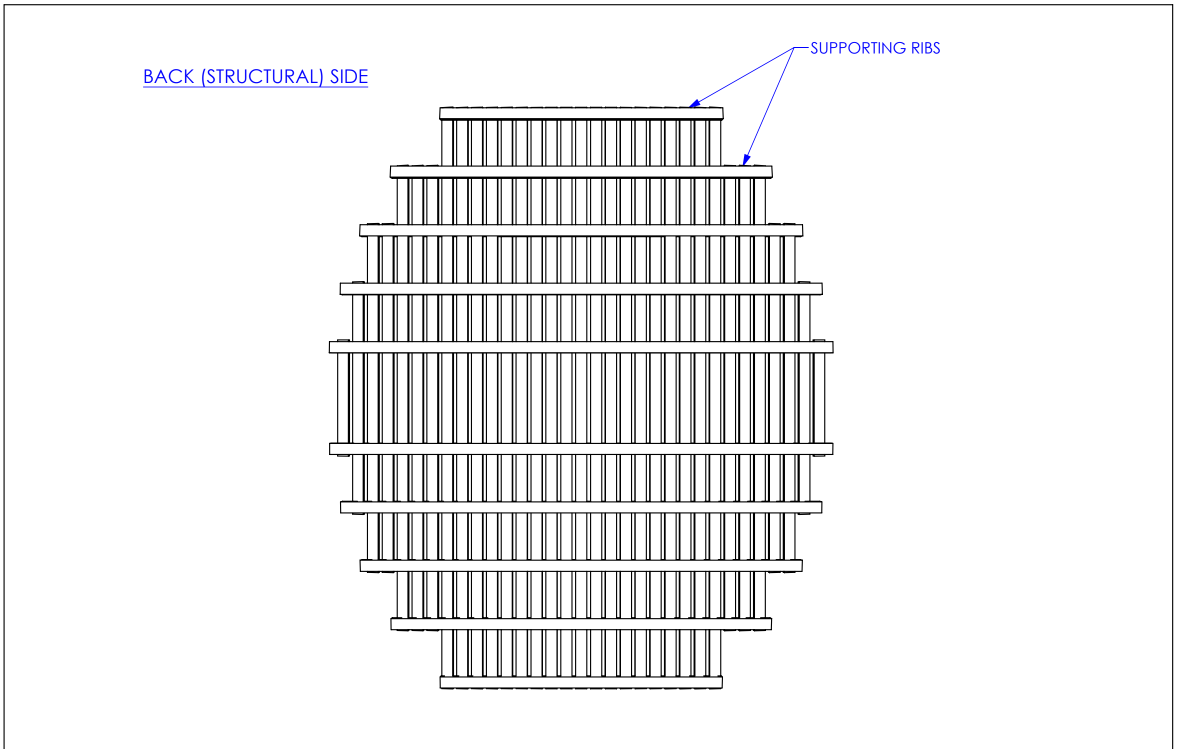
| | | | |
|---|---|---|---|
| | DATE: 5/9/2013 | UNITS: METERS | MATERIAL: N/A |
| | TOLERANCE: ±.001 | SCALE: 1:12 | TITLE: WOODEN SCHEFFLER DISH |
| | | NEXT ASSY: N/A | NAME: DARREN SHOLES |
| | | DRAWING #: N/A | SIGNATURE: |

**Figure 46 - Dimensioned drawing of Scheffler dish**




| | | | |
|---|---|---|---|
| | DATE: 5/9/2013 | UNITS: METERS | MATERIAL: N/A |
| | TOLERANCE: ±.001 | SCALE: 1:12 | TITLE: Wooden Scheffler Dish |
| | | NEXT ASSY: N/A | NAME: DARREN SHOLES |
| | | DRAWING #: N/A | SIGNATURE: |

**Figure 47 - Detailed drawing of front of Scheffler Dish**




| | | | |
|---|---|---|---|
| | DATE: 5/9/2013 | UNITS: METERS | MATERIAL: N/A |
| | TOLERANCE: ±.001 | SCALE: 1:12 | TITLE: Wooden Scheffler Dish |
| | | NEXT ASSY: N/A | NAME: DARREN SHOLES |
| | | DRAWING #: N/A | SIGNATURE: |

**Figure 48 - Detail drawing of back of Schefler Dish**

# I. EES CODE: ANALYSIS OF BOILING TEST RESULTS



*Group 15: Low-Cost Scheffler Solar Concentrator*

*ME 430*

*Analysis of Boiling Test*

*12/05/13*

*Performance Analysis of a Scheffler Solar Concentrator*

.......................................................................................................

*Geometry*

$n = 336$ *Day Number: December 2, 2013*

$\phi = 35.302335$ [deg] *Latitude of Exact Position on Solar Deck [Google Earth]*

$\omega = -14.2$ [deg] *Hour Angle at Time of Test*

$$\delta = 23.45 \cdot \sin\left[360 \cdot \left(\frac{284 + n}{365}\right)\right]$$ *Declination Angle*

$\theta = \cos[\omega]$ *Angle of Incidence*

*Solar Zenith Angle*

$$\theta_z = \arccos[\cos(\phi) \cdot \cos(\delta) \cdot \cos(\omega) + \sin(\phi) \cdot \sin(\delta)]$$

*Ratio of Beam Radiation on Tilted Surface to That on Horizontal Surface*

$$R_b = \frac{\cos[\theta]}{\cos[\theta_z]}$$

*Measured Geometric Data*

$A_a = 1.9$ [m$^2$] *Area, Aperture*

$A_f = 0.04$ [m$^2$] *Area, Focal Region*

$A_r = 0.02325$ *Area, Receiver*

$F_{fr} = \frac{A_r}{A_f}$ *Receiver Focal Fraction*

$C_t = \frac{A_a}{A_f}$ *Theoretical Concentration Ratio*

$$\eta_o = \frac{C}{C_t}$$

$m_w = 0.5$ [kg] *Measured Mass of Water for Test*

$t = 10$ [min] *Time of Flow Test*

$s = 0.003175$ [m] *Thickness of Kettle*

*Thermal Losses*

$T_i = 292$ [K] *Initial Temperature of Testing Water*

$T_f = 341.15$ [K] *Final Temperature of Testing Water*

$C_p = 4073.4$ [J/kg/K] *Specific Heat, Water [Eng. Toolbox]*

$q = m_w \cdot C_p \cdot [T_f - T_i]$ *Heat Transfer from Kettle to Water*

$\varepsilon = 0.86$ *Emissivity, Black Painted Aluminum Kettle [Eng. Toolbox]*

$\alpha = 0.9$ *Absorptance, Black Painted Aluminum Kettle [Eng. Toolbox]*

$\sigma = 5.67 \times 10^{-8}$ [W/m²/K⁴] *Stefan-Boltzmann Constant*

$k_w = 0.61065$ [W/m/K] *Thermal Conductivity, Water [Eng. Toolbox]*

$k_a = 215$ [W/m/K] *Thermal Conductivity, Aluminum [Eng. Toolbox]*

*Measured Temperature and Data*

$T_r = 450$ [K] *Measured Receiver Temperature: Thermocouple*

$T_a = 298.15$ [K] *Ambient Air Temperature [NOAA]*

$T_{dp} = 273.15$ [K] *Dew-Point Temperature [NOAA]*

$$T_{sky} = T_a \cdot \left[0.8 + \frac{T_{dp} - 273}{250}\right]^{0.5}$$ *Estimated Sky Temperature [Duffie & Beckman]*

$I_{bn} = 750$ [W/m²] *Average Normal Beam Irradiation, 11:00 AM*

$I_b = I_{bn} \cdot \cos[\theta]$ *Beam Radiation*

$U_{cond} = 0$ [W/m²/K] *Conduction Loss to Collector Support*

$$h_c = k_a \cdot A_r \cdot \left[\frac{T_r - T_f}{s}\right]$$ *Conductive Loss Through Kettle Thickness*

$h_w = 5$ [W/m²/K] *Convection Loss coefficienteerr [3.15]*

$h_{w,tot} = h_w \cdot [T_r - T_a] \cdot A_r$

$$h_r = A_r \cdot \varepsilon \cdot \sigma \cdot \left[\frac{T_r^4 - T_{sky}^4}{T_r - T_a}\right]$$ *Radiation Loss to Surroundings*

$h_{tot} = U_{cond} + h_c + h_{w,tot} + h_r$ *Total Thermal Losses During Testing*

$$p_w = m_w \cdot C_p \cdot \left[\frac{T_f - T_i}{t \cdot 60}\right]$$ *Total Power into water*

$p_{w,tot} = p_w + h_{tot}$ *Total Power*

$C = \frac{p_{w,tot} \cdot A_f}{I_{bn} \cdot A_a}$ *Concentration ratio*

*Surface Imperfections of Collector*

$r_r = 2.051$ [m] *Maximum Mirror Radius: [Wolfgang Scheffler]*

$a = 2.01$ [m] – 0.73 [m] *Aperture Length*

$\phi_r = \arcsin\left[\frac{a}{2 \cdot r_r}\right]$ *Rim Angle*

$\delta_d = 5$ [deg] *Assumed Dispersion Angle Based on Measured Image Width*

$\rho = 0.85$ *Reflectance, Highly Polished Aluminum [Table 4.7.1]*

$\gamma = 0.35$ *Assumed Intercept Factor Based on Focus Model [Attached]*

SOLUTION

**Unit Settings: SI C kPa kJ mass deg**

| | |
|---|---|
| $a = 1.28$ | $\alpha = 0.9$ |
| $A_a = 1.9$ [m$^2$] | $A_f = 0.04$ [m$^2$] |
| $A_r = 0.02325$ [m$^2$] | $C = 4.816$ |
| $C_p = 4073$ [J/kg/K] | $C_t = 47.5$ |
| $\delta = -22.24$ [deg] | $\delta_d = 5$ [deg] |
| $\varepsilon = 0.86$ | $\eta_o = 0.1014$ |
| $F_{fr} = 0.5813$ | $\gamma = 0.35$ |
| $h_c = 171374$ | $h_r = 0.2683$ [W/m$^2$/K] |
| $h_{tot} = 171392$ | $h_w = 5$ [W/m$^2$/K] |
| $h_{w,tot} = 17.65$ | $I_b = 749.9$ [W/m$^2$] |
| $I_{bn} = 750$ [W/m$^2$] | $k_a = 215$ [W/m/K] |
| $k_w = 0.6107$ [W/m/K] | $m_w = 0.5$ [kg] |
| $n = 336$ | $\omega = -14.2$ [deg] |
| $\phi = 35.3$ [deg] | $\phi_r = 18.18$ [deg] |
| $p_w = 166.8$ [W] | $p_{w,tot} = 171559$ |
| $q = 100104$ | $\rho = 0.85$ |
| $R_b = 1.947$ | $r_r = 2.051$ [m] |
| $s = 0.003175$ [m] | $\sigma = 5.670\text{E-}08$ [W/m$^2$/K$^4$] |
| $t = 10$ [min] | $\theta = 0.9694$ [deg] |
| $\theta_z = 59.1$ [deg] | $T_a = 298.2$ [K] |
| $T_{dp} = 273.2$ [K] | $T_f = 341.2$ [K] |
| $T_i = 292$ [K] | $T_r = 450$ [K] |
| $T_{sky} = 266.8$ [K] | $U_{cond} = 0$ [W/m$^2$/K] |

19 potential unit problems were detected.

## J. EES CODE: THEORETICAL MINUMUM CONCENTRATION FACTOR CALCULATION



*Group 15: Low-Cost Scheffler Solar Concentrator*

*ME 430*

*Minimum Concentration Ratio Necessary to Boil Water in 10 min.*

*12/05/13*

*Performance Analysis of a Scheffler Solar Concentrator*

*..........................................................................................*

*Geometry*

$n = 336$ *Day Number: December 2, 2013*

$\phi = 35.302335$ [deg] *Latitude of Exact Position on Solar Deck [Google Earth]*

$\omega = -14.2$ [deg] *Hour Angle at Time of Test*

$$\delta = 23.45 \cdot \sin\left[360 \cdot \left(\frac{284 + n}{365}\right)\right]$$ *Declination Angle*

$\theta = \cos[\omega]$ *Angle of Incidence*

*Solar Zenith Angle*

$$\theta_z = \arccos[\cos(\phi) \cdot \cos(\delta) \cdot \cos(\omega) + \sin(\phi) \cdot \sin(\delta)]$$

*Ratio of Beam Radiation on Tilted Surface to That on Horizontal Surface*

$$R_b = \frac{\cos[\theta]}{\cos[\theta_z]}$$

*Measured Geometric Data*

$A_a = 1.9$ [m$^2$] *Area, Aperture*

$A_f = 0.04$ [m$^2$] *Area, Focal Region*

$A_r = 0.02325$ *Area, Receiver*

$$F_{fr} = \frac{A_r}{A_f}$$ *Receiver Focal Fraction*

$$C_t = \frac{A_a}{A_f}$$ *Theoretical Concentration Ratio*

$$\eta_o = \frac{C}{C_t}$$

$m_w = 0.5$ [kg] *Measured Mass of Water for Test*

$t = 10$ [min] *Time of Flow Test*

$s = 0.003175$ [m] *Thickness of Kettle*

*Thermal Losses*

$T_i = 292$ [K] *Initial Temperature of Testing Water*

$T_f = 373.15$ [K] *Final Temperature of Testing Water*

$C_p = 4073.4$ [J/kg/K] *Specific Heat, Water [Eng. Toolbox]*

$q = m_w \cdot C_p \cdot [T_f - T_i]$ *Heat Transfer from Kettle to Water*

*$q=k_a*A_r*(T_{r-T,i})/s$*

$\varepsilon = 0.86$ *Emissivity, Black Painted Aluminum Kettle [Eng. Toolbox]*

$\alpha = 0.9$ *Absorptance, Black Painted Aluminum Kettle [Eng. Toolbox]*

$\sigma = 5.67 \times 10^{-8}$ [W/m²/K⁴] *Stefan-Boltzmann Constant*

$k_w = 0.61065$ [W/m/K] *Thermal Conductivity, Water [Eng. Toolbox]*

$k_a = 215$ [W/m/K] *Thermal Conductivity, Aluminum [Eng. Toolbox]*

*Measured Temperature and Data*

$T_r = 500$ [K] *Measured Receiver Temperature: Thermocouple*

$T_a = 298.15$ [K] *Ambient Air Temperature [NOAA]*

$T_{dp} = 273.15$ [K] *Dew-Point Temperature [NOAA]*

$$T_{sky} = T_a \cdot \left[0.8 + \frac{T_{dp} - 273}{250}\right]^{0.5}$$ *Estimated Sky Temperature [Duffie & Beckman]*

$I_{bn} = 750$ [W/m²] *Average Normal Beam Irradiation, 11:00 AM*

$I_b = I_{bn} \cdot \mathbf{cos}[\theta]$ *Beam Radiation*

$U_{cond} = 0$ [W/m²/K] *Conduction Loss to Collector Support*

$$h_c = k_a \cdot A_r \cdot \left[\frac{T_r - T_f}{s}\right]$$ *Conductive Loss Through Kettle Thickness*

$h_w = 5$ [W/m²/K] *Convection Loss coefficienteerr [3.15]*

$h_{w,tot} = h_w \cdot [T_r - T_a] \cdot A_r$

$$h_r = A_r \cdot \varepsilon \cdot \sigma \cdot \left[\frac{T_r^4 - T_{sky}^4}{T_r - T_a}\right]$$ *Radiation Loss to Surroundings*

$h_{tot} = U_{cond} + h_c + h_{w,tot} + h_r$ *Total Thermal Losses During Testing*

$p_w = m_w \cdot C_p \cdot \left[\frac{T_f - T_i}{t \cdot 60}\right]$ *Total Power into water*

$p_{w,tot} = p_w + h_{tot}$ *Total Power*

$C = \frac{p_{w,tot} \cdot A_f}{I_{bn} \cdot A_a}$ *Concentration ratio*

*Surface Imperfections of Collector*

$r_r = 2.051$ [m] *Maximum Mirror Radius: [Wolfgang Scheffler]*

$a = 2.01$ [m] – 0.73 [m] *Aperture Length*

$\phi_r = \textbf{arcsin}\left[\frac{a}{2 \cdot r_r}\right]$ *Rim Angle*

$\delta_d = 5$ [deg] *Assumed Dispersion Angle Based on Measured Image Width*

$\rho = 0.85$ *Reflectance, Highly Polished Aluminum [Table 4.7.1]*

$\gamma = 0.35$ *Assumed Intercept Factor Based on Focus Model [Attached]*

SOLUTION

**Unit Settings: SI C kPa kJ mass deg**

$a = 1.28$
$A_a = 1.9$ [m$^2$]
$A_r = 0.02325$ [m$^2$]
$C_p = 4073$ [J/kg/K]
$\delta = -22.24$ [deg]
$\varepsilon = 0.86$
$F_{fr} = 0.5813$
$h_c = 199714$
$h_{tot} = 199738$
$h_{w,tot} = 23.47$
$I_{bn} = 750$ [W/m$^2$]
$k_w = 0.6107$ [W/m/K]
$n = 336$
$\phi = 35.3$ [deg]
$p_w = 275.5$ [W]
$q = 165278$
$R_b = 1.947$
$s = 0.003175$ [m]
$t = 10$ [min]
$\theta_z = 59.1$ [deg]
$T_{dp} = 273.2$ [K]
$T_i = 292$ [K]
$T_{sky} = 266.8$ [K]

$\alpha = 0.9$
$A_f = 0.04$ [m$^2$]
$C = 5.614$
$C_t = 47.5$
$\delta_d = 5$ [deg]
$\eta_o = 0.1182$
$\gamma = 0.35$
$h_r = 0.3226$ [W/m$^2$/K]
$h_w = 5$ [W/m$^2$/K]
$I_b = 749.9$ [W/m$^2$]
$k_a = 215$ [W/m/K]
$m_w = 0.5$ [kg]
$\omega = -14.2$ [deg]
$\phi_r = 18.18$ [deg]
$p_{w,tot} = 200013$
$\rho = 0.85$
$r_r = 2.051$ [m]
$\sigma = 5.670E-08$ [W/m$^2$/K$^4$]
$\theta = 0.9694$ [deg]
$T_a = 298.2$ [K]
$T_f = 373.2$ [K]
$T_r = 500$ [K]
$U_{cond} = 0$ [W/m$^2$/K]

19 potential unit problems were detected.

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