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Solar absorption chiller

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Solar Absorption Chiller

BE ACCEPTED IN PARTIAL FUFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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Solar Absorption Chiller

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Abstract

In developing nations access to electricity is inconsistent at best, and food spoilage is a prevalent issue. The solar powered absorption chiller is a refrigeration system designed to provide refrigeration to these developing areas. This year, our team has worked to develop a system where the sun's rays are collected as heat to power an absorption refrigerator. The goal of this project was to take an existing solar tracker system and use its collected heat to power a refrigerator. Our team designed and built heat exchangers to extract heat from the concentrated solar system; assembled components for a fluid circulation loop; and retrofitted an absorption chiller refrigerator to be powered by our heated fluid. Additionally, we redesigned an existing solar tracking system to improve function and decrease power consumption. By the end of this year we assembled the entire system and performed months of solar testing as well as proof-of-concept testing that the refrigerator could receive necessary heat through a heated fluid. By the end of the school year, we concluded that the heated fluid would need to reach 150°C to begin the refrigeration cycle (with current heat exchanger design), which was 25° higher than our solar testing had achieved. With further improvements, the refrigerator could be designed to run with lower heat inputs and the tracker system could be designed to attain heat at higher temperatures. With these changes, a working refrigeration system could have dramatic impacts on farming communities in developing countries; reducing food spoilage, increasing family income, and preventing food-borne illnesses.

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Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Background

In the United States it is easy to take amenities like refrigeration for granted. However, developing countries cannot use traditional refrigeration because it requires electricity, which is unreliable or non-existent in most areas of the developing world. Disease, malnutrition, and economic struggle are just some of the debilitating trends that could be reversed if access to reliable and affordable refrigeration were an option.

In the country of Uganda, a developing nation, 82% of the labor force works in agriculture. Access to water is plentiful due to geographical location, but electricity is only available to 14.8% of the population (EIA). Therefore, average farmers cannot use electric refrigeration to store their perishable goods. Speaking to Thermogenn (an NGO based in Uganda), the main motivator for access to refrigeration is to reduce dairy spoilage. Currently, only milk produced in the morning can be taken to markets and the Food and Agriculture Organization estimates that about 27% of all milk produced in Uganda is lost due to spoilage, spillage, or waste. The value of these losses is US$23 million a year (FAO).

Figure 1.1: Ugandan girl with milk container. Milk spoilage hurts Ugandan community.

In addition to the economic incentives, lack of refrigeration is a contributing factor to malnutrition and food borne illness (33.9% of children in Uganda, under the age of 5, are severely underweight (CIA)). Conventional refrigeration is not a feasible solution due to lack of electricity; however, the implementation of a solar powered refrigeration system can provide much needed refrigeration to rural communities that currently lack such modern conveniences.

The benefits of an absorption chiller refrigerator powered by concentrated solar power (CSP) are many. First, concentrated solar power, on a residential scale, presents many opportunities for the use of heat. Although this project focuses on the application of CSP for absorption refrigeration, the heat from this could also be used for water desalination, electricity production, and heat for cooking or sterilization. Second, the absorption chiller refrigerator itself has no moving parts, making it an ideal choice for an area with little access to the outside world for replacement parts or maintenance. Ultimately, this refrigeration system combines several known technologies in a unique way to deliver refrigeration to areas that can greatly benefit from it.

1.2 Literature Review

Our team used previous research on refrigeration in developing nations as a way to understand potential problems in application as well as the needs of the communities where the system could be implemented. This began with a study of small-scale projects in solar absorptive refrigeration in Nigeria (Akinbisoye). This team recognized that there is a problem with the amount of energy consumed in refrigeration processes and sought a means to provide a sustainable and affordable solution. The method attempted was the use of adsorption refrigeration generated from the heat of the sun; however, the design proved very inefficient with a COP value of 0.025. COP stands for Coefficient of Performance and is a measure of efficiency for refrigerators showing how much cooling was produced from the amount of electricity input. For reference, traditional refrigerators have a COP of between 2.5 and 5 depending on several factors such as size, refrigerant, and manufacturer. However, even with the low COP of this adsorption system in Nigeria, the freezer was able to produce a reasonable amount of ice, indicating that with an improved design, absorption refrigeration is a viable (Akinbisoye). A different team of students from Purdue University developed a refrigerator powered by a battery that was charged using solar PV panels (Borikar). Their system worked, but had low efficiencies due to the use of cheaper solar panels to reduce system costs. Additionally, our team noted that solar panels and batteries have the downside of using rare earth elements and harmful chemicals. Ideally, we want to develop a system that doesn't pose a toxic threat to the environment where it is being used. A thorough analysis of state-of-the-art refrigeration possibilities allowed us to better understand the options available for solar powered refrigeration (Kim). This article divides the options into solar electric refrigeration and solar thermal refrigeration. Figure 1.2 shows how a solar electric system would work with a traditional refrigeration cycle, similar to what the students at Purdue built, but without a battery.

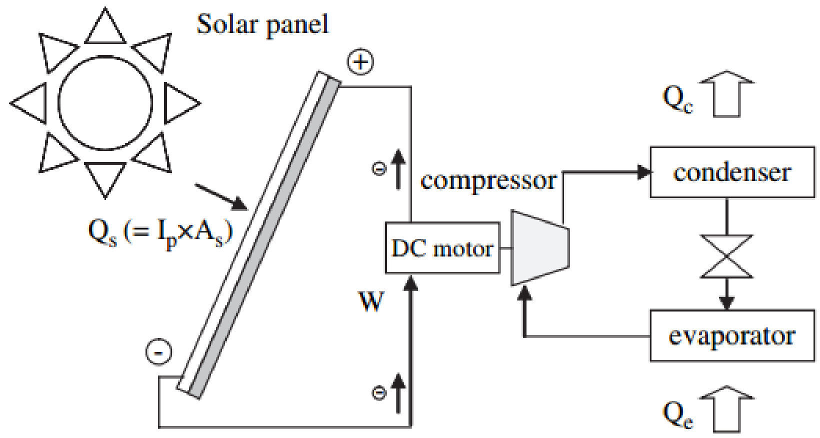


Figure 1.2: Schematic Diagram of a Solar Electric refrigeration system (Kim)

Second, Kim splits the options of solar thermal refrigeration into two categories: (1) Thermo-mechanical refrigeration and (2) Sorption Refrigeration. The first refers to a solar collector (non-concentrated) powering a heat powered engine, shown in Figure 1.3.

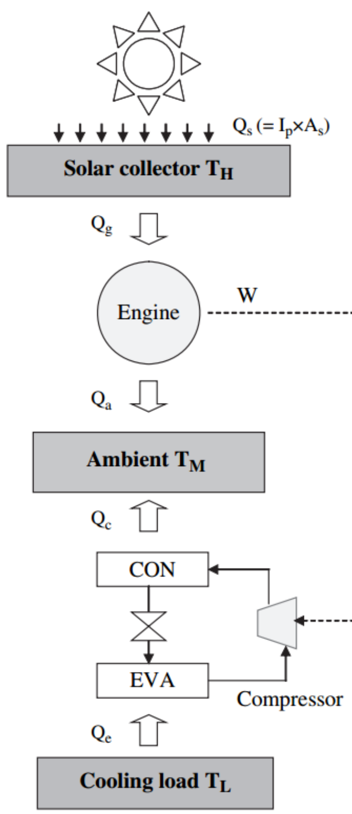


Figure 1.3: Solar Thermo-mechanical refrigeration system (Kim)

In a project cited by Kim, this thermo-mechanical refrigeration system was able to run on 101.7°C water from the solar collector with a solar-to-power efficiency of 5.8%. Kim notes that with a higher heat source temperature, a higher efficiency could be achieved.

Finally, Kim analyzes solar sorption refrigeration systems. This includes adsorption and absorption technologies, (Figure 1.4).

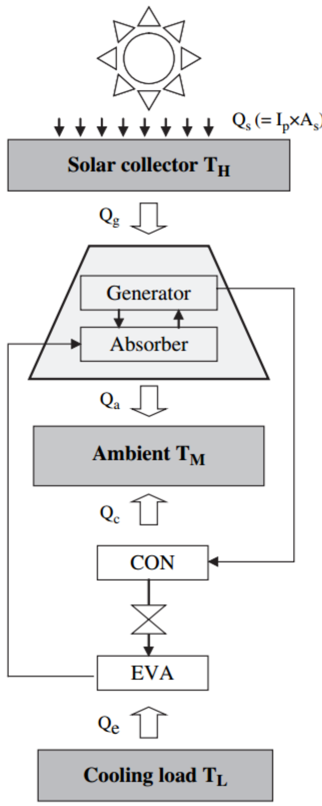


Figure 1.4: Solar Sorption Refrigeration System (Kim)

Sorption chillers are divided into two categories of Adsorption and Absorption chillers. Currently, adsorption systems are found in some industrial applications where waste heat is used to run water cooling sorption systems. Larger adsorption refrigeration units have been shown to run on heating temperatures from 55 to 95°C with a solar-to-cooling COP of 0.2 to 0.6. They can have an operation weight of around 5.5 tons and dimensions of 2.4 x 3.6 x 1.8 m^3 (Kim). Due to their size, they can run on lower temperature, but they are very expensive and therefore not applicable for developing nations. Residential scale absorption chillers can be purchased as wine coolers, hotel mini-fridges, and RV refrigerators for as little as $550 (Camping World).

Absorption, Kim notes, uses very little to no electric input and runs through an absorption-desorption process using refrigerants (usually ammonia/hydrogen or lithium/bromide). These absorption systems are the most popular choice for solar refrigeration and are more compact than their adsorption counterparts. Kim did note, however, that absorption systems were not ideal for flat solar collectors as they required a higher temperature to run. With this information, our team made the decision to use an absorption system. In our case, we were using concentrated solar power, which produces significantly higher temperatures than that of flat solar collectors.

Our background research into residential-scale solar collectors centered on previous research performed by SCU students in thermal energy harvesting (Neber et. al) and solar tracking (Barker et. al). Barker's team was able to develop a tracking system with a bi-axial structure to hold a parabolic mirror. The Arduino code and tracking system from this team was re-coded and retrofitted for a refrigeration system over the course of our senior design project. Neber's team developed several designs for the receptacle or receiver of the solar rays from the concentrated solar mirror. The conclusion of Neber's team was that a design focusing on a 2:1 ratio of cavity depth to opening diameter produced the ideal performance.

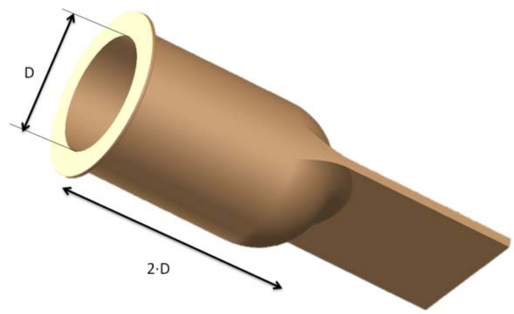


Figure 1.5: Design Ratio of Ideal Solar Receiver

This design shown in Figure 1.5 was developed by our senior design team by applying the ratio developed by Neber to maximize the blackbody potential of the cavity, which is to say that it maximized the cavity's ability to absorb and maintain radiation as heat.

1.3 Project Objectives

Based on review of previous works and social data, we determined that there is a market for a solar thermal refrigerator and experimental evidence of potential success. The goal of our project was to develop a refrigeration system that could be implemented in the developing world using a solar tracker system and an absorption chiller refrigerator. This would be done by

- Retrofitting an absorption refrigerator to be powered from a heated fluid
- Designing a test to determine initiation temperature for the absorption cycle
- Designing a fluid circulation system to deliver heat to the refrigerator from the receiver
- Retrofitting subsystems to use little to no electricity
- Lowering costs of system to be affordable for NGO's in developing nations

The process used to in developing this system is examined in the following Chapters.

2 System Overview

The Solar Absorption Chiller (SAC) is a refrigeration system made up of four main components as outlined in Table 1.

Table 1: Components of the Solar Absorption Chiller System

Component	Description
1. Concentrated Solar Tracker	Follows the sun and reflects sun's rays off a parabolic mirror.
2. Solar Receiver	Located at the focal point of parabolic mirror, converts sun rays into heat.
3. Fluid Circulation	Receives heat at solar receiver. Pumps heated fluid to heat exchanger attached to refrigerator. Pumps fluid back to receiver for "re-heat".
4. Absorption Chiller	Refrigeration system powered by heat. Receives heat from fluid through heat exchanger.

The SAC design is most easily understood by providing a technical background of the concentrated solar power and absorption chiller subsystems.

2.1 Concentrated Solar Power (CSP)

Concentrated solar power (CSP) is an energy harvesting technique that produces thermal energy. It is harnessed by using mirrors to reflect the light of the sun to a focal point. The intense heat that is centered at this focal point is collected in a solar receiver and can be used for many purposes including radiant heating, hot water production, electrical production, and in our case the powering of an absorption refrigerator. CSP is currently found in large commercial scale applications for energy production, as shown in Figure 2.1.

Figure 2.1: Industrial Scale Concentrated Solar Plant

These facilities use thousands of mirrors that concentrate solar rays on a single central tower. The innovation of our team's design is that we are taking this commercial-scale CSP model and scaling it to be used residentially. Building off the work of a previous senior design team (Barker et. al, Team Helios), we retrofitted, re-programmed, and installed a solar tracking mechanism as our source of solar radiation, (Figure 2.2).

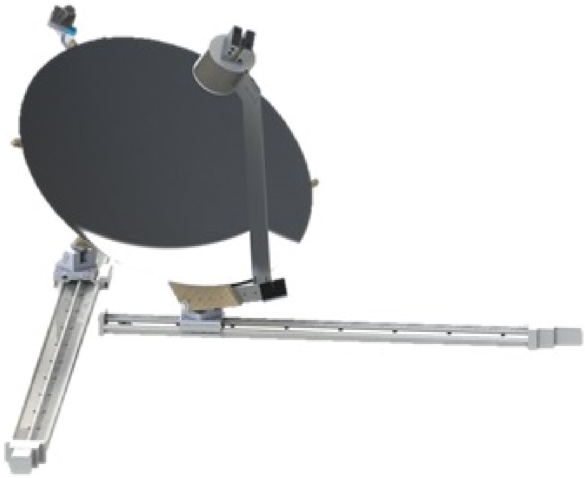


Figure 2.2: Residential Scale Concentrated Solar Power System (Barker et. al)

This solar tracking mechanism ensures that the mirror follows the sun by using motors that adjust the position of the mirror throughout the day. A summary of this tracker design from Team Helios can be found in Appendix 10. This appendix discusses the trigonometric design of the bi-axial tracker system, and the design of the Arduino control system for control of motor movement for the tracker along the axes.

2.2 Absorption Chiller Technology

Absorption chiller refrigeration is a form of refrigeration powered by heat. Whereas traditional refrigeration runs on electricity and has an electrical compressor, absorption chillers run on thermal absorption and desorption. Compression is used to induce the refrigerants to change phase and produce the cooling effect by absorbing heat. There are two different common types of refrigerant combinations used for absorption chillers, which are ammonia-hydrogen and lithium-bromide. Our team chose to use ammonia-hydrogen refrigerators because they were more accessible in the U.S. market and run using single stage refrigeration. This makes them smaller. Lithium-Bromide refrigerators are larger and can use double and even triple stage refrigeration. The single stage refrigeration cycle is shown in Figure 2.3.

2.2.1 The Absorption Refrigeration Cycle

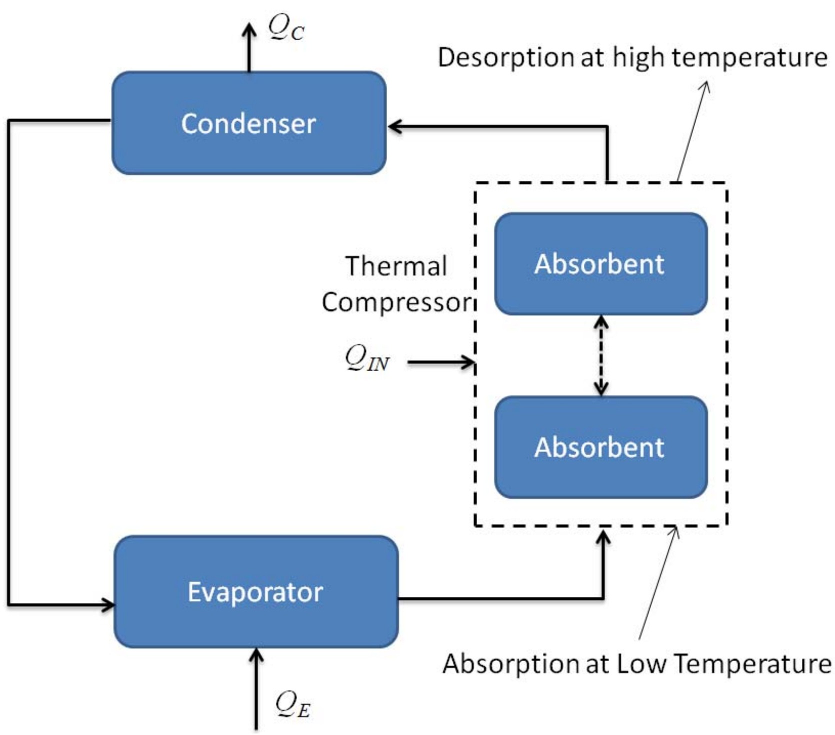


Figure 2.3: Diagram of the Absorption Chiller Cycle

Referring to Figure 2.3, the absorption chiller cycle begins with thermal compression. Heat is applied to a mixture of ammonia and water which results in desorption of the ammonia from water via boiling. The condenser cools the ammonia vapor and it becomes liquid. This liquid ammonia is absorbed by hydrogen gas in the evaporator. Here, the mixture experiences a chemical reaction that takes in heat, Q_E, which creates a cooling effect in the refrigeration chamber. The spent refrigerants of hydrogen and ammonia flow back towards the thermal compression chamber where the water re-absorbs the ammonia at a lower temperature and the hydrogen gas returns to the evaporator. This is an on-going cycle which will continue as long as heat is applied to induce thermal compression.

Specifics about initiation temperatures, pressurization of the refrigerants, and proportions of ammonia and hydrogen are proprietary information held by companies like Norcold™ and Dometic™, who are the commercial producers of absorption refrigerators in the USA. One of the goals of this project is to determine the required initiation temperature for the refrigeration cycle of one of these absorption chillers.

Our team used a prefabricated Norcold™ RV absorption chiller (traditionally run from the heat of a propane flame) for our refrigerator. Further information on how the absorption cycle fits into our system will be covered in Section 3.1.

2.3 Subsystems Overview

The main subsystems of our design are as follows:

- CSP System
- Solar Cavity Receiver
- Fluid Circulation Loop
- Absorption Chiller / Heat Exchanger System

The schematic containing these subsystems is shown in Figure 2.4.

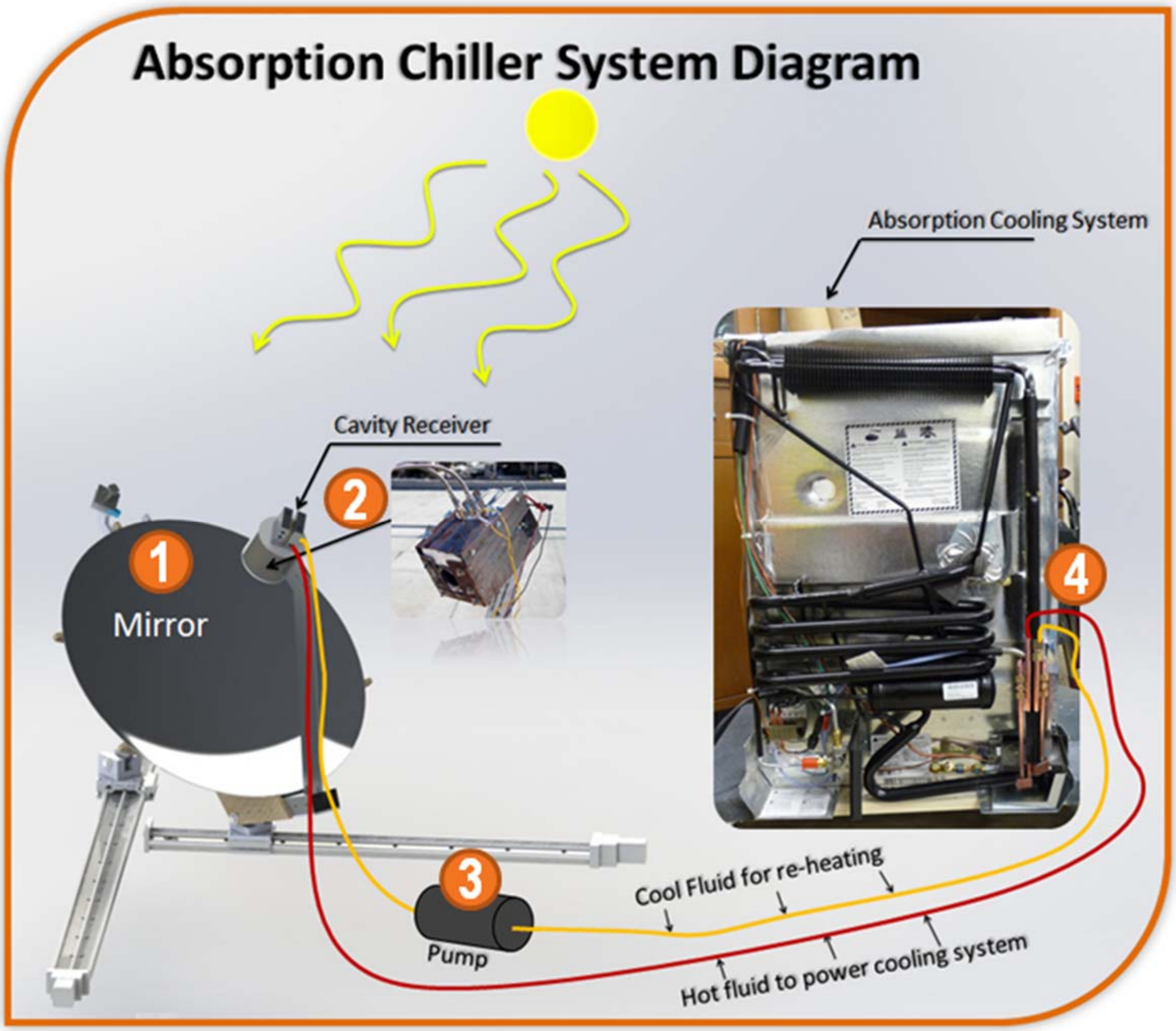


Figure 2.4: Solar Absorption Chiller System Schematic

As shown in Figure 2.4, the process of the system begins at the CSP system. Here, the sun's rays are reflected off the mirror (1) and concentrated in the solar receiver in the form of heat (2). Heat is transferred from the receiver to a thermal fluid that is pumped though the receiver subsystem. The heated fluid is pumped to the refrigerator (3) where it transfers its heat to the absorption chiller (4). This combination of concentrated solar power and absorption systems has never been studied for residential use and presents an exciting new field of study for small-scale, off-grid refrigeration.

The materials used for our system are as frugal as possible, which is an attempt to make sure that the accessibility and manufacturing of parts are feasible in the developing world. Specialized parts, such as the parabolic mirror and the absorption refrigerator, are relatively inexpensive in large quantities and require little maintenance since they have no moving parts. The motors, mirror support structure, fluid pump, and fluid piping can either be made on location or purchased from mass producers at very low cost. See Section 5.2 for further details on manufacturing.

2.4 Customer Needs

Our team's main customers are non-government organizations, or NGOs. Three potential customers were contacted for analysis of customer needs; these were Susan Kinne of Grupo Fenix, Promethean Power Systems, and Thermogenn. Susan Kinne is a social entrepreneur from Latin America who provides self-sustaining infrastructure for a small rural village in Nicaragua; Promethean Power Systems is an off-grid rural refrigerator manufacturer based in Mumbai, India; and Thermogenn is a Ugandan based NGO that provides off-grid dairy coolers. A survey was sent out to these NGOs and to Susan Kinne, and the results of this survey are summarized in the Table 2.

Table 2: Affinity Diagram of Four Most Desired Customer Traits

Most Desirable Features	
1st: Off-Grid	**2nd: Durable**
Solar tracker to power absorption chiller	Metal frame to hold mirror
PV Panels to power DC Pump	Pyramid style receiver holder
PV Panels to power Solar Tracker	Casing around exposed parts
3rd: Refrigerator Compartments	**4th: Freezer**
Modular shelves	Keep existing freezer box
Hanging Baskets	Only big enough for ice trays
Crispers/Drawers	OR make entire refrigerator a freezer

Based on feedback we received, we developed a set of system requirements, which are summarized in Table 3.

Table 3: System Requirements for Refrigeration System

System Requirement	Numerical Goal	Description
Refrigerator Operating Temperature	4°C	This is an established fridge temperature that will prevent dairy spoilage
Thermal Fluid Operating Temperature	130-150°C	Diagnostic tests were performed to determine ideal temperature to start refrigeration cycle
CSP System Size	5'x6'x6'	This CSP setup would likely fit on a roof
Cost of System	< or = $1000	This will fulfill our affordability requirement
PV Panels	3 x 60 Watt	The PV panels will power DC pump
DC Pump	180 Watt	This will pump thermal fluid
Freezer Operating Temperature	<0°C	This will provide ice
Freezer Size	0.5'x2'x3'	This will fit inside the absorption chiller
Solar Receiver Temperature	500°C~750°C	The concentrated solar power temperature required to heat the thermal fluid
Shelves	3: 2'x3'	This will give storage space for food such as fruits, meats, and dairy

2.5 Benchmarking Results

As part of background research, our current design was compared with three other benchmark systems. These were a traditional RV absorption refrigerator, a normal mini-fridge, and solar refrigerator produced by Cal-Maritime. Using a Targets and Benchmarks form, Appendix 1, we were able to create comparative goals in key categories such as weight, installation time, materials, cost, lifetime, and operating temperature. These specifications, which are included in Table 1, were of great importance in the design process. Below, we will elaborate on some of these key categories; comparing our current design to those of similar application.

2.5.1 Size and Weight

Of the three systems we chose to compare ours to, the RV refrigerator and the mini-fridge are the smallest. However, they are also self-sufficient and require no power source except electricity.

For the Cal-Maritime solar refrigerator, Figure 2.5, including the panels, is still smaller than our system.

Figure 2.5: Cal-Maritime Solar Refrigerator

This is because our refrigerator, though individually the same size as a traditional mini-fridge, is powered by a CSP system. The bi-axial tracker system and the fluid circulation system, that transfers heat from CSP to refrigerator, take up a lot of space. However, the portion of our system that would reside inside a home is the same size as an RV fridge or mini-fridge.

2.5.2 Maintenance and Installation

With regards to installation, our system is the most challenging. Although the goal is to take the system off-grid, it is currently not to that point. Unlike the Cal-Maritime fridge, which can be set up on location and immediately work, our system requires initial positioning of the mirror and tracker system. However, once this is done, the system can be easily started. A traditional mini-fridge would be plugged into a wall and an RV fridge would be connected to a propane tank. Both are easily installed, but only able to work in areas with access to electricity or propane. For the developing world, the Cal-Maritime fridge or our own model are most ideal.

One distinct difference, however, are the maintenance issues. The Cal-Maritime fridge is a traditional compression fridge which has moving parts that can break. In a rural developing nation there is not access to replacement parts or maintenance and this system could break and then be put in a junk-pile to never be used again. Our system, by employing an absorption cycle is maintenance free (at least on the refrigerator side) because an absorption refrigerator cycle is completely enclosed and has no moving parts. It can keep running over and over with no decrease in capability. As long as heat is applied it will run. This makes it an excellent choice for implementation in the developing world.

2.5.3 Initial and Operating Costs

Initial costs of an RV refrigerator, a normal mini-fridge, and the Cal-Maritime fridge are $550, $190, and $600 respectively. Our system was calculated to have a mass manufacturing cost of $710 dollars. This is elaborated on in Section 4.5. Although ours is the most expensive, it will have no operating costs once it is off grid. The RV refrigerator requires propane gas and a normal mini-fridge has an operation cost based on electricity cost. The Cal-Maritime fridge does not have an operating cost, but there is also no discussion in their report about the potential for broken parts and the cost effectiveness of replacing those.

2.5.4 Toxicity and Environmental Concerns

When planning to implement a system in the developing world it is important to be aware of any safety concerns for the environment. Especially with refrigeration, the issue of toxic refrigerants is a concern. For traditional refrigerators such as a mini-fridge or the Cal-Maritime fridge, they probably use refrigerants like R-410A or Freon, which are known to cause damage to the ozone layer. They are also toxic if they leak from the system. Absorption chillers, however, are made with ammonia and hydrogen gas. These are not toxic and are in small enough proportions and low enough pressures that they don't pose a serious environmental risk. Furthermore, absorption refrigerators are completely sealed and the likelihood of leakage is little to none.

2.6 Functional Analysis

The subcomponents and the ways in which they relate are shown in Figure 2.6. The system is most easily divided into the CSP portion and the Absorption Chiller portion. The CSP provides the power source, which is heat, to the Absorption Chiller. The Solar tracker system is the most independent of these and works to control the CSP system. Components of this system, including the Arduino control system, motors, brakes, lead screws, mirror, and mirror support work to make sure that the CSP system is able to track the sun and concentrate the solar rays into the solar receiver.

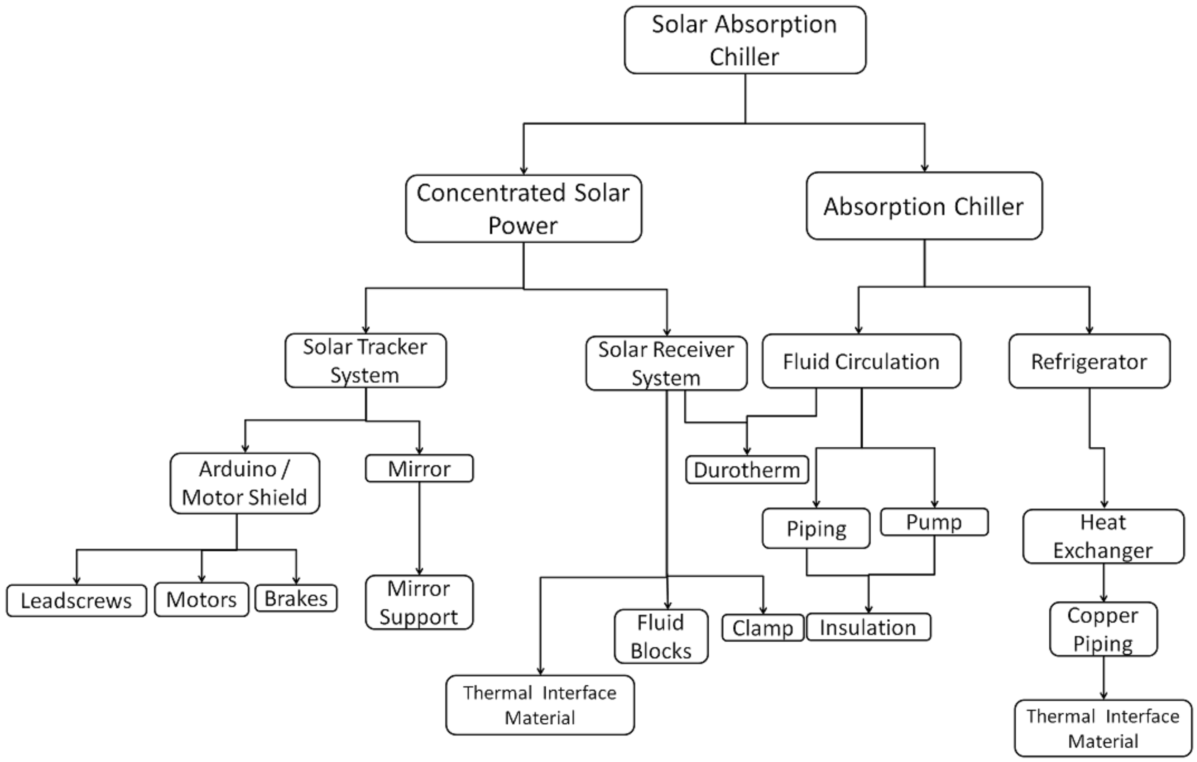


Figure 2.6: Functional Breakdown of Solar Absorption Chiller Subsystems

The thermal fluid, Durotherm, acts as a bridge between the solar receiver and the fluid circulation subsystem. Fluid blocks (which act as heat exchangers) attached to the body of the receiver using thermal interface material and a clamp have Durotherm pumping through them. As soon as the Durotherm leaves the fluid blocks it enters the fluid circulation subsystem. This system uses a pump and piping (both heavily insulated) to deliver the fluid to the refrigerator. The fluid is pumped through an insulated heat exchanger attached to the boiler column of the refrigerator. The fluid is then pumped back to the receiver.

2.7 Key Systems Level Issues

To understand the challenges for these subsystems, we divided them into the following two groups, Mechanical Tracking System and Thermal System.

2.7.1 Mechanical Tracking System

When considering the motor control system multiple components must be considered. The initial concern is the choice of motors. Our team inherited stepper motors from the previous design team (Barker et. al, Team Helios), which chose the stepper motors for their precise position control and easy operation. The process of the tracker control system is simplified in the following steps.

1. System is turned on and stepper motors adjust lead screws which move the bi-axial supports to align mirror to a pre-programed, date/time specific location of the sun.
2. Motors hold lead screws in place when not moving.
3. Every 4 minutes, stepper motors adjust lead screws to realign mirror with the sun.

The means to control the rotation of the motors was accomplished with an Arduino microcontroller. Although there are other inexpensive microcontrollers on the market, the Arduino is both affordable and widely used. Additionally, it is easy to learn and implement in any system. This allowed our team to take the code originally produced by the Helios team and adjust it to fit the needs of our system.

Although stepper motors are good for precision control, they are inefficient in their energy use because they constantly consume energy to maintain a lock at the intended stop position. This results in them constantly drawing electricity even when they are not moving the lead screws. Due to this inefficiency and the goal of decreasing electricity use from our system, mechanical brakes were added. These breaks allowed the motor to disengage while the brake provided a holding torque. One brake was used for each motor on the two axes.

The other key issue that was addressed in the mechanical tracking system was the tracker support system. We inherited Team Helios' designs and worked to improve their tracker support system. The original design can be seen in Figure 2.7. The support system was problematic due to its weight, size, and general instability. Section 3.2.3 expands on how our team created a more streamlined redesign of the tracker support. Our design now incorporates a skeleton-like frame that is significantly lighter and simpler.

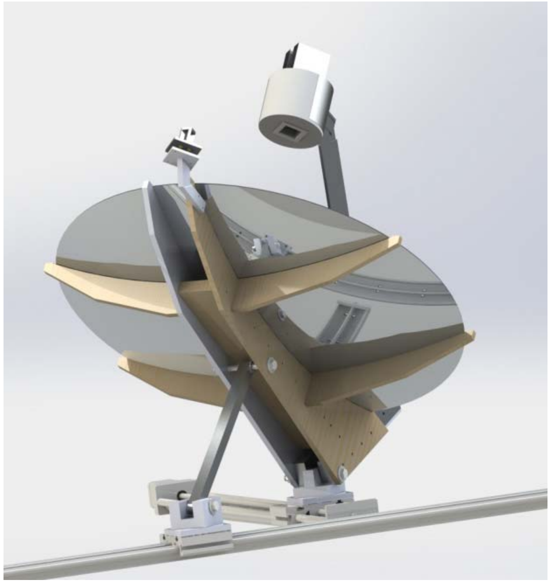


Figure 2.7 – SolidWorks rendering of initial tracker support system designed by Team Helios (Barker et. al)

2.7.2 Solar Thermal System

When most consumers consider solar power, they usually envision photovoltaic (PV) panels, which convert the sun's radiant light into DC voltage. Although these panels are a widespread approach to using solar energy, PV panels are very inefficient in converting from one form of energy (light) to another (electricity). Most estimates across brands put solar panel efficiency at 11-14% (Pure Energies). In contrast to this, CSP systems using the Stirling cycle at the residential scale have been shown to have efficiencies of 24% (Infinia), (Figure 2.8).

Figure 2.8: Infinia CSP system using the Stirling Engine

Because of the low efficiencies of PV panels as well as the promise of higher efficiencies for CSP systems, our project deviated from the traditional PV panel to use concentrated solar energy to heat our working fluid, Duratherm. By using CSP, there is no conversion to electricity as the heated fluid provides the necessary heat to run the absorption chiller. This means that the 24% solar-to-electricity conversion of the Infinia dish could be increased through elimination of inefficiencies in the Stirling cycle.

As mentioned previously, our system contains a thermal fluid, Duratherm, which transfers the thermal energy collected in the receiver to the absorption chiller. The main consideration affecting our choice to use Duratherm, specifically Durotherm 450, was that it can operate and maintain its properties in high temperature systems (up to 450°F). In addition, Duratherm has special additives, referred to as “metal deactivators,” which enable Duratherm to be used in the copper heat exchanger without producing any chemical reaction.

Throughout our system cycle the Duratherm passes through two different the heat exchangers. First, it is heated by passing through copper fluid block heat exchangers on the solar receiver. Second, it passes through a heat exchanger on the boiler column of the absorption chiller. The heat from this refrigerator heat exchanger causes the fluids within the absorption chiller to be heated sufficiently to initiate the refrigeration cycle.

2.8 Team and Project Management

2.8.1 Project Challenges

The design of our system has several constraints. These are summarized in Table 4.

Table 4: Summary of System Constraints and Solutions

Challenge	Solution	Target Values
"off grid"	Reduce electricity consumption in systems and plan for implementation of thermoelectrics.	Solar Tracker System: Reduce power usage to less than .25 kWh/day[1]
Maintaining temperature throughout night	Research energy storage[2]	Keep system running to prevent inside temperatures from rising above 4°C
Being affordable for low-income communities	Research mass manufacturing cost that is affordable for NGOs	Based on feedback from NGO Customer Feedback the target value is <$1000

The information shown in Table 4 refers to several key challenges the design faces. First is the issue of creating an off-grid system. Currently our solar tracker system uses energy from the grid to run the stepper motors. In preparation for further iterations[1] we aim to reduce power usage to less than .25 kWh/day. An additional challenge is maintaining temperature throughout the night. This will be achieved through energy or heat storage that could continue running the refrigeration cycle even when the sun is not out. Finally, our group is researching mass manufacturing methods to ensure that the cost of the final system is affordable to NGOs.

2.8.2 Budget

Because of generous funding from the California Energy Commission as well as the Roelandts Foundation and the SCU School of Engineering, the budget for this project was not a constraining factor. In order for ideal testing and collection of data we used mostly custom-made equipment. The ultimate goal was to have a working product before we figure out where to cut items to better fit our ultimate price goal of less than $1000. The full budget is laid out in Appendix 2.

[1] This benchmark was set because it refers to the potential power output of a thermoelectric. If these are added to the solar receiver in a later iteration of this design, they could produce the power necessary to run the tracker, allowing it to be off grid

[2] Currently being researched by graduate student Bernadette Tong

2.8.3 Timeline

Because our design requires solar testing, we began our design in the summer in order to take full advantage of good weather opportunities before winter quarter. Contingency plans for non-solar testing were made as well. Ultimately, our timeline allowed us to reserve spring quarter for documentation and analysis. This is all laid out in a Gantt chart in Appendix 3.

2.8.4 Design Process

Our design approach for this project was to split the system into the two main subsystems: the absorption chiller and the solar tracker. We assigned team members to each subsystem and divided tasks from there. The process for each part was:

1. Note problems from previous designs that we're dealing with
2. Brainstorm approaches to fixing problems
3. Narrow down approaches and test these narrowed approaches
4. Go back to drawing board if necessary
5. Implement this portion as part of the larger system

This process of growing from subsystems to the bigger system allowed for a smooth collaboration process, where team members could divide the work for greater team efficiency.

2.8.5 Risks and Mitigations

The two biggest risks involved in this system are the safety risks involved in system operation and the safety risks of food temperature. For system operation, the high temperatures of operation necessitate a level of safety both in testing and in final installation. To mitigate this risk, we will install safety notices and precautions on the device itself. Additionally, we will provide training to locals where the device is installed to warn them of the risk of burns. Second, the risk of food safety is an issue because the refrigerator's purpose is to maintain foods at a safe temperature for consumption. Over-compensating the refrigerator with insulation and doing ample testing with different food items for temperature fluctuations within the fridge during the cycle will mitigate this risk.

2.8.6 Team Management

Working with a team of four students, there were issues that arose. Figure 2.9 summarizes how some of these common ethical issues were dealt with.

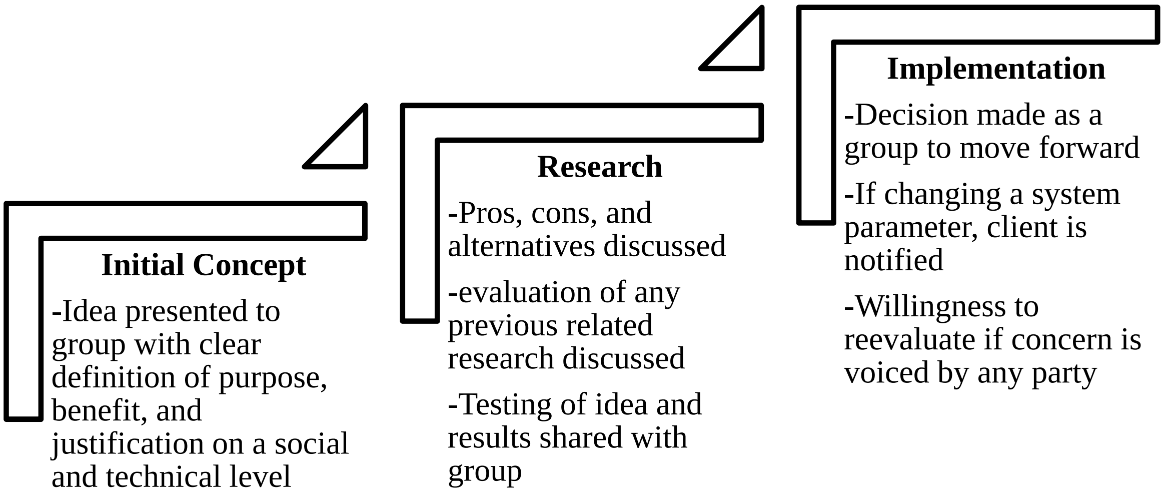


Figure 2.9: Ideal process for ensuring ethical awareness

This process ensured that our group approached ideas with openness to ethical dilemmas and a willingness to address the issue before it developed into a serious issue. This relates to team management because it identifies the process that our team used to resolve issues.

In relation to individual team roles, our team has taken Myers Briggs personality exams, which can be found in Appendix 9.

3 Subsystem Level Chapter

3.1 Absorption Refrigerator Subsystem

From the inside, our chosen absorption chiller refrigerator looks like any other mini-fridge with shelves and a small freezer compartment. However, this refrigerator has one large difference in that it is powered by heat. This is possible because of the heat powered gas absorption cycle that powers the refrigerator and creates the cooling effect.

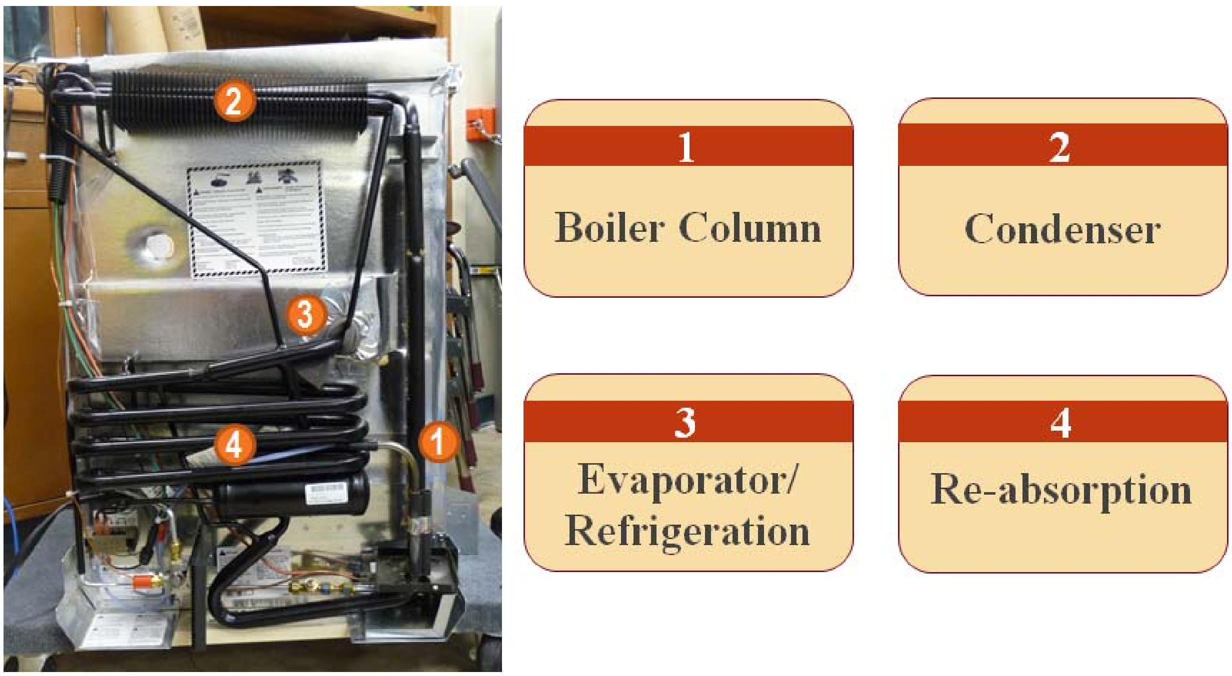


Figure 3.1 Absorption Refrigeration Cycle

As discussed in Section 2.2 on Absorption Chiller Technology, there is a specific cycle to the absorption refrigerator. These parts are shown in Figure 3.1, noting their location on the rear of the absorption chiller that our team used for testing. To initiate this cycle we used heat from a closed fluid loop that absorbs heat from the CSP receiver and transfers that heat to the absorption chiller using a heat exchanger.

3.1.1 Heat Exchanger

The heat exchanger is the device that transfers the heat from the working fluid into the boiler column to initiate, and run, the refrigeration cycle. This heat exchanger is made of copper tubing.

It is designed to wrap around the boiler column of the absorption system to provide heat to the ammonia mixture within. Copper was the chosen metal because of the following properties:

- High thermal conductivity
- Resistance to corrosion
- Availability
- Ease of manufacturing

Because the heat exchanger is filled with constantly moving high temperature fluids, up to 150°C, the properties of high thermal conductivity and resistance to corrosion make this heat exchanger efficient at heat transfer and durable for long periods without need of replacement. Durability is as important as availability and ease of manufacturing for developing nations. Luckily copper tubing is used throughout the world for plumbing applications and is very easy to cut, mold, and manufacture.

The surface that we designed the heat exchanger to go on is shown in Figure 3.2.

Figure 3.2: Boiler Column with Electric Heater

The boiler column had two, pre-welded black pipe sections and a boiler column (inside insulation) attached to it. In addition to the challenging surface on which this heat exchanger needed to be attached, the design for the heat exchanger needed to have as much surface area contact on the boiler column as possible. Larger surface area is one factor for increasing heat transfer. Given these challenges, we began using SolidWorks to design possible prototypes. Figure 3.3 depicts this first prototype designed for manufacturing with 3/8" copper tubing.

Figure 3.3: Proposed design and orientation of heat exchanger in SolidWorks

The length of this SolidWorks prototype was determined by heat exchanger calculations. In order to do these calculations, we determined the amount of heat that was transferred to the boiler column using the electric heater (the curved silver pipe in Figure 3.2). With a known value for the desired heat transfer, we could calculate the necessary length of the heat exchanger given an assumed fluid temperature of 120°C, a fluid mass flow rate of 0.3 cubic meters per second, and the physical properties of the copper tubing. The MatLab code for these calculations is in Appendix 4. The resulting critical heat exchanger length was 82cm.

Once the physical characteristics of the heat exchanger in Figure 3.3 were specified, our team searched for a manufacturing method. However, we soon learned that the bend radius of the copper tubing shown in Figure 3.3 was too tight for any manufacturing method. So we resorted to using pre-fabricated 3/8” copper piping and designing our own u-bed to create the tight radii we needed to fit the heat exchanger on the boiler column. Our custom u-bend design and final product are in shown in Figure 3.4.

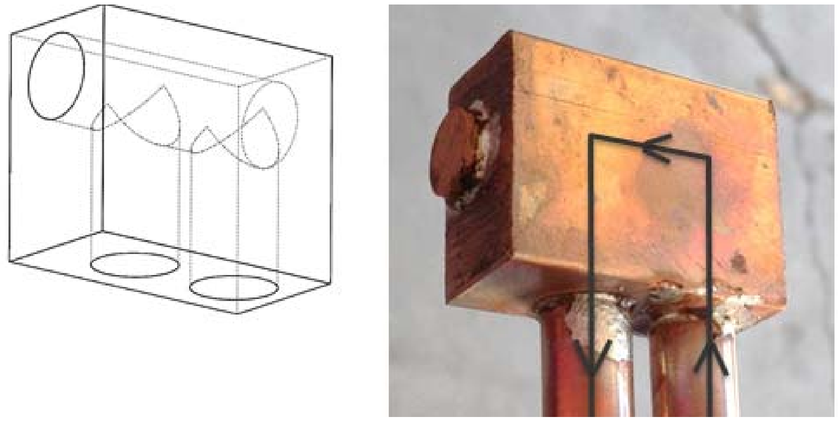


Figure 3.4: Custom Made U-Bend

The U-bend shown in Figure 3.4 was made from a copper block that was 1”x1”x1.2”. Three holes were milled into this block as shown on the left side of Figure 3.4. The final product shown in the right of Figure 3.4 had a small stopper soldered into its left-most opening to allow the fluid to flow in and out as the arrows depict. 3/8” piping and 90° copper elbows were used to make other components of this heat exchanger and the final product was constructed using a mix of soldering and compression fittings. The technical drawings for this can be found in Appendix 7 and the final product is shown in Figure 3.5.

Figure 3.5: Final design of heat exchanger attached to boiler column.

This final design in Figure 3.5 is more than double the surface area of electric heater column that came with the refrigerator, shown in Figure 3.4.

This is important because the rate of heat transfer via conduction from the wall of the heat exchanger to the wall of the boiler column is proportional to both the contact surface area and the temperature of heat exchanger, as shown in Equation 1.

$$\dot{Q} = -kA\frac{dT}{dx} \quad \text{(1, Bergman)}$$

Therefore, if contact area is higher, the temperature can be lower while still achieving the same rate of heat transfer. Since the temperature of the fluid in our system (which dictates the temperature of the copper contacting the boiler column for conduction) is limited by the CSP system, it was important to design our heat exchanger to maximize surface contact area; thus putting less emphasis on the performance of the CSP system.

3.1.2 Fluid Temperature

The functioning of the absorption refrigerator is dependent on the temperature of the thermal fluid that is pumped through the refrigerator heat exchanger. In order to determine the necessary temperature, a test was designed with a circulation heater rather than the CSP system and tests were run in-lab. Results of these tests are discussed in Section 4.4.

3.1.3 Insulation

Thermal fluid flowing through the refrigerator heat exchanger needs to sustain a high enough temperature for the refrigeration cycle to be initiated. Additionally, insulation was used around the receiver system to reduce losses to the environment. The receiver reached high temperatures of upwards of 500°C (discussed in Section 4.3). The options for insulation are shown in Table 5.

Table 5: Insulation possibilities for solar receiver

Name	Max Temperature	Price	Stiffness
High-Temperature Fiberglass	454°C	$48.34/3ft	Rigid
Mineral Wool	649°C	$38.90/3ft	Rigid

In order to assure that the insulation withstood the maximum system temperatures and to reduce cost, we opted for mineral wool insulation.

3.2 Solar Tracker Subsystem

3.2.1 Background

Our solar tracker was a continuation and improvement on an earlier prototype developed by a previous senior design group, Helios (Barker et. al et. al), which can be seen in its actual implementation, without a receiver module, in Figure 3.6. The previous team had designed the dual-axis tracker as an attempt to provide a strong but inexpensive alternative to solar tracking, without using the implementation of heavy and expensive support structures.

Figure 3.6 – Implementation of original Solar Tracker without receiver module (Barker et. al)

The heavy and expensive support structures mentioned before refer to the concrete mounts that are often used in solar tracking applications. These concrete mounts are also invasive to the environment as holes must be dug in the earth to accommodate the concrete foundation. The design developed by the Helios team provided an alternative to the concrete foundation approach with the use of their dual-axis tracker. This tracker system could follow the movement of the sun with the aid of two stepper motors turning lead screws that would orient the tracker supports, as previously illustrated in Figure 2.7.

The prototype primarily used medium density fiberboard (MDF) to construct the solar tracker supports, which created a relatively lightweight structure; however, it had several drawbacks in application. First, the MDF would need to be available and affordable for the developing nations, which is often not the case. Lower quality fiberboard, which is sometimes available, was not strong enough so the only option was quite expensive (See Appendix 2 for cost breakdown). In addition, pieces had to be fabricated using precision machinery, such as a laser cutter. Since the target customers for this system are in the developing world, they do not have access to laser cutters. These shortcomings of the previous design provided an opportunity for our team to create an improved support design.

In addition to the improvements regarding the support of the tracker, the previous design's control system consumed more power than was desired considering the goal of being off-grid. The system previously used stepper motors, which remained engaged even when the system was not in motion, producing a holding torque to maintain the correct orientation of the tracker. In order to decrease this power consumption, a mechanical brake was employed that enabled the motors to be toggled off when not moving. The energy savings from the use of the brake can be seen in the following section.

3.2.2 Subsystem Requirements

The main objective of the solar tracking system upgrade was that it would perform more efficiently than the previous model. Table 6 displays information obtained from a power consumption test with a “Watts Up” electrical consumption meter.

Table 6: Power Consumption Test of Solar Tracker System

Total Elapsed Time	0:29:09
Average Power (Watts)	64.17
Average Voltage	120.34
Average Current (Amps)	0.69
Total Watt Hours Used	31.5
kWh	0.032
Commercial Electricity Price (cents/kWh)	12.78
kWh/8hr day	0.52

As seen in Table 6, the average energy consumption of the tracker over an eight hour operating period was 0.52 kWh. Our goal was to lower this energy consumption by 75% with the implementation of the brake. This target was set because decreasing the energy consumption to 0.13 kWh would illustrate that this project can be optimized to use a minimal amount of energy. The installation of a relatively small solar panel with a peak power of 0.1 kW would be sufficient to power the every component, and the entire system could be made to function off grid.

Accordingly, several steps were taken:

- The tracking program for the system was altered so that the motors would cut power intermittently while the tracker was within +/- 1.5° of the sun’s position. Maintaining the tracker inside this range of error ensured the maximum efficiency for the system.
- The brakes were included in the system to lock the system in place while the motors did not have any power supplied, maintaining the tracker in the correct position.
- The power to the motors would be reengaged when the tracker needed to move again.

3.2.3 Concentrated Solar Tracker Structural Support

As previously mentioned, the solar tracker from the previous design team did not meet our requirement for frugal design. This inspired the creation of a new design that would improve the functionality and application in the developing world. Figure 3.7 depicts the design of the new tracker support system.

Figure 3.7: New Solar tracker Skeleton Design

This new design allowed for a minimal amount of materials to be used. The supports were constructed entirely of aluminum and steel, which gave the system a solid structure, while maintaining a minimal weight. This new tracker weighed approximately 15 pounds, which is 40% less than the previous design, which weighed in at 25 pounds and was comprised of wood, aluminum and MDF. This skeletal design also aided in the functionality of the tracker system by providing a minimal wind cross section, diminishing any wind loads that may be experienced by the system.

However, Figure 3.7 does not represent the actual construction of our new solar tracker support. Due to the complicated process of bending metal to the correct radius, and our inexperience in this area, the curved arms seen in Figure 3.7 were abandoned and redesigned to accommodate straight arms. Drawings for each of the support structures can be viewed in Appendix 6, and Figure 3.8 illustrates the new solar tracker in its final construction and implementation.

Figure 3.8 – Final Construction of New Solar Tracker

The movement of this tracking system and the components of the tracker were implemented by a previous design team and a brief overview of their work can be found in Appendix 10.

3.2.4 Motors and Braking

As mentioned before, stepper motors will consume energy even when they are not in motion, providing what is called a holding torque to maintain the load in desired proper position. When trying to create an energy efficient design, this constant energy consumption undesirable. Two alternative motor options were considered: brushless DC motors (BLDC) and servo motors. Table 7 demonstrates the potential benefits and drawbacks of the various motor types.

Table 7: Motor Types and Characteristics

Motor	Pros	Cons	Controls
Stepper	• Precise positioning • Easy control	• Requires controller • Consumes power when not in motion	Position
Brushless DC	• High efficiency • Long lifespan • Low maintenance	• Requires controller • Expensive • Difficult positioning control	Velocity
Servo	• Cheapest option • Easy control • Precise positioning	• Most cannot rotate continuously • Limited range • Usually for small loads	Position

When considering switching motors types, it was found that a Brushless DC motor, also known as a BLDC, could be beneficial, but would be the hardest choice to control as it would possibly require an additional Hall sensor. The Hall sensor would be able to sense the position of the motor as it turned. The alternate choice, the Servo motor, was equally unattractive as most inexpensive Servos would require additional gearing to move our tracker to its intended positions. Additionally, with the 68" lead screw, the gear ratio to implement a Servo motor would need to be around 500 to 1, which would be impossible for our size constraints. Since neither alternative was a desirable solution to our energy inefficiency problem, our group decided to pursue an alternative solution: a braking system that would allow the motors to be switched off when not in motion.

With the need for a braking solution that would allow for decreased energy consumption, we began devising solutions that would provide a mechanical brake for the system, without consuming any energy. The first idea was a Pawl brake mechanism, Figure 3.9, that would prevent any backlash.

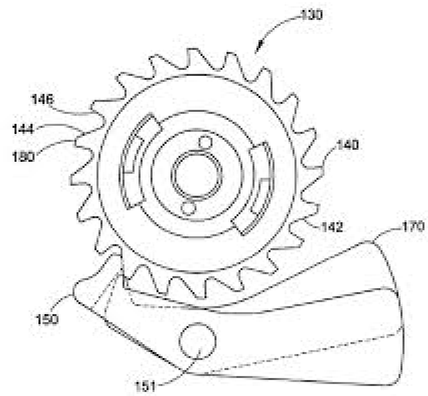


Figure 3.9 – Pawl brake mechanism

Although this brake mechanism would require no electrical energy, it would only allow the system to move in one direction. Our system needs to move back-and-forth in two directions. The next option was produced by the same company that made our lead screws. The PBC Linear, Figure 3.10, was a ratcheting device for motion of the carriage on the lead screw.

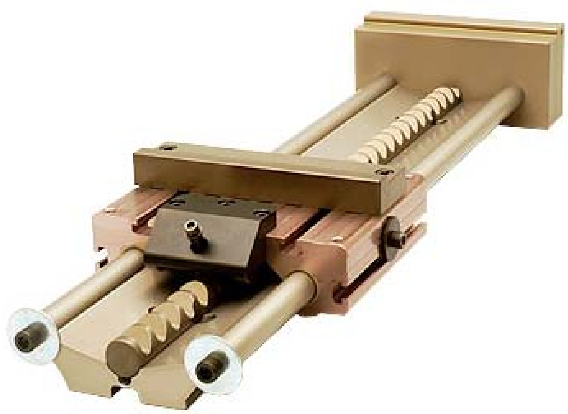


Figure 3.10 – PBC linear ratcheting motion system

After contacting PBC Linear, we found out this product was discontinued from manufacturing. With purely mechanical options exhausted, we settled on a braking solution that would consume a minimal amount of energy during operation. These brakes were spring-actuated, power-off brakes, designed for small stepper motors, (Figure 3.11).

Figure 3.11 – Spring-actuated, power-off stepper brake

As previously mentioned, this brake would consume energy, but only while the motors were in motion. Once the motors would lose power, the spring inside the brake could clamp down and prevent the spindle from moving. With the spindle being unable to move, the lead screw would lock the tracker into place even while the stepper motors were shut off, thus saving energy. Table 8 illustrates the significant impact the brakes had on our system's energy consumption.

Table 8: The effect of stepper brakes on tracker system energy consumption

	Energy Consumption* (kWh)	Duty Cycle	Energy Saved
Without Brakes	0.52	100%	--
With Brakes	0.058	2.55%	88.8%

*Based on 8 hour operating period

As can be seen from the table above, these brakes helped the system to consume almost 90% less energy than the original system, which had no brakes. This was accomplished by decreasing the duty cycle, or the amount of time that the motors would spend operating. By decreasing the amount of time the motors consumed power, less than one tenth of the energy was used throughout an eight hour operating period. This decrease of 88.8% in energy consumption showed that we met and exceeded our original goal of using 75% less energy to run the tracker.

3.3 Solar Receiver Subsystem

3.3.1 Receiver

The receiver for this system was made out of silicon carbide and the reason for this was twofold.

1. Silicon carbide can withstand very high temperatures without losing structural integrity.
2. Silicon carbide has a very low emissivity value, meaning it absorbs almost all of the electromagnetic energy that hits it.

These characteristics, combined with a shape that has no reflective 90˚ angles, ensured that our receiver approached a perfect blackbody absorber. The thermal energy that was absorbed was then transferred to the fluid using two fluid blocks via a conductive fin. The receiver setup is shown in Figure 3.12.

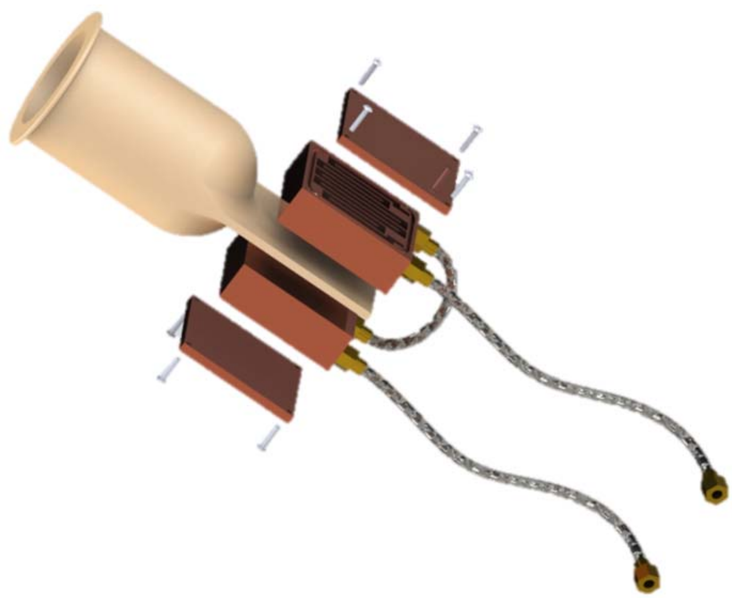


Figure 3.12: Exploded view of cavity receiver subsystem

As shown in Figure 3.12, the receiver subsystem has three main parts. These components and purposes are outlined in Table 7.

Table 7: Components for Solar Receiver Subsystem

Component	Description
Silicon Carbide Cavity Receiver	Absorbs sun rays in the form of heat and transfers heat from cavity to fin.
Fluid Heat Exchanger Blocks - Copper	Heat from fin is transferred into fluid flowing through these copper heat exchangers. Two blocks sandwiched on each side of fin.
Swagelok Piping	Pump fluid from one copper block to the other before exiting receiver subsystem.

Though included in Figure 3.12 and Table 7 as part of the receiver subsystem, the fluid blocks and Swagelok piping will be further discussed as part of the fluid circulation system.

3.4 Fluid Circulation Subsystem

3.4.1 Swagelok Piping

The heated fluid exiting the receiver subsystem is pumped from and to the refrigerator through the fluid circulation system made up of Swagelok piping. The thermal fluid used is Duratherm (Properties found in Appendix 11). The piping used in the system had two basic requirements

1. It needed to be flexible, because the tracker/mirror assembly was moving with the sun.
2. It needed to be insulated so the amount of thermal energy lost to the surroundings was minimized.

For these reasons we employed Swagelok piping, a flexible, stainless steel tubing specialized for temperatures up to 300°C.

3.4.2 Silicone Insulation

The Duratherm that flows to the refrigerator heat exchanger needed to sustain high temperatures, so insulation was needed. A high thermal resistance, R, for the insulation, is required to minimize heat loss. However, suppliers Grainger and McMaster protect the R-value of insulation as proprietary. Instead the maximum operational temperature is given. The insulation needed to be flexible, able to withstand temperatures of up to an estimated 120°C, and compatible with the

Swagelok piping. Table 8 lists the possibilities. The Silicone Foam was chosen because if it's high temperature and flexibility—both necessary qualities.

Table 8: Insulation possibilities for Swagelok feed pipe

Name	Max Temperature	Price	Stiffness
Polyethylene Foam Rubber	104°C	$6.45/6ft	Flexible
Silicone Foam	260°C	$55.63/6ft	Flexible
Mineral Wool	649°C	$10.23/3ft	Rigid
Fiberglass	177°C	$330/25ft	Flexible

3.4.3 Roller Pump

The Duratherm was pumped from the solar receiver to the absorption chiller using a roller pump, (Figure 3.13). Roller pumps have spinning rollers that create a vacuum, drawing in liquid to carry to the outlet port. They provide no metal-to-metal contact; only fluid contacts the rollers and the pump housing, which make the pump more resistant to high temperatures. The NSF roller model used pumps 3.8 gallons per minute on 115 volts AC, and can withstand extended exposure to temperatures up to 204°C.

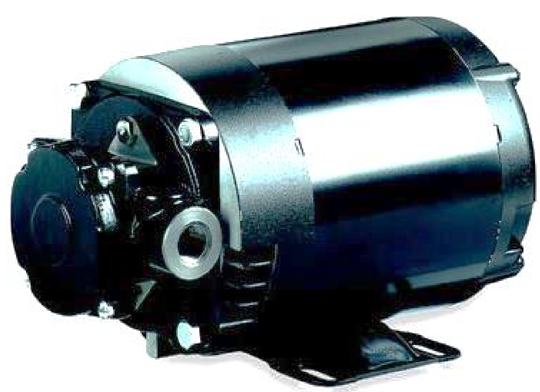


Figure 3.13: NSF High Temperature Roller Pump

This pump was chosen was because it is the smallest model of pump available that could withstand the high fluid temperatures our system creates. An advantage of using this pump is that its high power allows for the potential to connect multiple absorption chillers to the system with one pump transporting all the fluid. Although this is not currently in the scope of the project, future testing could be done to determine if this is a viable possibility. The disadvantage is the cost and weight this pump adds to the system. Additional roller pump specifications are found in Appendix 12.

3.4.4 Pressure Regulator

As Durotherm is heated in the circulation loop, there is the possibility of thermal expansion. To prevent any unwanted pressure on components of the fluid loop, an expansion tank was installed as a safety precaution. This expansion tank acts as a pressure regulator, eliminating fluctuations in pressure of the system. The model used was a stainless steel 46.6 in^3 tank able to withstand pressures up to 15 psi. Based on chemical information about the thermal expansion of Durotherm, it was calculated that the maximum pressure on the system would always be less than 1psi. Therefore, the expansion tank was more than capable of providing necessary pressure regulation. Additional expansion tank properties and a visual are found in Appendix 12.

4 System Analysis & Testing

4.1 Receiver FEA Analysis

4.1.1 System Diagram

The Receiver Module is where the first mode of heat transfer occurs in the concentrated solar system. As shown in Figure 4.1, the heat is collected in the receiver cavity and ultimately transferred to the fin via conduction.

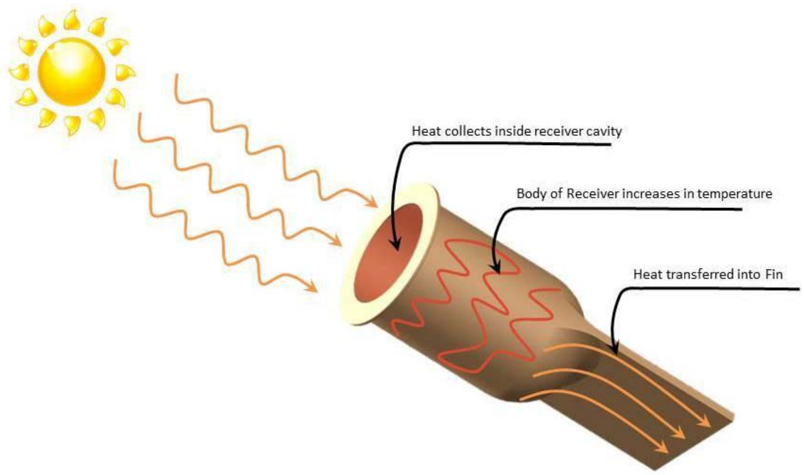


Figure 4.1: Solar Receiver Heat Flow Diagram

4.1.2 Assumptions for Modeling

A number of assumptions were made simplifying the design in order to perform successful computational analysis of the solar receiver. The assumptions and their corresponding effects on the simulation results are shown in Table 9.

Table 9: Receiver Simulation Assumptions and Effects on Results

Assumption	Effects on Results
No Insulation	Losses to environment lower simulation temperatures
No Water Blocks	Heat is not absorbed due to convection from the fin
No Material Imperfections	Heat is distributed evenly
System Is a Perfect Blackbody	The induced temperature from radiation is constant and 100% absorbed
Constant Temperature Induced	Results do not fluctuate
Radiation Evenly Distributed Not Focalized	Higher overall receiver temperature

4.1.3 Receiver Analysis Results

To gain a better understanding of how heat is transferred through the receiver, a SolidWorks FEA model was created. The model was set to an initial ambient air temperature of 22°C and a radiation of 400°C was induced on the inner surface of the cavity and the outer lip. Figure 4.2 shows a cut view of the temperature distribution. Where the radiation was induced, the maximum temperature was 370°C meaning 30° was lost to the environment. Via conduction, the fin's steady state temperature was 160°C. This aligns with the experimental test data for the fin, but the front of the receiver the model has about a 100°C higher temperature than the physical receiver; this can be attributed to the assumptions made for simulations. Despite this, the model does bring to light the temperature distribution for the receiver design showing us that the fin does work well to transfer heat from the cavity.

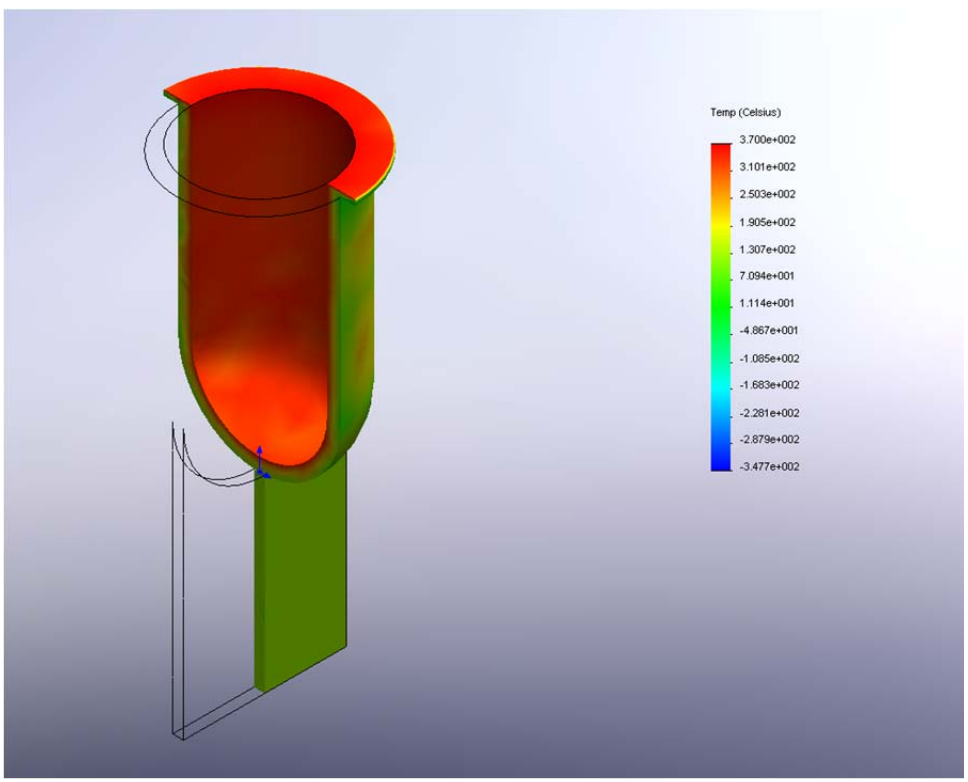


Figure 4.2: SolidWorks FEA Thermal Analysis of Receiver Cut View

From the receiver FEA analysis, and in conjunction with the experimental tests, multiple conclusions have been reached that will aid in the future improvement of the receiver and the overall system function. It was found in experimental testing a significant amount of heat is lost from the focal point at the front of the receiver to the fin at the rear of the receiver just like the FEA analysis. This result is likely because Silicon Carbide is a poor thermal conductor. Silicon carbide is a ceramic and is capable of absorbing large amounts of heat but ineffectively transfers heat throughout its body. In addition, an insufficient amount or poor application of insulation to the exterior surface of the receiver contributes to heat losses. With a better application of insulation, there will be fewer losses to the environment by convection. Additionally, if the wall thickness of the silicon carbide receiver was increased, this could allow it to maintain heat longer by increasing its mass.

A benefit from this analysis is the ability to approximate inner cavity temperatures for the receiver. Since both experimental and FEA tests produced a similar fin temperature, the FEA model can be used to roughly estimate how hot the radiation from the sun makes the cavity. We cannot directly measure this temperature since a thermocouple on the inner wall of the receiver cavity would need to be built in during manufacturing. Instead, we use a thermocouple attached to the outer wall of the receiver cavity. Knowing the inside cavity temperature analytically will allow us to better determine

4.2 Fluid Block FEA Analysis

4.2.1 System Diagram

The second elements in the receiver module are the fluid blocks that circulate the Duratherm fluid, in order to increase the fluid temperature. Two designs for this fluid block are shown in Figure 4.3.

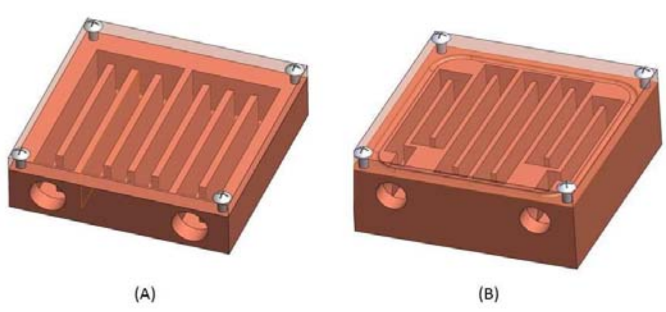


Figure 4.3: Fluid Blocks (A) Purchased Pre-fabricated and (B) Designed and made in-house

Both blocks in Figure 4.3 have a solid copper top plate that has been made transparent in the figure for the purpose of seeing the fluid path. Blocks A and B differ in the length of the path that the Duratherm travels. The comparison of these lengths is shown in Table 10.

Table 10: Comparison of Fluid Path for Blocks A and B

Block	Length of Fluid Path (inches)
A	15.71
B	22.27

In the context of the whole system, these fluid blocks are placed on either side of the fin in a pair as shown 3.12.

4.2.2 Assumptions for Modeling

As with the solar receiver, there were many assumptions made for the purposes of modeling the fluid blocks. These are listed in Table 11 along with their effects on the results of the simulation.

Table 11: Fluid Block Simulation Assumptions and Effect on Results

Assumptions	Effects on Results
No Insulation	Heat transferred from fin is lower than reality
One Water Block	All heat is absorbed by one water block – real system includes two
No Material Imperfections	Heat is distributed evenly
Constant Fluid Velocity for Thermal Analysis	Heat is distributed consistently
No Fluid Flow for Thermal Analysis	Unknown how much heat is absorbed by fluid

With respect to the last two assumptions in Table 11, these were only applicable for thermal FEA analysis of the fluid blocks. Since the computational analysis did not allow for both fluid and heat analysis combined, we performed separate analysis for each, which are explained in Section 4.2.3 and 4.2.4.

4.2.3 Thermal Analysis and Velocity Analysis

A SolidWorks FEA and velocity model were created for Block A. Block B could not be modeled because the inner walls were too thin for SolidWorks to mesh. The FEA model, Figure 4.4, was set to an initial ambient temperature of 22°C and a convection temperature of 250°C was induced on the base. Temperatures are shown in Figure 4.4 with yellows and red as the hottest, with temperatures between 215 and 224°C, and blues and greens as the coolest, with temperatures between 200 and 210°C. The channel walls within the block have the highest temperatures, while the outer body has the coolest temperatures. The model does not include the effects of the thermal fluid on the block, which would likely affect temperature. This is because the fluid blocks are intended to act as heat exchangers transferring their heat to the fluid.

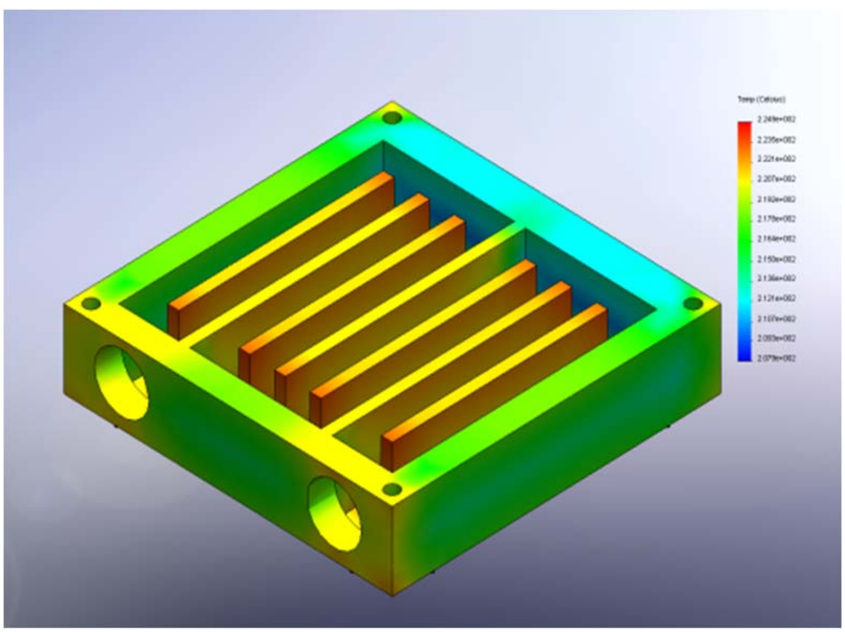


Figure 4.4: SolidWorks FEA Thermal Analysis

The velocity model, Figure 4.5, was set to an initial rate of 0.3m/s. The path shown is the most direct for the fluid to flow and suggests there is no fluid flow through these channels. Using the model's data of the actual length that fluid travelled, calculations for how much heat is absorbed by a fluid showed that after one pass through both blocks, the system could potentially increase the fluid temperature to 150°C (calculations in Appendix 4).

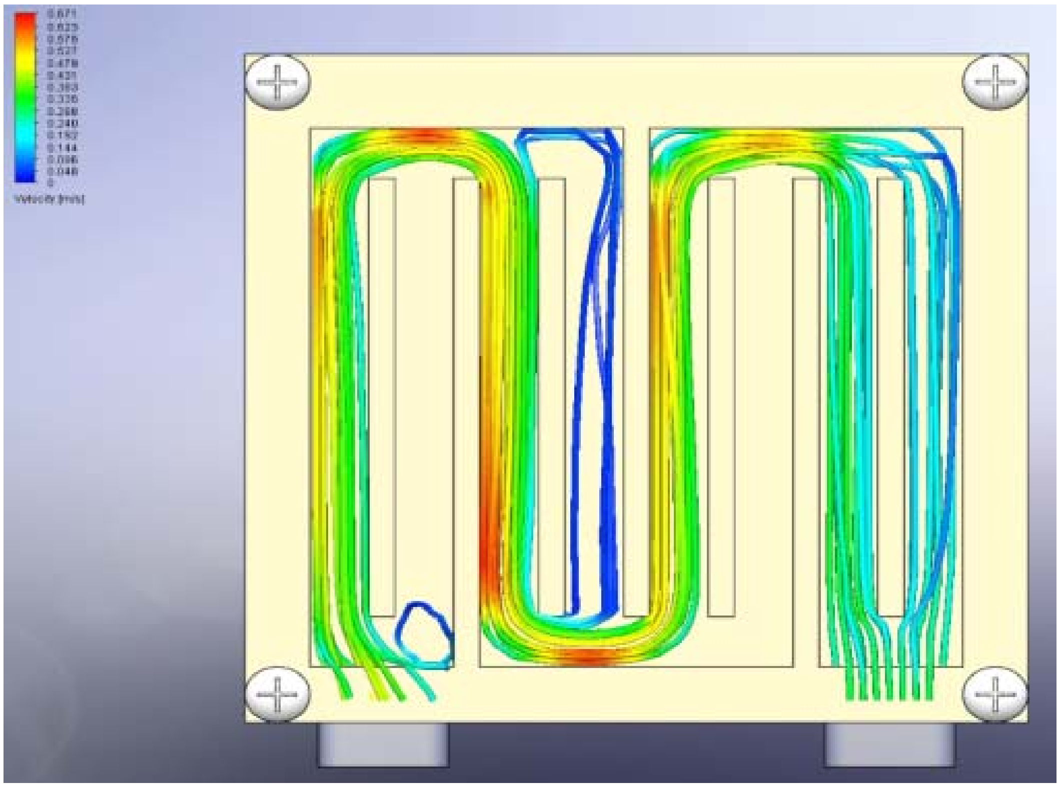


Figure 4.5: Velocity Analysis on Fluid Block

4.2.4 Fluid Block Analysis Results

The FEA model, Figure 4.4, shows a gradient of about 30°C difference between the induced convection, 250°C and the average block temperature, 220°C. This can be used to estimate how much heat the thermal fluid is exposed to given the temperature of the receiver. Because heat absorbed is concentrated in the channel walls, more walls increase the maximum amount of heat transferred to the fluid. Thus, fluid block B was likely to be more effective.

In the velocity model the stagnant areas suggest fluid does not flow through. This happens because the channel dividers do not attach to the body walls, which would guarantee a single fluid path. This may mean that in Block Alpha fluid is moving slowly through channels or is trapped and endlessly cycling. This may be useful to transferring more heat. However, the model also shows the fluid increasing velocity higher than the initial value. This is undesired as the fluid will receive more heat the longer time it spends passing through the block. Looking back at Figure 4.3B, though, it can be guaranteed that the fluid in Beta Block will go through all channels without stagnant space. Because of the advantage of the Beta Block, solar testing protocol was changed to implement this better fluid block iteration.

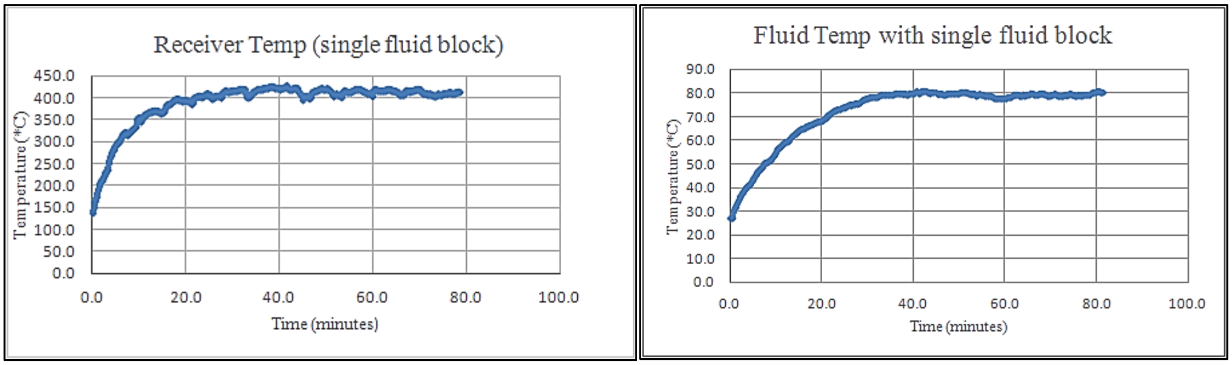
4.3 Solar Testing

Tests were run this past summer with the initial design of the receiver, "alpha." The alpha receiver, Figure 4.6, was slightly smaller than this current receiver and did not have a fin extending from the rear of the cavity.

Figure 4.6: Alpha Solar Receiver Design

With the lack of a fin, the surface area available for heat transfer to a fluid block was minimal, allowing for only one fluid block to be applied at the base of the cavity.

With our receiver design, tests have been run with various components such as the alpha and beta fluid blocks, one or two fluid blocks, and the incorporation of thermoelectric modules. The following Figures, 4.7A and 4.7B, represent the results obtained from a test run with only one fluid block attached to the fin.

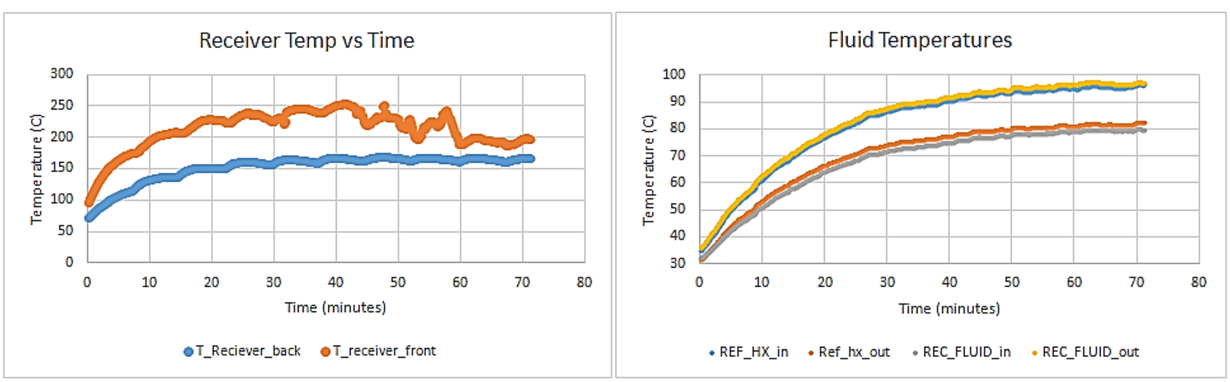


A **B**

Figure 4.7: Temperature response with one fluid block attached to the fin of:
a) Receiver **b)** Fluid Block

From Figure 4.7, the receiver temperature achieves a steady state temperature of approximately 430ºC, while the fluid reaches a steady state temperature of 80ºC.

After tests were conducted with the single fluid block attachment, the subsequent tests progressed to include a pair of fluid blocks. Since two fluid blocks were attached to the rear fin, it was expected that the fluid temperature would further increase, while the receiver temperature would decrease. The following plots in Fig. 4.8A and 4.8B illustrate the results of the temperature tests with two fluid blocks.



A **B**

Figure 4.8: Temperature response with two fluid blocks attached to the fin of:
a) Receiver, front and back **b)** System Fluid

From the above plots, it can be seen that the front of the receiver had a steady state temperature of 250ºC, while the rear of the receiver had a steady state temperature of approximately 165ºC, illustrating that there was a temperature drop along the length of the receiver. The location of these thermocouples on the receiver body is shown in Figure 4.9.

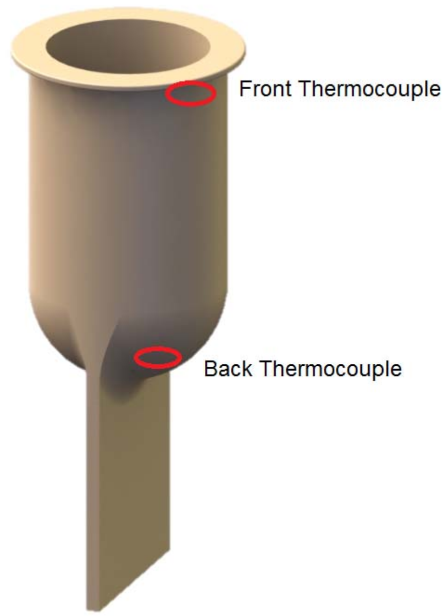


Figure 4.9: Location of thermocouples on the outer wall of the solar receiver

This temperature drop plays an important role in the amount of heat that can be transferred to the fluid at the fin. The fluid temperature plot illustrates that the fluid was able to reach a steady state temperature of approximately 100ºC. This higher temperature can be attributed to the amount of time the fluid is in contact with the fin, as the fluid travels through one block and through a hose to the other, increasing the contact time by a factor of two.

4.4 Refrigerator and Heater Testing

A Watlow Circulation fluid heater was purchased for a test to determine the required fluid temperature for running an absorption chiller refrigerator with our heat exchanger design. This was done using a simple iterative testing process. The system setup in Figure 4.10 had thermocouples attached to the inlet and outlet of both the circulation heater and heat exchanger, and to the inside of the refrigerator.

The testing procedure can be found in Appendix 14.

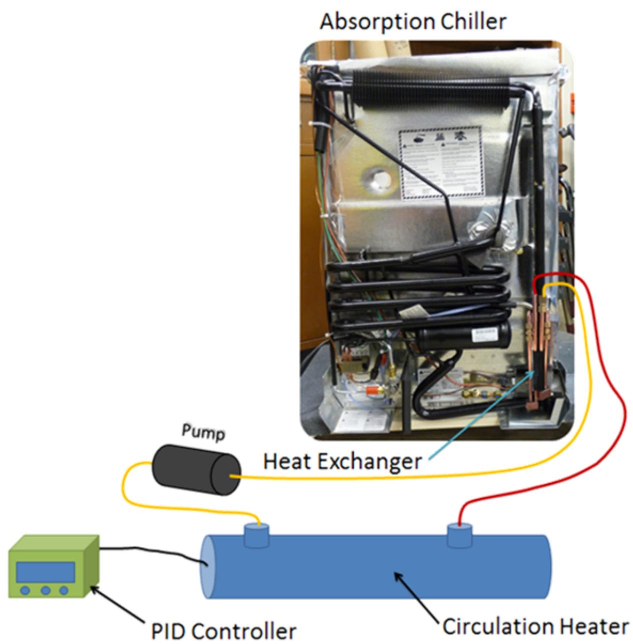


Figure 4.10: Circulation Fluid Test Design

Five tests were performed with increasing temperature ranges to see how the fridge reacted as heat was transferred into the boiler column. Our final test, with fluid temperatures at 150°C caused the boiler column to reach the temperature necessary to initiate the cycle. This necessary temperature is based on boiler column temperature measurements when the system is run with the electric heater (shown in Figure 3.4). Since this electric heater was able to initiate the refrigeration cycle, we know that by reaching the same boiler column temperature as the electric heater, we initiated the cycle. Figure 4.11 shows the initiation of refrigeration. The red dotted line represents the boiler column temperature with the electric heater, and the blue line is the temperature of the boiler column when the heater test was run. As shown the blue line did reach the threshold to initiate the refrigeration cycle. With a longer testing period, the effects would have likely been noticed within the refrigerator[3].

[3] The test pump broke due to a manufacturing issue and a replacement was ordered, but the test depicted in Figure 4.11 was cut short due to the malfunction.

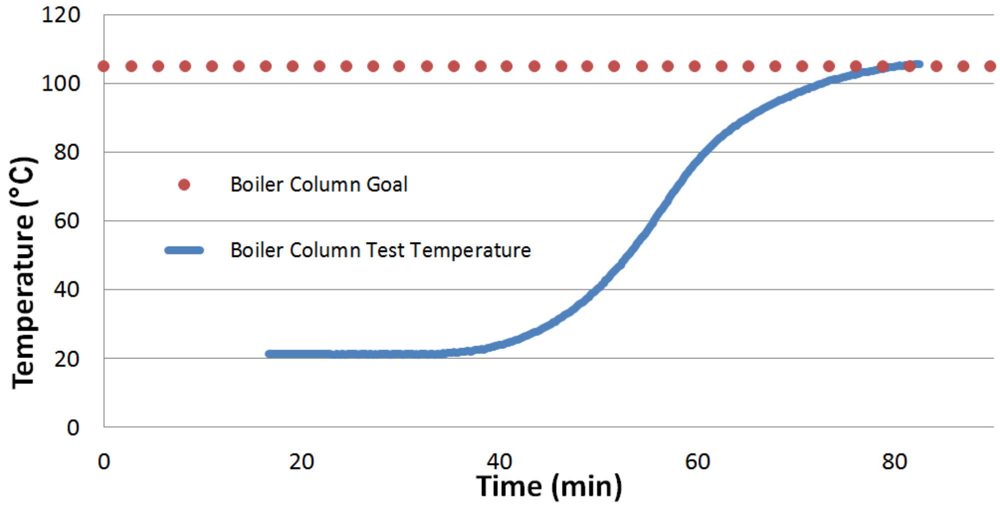


Figure 4.11: Heater Test Results

4.5 Cost Analysis

The cost of our current components was $5,475. The total grant money we received was $17,200, well above our prototyping cost. A precise budget breakdown of our existing expenditures and grant money is given in Appendix 2. Ultimately, we intend to create a product costing $500 to $1,000 (based on feedback from NGOs).

In preparation for mass manufacturing, we created a cost estimation. We chose to base our model on making 1,000 units. The biggest cost reduction potential is with the solar receiver, which cost $2,400 for the prototype. This is due to the cost of making a mold, and customizations when prototyping. When mass manufacturing, the main cost is materials. The company that produced our receiver, Saint-Gobain, estimates that the cost of an additional 1000 units would come out to about $100/receiver.

Another area where costs can be cut is the support materials and insulations. The use of local materials like PVC piping, local lumber, and discarded bicycle frames in the developing nations will cause the price to drop significantly too. This is similarly true for the other component systems, resulting in a total cost reduction from $5,475 to $710. Table 12 shows an estimated cost reduction per component system when mass manufacturing 1,000 units.

Table 12: Manufacture Cost Comparison

Component Systems	Manufacture Cost Now	Mass Manufacture Cost[4]
Solar Tracker	$875.00	$230.00
Solar Receiver	$2500.00	$100.00
Fluid Circulation	$1500.00	$300.00
Absorption Chiller	$600.00	$80.00
Total Cost	**$5,475.00**	**$710.00**

4.6 Patent Search

As part of the completion of the previous summer's design work, our team applied for a patent regarding the design of the receiver module. This patent application speaks of the unique ability of the receiver to transfer heat to the thermal fluid, unlike current research models for concentrated solar power on a residential scale. The provisional patent was filed for this on November 15, 2013 and is shown in Appendix 8.

[4] Assuming 1000 units produced

5 Engineering Standards and Constraints

When designing a device to be used in the developing world, there are several considerations that should be discussed. Below are the standards to which we hold our design and implementation in order to assure our goals are met.

5.1 Environment

The goal of our device first and foremost is to produce refrigeration. It does this by creating thermal energy. This is a change from the traditional refrigerator which uses electricity, and it is for this reason that environmental impact is of large importance in our design. The SCU Handbook describes how we, as engineers, must be aware of the negative effect that our work can have on the environment. For the solar absorption refrigeration system, our team has made great efforts to reduce environmental impacts.

Absorption chiller refrigerators are especially desirable in developing nations for the following reasons: they are low maintenance, powered by thermal energy (not electricity), make little noise, and use non-toxic refrigerants. All of these factors were considered in the design choices for this product. Particularly the use of non-toxic refrigerants such as ammonia, water, and hydrogen gas are appealing to environmental efforts. Freon, a common refrigerant, has been shown to destroy ozone layers and requires an energy intensive compression cycle. Comparatively, absorption refrigeration is very environmentally friendly. This is an issue especially in developing countries where most of the world's new pollution is coming from and where the demand for modern appliances like refrigerators is on the rise.

5.2 Manufacturing

The SCU Engineering Handbook states that designing for manufacturability is "concerned with designing a product in such a way that it can be manufactured efficiently, reliably and within acceptable costs." With our product, although all components mentioned in that quote are important, the factor of most importance is that resources are utilized as efficiently as possible.

This project is a variation of a previous project that designed a system for a solar tracker through means of lead screws that are turned by motors to control the direction the tracker is facing. Their system used a rather large, bulky support to hold the mirror that was tracking the sun. Construction of this support required precision tools that are not available in target markets. Our redesigned tracker system has used a modular approach that can be implemented with automated production by designing for components with simple shapes such as blocks or rods. This approach assists our ability to easily and quickly manufacture these components necessary for our product, while also making it easier for a consumer to easily assemble, fix, or retrofit the product without professional help.

Many of the cost reductions are in materials. The silicon carbide receiver, although designed by our group, requires specialized manufacturing. Some smaller cost reductions are possible by using frugal building supplies; specifically, the holder of the Solar Tracker Mirror. Initial designs for this system used high quality plywood and were cut using precision laser cutters. This design was changed for the final product and could now be built with scrap metal or recycled bicycle frames--both of which are available in Uganda and other sub-Saharan countries. Almost every element in this system, except the refrigerator heat exchanger, was purchased from a retailer, meaning that the manufacturing of these products are outside of our scope.

5.3 Economic

The goal of our device first and foremost is to produce refrigeration. It does this by creating thermal energy. This is a change from the traditional refrigerator which uses electricity, and it is for this reason that environmental impact is of large importance in our design. The SCU Handbook describes how we, as engineers, must be aware of the negative effect that our work can have on the environment. For the solar absorption refrigeration system, our team has made great efforts to reduce environmental impacts.

Absorption chiller refrigerators are especially desirable in developing nations for the following reasons: they are low maintenance, powered by thermal energy (not electricity), make little noise, and use non-toxic refrigerants. All of these factors were considered in the design choices for this product. In most cases the refrigerator is the single appliance that accounts for the most energy usage in a home or business building. A typical refrigerator can use between 500 to 1000 kWh of electrical energy per year. A coal fired power plant, typical of those used in developing nations, releases an average of 1.34 pounds of carbon dioxide into the atmosphere (Buyer's Guide). Our system has the capability of going completely off grid and as such replacing traditional refrigerators with our system will remove a major demand of electrical power, Thereby reducing the amount of greenhouse gases generated in coal power plants.

Also, our system utilizes ammonia, hydrogen gas and water in the refrigeration cycle, none of these chemicals are toxic to the environment and are relatively safe to handle. Typical refrigerants such as Freon and other hydrofluorocarbons (HFC's) are known to cause ozone depletion and have other detrimental impacts to the environment. As such our system effectively removes these chemicals from the environment by providing an alternative to traditional refrigerators.

5.4 Health and Safety

The health and safety of our project is dependent on taking the necessary precautions. Accidents happen, and people are injured. One of our most important tasks as engineers is to make sure that this happens as little as possible. Our device has two potentially hazardous apparatuses, the parabolic mirror and refrigeration temperature.

The reflecting mirror presents a serious danger to users if they put themselves in the path of the solar beam, which can reach temperatures up to 700°C. This could easily burn anyone severely, start a fire, or cause eye damage. Providing appropriate warnings and safety covers will help make sure people do not unknowingly put themselves in harm's way.

Another aspect which poses a risk to health and safety is the temperature of the refrigerator. Food needs to be kept at a low enough temperature to not spoil. The U.S. Food and Drug Administration recommend 1.7 to 5°C for standard refrigeration temperature (FDA). The proper insulation must be used to ensure the temperature stays within the required zone long after the device is no longer running. Following these precautions will help guarantee the health and safety of the users.

One possibility for future development to combat this food temperature safety problem is to incorporate a technical system that could provide an alert if the refrigerator drops below a safe temperature. Such an alert system would add another level of complexity and likely increase cost and need for electricity. Such an addition would need to be weighed with regards to cost and need of the specific communities where the system will be implemented.

5.5 Ethics

The ethical ramifications stem from how the project affects society. Acting ethically means providing truthful information and ensuring precautions are realized and acted upon. The engineering standards previously mentioned all have ethical components that must be addressed. The environmental impacts must be recognized and minimized. The manufacturing resources used must be sturdy enough to provide a working product as well readily available. Economically our product must be as inexpensive as possible and we must ensure that the operating costs are minimized because of the off-grid capability. Health and safety are widely dependent on proper warnings and covers being in place, as well as operators being properly educated about the potential risks of the system. Accidents happen, and products sometimes cause unintended harm. We as engineers have an ethical obligation to address all possible risks and to manage them with appropriate constraints. Knowing the ethical obligations can help manage how much time and effort is put forth.

6 Summary & Future Work

6.1 Summary

This senior design project began with an idea of applying residential-scale concentrated solar power (CSP) in a unique way to benefit the developing world. This progressed into the development of a refrigeration system powered by CSP. In the end, we've designed and built an entire refrigeration system with a working energy efficient solar tracking system, a retrofitted absorption refrigerator, and a custom designed fluid circulation system. With regards to the goals and specifications we set for ourselves at the beginning, we've succeeded in accomplishing some and have clear plans for the completion of goals that were outside our scope. To create a working system, we designed heat exchangers, solar receivers, and fluid circulation loops; we performed months of solar tests with our system as well as circulation heater testing in order to determine the necessary fluid temperatures to initiate our refrigeration cycle. To lower energy usage, we re-worked Arduino coding to achieve the best solar tracking cycle, and implemented an innovative braking system to lower power usage. Though the system is not completely off grid, there is a future possibility of incorporating thermoelectrics to make it totally self-sufficient. In order to decrease costs, we used manufactured fluid equipment to make a fluid circulation system, and an off-the-shelf refrigeration unit that can be mass manufactured at very low cost. We were able to estimate the mass production cost to be $710, which is affordable for the three NGOs we surveyed in Uganda, Nicaragua, and India.

Ultimately, our system, though not fully ready for implementation in the developing world, lays the groundwork for a new application of concentrated solar power (CSP). Because of the broad-ranging positive impacts that refrigeration could provide in developing nations, it is important that many channels of study be pursued. CSP is just one possibility for powering an absorption refrigerator, and we believe that there is promise in the continued study of this unique application of CSP for refrigeration purposes.

6.2 Future Work

One of the challenges with this design is ensuring that the refrigerator will be able to maintain low temperature overnight and during periods where cloud cover blocks the sun. Insulation is just one option for combating this problem, another alternative is thermal energy storage. Thermal energy storage would work to store excess heat from the daytime and use it during the night to maintain high fluid circulation temperatures. If a team chooses to continue this project, we believe that thermal energy storage would provide enough heat to keep the absorption cycle running for at least part of the night. This could be done using zeolite crystals, or a phase change material, like paraffin wax. There are many options available for thermal storage and these could be researched and used for the project.

An additional future project would be to design an absorption refrigerator that works at lower temperatures. Currently, we are using a mass manufactured RV absorption chiller refrigerator that is designed to be run with the heat of a propane flame. This means that the internal pressure of the system, and the ammonia to water ratios, are set to be run by propane. That operating temperature is considerably higher than what is easily obtained by concentrated solar power. A team at Georgia Tech is currently working to design a lower temperature absorption chiller, so there is a potential for a changed design.

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Appendix 1: Product Design Specifications

MECH 194 – Advanced Design I
Product Design Specification – Targets & Benchmarks
Fall 2013

Design Project: Solar Powered Absorption Chiller

Student Names: Claire Kunkle, Craig Carlson, Mark Coulter, Patrick Watson

Benchmark System 1: RV Absorption Refrigerator
Benchmark System 2: Normal Refrigerator (minifridge)
Benchmark System 3: Solar Refrigerator (Cal-Maritime)

Date: 10/16/2013

Characteristic / Parameter	Parameter Units	Design Criticality	Design Target	Benchmark 1 Range	Benchmark 2 Range	Benchmark 3 Range
Size	ft & inches		5'x6'x6'	30"x21"x21"	34"x20"x20"	12"x12"x12"
Mass	pounds		300	65	72	/
Safety	regulated?	x	yes**	yes	yes	no
Installation	hours		<1	<.5	<.5	/
Maintenance	$/year		$5/year	$30/year	$30/year	/
Assembly	hours		<5 hours	none	none	yes
Materials	$	x	local/cheap	expensive	expensive	expensive
Reliability	1-5		1	1	1	2
Cost	$		$1500	$600	$189	$600
Price for Mass Manufacture	$	x	$1000	$600	$189	/
Lifetime	years	x	15 years	8-14	8-14	/
Operating Temperature	Celcius	x	5 C	4 C	4 C	4.4 C
Power Usage	kW		0	.19	.4	0
Operation Costs	$/year		$0	$15	$25	$0
Availability	Local? y/n		n	y	y	n
Toxicity	1-5		1	y/n	y	n
Time to steady state	hours	x	4-5	4-5	2 hours	/
User Interface	1-5		2	1	1	4
Mobility	1-5		5	2	1	1
Ruggedness	1-5		1	4	4	3

* for 1-5 scale, 1 is the best/easiest/healthiest and 5 is the worst

** We hope to meet individual safety regulations for separate parts

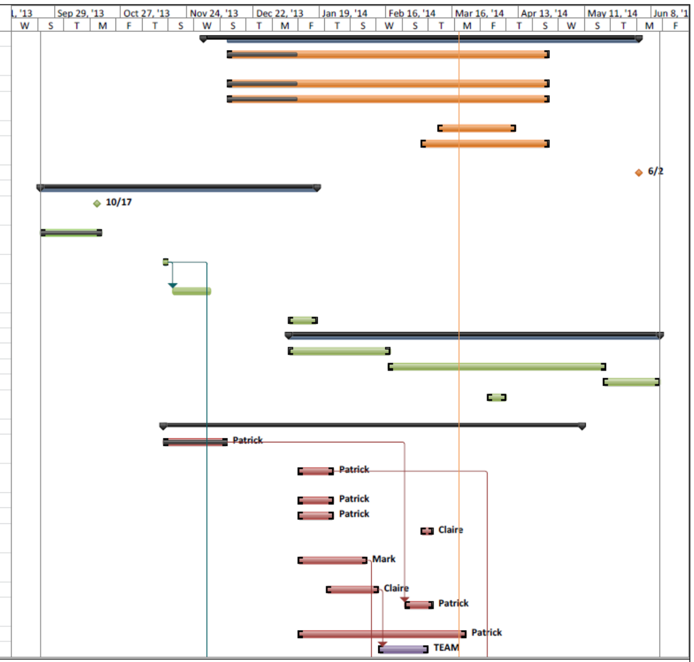
Appendix 2: Project Budget

INCOME				
Category	**Source**	**Sought**	**Committed**	**Pending**
Grant	Roelandts Grant	$10,000.00	$5,200.00	
Grant	School of Engineering	$5,000.00	$2,000.00	
Grant	CEC		$10,000.00	
	TOTAL	**$15,000.00**	$17,200.00	$0.00

EXPENSES				
Category	**Description**	**Estimated**	**Spent**	**Pending**
Solar Tracker Components	Clevis mount, linear actuators, controller, solar sensor, mirror, and supports		$1151.82	
Refrigerator Heat Exchanger	Copper Piping, Pipe Fittings, Soldering Kit & Torch, general safety equipment		$96.00	
Fluid Circulation	Swagelok Piping, Pump, Pump Fittings, Pipe Insulation		$1311.44	
Heater Testing	Circulation Heater & Components, Pump. Swagelok Piping, Fittings, Insulation		$3413.35	
New Mirror Support	Wood, Bolts, Insulation, Mirror		$231.00	
Office Supplies	Laptop, and misc.		$500.00	
	TOTAL	$0.00	$6,703.62	$0.00
	Net Reserve	$10,996.38	$10,496.38	$0.00

Appendix 3: Gantt Chart

ID	Task Name	Start	Finish	Duration	Predecessors	Resource Names
1	**Testing**	**Sun 12/1/13**	**Mon 6/2/14**	**132 days**		
2	Testing with Solar Tracker	Wed 12/11/13	Fri 4/25/14	98 days		
3	Testing Thermal Fluid	Wed 12/11/13	Fri 4/25/14	98 days		
4	Testing with/without TEM	Wed 12/11/13	Fri 4/25/14	98 days		
5	Heater Testing	Mon 3/10/14	Fri 4/11/14	25 days		
6	Testing with Large Mirror	Mon 3/3/14	Fri 4/25/14	40 days		
7	Experimental Results	Mon 6/2/14	Mon 6/2/14	0 days		
8	**Proposal**	**Mon 9/23/13**	**Fri 1/17/14**	**85 days**		
9	Preliminary Design Presentation	Thu 10/17/13	Thu 10/17/13	0 days		
10	Preliminary Design Report	Mon 9/23/13	Fri 10/18/13	20 days		
11	Draft of Conceptual Design Report	Thu 11/14/13	Fri 11/15/13	2 days		
12	Conceptual Design Report	Mon 11/18/13	Tue 12/3/13	12 days	11	
13	Project Proposal	Mon 1/6/14	Fri 1/17/14	10 days		
14	**Thesis**	**Mon 1/6/14**	**Wed 6/11/14**	**113 days**		
15	Thesis Draft 1	Mon 1/6/14	Mon 2/17/14	31 days		
16	Thesis Draft 2	Mon 2/17/14	Mon 5/19/14	66 days		
17	Thesis Final	Mon 5/19/14	Wed 6/11/14	18 days		
18	Table of Contents and Introduction	Mon 3/31/14	Mon 4/7/14	6 days		
19	**Parts Fabrication**	**Thu 11/14/13**	**Fri 5/9/14**	**127 days**		
20	Redesign Mirror Structure 1	Thu 11/14/13	Tue 12/10/13	19 days		Patrick
21	Design Large Mirror Holder	Fri 1/10/14	Fri 1/24/14	11 days		Patrick
22	Motor Shutoff Switch	Fri 1/10/14	Fri 1/24/14	11 days		Patrick
23	Clevis Mount Adapter	Fri 1/10/14	Fri 1/24/14	11 days		Patrick
24	Heat Exchangers Redesign	Mon 3/3/14	Fri 3/7/14	5 days		Claire
25	Reciever Housing Insulation	Fri 1/10/14	Fri 2/7/14	21 days		Mark
26	Design Heater Test	Wed 1/22/14	Wed 2/12/14	16 days		Claire
27	Redesigning Mirror Structure 2	Mon 2/24/14	Fri 3/7/14	10 days	20	Patrick
28	Brake for Lead Screws	Fri 1/10/14	Fri 3/21/14	51 days		Patrick
29	Build Heater Test	Thu 2/13/14	Wed 3/5/14	15 days	26	TEAM

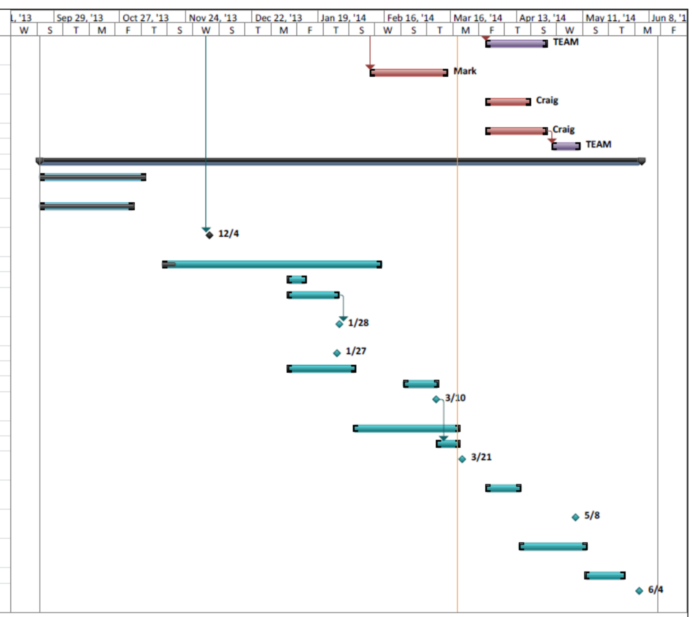


Project: SPAC schedule
Date: Wed 3/19/14

Task · Split · Milestone · Summary · Project Summary · External Tasks · External Milestone · Inactive Task · Inactive Milestone · Inactive Summary · Manual Task · Duration-only · Manual Summary Rollup · Manual Summary · Start-only · Finish-only · Deadline · Progress

Page 1

ID	Task Name	Start	Finish	Duration	Predecessors	Resource Names
30	Building Large Mirror Holder	Mon 3/31/14	Fri 4/25/14	20 days	21	TEAM
31	Redesign Solar Receiver	Mon 2/10/14	Fri 3/14/14	25 days	25	Mark
32	Refriderator Insulation Design	Mon 3/31/14	Fri 4/18/14	15 days		Craig
33	Design Pump Housing	Mon 3/31/14	Fri 4/25/14	20 days		Craig
34	Build Pump Housing	Mon 4/28/14	Fri 5/9/14	10 days	33	TEAM
35	**Course Milestones**	**Mon 9/23/13**	**Wed 6/4/14**	**183 days**		
36	Customer Needs Report	Mon 9/23/13	Wed 11/6/13	33 days		
37	Team Dynamic Reflective Report	Mon 9/23/13	Fri 11/1/13	30 days		
38	Conceptual Design Presentation	Wed 12/4/13	Wed 12/4/13	0 days	11	
39	Ordering Parts	Thu 11/14/13	Fri 2/14/14	67 days		
40	Parts List/Schedule	Mon 1/6/14	Mon 1/13/14	6 days		
41	Design Report Progress Review	Mon 1/6/14	Mon 1/27/14	16 days		
42	Oral Presentation Progress Review 1	Tue 1/28/14	Tue 1/28/14	0 days	41	
43	Budget Update 1	Mon 1/27/14	Mon 1/27/14	0 days		
44	Detail Drawings	Mon 1/6/14	Mon 2/3/14	21 days		
45	FEA Analysis Report	Mon 2/24/14	Mon 3/10/14	11 days		
46	Oral Presentaion Progress Report 2	Mon 3/10/14	Mon 3/10/14	0 days		
47	Assembly Drawings	Mon 2/3/14	Wed 3/19/14	33 days		
48	Progress Report	Mon 3/10/14	Wed 3/19/14	8 days	46	
49	Machine Shop Safety Test	Fri 3/21/14	Fri 3/21/14	0 days		
50	Experimental Protocal	Mon 3/31/14	Mon 4/14/14	11 days		
51	Senior Design Conference	Thu 5/8/14	Thu 5/8/14	0 days		
52	Environmental Impact Report	Mon 4/14/14	Mon 5/12/14	21 days		
53	Business Plan	Mon 5/12/14	Wed 5/28/14	13 days		
54	Open House Hardware	Wed 6/4/14	Wed 6/4/14	0 days		



Project: SPAC schedule
Date: Wed 3/19/14

Task · Split · Milestone · Summary · Project Summary · External Tasks · External Milestone · Inactive Task · Inactive Milestone · Inactive Summary · Manual Task · Duration-only · Manual Summary Rollup · Manual Summary · Start-only · Finish-only · Deadline · Progress

Page 2

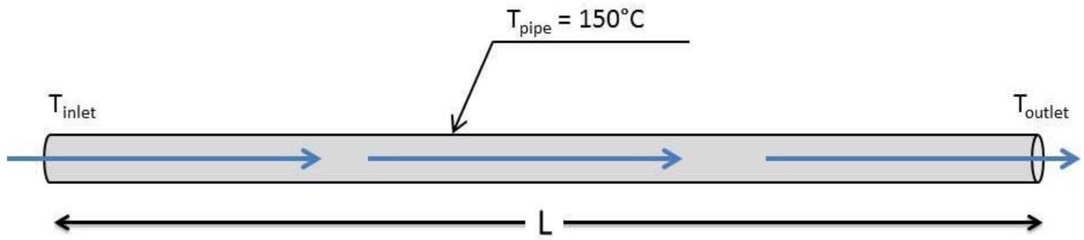
Appendix 4: Heat Exchanger Calculation

```
%Defining Constants
Tc_TEM = 200;
Tin_TEM = 150;
Th_refrig = 120;
Tin_refrig = 160;
temp = 155;
m = .03;
Q = 200;

k_pipe = 400;
dI = 5.6388^(-3);
dO = 6.35*10^(-3);
PI = pi*dI;
PO = pi*dO;

% %DOWTHERM A
T_DOWTHERM_A = [15:50:255];
p_DOWTHERM_A = [1063.5 1023.7 990.7 947.8 902.5 854];
Cp_DOWTHERM_A = [1.558 1.701 1.814 1.954 2.093 2.231];
u_DOWTHERM_A = [.005 .00158 .00091 .00056 .00038 .00027];
k_DOWTHERM_A = [.1395 .1315 .1251 .1171 .1091 .1011];
for i = 1:length(T_DOWTHERM_A)
    Pr_DOWTHERM_A(i) = (Cp_DOWTHERM_A(i)*10^3*u_DOWTHERM_A(i))/k_DOWTHERM_A(i);
end

      T_code = T_DOWTHERM_A;
      p_code = p_DOWTHERM_A;
      Cp_code = Cp_DOWTHERM_A;
      k_code = k_DOWTHERM_A;
      u_code = u_DOWTHERM_A;
      Pr_code = Pr_DOWTHERM_A;
      fluid = 'DOWTHERM_A';

for i = 1:length(T_code)
    if temp < T_code(i)
        break
    else
    end
end

%Interpolation of constants
x = (temp - T_code(i - 1))/(T_code(i) - T_code(i-1));
p = (p_code(i-1)*(1-x)) + p_code(i)*x;
k = (k_code(i-1)*(1-x)) + k_code(i)*x;
Cp = ((Cp_code(i-1)*(1-x)) + Cp_code(i)*x)*10^(3);
mu = (u_code(i-1)*(1-x)) + u_code(i)*x;
Pr = (Pr_code(i-1)*(1-x)) + Pr_code(i)*x;


%SOLVE FOR TEM HX

%Solve for Tex and Tavg
Tex_TEM = (Q/(m*Cp)) + Tin_TEM
Tavg_TEM = (Tin_TEM + Tex_TEM)/2;

%Use NTU/E Method
E_TEM = (Tex_TEM - Tin_TEM)/(Tc_TEM - Tin_TEM);
NTU_TEM = -log(1 - E_TEM);

%Solve for overall heat transfer coefficient
UA_TEM = NTU_TEM*Cp*m;

%Solve for fluid heat transfer coefficient
Re_TEM = (4*m)/(pi*mu*dI);
f_TEM = (0.79*log(Re_TEM)-1.64)^(-2);
Nu_TEM = ((f_TEM/8)*(Re_TEM-1000)*(Pr))/(1+12.7*(f_TEM/8)^.5*(Pr^(2/3)-1));
h_TEM = (Nu_TEM*k)/dI;

%Solve for length
L_TEM = UA_TEM*(log(dO/dI)/(2*pi*k_pipe) + 1/(h_TEM*PI))

%Solve for deltaP and head loss of refrig
deltaP_TEM = (m^2*L_TEM*f_TEM)/(2*p*pi^2*(dI/2)^5);
head_TEM = deltaP_TEM/(p*9.81);

%SOLVE FOR REFRIG HX

%Solve for Tex and Tavg
Tex_refrig = -1*((Q/(m*Cp)) - Tin_refrig)
Tavg_refrig = (Tin_refrig + Tex_refrig)/2;

%Use NTU/E Method
E_refrig = (Tin_refrig - Tex_refrig)/(Tin_refrig - Th_refrig);
NTU_refrig = -log(1 - E_refrig);

%Solve for overall heat transfer coefficient
UA_refrig = NTU_refrig*Cp*m;

%Solve for fluid heat transfer coefficient
Re_refrig = (4*m)/(pi*mu*dI);
f_refrig = (0.79*log(Re_refrig)-1.64)^(-2);
Nu_refrig = ((f_refrig/8)*(Re_refrig-1000)*(Pr))/(1+12.7*(f_refrig/8)^.5*(Pr^(2/3)-1));
h_refrig = (Nu_refrig*k)/dI;

%Solve for length
L_refrig = UA_refrig*(log(dO/dI)/(2*pi*k_pipe) + 1/(h_refrig*PI))

%Solve for deltaP and head loss of refrig
deltaP_refrig = (m^2*L_refrig*f_refrig)/(2*p*pi^2*(dI/2)^5);
head_refrig = deltaP_refrig/(p*9.81);


%Solve for overall head loss and pumping power
head = (deltaP_TEM + deltaP_refrig)/(p+9.81)
PP = (deltaP_TEM + deltaP_refrig)*(m/p)
```

```
%Defining Constants
Tc_TEM = 200;
Tin_TEM = 150;
Th_refrig = 120;
Tin_refrig = 160;
temp = 155;
m = [.02 : .005 : .05];
Q = 200;

k_pipe = 400;
dI = 5.6388^(-3);
dO = 6.35*10^(-3);
PI = pi*dI;
PO = pi*dO;

% %DOWTHERM A
T_DOWTHERM_A = [15:50:255];
p_DOWTHERM_A = [1063.5 1023.7 990.7 947.8 902.5 854];
Cp_DOWTHERM_A = [1.558 1.701 1.814 1.954 2.093 2.231];
u_DOWTHERM_A = [.005 .00158 .00091 .00056 .00038 .00027];
k_DOWTHERM_A = [.1395 .1315 .1251 .1171 .1091 .1011];
for i = 1:length(T_DOWTHERM_A)
    Pr_DOWTHERM_A(i) = (Cp_DOWTHERM_A(i)*10^3*u_DOWTHERM_A(i))/k_DOWTHERM_A(i);
end

      T_code = T_DOWTHERM_A;
      p_code = p_DOWTHERM_A;
      Cp_code = Cp_DOWTHERM_A;
      k_code = k_DOWTHERM_A;
      u_code = u_DOWTHERM_A;
      Pr_code = Pr_DOWTHERM_A;
      fluid = 'DOWTHERM_A';


for i = 1:length(T_code)
    if temp < T_code(i)
        break
    else
    end
end

%Interpolation of constants
x = (temp - T_code(i - 1))/(T_code(i) - T_code(i-1));
p = (p_code(i-1)*(1-x)) + p_code(i)*x;
k = (k_code(i-1)*(1-x)) + k_code(i)*x;
Cp = ((Cp_code(i-1)*(1-x)) + Cp_code(i)*x)*10^(3);
mu = (u_code(i-1)*(1-x)) + u_code(i)*x;
Pr = (Pr_code(i-1)*(1-x)) + Pr_code(i)*x;


for i = 1:length(m);

    %SOLVE FOR TEM HX
    Tex_TEM(i) = (Q/(m(i)*Cp)) + Tin_TEM;
    Tavg_TEM(i) = (Tin_TEM + Tex_TEM(i))/2;

    %Use NTU/E Method
    E_TEM(i) = (Tex_TEM(i) - Tin_TEM)/(Tc_TEM - Tin_TEM);
    NTU_TEM(i) = -log(1 - E_TEM(i));

    %Solve for overall heat transfer coefficient
    UA_TEM(i) = NTU_TEM(i)*Cp*m(i);

    %Solve for fluid heat transfer coefficient
    Re_TEM(i) = (4*m(i))/(pi*mu*dI);
    f_TEM(i) = (0.79*log(Re_TEM(i))-1.64)^(-2);
    Nu_TEM(i) = ((f_TEM(i)/8)*(Re_TEM(i)-1000)*(Pr))/(1+12.7*(f_TEM(i)/8)^.5*(Pr^(2/3)-1));
    h_TEM(i) = (Nu_TEM(i)*k)/dI;

    %Solve for length
    L_TEM(i) = UA_TEM(i)*(log(dO/dI)/(2*pi*k_pipe) + 1/(h_TEM(i)*PI));

    %Solve for deltaP and head loss of refrig
    deltaP_TEM(i) = (m(i)^2*L_TEM(i)*f_TEM(i))/(2*p*pi^2*(dI/2)^5);
    head_TEM(i) = deltaP_TEM(i)/(p*9.81);

    %SOLVE FOR REFRIG HX
    Tex_refrig(i) = -1*((Q/(m(i)*Cp)) - Tin_refrig);
    Tavg_refrig(i) = (Tin_refrig + Tex_refrig(i))/2;

    %Use NTU/E Method
    E_refrig(i) = (Tin_refrig - Tex_refrig(i))/(Tin_refrig - Th_refrig);
    NTU_refrig(i) = -log(1 - E_refrig(i));

    %Solve for overall heat transfer coefficient
    UA_refrig(i) = NTU_refrig(i)*Cp*m(i);

    %Solve for fluid heat transfer coefficient
    Re_refrig(i) = (4*m(i))/(pi*mu*dI);
    f_refrig(i) = (0.79*log(Re_refrig(i))-1.64)^(-2);
    Nu_refrig(i) = ((f_refrig(i)/8)*(Re_refrig(i)-1000)*(Pr))/(1+12.7*(f_refrig(i)/8)^.5*(Pr^(2/3)-1));
    h_refrig(i) = (Nu_refrig(i)*k)/dI;

    %Solve for length
    L_refrig(i) = UA_refrig(i)*(log(dO/dI)/(2*pi*k_pipe) + 1/(h_refrig(i)*PI));

    %Solve for deltaP and head loss of refrig
    deltaP_refrig(i) = (m(i)^2*L_refrig(i)*f_refrig(i))/(2*p*pi^2*(dI/2)^5);
    head_refrig(i) = deltaP_refrig(i)/(p*9.81);

    %Solve for overall head loss and pumping power
    head(i) = (deltaP_TEM(i) + deltaP_refrig(i))/(p+9.81);
    PP(i) = (deltaP_TEM(i) + deltaP_refrig(i))*(m(i)/p);

end
```

Appendix 5: Fluid Block Temperature Change Calculations

FOR THE COPPER WATER BLOCKS, IT IS POSSIBLE TO MODEL THEM AS A SIMPLE HEAT EXCHANGER. THE TEMPERATURE INLETS AND OUTLETS FOR DIFFERENT LENGTHS OF BLOCKS A & B CAN BE CALCULATED THEORETICALLY AS SHOWN BELOW.



<u>Objective :</u> Find T_{outlet} when

Block A Length = 398.59mm

Block B Length = 565.66mm

- **<u>Assumptions:</u>**
- Internal flow through a pipe
- Constant Surface Temp:
- T_{pipe} is constant across length
- T_{inlet} = 25°C
- Negligible tube wall conduction resistance
- Incompressible liquid
- negligible viscous dissipation.

<u>Equations Used:</u>

$$Nu_D = 3.66 + \frac{0.0668\, Gz_D}{1 + 0.04\, Gz_D^{2/3}} = \frac{hD}{k} \qquad (8.57)$$

$$Gz_D = D/_L \, Re_D \, Pr \qquad (8.56)$$

$$Re_D = \frac{4\dot{m}}{\pi D \mu} \qquad (8.6)$$

$$\frac{\Delta T_0}{\Delta T_i} = \frac{T_s - T_{m,o}}{T_s - T_{m,i}} = \exp\left[-\frac{P * L}{\dot{m}\, c_p} h\right] \qquad (8.41b)$$

$$T_{m,o} = \left(\exp\left[-\frac{P * L}{\dot{m}\, c_p} h\right] * T_s - T_{m,i}\right) + T_s \qquad (8.41b \text{ rewritten})$$

Fluid Block MatLab CODE:

```
%% Constants
D = 0.0055; % (meters) Diameter of Pipe
row = 862;  % (kg/m^3) Density of Duotherm
Velocity = 0.6;  % (meters/sec) Average of Velocity Flow
Ac = (pi/4)* (D^2); %  Cross Sectional Area of Pipe

Mdot = row * Velocity * Ac % Mass Flow Rate

Pr = 1.0; % Prandlt number - Assumption: similar to saturated water at 150 C
Mu = .000173; % Dynamic Viscosity - Assumption: similar to saturated water at 150 C
P = pi*D % Surface Perimeter
L = .39855;  % (meters) Length of pipe, Block A
L = .5656 % (meters) Length of pipe, Block B
Cp = 2.072; % (kj/kg K) Heat capacity of Duotherm
Ts = 423; % Tsurface of Pipe
Tmi = 298; % Tinlet
k = .019296; % thermal conductivity (W/mk)

%% Calculations

Red = (4* Mdot)/(pi*D*Mu) % Renyolds Number

Gzd = (D/L)*Red*Pr % Graetz number

Nud = 2.98 + [(0.0668 * Gzd)/(1+(0.04*((Gzd)^2/3)))] % Average Nussult Number 2.98 is a correction
% for a square tube from 3.66
h = (k*Nud)/D

Tmo = [-(((exp ((- (P*L)/(Mdot * Cp)*h)))* (Ts - Tmi)) - Ts)] - 273  %equation 8.41b
```

Block A - T_{outlet}	142.8 Celsius
Block B - T_{outlet}	147.8 Celsius

Conclusion:

These hand calculations support the decision to use the B-type water block. The reason for this is that the design of the B blocks effective adds approximately 0.2 meters of length to the distance the Duratherm needs to flow through. This increased length means the Duratherm takes more time to flow through the water block and as such more heat is transferred. This translates to a 5 degree difference between the two designs, a substantial difference for the same amount of energy provided.

Appendix 6: Detail Drawings

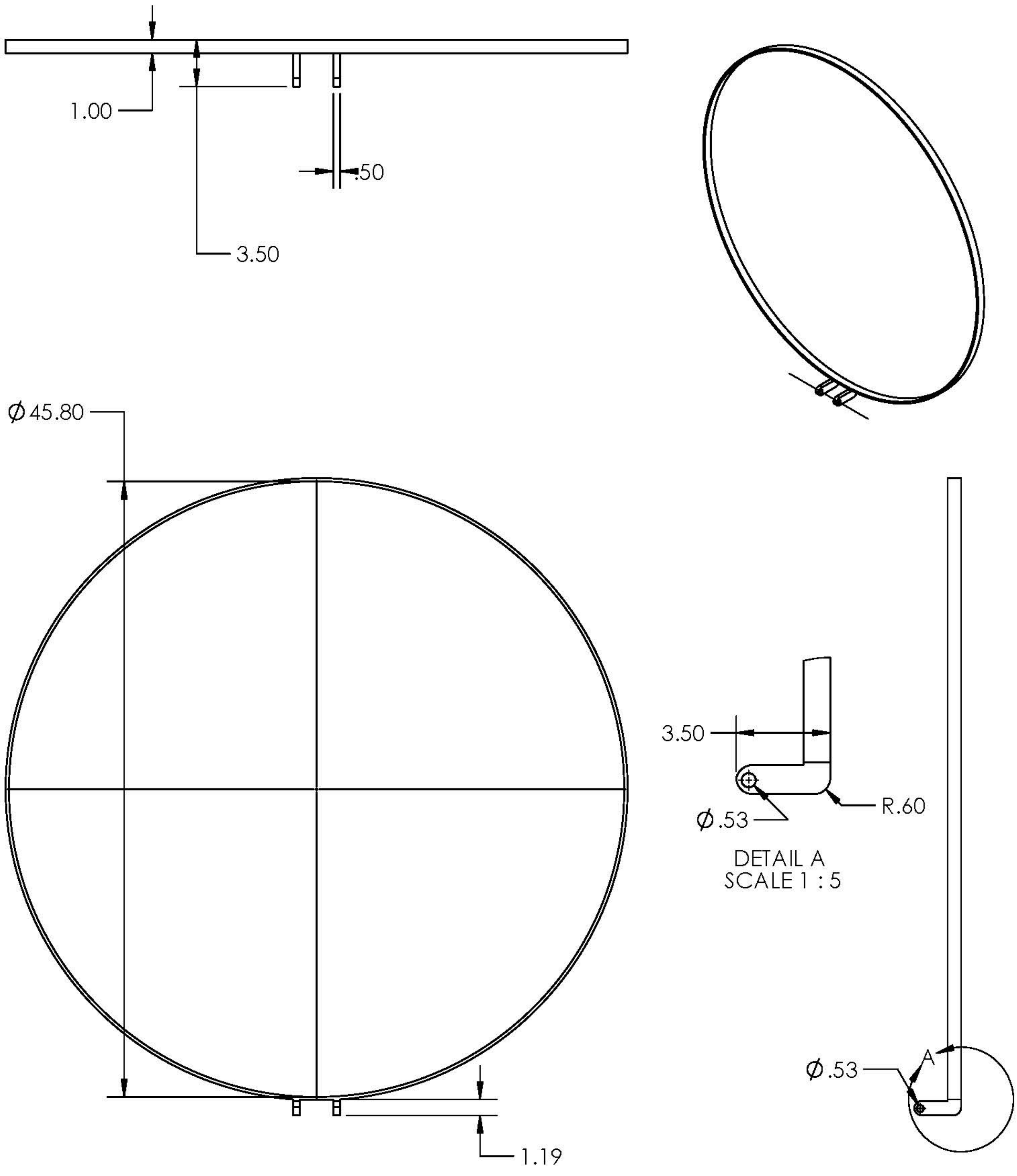
Sheet No	Sheet Name
A - 01	Tracker Assembly
A - 02	Mirror Ring
A - 03	Mirror Supports
A - 04	Receiver Arm
A - 05	Rear Arm
A - 06	Front Arm

B - 01	Heat Exchanger Assembly
B - 02	Custom U-Bend
C - 01	Receiver Holder
C - 02	Receiver with Fin

	Part Number	Part Name	Qty
Mirror Support	MS - 01	Rear Arm	1
	MS - 02	Front Arm	2
	MS - 03	3/8" Pin	3
	MS - 04	Mirror Ring	1
	MS - 05	Mirror Supports	2
	MS - 06	Receiver Arm	3
	MS - 07	1/4" nuts, bolts, and washers	6
	MS - 08	1/2" nuts, bolts, and washers	2
	MS - 09	Mirror Pan	1
	MS - 10	Misc wood	-
	MS - 11	Misc steel piping	-

Receiver Holder	REC - 01	Receiver with Fin	1
	REC - 02	Receiver Holder	1

Heat Exchanger	HX - 01	1/4" NPS Copper Piping 2"	2
	HX - 02	1/4" NPS Copper Piping 6"	2
	HX - 03	1/4" NPS Copper Piping 8"	2
	HX - 04	1/4" NPS Copper 90 Deg Angle	4
	HX - 05	Custom U-Bend	2
Mirror	MIR - 01	46" Acryllic Mirror	1



		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/64 ANGULAR MACH ± 1 deg TWO PLACE DECIMAL ± .05		NAME	DATE	
			DRAWN	Patrick	2/03/2014	TEAM NAME: Solar Absorption Chiller
			CHECKED	Craig	5/18/2014	
			ENG APPR.			Mirror Ring
			MFG APPR.			
		MATERIAL Aluminium	Q.A.			
			COMMENTS:			
NEXT ASSY	USED ON	FINISH				SIZE A · PART # MS-04 · Sheet # A-02 · REV.
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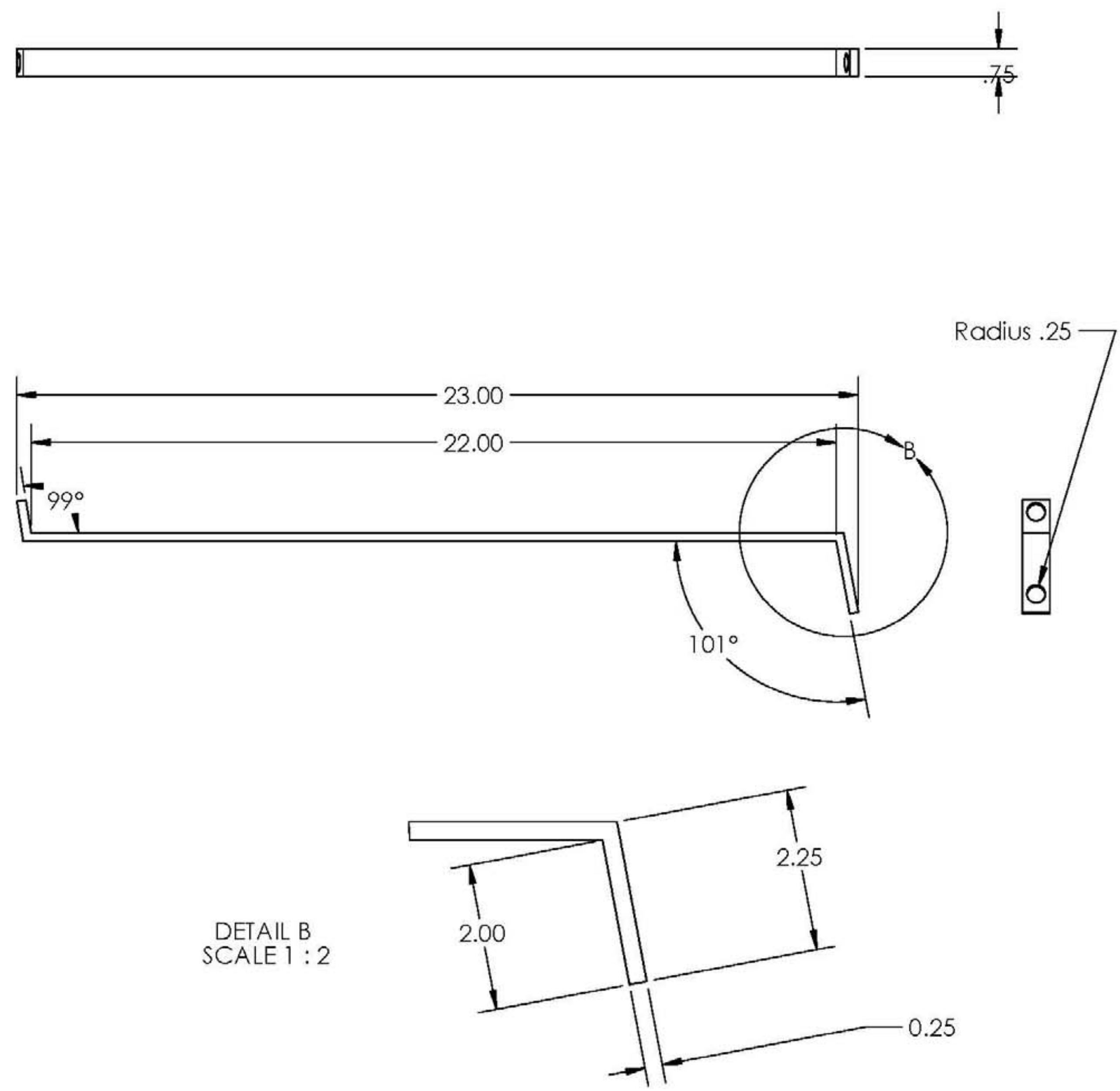
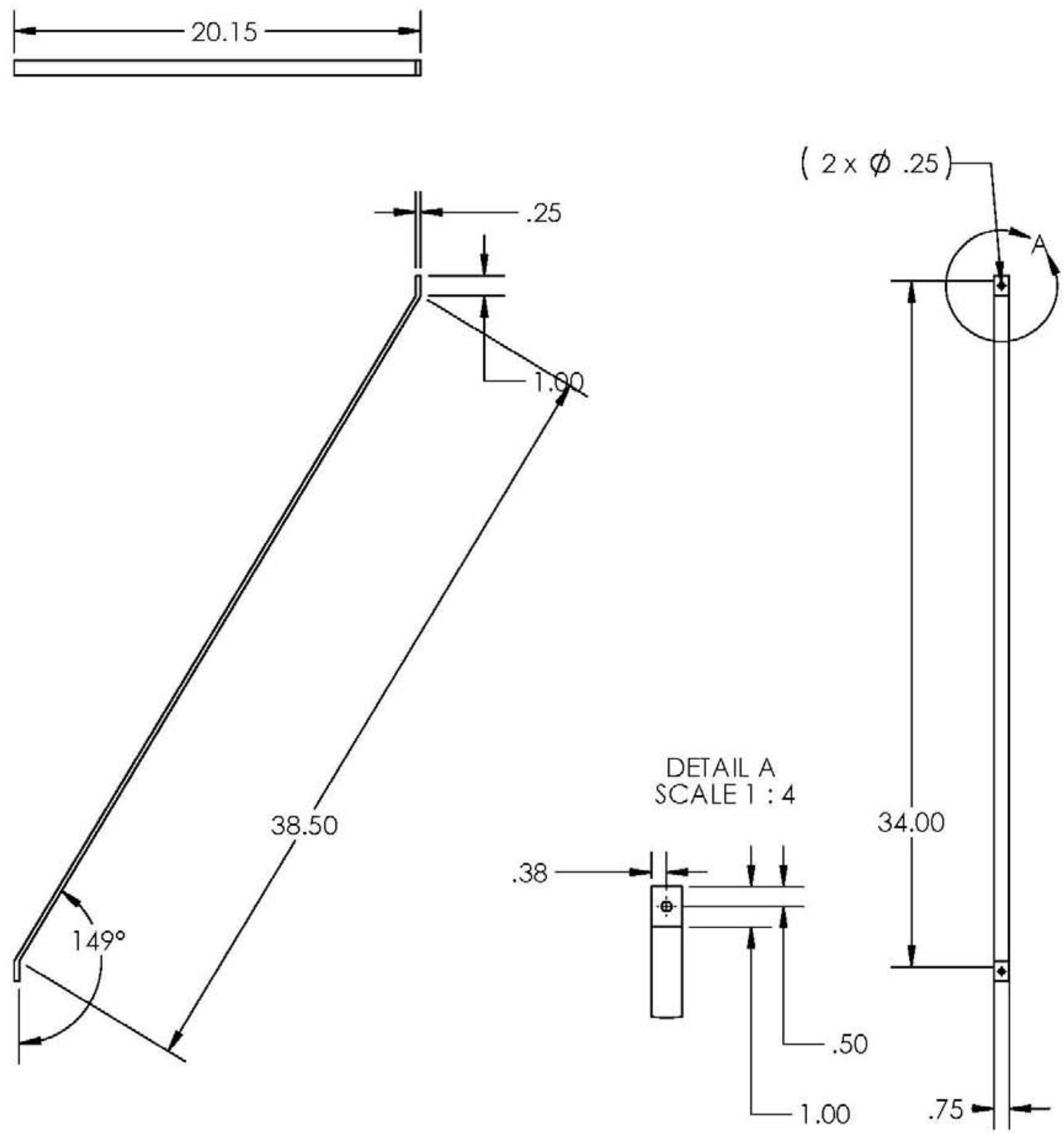


				NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/64 ANGULAR MACH ± 1 deg TWO PLACE DECIMAL ± .05	DRAWN CHECKED	Patrick Craig	2/03/2014 5/18/2014	TEAM NAME: Solar Absorption Chiller
			ENG APPR.			Tracker Assembly
			MFG APPR.			
		MATERIAL Aluminium	Q.A.			
			COMMENTS:			
NEXT ASSY	USED ON	FINISH				SIZE A · PART # MS-05 · Sheet # A-03 · REV.
						SCALE: 1:15 · WEIGHT: · SHEET 3 OF 10



NOTES:
1. Part duplicated for full assembly

		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/64 ANGULAR MACH ± 1 deg TWO PLACE DECIMAL ± .05		NAME	DATE	TEAM NAME: Solar Absorption Chiller
			DRAWN	Patrick	2/03/2014	
			CHECKED	Craig	5/18/2014	
			ENG APPR.			Rear Arm
			MFG APPR.			
		MATERIAL Aluminium	Q.A.			
		FINISH	COMMENTS:			
NEXT ASSY	USED ON					SIZE A; PART # MS-06; Sheet # A-05; REV.
						SCALE: 1:15; WEIGHT:; SHEET 4 OF 10

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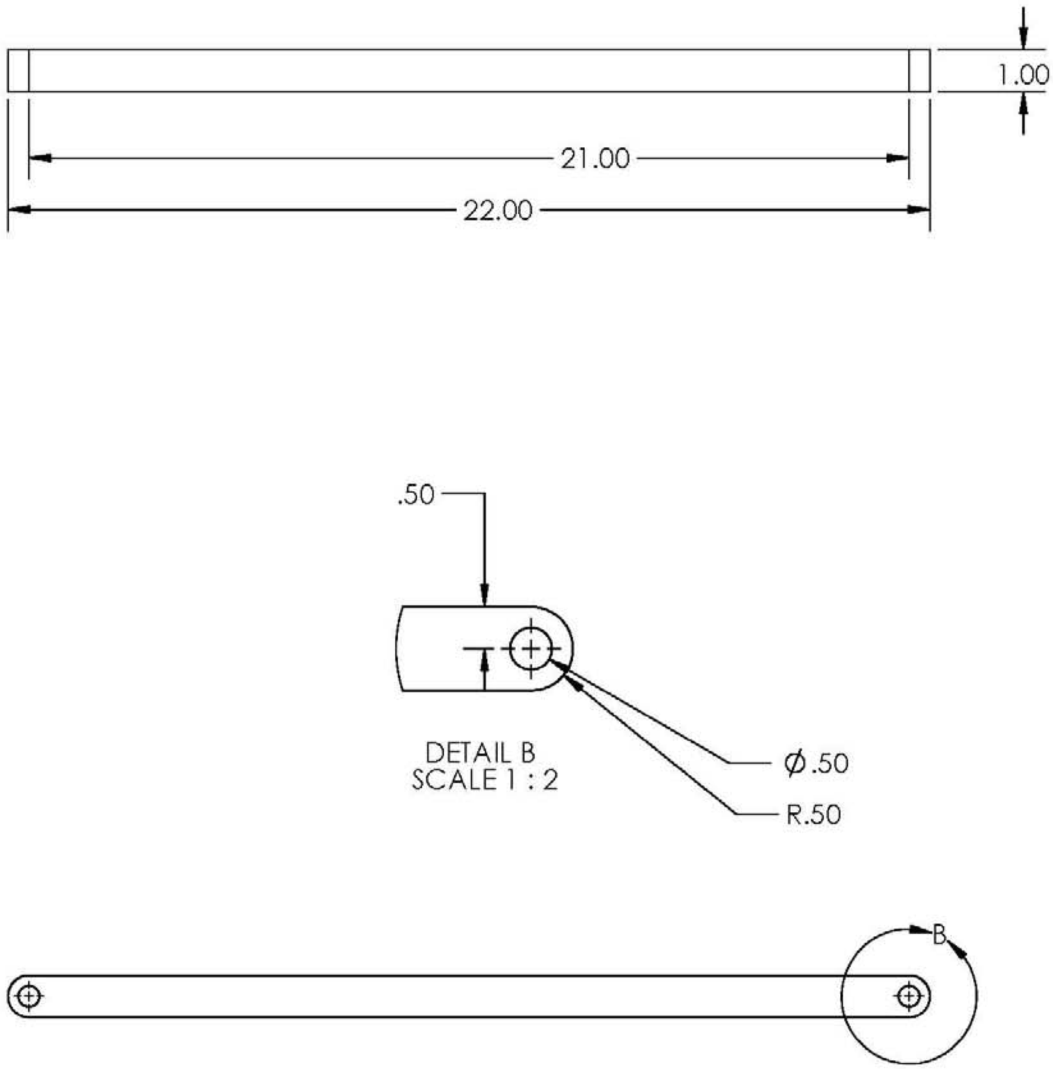

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			DRAWN	Patrick	2/03/2014	TEAM NAME: Solar Absorption Chiller
			CHECKED	Craig	5/18/2014	
			ENG APPR.			Rear Arm
			MFG APPR.			
		MATERIAL Aluminium	Q.A.			
			COMMENTS:			
NEXT ASSY	USED ON	FINISH				SIZE A · PART # MS-06 · Sheet # A-05 · REV.
						SCALE: 1:15 · WEIGHT: · SHEET 5 OF 10

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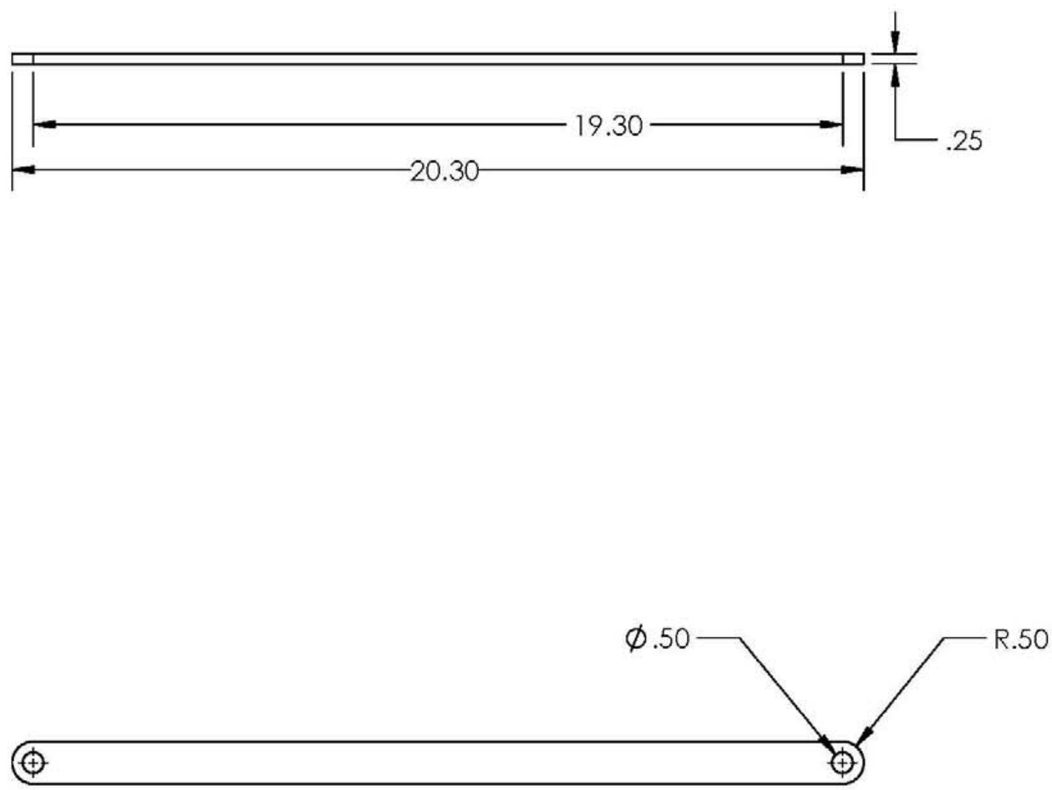

		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/64 ANGULAR MACH ± 1 deg TWO PLACE DECIMAL ± .05		NAME	DATE	
			DRAWN	Patrick	2/03/2014	TEAM NAME: Solar Absorption Chiller
			CHECKED	Craig	5/18/2014	
			ENG APPR.			Front Arm
			MFG APPR.			
		MATERIAL Aluminium	Q.A.			
			COMMENTS:			
NEXT ASSY	USED ON	FINISH				SIZE A PART # MS-02 Sheet # A-06 REV.
						SCALE: 1:15 WEIGHT: SHEET 6 OF 10

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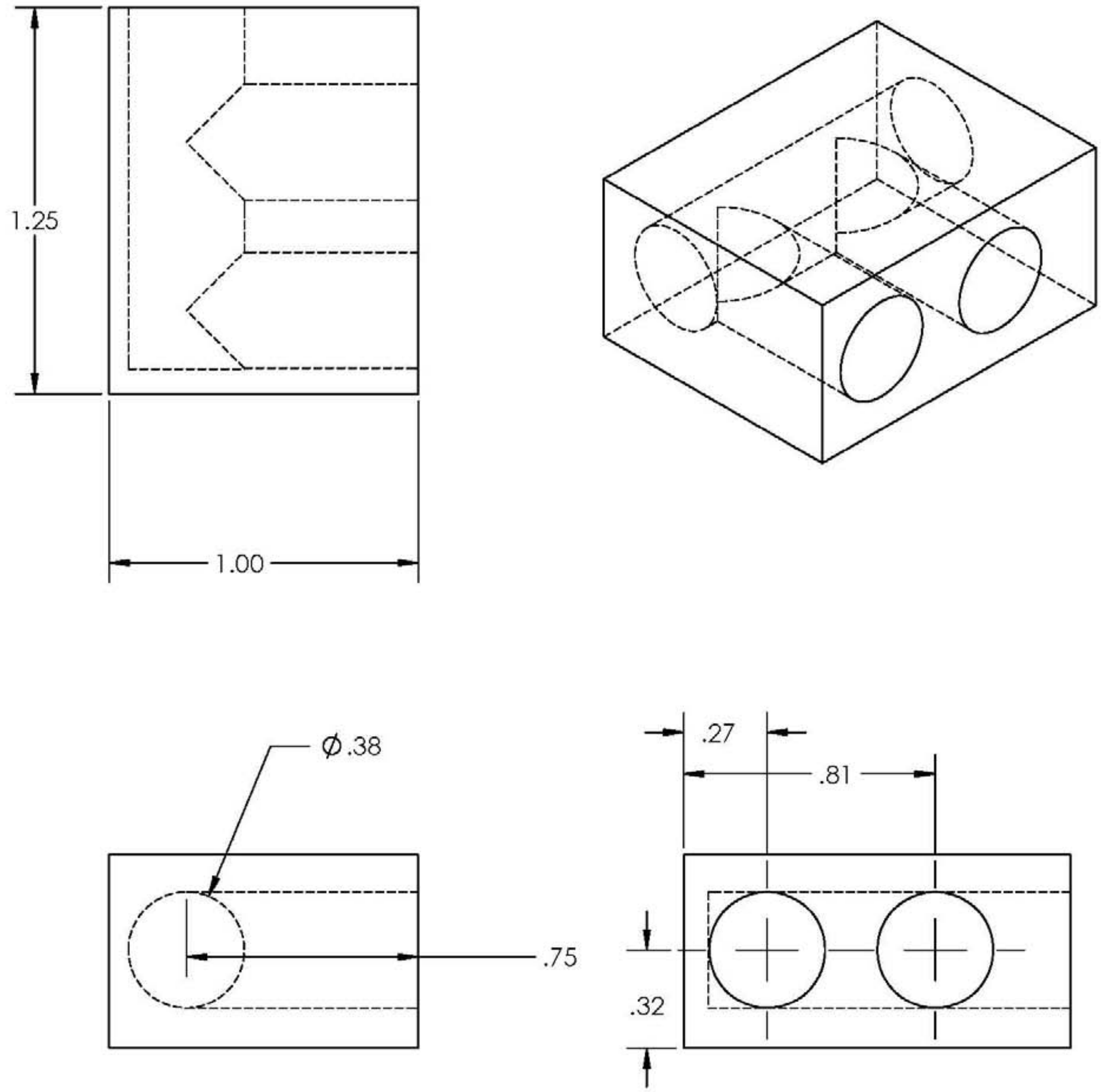

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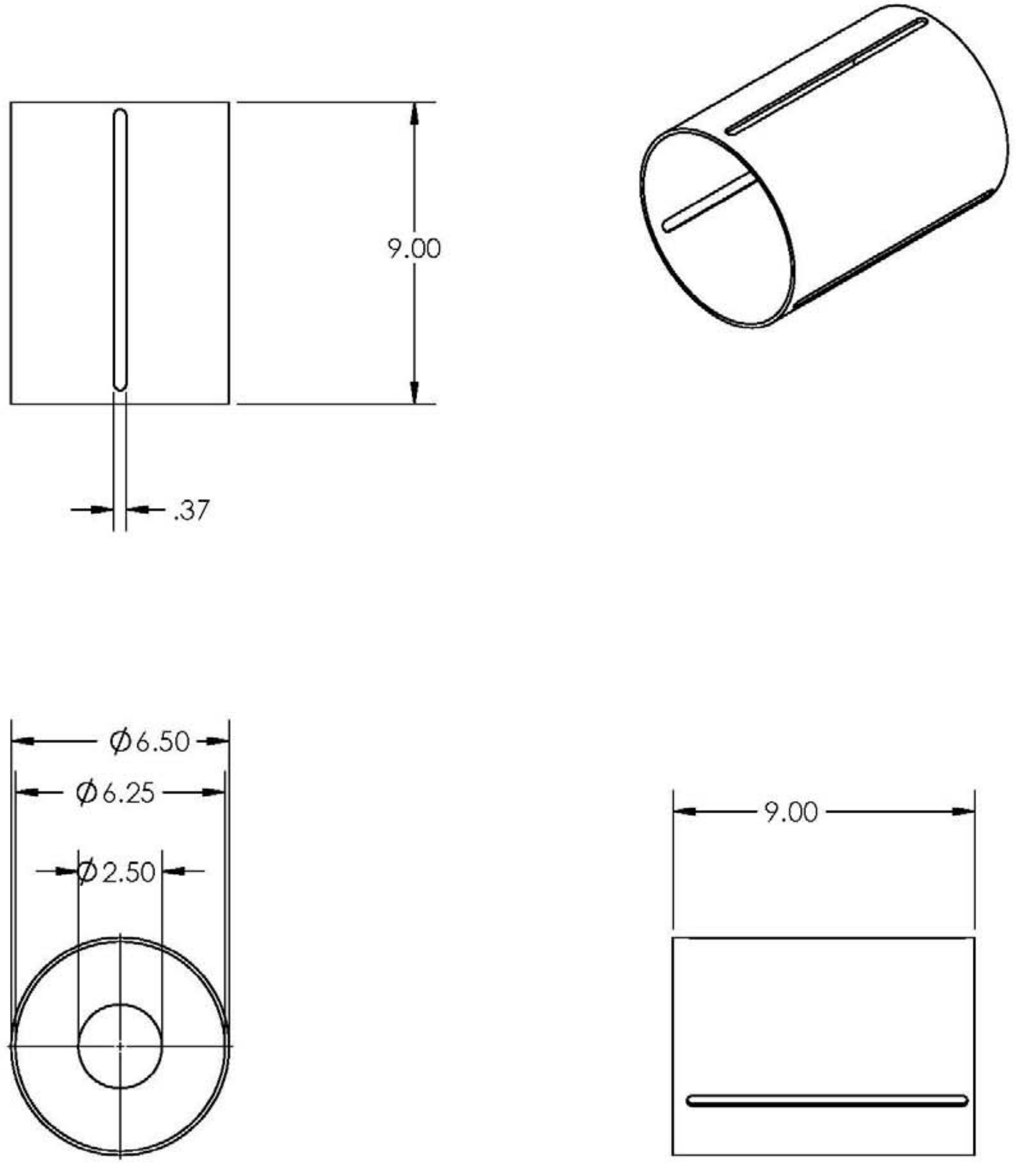
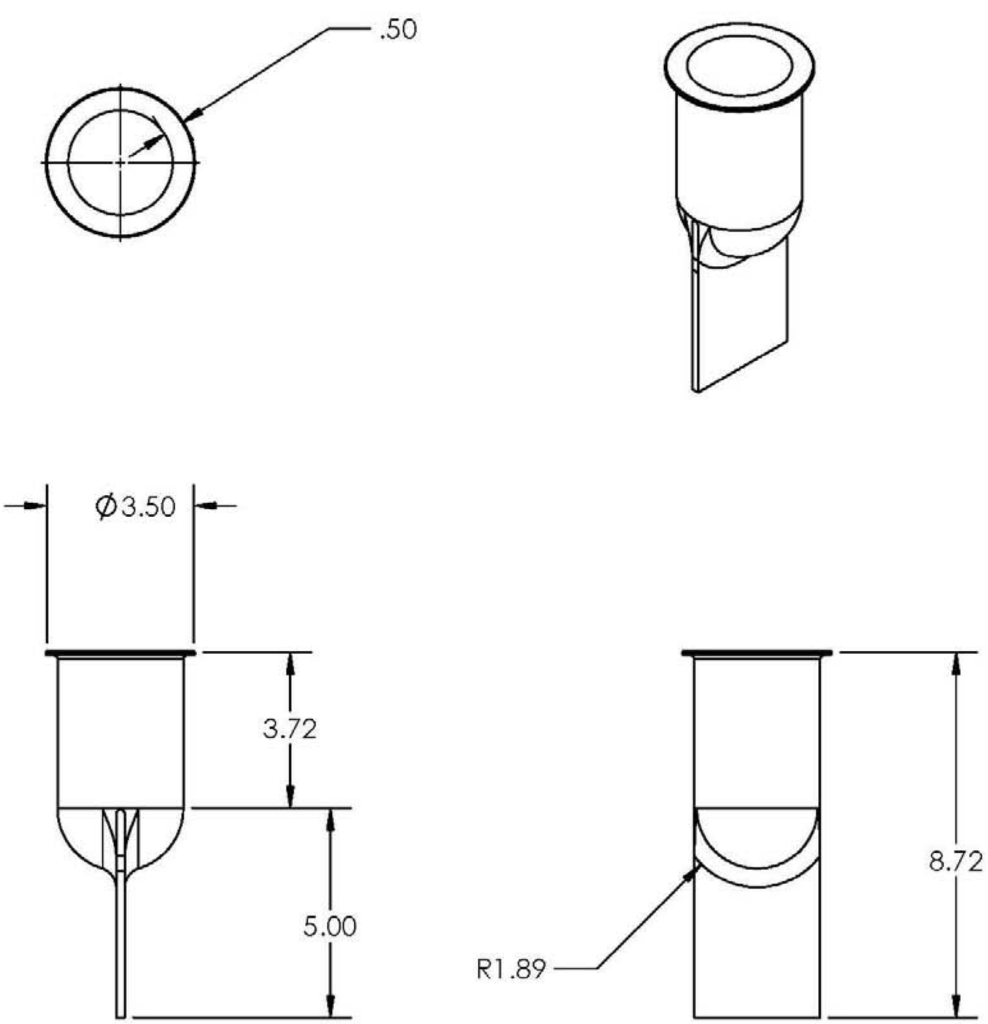
				NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/64 ANGULAR MACH ± 1 deg TWO PLACE DECIMAL ± .05	DRAWN	Claire	2/03/2014	TEAM NAME: Solar Absorption Chiller
			CHECKED	Craig	5/18/2014	
			ENG APPR.			Custom U- Bend
			MFG APPR.			
		MATERIAL Aluminium	Q.A.			
			COMMENTS:			
NEXT ASSY	USED ON	FINISH				SIZE A · PART # HX -05 · Sheet # B-02 · REV.
						SCALE: 1:15 · WEIGHT: · SHEET 8 OF 10



DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/64 ANGULAR MACH ± 1 deg TWO PLACE DECIMAL ± .05		NAME	DATE	TEAM NAME: Solar Absorption Chiller	
	DRAWN	Patrick	2/03/2014		
	CHECKED	Craig	5/18/2014		
	ENG APPR.			Receiver Holder	
	MFG APPR.				
MATERIAL Aluminium	Q.A.				
FINISH	COMMENTS:			SIZE A PART # REC - 02 Sheet # C-01	REV.
				SCALE: 1:15 WEIGHT:	SHEET 9 OF 10

NEXT ASSY	USED ON

PROPRIETARY AND CONFIDENTIAL



				NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/64 ANGULAR MACH ± 1 deg TWO PLACE DECIMAL ± .05	DRAWN	Clarie	2/03/2014	TEAM NAME: Solar Absorption Chiller
			CHECKED	Craig	5/18/2014	
			ENG APPR.			Receiver w/Fin
			MFG APPR.			
		MATERIAL Aluminium	Q.A.			
			COMMENTS:			
NEXT ASSY	USED ON	FINISH				SIZE A PART # REC-01 Sheet # C-02 REV.
						SCALE: 1:15 WEIGHT: SHEET 10 OF 10

PROPRIETARY AND CONFIDENTIAL

Appendix 7: Assembly Drawings

Sheet No	Sheet Name
A - 01	Tracker Assembly
A - 02	Mirror Ring
A - 03	Mirror Supports
A - 04	Receiver Arm
A - 05	Rear Arm
A - 06	Front Arm

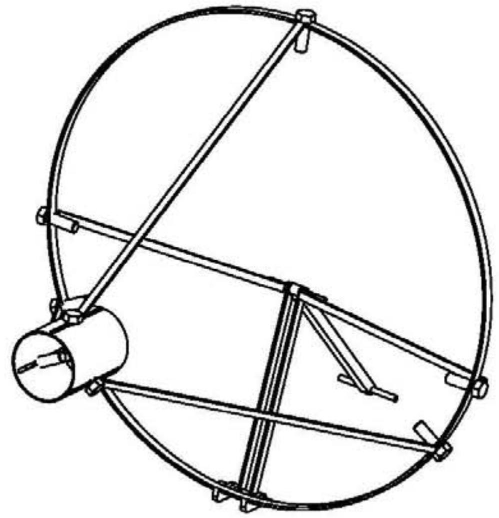
B - 01	Heat Exchanger Assembly
B - 02	Custom U-Bend
C - 01	Receiver Holder
C - 02	Receiver with Fin

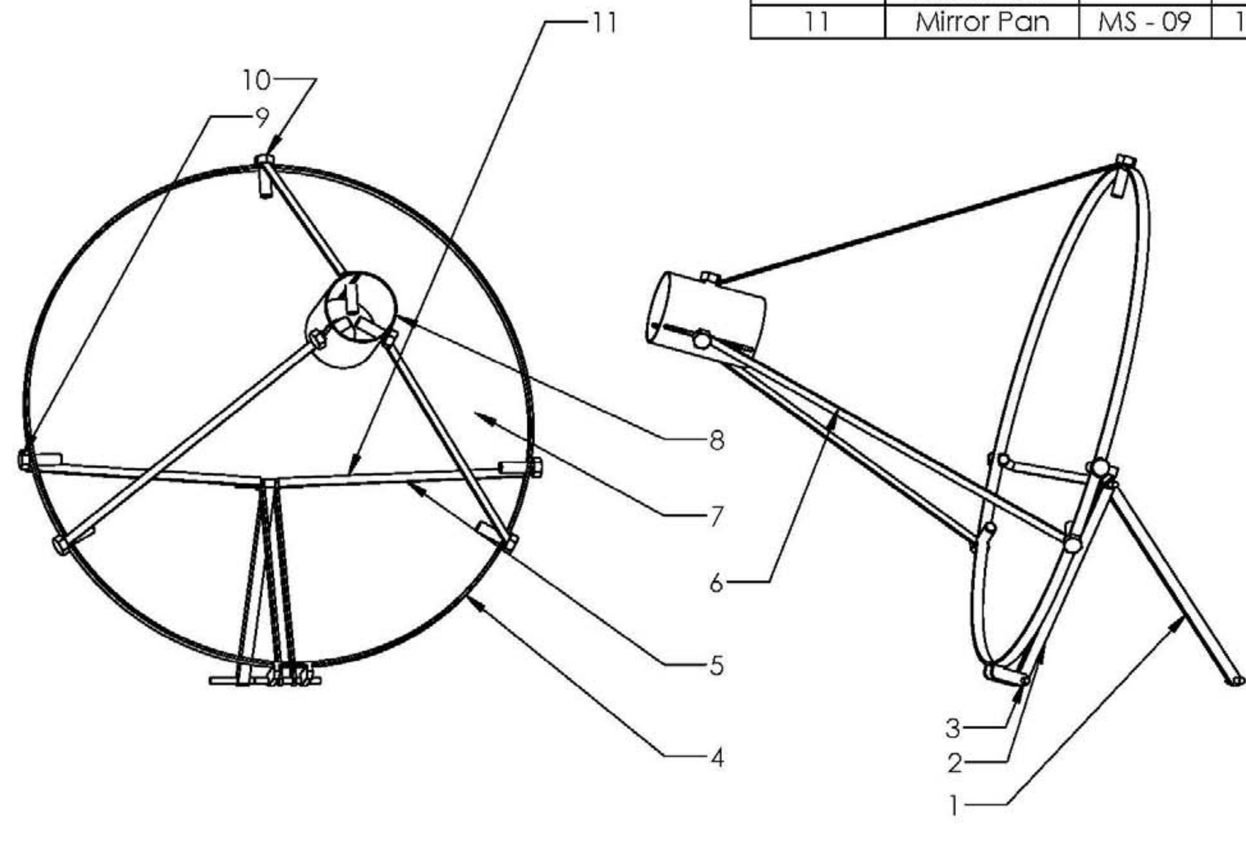
	Part Number	Part Name	Qty
Mirror Support	MS - 01	Rear Arm	1
	MS - 02	Front Arm	2
	MS - 03	3/8" Pin	3
	MS - 04	Mirror Ring	1
	MS - 05	Mirror Supports	2
	MS - 06	Receiver Arm	3
	MS - 07	1/4" nuts, bolts, and washers	6
	MS - 08	1/2" nuts, bolts, and washers	2
	MS - 09	Mirror Pan	1
	MS - 10	Misc wood	-
	MS - 11	Misc steel piping	-

Receiver Holder	REC - 01	Receiver with Fin	1
	REC - 02	Receiver Holder	1

Heat Exchanger	HX - 01	1/4" NPS Copper Piping 2"	2
	HX - 02	1/4" NPS Copper Piping 6"	2
	HX - 03	1/4" NPS Copper Piping 8"	2
	HX - 04	1/4" NPS Copper 90 Deg Angle	4
	HX - 05	Custom U-Bend	2
Mirror	MIR - 01	46" Acryllic Mirror	1

ITEM NO.	Part Name	Part Number	QTY.
1	Rear Arm	MS - 01	1
2	Front Arm	MS - 02	2
3	Pin	MS - 03	3
4	Mirror Ring	MS - 04	1
5	Mirror Supports	MS - 05	2
6	Reveiver Arm	MS - 06	3
7	45" Acrylic Mirror	MIR - 01	1
8	Reveiver Holder	REC - 02	1
9	1/4" Bolts w/nuts & washers	MS- 07	6
10	1/2" Bolts w/nuts &washers	MS - 08	2
11	Mirror Pan	MS - 09	1





DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/64
ANGULAR MACH ± 1 deg
TWO PLACE DECIMAL ± .05

	NAME	DATE
DRAWN	Patrick	2/03/2014
CHECKED	Craig	5/18/2014
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TEAM NAME: Solar Absorption Chiller

Tracker Assembly

MATERIAL: Aluminium

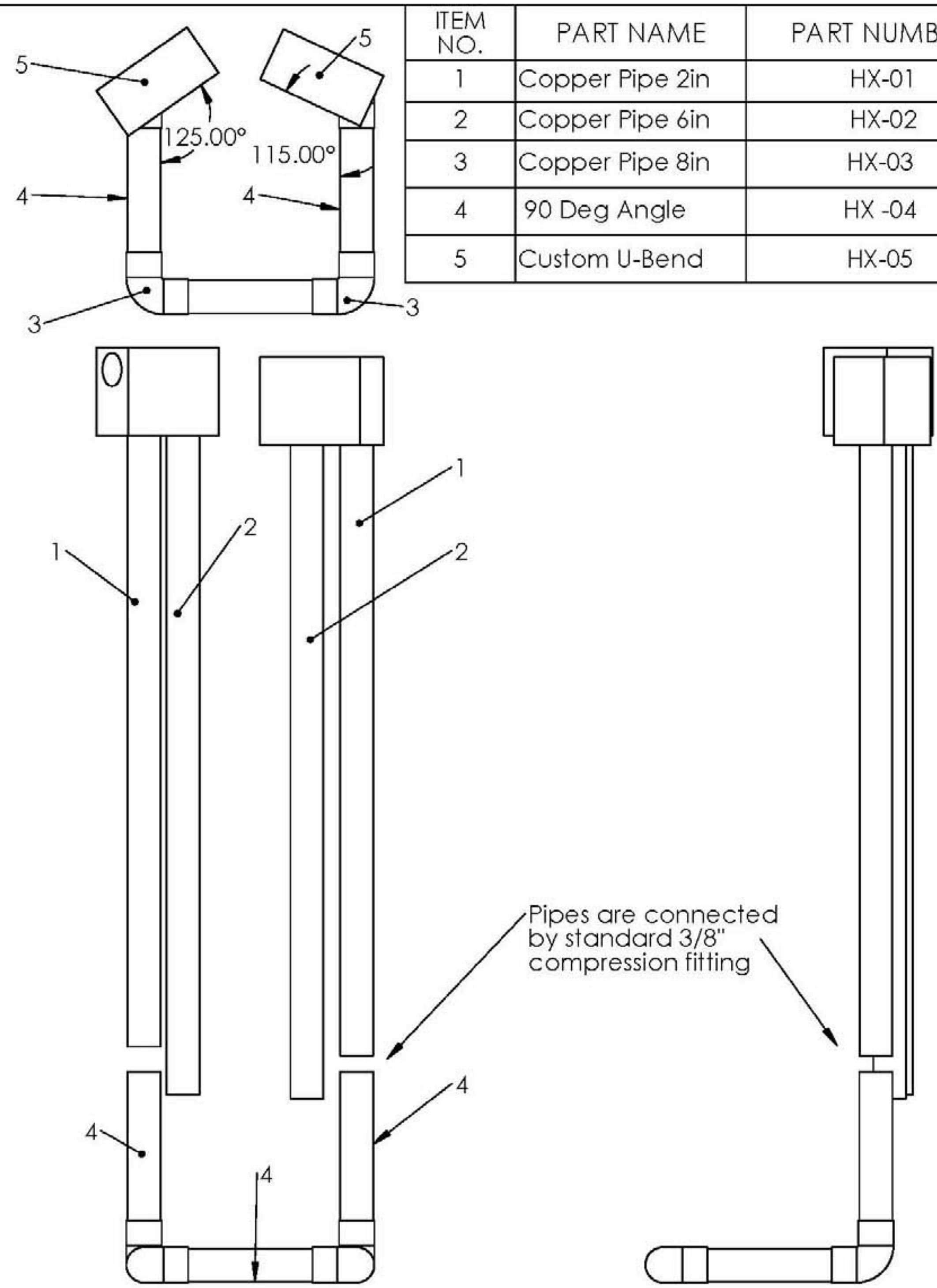
FINISH

NEXT ASSY | USED ON

SIZE A | PART # | Sheet # A-01 | REV.

SCALE: 1:15 | WEIGHT: | SHEET 1 OF 10

ITEM NO.	PART NAME	PART NUMBER	QTY.
1	Copper Pipe 2in	HX-01	2
2	Copper Pipe 6in	HX-02	2
3	Copper Pipe 8in	HX-03	2
4	90 Deg Angle	HX -04	4
5	Custom U-Bend	HX-05	2



DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± 1/64 ANGULAR MACH ± 1 deg TWO PLACE DECIMAL ± .05		NAME	DATE	TEAM NAME: Solar Absorption Chiller		
	DRAWN	Claire	2/03/2014			
	CHECKED	Craig	5/18/2014			
	ENG APPR.			Heat Exchanger Assembly		
	MFG APPR.					
MATERIAL Aluminium	Q.A.					
FINISH	COMMENTS:			SIZE A	PART #	Sheet # B-01 REV.
NEXT ASSY / USED ON				SCALE: 1:15	WEIGHT:	SHEET 7 OF 10

PROPRIETARY AND CONFIDENTIAL
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Appendix 8: Patent Disclosure

Provisional *e*Docket Data Sheet

*e*Docket™ generated 11/15/2013

Case Reference and Status

Lumen Ref. No.: **SCU-111/PROV**

Case Status: **Filed**

Client Ref. No.: **S13-S01**

Assoc. Ref. No.:

Title: **Solar Receiver Design for Thermoelectric Power Generation and Waste Heat Utilization**

Filing Data

Application No.: **61/904956**

Filing Date: **11/15/2013**

Assignment No.:

Recordation Date:

Applicant(s)

Assignee(s): Santa Clara University

Licensee(s):

Associate:

Gov. Agency:

Contract No.:

Inventor(s)

Hohyun Lee
Claire Kunkle
Mark F. Wagner
Rachel Donohoe

Prosecution History

0 1 2 3 4 5 6 7 8

11/15/2013 **SPROV**

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PROVISIONAL PATENT APPLICATION

OF

HOHYUN LEE

CLAIRE KUNKLE

MARK F. WAGNER

RACHEL DONOHOE

FOR

SOLAR RECEIVER DESIGN FOR THERMOELECTRIC POWER GENERATION AND WASTE HEAT UTILIZATION

FIELD OF THE INVENTION

This invention relates to solar receivers. In particular, the invention relates to methods, devices and systems of solar receivers for thermoelectric power generation and waste heat utilization.

DETAILED DESCRIPTION

The core of a concentrated solar power (CSP) system is the solar receiver. Current designs for CSP systems are focused on industrial scale operation, leaving the only residential solar systems to photovoltaic panels. Photovoltaic panels are an inefficient form of solar power because they only utilize a small portion of the solar spectrum and they operate at low efficiencies that are worsened by heat. CSP systems on a residential scale provide thermal energy, which can be used for a variety of purposes including hot water, space heating, and absorption refrigeration.

The invention involves a solar receiver to be attached to a residential scale CSP system. The invention incorporates thermoelectrics to produce electricity as well as waste heat that can be used for many residential applications that use thermal energy.

The invention is composed of a silicon carbide solar receiver, two thermoelectric modules (TEMs), a pair of copper water blocks, fluid piping, and a clamp to effectively utilize solar heat for the production of electricity and heating of a thermal fluid.

The key component in these is the solar receiver. In this cavity, solar rays are collected and contained. The silicon carbide material for our receiver (**Figure 1**) is particularly successful at absorbing and retaining the heat. This is heightened by the unique geometry of our receiver, designed to optimize blackbody performance.

The receiver can reach temperatures of up to 800°C. The addition of a fin for the receiver shown in **Figure 1** is a necessary element for the receiver to effectively transfer heat to the thermoelectrics that are attached to each side of the fin.

Thermoelectric modules (TEMs) produce heat due to the Seebeck effect. The temperature difference from one side of the module to the other produces a voltage which is proportional to the temperature difference. To maximize temperature gradient and their voltage output, the TEMs are placed on both sides of the receiver fin, with their respective hot sides placed flat against the fin. The high contact surface area achieved by the use of a fin will increase the performance of the TEMs. On the outer-facing cold sides of the TEMs, two custom designed copper water blocks are placed. This is shown in **Figure 2**.

When a thermal fluid is flowing through these blocks, they will assist in cooling the cold side of the TEM. This will increase performance of the TEM as well as heat the thermal fluid. The waste heat for the system will not be lost but will instead go from the TEM to the thermal fluid. This arrangement will be clamped on to the fin of the silicon carbide receiver as shown in **Figure 3**.

The clamping mechanism shown in **Figure 3** is beneficial because it provides pressure to assist in surface contact between all parts of the system. Additionally, the clamp connects the two cold sides, whereas designs with single thermoelectric clamps require a contact between the cold side and the hot receiver. This leads to unwanted heat transfer and an increase in the cold side temperature, and decrease in the TEM performance.

The clamping mechanism could have variations to accomplish different racking assemblies. The clamp could be done as shown in **Figure 3** or it could be part of a fuller stand that attaches to the concentrated solar system. These adjustments will be made based on the application or size of the system. One example is shown in **Figure 4**.

Also shown in **Figure 3** are the inlet and outlet hoses for the thermal fluid. These are able to be attached to various systems to provide heat. Possible applications include hot water heating, where a closed loop circulation of thermal fluid could act as assistance to the traditional hot water heater, reducing the need for gas or electric heating. Additionally, a thermal fluid could circulate in the floor or walls of a house to provide space heating; often called radiant floor heating. Thermal fluid could also be the heat provided to run a gas absorption refrigerator. Certain retrofits would be necessary on the refrigerator unit, but the heat provided from a thermal fluid could be the energy to run such a refrigerator.

Embodiments of the invention with the addition of a fin provides significant advantages over these other designs. First, water blocks can be easily exchanged or fixed if issues arise. Second, this design allows for the incorporation of thermoelectric modules. TEMs would not be able to get surface contact on these other designs, whereas a fin creates the ideal flat surface for maximum contact and heat transfer. The addition of TEMs creates a source of electricity which adds value to a system that would only provide thermal energy without TEMs.

Other embodiments, further teachings and/or examples related to the invention are described in **Appendix A** (12 pages) and **Appendix B** (1 page) as well as in **Figures 1-4** (2 pages). **Appendices A** and **B** and **Figures 1-4** are hereby incorporated to this provisional in their entirety.

SCU-111/PROV Figures

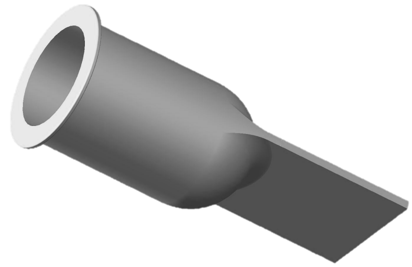

Figure 1: Silicon Carbide Receiver with Fin

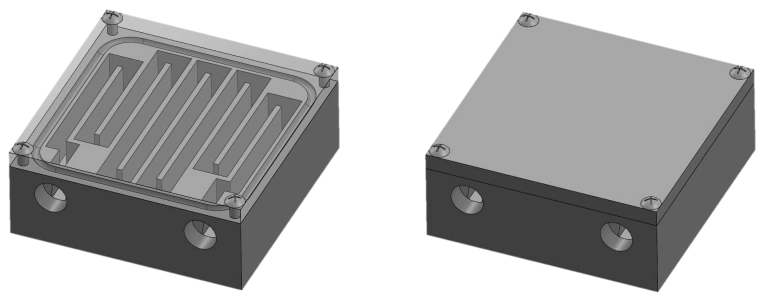

Figure 2: Copper water blocks for thermal fluid heating and TEM cooling

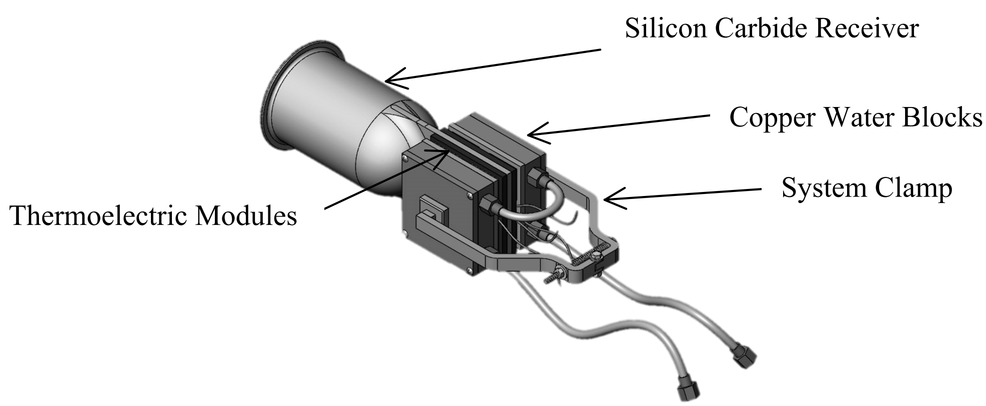

Figure 3: Receiver Device Design with TEMs, water blocks, clamp, and fluid piping

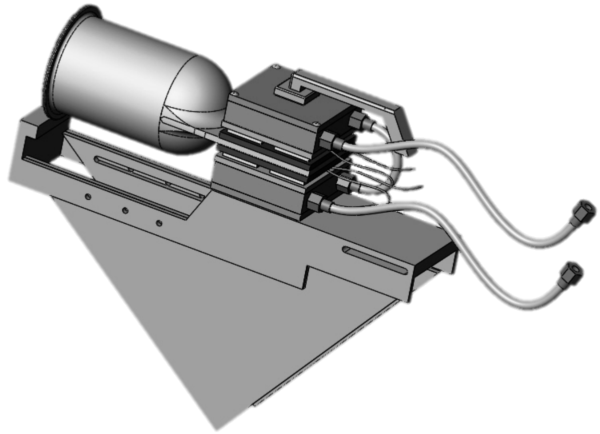

Figure 4: Full body clamping mechanism included in arm attachment.

SOLAR THERMOELECTRIC ENERGY FOR RESIDENTIAL SCALE COMBINED HEAT AND ELECTRICITY

Summary

The objective of this project is to provide heat and electricity to a single-family home from concentrated solar energy using thermoelectric modules. There are two major techniques to utilize solar energy; photovoltaics (PV) that directly convert light into electricity, and solar thermal energy that heats working fluids to run a turbine or to provide domestic hot water. Although solar thermal energy can generate both electricity and heat, application has been limited to utility-scale power generation due to expensive parts and high installation costs. In order to address these issues, we propose a combined thermoelectric and heat system that exploits a low-profile economic solar tracker. Concentrated solar thermal energy is firstly converted into electricity using thermoelectric modules, and rejected heat from the thermoelectric system will further be extracted for an absorption chiller, domestic hot water, or space heating. This system targets an overall cost of $3,000 to provide 1 kW of electricity and 9 kW of heat, with a payoff period of 4 years or less. In this project, we will evaluate optimized working conditions and demonstrate a scaled (1/10) model.

1) Goal

The goal of this project is to determine the feasibility of using thermoelectric modules to provide electricity and heat to a single-family home from concentrated solar power.

2) State-of-the-Art

Concentrated Solar Power (CSP) has historically been the most cost effective method of harnessing solar energy for electricity production on the utility scale [1]; solar energy is reflected using mirrors and concentrated into a receiver to heat a working fluid that runs a turbine. CSP also possesses a distinctive potential for combined cooling, heating, and power (CCHP) generation systems due to the high temperature of rejected heat. Waste heat present after electricity generation can be further extracted for space heating, domestic hot water, and absorption chiller/refrigeration. Energy systems with CCHP have a much higher energy conversion efficiency compared to other technologies [2-4]. Up to 75% of incoming solar radiation can be converted into useful energy including electricity. Despite of the benefits of CSP, the cost per energy produced is not competitive at the residential scale, since a small mechanical system has a large ratio of parasitic heat loss to power production and high component/installation costs per power output.

Although utility-scale CSP has developed and shown success over the past few decades [5], small-scale CSP for distributed combined heat and electricity has not developed mainly due to economic challenges. CSP requires a solar tracker, which alone constitutes up to 40% of the installation cost in CSP. Moreover, existing systems generate electricity mostly through the use of turbines, which are inefficient and expensive at the small scale. Turbines also cause noise and require regular maintenance. Up until 2009, CSP systems were only provided on the scale of 25 kW or more [6, 7]. The emergence of a 3 kW system in 2009 targeted the small scale, however, the cost of the system remained too high to appeal to single-family residences [8].

The objective is to provide an economically viable, residential scale concentrated solar power system through utilizing thermoelectric modules and a low-profile tracker. Thermoelectric materials directly convert heat into electricity at a solid state, making them reliable, easily scalable, and free of vibration or noise [9]. Thermoelectric systems have been served as the power systems of many deep space missions for more than 30 years. Unlike photovoltaics (PV), their energy conversion efficiency does not degrade with increasing temperature and the entire spectrum of solar energy can be utilized. Thermoelectric modules show higher power to area / weight ratios and generate more power under cloudy conditions than PV cells. The major drawback of this technology is low efficiency. With currently available materials, energy conversion efficiency is barely 10% under a temperature difference of 200K. Despite low efficiency, thermoelectric materials have the advantage of generating electricity from any temperature difference. They can generate electricity under small temperature differences, where the use of other energy conversion technologies cannot be economically justified. It is almost the only solution for energy harvesting from wasted heat, which is otherwise ignored. For combined heat and electricity, low conversion efficiency has less adverse effects, since rejected heat can be further extracted for other purposes. At the residential scale, most of electricity-intense appliances are related to heating or cooling, which can be replaced with thermal energy using absorption chillers. Hence, the thermoelectric system is an economically viable solution for the residential scale combined heat and electricity from concentrated solar power. Currently, most of research efforts have been focused on the development of highly efficient thermoelectric materials [10-12]. Consequently applications have only been restricted to niche markets, such as space missions or car seat cooling/heating. The system will also enhance public appreciation of this technology and stimulate practice of sustainable electricity generation.

Another key feature of the system is the use of a low-profile economic solar tracker that was recently developed by the principal investigator (PI) [13]. Because of the high installation and fixed costs of existing trackers, the U.S. Department of Energy (DOE) has challenged researchers to reduce the installation cost of heliostat fields from $200 per square meter to $70 to lower total capital costs on utility-scale power plants by 25% [14]. High fixed costs exist for conventional heliostats because of the robust steel supports needed for stability [15]. Specifically, the two main cost drivers beside installation in large heliostat fields are the drive motor assemblies and the mirror support/structure/foundation [16]. The installation of this heavy hardware is the other major component of tracker assembly cost and requires an automated assembly and deployment system [17].

The predominant two-axis tracker design is commonly termed a mast tracker. Mast trackers require a very stout pole, or "mast", to be drilled deep into the ground to support normal loading. The mast height is at least one half of the panel height above the ground so that the tracker can orient toward the sun at low elevation angles. The requisite foundations result in considerable geological concerns for site planning, as well as heavy machinery, contributing to the installation costs [18]. Since existing two-axis trackers control their load from a single central point, the drive assemblies must be very heavy duty and added trusses are often needed to keep the structure from flexing or sagging at the extremes. Several two-axis mast trackers have been designed with reduced installation costs as a motivating factor. The PVT 7.2DX, manufactured by PV Trackers, utilizes a tripod structure for support. The system is compatible with helical piles reducing installation costs by eliminating the need for concrete foundations [19]. The Google RE<C initiative designed a two-axis heliostat also with a triangular base, and ground securing is accomplished with a single helical pile [20]. The Opel SF-45 is a utility-grade tracker for use with PV panels. The manufacturer claims it can be installed by a two person team without any field welding [21]. Qbotix has developed a system which allows an entire array of PV panels to be adjusted discretely by a single robot that runs on a track from panel to panel [22]. While this can effectively cut costs by using a single actuation unit for multiple panels, the discrete nature cannot be used for solar thermal applications. In all cases above, the load is carried atop a tall mast and requires heavier materials to achieve the rigidity necessary to ensure acceptable pointing accuracy.

The new design (Fig. 1) for a low-profile, two-axis solar tracker is aimed at reducing the total installed cost by targeting component production, system assembly, and installation. The new tracker is built from components that are readily available, or commercial off-the-shelf parts to promote a low cost solution and fewer specialized parts. Comprised of two co-planar and perpendicular linear actuators, a unique triangular geometry exploits a statically stable truss structure allowing for lighter duty, and more economical components. The tracker is also easy to assemble or disassemble, so that it can be easily shipped to customers. A key design benefit is the ability to store the tracking array in a position near, and parallel to, the ground. This is intended to reduce loading during adverse weather conditions, in turn allowing for lighter and less costly components. The new tracker design is less vulnerable to wind, which is a major factor in the design of individual tracking mechanisms [23]. Moreover, a wide base distributes the load over the ground and is installed easily by the end user with helical piles instead of concrete foundations for a single mast. The project will utilize this new tracker for combined heat and electricity.

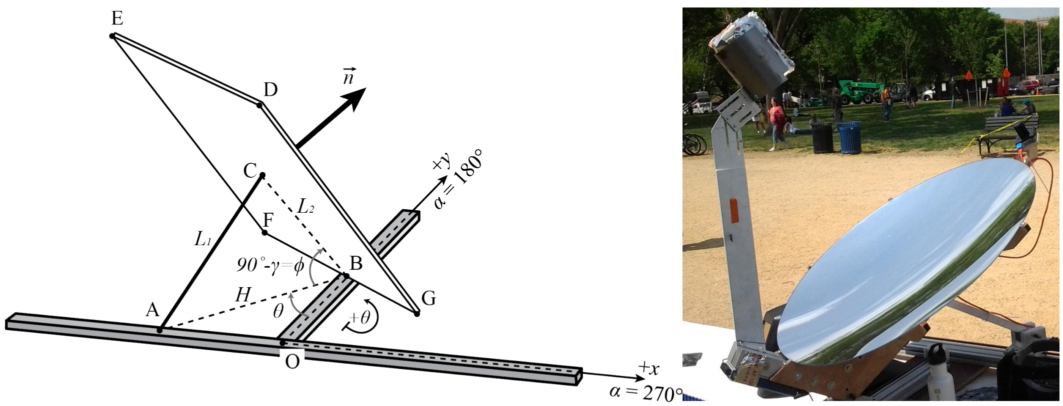

Fig. 1. Low-Profile Economic Solar Tracker

Last innovation of the system is ***the use of rejected heat for air conditioning, space heating, and domestic hot water***, where more than 50% of energy is consumed in a single-family home. Typical refrigerators or air conditioners operate under a vapor compression cycle, which uses ecologically destructive working fluids such as Freon gas. Most of the electricity is consumed in compressors of refrigerators, which cause noise and vibration that leads to an uncomfortable living condition. An absorption chiller or refrigerator replaces a mechanical compression cycle with a thermal compression cycle, which can be powered by rejected heat from the CSP system. During winter, the rejected heat can also be used for space heating or domestic hot water, which will also reduce natural gas consumption. The use of solar thermal energy for space heating, domestic hot water, or an absorption chiller is not new, and has been investigated for more than several decades [24]. Although successful implementation has been made for space heating or domestic hot water [25], there have not been many reliable absorption chiller systems powered by solar thermal energy. The operation temperature of an absorption chiller is usually much higher than the temperatures of typical solar collectors. Therefore, it usually requires concentrated solar collectors, such as a product from Chromasun, to reach the high temperatures of working fluids. Since the rejected heat of the system is still at a higher temperature than typical solar collectors, our system can provide energy to an absorption chiller as well as for space heating or domestic hot water. The optimum working condition will be determined through modeling work and the proper heat exchanger will be devised.

3) Energy Problem Targeted

According to the recent report from U.S. Energy Information Administration (EIA) [26], less than 6% of the electricity used in the United States is from the renewable energy sources, not including conventional hydroelectric power plant. Most of the electricity comes from typical power plants that burn fossil fuel, and are accompanied by green house gas emissions. The majority of sustainable power generation is from wind energy, while solar constitutes only 0.3% of entire energy generation in California [27]. Since solar energy is the most abundant and does not generate significant noise as in wind turbines, it is a more appropriate renewable solution at the residential level.

The energy system addresses these problems and has strong connection with the mission of the Public Interest Energy Research (PIER) electricity program. Particularly, we target three PIER R&D areas: Environmentally Preferred Advanced Generation, Renewable Generation, and Energy Technology System Integration. Distributed power generation can also reduce losses by transmission and distribution, which is about 7% of the total power generation in US [28]. Economically viable, concentrated solar systems will not only enhance the practice of using solar power, but also reduce peak energy demand during summer. The time for the maximum air conditioning load is synchronized with the time for the maximum solar energy. As such, electricity can be provided without interruption even with less number of power plants and thereby reduce the carbon footprint in California.

4) Primary Project Tasks and their associated Performance Objectives

The operation schematic of the system is described in Fig. 2. The solar energy is reflected onto a concave dish mirror and concentrated into a ceramic receiver. The mirror and the receiver will sit on the low-profile tracker. Thermoelectric modules will be attached to the surface of the receiver and generate 1kW of electricity. In order to achieve high efficiency, the other side of the thermoelectric modules will be cooled down using heat pipes. The rejected heat is further extracted by a working fluid that transfers heat from the cold side of the modules to an absorption chiller. The working fluid dissipates the heat into the boiler part of the absorption chiller, which enables for the refrigeration cycle.

Along with the energy savings for a regular refrigerator, the system is anticipated to save

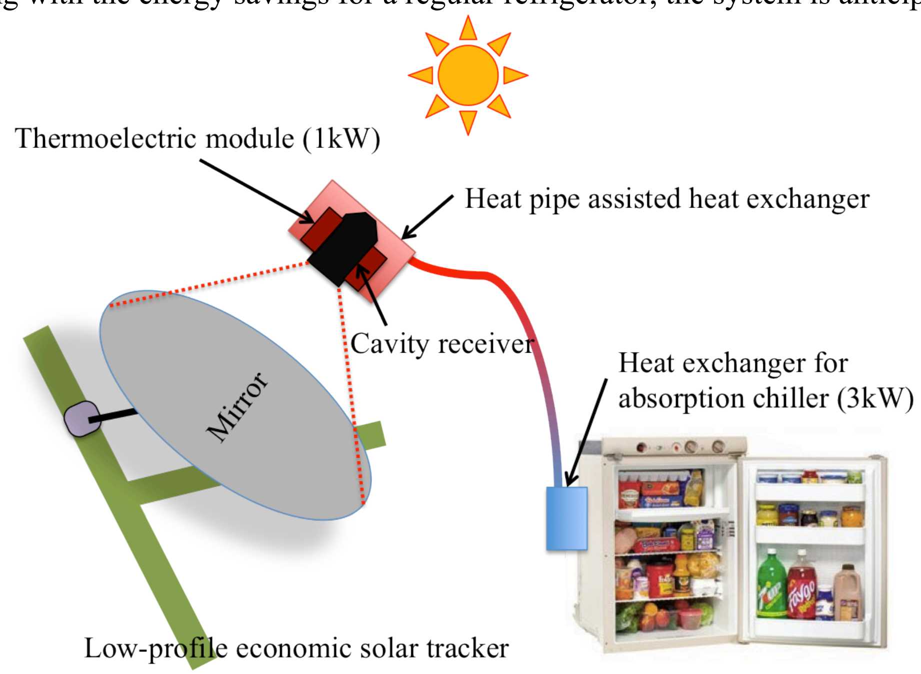

Fig. 2. Schematic of the system

32 kWh of electricity per day. The target price of the entire system is $3000 with a payoff period of four years. Low costs can be achieved through the use of the newly developed low-profile solar tracker. The system can be easily installed by the end user either on the ground or over the roof, with minimized work to get a good foundation. A scaled (1/10) model will be built and tested, in order to determine the feasibility of the system.

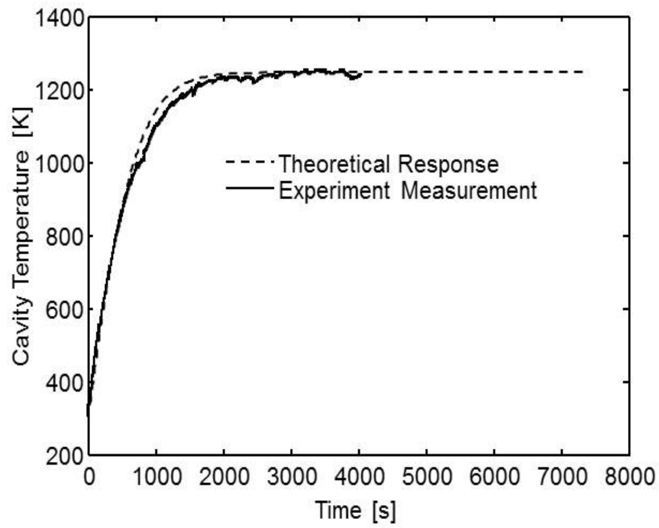

Fig. 3. Theoretical and experimental results of temperature response of a cavity receiver

a. Evaluate optimum working conditions

A heat source at a higher temperature is desirable for larger amount of electrical power and higher energy conversion efficiency of thermoelectric modules. However, high operation temperature also has a disadvantage of large heat loss to the ambient by radiation. Hence, it is necessary to find an optimum working temperatures and size of reflectors to assist the energy production for a single-family home. Our target energy production from the system is 1kW of electricity and 9kW of heat. Although 1kW of electricity (8kWh per day) is inadequate to meet the daily average-home electricity consumption (50kWh), the electricity-intense appliances, such as refrigerators or air conditioners, can be powered by thermal energy in the configuration. Hence, the actual electricity saving is targeted to be 32kWh per day. Analysis of the energy balance of incoming concentrated solar radiation, heat transfer to the thermoelectric generators, and heat loss to the ambient, will determine optimum working conditions.

In addition to operation temperature, the size of a solar receiver should be carefully chosen. With a given amount of electricity generation and space, the size of a solar receiver determines the solar concentration and thereby the temperature of the heat source for thermoelectric generators. The PI has an extensive experience with radiative heat transfer analysis, and presented optimized working conditions and receiver size for a small scale dish CSP generator [29]. Similar analysis will be carried out and optimum geometry of the receiver will be suggested to build a scaled (1/10) prototype.

The cavity receiver will be made of silicon carbide to ensure high emissivity and high thermal conductivity for better solar energy absorption and uniform temperature along the surface. The mirror and receiver will be installed on the low-profile tracker, and the maximum temperature will be measured to confirm our optimization study. Our previous experiments on a cavity receiver showed a maximum value within 5% of the calculated value and followed a similar transient response to theoretical expectation (Fig. 3).

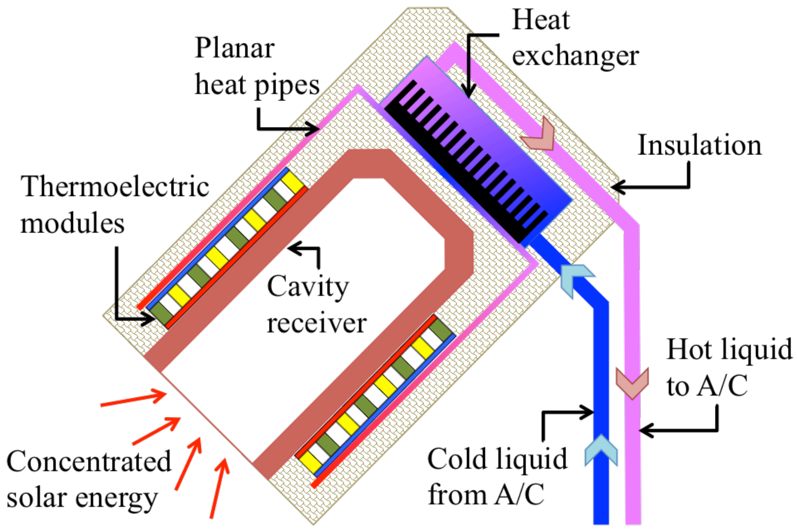

Fig. 4. Schematic view of cavity absorber integrated with thermoelectric modules, heat pipes, and heat exchangers

b. Integrate thermoelectric modules into a solar receiver

Eight thermoelectric modules (TEMs) will be installed on the surface of the receiver and connected in series. Each will generate 12.5W at 5V under temperature difference of 200K. Careful attention should be applied to the choice of thermoelectric modules that are available from various vendors, such as Marlow, Ferrotec, Laird Technology, etc. Several researchers, including the PI, have investigated the effect of thermal resistance on thermoelectric energy harvesting, and suggested new strategies on the electric load matching for the maximum power output [30-32]. Thermal resistance of heat dissipation should be as low as possible, and electric power should be collected at half of the open circuit voltage. Low heat sink thermal resistance is necessary to achieve larger temperature differences, and the electric load should be carefully chosen to minimize parasitic power loss by Joule heating. One should note that the condition for half of the open circuit voltage is a function of not only internal impedance of a TEM but also heat sink thermal resistances. A power management circuit will be devised out of a commercial energy harvesting circuit from Texas Instruments or Linear Technology.

Heat pipes from Cool TTM will be utilized to minimize the thermal resistance at the cold side of a TEM. Heat dissipation by phase change will ensure effective heat removal from the TEM and therefore large temperature difference across the TEM. Moreover, the use of heat pipes will enable easier implementation of heat exchangers that provides energy into an absorption chiller, which will be discussed in the later sections. Figure 4 shows how TEMs, heat pipes, and heat exchangers are integrated into a solar receiver.

In order to evaluate the performance of TEMs, open circuit voltage will be measured when a TEM is attached to a heat plate maintained at 700K. The temperature will be simulated with a hot plate and thermocouples will be used to measure the temperature. Properties of various modules will be characterized to choose the most appropriate module for this application.

c. Design of an absorption A/C

We will modify a commercially available absorption chiller into an air conditioner (A/C) system powered by solar thermal energy. Absorption refrigerators are widely used in leisure or hotel industries for reduced noise level in recreational vehicles or guest rooms. A heat exchanger will be attached on the surface of a steam generator and replace the existing electric heater. The modified A/C will be tested concurrently with a regular electric powered absorption chiller to ensure the same performance. Before the integration with the entire system, a water heater will be used to simulate solar thermal energy and test the modified absorption A/C. Each unit will be placed inside of two identical temporary buildings, and temperature as well as power consumption will be measured. The modified A/C is expected to have a cooling load of 300W, which will be verified through a comparative experiment.

Two custom heat exchangers enable heat transfer from the cold side of the TEMs to the boiler (or generator) of the absorption A/C. The geometry of the heat exchangers will be designed to achieve an effectiveness of 80% and a maximum temperature of 380K. Ethylene Glycol will be used as the working fluid.

d. Demonstration of scaled model and performance test / cost analysis

A scaled (1/10) prototype will be installed in a test structure. Santa Clara University (SCU) has two identical test structures for experiments related to building energy. They will be placed next to each other, and one of them will house the system. The other structure will be equipped with a conventional A/C for comparison. Demonstration of the system with 100W of electricity, 900W of heat, and 3kWh of total energy savings will be presented. Energy consumption and temperature will be monitored and evaluate the performance of the system. Furthermore, SCU has won the 3rd place prize in the 2007 and 2009 Solar Decathlon hosted by the Department of Energy. These two houses are currently located on campus, and they use solar thermal energy to run an absorption chiller (2007 house) and use electricity from PV to run a heat pump (2009 house). Both of the houses can provide an experimental comparison of the performance among various sustainable energy/cooling systems.

After successful demonstration of the scaled prototype, manufacturability study will be carried out for a real-scale system. The target price of the entire system to provide 1kW of electricity and 9kW of heat is $3,000. The business plan to reach this goal will be explored. Table 1 shows the cost analysis of the entire system. The system can be provided to the end users as a turnkey system or as a do-it-yourself kit. Individual parts will be acquired by subcontract with other manufacturers, and the system can be easily integrated and installed by either a contractor or the end users.

5) Technical Feasibility Issues

The major technical challenges and market barriers for the system are how to provide 1) **an economically viable system,** 2) **a combined heat and electricity system,** and 3) **how to incorporate the system into a relatively small space**. The economic low-profile tracker is the key element to reduce the cost through light and simple parts as well as easy installation.

Concentrated solar power with thermoelectric modules can provide both heat and electricity in a smaller area than PV cells. However, due to lack of high temperature applications, thermoelectric modules need to be customized, which may increase the cost of a prototype. The research will prove the feasibility of generating electricity by TEMs from concentrated solar power, and will enable mass production of thermoelectric modules. Various TEM manufacturers will be contacted to customize the module for solar power generation.

Amount of voltage and power is proportional to temperature difference across a TEM. In order to get more electricity, it is important to maintain the cold side as low as possible. Larger temperature difference leads to more amount of heat that has to be removed from the TE module. As in the semiconductor manufacturing industry, removing heat in a small area has been a challenge for many years. We propose thin heat pipes to address this issue, but large size heat exchanger may still be required. Moreover, temperatures that are too low may not be efficient enough to run absorption chillers. Hence, an optimized temperature range has to be determined by several experiments as well as a modeling study.

The last challenge is whether the system can be fitted into a small area. Although TEM can generate similar amounts of electricity in smaller spaces than PV cells, they cannot produce more energy than the incoming solar energy. More than $10m^2$ is required to meet 10kW of total energy. An array design of several reflectors will be suggested to cover the area combined with our low-profile trackers.

6) Innovations

The innovations of the system include;

1. Concentrated solar energy for residential scale,
2. Combined heat and electricity with TEMs and an absorption chiller,
3. Economically viable system assisted by low-profile tracker.

To the best of our knowledge, there is no commercially available residential scale combined heat and electricity system using TEM from concentrated solar power. Using our new low-profile solar tracker, we seek to provide such system at $3,000 with payoff period of four years or less.

7) Impact on Energy Problem / Benefit to California electric market

The average amounts of residential electricity energy and natural gas consumptions in California are 6,804 kWh [33] and 454 Therms [34] per year. The average prices of electricity and natural gas are $0.15 per kWh [33] and $0.94 per therm [35], respectively; thus annual energy cost for single-family homes is $1,386, the majority of which is for electricity. The project not only provides 8 kWh of electricity daily (2,920 kWh per year), but also reduces the use of electricity-intense appliances, such as refrigerators and A/C, which constitutes almost 30% of electricity consumption in an average single-family house [27]. If thermal energy can replace electricity in the refrigerators and A/C, there will be an additional saving of 2,041 kWh per year. Hence, **the system can save 4,961 kWh of electricity per year, which is equivalent to $744**. Therefore, **a payoff period for $3,000 is approximately four years**. Natural gas consumption can be reduced, if the rest of thermal energy is utilized for space heating or domestic hot water. The system is expected to save 100 Therms during three months of winter or $94 per year. With this, a payoff period can be less than three years. Moreover, there will be additional savings from the energy incentive or carbon credit as well.

The system benefits are not only for the end user, but also for the State of California. Based on a recent report from the California Energy Commission, electricity consumption will increase at an annual growth rate of 1.7% for next ten years [36]. The increased electricity demand should be accompanied by more number of power plants. The system can reduce the number of new power plants. Operational cost for electricity generation can be reduced as well. The cost to produce 1 MWh of electricity is $33 [37]. If 10% of 12 million households in California adopt the system, it can save approximately six million MWh per year, which is equivalent to 212 million dollars of saving in electricity production cost including savings from the energy loss by transmission and distribution. Moreover, by reducing peak energy demand, the state can minimize new power plant construction and the power generation from reserve power plants, which have high operation costs.

8) Market Connection

The system will create new market opportunities for many different industries. It will not only benefit solar thermal industries, but also enhance public appreciation of absorption chillers and thermoelectric modules. Mirror manufacturer, such as AGC solar, will be approached for solar reflectors. Kyocera or Saint-Gobain, leading ceramic companies, will manufacture the solar receivers. Both of the companies showed interest in our receiver design. We will also seek for collaboration with Laird Technology, Tellurex, or Marlow Industries on the manufacturing of the customized thermoelectric modules. Dometic will be able to modify their absorption refrigerator into solar powered refrigerators or A/C.

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Solar Thermoelectric Energy for Residential Scale Combined Heat and Electricity

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Santa Clara University
School of Engineering

California Energy Commission:
Energy Innovations Small Grant (EISG) Natural Gas Program
#57517A/12-08G

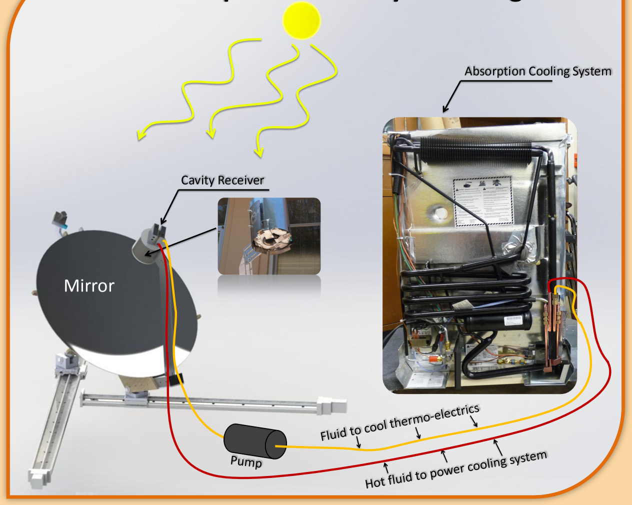
ABSTRACT

A Concentrated solar power (CSP) device on a residential scale can generate electricity and use rejected heat for many applications including domestic hot water, space heating/cooling, and absorption refrigeration.

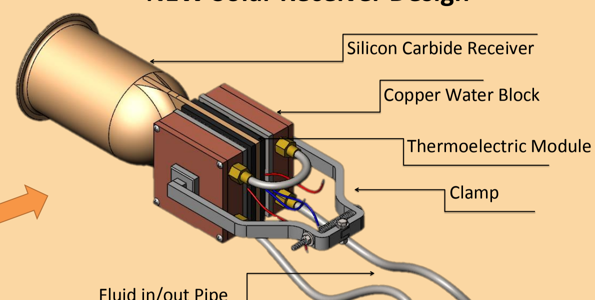
DEVICE PROCESS

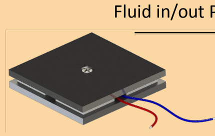
1. Sun Rays Captured
   - ❖ A mirrored parabolic disc follows the sun using a low-profile solar tracker.
2. Reflected into receiver
   - ❖ Sun is reflected off the mirrored parabolic disc and focused in a small , very hot point and heats up the silicon carbide receiver cavity.
3. Heat to Electricity
   - ❖ Thermoelectric modules (TEMs) produce electricity through the temperature differential between two plates.
4. Excess Heat Extracted
   - ❖ A thermal fluid is heated by flowing through the water block.
     ·cools the TEMs and increases their performance.
5. Heat Powered Refrigeration
   - ❖ Absorption Refrigerators are a heat-powered alternative to compression refrigeration. The thermal fluid will be the heat source for our design.

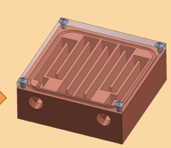
CSP & Absorption Chiller System Diagram



NEW Solar Receiver Design



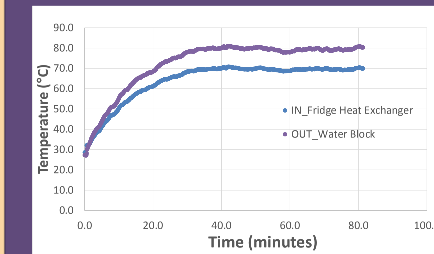




SOCIAL, ECONOMIC, AND ENVIRONMENTAL CONTEXT

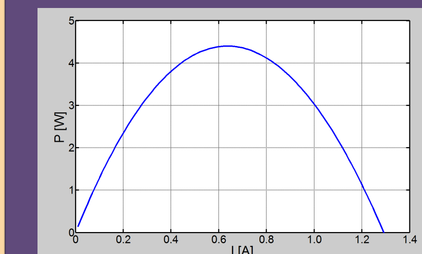
- ❖ 79% of people in 50 poorest nations lack electricity
- ❖ Affordable
- ❖ Higher efficiency than PV solar panels
- ❖ HVAC and hot water are 50% of residential energy usage.

COLLECTED DATA



Thermofluid Temperature for Single Water Block Receiver

Electric Heater Fridge Data	T_{min} = 5°C
	Power Usage: 190 W
	T_{max} = 217°C



Power Generated as Function of Current in TEM

FUTURE TESTING

Test	Goal
2nd Water block	Increase fluid temperature faster with new receiver design
Pipe Insulation	Reduce temperature loss between water block and fridge heat exchanger
Without TEM	Compare fluid temperature gains with and without TEM

ACKNOWLEDGEMENTS

❖Thetford Inc. for the Norcold Absorption Refrigerator
❖Santa Clara University for use of their lab space
❖California Energy Commission for their grant funding

Appendix 9: MBTI Results

Table A9: MBTI Results for Solar Absorption Chiller Team

Team Member	Personality Type	Team Position
Claire Kunkle	ESTJ	Manager/Supervisor
Mark Coulter	ENFJ	Orator/Teacher
Patrick Watson	ESFJ	Benefactor/Provider
Craig Carlson	INFJ	Conserver/Protector

As shown in Table A9, The Solar Absorption Chiller (SAC) group is composed of a manager, orator, benefactor, and conserver. This made a successful group because of our diverse backgrounds as well as our personalities. An ideal group consists of an EN-- personality type that is innovative and good at getting ideas moving. This person, for SAC, was Mark Coulter. Second, a group should have an IS-- personality, who is good on following through and detail orientated. Our group does not explicitly have an IS, but Patrick Watson and Claire Kunkle are ES-- and together fulfill this 2nd role, as well as the 3rd role of a group, which is to be hands-on and results oriented. Finally, a group should have someone that is an IN--, who is imaginative and introspective. This person was Craig Carlson. If anything, our group was more heavily weighted on the E-F- side, which means that we greatly relied on team members like Claire, who represented the only ‘thinking’ personality and Craig, the only introverted person to keep the team on target and within reasonable limits.

Appendix 10: Tracking System Overview

Tracking System Motors & Lead screws

The tracking system utilizes lead screws as linear actuators turned by stepper motors for the motion in both axes, as shown in Figure 10. The lead screws are 68 inches and 36 inches on the x- and y-axes, respectively. The orientation of the axes is represented in the following figure.

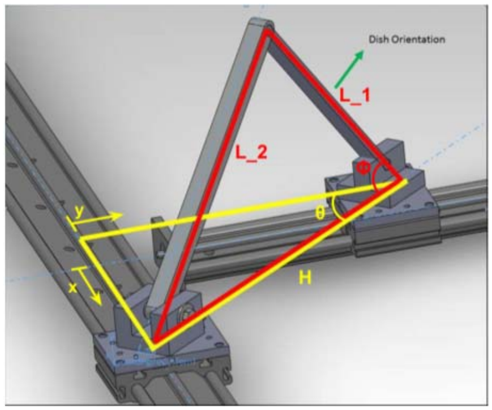


Figure A10-1: Application of Trigonometry to Solar Tracker Design (Neber)

Lin Engineering 5718X-05E stepper motors are utilized to turn the lead screws and orient the solar tracker correctly, due to their ease of control.

3.2.4 Tracking Control

To ensure that the tracker follows the path of the sun and remains normal to the sun at all times, a tracking program was implemented by means of an Arduino Mega 2560 to control the stepper motors. The Arduino program utilized a sun tracking library that calculated the position of the sun based on the solar tracker's longitudinal and latitudinal positions. Once the sun's position was determined, the program then commanded the motors to turn the lead screws to move the tracker until the desired angles were achieved. The total system is shown in in Figure 11.

Figure A10-2: The parabolic mirror is supported and moved by two separate tracks which are computer controlled. This ensures the mirror stays at an angle normal to the sun so that the energy produced is maximized.

Appendix 11: Properties of Durotherm

DURATHERM
EXTENDED LIFE FLUIDS

DURATHERM 450

OVERVIEW

Duratherm 450 is specifically engineered for applications requiring process heating and cooling efficiently between 30˚F and 450˚F.

Economical and thermally stable, Duratherm 450 heat transfer fluid offers an excellent alternative to costly synthetics and aromatic fluids while delivering precise and efficient cooling down to 30˚F.

APPLICATION

Duratherm 450 is specifically engineered for applications requiring process heating and cooling efficiently between 30°F and 450°F.

Economical and thermally stable, **Duratherm 450** offers an excellent alternative to costly synthetics and aromatic fluids while delivering precise and efficient cooling down to 30°F. **Duratherm 450** is an oxidative and thermally stable, high performance, long lasting, environmentally friendly heat transfer fluid. Offering precise temperature control and long life at an economical cost.

THE DIFFERENCE

Duratherm 450 heat transfer fluid contains the industries most effective and resilient blend of additives to ensure long-lasting, trouble-free service.

Our exclusive system includes a proprietary, dual stage anti-oxidant and a special blend of metal deactivators, extenders, and other agents that prolong fluid life and help keep systems clean. That also means longer life for parts like pumps and rotary seals.

LASTS LONGER

Oxidation can cripple your system. Left unchecked, it will ultimately cause catastrophic failure and costly downtime. That's why **Duratherm 450** heat transfer fluid offers unsurpassed levels of protection against oxidation, and a service life that other fluids simply can't match.

RUNS CLEANER

Duratherm 450 heat transfer fluid delivers superior resistance to sludging, a problem plaguing most other fluids. That makes it the best defense against extreme oxidation found in many of today's demanding manufacturing environments, including plastics processing, molding, casting, asphalt, paint, chemical and a wide variety of other applications.

In fact, our exclusive additive technology makes **Duratherm 450** heat transfer fluid the perfect solution for all applications, large or small requiring precise temperature control up to 450°F (232°C).

ENVIRONMENTAL

Duratherm 450 is environmentally friendly, non-toxic, non-hazardous and non-reportable. It poses no ill effect to worker safety and does not require special handling. After its long service life, **Duratherm 450** heat transfer fluid can easily be disposed of with other waste oils.

DURATHERM 450 PROPERTIES

Appearance: colorless, clear and bright liquid

Maximum Bulk/Use Temp.*	450°F	232°C
Flash Point ASTM D92	302°F	150°C
Fire Point ASTM D92	327°F	163°C
Autoignition ASTM E-659-78	625°F	329°C
Viscosity ASTM D445		
cSt at 104˚F / 40˚C	4.8	
cSt at 250°F / 121°C	1.3	
cSt at 450°F / 232°C	0.6	
Pour Point ASTM D97	-49°F	-45°C
Density ASTM D1298	**lb/ft3**	**g/ml**
at 100˚F / 38˚C	53.1	0.850
at 250°F / 121°C	49.5	0.793
at 450°F / 232°C	44.8	0.717
Average Molecular Weight	372	
Carbon Residue ASTM D189	0.005	% Mass
Sulphur Content X-RAY	<.001	weight %
CU Strip Corrosion ASTM D130	1a	
Thermal Expansion Coefficient	0.0564 %/˚F	0.1011 %/˚C
Thermal Conductivity	**BTU/hr F ft**	**W/m.K**
at 100˚F / 38˚C	0.082	0.142
at 500˚F / 260˚C	0.079	0.137
at 600˚F / 316˚C	0.074	0.128
Heat Capacity	**BTU/lb F**	**kJ/kg K**
at 100˚F / 38˚C	0.510	2.135
at 250°F / 121°C	0.57	2.386
at 450°F / 232°C	0.650	2.721
Vapor Pressure ASTM D2879	**psia**	**kPa**
at 100˚F / 38˚C	0.09	0.62
at 250°F / 121°C	0.33	2.28
at 450°F / 232°C	3.23	22.27
Distillation Range ASTM D2887	10%	481°F (249°C)
	90%	851°F (455°C)
***Maximum Film Temp.**	490°F	254°C

The values quoted are typical of normal production. They do not constitute a specification.

1-800-446-4910 www.heat-transfer-fluid.com

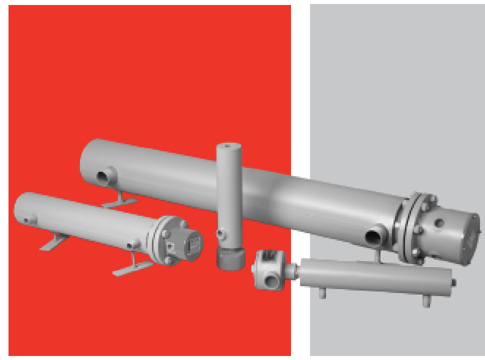
Appendix 12: Purchased Component Information

NSF Roller Pump: EW-70608-00

Specifications	
Wetted materials	Cast iron pump body, PTFE roller, Viton® seal
Port size	1/2" NPT
Max flow rate (LPM)	14.4
Max viscosity (cp)	108
Max pressure	50 psi
Min temperature (º C)	4
Max temperature (º C)	204
Min temperature (º F)	40
Max temperature (º F)	400
Motor phase	1
Suction lift (dry)	10 ft
Self-priming	Yes
Motor (hp)	1/3
Power (VAC)	115
Product Type	Roller Pumps
Duty cycle	Continuous
Motor speed	1725 rpm
Motor type	ODP

Circulation Heaters

Heaters Designed to Heat Forced-Circulation Air, Gases or Liquids



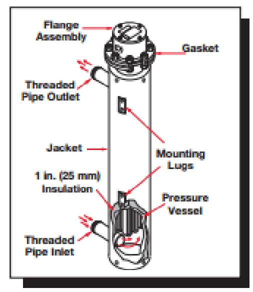
Circulation heaters provide a ready-made means to install electric heating with a minimal amount of time and labor. This is accomplished by combining heating elements, vessel, insulation, terminal enclosure, mounting brackets and inlet and outlet connections into a complete assembly.

Made from National Pipe Thread (NPT) screw plug or ANSI flange heater assemblies mated with a pressure vessel (tank), circulation heaters are designed to heat forced-circulation air, gases or liquids. Ideal for either in-line or side-arm operations, these assemblies direct fluids past FIREBAR® or WATROD™ heating elements, to deliver fast response and even heat distribution.

Watlow® meets virtually all circulation heater assembly needs with made-to-order units. Watlow circulation heaters can be made from a wide range of heating element sheath materials, wattages, vessel sizes and materials, pressure ratings, terminal enclosures and controls.

Performance Capabilities

- Watt densities up to 120 W/in² (18.6 W/cm²)
- Wattages up to three megawatts
- UL® and CSA component recognition up to 690VAC
- Ratings up to ANSI Class 600 pressure class
- Alloy 800/840 sheath temperatures up to 1600°F (870°C)
- Passivated 316 stainless steel sheath temperatures up to 1200°F (650°C)
- Steel sheath temperatures up to 750°F (400°C)



Features and Benefits

Catalog screw plug and flange part numbers

- Provides a wide selection of WATROD and FIREBAR elements to meet specific application requirements

Type	Sizes (in.)
NPT Screw Plugs	1¼, 2½
ANSI flanges	3, 4, 5, 6, 8, 10, 12, 14

ANSI B16.5 Class 150 on 4 or 6 inch FIREBAR element flanges and 3 to 14 inch WATROD element flanges

- Meets recognized agency standards

FIREBAR assemblies pack more wattage in a smaller heater bundle

- Replaces larger flanges with round tubular elements, with a smaller package

Compacted MgO insulation filled elements

- Maximizes dielectric strength, heat transfer and life

WATLOW®

HAN-CIR-0713

Features and Benefits *(Continued)*

1 inch (25 mm) thermal insulation rated to 750°F (400°C)

- Reduces heat loss from the vessel

Heavy-gauge steel jacket (shroud)

- Protects thermal insulation and heating vessel and comes with protective primer coating

All catalog units are rated to ANSI pressure Class 150

- Provides pressure vessels (tanks) that are either carbon, 304 or 316 stainless steel

Standard offering includes units rated for up to and including ANSI pressure class 600 (application review required)

- Provides pressure vessels (tanks) available in carbon steel, 304 or 316 stainless steel materials
- Includes schedule 40, standard and 80 pipe used in the pressure vessel construction

Catalog units provided with NPT or ANSI Class 150 nozzle connection

- Makes installation easy. Inlet and outlet nozzle connections are threaded MNPT on 8 in. (203 mm) and smaller tanks. Class 150 flanged connections on 10 in. (254 mm) and larger tanks

Mounting lugs are welded onto the tank wall of all 2$^1/_2$ in. (64 mm) NPT and larger units

- Provides mounting support

General purpose, moisture resistant enclosures available

- Offers easy access to terminal wiring

Flange mounting holes

- Straddles centerline to comply with industry standards

UL® and CSA component recognition under file numbers E52951 and 31388 respectively

- Meets industry safety standards

Typical Applications

Water:

- Deionized
- Demineralized
- Clean
- Potable
- Process
- Industrial water rinse tanks
- Hydraulic oil, crude, asphalt
- Lubricating oils at API specified watt densities
- Heat transfer oil
- Paraffin
- Caustic cleaners
- Nitrogen, hydrogen and other air/gas systems
- Superheating steam

Options

Terminal Enclosures

General purpose terminal enclosures, without thermostats, are supplied on all Watlow circulation heaters. Moisture and explosion resistant ratings are available to meet specific application needs.

Stand-off Terminal Enclosures

Stand-off terminal enclosures help protect terminal enclosures against excessive temperatures.

ASME Pressure Vessel Code Welding

Flange or screw plug assemblies can be provided with an ASME Section VIII or Section I, Div. I pressure vessel stamp upon request.

Branch Circuits

Branch circuits are designed for 48 amperes per circuit maximum. Contact a Watlow representative for circuit requirements other than those listed in the stock charts.

Certified Enclosures

CSA, ATEX or IECEx certified enclosures protect wiring in hazardous gas environments. These terminal enclosures, covered under CSA file number 61707, ATEX certificate # SIRA 10ATEX 1155X or IECEx certificate # IECEx CSA 09.0010 are available on WATROD flange heaters.

For products that will be installed in hazardous locations, please provide the following information:

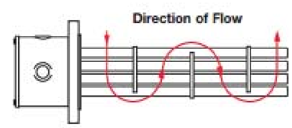
- Operating conditions
- Minimum and maximum ambient temperatures for the installation location
- Mounting orientation

Watlow must understand this information so that an appropriate design can be provided.

Thermostats

To provide process temperature control, Watlow offers optional single- and double-pole thermostats. Thermostats are typically mounted in the terminal enclosure. Optional side mounting on vessel also available.

Baffles



Baffles mounted on the heating element bundle enhance and/or modify liquid or gas flow for better heat transfer.

For critical sheath temperature and low flow conditions, baffles may be required.

Contact a Watlow representative for details.

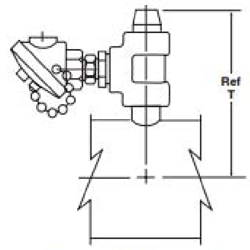
Thermocouples

To sense process or element sheath temperature, ASTM Type J or K thermocouples are available.

Options *(Continued)*

Process Thermocouple in Nozzle

(Must specify which nozzle)



Ref. Tank Size	Ref. Nozzle Size	Dimension "A"
$1\frac{1}{4}$	$\frac{3}{4}$ NPT	$8\frac{3}{16}$
$2\frac{1}{2}$	1 NPT	$8\frac{3}{16}$
3	1 NPT	$8\frac{3}{16}$
4	$1\frac{1}{2}$ NPT	$10\frac{3}{8}$
5	2 NPT	$11\frac{1}{16}$
6	$2\frac{1}{2}$ NPT	$13\frac{3}{8}$
8	$2\frac{1}{2}$ NPT	$14\frac{3}{8}$

For 10 in. (254 mm) and larger tanks contact your Watlow representative for dimension.

Sheath Materials

The following sheath materials are available on WATROD and FIREBAR heating elements:

Standard Sheath Materials

WATROD	Alloy 800/840 316 SS Steel
FIREBAR	Alloy 800, 304 SS

Made-to-Order Sheath Materials

WATROD	304 SS Alloy 600 Titanium Hastelly C276

Wattages and Voltages

Watlow routinely supplies circulation heaters with 120 to 690VAC as well as wattages from 500 watts to one megawatt. If required, Watlow will configure circulation heaters with voltages and wattages outside these parameters.

For more information on special voltage and wattage configurations, contact a Watlow representative.

Protective Steel Jacket (Shroud)

To protect circulation heaters from weather or wash-down conditions, partially welded (standard) outer protective steel jackets are available. Standard steel, or made-to-order 304 or 316 stainless steel or aluminum can be supplied. Jacket diameter is dependent upon thermal insulation thickness.

To order, specify **protective steel jacket, material type** and **weatherproof**, if desired.

Passivated Finish

For critical applications, passivation will remove free iron from all wetted surfaces.

Contact a Watlow representative for details.

Gaskets

Rubber, asbestos-free and spiral wound gaskets are available for all heater flange, and inlet and outlet flange sizes.

Watlow recommends ordering spares in case replacement becomes necessary.

To order, specify **gasket type, flange size/rating** and **process operating temperature**.

Inlet and Outlet Nozzle Connections

All inlet and outlet materials are compatible with the pressure vessel material and pressure class rating.

Vessel sizes from 1¼ to 8 inches are typically configured with Male National Pipe Thread (MNPT) nozzles. Optional NPT and flange sizes can be supplied to mate with existing piping.

10 inch and larger vessels are supplied with Class 150 inlet and outlet flanges. Optional Class 300 or Class 600 can be provided to mate with existing piping.

To order, specify **type, size** and **pressure class** rating for both inlet and outlet nozzle/flange connections.

Support Saddles

To mate with an existing installation, customized support saddle(s) and/or mounting lugs are available.

To order, specify **mounting lugs** or **support saddles** and supply a dimensional drawing.

High-Temperature Thermal Insulation

To further minimize heat loss, the pressure vessel's standard one inch thermal insulation wrap may be replaced with thicker and/or higher temperature insulation.
For more information, contact your Watlow representative.

To order, specify **insulation thickness, standard** or **high temperature insulation** and **temperature rating**.

Vessels may be supplied with a primer coating without insulation.

To order, specify **no insulation**.

Pressure Vessels

All catalog pressure vessel (tank) materials consist of standard schedule and 150# class forged fittings and are made from one of the following materials:

- Carbon steel
- 316 stainless steel

All catalog pressure vessels (tanks) are steel unless otherwise noted.

316 stainless steel pressure vessels (tanks) are passivated on all wetted surfaces. Available from assembly stock on $2\frac{1}{2}$ inch NPT and 4 or 6 inch ANSI flange circulation heaters.

Made-to-order units can be made in a variety of materials, flange sizes and pressure classes. Ratings to ANSI class 2500 pressure class are available for high-pressure applications.

Ordering Information

Part Number

① Stock Plug or ANSI Flange Part Number	② Optional Terminal Enclosures	③ Optional Process Sensors	④ Sheath Limit Sensors

①	Stock Plug or ANSI Flange Part Number
Insert Part Number	
Note: Catalog part numbers include optional enclosures and process sensors. To order optional enclosures or sensors, substitute the appropriate suffix.	

②	Optional Terminal Enclosure
S =	General purpose enclosure
W =	Moisture resistant enclosure
E =	Explosion resistant enclosure
C =	Moisture/explosion resistant enclosure
Note: Catalog listings include either a general purpose enclosure or moisture/explosion resistant enclosure. Substitute enclosure options are noted.	

③	Optional Process Sensor
2 =	30 to 250°F (-1 to 121°C), SPST
3 =	175 to 550°F (79 to 288°C), SPST
4 =	40 to 110°F (-1 to 43°C), DPST
5A =	60 to 250°F (16 to 121°C), DPST (FIREBAR)
7A =	100 to 500°F (38 to 288°C), DPST (FIREBAR)
J =	Type J process thermocouple in thermowell
K =	Type K process thermocouple in thermowell

④	Sheath Limit Sensor
HJ =	Type J high-limit thermocouple, horizontal mount
TJ =	Type J high-limit thermocouple, vertical/housing at top
BJ =	Type J high-limit thermocouple, vertical/housing at bottom
HK =	Type K high-limit thermocouple, horizontal mount
TK =	Type K high-limit thermocouple, vertical/housing at top
BK =	Type K high-limit thermocouple, vertical/housing at bottom
Note: Heater orientation is critical to accurate sensing of limit conditioners. Use the appropriate code to indicate heater mounting orientations.	

To be automatically connected to the nearest North American Technical Sales Office:

1-800-WATLOW2 • www.watlow.com • inquiry@watlow.com

International Technical Sales Offices: Australia, +61 3 9335 6449 • **China,** +86 21 3532 8532 • **France,** +33 1 41 32 79 70
Germany, +49 (0) 72 53 / 94 00-0 • **India,** +91 40 6661 2700 • **Italy,** +39 024588841 • **Japan,** +81 3 3518 6630 • **Korea,** +82 2 2628 5770
Malaysia, +60 3 8076 8745 • **Mexico,** +52 442 217 6235 • **Singapore,** +65 6773 9488 • **Spain,** +34 91 675 12 92
Taiwan, +886 7 288 5168 • **United Kingdom,** +44 (0) 115 964 0777

Fluid Expansion Tank

Expansion Tank

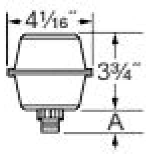
25 Cubic Inch Capacity, 3/4" NPT Male Pipe Size

Each

ADD TO ORDER

In stock
$70.11 Each
2269K23

Capacity, cu. in.	25
Opening Pipe Size	3/4"
(A)	1 1/4"
Wall Gauge	20
Additional Specifications	Miniature Type 304 Stainless Steel Tanks



Use these tanks to accommodate the expansion of heated water and provide a cushion of compressed air in closed water-heating systems. They prevent water loss by eliminating the need to expel hot water from systems during each heating cycle.

All of these tanks can be used vertically as well as horizontally. Openings are NPT female, unless noted.

Offering excellent corrosion resistance, these miniature tanks are made of Type 304 stainless steel. A rolling fluoroelastomer rubber diaphragm maintains tank pressure at or near 0 psi, which extends seal life and prevents leakage. Maximum pressure is 15 psi. Maximum operating temperature is 350° F. Opening is NPT male.

Appendix 13: Experimental Testing Procedure

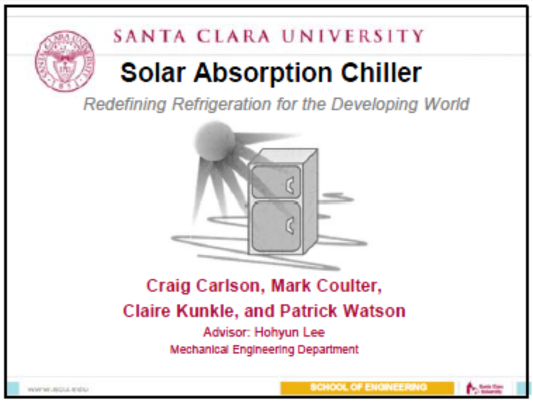
Circulation Heater Testing:

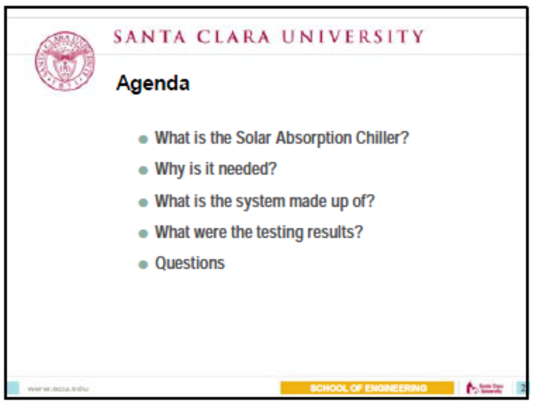
1. Fill Circulation Loop with Duratherm
2. Run LabView to record temperatures
3. Set PID controller to 80°C and turn on pump
4. Run for 5 hours and observe refrigerator temperatures
5. Turn up PID controller by 10 degrees and run for 1 hour
6. Repeat step 5 until a change in fridge temperature is noted
7. Record this temperature and allow cycle to run for 5 hours at this temperature
8. Run test again with different heat exchangers.

Solar Tracker Testing:

1. Connect Arduino to computer via USB cable
2. Connect wires to external power supply for motors
3. In Arduino interface, go to Tools > Serial Monitor
4. Motors will begin moving to limit switches, and the tracker system is completely automated from this point
5. When the tracker is correctly oriented, mirror can be implemented in the system
6. Plug NI-DAQ via USB cable into computer
7. Open LabView testing program
8. Begin continuous data acquisition for temperature measurements/power production
9. When test is finished, remove mirror
10. Stop LabView program and save data
11. Unplug motors and disconnect Arduino from computer

Appendix 14: Power Point Slides


SANTA CLARA UNIVERSITY
Solar Absorption Chiller
Redefining Refrigeration for the Developing World
Craig Carlson, Mark Coulter,
Claire Kunkle, and Patrick Watson
Advisor: Hohyun Lee
Mechanical Engineering Department
SCHOOL OF ENGINEERING


SANTA CLARA UNIVERSITY
Agenda
What is the Solar Absorption Chiller?
Why is it needed?
What is the system made up of?
What were the testing results?
Questions
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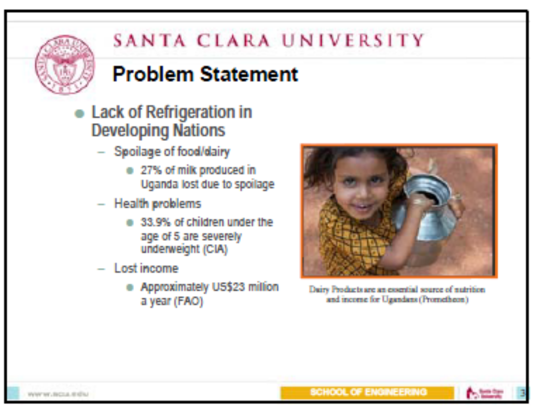
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Problem Statement
Lack of Refrigeration in Developing Nations
Spoilage of food/dairy
27% of milk produced in Uganda lost due to spoilage
Health problems
33.9% of children under the age of 5 are severely underweight (CIA)
Lost income
Approximately US$23 million a year (FAO)
Dairy Products are an essential source of nutrition and income for Ugandans (Promethean)
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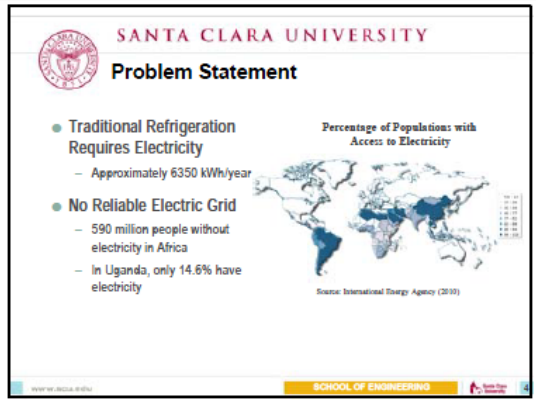
SANTA CLARA UNIVERSITY
Problem Statement
Traditional Refrigeration Requires Electricity
Approximately 6350 kWh/year
No Reliable Electric Grid
590 million people without electricity in Africa
In Uganda, only 14.6% have electricity
Percentage of Populations with Access to Electricity
Source: International Energy Agency (2010)
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Motivation
Provide Sustainable Refrigeration Solution
Utilizing Concentrated Solar Power
UN Millennial Development Goals
Reduce Pollution, Increase Energy Independence
UN Universal Declaration on Human Rights
Right to standard of living for health and well-being
United Nations
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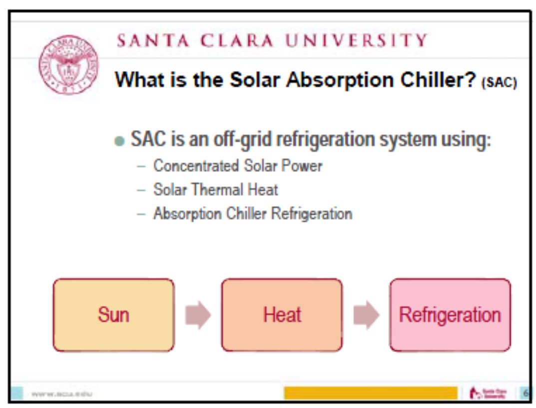
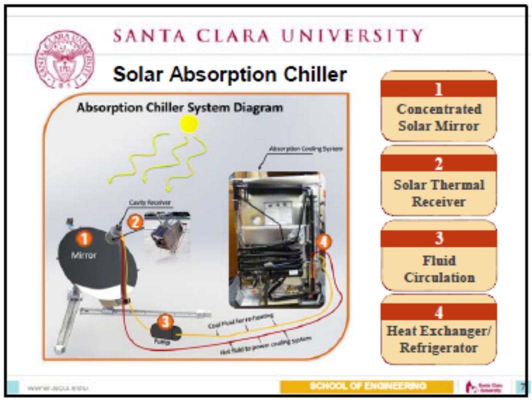
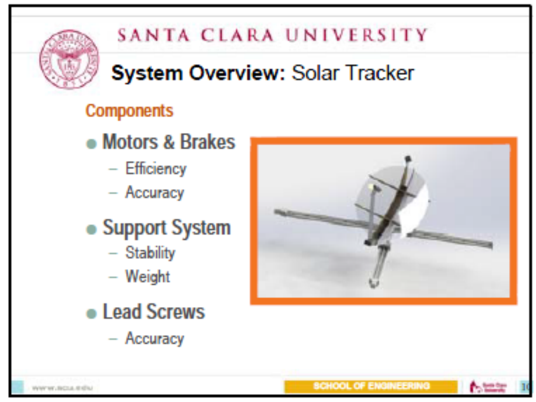
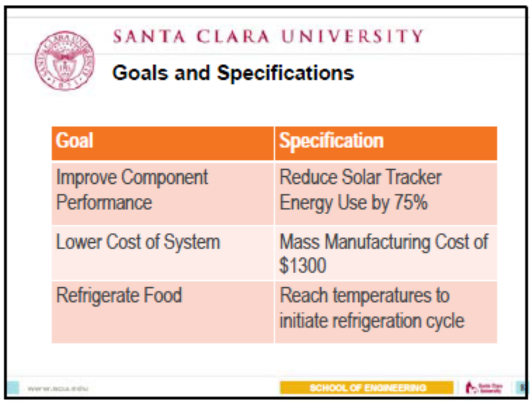
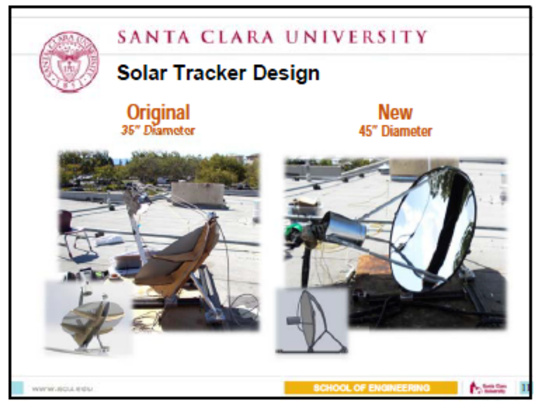

SANTA CLARA UNIVERSITY
What is the Solar Absorption Chiller? (SAC)
SAC is an off-grid refrigeration system using:
Concentrated Solar Power
Solar Thermal Heat
Absorption Chiller Refrigeration
Sun
Heat
Refrigeration

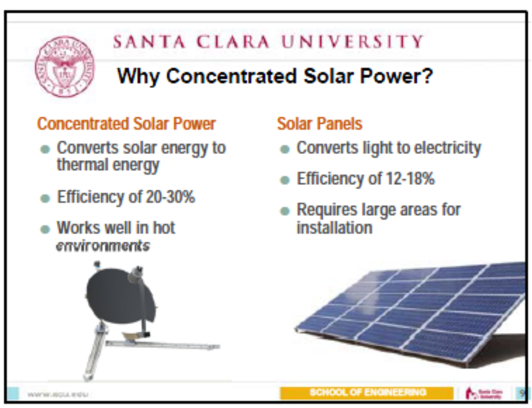


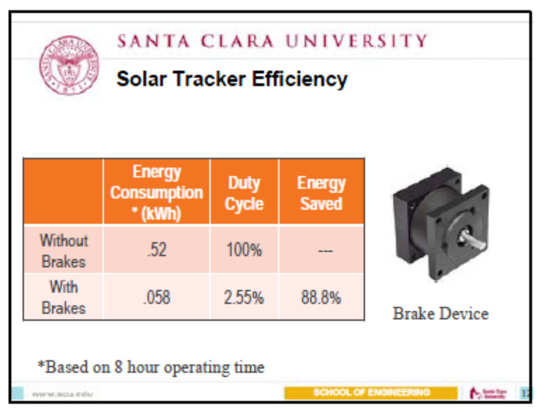




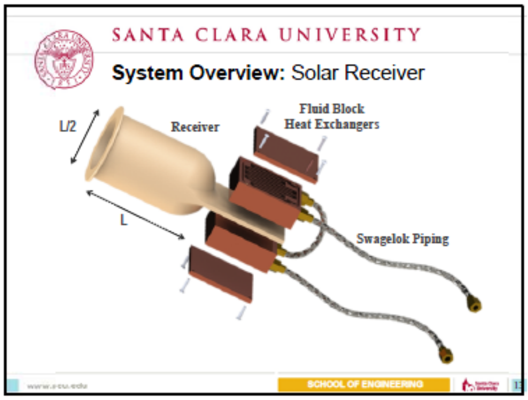
Goal	Specification
Improve Component Performance	Reduce Solar Tracker Energy Use by 75%
Lower Cost of System	Mass Manufacturing Cost of $1300
Refrigerate Food	Reach temperatures to initiate refrigeration cycle

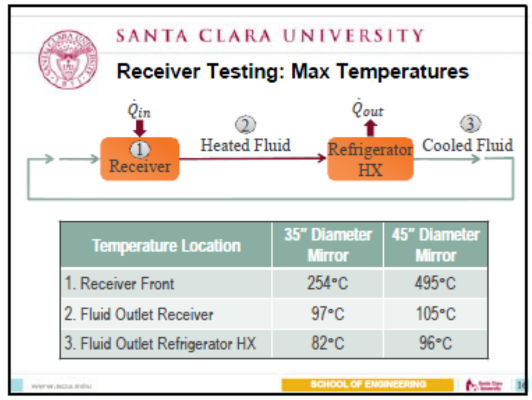




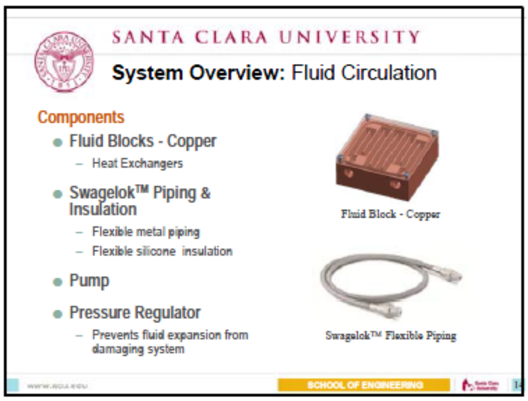


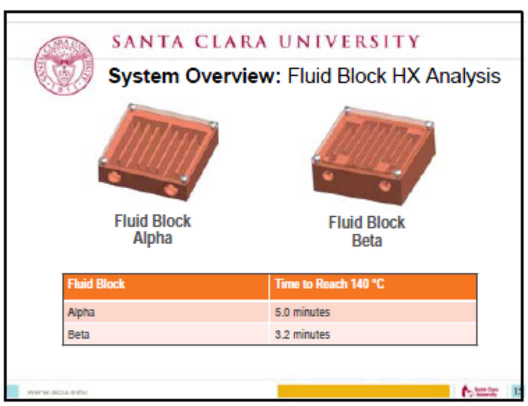
	Energy Consumption * (kWh)	Duty Cycle	Energy Saved
Without Brakes	.52	100%	---
With Brakes	.058	2.55%	88.8%



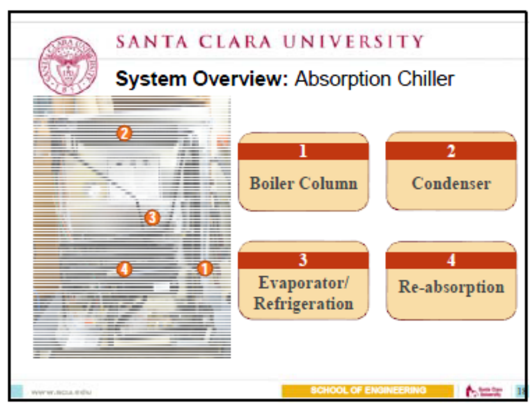


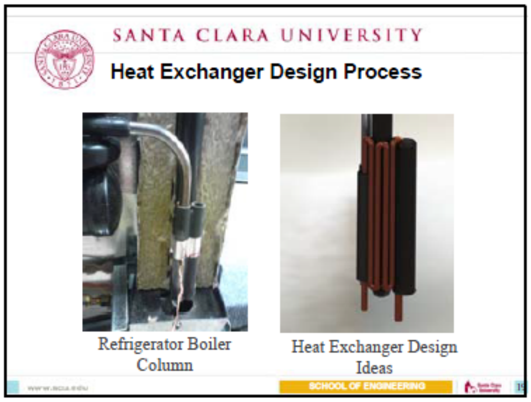
Temperature Location	35" Diameter Mirror	45" Diameter Mirror
1. Receiver Front	254°C	495°C
2. Fluid Outlet Receiver	97°C	105°C
3. Fluid Outlet Refrigerator HX	82°C	96°C

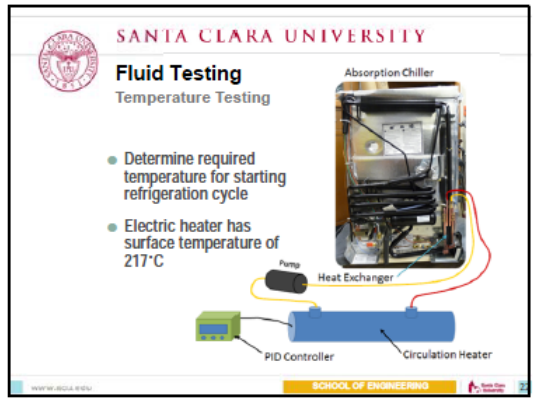


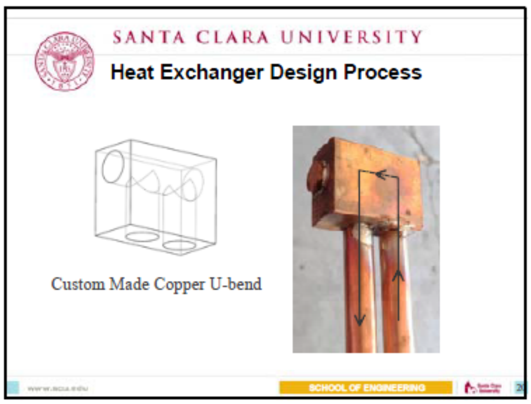


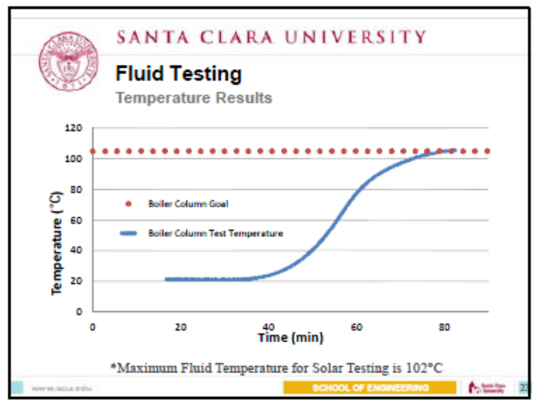
Fluid Block	Time to Reach 140 °C
Alpha	5.0 minutes
Beta	3.2 minutes

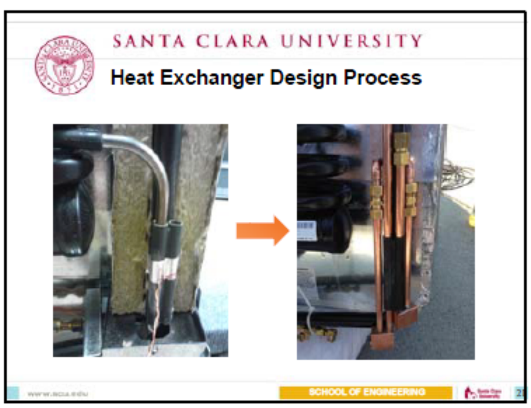












Component Systems	Prototype Cost	Mass Manufacture Cost*
Solar Tracker	$875.00	$230.00
Solar Receiver	$2500.00	$100.00
Fluid Circulation	$1500.00	$300.00
Absorption Chiller	$600.00	$80.00
Total Cost	$5,475.00	$710.00

*Assuming 1000 units made

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Goals Reached

Goal	Specification	Final Design
Improve Component Performance	Reduce Solar Tracker Energy Use by 75%	Reduced Solar Tracker Energy Use by **88.8%**
Lower Cost of System	Mass Manufacturing Cost of $1300	Mass Manufacturing Cost of **$710**
Refrigerate Food	Reach temperatures to initiate refrigeration cycle	Reached Boiler Column Temperature of 105°C in testing

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Questions?

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Summary & Moving Forward

- Refrigeration in the Developing World
- Healthier Eating
- Better Income

Moving Forward

- Custom Built Absorption Chiller
- Implement Thermo-electric modules

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Previous Works

- On-going from Summer 2013
- Inherited work from:
  - Solar Tracking Design
  - Solar Receiver Design

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A Special Thanks to…

- Financial Support from:
  - California Energy Commission
  - Roelandt's Grant Program
  - SCU School of Engineering
- Our Advisor Dr. Hohyun Lee
- Grad Students: Mark Wagner, Brandon Ohara, and Bernadette Tong
- SCU Mechanical Engineering Professors
- Jeff Charles, SCU Facilities
- Family and friends for their continued support

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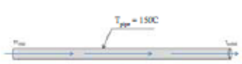
Appendix: Fluid Block HX Analysis

- Assumptions:
  - Constant Surface Temp (140 °C)
  - Initial Temp – 25 °C
- Equations Used:
  - Reynolds Number = $\frac{4\ \dot{M}}{\pi D \mu}$
  - Nusselt Number(Nu) = 3.66
  - Heat Transfer Coefficient = h = $\frac{k(Nu)}{D}$
  - Temp Out = ($e^{-PL/\dot{M}Cp}$)*(Tsurface –Tin) - Tsurface



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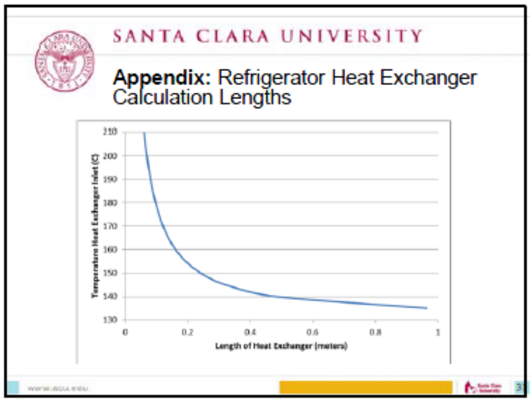
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Appendix: Refrigerator Heat Exchanger Calculation Lengths
Temperature Heat Exchanger Inlet (C)
Length of Heat Exchanger (meters)
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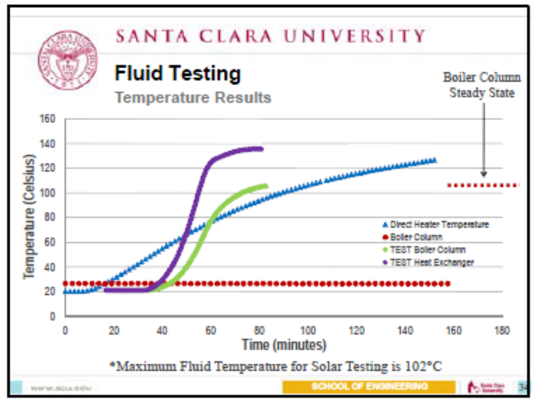
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Fluid Testing
Temperature Results
Boiler Column Steady State
Temperature (Celsius)
Time (minutes)
Direct Heater Temperature
Boiler Column
TEST Boiler Column
TEST Heat Exchanger
*Maximum Fluid Temperature for Solar Testing is 102°C
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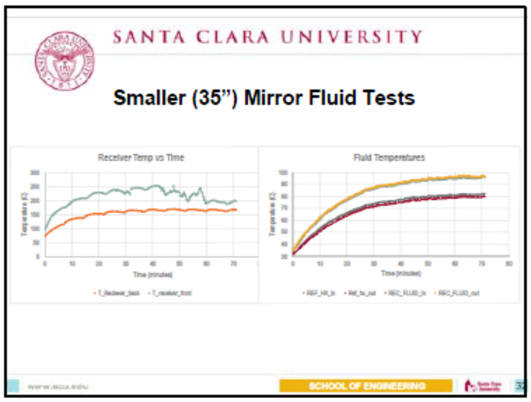
SANTA CLARA UNIVERSITY
Smaller (35") Mirror Fluid Tests
Receiver Temp vs Time
Fluid Temperatures
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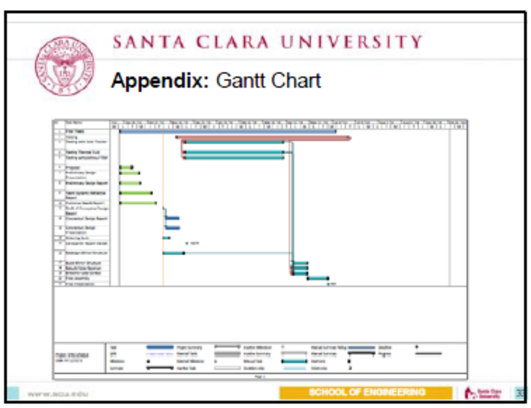
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Appendix: Gantt Chart
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Appendix 15: Judges' Presentation Score Sheets

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MAY 8, 2014

PROJECT EVALUATION FORM

Session: *MECH 1*
Room #: *Kennedy Commons* Judge's Name: Collin Burdick

Project Title:	**Solar Powered Absorption Chiller**
Group Members:	Mark Coulter, Claire Kunkle, Craig Carlson, Patrick Watson
Advisors:	Hohyun Lee

Please evaluate senior engineering design projects and presentations using the following point system:

5 = Excellent (at the level of an entry-level engineer you would hire)
4 = Good (at the level of an accomplished college senior)
3 = Average (at the level typical of a college senior)
2 = Below Average (not up to the expectations for a college senior)
1 = Poor (significant errors or omissions)
N/A if no appropriate score applies

DESIGN PROJECT

A. Technical Accuracy	4	E. Addresses Project Complexity Appropriately	4
B. Creativity and Innovation	3	F. Expectation of Completion (by term's end)	4
C. Supporting Analytical Work	4	G. Design & Analysis of tests	4
D. Methodical Design Process Demonstrated	4	H. Quality of Response during Q&A	5
			/32

PRESENTATION

A. Organization	4	C. Visual Aids	~~3~~ 5
B. Use of Allotted Time	5	D. Confidence and Poise	5
			/19

GRAND TOTAL (Sum of Design Project and Presentation Totals): 51

Please circle each of the following considerations that were addressed by the presentation:

economic (circled) environmental (circled) sustainability (circled) manufacturability
ethical health and safety social (circled) political

Comments (Optional): Great presentation! Would have liked to see a bit more market analysis, manufacturability, and implementation information. A great start on the design!

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School of Engineering

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SCHOOL OF ENGINEERING SENIOR DESIGN CONFERENCE
MAY 8, 2014

PROJECT EVALUATION FORM

Session: ***MECH 1***
Room #: ***Kennedy Commons*** **Judge's Name:** JOHN ERTEL

Project Title:	**Solar Powered Absorption Chiller**
Group Members:	Mark Coulter, Claire Kunkle, Craig Carlson, Patrick Watson
Advisors:	Hohyun Lee

Please evaluate senior engineering design projects and presentations using the following point system:

5 = Excellent (at the level of an entry-level engineer you would hire)
4 = Good (at the level of an accomplished college senior)
3 = Average (at the level typical of a college senior)
2 = Below Average (not up to the expectations for a college senior)
1 = Poor (significant errors or omissions)
N/A if no appropriate score applies

DESIGN PROJECT

A. Technical Accuracy	5	E. Addresses Project Complexity Appropriately	4
B. Creativity and Innovation	4	F. Expectation of Completion (by term's end)	4
C. Supporting Analytical Work	5	G. Design & Analysis of tests	4
D. Methodical Design Process Demonstrated	4	H. Quality of Response during Q&A	5

PRESENTATION

A. Organization	5	C. Visual Aids	4
B. Use of Allotted Time	5	D. Confidence and Poise	5

GRAND TOTAL (Sum of Design Project and Presentation Totals): 54

Please circle each of the following considerations that were addressed by the presentation:

economic (circled) | environmental (circled) | sustainability | manufacturability
ethical | health and safety (circled) | social | political

Comments (Optional): SMART TO USE A PREDICTIVE SYSTEM TO MOVE THE COLLECTOR RATHER THAN A SUN TRACKER

USE CLOCK RATHER THAN TRACKER?
WORM GEAR? PUMP

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SCHOOL OF ENGINEERING SENIOR DESIGN CONFERENCE
MAY 8, 2014

PROJECT EVALUATION FORM

Session: ***MECH 1***
Room #: ***Kennedy Commons*** **Judge's Name:** Phillip Setterfield

Project Title:	**Solar Powered Absorption Chiller**
Group Members:	Mark Coulter, Claire Kunkle, Craig Carlson, Patrick Watson
Advisors:	Hohyun Lee

Please evaluate senior engineering design projects and presentations using the following point system:

5 = Excellent (at the level of an entry-level engineer you would hire)
4 = Good (at the level of an accomplished college senior)
3 = Average (at the level typical of a college senior)
2 = Below Average (not up to the expectations for a college senior)
1 = Poor (significant errors or omissions)
N/A if no appropriate score applies

DESIGN PROJECT

A. Technical Accuracy	3	E. Addresses Project Complexity Appropriately	4
B. Creativity and Innovation	4	F. Expectation of Completion (by term's end)	4
C. Supporting Analytical Work	3	G. Design & Analysis of tests	3
D. Methodical Design Process Demonstrated	3	H. Quality of Response during Q&A	3

PRESENTATION

A. Organization	3	C. Visual Aids	4
B. Use of Allotted Time	4	D. Confidence and Poise	3

GRAND TOTAL (Sum of Design Project and Presentation Totals): 41

Please circle each of the following considerations that were addressed by the presentation:

(economic) (environmental) (sustainability) manufacturability
ethical (health and safety) (social) political

Comments (Optional): ______________________

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SCHOOL OF ENGINEERING SENIOR DESIGN CONFERENCE
MAY 8, 2014

Santa Clara University
School of Engineering

PROJECT EVALUATION FORM

Session: *MECH 1*
Room #: *Kennedy Commons* **Judge's Name:** GEORGE C. SKODA

Project Title:	**Solar Powered Absorption Chiller**
Group Members:	Mark Coulter, Claire Kunkle, Craig Carlson, Patrick Watson
Advisors:	Hohyun Lee

Please evaluate senior engineering design projects and presentations using the following point system:

5 = Excellent (at the level of an entry-level engineer you would hire)
4 = Good (at the level of an accomplished college senior)
3 = Average (at the level typical of a college senior)
2 = Below Average (not up to the expectations for a college senior)
1 = Poor (significant errors or omissions)
N/A if no appropriate score applies

DESIGN PROJECT

A. Technical Accuracy	3	E. Addresses Project Complexity Appropriately	4
B. Creativity and Innovation	4	F. Expectation of Completion (by term's end)	3
C. Supporting Analytical Work	3	G. Design & Analysis of tests	3
D. Methodical Design Process Demonstrated	3	H. Quality of Response during Q&A	4

PRESENTATION

A. Organization	4	C. Visual Aids	5
B. Use of Allotted Time	4	D. Confidence and Poise	4

GRAND TOTAL (Sum of Design Project and Presentation Totals): 44

Please circle each of the following considerations that were addressed by the presentation:

economic (circled) environmental (circled) sustainability manufacturability (circled)
ethical health and safety social political

Comments (Optional): ______

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MAY 8, 2014

PROJECT EVALUATION FORM

Session: ***MECH 1***
Room #: ***Kennedy Commons*** **Judge's Name:** Donald Van Buren

Project Title:	**Solar Powered Absorption Chiller**
Group Members:	Mark Coulter, Claire Kunkle, Craig Carlson, Patrick Watson
Advisors:	Hohyun Lee

Please evaluate senior engineering design projects and presentations using the following point system:

5 = Excellent (at the level of an entry-level engineer you would hire)
4 = Good (at the level of an accomplished college senior)
3 = Average (at the level typical of a college senior)
2 = Below Average (not up to the expectations for a college senior)
1 = Poor (significant errors or omissions)
N/A if no appropriate score applies

DESIGN PROJECT

A. Technical Accuracy	4	E. Addresses Project Complexity Appropriately	4
B. Creativity and Innovation	4	F. Expectation of Completion (by term's end)	4
C. Supporting Analytical Work	4	G. Design & Analysis of tests	5
D. Methodical Design Process Demonstrated	4	H. Quality of Response during Q&A	5

PRESENTATION

A. Organization	5	C. Visual Aids	4
B. Use of Allotted Time	5	D. Confidence and Poise	4

GRAND TOTAL (Sum of Design Project and Presentation Totals): 52

Please circle each of the following considerations that were addressed by the presentation:

(economic) (environmental) sustainability (manufacturability)
(ethical) (health and safety) (social) political

Comments (Optional): ______________________