Senior Design Project: Solar Still Using Active Mirrors

Professor: Richard LaGrotta
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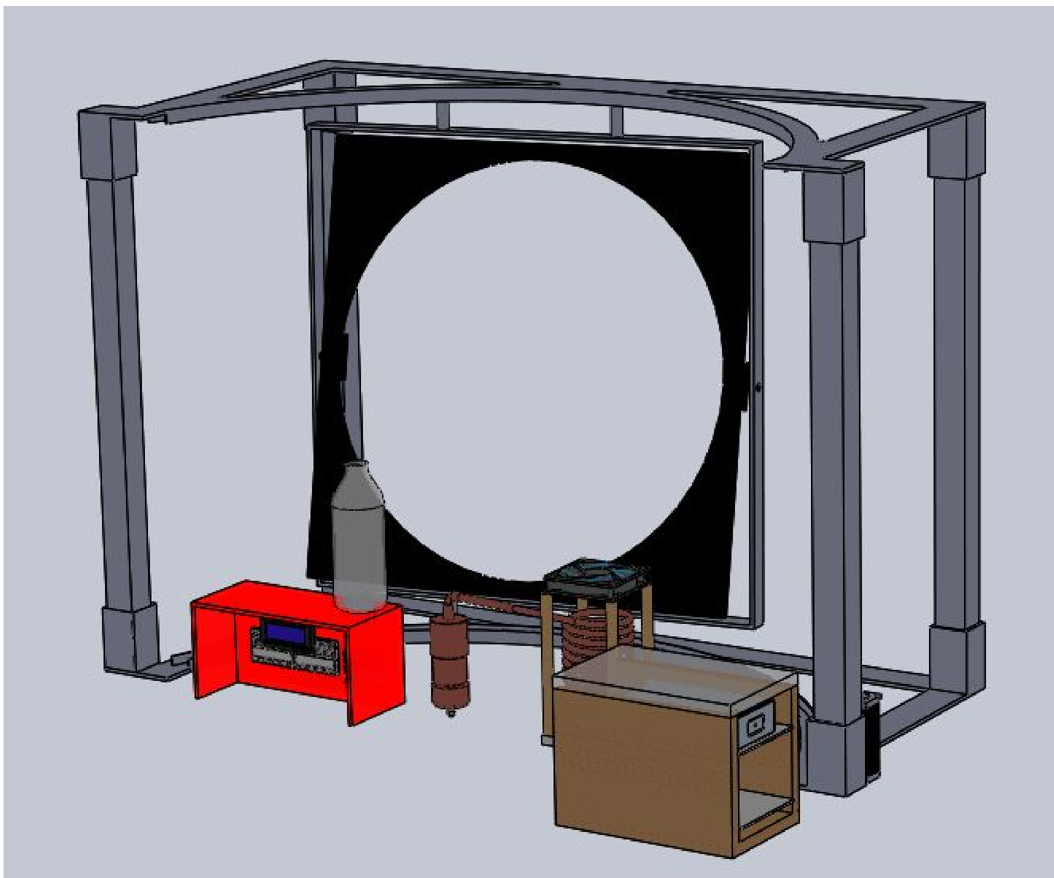

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I. Executive Summary

The purpose of a solar still system is purifying water through contaminant removal process of boiling, followed by the condensation of the water-vapor. The goal of the project is to create an automated, low cost and efficient system. The project is broken down into subsections, problem description, trade studies, solution summary, predicted product performance, test plan, test results and possible future improvements.

Trades studies were performed on each component of the system before the selections were made. With the assistance of our sponsor ConEd, the components were successfully manufactured and assembled into a fully functioning system. The overall cost of the system was (insert amount) excluding materials and labors provided by ConEd.

After trial and error, we have found out our original goal of boiling one liter of water hardly achievable, thus modifications were made to the original design and the volume of water to be boiled was reduced down to 170 milliliters (half of the new boiler volume). Before any actual testing was executed, we theoretical predicted that it would require 36.17 minutes to boil 170 milliliters of water. After several trials of testing, collected data of times required to reach boiling were 30 minutes, 35 minutes, 28 minutes, and 37 minutes respectively. We believed these were acceptable values because in the real world, there are many transient factors that could have affected the boiling time. For example, in the theoretical prediction, we used fixed wind speed and fixed ambient temperature in time calculation, but in real life, these are constantly changing factors. During the testing, condensation of the water vapor was observed and collected in containers, hence our design of solar still system was deemed to be successful.

II. Problem Description

Nearly 70 percent of planet Earth is covered in water, yet only 2.5 percent is considered fresh water. Not only that, but most of the freshwater is trapped in glaciers leaving us with 1 percent of drinkable water. Considering the human body is mostly composed of water, this resource is one of the most important for our survival. This element is not only used for consumption, but it is also important for food production, clothing, and keeping the environment in homeostasis. With recent changes in climate and population growth, the United Nations estimates that by 2025, more than 1.8 billion people will be living in areas where water will be scarce. For this reason, it is important to manage, conserve, and purify water in order to improve the outlook of our future.

Water purification is the process of removing undesirable chemicals, contaminants, and bacteria from water in order to make it safe for human consumption. There are many different methods for purifying water such as boiling, filtration, distillation, and chlorination. However, boiling is the cheapest and safest purification method because other methods tend to contaminate the water if not done correctly. Other than abundant untreated water, we have an unlimited amount of solar energy that can be used in the process of purification. Rather than contributing to the problem by burning fossil fuels or natural gas, we aim to find a safe way to purify water using renewable energy. With the help of a reflector, we can redirect the sun's energy into a boiler for purification purposes.

One of the biggest requirements for this design to work is the availability of sun power. The importance of a project like this to be explored is for the prognostication of the drought that will affect more than 1.8 billion people. Currently there are many other purification systems out there that use electricity, chemicals, and other contaminants to solve this problem.Yet, using the sun’s energy for purification purposes is a method that has been ignored because the importance of renewable energy has been overseen.

This matter can no longer be ignored since the burning of fossil fuels have seriously impacted climate change and the reserves will run out eventually. Therefore, using renewable energy to purify water is of great importance for our project. However, we must stay within budget to make sure we find a cheap and effective way to redirect the sun’s energy to clean water. Boiling occurs when the temperature of the water reaches 100 degrees celsius and so harmful bacteria in the water dies due to high temperature. We aim to catch the steam and condensate it back to liquid state. This process will not require burning fossil fuels to boil water so we can avoid contaminating the environment.

In order to successfully complete this project, there were a few essential conditions or driving requirements that required additional attention. For instance, collecting and redirecting the energy emitted by the sun using an active mirror. Purifying contaminated water by boiling it.

III. Trade Studies

Microcontroller Selection

Raspberry Pi Model B+	ELEGOO UNO R3
	
Price: $35 Functionality: Multi-tasking Flexibility: Pyton, Ruby, C/C++, Java, Scratch Convenience: Programs will be erased after powering off Portability: Support Power supplies outside of USB connection	Price: $11 Functionality: Good execution one program Flexibility: C/C++ Convenience: Programs are stored inside the memory until next modification Portability: Support power supplies outside of USB connection

Trade Study for Microcontroller						
1-Need Improvement 2-Good 3-Excellent						
MicroController	Price	Functionality	Flexibility	Convenience	Portability	Total
Rasberry Pi 3 Model B	1	3	3	2	3	26
Arduino Uno R3	3	2	3	3	3	28

Table 1: Trade study for microcontroller

Raspberry Pi and Arduino are among the most popular microcontrollers today. According to the trade study, although Raspberry Pi is better than the Elegoo (Arduino clone) in many aspects, our project doesn't require multitasking or multiple languages support. Elegoo was the most convenient for our project in terms of memory storage as well as price range and existing clones.

Pump Selection

SUKRAGARHA Mini Mirco Pump	Mini DC6V Water Pump
	
Price: $ 5.99 Maximum flow rate 120 L/h Dimensions: 1.6 inch Applications: Used recirculating water Compatible with Arduino	Price: $13.95 Maximum flow rate 56 L/h Dimensions: 1.5 inch Applications: Used to pump water or oil Compatible with Arduino

Trade Study for Pump Selection						
1-Need Improvement 2-Good 3-Excellent						
Pump	Size	Arduino Compatible	Application	Flow Rate	Price	Total
SUKRAGRAHA	2	3	2	3	3	24
Mini DC6V	3	3	2	2	1	19

Table 2: Trade study for pump

After doing the trade study we choose the SUKRAGRAHA Mini Micro Submersible Pump. Although the pump is programmable with Arduino Uno, the chosen pump has a higher flow rate, it's submersible and cheaper. The pump will be connected to the dirty water container and the boiler, it will be powered by the Arduino to pump water from the container to the boiler. The pump will activate when the float sensor switches, through the Arduino board, when water needs to be pumped into the boiler.

Level Sensor Selection

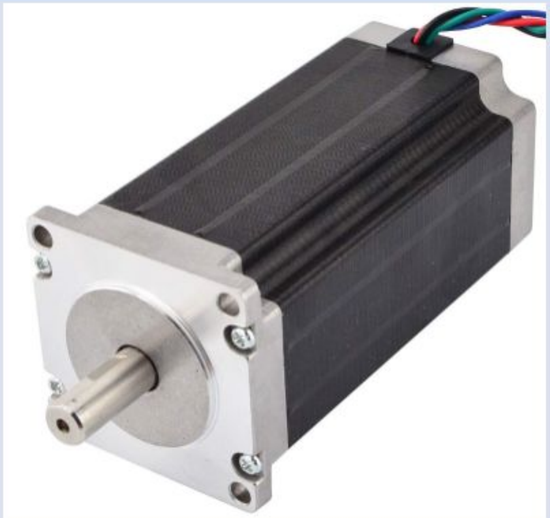
Honeywell Liquid Level Sensor LLC103101	Uxcell Stainless Steel Float Switch M10 Vertical Level Sensor
	
Price: $ 56.00 Operative Temp.: -40˚C to 125˚C Output Type: Switch Requires contact with water	Price: $11.39 Operative Temp.: -10˚C to 115˚C Output Type: Switch Requires contact with water

Trade Study for Level Sensors				
1-Need Improvement 2-Good 3-Excellent				
Sensor	Size	Convenience	Price	Total
Honeywell Liquid	3	2	1	16
Uxcell Float Switch	3	3	3	24

Table 3: Trade study for level sensor

Since our system withdraws water from the dirty water container, boils it, condenses it and then transfer that condensing water to clear water container, there was a need to determine when it’s suitable moment to add more unclean water to the boiler. Originally we were planning to use a liquid level sensor but it was switched to the float switch level sensor since it's more affordable and provides similar function as a liquid level sensor. The sensor is used to detect the level of liquid within a tank and the switch can be used to command the pump. When the water drops below a certain level, it will turn on the pump until the boiler is filled up to a desired level.

Motor Selection

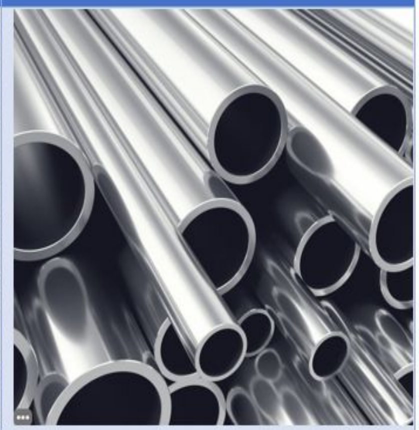
Nema 34 CNC Stepper Motor	Nema 23 Stepper Motor
	
Price: $85.68 Torque: 6.17 N-m (874.8 oz-in) Weight: 4.9 kg 200 steps per revolution	Price: $69.05 Torque: 3 N-m (425 oz-in) Weight: 1.8 kg 200 steps per revolution

Trade Study for Motor Selection				
1-Need Improvement 2-Good 3-Excellent				
Motor	Precision	Torque	Price	Total
Nema 34	2	3	1	18
Nema 23	3	1	3	15

Table 4: Trade study for Motor

According to our trade study we originally bought the Nema 34 motor but do to its high torque it wasn’t necessary for our purpose. We decided to go with the Nema 23 motor, it was both convenient and affordable. Also, the power supply we originally purchased wasn’t providing enough power to the Nema 34 motor, so we purchased the Nema 23 which was compatible with the power supply and it came with a digital stepping driver for a lower price than the Nema 34 stepper motor.

Pipe Material Selection

Copper	Aluminum	Steel
		
Price (USD/lb): 254.72 Thermal Conductivity (W/mK): 385.69 Thermal Absorptivity: 0.4-0.65	Price (USD/lb): 0.84 Thermal Conductivity (W/mK): 204 Thermal Absorptivity: 0.09	Price (USD/lb): 1.58 Thermal Conductivity (W/mK): 50.2 Thermal Absorptivity: 0.4-0.65

Trade Study for Pipe Material							
1-Need Improvement 2-Good 3-Excellent							
Pipe	Thermal Conductivity (W/mK)	Less Weight	Price (USD/lb)	Safety	Corrosion Resistance	Forming	Total
Copper	3	2	1	1	3	1	11
Aluminum	2	3	2	3	3	3	16
Steel	1	1	3	1	3	1	10

Table 5: Trade study for Pipe Material

The trade study was a comparison between three types of metal piping. It was performed based on six categories: thermal conductivity, less weight, price, safety, corrosion resistance and forming. All pipes are very functional and are corrosion resistance. when in safe practices, the aluminum is the best advantage is that it is easy to modify and lightweight and that's the reason why it was chosen for this trade study. Other two materials has it perks, but safety is a big concern when it comes to fabrication.That's why the aluminum is better in terms of weight and costs. Finally, other materials are prone to repairs, leaks and are not easily modified.

Frame Selection

Wood	Steel	Aluminum
		
Price (USD/lb): 0.56 Thermal Conductivity (W/mK): 0.022 Thermal Absorptivity: 0.2-0.8	Price (USD/lb): 1.58 Thermal Conductivity (W/mK): 50.2 Thermal Absorptivity: 0.4-0.65	Price (USD/lb): 0.84 Thermal Conductivity (W/mK): 204 Thermal Absorptivity: 0.09

Trade Study for Frame Material					
1-Need Improvement 2-Good 3-Excellent					
Frame	Stability	Corrosion Resistance	Price (USD/lb)	Safety	Total
Wood	2	1	3	3	9
Steel	3	2	2	1	8
Aluminum	3	3	2	3	10

Table 6: Trade study for Frame Material

The trade study was a comparison between three types of frames. It was performed based on four categories: stability, price, corrosion resistance, and safety. Aluminum is chosen to be best fit. It can be very customizable. While wood is prone to warping, contracting, and expanding as temperatures and humidity levels change throughout the year. Lastly, steel frames are impervious to pests and resistant to fire. The only weakness is condensation and moisture penetration which is mitigated by the use of high quality coatings, insulation and moisture barriers. In conclusion Aluminum is the final winner because of its safe practices when it comes to construction aspect of it for the project and for its flexible restraints.

Mirror Selection

24” Diameter	29" Diameter	35” Diameter
		
Price: $109.00 + 20.00 s&h Height, 18” Focal Length Material: Acrylic Max Temp: 1051˚F Weight: 2lbs	Price: $159.00 + 28.00 s&h Height, 24” Focal Length Material: Acrylic Max Temp: 1451˚F Weight: 3.5lbs	Price: $199.00 + 38.00 s&h Height, 23.3” Focal Length Material: Acrylic Max Temp: 1551˚F Weight: 4lbs

Trade Study for Parabolic Mirror Reflector						
1-Need Improvement 2-Good 3-Excellent						
Concave Mirror	Size	Material	Price	Focal Length	Weight	Total
Green Power Science Acrylic 24"	1	2	3	1	3	24
Green Power Science Large Acrylic 35"	3	2	1	3	3	30
Acrylic parabolic Mirror 29"	2	2	2	2	3	27

Table 7: Trade study for Parabolic Mirror Reflector

In choosing the appropriate mirror, we decided to consider effectiveness over cost, so we originally chose the 35” Acrylic Concave Mirror over the other mirrors but due to unavailability we couldn’t purchase this mirror so we went with the second best option, the 29” mirror. This mirror proved to be the most convenient mirror for our project with a price of $159.00, a focal length of 24” and generating a maximum temperature of 1451°F, which is ideal for our project. The temperature is high enough to boil water and below the melting point of copper (1984°F). This mirror is made of acrylic, which makes it very light weight compared to its aluminum counterpart. Using a light weight mirror was one of our priorities because it reduces the stress on the track and pulley system. In the selection of the ideal mirror we considered the placement of our boiler mechanism, because this would help us select a mirror with an appropriate focal length.

Boiler Selection

Copper	Silver	Aluminum
		
Price (USD/lb): 254.72 Thermal Conductivity (W/mK): 385.69 Thermal Absorptivity: 0.4-0.65	Price (USD/lb): 2.96 Thermal Conductivity (W/mK): 429 Thermal Absorptivity: ~0	Price (USD/lb): 0.84 Thermal Conductivity (W/mK): 204 Thermal Absorptivity: 0.09

Trade Study for Boiler Material				
1-Need Improvement 2-Good 3-Excellent				
Material	Thermal Conductivity (W/mK)	Thermal Absorptivity	Price (USD/lb)	Total
Copper	2	3	2	21
Silver	3	1	1	15
Aluminum	1	1	3	15

Table 8: Trade study for Boiler Material

A trade study was performed on common metals to determine which metal would be most suitable for the material of the boiler. When it comes to the boiler, we would like it to have efficient thermal properties in order to boil the water, but at the same time, remain reasonably priced. Therefore, the evaluation was done in three aspects, thermal conductivity, thermal absorptivity, and price. After careful consideration, we decided to go with copper as the material of our boiler.

Pulley Selection

V-Type Stainless Steel Pulley Block	JCBIZ M75 Stainless Steel Pulley
	
Price: $17.99 Type: Single Pulley Max Load: 362.6 kg Material: Stainless Steel	Price: $23.79 Type: Single Pulley Max Load: 750 kg Material: Stainless Steel

Trade Study for Pulley System					
1-Need Improvement 2-Good 3-Excellent					
Pulley	Size	Convenience	Functionality	Price	Total
V-Type	3	3	3	3	21
JCBIZ	3	2	3	2	17

Table 9: Trade study for Pulley System

A trade study was performed on common metals to determine which metal/design would be most suitable for this project.General purpose drive or idler, V-shape makes it easier to keep fast-moving belts in sheave grooves than it is to keep a flat belt on a pulley. The biggest operational advantage of a V-belt is the wedging action into the sheave groove. This geometry multiplies the low tensioning force to increase friction force on the pulley sidewalls. Most of us are not designing machinery to precisely traverse interdimensional portals into alternate realities.

IV. Solution Summary

Flow Chart

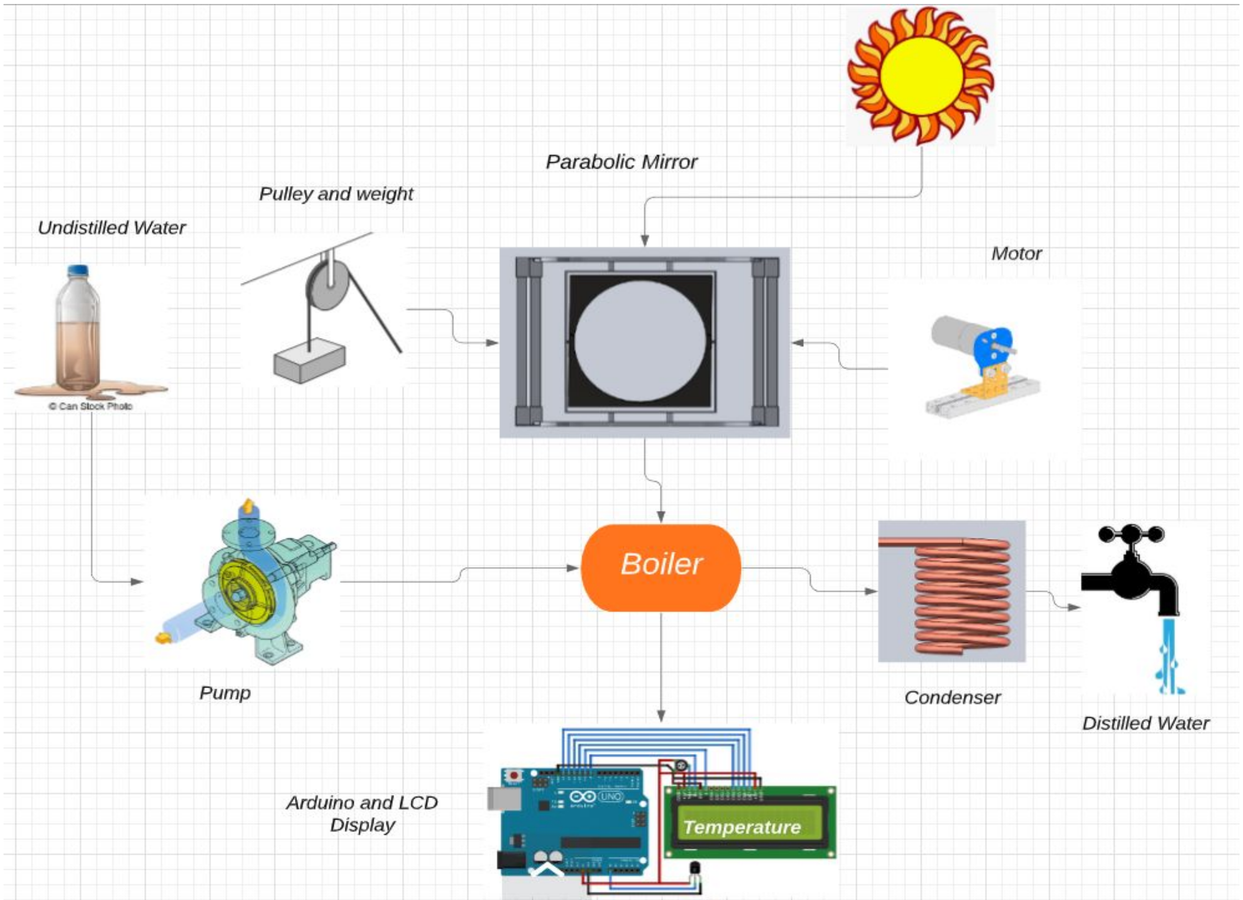


Figure 1: Solar still system flowchart

The flow chart above illustrates the mechanics of the solar still system. The flow chart depicts the following:

1. The process begins by pumping undistilled water from a container with the use of an electric pump.
2. The pumped undistilled water is then released into a copper boiler.
3. A pulley and weight system maintain the parabolic mirror in a stationary location
4. An electronically controlled motor overcomes the weight of the pulley system to adjust the lateral position of the mirror, allowing the mirror to be placed in the direction of the sun
5. The energy of the sun's rays will be reflected through the focal point of the mirror to a point on the boiler which will subsequently heat up the boiler
6. As the boiler heats up an embedded thermocouple will sense the temperature and feed it to an arduino microcontroller and then display it on an lcd screen
7. Finally the condenser will convert the extracted steam from the boiler into distilled water

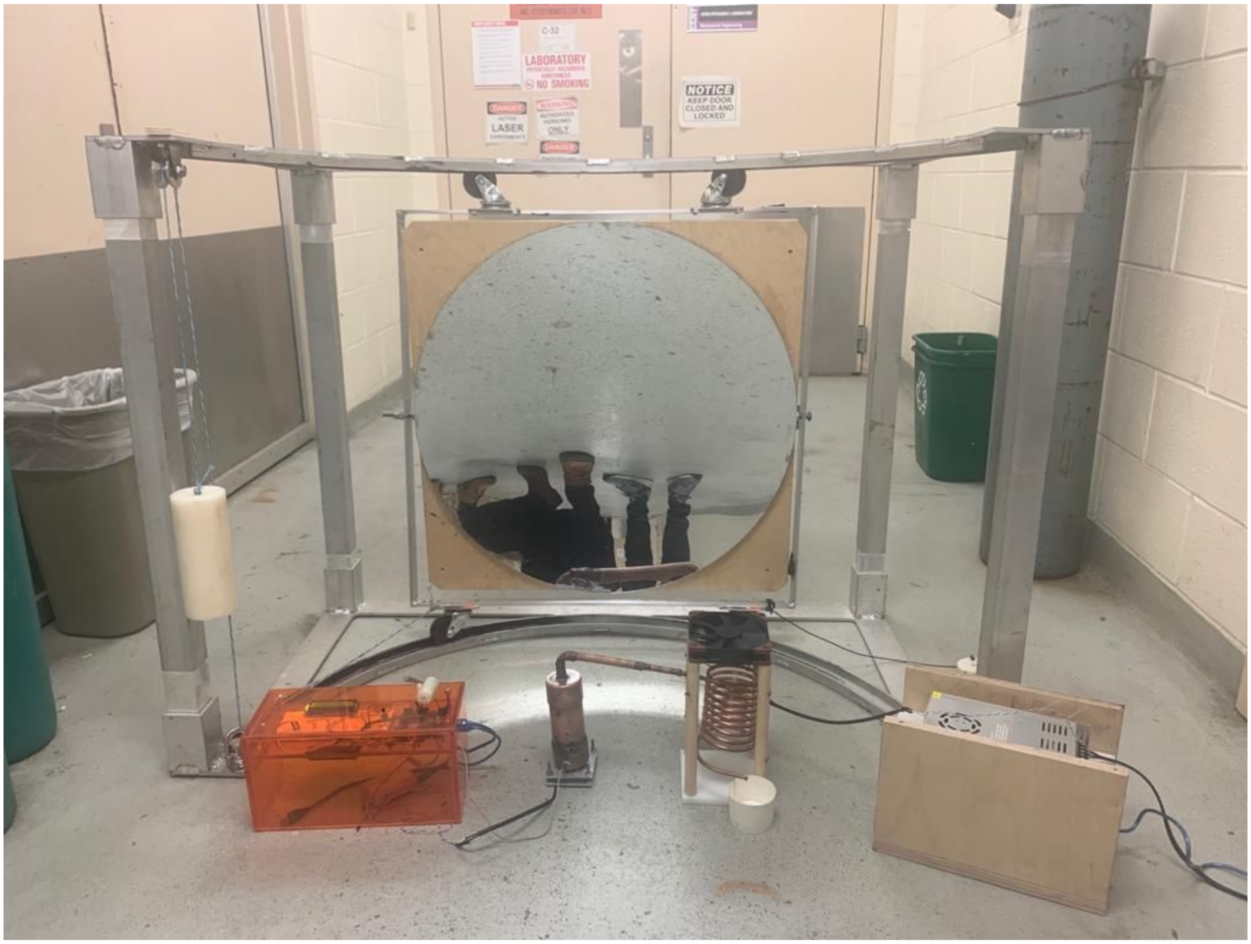


Figure 2: Solar Still complete set-up

As described in the flow chart above, the main purpose for this project was to boil water for purification purposes. The major components required for our system are: a parabolic mirror, boiler, condensation system, pump, and frame that aligns the mirror to the sun. After conducting a few tests, the frame was adapted to follow the sun's path. In fact, the frame has a guiding system for the mirror to slide in, powered by a motor, pulley, and a counter weight. The motor was programmed using an "Arduino" board, to move the mirror in small intervals as the sun changed position. A pulley and weight system was installed to keep the mirror from sliding too much and to bring it back to the starting position. Caster wheels were attached to the bottom of the mirror to make the sliding process smother. Testing also revealed the energy intensity being reflected with our mirror was able to reach temperatures up to 900 degrees celsius. Therefore, we manufactured a boiler using copper since its melting point starts at 1200 degrees celsius.

To make sure there's always water at the boiler, we added a float sensor that lets the pump know when to send more water. We placed a thermocouple inside the boiler to let us know the water temperature, which can be read from an LCD display. Vapor was expected to raise and travel through a copper pipe to the “condenser.” This component was designed to help extract heat and turn vapor back into liquid phase. The condenser was composed of a set of coils made out of ¼” copper piping and a computer fan that blows air directly to the coils.

Human Factor Considerations

In constructing our solar still system we took into consideration many human factors, physical and visual. Eventually we would have to carry and transport the entire system, so we made it light enough to carry. The frame and parabolic mirror are made of light materials, aluminum and acrylic respectively, with a combined weight of 54 lbs (the mirror weighing 4 lbs and the frame 50 lbs). To make the transportation of the system more convenient we decided to divide the weight of the frame by making it out of several parts (top frame, bottom frame, and four base pillars), making it easier to carry and pass through doorways. The condenser and boiler are also light and mobile. In our system we are using arduino microcontrollers to control our mechanical components in order to safely transport and operate the microcontrollers we housed them in a portable box made of acrylic which made it easy to transport while protecting the electronics.

Since our frame is made out of metal we had to assure that we don't injure ourselves when handling it, the frame was grinded to eliminate sharp edges. Temperature plays a key role in this system, the energy reflected by the parabolic mirror raises the temperature of the boiler subsequently raising the temperature of the water in the boiler. To monitor the temperature of the water we used a thermocouple sensor which we attached to the inside of the boiler. To make the system more user friendly we decided to display the retrieved temperature data on an LCD display, showing the continuous fluctuating temperature.

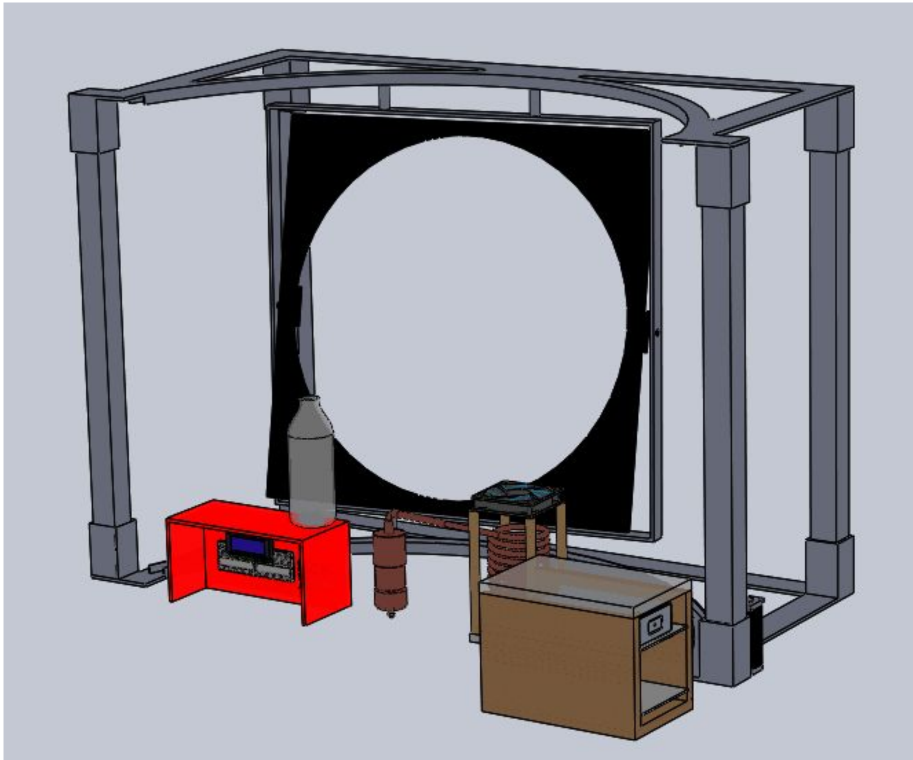


Figure 3: 3D SolidWorks Assembly

Material Selection

After putting in the research and cost analysis our group selected copper for the boiler, wooden pegs to uphold our fan cooling mechanism, and aluminum for our base and outer frame design. With that in mind we thought of designed based on our measurements of our mirror calculations. The design was made in such a way to provide support and prove more stability at the base. Our design for our bases altered because it was not easy to transport. The idea we later came up with was more of assembly then one whole still project.

Figure 4: Manufacturing of the frame

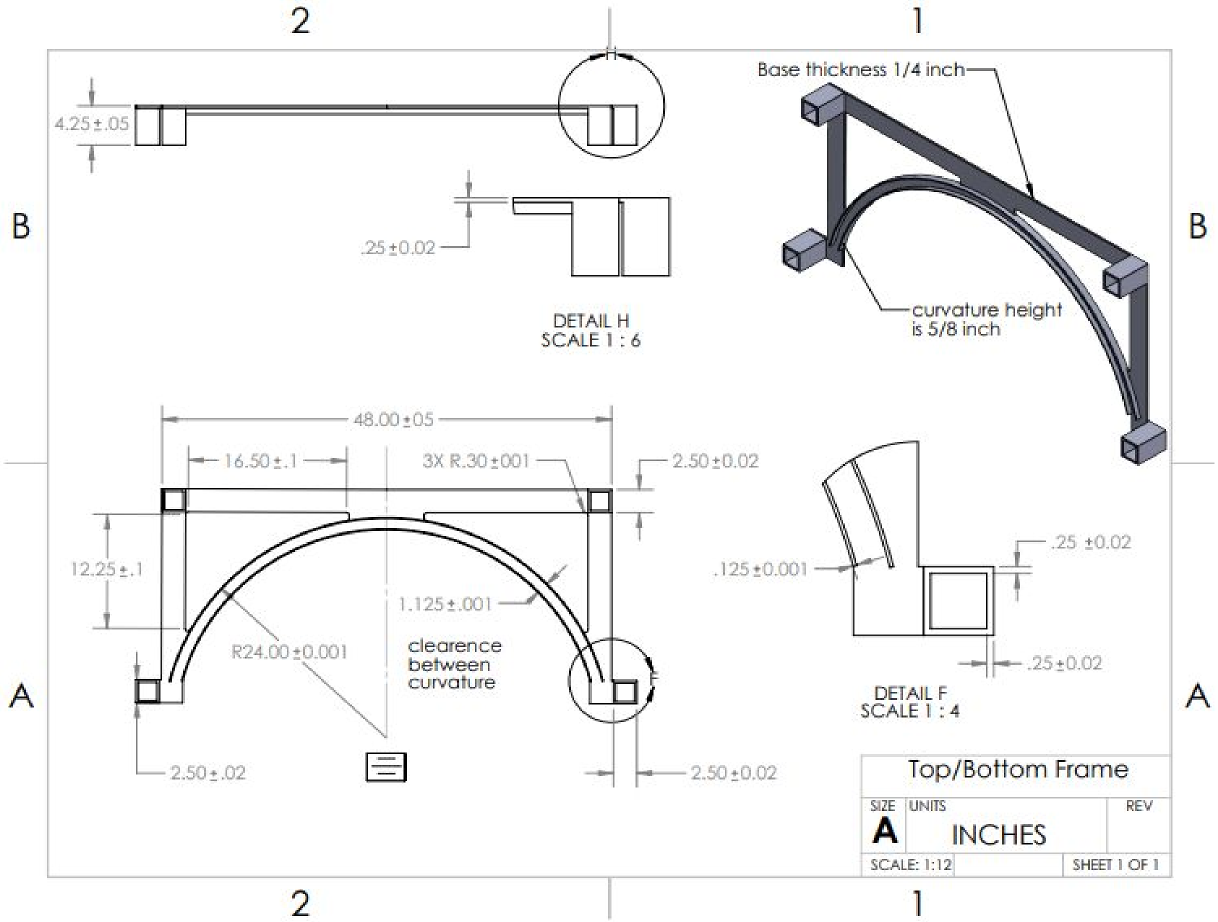


Figure 5: Critical piece part drawing

The frame and rail was the most important piece of our project. This component holds, aligns, and guides the mirror. Not only that, but the frame was designed so that the same component works as top and bottom of the frame. Therefore, two of the parts of the same piece had to be manufactured. Unfortunately, we did not have the necessary equipment to build this frame at the laboratory, but we manage to have ConEdison to donate and manufacture the frame for us. They required engineering drawings, dimensions, pictures, and concept so they can build it accurately for us. Considering the frame was a donation we selected aluminum 1060 so the frame will be lightweight. Even though there was constant communication with the manufacturer, the rail was made with extra space and so we needed to replace the wheels to a bigger size.

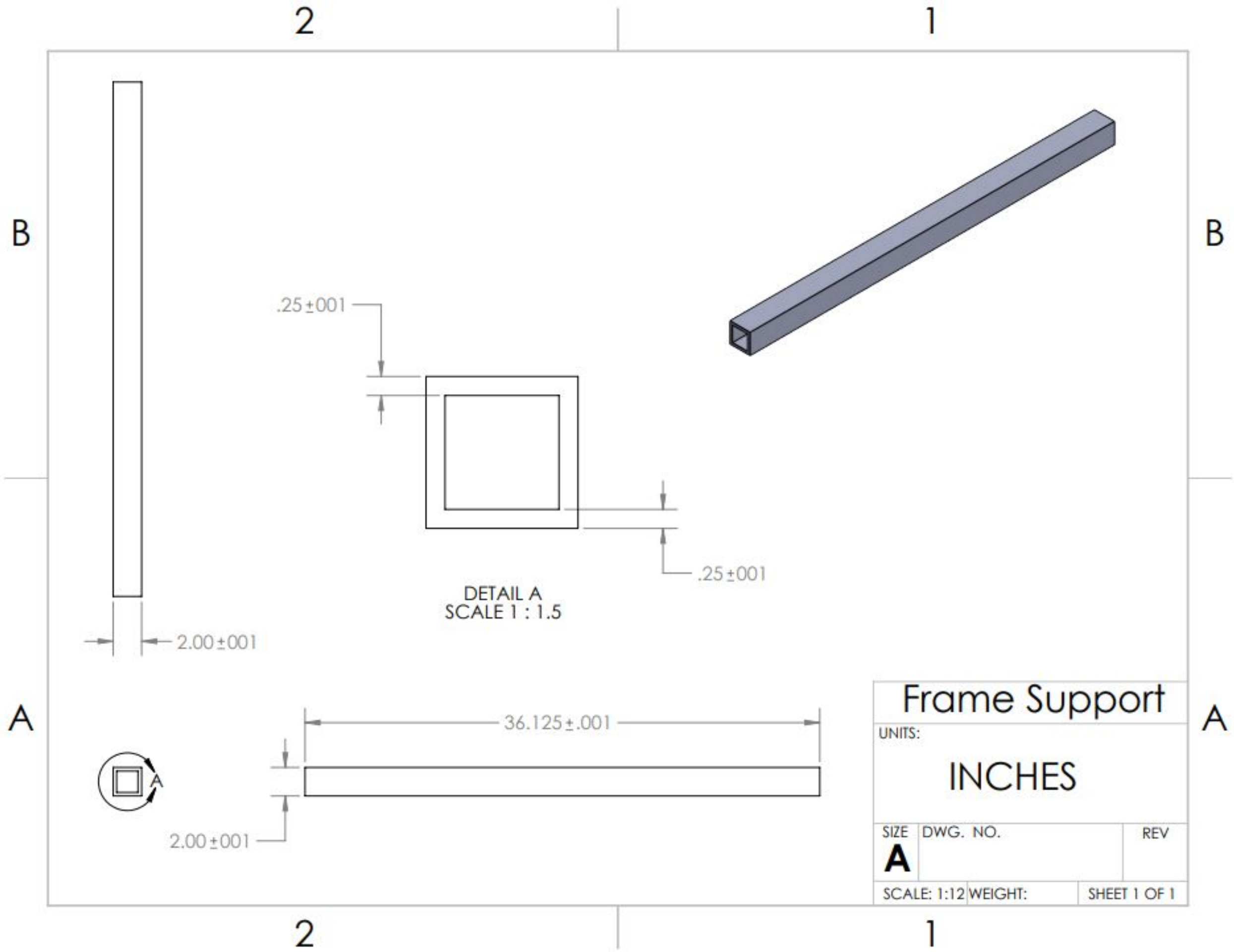


Figure 6: Frame Support part drawing

This component was the support for the frame so, 4 of the same pieces were manufactured to piece everything together. This piece was made out of the same material as the previous component. The entire frame was designed to be an assembly for better mobility and storage.

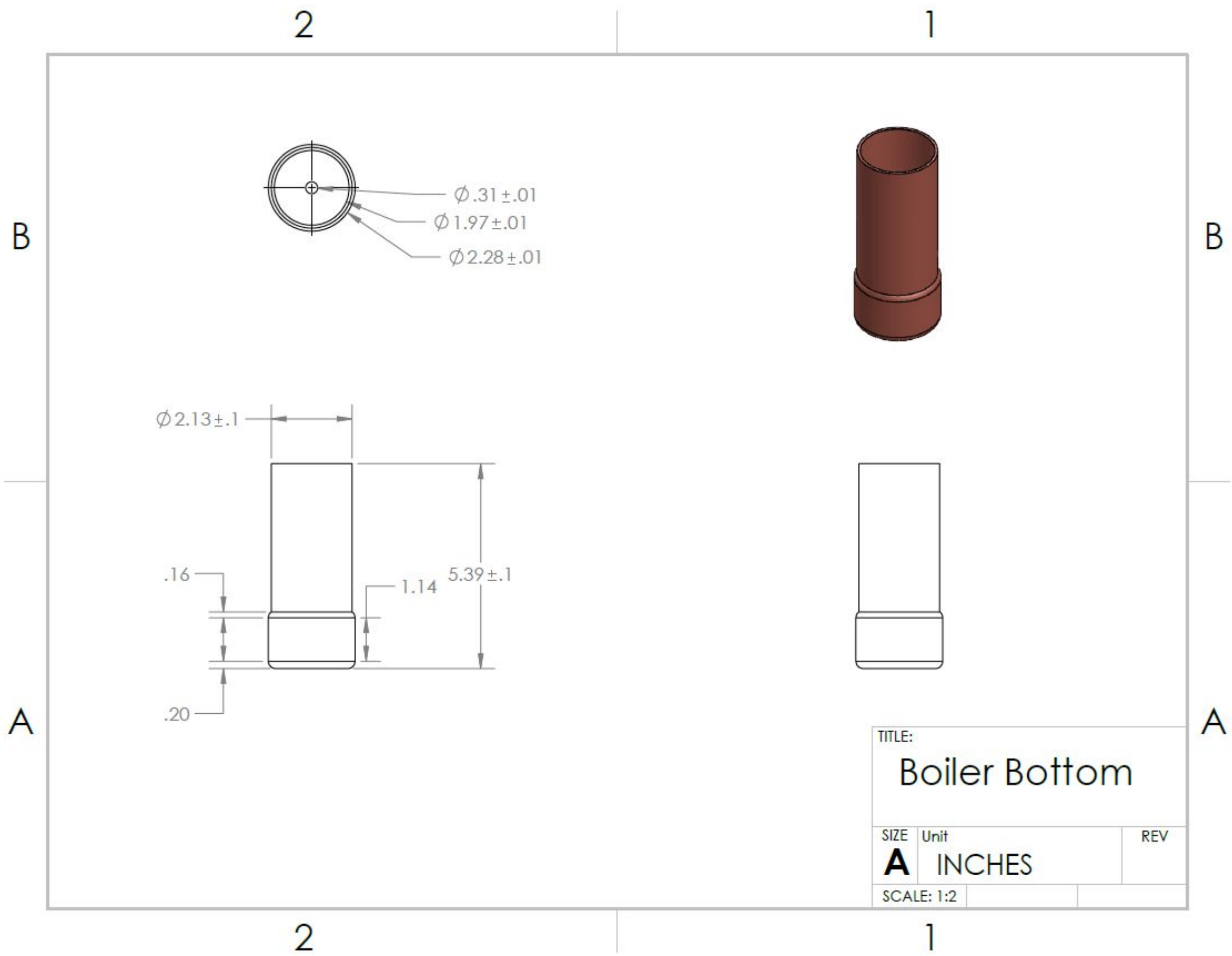


Figure 7: Boiler Bottom part drawing

Boiler is the container where the contaminated water is going to be boiled. The part was made by a segment of a 2 inch copper pipe, the ends were capped with copper pipe end caps. A tube cutout was made for the tube to be inserted and welded for the water pump.

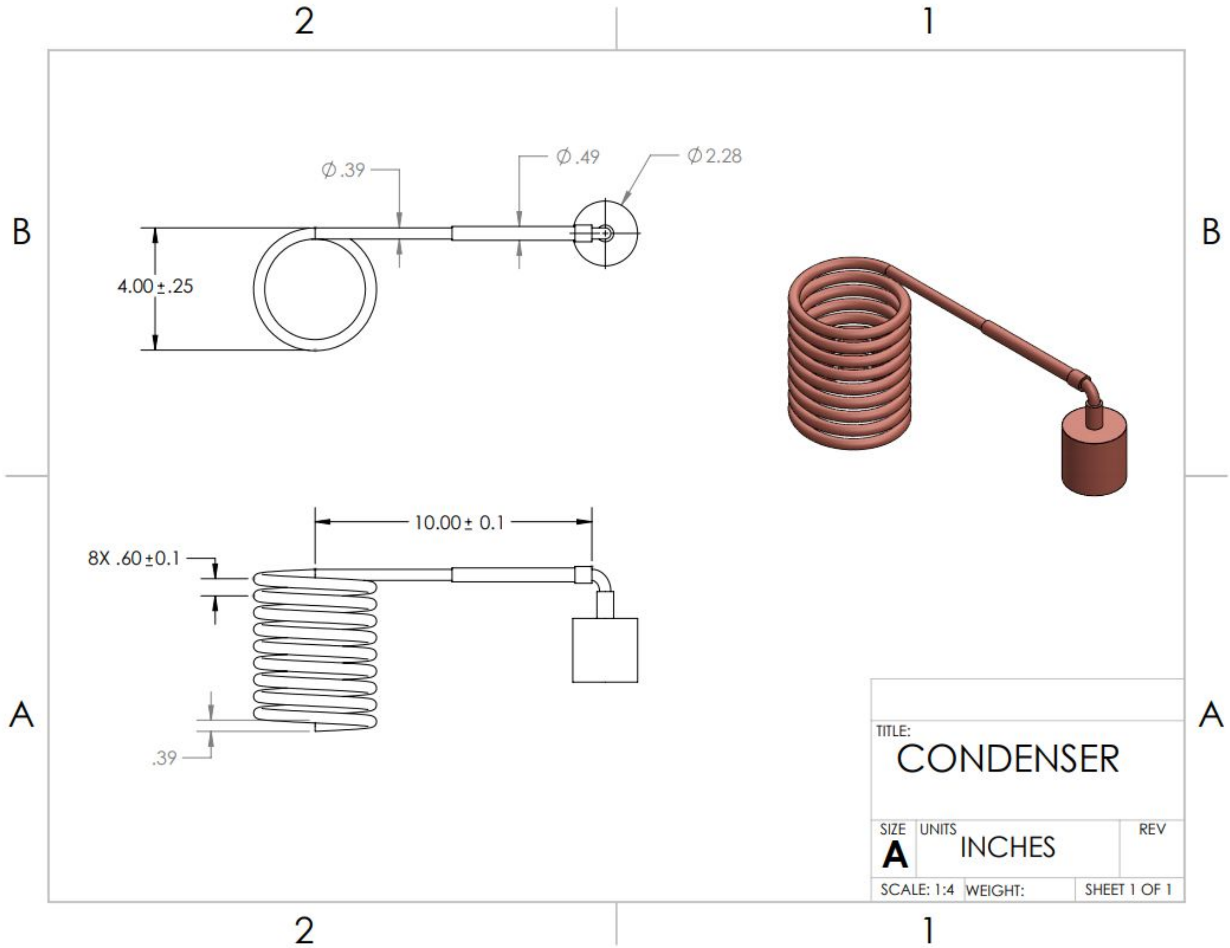


Figure 8: Condenser part drawing

The main purpose of our condensing unit is to turn steam to water. Using a ¼ inch copper pipe, we manufactured a coil system to help heat escape. As the steam travels through the coil, a phase change from gas to liquid must occur, leaving us with clean water. In order to help the heat escape, we added a computer fan to bring more air into the system.

V. Summary of analysis/Predicted Product Performance:

Heat Transfer Analysis:

The reason behind performing the analysis was to determine if the heat collected and reflected by the mirror will be enough to boil the given amount of water and to measure the amount of heat lost, to make sure that the system will work efficiently and will return a sufficient amount of clean water.

To proceed with the calculation of the heat gain, an average of the solar heat supply per unit area had to be determined. After doing some research, it was determined that heat supply per

unit area in mid November is usually around 131.25 W/m^2. Then all that was left to be calculated was the surface area of the mirror. To do that, the surface area of a hemisphere of the same radius was determined and then the area of the mirror was calculated by finding a ratio that describes the relation between the mirror and the hemisphere.
Givens: mirror radius = 14.5 in, mirror height = 4 in
First, the area of the hemisphere was determined to be:

$$A_{hemisphere} = \frac{4\pi r^2}{2} = 2\pi(14.5)^2 = 1321.0\ in^2 = 0.85\ m^2$$

Using the given parameters, a relation between the arcs of the mirror and the hemisphere was obtained by measuring the angle between the end tips of the mirror with respect to the center point of curvature to get an angle of 60.90 degrees as shown in figure 9.

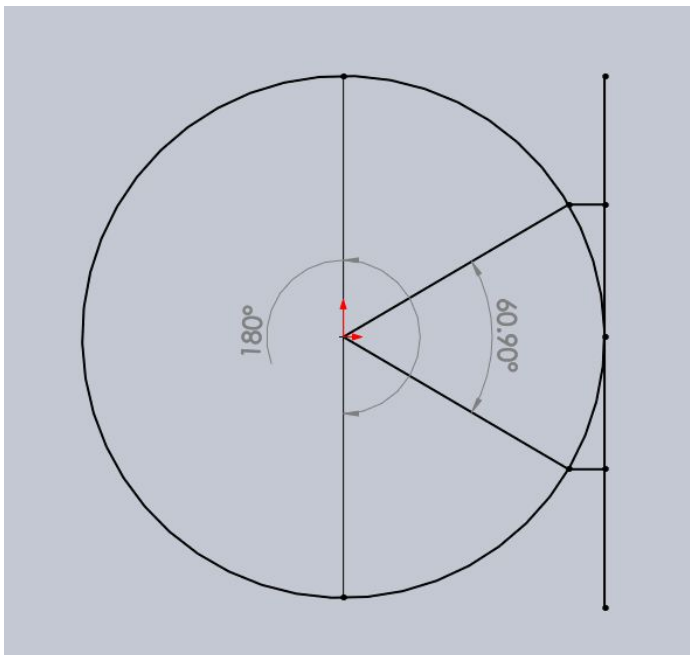


Figure 9: Relation between the mirror and the hemisphere.

And so the ratio will be

$$r = \frac{60.90}{180} = 0.338$$

The area of the mirror is then calculated as follows:

$$A_{mirror} = A_{hemisphere} * r = 0.85 * 0.338 = 0.288\ m^2$$

Finally, the heat gain was determined to be:

$$q_{gain} = 131.25 \frac{W}{m^2} * 0.288\, m^2 = 37.8\, W$$

Outer Heat Transfer Coefficient

To solve for the actual outer heat transfer coefficient, forced convection was assumed to occur and empirical formulas that relate Reynold’s and Nusselt’s numbers to the coefficient were used as follows:

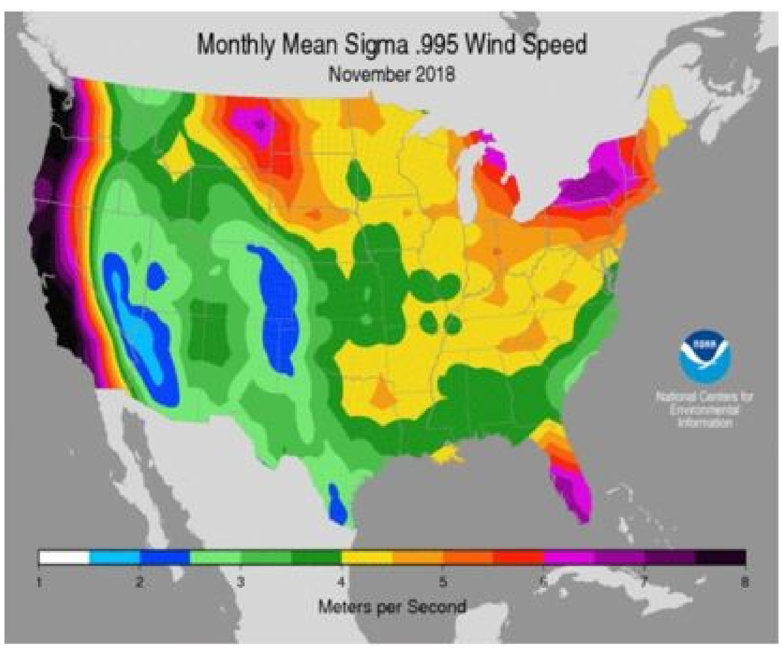
$$Re_D = \frac{VD}{v} = \frac{5.5 * 0.054}{13.71 * 10^{-6}} = 21663.02$$

$$\overline{Nu_D} = 2 + \left(0.4Re_D^{\frac{1}{2}} + 0.06Re_D^{\frac{2}{3}}\right)Pr^{0.4}\left(\frac{\mu}{\mu_s}\right)^{1/4}$$

$$= 2 + \left(0.4 * 21663.02^{\frac{1}{2}} + 0.06 * 21663.02^{2/3}\right)0.710^{0.4}(1)^{1/4} = 93.99$$

$$h_2 = \frac{\overline{Nu_D}k}{D} = \frac{93.99 * 0.0245}{0.054} = 42.64$$

Where ‘V’ is the main stream velocity which in this case is the wind speed. According to the national oceanic and atmospheric administration wind speed plot (as shown in the figure below) mean wind speed during November 2018 was 5.5 m/s.



November 2018 Monthly Mean Wind Speed

Figure 10 - Typical wind speed during November 2018

Heat Loss Calculation

Heat loss is calculated by first determining the areas affecting conduction and convection heat transfers:

$$A_1 = \frac{4\pi r^2}{2}\frac{90}{180} = 0.051\ m^2$$

$$A_2 = \frac{\pi}{2}(r_2^2 - r_1^2)\left(\frac{90}{360}\right) = \frac{\pi}{2}\left(\left(\frac{127}{1000}\right)^2 - \left(\frac{125}{1000}\right)^2\right)\left(\frac{90}{360}\right) = 1.98 * 10^{-4} m^2$$

$$q_{loss} = \frac{T_{\infty 1} - T_{\infty 2}}{\frac{1}{A_1 h_1} + \frac{L}{A_2 k} + \frac{1}{A_1 h_2}} = \frac{100 - 10}{\frac{1}{0.051 * 0.707} + \frac{2 * 10^{-3}}{1.98 * 10^{-4} * 1.005} + \frac{1}{0.051 * 27.35}} = 8.3\ W$$

Time Needed To Boil Water

Since the heat gain was determined in the previous step, by performing some simple steps the time needed for water to start boiling can be determined. First, the energy needed to boil the amount of water in the boiler had to be determined.

$$E_{water} = mC_p\Delta T = (0.17\ kg)\left(4184\frac{J}{kg.K}\right)(100\ C - 10\ C) = 64015.2\ J$$

By dividing the energy needed to start boiling by the heat gain, the needed time for boiling to start can be found as:

$$t = \frac{E_{water}}{q_{gain} - q_{loss}} = \frac{64015.2\ J}{37.8\ W - 8.3\ W} = 2170.01\ s = 36.17\ minutes = 0.60\ h$$

Note that ambient temperature was set to 10 C. During testing, the ambient temperature was usually higher than that sometimes it reached 25 C which changes the required time for boiling to 23.52 minutes (0.39 hours.)

Also note that the analytical results don't take into consideration the superposition of sun rays on the focal point due to the mirror's concavity nature so the actual time is even less.

Copper Heat Transfer Allowance

This part of the calculation is an analytical proof of why copper was chosen as the material for the boiler. Simply, we will calculate the conductive heat rate allowed by copper based on its relatively high thermal conductivity.

$$q_{copper} = kA\frac{dT}{dx} = (385.69)\left(\pi\left(\frac{27}{1000}\right)^2\right)\frac{100-10}{\frac{2}{1000}} = 39.7\ kW$$

By comparing this heat rate by the heat gain from the sun that was calculated previously to be 37.8 W, It is obvious that copper, as a thermal conductive metal, exceeds our needs. Based on those results, we could have implemented a focusing lens to further increase the heat gain from the sun so that to decrease the time to boil water and so increase the system's efficiency.

VI. Test plan

Identify tests to be run

In order to successfully execute the manufacturing of our designed system, we realized that multiple tests were necessary. First, we ordered the most essential components for our design such as a parabolic mirror. We predicted the weather will change drastically from summer to winter, so we decided to test the mirror, boiler, and condensation system as early as possible during the fall semester. Second, we expected to make adjustments as each component arrived. Therefore, each component had to be tested as soon as possible to make sure it would fully satisfy its requirements. If not, then we had to replace the component for a better fit. Some components required an Arduino board and programing so various tests were scheduled to have every component ready for assembly. Next, we scheduled testing for our main frame after our sponsor ConEdison delivered the manufactured parts. Lastly, we assigned two weeks for adjustments and assembly of entire system towards the end of the semester.

Multiple tests were conducted to ensure that the parts of the system would work separately and collectively. The following is a list of the conducted tests:

Manual Setup Test:

Test Description:

The test was conducted to prove the system's validity in terms of tracking the sun movement by manually moving the mirror while maintaining a fixed focal point.

Test Cases:

The test was conducted by manually moving the mirror with and without the original frame.

Data To Be Collected:

From the testing, we should be able to obtain or verify the focal length of the mirror, path for the mirror to move in, and the time gap for mirror movement to maintain a fixed focal point position. These will later be used to create prototypes for future testing.

Thermocouple Test:

Test Description:

The thermocouple will be tested using Arduino by placing it in different environments for its responsiveness.

Test Cases:

The thermocouple will be used to measure the room temperature, cold water temperature, and boiling temperature.

Data To Be Collected:

The validity of the measurements.

First pump test:

Test Description:

The pump will be tested using Arduino by pumping water from a filled cup to an empty one.

Test Cases:

Case 1: two cups will be placed at the same height level.

Case 2: two cups will be placed at different height level.

Data To Be Collected:

The head and flow rate of the pump.

Second pump test:

Test Description:

The pump will be tested using Arduino while signaled by a float sensor.

Cases:

The float sensor will be manually activated and deactivated to see if the pump will be turned on and off based on the sensor's switch signals.

Data To Be Collected:

Validate the coordination between pump and float sensor.

Motor test:

Test Description:

Observing the behaviors of motor using different Arduino codes

Cases:

We will be uploading and adjusting different motor control codes into Arduino and trying to understand what each line of code means based on the outputs observed on the motor.

Data To Be Collected:

Lines of code that suit our project needs.

Automatic Setup Test:

Test Description:

Based on the data obtained on prior manual mirror test, we should be able to make a prototype of track for mirror to slide on to mimic the movement path to track the sun, then we can program the motor to rotate once per time gap to maintain a fixed focal point position.

Test Cases:

The mirror will be locked inside the track and connected to the shaft of the motor using a cable, as the motor rotates, it pulls and forces the mirror to move on the path of designed track.

Data To Be Collected:

Time required for the water to reach boiling temperature as well as the additional time needed for condensation to happen, lastly, the amount of water produced after testing session.

Instruments Used To Collect Data:

To collect the data, required instruments are quite simple. We needed a digital time to record the time needed for the water to reach boiling temperature and condensation. A graduated cylinder/beaker to measure the volume of the water collected.

How Data Will Be Analyzed:

The collected data will be compared with the theoretical predictions, details will be presented in the test results section.

VII. Test Results

Pump Testing - September 5

Attempted to command water pump by using Arduino Uno. Shown in Figure, the pump was submerged in a cup of water and wired to Arduino board powered by a portable charger. A plastic straw was attached to the output of the pump. We were able to successfully command the pump for the duration of pumping and stop. The head of the pump was found to be around 13 centimeters.

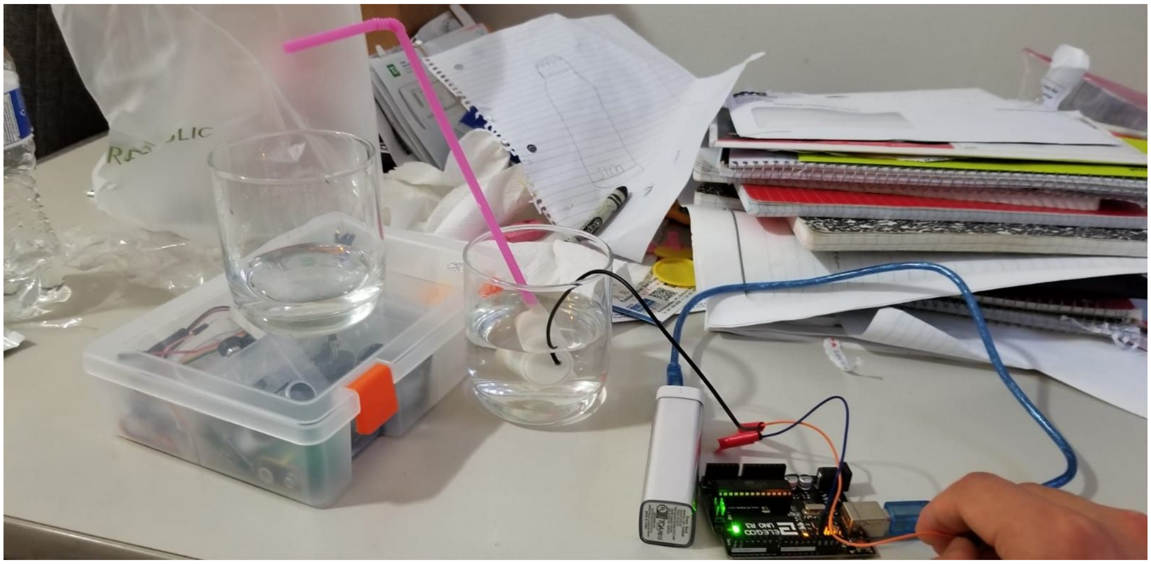


Figure 11: Pump testing using Arduino Uno

Mirror Testing - September 8

As soon as mirror was delivered, we set up a simple test to determine if the mirror was able to focus sunlight on one point. As shown in Figure 12, the mirror failed to focus sunlight onto one point due to the lack of support. Hence a wooden frame was manufactured to support the mirror and prevent deformation. The mirror was secured on the frame by silicon (Figure13).

Figure 12 and 13: Mirror Testing and securing mirror

Sun path testing - September 11

Realized the sun moved in different way than expected. (therefore we studied sun patterns)
September 16 (tested new approach using mobile app to track solar movement)
This test allowed us to modify the frame to final draft.

Temperature/controls testing - September 15

A thermocouple was obtained and it was paired up with Arduino board and an LCD screen. By inserting the head of thermocouple into boiler, the temperature reading of the water would be displayed on the LCD screen.

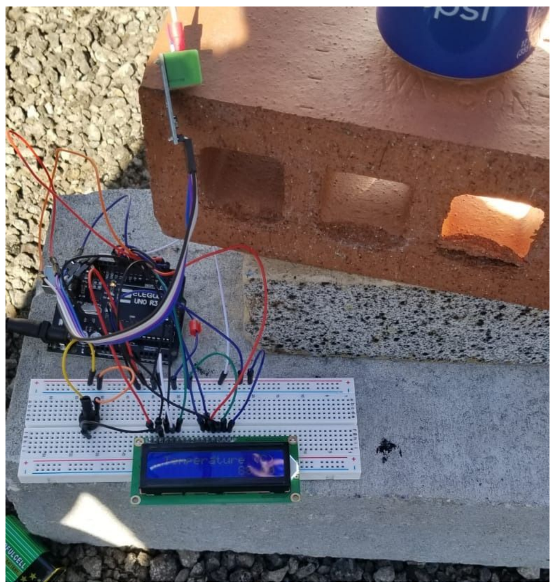


Figure 14: Temperature and controls testing

Boilers testing - September 17

To achieve the best possible heat transfer efficiency, we would like the boiler to have a thin wall thickness so the heat energy can be transferred to water faster. We initially thought about using a boiler made out of copper, however the manufacturing process would be difficult. Therefore, we decided to use aluminum soda can for initial testing. However, as shown in Figure, a hole was melted through the can due to the intensity of focused sunlight.

Figure 15: Boiler Testing

Energy intensity testing - September 18

To have a better estimate of solar energy concentration on the boiler, we decided to place a thermocouple on the focal point to measure its temperature. The temperature was found out to be 900 degrees celsius. This test also helped us determine the required material of the boiler, as the metal can't have a melting temperature less than 900 degrees celsius. That's one more reason why copper was again selected since its melting point is above 1200 degrees celsius.

Water boiling/condensation test - September 19th

A boiler was manufactured by using a segment of 4 inch diameter copper pipe, and both ends were sealed. A condensation system was also manufactured using copper coils of ¼ inch that is attached to the boiler. The initial test was conducted by placing the boiler on the constant heating stove, the coils were placed in a pan of cold water to speed up the process. Condensation was achieved (Figure 16). Boiler was ready for actual testing.

Figure 16: Water boiling and condensation testing

Boiling/condensation test 2 - September 20

After determining that the copper will be used to build the boiler, we created our initial design to test if it's going to make water boil and produce steam. The test was a failure because no steam was produced. It was determined that the container's geometry was the reason for this failure. The front surface area was deemed to be too large and so the boiler's wall thickness so the collected energy on the focal point had a hard time penetrating the wall to reach the water.

Boiling/condensation test 3 - September 26

A new boiler was made using smaller pipe diameter 2.5 inch.

Adding to the geometric problems of the first boiler, the height of the boiler was too short since there are many components that will be connected to the boiler especially the float water sensor, thermocouple and the pump connection. So the boiler was decided to have a thinner wall, narrower cross-section and more height. The new boiler was tested and it was a successful test since, for the first time, the system was able to produce condensed water. The first water drop was spotted after 27 minutes from the start of the test.

Figure 17: Boiling and condensation with actual mirror

Boiling/condensation test 4 - October 2

The testing was conducted again in order to find out the time required for the condensation to happen. At 84 degrees Fahrenheit water inside the boiler reached boiling temperature (100 C) in 28 minutes and condensation of water happened 6 minutes later.

Manufacturing/testing mirror frame - October 21

In order to align the focal point with the sun, we manufactured an outer frame to give the mirror an additional degree of freedom. This modification allowed the mirror to be adjusted in the required inclination angle manually. We ran a quick test to make sure the angle had to be adjusted only once during the duration of our purification process. Test was successful, our assumptions were correct.

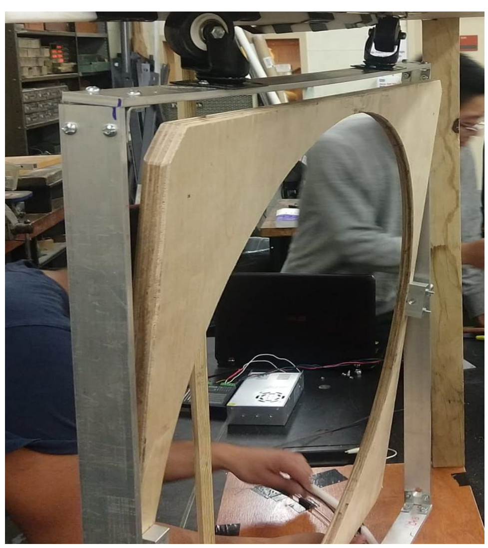


Figure 18: Manufacturing and testing of mirror frame

Condensation system and boiler assembly - October 24

Figure 19: Condensation system and boiler assembly

Frame and mirror assembly test - November 22

The main frame was manufactured by our sponsor Con Edison so we tested the main components together. First thing we realized the rail was too big, this lead our caster wheels to rotate and drag as opposed to slide on the created path. After further inspection, we realized the manufacturer had made the rail 0.5 inch bigger to accommodate for stress tolerances than expected which created room for the wheels to turn, that was due to our tolerance. From this test we realized we needed to either change the wheels or fill in the gap.

Figure 20: Frame and mirror assembly test

Track testing - November 25

Although the wheels were getting stuck in the rail, we still tested the frame to make sure our design properly followed the sun's path. As shown on the image below, the focal point was always on the same spot even though we kept moving the mirror as the sun progressed.

Figure 21 and 22: Track Testing

Final Design

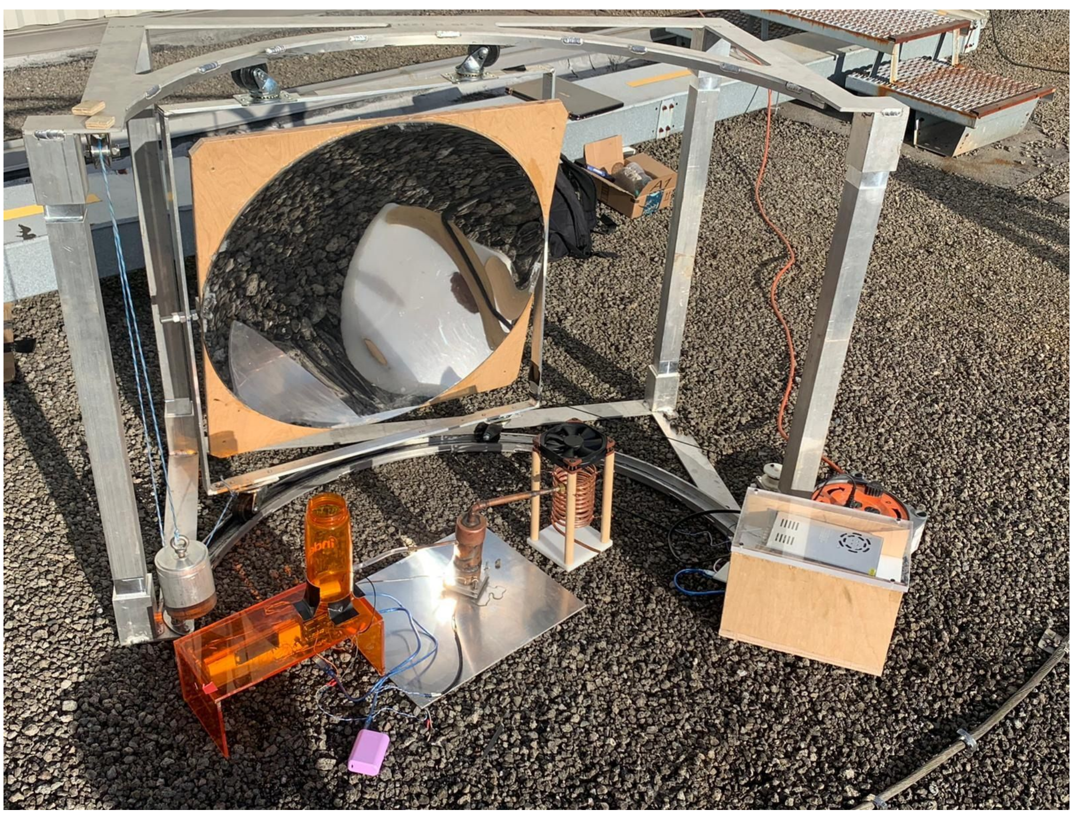


Figure 23- Final Design

Test Date and Starting Time	First Drop Time (minutes)	First Drop Temperature (C)	Boiling Time (minutes)	Condensation Time (minutes)	Boiling Time Percent error	Amount of Water per Hour (L/h)
September 17, 12:30 PM	N/A	N/A	1:00 (30)	N/A	17.06 %	N/A
September 26, 12:45 PM	1:12 (27)	80	1:20 (35)	1:25 (40)	3.23 %	0.138
October 2, 12:15 PM	12:31 (16)	84	12:43 (28)	12:47 (32)	22.59 %	0.141
November 26, 12:00 PM	12:30 (30)	82	12:43 (37)	12:48 (42)	2.29 %	0.134

Table 10: System testing results

The theoretical results that were used to get the percentage error were done based on the 10 C ambient temperature assumption because we wanted to get as accurate results as possible even though some of the testing days felt like summer. There were several notes that we took from those results, concerning time and temperature changes which will be discussed independently as follows:

1. Starting Time:
   It can be noticed from the table above that the starting time is around noon. In comparison to that, almost all of the failing experiments occurred after 2:00 PM. And so it makes sense that all of the successful experiments occurred at noon since it's known that the sun tends to be more focused in the period between 10:00 AM to 2:00 PM. To further prove this assumption we did another test later on November 26 at 2:45. And as expected the system didn't work, the maximum temperature achieved was 76 C which wasn't even enough to get some steam.
2. Boiling Time:
   By comparing the time needed for boiling, it is clear that when the date is closer and closer to winter time the time needed increases, the only exception happened on October 2nd which was unexpectedly a hot day. It appears that the percentage error increases as the winter approaches, which might suggest that the theoretical results were created for summer time. However, what is happening is that the theoretical result assumes that there

is no boundary between the reflected sun rays and the water except air unlike the reality in other words, the analysis doesn't take the boiler's copper wall in consideration. This assumption is justifiable from the copper heat transfer allowance section in the analysis.

3. Condensation Time:
   The results show consistency of the condensation time since the condensation merely depends on the coil which is not really affected by outer temperature. The condensation time, which is the time when the first drop of water came out after the boiling temperature was reached, was found to be approximately 5 minutes.
4. First Drop:
   Before boiling temperature is achieved, steam can still be produced from water at a certain temperature and so some steam actually condenses. According to our data, that condensation usually occurs after 30 minutes of the beginning of the experiment. From the condensation time section discussed earlier it appears that it takes 5 minutes for the steam results from water boiling to be condensed but in the case of the first drop the vapour pressure is much less so it would make sense if the steam was produced at least 10 minutes prior to condensation.
5. Water Amount per Hour:
   From the results above it can be shown that the amount of water the system produces is around 0.14 L/h which is approximately 4 times what the system produces before the bump is activated (displacement volume of the float sensor is about 0.14/4 = 0.0425 L.) Those results are basically an extrapolation of the amount of water produced before the float sensor was activated.

What went wrong

Although we spent an entire semester planning and designing our system, there were too many unknowns and so many assumptions had to be made. We encountered problems from day one so most of our system had to be redesigned in order to make our system work. For example, we discovered our frame would not follow the sun's path because the sun moves from east to west in an angle so we had to add a frame to the mirror to give it an extra degree of freedom. Not only that, but the entire frame/rail system had to be redesigned. Most of the problems we encountered could have been solved by doing preliminary testing. We believe, instead of jumping to quick conclusions and use assumptions to move on with the design process, it would have been far more productive to do small tests to make sure our assumptions were correct. Another major problem we encountered was translating our design from the "drawing board" into a real object. Realistically dimensions are not exact so adjustments are always in order. In fact, ConEdison sponsored us with the frame, they manufactured it using the engineering drawings we provided. However, when they delivered our wheels did not fit the rails because they left too much slack. Therefore, we had to look for wheels with the corresponding size.

Too many things went wrong and we learned how to overcome each problem one at the time as a group. We realized things will not always go the right way, but thinking outside the box and working hard can solve any problem.

VIII. Next Steps

•Based upon the test results how would the design change

Even though we made the process of sun tracking automatic, however, not the overall system as a whole. Before running the tests, we had to manually adjust the inclination angle to focus the focal point before we can let the motor do its job. Therefore, in order to improve the current design, we would like to incorporate a linear actuator that can be attached on the back of the mirror which will be commanded by a sensor, which automatically adjust the inclination angle at different times of the year. With this additional component, the system will be fully automatic without any manual input.

We will also need to incorporate coating layers on the inside of all the copper components (boiler, condensation coils) to avoid the presence of extra substances that could be carried into the distilled water.

Finally, we would like to make the system more compacted by combining all the components into one large piece that can be assembled altogether, this modification will give every component fixed positioning, which will improve the consistency of every purifying cycle compared to the manual displacement of individual components.

•What additional analysis would you have done given what you learned

One of the additional analyses that should have been done was the calculation of the amount of water that can be produced given a day's weather and testing time period. Even though we have done calculations on the time required for a specific amount of water to reach boiling temperature, but the ultimate goal of the project is to produce distilled water. If we would have done the calculation on the condensation, we would have a way to compare or validate our empirical data with.

•What would be your next steps to turn this into a product

To turn our design into a product, first we would need to file a patent with U.S. Patent and Trademark Office to ensure that no one else can steal our design idea. Next, we would like to mass produce or buy in bulk for all the components required to build a system. In addition, many parts of the system can be produced with cheaper materials such as woods and polymers. This act will greatly reduce the overall cost of the system compared to our current model. The lower cost can potentially help us to attract more customers and increase its feasibility.

Cost Analysis

Cost Analysis					
Item	Order Number	Company	Date Purchased	Cost	Description and Purpose
Elegoo EL-KIT-003 UNO Project Super Starter Kit with Tutorial for Arduino	113-5842244-2764227	Amazon	Feburary 25, 2019	$38.11	Arduino microcontroller used to control the mechanical components of our project.
inShareplus 24V DC Universal Regulated Switching Power Supply, 16.5A 400W, 100-240V AC to DC 24 Volt LED Driver, Converter, Transformer for LED Strip Light	114-2442353-9661837	Amazon	September 4, 2019	$29.39	A 24V DC Power Supply, it was purchased to provide power to our Nema 23 Stepper Motor.
SUKRAGRAHA Mini Micro Submersible Motor Pump Water Pumps DC 3-5V 120L/H (1.6 inch Horizontal, White)	112-4930104-8165034	Amazon	August 29, 2019	$6.52	Water Pump that will be used to pump water from resevoir into water boiler.
STEPPERONLINE 1 Axis CNC Kit 3Nm(425oz.in) Nema 23 Stepper Motor & Driver CNC Mill Router Lathe Robot	114-4203429-5325031	Amazon	September 16, 2019	$74.04	Nema 23 Stepper Motor used to adjust the posititon of the parabolic mirror
Accessbuy 2" Heavy Duty Caster Wheels PU Rubber Swivel Casters with 360 Degree Top Plate & Bearing Heavy Duty Pack of 4 (4 Pack Without Brake)	114-7669781-4929835	Amazon	October 18, 2019	$16.32	Caster wheels that will be used to help the mirror travel on the track system and track the sun's path.
Noctua NF-F12 iPPC-24V-3000 Q100 IP67 PWM, Heavy Duty Cooling Fan, 4-Pin, 3000 RPM, 24V Version (120mm, Black) Sold by: Noctua Cooling Solutions	113-6826808-6060259	Amazon	September 24, 2019	$32.61	120 mm Black Fan that will be used to cool the copper tubing in our boiler system and promote condensation.
HiLetgo DC 3-5V MAX6675 Module + K Type Thermocouple Temperature Sensor Thermocouple Sensor Set M6 Screw for Arduino	111-8215211-9069863	Amazon	September 10, 2019	$7.61	Thermocouple sensor set that will be used to monitor the temperature of our boiler.
Uxcell Stainless Steel Mini Vertical Liquid Water Level Sensor F	111-4882506-8642642	Amazon	September 22, 2019	$9.92	Water level sensor float switch that will measure the amount of water in the boiler and shut off the water pump once it reaches the specified limit.
29 INCH PARABOLIC MIRROR USA	29PBMUSA	GreenPowerScience	September 3, 2019	$187.00	29 inch Parabolic Mirror used to capture the sun's energy and used that energy to heat the boiler.
1/8 Flexible rope	X876252	Sugar Hill Hardware	December 3, 2019	$18.00	34 inches of 1/8 rope used for pulleys
4-(2-1/2) Caster W/Brake	X565644	Sugar Hill Hardware	December 3, 2019	$34.80	Caster wheels that will be used to help the mirror travel on the track system and track the sun's path.
2- Frames - 4 Legs	Material /Donated	Con Edison	November 20, 2019	$0.00	House all the components to ensure stability and functionality
Total	$454.32				

The above table details the cost for the parts we purchase for the assembly of our project. Previous cost that we estimated was around to **$416.28**. Each part was carefully selected based on conducted trade studies (shown above) for some parts we weighed effectiveness more than cost and for some cost was more important. There were changes in design, size of the mirror and obtain material from Con Edison. Therefore,you can see the total cost came out to **$454.32**. This was because of additions of the new wheels.Fortunately we have managed to stay below budget.

Conclusion and Recommendations

The current design could have major improvements, based on the budget provided to us we were able to design and manufacture a test stand. The current design has its advantages and disadvantages. The advantages are that it’s easy to modify, disassemble and add components to the current set up.

Although we had presented an overview of how we managed our design, and even strictly adhered to our responsibilities. We had rigorous time figuring out the time it takes to condense our vapor into water.We had to vary a lot of parameters one would be changing the design from using pump to gravity system. From design, change the mirror angle with linear actuator rather than manual approach. Leading to spring pull system to have our mirror into original position then using a pulley and weight.

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