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December 7, 2012

Dr. Brent Nelson
Northern Arizona University
15600 S. McConnell Dr.
Flagstaff, AZ 86011-5600

Dear Dr. Brent Nelson,

Certain developing areas around the world have limited availability to sterilized medical equipment. Knowing this problem, our team developed a goal for the senior capstone design: to create a solar autoclave that can be easily operated at remote clinics in rural areas. To achieve sterilization in westernized countries, an autoclave is the main tool that hospitals currently use. Unfortunately, these devices require grid power or fossil fuels, which in rural areas are not always readily available. To reach our goal, the renewable power of the sun will be utilized to reach a temperature of 121˚C of saturated steam for at least 15 minutes. After extensive research and concept generation, a final design has been chosen.

The final design we chose was the solar trough/boiler design. This design requires far less time, water, and overall resources. The boiler concept consists of an inclined parabolic trough for solar collection with a boiler at the focal point. This boiler will be made from a schedule 40 galvanized pipe rated for pressures of 10 bar or higher. Located at the top of the pipe, a spring pressure valve regulates the pressure within the boiler. This in turn regulates the temperature of the steam leaving the boiler. The steam then will slowly flow down a hose into the pressure vessel. The steam evacuates the air from the vessel, allowing for better thermal contact and more efficient sterilization. This design is far lower in cost than current westernized designs ranging anywhere from $3,000.00 to over $15,000.00. The actual cost of the solar autoclave is hard to determine because the pressure vessel containing the medical supplies will be “home-made”, but a good estimate of the cost is around $300.00, not including tax or machining costs. This cost also does not account for parts that may be able to be found from recycled goods.

Once building is complete, the majority of the semester will be dedicated to testing and improving the design. We hope to begin construction on the trough within the first couple of weeks of the spring semester. Once the trough is near complete, the month of February will be dedicated to building the pressure vessel stand and all other components. The month of March will consist of testing, evaluation and modifications to ensure the solar autoclave is both safe and effective. After full construction and testing, we would like to have a fully functional autoclave by April 2012.

Sincerely,

Eric Brettner, Blake Lawrence, Yuchen Liu, Kyle Godwin, and Adam Compton

Enclosed: Project Proposal

Solar Autoclave for Rural Areas

By:
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Team 6

Project Proposal

Document

Submitted towards partial fulfillment of the requirements for
Mechanical Engineering Design – Fall 2012

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Problem Statement

Introduction

An autoclave is a device used to sterilize medical equipment. While there are many sterilization techniques available, the preferred method is steam sterilization. In this process, water is pressurized to raise its boiling point. When this occurs, steam will be created at a temperature higher than 100^{o}C. In fact, in order to fully eliminate all prions and bacteria associated with disease, saturated steam needs to be at least 121^{o}C when in contact with the equipment being sterilized. Currently, many advanced designs are being used in western countries. These designs are usually powered with electricity and use computers to monitor the internal temperatures and pressures. Unfortunately, many developing areas around the world do not have the technology available to operate these types of autoclaves. As a result, nurses and doctors at remote health clinics in these rural areas are continually challenged with the decision to operate with unsanitary equipment, risking the spread of infection, or to not operate at all. A solar autoclave provides an alternative solution to this problem. Using only solar radiation, a solar autoclave can provide remote health clinics with an inexpensive, efficient way to sterilize medical equipment.

Background Research

The sponsor of the solar autoclave project is Dr. Brent Nelson. Dr. Nelson is a professor at Northern Arizona University in the College of Engineering, Forestry, and Natural Sciences (CEFNS). He teaches several courses, but specializes in the subjects of Heat Transfer and Thermodynamics. He has been interested in the idea of a solar autoclave for some time, and presented the project to our team in the fall semester of 2012. Dr. Nelson explained the current situation and the difficulty for developing areas to obtain sterile medical equipment.

After defining a problem statement, research began. First, different types of sterilization were considered. The big debate was between dry air sterilization and steam sterilization. After learning about both types, the choice was clear. Both methods offer advantages and disadvantages, but steam sterilization was determined to be the dominant method. The pros and cons for dry sterilization are listed below:

Pros:

- Does not require water
- Produces a lower gauge pressure, meaning the process is safer

Cons:

- Takes 2 hours at 160°C to clean equipment
- Does not fully sterilize medical equipment
    - Does not kill all prions and proteins associated with bacteria

Although dry heat sterilization is safer to operate, it takes much longer than steam sterilization and does not fully sterilize the medical equipment. Further research showed that saturated steam sterilization requires a temperature of 121°C for only 15 minutes and fully sterilizes the medical equipment.

Needs Identification

Many developing areas around the world have limited availability to sterilized medical equipment. Currently, several countries in rural areas cannot properly sterilize what limited medical equipment is available. This results in medical treatment or surgery with unsafe equipment, risking the chance of infection and possibly the life of the patient. Sometimes, no treatment is done at all.

Project Goal and Scope of Project

i. Overall Goal Statement – To create a solar autoclave that can be easily used at remote clinics in rural areas.

ii. Overall Scope of Goal - The project will be aimed for several regions across the globe in need of sterile medical equipment, with ample amounts of sunlight to power the solar autoclave.

Objectives

The three main objectives for this project include:

- To provide remote clinics in rural areas with the means to sterilize medical equipment.
- To create a flexible design from location to location.
    - A solar autoclave can be implemented in any region with enough sunlight available. This design will be able to me modified using the resources and materials locally available.
- The individual parts can be repaired or replaced from local, readily available materials.

Below is a table of the objectives listed along with the basis for measurement for each.

Table 1 – Table of Objectives

Objective	Basis for Measurement	Units
Provide remote health clinics with the means to sterilize medical equipment	Temperature & Pressure	°C & bar
Create a flexible design from location to location	N/A	N/A
Parts can be repaired / replaced with local, readily available materials	Cost	$

Constraints

There are not many constraints for this project. The most important one is to sterilize the medical equipment. This constraint can be broken up into two categories: temperature and pressure. These two sub constraints include:

- Temperature of steam must reach and hold 121°C for at least 15 minutes.
- Pressure must reach and hold 2.05 bar for at least 15 minutes.

Functional Diagram

Our design consists of five major steps. These steps describe the autoclave process, and can be seen in the functional diagram below.

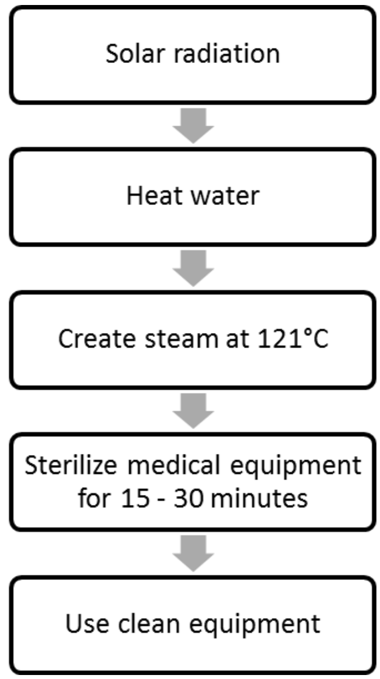

Figure 1 – Functional Diagram

Criteria Tree

Using these objectives and constraints, a criteria tree was created. This can be seen in Figure 1 below.

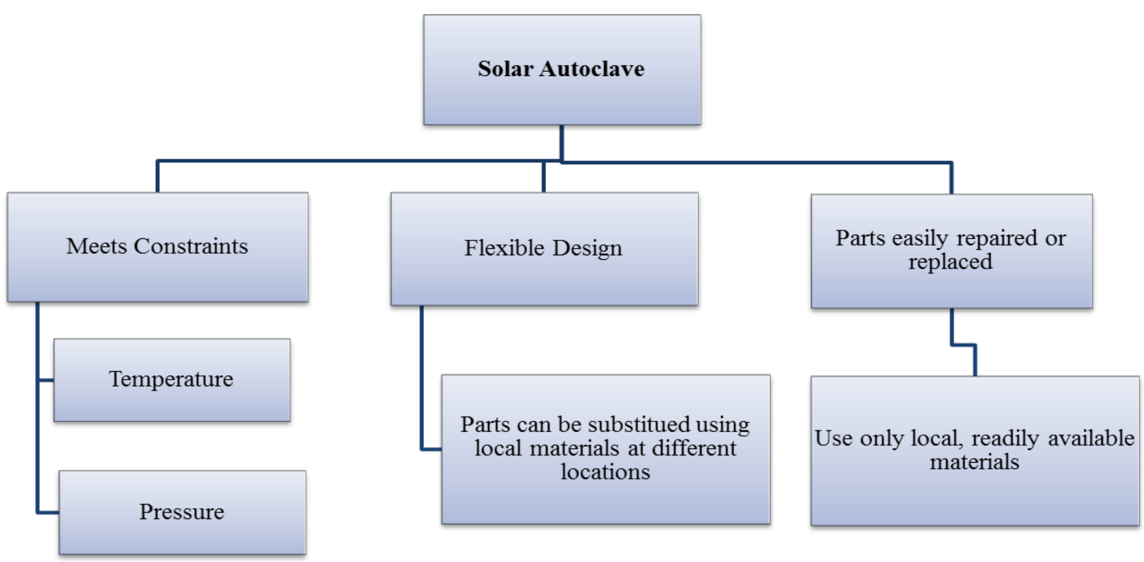

Figure 2 – Criteria Tree

Quality Function Deployment

Additional engineering requirements were developed for the solar autoclave. The following house of quality displays these requirements, and shows how each requirement affects the others.

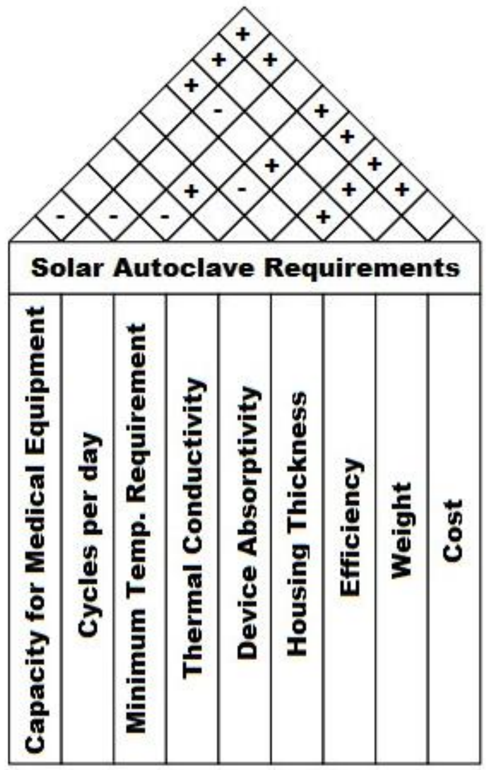

Figure 3 – House of Quality

This house of quality shows how each engineering requirement relates to one another. Plus signs indicate a direct correlation, while minus signs show that the two requirements are not directly related. For example, housing thickness and cost are directly related. As the housing thickness is increased, the cost will be as well.

In addition to developing engineering requirements, the corresponding customer requirements were determined. Both sets of requirements were related to one another, and can be seen in the quality function deployment below.

	Engineering Requirements								
Customer Requirements	Capacity for Medical Equipment	Cycles per Day	Minimum Temperature Requirement	Thermal Conductivity	Device Absorptivity	Housing Thickness	Efficiency	Pressure	Cost
Easy to use	X	X							
Portable	X								
Readily Available Materials				X	X		X		X
Use Energy as efficiency as Possible		X		X	X		X		
Durable						X			X
Achieve the Required Internal Eviornment			X					X	
Safe			X					X	
Inexpensive	X					X			X
Units	cm^3	min	°C	$W \cdot m^{-1} \cdot K^{-1}$	$W \cdot m^2$	mm	%	bar	$
Engineering Targets			121					2.05	

Figure 4 – Quality Function Deployment

This diagram shows the correlation between customer and engineering requirements for the solar autoclave. Each 'X' means the two requirements are related to each other in some way. For example, a customer requirement of being safe to use is directly related to the minimum temperature and pressure required to sterilize the medical equipment. Too much pressure can cause a catastrophic failure, shooting out large amounts of dangerous, saturated steam.

Concept Generation

The initial phase of the solar autoclave project included generating ideas for each of the major component of our design. Five components were identified, and include:

- Thermal Capture
- Heat Transfer into Fluid
- Maintaining High Pressure
- Insulation
- Thermal Storage

Thermal Capture

For solar thermal capture, there are three main designs that are used for efficiently harnessing the power of the sun. A parabolic trough, dish, and Fresnel lens all focus the radiation of sun to a single focal point. Focal points are different depending on the size and shape of the mirror or lens. Having a mirror or lens with a larger area than the pressure vessel and focusing the energy to a smaller point allows the system to reach and maintain the required temperature to superheat the steam at 121˚C.

Parabolic troughs, shown in Figure 5, focus heat onto a long cylinder of fluid which lies parallel to the trough at the focal point. These require a large area to operate. Parabolic dishes, shown in Figure 6, use a circular mirror to focus the heat onto a container held at the focal point. These are effective if used correctly and also require a large area. Both parabolic dishes and troughs can be made from a mosaic of smaller mirrors, allowing them to be made cheaper than a single mirror. Finally, a Fresnel lens uses concentric rings over a plastic lens. These rings are all manufactured to focus light to one location: the focal point. Since the amount of heat and radiation is intensified at this point, the rate of heat transfer is dramatically higher. This process takes a larger surface area of thermal collection than our pressure vessel, and focuses the heat onto that vessel, heating the system. Fresnel lenses can be found in rear projection televisions. Usually made from plastic, these lenses are lighter, cheaper, and more durable than mirrors. A downfall of lenses is that they act as a filter and can absorb some of the energy. For this application, this may or may not be a factor. A major problem with Fresnel lenses is their availability in remote countries. Locating one of these lenses or the flat panel televisions they are removed from may be difficult, if not impossible. A Fresnel lens is pictured in Figure 7. All three of these options offer feasible ways to capture the sun's energy and are under consideration for our finial design.

Figure 5 - Parabolic Trough

Figure 6 - Parabolic Dish

Figure 7 - Fresnel lens

Heat Transfer into Fluid

Another important part of the solar autoclave is how the heat will transfer into the fluid. This is essential to the design because if heat cannot transfer into the fluid, steam cannot be created, and therefore the autoclave will not work.

In heat transfer, fins or fin arrays are used in order to heat or cool objects more effectively. Because of this, our team considered using an array of fins that would be directed internally, resting inside the container holding our fluid. If this container were placed at the focal point of a Fresnel lens or parabolic trough, all the light and heat would be directed toward it, and it would begin to heat up. Once the heat conducted to the fins, it would then convect into the liquid, heating it more rapidly. A fin array can be seen in Figure 8.

Figure 8 – Fin Array

Regardless if fins are present, having the container or boiler at the focal point is critical. Thus, it is undecided if additional effort will be needed outside of the absorption process to magnify the heat transfer rate.

Maintaining High Pressure

For an autoclave to work, a high pressure is required in addition to high temperature. The constraints are a temperature of at least 121^{o}C and a pressure of at least 2.05 bar for a minimum of 15 minutes. During the process, the medical equipment will sit in a pressure vessel and saturated steam will kill the bacteria, creating sanitary medical equipment. In order to achieve this high pressure, our team considered using a pressure vessel, seal the lid, and then clamp or screw down the lid. Pressure vessels can be copper pipes, in the case of troughs, cooking pots, for the case of dishes, or even an old pressure cooker, which can be seen in Figure 9 below. A combination of these different pressure vessels can be used with a boiler design as well. Maintaining high pressures and high temperatures are essential to the function of the device, thus this is one of the most important parts of the autoclave. Unfortunately high stresses develop on the inner surface of the pressure vessel and must be considered. The stress analysis for the pressure vessel will be detailed within the engineering analysis section of the report.

Figure 9 - Example of a pressure vessel **Figure 10 -** Metal Clamp

An additional consideration for our design regarding pressure is the hose line from the fluid container to the pressure vessel. This hose can be composed of multiple types of materials depending upon what is available for the specific region. Several options for this hose line include:

- Copper pipe
- Garden Hose
- Radiator Hose

The disadvantages of using a copper pipe are that bends in the pipe would contribute to head loss. Also, a garden hose may not be able to withstand the interior pressure. Therefore, a radiator hose is most likely the best option.

Insulation

The purpose of insulation in the autoclave is to retain heat as efficiently as possible to temperatures greater than 121°C. The insulation must work well enough to maintain the sterilization temperature and pressure over an extended period of time while maintaining its shape by not deforming under high temperatures.

A great insulator for an autoclave would be NASA's Thermablok Aerogel, which can be seen in Figure 13. Thermablok Aerogel has a phenomenally low thermal conductivity of 0.014 $\frac{W}{mK}$. Unfortunately, obtaining this material is difficult. The cost is high, and it could possibly take months to acquire. Furthermore, because Thermablok Aerogel is so hard to obtain, it would be impossible for remote clinics to obtain any surplus, in case any needed to be replaced. Other options for insulation include typical household insulation and various other natural and manufactured insulations listed below:

- Clay-coated straw
- Mineral Wool
- Styrofoam
- Fiberglass
- Phenolic Foam
- Liquid Cement
- Cork

Figure 11 - Fiberglass

Figure 12 - Mineral Wool

Figure 13 - Thermablok

These materials are easy to obtain, especially in certain developing areas. Also, these are all much cheaper, which is another factor to consider when choosing insulation. A well-insulated system would work efficiently and reduce the amount of time it would take to reach the required temperature.

Thermal Storage

Solar thermal energy can be stored in an energy reservoir for later use. Thermal storage can save cost as well as deal with the intermittency of the sun. There are two forms of thermal storage: sensible heat storage and latent heat storage. For sensible heat storage, energy can be stored by raising the temperature of the storage medium. Likewise, latent heat storage works by altering the physical state of the storage medium. Latent heat storage is more effective and results in a high solar collection efficiency compared to sensible heat storage. Energy can be stored under isothermal conditions in relatively small volumes using phase change materials. Examples of this include molten salts, as seen in Figure 14, sand, and packed beds of metallic spheres. An insulated hot thermal storage tank can be used to hold the phase change material where the energy can be stored with minimal energy losses.

Figure 14: Molten Salts

Concept Selection

After generating concepts for the five categories, several decision matrices were constructed to help with the decision making process. First, a decision matrix for thermal capture was created. Table 3 shows this matrix while Table 2 represents our numerical rating system.

Table 2 - Numerical Rating System

Judgment of Importance	Numerical Rating
Best Option	1
	2
Worst Option	3

Table 3 - Thermal Capture

Thermal Capture Design Options	Criteria	Column1	Column2
	Reliability	Cost	Flexibility
Parabolic Dish	2	2	3
Parabolic Trough	1	1	2
Fresnel Lens	3	1	3

As can be seen in Table 3, our team believes the parabolic trough will be the best option for our design. Troughs are much easier to construct than parabolic dishes, which makes them more reliable in rural areas. Sheet metal can be used for the base of the trough, and can be found on automobiles, mailboxes, and other structural materials. The trough will then be lined with reflective material that can be focused onto boiler to heat it to the required temperature. This reflective material is also reusable as it can be made of Mylar, aluminum foil, or even glass shards.

The next decision matrix deals with insulation and can be seen in Table 4. Obviously, the Thermablok Aerogel would be the best material to use, but because of the cost and availability, the material is not practical. Mineral wool and fiberglass would be the next two best choices. These both have great thermal conductivities, and are much easier to obtain. Using one of these materials is more realistic than using the Aerogel.

Table 4 - Insulation Decision Matrix

Insulation Design Options	Criteria	Column1	Column2
	Weight	Cost	Thermal Conductivity
Aerogel	1	3	1
Mineral Wool	2	1	3
Fiberglass	2	1	2

Another method used in our concept selection is the analytical hierarchy process. This chart introduces a new rating system, which can be seen in Table 5. The analytical hierarchy process compares each of the five concept categories with one another, and determines the overall importance of each category compared amongst one another. In the pairwise comparison matrix, which can be seen in Table 6, the row of totals is used to determine the overall importance. Each value for the columns is then divided by the total from each category, and then summed along the rows in Table 7 to obtain the overall importance. Thermal capture was determined to be the most important. If adequate thermal capture is not obtained, the liquid will not be able to heat up, the pressure will not rise, and the medical equipment will not become sterilized. Likewise, thermal storage is categorized as the least important category.

Table 5 - Numerical Rating System for Analytical Hierarchy Process

Judgment of Importance	Numerical Rating
Extremely more important	9
	8
Strongly more important	7
	6
Moderately more important	5
	4
Slightly more important	3
	2
Equally important	1

Table 6 - Pairwise Comparison Matrix

Column1	Thermal Capture	Heat Transfer into Fluid	High Pressure Maintenance	Insulation	Thermal Storage
Thermal Capture	1	1	2	5.00	9.00
Heat Transfer into Fluid	1	1	2	4.00	9.00
High Pressure Maintenance	0.5	0.5	1	6.00	9.00
Insulation	0.2	0.25	0.17	1	5
Thermal Storage	0.11	0.11	0.11	0.2	1
Total	**2.81**	**2.86**	**1.28**	**16.20**	**28.00**

Table 7 - Overall Importance Matrix

Column1	Thermal Capture	Heat Transfer into Fluid	High Pressure Maintenance	Insulation	Thermal Storage	Overall Importance
Thermal Capture	0.36	0.35	1.56	0.31	0.32	2.90
Heat Transfer into Fluid	0.36	0.35	1.56	0.25	0.32	2.84
High Pressure Maintenance	0.18	0.17	0.78	0.37	0.32	1.83
Insulation	0.07	0.09	0.13	0.06	0.18	0.53
Thermal Storage	0.04	0.04	0.09	0.01	0.04	0.21

Our final design will incorporate three of the five analyzed elements from above and include:

- Thermal Capture: Parabolic trough
- Heat Transfer into Fluid: Metal Pipe at focal point (Painted matte black)
- High Pressure Maintenance: Pressure Vessel (Pot with metal clamps or modified pressure cooker)

Engineering Analysis

Thermodynamic Properties of Water

In an autoclave, the water needs to be pressurized in order to raise its boiling point to 121°C. In other words, an increase in pressure will result in an increase in the water's boiling point. The heat within the autoclave will cause the water to evaporate and the pressure to rise. After the water is evaporated, the steam used to sterilize the equipment can either be saturated steam or superheated steam. Although superheated steam is hotter than saturated steam and contains more energy, it has a low heat transfer capacity and therefore transfers heat poorly. Saturated steam is preferable because it has a better energy exchange capacity. Figure 15 below shows the comparison between superheated and saturated steam.

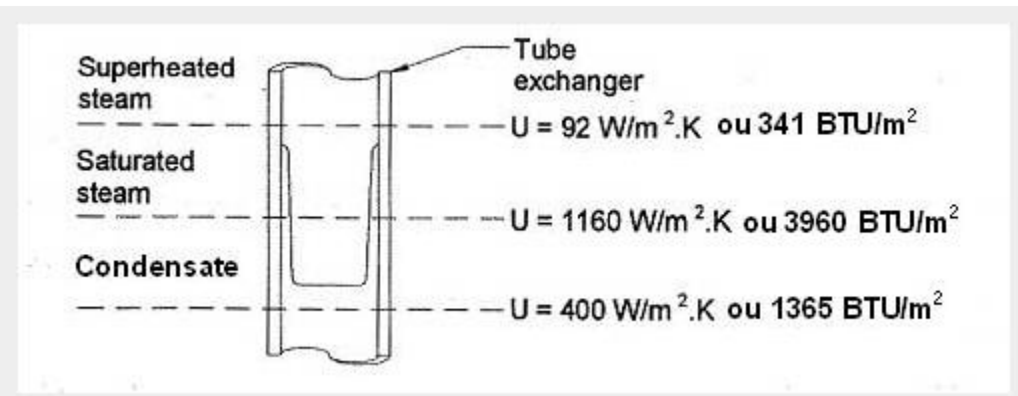

Figure 15 - Heat Transfer Capacity (U) for Water

In order to determine how much energy is required to heat the water, the following equation can be applied:

$$E = m \cdot (u_2 - u_1) \tag{1}$$

Where:

E = Energy, in kJ

m = Mass of water, in kg

u = Internal energy, in $\frac{kJ}{kg}$

For the solar autoclave to properly sterilize the medical equipment, the temperature of the steam will need to be brought from room temperature (20˚C) to 121˚C. After using Shapiro's *Fundamentals of Engineering Thermodynamics* [1], the internal energy values at room temperature and 121°C can be found as shown in the table below. Based on these values and Equation 1 above, the energy, or heat transfer value can then be determined once the mass of water is known. The boiler will use 1 Liter of water to fill a larger pressure vessel. At room temperature, 1 liter of water equates to 1 kilogram. Therefore, the mass of water in the system will be approximately 1 kilogram within the boiler:

Table 8 - Thermodynamic Properties for Saturated Liquid

		Internal Energy, u [$\frac{kJ}{kg}$]
Temperature [°C]	**Pressure [bar]**	**Saturated Liquid**
20	0.02339	83.95
121	2.05050	507.752

Using Equation 1 above, the energy required to heat the water in the autoclave is found to be 423,802 Joules. Once the energy has been transferred to the water within the boiler, the pressure rises, allowing the water to reach 121 ˚C. The pressure will then overcome the stiffness of a spring pressure valve, allowing steam to release into the hose and down to the pressure vessel. With a valve head surface area of $5.07 \cdot 10^{-3}$ square meters, the pressure of 2.05 bar will overcome the spring stiffness of 270 $\frac{kN}{m}$, moving the piston 1 millimeter. An illustration of the concept is shown in Figure 16.

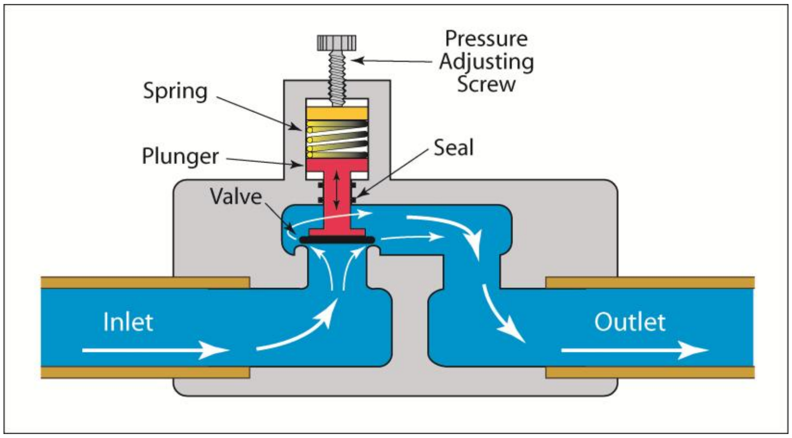

Figure 16 - Spring Pressure Valve

Thermal Capture

Thermal capture is determined from the radiation being emitted from the sun. Applying the equations from above, the projected area needed to acquire the necessary power is found from Equation 2 below:

$$q_{rad} = \alpha \cdot \rho \cdot G \cdot A_{proj} \qquad (2)$$

Where:

q_{rad} = the incoming power of the sun, in W

α = the absorptivity of the bottom of the pressure vessel

ρ = the reflectivity of the material on parabolic trough

G = the solar irradiance, in $\frac{W}{m^2}$

A_{proj} = the projected area from the trough, in m^2

This equation can then be manipulated to solve for the projected area, shown in Equation 3 below:

$$A_{proj} = \frac{E}{t \cdot \alpha \cdot \rho \cdot \epsilon \cdot G} \qquad (3)$$

Where:

E = the energy required to raise the water temperature, in J

t = the time allotted to reach goal temperature, in seconds

ϵ = the estimated efficiency of the trough

Emissivity is a significant factor in how efficient the solar autoclave can be. Emissivity, ε, is equal to absorptivity, α, and directly related to reflectivity, ρ. Therefore, a lower emissivity value results in a higher reflectivity value. For the parabolic trough to effectively collect solar power, reflectivity is very important. Equation 4 below shows the correlation between the two:

$$\rho = 1 - \varepsilon \tag{4}$$

Where:

ε = the emissivity constant

Table 9 below shows the different emissivity and resulting reflectivity values of various materials being considered for the parabolic trough.

Table 9 - Material emissivity and reflectivity

Reflective Material	Emissivity, ε	Reflectivity, ρ
Aluminum - Highly Polished	0.039	0.961
Aluminum - Commercial Sheet	0.090	0.910
425-3M Aluminum Foil	0.030	0.970
Y9360-3M Aluminized Mylar	0.030	0.970

The importance of reflectivity requires a reliable material which can be easily replaced. Mylar is affordable, abundant, and lightweight. The absorptivity of black spray paint was found to be 0.95, which was then lowered to 0.9 in order to be conservative in calculations. The solar irradiance constant is assumed to be 850 $\frac{W}{m^2}$, but may vary between regions. In addition, a half hour of time was estimated to heat the required amount of water, which equates to 1,800 seconds. A 60% efficiency for the homemade trough was estimated. Finally, Equation 3 from above is used to solve for the projected area of the parabolic trough.

$$A_{proj} = \frac{423802\,[J]}{(1800[s])(.9)(.97)(.6)(850\left[\frac{W}{m^2}\right])} = .528[m^2]$$

Doubling the projected area will help to ensure the sterilization temperature is reached even if the efficiency of the home made trough is less than 0.6 since the reflective surface will not be perfect. This measurement is on a square meter basis, and can be used to solve for the required dimensions for the trough. The trough will have a length 1.5 meters and width of 0.75 meters.

A parabolic trough functions by reflecting the solar irradiance to a point along the length of the trough, or focal point. To optimize the power reflected by a parabolic trough, the boiler must be placed at the proper location depending on shape and dimensions of the parabola. Using the known length and width needed to obtain goal temperature as well as an arbitrary focal length of 0.15 meters, the depth of the trough can be found. Figure 17 below shows the variables of the parabolic trough.

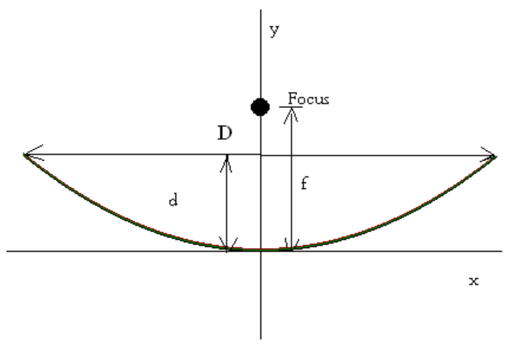

Figure 17 - The variables of the solar collector

Equation 5 can then be used to solve for the depth of the trough.

$$d = \frac{\left(\frac{D}{2}\right)^2}{4f} \tag{5}$$

Where:

d = the depth of the trough, in m

D = the diameter, in m

f = the focal length, in m

Solving for the depth with the diameter and focal length stated above will be 0.234 meters. Equation 6 below will then solve for the shape of the parabola of the trough.

$$y = \frac{x^2}{4f} \tag{6}$$

Thermal Circuit

A thermal circuit is a graphical representation of the various paths of heat flows. Heat will always flow from hot to cold in order to achieve equilibrium in the system. When this occurs, the heat will encounter different resistances. These resistances can be anything in the system trying to resist the flow of heat, whether it is a fluid or solid. Fluids deal with convection resistances while solids involve conduction resistances.

For this form of analysis, we will consider the pressure vessel that holds the actual medical equipment as well as the insulation around it. The heat flow traveling into the system follows several different paths as it makes its way into the water and eventually out of the system. Below is a diagram of the entire system followed by two diagrams of the circuit broken up into separate sections.

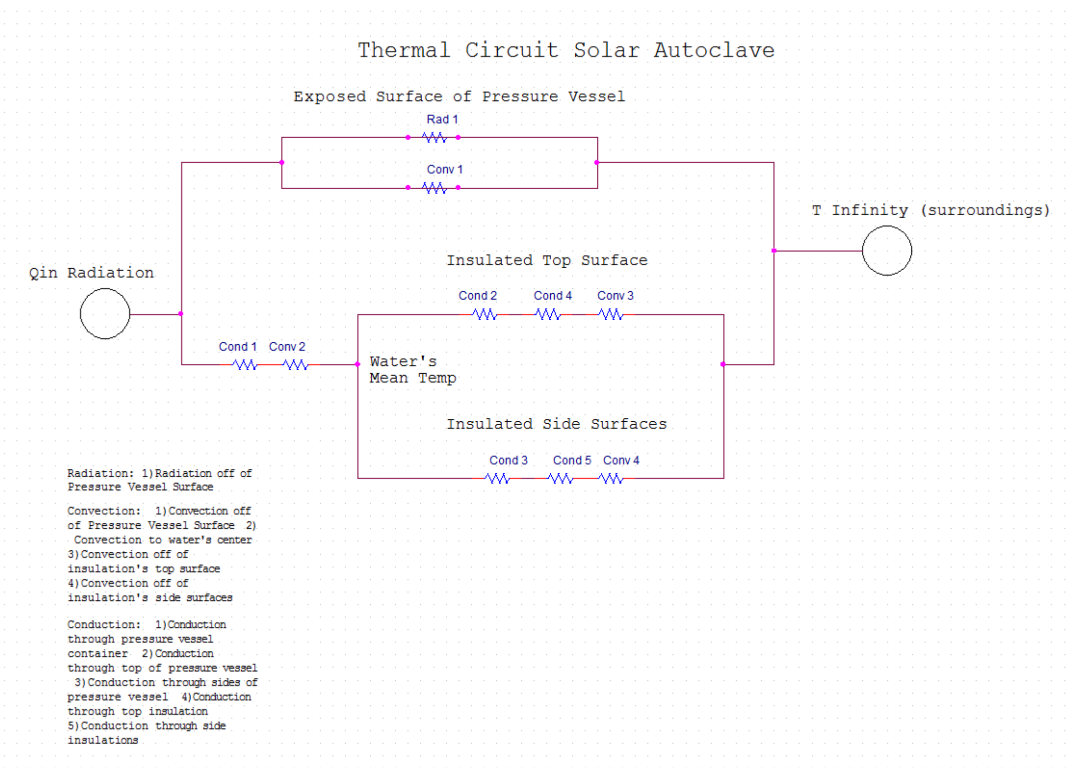

Figure 18 - Thermal circuit for system

Figure 18 above shows the thermal circuit for the entire autoclave system. Initially, heat is transferred into the system in the form of radiation. However, radiation does not turn into heat until it is absorbed somewhere. In this case, the radiation is absorbed into the bottom of the pressure vessel, which will be painted black.

At this point the heat is presented with two paths; either the heat conducts into the vessel, Cond 1, or it is lost in the form of radiation or convection. The parallel circuit at the top represents the heat that could potentially be lost from the bottom surface of the pressure vessel. Rad 1 represents the infrared radiation that would be emitted from the vessel itself. Conv 1 represents the heat that would convect off of the surface, into the surrounding air, $T_{infinity}$.

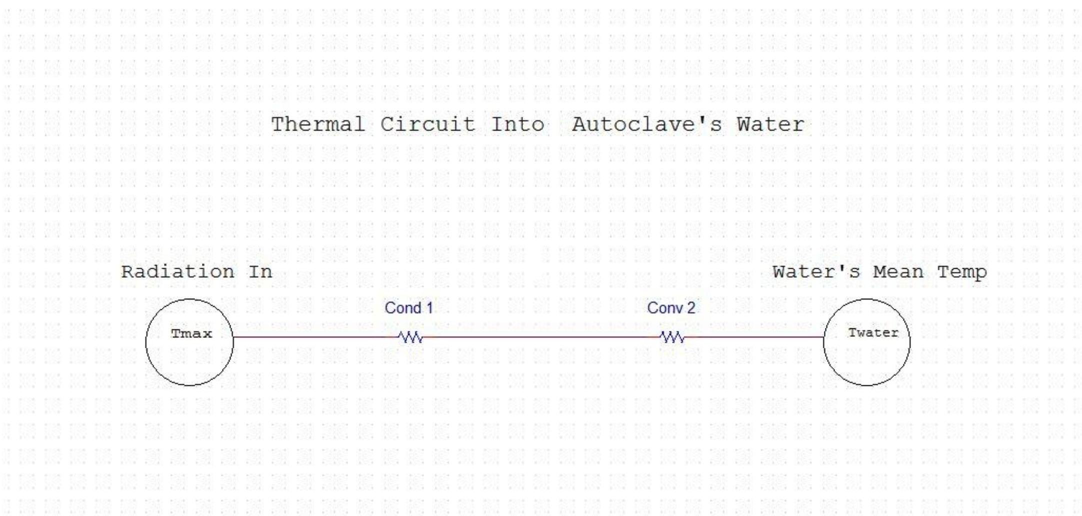

Figure 19 - Thermal circuit of heat entering pressure vessel

Figure 19 above shows a closer look at the thermal circuit of the heat transfer into the pressure vessel once the radiation is absorbed. As mentioned before, the heat will conduct through the bottom surface of the pressure vessel, and then convect through the water inside of the vessel.

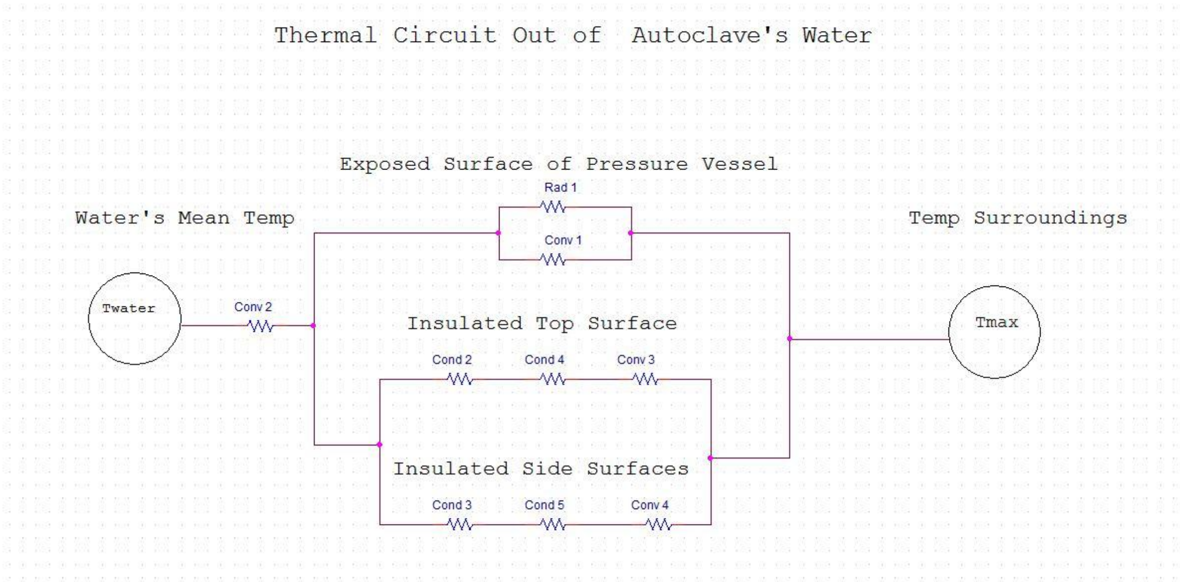

Figure 20 - Thermal circuit of heat leaving pressure vessel

Figure 20 above shows a closer look at the thermal circuit of the heat transfer out of the pressure vessel. The T_{water} that starts the circuit in this figure continues from the end of Figure 19.

Equations:

The following equations determine the resistances of the thermal circuits, and can be applied to Figures 18, 19, and 20 above.

For two or more paths of heat transfer in parallel we use the three following equations:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n} \tag{7}$$

$$R_{eq} = \frac{R_1 R_2}{R_1 + R_2} \tag{8}$$

$$R_{eq} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}} \tag{9}$$

Each of these equations allow for different ways to solve for the equivalent resistance of the parallel sections of the circuit.

For two or more heat transfer resistances in series we use the equation:

$$R_{eq} = R_1 + R_2 + \cdots R_n \tag{10}$$

Convection resistances are defined as:

$$R_{convection} = \frac{1}{h_{convection}A_{surface}} \tag{11}$$

Conduction resistances are defined as:

$$R_{conduction} = \frac{L}{k_{conduction}A_{surface}} \tag{12}$$

Thus using these equations we are able to define the thermal resistance into the water, as seen in Figures 4 and 5, as:

$$R_{eq} = R_{cond\ 1} + R_{conv\ 2} \tag{13}$$

$$R_{eq} = \frac{L}{k_{conduction}A_{surface}} + \frac{1}{h_{convection}A_{surface}} \tag{14}$$

These resistances will allow for a full analysis of the entire system.

Thin Walled Pressure Vessel

For the sterilization chamber of the medical equipment as well as the boiler, a thin walled pressure vessel can be modeled. A thin-walled pressure vessel is defined as a pressure vessel which has a radius, *r*, larger than 10 times its wall thickness, *t*. The pressure vessel experiences stress in three directions: longitudinal, tangential, and radial. However, the radial stress is much smaller than the other two, and can be considered negligible. If failure were to occur, it would happen due to either the longitudinal or tangential stresses. Both the longitudinal and the tangential stresses are due to an internal gage pressure given to us by the resultant pressure after the water has reached a final temperature of 121ºC.

The maximum tangential stress, or hoop stress, accumulated inside the cylinder is given to us by the following diagram and equation:

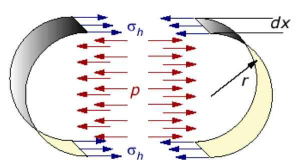

Figure 21 - Hoop Stress inside of Cylinder

$$(\sigma_h)_{max} = \frac{pr}{t} \qquad (15)$$

The maximum longitudinal stress accumulated inside the cylinder is then given to us by the following diagram and equation:

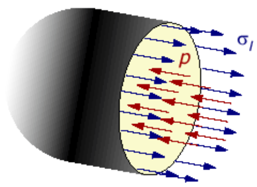

Figure 22 - Longitudinal Stress inside of Cylinder

$$(\sigma_l)_{max} = \frac{pr}{2t} \qquad (16)$$

Where, for both equations:

p = pressure inside vessel, in Pa

r = inner radius of vessel, in m

t = wall thickness, in m

The hoop stress for a pressure vessel of this geometry is half as large as the longitudinal stress. This is a good explanation as to why overcooked hot dogs break at the seam as opposed to at the ends. From this comparison, we can conclude that we want the accumulated hoop stress to be no more than half the stress of the material, giving us a factor of safety greater than 2.

Below is a prototype model of a thin-walled pressure vessel we are considering using for our solar autoclave:

Figure 23 - Prototype of Thin-Walled Pressure Vessel

As one can tell from the figure above, there are also bolts connecting and tightening the lid and the vessel. These bolts undergo a deflection stress when the gage pressure is created inside the vessel. This can potentially force the lid to rise to an unsafe level if a high enough factor of safety is not used when choosing the bolt material and geometry. The equation used to calculate the deflection of the bolts is modeled as:

$$\delta_b = \frac{F_b L}{A_b E_b} \tag{17}$$

F_b is the force applied to each bolt due to the gage pressure, calculated by the equation:

$$F_b = \frac{p(\pi r^2)}{N} \tag{18}$$

Where:

L = overall length of the cylinder, in m

A_b = area of each screw, in m

E_b = modulus of elasticity, in Pa

r = inner radius of the vessel, in m

N = number of bolts used

In conclusion, the most important analysis inside the pressure vessel is the gage pressure built up due to the heating of the water and creation of the steam. In turn, this gage pressure creates a longitudinal stress as well as a hoop stress inside the cylinder. It is helpful to know and understand these stresses when selecting the material and dimensions of the pressure vessel.

Insulation

Reaching 121 ˚C is the goal for obtaining sterility, but this temperature must be maintained for a certain time span in order to guarantee every piece of equipment is clean and safe to use. Using insulation can help to retain heat and minimize heat loss. The thin walls of the pressure vessel and the hose are two crucial places where heat will try to escape. The boiler will remain exposed as this is portion of the system where the radiation will be absorbed. The table below lists a variety of materials with low thermal conductivity. Materials with a low thermal conductivity will maximize the thermal resistance preventing heat loss.

Table 10 - Thermal conductivity values of insulation materials

Insulation Material	k value $[\frac{W}{mK}]$
Thermablok Aerogel	0.014
Balsa wood	0.048
Cork	0.07
Cork, regranulated	0.044
Corkboard	0.043
Fibreglass	0.04
Mineral wool	0.04
Styrofoam	0.033

Thermablok Aerogel is clearly the best choice, but unfortunately Thermablok Aerogel is very expensive and hard to obtain. The next best material for insulation was chosen as Styrofoam, which has both a lower thermal conductivity than other materials and is readily available. Styrofoam was considered to be readily available because of its common use in shipping and packaging. Another large benefit is the cost, Styrofoam is cheap and in many occasions free, so if the insulation was damaged, it could easily be repaired or replaced.

Final Design

The final design harnesses the power of the sun using a trough, shaped from sheet metal, to collect the energy and focus that energy along a pipe or boiler. The reflectivity of the surface facing the boiler is extremely important. To improve this, the surface will be lined with Mylar. This boiler then heats the water while simultaneously raising the pressure. The boiler will be both handling high pressure and temperature so corrosion is a large factor, especially when water is a main component of this system. For these reasons, schedule 40 galvanized steel was chosen for the material of the pipe, because it is both strong and resists corrosion. A spring pressure valve, located at the top of the inclined boiler, regulates the pressure within the boiler while allowing steam to pass through the hose to the secondary chamber containing the medical equipment. The steam, being less dense than the air within the chamber, slowly pushes the air out of the valve located at the bottom of the chamber. Evacuating the air creates a better environment to sanitize the equipment. The valve should be closed once it begins discharging steam. After the valve is closed, the secondary chamber and the boiler will slowly equalize pressure. This is because the boiler must exceed the force behind the spring valve and the force from the pressure within the secondary chamber after the valve is closed. The pressure and temperature will continue to rise in the boiler because of the increasing force from the opposite side of the valve, allowing increasingly hotter steam to flow into the secondary chamber. This process will continue for at least 15-30 minutes until the equipment is safe for medical purposes.

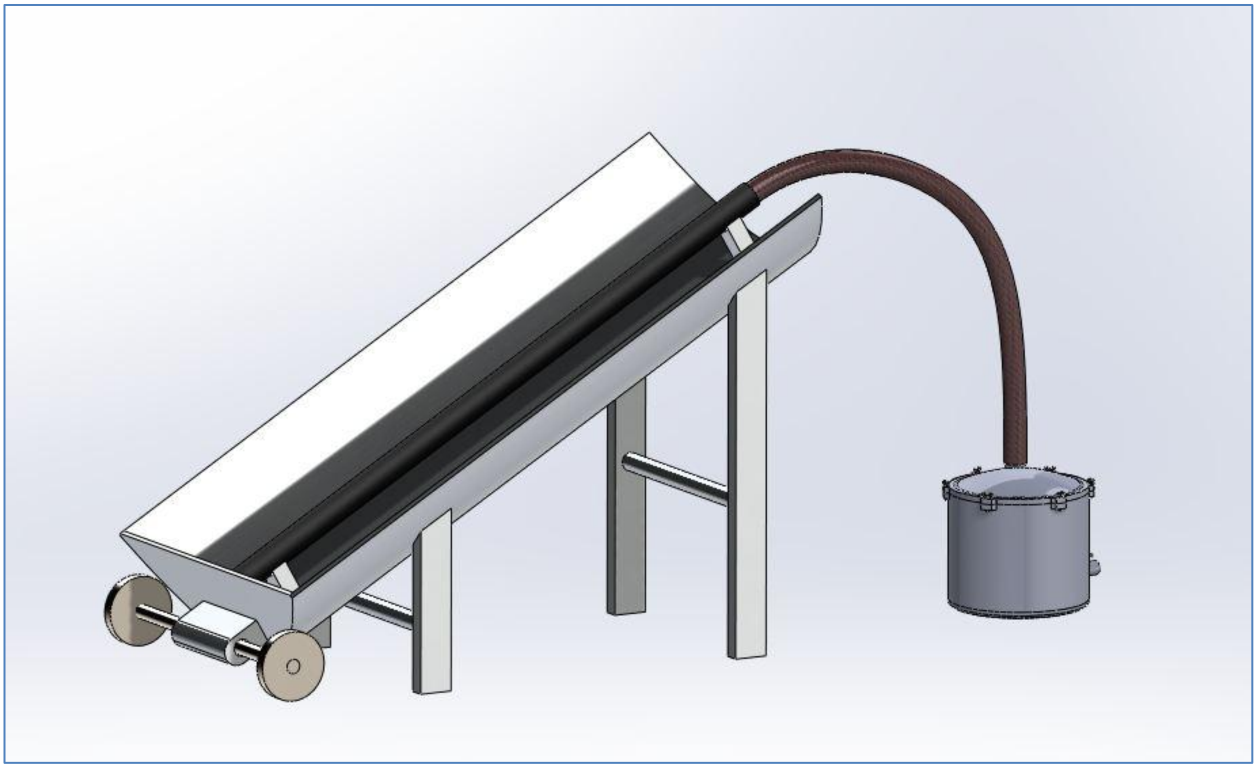

Figure 24 - Solar Autoclave for Rural Areas Prototype designed in SolidWorks

As you can tell from Figure 24, the Solar Autoclave Prototype, nicknamed “Troughdor”, has several parts that involve its working process. The water is placed in the boiler pipe, directly at the focal point of the trough. The pipe is held in place by two stands protruding off the bottom of the trough. The capped end of the pipe slides into place via a pocket at the end of the trough design. A closer look at the placing of the pipe can be seen in the appendix, which gives an auxiliary view of the autoclave with the pipe suppressed. Since this design is only a prototype, it was decided that a lowering and raising mechanism was not necessary in this design. Therefore, the trough is held in place at a 30 degree angle by four stands. However, mobility of the prototype is essential at this stage. The prototype carries a ‘wheelbarrow’ design with two wheels hanging on the end of the trough design.

An estimated cost analysis was developed for the final design. Table 11 below shows the current cost analysis, however, certain costs may change depending on the materials being used. For example, reflective materials can be substituted with aluminum foil, a mosaic of small mirrors, or even polished aluminum cans. The total cost of around $300 is much better compared to standard autoclaves, ranging from $1,500 to $15,000.

Table 11 – Cost Analysis

Material	Quantity	Cost
Schedule 40 Galvanized Pipe	1	$ 30.00
Mylar (Emergency Blanket)	3	$ 15.00
Steel Sheet (1.2192 X 2.4384[m])	1	$ 50.00
Hose (1.5 [m])	1	$ 10.00
Modified Pot	1	$ 50.00
Spring Apparatus	2	$ 20.00
Miscellaneous (Hose Clamps, O-rings, etc.)		$ 75.00
Stand for Trough	1	$ 50.00
Total		$ 300.00

Future Tasks

Given that a prototype for the solar autoclave has finally been designed, our team is determined to acquire the materials necessary for building so that we may begin construction spring semester. Our first step after we obtain the materials necessary will be to begin building the trough, as it will be our most important component of the solar autoclave to build. The building of a pressure vessel will then follow; this and the boiler are also very important and will require extreme attention to detail. Both these components handle pressurized steam and must be built well to ensure safe operation. Simultaneously the stand for the trough will be erected because orientation to the sun is important to achieve the temperature.

Project Plan

Our project plan for the fall semester went better than expected, and this can be exemplified in Figure 25. After discussing with our sponsor, it became evident that our project would be heavily research-based in the fall, while also developing a design. We split the semester into four sections of research – current design research, sterilization technology, material constraints, and financial constraints. Financial constraints became less relevant as discussion progressed with our sponsor, however we utilized this extra time by putting more time into our other three depths of research. Additionally, we managed to maintain a strong basis for communication with our sponsor by scheduling frequent meetings with Dr. Nelson.

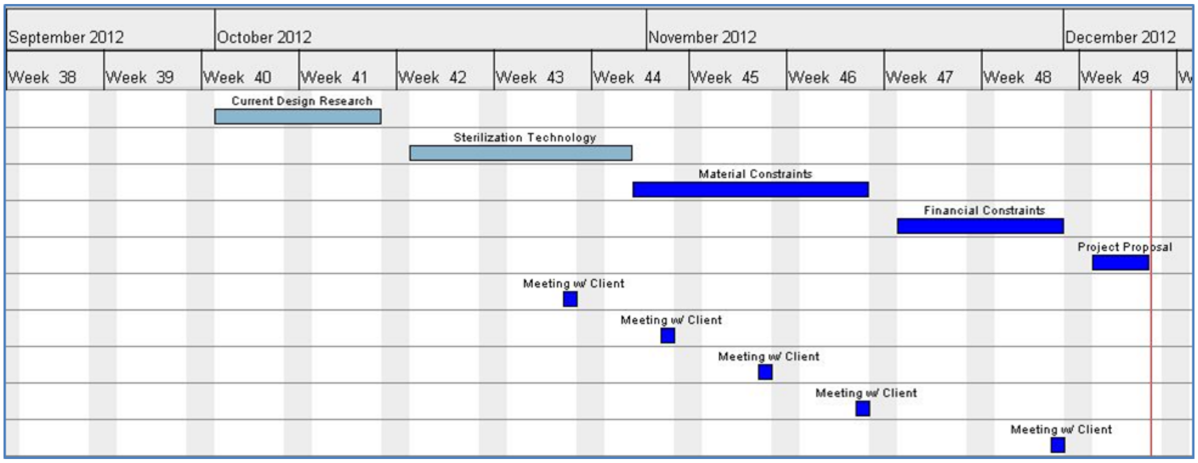

Figure 25 – Timeline for fall semester, 2012

For the upcoming semester, planning is absolutely essential to maintain efficiency and organization. We would like to have the entire semester planned out in advance to give us sufficient time for testing, as we anticipate most of our time will be dedicated towards trial-and-error in the final stages of testing the prototype. The trough must be built first so that we can account the solar irradiation and efficiency of the trough into the rest of the system. The pressure vessel must be obtained and constructed next, which can simultaneously be completed with the construction of the frame and concluded with the collaboration of all the parts of the autoclave by the end of February. A fully-functional solar autoclave should be completed by the beginning of April 2013.

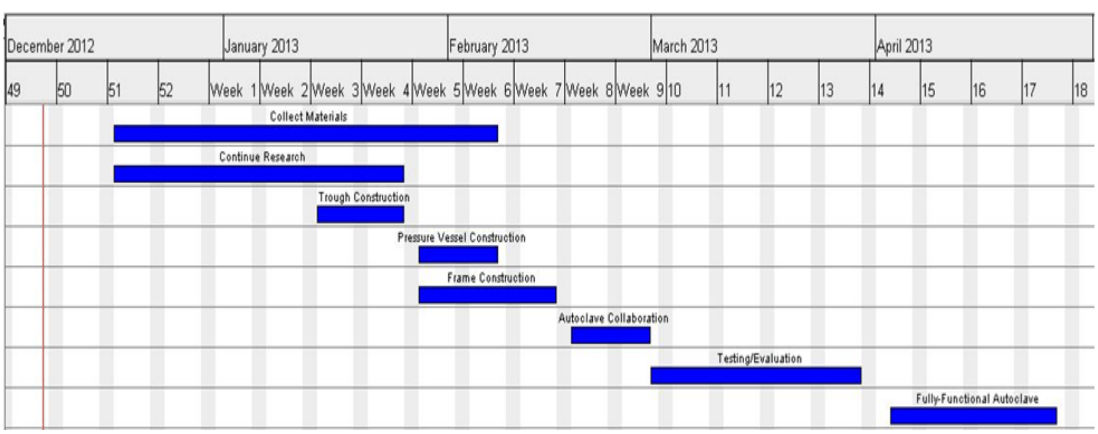

Figure 26 – Timeline for spring semester, 2013

Conclusion

In summary, our task is to develop a solar autoclave - a solar-powered surgical instrument sterilizer for rural areas that uses the energy of the sun's radiation to directly heat surgical instruments to meet sterilization requirements. By identifying the need, generating the concepts, making engineering analysis, and researching on existing design approaches, we seek to develop a flexible, easily constructed, and user friendly design that improves on the existing approaches.

The design objectives for this project are to provide remote clinics in rural areas with equipment that utilizes solar energy to sterilize medical tools; the design should be flexible from location to location; the materials used should be readily available and the parts in our design can be repaired or replaced from local, readily available materials.

To ensure that medical instruments are sterile, the constraints of our design are to heat them to at least 121°C and hold the pressure of at least 2.05 bar for 15 minutes.

There are 5 categories in our concept generation. The thermal capture and heat transfer into the fluid are the most important functions that the solar autoclave must perform. They are the most basic concepts to ensure that the autoclave reaches the necessary temperature in order to sanitize the medical equipment inside. A close second is the autoclave's potential to maintain the high pressure. Insulation and thermal storage are other functions of the solar autoclave, but have been established as less important.

The final design has two main parts: a parabolic trough concentrator and a pressure vessel. The parabolic trough consists of a boiler where the radiation is absorbed and converted to the water inside. The trough is purposely inclined, to allow steam to build at the top before being released into the pressure vessel. The pressure vessel holds the surgical instruments that need to be sterilized.

These concepts will be applied in the spring of 2013, when prototyping and testing of the solar autoclave will be initiated.

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Sponsor:

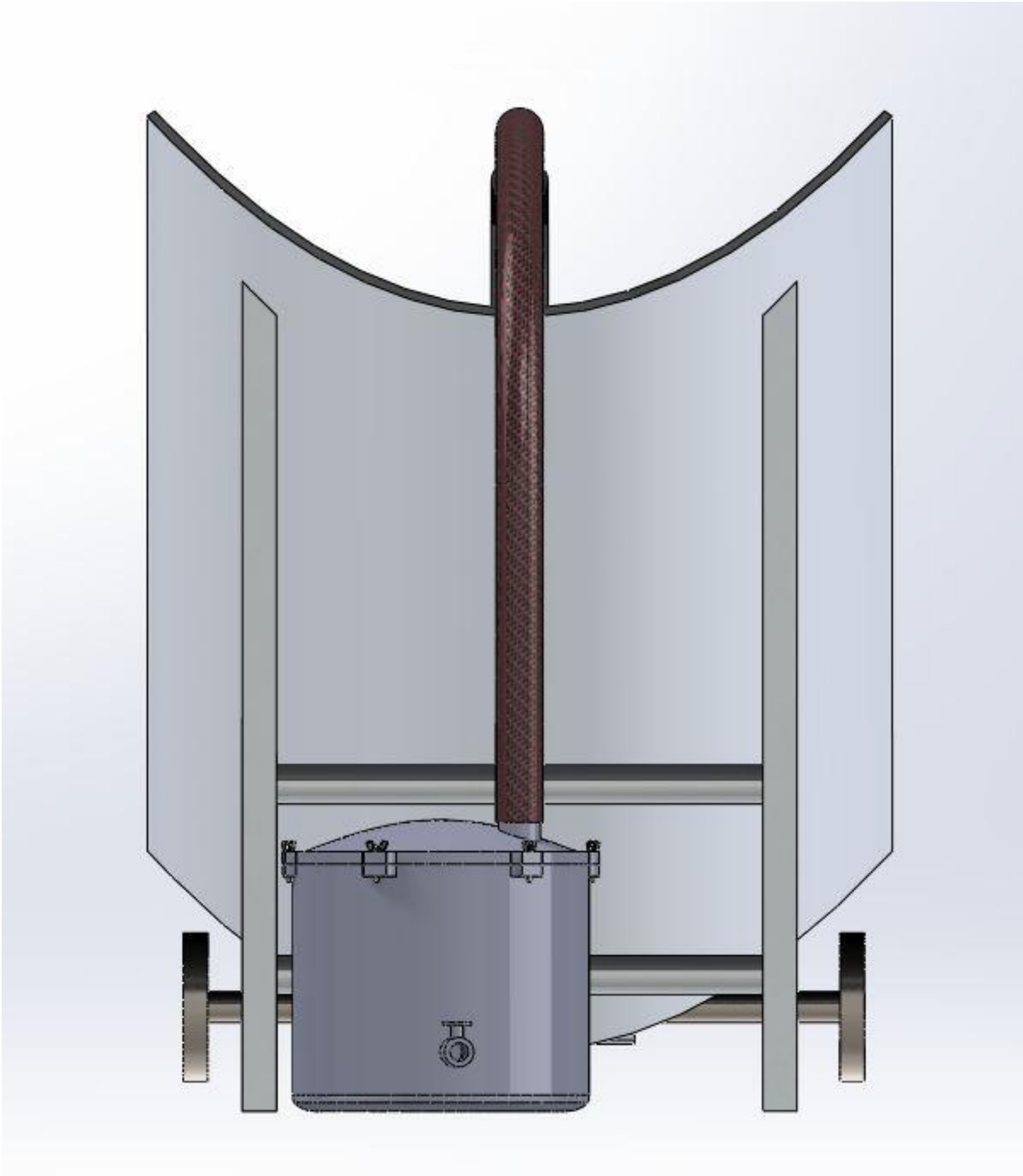
[19]. Dr. Brent Nelson. Email: Brent.Nelson@nau.edu

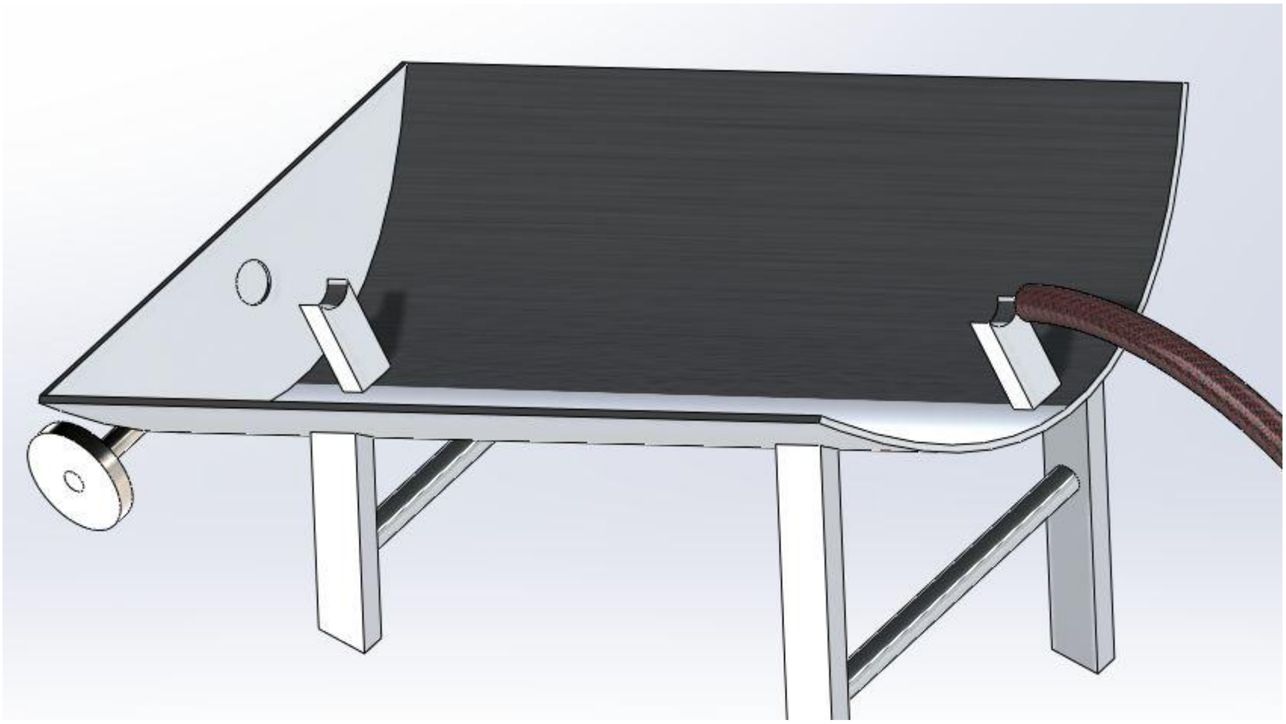
Additional Resources:

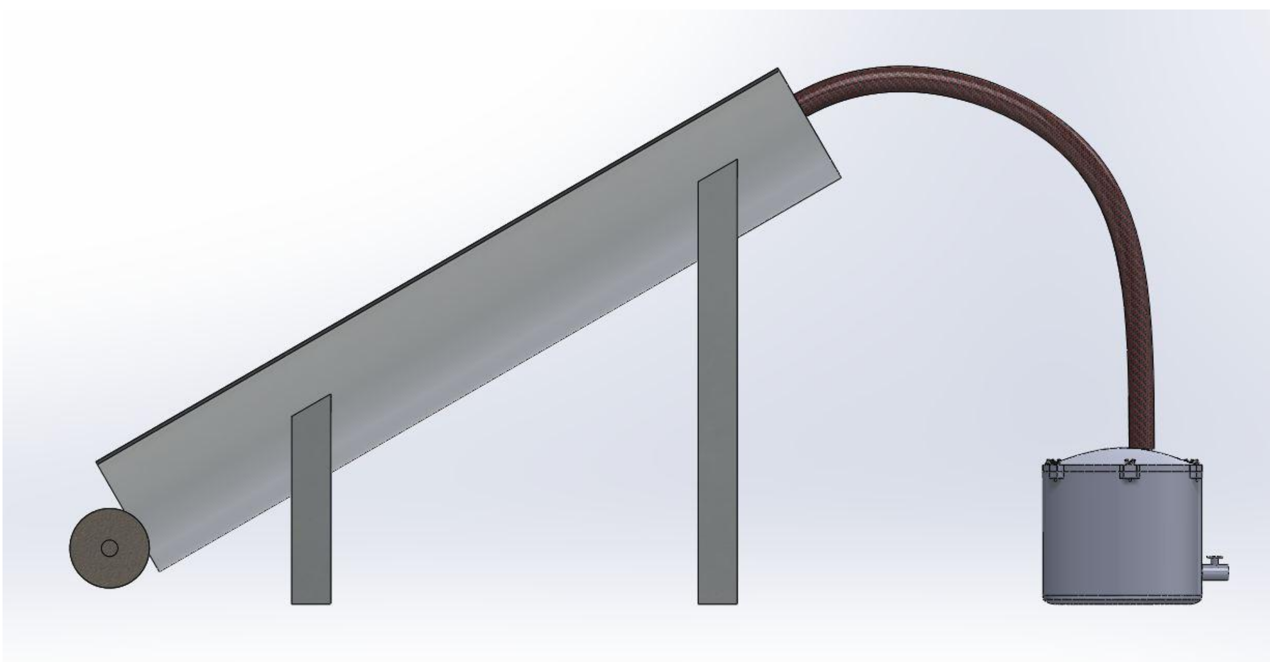
[20]. Program OrCAD Capture 9.1, Version 2.0, Build 28, Feb 18 2000, OrCAD, Inc.

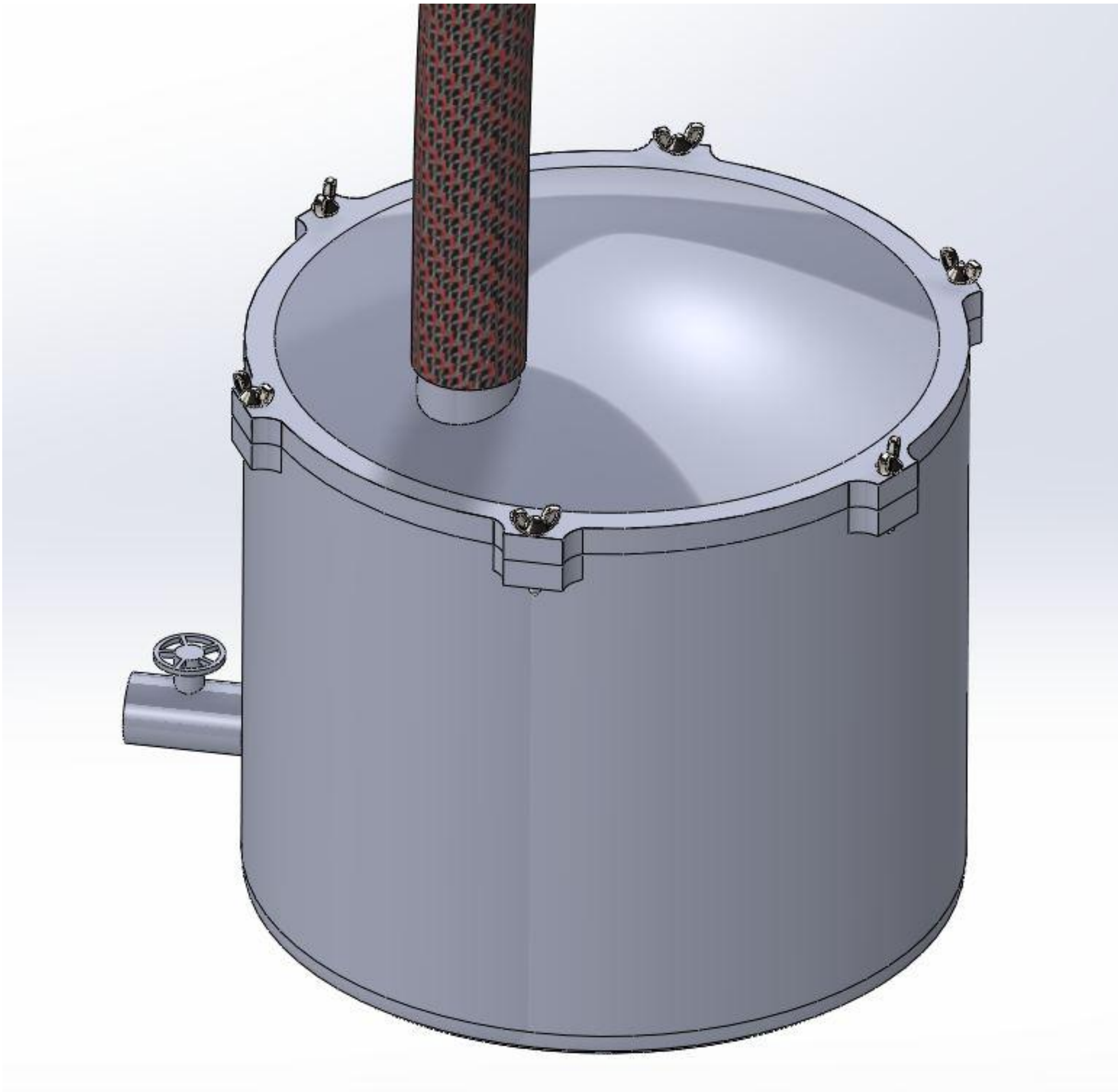
Appendices

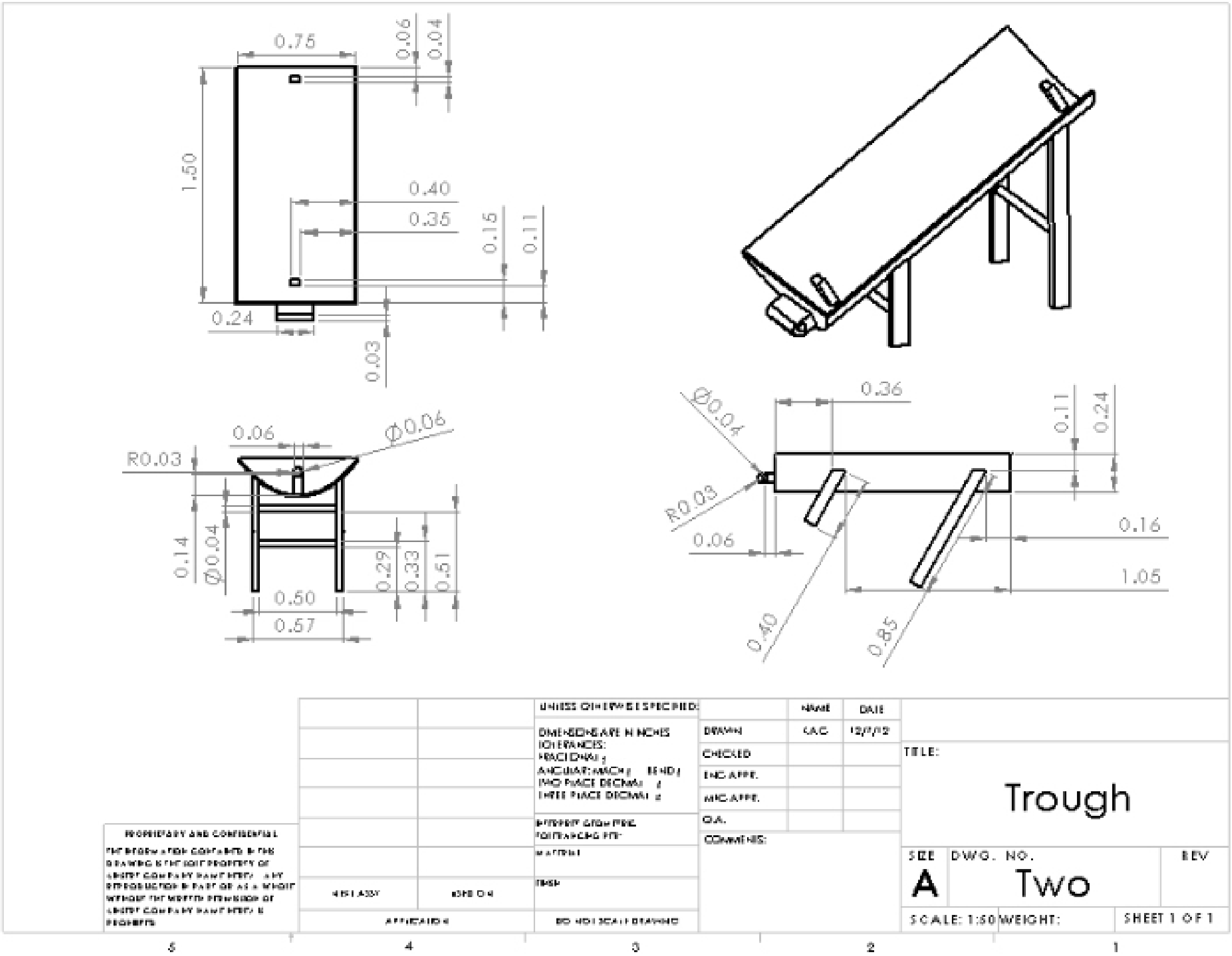
Appendix A: Additional CAD drawings







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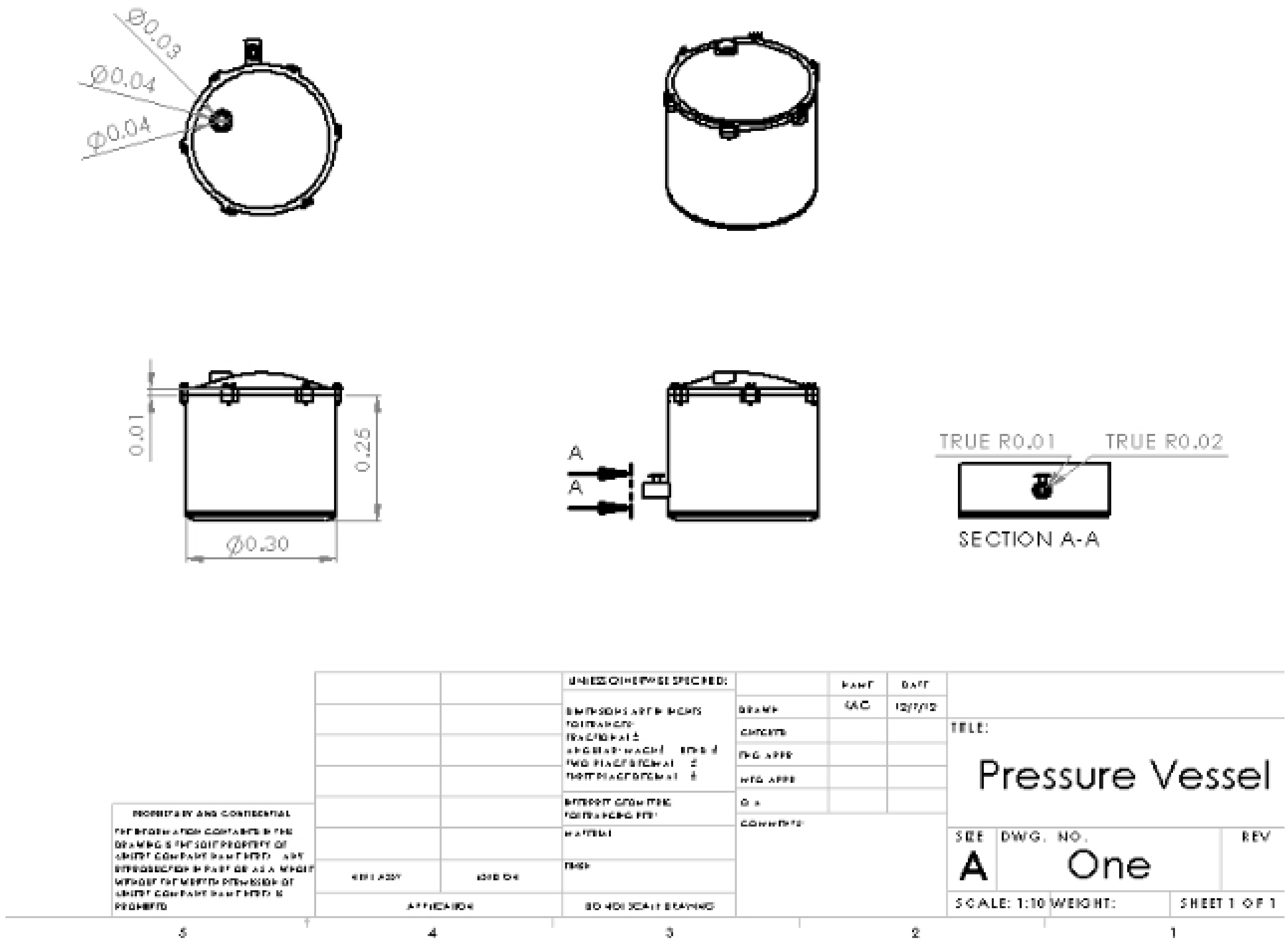
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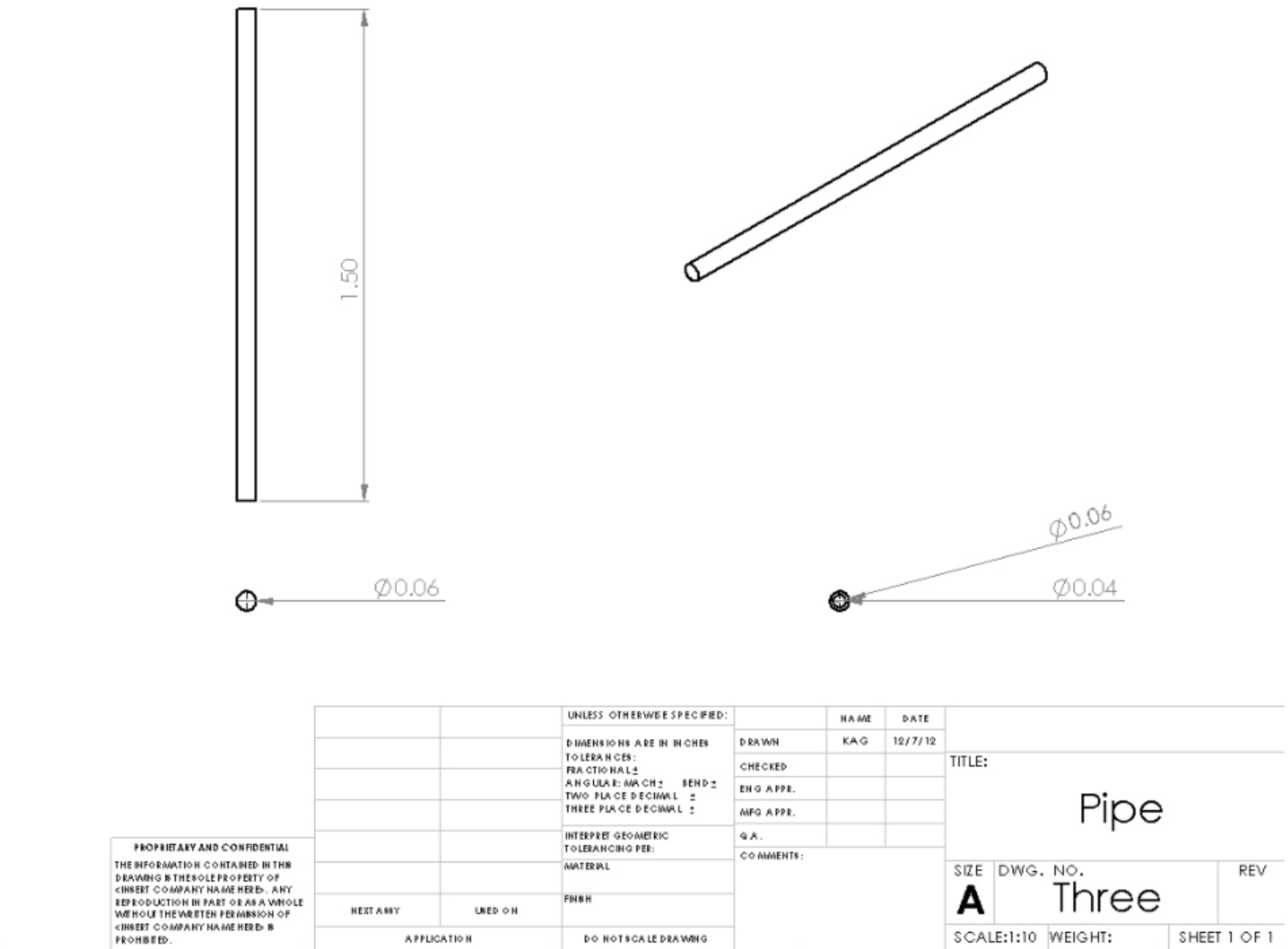
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