Sterilizing Medical Equipment With The Sun

A Non-Electric Autoclave For Rural Medical Clinics

FINAL DESIGN REPORT

Duke University Certificate in Energy & Environment 2014 - 2015

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1 Executive Summary

The purpose of this capstone design course was to explore global issues related to the topics of energy and the environment, and then attempt to design a technical solution to a specific problem of our choice. While brainstorming about sustainable development, our group began to gravitate towards the lack of reliable electricity in many parts of the world, and all of the health issues created as a result. It was eventually decided to address the need to sterilize medical equipment in rural health clinics without a reliable connection to an electrical grid.

The group then explored the current technologies used for sterilizing medical equipment, and settled on pressurized steam as the most viable option for a rural community. The preliminary design called for purchasing a commercially-available pressure cooker, and using a curved solar reflector to concentrate sunlight on the pressure cooker. Once heated to the requisite temperature to create steam, the pressure cooker would pressurize and maintain a steady pressure for as long as necessary to sterilize the equipment inside. The heat would come from the concentrated sunlight, which will be further explained in Section 3. This would completely eliminate the need for an expensive electric autoclave and a reliable grid infrastructure.

In addition to the design aspect of this project, a thorough analysis of the product was conducted. Environmental impacts and benefits of the solar autoclave were evaluated, as well as the social impacts. A business plan was created that outlines specifically how a product like this would be funded, produced, sold, and implemented in rural communities.

According to theoretical calculations, after just under two hours in the sun, the water in the interior of the pressure cooker would be hot enough to vaporize and create pressurized steam. During testing, it became apparent that exceeding 100°C was not a simple task, and we were unable to reach the standards for certified sterilization. There are a variety of factors that our group believes contributed to this. First and foremost, the weather and solar irradiance differences between North Carolina and Nicaragua (where this product is intended to function) are vast during the time of year that it was tested. Secondly, there was only a limited amount of time to update the design after the tests. While this failure was certainly a disappointment, the project is not scrapped simply because the goals were not met by the end of the semester. A member of the team will be continuing to work on the project during the summer to iterate the design further, and we expect to see better results by the start of the 2015-2016 school year. It is also possible that another Bass Connections team could pick up the project and see it through to completion.

Section 9 contains an instruction manual (in English and in Spanish) for users of the solar autoclave.

2 Introduction To The Problem

When deciding which problem we would attempt to address our group sought to identify a significant need and furthermore somewhere we thought we could make a difference. During this search we discovered Grupo Fenix, a non-profit organization who had identified a need for “An inexpensive, non-electric autoclave that would guarantee sterile medical instruments” in remote locations such as Nicaragua.

An autoclave is defined as a pressure vessel used for sterilizing medical equipment, generally with pressurized steam. We thought this represented the perfect opportunity for us to make a meaningful impact, because without a reliable electrical grid, this technology is unable to function in the same way as in an industrialized country. We further clarified the problem by addressing exactly what was necessary to sterilize medical equipment. This requires reaching a certified (by the World Health Organization) standard of 121°C and 15 psi inside the pressure cooker for a duration of 30 minutes. Additionally we needed to accomplish this without the use of electricity. The two major design considerations for our project were (1) how to achieve/hold pressure and (2) how to heat the system. Furthermore, for use in these rural areas we needed our device to be transportable by public bus as this is the only effective and reliable means of transportation in these areas. Finally, we recognized that in order for our product to be realistic it must be cost efficient, and this was another important factor in our analysis of the issue.

The following is a summary of the critical to quality (CTQ) objectives:

- Create an effective solar autoclave for use in rural Nicaragua to fill the need identified by the non-profit *Grupo Fenix* “that would guarantee sterile medical instruments in these remote locations”
- Design a product that will consistently sterilize instruments to a certified standard of 121°C and 15 psi for 30 minutes.
- Must be cost effective and feasible for use by local communities without means to repair complex equipment.
- Achieve a final prototype by May 2015

3 Technical Design

3.1 Description Of Approach

(a) Solar Concentrator/Reflector

Basic structure and form of the solar reflector is provided by a drip pan made of molded plastic. The drip pan measures approximately 1 meter by 1 meter (see below). This represents the second iteration of the design; the first was a wood frame that would not hold a vacuum seal, and thus was scrapped.

Figure 1: Plastic Drip Pan

Mylar, a highly reflective material commonly used in emergency/survival blankets, was stretched and then attached to the open side of the pan using hot glue and construction adhesive.

Figure 2: Mylar Emergency Blankets

We carefully and thoroughly applied these substances to ensure an optimal seal. A check valve was also inserted into the pan through a predrilled hole and then sealed using a combination of hot glue and construction adhesive. This valve allows for the creation of a vacuum inside the sealed pan, which sucks in the Mylar and provides the intended (nearly) parabolic shape of the reflector. Finally the edges of the Mylar were taped down. This taped provided a dual effect. It both protected the edges of the Mylar and cosmetically improved the product by eliminating any loose material.

(b) Pressure Vessel

The pressure vessel was a stovetop pressure cooker that was obtained commercially (from Amazon.com). We tested two separate cookers, a Mirro 22 quart model and a Presto 8 quart model.

Figure 3: 22-quart and 8-quart pressure cookers

(c) Insulation

Two separate substances provided the insulation. First we attached cotton quilt batting to the pressure cooker using hot glue. We then added a layer of R-10 foam insulation also using hot glue. We then repeated this entire process so that we ended up with two alternating layers of each material. We insulated all surfaces except the bottom of the pressure cooker, as this is where the heat was applied. To this surface we applied black spray paint to increase the heat absorption and decrease reflection. In future prototype iterations, we suggest testing alternate types of insulation as well as different methods of adhesion in order to prevent as much heat loss as possible.

(d) Tripod

To hold our pressure cooker at its appropriate height we designed a tripod to provide support for it to hang beneath. This was created quite simply. We drilled holes in one end of three separate pieces of metal conduit and lashed them together with rope. We then applied a rubber foot to the bottom end of each pipe so that these ends would be able to generate sufficient friction to support our pressure cooker on slick surfaces.

3.2 Analysis

Our project centers around the ability of our pressure cooker to reach 121°C and 15 psi using only energy from the sun. Therefore, the main analysis to be carried out is a heat transfer analysis. We also include a stress analysis for completeness.

3.2.1 Stress Analysis

We verified that the pressure cooker could hold the required amount of pressure by performing an analysis on Solidworks.

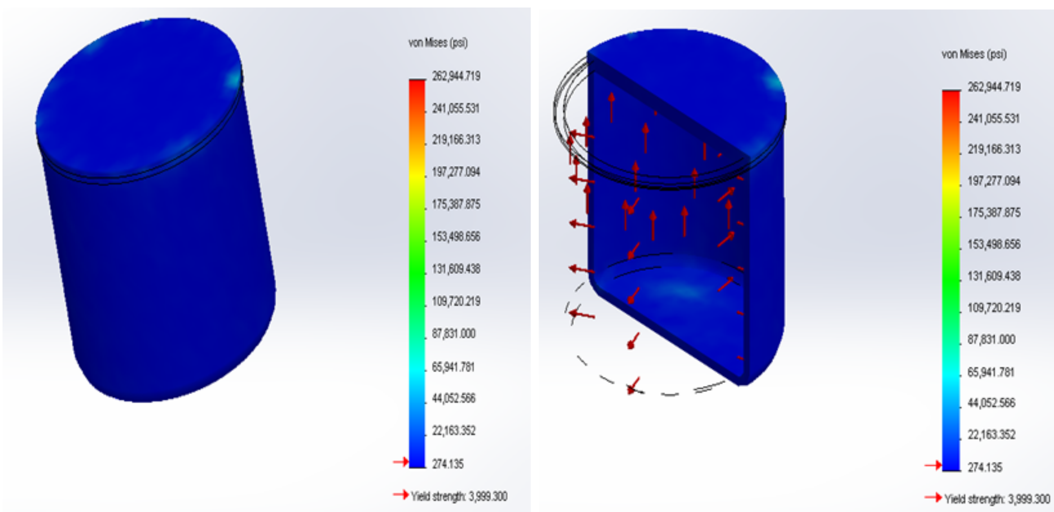


Figure 4: Pressure Cooker with Internal Pressure of 15 psi

These figures show a simplified model of the pressure cooker with a internal pressure of 15 psi. This is the pressure that the pressure cooker needs to reach to achieve sterilization. The model is completely blue, and thus significantly below its yield strength. There are also no stress concentrations on the pressure cooker. This is all to be expected because the pressure cooker was manufactured to withstand this pressure.

The solar reflectors are both strong enough to withstand being dropped from the normal height of a person carrying the reflectors. The figure below shows the stress concentration when the solar reflector is dropped on its side and corner.

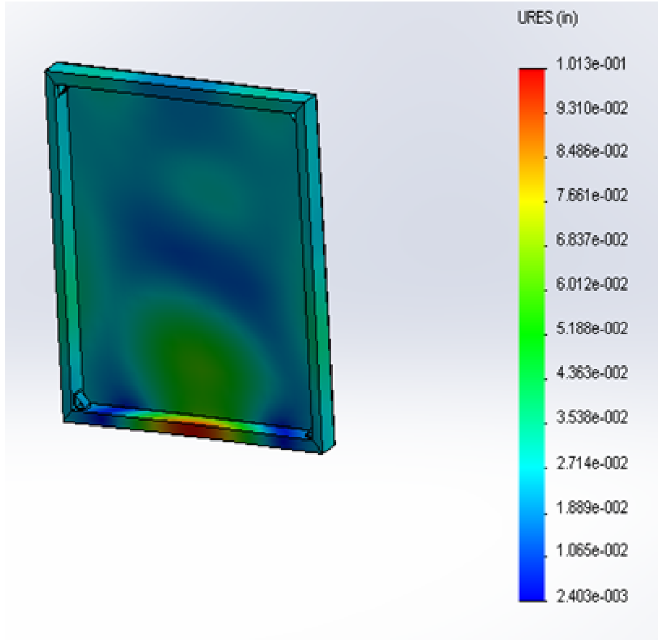


Figure 5: Displacement when dropped on bottom edge at a height of 3 feet from the center

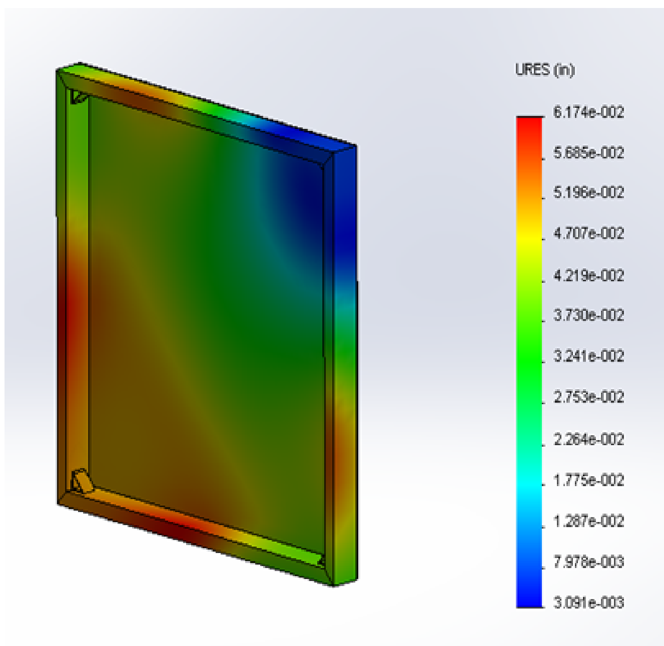


Figure 6: Displacement when dropped on corner at a height of 3 feet from the center

As shown in Figures 5 and 6, The displacement from dropping the solar reflector on either its side or corner is negligible and on the order of 0.0001. The main stress concentration on the solar reflectors is the mylar sheet because it can easily be punctured with a rock or sharp object. This model was created to be used in the developing world and thus is easily repairable. The mylar sheet can be easily replaced with minimal materials (tape and glue) and unskilled labor.

3.2.2 Heat Transfer Analysis

A first round of calculations were carried out immediately to prove the project was viable. First, the necessary energy to heat the system from 25°C (the temperature we believed the equipment would be after sitting outside on an average day in Nicaragua) to 121°C was calculated. This includes energy to heat water, energy to heat the metal of the vessel, and latent heat associated with vaporizing a portion of the water within the autoclave. The calculations shown below are associated with the first prototype, the 22 quart cooker.

$$Q_{heat\ water} = cm\Delta T = (4.19\tfrac{J}{g\circ C})(2521.97g)(121 - 25 \circ C) = 1,014,437\ J$$

$$Q_{heat\ Al} = cm\Delta T = (0.900\tfrac{J}{g\circ C})(5897\ g)(96 \circ C) = 509,500.8\ J$$

$$Q_{latent} = m_{vaporized}L$$

$$pV = nRT = 2.022atm(20.82\ L) = n(.08206\tfrac{L\ atm}{mol\ K})(373.15K)$$

$$n = 1.4\ mol\ H_2O$$

$$m = 18\tfrac{g}{mol}(1.4\ mol) = 25.2g\ H_2O$$

$$Q_{latent} = (0.0252kg)(2.26x10^6\tfrac{J}{kg}) = 56,952\ J$$

$$Q_{total} = 1,014,437J + 509,500.8J + 56,952J = 1,580,889.8\ J$$

To account for shadows cast by the vessel itself, we assumed 90% of the sun hitting our $1m^2$ reflector would be focused onto the cooker. With a solar intensity of $1000\frac{W}{m^2}$ and the absence of losses, the system would take about 30 minutes to reach 121°C and another 30 minutes to sterilize the equipment. One hour was well within our requirements, so we knew the concept was viable.

After proving that the system could theoretically get up to temperature, we had to account for radiation and convection. The losses from radiation were straightforward to calculate, assuming that we are radiating to the average daily temperature of Nicaragua, about 25°C.

$$Q'_{rad} = \varepsilon\sigma A(T_{pot} - T_{surr})^4 = (0.3)(5.67x10^{-8}\tfrac{W}{m^2K^4})(0.62m^2)(394.15 - 299.82K)^4 = 0.835W$$

Radiation losses were negligible. Convection was much more complicated to calculate because the convective heat transfer coefficient depends on a number of conditions. Modeling our pressure cooker as a sphere, the Nusselt number was calculated using the Whitaker correlation for forced flow over a sphere ("Part B" 2015). This allowed us to solve for convective heat transfer coefficient, and thereby calculate convective losses at various wind speeds. We calculated losses at 3.6 m/s (the maximum monthly average wind speed in Nicaragua) and at 7.6 m/s (the maximum monthly maximum wind speed). For 3.6 m/s,

$$Re = \frac{u_\infty D}{\nu} = \frac{(3.6\ m/s)(.45m)}{2.056x10^{-5}\ m^2/s} = 78,794$$

$$\overline{Nu} = 2 + (.4Re^{1/2} + .06Re^{2/3})Pr^{2/5}\left(\frac{\mu}{\mu_s}\right)^{1/4} = 225.4$$

$$\overline{h} = \frac{\overline{Nu} * k}{D} = \frac{(225.4)(.0295\frac{W}{mK})}{.45m} = 14.8\ \frac{W}{m^2K}$$

$$Q'_{conv} = h_c A \Delta T = (14.8\frac{W}{m^2K})(.62m^2)(394.15 - 299.82K) = 865.6W$$

Losses of 865.6 W account for almost all of our incoming solar energy (900 W). At the maximum wind speed,

$$\overline{h_{max\ wind}} = 23.2\ \frac{W}{m^2K}$$

$$Q'_{conv,max\ wind} = 1357\ W$$

Meaning that losses exceed incoming energy and our vessel would never get up to temperature. Faced with these results, we had to find a way to reduce the losses to a more reasonable number. We decided that we should design for losses less than or equal to 700 W on the windiest day, which would allow the system to get up to temperature (albeit slowly). This was the requirement with which we calculated a critical insulation thickness of 0.0018m.

$$Q'_{out,\ max\ wind} = \frac{\Delta T}{\frac{1}{hA} + \frac{L}{kA} + \frac{L}{kA}} = \frac{394.15 - 299.82}{\frac{1}{23.2(.62)} + \frac{.00587}{167(.62)} + \frac{t_{insulation}}{.045(.62)}} \leq 700\ W$$

$$t_{insulation} = 0.0018\ m$$

Calculating for losses on a more average day:

$$Q'_{out,\ average\ day} = \frac{\Delta T}{\frac{1}{hA} + \frac{L}{kA} + \frac{L}{kA}} = \frac{394.15 - 299.82}{\frac{1}{14.8(.62)} + \frac{.00587}{167(.62)} + \frac{.0018}{.045(.62)}} = 543.5\ W$$

With the addition of insulation, losses for an average windy day come out to 543.5W. Using the 900W input as explained earlier, the time to heat the system comes to about 74 minutes. Although this is greater than initially anticipated, we still believe it is in a reasonable timeframe for use of the autoclave.

3.3 Testing

In order to verify our heat transfer analysis and check for any oversights, we needed to carry out testing of our autoclave.

3.3.1 Initial Test Plan

Once our autoclave was built, we decided we wanted to test in the most realistic conditions possible. This meant setting the autoclave up outside on a sunny day and tracking the internal temperature over time. As shown in Figure 7, our set up consisted of a stand to hold up the reflector (we used a chair), the reflector itself, and the tripod with our insulated pressure cooker hanging from it. We placed a thermocouple inside of the pressure cooker, taking care to make sure that the thermocouple stayed in the air and did not get submerged into the water. We would manually draw the vacuum to a focus of about 0.5 square feet onto the bottom of the pot. As the sun moved, we gradually moved our reflector to make sure the sun was being efficiently focused the whole time. In addition, more air had to be sucked out of the reflector every few minutes to account for leaks and diffusion (a problem that was addressed and fixed in the third prototype). We recorded the temperature inside the pressure cooker every five minutes. The biggest issue we faced were overcast days: after our prototype was finished being built we had very few days of full sun to test.

Figure 7: Outdoor testing setup

3.3.2 Initial Results

As you can see in Figures 8 and 9, in both sizes of pressure cookers we experienced the same trend. The temperature initially followed the predicted curve, but eventually plateaued off. On the test of the larger vessel, we reached 90°C. This was our peak in our initial test run. We attribute the plateau to the latent heat associated with evaporating water--we expect that eventually, with enough energy input, the curve would continue climbing after the plateau.

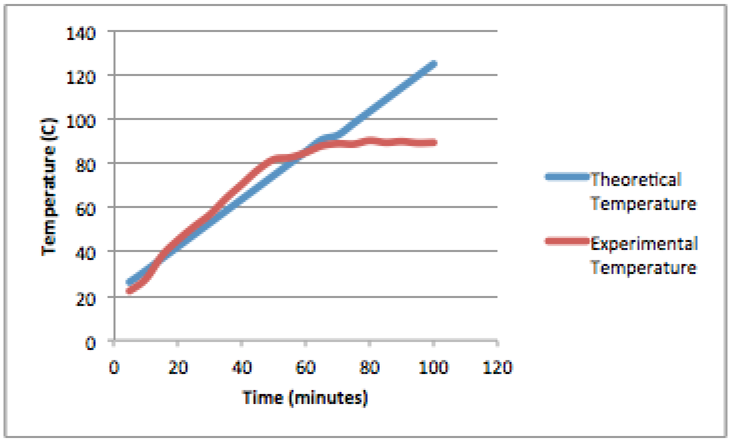


Figure 8: 22 quart pressure cooker, 14 mph winds

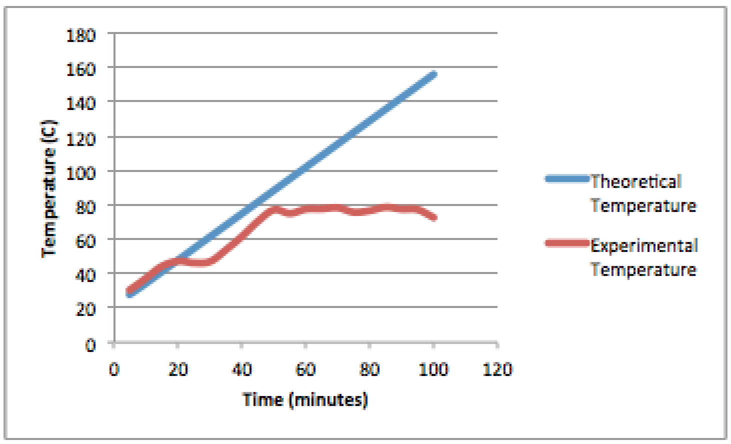


Figure 9: 8 quart pressure cooker, 6 mph winds and partly cloudy

We also built a second reflector to test with. Unfortunately, after it was built there were no more sunny days on which our group could accommodate a test. A second reflector would double our energy input, thereby halving the time to heat (not accounting for losses). Our group proposes a test with two reflectors and the 8 quart pressure cooker as soon as there is a day with no clouds. More design modifications could be made depending on the results of this test.

3.3.3 Modified Test Plan

Because we could get so little data with natural sunlight, we decided to carry out tests using UV lamps that were available in the MEMS lab. We had a 1500 W lamp available to simulate the sun. Because the lamp gives off rays in all directions, as opposed to the sun's rays which are always parallel, the focusing mirror would not be helpful for this application.

Therefore, instead of testing as if it were a sunny day, we utilized the setup to optimize water level in our cooker. Because the latent heat was what we believed to be causing the plateau of our temperature data, we wanted to look into it further. Increasing the water level in the pot would decrease the mass of water that evaporates because it has less volume to fill. Reducing the amount of water evaporated reduces the energy required to evaporate it. However, the energy input to heat the water will be greater with more water in the system. Therefore, we tested at two different water levels (10 oz. and 100 oz.) to see which was most effective.

Figure 10: Indoor Testing Setup

The setup involved our normal tripod with the 8 quart pressure cooker hanging from it, as seen in Figure 10. Instead of placing the mirror to reflect the sun, we placed the 1200 W lamp 10 inches below the pot, with the light directly hitting the bottom. The dimensions of the lamp are approximately 7” x 9” which is roughly the size that incoming solar energy would be focused on to the bottom of our pot in a normal application. Therefore, we believed this to be a suitable approximation.

3.3.4 Modified Test Results

The results are shown in Figure 11. As expected, the slope of the 100 oz. curve was much shallower than that of the 10 oz. curve. We had anticipated that the 10 oz. curve would be steeper but have a longer plateau, and the 100 oz. curve would be less steep but have a shorter plateau. Unfortunately, the 100 oz. took so long to heat that we never reached a plateau. After 155 minutes, we had still not reached 90°C. We believed that at the current rate, the time to reach

121°C would be too long to be practical. Therefore, we concluded that a smaller amount of water is better.

However, the length of the plateau with the 10 oz. test is unexpected based on theoretical calculations. As shown in section 3.2.2, the latent heat required to vaporize the water should only be about 57,000 J. If this were the case, with an input of 1000 W the plateau region should only last about one minute. Clearly, there is something we have not accounted for that is causing the plateau to last more than 50 minutes.

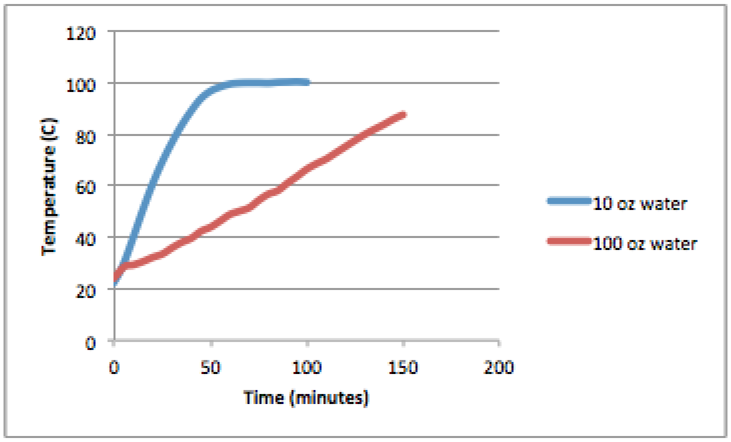


Figure 11: Heating times for 10 oz vs. 100 oz of water

Interestingly, on the 10 oz. test, our sterilization strips changed color. It was hard to tell if the 'K' indicating sterilization had turned black or dark gray (see Figure 12). They are supposed to change to black only when they experience 121°C and 15 psi for 30 minutes in the presence of steam. However, a light gray could be an indicator of wet steam or over processing as well.

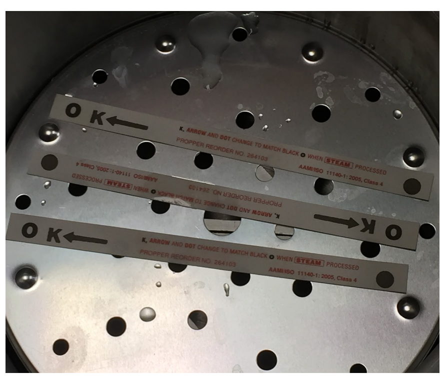


Figure 12: Sterilization strips after 10 oz indoor testing

3.3.5 Testing Conclusions

As seen in Figure 13, our average monthly wind speed is less than Nicaragua every month of the year. This will greatly reduce the convection losses that we experienced during testing. Additionally, as seen in Figure 14, the solar irradiance varies drastically between North Carolina and Nicaragua. They are similar in summer months, but the irradiance is much less in North Carolina over our testing months than it will ever be in Nicaragua.

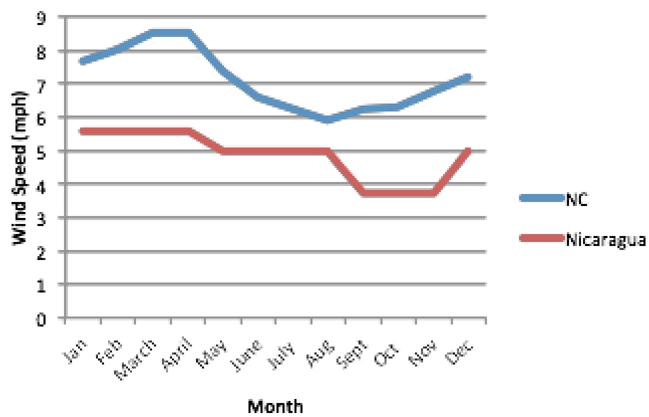


Figure 13: Average monthly wind speed

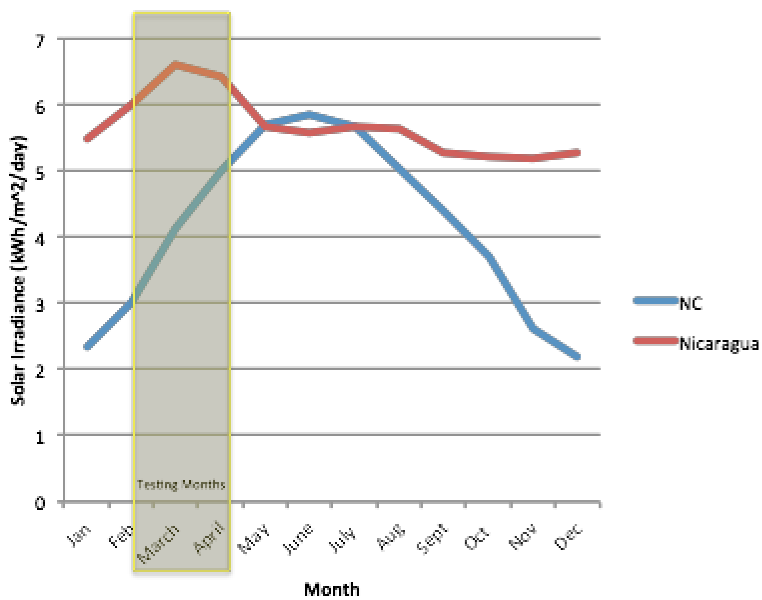


Figure 14: Solar Irradiance

Due to these differences, our team concludes that our testing months were some of the worst we could have chosen. Ideally, more testing would occur over North Carolina's summer months, when the wind speeds and solar irradiance are closer to that of Nicaragua.

We also propose some additional indoor testing given the perplexing results with the latent heat plateau. Specifically, we propose that we test a pressure cooker on a hotplate and meter the outlet that it is plugged into. Monitoring the temperature until it reaches 121°C will allow us to read the meter to know exactly how much energy input the system needs to get up to temperature and pressure.

If we are eventually able to reach 121°C in outdoor testing in North Carolina, the next steps will be preparing the autoclave for deployment in Nicaragua.

4 Environmental Analysis

4.1 Environmental Impact Assessment

Our solar autoclave design has minimal soil and groundwater impacts. This is due to their self-contained nature and mobility. The potential negative impacts of the autoclave include damage to vision (due to prolonged exposure to the reflected rays) and usage of flat ground that might have been used for other purposes. The vision concern can be addressed by consistently monitoring the setup when in use to ensure children and oblivious passers-by do not stray too close to it. The land usage issue is marginal as the autoclave will only need to be setup for 1-2 hours a day and can be moved as the need arises.

The solar autoclave also presents environmental benefits in the form of energy conservation and consequently, carbon offsets. While the target communities for the solar autoclave have limited access to electricity, it is still possible to quantify the amount of carbon emissions offset by the solar autoclave. There are several certified third party standards for the measurement of environmental offsets such as Clean Development Mechanism, Verified Carbon Standard, Climate Action Registry and the American Carbon Registry.

The Clean Development Mechanism (CDM) program is of particular interest due to its extensive global participation and the breadth of projects. The CDM program is a flexibility mechanism defined by Article 12 of the Kyoto Protocol, an international treaty extending the 1992 United Nations Framework Convention on Climate Change (UNFCCC), committing member states to reduce greenhouse gas emissions. As part of the program, developing nations can sell certified emission reduction (CER) credits, a standardized emissions offset instrument, to industrialized nations. In the first commitment period of the Kyoto Protocol from 2008-2012, the mechanism registered more than 1,650 projects producing CERs that amounted to more than 2.9 billion tonnes of CO_2. There is a significant opportunity for our project to access funding as there are multiple CDM projects in Nicaragua, but none dealing with solar autoclaves. The main challenge to this endeavor is the scalability of solar autoclaves to make any significant environmental offsets.

4.2 Life Cycle Analysis

The three main components of our design consisted of mylar blanket, a plastic drip pan and a pressure cooker. Mylar blanket presents the most notable environmental concern as it must be regularly replaced in the solar reflector as it experiences wear and tear. The drip pan and pressure cooker present a lesser challenge as they are fixed assets in the 2-3 year range. As such, we conducted a life cycle analysis of our system based on mylar as the key component.

Mylar is created by depositing vaporized aluminum on a very thin plastic sheet. The plastic used in mylar is polyethylene terephthalate (PET), and is its primary component.The following observations were made from the calculation of PET's ecological properties:

- Weight of each mylar blanket: 0.05 kg
- CO_2 use in primary PET production per blanket: 0.185-0.205 kg
- Water use in primary PET production per blanket: 0.735-2.21 L

The details of our analysis are compiled in Table 1.

Eco Properties: PET		
Global Production, main component	9.5×10^6	metric ton/yr
Embodied energy, primary production	81 – 89	MJ/kg
CO_2 footprint, primary production	3.7 – 4.1	kg/kg
Water usage	14.7 – 44.2	l/kg
Eco-indicator	276	millipoints/kg

Table 1: Eco Properties of PET

5 Social Benefits

Grupo Fenix would like to start by implementing 50 solar autoclaves. They currently support about 1,000 clinics, so this would only be an initial roll out of the device. If all is successful, they would expect to see this implemented in all of their clinic over time.

This solar powered autoclave will provide medical instrument sterilization to underserved, off-grid communities. It can be made by leveraging the manufacturing skills of the Mujeres Solares. It also creates local jobs. Due to the time required for sterilization, the pressure cooker can get up to temperature once per day and sterilize one set of medical equipment per day. The only drawback of this implementation is that if someone is using the autoclave and does not allow it to get all the way up to temperature, there is a potential for using medical equipment that has not reached sterilization.

6 Business Plan

6.1 Solar Autoclave LLC Corporate Overview

In December of 2014, our team planned to found Solar Autoclave LLC, ("Solar Autoclave" or the "Company"), a nonprofit limited liability company recognized under section 501(c) of the Internal Revenue Code. Solar Autoclave would intend to provide off-grid, solar-powered medical sterilization devices to the one billion people around the world who lack proper access to healthcare facilities (Bovarnick & Dach 2014). The 501(c) designation would provide three main advantages to the Company. First, Solar Autoclave would be federal income tax exempt, avoiding the standard 35% corporate tax rate. The limited liability aspect of Solar Autoclave would protect the founders' individual assets in the event of bankruptcy or default, as well as enable the easy transferability of ownership in the event of a management change or corporate sale.

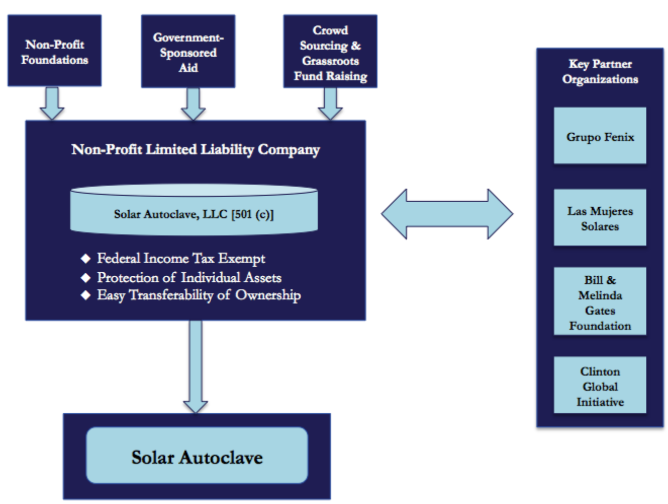


Figure 15: Solar Autoclave LLC Corporate Structure

Solar Autoclave would attempt to raise capital from non-profit foundations, including the Bill and Melinda Gates Foundation, through government-sponsored aid and through traditional crowdsourcing and grassroots fundraising. The Company would collaborate with local partners including Grupo Fenix and Las Mujeres Solares to ultimately produce and deliver solar-powered autoclaves to our target markets and consumers.

6.2 Cost Structure and Profitability

As our team navigates the prototype and final design review processes, most of the Company's budget has been allocated to research and development (R&D). To date, as shown in the table below, the total R&D budget has reached $502.42, with 47.2% of the total budget going towards spill trays for the solar reflector aspect of the autoclave. The two pressure cookers purchased during experimental trials are responsible for 20.3% of the total budget.

Category	Expenditures	% of Total Budget
Mylar Roll	$37.81	7.5%
Pressure Cookers	$102.10	20.3%
Wood + Screws	$49.33	9.8%
Adhesive Materials	$62.90	12.5%
Spill Trays	$237.20	47.2%
Sterilization Indicator Kit	$13.08	2.6%
Total	**$502.42**	**100.0%**

Table 2: Total Project Research & Development Budget

However, it is important to note that the R&D budget does not accurately reflect the unit costs of production or the costs to the consumer. In the experimental phases, Solar Autoclave purchased large amounts of materials, which enables economies of scale to reduce the material costs. In addition, the research and development process has allowed the Company to select the materials that compose each autoclave more effectively. For instance, the spill trays will be replaced with lower-cost plastic swimming pools, as shown in the table below. The unit cost is $53.23, as compared to the first prototype cost of around $85.00. The majority of the unit cost of an autoclave (66.6%) is allocated towards the pressure cooker, which is essential to maintaining sufficient pressure for adequate sterilization. The aforementioned swimming pools account for 22.5% of the unit cost, while the Mylar roll for the solar reflector is responsible for 7.1% of the total cost.

Conventional portable autoclaves typically range in the $100-$250 price level. Therefore, the solar-powered autoclave will cost the consumer $75.00. This competitive pricing strategy will will lead to a profit margin of 29.0% per unit sold ($21.77).

Category	Cost	% of Total Cost
Mylar Roll	$3.78	7.1%
Pressure Cooker	$35.45	66.6%
Plastic Swimming Pool	$11.99	22.5%
Adhesive	$1.96	3.7%
Sterlization Indicator Kit	$0.05	0.1%
Total	**$53.23**	**100.0%**
Sales Price	Profit per Autoclave	Profit Margin
$75.00	$21.77	29.0%

Table 3: Unit Cost of Solar Autoclave

The lead-time, or the consumer timetable from placing the order to delivery, will depend on the location of the market. Typically, a consumer can expect a delivery time within two weeks (ten business days) after placing an order. Shipping times will vary from market to market, however as our production process continues, we expect significant time savings as efficiency improves.

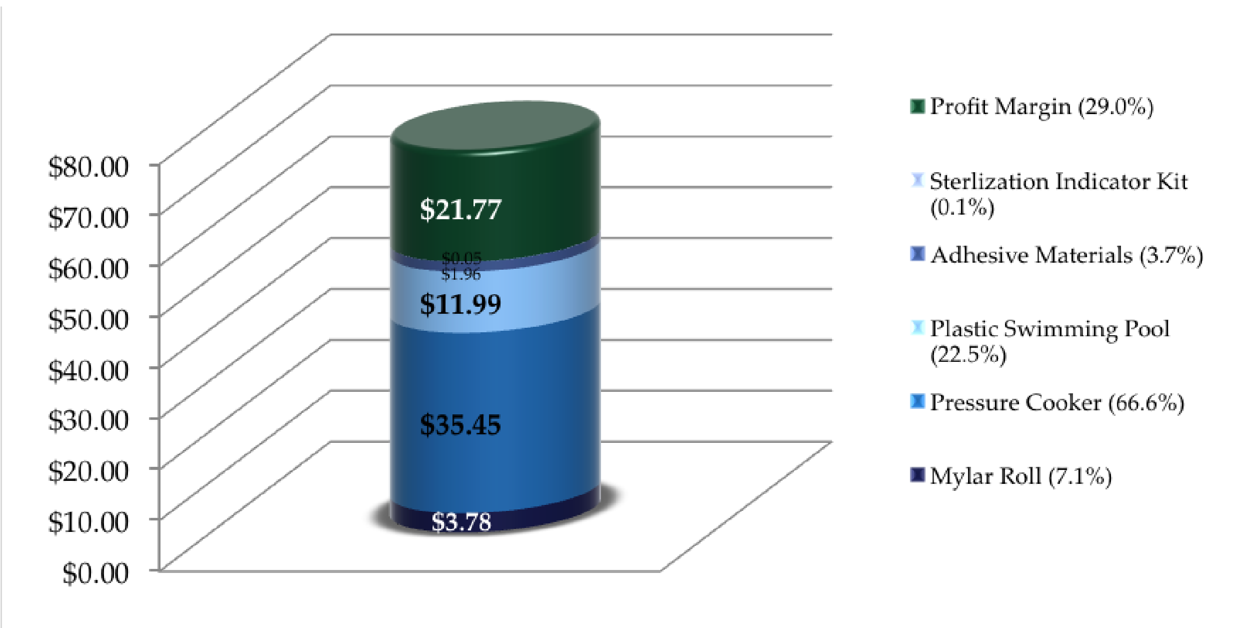


Figure 16: Unit-Level Economics and Profit Margin Build

6.3 Target Market Analysis

The Solar Autoclave team will initially partner with Grupo Fenix, a non-governmental organization (NGO) based in Nicaragua. Grupo Fenix is committed to the promotion of renewable energy technologies in order to further the advancement of lifestyle and technology in developing nations. In Nicaragua alone, about 1,000 rural clinics (~50%) lack access to electricity (GlobalGiving 2015). Therefore, as we partner with Grupo Fenix, our initial target market is approximately 1,000 rural clinics in Nicaragua.

Beyond the scope of Nicaragua, energy poverty leaves one billion people worldwide without access to reliable healthcare, as facilities are unable to store medical equipment in refrigerated, sterile conditions. For instance in India, the second most populated country in the world, 46% of all healthcare facilities do not have access to electricity. This augments our initial target market by an additional 580 million people in India (Bovarnick & Dach 2014). Worldwide, the total addressable market encompasses the one billion people without proper access to healthcare facilities (Bovarnick & Dach 2014).

Given the large opportunity to address the problem of inadequate health facilities around the world, the Solar Autoclave team has a large market opportunity. We hope to partner with key organizations such as the Bill and Melinda Gates Foundation to fund the continued testing, development, and distribution of the solar-powered autoclave. Our ultimate goal is to expand our global reach and benefit as many individuals as we can. Although some of our target consumers will not be able to purchase the autoclave themselves due to insufficient funds, we hope that other organizations such as the Clinton Global Initiative and government-aid programs will purchase the final product for our consumers as a part of their charitable mission.

6.4 Timetable of Financing and Sales Strategies

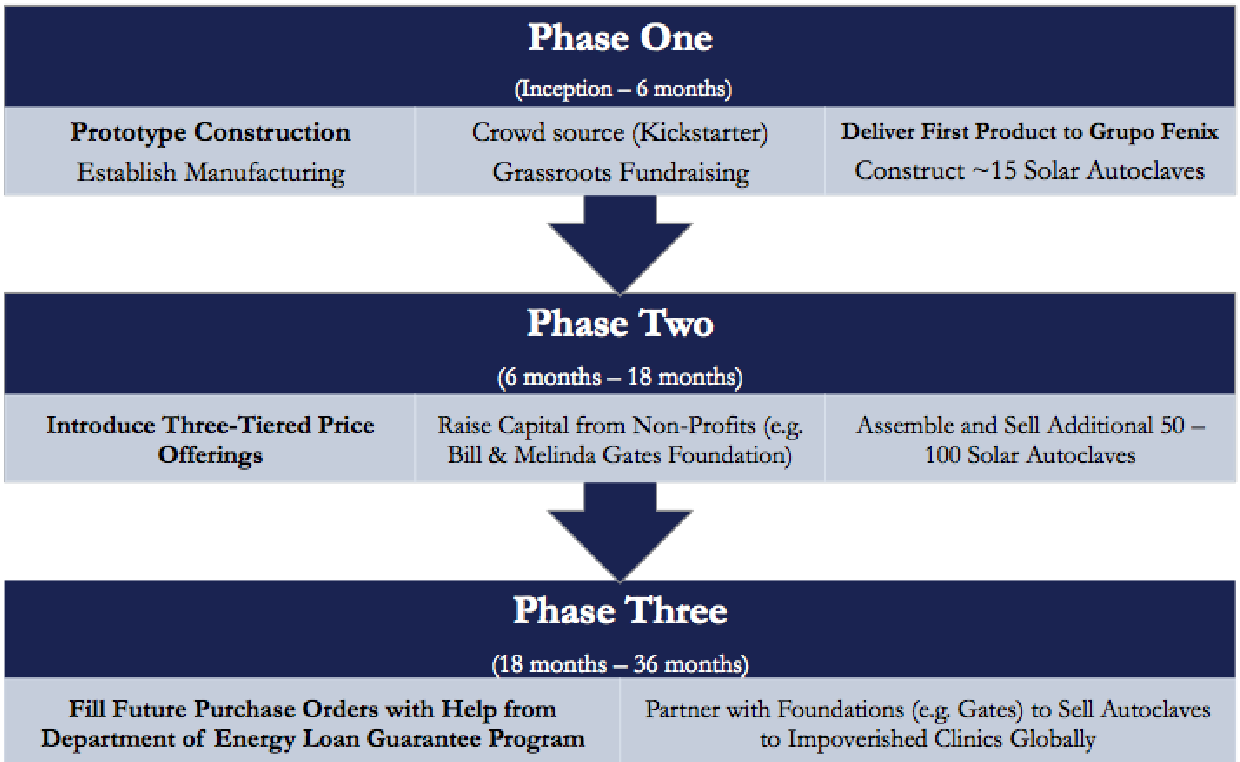


Figure 17: Solar Autoclave Moving Forward

6.4.1 Phase One (Inception – 6 months)

In the first phase Solar Autoclave continues to perfect the manufacturing process involved with transforming our prototype into a commercially available final design. As its tenure with Duke University comes to a close, the Company would continue to seek financing through grassroots fundraising and crowdsourcing. Solar Autoclave would seek to facilitate its first relationship with a local organization, Grupo Fenix of Nicaragua.

6.4.2 Phase Two (6 months – 18 months)

Solar Autoclave would introduce three price offerings to align with varying pressure cooker sizes and number of solar reflectors requested by the consumer. The Company would seek to develop strong customer and capital-raising relationships with non-profit organizations (e.g. Bill and Melinda Gates Foundation, Clinton Global Initiative). At the end of 18 months, the Company would seek to improve the efficiency of the manufacturing process to handle approximately 100 to 150 autoclave products.

6.4.3 Phase Three (18 months – 36 months)

After the manufacturing process has proved sufficiently efficient, Solar Autoclave would be healthy enough to incur debt financing from private sector sources. The proceeds of the credit instrument would help Solar Autoclave fulfill future purchase orders. In addition, the Department of Energy Loan Guarantee Program would help lower Solar Autoclave's cost of capital, or borrowing cost, by enabling it to effectively adopt the credit rating of the U.S. government. At this point, Solar Autoclave would be able to leverage its relationships with the aforementioned non-profit organizations to grow its revenue generating capabilities.

6.5 Overview of Government Incentive Programs

Federal programs have been implemented to help renewable energy projects, such as Solar Autoclave, overcome financing hurdles. The primary federal public policy incentive programs include tax credits and loan guarantees that reduce a renewable energy developer's borrowing costs. Recent programs that offer direct or indirect forms of financial support that Solar Autoclave would take advantage of in order to promote the large-scale development of solar-powered medical sterilization include:

(1) Investment Tax Credit (ITC),
(2) Department of Energy Loan Guarantee Program

6.5.1 Investment Tax Credit (ITC)

The Energy Tax Act of 1978 first established ITCs for renewable energy projects, such as a solar-powered autoclave (DSIRE 2015). Solar projects currently receive an ITC equal to 30% of total expenditures, with no credit limit, with the credit amount expected to decrease to 10% of expenditures in 2017 (DSIRE 2015). In addition to solar projects, the ITC is also available for fuel cells, small wind turbines, geothermal systems, microturbines and combined heat and power (CHP) systems. Contrary to the production tax credit (PTC), the ITC is not linked to the generative performance of the project, but rather to the capital investments in property and equipment. Although Solar Autoclave will already have no tax incidence due to its 501(c) classification, the Company may be able to partner with a specialized pool of third-party tax equity investors. Such investors, primarily investment banks and insurance companies led by J.P. Morgan and GE Capital, can help Solar Autoclave grow by providing credit that may supplement any financing received under the Department of Energy Loan Guarantee Program in exchange for interest payments.

Business Energy Investment Tax Credit (ITC)		
Resource Type	In Service Deadline	Credit Amount
Solar	December 31, 2016	30% of expenditures
Fuel Cells	December 31, 2016	30% of expenditures
Small Wind Turbines	December 31, 2016	30% of expenditures
Geothermal Systems	December 31, 2016	10% of expenditures
Microturbines	December 31, 2016	10% of expenditures
Combined Heat and Power (CHP)	December 31, 2016	10% of expenditures

Source: U.S. Department of Energy (DOE)

Figure 18: Investment Tax Credit Overview

6.5.2 Department of Energy Loan Guarantee Program

Solar Autoclave would apply to receive a loan guarantee from the Department of Energy (DOE). Title XVII of the Energy Policy Act of 2005 authorizes the DOE to pledge to cover the full debt obligation of a loan in the event of a borrower default, which would materially lower Solar Autoclave's borrowing costs (DOE 2015). Essentially, Solar Autoclave would be able to adopt the creditworthiness of the U.S. government. The Loan Guarantee Program fills a unique gap in the marketplace by facilitating credit to clean energy projects like Solar Autoclave that may otherwise have difficulty securing attractive private sector financing. To date, the program has helped support the world's largest utility scale photovoltaic generation facility and the largest concentrated solar power plant in the world (DOE 2015). There have been $32.4 billion in loans guaranteed to companies including Solyndra, Inc. and Tesla Motors, Inc (DOE 2015).

7 Regulatory Issues

Environmental Impact Assessments (EIA) in Nicaragua are under the authority of the Ministry of Environment and Natural Resources (MARENA). The legal charter of EIAs demarcates them as instruments for environmental policy and management, covering procedures, studies and technical systems for predicting the impacts of specific projects. In Nicaragua, there is no formal scoping procedure i.e. the dissemination of information to stakeholders and consultation on planned activity. However, the regulations of the EIA define the minimum scope. For a technology with as limited environmental impact as the solar autoclave, it is unlikely that it would be subject to an EIA. However, this determination is the prerogative of MARENA, in consultation with sectoral organizations and municipal governments.

Once the EIA is approved, MARENA publishes a notice in a national periodical of the public availability of the Environmental Impact Statement (EIS). This EIS must include alternatives to the project. There are no provisions for reports to be submitted to MARENA or the public throughout the project's development. However, MARENA's environmental licence sets monitoring requirements and specifies how monitoring and compliance with its provisions must be carried out. An Environmental Management Plan (EMP) is also required outlining planned measures during project implementation to address issues and meet requirements identified in the environmental analysis process.

8 Conclusion

The results achieved in our testing were extremely promising. Although we were only able to reach a maximum of 100°C, there are a few notable differences in testing conditions that may make an important difference. Mainly, the solar irradiance is always higher in Nicaragua than it was in North Carolina during the months that testing occurred. The area in Nicaragua is also significantly less windy than where the setup was tested in North Carolina. Overall, the conditions in Nicaragua are favorable towards the success of the solar autoclave.

Our group very much enjoyed this project and learned a lot about engineering, science, economics, building, and North Carolina weather. The next steps that we would like to see taken with this project are tests done with two solar reflectors, and other tests done with both sized pressure cookers under more optimal conditions in the summer. It is our hope that this project will reach the required 121°C need to sterilize medical equipment and be able to be implemented with Grupo Fenix in Nicaragua.

9 Instruction Manual (Manual de Instrucciones)

Materials:

a.	Solar Reflector	*Reflector del sol*
b.	Chair, stool or easel	*Silla, banqueta, o caballete*
c.	Tripod	*Tripode*
d.	Autoclave/pressure cooker	*Olla a presión*
e.	~2 meters of rope	*2 metros de cuerda*
f.	Metal rack	*Estante metalico*
g.	2 cups of water	*2 vasos de agua*

(a) (b) (c) (d) (e) (f) (g)

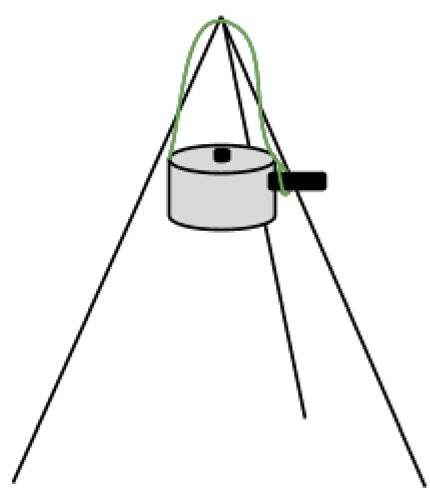
To sterilize medical equipment:

1. Clean the pressure cooker, and then pour in the two cups of water.
   Lave la olla a presión y luego verter en las dos tazas de agua.

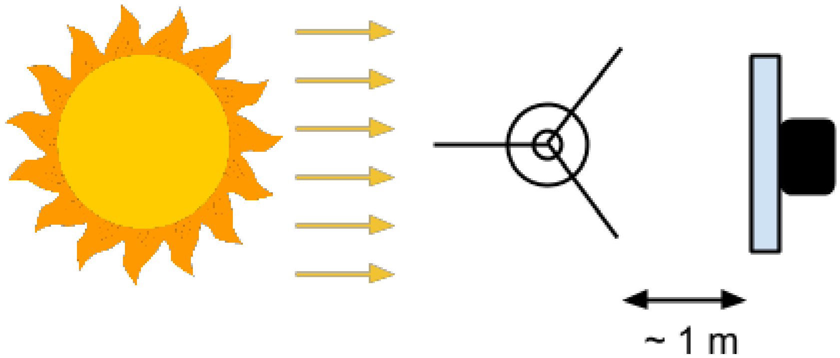
2. Place the circular rack in the pressure cooker, ensuring that it remains above the water line.
   Coloque el estante metálico en la olla a presión, asegura que sigue sobre la fila de agua.

3. Place the medical equipment to be sterilized on the rack - the equipment should not be touching the water.
   Coloque el equipo medical para ser esterilizadas en el estante – el equipo no debe tocar el agua.

4. Close the lid of the pressure cooker and hang it from the tripod using the rope (see figure to the right).
   Cierra la tapa de la olla a presión y colgarla de un trípode usando cuerda (ver la figura a la derecha).



5. Lean the reflector against the chair approximately 1 meter from the tripod, facing the sun and oriented as in the figure below:
   Apoye el reflector contra una silla aproximadamente un metro del trípode, frente al sol y orientado como la figura abajo.



6. Using your lungs, suck air out of the reflector until there is a noticeable curve in the reflective material. Adjust the reflector until a concentrated spot of sunlight appears on the side or bottom of the pressure cooker. Suck out more air to make the spot smaller, until the entire rectangle of sunlight fits on the bottom of the pressure cooker. See images below.
   Con tus pulmones, succionar el aire fuera del reflector hasta que sea un diferencia noticiable en la material reflexiva. Ajuste el reflector hasta que un punto concentrado de sol aparezca en el lado o fondo de la olla a presión. Ver la imagen abajo.

7. For 1 - 2 hours, keep the reflector adjusted so that the entire sun spot remains on the bottom of the pressure cooker. The sun moves several degrees per hour, so adjustments will need to be made every few minutes.
   Por 1 -2 horas, mantener el reflector ajustado de manera que entero del punto de sol permanece en el fondo de la olla a presión. Se mueve el sol varios degrades cada hora. Necesita ajustarla cada pocos minutos.

8. Once the autoclave pressurizes, steam will begin to come out the top and rattle the weight. Allow this to happen for 30 minutes - keep the sunlight concentrated on the bottom of the pressure cooker.
   Cuando la olla a presión se presuriza, el vapor comenzara a salir de la parte superior y agitar el peso. Permita que esto pase para 30 minutos – mantener la luz del sol concentrado en el fondo de la olla a presión.

9. After 30 minutes, dismantle the solar reflector and allow the pressure cooker to cool for 15 minutes. Carefully remove the **hot** pressure cooker from the tripod and cool it with cold water.
   Después de 30 minutes, desmantelar el reflector solar y permita que la olla a presión se enfrié por 15 minutos. Cuidadosamente, retire la olla a presión caliente del trípode y enfriarla con agua frio.

10. Open the pressure cooker; your equipment will be sterilized. Everything inside the cooker will be very hot.
    Abre la olla a presión; su equipo seria esterilizado. Todo dentro de la olla estará muy caliente.

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