Solar Water Pasteurization and Indoor Lighting in the Developing World

Kerri Devine
Electrical and Computer Engineering, Computer Science

Jane Hamm
Public Policy

Emmanuel Lim
Mechanical Engineering and Materials Science

Henry Meyer
Economics

Logan Shoop
Mechanical Engineering and Materials Science

Faculty advisor:

Dr. Josiah Knight
Associate Professor,
Mechanical Engineering and Materials Science,
Duke University

Abstract

The main objective of this project was to design and prototype a compact solar water pasteurization device that is easy to use, easy to construct, and reliable. The secondary goal of the project was to design the device to introduce heatless light into indoor spaces via a transparent opening on the bottom of the device. Both of these objectives were reasonably achieved. Future work will involve (i) the design and implementation of a permanent windshield to reduce convective heat transfer; and (ii) the development of a screw-top seal that will allow for convenient introduction and removal of water and temperature indicator. Our design has demonstrated a high potential for reliably pasteurizing water in the field, whether it be in our target market in the Gambia, or in any equatorial developing country that is facing a clean water problem. We have identified the Gambia as a potential location to deploy our technology due to societal, economic, and governmental conditions that foster a receptive market. Behind on its Millenium Development Goal to provide water sanitation to 65% of rural inhabitants, the Gambia will have to spend aggressively in the coming years to provide safe drinking water to 30.5 million additional people. We believe that our product can be a cheap, socially viable option for the Gambia, and have explored the market potential that the Endo-Clear might have.

Table of Contents

1. Project Definition

According to the World Health Organization, more than 1.8 million people die per year as a result of diarrheal diseases (the vast majority of which are children under the age of 5)[1], making it the second leading cause of death in the developing world at the moment[2]. Most of these illnesses are a direct result of consuming water that has been contaminated with raw sewage, which is especially common in densely populated and low-income areas such as slums. With an additional 60 million people being added to cities each year[3], these deaths will certainly rise in number. Our goal is to provide an effective and sustainable solution to this water resource problem.

Through this project, we have designed a device for the developing world that will (i) use solar thermal energy to pasteurize water, and (ii) collect excess light to illuminate indoor living spaces.

The simplest way to pasteurize water is to boil it. However, almost all harmful bacteria and viruses can be rendered harmless at only 65 °C[4] (this is already a generous estimate). Existing solutions have approached a solution to this problem in four main ways[5]:

1. Chemical disinfection, e.g. with chlorine bleach;
2. Filtration of bacteria and pathogens from water;
3. UV radiation disinfection;
4. Pasteurization, or thermal disinfection, which is typically done with reflective surfaces to concentrate sunlight.

We have decided to tackle the problem using solar thermal energy. An ideal system would be passive, portable, very cheap to produce, and highly robust. As such, we have avoided using concentrating technologies in exchange for a longer solar thermal pasteurization time (~5 to 6 hours, which is still reasonable given the amount of sunlight available to our target users[6]). We have carefully chosen materials with high absorptivity to serve as a thermal energy collector, and materials with high transmissivity in the solar spectrum to transmit sunlight while providing an enclosure for our water.

---

[1] *See* http://www.who.int/water_sanitation_health/publications/combating_diseasepart1lowres.pdf
[2] *See* http://who.int/mediacentre/factsheets/fs310/en/
[3] *See* http://www.who.int/gho/urban_health/situation_trends/urban_population_growth_text/en/
[4] *See* http://solarcooking.wikia.com/wiki/Water_pasteurization
[5] *See* http://www.nrel.gov/docs/legosti/fy98/23110.pdf
[6] *See* http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisRegion=Africa&ThisCCode=GMB

It is important to note that while over 90% of pathogens can be rendered harmless after several minutes of heating at 65 °C, significant deactivation will already occur at 5 °C below the optimal temperature, though a longer heating time will be necessary[7].

Our device, the Endo-Clear, is highly portable. This makes water collection easy and allows users to position it according to local solar conditions. Users simply fill the device with contaminated water, seal it, and wait for the water to reach temperature. An indicator has been installed within the device to tell if a safe temperature has been reached. This attached device is made from transparent plastic tubing and contains a wax that melts at a temperature that has been found to render disease causing pathogens inactive. The solid wax will begin at the upper end of the vertical plastic tube. If the temperature of the water reaches the necessary 65 °C, the wax will fall to the bottom of the tube. Each use will require the user to turn the tube so that the wax is at the top of the tube before heating begins. Endo-Clear holds 14 L of water. According to the UN, each person needs 2L of water per a day. Thus, Endo-Clear will provide enough water for 7 people a day if it is filled only once.

[7] *See* http://www.solarcookers.org/basics/water.html

2. Waterborne Illnesses

The improper disposal and treatment of human waste is a significant cause of many waterborne illnesses. The development of proper sanitation and water treatment systems is essential to the reduction of these illnesses and the many deaths that are a result of them. A market-ready and economical device that can be conveniently filled to clean drinking water could play a major role in this reduction.

Human excreta contain a significant variety of pathogens that can lead to disease such as diarrhea, and in many cases, death. Some of these pathogens include several viruses, salmonellae, cholera, faecal coliforms, protozoans cysts, ascaris eggs, tapeworm eggs, and trematodes[8]. These pathogens can survive in freshwater for as little as several days to 1.5 years, and it is therefore paramount that they be prevented from entering drinking water sources. In most cases however, the development of a reliable and sustainable disposal or treatment system for human excreta is prohibitively expensive and hence avoided. Even when a local treatment system exists, contaminated water can still enter a household through groundwater that has been contaminated from other sources. Sterilizing contaminated drinking water can therefore play a significant role in preventing the spread of diseases such as diarrhea, especially in areas with poor, unreliable or nonexistent infrastructure.

Previous studies have demonstrated the temperature-time relationship for safe water pasteurization of several harmful pathogens[9]. This relationship demonstrates the time that a pathogen must be in water at a certain temperature before it is effectively rendered inactive [10]. Safe water pasteurization of the following pathogens have been demonstrated to occur at a 1 hour length at the following temperatures[11] (Figure 2.1):

- Vibrio cholerae: 45 °C
- Entamoeba histolytica: 50 °C
- Taenia: 52 °C
- Salmonella: 57 °C
- Ascaris: 57 °C

---

[8] *See* http://www.who.int/water_sanitation_health/dwq/iwachap5.pdf
[9] Feachem et. al, 1983.
[10] *See* http://www.nrel.gov/docs/legosti/fy98/23110.pdf
[11] *See* http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/1999/12/23/000178830_98101911180473/Rendered/PDF/multi0page.pdf

● Shigella: 59 °C
● Enteric viruses: 62 °C

According to Feachem et al, a pasteurization time of 1 hour would require a temperature of ≥62 °C. This would classify a sample of water as being in Feachem's 'safety zone'. A pasteurization time of 1 day would require temperatures of ≥50 °C. These findings provide the background for our water pasteurization criteria. Based on available data on our target market and confirmation by computer and computational simulation, we came to the conclusion that a 1 hour pasteurization time with a target temperature of 62 °C is realistic.

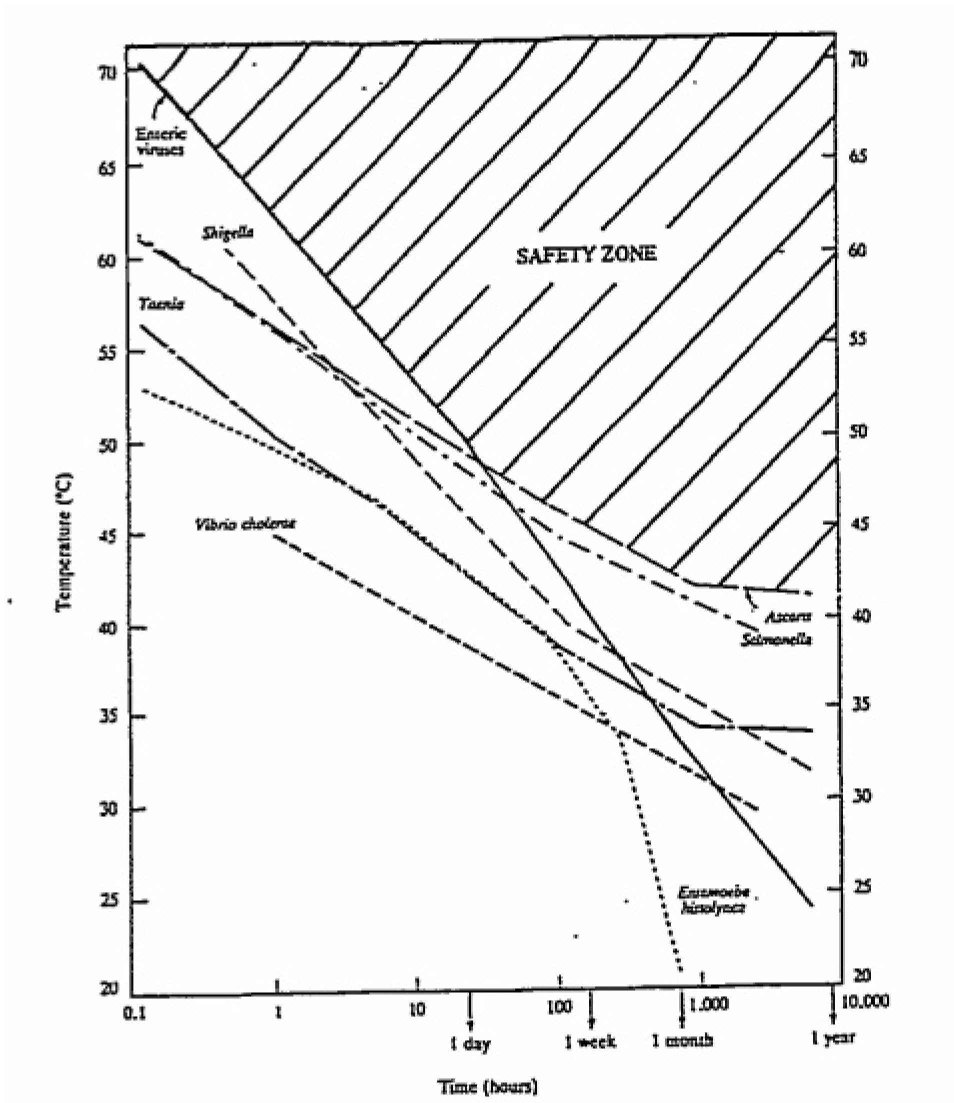


Figure 2.1 Temperature-Time plot for safe water pasteurization (Feachem et al, 1983).

3. Market Research and Concept Evaluation

Endo-Clear technology redefines the design of solar water pasteurizers and introduces an inexpensive way to purify water with minimum environmental damage. We intend to distinguish ourselves from the competition by offering inexpensive solar pasteurizer that is easy to use and provides a large amount of clean water in a short amount of time. Our device is cheaper than the current competing products and provides more water. Our goal is to significantly decrease waterborne illnesses within the communities that use the Endo-Clear, with an initial regional focus on Gambia. We intend to accomplish this goal by offering a cheaper product that is easier to use than any of our competitor products. We will adjust our product to the specific needs of each country we introduce Endo-Clear too. We understand that each country has a different situation and we will modify our product so that it best suits each country's needs.

Endo-Clear's differentiated design is minimally intrusive to the daily activities of a household. By using Endo-Clear, a household could spend less time ensuring the safety of their water given the available alternatives. There are two common scenarios by which people use and clean water in Gambian households.

> In the first scenario, a household does not purify their water. A family or community member will fetch water for the entire day's drinking cooking and washing. Because the water is shared, many individuals will come to the water source for a variety of purposes, and contaminating it throughout the day. This results in members of the household becoming ill. The consequences of sickness are: loss of work time and thus loss of wages and death.
>
> In the second scenario, a household purifies water by boiling it with wood fires. Wood itself is a valuable commodity, and burning it to purify water puts an added stress on the family to gather more wood. The inconvenience of boiling water to purify it is sometimes a deterrent for households. For the families that do boil their water, indoor pollution and local deforestation are chronic associated costs. The indoor pollution results in smoke inhalation and health problems, which result in shorter life spans. In Gambia, "the burning of wood for cooking and other uses accounts for over 80% of total energy consumption in Gambia…According to the 2004 Energy Balance, in

Gambia, 485,00 tons of firewood is used annually to meet the energy needs of 90% of the population."[i] Deforestation is a problem directly facing Gambia; by using less fire to purify water there is a decrease in demand for wood. It is also a time consuming process.

The Endo-Clear is distinct in that it offers a safer, cheaper way to pasteurize water that is designed to be seamlessly integrated into the daily social routine of gathering water. One full tank from the Endo-Clear provides sufficient water for an entire day, and given the 5-hour cycle needed to pasteurize its contents, a family should be able to consume 14L of clean water each day. Endo-Clear's process is preferable to that of boiling water because it saves resources and effort. In fact, if used appropriately, all physical costs of using this method should be identical to those from the first scenario above.

The concept was designed around a typical daily routine. Before noon, the Endo-Clear, that has been left out from the day before, will be emptied into a container in the house that can be drawn from throughout the day. The device should then be refilled and placed back in good sunlight. In this cycle, clean water will be accessible even in the mornings, and will allow the pasteurizer to be left untouched in the sun over the best hours of the day.

It is evident that by using Endo-Clear most households and communities will be better off. It can enrich a household by reducing the risk of waterborne illness, minimizing the resources that need to be spent on pasteurizing water, and overall decreasing the amount of time and hassle associated with safe drinking water water.

3.1 Competition

We see our competition as all other passive water pasteurization methods. Specifically, we identify competitive threats from pasteurizers that use solar-thermal energy to disinfect water. The competitive strength of the Endo-Clear is in the fact that is is cheaper, provides more water, and is more easily integrated into the social and societal habits that surround drinking water.

Indirect Competition

Disinfectant Tablets: Using pills and tablets to purify water has proven minimally successful throughout the world. Although effective in pasteurizing large quantities of water quickly and effectively, chemical and germacidal pills have mostly been rejected by the locations in which they were distributed. A social stigma surrounds the procedure to the point where communities in a water safety development program in Pakistan refused to use the pills for fear that they were infact contraceptives. We see this alternative as a less viable competitor because of the social barriers that are dificult to overcome through contemporary education and training approaches.

Charcoal filtration systems: There are many cheap and effective systems that use charcoal filtration currently present in the developing world. These systems rely on the inherent sanitation benefits that charcoal has on water that is filtered through. Like our systems, they are effective at reducing the prevalence of waterborne illnesses. However, these the effectiveness of charcoal filtration systems decreases over time as the filter loose their marginal ability to purify water until these components need to ultimately be replaced. As we see our system out compete these filters in longevity and continued effectiveness, we aim to capture the portion of the market who believe these to be the cheapest solution to water sanitation.

Direct Competition

Although no existing product is quite like the Endo-Clear, a variety of solar-thermal water disinfection systems exist in the developing world today. Solar-concentrators have shown some promise, but because they are cumbersome and require manual operation, we believe a passive system will prove higher levels of use. Passive systems such as the Aquapak use energy from direct sunlight to reach temperature levels of water that can pasteurize water. Through our research,we have found that alternatives to the Endo-Clear that use similar techniques are not designed to meet the specifications of typical households in need of water sanitation systems.

The Aquapak uses solar energy to pasteurize water and has a unit cost of $29.95. The Aquapak has aspects that make it less than desirable to use in third world countries. It is fairly small, the Aquapak can only pasteurize 4 liters at a time. The Aquapak does not have the capacity to provide enough water for a family at one time. It would require a member of the family to refill the Aquapak several times to adequately meet their water needs. This would require a change of behavior by the family and is not likely to happen. The other problem with the Aquapak is that it is not durable. It has seems on the sides and is easy to break if it falls from over 4 feet and is not easily repairable according to an Amazon reviewer. Endo-Clear does not have these flaws. It provides enough water for an entire water without requiring them to refill it more than once. It also is easy to repair.

4. Economics and Market Analysis

4.1 Economics

The Endo-Clear was designed to minimize cost in terms of both materials used and methods for fabrication. The materials consist of cheap, readily accessible plastics and glue, and the device is constructed using only basic tools. We hope that in such a low cost paradigm, that the social, economic, and governmental climate in the Gambia will be sufficient to support a strong market for the Endo-Clear pasteurizer.

4.2 Material Costs

Our initial manufacturing process was wasteful and did not take advantage of economies of scale due to our producing just one unit. If we are to call is our cost before economies of scale, it should be interpreted only for the purposes of understanding the costs of our project. These costs will not be reflected once large scale fabrication is a possibility.

In purchasing the Polyethylene Drums, Silicone Glue, and Polycarbonate Sheets in bulk, we are able to minimize the marginal cost of individual components. In the figure below, it can be seen the how the marginal cost of the materials used in one Endo-Clear device total $22.01. This is a low projection, because it assumes the sales of 10,000 units, however it will help us set an initial price point and gage the price elasticity of demand.

Table 4.1 The results displayed below summarize our cost breakdown after considering economies of scale.

	Cost of Individual Device Before Economies of Scale				
Materials		Unit	Quantity		Price
Polyethylene Drum (PET)		55 fl.oz. Drum	1	$	95.90
Silicone Glue		2.8 fl.oz. Tube	1	$	6.06
Polycarbonate Sheet		0.3 Sq. Meters	1	$	77.64
Total Cost of Unit			**1**	**$**	**179.60**

	Cost of Bulk Purchase				
Materials		Unit	n. Quantity to lock in low Pri	Per Unit Price	
Polyethylene Drum (PET)		55 fl.oz. Drum	1000	$	19.00
Silicone Glue		2.8 fl.oz. Tube	10,000	$	0.70
Polycarbonate Sheet		1 Sq. Meters	2000	$	3.50
Cost of Bulk Purchase				**$ 33,000.00**	

	Cost of Individual Device After Economies of Scale				
Materials		Unit	Quantity	Per Unit Price	
Polyethylene Drum (PET)		55 fl.oz. Drum	1.0	$	19.00
Silicone Glue		2.8 fl.oz. Tube	2.8	$	0.70
Polycarbonate Sheet		Sq. Meters	0.3	$	3.50
Cost of Device After Economies of Scale			**1**	**$**	**22.01**

In this analysis, we focused on only the device itself and not the attachments that could be sold separately. Namely, pumps and wax indicators have been identified as additional components that would complement our system, but projecting their costs was beyond the scope of our analysis. Namely, we were unable to confidently assess whether the was that melts at 65º would be available within the country of manufacture.

4.3 Overhead Costs

We are confident that overhead will be a minimal expenditure. The production of one

Endo-Clear device will not call for heavy machinery or expensive equipment. Because they can be made with a simple hand saw, we feel that overhead will be considerably cheap no matter where production is. Production can be brought to the Gambia, we feel that we will be minimizing an already low overhead cost due to low average rents on facilities and land.

4.4 Labor Costs

Skilled labor is unnecessary, which will call for low overall expenses on the labor used to create Endo-Clear pasteurizers. Again, where labor could be cheaper in economies like China, the benefit of producing it within the market that the device will be sold into comes with inherent benefits like minimal transportation costs and positive cultural integration. If production were modeled for the Gambia, labor costs would average around 50 Dalasi per day, or roughly $1.47/day. We would not be confident projecting the number of Endo-Clear devices that can be manufactured in a day without knowing the marginal product of labor within a hypothetical fabrication shop.

4.5 Market Analysis

We believe the Gambia has favorable societal, economic, and governmental conditions for the development of a market for the Endo-Clear device. The social routine allows the Endo-Clear to an effective substitute to traditional means of gathering drinking water reserves. The economic conditions within the country are sufficient to support a commercial market as well as a federally assisted implementation scheme. Lastly, the governmental concerns and global Millenium Development Goals for Gambia emphasize water sanitation, and have delegated funding to be spent on large scale water sanitation efforts. [12]

As mentioned in the Market Research and Concept Generation segment, the Endo-Clear can be easily integrated into the daily routine of a typical Gambian household. With this ease of use, we see no inherent barriers to using the device other than the initial cost of purchasing it.

---

[12] Gambia. The National Planning Commission. *Level of Achievement of the Millenium Development Goals: MDG Status Report, 2009 Final Report*. N.p.: n.p., n.d. Print.

The economic conditions are favorable due to the recent increase in national economic statistics. GDP has grown from $630M in 2005 to $1001M in 2010. GNI per capita also increased from $545.8 in 2010 to $380 in 2005. On the front end of hopefully sustained growth, we see our price point of $25-$30[13] as a reasonable expense in the budget of a typical household.[14]

Government and international initiatives have put pressure on the current state of water sanitation in the Gambia. The national government has set a target to increase rural water sanitation to 65% and rural water access to 90% by 2015. However, being the 155th poorest country out of 177 studied by the IMF's Human Development Index, they were cut off from the IMF Poverty Reduction and Growth Facility (PRGF) loan in 2002. Combined with the drop-off in international development funding, the Gambian %GDP spent on water sanitation has fallen well short of the projected cost of reaching their goals. [15]

Despite the negative connotations of the state of government and international development money that is to be spent on water sanitation, these may actually be interpreted as an opportunity. The targets of 65% and 90% are still on the Gambian agenda, and so the government is looking for cheap alternatives that can help boost their numbers. We hope to see that the government of gambia would encourage personal spending on Endo-Clear devices and hopefully set aside resources that can be directed toward this pasteurization technique.

As a World Bank report from 2012 shows, water sanitation investments are among the highest ranking investment opportunities because of their annual rate of return that exceeds 20%. Over 60 large-scale development bank projects in african water sanitation were studied, showing returns of 1.6x each dollar spent on the cost of water supply, and more importantly a 2.8x return on the cost of water sanitation. Because we recognize that the Gambia will have to step up its water sanitation spending if it is to reach its 2015 MDG's, and because increased documentation of successful projects could bolster this 2.8x Rate-of-Return figure, we believe that governmental spending will help to catalyze investment from other sources such as the UN, the IMF, and NGO organizations. We

---

[13] The price point will be set according to our specifications for desired Gross Margin and applicable Price Elasticity of Demand.

[14] "Gambia." *UNdata*. United Nations, n.d. Web. 30 Apr. 2013. <http://data.un.org/CountryProfile.aspx?crName=Gambia>.

[15] "Gambia." *UNdata*. United Nations, n.d. Web. 30 Apr. 2013. <http://data.un.org/CountryProfile.aspx?crName=Gambia>.

believe that by proving a low cost and framing Endo-Clear as an investment opportunity in the water sanitation space within Gambia, this product will find a competitive advantage when spending on this solution is weighed against other water sanitation alternatives. [16]

With all of these market factors to consider, one metric should be highlighted. There are 1.7 million people in the Gambia. 42.7% of the population resides in a rural area, or 72.6 million people. Currently, only 23% of rural communities have access to water sanitation. The Gambian goal is to increase this percentage to 65%. If the Gambia is to hit their goals, they will need to increase the rural access to water sanitation 42%. This means that before 2015, an additional 30.5 million people (or 42% of the 72.6M) will need to gain access to water sanitation techniques. This metric is especially important to highlight, considering that spending on water sanitation for 30.5 million individuals represents a large and attractive market opportunity for the Endo-Clear water pasteurizer. [17]

---

[16] "The Gambia. Briefing: Economic Impact of Water and Sanitation." *Sanitation and Water For All*. N.p., Mar. 2012. Web. 30 Apr. 2013.
<http://www.sanitationandwaterforall.org/files/The_Gambia_-_2012_Economic_Briefing_EN.pdf>.
[17] "Gambia." *UNdata*. United Nations, n.d. Web. 30 Apr. 2013.
<http://data.un.org/CountryProfile.aspx?crName=Gambia>.

5. Investment Consideration and Start-Up Opportunity

5.1 Startup Opportunity

We see a strong potential in the Endo-Clear device. We recognize the health and development benefits that the pasteurizer can bring, and see it as a competitive solution to water sanitation needs. After considering the favorable market conditions in the Gambia, our team realized this product could be a commercially viable product. There is a large target segment of the Gambian population that we wish to capture, and felt that there are two ways to go about monetizing this concept and design.

We determined that setting up fabrication facilities within the Gambia, and selling it directly into rural communities would be the most efficient way to have the greatest social impact. Not only would our product help communities in terms of health and sanitation, but it could embrace other social initiatives to maximize the social benefits that Endo-Clear brings with it. Employing women could be mutually beneficial for both the Endo-Clear's mission and the Gambian initiative to increase the rate of female employment. Endo-Clear could minimize cost with women employees, and hopefully could receive some synergies from the Gambian efforts to incentivize women employment.

During the process of building and testing our solar water pasteurizer we met with people that had an interest in our project. One contact in particular highlighted the need in Gambia, and helped us to tailor our specifications to make sure that not only our thermodynamic models would function in the Gambia, but also that our social assumptions and cost structure were consistent with the observed conditions in the country.

We could choose to minimize labor costs by setting up fabrication facilities within the countries we wish to sell these pasteurizers to. Although our margins may suffer from a less efficient manufacturing process, this choice may prove to be more sustainable because it could employ local workers due to the fact that no heavy machinery or expensive equipment is necessary in the construction process. Localized fabrication will also be a great way to readily match supply with demand, as well allowing our manufacturing process to more quickly adapt to the wants of the market we hope to create.

5.2 Conditions within the Gambia and Start-Up Interpretations

Demand Side Conditions:

- Societal Conditions
  - Product can be seamlessly integrated
- Nationwide Economic Conditions
  - Sufficient market exists sourced by either governmental capital expenditures and household budgets or a combination of both through the help of subsidies.
- National and International Government Initiatives
  - Set targets to increase water sanitation levels, which will force expenditure on devices that can pasteurize water.

Supply Side Conditions

- Overall cost can sustain viable price point
  - Material Cost are low through economies of scale
  - Overhead costs are low considering fixed costs of facility and equipment
  - Requires cheap, unskilled labor
- Manufacture in the Gambia could minimize costs
  - Low overhead, low materials cost, and low labor costs
  - Minimizes the cost of transportation and distribution
  - Incentives to employ women and contribute to women empowerment

6. Environmental and Social Evaluation

Our initial focus will be on The Gambia. The Gambia receives 2,500 hours of sunshine yearly and has a daily solar energy potential of 2.5KJ per square centimeter area.[i] Unfortunately, the technology for solar powered energy has not been affordable until now. We have an opportunity in a new market where solar energy comprises less than 1% of energy consumed. We picked The Gambia as the first country to test out our product because there is a need, little competition, and an abundance of sunlight.

Our largest consideration in the creation of our product was that the product was sustainable and a better alternative to the current methods. The current processes done before drinking water in The Gambia are a water filtration system, boiling the water over a fire, filter through a cloth and not purifying the water. The Gambian water filtration system is fairly effective at removing microbial contamination. Our target audience will be the Gambians who boil water over a fire, filter through a cloth, and do not purify their drinking water.

Our target customers are the Gambians who boil water over a fire, filter through a cloth, and do not purify their drinking water. The greatest environmental benefits will come from the Gambians who switch from boiling water over a fire to using the Endo-Clear.

6.1 Water Consumption in The Gambia

Water consumption in The Gambia is primarily from the Agriculture industry at 67%. Surprisingly, water consumption for domestic use is higher than for industry at 22%.

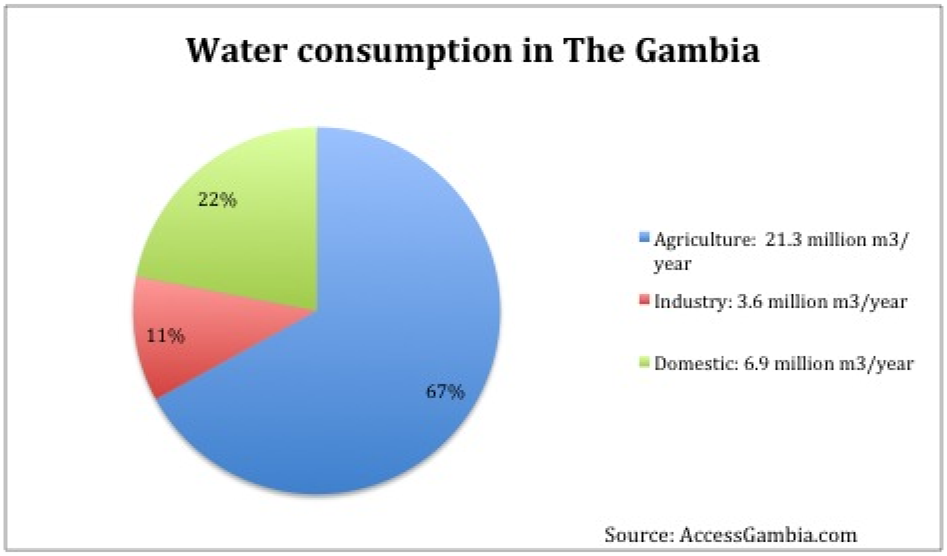


Figure 6.1 Water consumption in The Gambia in 2000

Breaking down the usage of water domestically, of the 6.9 million m3/year of water used, 3.42 million liters of water are drank every year. According to the Gambia Bureau of statistics, the following household water treatments were used for the drinking water:

Table 6.1 Household Water treatments to purify water prior to drinking

Household Water Treatment: Percentage distribution of household population according to drinking water treatment method used in the household, and percentage of household population that applied an appropriate water treatment method, The Gambia, 2006										
	Water treatment method used in the household in The Gambia									All drinking water sources
	None	Boil	Add bleach/ chlorine	Strain through a cloth	Use water filter	Solar disinfection	Let it stand and settle	Other	Don't know	Appropriate water treatment method
Urban	92.1	.4	3.1	4.1	.4	.0	.1	.1	.0	3.8
Rural	68.8	.1	2.3	29.2	.1	.0	.5	.0	.0	2.5

In total .5% of drinking water is boiled, 17,100 liters are boiled annually by open fire. Assuming that 1 liter of water weighs 2.20 lbs and the average temperature is 70 F, it would take 5,342,040 btu to boil the water annually. (. $17,100\ liters * 2.20\ lbs * 142\ F = 5,342,040\ btu$) The carbon emissions as a result of boiling the water to disinfect are 213 lb CO2/mmbtu * 5.34204 mmbtu= 1,137.85 lbs of CO2.

Our product, the Endo-Clear will not emit any CO2 emissions while in use. The only time it will emit CO2 is in the production phase of our product. The carbon emissions of 1,137.85 lbs of CO2/ year is our maximum rate for the CO2 emissions emitted during production if we completely replaced all fuel wood for water purification. For a per household emission rate of our device, it will be .1205 lbs of CO2/ unit in a year.

6.2 Life Cycle Analysis of our Product

According to the EPA, our product, composed of the following materials would emit less than .1205 lbs of CO2/ unit as seen in Table . One tube of silicone glue will be used for several units and the remainder of the Drum will be recycled. We are fully confident that our product will have lower CO2 emissions than the current method of boiling water.

Table 6.2 The sustainability of the materials used for our product

Sustainability				
	CO2 emissions	Recycled material	Reusable	VOC Content
Polyethylene Drum	< .1 lb	Yes	Yes	<50g/L
Silicone Glue	< .1lb	50-75% recycled packaging	no	<50g/L
Polycarbonate Sheet	< .1 lb	1-30%	Yes	none

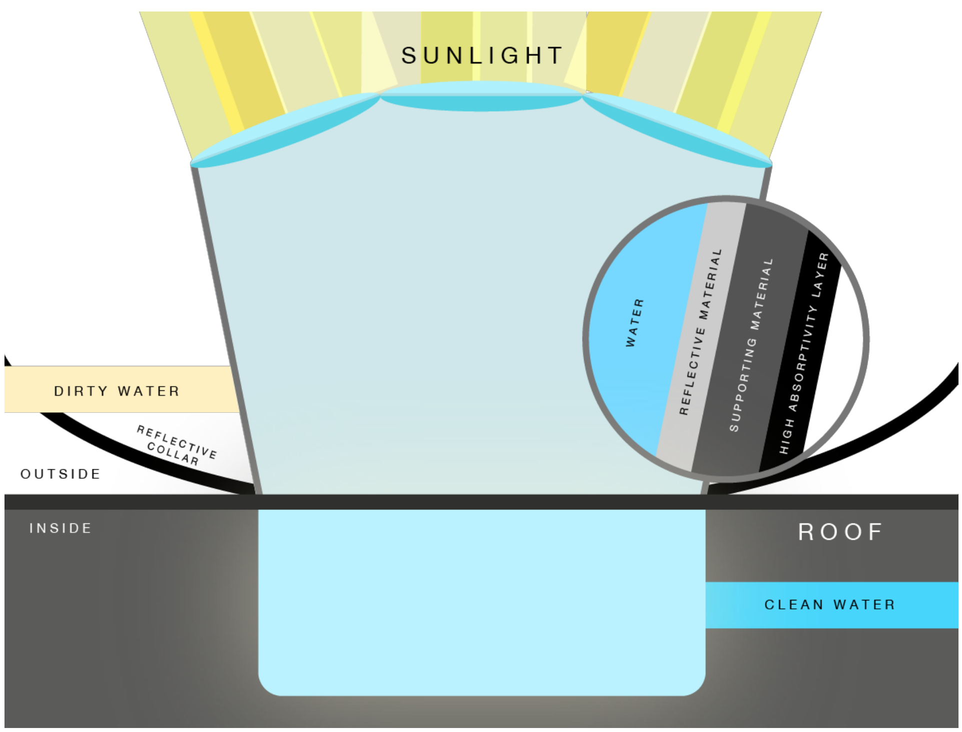
6.3 Community Impact

The Gambian President, Yahya Jammeh, is pursuing a policy of women empowerment through multiple projects including the United Nations' Millenium Development Goals (MDG). This project aims to increase women's role in decisions-making in the local communities, politics, and the home. For our business model we intend to enter the market through the local women community leaders. In this way, we will be helping The Gambia achieve its goals of women empowerment.

7. Concept Designs

7.1 Soda Bottle Design

The first design that was considered was inspired by A Liter of Light[18], which is a simple solution to poorly lit homes in slum areas that involves filling an empty soda bottle with water and a small amount of chlorine, and setting the bottle on the user's roof to allow light to pass into the home. Water would be contained in a bottle that would be partially exposed to the sun above the roof, and partially inside the home to introduce heatless light to facilitate daily, household tasks. The main structural component, the "soda bottle", would either be adapted from existing plastic materials such as small drums/bottles through recycling programs, or mass produce with conventional bottle manufacturing techniques. The external surface of the portion exposed to the sun would be treated with a high absorptivity material so that high temperatures can be reached. A reflective collar would allow sunlight to be redirected to this exterior surface. The top surface of the device would be transparent to allow sunlight to pass into the water. The portion of the device inside the home would also be transparent.



[18] *See* http://aliteroflight.org/

Figure 7.1 This design was inspired by A Liter of Light, and would sit on a roof. Part of the device would be exposed to the outside, and the remaining part would be indoors to allow light to pass through.

7.2 Stationary Pipe Design

The stationary pipe design is a passive system that we thought could help us minimize cost while still pasteurizing a large quantity of water in a given cycle. This design calls for a blackened pipe to be filled with water and uses solar-thermal energy to heat the water inside to the necessary 65º threshold. This passive system would operate much like our cylindrical design in that thermal energy would build up over a long period of time. We saw the potential for this design to take advantage of the same social routines as the design for the Endo-Clear. The decision to move forward with our wafer design instead was made because it increased the amount of water that could be confidently pasteurized in a given cycle, while maximizing the absorptivity of the system by increasing its surface area.

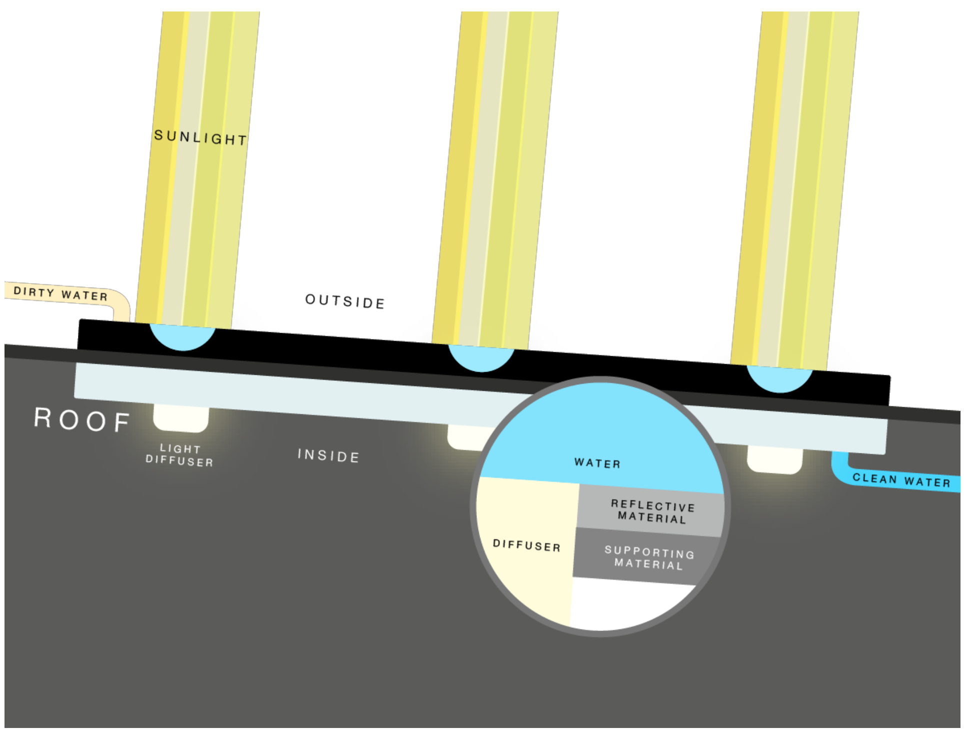


Figure 7.2 Stationary pipe design was inspired by conventional tube rooftop solar water heaters.

7.3 Moving Fresnel Lens Design

This design was the only dynamic one that we considered. Given the resource constraints, we were immediately discouraged from exploring any designs that were too complex, i.e. involved moving parts, or required electrical components that would incur high maintenance costs. This design involved a concentrating a fresnel lens that would track the motion of the sun based on photosensitive actuators. The concentrated sunlight would help to achieve pasteurization temperatures in a shorter period of time. The largest drawback to this concept was its feasibility in the developing world.

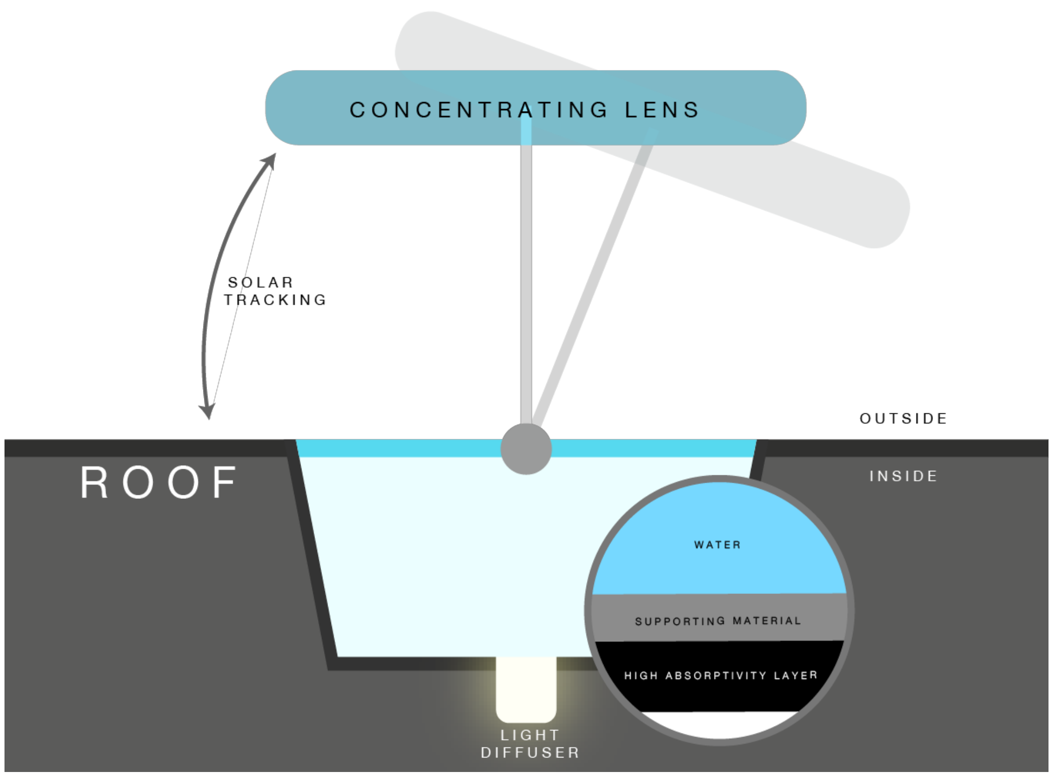


Figure 7.3 This design contained a dynamic concentrating lens that would track the movement of the sun in the sky and thereby amplify/maximize solar radiation.

We evaluated these different designs by constructing Pugh Matrices, which can be referenced in the PUGH MATRIX Appendix A1 - A3. Through these charts, we quantified the value of certain collector shapes, absorbent coating, and water replacement mechanism.

8. Modeling and Analysis

The team settled on an amalgamation of the best features of the “soda bottle” and “stationary pipe” designs”. To facilitate manufacturing, we settled on a passive dish that could be adapted from existing black plastic drums that are typically used in the developing world to store water or grain.

8.1 Design Parameters

After carrying out the extensive market and economic analysis shown above, the next step was to translate our findings into engineering criteria that we could base our modelling, analyses and design considerations on. We determined the following criteria to be critical to quality (CTQs):

Water must be held at 338 K (or 65 °C) for 2 minutes to make bacteria and viruses harmless. It is a well studied fact that water pasteurization can be achieved without boiling. This relatively low temperature is easier to achieve and will allow us to utilize lower quality materials that tend to be lower in cost.

Device must produce 14 liters of potable water. The average family in urban areas in the Gambia has 6.6 people[19]. We have chosen to design for 7 members to provide an extra buffer, and to produce a reasonable proof-of-concept. According to the UN, each person needs 2-4 L of drinking water per day[20], which amounts to 14 liters.

Device should introduce at least 20 Watts of heatless light into space. 20 W of light is a reasonable amount, and should be enough to perform daily household chores in.

Cost must not exceed current filtration or concentrating techniques. Some of the biggest drawbacks to existing solutions for solar water pasteurization are high capital and maintenance costs. Both of these costs should be kept as low as possible.

---

[19] *See* http://www.columbia.edu/~msj42/pdfs/Chapter3_Household_housing.pdf
[20] *See* http://www.unwater.org/statistics_sec.html

8.2 Computational Model

The device was modeled with a thermal energy balance via the lumped parameter model. It is reasonable to assume that the water will have a uniform temperature profile. While its biot number was not found to be < 0.2, internal convection should help to maintain internal temperature uniformity.

Solar energy was modelled as internal energy generation. This was a simple and convenient way to model solar irradiation without having to involve complex radiation calculations. It was done by estimating the amount of attenuation that would be experienced by sunlight when it reached our device, the further attenuation that it would experience as it passed through the transparent material that sits on the top face of our device, and the amount of sunlight that was reflected and therefore discounted. With an incident solar radiation assumed to be 1000 $\frac{W}{m^2K}$, the transparent plastic top sheet was assumed to receive solar energy that was attenuated by 95%, which is reasonable considering it was modelled as transparent. On the other hand, the bottom sheet was estimated to receive only 30% attenuated sunlight, and the side material, 90% attenuated sunlight.

Careful consideration was given to convection heat transfer coefficients on the exposed surfaces. The exterior surfaces were assumed to observe a convection heat transfer coefficient equivalent to 8 $\frac{W}{m^2K}$. This is equivalent to a typical breeze experience on an average day with typical weather. The outside temperature was assumed to be 25 °C. This was a very conservative estimate because average temperatures in the Gambia regularly exceed 30 °C, and summer temperatures reach 42 °C.

The model was broken down into the four main components of the device, and the governing equations were then solved in tandem to produce the temperature of the water over time. The four main components were: water, top surface, side surface, and bottom surface.

The water contained inside the device was modeled via the lumped parameter method, and accounted for the rate of heat lost to the sides and the top surface, and the heat gained from the highly absorptive and therefore warmer bottom surface. This is demonstrated in the following thermal energy balance:

$$[\rho Vc]_w \frac{dT_w}{dt} = q_{free-} q''_{cond,s} A_{s,i} - q''_{cond,t} A_t + \dot{E}_{g,w} \qquad [1]$$

To calculate the individual terms shown on the RHS of equation [1], we performed a thermal energy balance of each individual surface. In order to determined the rate of heat being lost through conduction through the top surface, we performed a thermal energy balance of the transparent top plastic sheet. The following two equations are the conductive heat transfer term [2] that will be substituted into [1], and the temperature term calculated for the temperature of the top sheet [3]:

$$q''_{cond,s} A_{s,i} = \frac{k_{PET} A_{s,i}}{H_s} \left(T_{w-} T_{s,0} \right) \qquad [2]$$

$$T_{s,0} = \frac{1}{\frac{k_{PET} A_{s,i}}{H_s} + h_a A_{s,0}} \left(\frac{k_{PET} A_{s,i}}{H_s} T_w + h_a A_{s,0} T_{s,0} + \dot{E}_{g,s} \right) \qquad [3]$$

Similar equations were calculated for the bottom surface. On this surface however, we modeled internal convection heat transfer as free convection. This allowed us to model the uniform heat transfer of solar thermal energy that was generated by the high absorptivity plastic and that was transferred to the water. This was convection heat transfer correlation was adapted from convection coefficients for a horizontal cavity heated from below, as proposed by Globe and Dropkin and found in Incropera et al [4]:

$$\overline{Nu_L} = \frac{\overline{h_{free}} L}{k} = 0.069 Ra_L{}^{1/3} Pr^{0.074} \qquad [4]$$

The convection heat transfer to the water [5] and temperature equation of the bottom surface [6] were also calculated, the latter of which was solved from a thermal energy balance of the bottom surface.

$$q_{free} = h_{free}(T_{b,0} - T_{t,0}) \qquad [5]$$

$$T_{b,0} - T_{t,0} = \frac{1}{h_{free}+h_a A_b}\left(A_b T_a + \dot{E}_{g,b}\right) + \left(\frac{h_{free}}{h_{free}+h_a A_b} - 1\right) T_{t,0} \qquad [6]$$

Finally, the side surfaces were treated in the same way as the others. The conductive heat transfer rate was determined for the surface [7], and a thermal energy balance of the surface allowed us to determine its temperature [9]:

$$q''_{cond,t} A_t = \frac{k_{PC} A_t}{H_t}\left(T_{w-} T_{t,0}\right) \qquad [7]$$

$$T_{t,0} = \frac{1}{\frac{k_{PC} A_t}{H_t} + h_a A_t}\left(\frac{k_{PC} A_t}{H_t} T_w + h_a A_t T_a + \dot{E}_{g,t}\right) \qquad [8]$$

Finally, the equations [3], [6] and [8] were substituted into equations [2], [5] and [7] respectively. This provided us with expressions for the RHS terms of equation [1] with respect to constants, and the desired variable T_W, the temperature of the water.

From here, the new form of equation [1] was a linear first-order differential equation that was easily solved in MATLAB. A function of temperature with respect to time was calculated:

$$T_w(t) = 349.26 - 51.26 \cdot e^{-6.75 \cdot 10^{-5} \cdot t} \text{ [K]} \qquad [9]$$

This function was plotted respect to time, and the resulting plot is shown below:

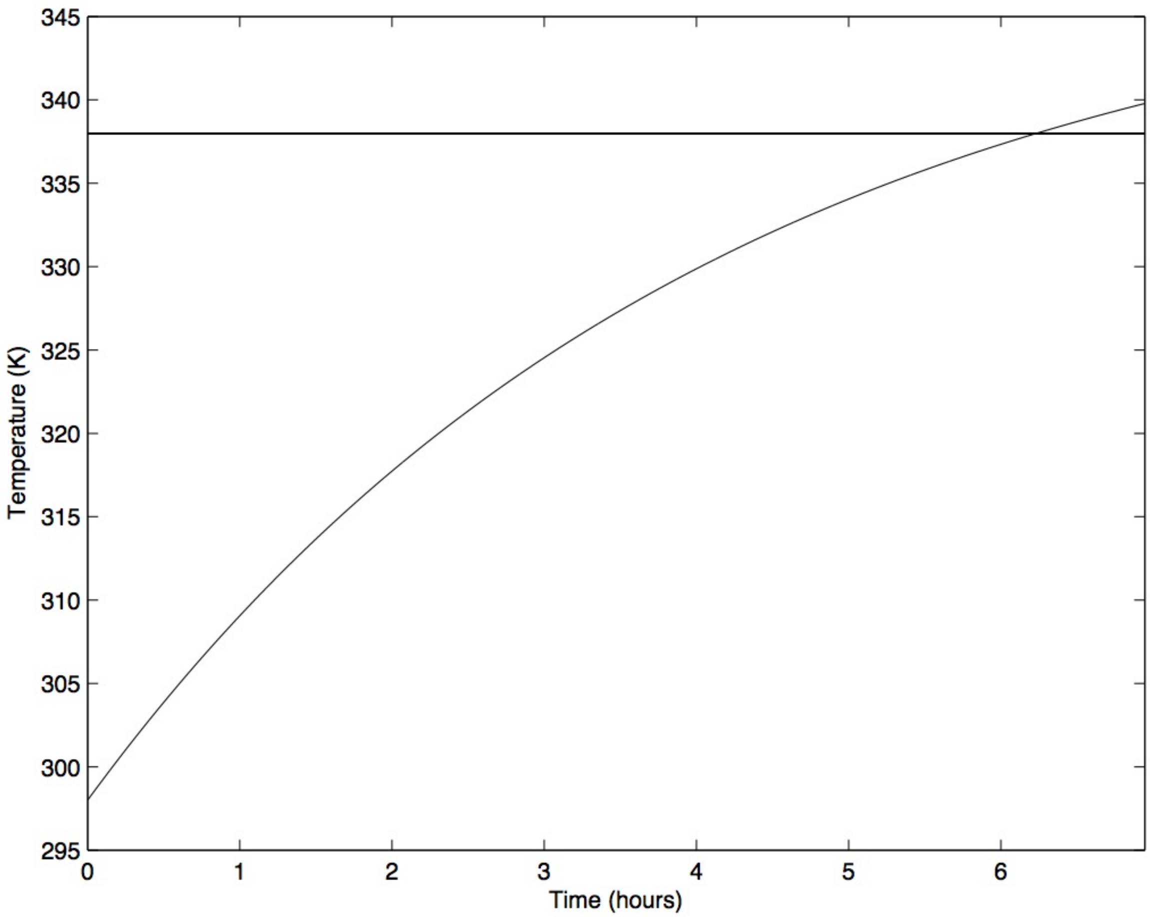


Figure 8.1 Plot of water temperature with respect to time, as calculated by our theoretical model.

These computational results demonstrated that despite very conservative estimates, we should be able to achieve pasteurization in approximately 6 hours (in fact, less, if more realistic conditions were used).

8.3 Solidworks Model

After producing a mathematical model on paper, the designs were transferred to Solidworks and generated. Doing so allowed creation of our design in 3-D space, allowing a full perspective on how the system would operate and whether it needed more tweaking or not. Several design iterations were done, weighing the importance of the pasteurization to the necessity of light. These varied from a rectangular box designed for its simplicity and strength in fabrication to a pipe coated with selective absorbent paint to maximize surface area per volume. The final design of the circular disc was decided upon for several reasons. First, the convection currents for such a design created better internal flow, leaving no "cold spots" in which temperatures would not reach the desired values. Second, based on the materials available in The Gambia, a circular shape would be easy to fabricate from drums used to store high volume goods, such as rice or water. Third, a circular pasteurizer can be set up on most roofs and/or other ideal places, loosening implementation restrictions on its use.

We used an add-in known as Solidworks Flow Simulation (SFS) to show how the system would work in real conditions. Solidworks Flow Simulation takes an assembly from Solidworks and allows the insertion of fluids into the assembly, taking up volumes Solidworks left empty. By doing this, the interaction between solids and fluids are traceable, accounting for both mass and heat transfer. Table (TABLE NUMBER) shows the conditions the system was put under in SFS to achieve accurate results.

Table 8.1 Summary of the parameters that were used to model the device in Solidworks Flow Simulation.

Condition	***Value Input***	***Reasoning***
Initial Temperature	300K	Average temperature for the modeled day in The Gambia is about 27 °C
Initial Pressure	101 kPa	Standard atmospheric pressure for most locations

Top Material	Acrylic	Acrylic was the closest material to polycarbonate available in Solidworks;
Top Boundary Condition	15 W/m^2	Calculated from mathematical model, top experiences the highest wind velocity
Top Heat Loss Condition	Real Wall	Accounts for both conduction and convection heat loss
Top Radiation Condition	Transparent	Transparency was added for solar radiation, not thermal
Wall Materials	High Density Polyethylene	Accurate to common plastic storage drum, fabricated black for the purpose of absorption
Wall Boundary Condition	10 W/m^2	Applied all around the outside to account for convection losses, not 100% accurate as not all sides will experience the same heat loss
Wall Heat Loss Condition	Outer/Real Wall	Given the outer wall condition, shows Flow Simulation where to account for certain losses; Real wall for losses
Wall Radiation Condition	Absorbent	Converts 100% of radiation into heat, but does not radiate heat at the same level

Hole Material	Diffusive Plastic	Generic plastic with light diffusive properties; Given same heat transfer properties as the walls
Roughness	0 micrometers	Not accurate to system because physical model was sanded to create roughness, too difficult to accurately measure
Flow Type	Internal	Flow Works requires a type of flow to analyze, internal for the water in the collector
Conduction Limitations	All Materials	Conduction was accounted for in all materials, not only solids
Environmental Radiation	Standards at 300 K	Allowed the influx of environmental radiation at the given temperature
Latitude	13.4171 N	Also modeled for Mexico City due to similarity in latitude and simplicity to input (Mexico City was pre-input)
Angle	0 °	Assume sitting flat on roof; This could be adjusted for better conditions but assume worst practical set up
Albedo	.2	This value seems to be the average for The Gambia as cited by weather sources

Solar Spectrum	Standard	Spectrum can be adjusted to specific wavelengths but assume the standard influx and wavelength distribution
Time	6 hours (10AM to 4PM)	Prime hours of sunlight range from 8AM to 8PM, so the highest intensity should fall in the range accounted for
Humidity	Considered, but not implemented	Humidity can range from 20% to 80% from day to day in The Gambia, making it difficult to model

The final dimensions of the design closely followed the materials available to fabricate the system cheaply. From the standard plastic storage drum, the diameter of the circular design averaged 23 inches with a wall thickness of about an 1/8 of an inch. In order to achieve the target volume purified per day, the system was required to be at least 2 inches in depth. With the goal of 20 Watts of light, the light diffusive circular hole was cut to take .02 square meters, assuming that about 1000 Watts of energy comes from the sun per square meter. This resulted in a hole with diameter of 6.25 inches, assuming a high diffusivity plastic to spread the light around the room.

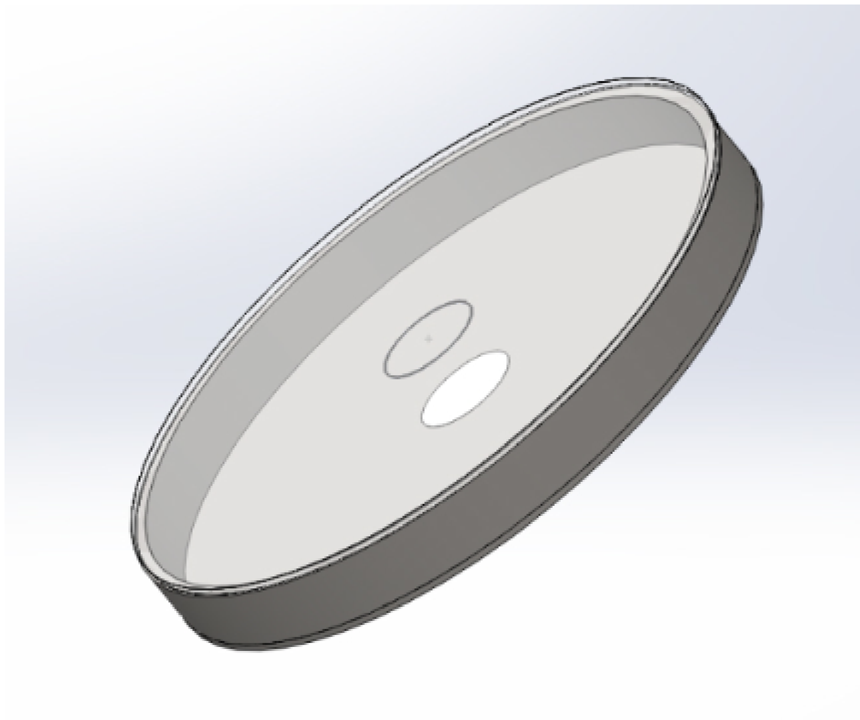


Figure 8.2 Solidworks CAD model of design that was simulated in Flow Simulation.

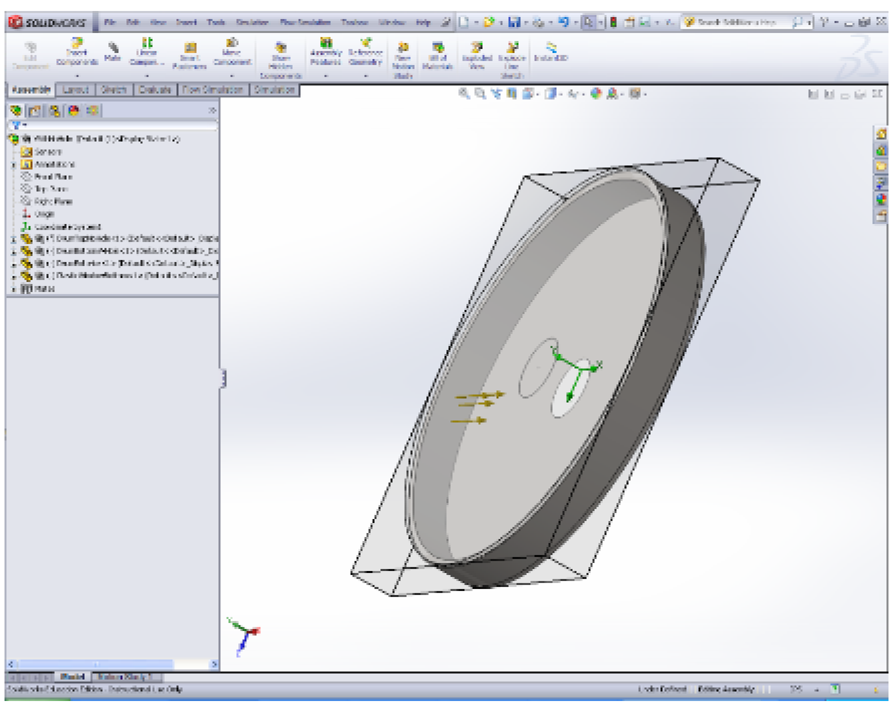


Figure 8.3 Solidworks model with solar radiation based on local Gambia conditions (yellow arrows).

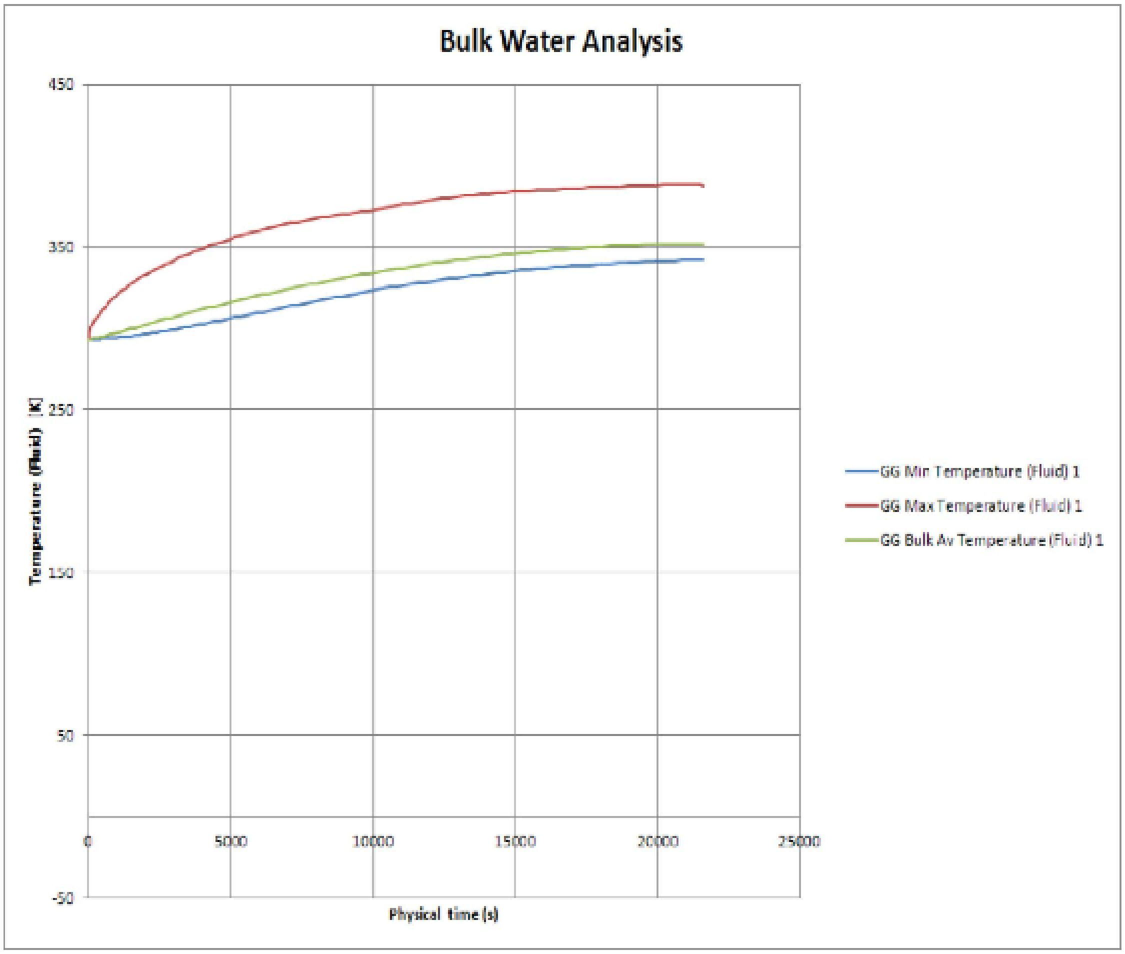


Figure 8.4 Plot of bulk water analysis of water temperature with respect to time from Solidworks Flow Works.

Putting in the parameters discussed in Table 8.1, the results proved that the pasteurization system would indeed reach the required temperature. As shown in Figure 8.4, the bulk average reaches about 350 K over the projected time of six hours. While minimum temperatures of the bulk fluid over that time are lower than initially hoped for (338 K), this value is still higher than the minimum required for pasteurization, showing the system is designed well enough to reach the temperature CTQ.

9. Product Description

9.1 Building the Prototype

Constructing the prototype was more based on the materials available than anything else. Fabrication began with the bottom black part seen in Figure XXXX. This was cut out of a black HDPE storage drum for both realistic and practicality purposes. The inside of this was roughened with sandpaper to increase absorptivity. Following this, we cut a piece of polycarbonate to become the top transparent part of the pasteurizer. This process was simply taking the factory sent piece and sawing it to an appropriate size. The light diffusing part was cut in a same way and a circular hole of about 5 inches in diameter was cut in the absorbent material to allow the light through. In order to have a system that could dynamically give and remove water from the system, two holes were drilled in the bottom and tapped to allow two valves to be implemented, one to pump water into and a second to act as a spigot. The system was then placed on the roof with a "shack" constructed of prefabricated steel beams and was darkened by a draped duck cotton tarp to test the effectiveness of our light diffusing component.

Figure 9.1 The full-scale prototype was placed on an area of a roof that allowed undisturbed sunlight. The device was rated to hold 15-16 liters of water. To allow convenient testing,

9.2 Testing

In order to simulate typical use conditions and put to test our theoretical models, a simple shack was constructed to house the Endoclear. Three holes were cut into the roof of the shack to allow for the device's inlet, outlet, and light disperser. We then sat the unfilled device on the roof and tested using the following repeatable procedure:

1. Water was pumped up to device from ground level using a simple hand pump
2. 5 thermocouples were dispersed throughout the device to monitor temperatures
3. Between the hours of 10AM-6PM, temperatures were recorded at 30 minute intervals
4. Water was released through a simple spigot valve

10. Experimental Results

10.1 Temperature Profiling

The device's internal temperature was monitored using an array of thermocouples placed strategically throughout the interior. Two thermocouples were held near the surface, one was in the middle, and two more rested near the bottom of the device. This distribution ensured that we could measure temperature throughout the device without bias.

The thermocouples were fed out of the device through small holes drilled through the bottom wall and laced through the outlet hole in the roof for measuring access. We then regularly recorded the temperature readings of each thermocouple at 30 minute intervals over 8-hour periods. The results from two days of testing can be seen in Figure 10.1.

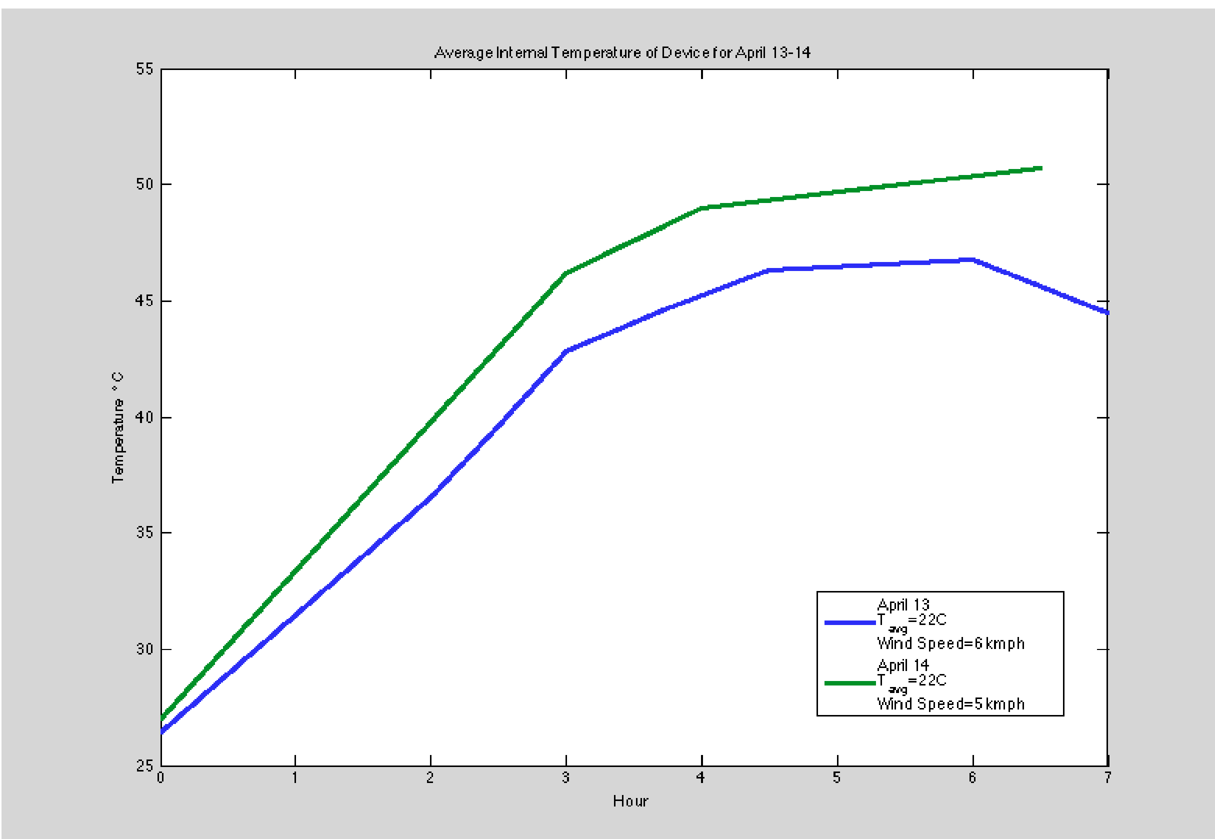


Figure 10.1 Average Internal Temperature for Device on April 13-April 14

From Figure 10.1, it is clear that the Endoclear did not reach desired temperatures. However, this shortcoming can be attributed to the low ambient temperature and considerable wind speeds experienced on testing days during spring in North Carolina. To ensure the temperatures were not distorted by incident light, a tarp was temporarily placed over the lid during measurement.

10.2 Light Characterization

The lighting feature of the device was evaluated using a simple qualitative test. A thick cotton duck canvas tarp was wrapped around the perimeter of the shack to serve as makeshift walls. These 'walls' ensured that the only light coming into the shack was indeed from the light disperser overhead. We then entered the shack with a textbook and attempted to read inside.

Although we had proposed a quantitative test using a luminosity meter, it was not available.

Figure 10.2 Luminosity

10.3 Testing Modifications

After the results of our testing indicated that the Endoclear did not regularly reach 65°C in Durham, NC's cool and windy conditions, we introduced two mechanisms for enhancing performance:

1. Foam Insulation
2. Wind Shield

The foam insulation chosen to wrap around the polyethylene frame was a .25" black flexible rubber material with a thermal conductivity (k) value of .25. The purpose of this addition was to reduce thermal radiative losses through the sides of the Endoclear. Results from this test can be shown in Figure 10.3 below.

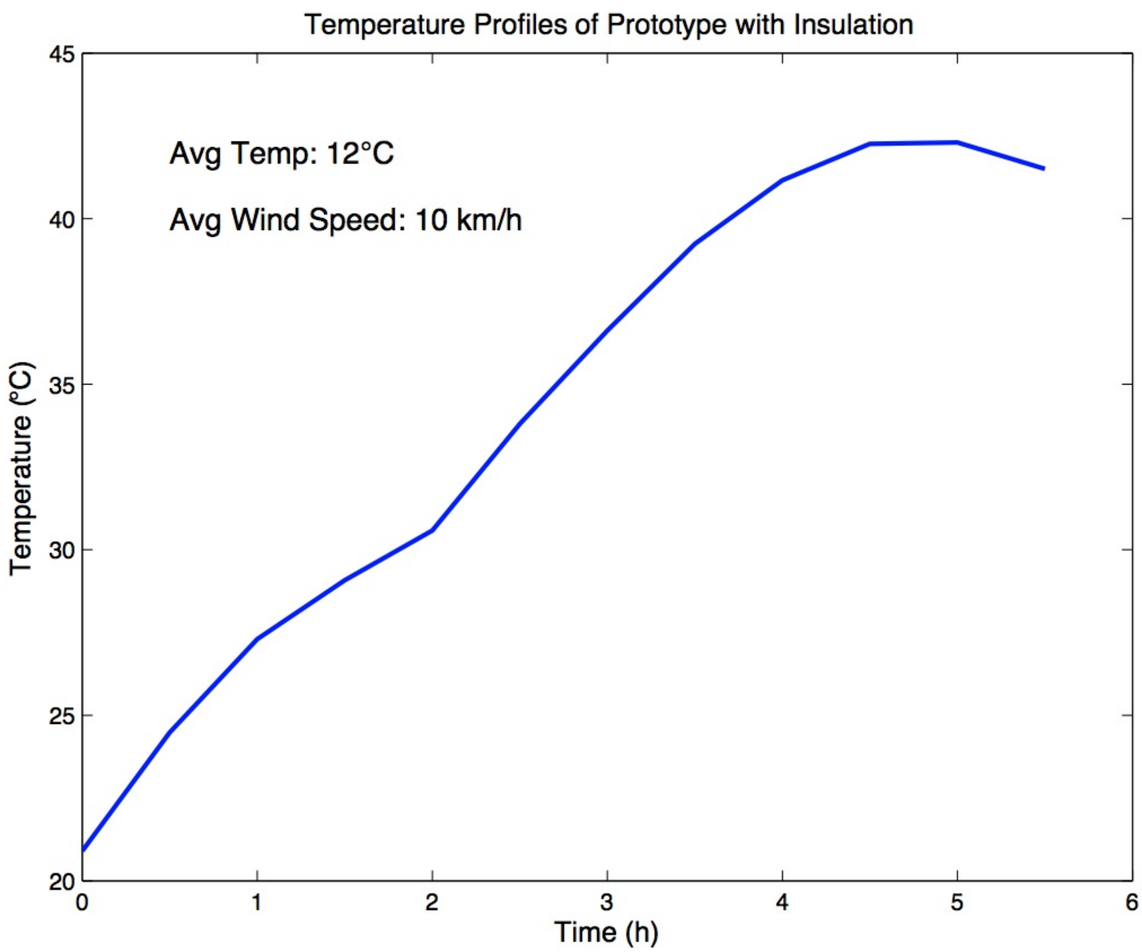


Figure 10.3 Temperature of Prototype with Insulation

The results demonstrated so far are inconclusive due to the fact that the ambient conditions were so adverse to testing. Temperatures did not go above 12 °C on the weekend we tested, which is nearly 20 °C below the average temperature in The Gambia. Ideally, temperatures would have been similar to temperatures seen on days we tested without foam insulation, however this variable could not be controlled for. Given more warm, sunny days, a more conclusive test could have been conducted.

The second modification, the windshield, was only tested on a smaller scale. Two scaled down replicas of the Endoclear were 3D printed, filled with water, and tapped for measurement access. One mini-Endoclear was placed inside a desiccant while the other was left exposed sitting next to its twin. The purpose of the desiccant was to act as a barrier to the elements and reduce convective losses. This experimental setup can be seen in Figure 10.4.

Figure 10.4 Experimental setup comparing the results in a scaled-down model of the device, with and without a windshield.

Results from this test are encouraging and can be seen below in Figure 10.5. Despite temperatures of only 12 °C and strong winds, the protected model Endoclear reached near target levels of 65 °C and sustained significantly higher temperatures than the unprotected model. At its peak, the windshield helped the Endoclear reach 9°C higher than it otherwise would have. Clearly, the windshield is an efficient means of reducing convective losses.

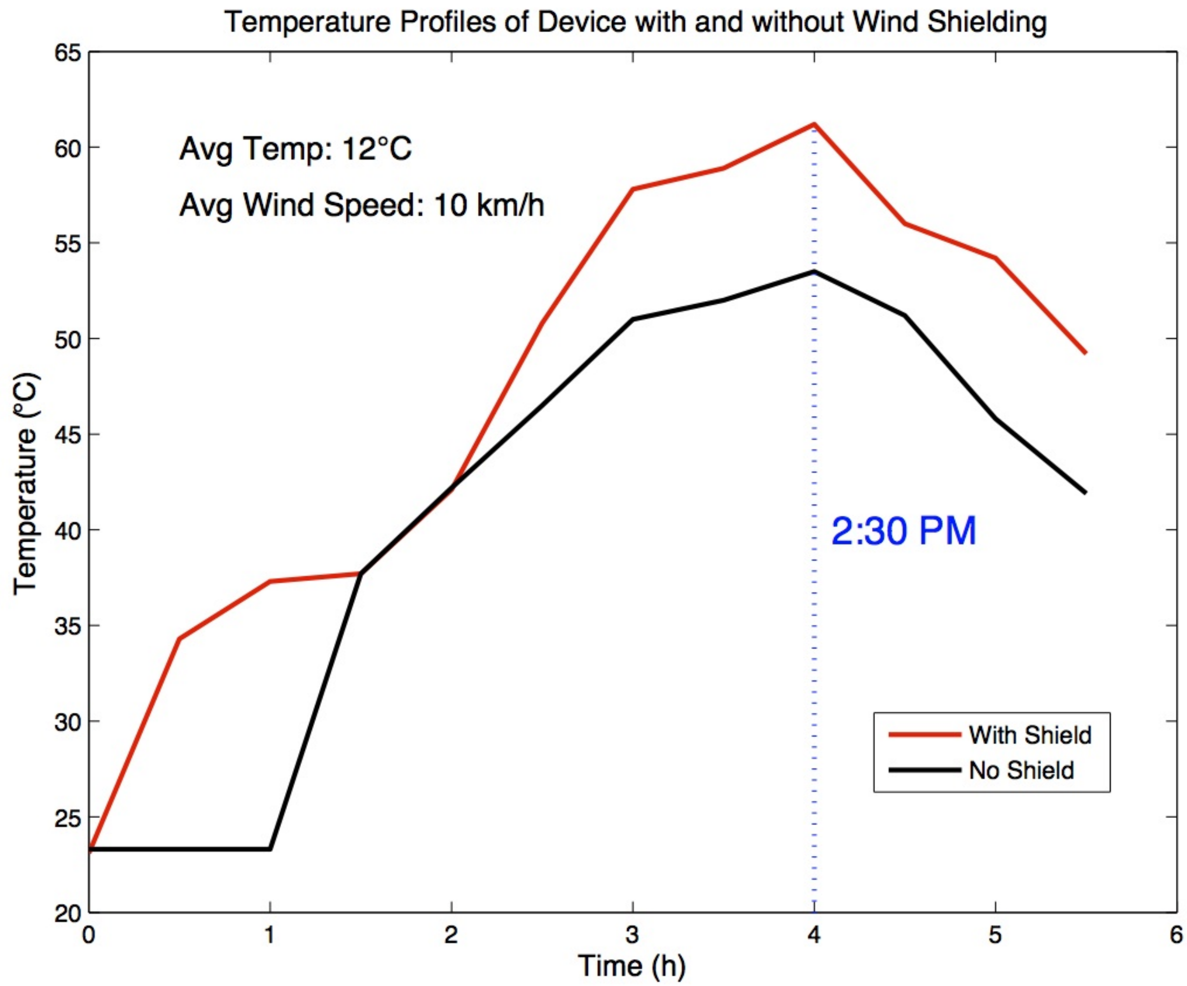


Figure 10.5 Temperature Profiles of Device With and Without Windshield

The following table summarizes this study's findings. We compare the desired critical to quality (CTQs) goals, and what we were able to achieve:

Table 10.1

CTQ	Goal	Achieved
Pasteurization	Entire volume must be 65C for 1 minute	61 C for 2 hours
High Volume	The average family size is	15-16 L

	6.5, and with 2L of drinking water needed per day, we must have at least 14L	
Accessibility	Materials must be local, cheap, and easy to maintain	All materials were basic, and easy to obtain.
Light	At least 20W should shine through	Light was sufficient for reading/basic activities.
Resilience	Life span should be at least 3 years	Actual lifetime difficult to predict, but device was completely stable over ~1 month test outdoors.
Unobtrusiveness	Should not introduce extra heat to room	Can be placed anywhere.

11. Future Work

There is a clear place on the market for a device that can cheaply and simply purify large batches of water. The Endoclear's ease of use and low cost make it an attractive filler for the void on the market. However, in interviewing people familiar with homes in the third world, it has become apparent that users do not actually have a pronounced need for indoor lighting. As such, they are reluctant to cut holes in their roofs and would most likely turn away from adopting use of the Endoclear.

In order to make the device a more attractive and feasible solution, we would eliminate the lighting aspect. This decision allows us to market the Endoclear as a completely unobtrusive device requiring zero modifications to the home. With no need to be on the roof, we can also simplify the inlet and outlet means. A simple lid mechanism would allow the device to be filled directly from the source of water. Users can take the Endoclear to a river, dump it under water, fill it, replace the lid, and sit the device in any convenient location. When the batch is pasteurized, users can simply unscrew the lid, pour out the water, and refill.

There are two possible construction mechanisms we discussed for implementing this lid-based prototype.

1. The clear plastic top would serve as the removable lid and would be screwed onto the main body component of the device.
2. The bottom of the Endoclear would be constructed from the top component of the old drum in order to take advantage of its clip-hoop-seal method.

Choosing the second alternative limits the recyclability of our design. Users can only use the top slice of the plastic drum if they must rely on the clip lid. However, using this feature of the drum greatly simplifies construction, as users would only need to attach the plastic lid.

By prioritizing usability over the need for heatless light, we have conceived a future prototype that we believe will better serve real people.

12. Conclusion

Over the course of this project, the design, fabrication and implementation of the water pasteurizer has given mixed results. The first of these is evident in the actual function of the system. After multiple days of testing in various sunlight, the water in the pasteurizer never reached the desired temperature, a task that seemed easily accomplished by our three dimensional model. While our model reached 350K easily after 6 hours, the best our fabricated system performed was 325 K over the same time span. The most reasonable assessment for this shortcoming comes from the fact none of the tests taken in Durham, North Carolina were representative of the typical day in The Gambia. Due to the high variability of weather for a Durham spring season, no day was the right combination of sunny, warm and windy to be accurate.

To account for some losses not fully conceived in the computer model, two measures were taken to lessen heat loss from wind. The first method added insulating foam to the outer walls of pasteurizer to keep heat from leaving the system. This method resulted in little increase in maximum temperature, but the testing conditions during this remeasuring were far worse than on previous occasions, showing this data as somewhat unreliable. The second method, however, of covering the system with a wind shield proved to be more effective. Two ¼ length scale models of the pasteurizer were created to test the effectiveness of an object that blocked the wind from reaching the actual pasteurizer. The one placed inside the shield reached a temperature 9 K higher than the one in atmospheric conditions, suggesting that a wind shield would dramatically increase efficiency and reliability.

The light producing side of our device, which would be ignored in future production due to limited need, worked perfectly in a qualitative test, giving a person enough light to read in a small room. Given the materials available, the pasteurizer can be fabricated for USD $20-30, proving that our product can also be implemented in The Gambia at a cheap enough price for residents to purchase while still maintaining reasonable profit.

12. References

"AquaPak Solar Water Pasteurizer." *Amazon.com: : Camera & Photo*. N.p., n.d. Web. 22 Apr. 2013.

Bergman, T.L., Lavine, A. S., Incropera, F.P., Dewitt, D. P. *Fundamentals of Heat and Mass Transfer, Seventh Edition*. John Wiley & Sons, 2011.

"Better Empowerment of Women in Gambia." *Better Empowerment of Women in Gambia*. N.p., 15 Feb. 2008. Web. 30 Apr. 2013.

Blum, D., Feachem, R.G. *Measuring the Impact of Water Supply and Sanitation Investments on Diarrhoeal Diseases: Problems of Methodology.* International Journal of Epidemiology Vol. 12, No. 3, 1983, 357.

Carr, R. *Excreta-related infections and the role of sanitation in the control of transmission*. World Health Organization, 2001. <http://www.who.int/water_sanitation_health/dwq/iwachap5.pdf>

Feachem, R.E., Bradley, D.J., Garelick, H., Mara, D.D. *Sanitation and Disease: Health Aspects of Excreta and Wastewater Management*. New York: John Wiley and Sons, 1983.

Food and Agriculture Organization (FAO) of the United Nations. *Water, Agriculture and Food Security.* United Nations Water, 2012. <http://www.unwater.org/statistics_sec.html>

Gambia Bureau of Statistics (GBoS), 2007, The Gambia Multiple Indicator Cluster Survey 2005/2006 Report, Banjul.

"Gambia." *UNdata*. United Nations, n.d. Web. 30 Apr. 2013. <http://data.un.org/CountryProfile.aspx?crName=Gambia>.

"Gambia Economy." *Gambia Economy*. Access Gambia, n.d. Web. 30 Apr. 2013. <http://www.accessgambia.com/information/economic-profile.html>.

Gambia. The National Planning Commission. *Level of Achievement of the Millenium Development Goals: MDG Status Report, 2009 Final Report*. N.p.: n.p., n.d. Print.

Jaiteh, M.S. *Housing and Housing Characteristics, The Gambia*. Columbia University Earth Instiitute, <http://www.columbia.edu/~msj42/pdfs/Chapter3_Household_housing.pdf>

"The Gambia. Briefing: Economic Impact of Water and Sanitation." *Sanitation and Water For All*. N.p., Mar. 2012. Web. 30 Apr. 2013. <http://www.sanitationandwaterforall.org/files/The_Gambia_-_2012_Economic_Briefing_EN.pdf>.

"Water Sanitation and Hygiene." *UNICEF Gambia*. N.p., n.d. Web. 30 Apr. 2013. <http://www.unicef.org/gambia/activities_701.html>.

Appendix A: Additional Materials

Figure A1: Proposed GANTT chart as displayed in our PDR.

Solar Pasteurization System Gantt Chart	Dec.	Jan.	Feb.	Mar.	Apr.
Concept Design	x	x			
Detail Design		x x			
SolidWorks Design Test		x x			
Materials Purchased		x	x		
Disk Assembled			x x x x	x	
Shack Assembled			x	x x	
Test Temperature Achieved				x x	
Light Testing				x	
Test Pasteurization				x x	x
Pump Testing					x
Pump Integration and Test					x
Full Assembly and Testing					x x
Improvements / Final Report					x x

MATLAB Code A1: Code that was used to generate the theoretical model displayed in the main text.

```
clear;
format short e;

%% Constants
h_a = 8; %W/m^2*K
T_a = 25+273; %K
Ins = 1000; %W/m^2
D   = 22*0.0254; %m

k_pc = 0.205; %W/m*K
http://en.wikipedia.org/wiki/Polycarbonate
A_t  = (pi*(D)^2)/4; %m^2
H_t  = (1/4)*0.0254; %m
f_t  = 0.05;
E_gt = f_t*Ins*A_t; %W
```

```
    g     = 9.81; %m/s^2
    Beta  = 436.7*10^-6; %K^-1
    k_w   = 0.64; %W/m*K
    Tb    = 65+273; %K
    Tt    = 25+273; %K
    L     = 0.057085441; %m
    cw    = 4180; %J/kg*K
    rho   = 1/(1.011*10^(-3)); %kg/m^3
    V     = (pi*D^2/4)*L; %m^3
    Pr    = 3.77;
    alpha = k_w/(rho*cw); %m^2/s
    RaL   = (g*Beta*(Tb-Tt)*L^3)/(alpha^2*Pr);

h_free = (0.069*RaL^(1/3)*Pr^0.074*k_w)/L; %W/m^2*K
A_b    = (pi*(D)^2)/4; %m^2
f_b    = 0.7;
E_gb   = f_b*Ins*A_b; %W

k_pet  = 0.465; %W/m*K
http://www.engineeringtoolbox.com/thermal-conductivity-d_4
29.html
A_si   = pi*(22*0.0254)*L; %m^2
A_so   = pi*(D+H_t)*L; %m^2
H_s    = (1/8)*0.0254; %m
f_s    = 0.1;
E_gs   = f_s*Ins*(A_si+A_so)/2; %W

f_w    = 0.05;
E_gw   = f_w*Ins*A_t

%% Energy Balance

%T_to = (1/((k_pc*A_t)/H_t +
h_a*A_t))*(((k_pc*A_t)/H_t)*Tw + h_a*A_t*T_a + E_gt);

%T_bo = (1/(h_free+h_a*A_b))*(E_gb + h_free*T_to +
h_a*A_b*T_a);
```

```
%T_so = (1/((k_pet*A_si)/H_s +
h_a*A_so))*(((k_pet*A_si)/H_s)*Tw + h_a*A_so*T_a + E_gs);


syms Tw(t);

dsolve(rho*V*cw*diff(Tw) ==
h_free*((1/(h_free+h_a*A_b))*(E_gb +
h_free*(1/((k_pc*A_t)/H_t + h_a*A_t))*(((k_pc*A_t)/H_t)*Tw
+ h_a*A_t*T_a + E_gt) + h_a*A_b*T_a) - (1/((k_pc*A_t)/H_t
+ h_a*A_t))*(((k_pc*A_t)/H_t)*Tw + h_a*A_t*T_a + E_gt)) -
((k_pet*A_si)/H_s)*(Tw - (1/((k_pet*A_si)/H_s +
h_a*A_so))*(((k_pet*A_si)/H_s)*Tw + h_a*A_so*T_a + E_gs))
- ((k_pc*A_t)/H_t)*(Tw - (1/((k_pc*A_t)/H_t +
h_a*A_t))*(((k_pc*A_t)/H_t)*Tw + h_a*A_t*T_a + E_gt)) +
E_gw);

t=linspace(0, 25000, 100000);

figure(1)
plot(t/3600, 349.26-51.2617*exp(-0.0000675144*t), 'k-',
t/3600, 338, 'r-')
xlabel('Time (hours)')
ylabel('Temperature (K)')
axis([0 25000/3600 295 345])
print -deps temperatureplot
```

MATLAB Code A2: Code that was used to generate the plots displaying our experimental data.

```
clear;
format short e;

Hours    = linspace(0, 5.5, 12);

NoShield = [23.3, 23.3, 23.3, 37.7, 42.2, 46.5, ...
            51, 52, 53.5, 51.2, 45.8, 41.9];
```

```
WShield  = [23.1, 34.3, 37.3, 37.7, 42.1, 50.8, ...
            57.8, 58.9, 61.2, 56, 54.2, 49.2];

WInsul   = [20.9, 24.48, 27.3, 29.08, 30.58, 33.8, ...
            36.62, 39.24, 41.16, 42.26, 42.3, 41.5];

Hours13  = [0 2 2.5 3 3.75 4.5 6 7];
Apr13    = [26.4 36.56 39.62 42.86 44.7 46.34 46.74 44.5];

Hours14  = [0 3 4 6.5];
Apr14    = [27 46.2 48.98 50.72];

figure(1)
plot(Hours, WShield, 'r-', Hours, NoShield, 'k-',
'linewidth', 2)
xlabel('Time (h)', 'fontsize', 12)
ylabel('Temperature (\circC)', 'fontsize', 12)
title('Temperature Profiles of Device with and without
Wind Shielding', 'fontsize', 12)
legend('With Shield', 'No Shield', 0)
line([4 4],[20 61.2], 'LineStyle', ':', 'linewidth', 2);
text(4.1, 40, '2:30 PM', 'color', 'b', 'fontsize', 16);
text(0.5, 60, 'Avg Temp: 12 \circC', 'fontsize', 13)
text(0.5, 57, 'Avg Wind Speed: 10 km/h', 'fontsize', 13)

print -depsc WindshieldPlot

figure(2)
plot(Hours, WInsul, 'b-', 'linewidth', 2)
xlabel('Time (h)', 'fontsize', 12)
ylabel('Temperature (\circC)', 'fontsize', 12)
title('Temperature Profiles of Prototype with Insulation',
'fontsize', 12)
text(0.5, 42, 'Avg Temp: 12 \circC', 'fontsize', 13)
text(0.5,40, 'Avg Wind Speed: 10 km/h', 'fontsize', 13)

print -depsc InsulationPlot
```

PUGH MATRIX A1: COLLECTOR SHAPE

	Weight	Soda Bottle	Cylindrical Tube	Moving Fresnel Lense
Cheap	**.7**	1	0	-1
Locally Obtainable Materials	**.7**	1	1	-1
Easily Maintainable	**.5**	1	1	-1
High Volume	**.4**	-1	1	1
Light Diffusing	**.4**	1	0	1
Resilient	**.3**	0	1	0
Unobtrusive	**.3**	1	1	-1
Unweighted Sum		**4**	**5**	**-2**
Weighted Sum		**2.2**	**2.2**	**-1.4**

PUGH MATRIX A2: Absorbent Covering

	Weight	Black Paint	Asphalt/Tar	Selective Surface Vacuum Coating
High Absorptivity	**.7**	1	1	1
Locally Obtainable	**.7**	1	1	-1
Cheap	**.6**	1	0	-1
Easily Maintainable	**.5**	1	1	0
Efficient	**.4**	-1	-1	1
Resilient	**.3**	0	0	1
Unobtrusive	**.3**	1	1	1
Unweighted Sum		**4**	**3**	**2**
Weighted Sum		**2.4**	**1.8**	**0.4**

PUGH MATRIX A3: WATER REPLACEMENT MECHANISM

	Weight	Batch Replacement - Manually Pour	Gravity Feed System	Ram Pump	Motorized Pump
Easy to Use	**.7**	0	1	1	1
Cheap	**.7**	1	1	0	-1
Easily Maintainable	**.6**	1	1	0	-1
Resilient	**.5**	1	0	1	0
Efficient	**.4**	-1	1	1	0
Minimal Design Complexity	**.3**	1	-1	-1	0
Unweighted Sum		**3**	**3**	**2**	**-1**
Weighted Sum		**1.7**	**2.1**	**1.3**	**-0.6**