CAPSTONE DESIGN COURSE

MIM-U702

Technical Design Report

Solar Powered Water Distillation Device

Second-Quarter Report

Design Advisor: Prof. Taslim

Design Team
Stephen Coffrin, Eric Frasch
Mike Santorella, Mikio Yanagisawa

December 4, 2007

Department of Mechanical, Industrial and Manufacturing Engineering
College of Engineering, Northeastern University
Boston, MA 02115
Solar distillation is an often overlooked method for providing potable water to coastal, poverty stricken nations with abundant amounts of solar energy available. A single asymmetrical, automatic feed solar distiller was designed to take advantage of the solar energy available in these regions, such as Somalia, Africa. During this process, factors that will optimize single day productivity while minimizing costs have been explored. All aspects that will affect clean water output have been analyzed including: effect of surface area on productivity, material selection and analysis, overall thermal efficiency, and the potential effectiveness of an automatic water feed system. Factors that will directly impact overall build cost per unit have also been evaluated, such as material selection, size, and simplicity. The final design adds numerous features to increase the efficiency of a basic asymmetrical solar still.
# TABLE OF CONTENTS

1.0 Introduction .................................................................................................................. 5
   1.1 Problem Description and Significance ...................................................................... 5
      1.1.1 Target Country .................................................................................................. 6
   1.2 Project Statement ..................................................................................................... 7
2.0 Design Goals .................................................................................................................. 7
   2.1 Solar Power .............................................................................................................. 7
   2.2 Affordability .......................................................................................................... 8
   2.3 Output .................................................................................................................... 8
   2.4 Size ....................................................................................................................... 8
   2.5 Practicality ............................................................................................................. 8
3.0 Background Information and Research ........................................................................ 8
   3.1 Water Distillation .................................................................................................. 9
   3.2 Basic Concept of Solar Powered Water Distillation ................................................ 9
   3.3 Research of Periodicals ........................................................................................ 10
      3.3.1 The Effect of Water Depth .............................................................................. 10
      3.3.2 The Effect of Different Designs ...................................................................... 11
      3.3.3 Comparison between a Single-slope Still vs. a Pyramid-shaped Still Configuration 12
      3.3.4 Enhancing Single Solar Still Productivity ....................................................... 12
      3.3.5 Conclusion to Periodical Research ................................................................. 12
   3.4 Patent Research ..................................................................................................... 13
      3.4.1 Solar Collection System with Radiation Concentrated On Heat Absorber Vanes 13
      3.4.2 Solar Water Distillation System ...................................................................... 14
      3.4.3 High Output Solar Distillation System ............................................................ 14
      3.4.4 Method and Apparatus for Solar Distillation .................................................. 15
      3.4.5 Patent Search Conclusion ............................................................................. 16
   3.5 Market Search .......................................................................................................... 16
      3.5.1 The Watercone® ............................................................................................... 16
      3.5.2 The Rainmaker 550™ ..................................................................................... 17
      3.5.3 El Paso Solar Energy Association ................................................................. 18
      3.5.4 Market Search Conclusion ........................................................................... 19
4.0 Design .......................................................................................................................... 19
   4.1 Thermal Circuit Analysis ......................................................................................... 20
      4.1.1 Validation of Thermal Circuit through Prototypes ....................................... 22
      4.1.2 Description of Prototypes ............................................................................. 22
   4.2 Overall Design Outline .......................................................................................... 24
   4.3 Basin Design .......................................................................................................... 25
      4.3.1 Basin Features ................................................................................................. 25
   4.4 Input Design .......................................................................................................... 26
      4.4.1 Float Valve ..................................................................................................... 27
   4.5 Output Design ........................................................................................................ 27
      4.5.1 Collection Mechanism .................................................................................. 27
      4.5.2 Output Tank ................................................................................................. 28
   4.6 Design Overview .................................................................................................... 28
   4.7 Construction .......................................................................................................... 29
   4.8 Cost Analysis ......................................................................................................... 33
5.0 Future Work .................................................................................................................. 33
   5.1 Further Testing ..................................................................................................... 33
   5.2 Improving Manufacturability and Affordability .................................................... 34
   5.3 Marketing .............................................................................................................. 34

REFERENCES .................................................................................................................... 35

Appendix A: Spreadsheet program .................................................................................. 37
Appendix B: Material Costs & Costs of Materials Used

TABLE OF FIGURES

Figure 1: Clean Water Access around the World [2] ................................................................. 6
Figure 2: Somalia ............................................................................................................................... 7
Figure 3: Distillation Illustration ..................................................................................................... 9
Figure 4: Basic Solar Powered Water Distiller ................................................................................ 10
Figure 5: Asymmetrical Solar Still Design ..................................................................................... 11
Figure 6: Symmetrical Solar Still Design ....................................................................................... 11
Figure 7: Multiple Effect System with Fresnel Lenses (cross section) ........................................... 13
Figure 8: Complex Solar Distillation System .................................................................................. 14
Figure 9: Multiple Effect Wicking System ..................................................................................... 15
Figure 10: Single Basin Wicking System ....................................................................................... 15
Figure 11: The Watercone® ........................................................................................................... 17
Figure 12: The Rainmaker 550TM .................................................................................................. 18
Figure 13: EPSEA Solar Still ......................................................................................................... 19
Figure 14: Simple Thermal Circuit ................................................................................................. 20
Figure 15: 1st Prototype .................................................................................................................. 23
Figure 16: 2nd Prototype ................................................................................................................ 23
Figure 17: 2nd Prototype Testing Thermocouple Results ............................................................... 24
Figure 18: Overall Design ............................................................................................................... 25
Figure 19: Basin Tray ...................................................................................................................... 25
Figure 20: Float Valve ..................................................................................................................... 26
Figure 21: Input Tank ...................................................................................................................... 27
Figure 22: Collection Mechanism ................................................................................................. 28
Figure 23: Output Tank .................................................................................................................... 28
Figure 24: Design Overview .......................................................................................................... 29
Figure 25: Final prototype ............................................................................................................. 29
Figure 26: Basin construction ......................................................................................................... 30
Figure 27: Insulated walls .............................................................................................................. 30
Figure 28: Fiberglass insulation ..................................................................................................... 31
Figure 29: Back wall ....................................................................................................................... 31
Figure 30: Mirrored walls .............................................................................................................. 32
Figure 31: Levels ............................................................................................................................ 32
Figure 32: Adjustable feet ............................................................................................................. 33
1.0 Introduction
Easy access to clean, uncontaminated water is an integral part of daily life. Its impact on agriculture, industry, overall health, and well-being is impossible to ignore. The majority of water on Earth is contaminated with impurities and/or chemical substances. Therefore it cannot be used for agriculture, industry, and daily human consumption. The unavailability of healthy drinking water in impoverished regions is increasing at an alarming rate parallel to increasing populations throughout the world. Rather than use expensive non-renewable resources to meet this demand, solar energy can be harnessed to power a simple distiller. Solar distillation is an affordable and reliable source for potable water that is often ignored and underutilized. In areas with ample amounts of sunlight and access to sea water, a solar distiller can potentially provide a family or small community with sufficient water for daily consumption.

1.1 Problem Description and Significance
Many parts of the world do not have access to a suitable source of clean drinking water. Most of the water available in streams, lakes, rivers, sea, etc. carries parasites or diseases, or is simply not fit for consumption and therefore is a significant health hazard. Areas without access to clean water are also usually poverty stricken and do not have the infrastructure necessary to create and support large scale water purification plants. Thus, there is need for a small scale, affordable water purification system for individual families or villages.

Africa has the second largest population of people without access to clean drinking water. As illustrated in Figure 1, 288 million people in sub-Saharan Africa currently face this problem [1]. This population constitutes about 26.8% of the one billion people worldwide without easy access to clean water [1]. In some of these regions, if there is clean water available, it is not easily accessible and several miles must be traveled by foot to reach the source. This issue is so severe that on average a child dies every 15 seconds from diseases contracted from drinking contaminated water [1]. Africa also has a large amount of coastline and an abundance of solar radiation that can be harvested to power a water distillation device.
1.1.1 Target Country

A target country was chosen based on the GDP-per capita, solar energy rates, and coastal access to seawater for distilling and desalination. Solar energy rates in Africa were researched heavily and it was discovered that most countries in Africa receive anywhere from 5000 to 8000 Wh/m² of solar energy per day [3]. For comparison, Boston receives between 1200 and 6000 Wh/m² per day depending on the season. In the summer, Boston reaches about 6000 Wh/m² only on the hottest days. Throughout sub-Saharan Africa, minimal access to clean water is a very common problem making this an optimal area for the implementation of a low cost, easy to operate, high efficiency, solar powered water distiller.

For prototyping purposes, Somalia was chosen as a target country. The GDP per capita of Somalia is very low, 600 USD. Poor economic numbers such as these have been shown to be the case for most countries without widespread access to clean water in the sub-Saharan area of Africa [4]. About 65% of the population in Somalia does not have access to clean drinking water on a regular basis [4]. Somalia receives a large amount of solar radiation per day (5500 to 7000 Wh/m²) [3]. The country also has 3025 km of
coastline, which means there is an ample amount of solar energy and water available for use in the device [5]. Somalia not only has ample amounts of sea water to purify and solar energy for power, it constantly struggles to battle widespread diseases that are circulated through contaminated water.

\[\text{Figure 2: Somalia}\]

1.2 Project Statement
The goal of this project is to create a solar powered water distillation device that achieves maximum efficiency while minimizing manufacturing costs per unit. The input of this device would be salt water from coastal regions. The solar distiller should be able to provide a small family with two to four gallons of drinking water per day. The distiller will also allow for the user to maintain a constant supply of water, with easy cleaning and minimal user interaction.

2.0 Design Goals
Based on the project statement, several design goals have been developed in order for this device to be successful.

2.1 Solar Power
The abundance of solar energy available in Somalia is an untapped renewable resource that can be harnessed for the proposed device. Other sources of energy such as fossil fuels are expensive, limited, and
simply not available in many parts of Somalia. Somalia’s abundant solar radiation is a highly effective and completely renewable resource.

2.2 Affordability
It is unrealistic to expect the average Somali, who makes 50 USD a month, to buy a distilling device for anything more than 10 USD. Since it may not be possible to manufacture the device for this little, the device will need to be targeted towards aid organizations like the Red Cross and CARE (Cooperative for Assistance and Relief Everywhere). This device has the potential to make an enormous impact in the daily lives of people without access to a reliable source of safe drinking water. However, if the cost to manufacture the distiller is too high, organizations will be unable to purchase it.

2.3 Output
The device should be able to produce two to four gallons of clean drinking water per day. This would be enough water to hydrate a small family on a daily basis. A higher output may require electricity and/or heat exchangers, and would require a larger than practical evaporation surface. Aspects such as these would make the device expensive and impractical.

2.4 Size
The goal of the distiller is to minimize size while maximizing the output of clean drinking water. In addition, the device must be portable and moveable by a maximum of two people. The amount of solar energy available in a region, along with the desired output, will theoretically dictate the overall size of the device. However, the size of the device could be minimized by experimentally testing and optimizing specific design factors incorporated into the distiller.

2.5 Practicality
All of the contaminants contained in the feed water will remain in the distiller after the water has evaporated. Therefore the device must be easy to clean, since frequent cleaning will be a requirement for efficient operation. Also, the device should be easy to level when being installed to ensure uniform water depth. This will allow for a more efficient operation.

3.0 Background Information and Research
Solar distillers are often ignored and overlooked as a method of producing of clean water. Many superior techniques have been developed to maximize production of potable water; however these techniques are
more prevalent and practical in developed countries. For example, it is not practical to build a multi-
million dollar desalination plant in an underdeveloped region that cannot afford the cost.

The origins of the solar distiller can be traced back to 1551 when Arab alchemists used simple solar stills to
keep mine workers hydrated during the work day [6]. Designs similar to these ancient distillers still exist
today. However, adaptations to that simple design now incorporate changing factors, such as sun position,
geographical location, and weather conditions. A simple, single-basin design which incorporates the
previously mentioned design features proves to be reliable, cost effective, and efficient.

3.1 Water Distillation
The process of water distillation involves heating water to the point of vaporization, at which point the
water will undergo a phase change from liquid to vapor. The water vapor then condenses onto a cooler
surface where it can be collected. Any contaminants contained in the original feed water (such as salt, silt,
and heavy metals) will remain in the distiller basin. The collected water vapor is now free of all prior
contaminants and is fit for consumption. Refer to Figure 3 below.

![Distillation Illustration](image)

Figure 3: Distillation Illustration

3.2 Basic Concept of Solar Powered Water Distillation
A solar powered distillation device will contain three basic components: a basin in which the contaminated
water is contained, a surface above said feed water for the water vapor to condense onto (i.e. a glass pane),
and a catch basin for the distilled water to drain into.
During operation of the distiller, solar energy is collected by the feed water. When enough energy is absorbed by the water, the water undergoes a phase change. The water vapors then rises and comes into contact with the cooler transparent, inclined surface. Here the vapor once again goes through a phase change from vapor back to liquid. The water then condenses and runs off the transparent inclined surface into a collection bin. The distillation process rids the contaminated water of any impurities and most commonly found chemical contaminants within the environment. These contaminants are left behind in the basin. This process is illustrated in Figure 4 below.

![Figure 4: Basic Solar Powered Water Distiller](image)

### 3.3 Research of Periodicals

There are numerous periodicals and formal research papers on solar water distillation that were evaluated for useful information and ideas. Many ideas were obtained from these papers. In this section, useful information and features are outlined from each periodical.

#### 3.3.1 The Effect of Water Depth

In this periodical different water depths were used in the basin of a simple asymmetrical distiller. The amount of water output for each water level was measured daily over a time period of one year in New Delhi, India. The effect of increasing basin absorptivity was also tested during this span of time.

The results show that the daily water output is consistently greater for a shallower water depth. The shallowest water depth used was 2 cm, while the largest water depth used was 18 cm. Above a depth of 8 cm, it was discovered that output remains constant. The output for the 2 cm water depth was over 30% more than the water depth of 18 cm. However, the deeper water levels did yield a higher water temperature. This is mostly due to the higher heat capacity of a larger body of water. Higher basin absorptivity was also found to lead to a greater water output.
In conclusion, the majority of solar radiation is absorbed in the first 2 cm of water depth. Also, the basin absorptivity is a major factor in the design of a solar still. These two pieces of information are highly valuable for increasing water output. [7]

3.3.2 The Effect of Different Designs
In this periodical two different solar still designs are compared. The first design is an asymmetrical still with mirrors on the walls (Figure 5). The second design is a symmetrical still (Figure 6). The water output of the asymmetrical still was measured to be 30% higher than the symmetrical version. The asymmetrical design operated at a higher temperature. This is mostly due to the mirrors on the side and back walls. The mirrors reduced heat energy loss and reflected all incoming solar radiation towards the basin. Since the asymmetrical design has three insulated walls where the mirrors reside, there is less area for heat energy to escape. The symmetrical design has more area where heat loss occurs. In conclusion, the asymmetrical solar still with mirrors is a superior design with greater efficiency and higher overall water output. [6]
3.3.3 Comparison between a Single-slope Still vs. a Pyramid-shaped Still Configuration
In this paper, the single-slope still design received better efficiency and economical performance ratings than the more complex, pyramid-shaped still design. The researchers chose Aswan, Egypt, which has a latitude of 24°, for the location of their experiment. While both designs had equivalent basin areas, the pyramid-shaped still had a greater glass area, which caused more heat to be lost to the environment. The pyramid-shape resulted in 8% less solar energy to be received by the basin during the winter and 5% more solar energy to be received by the basin during the summer. However, because of the pyramid-shaped still had a greater glass area, the daily yield of the single-sloped still was 30% greater in the winter and 3% greater in the summer. Additionally, the estimated cost of water for the single-sloped still was about .03 $/L. In conclusion, the basic asymmetrical still design is more efficient and less expensive. [8]

3.3.4 Enhancing Single Solar Still Productivity
In this article, various enhancements are discussed that can increase overall clean water output, as well as other information that is useful for the design of a solar still. Once again the idea of using the smallest water depth possible is explored. As the water depth increases, the output of the still steadily declines. A small decrease from 3.5 cm to 2 cm increased output 26%. For areas with large amounts of solar radiation near the equator, it was found that an angle around 23° for the glass is optimal. This angle works well with the angle of the incoming solar radiation.

In the experiments conducted, it was also discovered that about 16% of the water output occurred at night, without solar radiation. This is due to the increased temperature difference between the water and glass cover, as well as the overall decrease of heat capacity. It was also found that a sprinkler (cooling film) applied to the outer layer of glass will lead to a substantial increase in clean water production. The sprinkler lowers the temperature of the glass and increases the temperature difference between the water and glass, thus increasing production. [9]

3.3.5 Conclusion to Periodical Research
A great deal of important information was discovered during research of periodicals:

- Water depth was found to be one of the main factors of clean water production. It is important to maintain a water depth of 2 cm or less.
- An asymmetrical design was found to be the most inexpensive and efficient type of solar still.
- The optimal angle of the glass for regions near the equator was found to be around 23°.
• The largest temperature difference possible between the glass and water will lead to increased water production.
• The greatest absorptivity possible for the basin will lead to the maximum water output.
• Minimizing heat loss is a key to increased production.

3.4 Patent Research
A patent search revealed numerous designs and ideas related to the use of solar power to distill water. Many of the patents which emerged during the search are currently not being manufactured, and are simply outlined ideas and concepts. Other patents were too complex in geometry or operation, and were impractical for a cost effective device.

3.4.1 Solar Collection System with Radiation Concentrated On Heat Absorber Vanes
This patent contained a few key ideas such as the use of Fresnel lenses to increase the efficiency and overall production of the distiller by focusing the incoming radiation onto a trough of water. The second idea that this patent introduced was the use of individual water troughs instead of a large water basin in the distiller. At the base of the troughs were tightly spaced vanes that utilize the capillary action of water to increase the surface area of the water being exposed to the incoming solar radiation, further increasing overall efficiency. By using troughs, the distiller is able to maximize available surface area and minimize water volume in the distiller. As shown in Figure 7 below, each trough has a Fresnel lens focusing energy onto the water. When applying the ideas outlined in this patent to the design goals listed in Section 2 of this paper, it becomes apparent that incorporating the Fresnel lenses and the vanes in each trough would defeat our requirements of a low cost and practical device. [10]

Figure 7: Multiple Effect System with Fresnel Lenses (cross section)
3.4.2 Solar Water Distillation System
One elaborate patent available outlines the utilization of electrical power generation to aid in increasing the fresh water output. Through the use of heat exchangers and a complicated water plumbing system (refer to Figure 8), the phase changes from water to water vapor can be completed and maintained at a constant rate. Although this patent outlines a design that increases the overall water output of the system, the construction of heat exchangers, complicated plumbing, and electrical power generation lead to a device that is simply too expensive and impractical to be utilized in the areas that would require such a device. [11]

![Heat Exchanger][1]

Figure 8: Complex Solar Distillation System

3.4.3 High Output Solar Distillation System
This patent describes a useful multiple effect system. The term “multiple effect” refers to a system designed in such a way that evaporated water from one surface condenses on the bottom of another surface and subsequently transfers thermal energy to the second surface which also contains evaporating water. The design uses an inclined wicking system in an enclosed area, similar to a basic distiller, to supply a constant feed of water through the still. The saturated wick allows for some of the feed water to be vaporized for condensate and the rest of the feed water run out of the distiller as hot water. Figure 9 shows the multiple wicks absorbing solar radiation. The design is simple, cost effective, but less efficient as it does not convert all of the feed water to distilled water. [12]
3.4.4 Method and Apparatus for Solar Distillation
This device uses a more traditional single basin design, but again uses a water wicking system. The wick system maintains a constant feed rate that can be predetermined based on the wick size. It also introduces the idea of preheating the feed water to increase efficiency, and creating a vapor circulation system inside the distiller to further increase efficiency. However, as with all wicking systems, the ability to clean the still effectively is compromised because each of the wicks would have to be cleaned with water at the end of each day of use. Refer to Figure 10. [13]
3.4.5 Patent Search Conclusion
Patents of many different solar distillers exist, from simple one step single basin designs, to multi-step heat exchangers. However most of the patents outlined contained aspects that made the design unfit to meet the design goals of this project. Many beneficial ideas were outlined such as utilizing a water feed system to eliminate any required user interaction during the course of the day. Also, the idea of limiting the total volume of water in the still at any single time should help increase the efficiency of the still by constantly heating a small volume of water as opposed to having to heat a larger volume.

The small market for a commercial solar still appears to be filled by devices that are built on an “as-needed” basis instead of being purchased. Many patents incorporate new ideas, however no patent seems to address the need for an efficient, easy to maintain, simple, cost effective design. Overall, the potential for an effective solar distiller is something that many neglect to realize or utilize effectively.

3.5 Market Search
A product search for a solar powered water distillation device produced a small handful of actual products. During this research it has become evident that the market for such a device is not a strong one. When the need arises for a solar powered water distillation device, instead of buying a ready made product, an improvised distiller is usually constructed on site. This is probably because the typical area in need of a water distillation device is a low income area and the local population simply cannot afford to spend upwards of $400 on a device. [14]

3.5.1 The Watercone®
The Watercone® is possibly the simplest design for a solar water distiller. It is a plastic molded hollow cone with a spout at the top and a lip on the inside of the cone at the bottom to collect the distillate as it runs down the inside of the cone (see Figure 11).
The Watercone® is also the most versatile device on the market. It is portable, lightweight, has no moving parts, and easy to clean and maintain. However the Watercone® does have a few shortcomings. One of which is its low output of fresh water (less than half a gallon per day). This amount would not prove adequate for a small family. The other major drawback of the Watercone® is that is it constructed of plastic instead of glass. The cohesive properties of water cause it to bead up much more regularly on plastic than it would on glass. This leads to an effect demonstrated in Figure 11. Instead of the water running off the plastic surface, it simply beads up and blocks the incoming solar radiation from reaching the water in the bottom of the still. Also, the Watercone® is not currently in mass production, demonstrating that the market for such a device is weak. [15]

3.5.2 The Rainmaker 550™
The Rainmaker 550™ (Figure 12) is the only product currently on the market available for purchase. The product features a tempered glass condensing surface, weighs about 70 pounds, and claims efficiencies of about 0.8 gallons of water output per kWhr/m².
The key disadvantage to The Rainmaker 550™ is its high cost of $480. This amount is simply not affordable to be able to market this device to the families and communities that would benefit most from the device. [16]

3.5.3 El Paso Solar Energy Association
In 1995, the El Paso Solar Energy Association (EPSEA) in conjunction with the State of Texas and the State Energy Conservation Office constructed solar distillation devices that were to be targeted to the low income communities that reside along the Texas/Mexico border. These communities typically have limited access to fresh drinking water and are not able to afford a solar distillation device to provide the needed water. Through these organizations, the cost of each solar still was reduced to about $50 for each family who was willing to buy one. The estimated cost of these solar distillers was between $650 for an 18 ft² distiller up to $850 for a 24 ft² distiller (see Figure 13).
Typical fresh water output is claimed to be around 3 gallons per day in the summer months. Advantages of this device are the high fresh water outputs claimed. Drawbacks of this solar water distiller include its high cost, large overall size and weight, and the fact that the distiller is not being sold on the market. [14]

3.5.4 Market Search Conclusion
The market for a solar powered water distiller is not strong enough to support a variety of products. Currently, when the need for a solar water distiller arises, it is met by simply constructing a still from readily available materials. The few products and plans currently available are too expensive to be implemented in areas where the distillers are needed the most. In order for a device to be successful in this market, the most practical method would be to make the device affordable to an aid organization, such as the Red Cross, which would then be able to supply the stills to low income families and communities.

4.0 Design
Many different designs and theories were evaluated. After this preliminary research, it was concluded that a simple asymmetrical distiller, similar to that shown in Figure 4, is the most efficient and inexpensive solar distiller design. In order to improve the overall design and to remain innovative, numerous attributes and features from other designs and periodicals were also added. In this section, the final design will be described, as well as the specific features that make this design unique and efficient.
4.1 Thermal Circuit Analysis
The first step in the design process was to develop and analyze the thermal circuit for a simple asymmetrical solar distiller. The simplified thermal circuit that was developed is shown in Figure 14. This thermal circuit models the convection, conduction, and radiation of energy throughout the device, as well as the evaporation and condensation processes. From this thermal circuit, an energy balance at three nodes and a spreadsheet program was developed. The energy balance is shown below along with pertinent definitions. See Appendix A for spreadsheet program.

![Figure 14: Simple Thermal Circuit](image-url)

Figure 14: Simple Thermal Circuit
Definitions:

- **T<sub>water</sub>** – Temperature of the water in the basin
- **T<sub>glass</sub>** – Temperature of the glass surface above the basin. As seen in Figure 4, this is the surface that water will condense onto.
- **T<sub>air</sub>** – Temperature of the air between the water and glass.
- **T<sub>∞</sub>** - Ambient temperature around the solar still
- **Q<sub>solar</sub>** – Solar energy entering the system
- **Q<sub>evap</sub>** – Energy required to evaporate a given amount of water
- **Q<sub>cond</sub>** – Energy required to condense a given amount of water
- **A** – Area of the basin
- **A<sub>g</sub>** – Area of the glass
- **k<sub>ins</sub>** – Thermal conductivity of insulation
- **l<sub>ins</sub>** – Length of insulation
- **h<sub>∞</sub>** - heat transfer coefficient for convection from T<sub>g</sub> to T<sub>∞</sub>
- **h<sub>g</sub>** – heat transfer coefficient for convection from T<sub>air</sub> to T<sub>g</sub>
- **h<sub>w</sub>** – heat transfer coefficient for convection from T<sub>w</sub> to T<sub>air</sub>
- **σ** – Stefan-Boltzmann Constant (5.670 x 10<sup>-8</sup> W/m<sup>2</sup> * K<sup>4</sup>)
- **ε** – emissivity of glass

Assumptions:

- Temperature difference between one side of the glass to the other is negligible
- Temperature difference between T<sub>w</sub> and the basin is negligible
- There is no heat loss through the side walls
- T<sub>w</sub> is uniform
- No vapor leakage
- Q<sub>evap</sub> = Q<sub>cond</sub>

Eq 1: at node T<sub>w</sub>

\[
Q_{solar} = Q_{evap} + k_{ins} A \frac{(T_w - T_\infty)}{l_{ins}} + h_w A (T_w - T_{air}) + A \varepsilon \sigma (T_w^4 - T_g^4)
\]

Eq 2: at node T<sub>air</sub>

\[
h_w A (T_w - T_{air}) = h_g A (T_{air} - T_g)
\]

Eq 3: at node T<sub>g</sub>

\[
A_g \varepsilon \sigma (T_g^4 - T_\infty^4) + A_g (T_\infty - T_g) = Q_{cond} + h_g A_g (T_{air} - T_g) + A \varepsilon \sigma (T_w^4 - T_g^4)
\]
Heat transfer coefficients for natural and forced convection were determined using necessary correlations. From these energy balances, a spreadsheet program was developed that allows for an iterative process to determine required area for a specified water output. Variable inputs include area of still, area of glass, outside temperature of test location, insulation length and thermal conductivity, known daily sum of solar radiation (based on location), average wind velocity of location, number of daylight hours, and desired water output, as well as correlations for natural and forced convection heat transfer coefficients on involved surfaces.

Based on data from a specific location, in this case Somalia, the area required to distill 2 gallons was determined. With approximately 6300 Whr/m² of solar energy available in a single day in Somalia, the solar still was determined to be about 1 m² to output 2 gallons of clean drinking water. These inputs also gave a glass temperature of 334 K and a water temperature of 354 K. This temperature difference indicates that water will condense onto the glass.

4.1.1 Validation of Thermal Circuit through Prototypes
The thermal circuit was validated by building and testing two small-scale prototypes, and recording nodal temperature values. Thermocouples were attached to the sections of the prototypes that represent nodes in the thermal circuit, and temperature values were recorded for $T_\infty$, $T_{glass}$, $T_{air}$, and $T_{water}$ using a data logger. The volume of input water, the area of the basin, the area of the glass, the insulation thermal resistance, the thermal radiation value, and the wind speed were also known. When these variables, along with the final water output volume, were inserted in the thermal circuit spreadsheet, the temperature outputs for the nodes approximately matched the recorded temperature values, thus validating the thermal circuit.

4.1.2 Description of Prototypes
As mentioned above, in order to validate the thermal circuit, two small-scale prototypes were built. The first prototype was built for under $10 out of on-hand materials (see Figure 15).
When the thermocouple temperature data was analyzed, it was obvious that the prototype was not robust enough and lacked appropriate insulation. The temperature $T_{water}$ was lower than $T_{air}$, which did not agree with the thermal circuit, so another more robust prototype was constructed with a better insulated basin (see Figure 16).

When the second prototype was tested, $T_{water}$ was greater than $T_{air}$ with $T_{water} > T_{air} > T_{glass} > T_{\infty}$; this is the appropriate order of magnitude. The data from the thermocouples of this test are in Figure 17. This temperature difference between the water and glass validates the thermal circuit spreadsheet program. It also insures that the water vapor will condense onto the cooler glass surface. The output of the second prototype yielded 200 mL of water based on an input of 2 liters. The low output is a result of the minimal
amount of solar radiation available, the steep angle of the sun in the autumn sky, and the near freezing air temperatures. The test was conducted in October in the Boston area, with only about 1800 Whr/m² of solar radiation total throughout the day. This is a fraction of the energy available in Somalia.

![2nd Prototype Testing Thermocouple Results](image)

**Figure 17: 2nd Prototype Testing Thermocouple Results**

### 4.2 Overall Design Outline

The final still prototype is a singular, easy to maintain unit (see Figure 18 below), and is made of relatively inexpensive materials. It is easy to use and easy to clean, and can provide enough water for a small family. The device incorporates several innovative features including a modular design and a water-depth regulating system. The device is superior to competing devices because it can provide enough water to hydrate a family, while still exhibiting the lowest output to cost ratio.
4.3 Basin Design
The basin is the area of the still where solar radiation is being absorbed in order to evaporate water. The first step in designing the basin is to determine the required size based on a desired output. In this case, the device needs to produce between 2 and 4 gallons of distilled water per day. In order to roughly calculate the basin size, a simplified thermal circuit was developed (refer to Section 4.1).

4.3.1. Basin Features
With a firm estimate of the required size, specific features were added in order to increase efficiency and output. The basin itself will be a molded thermoset tray with slots going through the tray at equal intervals as seen in Figure 19. This allows for minimum water volume with maximum surface area. Several smaller bodies of water will heat up at a much faster rate than one larger body of water.

Based on previous research, the optimal water depth was determined to be a maximum of 2 cm [7]. The majority of the solar radiation will be absorbed within the first 2 cm of water. Water below the first 2 cm threshold will not receive significant radiation and will only slow evaporation. This water level in the
slotted tray is regulated by a float valve. Figure 20 shows the float valve and slotted tray. This valve is set so that it maintains a 1.5 cm water depth consistently throughout a day.

After one day of use, there will be a residue of salt left in the basin tray. Due to the material properties of the basin, the residue from the salt water can easily be wiped away with a damp cloth or sponge.

4.4 Input Design
The water feed system includes a fill-tank that both holds sea water and feeds it into the distiller. The back wall is attached to the device by hinges and is sealed shut by latches. To fill the basin, the back wall is opened and the basin is half-filled with sea water. The 2 gallon input tank, shown in Figure 21, is then filled with sea water and a float valve fills the basin to a depth of 1.5 cm. As mentioned in Section 4.3.1, once evaporation starts to take place, the float valve maintains a water depth of 1.5 cm. The input tank is attached to the back wall above the basin water level; this will allow gravity to provide flow throughout an entire day. A red plastic gasoline container has been modified to become the input tank. The color red tends to have particularly high emissivity values, normally within the range of $0.84 \leq \epsilon \leq 0.95$. When left in the hot Somali sun, the feed-water will warm to $T_o$ (the outside temperature). A black screen-cover keeps debris from entering tank.
4.4.1 Float Valve
As previously mentioned, the fill tank is piped to a float valve. The float valve assembly is an off-the-shelf ½” stainless valve connected to a stainless steel rod and a plastic float, and allows the distiller to control the depth of the feed-water.

4.5 Output Design
As already mentioned, the glass roof is set at a 22° angle. This angle has been found in the various literatures to be steep enough to allow condensate to run down to the collection assembly. When the two prototypes were tested, the effectiveness of the 22° angle was verified. In addition, this shallow angle minimizes deflection of incoming radiation based upon the height of the sun in the Somali sky. When the design was tested in Boston, the shallow angle deflected a percentage of the solar radiation because in autumn, the sun traverses the sky at a steeper angle.

4.5.1 Collection Mechanism
In order to collect the distillate, the angled glass is positioned so that the distillate drops directly into the angled Lexan collection mechanism seen below in Figure 22. Distillate condensates on the bottom surface of the glass, runs down to the bottom edge of the glass, drops into the collection mechanism, and flows into the output tank through a vinyl hose.
4.5.2 Output Tank
The output tank receives and holds distillate, and has a capacity of 5 gallons. The output tank is removable and hangs on a hook attached to the bottom of the frame, which will keep the distillate from absorbing solar radiation (see Figure 23). In order to construct the output tank, a 5 gallon gasoline tank was painted black and the nozzle was replaced with a screen with a hole for the vinyl output hose.

4.6 Design Overview
Solar energy enters the device through the inclined glass surface. Mirrors reflect all radiation towards the basin. Highly insulated basin minimizes heat loss. Several small bodies of water heat up and evaporate from basin and then condense onto cooler glass surface. Float valve keeps water in basin at a constant 1.5 cm throughout the day. Clean water runs down glass surface and feeds into collection mechanism, which then feeds into removable output tank. Salt residue is wiped away at the end of the day. See Figure 24.
4.7 Construction
The final prototype is built out of framed 2x4’s (see Figure 25). The basin rests within the framed 2x4’s. Due to cost restraints, the basin was not constructed out of a molded thermoset. Instead, the basin was built out of a salvaged aluminum basin. This basin was then built up with two 1.5” thick 25”x25” squares of insulation (R value of 10). .75”x.5”x22” pieces of wood were then glued to the insulation at 1.5” intervals to create slots (see Figure 26). Creases were sealed with silicone aquarium sealant and then the basin was painted with seven coats of black latex paint to fully waterproof the basin.

Figure 25: Final prototype
The side walls were constructed by gluing 5/16” sheets of poplar plywood to 1.5” thick pieces of insulating foam, to ½” pieces of plywood, and a bottom wall was constructed out of ½” plywood (see Figure 27).

Fiberglass insulation with an R value of 13 was then fit between the bottom and the sides of basin, and the bottom and side walls (see Figure 28 below).
As mentioned in Section 4.4, the back wall is attached to the device by hinges and latches (see Figure 29).

The door is constructed in the same manner as the side walls. The inside walls are waterproofed with black ABS sheets 4 mils thick, and mirrors are glued on top of the black ABS. As already mentioned in Section 3.3.2, side-wall mirrors help increase overall still efficiency by reflecting ambient solar energy back into the still, rather than absorbing that energy into the side walls (see Figure 30 below).
Figure 30: Mirrored walls

The still stands on 2x4 legs attached to adjustable feet, and levels are permanently attached to the front and right sides of the outside walls. These two combined features are useful for leveling the basin water (see Figures 31 & 32).

Figure 31: Levels
4.8 Cost Analysis
The total cost of all material purchased for the final prototype was $528.39. However, the pro-rated cost of the materials that were actually used to build the prototype came to a total of $379.37. See Appendix B for cost tables. This cost may still be too high for a low income area such as Somalia. Therefore, as stated earlier, the final device will be marketed towards aid organizations. The cost per unit will decrease substantially for mass production. See section 5.2.

5.0 Future Work
A design prototype was developed and constructed, however there is still much to accomplish. More time is needed to finalize this design and fully cover the original objective of this project. In the future, the final design prototype must be subject to further testing, improved to increase manufacturability, and marketed to the appropriate organizations.

5.1 Further Testing
The design prototype constructed was not fully tested for a number of reasons. The first being the limited amount of solar radiation available. It is currently December in Boston, MA, USA. There is only a minimal amount of energy available, around 1800 Whr/m² per day. This is a fraction of the solar energy available throughout the year in Somalia, where 6000+ Whr/m² is the daily average. The prototype will be fully tested in the upcoming spring and summer seasons when more solar radiation will be available.

There is much confidence in the ability of the prototype to meet the design goal of 2 to 4 gallons of water as a daily output. This confidence is due to the testing of smaller prototypes, development of a working thermal circuit, and knowledge obtained from various periodicals. The prototype is fully insulated and should have a large temperature difference between the glass cover and water in the basin. Along with a
regulated water height of 1.5 cm, and the other features of the prototype, it is highly probable that the device will have a higher output than the original design goal. All documented data and evidence suggests that this will be the case.

5.2 Improving Manufacturability and Affordability

One of the original goals of this project was to create a device that is highly affordable. Consequently, this means the device must also be easy to manufacture. The current method of construction seems to be inefficient for large scale production of the final device with a unit price of $379.77. There are several areas where the manufacturability and affordability of the device can be improved.

The basin used for the prototype was a discarded piece of aluminum that was salvaged from a previous project. This piece is estimated to be worth approximately $175.00. It is impractical to use a piece that is so expensive. Therefore the basin for the final design will be a thermoset plastic. This will greatly reduce the cost, and allow for the entire basin to be molded as one unit, including the dividers between slots (see Section 4.3.1).

The input and output containers used for the prototype were purchased gasoline containers that were cut down. The input and output containers for the final design should also be molded and produced on a larger scale. This will greatly reduce time and cost.

The rest of the cost reduction would be to buy all materials used in bulk amounts. This will lead to the lowest unit cost possible. For example, bought as one unit, the float valve cost $40.00. This price would greatly decline for a larger volume purchase. It is estimated that the cost of the final device manufactured on a large scale will be approximately $90.00 or about 25% of the prototype cost.

5.3 Marketing

As stated earlier, the GDP per capita of most regions without access to clean water is very low. In the target country Somalia, the GDP per capita is only 600 USD. This suggests that final device may not be affordable for the average family in Somalia. Therefore the device will have to be marketed towards the various aid organizations that work throughout Africa.

The estimated cost of the device manufactured on a large scale is around $90.00. Each family would require one or two of these devices depending on the number of people. This $90.00 would be a good investment for an aid organization for multiple reasons. The device will pay for itself over time. Rather than import water from other locations, the device will be a one time investment that will cover the cost of importing water over time, and continue to be productive well after the investment is covered.
REFERENCES


http://www.unicef.org/somalia/wes.html


http://practicalaction.org/docs/technical_information_service/solar_distillation.pdf

http://www.thefarm.org/charities/i4at/surv/sstill.htm

http://www3.telus.net/farallon/

http://www.worldbook.com/wb/Students?content_spotlight/climates/about_climates
Appendix A: Spreadsheet program
Appendix B: Material Costs & Costs of Materials Used

In this appendix, the first table lists the cost of all the material purchased for the final prototype. The second table has the pro-rated cost of the materials that were actually used.

<table>
<thead>
<tr>
<th>Table 1: Material Costs (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
</tr>
<tr>
<td>2&quot;x 4&quot;x 96&quot; Lumber</td>
</tr>
<tr>
<td>2' x 4' Poplar Plywood</td>
</tr>
<tr>
<td>6 Mil Poly Sheeting</td>
</tr>
<tr>
<td>Adhesive Type 1</td>
</tr>
<tr>
<td>Adhesive Type 2</td>
</tr>
<tr>
<td>Stainless Steel Screws</td>
</tr>
<tr>
<td>4' x 8' x 7/16&quot; OSB</td>
</tr>
<tr>
<td>4' x 8' x 2&quot; Insulating Foam Sheet</td>
</tr>
<tr>
<td>4' x 8' x 1&quot; Insulating Foam Sheet</td>
</tr>
<tr>
<td>6 Pack 12&quot; x 12&quot; Mirrored Tiles</td>
</tr>
<tr>
<td>Door Handle</td>
</tr>
<tr>
<td>Tie Plates</td>
</tr>
<tr>
<td>Hinge</td>
</tr>
<tr>
<td>Pack of Wood Screws</td>
</tr>
<tr>
<td>2 Door Catches</td>
</tr>
<tr>
<td>Sealant</td>
</tr>
<tr>
<td>2 pack of Line Levels</td>
</tr>
<tr>
<td>Pack of Cable Ties</td>
</tr>
<tr>
<td>30&quot; x 36&quot; x 1/8&quot; Glass Panel</td>
</tr>
<tr>
<td>2 Gallon Gasoline Can</td>
</tr>
<tr>
<td>5 Gallon Gasoline Can</td>
</tr>
<tr>
<td>Rafter Hangers</td>
</tr>
<tr>
<td>24&quot; x 36&quot; x 0.093&quot; Acrylic Sheet</td>
</tr>
<tr>
<td>Hollow Wall Anchors</td>
</tr>
<tr>
<td>Washers</td>
</tr>
<tr>
<td>10' Roll of Weather Stripping</td>
</tr>
<tr>
<td>Roll of Fiberglass Insulation</td>
</tr>
<tr>
<td>Float Valve</td>
</tr>
</tbody>
</table>

**Miscellaneous Costs**

<table>
<thead>
<tr>
<th>Item</th>
<th>Qty</th>
<th>Price</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screws, Tape, Paint, Brackets</td>
<td></td>
<td></td>
<td>25.00</td>
</tr>
</tbody>
</table>

**Anticipated Costs**

<table>
<thead>
<tr>
<th>Item</th>
<th>Qty</th>
<th>Price</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Basin</td>
<td>1</td>
<td>175</td>
<td>175.00</td>
</tr>
<tr>
<td>5' Silicone Tubing</td>
<td>1</td>
<td>3.1</td>
<td>3.10</td>
</tr>
<tr>
<td>Adjustable Legs</td>
<td>4</td>
<td>2.5</td>
<td>10.00</td>
</tr>
</tbody>
</table>

**Total** $528.39
Table 2: Cost of Material Used (USD)

<table>
<thead>
<tr>
<th>Item</th>
<th>Qty</th>
<th>Actual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>2&quot;x 4&quot;x 96&quot; Lumber</td>
<td>293&quot;</td>
<td>6.41</td>
</tr>
<tr>
<td>2' x 4' Poplar Plywood</td>
<td>1950 sq in.</td>
<td>10.63</td>
</tr>
<tr>
<td>6 Mil Poly Sheeting</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Adhesive Type 1</td>
<td>All</td>
<td>7.96</td>
</tr>
<tr>
<td>Adhesive Type 2</td>
<td>All</td>
<td>8.94</td>
</tr>
<tr>
<td>Float Valve</td>
<td>1</td>
<td>40.00</td>
</tr>
<tr>
<td>4' x 8' x 7/16&quot; OSB</td>
<td>1401 sq in.</td>
<td>15.66</td>
</tr>
<tr>
<td>2&quot; Insulating Foam Sheet</td>
<td>743 sq in.</td>
<td>17.34</td>
</tr>
<tr>
<td>1&quot; Insulating Foam Sheet</td>
<td>1817 sq in.</td>
<td>23.94</td>
</tr>
<tr>
<td>6 Pack 12&quot; x 12&quot; Mirrored Tiles</td>
<td>602 sq in.</td>
<td>6.95</td>
</tr>
<tr>
<td>30&quot; x 36&quot; x 1/8&quot; Glass Panel</td>
<td>All</td>
<td>12.99</td>
</tr>
<tr>
<td>24&quot; x 36&quot; x 0.093&quot; Acrylic Sheet</td>
<td>159 sq in.</td>
<td>2.50</td>
</tr>
<tr>
<td>Roll of Fiberglass Insulation</td>
<td>3 ft</td>
<td>1.45</td>
</tr>
</tbody>
</table>

Miscellaneous Costs (USD)

<table>
<thead>
<tr>
<th>Item</th>
<th>Actual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screws, handles, containers, tape, sealant, latches, paint/brushes, levels, cable ties, hardware, etc</td>
<td>50.00</td>
</tr>
<tr>
<td>Aluminum Basin (Free)</td>
<td>175.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$379.77</strong></td>
</tr>
</tbody>
</table>