NORTHERN
ARIZONA
UNIVERSITY

TASK 2-DEVELOPMENT OF AN IMPROVED SOLAR DISTILLATION STILL

(WERC COMPETITION)

NORTHERN ARIZONA UNIVERSITY DESIGN TEAM

Dr. Wilbert Odem (Advisor)

Banning Burt,

Yiguo Chen,

Chaz Enbody,

Benjamin Shields,

Yang Yang

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REPORT FOR

DEVELOPMENT OF AN IMPROVED SOLAR DISTILLATION STILL

Prepared for:

New Mexico State University
Institute for Energy & the Environment
MSC WERC
PO BOX: 30001
Las Cruces, NM 88003-8001
Attn: Rosanne Thompson

Submitted by:

Northern Arizona University
Solar Distillation Still Design Team
2112 S Huffer Ln
Flagstaff, AZ 86001

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EXECUTIVE SUMMARY

By

Banning Burt, Yiguo Chen, Chaz Enbody, Benjamin Shields, Yang Yang

Introduction

In many areas around the world, there is a shortage of clean drinking water. Poorer communities have drinking water high in chemical and bacterial content, and many of these small communities also have a lack of technology with poor access to electricity. Therefore, solar distillation stills are an excellent solution to purifying water sources in order to provide clean drinking water to these communities.

The purpose of this report is to create an improved solar distillation still that is low cost with a high production rate. The steps taken in order to complete these requirements include: research, design process, performance documentation based on the efficiency, cost and maintenance requirements and a business plan.

In order to understand the performances of distillation stills, there are several stills that have been made to document the energy input, output of distilled water, efficiency and purified water quality. The final design goal meets the Waste-management Education and Research Consortium (WERC) competition elevation criteria.

Background

Solar water stills have been used for thousands of years. The original use was to remove salt from salt water, but over time, it was used to purify contaminated water and make it potable. The first documented solar stills were in the sixteenth century, with the first large-scale solar still built by a mining community in Chile in 1872. Inflatable plastic solar stills were commonly used by the US Navy during World War II for drinking water purposes.[2] Developing countries are interested in solar distillation treatment process because of their need for clean water. The water being analyzed in this competition is brackish water with a variety of dissolved chemicals and minerals. The objective for the final design is to reduce the amount of contaminants in the water with the most efficient and cost effective design. The brackish water contains a multitude of contaminants, which are outlined in the following table:

Table 1-Brackish Water Conditions According to the WERC Competition [1]

Component	Value
Conductivity	6100 µS/cm
Sulfate	3300 mg/L
Chloride	550 mg/L
Hardness (as CaCO3)	3000 mg/L
Sodium	700 mg/L
Calcium	600 mg/L
Magnesium	375 mg/L
Silica	25 mg/L
Strontium	10 mg/L

The still is going to be designed to scale, and will be implemented in Flagstaff, AZ. Flagstaff's geological location will be a factor in the overall design. The materials being used will depend upon what is available in the City of Flagstaff. Overall, the unit producing the largest amount of distilled water for the lowest price possible will be the final design.

Proposed Solution

The final design will be a parabolic trough still, which is named by its shape and is the combination of a basin still and a concentrating collector still. The parabolic trough is a creative design, which has not been used commercially. The research results show: the concentrating collector still has the highest efficiency and is easy to construct, and the basin still has the highest safety and lowest cost. As a combination, the parabolic trough is the best alternative design. The parabolic trough design considers energy consumption, overall efficiency, material selection, cost, legal and regulatory issues, and health standards in selecting the best alternative recommended by WERC. Additionally, the proposed solution meets the WERC's design judging criteria.

PROJECT STATEMENT

Introduction

The purpose of this project is to develop a new improved version of a solar distillation still and document the performance based on the efficiency of purifying brackish groundwater without the use of electricity. Through the use of solar distillation, heat from the sun can be used to evaporate potable water from the brackish water. The goal of this project according to the WERC Competition is to design a still with the highest possible water production per unit cost of the process equipment. [1]

Key Factors

The key factors for success concerning the improvement of the solar distillation still are listed below:

Materials - Considerations for system performance, as well as material availability and durability at the selected location are essential for project success.

Unit Construction and Maintenance - Ease of both unit set up and maintenance play an important role in project success.

Production Rate - The highest production rate of potable water that can be obtained from the unit will impact the size of population that can feasibly be supported from this project.

Cost – Water production as well as construction and maintenance are included in the overall cost. Keeping the overall cost as low as possible is a key factor for the success of the project.

Design Challenges

There are several potential challenges for the creation of a solar distillation still. These challenges are listed below:

Cost - Providing a low cost product at a high efficiency will allow the final design to be easily replicated and maintained.

Electricity - Without an outside source of electricity, other means will be utilized to heat and pump the water throughout the system.

Location’s water - The water presented at the competition may be different than the water presented at the test site.

Efficiency - Theoretical water production efficiency may differ from actual efficiency of the still, resulting in lower production of water.

Weather - Due to inconsistent weather conditions, it will be difficult to have ideal heating conditions for distilling the water.

SELECTION OF OPTIMAL DESIGN

Flagstaff is located in Northern Arizona and will be the location in which the thermal distillation unit will be tested. Flagstaff's weather conditions are dry and sunny most days. According to the National Oceanic and Atmospheric Administration, the average sky cover is 0.2, which means there will be high solar radiation received.[3] As shown in figures below, there are five design alternatives: a concentrating collector still, multiple tray tilted still, tilted wick solar still and a basin still; all in which are existing commercial stills commonly available today.[4]

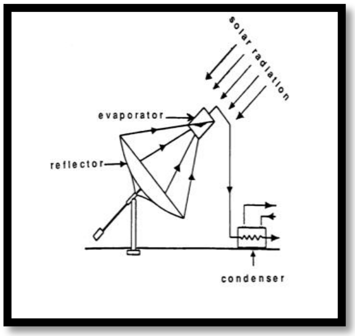


Figure 1, Concentrating Still

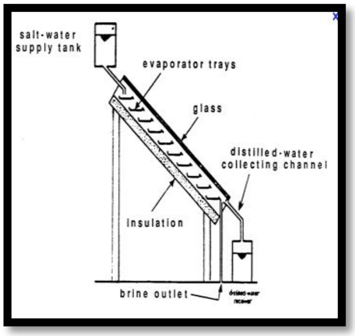


Figure 2, Multiple Tray Still

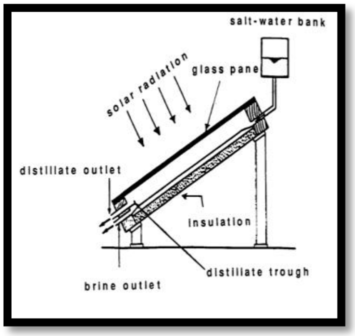


Figure 3, Tilted Wick Still

The concentration still uses satellite dish shaped mirrors to focus sunlight on a particular point of a container containing contaminated water. The water then vaporizes and condenses in a different container. The second design is a multiple tray tilted still. It is an insulated container with a series of shallow trays. The water on the trays evaporates until it hits the glass cover where it travels into a storage container. The third design alternative is a titled wick solar still. It is very similar to the multiple tray still with the exception that a fiber cloth feeds contaminated water into the still rather than multiple shallow trays.

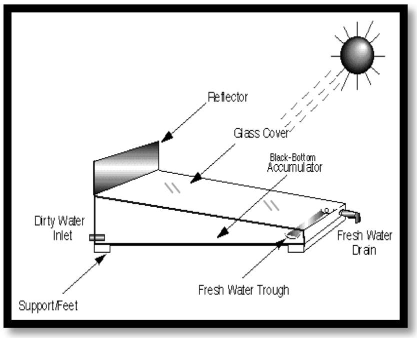


Figure 4, Basin Still

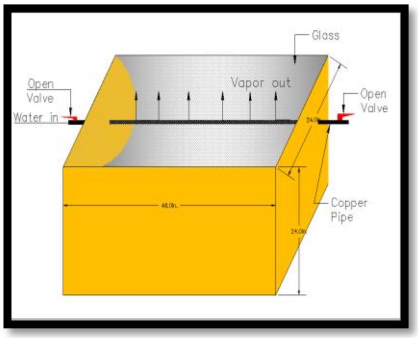


Figure 5, Parabolic Trough Still

The next design alternative is a basin still, a large basin that is covered by an angled piece of glass stores the contaminated water. The water evaporates from the basin until it hits the glass where it travels into a gutter where it is then stored in a container. The final design alternative is a parabolic trough. It was an alternative created by our team and is a combination of a concentrating collector still's efficiency and basin still's stability. Rather than using a satellite shaped mirror to focus light on a point, it uses a parabolic shaped mirror to focus light on a line segment. The water is in a copper pipe container and evaporates through drilled out holes. The escaped vapor travels to a plate of glass where it travels into a gutter and then into a storage container.

Eleven design criteria were selected for evaluation of the alternatives. They include the ability to scale up, cost, overall efficiency, construction material access, creativity, ease of construction, unit stability, ease of maintenance, ease of operation, unit life and safety. To evaluate the stills a precisely as possible, the design criteria were categorized and weighed by 20%, 15%, 10% and 5%. As seen in Table 2, the percentage depends on the judges' criteria from the WERC Competition.[1] The sum of these weighted percentages is 100%. The design criteria with the largest weight of 20% are ability to scale up and cost. The ability to scale up is the unit's ability to maintain efficiency despite making the system larger. For cost, the smaller the total cost of maintenance and construction per production of water, the better the chances to win the WERC Competition. The overall efficiency is the second largest weighed design criteria at 15%. One of the primary goals is to have a unit with the largest production of water possible. Construction material access is weighed at 10% and includes the ability to construct the unit from local materials that are easily accessible. This would facilitate the reconstruction of unit in other areas. Creativity, ease of construction, unit stability, ease of maintenance, ease of operation, unit life and safety are the other design criteria individually weighed at 5%. Creativity was made part of the criteria with the idea that the more unique a unit is, the more likely our unit at the WERC Competition would stand out. Ease of construction is a criteria made so that less specialty tools would be needed to build the unit, making our design easier to build in poorer parts of the country. Unit stability would allow the unit to withstand and not be damaged by harsh winds, rain and snow. Ease of maintenance would allow the unit to operate for a longer period of time and lessen the need to rebuild it repeatedly. The next design criterion was ease of operation. The easier the unit is to operate, the more people from all educational backgrounds would be able to operate the unit. Unit life was made a criterion so that if a community used the design, the more the unit can be used without the worry of having to consistently rebuild it. The final design criterion was safety. The unit must be safe to operate, build and maintain. The score to evaluate the eleven design criteria is 0 to 5, where 0 marks the lowest score, while 5 marks the highest score. These scores are multiplied by their weighed percentages to obtain the final score. These scores were then summed to get each unit's total. The evaluations of the design alternatives with the weighted values are shown in Table 2.

Table 2-Evaluation of Alternatives with Weighted Values

Design Criteria	Weighed Percentage	Concentrating Collector Still	Multiple Tray Tilted Still	Tilted Wick Solar Still	Basin Still	Parabolic Trough
Ability to Scale up	20%	0.2	0.6	0.6	1	0.8
Cost	20%	0.8	0.2	0.4	1	0.8
Overall Efficiency	15%	0.75	0.45	0.45	0.15	0.75
Construction Material Access	10%	0.4	0.2	0.2	0.4	0.4
Creativity	5%	0.1	0.1	0.1	0.05	0.25
Ease of Construction	5%	0.15	0.05	0.1	0.25	0.15
Unit Stability	5%	0.05	0.2	0.2	0.2	0.2
Ease of Maintenance	5%	0.2	0.1	0.05	0.15	0.25
Ease of Operation	5%	0.2	0.1	0.1	0.25	0.15
Unit life	5%	0.15	0.1	0.05	0.25	0.25
Safety	5%	0.25	0.25	0.25	0.25	0.25
Total	100%	3.25	2.35	2.5	3.95	4.25

As Table 2 shows, the two design alternatives with the smallest weighted values are the multiple tray still and tilted wick solar still at 2.35 and 2.5. The next best design alternatives are the concentrating collector still and basin still at 3.25 and 3.95. As the calculation results show, the highest scored design alternative was the parabolic trough created by our group at 4.25.

PROCESS DESIGN

The process design is separated into two main sections: energy requirements and materials. The energy input is estimated to show the required energy to produce fresh water. The materials section is the evaluation of materials based on considerations for system performance, as well as material availability and durability at the selected location, which are essential for project success.

Energy Requirement

In a solar still, the water needs to be heated in order to reach the saturated vapor state. The energy within the still will increase the evaporation rate. After the water reaches the saturated vapor state, the water vapor will be collected by a pipe to condense and collect in a water container. In order to determine how much energy is required to heat the water, the following equation can be applied:

$$E = m * (u_2 - u_1)^{(1)}$$

Where E= Energy, in kJ, M= Mass of water, in kg, and U= Internal energy, in kJ/kg. For the solar still, the water needs to be brought from liquid state to saturated vapor state. The liquid state temperature is assumed to be 20°C; however, the atmospheric pressure varies, therefore the saturated vapor state temperature may differ. Flagstaff's atmospheric pressure is 30.34 inhg.[5] When water is at saturated vapor state, the water quality (x) equals 1. According to Shapiro's *Fundamentals of Engineering Thermodynamics*, as shown in Appendix A Table A-2 and A-3, the internal energy values at a liquid state and saturated vapor state can be found as 83.93 and 2506.1kJ/kg shown in Table 3. [6]

Table 3-Thermodynamic Properties for Water

Temperature (°C)	Pressure (bar)	Internal energy($\frac{kJ}{kg}$)
20	1 bar	83.93
	1 bar (x=1)	2506.1

The water volume required is 5 gallons (18.9 L). It is assumed the copper pipe is filled with 5 gallons of water and the pressure stays the same during heating process. At 20°C, the density of water is 1 kg/L and the 5-gallon water in mass is 18.9 kg. Using the equation above, the energy required to heat 18.9kg of water is 45,780 kJ. In reality, the pressure in the pipe will experience a little change. The pipe selection is introduced in next section. If 5 gallons of water full the pipe, a large diameter pipe would be required making the unit more expensive. The energy requirement for the selected pipe is analyzed in final design section.

Materials

Materials in the structure of the solar distillation still have a large effect on the overall efficiency. When choosing the materials to be used, a number of characteristics should be evaluated and compared. The material properties are shown in Table 5. “I” represents inexpensive and “E” represents expensive.

Table 4-Evaluation of Materials

Structure	Local Availability	Cost	**Pipe**	Apportions	Cost	**Reflection**	Efficiency	Cost
Wood	High	I	Copper	0.94	I	Mylar	0.97	E
Cement	Low	E	Iron	N/A	E	Aluminum	0.95	I

Cost is a primary factor in the overall evaluation because the design purpose is cost per production volume. The structural materials do not have an effect on the overall efficiency; however, for the WERC competition the materials need to be considered for material availability and durability at the selected location. Wood is a reasonably priced structural material and easy to find in Flagstaff. The materials involved with solar collection and thermal absorption directly affect the overall efficiency. The characteristics of importance concerning the materials that directly affect overall efficiency are reflection and absorption. The high absorption efficiency of copper could not be neglected. It affects how much heat can be transferred into the water in order for the water to evaporate. The reflector’s effectiveness is also important for the overall efficiency. The parabolic trough has the lowest heat loss, because all of the sunlight is reflected onto the pipe. Therefore, high reflection efficiency is importation to determine the materials. The research results concluded that mylar has the highest reflection efficiency. By comparing results, the following materials were chosen: wood for structure, copper pipe for absorption, mylar for reflection.

FINAL DESIGN

Design Description

Basin stills have a basin, support structure, transparent glazed cover and a distillation trough. This still design is the most commonly used; however, large units usually do not have a high overall efficiency. The parabolic trough adopted the idea of focusing sunlight onto an enclosed evaporation container. The original parabolic trough design combined the basin still structure and the concentrating collector still efficiency. However, instead of using a glass enclosed evaporation container, the final design used a pipe connected to a condenser. It can only be used when there is light outside and must be angled directly towards the sun. Contaminated water enters the system through the top of the pipe where it is heated to the point of evaporation. The evaporated gases then travel back up the pipe and exits an alternative valve into a tube where it condenses into a storage container. The Drawing of final design is shown in Figure 6&7.

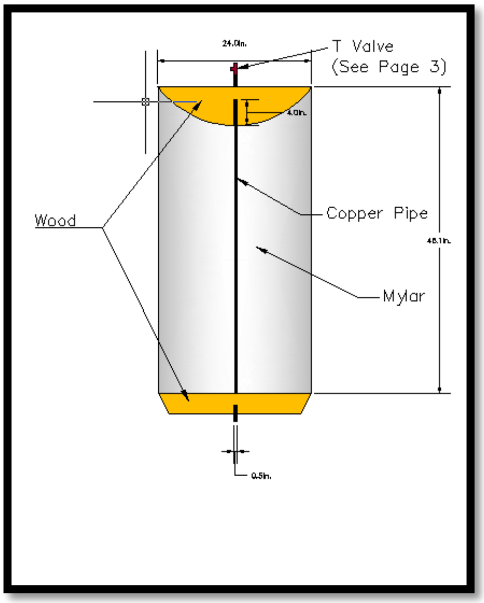


Figure 6, Final Design Front View

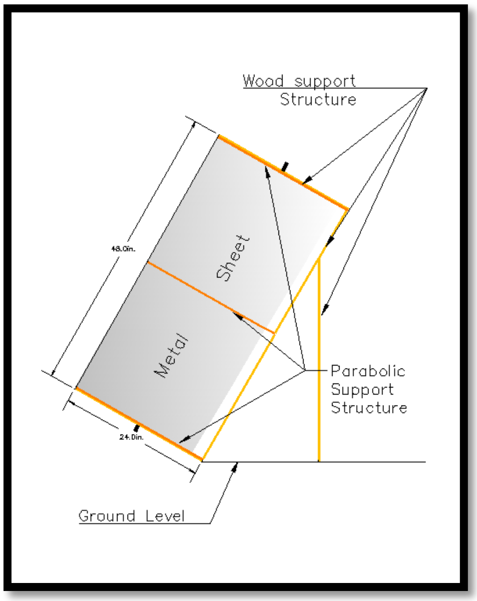


Figure 7, Final Design Side View

As shown in Figure 6 & 7, the structure has the dimensions 48-inch by 24-inch by 24-inch. Before laying the 36-inch by 24-inch metal sheet into the wood structure, parabolic shapes were lined in the wood to make the metal parabola as exact as possible. To do this, Excel was used to create over 2,200 coordinates, which was then converted to “G-code”. G-code is a type of programming language used by the Super-Max Drilling Mill to cut the parabola shape to a ±0.1 inch accuracy.

After making the parabola shape, the focal point in the parabolic shape needed to be found. By placing the copper pipe at a focal point, the copper pipe gathers as much heat as possible.[7] The focal point equation is:

$$y = \frac{x^2}{4p} \quad (2)$$

p= the distance from the origin of the parabola, y= the vertical distance and x=the horizontal distance. The selected p value is 4 inches, which means the conductor or copper pipe must be located 4 inches above the bottom of the reflector. The pipe acts as the evaporation container and the sun’s absorption media. The pipe has been painted black to absorb more heat. There is a T-valve located at the inlet of the pipe on top of the unit. One of the T-valve openings acts like an inlet for contaminated water and the other is used as an exit for the vapor. The drawing of the connection is shown in Figure 8.

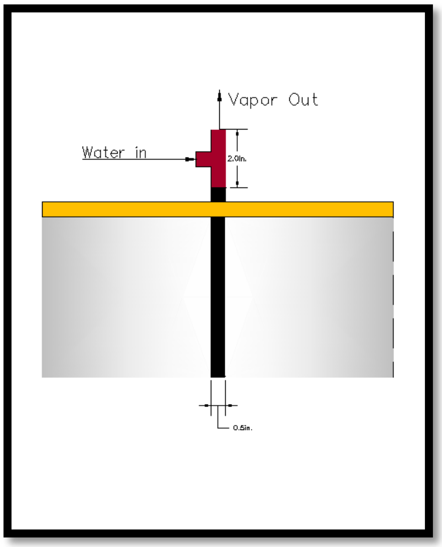


Figure 8 - T-Valve Connection

As shown in Figure 8, the water inlet will be connected with a constant flow dripper. The vapor out will be connected with a tube that condenses the vapor into water. The condenser can be snow or a tube in a bucket of water. Steam exits from the pipe and condenses when it hits the condenser, allowing the water to be collected by a container.

Design Materials

Cost is an important factor for choosing the materials causing low cost to be a goal for the entire design. Heat loss is the biggest consideration for the overall efficiency. High heat absorption of the cooper pipe along with the reflectivity of mylar were essential in accomplishing these two goals. Location availability was another factor to determine the cost. Materials were purchased from Home Depot and Ace Hardware. For the structure, wood was a cheaper material to use because of its high location availability compared to other materials. The materials purchased for the final design are shown in Table 5.

Table 5, Material Properties

Material Type	Size	Efficiency Factor
Wood	3’ by 4’	Does not apply
Copper Pipe	Diameter:1/2", Length : 1	0.94
Metal sheet	4' by 3'	Does not apply
Mylar	1 package	0.97

As seen in Table 5, the size of materials is determined by location availability in store and the design size. The copper pipe needs to be cut in order to get the length to fit the unit. The cost for all materials is reasonable and cheaper than the alternatives. For the efficiency, the wood and metal sheet does not apply, because those materials don't affect sunlight absorption efficiency. The absorption efficiency used for copper pipe is 0.94. The absorption rate cannot be determined in the store, the online *GlobalMarket* recorded the solar copper pipe with a 0.94 efficiency rate.[8] and the mylar reflection efficiency is 0.97. The efficiency factor is used to determine the overall energy consumption.

Energy Analysis

During the summer months when the Sun is located at the highest point in the sky, solar radiation at the Earth's surface is approximately 1000 W/m^2 assuming weather conditions are clear.[9] The cover of the solar distillation unit should provide the largest area possible allowing the most heat to be absorbed in a fixed amount of time. In the final design, the structure is 48in by 24in by 24in; the area catching the sunlight is 1152 ft^2. The energy input can be calculated using the equation below:

$$E = R * A * N_{reflection} * N_{absorption} \quad ^{(3)}$$

Where E is energy input in kJ/h, R is solar radiation W/m^2, A is the area catching the sunlight in m^2, $N_{reflection}$ is mylar reflection efficiency at 0.97 and $N_{absorption}$ is pipe absorption efficiency at 0.94.

After applying all the values into the equation, the total energy input is 2440 kJ/h. The analysis neglects the thermal losses to the environment. To determine the thermal losses, the following equation can be applied:

$$q = h * A * (T_s - T_\infty)^{(4)}$$

q is the energy loss in kJ/h, h is the conductivity coefficient in W/m^{2}K, A is the surface area of the pipe in m^2, T_s is the pipe surface temperature in K and T_∞ is the ambient temperature in K. The convection coefficient is typically between 5 to 10 W/m^{2}K for still air. The pipe has a 1/2 inch diameter and is 48-inch long. The surface area of the pipe is 24 square inches (0.15m^2). The surface temperature of the pipe was determined to be 372.5K by the unit's vapor temperature and Flagstaff's boiling point temperature which are listed in Table 6.

Table 6, Temperature

Flagstaff Boiling Point Temperature	93°C
Vapor Temperature	106°C

The ambient temperature is 287.15 K. The conductivity coefficient used was 7.5 W/m^{2}K. Through applying equation number 4, the energy loss is 345.4kJ/hr. The total energy input is estimated by subtracting the total energy without loss by the energy lost to get a value of 2094.6kJ/hr.

To avoid backflow, the depth of the water should be located halfway through the pipe length. Therefore, the water volume in the pipe should contain half the volume of the pipe, which is 4.7 in^3 (7.7e^{-5} m^3). The mass of the water in a half volume pipe is 0.08 kg. Applying the mass of water in the pipe to the energy requirement equation, it needs 194 kJ of energy to reach vapor conditions, which will take 0.09 hours. The flow equation can be seen below:

$$Q = \frac{V}{t} \quad (5)$$

Q is the flow rate in gallons/hr, V is the volume required to boil in gallons and t is time consumed for 0.08 kg water vaporized. As the calculations show, the flow for inlet water needs to be at 0.2 gallons/hr.

Efficiency Testing

The efficiency testing was conducted at 9:30 am March 12, 2013. The operating conditions consisted of an outside temperature of 45^{o}F with a 10 mph wind speed. 50ml of water was placed in the pipe. After a 36-minute period, 10 mL of purified water was collected. Once the unit was cooled for three to four minutes, the pipe was drained. The drained water volume was measured to be 20mL which contained a higher concentration of contaminants. Concentration values were calculated using the following mass balance equation:

$$V_{in} * C_{in} = V_{vapor} * C_{vapor} + V_{left} * C_{left} \quad (6)$$

V is the volume of water and C is the concentration of contaminants. The C_{vapor} was assumed to be 0. As a result, $C_{left} = \frac{V_{in} * C_{in}}{C_{left}}$. There were 30mL out of 50 ml water vaporized. The left over water volume was measured at 20mL. The ratio of water into the pipe and water left in the pipe is 2.5. Concluding C_{left} is 2.5 times C_{in}. Insight for dealing with high contaminant water is discussed in the legal issues section. The efficiency for water condensed from 30mL of water vapor is 10mL divided by 30mL which is 33.3%. The efficiency for water vaporized is 30mL divided by 50mL which is 60%. The approximate estimation of the solar still output is given by:

$$Q = \frac{E * G * A}{2.3} \quad (7)$$

Q is the daily output of distilled water (liters/day), E is overall efficiency, G is the daily global solar irradiation (MJ/m^2) and A is aperture area of the still ie, the plane areas for a simple basin still.[2] As seen by the definition of the aperture area, this formula is used for basin stills. There is no existing formula for the parabolic shape thereby making the formula above the best one to use. The daily global solar irradiation varies at different locations and times of day. To estimate the daily output of distilled water, the daily global solar irradiation is used in the same manner as solar radiation that is experienced at the Earth's surface with a value of 1000 W/m^2 (daily sunlight is assumed as 10 hours, the solar irradiation is 36 MJ/m^2).[2] The overall efficiency of a parabolic trough still is 60%, The aperture area of the still is $0.001m^2$. Calculations show, the daily output of distilled water is 0.009 liters per square meter. This daily output value is dependent on the area of the still and if there is a constant source of water in the pipe. If there is always water in the pipe, the daily output of distilled water will be more than 0.009 liters per square meter. For example if 1 m^2 of pipe was used for the design area, the daily output would be 9.4 liters per square meter.

Evaluation

The single-basin stills are the most common solar stills used today. The efficiency of a single-basin still is typically 25%.[2] The parabolic trough still has an efficiency of 60%, which is an increase in efficiency by 35 %. The daily output of a basin still is 2.3 to 3.0 liters per square meter.[2] The parabolic trough still with an area of 1 m^2, has a daily output of 9.4 liters per square meter. Not only does it produce 3 times the amount of purified drinking water, but it does so at a rate that is 3 times faster than the single basin still. The advantages of a basin still include: low cost and can be built with recycled materials. However, the parabolic trough has a total cost of $75, which is lower than other still constructions and can process a larger amount of contaminated water at a faster rate. Overall, the parabolic design is an improvement over a basin still.

ECONOMIC ANALYSIS

The budget for designing a new solar distillation still is provided in this section. The average payment of an environmental engineer is $39.72 per hour. [10] However, the Solar Distillation Still Design Group members are non-professional engineers. The hourly rate decided was $20 per hour which is an engineering internship rate.[11] There are five members in the Northern Arizona University Solar Distillation Design Team. The cost is based on the services provided to design a solar distillation still. The cost summary is shown in Table 7.

Table 7, Cost for Design a Solar Distillation Still

Direct Labor Cost

Task Name	Hourly Rate($)	Number of Person	Number of Hours	Total Cost($)	$	$	Symbols
Research Phase							
Overall Project	20	5	6	600			
Location	20	5	6	600			
Materials	20	1	3	60			
Structure	20	1	3	60			
Cover	20	2	3	120			
Collection System	20	1	3	60			
				Research Phase Subtotal	1,500.00		
Testing Phase							
Materials	20	5	3	300			
Structure	20	5	3	300			
Cover	20	5	3	300			
Collection System	20	5	3	300			
				Testing Phase Subtotal	1,200		
Construction Phase							
Building Models	20	5	80	8,000			
Testing	20	5	24	2,400			
Final Model	20	5	10	1,000			
				Construction Phase Subtotal	11,400		
Report Phase							
AutoCAD	20	1	3	60			
Project Study Report	20	3	40	2,400			
				Report Phase Subtotal	2,460		
Direct Labor Subtotal						**16,560.00**	X_1
Adjusted Direct Labor Cost							
					Direct Labor Multiplier (#)*X_1	38,088	X_2
Adjustment Direct Labor + Profit							
					Percent of Profit 10 %{(1+(%/100))*X_2}	41,896.8	X_3

Direct Non-Labor Cost

Construction Material Cost		300		
Competition Application Fee		800		
Travel (Gas)		200		
Hotel		1,000		
Meal		1,575		
Overhead	Provided by the school, zero cost			
Direct Non-Labor Cost Subtotal			**3,875**	X_4
TOTAL FEE REQUESTED [X3+X4]			**45,772**	

As seen in the table above, the total fee requested is $45,772. There are two main parts of cost including direct labor cost and direct non-labor cost. Direct labor cost consists of 4 phases. Each phase includes different tasks. Some of the tasks were worked on individually, and others in groups, the cost of each task is varies. The numbers of person involved in each task is listed in the table. The numbers of hours for each task were estimated. The research phase and testing phase were finished in 3 hours each Sunday. The overall project and location research took two Sundays to finish up which is 6 hours total. The construction phases took approximately 2 months. Most of the building processes were finished during weekend, some of were done by the weekday. The approximated building hours was 80 hours, approximated testing hours was 24 hours, and the approximated final model building hours was 10 hours. The time spent on the final report where 43 hours. The total direct labor cost is $16,560 and includes the research phase, testing phase, construction phase and the report in the subtotal. Using the multiplier of 2.3, the adjusted direct labor cost is $38,088. In order to make a 10 % profit, the direct labor cost is adjusted to $41,896.8. The non-labor cost includes construction material, competition application, travel, hotel and meals. The estimated cost for the total direct non-labor charge is $3,875. The construction material cost is summarized in Table 8.

Table 8-Material Cost Summary

Material	Quantity	Cost ($/ one)	Total
Wood	2	12	24
Mylar	1	10	10
Open Valve	2	5	10
Container	2	7	14
Copper Pipe	1	17	17
Total			75

The construction material is based on the final design materials used. As a whole construction process, three units were constructed, the first two failed. The cost of the first two units was more than the final one, at approximately $200. All three designs cost $300 to build.

SET-UP AND MAINTENANCE

The parabolic trough is easy to build and maintain. There are only several materials needed to be used in building: wood, copper pipe, mylar, open valve, and containers. All specified materials are available in most hardware stores. The wood needed to be cut in order to support the metal's parabolic shape. The focal point is easy to calculate by Excel. It requires 10 minutes to set-up the parabolic equation and extract the coordinates the drilling mill. The wood is painted with an oil based paint, which adds stability by avoiding the damage caused by rain and snow. The mylar is easy to break, however, it is cheap and easy to replace. The pipe is removable, and it can be replaced, or cleaned with an iron brush. The total maintenance cost will be much cheaper than the reconstruction cost.

LEGAL AND REGULATORY CONSIDERATIONS

All operator and manufacturing processes will adhere to the federal and state regulations. The Arizona Department of Environmental Quality enforces federal standards and regulations. Most of the hazardous processes and air pollution emissions occur in the manufacturing phase of the solar distillation unit. Therefore, operator considerations will be provided and the majority of legal and regulatory considerations will be based on the manufacturing phase.

According to the Environmental Protection Agency (EPA), none of the contaminants in the brackish water treated by the solar distillation unit are regulated as a primary drinking water contaminant. Two of the contaminants are regulated under the National Secondary Drinking Water Regulations (NSDWRs). The NSDWRs are a list of non-enforceable recommendations to ensure cosmetic quality and reduce water delivery system upkeep. The drinking water produced by the unit is not regulated by enforceable drinking water laws due to the composition of the water. According to NSDWRs, the maximum concentrations of sulfate and chloride are recommended to not exceed 250 mg/L. Total Dissolved Solids (TDS) are also regulated under the NSDWRs. The EPA recommends that TDS concentration not exceed 500 mg/L. Many of the contaminants listed by the condition of the brackish water contribute to both hardness and TDS. The operator legal and regulatory considerations take into account the higher concentration of secondary contaminants in the waste stream of the solar distillation unit. Depending on the volume and concentration of the stream, disposal into surface water is not recommended, and a permit would be needed under the Clean Water Act (CWA). Pretreatment would most likely be needed in order to obtain a permit from the National Pollutant Discharge Elimination System (NPDES). Instead, irrigation for salt tolerant crops or plants is recommended as a disposal consideration. For example, suitable salt-tolerant plants include Zoysia for low maintenance park areas [12] and Seashore Paspalum for golf courses.[13]

Rather than water quality legal and regulatory considerations, the manufacturing process involves air quality considerations. Fabrication of the reflector and painting of the pipe results in the release of Volatile Organic Compounds (VOCs) into the environment. For this reason, air pollution control technologies should be put into place for large scale manufacturing of the unit. Regulations set forth by the Clean Air Act (CAA) should be observed. Considerations for the air pollution control technology to use can be found at the Environmental Protection Agency's website under the search term, "Best Available Retrofit Technologies".

HEALTH ISSUES

The primary health concern considered by the solar distillation design team was human health. The distilled water produced by the unit is an acceptable method of producing potable water. Therefore, the only process streams that will be of health concern are the incoming brackish water and the exiting concentrate solution stream after distillation. Since the incoming brackish water contaminants were given, the following formula was used to find the concentration of contaminants in the effluent.

$$C_{eout} = (C_{in}Q_{in} - C_{CWout}Q_{CWout}) / (Q_{eout})^{(8)}$$

C_{eout} is the concentration of effluent or the waste stream, C_{in} is the concentration feed into the system, Q_{in} is the flow into the system, C_{CWout} is the concentration of the cleaned water, Q_{CWout} is the flow of the clean water and Q_{eout} is the flow of the waste stream. The flows used in this equation were based on the efficiency tests. Flow into the system was 50mL, the flow of clean water out of the system was 30mL and the effluent flow was 20mL. Since the potable water stream that was treated by the solar distillation unit is not a health concern, and the incoming brackish water conditions are known; contaminant concentration levels of the waste stream were of interest. In order to advise for the worst case scenario of the waste water stream concentration levels, the concentration of the cleaned water was assumed to be 0mg/L. This information is essential for the protection of people handling or in contact with the waste water stream. Table 9 shows the human health effects of the contaminants and their acceptable dosage levels as compared to the incoming and exiting contaminated streams.

Table 9: Component Human Health Effects

Component	Concentration in Feed Stream	Concentration in Waste Stream	MCL or Acceptable Safe Level	Health Effects
Sulfate	3300 mg/L	8250mg/L	1000mg/L[14]	Laxative effect leading to dehydration[15]
Chloride	550 mg/L	1375mg/L	14000 to 28000 mg/day[16] (7000 to 14000 mg/L)	Associated with heart failure and hypertension[16]
Hardness (as CaCO3)	3000 mg/L	7500mg/L	Harmful in powder form, used as a form of Ca in vitamins[17]	Eye and skin irritation[17]
Sodium	700 mg/L	1750mg/L	1500mg/day[18] (750mg/L)	Edema, hypertension, stroke, dizziness, gout, kidney damage, kidney stones, nausea, vomiting and coma[18]
Calcium	600 mg/L	1500mg/L	1000mg/day[19] (500mg/L)	Renal insufficiency, vascular and soft tissue calcification, hypercalciuria and kidney stones[19]
Magnesium	375 mg/L	937.5mg/L	350mg/day[20] (175mg/L)	Diarrhea, abdominal cramping, and kidney failure[20]
Silica	25 mg/L	62.5mg/L	760mg/day[21] (380mg/L)	Bruising, stomach irritations, skin rashes/irritation[21]
Strontium	10 mg/L	25mg/L	4mg/L[22]	Strontium ricket can develop (bones are thicker, shorter or deformed)[22]

As seen in Table 9, many of the acceptable dosage levels were presented in units of mg/L rather than how the EPA provided the acceptable dosage level in units of mg/day. Since the average adult consumes about two liters of water per day, the doses presented in mg/day were divided by 2 liters to get mg/L. The contaminants in the feed stream with concentrations above the maximum dosage level are sulfate, calcium, magnesium and strontium. The contaminants in the waste stream with concentrations above the maximum dosage level are sulfate, chloride, sodium, calcium, magnesium and strontium. The only regulated contaminant in the list is strontium. This form of strontium is not the radioactive type associated with nuclear power plants or nuclear weapons testing. The form of strontium found in the brackish water is naturally occurring. It dissolves from bedrock and soil to enter the groundwater. [22] The EPA has established a Maximum Concentration Level (MCL) for strontium of 4mg/L daily. None of the brackish water contaminants with the exception of strontium are in a concentration range to be harmful to humans. Even though strontium is the only regulated contaminant, this does not mean that the other contaminants are not toxic at high levels. Therefore the incoming brackish water will be piped into the unit in order to keep humans from coming into contact or ingesting the brackish water.

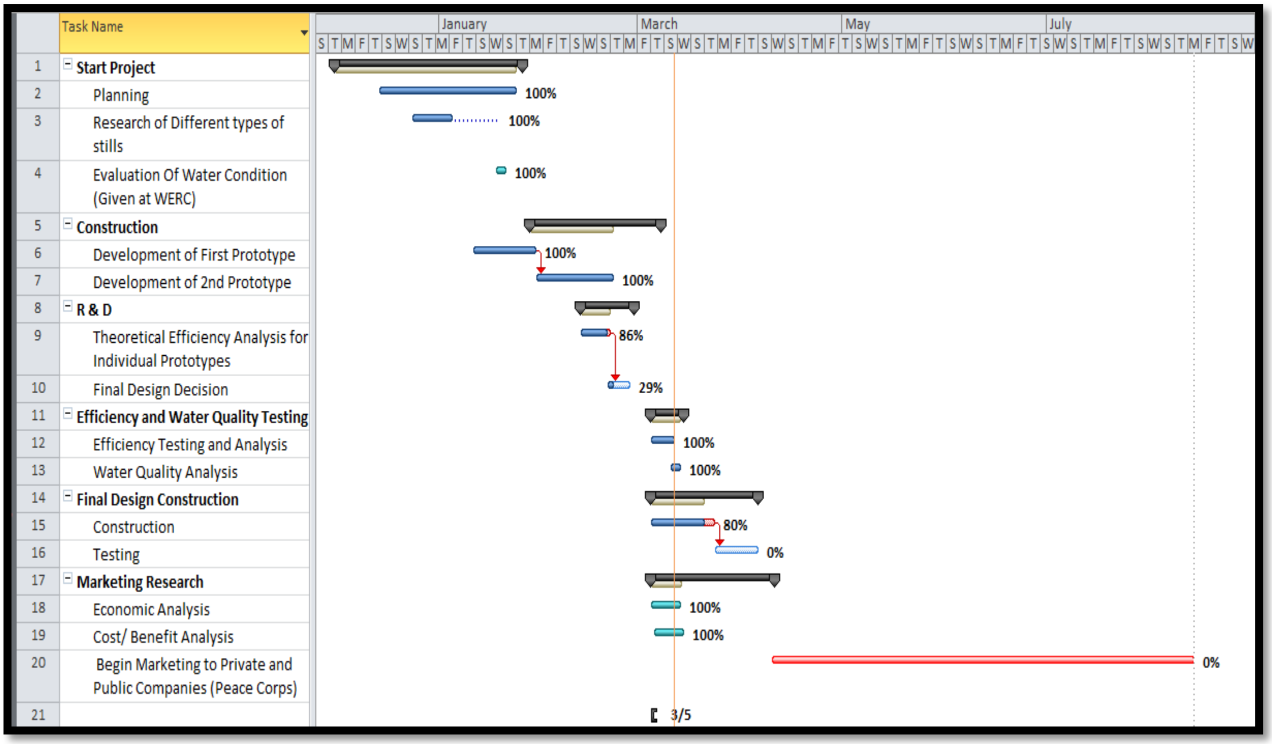
The waste stream of non-potable water produced by the unit will have a high concentration of strontium, hardness (calcium carbonate), sulfate, chloride, sodium, calcium, magnesium and strontium causing the handling of the effluent to be a concern. In order to limit the potential for ingestion and dermal contact, the water should be piped out as well. If the pipe is to be cleaned, operators should know that calcium carbonate in a solid form can irritate the eyes and skin. If this substance is inhaled, it can cause irritation to the respiratory tract. [17] Calcium carbonate solid is considered not harmful and is often the form of calcium present in vitamins. [17] No dermal absorption information on strontium, sulfate, chloride, sodium, calcium, magnesium and strontium calcium carbonate was listed on the EPA's Integrated Risk Information System (IRIS) Database.[23] Treatment of the waste stream produced by the unit is outside the scope/requirements of the solar distillation design.

However, health and safety of operators who could be in contact with the input brackish water stream and the exiting concentrate stream has been considered. Operators in contact of waste streams must wear proper Personal Protective Equipment (PPE). Recommended PPE for these streams include: safety goggles, water-resistant gloves, dust masks, long-sleeved shirts, closed-toe shoes and long pants.

Another human health consideration involves the manufacturing phase of the distillation unit. Due to the construction method, VOC emissions from the black paint will be encountered by manufacturers and without proper air pollution control technologies or proper Personal Protective Equipment (PPE), these VOC emissions can be a health concern. Considerations to minimize these health risks should include: implementing proper ventilation techniques during use, and providing and adhering to MSDS suggested practices. Recommended PPE for manufacturers include: safety goggles, VOC-specific respirator, gloves, long sleeves, long pants and closed-toe shoes.

BUSINESS PLAN

The distillation of brackish water requires multiple steps before a business plan can be formulated. The first step in marketing our solar still is to plan and design the most efficient still possible. The planning phase began in December, and ended in January as seen in Figure 9.



	Task Name
1	**Start Project**
2	Planning
3	Research of Different types of stills
4	Evaluation Of Water Condition (Given at WERC)
5	**Construction**
6	Development of First Prototype
7	Development of 2nd Prototype
8	**R & D**
9	Theoretical Efficiency Analysis for Individual Prototypes
10	Final Design Decision
11	**Efficiency and Water Quality Testing**
12	Efficiency Testing and Analysis
13	Water Quality Analysis
14	**Final Design Construction**
15	Construction
16	Testing
17	**Marketing Research**
18	Economic Analysis
19	Cost/ Benefit Analysis
20	Begin Marketing to Private and Public Companies (Peace Corps)
21	

Figure 9 - Business Plan Timeline

As seen in Figure 9, after planning of the unit design has been completed, the next step is to construct the unit and perform research on the efficiency and overall water quality of the end product, which takes about 31 days. A conductivity analysis testing for mineral deposits as well as overall water quality in the end product will be conducted using a Hannah HI 9828 Conductivity Meter. After all appropriate steps have been taken for water quality testing, the next step in the marketing and business phase is a cost benefit and economic analysis to show clients the benefits of owning a solar still. Once the economic analysis has been performed, the next step is the acquisition of bids from clients.

Marketing will begin on the 12th of April, and will last for 90 days. The target audience for marketing and retailing of our solar distillation unit is Non-Governmental Organizations (NGO's) as well as federally funded programs such as the Peace Corps. The reason for marketing to these organizations is due to the fact that these organizations are in need of water in areas of the world where clean water or electricity is not readily available. Bidding will take about a month once marketing of the solar still begins. This time allotment allows for clients to make well-formed decisions on the scale up and cost of the units they wish to use. Once a bid has been awarded, the next step in the business plan is permitting. In order to scale up a larger version of our solar distillation still, soil analysis and permitting is required in order to ensure the still is up to date on current codes and regulations regarding water quality, safety, and building permit.

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Business Plan Audit by Kelly Burt – VP Sales, Rich Ltd. Oceanside, CA

The business plans seems to be incomplete. It adequately covers the steps necessary to complete the building of the Still however it doesn't adequately define the target market and the economic analysis of the project. It also fails to identify the scope and scale of the problem and does not address the other agencies that it will be competing with for business.

I'm unclear how the marketing plan will be implemented and what the marketing plan is however the outline for the timeline is clearly stated and the reasons for marketing to the NGO's is clear. Marketing channels need to be defined. Budgets for Marketing need to be outlined as well and incorporated into the overall plan.

Also needed is an overall plan for the growth of the company and the financial needs for the start up as well as pricing, gross margins and financial projections over the next few years. Funding has not been addressed. The bidding process can use more definition however the timeline seems short. Soil analysis and permitting is adequately covered. I'd like to see some more information on who the company officers are and who will be in charge of each process i.e.… who is the salesman, who is the financial person and what are their backgrounds.

Legal/Regulatory Audit for NAU Solar Still Team

W. Odem, March 17, 2013

The NAU Solar Still Team has identified two areas of possible legal/regulatory concern with respect to the Solar Still Development Project: 1) manufacturing phase and 2) operations phase. The Team identified the manufacturing phase in the event that the still design went into full-scale production. During construction of the unit, the Team notes that volatile organic compounds are released during reflector fabrication and painting. The Team correctly notes that large-scale manufacturing would require air pollution control equipment for VOCs under the Clean Air Act's New Source Performance Standards. I note, however, that as production scales up, and perhaps even at full-scale mode, construction of the unit could be outsourced, and therefore air pollution control and permitting would be handled by the contracted facility. Additionally, all local (city/county) and state air quality regulations need to be considered, as the states typically manage Clean Air Act programs under EPA auspices and may add to them.

The Team also identified the operations phase as a regulatory concern due to 1) Safe Drinking Water Act secondary standards, and 2) Clean Water Act oversight of discharges. The Team notes that the raw source water violates secondary standards for SO_4^{2-}, Cl^-, and TDS. Though secondary standards are not enforceable, they are potentially associated with aesthetic and maintenance concerns. The distillation process should remove most of these constituents and product water will be evaluated via conductivity meter testing for TDS, which can serve as a surrogate parameter for all three constituents for monitoring distillation performance.

The second concern addressed by the Team during operations was Clean Water Act oversight of discharges, in this case a concentrated brackish reject stream. The Team correctly notes that a discharge to a receiving water in the US would require a NPDES permit. The team suggests that facilities employ a non-discharge approach, namely the cultivation of salt tolerant landscaping species. This would likely be a viable option for small systems, which the solar still applications would be.

In summary, the NAU Solar Still Team's identification of legal/regulatory concerns, i.e. Clean Air Act for manufacturing, and Safe Drinking Water Act and Clean Water Act for operations, are appropriate and adequate. The Team’s planned and suggested responses to these concerns are also appropriate and adequate.