Task 2: Passive Solar Distillation of ARD Waters

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Table of Contents

1.0 EXECUTIVE SUMMARY

[redacted] Distillers (A.R.D.) has developed a passive solar distillation system for treating acid rock drainage (ARD) from legacy (i.e., abandoned) mines. The solar still addresses the need to reduce both the metal sulfate contaminants as well as the acidity of acid rock drainage. During the design phase, A.R.D. addressed the need for the system to be low cost, simple, and effective for general use as well as for a specified location. To demonstrate the applicability of the solar still, A.R.D. used the Freeport McMoRan Inc. Copper Queen legacy mine in Bisbee, Arizona, as a base case scenario. The mine was visited to gain insight regarding the problem and its solution.

Research was conducted to evaluate treatment technologies including, solar stills, bioreactors, solar ponds and reverse osmosis to determine the best method to treat contaminated water. The key factors in choosing the appropriate technology included long-term cost, durability, required maintenance, simplicity, and efficiency. A.R.D's design is close to that of a traditional solar still with the exception that water vapor is not reclaimed. In the full-scale unit, five gallons per minute of ARD water is evaporated, and the vapor is not condensed because no economical use for the water was determined.

In the full-scale design, sunlight enters through a six-millimeter thick double pane polycarbonate roof, heating the water and vaporizing it. The water vapor/air mixture is forced from the still and ambient air is pulled into the still via a thermosiphon. The purpose of introducing the outside air is to maintain a low relative humidity within the still to increase the driving force for greater evaporation rates. In the bench-scale design, the thermosiphon effect is demonstrated by using exhaust fans. Rather than removing the salt brine continuously throughout the process, A.R.D. decided to allow the salts to precipitate and collect at the bottom of the solar stills. The salts will be removed in a batch process every twenty years with little effect on the efficiency of the solar still. The removal of salts after twenty years simplifies the operation of the still as well as reduces operating costs.

The solar still will be positioned near mining stockpiles where the acid rock drainage originates. Rather than building one large solar still, A.R.D.'s design uses multiple smaller solar stills in parallel to achieve the same results. In the full-scale system, there are 27 individual stills, and each solar still is 102 feet long, 22 feet wide and 10.5 feet high. The full-scale solar distillation unit was designed to handle the task mandated five gallons per minute of contaminated water. Each solar still will cost about $40,000, which includes the cost of materials and construction. The total initial capital cost for twenty years for the system is $1,100,000. This corresponds to $18 per square foot.

The design parameters of the still were determined by testing a 4-foot by 8-foot bench-scale apparatus and developing a mathematical model. A.R.D. has shown that the bench-scale can achieve a daily average flow rate of 7.6 mL per minute. Recommendations to improve the still to achieve ten mL/min are included.

This report provides a detailed explanation of the location, technology, process summary, economic analysis, experimental results, regulations, safety considerations, and scalability for a solar distillation system at the legacy Copper Queen Mine in Bisbee, Arizona.

2.0 PROBLEM STATEMENT

Acid rock drainage (ARD) poses a threat to water quality throughout the western United States. An estimated 33,000 mines have caused surface or groundwater contamination on federally regulated lands alone. Of these, 8,474 have recorded environmental impacts that remain to be addressed[1]. A geographical distribution of these mines is shown in Figure 1.

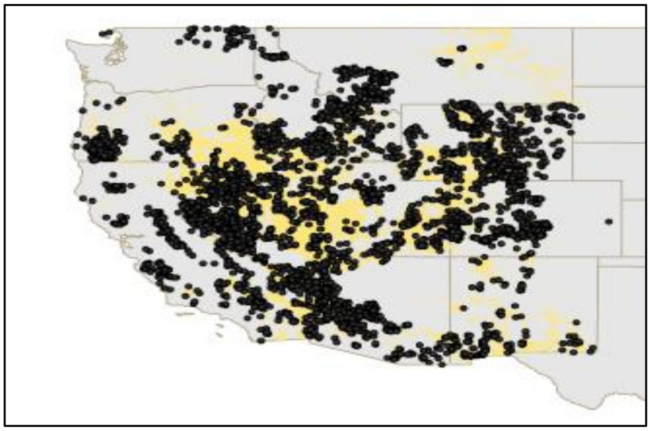


Figure 1: Map of Abandoned Mines Controlled by the Bureau of Land Management[1]

The precise makeup of ARD is dependent upon the geological formations in the area. Iron (II) sulfate, the oxidized form of pyrite, is a ubiquitous contaminant, imparting ARD streams with a distinctive red tint. ARD is produced when water contacts mineralized rock containing metal sulfides. The mineral deposits are oxidized, often forming metal sulfate salts. ARD brine streams are corrosive and acidic, with a pH as low as three.

In accordance with WERC Task 2, the A.R.D. team developed a solar distillation system to treat acid rock drainage passively. Many of the heavy-metal contaminants in ARD water have the potential to be economically valuable when purified. For example, iron (II) sulfate is used in the production of dyes. However, the dried solid mixture produced by solar distillation provides little value without further treatment.

The task specified ARD water includes the following sulfates:

Aluminum sulfate	0.25 g/L
Magnesium sulfate	0.5 g/L
Calcium sulfate	1 g/L
Ferrous sulfate	0.5 g/l
Zinc sulfate	0.25 g/L

Due to the remote location in which the design would be utilized, no available utilities could be relied upon beyond basic gravity feeding infrastructure. The projected useful life of the solar distillation system is 20 years. This is limited by the expected lifetime of high-grade polycarbonate and treated plywood.

3.0 SITE BACKGROUND

Following the recommendations of the team's contacts at Freeport-McMoRan Inc., A.R.D. has identified the Copper Queen legacy mine in Bisbee, Arizona as an ideal initial location for the solar still system. A.R.D. specifically focused on the Copper King Canyon "Jones Canyon" stockpile at the site shown below. The Copper Queen mine ceased operations in 1974 but approximately twenty personnel still work at the site for controlling the environmental impacts. Bisbee, AZ and the Copper Queen mine were both founded in the late 1800's and operations were discontinued before environmental regulations were enacted. As a result, there are many mineral rich stockpiles in the area generating acid rock drainage.

Figure 2: Jones Canyon View[2]

When a stockpile is capped, the operations crew at the Copper Queen mine applies a two-foot layer of dirt and vegetation on the stockpile as an evapotranspiration barrier to prevent ARD generation. This barrier will remain in place as a first layer of defense. Currently, any generated ARD is collected in a central area for natural evaporation. This method is inexpensive; however, not completely effective since some ARD water is not contained in the barrier. The purpose of A.R.D.'s proposed design is to improve the way ARD water that does infiltrate through this barrier is treated. The system will operate near the source of the ARD to remove the necessity of pumping the water long distances. The environment in the Bisbee area is ideal for the A.R.D. proposed system because of the high solar availability (285 sunny days per year) and an average solar irradiance of 6.59-kilowatt hour per square meter per day. Both of these parameters are higher than the United States average. These and other important environmental information is shown in Table 1 below.

Table 1: Environmental Conditions of Bisbee, AZ[3]

Month:	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Average High Temperature: (°F)	56	60	66	73	81	89	87	84	82	74	64	56
Average Low Temperature (°F)	32	34	37	43	51	59	62	61	56	46	37	32
Average Rainfall: (inch)	1.46	1.3	.94	.51	.31	.75	4.21	4.21	1.81	1.1	1.06	1.42
Average Solar Irradiance: (kWh/m2/day)	5.67	6.09	7.02	7.51	7.32	7.19	6.47	6.87	7.06	6.7	5.96	5.24

4.0 TECHNOLOGY BACKGROUND RESEARCH

Literature research revealed several possible technologies that could be used in ARD treatment: reverse osmosis, bioreactors, ionic exchange systems, permeable-reactive barriers, catalytic bed reactors, gas redox displacement, zeolites absorption, and several distillation technologies including solar ponds and solar stills. For this project, long-term costs, durability, passiveness, and simplicity were the primary parameters used in the technology selection. The majority of these technologies are not viable options, given the problem at hand. Permeable-reactive barriers, ionic exchange membranes, catalytic bed reactors, gas redox displacement, and zeolites absorption were all quickly disregarded due to the high material cost, continuous monitoring, and high metal selectivity[4]. While several methods of treatment were considered, the most common techniques are listed in Table 2 where advantages and disadvantages are included.

Table 2: Alternate Technologies Summarization[5, 6, 7, 8, 9, 10, 11]

Technology	Advantage	Disadvantages
Solar Pond	• Inexpensive • Passive • Ease of construction	• Inefficient • Requires a large area • Wildlife is not protected
Bioreactor	• No power required once implemented • Uses naturally occurring anaerobic bacteria from dirt • Proven technology	• H_2S Production • Quality of discharge is inconsistent • Constant monitoring and maintenance • Requires additional chemicals to feed bacteria
Reverse Osmosis	• Easily scaled to desired capacity • Widely applicable • Proven technology	• Expensive membrane replacement • Needs large solar array for powering pumps • Temperature sensitive • Lower recovery than distillation processes • Potential for membrane scaling • Constant monitoring and maintenance
Solar Still	• Simple operation and maintenance • Passive system • Reduced heat losses • No re-release of contaminants	• Requires a large area for high production rates • Needs adequate sunlight • Air flow required

Solar ponds are large pools of impure water that utilize solar radiation to evaporate water to the atmosphere. This method was not chosen because of the inefficient rate of evaporation.

Passive sulfate-reducing bioreactors are synthetic bio-systems that capitalize on ecological and geochemical reactions to purify ARD water. This method was rejected due to high cost and probable hydrogen sulfide (H_2S) production[11]. The Copper Queen mine in Bisbee has implemented this process in the past to treat ARD water. There was an incident where an H_2S leak occurred and shortly after the system was retired[12].

RO systems utilize membranes purify water[10]. While RO is capable of higher production than the solar still, the disadvantages associated with the energy requirements, complex operation, fouling, and maintenance outweigh the production rate for the conditions specified in the problem statement.

A.R.D. selected the solar still as the most cost effective technology for its passivity, simple operation, and lower energy requirements.

5.0 FULL-SCALE PROCESS SUMMARY

5.1 Overview

A.R.D has designed a system composed of multiple basin-type solar stills with a single slope roof. It is modeled after the generic design of a bio-solids management facility in Fayetteville, Arkansas, that utilizes greenhouses. In Figure 3, the basic overview of the process is shown. Acid rock drainage water is distributed evenly throughout the parallel stills through pipes that enter the back wall. Sunlight enters through the polycarbonate roof of each still and ambient air enters through one hundred one-inch diameter round holes just above the water level on the long (102') side of the still. The water absorbs the sun's radiation and vaporizes pure water vapor to the atmosphere. The water concentration difference between the surface of the water and the air/water vapor mixture in the still promotes evaporation. Water vapor and air exit the top of the back wall through ten, six-foot tall chimneys. Ambient air is pulled into the still by the thermosiphon effect from the difference between the air density and the vapor density within the still.

The required 27 stills have been determined from experimental data, heat and mass transfer calculations, and a mathematical model. As the water vaporizes, it leaves behind the sulfates and other impurities, and these solids accumulate over time in the basin. Having 27 stills in parallel reduces the issue of re-wetting of the solid sludge by a high flow rate of water. Re-wetting of the solids gives the water a higher specific gravity and increases the boiling point. The overall amount of water fed to the stills is five gallons per minute. The amount of water being evaporated to the atmosphere during peak sunlight is equal to or greater than the inlet flow rate of water. Some water continues to evaporate following sunset due to heat retained inside the still. The stills are designed to maximize the heat in, minimize the heat lost, and to control the relative humidity inside, in order to be as efficient as possible. Full-scale dimensions are chosen for ease of construction and are also based on the surface area necessary to obtain the energy from the sun required to evaporate five gallons per minute of water.

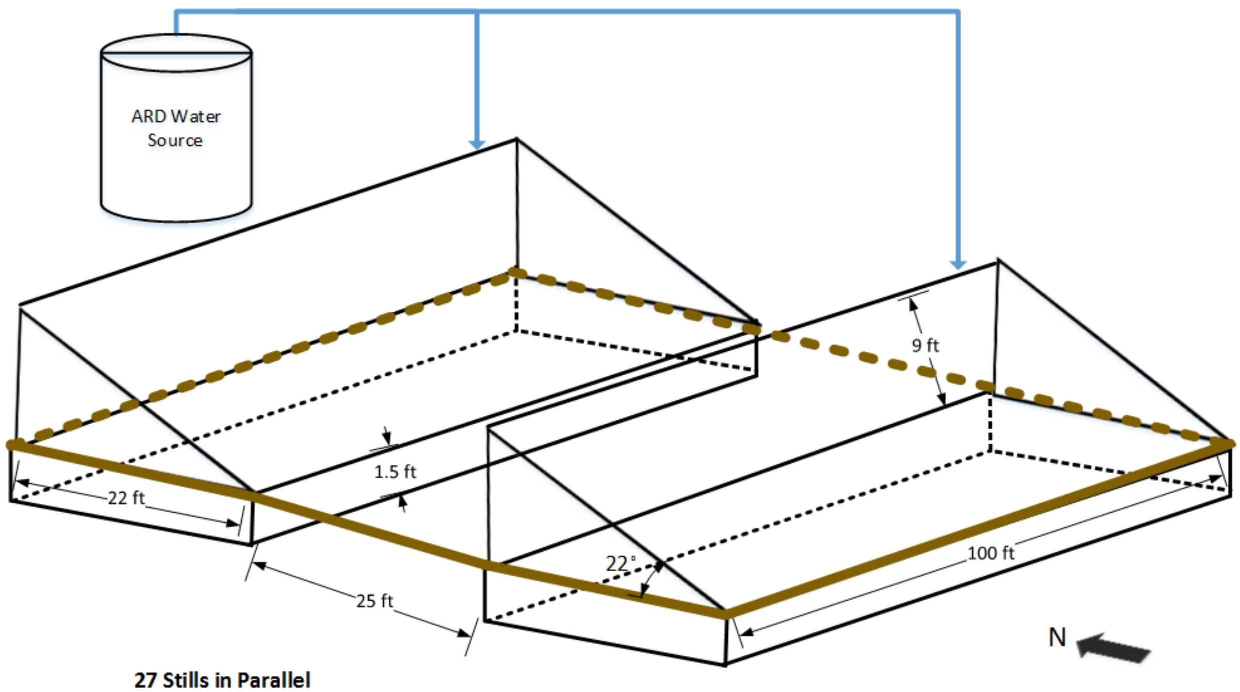


Figure 3: Basic Model Process Overview

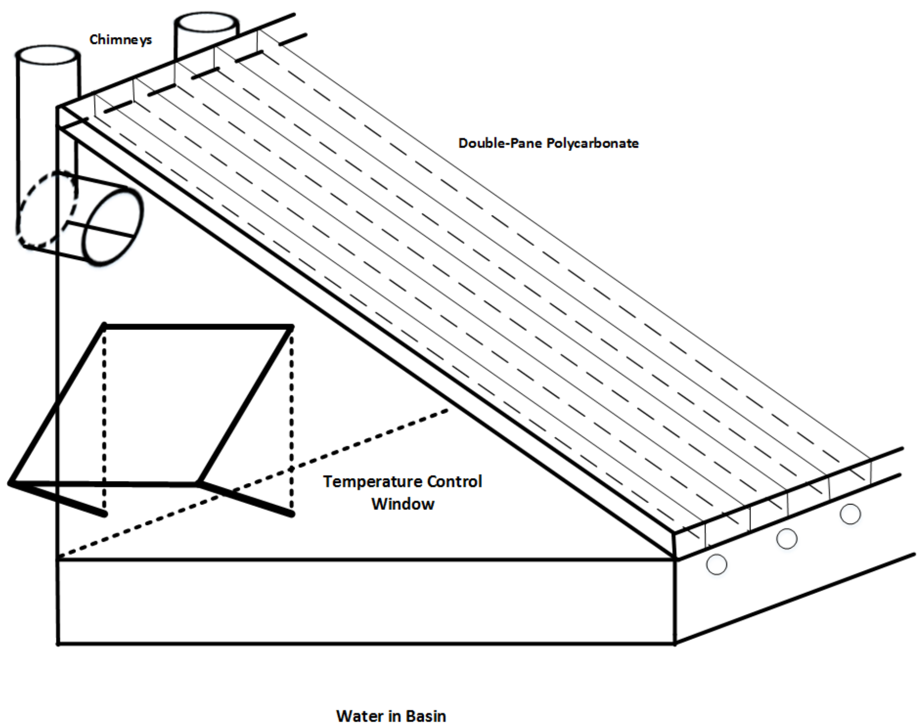
5.2 Construction

ARD enters the basin above ground through insulated, 1-inch Sch. 40 PVC pipes that are inserted into each still at two water-sealed points to distribute inlet flow. The legacy Copper Queen mine in Bisbee has existing gravity feed infrastructure that will allow ARD water to be fed to the stills at the desired flow rate. Holding basins are included in the feed system to allow for control of ARD flow during reduced sun activity or maintenance down time.

Each basin is a 102-foot by 22-foot rectangle, lined with a polymer sheet of ethylene-propylene-diene-monomer (EPDM), and is supported by a dirt berm with concrete posts everywhere there is a plywood support. Soil for the berm should be at the optimal angle of repose. The soil is at minimum six inches of native material compacted to 95 percent maximum dry density[13]. A secondary containment berm should be considered to ensure the ability to control an accidental release of the concentrated metal salt sludge. The bottom of the basin is insulated with two-inch rigid polystyrene foam panels under the EPDM liner. The two-inch thick polystyrene foam insulation is the recommended optimum thickness[14]. The walls of the stills are constructed of ½-inch treated plywood that is insulated with polystyrene sheets.

Clear, six-millimeter-thick, double-pane polycarbonate is the material of construction for the roof, and it is secured with an aluminum support structure. The selection of polycarbonate balances low cost, good mechanical properties, and transmission of solar radiation. While there are thicker polycarbonate sheets that minimize the heat lost through the sheet, it is at the cost of losing some of the transmittance of the polycarbonate, and A.R.D determined that this trade-off was not worthwhile. The polycarbonate sheet has a light transmittance of 82 percent[15]. The angle at which the polycarbonate is installed is 22 degrees to ensure that the average direction of solar radiation is directed into the still. In addition to the angle, it is important that the stills are facing due south, as this is the most convenient position for capturing the sun's energy over a whole year. Similar to how typical greenhouses are constructed, multiple 6-foot wide and 24-foot long polycarbonate sheets are fitted together in a support system and connected with aluminum glazing. The channel openings in the polycarbonate sheets are sealed with U-shaped aluminum channels to prevent condensation build-up inside the channels, as well as prevent the presence of fouling within the panels. The channels of the polycarbonate sheet are oriented in the vertical direction to allow the maximum amount of solar radiation to enter the still.

A failsafe is in place to ensure that the solar still system never reaches an inside temperature that exceeds the upper limit of the temperature range for the polycarbonate rooftop which is 120 degrees Celsius[15]. Two spring operated greenhouse windows on each short end of the still, open upon the melting of a choice material that will melt instantaneously when the temperature reaches 120 degrees Celsius. This allows heat to be purposefully lost from the system in order to cool



down the still. The windows will re-close upon contraction of the material back to its locked position.

5.3 Thermosiphons

Vapor is continuously expelled through ten thermosiphon chimneys evenly spaced along the back wall of each still. The chimney pipes are constructed of three-inch diameter PVC pipes that are each six feet tall. These dimensions were determined based on the amount of water vapor and air mixture that needs to be expelled from each still to achieve five gallons per minute of evaporation in total. The density difference between the ambient air and the vapor inside the still and inside the chimneys is the mechanism that moves the gases through the still[16]. The natural draft creates a pressure differential between the entering air and the exiting gases, which provides the motive force for flow to occur. Bernoulli's equation for flow into and through a hole was utilized to size the one hundred, one-inch diameter holes that allow air in. The purpose of this natural thermosiphon system is to minimize the relative humidity within the still. If the relative humidity exceeds 45 percent, the concentration difference that drives evaporation precedes in the opposite direction as shown in Table 3. Increased condensation on the inside surface of the polycarbonate also occurs at higher relative humidity. This condensation rolls off the roof and back into the basin, and the recirculation of this water decreases efficiency. A thermosiphon system is ideal because it eliminates the need for fans and the accompanying required solar power.

Table 3: Calculations for Relative Humidity Limit

RH %	$C_{A,\infty}$ (gmol/m³)	$C_{A,s}$ (gmol/m³)	$(C_{A,s}-C_{A,\infty})$ (gmol/m³)
0	0	7.190831548	7.190831548
10	1.612351763	7.190831548	5.578479784
20	3.224703527	7.190831548	3.966128021
30	4.83705529	7.190831548	2.353776257
40	6.449407054	7.190831548	0.741424494
50	8.061758817	7.190831548	-0.87092727

5.4 Life Time of Project

One important feature of the design by A.R.D is the long lifetime of the solar evaporator system and the minimal operation after start-up that makes the system almost fully passive. The lifetime of a sheet of double pane polycarbonate is ten years, therefore the polycarbonate sheets will need to be replaced once during the lifetime of the project. A schedule will be implemented to service the replacement of the polycarbonate sheets during the winter when efficiency is lowest. The remainder of the design includes the metal support system and concrete reinforcements, which will have a lifetime greater than 20 years. Solids will continuously accumulate in the bottom of the basin, and after 20 years, there will be 1.3 inches of dried particle accumulation within each of the 27 stills. This is calculated by determining that the mass of the sulfates left behind is 2.5 grams per liter of feed water, the solids average a specific gravity of 2.5, and the bottom surface are of one basin is 2,244 square feet. Since the water is fed at approximately the same rate at which the water is evaporated, the solids will be relatively dry. The solids will be removed using pneumatic solids removal trucks, which are similar to vacuum trucks. There will be multiple access points constructed in the unit to allow the truck to access the entire area of the still. A schedule should be determined to remove solids so that it is done one still at a time and does not disturb the system overall. A use for the removed metal sludge should be determined to improve the rate of return on this project. The best use would be to use a method to separate the sulfates into their individual species to be sold.

The minimum amount of maintenance required to ensure the success of the system will be to survey the system of solar stills once every two to three months. Maintenance will include, clearing the polycarbonate roof of any debris and ensuring that the one-inch feed water pipes are clear of build-up by using pressurized air. Iron oxidation can be a problem in transporting ARD water through the PVC pipes, therefore more frequent maintenance will be required. In total 6,480 hours of maintenance is required over the lifetime of all the stills.

6.0 ECONOMIC ANALYSIS

An analysis of the capital cost associated with each component of the construction materials and upfront construction labor costs for the solar still is shown in Table 4. The total maintenance cost is projected to be $360 annually per still. Labor costs reflect that three workers are present for one hour, four times a year. Three employees will be present throughout maintenance to ensure workplace safety. The total cost per square foot of this solar still design is compared to that of a 100-foot by 30-foot greenhouse that was analyzed by the Department of Agriculture at the University of Arkansas[17]. Waste disposal costs are neglected in the capital cost analysis due to the desire of Freeport McMoRan Inc. to find a beneficial end use of the solid sludge, as informed during the Copper Queen mine visit.

Table 4: Single Still Cost Analysis[17,18,19,20,21,22,23,24,25,26,27,28,29]

	Material	UOM	Amount	Rate	Contribution
Base and Dirt work	**2' X 18" X 18" Concrete Footers**	ft^3	333	$ 12.00	$ 3,996
	Pad Leveling Dirt Work	ft^2	2224	$ 0.34	$ 756
	Labor and Rebar				$ 1,100
	Polystyrene Insulation 8' X 4' X 2"	sheet	70	$ 30.00	$ 2,100
	Drivable Gravel Road	ft^2	1200	$ 1.00	$ 1,200
	EPDM Pond Liner 30' x 100' 45 mil	unit			$ 1,830
	Topsoil Excavation	yd^3	40	$ 100.00	$ 4,000
	Turf	ft^2	1056	$ 0.45	$ 475
	Land Cost	Acre	2	$ -	$ -
Walls and Supports	**Polystyrene Insulation 8' X 4' X 2"**	sheet	35	$ 30.00	$ 1,050
	Plywood 1/2"X 8' X 4'	sheet	78	$ 20.00	$ 1,560
	Treated Wood Supports 2'' X 4'' X 10'	board	74	$ 4.00	$ 296
	Frame Assembly	ft^2	2224	$ 0.53	$ 1,179
Roofing	**Polycarbonate 6 mm 6' X 24'**	sheet	17	$ 204.00	$ 3,468
	Aluminum Glazing Cap 8'	unit	52	$ 10.00	$ 520
	Aluminum End Cap 8'	unit	25	$ 17.00	$ 425
	Polycarbonate Replacement (10 years)				$ 5,250.00
	Miscellaneous Hardware				$ 2,500
	Roofing Structural Support				$ 5,000
Safety and Permitting	**Outbuilding Permitting**				$ 979
	Automatic Spring Vent	unit	2	$ 63.00	$ 126
Solids Management	**Pneumatic Solids Removal 700 Gallon Truck**	hr	6	$ 71.14	$ 427
Thermosiphons	**SCH 40 PVC 3"**	ft	65	$ 4.60	$ 299
	90° 3" PVC Elbow	unit	10	$ 2.78	$ 28
	3" Tank Vent Cap	unit	10	$ 13.50	$ 135
	Cable Support System				$ 500
Conclusions	**TOTAL ESTIMATION**				**$ 39,199**
	Useful Life Cost per Year				$ 1,959.94
	Cost per ft^2				$ 17.63
	Average Cost of Greenhouse per ft^2				$ 25.00

7.0 BENCH-SCALE TESTING

The bench-scale solar distillation unit consists of two parts: a basin and a sloped top, as shown in Figure 5. The 8-foot by 4-foot by ½-foot basin was constructed with ½-inch plywood. This material was chosen as the frame for its insulating characteristics and low price. The basin is lined with a dark-grey, 40-mil PVC liner that absorbs solar radiation and maintains a waterproof interior. PVC was chosen over other polymer liners due to its durability and local availability. The sloped top consists of a tilted plywood back, two triangular sides, a front piece, and a bottom connection channel that fits tightly over the basin. The perimeter of the plywood supports a ten-millimeter clear polycarbonate sheet. The bench-scale contains a ten-millimeter polycarbonate sheet for convenience of ordering as well as experimental curiosity. Polycarbonate is inexpensive, transparent in the visible/near-IR region, opaque to long-IR radiation, has high impact resistance, and has a large service temperature range. The polycarbonate edges lie inside aluminum channels, which permanently fasten it to the wooden frame of the still. The aluminum channels block wind from entering the gap in-between the two layers of the polycarbonate, ensuring maximum insulative properties. The wooden frame is surrounded by two-inch polystyrene insulation for added heat retention.

Figure 5: Front View of Bench-Scale Design

The maximum temperature observed in the vapor space of the still is 85 degrees Celsius and the maximum in the water is 65 degrees Celsius. A typical temperature profile for over a 24-hour period of testing is given in Figure 6.

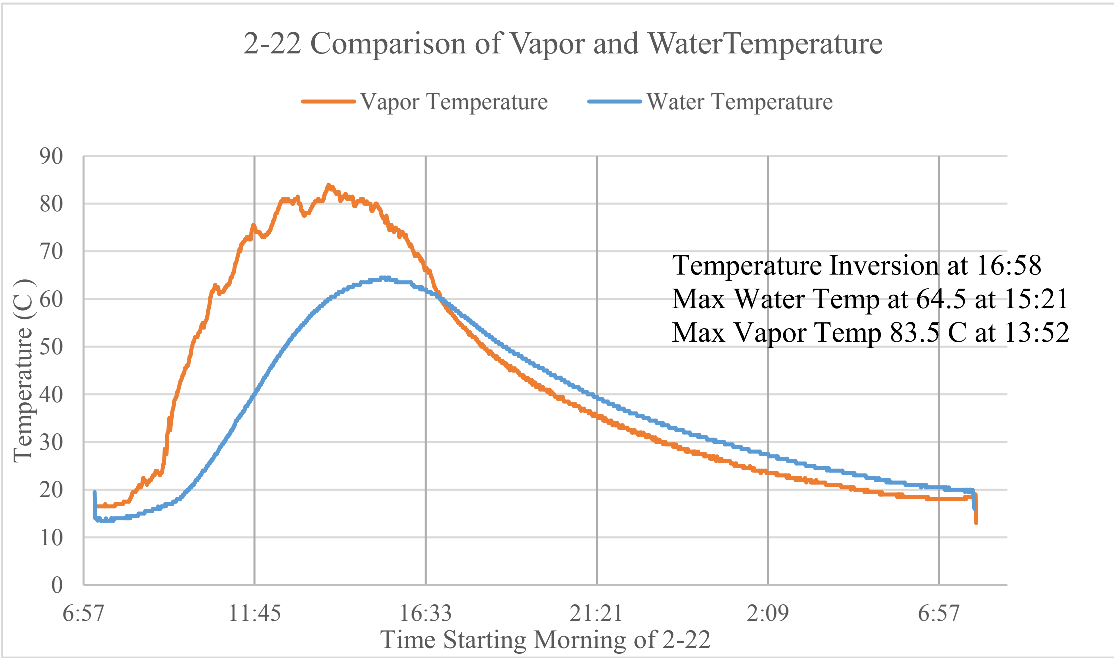


Figure 6: Temperature Profile of Still for February 22nd Test

Two exhaust fans on the back wall remove water vapor from the still. Dry air is provided to the still through ¼-inch holes on the opposing side, decreasing the relative humidity inside the still. Lower humidity in the still vapor space creates a larger driving force for evaporation to occur. Lower relative humidity prevents condensation from covering the inside face of the polycarbonate. Condensation on this surface increases light scattering of incoming solar radiation, which in turn diminishes the efficiency of the still. The purpose of the fans on the bench-scale still is to provide airflow, which will be provided in the full-scale unit by a thermosiphon system. A thermosiphon on the bench-scale will not create sufficient hydraulic head to provide the required air movement without needing a disproportionately tall chimney.

The first step in proving the need for airflow in the still was to install one exhaust fan paired with a four-inch dryer vent on the opposite side. The comparison of two similar days of testing shows that the evaporation rate increased 18 percent in the presence of fans, while the temperature profile in the still did not change much. The heat-up rates for these days are shown in Figures 7 and 8. In Trial 1, the four cfm fan was choked down to about half the flow rate. In Trial 2, the four cfm was operated without any additional constraint. Each trial was conducted over the course of 12 hours, specifically sunrise to sundown. Similar weather conditions were observed for each trial: few clouds, frequent wind gusts, and a high ambient temperature of 15.5 degrees Celsius. Over the course of Trial 1, the vapor space and water in the basin reached temperatures of 84 and 64.5 degrees Celsius respectively. Trial 2 experienced a maximum vapor space and water temperature of 84 and 64 degrees Celsius, despite higher airflow. Heat-up rates were comparable for each trial, but were slightly higher when airflow was lower. Faster condensation formation was observed on the polycarbonate surface when utilizing the lesser airflow, which decreased overall evaporation. The daily average evaporation rate was 5.8 mL/min in Trial 1, and 7.1 mL/min in Trial 2. This was determined through suctioning the remaining water with a shop vacuum and recording the difference in weight of the empty vacuum and the water-filled vacuum.

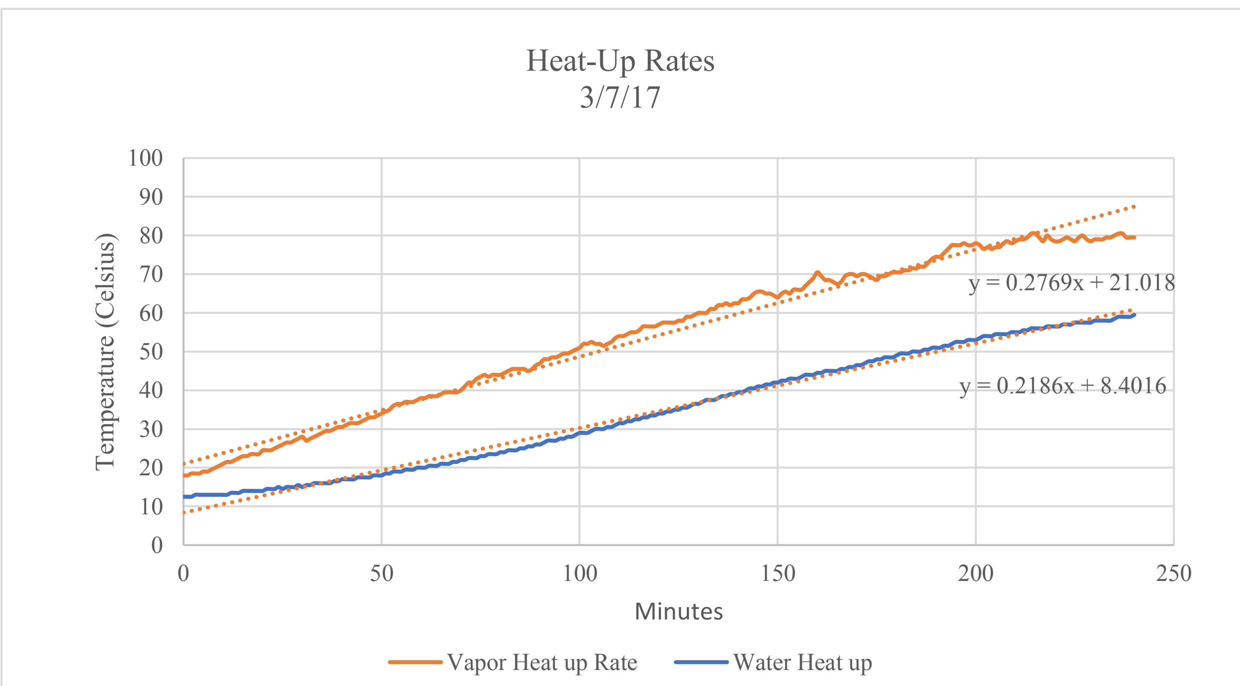


Figure 7: Heat-Up Rate Trial

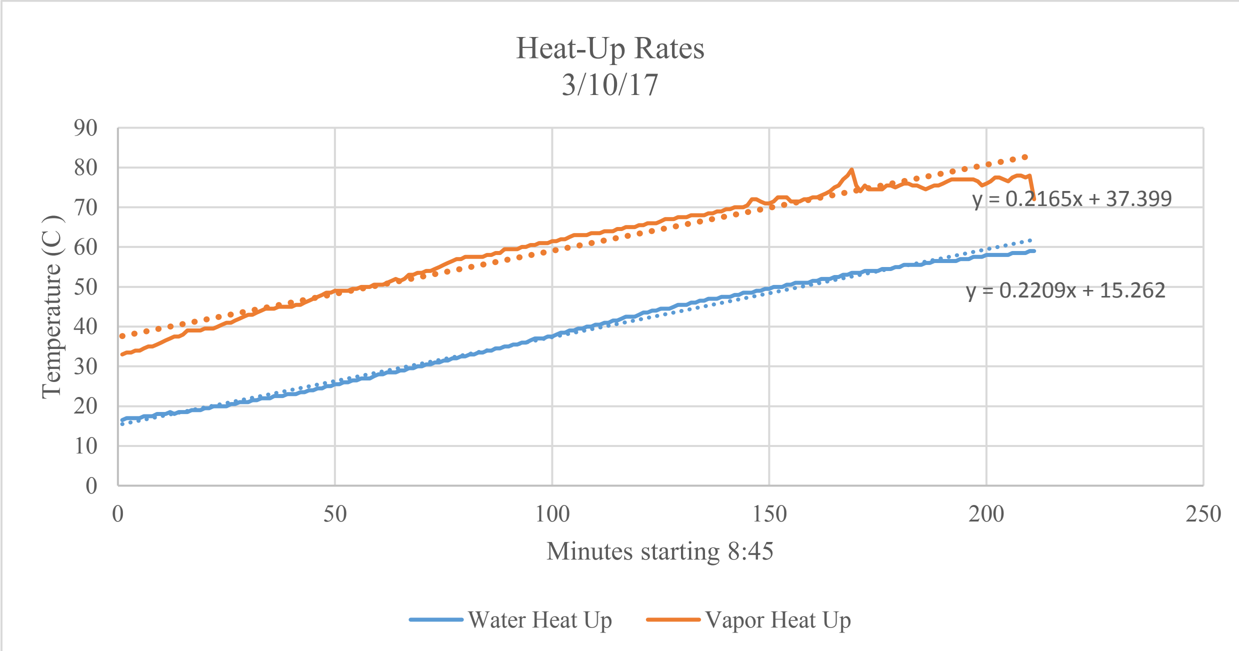


Figure 8: Heat-Up Rate Trial 2

8.0 MATHEMATICAL MODEL

The model developed by A.R.D. aims to compute the rate at which water evaporates and exits the solar still. The four parameters that have the greatest influence on the rate of evaporation are solar radiation, water temperature, fresh airflow into the still, and saturated air relative humidity. Heat and mass transfer are the mechanisms by which these factors vary. A set of nine ordinary differential equations were developed to illustrate how the four parameters affect the performance of the still.

The nine differential equations are based on material and energy balances corresponding to specific sub-regions of the still as shown in Figure 9. These nine regions are as follows: the top layer of the polycarbonate, the air gap between the polycarbonate, the bottom layer of the polycarbonate, the vapor space (volume where liquid water is not present), the low density polyethylene liner in the vapor space, the liquid water layer, the polyvinyl chloride layer in the basin, the concentration of water vapor at the polycarbonate-vapor space interface, and the amount of water vapor leaving the still.

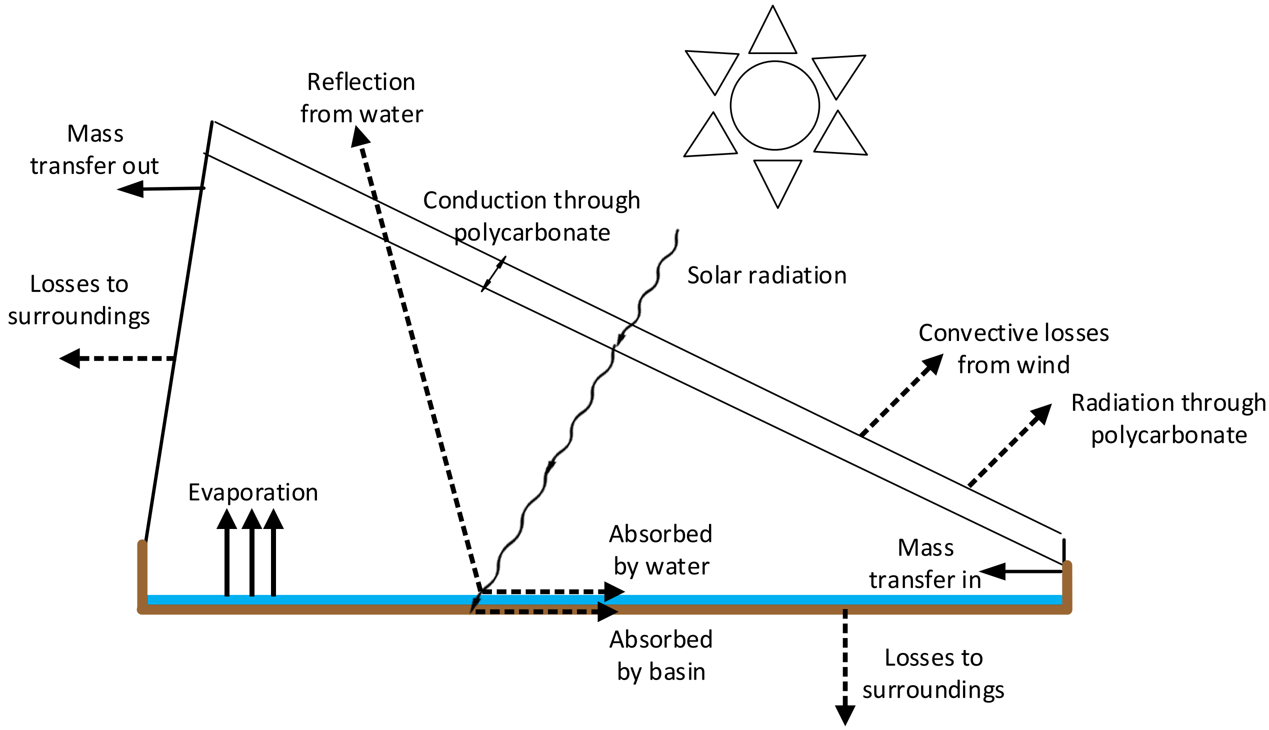


Figure 9: Heat and Mass Transfer in Still

Solar radiation is the initiating parameter for each energy balance. Data for the average solar flux reaching the Earth's surface, daily average temperatures, outside relative humidity, and wind speed were researched for Fayetteville, AR and Las Cruces, NM. These two locations were chosen because they are where the still is being tested. Curves were fitted to each set of data. The process of fitting curves to data is a simple way to get the variance required for the transient behavior of the still.

The following assumptions were made to simplify the calculations: each region of the still is at a uniform temperature, the amount of radiation emitted from the liners is negligible, long wavelength radiation cannot escape through the double paned polycarbonate sheet, the change in water level is negligible, and average physical properties over the temperature range. Each of the differential equations that are coded into the mathematical model are shown below in equations (1) through (9).

(1) $$\frac{dT_{pct}}{dt} = \frac{fraction\ absorbed_{pc}*Qrad_{s}*SA_{pc}+h_{ag}*SA_{pc}*\left(T_{ag}-T_{pct}\right)-h_{outside}*SA_{pc}*\left(T_{pct}-T_{ambient}\right))}{\rho_{pc}*SA_{pc}*x_{pc}*Cp_{pc}}$$

(2) $$\frac{dT_{ag}}{dt} = \frac{h_{ag}*SA_{pc}*\left(T_{pcb}-T_{ag}\right)-h_{ag}*SA_{pc}*\left(T_{ag}-T_{pct}\right)}{\rho_{air}*SA_{pc}*x_{ag}*Cp_{air}}$$

(3) $$\frac{dT_{pcb}}{dt} = \frac{fraction\ absorbed_{pc}*Qrad_{trans_{pct}}*SA_{pc}+15*h_{ldpe_{vs}}*SA_{pc}*\left(T_{vs}-T_{pcb}\right)-h_{ag}*SA_{pc}*\left(T_{pcb}-T_{ag}\right)}{\rho_{pc}*SA_{pc}*x_{pc}*Cp_{pc}}$$

(4) $$\frac{dT_{vs}}{dt} =$$

$$\frac{fraction\ absorbed_{vs}*Qrad_{trans_{pcb}}*SA_{vs}-15*h_{ldpe_{vs}}*SA_{vs}*\left(T_{ldpe}-T_{vs}\ \right)+\dot{N}_{A}*SA_{water}*Mw_{water}*H_{vaporization}* \dot{m}_{air_{leaving}}Cp_{air}*(T_{vs}-T_{ambient})-\dot{V}_{wv_{leaving}}*\rho_{wv}*H_{vaporization}}{\rho_{wva}*V_{vs}*Cp_{wva}}$$

(5) $$\frac{dT_{ldpe}}{dt} = \frac{fraction\ absorbed_{ldpe}*Qrad_{trans_{pcb}}*SA_{vs}*0.75-15*h_{ldpe_{vs}}*SA_{vs}*\left(T_{ldpe}-T_{vs}\right)-\frac{(T_{ldpe}-T_{ambient})}{Rt_{woodstyrene_{vs}}}}{\rho_{ldpe}*SA_{ldpe}*x_{ldpe}*Cp_{ldpe}}$$

(6) $$\frac{dT_{water}}{dt} =$$

$$\frac{fraction\ absorbed_{water}*Qrad_{trans_{pcb}}*SA_{water}+h_{water}*Sa_{PVC}*(T_{PVC}-T_{water}) -\dot{m}_{water}*Cp_{water}*\left(T_{water}-T_{water_{0}}\right)-\dot{N}_{A}*Mw_{water}*H_{vaporization}+15*h_{ldpe}*SA_{water}*(T_{vs}-T_{water})}{\rho_{water}*SA_{water}*x_{water}*Cp_{water}}$$

(7) $$\frac{dT_{PVC}}{dt} =$$

$$\frac{fraction\ absorbed_{PVC}*Qrad_{trans_{w}}*SA_{PVC}-h_{water}*SA_{water}*(T_{PVC}-T_{water})-\frac{\left(T_{PVC}-T_{ambient}\right)}{Rt_{woodstyrene_{wg}}}-\frac{(T_{PVC}-T_{ambient})}{Rt_{woodstyrene_{wsides}}}}{\rho_{PVC}*SA_{PVC}*x_{PVC}*Cp_{PVC}}$$

(8) $$\frac{dC_{A\infty}}{dt} = \frac{V_{fan}*Mw_{water}*C_{A_{outside}}+\dot{N}_{A}*SA_{water}*Mw_{water}-V_{fan}*\dot{Mw}_{water}*C_{A\infty}}{RH_{pc_{interface}}*Mw_{water}*SA_{water}*x_{water}}$$

(9) $$\frac{dm_{wv_{still}}}{dt} = V_{fan} * \dot{Mw}_{water} * C_{A\infty}$$

A comparison between the experimental data taken on March 10, 2017 and the mathematical model data for the conditions seen on that day is shown in Figure 10. The model accurately predicts the temperature profile for the water and vapor space temperatures to what is observed in the bench-scale. The difference in the water temperature profile can be attributed to the way the water temperature is measured for the bench-scale. A thermocouple with a data logger is inserted inside the still touching the water. However, the water level is distributed very thin across the basin, and therefore the thermocouple may not remain in the water throughout the twelve-hour testing time.

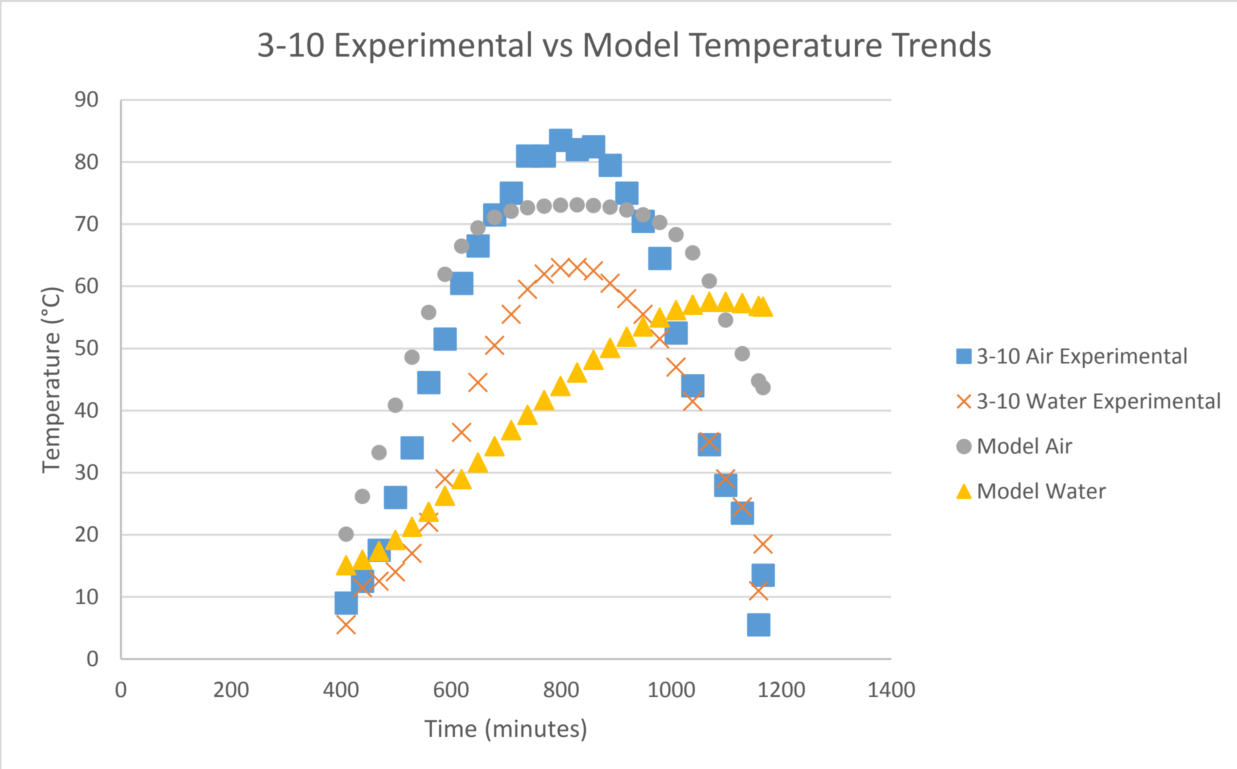


Figure 10: Experimental Data and Model Data

The trial conducted on March 10 evaporated five liters of water and the MatLab model predicted that 14 liters would be evaporated. The current bench scale output is only 36% of the predicted output, therefore there are some discrepancies between the model and experimental unit that are being investigated, and there are plans to improve the efficiency. Some sources of the discrepancy are the non-ideal weather conditions experienced in Fayetteville, AR during testing. These weather conditions have limited the amount of solar radiation that is able to penetrate the polycarbonate barrier into our water.

The mathematical model will be used in future experimentation to determine what the optimum airflow throughout the still is to maximize the evaporation rate of the still.

9.0 REGULATIONS

The enforcement of water treatment and discharge regulations falls under the jurisdiction of the individual states through the Environmental Protection Agency (EPA). Each state is responsible for regulating the waters within its boundaries and can tailor regulations to their specific needs, provided the state adopts regulations that meet or exceed minimum federal standards[30].

The primary regulatory means for ensuring public water quality in the United States is the Clean Water Act (CWA)[31]. The goals of the CWA are to protect water quality for wildlife and recreation and to eliminate the discharge of pollutants into navigable and surface waters. The National Pollutant Discharge Elimination System (NPDES), established under Section 402 of the CWA, regulates sources that discharge pollutants into U.S. public waters or publicly owned treatment works (POTW) [32]. This design evaporates the water and will not discharge to U.S. public waters or POTW, therefore an NPDES permit is not necessary.

Arizona Pollution Discharge Elimination System (AZPDES) is responsible for mine drainage discharge for the state of Arizona. AZPDES requires an individual permit to discharge water through a point source into U.S. waters. Since only water vapor will be exiting the still, an AZPDES individual permit will not be required[33].

The excess sludge is considered hazardous due to the zinc and iron sulfates present and its low pH, therefore Large Quantity Generator (LQG) EPA regulations must be considered[34]. The left over salts are retained in the still until a final cleaning out procedure. Due to this technicality, they are still in a process vessel, and not a generated waste and are therefore exempt from LQG regulations during operation[35,36]. This was determined when visiting the Fayetteville Biosolids Management facility.

Building codes and regulations will also need to be considered before constructing the solar stills. The stills will not be considered confined spaces since there will be many entries and exits available for workers[37]. The structure is considered a membrane structure. According to section 3102 of the International Building Code, facilities not intended for human occupancy are required to meet only sections 3102.3.1 and 3102.7 requirements. Section 3102.3.1 states that the interior liner must be noncombustible unless the liner is 0.5 mm thick plastic or less for use in greenhouses. The structure will also need to be able to sustain dead loads, seismic loads, those due to tension, and live loads, which include wind, flood, or snow[38]. This is accounted for in the design with the concrete support for the basin of each still.

When constructing a dirt berm, the Cochise Country zoning regulations require adequate plant material or ground cover treatment to prevent erosion[39]. AZDEQ regulations require a composite liner of at least 30-mil thick to line the bottom of the dirt berm pond[13].

10.0 SAFETY CONSIDERATIONS

The prominent health and safety concerns include thermal hazards, installation, and maintenance. Since the solar stills will be constructed in a desert area, construction is best accomplished in early mornings and late evenings to prevent the effects of dehydration and heat exhaustion. The same precaution will need to take place when doing maintenance on the still since it will operate at approximately 80 degrees Celsius. The maintenance team will need to wait until the still has cooled below 60 degrees Celsius before entering it. Proper hydration and safety techniques must be taught and always followed. Since the concentrated sulfate sludge is hazardous, maintenance workers will need to wear chemical suits when cleaning the still. The still could become a confined space so it is necessary to ensure that in the construction of the still, multiple points of entry are included. Before construction begins, a meeting will be held to address safety concerns. Bacteria growth is a potential problem in any moist, enclosed space, especially Legionnaire organisms. However, since the stills operate at temperatures above 60 degrees Celsius, conditions are sufficient to prevent normal bacteria growth.

11.0 PUBLIC INVOLVEMENT

An important element for the success of this design process is informing the local communities, the closest one being the town of Bisbee. Citizens should be made aware of the treatment process and learn how it can improve their environment. To accomplish this task, an informational presentation will be given at a Bisbee town hall meeting. This presentation will discuss what ARD water is, the negative effects it has, and how to solve this problem. In addition, there will be a short tutorial at the end teaching community members how to spot ARD water, and whom they should report any sightings to. This presentation will also address any concerns the local residents may have.

12.0 SCALABILITY

Ease of construction is important for both scaling up and down any design. A.R.D. designed the full-scale solar distillation system prior to testing the bench-scale apparatus. Therefore, the bench scale accurately represents the efficiency of the larger full-scale version. The only significant difference between the two scales is that the full-scale will have a significantly larger vapor space to liquid space ratio. This occurs because the desired water level will remain low to decrease the time required to heat up the still each day. This will increase the driving force for evaporation because more vapor will need to be generated to effect the humidity level. Taking into account that the full scale will have a thermosiphon to keep the humidity low as well, the driving force to cause evaporation will only increase.

13.0 CONCLUSIONS

The total initial capital cost for 27 stills is $1,100,000. The monthly payment if amortized over twenty years, with a 5% interest, is $7,128. The yearly cost of operation checks for all units is $10,000. The end of life labor cost for removing the solids is $3,800 for all units. Therefore, the cost of this system at the end of the project lifetime is $1,900,000. This cost includes the interest on the necessary loan. There are 52,560,000 gallons of water distilled over the lifetime of this project, which amounts to $36 per 1,000 gallons. The main objective of this report was to present a description of the multiple solar still system designed by A.R.D. If this design is implemented, it should be an excellent method for passively treating acid mine drainage and evaporating it to the atmosphere. This design was created from research, site characteristics, bench-scale experiments, and data collection. The solar still system was designed with safety, the community, and sustainability in mind.

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AUDITS

[redacted]

[redacted]

March 14, [redacted]

[redacted]

RE: Review of WERC proposal
<u>Passive Solar Distillation of ARD Waters</u>

Dear [redacted]

Thank you for the opportunity to review your design and report for a passive solar distillation system for acid rock drainage (ARD). As you witnessed at the Copper queen Mine facility during your visit in January, management of ARD is the primary function of the approximately twenty individuals here.

A couple of housekeeping comments first. Since "ore" is an economic term used to denote mineralization from which materials can be profitably extracted, I recommend changing the sentence in the second paragraph of the introduction to: "ARD is produced when water contacts mineralized rock containing metal sulfides." Also, the experimental bio-system that was operated at the Copper queen Mine produced hydrogen sulfide gas, by feeding sulfur to microbes, which was then sparged through a column of ARD. The metal ions in the ARD reacted with the H2S and produced a metal sulfide concentrate that was then sent to our smelter for further processing. We are currently using a similar method using purchased H2S to treat groundwater at a site in Oklahoma. Additionally, we have successfully used passive sulfate-reducing bioreactors (SRBRs) that utilize lime, microbes and a source of cellulose such as wood chips, sawdust or cow manure at sites in Western New Mexico, Northwest Arizona and Central Colorado to treat small ARD streams.

As you mention in your report, evaporation is an effective method for treating ARD that utilize the advantages of relatively low precipitation and high evaporation rates found in the desert Southwest. Large solar evaporation ponds have been used historically at some mining operations that produce large quantities of excess water above that needed for operations. A disadvantage of using the large solar ponds is the annul re-wetting and subsequent dissolution of the precipitated salts during the months of July and August resulting in solutions with a high specific gravity that become increasingly difficult to evaporate.

Your design for a solar still to treat smaller ARD streams removes the possibility of re-wetting the precipitated salts and has the potential to be an economic technology. The costs that you have generated seem to be reasonable with the exception of the low annual operational and maintenance (O&M) cost. This comment is based on a minor problem that we have encountered in our SRBR's at other sites. The plugging of small diameter pipes that carry ARD to the treatment facility by encrustations of a combination of precipitates, iron oxidizing microbes and sedimentation is a continual problem that requires more frequent attention than possible on a six month interval. Also, the reliance on fans that utilize bearings as a critical element of the design, I believe, warrants more frequent inspections to ensure the fans are operational.

Your decision to design a scaled-up version of the system before building a bench scale version and your inclusion of costs for earthwork items is commendable and demonstrates your understanding of constructability issues. Your verbalization of the problem and of a well thought out potential solution are also commendable.

Good luck in the competition. Please let me know how your team fares.

Sincerely,

WERC 2017

Passive Solar Distillation

Of ARD Waters – Task 2

Biosolids Management Site Lead Operator

I have had the privilege of reviewing the Team's paper on "Passive Solar Distillation of ARD Waters". I manage the day to day activities at the Biosolids Management Site where six Solar Drying Houses are operated. I have a background in EPA and OSHA compliance related to the General Industry sector and hold a Level 3 Wastewater License. The report generated by the Team is well researched and captures the fundamental steps of an intriguing process to treat acid rock drainage waters.

A few observations and comments:

§ Evaporators are often used to treat hazardous wastes. Would the regulating agency consider ARD waters a hazardous waste and therefore the use of the evaporator as a treatment method? That tie could bring in the need for an Air Permit evaluation.

§ The conditionally exempt small quantity generator status is the correct category based on the report data. However, the continued search for an end point recycler for the metals laden sludge would make the process even more environmentally friendly, possibly support a quicker return on investment, and reduce regulatory compliance reporting.

§ Placement of the single entry door into the still is important as related to the Confined Space issue. If the single door is located at the end of the 102 foot long still, that may be considered "limited" means of entry or egress. Couple that with the still containing or having the potiental to contain a hazardous atmosphere and it becomes a Permit Required Confined Space. Placement of the entry door and further research into the makeup of the still's atmosphere may be necessary.

§ Building in a secondary containment concept may be worth investigating. If the still is damaged in some fashion, the ability to control the release of the concentrated metal laden sludge would be advantageous.

The Team's report is very well thought out and researched. Most impressive is the low technology approach that keeps investment costs and inputs to a minimum. I was impressed with the Team's resourcefulness to use the Biosolids Management Site as a source of information. It is encouraging to see the Team working to resolve identified issues and improve system efficiency.

March 15, [redacted]

AUDIT

Issuing Organization:
New Mexico State University
2017 International Environmental Design Contest
Task 2: Passive Solar Distillation of ARD Waters

Submitting Organization:

[redacted]

Reviewer:

[redacted]

I am privileged to have been asked to conduct an audit review for the written report of WERC's Task 2 that has been prepared by students at the [redacted]

Task 2 requires the design of a passive solar distillation system that can treat up to 5 gallons per minute of acid rock drainage (ARD). The solar system is to be specifically designed for a remote site with limited access and no utilities other than solar energy. The system must produce clean water suitable for discharge and precipitated salts for disposal.

Task 2 guidelines state that the design should provide specific details and outcomes as follows:

- Estimate the total surface area of solar capture that will be required to treat the flow.
- The design should require no outside power source. All equipment should operate using gravity or solar power.
- Address materials of construction for this acidic water.
- Address design considerations for variable solar availability (i.e. nights, cloudy days and winter).
- Address how the solids generated from salts in the water will be stored and managed.
- Address expected water quality of the clean water at discharge.

Review Comments

Overall, the written report is well organized, concise and written clearly. WERC's written report guidelines for page length, formatting and required components i.e., public involvement, economic analysis and safety all appear to be complied with.
Members of the team visited the [redacted] mining site in [redacted], the proposed site for the full-scale installation of their solar still design. Very commendable.

Several technologies were evaluated based on a literature review and resulted in the selection of a solar still design due to the economics and ease of operation. Health issues of operating and maintaining the still are addressed (may be add some info on the lead/acid batteries) and a public education/information town hall are planned. It is not clear how close the nearest town is to the mine site.

Regulatory requirements for discharge of the evaporated water and construction permits for the 27 stills are discussed.

The following comments are offered for consideration in the hopes some may be used to strengthen the team's efforts and increase the likelihood for the full-scale construction of their design:

- Show the calculations you use to derive data, i.e., "there would be 1.3 inches of particle accumulation throughout each of the 27 stills". (pg 11)
- Include costs for the land required for the stills.
- Develop cost savings of using solar stills to that of the current mitigation process.
- Include the cost for transporting and disposing of the hazardous precipitates.
- Discuss any potential for volatile organic compounds (VOCs) found in permanent anti-fog coatings and EPDM that could degrade the quality of the discharged water vapor.
- Identify potential beneficial uses for the 52,560,000 gallons of evaporated water that will be discharged, it's in a desert environment.
- Expand upon creative ways like the vertical wicks to increase efficiency i.e., heat exchangers; pre-heating the air used to control the relative humidity; rather than insulating the 1" feed lines paint the pipes black and expose them to the sunlight.

My congratulations to each of the team's members on a great team effort, it was encouraging to read your report and it gives me great hope to see how our talented university students are preparing to lead us into a brighter future.

Project Audit

March 14, [redacted]

[redacted]

[redacted]

Re: WERC 2017 - Passive Solar Distillation of ARD Waters

As requested, I have reviewed the [redacted] report on Passive Solar Distillation of ARD Waters. My observations are as follows:

- The team has performed a good technology background research, outlining advantages and disadvantages of principal water treatment technologies.
- The suggested design contains no provisions for the feed water flow control. Despite the use of gravity feed, the team should consider designing an active flow control to maintain the desired water levels in the still holding basins during periods of decreased sun activity and/or reduced still efficiency.
- The cost of the auxiliary lead acid battery storage system (replacement and maintenance) should be added to the system cost analysis.
- The team has suggested an elegant maximum temperature control mechanism using spring operated wax sealed windows. However, it is not clear how the system would return to normal operation once the safety action is triggered and the temperature decreases to safe levels.
- Feed water contains sulfates which could cause scaling on all surfaces contacted by the process water. Future experimentation section should be used to evaluate and retire the scaling risks and suggest the desired cleaning frequency and methods.

Overall, this is a good system design and I expect that the bench scale demonstration will yield positive results for this team.

Sincerely,