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Water purification for rural communities using ultraviolet light and bleach systems

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Water Purification for Rural Communities Using Ultraviolet Light and Bleach Systems

An Undergraduate Honors College Thesis

in the

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Fayetteville, AR

by

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I participated in a senior capstone design course called WERC. Our project was Task # 7 Clean Energy Water Disinfection for Small, Remote, Rural Communities. I was the team coordinator and was in charge of organization and planning. I led team meetings and assigned work to individuals. I operated essentially as a manager and worked on just about everything in the project.

During the start of the project, I researched various chemicals as a means for water disinfection. I focused on ozonation, iodine, hydrogen peroxide, and household bleach. I weighed each chemical technology according to its advantages and disadvantages. I was also instrumental in ordering several filters from online vendors and from Lowes. I helped design experiments to determine which technology to use. I tested alternative filtration technologies such as microfiltration and sand filters. I also tested the one micron bag filter, activated carbon, treadle pump, mixing tank, and the Ultraviolet light (UV) and bleach disinfection methods. The UV and bleach disinfection methods were testing using clarified water from Noland Waste Water Treatment Facility in Fayetteville, Arkansas and water from Mullins Creek. The overall system was tested a couple times at Mullins Creek on the campus of the University of Arkansas. I also ran several experiments involving activated carbon and bleach. The first experiment was to determine the loading capacity of activated carbon. The second experiment determined the amount of time required for bleach disinfection. The third experiment was to determine if bleach could be flushed from the activated carbon so the activated carbon could be reused.

During the building phase, I played a vital role helping build the system and buying parts for the system. I also helped build and design parts of the systems. I helped build the treadle pump and sand filter. I also designed the paddle for the storage system.

For the paper, I was in charge of putting the sections of the paper together in one file and formatting it to meet WERC's guidelines. I wrote the sections on design premises, ozonation, iodine, hydrogen peroxide, proposed treatment schedule, and economic analysis. I helped edit the entire paper. I was also in charge of acquiring peer reviews from professionals within the community. For the presentation, I focused on the bleach system as well as the economic analysis. I helped edit the presentation and place the slides in a logical order. For implementation, I helped receive funding from the University of Arkansas Honors College to take our project to a community in need. I wrote the economic section of the proposal. I also talked with contacts within the University of Arkansas and outside about implementation.

The conclusion of our project occurred at New Mexico State University in Las Cruces, New Mexico. I helped present our project to judges, faculty, and students for a period of three days. During question and answer sessions, I directed questions to the appropriate team member. Our team ended up winning 2nd place in Task # 7 and won the Intel Innovation Award.

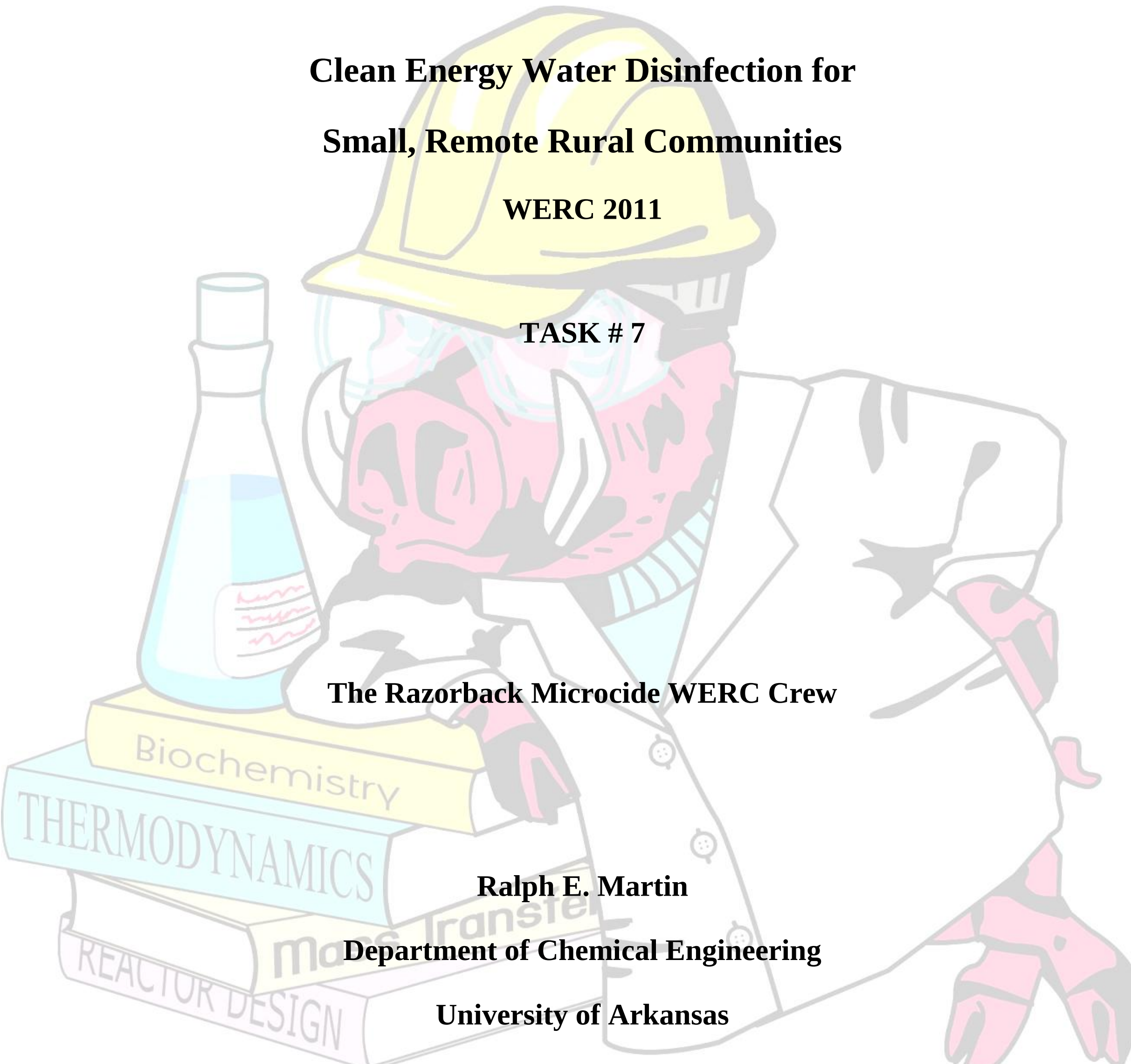
Appendix

Clean Energy Water Disinfection for

Small, Remote Rural Communities

WERC 2011

TASK # 7



The Razorback Microcide WERC Crew

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Clean Energy Water Disinfection for
Small, Remote Rural Communities

TASK # 7

WERC 2011

April 3-7, 2011

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1.0 EXECUTIVE SUMMARY

Access to drinking water is essential to all life, yet in many developing and remote communities, it is often contaminated with disease causing pathogens. This project developed human powered, stand-alone, effective, easily implemented, and economical water disinfection systems. Many technologies were evaluated; however, bleach and ultraviolet (UV) light treatments were determined to be most applicable to satisfy the requirements of Task # 7 of the 2011 WERC Design Contest. The Razorback Microcide WERC Crew designed and demonstrated two systems independently featuring bleach and UV disinfection technology.

In both designs, the pretreatment system consists of the following: a sand filter which removes debris and turbidity, a treadle pump which moves water through the system, a granular carbon bed which removes organic chemicals and turbidity, and a one micron bag filter which removes cysts and larger pathogens. Both systems also include a high capacity, inexpensive, reliable, human powered treadle pump which can sustainably operate at 15 gpm. Following pretreatment, either bleach or UV is utilized to kill pathogens. In the bleach treatment, the pathogens are killed after bleach is blended with the water in 1,500 gallon storage tanks; the UV system kills pathogens in-line as the water flows through a UV unit. The bleach system, which operates using only human power, treats 3,000 gallons of water in five hours. The UV system treats 3,000 gallons of water in 9 hours and operates using solar power. Both systems are portable via light truck. They both can be operable within two to five days and be built on-site in remote communities and in third world settings, such as Haiti.

The first cost of the UV system is $1,485 and the weekly operating cost is $41, including $28 for bacterial testing. The first cost of the bleach system is $550 and the weekly operating cost is $20.

The Razorback Microcide WERC Crew prefers the bleach system because it has a low initial cost, is very reliable, needs only eight cups of bleach per day to treat 3,000 gallons of water, requires only human power, and is easy to maintain. Bleach is available in remote places, and is a well-established, trusted, and EPA recommended method for water disinfection. The UV technology is also a feasible option which requires no chemicals but reliably kills bacteria and viruses; however, it is moderately more expensive than the bleach process. The UV system produces no disinfection byproducts and is less prone to deviation primarily arising from human errors. The Microcide Crew has provided two excellent choices for water treatment in the absence of outside power. The communities in need can weigh the advantages and disadvantages and choose which system best suits their needs.

The Crew's water disinfecting systems meet all the design premises for WERC Task # 7. Both utilize only clean energy. Both produce 3,000 gallons per day of potable and palatable water which meets WHO standards. Both systems are easily implemented, easily maintained and operated, cost effective, and portable using one light truck. The bleach system is ideal for third world settings; whereas the UV system is ideal for any community in the US and could be implemented in third world countries with proper training and maintenance.

The Crew has no firm commitments at the due date of this report; however, the Crew is actively pursuing avenues to implement this technology in Haiti with an objective of having one system in operation by June 1, 2011.

2.0 INTRODUCTION

Water-borne illness continues to trouble developing countries as well as disaster-stricken areas. The United Nations estimates that water-borne diseases account for nearly 80 percent of all deaths in the developing world and one in six people do not have access to clean water.[1] This project proposes methods to treat 3,000 gallons of water per day to WHO drinking standards for a small community of around 500 people that use only clean energy.

2.1 Currently Implemented Systems

Many technologies are used for water disinfection. Chlorine, iodine, and ozone are some chemical methods of water disinfection. Filtration, including microfiltration, ultrafiltration, and reverse osmosis, is used to remove bacteria. In addition to chemical and filtration technologies, one can disinfect water using UV irradiation, ultrasonic treatment, electrolysis, solar disinfection, and slow sand filtration.

Currently, there are few solutions being employed in third world settings for communities. The current solutions are either for one household or are part of an existing infrastructure and therefore are not portable. Slow sand filtration is used successfully to provide potable water for individual households.[2] Tablet chlorine systems have been implemented to disinfect municipal water supplies.[3] General Electric has implemented an ultrafiltration unit in several locations in Haiti which can produce 5,000 gallons of clean water per day, although the system costs roughly $25,000.[4] Many solutions have been implemented in the third world through philanthropic sponsors and various organizations. However, there are not enough sustainable drinking water systems in third world countries. The WERC Crew has an active effort to implement these technologies in Haiti.

3.0 DESIGN PREMISES

The design premises are:

1. Utilize clean energy (i.e. solar, wind, human)
2. Disinfect water to World Health Organization (WHO) drinking water standards for bacterial contamination
3. Provide 3,000 gallon per day of disinfected drinking water.
4. The system must be designed so it is:
   A. Easy to implement
   B. Easy to maintain and operate
   C. Portable
   D. Cost effective
   E. Applicable to rural and third-world settings

4.0 TECHNOLOGIES CONSIDERED

While many different technologies were considered, not all fit the requirements. The advantages and disadvantages of various systems will be discussed. The primary reason for rejection will also be stated.

4.1 Slow Sand Filtration

Slow sand filtration is most often implemented in a single family setting. Slow sand filtration is essentially a multimedia filter with different layers of sand and gravel. Over a period of 1-2 months, a biological layer called a schmutzdecke develops on the surface, which digests disease causing parasites and viruses. After passing through the schmutzdecke, the water enters the filter bed where screening and sedimentation take place. The operation yields potable water, but the limited capacity and slow startup of the system were severe disadvantages for satisfying the stated requirements of Task # 7.

4.2 Membrane Filtration

Ultrafiltration (UF) is an excellent defense against bacteria, viruses, protozoa, and cysts, provided membrane integrity is conserved. The small pore size (0.001-0.02 µm)[6] of UF units rejects all harmful microbes including *Giardia lamblia* and *Cryptosporidium*, which are resistant to chlorine treatments. Ultrafiltration can be implemented with only a sediment filter before the unit to produce potable water; it represents a very complete solution itself. The primary disadvantage of UF is the relatively high pressure drop. Seader and Henley report that UF membranes require a pressure drop from 10-100 psi while microfiltration membranes require only 1-10 psi.[6] A disadvantage of a UF system is the power requirements are greater than can be provided by human power. Another disadvantage is the need for backwashing to mitigate fouling.

As with ultrafiltration, microfiltration provides ample removal of bacteria. According to WHO[8], microfiltration removes 99.9% of bacteria and 90% of viruses. Microfiltration, like UF, also requires a preceding sediment filter. Microfilters pose the same problems as ultrafiltration to an extent. Microfilters require less pressure drop than UF, but the increased pore size (0.02-10 µm)[6] leads to the need for more frequent backwashing and unrecoverable fouling due to pore pluggage. Like all membrane systems, membrane integrity is another issue because of possible rupture. Another disadvantage of microfiltration compared to UF is shorter membrane life. The smaller pores of UF completely reject particles which can lodge in a microfilter, making the microfilter more susceptible to fouling.[5] These disadvantages combined with the high capital cost make both micro and ultrafiltration unacceptable for Task # 7.

The third membrane separation process considered was reverse osmosis (RO). RO removes nearly all contaminants. The high pressure drop (40-60 psi), high cost of membrane units in parallel, and membrane integrity makes RO very uneconomical.

4.3 Solar Disinfection

Both solar distillation and radiation were considered as methods of disinfection. While both provide ample bacteria removal, both require large heat transfer areas, thus portability is a key issue.

4.4 Ultrasonic Disinfection

Most ultrasonic disinfection systems are used in conjunction with UV systems to help inactivate *Giardia lamblia* and *Cryptosporidium*. Ultrasonic systems are effective, but the amount of energy input required outweighs the potential benefits.

4.5 Ozonation

Ozone is widely used in water treatment. It causes fewer dangerous byproducts than other chemical treatments and disinfects 3000 times faster than chlorine.[17] Treating water with ozone kills 99.9% of bacteria and also kills viruses. Ozone was eliminated because it has high first costs and requires large amounts of energy.

4.6 Iodine

Iodine is mainly used as a field water disinfectant. It is added in tablet or crystallized form. It works best when the water is over 68^oF. Iodine is available in kits and is more effective than chlorine in removing *Giardia lamblia* cysts. Disadvantages of iodine, however, outweigh the benefits for this application. Iodine kills many pathogens, but not all. It was eliminated because it leaves a bad taste, is sensitive to light, and causes allergic reactions in some people.

4.7 Hydrogen Peroxide

Hydrogen Peroxide (H_2O_2) acts in a similar manner as ozone. Free radicals decompose pollutants. It reacts very fast and decomposes into oxygen and water. H_2O_2 is easy to use and prevents formation of colors and byproducts. Yet H_2O_2 is phytotoxic in high dosages, decreases pH, requires high concentrations to be effective, and is expensive.

4.8 Pumping Technology

In addition to alternative disinfection techniques, the team evaluated several technologies for the pumping of water.

4.8.1 Bicycle pump

The bicycle pump is a proven, effective means of pumping water. The biggest drawbacks of bicycle pumps are (1) the limited sustainable flow rate and (2) the required energy input from humans. Harvest H_2O[7] estimates a sustainable flow rate for a healthy male is about three gallons per minute. A treadle pump is more efficient than a bicycle pump because the treadle pump is operated with a natural stepping motion rather than a rotary motion. The piston pump has a higher pumping efficiency than a centrifugal or tubing pump, which are the pumps normally powered by bicycle.

4.8.2 Electric Pumps

Electric pumps provide a steady stream of water at a constant pressure, and given sufficient electrical power, are ideal pumps. For Task # 7, power is the biggest issue associated with electrical pumps. Battery systems charged by solar panels or other renewable energy sources are necessary. The pumps and their power systems are also expensive compared to human powered pumps. Electric pumping systems are complicated thus skilled labor is required should repairs become necessary. In small sizes, the pump and motor are inefficient, so electricity becomes uneconomical, thus electric pumps are unacceptable for Task # 7.

4.9 Alternative Energy

4.9.1 Hydroelectric Power

If available, hydroelectric power (HEP) is another reliable source of alternative energy. But HEP comes with some major disadvantages. The availability severely hinders the applicable sites. Also, small HEP systems are not economical.

4.9.1 Wind Power

Wind power is potentially one of the cheapest sources of alternative energy, but wind power, like hydroelectric, is reliable only in certain locales.

5.0 EXPERIMENTAL

Experimentation was divided into three major categories: pre-filtration, pumping, and disinfection. The decontamination methods were narrowed down to UV and bleach disinfection for the reasons stated above. System designs and operations were varied in order to determine the optimum effectiveness.

5.1 Pre-filtration

Both bleach and UV systems require turbidity reduction in order to provide the greatest effectiveness. Effectiveness of the pre-filtration system was determined based on turbidity reduction of the filtered water. Turbidity was tested using a nephelometer. A gravity fed five gallon sand filter was initially used. This design fed water through the bottom of a sand filter, then rose and flowed into a bag filter. This filter system was found to have too high pressure drop and insufficient turbidity reduction. The final design for the pre-filter is an 18 gallon submersible sand filter, which is described below. Turbidity tests were conducted using two sources of water. Turbidity within creek water was reduced from an average of 5.1

nephelometric turbidity units (NTU) to 2.2 NTU. Water from a standing pond had a turbidity reduction from an average of 22 NTU to 10 NTU. Both cases showed a 55% reduction in turbidity. The sand filter effectively removed all sediment from the water.

The water from both sources still had a mild green tint, caused by organic molecules, after flowing through the sand filter. A second filter containing activated carbon was found to remove all color and further reduce turbidity, because of activated carbon's adsorptive abilities. In the case of creek water, carbon reduced turbidity from 2.2 NTU to 1.5 NTU. With pond water, carbon reduced the turbidity from 10 NTU to 4 NTU.

A one micron bag filter was also tested for reducing turbidity. It removed sand, carbon, and residual sediment; however, it had little effect on reducing turbidity. The one micron bag filter is also capable of removing larger bacteria and protozoa such as *Cryptosporidium* and *Giardia lamblia* not removed by the sand filter. According to the Washington State Department of Health[10], *Cryptosporidium* cysts range from four to seven microns and can effectively be removed by filters of pore size one micron or less.

5.2 Pumping

To eliminate the need for energy outside the local community, a human powered pumping system was designed and constructed. The treadle pump uses a natural stepping motion to create suction of water into the pump and pressure to discharge the water. A two piston prototype treadle pump was built that had a 4' x 4' footprint and was successfully tested. This pump produced a flow rate of 5-7 gpm with a sand filter on the suction side. After its use, stability and efficiency issues were addressed, such as heavy frictional losses within the pulley system. To improve pumping performance, a two person, four piston treadle pump was designed and constructed. This two person design eliminated the need for a pulley system. The improved pump increased the flow rate to 15 to 20 gpm, thus shortening the time required to pump 3,000 gallons to less than four hours.

5.3 UV Disinfection

According to WHO[8] the minimum energy flux required to kill 99% of bacteria and 99% of viruses is 7 mJ/cm^2 and 59 mJ/cm^2, respectively.[8] The EPA's strict requirement of zero coliform bacteria in the water was chosen to be the goal of this project.[18] While the task does not require addressing virus inactivation, the UV system kills a significant fraction of viruses. The UV system operates at five gallons per minute with a flux of 54 mJ/cm^2. The system is gravity fed, and the flow is achieved by adjusting the height of the exit tube from the UV chamber (see Figure 6). Efficiency of disinfection was tested using water from three different locations within the city of Fayetteville, AR: Mulline Creek, Goose Creek, and Paul R. Noland Waste Water Treatment Facility. Bacteria counts were determined using an agar test strip before and after the treatment system. The UV system completely deactivated all coliform bacteria from Mulline Creek and Goose Creek. As a worst case scenario, clarified water from a waste water facility, containing roughly 100,000 colony forming units per milliliter (CFU/mL), was run through a one micron bag filter and tested. After treatment, the water was found to have 52 CFU/mL total coliform, a 99.96% reduction, and 2 CFU/mL E. coli, 99.94% reduction. These test results were obtained by the Arkansas Water Resources Center at the University of Arkansas, Fayetteville. These tests show that except for severely contaminated sewage water, the UV system meets EPA guidelines.

5.4 Bleach Disinfection

Bleach systems have been used to provide potable water for remote communities and in the third world. According to EPA guidelines[9] for drinking water, bleach can be used to disinfect water by adding 1/8 teaspoon of 6wt% solution of sodium hypochlorite (NaOCl) per gallon of contaminated water and allowing a 30 minute residence time. That corresponds to about half a gallon of bleach per 3,000 gallons of drinking water. Experiments using source water from two water sources, Goose Creek and Mulline Creek, confirmed this recommendation with complete disinfection of coliform and E. coli bacteria. The test results for the current study found that 15 minutes is the minimum residence time required for complete disinfection. This finding confirms EPA's[9] recommendation, "*….Mix the treated water thoroughly and allow it to stand, preferably covered, for 30 minutes. The water should have a slight chlorine odor. If not, repeat the dosage and allow the water to stand for an additional 15 minutes."* The Crew design incorporates a residence time of 30 minutes as a safety factor to insure all pathogens are killed.

Experiments were conducted for the removal of chlorine. WHO[16] states "*…the guideline value is 5 mg/litre (rounded figure). It should be noted, however, that this value is conservative, as no adverse effect level was identified in this study.*" It was found that chlorinated water flowing through activated carbon reduced the chlorine concentration from 5 ppm to less than 0.5 ppm; however, adding a carbon filter to improve taste is not normally justified because water containing the recommended level of NaOCl is quite palatable. Consequently, The Razorback Microcide WERC Crew does not recommend removing the residual chlorine.

6.0 FULL SCALE DESIGN

This project consists of two separate systems: bleach and UV disinfection. Both contain the same pre-disinfection components, which include a sand filter, a treadle pump, and a one micron bag filter containing activated carbon. After these common steps, both systems then follow their respective disinfection processes.

6.1 Pre-Disinfection

6.1.1 Sand Filter

Figure 1. Sand filter.

The sand filter removes debris and turbidity from the source water. The suction of the pump connects to a one inch PVC pipe which terminates at the bottom of an 18 gallon bucket in an inlet flow distributor. The flow distributor consists of cloth-covered perforated (1/8” holes) pipes as shown in Figure 1. The distributor is positioned at the bottom of the bucket. Above the distributor is placed 4” of gravel covered with 14” of sand. A cloth is secured by bungee cords over the bucket top for protection of the sand filter against mud and debris and to prevent the loss of sand. The distributer, bucket, sand, and cloth are all shown in Figure 1. The filter is immersed in the source water. The pressure drop through the sand filter is about 2” water column while operating at 7.5 gpm, which is minimal for the treadle pump.

6.1.2 Pump

Figure 2. Two person treadle pump.

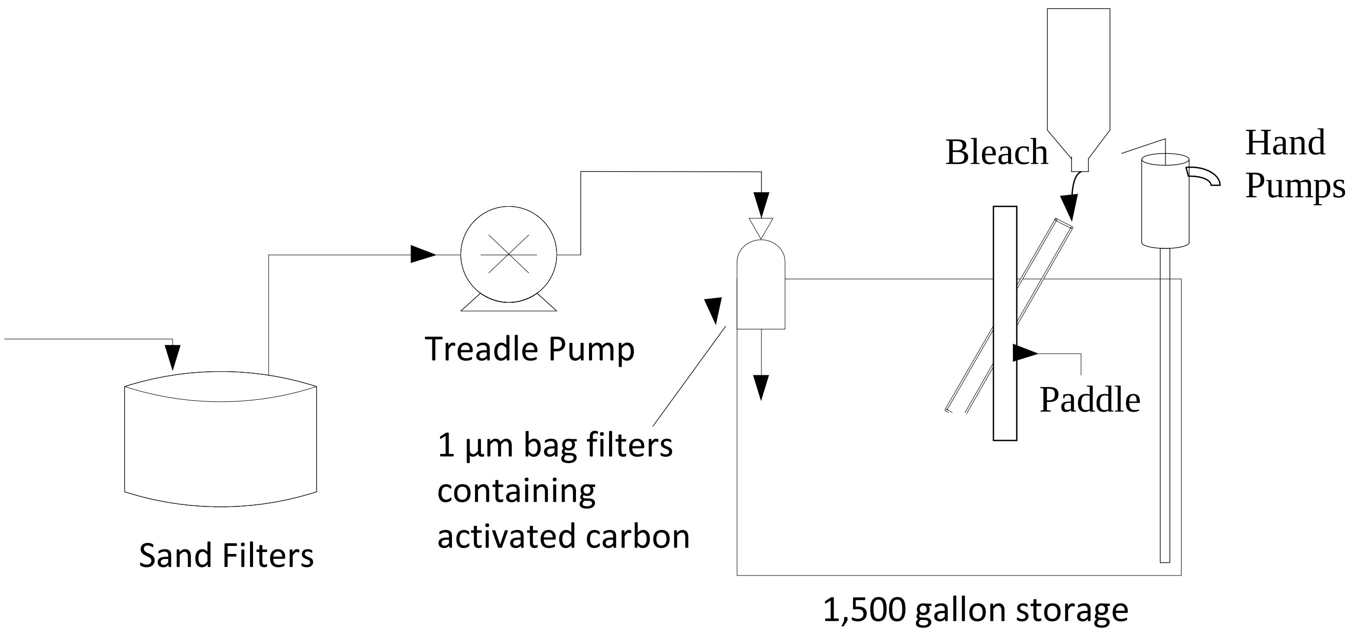
The source water is pumped from the sand filter by a human powered treadle pump. The pump, shown in Figure 2, which is used in both processes, was constructed in a laboratory room at the University of Arkansas without the use of machined parts, using unskilled labor. The suction of the pump is connected to the sand filter, which is submersed in the water feed source. The sand filter is connected to the treadle pump. Each pumping stroke of each piston delivers two liters of water. With minimal effort, two people can operate this treadle pump with a sustainable output of over 15 gpm. The pumping operation may be compared to slowly walking up stairs and does not require the exhaustive effort required to operate a bicycle pump. While lumber for the pump can be bought, cut, drilled, and then shipped with instructions, the pump can also be constructed with local materials or may be improvised depending on the materials and tools available. Weighing about 100 pounds it can be carried short distances or transported long distances via light truck.

The treadle pump requires minimal maintenance, which primarily involves greasing the journal bearings of the walking beams and piston rod supports once a week and replacing the leather pistons about once a year.

A detailed set of plans for constructing the treadle pump is available on the University of Arkansas Department of Chemical Engineering website (see WERC DOCUMENTS).

6.2 Bleach Process

The bleach system, as shown schematically in Figure 3, consists of the following sections: (1) sand filter, (2) treadle pump, (3) one micron bag filter filled with activated carbon, and (4) disinfection and storage. An advantage of the bleach system is it only takes thirty minutes to disinfect the water in a well-mixed tank using a small amount of bleach. The power requirement is limited to two humans pumping less than four hours a day. At a pumping rate of 15 gpm, treated water is available in



the first 1,500 gallon storage tank two and a half hours from the start of pumping.

Figure 3. Process flow diagram of bleach process.

6.2.1 Bleach Disinfection

After the sand filter, water is pumped through a one micron bag containing nine ounces of activated carbon into a 1,500 gallon holding tank. The one micron filter is held in place by a casing on the side, inside of the 1,500 gallon tank, and is effective at removing cysts and larger bacteria. Four cups of household bleach (6% sodium hypochlorite) are added and blended with a paddle which is positioned in the tank through an oarlock. Five minutes is required to blend the bleach into the tank contents. Once the tank is well mixed, the bleach treatment stands for a minimum of 30 minutes. According to the EPA[9], the disinfected water "*should have a slight chlorine odor*." [9] The slight odor of bleach gives an affirmation that the water has been disinfected. Bacteria test strips are another possible option for verification, although the daily cost is about $4. At 15 gallons per minute, the pump will fill one 1,500 gallon tank in less than two hours and fill the second 1,500 gallon tank in another two hours. The first tank is ready for consumption within two and a half hours and the second is ready within five hours from the start of pumping. Thus, consumers can draw water for 21 hours every day.

The storage tanks will be constructed locally using a flexible design. A sturdy option for storage uses 4’ X 8’ plywood sheets, 2”x4”x8’ supports, plastic (polyethylene) lining, and a tarp covering as shown in Figure 4. A square of four 4’ X 8’ plywood sheets, placed in a two foot deep 8’x8’ hole in the ground, provides the sides for a 1,900 gallon (1,500 gallons working volume) storage tank. The tank will be placed in a two foot deep hole to provide support. Other possibilities include digging a similar sized hole and lining with sand, clay, plastic or some combination. The choice of construction of the storage tanks is dependent upon the availability of materials and tools.

With four barrel pumps total (two on opposite sides of each tank), giving a draw capability of 20 gpm, the minimum time to dispense 3,000 gallons is about three hours; consequently, on the average, water needs to be drawn only 14% of the time. With two 1,500 gallon tanks and four barrel pumps there will be virtually no waiting for water draw.

The plastic lining has the potential to incur growth of bacteria and algae and should therefore be cleaned or replaced as required.

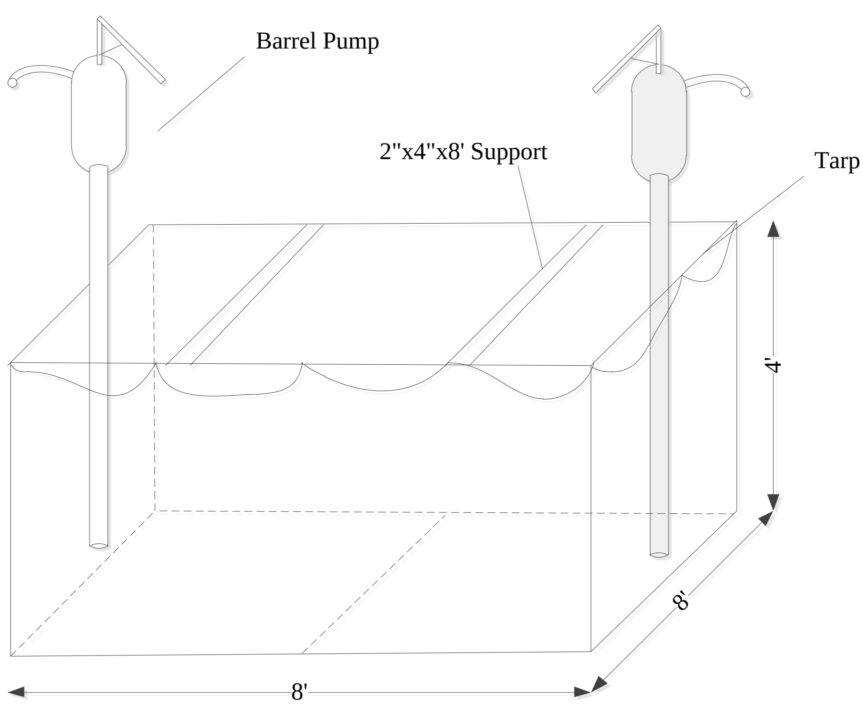


Figure 4. Water reservoir system with barrel pump.

6.2.2 Proposed Treatment Schedule

At 6:30 a.m. start pumping into the first 1,500 gallon tank. At around 9:00 a.m., pumping into the first tank is complete and pumping will start into the second tank. Four cups of bleach are added in the first tank, blended, and allowed to sit for 30 minutes. The blending is done by hand by oscillating the boat paddle style agitator back and forth about 40 times in less than two minutes. By 9:00 a.m. the first tank is ready for consumption. At around 11:30 a.m., pumping into the second tank is complete; treatment and blending ensues and, by 12:00 p.m., an additional 1,500 gallons of disinfected water is ready for consumption.

6.2.3 Chlorine Removal

As mentioned earlier, WHO gives a guideline of 5 mg/liter or 5 ppm for the safe concentration of chlorine in water.[8] This study verifies that 5 mg/liter is safe to drink; however, to implement a conservative treatment, eight cups per 3,000 gallons, which is 10 mg/liter and is the EPA recommended treatment level, is recommended. This level of bleach is completely safe in drinking water; consequently, except for aesthetic reasons, there is no need for chlorine removal. If chlorine removal is still desired, for whatever reason, a simple carbon filter may be added at the suction of the barrel pumps.

The optional post carbon filter can be constructed easily using a bucket, lid, cloth, and four inch PVC pipe as shown in Figure 5. Holes must be drilled in the bucket and in the pipe. Both the inside pipe and the outside of the bucket are wrapped with cloth. Carbon is poured into the annulus between the pipe and the inside of the bucket.

The delivered water will be drawn by the consumer using a hand operated barrel pump as shown in Figure 5. The barrel pump will be installed above the post carbon filter, provided the post carbon filter is utilized. The post carbon filter will be submerged in the storage tank. The piping between the carbon filter and the barrel pump will be the proper length to place the barrel pump at the proper height for operating ease. The extra cost of replacement carbon for the post carbon filter greatly outweighs the benefits of removing the chlorine, strictly to make the water a bit more palatable.

Figure 5. Optional post carbon filter housing

6.3 UV Process

The components of the UV system include the following: (1) a sand filter, (2) a treadle pump, (3) a carbon filter plus surge tank, (4) a level controlled reservoir, (5) a UV lamp, and (6) two storage tanks, as shown schematically in Figure 6. The UV system can sanitize 3,000 gallons of contaminated water in 8-10 hours with a demonstrated 3-log reduction in *E.coli* and total coliform bacteria. Test strips will ensure the water is safe at the end of the day and readily available for consumption for the following 19 hours.

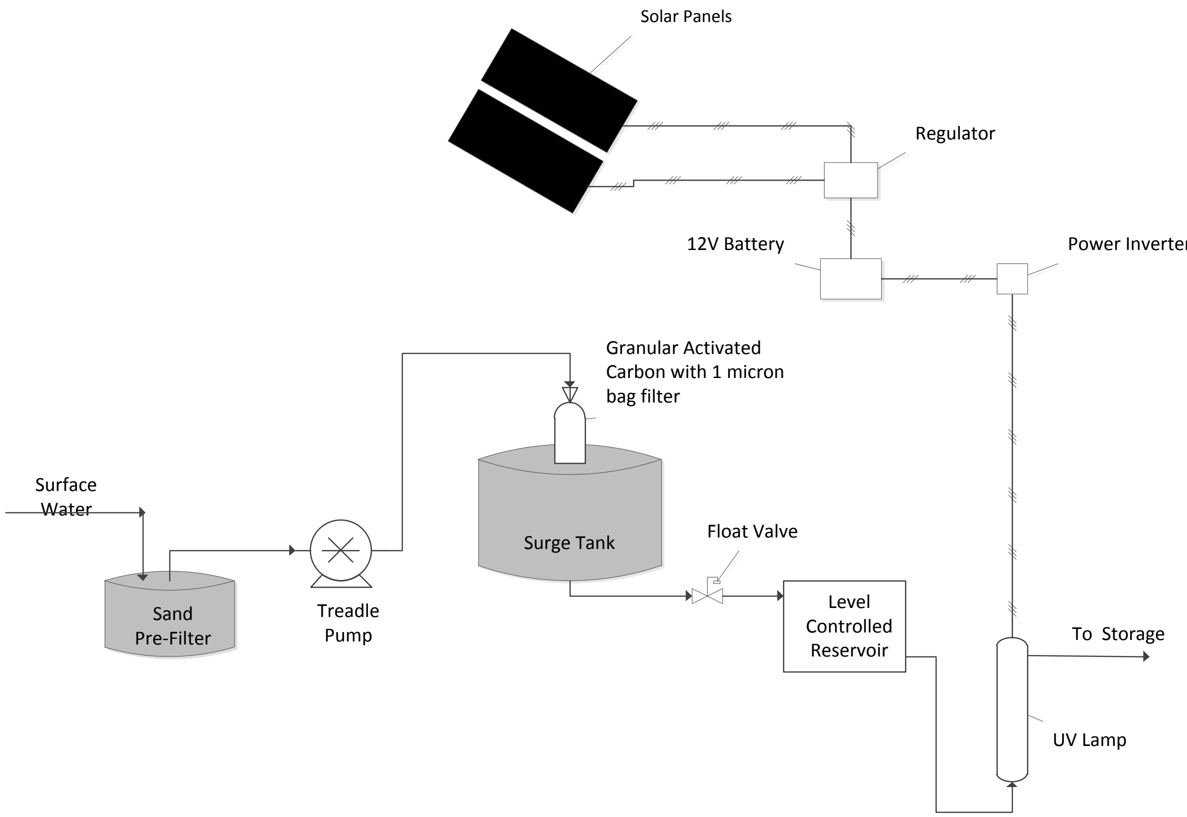


Figure 6. UV process flow schematic

6.3.1 Carbon Filter plus Surge Tank

Water is pumped from the sand filter through a one micron bag filter containing nine ounces of granular activated carbon into a 300 gallon tote. The activated carbon removes any free organics, color, and some turbidity. The one micron bag filter eliminates large protozoa and large bacteria. The rate at which the activated carbon must be replaced is dependent on the source water but typically needs replacing weekly. The 300 gallon tote is a surge tank that allows the pump to be operated at a variable pace without affecting the flow rate through the UV chamber.

6.3.2 Level Controlled Reservoir

An 18 gallon storage bin equipped with a float valve allows a flow rate up to 6 gpm through the UV chamber. The level in the controlled UV feed reservoir will be maintained approximately 40” above the overflow outlet of the UV unit. This constant level will ensure that the flow rate through the UV unit remains constant, even though the pumping rate into the surge tank is variable. This also prevents the treadle pump from being required to operate continuously.

If the 40” is exceeded, the flow rate through the UV chamber may be too great and will therefore become less effective at bacterial disinfection due to a decreased residence time.

6.3.3 UV Disinfection

The UV bulb requires 50 Watts which is powered from a 12V battery through a DC-AC power inverter. One 12V, 16 Amp-hour battery will provide power to the UV lamp while the two 45 Watt solar panels recharge another 12V battery in order to provide continuous operation of the UV bulb. The UV chamber has a residence time of 8.5 seconds and provides an energy flux of 54 mJ/cm^2, which is capable of greater than 99.9% inactivation of all bacterial and protozoan contamination. After exiting the UV unit the treated water is then pumped to one of two 1,500 gallon reservoirs as described above. The water contained in the storage tanks will need to be tested daily for the presence of residual coliform bacteria before consumption. The bacteria test is an antibody-based kit that detects bacterial presence within twenty minutes. The kit includes a sterilized pipette, vial, and test strip with basic, easy to follow instructions.

The UV system is susceptible to short circuiting due to adverse weather and will therefore be fitted with a waterproof housing to protect the ballast and all electrical connections. Over time, minerals in the water can form a coating over the protective quartz sleeve, which decreases the energy flux of the UV lamp to the water. To insure the full energy flux is provided, the quartz tube must be removed and wiped with a dilute bleach solution on a weekly basis. The UV system is dependent on full solar flux to provide sufficient power to recharge the 12V batteries. If adequate sunlight is not available, the system is limited to the power stored in the batteries. A fully charged 16 Amp-hour battery will operate the UV bulb for two and a half hours. UV bulbs should be replaced yearly. An alarm will sound if the bulb prematurely goes out or breaks.

In virtually every community in the US, sufficient technical talent is available to operate and maintain a UV system, however, in less developed countries, this is not the case. Thus, the bleach system is much preferred outside the US; whereas, the UV system, because it produces potable water of similar characteristics to most city water, may be the logical choice even though the UV system is more expensive.

7.0 ECONOMIC ANALYSIS

The itemized materials and price list for the components of the bleach system are presented in Table 1. The first cost is $550. The operating costs are $20 and $944 for a week and a year, respectively. The operating cost includes buying bleach, replacing the activated carbon in the one micron bag filters every week, and replacing the one micron filter bag every other week. The price of the disinfected water after the first week of operation is $0.027 per gallon, including first costs. After a month (assuming four weeks in a month) the price of water is $0.0074 per gallon. After a year, the price of water is only $0.0013 per gallon.

Most of the materials of construction, such as lumber and PVC, can be acquired in Haiti. The one micron bag filters, carbon, and fittings for the tubing will be shipped into Haiti.

Table 1. Itemized materials and price list for the bleach system.

Pre-Filter				**Storage**			
Item	Unit Price	Quantity	Price	Item	Unit Price	Quantity	Price
18 Gallon Tub	$5.97	2	$11.94	Carbon	$1.35/9oz	1	$2.70
Play Sand	$3.66	4	$14.64	1 Micron Bag Filter	$4.49	2	$8.98
All Purpose Gravel	$3.28	2	$6.56	Polyethylene 10' by 100'	$18.00	1	$18.00
1" Sch 40 Tee	$0.64	6	$3.84	Tarp 12' by 16'	$21.99	2	$43.98
1" PVC Endcap	$0.51	8	$4.08	Wood 2"x4"x8'	$1.59	12	$19.08
1" Sch 40 10' Pipe	$2.48	2	$4.96	Plywood 1/4"x4'x8'	$11.77	8	$94.16
Nylon Barb 3/4"	$2.24	2	$4.48	Paddle	$10.00	2	$20.00
Bushing threaded 1" x 3/4"	$0.47	2	$0.94	**Total**			**$206.90**
1" Adapter (slipxthread)	$0.66	2	$1.32				
Cloth 2 yards	$3.00	2	$6.00	**Miscellaneous**			
Total			**$58.76**	Item	Unit Price	Quantity	Price
				Purple Primer	$3.78	1	$3.78
Treadle Pump				All Purpose Cement	$4.58	1	$4.58
Item	Unit Price	Quantity	Price	Sealant	$5.00	1	$5.00
Wood 2"x4"x8'	$1.59	16	$25.44	1" Hose Clamp (Box of 10)	$4.50	2	$9.00
Scrap Leather	$5.99	1	$5.99	4" Hose Clamp	$1.29	8	$10.32
3/4" PVC Check Valve	$7.19	8	$57.52	Bleach	$1.87/3 quarts	0.67	$1.25
3/8" All Thread 6'	$5.37	1	$5.37	Screws	$3.98	1	$3.98
3/8" All Thread 3'	$2.68	1	$2.68	3/4" Washers	$0.10	16	$1.60
1" Dowel Rod 3'	$4.69	1	$4.69	3/4" Nuts	$0.15	24	$3.60
1/2" Metal Rod 3'	$4.82	1	$4.82	Thread Tape	$3.20	1	$3.20
1/2" Weld Steel Tube	$5.23	2	$10.46	Barrel Pump	$25.99	2	$51.98
4" Sch 40 Pipe 10'	$10.14	1	$10.14	Zip Ties	$1.25	1	$1.25
4" Cap	$0.92	4	$3.68	**Total**			**$99.54**
3/4" Sch 40 PVC 10'	$1.99	1	$1.99				
3/4" Braided Tube per ft	$1.47	20	$29.40				
1" Braided Tube per ft	$2.24	6	$13.44				
3/4" Barb Tee	$0.71	5	$3.55				
Nylon Barb 3/4"	$2.24	4	$8.96				
3/4" x 1" Reducer	$1.12	1	$1.12				
Miscellaneous PVC parts	$8.47	1	$8.47				
Total			**$197.72**				

The itemized materials and price list for the components of the UV system are presented in Table 1 and Table 2. The price of the sand filter, treadle pump, and miscellaneous costs are in Table 1, while the UV and storages costs are in Table 2. The first cost of the system was $1,485. The operating costs for a week and a year are $41 and $2,016, respectively. The operating costs include buying bacteria test strips, replacing the activated carbon in the one micron bag filters every week, and replacing the one micron filter bag every other week. Provided the system only operates for one month (assuming four weeks in a month), the price per gallon of potable water is $0.02 and provided the system operates for an entire year is $0.0032. Both of these include first costs. If bacterial testing is removed from the UV system the operating cost would be $12 per week and $491 per year. The solar panels, UV disinfection chamber, DC/AC inverter, one micron bag filters, carbon, and test strips will be shipped to Haiti.

Table 2. Itemized materials and price list for the UV system.

UV				**Miscellaneous**			
Item	Unit Price	Quantity	Price	Item	Unit Price	Quantity	Price
Battery	$19.00	2	$38.00	Purple Primer	$3.78	1	$3.78
350W Inverter	$69.99	1	$69.99	All Purpose Cement	$4.58	1	$4.58
Model C4	$399.00	1	$399.00	Sealant	$5.00	1	$5.00
Solar Panels	$179.99	2	$359.98	1" Hose Clamp (Box of 10)	$4.50	2	$9.00
3/4" Barb	$0.79	2	$1.58	4" Hose Clamp	$1.29	8	$10.32
Total			**$868.55**	Bleach	$1.87/3 quarts	1	$1.87
				Screws	$3.98	1	$3.98
Storage				3/4" Washers	$0.10	16	$1.60
Item	Unit Price	Quantity	Price	3/4" Nuts	$0.15	24	$3.60
1 Micron Bag Filter	$4.49	2	$8.98	Thread Tape	$3.20	1	$3.20
Carbon	$1.35/9oz	2	$2.70	Barrel Pump	$25.99	2	$51.98
300 gallon tote	$50.00	1	$50.00	Test Strips	$20.95	1	$20.95
18 Gallon Tub	$5.97	1	$5.97	Zip Ties	$1.25	1	$1.25
Float Valve	$16.00	1	$16.00	**Total**			**$121.11**
Ball Float	$1.00	1	$1.00				
Polyethylene 10' by 100'	$18.00	1	$18.00				
Tarp 12' by 16'	$21.99	2	$43.98				
Wood 2"x4"x8'	$1.59	12	$19.08				
Plywood 1/4"x4'x8'	$11.77	8	$94.16				
Paddle	$10.00	2	$20.00				
Total			**$279.87**				

8.0 SAFETY AND ENVIRONMENTAL

8.1 Chemical Considerations

Common household bleach contains the following hazardous ingredients: 6% sodium hypochlorite (active ingredient) and 1% sodium hydroxide. According to the MSDS's, none of these ingredients are on the IARC, NTP, or OSHA carcinogen lists. Rubber or nitrile gloves, safety glasses, closed toe shoes, and long pants should be worn while handling bleach. Bleach irritates the skin and can cause eye damage and even blindness. Complete safety and environmental information is found on the MSDS[11], which will be provided to all users. Based on experiments conducted by WHO[16], "*the guideline value for free chlorine in drinking-water is derived from a NOAEL* [No Observable Adverse Effect Level] *of 15 mg/kg of body weight per day.*" This gives a conservative total daily intake (TDI) value of 5mg/L, which is well above the chlorine concentration in the bleach process. Activated carbon is a stable, non-toxic substance.[15]

8.2 Environmental Considerations

Guidelines state that sodium hypochlorite is not a threat to the environment according to EPA 40 CFR Parts 9, 156, and 165 because of its rapid decomposition. Waste is created only from activated carbon and the bag filters. The weekly replacement of nine ounces of carbon and the three ounce bag filter will generate 39 pounds of non-hazardous waste yearly. This will create a minimal impact on the environment.

8.3 User Safety

The users will be trained on how to appropriately handle bleach, the equipment, and troubleshooting procedures. A detailed operation manual will be provided to the users and can also be found from the Ralph E. Martin Department of Chemical Engineering at the University of Arkansas. The OSHA regulation 29 CFR 1926.501(b) (1) Subpart M states, "each employee on a walking/working surface (horizontal and vertical surface) with an unprotected side or edge which is 6 feet (1.8m) or more above a lower level shall be protected from falling by the use of guardrail systems, safety net systems, or personal fall arrest systems." The treadle pump does not require an operator to be six feet off the ground. However, guardrails will be used for the operation of the treadle pump.

8.4 UV System Regulations

There are no OSHA-mandated employee exposure limits to ultraviolet radiation except ultraviolet light regarding lasers.[14] For UV water disinfecting systems in the United States, the EPA UV Guidance Manual is typically used. The EPA's UV Guidance Manual requires that all UV reactors that disinfect water be tested to determine the disinfecting performance with either MS2 or T1 bacteriophages at various flow rates.[13] The manufacturer affirms that the UV unit used by the team meets all legal standards. The lamp used in the UV disinfection unit contains mercury. The following OSHA regulations for mercury include the following: the ceiling permissible exposure limit (cPEL) is 0.1 mg-Hg/m^3 and the NIOSH immediately dangerous to life or health (IDLH) is 10 mg-Hg/m^3. The lamp is well protected and is not likely to present a mercury hazard. If, however, the lamp does burst, the power box will alert the operators of the loss of current. The water contaminated by the mercury must not be ingested. The mercury present, however, is in small enough concentrations to be released to the environment for safe dilution.

8.5 Other Recommendations

Chlorine reacts with organic substances such as leaves, bark, sediment, urine, sweat, hair, and skin particles, to make disinfection by-products (DPB) such as trihalomethanes which include chloroform, bromoform, bromodichloromethane, and dibromochloromethane. In the United States, the EPA limits the maximum contaminant level (MCL) of total trihalomethanes (TTHMs) and total haloacetic acid in treated water to 80 parts per billion and 60 parts per billion, respectively.[12] TTHMs have been associated with an increased risk of certain types of cancer and other health effects as stated in the *EPA Guidance Manual: Alternative Disinfectants and Oxidants.*[12] According to the EPA, granular activated carbon is the best available technology to remove organic matter, chlorine, and chlorine DPB from water. People operating the water purification device should be cautious when taking samples in order to not contaminate the water.

9.0 CONCLUSIONS AND RECOMMENDATIONS

1. The **Razorback Microcide WERC Crew has determined that the bleach and UV systems meet the requirements of Task # 7.**
2. **The bleach system is more appropriate as it has the smallest first cost of $**550 and smallest operating cost of $944 per year.
3. The bleach system is an ideal system for third-world, developing countries because it lends itself to construction and operation using unskilled labor, its moderate first costs, its operating costs are minimal, and its maintenance requirements are very low.
4. The UV system provides clean, safe water which tastes as chemical free as tap water. For communities, especially in the US, where taste may be a primary consideration and costs a secondary consideration, the UV system may be preferred.

5. One key difference between the operating cost of the bleach system and the UV system is the $1,485/year costs for conducting two bacteria tests per day.
6. The assembled systems are easily portable by light truck or, alternatively, can be easily assembled on site.

The Crew designs documented in this report, satisfy the requirements of Task # 7 significantly better than any of the other evaluated alternatives. The bleach system is portable, reliable, requires only human power, and is very economical. The UV system is ideal for niche applications in more affluent communities which are not adverse to the moderately higher costs, but who value water which tastes similar to tap water.

The team is now actively investigating the possibilities for implementing a bleach system in Haiti by June 1, 2011.

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March 9, 2011

Mr. Ryan Lee
Chemical Engineering
3202 Bell Engineering Center
Fayetteville, AR 72701-1201

Re: Clean Energy Water Disinfection for Small, Remote Rural Communities

Dear Mr. Lee:

Thank you for providing me with the opportunity to audit your project titled, "Clean Energy Water Disinfection for Small, Remote Rural Communities". The project tackles a very serious issue in today's world, that of providing safe drinking water to communities in undeveloped countries. You and your team have provided reasonable and potentially effective solutions to the issue. Regarding your report, I have the following general and specific comments:

General comments:

- Can you provide an estimate of the size of population that the system is designed to serve?
- In remote regions, the availability of replacement parts is often the choke point on water systems. Your bleach system seems to have taken this into account mostly. I especially like the treadle because it can be produced with local materials. Have you verified that all of the working components of the pump can be acquired or fabricated locally in case of breakdown?
- Along those same lines, the UV system may be too complicated for dependability unless replacement bulbs, batteries and other parts are readily available.
- What is the nature of the distribution system? If community members are coming to the site to collect and haul water, then the point of contact with the system may be a post disinfection site of contamination. It seems like a small point, but it should be mentioned.
- You speak of treatment efficiencies for different components of 99 (2 log) or 99.9 (3 log) percent removal. According to the World Health Organization (WHO) guidelines for drinking water quality, removal efficiency for crypto needs to be 99.994%, for Campylobacter 99.999987% and for Rotavirus 99.99968%. In fact, the goal is 0 pathogen detections. In your report, you have reported on efficiency of individual treatment units, but not the overall treatment efficiency. Does your overall system meet the WHO targets?

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Specific comments:

- On page 9, third paragraph in "Pre-filtration" you make the statement, "The one micro bag filter is also capable of removing larger bacteria such as *Cryptosporidium* and *Giardia lamblia* not removed by the sand filter. Both of these organisms are protozoa, not bacteria.
- On page 13 and 14, regarding the plywood reservoir. You need to verify the structural integrity of the plywood when filled with 4 feet of water. The water pressure at the bottom will be significant. You may need some reinforcing around the reservoir. Also, the thickness of the plywood should be stated.
- Plywood is not included in itemized material list.
- Page 16, Economic Analysis: your cost figure of $0.023/gallon/week assumes only one week of operation (($467+$15)/(3000gpd*7days/week)= $0.023/gal/week). The costs clearly go down if the system is more permanent. If the system lasts for a year, then the cost is only $0.0011 per gallon.
- Also on page 16, because one micron bags, carbon and fittings are not available in Haiti, you should include several sets as required for maintenance over the expected life of the unit.

Overall, you have provided a simple and elegant solution to a pressing problem. As engineers in the developed world, we often overlook human power as a source of energy. However in situations such as Haiti, human power may well be the least expensive solution. Most of the material required for you treatment unit should be available locally. That will minimize the amount of shipping required.

Good luck in your competition.

Sincerely,

Robert Morgan

Robert Morgan, PhD, PE
Manager of Environmental Quality

Industry audit of: Clean Energy Water Disinfection for Small, Remote Rural

Communities

WERC 2011

TASK # 7

After reviewing the report it is my opinion that the Razorback Microcide WERC Crew (the Crew) has successfully tackled a worthy project and has developed an essentially viable method. It affords economic advantages over current technologies and seemingly meets all specified criteria.

The Crew did a fine job in defining advantages and disadvantages of several alternatives. I was grateful for the detailed explanations such as the description of how the larger pore microfilters were more vulnerable to fouling than the smaller pore ultrafilters.

However, in reviewing their report I was left hungry for additional information. In most instances, the Crew provided supporting data and/or references for statements which might be debatable. With regard to the potential use of electric pumps, they stated, "In small sizes, the (electric) pump and motor are inefficient…" yet they do not provide any quantifiable evidence in support of the claim. Otherwise, they effectively promote the advantages of the human-driven pump.

The pre-filtration method was novel and reportedly effective on the waters tested. It would be interesting to know whether the levels of suspended solids which were evaluated correspond to those which might be encountered where the system would be deployed. During periods of heavy rainfall, turbidity of surface waters often exceeds the tested 20 NTU by an order of magnitude. It would also be interesting to know the level of turbidity and/or suspended solids which is acceptable to the pump.

The Crew prefers using chlorine for disinfection and the technology is well established. They cite a maximum tolerable residual of 5 ppm and propose adding approximately 10 – 12 ppm of chlorine, assuming that the bleach is 6% active. On page 4 the Crew states that bleach is available in remote places. In a third world locale, the expectation of appropriate bleach activity may be unrealistic given that decomposition occurs with temperature and time. Bleach strength can be measured with simple test kit which is available for roughly $50. Alternatively, bleach could be added to obtain a measureable free residual in the treated water. Assessing the residual in the treated water would also limit the consumer's exposure to elevated chlorine residuals as will be discussed shortly. The same supplier can provide a simple test to measure chlorine residuals at use concentrations. In addition to the chlorine demand exerted by the filtered water, the polyethylene liner, the tarp and even the paddles should be expected to initially impose some chlorine demand which could call to question the anticipated efficacy based upon volumetric addition of bleach. When dealing with the issue of human health I would not depend on sensing the presence of a bleach odor nor would I rely upon the addition of a specified volume of bleach with an assumed concentration. A chlorine test can be performed for less than $1 with a cost of $0.0007 per treated gallon, assuming a 1,500 gallon batch.

The bacterial test strips which are proposed for the UV system would provide an additional layer of protection for the produced water from the bleach system.

The pump is seemingly reliant upon an upstream filter to perform properly. In higher turbidity water, the filter might foul sufficiently to starve the pump. That could retard pumping and potentially damage the pump. Provision of a vacuum gage might avert such damage.

Storage will occur in lined plywood tanks. After examining the diagram on page 14, I must wonder whether the proposed vessel is adequately robust to safely retain nearly eight tons of water, especially on the ends which are not bound by 2 X 4s.

I lack the background to conclusively assess this but encourage the Crew to validate the integrity if it has not already been done.

While the proposed dimensions will provide slightly more than 1,900 gallons by calculation, the practical working volume would be somewhat less, especially while stirring in the bleach. Capacity is sufficient to meet the stated objective for daily water production.

The Crew identifies the presence of mercury in the UV bulbs but offers no comment as to whether or not this is an issue worthy of concern.

The observations and unanswered questions posed within this document are germane to the version of the report which was reviewed and are intended to aid in developing a system which currently shows promise in addressing the human need for drinkable water. Once again, I wish to commend the Crew for their fine effort.

Respectfully submitted,

Michael S. Dalton

Consultant

WERC 2011 Audit

The Razorback Microcide WERC Crew

Auditor:

Breck Speed

Mountain Valley Spring Water Company

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The written report of team's proposed solution is well laid out and generally supported by well reasoned analysis. The following comments are more in the line of some additional factors the team may want to consider in framing their overall solution.

Health Comments

There was no discussion about the distribution method of the water post treatment. In the solution proposed, the water is going to have the chlorine removed by carbon filter and, as a result, could be re-contaminated in distribution or while in storage. Chlorine doesn't taste great but will help keep water sanitary in pipes, buckets, and in storage (if the water is enclosed and outgassing doesn't occur.)

I am highly suspect of the durability of the proposed water reservoir. This is a crucial piece of the proposal. If it fails in short order, is not fully sealed, or even simply leaks, it will seriously affect the quality of the water as well as the economics of the project. A tank made from HDPE (or other suitable plastic) would be pretty inexpensive, much more durable and easily transportable. You might even find some rotomolder who would make it out of recycled milk jugs to give it a "greener" face. These are common types of tanks and you can probably find one or maybe a series of smaller tanks to link together. Maybe plastic 40 gallon drums who served a prior food grade purpose could be sanitized and linked together as I've seen in cistern systems created for houses?

The other negative factor for the water reservoir as conceived is the difficulty of cleaning. Even reservoirs holding water with chlorine in them develop "bio film" after a period of time and must be cleaned or flushed. In this case, there will be no chlorine in the water and the bio film will happen pretty quickly.

Measurement and transport of the bleach seems to have been a concern in the proposed solution. Why not find a tablet form that would have a premeasured dosage much like a swimming pool chlorine tablet? It would be easier to transport and the training of the locals in charge of the water process would be much easier.

The legal issues addressed were primarily US legal issues although WHO testing of chlorine was cited. I would state up front the US is cited because of the generally high standards in the US and the difficulty in assessing legal issues in a universal sense when talking about multiple countries. Are there other health standards for water purification promulgated by other groups? Doctors Without Borders? UN Disaster Relief Standards? Red Cross or Red Crescent?