Clean Energy Water Disinfection for Small, Remote, Rural Communities

Northern Arizona University

JAMM, Inc.

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EXECUTIVE SUMMARY

This report details JAMM, Inc.'s design of a drinking water disinfection system and provides results and a technical performance evaluation based on system testing and analysis. Also included are recommendations for implementation of the system. A full-scale disinfection system was designed for the Waste-Management, Education, and Research Consortium's (WERC) environmental competition, and a working bench-scale system was constructed to be judged at the competition based on its ability to meet the given criteria. The intent of the disinfection system is to help alleviate the need for safe drinking water in rural, third-world areas by meeting the World Health Organization's (WHO) guidelines for bacterial contamination, which state there should be no coliform present in any sampled drinking water. In addition, the system was designed to be capable of disinfecting 3,000 gallons of water per day, be cost effective based on initial capital cost and operating cost per gallon of water disinfected, be easily implemented, operated, and maintained by ordinary citizens in third-world environments, and it should be mobile. Finally, any power requirement for the system must be met with clean renewable energy sources.

The chosen design for the system consists of both a pretreatment and a disinfection stage. The pretreatment portion of the drinking water disinfection system serves primarily to reduce solids in the water. Solids removal will lower the turbidity of the water which will allow the disinfection system to perform more efficiently. Removal of solids earlier in the operation will also elongate the system's lifetime and reduce maintenance. For pretreatment, both a roughing filter and rapid sand filter will be used. Using both systems will help to lengthen the lifetime and reduce maintenance of the rapid sand filter by removing some solids with the roughing filter.

The disinfection portion of the drinking water system serves to remove or deactivate all microorganisms in the water. This is necessary to ensure the drinking water is no longer contaminated and is safe to drink. For this stage of treatment, ultraviolet (UV) radiation administered by an ultraviolet light was chosen as the method for disinfection. This device, coupled with pretreatment, will efficiently deactivate all microorganisms in the drinking water.

As designed, the pretreatment and disinfection stages have a power requirement of 150 watts for one pump and the UV device. Therefore, a renewable energy system also had to be included in the design. It was decided that a photovoltaic system will be used as the primary source of power with a human-powered bicycle generator as a backup source. Using both

systems to create energy to charge a battery will ensure the system always has adequate power to operate and produce safe drinking water.

Once the design was completed, a bench-scale model was constructed and tested. Testing of this system demonstrated that it worked very well with total reduction of turbidity during pretreatment of more than 85%. In addition, all bacteria in the water was deactivated, verifying its compliance with WHO's guidelines. A cost estimate for the system was also completed. Based on this estimate, the total cost of the system is $2,251 with a cost of disinfection per day of $1.41 after six years (including implementation and maintenance costs). This is equivalent to disinfecting 20 gallons of water for one cent after 6 years. In addition, the system has a short payout period of 7 months and rate of return of 196% indicating it is a good investment. All other criteria were also evaluated, and it was determined the final system meets all requirements.

Finally, recommendations for implementation are given to help with the integration of this system within a third-world community. These recommendations include community education about system benefits, site analysis to investigate water parameters, development of a construction plan, development of maintenance plan, and training of a system operator. Lastly, an expected timeline for system construction is offered.

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I. INTRODUCTION

1.1 Project Understanding One of the most serious problems developing countries face is the lack of safe drinking water. Often, the water available to people in rural and third-world areas is contaminated with microorganisms that cause diseases such as cholera, schistosomiasis, diarrhea, typhoid fever, dysentery, and intestinal worms. Water-borne diseases such as these account for 3.6 million deaths each year and cause one child to die every 20 seconds.[1] Even in developed areas such as the United States, where safe drinking water is generally available, people become ill and die from disease after natural disasters when drinking sources become contaminated.

In an effort to provide clean drinking water to more people in developing countries, the Waste-management, Education, and Research Consortium (WERC) has challenged college students to design a water disinfection system for use in rural, third-world areas and emergency situations. The system developed by JAMM, Inc., a senior design team at Northern Arizona University, will be judged at the competition based upon its ability to meet WERC's design criteria, which dictate the system must:

- Harness clean energy to disinfect water to World Health Organization (WHO) drinking water guidelines for bacterial contamination
- Be a mobile unit
- Be cost effective based on initial capital cost and operating cost per gallon of water disinfected
- Be applicable to rural, third-world settings
- Be able to be scaled to meet a flow of 3,000 gallons per day
- Be easy for ordinary citizens in third-world environments to implement, operate, and maintain.

Although existing technologies capable of achieving these goals are available, WERC wishes for students to design a system that couples these available technologies in a new way to meet the objectives of this design challenge.

Because the most serious problem with drinking water in developing countries is contamination by pathogenic microorganisms, the effectiveness of disinfection is the only parameter that will be tested by judges at the WERC competition. Water disinfection is the method used to remove, deactivate, or kill these microorganisms, and it is accomplished by physical or chemical disinfectants.[2] For the purposes of this project, it is necessary to satisfy the WHO drinking water guidelines for bacterial contamination. These guidelines recommend there be no coliform, an indicator organism, present in any sampled drinking water.[3] Indicator organisms are microbes whose presence indicates fecal contamination and potentially harmful pathogens such as bacteria.[4] The disinfection system designed by JAMM, Inc. for this project aims to produce effluent water with no bacterial contamination.

There are many technologies available to achieve disinfection, though the choices for this project are limited due to WERC's design constraints. Among the possible solutions that will be investigated are ozone, ultraviolet light (UV), chlorine, electrolysis, reverse osmosis, and the use of magnetic fields. In addition, solar technologies such as distillation and solar cookers to boil the water and filtration methods such as ultrafiltration and slow sand filtration will be evaluated. It has also been noted by JAMM, Inc. that a pretreatment stage will likely be necessary in the system to remove solids from the water prior to disinfection. Pretreatment will help to reduce the required maintenance and lengthen the overall lifetime of the system. Some pretreatment options include rapid sand filtration, membrane filtration, and the use of ceramic or roughing filters, grit chambers, and inclined settling tubes.

One challenge JAMM, Inc. will face in the design of this disinfection system will be the integration of clean, renewable energy for any power requirements in the case that electricity is not available in the area of intended use. Forms of renewable energy include any sources of power which can be replenished by natural processes at a rate comparable or faster than its rate of consumption, and include such sources as sunlight, wind, rain, tides, and geothermal heat.[5] Applying renewable energy to the final design will be difficult mainly due to the fact that the system must be mobile. However, some possible solutions have been identified including the use of wind or solar energy, biomass, and manpower.

The project is further complicated by the lack of a specific location at which the final design will be implemented. Without a location of intended use, specific water quality parameters are unknown and the system cannot be designed to account for these issues. Instead, the disinfection system must be designed to be as universally applicable as possible. This will also mean designs for the input and output of water will not be included, as this will depend on the current infrastructure in the community and how they wish to store and distribute the disinfected water.

In addition, it will be difficult to design a system capable of disinfecting 3,000 gallons of water per day while retaining the system's mobility. The last challenge is the short amount of time allotted to complete the project, as design, construction, and testing must be completed in 4 months.

II. SELECTION OF DESIGN

2.1 Identification of Potential Solutions Many potential solutions for pretreatment, disinfection, and alternative energy have been identified for use with a disinfection system. Some of these solutions were immediately dismissed as they were found to be impractical for the necessary application. For example, some solutions were eliminated because they were unable to meet the flow requirement, were too expensive to justify the benefit in a third-world area, required the addition of a chemical, or were complex and difficult to operate and maintain. The use of chemicals was not considered for the system as concerns for safety and resupply were too great.

2.1.1 Pretreatment The pretreatment portion of the drinking water disinfection system serves primarily to reduce solids in the water. Solids removal will lower the turbidity of the water which will allow the disinfection system to perform more efficiently. The required turbidity of the water entering the disinfection stage after pretreatment will depend upon the type of disinfection used. Removal of solids earlier in the operation will also increase the system's lifetime and reduce maintenance. For this project, rapid sand filtration, roughing filters, sedimentation, and washable sediment filters were considered for pretreatment, based upon their expected ability to meet the evaluation criteria presented in the Project Understanding. Each of these is discussed below.

2.1.1.1 Rapid Sand Filters Rapid sand filters are a common means of reducing the turbidity of water in rural areas due to their simple operation and low costs. A rapid sand filter uses various layers of sand and gravel along with the force of gravity to remove solids from water. Solids within the water are removed through straining, sedimentation, impaction, and adhesion. Rapid sand filters are capable of handling a flow of 65 feet per hour and can reduce turbidity to a value of 1 NTU.

Rapid sand filters require frequent cleaning through backwashing. This is achieved by passing clean water up the filter at in increased pressure. The amount of backwashing and pressure required varies for each system. It is often necessary to treat the water prior to the rapid sand filter in order to reduce the amount of backwashing necessary. [6]

2.1.1.2 Roughing Filters A roughing filter is a simple means of initial treatment of water. In this technique water is passed through layers of gravel ranging in size from 5-35 millimeters. Roughing filters can be used by passing the water down through the gravel using gravity, up through the gravel, or horizontally through the gravel. Passing the water up through the gravel allows gravity acting against the water to aide in the removal of the sediments. These filters are capable of removing the initial water turbidity by 40-85% and can handle high flow rates. Roughing filters can easily be cleaned by passing water down through the rocks and gravel to remove and solids that have been collected. [7]

2.1.1.3 Sedimentation A simple means of initial treatment is sedimentation. In this process water is allowed to remain still for a period of time. This process can remove a considerable amount of solids from the water, but requires too much time and space to meet the 3,000 gallons per day flow requirement and retain mobility. Sedimentation is often preceded with coagulation and flocculation in order to increase the amount of solids that are able to settle, requiring the use of chemicals.[8]

2.1.1.4 Washable Sediment Filters Sediment filters are perhaps the most conventional form of filtration. These filters pass water through a polyester fabric which prevents the passage of small particles. Currently on the market are pleated filters which can be washed many times before they need to be replaced. These filters are available in many sizes including 5 and 20 microns, both of which are capable of a 3,000 gallon per day flow rate. In addition, the filters are inexpensive and the maintenance required is very simple.[9]

2.1.2 Disinfection The disinfection portion of the drinking water disinfection system serves to remove or deactivate all microorganisms in the water. This is necessary to ensure the drinking water is no longer contaminated with bacteria and is safe to drink. For this project, ceramic filters, ozone, ultrafiltration, and ultraviolet disinfection were considered for disinfection. Each of these is discussed below.

2.1.2.1 Ceramic Filters Ceramic drinking water filters have a pore structure which has an absolute filtration rating, defined as >99.99%, of 0.9 microns. These filters are capable of removing both sub-micron particles and pathogenic bacteria from drinking water. Therefore, the ceramic filter could be used both for filtration and for disinfection of bacteria. However, these filters do not remove viruses. Ceramic filters tend to have long life, but need periodic cleaning in order to prolong the life of the filter. In this way, the filter can be re-used rather than replaced, giving it a longer overall lifetime. On average, a ceramic filter element will remain effective for up to 6 months (depending on usage and water quality) before it will need to be replaced. Normally, the ceramics used in the filters contain trace elements of silver. Silver inhibits microbiological growth, meaning that there is no need to sterilize filter candles, even when they are used over an extended period. Ceramic filters do, however, require high pressures to reach high flows, such as the one required for this system, meaning that a large amount of power would need to be supplied to the system.[10]

2.1.2.2 Ozone Ozone is one of the most effective means of ensuring all bacteria in drinking water are eliminated. An ozone generator can be used to create ozone in-situ and would be able to meet the water demand of 3,000 gallons per day. The generation of ozone is a fairly complex process involving the need for the addition of dry air, gas destruction, and a reliable source of power. Ozone generators can be dangerous because ozone leaks are hazardous. Therefore, a monitor should be used to detect the colorless, odorless gas. Once an ozone disinfection system is installed, very little maintenance is needed as it is highly automated. However, a highly skilled technician is needed to repair and service the components associated with the ozone disinfection system.[11]

2.1.2.3 Ultrafiltration Ultrafiltration utilizes semipermeable membranes and hydrostatic pressure to remove contaminants from water. Ultrafiltration systems are capable of removing suspended solids and other particles in water, along with pathogenic microorganisms such as bacteria. Although ultrafiltration systems consistently remove bacteria and use no chemicals, they are very expensive and require extensive training to operate. In addition, sediment builds up on the membranes requiring frequent cleaning. The systems also need large amounts of head (or energy) to gain the pressure necessary for operation.[12]

2.1.2.4 Ultraviolet Disinfection Ultraviolet radiation is generated by a special UV lamp. When this radiation penetrates the cell wall of an organism, the cell's genetic material is disrupted and the cell is unable to reproduce. UV radiation effectively destroys bacteria and viruses. UV radiation can be attractive as a primary disinfectant for small systems because it's readily available, produces no known toxic residuals, requires short contact time, and the equipment is easy to operate and maintain. UV radiation is unsuitable for water with high levels of suspended solids, color, or soluble organic matter, and requires the turbidity of input water to be less than 5 NTU. These materials can react with, block, or absorb the UV radiation, reducing the disinfection performance.[13]

2.1.3 Renewable Energy If the chosen disinfection system requires power, it will be necessary to supply the required amount to the system with a form of renewable energy. For this project, wind power, solar power, and human power were considered for power sources. Each of these is discussed below.

2.1.3.1 Wind Power Wind power is defined as the conversion of the kinetic energy of wind into usable energy and is currently one of the most promising sources of clean, renewable energy. The most current and advanced method used today is wind turbines. Advancements in wind power research have resulted in wind power's ability to compete with fossil fuels both economically and efficiently. [14] Given the portability constraint of this project, only portable wind power generators will be considered during this project. Currently the market holds portable wind power generators that can charge small 5 volt appliances while larger more extensive options have been engineered to generate up to 400 watts. [15]

2.1.3.2 Solar Power Solar power relies on the nuclear fusion power from the sun. The use of solar power comes in two forms, thermal and photovoltaic. Thermal converts sunlight into heat and applies it to steam generators or engines to be converted into electricity or radiant heat. Given this form of solar energy's lack of applicability to the project, it will not be considered. Photovoltaic consists of silicon cells that use sunlight to create an electric current. PV cells have been engineered to be portable and reliable enough to be considered a viable source of energy.[16]

2.1.3.3 Human Power Human power is the broadest of the available alternative energy methods. For the purposes of this project, only hand powered or bike powered modes of energy generation will be considered. Hand power generators currently on the market can produce typically 50 watts and charge 12 volt batteries.[17] Bike or pedal powered generators can produce up to 125 watts of power.[18] Both options are limited to disinfection systems that require a low level of wattage. However, these are still viable methods of power given they can be portable and easily operated by a wide audience.

2.2 Evaluation of Solutions After various technologies were identified for pretreatment, disinfection, and power, they were evaluated based on the criteria established in the Project Understanding section in order to determine which combination of solutions would work best for this application. Because of the large number of potential design solutions being evaluated, it was economically impractical to acquire and test each technology. Instead, decision matrices were created to assist during the evaluation, and the criteria used within these matrices were weighted depending on their importance for the project.

For pretreatment, the most important required criteria were the system's ability to reduce turbidity and its ability to meet the required flow of 3,000 gallons per day. Each of these criteria was given a weighting of 0.18. In order to achieve the required flow rate the system will meet a flow of 5 gallons per minute, with the assumption that the system realistically will only be operating 12 hours per day. This will also allow a factor of safety to ensure the system meets the flow requirements as a system supplying 5 gallons per minute for 12 hours a day will actually disinfect 3,600 gallons of water per day. The next criteria, "applicability to rural, third-world settings" and "ability to be simple for ordinary citizens in third-world environments to implement, operate, and maintain" work together to ensure the system will be viable in a real life situation. Important considerations for these criteria include complexity and lifetime of the technology, availability of building materials, requirements for operation and maintenance, and training needed to operate the technology. These were chosen to be the next most important criteria and were given a weighting of 0.12.

Each alternative was also evaluated based on its safety, and its potential to be mobile. Safety received a weighting of 0.10 and mobility received 0.08. For the purposes of this design project, "mobile" is defined simply as movable by horse, mule, or automobile if the system is built on a trailer. The system will, however, be designed to be as small as possible.

In addition, technologies were compared to one another with regard to cost. Both initial capital cost, or how much it costs to implement the system, and the cost throughout the system's lifetime, mainly for replacement parts, were considered. Initial capital cost was weighted as 0.07 and ability to be cost effective was weighted as 0.05. Potential solutions were also evaluated based on their power consumption, as the power must be considered and supplied by the system. Power requirement was given a weighting of 0.05. Finally, the type and amount of waste generated by each technology was considered. Waste generation was also given a weighting of 0.05.

Similar criteria were used to evaluate the disinfection and renewable energy portions of the system. For the disinfection technology, it was most important that it be able to disinfect water to WHO drinking water guidelines to ensure no presence of coliforms remaining in the water while meeting the specified flow rate of 3,000 gallons per day to ensure community members always have enough clean water. The remaining criteria used to evaluate the potential solutions are the same as for pretreatment, with the exclusion of turbidity reduction. Alternative energy solutions were evaluated with these same criteria, with the additional comparison of their ability to power the disinfection system.

2.3 Decision Matrices Decision matrices were created for each portion of the disinfection system to help determine which technologies would work best for the specialized application. All solutions were evaluated against each criterion and given a score from zero to five (low to high). Final scores were then calculated for each solution using the chosen weighting for each criterion. The decision matrices created for pretreatment, disinfection, and renewable energy can be found in Appendix A. Table 1 shows the final results obtained during the evaluation process.

Table 1 – Results from Evaluation of Alternative Solutions

Potential Solutions					
Pretreatment	**Score**	**Disinfection**	**Score**	**Renewable Energy**	**Score**
Rapid Sand Filter	4.44	Ultraviolet Disinfection	3.70	Solar Power	4.16
Roughing Filter	4.38	Ozone Generator	3.39	Human Power	4.00
Washable Sediment Filter	4.25	Ultrafiltration	3.12	Wind Power	3.02
Sedimentation	3.83	Ceramic Filter	2.61		

2.4 Selection of Design Using the decision matrices and the team's collective judgment, a design was chosen for the disinfection system. Based on this analysis, it was determined that both a roughing filter and a rapid sand filter would be used for pretreatment because they received similar scores during evaluation. Using both systems will help to lengthen the lifetime and reduce the required maintenance of the rapid sand filter by removing some solids with the roughing filter prior to the rapid sand filter. Together, these systems have the potential to reduce the turbidity of the water to less than 5 NTU allowing for complete disinfection. Additionally, they will be inexpensive, simple to implement, operate, and maintain, and will be capable of a 3,000 gallon per day flow rate.

Ultraviolet radiation administered by an ultraviolet light was chosen as the method for disinfection. This device, coupled with the pretreatment, will efficiently deactivate all microorganisms in the drinking water. A UV disinfection system will easily be capable of treating 3,000 gallons of water per day while retaining mobility. Training of operating personnel will be required to ensure proper maintenance of the system. However, the UV device is highly automated and will demand little attention. Finally, the system has a high initial cost, but subsequent operation and maintenance costs will be low.

Using the third decision matrix, it was determined that power will be provided to the system via a combined system of solar power and a human-powered bicycle. The combined approach allows a battery to be charged by solar panels if the sun is shining allowing the system to operate automatically. However, if it is cloudy or the solar system is under maintenance or not working properly, a bicycle can be pedaled to generate electricity to ensure the community will always have access to clean drinking water. Together, the solar panels and bicycle will easily provide enough power to charge the battery to operate the UV light and one pump for backwashing the rapid sand filter. The human-powered bicycle will have low initial and maintenance costs; the solar system will have a high initial cost, but low maintenance costs and a long lifetime. In addition, the solar system and bicycle take up little space, so the system will retain mobility.

2.5 Development of the Design After the components of the disinfection system were chosen, development of the design began. A bench-scale model of the system was constructed for testing to ensure the design worked properly, and also to aid in sizing the full scale system. The pretreatment portion of the system was first constructed and tested. During this stage, many different configurations for the roughing filter and rapid sand filter were built and tested, until arriving upon the final design which was found to work best for the system. Diagrams of each configuration, results from testing, and reasons for abandoning the designs can be found in Appendix B.

Once the designs for the roughing and rapid sand filters were finalized, the remainder of the bench-scale model was constructed. The sizing and flow rates from this model were then used to develop proper sizing for the full scale disinfection system. Descriptions of both the bench-scale model and the full scale system are given in the following sections.

III. BENCH SCALE DESIGN

3.1 Description of Design For the purposes of demonstrating the system's applicability and effectiveness during the WERC competition, a bench-scale system was constructed. A photograph of the system can be seen in Figure 1 and schematic for the model can be seen in Figure 2. A larger schematic can be found in Appendix C. The bench-scale model is designed to operate at a reduced flow rate of0.75 gpm as compared to the full sized system which will have a flow rate of 5 gpm. The layout of the system including direction of flow and location of filter inputs is designed to have the same specifications as the full scale system.

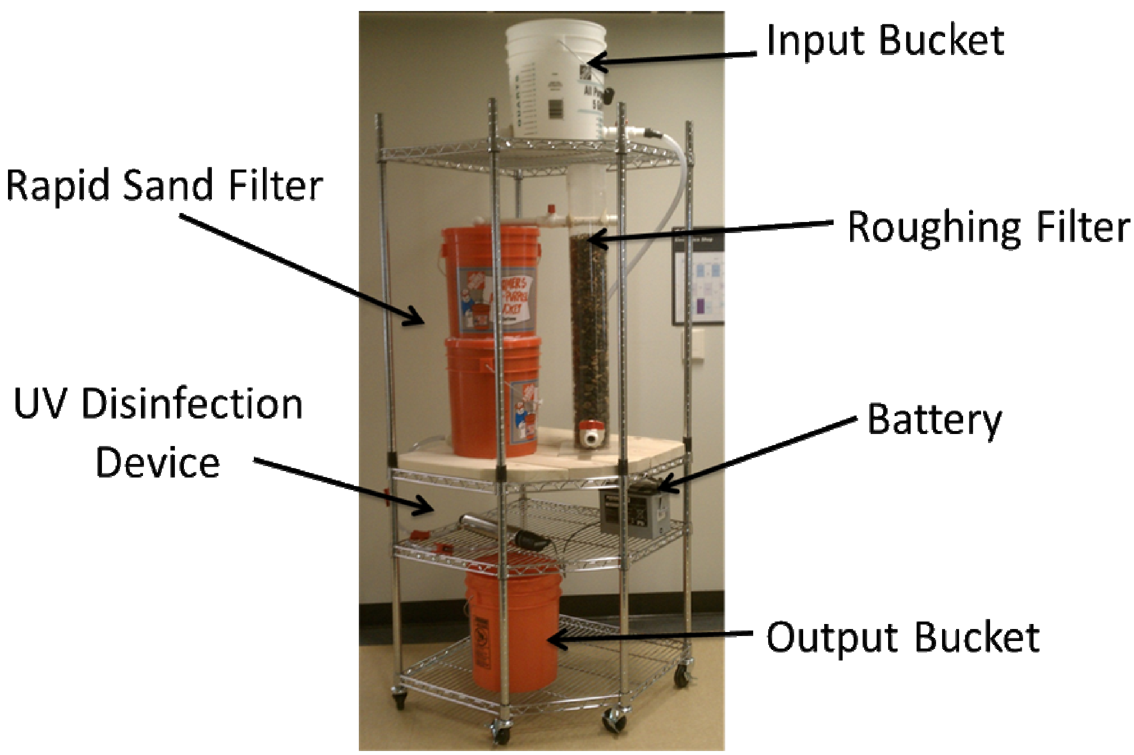


Figure 1 – Photograph of Bench-Scale System

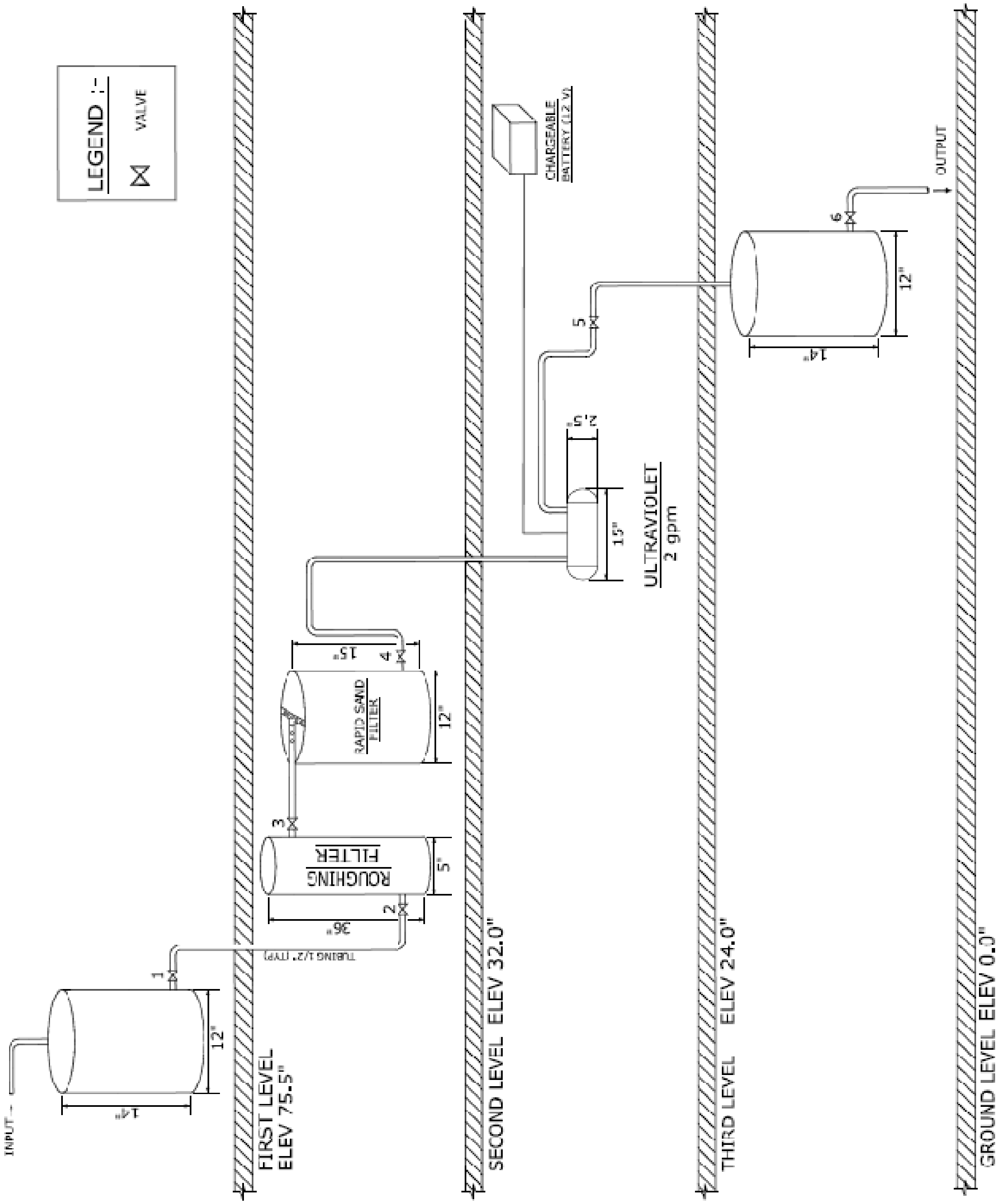


Figure 2 – Bench-Scale Schematic

As seen in Figures 1 and 2, the bench-scale system consists of a roughing filter, a rapid sand filter, and a UV disinfection system with buckets for input and output. The roughing filter was built using a five-inch diameter clear PVC pipe with a height of 35 inches, and consists of three 9 inch layers of gravel as seen below in Figure 3. The rapid sand filter was constructed using two stacked five gallon buckets. The layer configuration within the rapid sand filter can be seen in Figure 4 below.

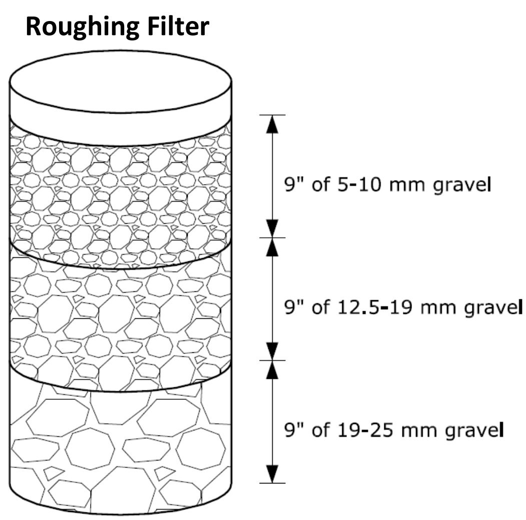


Figure 3 – Roughing Filter Layers

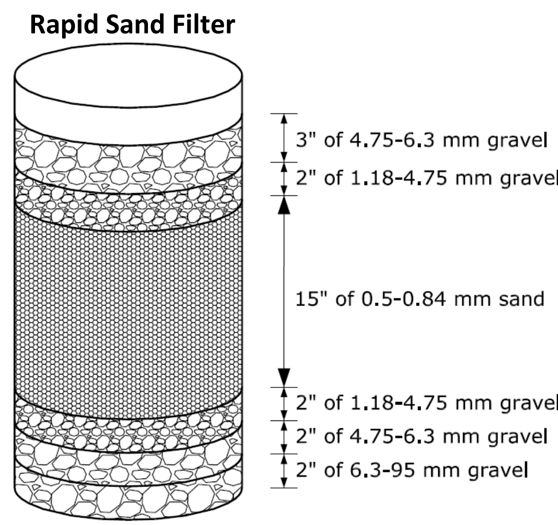


Figure 4 –Rapid Sand Filter Layers

After passing through the rapid sand filter, water will flow through a UV disinfection device powered by a 12-volt battery with a maximum flow rate of 2 gpm. After passing through the filter, the water will end in another five gallon bucket. All of the components mentioned will be positioned on differing elevations to allow for the proper amount of head required to operate each component. This allows the system to flow at 0.75 gpm through the roughing filter and the rapid sand filter without the use of a pump.

Given that the bench scale system will only be processing a small amount of turbid water for demonstration purposes, the system will not reach a point where backwashing will be necessary. Therefore, it was determined the construction of a backwashing system was not necessary for the bench-scale design.

3.2 Operation At the competition, 3.5 gallons of water was supplied to the team to disinfect using the bench-scale system. To successfully treat the water, the battery was attached to power the UV system and all necessary valves were opened to allow proper flow through the system. The contaminated water was then poured into the input bucket and was sequentially fed through the roughing filter, rapid sand filter, and the UV disinfection system.

The team monitored the volume of exiting water by keeping track of the time. This ensured that all of the water contained in the system prior to the addition of the sample water was completely flushed out of the system. After 8 minutes and 40 seconds had passed, the water initially contained within the system had passed through allowing the 3.5 gallons of contaminated sample water to reach the end of the system and be collected. The team continued to feed inflow water to the system until all 3.5 gallons of contaminated water had been collected in the output bucket.

3.3 Bench-Scale System Performance To evaluate the performance of the system, the reductions of turbidity and bacteria were tested three times with the bench-scale system. To complete the testing, five gallons of water with known turbidity and bacteria levels were added to the system. Samples were then taken after the roughing filter and rapid sand filter every minute until all five gallons of the water had gone through the system to use in the turbidity and bacteria analyses.

Using water from these samples, the level of turbidity was found after the roughing and rapid sand filter. To test the turbidity of the water, a HACH turbidimeter was used. With the data collected during this test, percent reduction after the roughing filter and rapid sand filter was calculated and graphed as seen in Figure 5. This graph shows the roughing filter on average reduced turbidity by 43%, with an additional 43% reduction provided by the rapid sand filter. Total turbidity was reduced by about 86% during the entire filtration process, resulting in a turbidity reduction from an average of 25 NTU to about 3.5 NTU. This turbidity is adequate for the UV disinfection system which requires input water with turbidity less than 5 NTU. In addition, this turbidity meets WHO’s standards, which state the turbidity of drinking water should not be more than 5 NTU.[3] All data collected during testing of the final bench-scale model can be found in Appendix D.

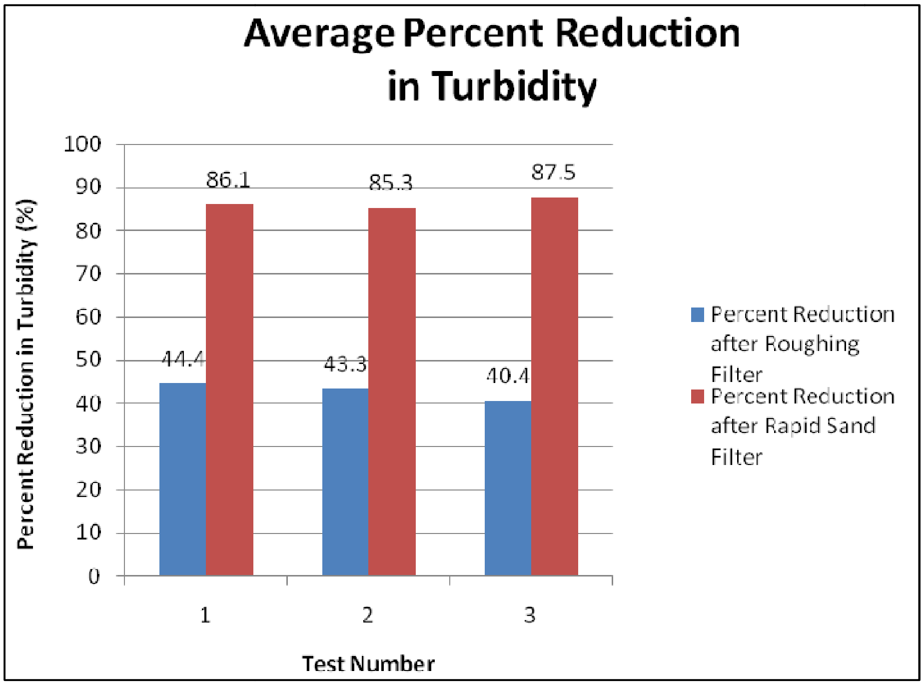
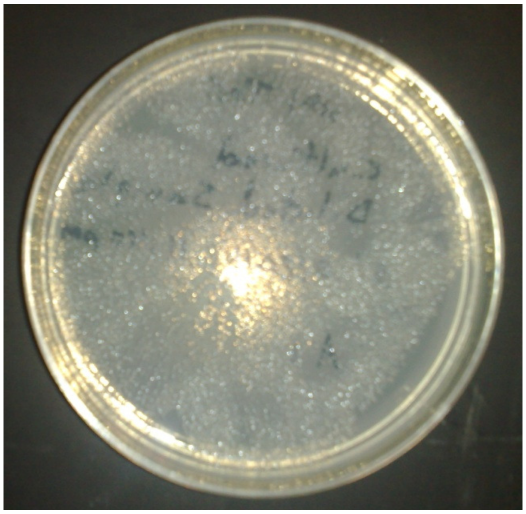


Figure 5 – Average Percent Reduction of Turbidity

The samples were also tested for bacteria by adding water with a bacteria concentration of 3.00×10^7 CFU/mL to the system. Water samples were taken prior to disinfection and after disinfection in conjunction with the samples used for turbidity analysis. The water was then tested for bacteria using the heterotrophic plate count method with a nutrient agar medium for cultivation and determination of microorganisms. The tests were performed with three plates for every sample taken prior to or after treatment with the UV disinfection system. The multiple plates ensure data quality assurance and control. The plates were left for 48 hours at which point the percentage of growth on each plate was determined. After 48 hours, results from these tests showed conclusively that large amounts of bacteria were present in the input water and no growth of bacteria was found in the output water as seen in Figures 6 and 7, respectively. The shimmer seen in Figure 6 indicates the presence of bacteria. All data collected during testing of the final bench-scale model can be found in Appendix D.



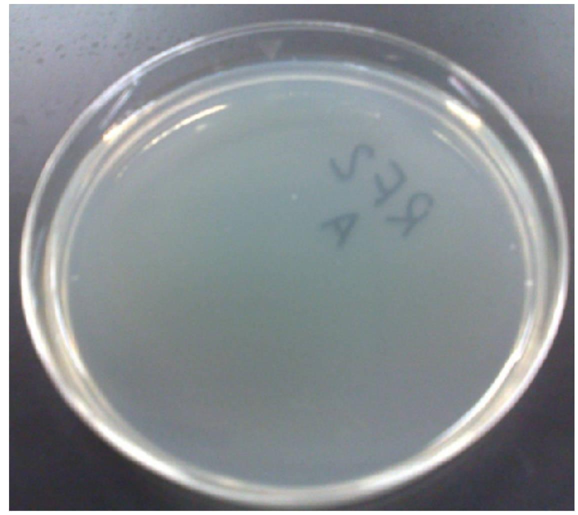


Figure 6 – Input Water Bacteria Growth **Figure 7 – Output Water Bacteria Growth**

IV. FULL SCALE DESIGN

4.1 Description of Design The design for the full scale disinfection system was developed based upon the sizing and performance of the bench-scale model. The bench-scale model was used to determine the flow rate per unit area of each component. This was then used to determine the necessary sizes of all components in the system. All calculations performed during the design of the full scale system can be found in Appendix E.

The full scale disinfection system, seen in Figure 8, is designed to be constructed and operated on a 6 ft. by 7 ft. trailer that can be pulled behind a vehicle or animal depending upon local resources. A larger schematic can be seen in Appendix C. The input water will be sent into the bottom of the two roughing filters and flow up through the contents of the filter into the top of the rapid sand filters. The system is designed using two pretreatment systems operating in parallel to ensure water can continue running through the system while one series is down due to maintenance or other problems. The water will then pass down through the rapid sand filter where it will be directed to a storage tank. After the storage tank has sufficient water to meet the needs required for backwashing, water will begin to flow out of the storage tank into the UV system where the water will be fully disinfected prior to exiting the system. The UV system exposes the water to a light intensity of 40 mJ/cm^2, which meets the Environmental Protection Agency standards for ultraviolet disinfection. The UV light and the pump required for periodic backwashing will be powered using a combination of photovoltaic cells and a power-generating bicycle as discussed in the proceeding section. The water disinfection system is designed to treat

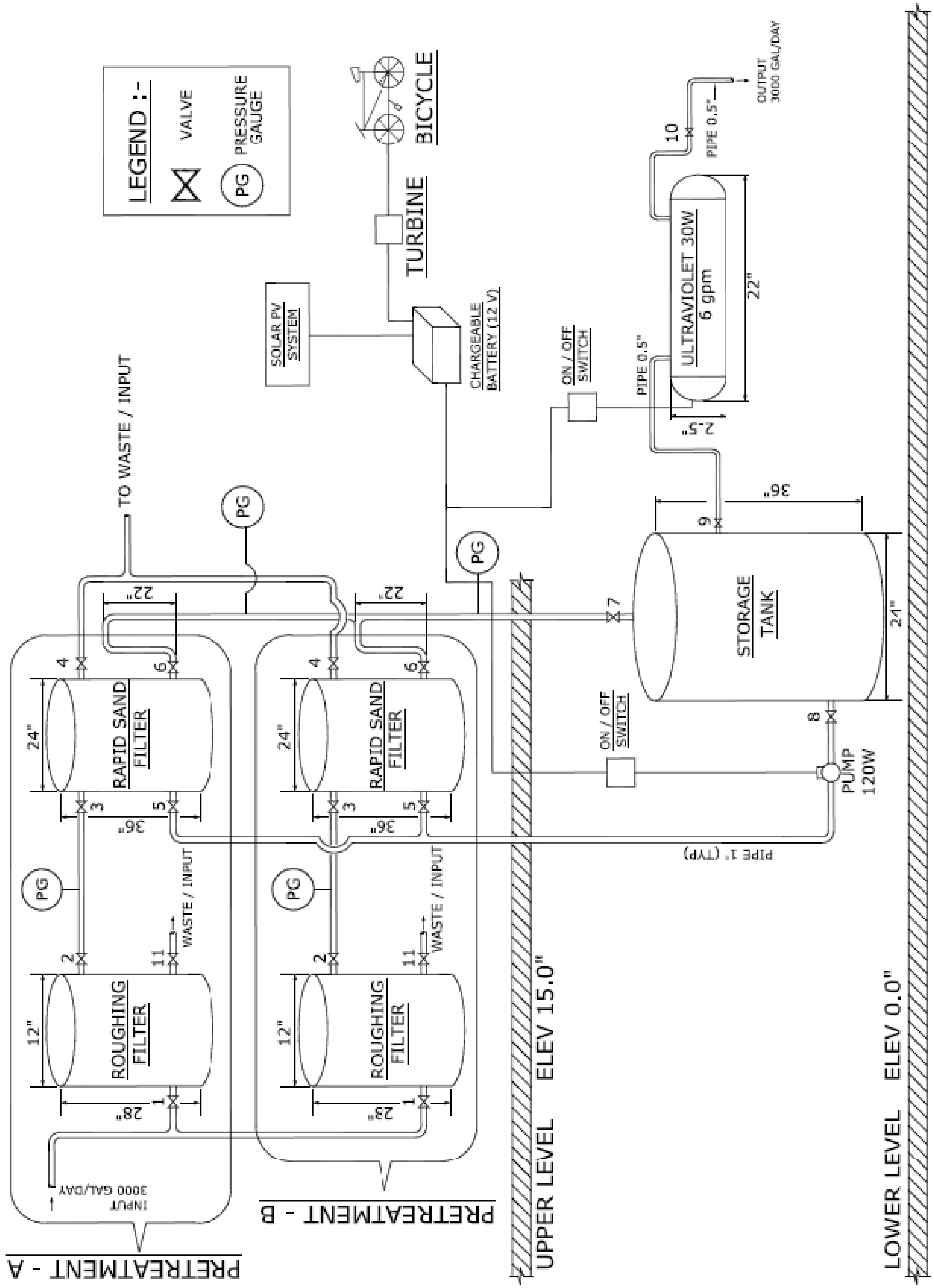


Figure 8 – Full Scale Schematic

up to 3,000 gallons of water in 12 hours of operation, resulting in a flow rate of 250 gallons per hour or about 5 gallons per minute. The input of the water and storage or distribution after output from the system is beyond the scope of work for this project and must be designed on a case-by-case basis depending on the infrastructure of each particular location. A description of the design is detailed in the following sections.

4.1.1 Water Treatment The raw, untreated water enters the system and is first sent into the roughing filter. This will be constructed within a container 28 inches high and 12 inches in diameter, which is the equivalent of two stacked five-gallon buckets. A one-inch PVC pipe will carry the water into the bottom of the roughing filter, where it will exit the pipe via perforations in a series of parallel pipes. The water will then flow upward to the top of the roughing filter. The media inside the roughing filter can be constructed using locally available material. This can include gravel, crushed bricks, coconut fibers, or any other insoluble material. The material inside the filter should be arranged according to size, with the larger media at the bottom and the smallest media at the top. The size of the media should be equivalent to that used in the bench-scale model which can be seen in Figure 3. This gradual decrease in media size will help prevent the roughing filter from clogging, therefore prolonging time between cleanings. Once the water reaches the top of the roughing filter it will flow through holes located in the PVC pipe at the top of the filter into the top of the rapid sand filter.

The top of the rapid sand filter will contain a series of perforated pipes that will allow the water to exit and disperse evenly over the area of the filter. This filter is designed to have the same layer configuration as the bench-scale model which is illustrated in Figure 4. These layers will be constructed within a container 24 inches in diameter and 36 inches tall, which is equivalent to a 55 gallon drum. The size of the rapid sand filter was determined based on the flow rate of the constructed bench scale model. The full scale model was slightly oversized to reduce the frequency of backwashing.

The water will exit through the bottom of the rapid sand filter via perforated pipes which will then extend upwards to a height of 22 inches. This will ensure the sand layer of the filter will always remain wet preventing the layer of sand from drying out and cracking. This water will then flow into a 55 gallon storage tank where it will remain until it is either sent to the UV system for disinfection, or used for backwashing the rapid sand filters. The top of this storage tank will need to be located less than 22 inches above the base of the rapid sand filter to ensure adequate head is available to fill the tank. In order to accomplish this, the two levels of the trailer should have a difference in elevation of at least 15 inches.

Water will exit the storage tank via a half-inch stainless steel pipe and flow through the attached ultraviolet light. This pipe must be constructed of stainless steel to prevent the UV radiation from degrading the PVC pipe. This light is contained within a stainless steel enclosure 2.5 inches in diameter and 22 inches long. The UV lamp inside the enclosure is covered by a quartz sleeve to protect the bulb from the water. The water will then pass through a thin annulus around the UV lamp allowing for complete penetration of the UV rays. At this point, the water will be disinfected and will be available for collection or distribution.

4.1.2 Power The full-scale system will be equipped with a backwashing pump and a UV disinfection device, which will be powered by a 12-volt battery capable of supplying 150 Amp-Hours. The battery is sized to meet the collective energy needs of the 120 Watt and 30 Watt requirements for the water pump and UV disinfection device respectively. The 12-volt, 150 Amp-Hour battery is charged by a photovoltaic panel, and is backed up by human-powered bicycle DC generator.

4.2 Operation and Maintenance The water disinfection system is designed using two pretreatment systems, each consisting of a roughing filter and rapid sand filter, operating in parallel. This will allow water to continue running through the system while ones series is down due to maintenance or other problems. During normal operation valves 1, 2, 3, 6 and 7 should remain open and valves 4, 5, 8 and 11 should remain closed. Valves 9 and 10 should not be opened until the user ensures the UV light is powered on. Valve numbering can be seen in Figure 8.

The roughing filter should be cleaned periodically. The frequency of this cleaning will depend on the quality of the input water. Cleaning of the roughing filter will be done by closing valves 1 and 2 in the series to be cleaned and opening valve 11 on the same series. This will allow the water to drain quickly out of the roughing filter, carrying the sediments out with it. The drained water will not contain any harmful chemicals; therefore, it can be released into the environment or sent back to the input, depending on the needs of the community.

Pressure gauges will be located immediately prior to and after each of the rapid sand filters. This will allow the user to check for an increase in pressure, which will indicate that the filter needs to be cleaned through backwashing. The frequency of backwashing will vary depending on the quality of input water. When backwashing is needed, valves 1, 2, 3, and 6 of the series in which the dirty filter is located should be closed. Valves 4 and 5 on the rapid sand filter to be cleaned should be opened along with valve 8. The pump should be powered on and allowed to run for 3 minutes. This will force water up through the sand filter at a velocity of 16 gpm, as determined using equations [1] and [2], which will create 30% bed expansion. Calculations done to obtain these values can be seen in Appendix E.

$$V_s = [\frac{4g}{3c_d}(S_s - 1)d]^{1/2} \qquad [1]$$

$$V_b = V_s \varepsilon_e^{4.5} \qquad [2]$$

While one of the parallel filtration systems is off duty to be backwashed, the other is able to continue normal operation. To ensure the 48 gallons of water required for backwashing are always available for one of the rapid sand filters, the exit from the storage tank leading to the disinfection system is located 24 inches above the base of the tank.

Proper maintenance will prolong the life of the UV disinfection system. The quartz sleeve located within the disinfection system should be cleaned periodically. The frequency of cleaning will vary depending on the hardness of the water along with its iron and manganese concentration. To clean this sleeve, valves 9 and 10 should be closed and the power to the ultraviolet light should be switched off. The drain plug should then be opened allowing all water to exit the UV system. The top of the ultraviolet system can then be opened and the quartz sleeve should be carefully pulled out. Cleaning can be done using a soft cloth and a mild acid, such as vinegar, which should be kept on site with the disinfection system.[18]

The UV disinfection system comes with an audible alarm to alert users that the light has failed. This will ensure users do not continue to operate the water treatment system with a nonfunctioning UV light as this would cause the system to fail to disinfect the water. A spare UV bulb should be kept on site at all times. This light should be properly packaged and stored to prevent breakage.

With proper maintenance, it is anticipated the system will be able to operate for about 6 years while replacing only the UV bulb and the battery. After 6 years it is likely the media in the roughing filters and rapid sand filters will need to be replaced, though the frequency of this will depend on the quality of the raw water used in the system. However, all components of the system are simple to replace, which will allow the system to continue operating with no finite lifetime.

4.3 Waste Generation The system is designed to rely mainly on natural material found locally such as sand and gravel for use as the media in filtration system. This serves to minimize the amount of waste generated by the system. Waste water that results from backwashing the system will be free of any harmful chemicals; therefore, strict disposal guidelines will not be necessary. The waste water generated can be allowed to flow freely into the environment, though care should be taken to ensure the water does not create flooding or excessive erosion in the area or pool to create stagnant ponds near populated areas. This can be prevented by channeling the water to a nearby pond or stream. Operators may also choose to reuse this waste by piping it back into the input of the water treatment system if water is at a premium.

Each ultraviolet light is designed to operate for 9,000 hours, or 2 years, of continuous use. The retired ultraviolet lights will need to be disposed of in a manner consistent with hazardous waste disposal guidelines in the operating area. The chargeable 12-volt battery will also need to be replaced periodically. The waste battery should also be disposed of or recycled in the appropriate manner to comply with local hazardous waste guidelines.

4.4 Safety Considerations Care should be taken when operating the water disinfection system. Operators should ensure the ultraviolet light is installed correctly within the provided enclosure prior to powering on the ultraviolet disinfection system. Direct exposure to ultraviolet rays may be harmful to unprotected eyes and skin.[19] Precautions should be taken when relocating the ultraviolet system as well as the extra ultraviolet bulb to prevent damage to the system. The bulbs should be stored in a safe protected area with padding around the light to prevent it from cracking. A broken ultraviolet light poses hazards to the operator including sharp pieces of broken glass along with the presence of hazardous mercury. In the event that an ultraviolet light is damaged, proper protective equipment including gloves and eye protection, should be used to properly dispose of the ultraviolet light.

Safety precautions should be followed when maintaining and operating the 12-volt battery used to store power generated by the photovoltaic cells and bicycle generator. Intact batteries do not pose any specific hazards. Proper maintenance should be conducted to ensure batteries remain safe and intact. The battery should be inspected regularly to check for defective cables, loose connections, corroded terminals, cracked cases, and deformed or loose terminal posts.[19] The battery should be stored in a well-ventilated area, as lead acid batteries produce flammable hydrogen and oxygen gasses during charging. For this reason, batteries should not be exposed to high temperatures or sparks.[20] Proper personal protective equipment including gloves and eye protection should be worn when handling a damaged battery to ensure battery acid does not contact skin or eyes. If contact does occur the area should be flushed with water immediately for 15 minutes.[21]

4.5 Cost of the system

4.5.1 Cost of Implementation The cost for implementation of the disinfection system was developed based on the cost of materials in the United States since no location of intended use has been specified. The total cost is expected to be $2,251. This cost is largely based on the cost of the UV system, pump, battery, solar system, and a human-powered bicycle. Costs of media in the roughing and rapid sand filters have been neglected as it is assumed these materials will be available for free in the location of implementation. In addition, no labor costs have been estimated for two reasons. First, it is expected that all manual labor will be performed for free by members of the community who will eventually use the system themselves. Second, if this is not the case, labor costs vary too widely to provide an accurate cost estimate. The cost for each component and the total cost for materials for the disinfection system can be seen in Table 2.

Table 2 – Cost Estimate for Initial Implementation

Item	Quantity	Place of Procurement	Unit Price ($)	Sub-Total ($)
1" PVC Ball Valve	18	Home Depot	$ 2.00	$ 36.00
1" Pipe (20 feet)	1	Home Depot	$ 5.00	$ 5.00
Tank, 25" Diameter, 36" Height	3	Home Depot	$ 45.00	$ 135.00
Tank, 12" Diameter, 28" Height	2	Home Depot	$ 47.00	$ 94.00
Backwash Pump 12v	1	Sureflow	$ 150.00	$ 150.00
UV Disinfection Device 5 GPM	1	Sterilight	$ 274.00	$ 274.00
Chargeable Battery 12v 150 Amp-H	1	Battery Plus	$ 200.00	$ 200.00
ON/OFF 12v Switches	2	Home Depot	$ 3.50	$ 7.00
PV Panel & Battery charger 230 Watt	1	Grape Solar	$ 690.00	$ 690.00
Man Powered Bicycle 200 Watt DC generator	1	Pedal Power Generators	$ 660.00	$ 660.00
			Total	$ 2,251.00

4.5.2 Cost of Maintenance and Operation The cost for operation was calculated based on the implementation cost and expected maintenance costs over the system's lifetime. Table 3 shows the cost of operation per day and the cost of operation per gallon after the first, third, and sixth years of service. The cost per day after 6 years totals $1.41 per day, which is equivalent to disinfecting 20 gallons of water for one cent.

Table 3 – Cost of Operation per Day and per Gallon

Maintenance Parts	Replacement Frequency (Approx.)	Unit Price ($)	1 Year Cost	3 Year Cost	6 Year Cost
Initial Capital Cost		$ 2,251.00			
UV Disinfection Lamp	Every 2 Years	$ 61.00	-	$ 61.00	$ 183.00
Chargeable Battery 12v	Every 3 Years	$ 200.00	-	$ 200.00	$ 400.00
Miscellaneous	Every 1 Year	$ 45.00	$ 45.00	$ 135.00	$ 270.00
		Cost per Day of Operation	$ 6.29	$ 2.42	$ 1.41
		Cost of Operation per Gallon	$ 0.0021	$ 0.00081	$ 0.00047

V. TECHNICAL EVALUATION

5.1 System Performance Analysis Through testing of the system, it was determined that the bench-scale model provides a significant reduction in bacteria and solids. The roughing filter reduced turbidity by about 43% for each test, and the rapid sand filter resulted in an additional 43% reduction. In total, the pretreatment system reduced turbidity by 86% on average, with a final input into the UV system of about 3.5 NTU. This reduction in solids was sufficient for the UV system, and allowed for complete disinfection of the water. This turbidity also meets WHO's standards, which state the turbidity of drinking water should not be more than 5 NTU.[3] In addition, the disinfection system performed as anticipated during the bench-scale demonstration at the competition, though no feedback was acquired from the judges. Based on these results, it is expected the full-scale system will produce similar results.

Assuming similar results from the full-scale system, the requirements for the disinfection system were all adequately met. Most importantly, the system is capable of disinfecting 3,000 gallons of water in 12 hours to WHO drinking water standards, which dictate there is no presence of coliform in the water. The system also utilizes clean, renewable energy in the form of solar panels and a human-powered bicycle to power the system and ensure it will always have access to sufficient energy to disinfect drinking water for the community.

The disinfection system is also applicable to rural, third-world areas as it is simple, inexpensive, and durable with a long lifetime. Community members using the system will be responsible for its operation. However, the system will require a trained operator to ensure it is always working properly and producing disinfected water. As it is a highly automated system, daily maintenance is simple and will consist of the completion of a short checklist and will take only a few minutes each day. The final cost for implementation of the system is $2,251 and the operating cost per day after six years is approximately $1.41, or one cent per 20 gallons. Additionally, the payout period for the system is 7 months and the rate of return is 196%. Calculations done to obtain these values can be seen in Appendix F. These calculations were based on a lifetime for the system of 6 years, as it is expected the media in the roughing and rapid sand filters will need to be replaced at this time. However, all components of the system are simple to replace, which will allow the system to continue operating with no finite lifetime. The short payout period and the high rate of return indicate the system is a good investment, and the benefits the system will provide justify the cost.

While the system is large and heavy, it can be mobile if built on a trailer or installed in the bed of a pickup truck. If it is built on a trailer, a large work animal or a vehicle can move it. The disinfection system was also designed to be safe, generate little waste, and have a low power requirement. The system does have several safety issues regarding the battery and UV light. However, with a properly trained operator, injuries resulting from use of the disinfection system can be eliminated. Backwashing water from the roughing and rapid sand filters and used UV bulbs and batteries account for most of the waste generated by the system. Total waste may be reduced if the community chooses to recycle their backwashing water in the system. UV bulbs and batteries will be properly disposed of by the trained operator when new bulbs or batteries are purchased for the system. Lastly, the disinfection system has a very low power requirement of only 150 watts required by the UV light and backwashing pump.

5.2 Recommendations for Implementation There are many factors that must be considered before implementation of this system can occur within a community. First, it will be necessary for a cultural expert to educate the community members about why a disinfection system is necessary and how it can be beneficial to them. In addition, the expert should ensure any possible cultural issues are rectified so the system can be easily integrated into the community and will be used to its full extent.

Once the community has been educated about the disinfection system and is interested in implementing one for their use, a site analysis must be conducted. The purpose of this analysis will be to investigate water parameters such as pH, hardness, and elevated levels of suspended solids which may cause problems for the system. Plans for the resolution of these issues have not been developed because they are beyond the scope of this project as it was not designed for a specific location. Instead, the problems will need to be addressed individually by the water quality analyst.

During the next stage of implementation, the community should be assisted in developing a plan for construction. It is likely that the "project manager" for this task should also be the community member who will receive training to become the system operator. The plan for construction should include a materials list with proposals for procurement of all materials and a cost estimate, simple designs for how the system will be built if additional building plans are necessary, and a method for testing the system after it is constructed to ensure it is working properly. In addition, designs for input and output of the water should be developed, which account for the current infrastructure in the community and how they wish to store and distribute water. A plan should also be developed which details the steps that should be taken when parts need to be replaced. At this point, construction of the system can occur.

Once the system has been built, the disinfected water should be tested to ensure the system is working properly. If it is not working as designed, alterations must be made to resolve the issues. After the system is found to be effective, the community members and the system operator will need to be educated and trained. The community members should be taught basic operational procedures, as they will primarily be responsible for everyday operation of the system. They should also be educated about the importance of preventing recontamination during storage and distribution after disinfection. The operator will be responsible for completing a daily maintenance checklist to help extend the lifetime of the system, backwashing the system when needed, and replacing any broken or used parts. Plans for the completion of each of these tasks should be developed. Finally, the system operator should be provided with contact information for a professional who can assist the community if necessary. Figure 9 below shows an example of a possible schedule for construction and implementation and suggests this process will take about three months.

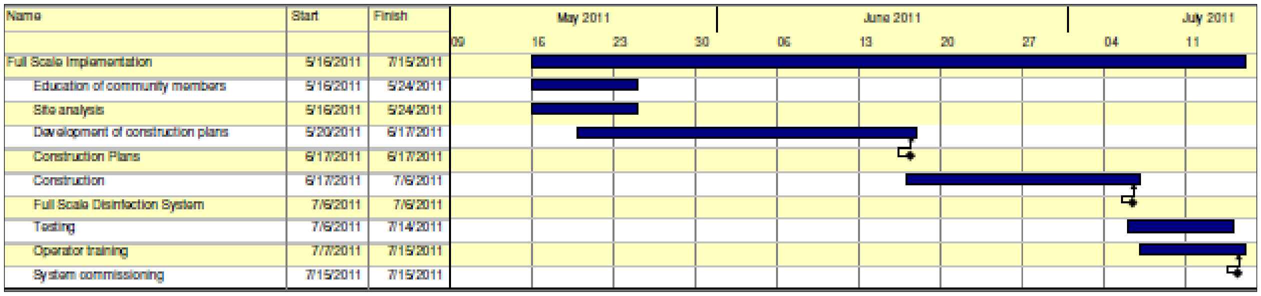


Figure 9 – Example Schedule for Full Scale Implementation

5.3 Conclusion Based on the testing and analysis of the bench-scale system, the disinfection system was found to have met all requirements for WERC. The system successfully eliminated all bacteria from the water to WHO guidelines. In addition, the full-scale system will be capable of providing 3,000 gallons of water per day to a community in a third-world area. The system will also be mobile, cost effective, and is powered by renewable energy. Finally, the team and the disinfection system performed very well during the WERC Environmental Design Competition.

The team stayed on schedule throughout the project and met the required deadlines for all deliverables. However, the total time spent on the project increased from the projected 532 hours to 728 man-hours for a total of 196 hours. The time spent on this project was equivalent to 12 hours of work per person per week for 16 weeks. The additional time was primarily spent constructing and testing the system, as it was not initially understood how time intensive these tasks would be. The increase in time spent on the project also caused the engineering cost for the completion of the project to increase by $9,791; the cost of all non-labor items remained the same. The client was made aware of the increased cost and approved the additional work by the team. Specific changes to the hours and budget can be seen in Appendix G.

JAMM, Inc. completed the proposed scope of work for the clean energy drinking water disinfection system on schedule, and designed a system which meets all of WERC's design criteria and is capable of disinfecting 3,000 gallons of water in 12 hours to the WHO drinking water guidelines for both bacteria and turbidity. Additionally, the system has a short payout period and high rate of return indicating it is cost effective. Throughout the project, JAMM, Inc. communicated well with the client and worked effectively as a team to minimize the total time spent on the project and maximize the quality of the final design. Based on these findings, it has been determined the system will be very useful in rural, third-world areas, and is a good investment.

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APPENDIX A

Appendix A contains the decision matrices used to evaluate the design alternatives for the disinfection system. Included are decision matrices for the pretreatment and disinfection stages of the system, and for the power source.

Table A-1- Decision Matrix for Pretreatment Alternatives

Pretreatment Criteria	Weight	Roughing Filter	Sedimentation	Rapid Sand Filtration	20 Micron Washable Sedimentation Filter
Ability to reduce turbidity	0.18	Has the potential to reduce initial turbidity by 50% (5)	Can remove a considerable amount of solids from the water (5)	Can remove a considerable amount of solids and reduce turbidity to as low as 1 NTU (5)	Can remove solids larger than 20 microns (5)
Ability to be scaled to meet a flow of 3,000 gallons per day	0.18	Can meet flow requirement with proper pressure; a pump or elevated input tank will be necessary (4)	Can meet flow requirement with large system and long retention time (1)	Capable of handling a flow of up to 65 feet per hour with proper pressure (4)	Can meet flow requirement with proper pressure; a pump or elevated input tank will be necessary (4)
Applicability to rural, third-world settings	0.12	Simple design with everyday, renewable materials; long lifetime (5)	Simple design with a long lifetime (5)	Simple design with everyday, renewable materials; long lifetime (5)	Simple technology with washable filters that may eventually need to be replaced; long lifetime (4)
Ability to be simple for ordinary citizens in third-world environments to implement, operate, and maintain	0.12	Easily understood technology with infrequent and simple cleaning, and no operation requirements (5)	Easily understood technology with infrequent and simple cleaning, and no operation requirements (5)	Easily understood technology with no operation requirements; backwashing is necessary to maintain the system (4)	Easily understood technology with infrequent and simple cleaning, and no operation requirements (5)
Safety	0.1	Very safe system with no chemicals or moving parts (5)	Very safe system with no chemicals or moving parts (5)	Very safe system with no chemicals or moving parts (5)	Very safe system with no chemicals or moving parts (5)
Ability to be a mobile unit	0.08	System uses rocks, so it will be large and heavy but still potentially mobile (2)	Could not be mobile if the system is sized to meet flow requirements (0)	System uses sand and gravel, so it will be large and heavy but still potentially mobile (2)	System is very small and light (5)
Ability to be cost effective based on initial cost	0.07	Low cost system to implement; most materials (rocks) can be collected and used for free (5)	Low cost system to implement (~$50) (5)	Low cost system to implement; most materials (sand and gravel) can be collected and used for free (5)	Low cost system to implement (~$50) (5)
Ability to be cost effective throughout the system's lifetime	0.05	Low cost system to operate; the only costs incurred will be when the system needs to be replaced (5)	Low cost system to operate; the only costs incurred will be when the system needs to be replaced (5)	Low cost system to operate; the only costs incurred will be when the system needs to be replaced (5)	System may need to have filters periodically replaced (~$10 per filter) (2)
Power requirement	0.05	System will require some energy input to generate necessary pressure (2)	System will not require any power to operate (5)	System will require some energy input to generate necessary pressure (2)	System will require some energy input to generate necessary pressure (2)
Waste generation	0.05	Sediment from the water will be the only waste collected by the roughing filter (4)	Sediment from the water will be the only waste collected by the roughing filter (4)	Sediment collected while the system is being backwashed will be the only waste (4)	Used filters will need to be disposed of (2)
TOTAL	1	4.38	3.83	4.44	4.25

Table A-2- Decision Matrix for Disinfection Alternatives

Disinfection Criteria	Weight	Ozone Generator	Ceramic Filter	Ultraviolet Radiation	Ultrafiltration
Ability to disinfect water to WHO drinking water standards for bacterial contamination	0.18	Very effective at eliminating microorganisms in water (5)	Can remove more than 99.99% of bacteria; does not remove any viruses (2)	Very effective at eliminating microorganisms in water with low turbidity (4)	Very effective at eliminating microorganisms in water with low turbidity (4)
Ability to be scaled to meet a flow of 3,000 gallons per day	0.18	Could easily meet flow requirement (5)	Capable of handling required flow with proper pressure; a pump will be necessary to generate this pressure (2)	Could easily meet flow requirement (5)	Could easily meet flow requirement; a pump will be necessary to generate this pressure (2)
Applicability to rural third-world settings	0.12	Complex system that would be difficult to understand; long system lifetime (2)	Relatively complex system with disposable parts; overall lifetime of the system is long, but shorter for ceramic elements (2)	Complex system that would be difficult to understand; long system lifetime (2)	Complex system that would be difficult to understand; long system lifetime (2)
Ability to be simple for ordinary citizens in third-world environments to implement, operate, and maintain	0.12	Complex system would require extensive training for maintenance and safety (1)	More complex system would take some training to understand when the system needs to be cleaned and ceramic elements replaced (3)	System is highly automated but would require training to ensure it is working properly (4)	Will require extensive training to understand maintenance and backwashing (2)
Safety	0.1	Dangerous system to operate, as ozone leaks are difficult to detect and can be lethal (0)	Very safe system with no chemicals or moving parts (5)	Safe system with no chemicals or moving parts, UV radiation can be harmful (4)	Very safe system with no chemicals or moving parts (5)
Ability to be a mobile unit	0.08	System is very small and light (5)	System is very small and light (5)	System is very small and light (5)	System is large and light (4)
Ability to be cost effective based on initial cost	0.07	Systems are expensive (~$200) (4)	Systems are expensive (~$400) (2)	Systems are expensive (~$300) (3)	Systems are very expensive (~$1000) (0)
Ability to be cost effective throughout the system's lifetime	0.05	Low cost system to operate; the only costs incurred will be when the system needs to be replaced (5)	System will need to have ceramic elements periodically replaced (~$50 per element) (1)	System will need to have UV bulbs periodically replaced (~$50 per element) (1)	Low cost system to operate; the only costs incurred will be when the system needs to be replaced (5)
Power requirement	0.05	Large power requirement to operate (1)	System will need a large energy input to meet presure requirement (1)	Large power requirement to operate (1)	System will need a large energy input to meet presure requirement (1)
Waste generation	0.05	No waste is generated by this system (5)	Used ceramic elements will need to be disposed of (3)	Used UV bulbs will need to be disposed of (3)	Backwashing water collected while the system is being backwashed will be the only waste (4)
TOTAL	1	3.39	2.61	3.6	2.88

Table A-3- Decision Matrix for Renewable Energy Alternatives

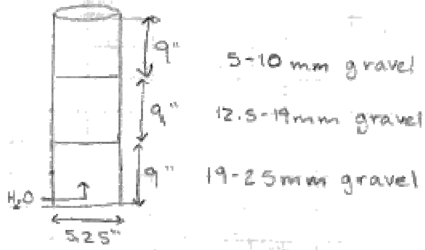
Renewable Energy Criteria	Weight	Wind Power	Solar Power	Man Power with a Bicycle
Applicability to rural, third world settings	0.20	Fairly simple technology with a long lifetime; unreliable because it would work only in environments with high and constant winds (1)	Complex system with a long lifetime; somewhat unreliable because sunlight is needed to operate (3)	Simple system with a long lifetime if properly cared for; very reliable as man power is always available (5)
Ability to power the disinfection system	0.20	Could power the system (5)	Could power the system (5)	Could power the system (5)
Ability to be simple for ordinary citizens in third-world environments to implement, operate, and maintain	0.18	Requires little maintenance and no operational tasks; training would be necessary to conduct maintanence (4)	Requires little maintenance and no operational tasks; training would be necessary to conduct maintanence (4)	Requires monthly maintanance to keep the bicycle in good condition, though little training would be needed; pedaling would be necessary to operate it (2)
Safety	0.14	Moving parts, but safe overall (4)	Very safe system (5)	Moving parts, but safe overall (4)
Ability to be a mobile unit	0.11	System must be tall to have access to best wind conditions (1)	Portable systems are small and light (5)	Bicycle would be stationary, but still small and mobile (3)
Ability to be cost effective based on initial cost	0.08	Initial cost would be high (1)	Initial cost would be relatively high (~$690) (3)	Initial cost would be low (5)
Ability to be cost effective throughout the system's lifetime	0.07	Low cost system to operate; the only costs incurred will be when the system needs to be replaced (5)	Low cost system to operate; the only costs incurred will be when the system needs to be replaced (5)	Low cost system to operate; the only costs incurred will be when the system needs to be replaced (5)
TOTAL	1	3.02	4.16	4.00

APPENDIX B

Appendix B details the design iterations for the roughing and rapid sand filters for the bench-scale model. Included are diagrams of each configuration, results from testing, and reasons for abandoning each filter.

Roughing Filter Tests

Roughing Filter #1



• 3 layers of gravel decreasing in size as the water flows up through the filter.

Turbidity Test #1

INPUT TURBIDITY: 21.3 NTU

DATE: JAN 20, 2011
TIME: 12:40 pm
LOCATION: NAU ENV. LAB
INPUT TURB: 21.3 NTU

SAMPLE	TURBIDITY (NTU)	% REDUCTION
1	12.8	40
2	12.6	41
3	11.9	44
4	12.7	40
5	13.4	37
6	12.9	39

avg % reduction: 40%

Turbidity Test #2

INPUT TURBIDITY: 27.2 NTU

DATE: JAN 20, 2011
TIME: 1:30pm
LOCATION: NAU ENV. LAB
INPUT TURB: 27.2 NTU

SAMPLE	TURBIDITY (NTU)	% reduction
1	15.4	43
2	14.9	45
3	14.3	47
4	14.7	46
5	14.7	46
6	13.9	49
7	12.7	53
8	14.2	48

avg % reduction: 47 %

Turbidity Test #3

DATE: Feb 24, 2011
TIME: 11:45am
LOCATION: NAU ENV. LAB
INPUT TURB. 34.8

SAMPLE	TURBIDITY (NTU)	% reduction
1	24.7	29
2	23.5	32
3	18.7	46
4	19.2	45
5	17.8	49
6	18.3	47
7	18.2	48

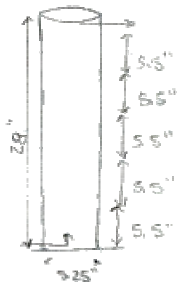
} low due to disintegrated rock pieces (samples 1–2)

avg % reduction: 42 %

• Rocks began to disintegrate

Roughing Filter Tests

Roughing Filter #2



- Constructed 2nd roughing filter with smaller gravel
- This would clog easier so may not be worth it unless it performs significantly better than others.
- Built to use in addition to other RF

Turbidity Test #1

Date: Jan 24, 2011
Time: 3:30 pm
Location: NAU Env. Lab
Input Turb: 33.8

Input Turbidity: 33.8 NTU

Sample	Turbidity (NTU)	% Reduction
1	19.7	39
2	19.5	42
3	19.1	43
4	18.7	45
5	18.9	44
6	19.2	43
7	18.7	45

avg % reduction: 43%

Roughing Filters #1 and #2 in Parallel

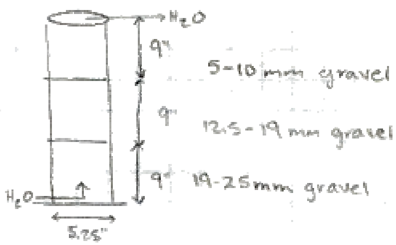
Date: Jan 24, 2011
Time: 4:30 pm
Location: NAU Env. Lab

	1	2	3	4	5
Influent:	75.7	36	35.2	34.8	34.6
After RF#1:	41% 44.7	32% 24.4	32% 23.8	34% 22.9	38% 21.3
After RF#2:	10% 40.4	14% 20.9	13% 20.7	12% 20.1	8% 19.7

The cost and space required for an additional roughing filter is not worth the additional 10-15% turbidity reduction the sand filter and one roughing filter will be adequate pretreatment.

Roughing Filter Tests

Roughing Filter #3



• Rebuilt RF #1 using insoluble gravel that wont disintegrate over time

Turbidity Test #1

DATE: MARCH 1, 2011
TIME: 12:40 pm
LOCATION: NAU ENV. LAB
INPUT TURB: 32.9 NTU

INPUT TURBIDITY: 32.9 NTU

SAMPLE	TURBIDITY (NTU)	% REDUCTION
1	15.3	53
2	14.5	56
3	13.8	58
4	13.5	59
5	13.0	60

avg % reduction: 57 %

Turbidity Test #2

DATE: MARCH 3, 2011
TIME: 11:50 am
LOCATION: NAU ENV. LAB
INPUT TURB: 33.7

INPUT TURBIDITY: 33.7 NTU

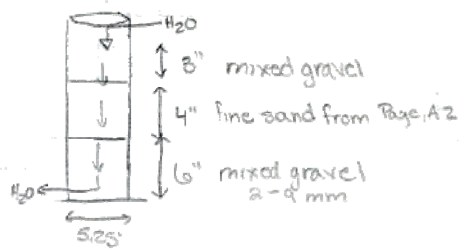
SAMPLE	TURBIDITY (NTU)	% REDUCTION
1	16.2	52
2	15.8	53
3	16.0	53
4	14.6	57
5	15.4	54
6	16.2	52
7	15.0	55

avg % reduction: 47 %

*Used this as final roughing filter

Rapid Sand Filter Tests

Rapid Sand Filter #1



- Used fine grain sand gathered from Page Arizona.
- Constructed in clear plastic tube

Turbidity Test #1

Date: Jan. 28, 2011
Time: 10:30am
Location: NAU Env. Lab
Input Turb: 36.7

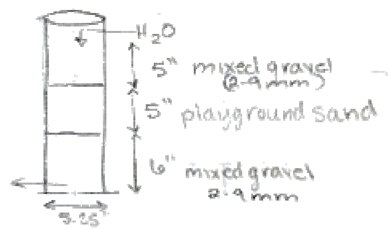
Sample	Output Turbidity (NTU)	% Reduction
1	21.7	41
2	23.9	35
3	24.6	33
4	22.7	38
5	23.4	36

avg % reduction: 37%

Analysis
- The flowrate for this filter was extremely slow (≈ 1 gal/hr)
- This is not enough turbidity reduction for pretreatment prior to disinfection.

Rapid Sand Filter Tests

Rapid Sand Filter #2



- Used playground sand purchased from Home Depot.
- Constructed in a clear plastic tube

Turbidity Test #1

DATE: JAN 31, 2011
TIME: 4:00pm
LOCATION: NAU ENV. LAB
INPUT TURB: 37.4

Sample	Output Turbidity (NTU)	% Reduction
1	19.6	48
2	18.9	49
3	18.3	51
4	17.9	52
5	16.4	56
6	17.3	54
7	17.5	53
8	18.2	51

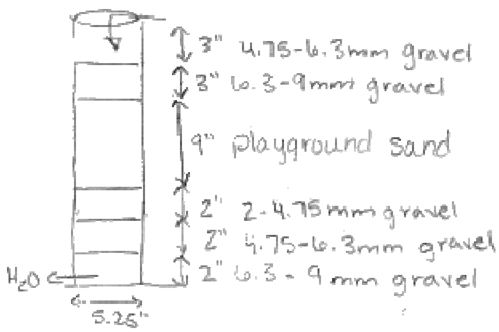
avg. % reduction: 52%

Analysis

- Does not reduce turbidity enough for disinfection
- Need more sand and layers of different sized gravel

Rapid Sand Filter Tests

Rapid Sand Filter #3



- Used more playground sand
- layered the gravel for more adequate, deep filtration

Turbidity Test #1

DATE: Feb 1, 2011
TIME: 6:30pm
LOCATION: NAU ENV. LAB
INPUT TURB: 36.8

Sample	Output Turbidity (NTU)	% Reduction
1	15.4	58
2	14.7	60
3	14.9	60
4	15.2	59
5	14.6	60
6	15.4	58
7	14.9	60
8	14.9	60

avg % reduction: 59%

Turbidity Test #2

DATE: Feb 1, 2011
TIME: 8:30pm
LOCATION: NAU ENV. LAB
INPUT TURBIDITY: 32.9

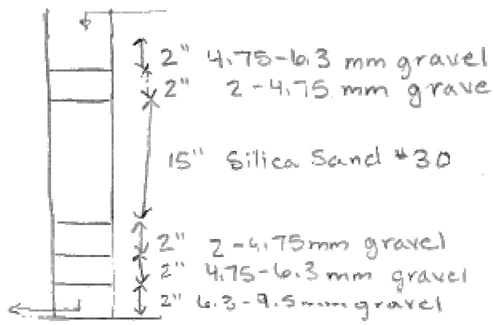
Sample	Output Turbidity (NTU)	% Reduction
1	15.3	53
2	14.9	55
3	14.9	55
4	14.5	56
5	16.7	49
6	13.2	60
7	16.2	51
8	15.4	53

avg % reduction: 48%

Analysis
- Need more sand
- Should use better graded sand
- Not enough reduction in turbidity

Rapid Sand Filter Tests

Rapid Sand Filter #4



Turbidity Test #1

Date: Feb. 3, 2011
Time: 11:30am
Location: NAU Env. Lab
Input Turb: 42.7 NTU

Sample	Output Turbidity (NTU)	% Reduction
1	9.7	77
2	9.4	78
3	9.4	78
4	8.9	79
5	10.2	76
6	9.2	78
7	9.7	77
8	9.4	79

avg % reduction: 78%

Turbidity Test #2

Date: Feb 3, 2011
Time: 12:45pm
Location: NAU Env Lab
Input Turb: 37.9 NTU

Sample	Output Turbidity (NTU)	% Reduction
1	9.3	75
2	9.1	76
3	9.3	75
4	10.1	73
5	8.7	77
6	9.1	76
7	8.7	77
8	8.7	77
9	8.9	77

avg % reduction: 76%

Rapid Sand Filter Tests

Rapid Sand Filter #4 (cont'd)

Turbidity Test #3

Date: Feb 9, 2011
Time: 3:30 pm
Location: NAU Env. Lab
Input Turbidity: 34.7 NTU

Sample	Output Turbidity (NTU)	% Reduction
1	13.2	62
2	12.9	63
3	12.7	63
4	12.4	64
5	11.9	66
6	12.4	64
7	13.7	61
8	12.2	65

avg % reduction: 64 %

Turbidity Test #4

Date: Feb 17, 2011
Time: 11:45pm
Location: NAU Env Lab
Input Turb: 33.9 NTU

Sample	Output Turbidity (NTU)	% Reduction
1	14.1	58
2	14.7	57
3	14.7	57
4	15.2	55
5	14.5	57
6	14.7	57
7	13.9	59
8	15.4	55

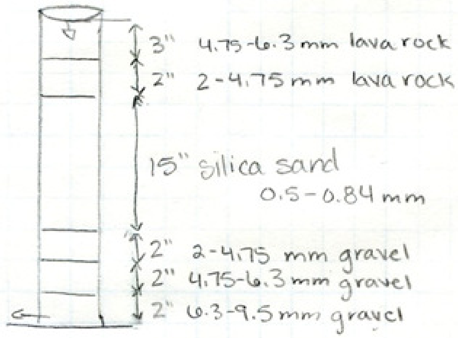
avg % reduction: 57 %

Analysis

- Predict air entered the system during construction or operation if water level dropped below top of sand.
- It is likely channeling was occurring

Rapid Sand Filter Tests

Rapid Sand Filter #5



- Sieved the silica sand to obtain a more uniform distribution
- Used low density lava rock on bottom to decrease the weight on the sand and prevent mixing during backwashing
- kept sand in tube during construction to prevent air from entering the system.

Turbidity Test #1

DATE: Feb 19, 2011
TIME: 12:00 pm
LOCATION: NAU ENV LAB
INPUT TURBIDITY: 34.2 NTU

Sample	Output Turbidity (NTU)	% Reduction
1	8.4	75
2	8.7	75
3	8.7	75
4	9.1	73
5	8.7	75
6	8.5	75
7	8.4	75

avg % reduction: 75 %

Turbidity Test #2 (tested as upflow filter)

DATE: Feb 19, 2011
TIME: 1:30 pm
LOCATION: NAU ENV LAB
INPUT TURBIDITY: 37.1

Sample	Output Turbidity (NTU)	% Reduction
1	8.7	77
2	9.0	76
3	8.9	76
4	8.9	76
5	8.7	77
6	9.1	75
7	7.4	80
8	8.7	77

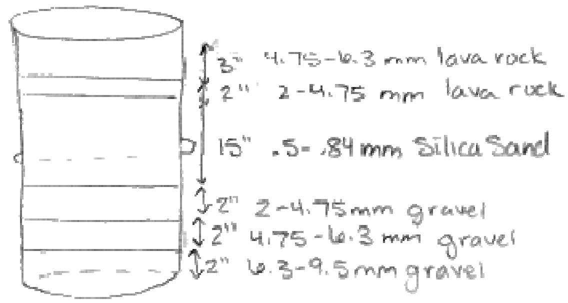
avg % reduction: 77 %

Analysis

- Flow of about 600 ml/min or 0.16 gal/min
- Still need more reduction in turbidity. May help to have larger area so smaller percentage is against surface of container.

Rapid Sand Filter Tests

Rapid Sand Filter #6



- Constructed in two 5-gall buckets glued together wit bottom of the top bucket cu
- kept water in buckets at times to keep air out of th system

Turbidity Test #1

DATE: Feb 23, 2011
TIME: 3:00 pm
LOCATION: NAU ENV. LAB
INPUT TURB: 37.4 NTU

Sample	Output Turbidity (NTU)	% Reduction
1	4.3	89
2	3.9	90
3	3.9	90
4	4.1	89
5	3.7	90
6	3.9	90
7	3.4	91
8	3.7	90

avg % reduction: 90%

Turbidity Test #2

DATE Feb 28, 2011
TIME: 3:00pm
LOCATION: NAU ENV. LAB
INPUT TURB: 29.4 NTU

Sample	Output Turbidity (NTU)	% Reduction
1	3.4	88
2	3.7	87
3	3.7	87
4	2.9	90
5	3.6	88
6	2.4	92
7	2.9	90
8	3.4	88

avg % reduction: 89%

Analysis

- This filter is reducing turbidity enough for disinfection and will be tested in the final design.
- Flowrate of about 0.75 gal/min is adequate for a reasonable full scale

APPENDIX C

Appendix C includes larger schematics for both the bench-scale system and the full scale system.

APPENDIX D

Appendix D includes turbidity and bacteria results from testing the performance of the finalized bench-scale system.

Final Turbidity Data

Date: 3/10/2011
Time: 8:00 pm
Location: NAU env. lab
Tested by: Marilla Lamb

Test 1

Raw water	After RF	After RSF
25.2	15.4	3.31
25.2	13.2	3.83
25.2	14.9	3.5
25.2	12.7	3.61
25.2	13.8	3.24

Test 2

Raw water	After RF	After RSF
30.8	23.5	3.26
30.8	23.5	4.22
30.8	17.2	4.85
30.8	13.9	5.04
30.8	9.15	5.31

Test 3

Raw water	After RF	After RSF
20.1	12.2	2.02
20.1	13.5	2.4
20.1	11.7	2.7
20.1	10.5	2.92
20.1	11.1	2.51

Bacteria Test # 1 (Plate $ Count) "Agar"

Date: 3/10/2011
Time: 10:30 pm
location: NAU Env. Lab

All samples are tested after 24 hours

Raw Sample mixed with cultivated bacteria from MLSS

Sample	Plate #	Discription (observation)
Raw	A1 (Red)	Full plate of bacteria
Raw (Dup)	A2 (Red) *	" " " "
Blank	A3 (Red)	None
Treated 1	1A (Blk)	No Bacteria
Treated 1 Dup	1B (Blk)	" "
Treated 2	2A (Blk)	" "
2 Dup.	2B "	" "
Treated 3	3A "	3 small dots
3 Dup	3B "	Non Bacteria
Treated 4	4A "	No Bacteria
4 Dup	4B "	" "
Treated 5	5A "	" "
5 Dup	5B "	1 small dot
Treated 6	6A "	No Bacteria
6 Dup	6B "	" "
Blank	7A (Blk)	" "

tester: Meshal Hussain

Bacteria Test # 2 (Plate & Count) "Agar"

Date: 3/10/2011
Time: 11:40 pm
location: NAU ENV Lab

All samples are observed 24 hours after testing

Raw Sample Diluted with cultivated bacteria from MCSS

Sample	Plate #	Discription (observation)
Raw	A1 (Red)	Full of bacteria
Raw Duplicate	A2 (Red)	" " "
Blank	A3 (Red)	No bacteria present
Treated 1	1A (Black)	None
1 Dup	1B "	None
Treated 2	2A "	None
2 Dup	2B "	None
3	3A "	2 small dots
3 Dup	3B "	None
4	4A "	None
4 Dup	4B "	None
5	5A "	3 small dots
5 Dup	5B "	3 small dots
6	6A "	1 small dot
6 Dup	6B "	None ~~None~~
7	7A "	None
7 Dup	7B "	None
8	8A "	None
8 Dup	8B "	None
Blank	9A "	None

Tested By: M. Hussain

Bacteria Test #3 (Plate & Count) "Agar"

Date: 3/11/2011
Time: 12:40am
location: NAU ENV LAB

All samples are observed 24 hours after testing

Raw Sample diluted with cultevated Bacteria from MLSS.

Sample	Plate #	Observation
Raw	A1 (Red)	Full of Bacteria
" Dup	A2 "	" " "
Blank	A3 "	None
Treated 1	1A Black	1 small dot
" 1 Dup	1B "	2 small dots
2	2A "	None
2 Dup	2B "	None
3	3A "	None
3 Dup	3B "	None
4	4A "	1 small dot
4 Dup	4B "	None
5	5A "	None
5 Dup	5B "	None
Blank	6A "	None

Tested By: M. Hussain

APPENDIX E

Appendix E includes all calculations performed during the design of the full scale system.

FILTER SIZING

RAPID SAND FILTER:

REQUIRED FLOW: $Q_2 = 3000 \frac{gal}{day} \times \frac{1\ day}{12\ hrs} \times \frac{1\ hr}{60\ min} \times \frac{1}{2\ filters} = 2.08 \frac{gal}{min}$

FROM BENCH SCALE: $Q_1 = 0.73 \frac{gal}{min}$
$A_1 = 0.69\ ft^2$

$V_1 = V_2$ because same layer configuration

$Q_1 = V_1 A_1 \qquad Q_2 = V_2 A_2$

$$\frac{Q_1}{A_1} = \frac{Q_2}{A_2}$$

$$A_2 = \frac{A_1 Q_2}{Q_1}$$

$$A_2 = \frac{(0.69\ ft^2)(2.08 \frac{gal}{min})}{0.73 \frac{gal}{min}}$$

$$A_2 = 1.97\ ft^2$$

$$A = \frac{\pi}{4} d^2 = 1.97\ ft^2$$

$d = 1.58\ ft = 1'\ 7''$ → minimum diameter to meet required flowrate of $2.08 \frac{gal}{min}$ in clean filter bed

MUST OVERSIZE THE FILTER BECAUSE:

- The flow will decrease as the sand filter gets dirty
- Reduce the frequency of backwashing
- Community can still disinfect 3,000 gal/day if they don't operate all 12 hours due to maitenance or other issues.

• chose to use 55-gallon drums (d=2') because easy to come by

- This makes area 1.62 times larger than absolute minimum.

FILTER SIZING

ROUGHING FILTER

REQUIRED FLOW: $4.17 \frac{\text{gallons}}{\text{min}} \div 2$ ROUGHING FILTERS = 2.08 gpm

$2.08 \text{ gpm} = 0.2787 \frac{ft^3}{min}$ through each filter

- The slower the velocity going up the filter, the more turbidity reduction will occur because this allows more time for settling.
- Chose the diameter of a 5 gallon bucket because they are relatively easy to come by. (d = 11.25in)
- Need height of 28" to fit three 9" layers of gravel.
- The larger size reduces the frequency of cleaning

$$A = \frac{\pi}{4}\left(\frac{11.25\text{in}}{12\frac{\text{in}}{\text{ft}}}\right)^2 = 0.69 \text{ ft}^2$$

$$Q = VA$$

$$V = \frac{Q}{A} = \frac{0.2787 \text{ ft}^3/\text{min}}{0.69 \text{ ft}^2}$$

$$V = 0.404 \text{ ft/min}$$

- This is low velocity (<1 ft/min) so turbidity will be effectively reduced even if flow is increased.

Backwash Velocity

For rapid sand filter

Settling velocity (for silica sand #30)

$$V_s = \sqrt{\frac{4g(S_s - 1)d}{3C_D}}$$

$g = 9.81\ m/s^2$
S_s = Specific gravity = 2.6
C_D = Drag coefficient = 2.7
d = particle size = $5.5\times10^{-4}\ m$

$$V_s = \sqrt{\frac{4(9.81\ m/s^2)(2.6-1)(5.5\times10^{-4}\ m)}{3\ (2.7)}}$$

$$V_s = \underline{0.0653\ m/s}$$

Backwash velocity

$$V_{BW} = V_s\, \varepsilon_e^{4.5}$$

V_{BW} = Backwash velocity
V_s = Settling velocity = 0.0653 m/s
ε_e = porosity of expanded bed
ε = porosity = 0.4 (for finely graded silica sand)

Using 30% bed expansion:

$$\varepsilon_e = \varepsilon + (\varepsilon \cdot 0.30)$$
$$\varepsilon_e = 0.52$$

$$V_{BW} = V_s\, \varepsilon_e^{4.5}$$

$$V_{BW} = (0.0653\ m/s)(0.52)^{4.5}$$

$$V_{BW} = \underline{0.0034\ \tfrac{m}{s}}$$

$$Q_{BW} = 0.0034\ \tfrac{m}{s} \cdot 1000\ \tfrac{L}{m^3} = 3.44\ \tfrac{L}{s \cdot m}$$

$$3.44\ \tfrac{L}{s \cdot m} = 0.9094\ \tfrac{gal}{s\ m^2} \cdot \tfrac{1\ m}{10\ ft^2} = 0.0845\ \tfrac{gal}{s\ ft^2}$$

(Area of SSF)

$$0.0845\ \tfrac{gal}{s \cdot ft^2} \times 3.14\ ft^2 = 0.2653\ \tfrac{gal}{s} = \boxed{15.92\ \tfrac{gal}{min}}$$

Volume for 3 min. Backwashing

$$15.92\ \tfrac{gal}{min} \times 3\ min = 47.76\ \text{gallons} \approx \underline{48\ \text{gallons}}$$

height of 55 gallon drum needed

$$48\ \text{gallons} = 6.42\ ft^3 \times \frac{1}{3.14\ ft^2} = \underline{2\ ft}$$

Energy Balance

Headloss in roughing filter: (Darcy's law)

$$V = k_p \frac{h_f}{L}$$

$V \rightarrow$ superficial velocity

$K_p = D_{10} D_{60}$

$$\frac{VL}{K_p} = h_f$$

$L \rightarrow$ length of filter

$$V = \frac{Q}{A} = \frac{.278 \frac{ft^3}{min}}{0.69\ ft^2} = 0.403\ ft/min$$

9 in	5 - 10 mm
9 in	12.5 - 19 mm
9 in	19 - 25 mm

$K_p = 6.3\ mm\ (9\ mm) = 56.7\ cm/sec = 111.61\ ft/min$

$$h_f = \frac{0.403\ ft/min\ (0.75\ ft)}{111.61\ ft/min} \qquad h_f = 0.0027\ ft$$

$K_p = 12.7\ mm\ (16\ mm) = 203.2\ cm/sec = 400.00\ ft/m$

$$h_f = \frac{0.403\ ft/min\ (0.75\ ft)}{400.00\ ft/min} \qquad h_f = 7.56 \times 10^{-4}\ ft$$

$K_p = 19\ mm\ (22.6\ mm) = 429.4\ cm/sec = 845.28\ ft/m$

$$h_f = \frac{0.403\ ft/min\ (0.75\ ft)}{845.28\ ft/min} \qquad h_f = 3.58 \times 10^{-4}\ ft$$

$h_f = .0038\ ft \times (2\ filters) = h_f = 0.0076\ ft$

Headloss in Pipes:

$A_{pipe} = \frac{\pi}{4}(1")^2 = 0.785\ in^2 = 0.00545\ ft^2$

$Q_2 = 3{,}000\ gal/day = 401\ ft^3/day \times \frac{1\ day}{12\ hrs} \times \frac{1\ hr}{3600\ s} = 0.00928\ ft^3/s$

$Q_1 = 1500\ \frac{gal}{day} = 200.52\ ft^3/day = 0.00464\ ft^3/s$

$$V_2 = \frac{Q_2}{A} = \frac{0.00928\ ft^3/s}{0.00545\ ft^2} = 1.70\ ft/s$$

$$V_1 = \frac{Q_1}{A} = \frac{0.00464\ ft^3/s}{0.00545\ ft^2} = 0.851\ ft/s$$

$\nu_{water} = 1.08 \times 10^{-5}\ ft^2/s$

Energy Balance (cont'd)

$Re = \frac{vD}{\nu}$

$Re_1 = \frac{(0.851\ ft/s)(\frac{1}{12}\ ft)}{1.08 \times 10^{-5}\ ft^2/s} = 6566.36 = 6.566 \times 10^3$

$Re_2 = \frac{(1.70\ ft/s)(\frac{1}{12}\ ft)}{1.08 \times 10^{-5}\ ft^2/s} = 13117.28 = 1.31 \times 10^4$

$\varepsilon_{pvc} = 1.64 \times 10^{-5}\ ft \quad \therefore \quad \frac{\varepsilon}{D} = \frac{1.64 \times 10^{-5}\ ft}{\frac{1}{12}\ ft} = 1.976 \times 10^{-4} \approx 0.0002$

using Moody Diagram:

$f_1 \approx 0.035$
$f_2 \approx 0.030$

1.84' @ Q_1
2.67' @ Q_2

run of pipe: $h_L = f_2\left(\frac{L_2}{D}\right)\left(\frac{V_2^2}{2g}\right) + 2f_1\left(\frac{L_1}{D}\right)\left(\frac{V_1^2}{2g}\right)$

$h_L = 0.03\left(\frac{2.67\ ft}{0.083\ ft}\right)\left(\frac{(1.7\ ft/s)^2}{2(32.2\ ft/s^2)}\right) + 2(0.035)\left(\frac{0.92\ ft}{0.083\ ft}\right)\left(\frac{(0.851\ ft)^2}{2(32.2\ ft/s^2)}\right)$

$h_L = 0.0433 + (2 \times 0.00436) = 0.052\ ft$

valves: 6 ball valves ; $k = 0.05$

$h_L = nk\frac{V^2}{2g} = 6(0.05)\frac{(6.851\ ft/s)^2}{2(32.2\ ft/s^2)} = 0.00337\ ft$

elbows: 2 at V_2 ; 2 at V_1 ; 90° $k = 0.7$

$h_L = nk\frac{V_2^2}{2g} + nk\frac{V_1^2}{2g} = 2(0.7)\frac{(1.7\ ft/s)^2}{64.4\ ft/s^2} + 2(0.7)\frac{(0.851\ ft/s)^2}{64.4\ ft/s^2}$

$h_L = 0.0628 + 0.01574 = 0.07854$

Tee: 1 at V_2; $k = 0.55$

$h_L = K\frac{V_2^2}{2g} = 0.55\frac{(6.851\ ft/s)^2}{64.4\ ft/s^2} = 0.00618\ ft$

entrance/exit: 4 protruding at V_1, 1 prot. at V_2 ; $k = 0.8$

$h_L = 4 \times 0.8\left(\frac{(.851\ ft/s)^2}{64.4\ ft/s^2}\right) + 0.8\left(\frac{(1.7\ ft/s)^2}{64.4\ ft/s^2}\right)$

$h_L = 0.0035 + 0.0359 = 0.0394\ ft$

$\Sigma h_L = 0.0076 + 0.0394 + 0.00618 + 0.07854 + 0.00337 + 0.052$

$\Sigma h_L = 0.18329\ ft = 2.2"$

Energy Balance (cont'd)

0, gage; 0, small; 0, no pump; 0, gage; 0, small; 0, no turb

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + Z_1 + h_{pump} = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + Z_2 + h_{turb} + \Sigma h_{losses}$$

0, datum

$$Z_1 = Z_2 + \Sigma h_{losses} + 28''$$

$$Z_1 = 28'' + 2.2''$$

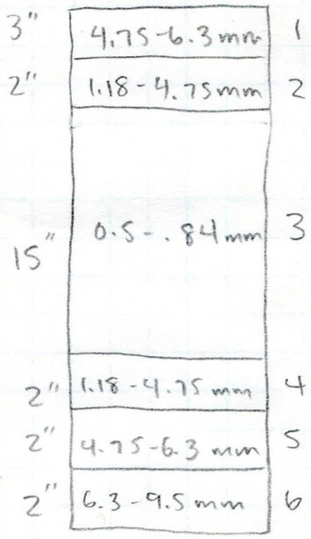
$$\boxed{Z_1 = 30.2''}$$ → height input bucket must be above RSF if used as point source w/ out pump

* This analysis was conducted using the water surface in the input as point 1 and the surface of the water on top of the Rapid sand filter as point 2.

Sizing the Pump

Headloss in RSF:

$V = K_p \frac{h_f}{L}$ $\quad V = \frac{Q}{A} = \frac{15.92 \text{ gpm}}{3.14 \text{ ft}^2} = 0.678 \text{ ft/min}$



Layer 1: $K_p = 5.3(6) = 31.8 \text{ cm/s} = 62.6$

$h_f = \frac{0.678 \text{ ft/min} (3 \text{in})}{62.6 \text{ ft/min}} = 0.0027 \text{ ft}$

Layer 2: $K_p = 2(3.6) = 7.2 \text{ cm/s} = 14.$

$h_f = \frac{0.678 (2 \text{in})}{14.17 \text{ ft/min}} = 0.0080 \text{ ft}$

Layer 3: $K_p = 0.55(0.77) = 0.8337 \text{ ft/}$

$h_f = \frac{0.678(15)}{0.8337}$ $\quad h_f = 1.017 \text{ ft}$

Layer 4: $h_f = 0.0080 \text{ ft}$

Layer 5: $h_f = \frac{0.678(2)}{62.6} = 0.0018 \text{ ft}$

Layer 6: $K_p = (6.73)(8) = 105.98 \text{ ft/min}$

$h_f = \frac{.678(2)}{105.98} = 0.00107 \text{ ft}$

$\Sigma h_f = 1.039 \text{ ft}$

Velocity in RSF $= 0.678 \text{ ft/min}$

$A_{pipe} = 0.00545 \text{ ft}^2$

$V_{pipe} = 15.92 \frac{\text{gal}}{\text{min}} = \frac{2.128 \text{ ft}^3\text{/min}}{0.00545 \text{ ft}^2} = 390 \text{ ft/min} = 6.508 \text{ f}$

$Re = \frac{6.508 \text{ ft/s} \left(\frac{1}{12}\right)}{1.08 \times 10^{-5} \text{ ft}^2\text{/s}} = 50216 = 5 \times 10^4$ $\quad \varepsilon_{pvc} = 1.64 \times 10^{-8}$

14" pipe

2 elbows

protruding entrance & exit

$$\frac{v^2}{2g} = \frac{(6.508\ ft/s)^2}{(64.4\ ft/s)} = 0.6577\ ft$$

elbows: $2 \times 0.6577 \times 0.05 = 0.06577\ ft$

prot: $2 \times 0.8 \times 0.6577 = 1.052\ ft$

$f = 0.023$ run of pipe $= 0.023\left(\frac{1.167\ ft}{0.083\ ft}\right)\left(\frac{6.508\ ft/s^2}{64.4}\right) =$

total $h_L = 2.37\ ft$

bottom of storage tank: $1000\frac{kg}{m^3}\left(9.81\frac{m}{s^2}\right)(0.9144m) = 89$
$= 1.301\ psi$

top of RSF: $p_2 = 0$, gage

$$P_1 = 1.301\frac{lb}{in^2} \times \frac{144\ in^2}{1\ ft^2} = 187.348\frac{lb}{ft^2}$$

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g}\ (0, \text{small}) + z_1\ (0, \text{datum}) + h_{pump} = \frac{P_2}{\gamma}\ (0, \text{gage}) + \frac{V_2^2}{2g}\ (0, \text{small}) + z_2 + h_{turb}\ (\text{lam.}) + \Sigma h_{losses}$$

$$\frac{187.348\frac{lb}{ft^2}}{62.4\ lb/ft^3} + h_{pump} = 4.17\ ft + 2.37\ ft$$

$h_{pump} = 3.54\ ft$

Small amount of head & low flow rate can be met by the Sureflow 12V 16gpm pump.

(pump curves don't go low enough)

APPENDIX F

Appendix F includes calculations used for the cost-benefit analysis of the full scale disinfection system.

PAYOUT PERIOD

$V_{month} = \$0.0041 / gallon \times 3{,}000 \frac{gal}{day} \times \frac{30 \text{ days}}{month} = \$369$

↳ average cost per gallon of water in the U.S in 2010

month	Value
0	-2251
1	369 - 2251 = -1882
2	369 - 1882 = -1513
3	369 - 1513 = -1144
4	369 - 1144 = -775
5	369 - 775 = -406
6	369 - 406 = -37
* 7	369 - 37 = +332

*Assuming no maintenance costs in first 7 months

RATE OF RETURN

Present worth = \$2,251
Annual amount = \$45
Future worth (UV) = \$61 every 2 years
Future worth (Battery) = \$200 every 3 years

system lifetime(n) = 6 years
Value = \$4,489.5
RATE OF RETURN: 1.96 = 196%

PROOF

$$\text{VALUE} = \$0.0041/\text{gallon} \times \frac{3{,}000 \text{ gal}}{\text{day}} \times \frac{365 \text{ days}}{\text{yr}} = \$4{,}489.5$$

i at P=0 is rate of return, test with i=1.96 (found using spreadsheet)

$$P = -2{,}251 + (4{,}489.5-45)\left(\tfrac{P}{A},1.96,6\right) - 61\left(\tfrac{P}{F},1.96,2\right) - 61\left(\tfrac{P}{F},1.96,4\right) - 61\left(\tfrac{P}{F},1.96,6\right)$$
$$-200\left(\tfrac{P}{F},1.96,3\right) - 200\left(\tfrac{P}{F},1.96,6\right)$$

$$\left(\tfrac{P}{A},1.96,6\right) = \frac{(1+i)^n-1}{i(1+i)^n} = \frac{(1+1.96)^6-1}{1.96(2.96)^6} = 0.510$$

$$\left(\tfrac{P}{F},1.96,2\right) = (1+i)^{-n} = (1+1.96)^{-2} = 0.1141$$

$$\left(\tfrac{P}{F},1.96,3\right) = 2.96^{-3} = 0.0386$$

$$\left(\tfrac{P}{F},1.96,4\right) = 2.96^{-4} = 0.0130$$

$$\left(\tfrac{P}{F},1.96,6\right) = 2.96^{-4} = 0.00149$$

$$P = -2{,}251 + (4{,}489.5-45)(0.510) - 61(0.1141) - 61(0.0130) - 61(.00149) - 200(.0386) - 200(0.00149)$$

$P = -0.17 \approx 0$ ✓

TOPS 35500

APPENDIX G

Appendix G includes changes to the project schedule and the budget.

Initial estimated time allotments for the project:

Phase	Task	Ashley Ullstrom	Jo-Anne Barcellano	Marilla Lamb	Meshal Hussain	Total
PHASE 1	1.1 PDT Meetings	16	16	16	16	**64**
	1.2 Coordination Meetings	10	10	10	10	**40**
	1.3 Quality Control	7	7	7	7	**28**
	2.1 Research Disinfection Systems	16	-	16	16	**48**
	2.2 Research Types of Alternative Energy	-	16	-	-	**16**
	3.1 Comparison of Alternatives	8	8	4	4	**24**
	3.2 Cost Estimates	-	-	4	4	**8**
	3.3 Pretreatment Disinfection Decision Matrix	8	4	8	4	**24**
	3.4 Power System Decision Matrix	-	4	-	4	**8**
	4.0 Selection of Final Design	10	16	16	16	**58**
	5.0 Documentation of Design	6	6	6	20	**38**
PHASE 2	1.0 Procurement of Materials	10	-	6	-	**16**
	2.0 Construction	16	16	14	16	**62**
	3.0 Testing and Analysis	14	14	14	4	**46**
	4.0 Documentation	12	16	12	12	**52**
	TOTAL HOURS	**133**	**133**	**133**	**133**	**532**

Final time allotments for the project, totaling 728 hours:

Phase	Task	Ashley Ullstrom	Jo-Anne Barcellano	Marilla Lamb	Meshal Hussain	Total
PHASE 1	1.1 PDT Meetings	16	16	16	16	**64**
	1.2 Coordination Meetings	6	6	6	6	**24**
	1.3 Quality Control	2	2	2	2	**8**
	2.1 Research Disinfection Systems	16	-	16	16	**48**
	2.2 Research Types of Alternative Energy	-	16	-	-	**16**
	3.1 Comparison of Alternatives	2	2	2	2	**8**
	3.2 Cost Estimates	-	-	4	4	**8**
	3.3 Pretreatment Disinfection Decision Matrix	8	4	8	4	**24**
	3.4 Power System Decision Matrix	-	4	-	4	**8**
	4.0 Selection of Final Design	10	16	18	14	**58**
	5.0 Documentation of Design	8	8	8	14	**38**
PHASE 2	1.0 Procurement of Materials	10	-	6	16	**32**
	2.0 Construction	64	64	56	64	**248**
	3.0 Testing and Analysis	28	28	28	8	**92**
	4.0 Documentation	12	16	12	12	**52**
	TOTAL HOURS	**182**	**182**	**182**	**182**	**728**

Initial project budget:

Project Labor

Phase	Task	Project Manager	Environmental Engineer	Lab Technician	CAD Technician	Technical Writer	Task Total	Sub-total
PHASE 1	1.1 PDT Meetings	16	48	0	0	0	$ 2,360.00	$ 2,360.00
	1.2 Coordination Meetings	10	30	0	0	0	$ 1,475.00	$ 3,835.00
	1.3 Quality Control	7	15	0	0	6	$ 918.50	$ 4,753.50
	2.1 Research Disinfection Systems	16	32	0	0	0	$ 1,800.00	$ 6,553.50
	2.2 Research Types of Alternative Energy	0	16	0	0	0	$ 560.00	$ 7,113.50
	3.1 Comparison of Alternatives	4	20	0	0	0	$ 870.00	$ 7,983.50
	3.2 Cost Estimates	4	4	0	0	0	$ 310.00	$ 8,293.50
	3.3 Pretreatment and Disinfection System Decision Matrices	4	20	0	0	0	$ 870.00	$ 9,163.50
	3.4 Power System Decision Matrix	4	4	0	0	0	$ 310.00	$ 9,473.50
	4.0 Selection of Final Design	16	42	0	0	0	$ 2,150.00	$ 11,623.50
	5.0 Documentation of Design	0	8	0	20	10	$ 800.00	$ 12,423.50
PHASE 2	1.0 Procurement of Materials	0	16	0	0	0	$ 560.00	$ 12,983.50
	2.0 Construction	16	46	0	0	0	$ 2,290.00	$ 15,273.50
	3.0 Testing and Analysis	0	10	36	0	0	$ 1,023.20	$ 16,296.70
	4.0 Documentation	0	15	0	12	25	$ 1,141.00	$ 17,437.70
							Direct Labor Total:	$ 17,437.70
				Multipier:	2.75			
							Total = multiplier x Direct labor:	$ 47,953.68

Project Non-Labor

Item	Unit price	Qty	Extended Price
Bench scale construction material	-	-	$ 500.00
WERC Competition Registration	$ 895.00	1	$ 895.00
Printing - Full size drawing sheets	$ 0.50	20	$ 10.00
Mileage	$ 0.48	1052	$ 504.96
Lodging	$ 200.00	5	$ 1,000.00
		Non-Labor Total:	$ 1,514.96
	Mark-up:	0.1	
		Total - (1+Markup)xNon-Labor:	$ 1,666.46

Estimate:	$ 49,620.13

Final project budget:

Project Labor

	Task	Project Manager	Environmental Engineer	Lab Technician	CAD Technician	Technical Writer	Task Total	Sub-total
PHASE 1	1.1 PDT Meetings	16	48	0	0	0	$ 2,360.00	$ 2,360.00
	1.2 Coordination Meetings	6	18	0	0	0	$ 885.00	$ 3,245.00
	1.3 Quality Control	2	3	0	0	3	$ 238.00	$ 3,483.00
	2.1 Research Disinfection Systems	16	32	0	0	0	$ 1,800.00	$ 5,283.00
	2.2 Research Types of Alternative Energy	0	16	0	0	0	$ 560.00	$ 5,843.00
	3.1 Comparison of Alternatives	2	6	0	0	0	$ 295.00	$ 6,138.00
	3.2 Cost Estimates	4	4	0	0	0	$ 310.00	$ 6,448.00
	3.3 Pretreatment and Disinfection System Decision Matrices	4	20	0	0	0	$ 870.00	$ 7,318.00
	3.4 Power System Decision Matrix	4	4	0	0	0	$ 310.00	$ 7,628.00
	4.0 Selection of Final Design	16	42	0	0	0	$ 2,150.00	$ 9,778.00
	5.0 Documentation of Design	0	8	0	20	10	$ 800.00	$ 10,578.00
PHASE 2	1.0 Procurement of Materials	4	26	1	0	1	$ 1,114.70	$ 11,692.70
	2.0 Construction	15	56	177	0	0	$ 5,907.40	$ 17,600.10
	3.0 Testing and Analysis	2	30	60	0	0	$ 2,257.00	$ 19,857.10
	4.0 Documentation	0	15	0	12	25	$ 1,141.00	$ 20,998.10
							Direct Labor Total:	$ 20,998.10
				Multipier:	2.75			
							Total = multiplier x Direct labor:	$ 57,744.78

Project Non-labor

Item	Unit price	Qty	Extended Price
Bench scale construction material	-		$ 500.00
WERC Competition Registration	$ 895.00	1	$ 895.00
Printing - Fullsize drawing sheets	$ 0.50	20	$ 10.00
Mileage	$ 0.48	1052	$ 504.96
Lodging	$ 200.00	5	$ 1,000.00
		Non Labor Total:	$ 1,514.96
	Mark-up:	0.1	
		Total - (1+Markup)xNon-Labor:	$ 1,666.46

Estimate: $ 59,411.23