SURFACE WATER PUMP FOR USE IN A RURAL COMMUNITY IN A DEVELOPING AFRICAN NATION

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EXECUTIVE SUMMARY

Worldwide there are 1.1 billion people who do not have a way to get clean drinking water. Every year, 1.8 million people die from diarrheal disease, and it is estimated that 88% can be attributed to the lack of clean drinking water[1]. This project will partner with the non-profit organization Clean Water for the World which provides simple water filtration systems to communities in need of clean water. Our major objective is to provide the Kyeamekrom community in the Brong-Ahafo region of Ghana with a clean, safe, drinkable water source. In order to do this our goal is to create a surface water pump made entirely of locally available materials that will interface with the Clean Water for the World filtration system.

Initially a comprehensive literature review was conducted in order to have a full and complete understanding of all background material. With the help of our sponsor and mentors we were able to revise our list of customer requirements and engineering specifications in order to get very specific targets with which to evaluate our prototype.. A list of the key specifications can be seen in Table A.

Table A: Key Engineering Specifications and Targets

Engineering Specifications	Target
Number of users required	1 user/time
Force required for operation	≤ 20 lbs
Does not underutilize filter	5 gallons/minute
Pressure leaving pump	10 feet head
Percentage of locally available materials	100%

We underwent an instensive reiterative generation and selection process in order to create the alpha prototype. It consisted of a piston pump, a hand lever, a pre-filter, tubing from the water to the pump, and piping from the pump to the Clean Water for the World filtration system. Through rigorous testing and engineering analysis a final design was converged upon. The final design includes several subsystems: a pre-filter, tubing, two identical one way valves, two piston seals, and a handle. We selected materials and dimensions based on the engineering specifications and validated the prototype against these specifications. A construction manual was also developed in order to show how to manufacture the complete pump or simply to manufacture a particular subsystem.

There are several areas of our design that require further consideration, testing and refinement. Given more time we would have continued experimenting with sizes and materials for both the one way valves and the piston seal. We have recommended plans for implementing the current prototype as well as goals for future work.

Surface Water Pump for Use in a Rural Community in a Developing African Nation

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***Abstract* - Nearly 5000 people die each day from diseases related to the consumption of contaminated water, ninety percent of which are children under the age of five. Clean Water for the World is a nonprofit 501c3 organization whose mission is to provide simple adaptable water purification systems at no charge to communities without access to clean drinking water. The goal of this project is to design and manufacture a surface water pump entirely out of materials local to the Brong-Ahafo region of Ghana that will interface with the Clean Water for the World water purification system. The integrated system prototype is targeted specifically for the rural Kyeamekrom community. The pump will be co-located at the water source and will deliver water to the solar powered water purification system.**

Index Terms – Ghana, Local Materials, Pump, Surface Water

INTRODUCTION

Worldwide there are 1.1 billion people who do not have a way to get clean drinking water. Every year, 1.8 million people die from diarrheal disease, and it is estimated that 88% can be attributed to the lack of clean drinking water [1]. Clean Water for the World is an organization which provides simple water filtration systems to communities in need of clean water. Our major objective was to provide the Kyeamekrom community in the Brong-Ahafo region of Ghana with a clean, safe, drinkable water source. In order to do this our goal was to create a surface water pump made entirely from materials local to rural Ghana that interfaced with the Clean Water for the World filtration system.

BACKGROUND

To understand the scope of this project, we researched the water sources currently used in the target region, the consequences of unsafe drinking water, the Clean Water for the World organization, and relevant background information on pumps.

Water Sources Currently Used in the Target Region:

Ghana is a country in West Africa known for its agriculture as well as for its gold coast. It is approximately 238, 500 square kilometers. Ghana has a population of approximately 20 million people, divided into 10 regions [8]. Kyeamekrom is our target community and it has a population of approximately 9,000 [9]. Kyeamekrom is located in the Sene district which is one of nineteen districts in the Brong-Ahafo region of Ghana. This region has extremely limited usable electricity as well as almost no clean, drinkable water sources.

Through a survey conducted by the University of Michigan GIEU (Global Intercultural Experience for Undergraduates) students we know that there are three water sources in the region that most community members utilize [3]. They currently use one or some combination of hand dug wells, bore holes, and a dam. Hand dug wells are manually dug shafts generally less than 65 feet deep [4] and bore holes are narrow shafts drilled in the ground for the extraction of water [5]. The final source which becomes the main water source for the region in the winter months, is a swamp area created by a dam. 32% of the community uses only surface water from the dam area, 25% uses only hand dug wells, 11% uses only boreholes, 5% use both a borehole and the dam, 1% use both a borehole and a well, and 27% use a hand dug well, a borehole, and the dam.

Consequences of Unsafe Drinking Water:

Water is contaminated by viruses, bacteria, parasites and other micro organisms that live in the water. Surface water is susceptible to a lot of contaminants from organisms in the environment, elements in the atmosphere, and elements in the bedrock. Micro organisms are also present due to the waste products produced by humans in the area and animals which may live in or around the water [6,7]. These organisms flourish in surface water and swamp water [11]. Once contaminated water is ingested there are numerous possible illnesses to which the drinker becomes susceptible [11]. Some illnesses associated with the consumption of contaminated water are Gastroenteritis which is caused by E coli, Cholera which is caused by the bacteria vibrio cholera, Hepatitis A which is caused by the Hepatitis A virus, and polio which is caused by an Enterovirus [11]. One common symptom of these diseases is diarrhea. Diarrhea is an increase in the frequency of bowel movements or an increase in the looseness of stool. This can lead to dehydration because of the excessive loss of fluids and minerals from the body [10].

Clean Water for the World:

Clean Water for the World (CWftW) is a 501c3 organization whose goal is to provide "simple adaptable water purification systems at no charge to communities without access to clean water." The organization has previously supplied and installed filtration systems to communities in El Salvador, Honduras, Guatemala, Nicaragua, Haiti, Ghana, Kenya, and Ecuador. The system costs approximately $750, with CWftW relying on donations to cover manufacturing and installation costs [2].

The CWftW filtration system consists of two filters and an electrical tracking subsystem attached to a solenoid valve, all contained inside a wooden box. This system can be seen in Figure 1 below. The first filter is a simple paper filter used to remove particles and the second is a stainless steel ultra-violet light chamber which sterilizes any pathogens [2].

FIGURE 1
CLEAN WATER FOR THE WORLD FILTRATION SYSTEM

When working properly, the system requires minor maintenance [2]. The paper filter must be replaced every 1-2 months, the UV bulb must be replaced after two years, and the glass sleeve (separating the UV bulb from the water) must be cleaned when the paper filter is changed (every 1-2 months). A two year supply of filters is provided with the unit upon installation and is subsequently restocked every two years [2].

Last year, CWftW provided a filtration system to the Kyaemekrom community in Brong-Ahafo Region of Ghana. While the system was successfully installed and tested, the installation team faced a number of challenges. There was no simple way to get water from the user's container into the filter. In addition, the filter was located at the chief's house (the only close source of electricity) which was approximately one kilometer from the swamp. As it turned out, shortly after installation, a power surge destroyed the electrical tracking subsystem rendering the system inoperable. It was subsequently returned to the United States.

Background Reaseach:

Due to our limited incoming knowledge of pumps we performed an extensive literature review including searches of U.S. patents, journal articles, and websites.

We based our design off of a bilge pump, which is a type of displacement reciprocating pump typically used in marine applications to remove excess water that does not drain off the side of the deck [1]. These pumps can either be powered by electricity or by hand. Most bilge pumps that are powered by hand are diaphragm pumps, meaning the top of the main chamber is a flexible diaphragm. This diaphragm is attached to a hand lever, and the rotary motion of the lever causes the diaphragm to move up and down. This motion causes a volume change, and therefore a pressure difference which "pulls" the water into the chamber and "pushes" the water out of the chamber. The other type of bilge pump uses a piston enclosed in a tube. As the user pulls the handle out, the pressure difference sucks up the water through a foot valve. When the handle is pushed back in, it forces the water out through the check valve and out through a tube. The diaphragm bilge pump can be seen in Figure 2 below [12].

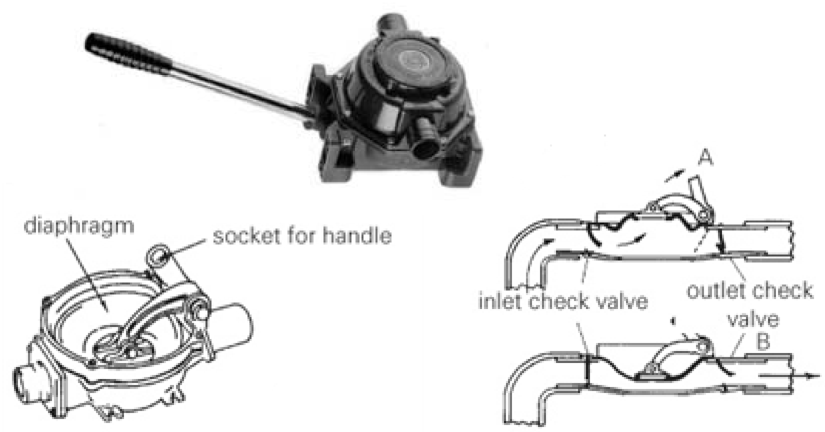

FIGURE 2
MANUAL BILGE PUMP (DIAPHRAGM)

USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

In order to quickly and effectively generate concepts we defined clear user requirements and translated those requirements into engineering specifications with specific numerical targets

User Requirements:

The user requirements were based on the needs of the Kyeamekrom community in Ghana. These requirements were generated through team brainstorming, discussions with our sponsors (specifically, Paul Flickinger and Professor Sienko), and a discussion with Domitilla Debpuur, a representative for the Kyeamekrom region, via Skype.

Once we had a final list, each team member (individually) ranked each requirement and we averaged our rankings. We then surveyed a group of GIEU students who had previously visited the region and incorporated their feedback into our rankings. This process yielded the prioritized list of user requirements that can be seen in Table I on page 7.

TABLE I

USER REQUIREMENTS RANKED FROM MOST TO LEAST IMPORTANT

Requirement	Rank
Easy to Use	1
Safe to Use	2
Efficient	3
Durable	4
Easy to Maintain	5
Easy to Repair	6
Transportable	7
Low Cost	8
Includes Pre-Filter	9

The team initially assembled over 20 user requirements. We then consolidated requirements where possible and eliminated requirements identified as insignificant or extraneous. Each user requirement stems from a specific need that future users will have of the final system. In their current form these user requirements are of limited help when it comes to creating an actual design and cannot be used to evaluate potential designs. Therefore, they were translated into engineering specifications with numerical targets.

Engineering Specifications:

Through discussion with our sponsor and mentors we indentified the engineering specifications that correspond to each of the above user requirements. For each engineering specification, we determined a specific, logical numerical target based on input from our mentors as well as through our literature review. Initially, we designed our system to meet these targets, and ultimately we evaluated our final prototype against them. 25 engineering specifications were identified in total. The 6 most important specifications can be seen in Table II.

TABLE II

KEY ENGINEERING SPECIFICATIONS DERIVED FROM USER REQUIREMENTS

Specification	Target
Number of users at a time	1 user/ time
Force required for operation	≤20 lbs of force
Does not underutilize filter	5 gallons/minute
Pressure leaving pump	10 ft. head
Environment proof materials	Weather and wild-life resistant
Percentage of locally available materials	100%

Through our discussion with Domitilla we learned that a number of people will make their trip to the swamp solo. This makes it vitally important that the pump be operable by one user in order to remain convenient and easy to use. We also learned that the most common operators of the pump will be women and children which is why a target of 20 lbs was set for maximum force required for operation. This number was based upon the fact that Kyeamekrom residents traditionally carry buckets of water containing about 3 gallons of water and weighing approximately 25 lbs. In order for the pump to remain efficient it was important that it not underutilize the filter which is capable of purifying water at a flow rate of 5 gallons/minute with an incoming pressure of 10 feet of head. In addition, since the pump will be located outdoors it was important to choose weather proof and wild-life resistant materials. This will help the pump operate efficiently and extend the lifetime of the system. In order for the pump to be easily repaired and maintained it was important to choose materials that are all locally available in Ghana.

In addition to the engineering specifications a functional decomposition was used to aid in concept generation and selection. The functional decomposition helped to break the complete system down in to mutually exclusive subsystems, such that overlap between components was minimized. It also ensured that the subsystems would be collectively exhaustive. Once components were chosen for each subsystem, the compilation of those components gave way to a complete system design.

CONCEPT GENERATION AND ALPHA DESIGN SELECTION

The generation of concepts was a multi-step, reiterative process consisting of initial research, brainstorming (both individually and as a group), and design selection. The outcome of the initial concept generation was the piston pump described in the alpha design section. Throughout this process, we kept in mind the engineering specifications and their targets, using them as points of discussion during group brainstorming, selection and consolidation. In the end, each component was chosen based on its ability to meet the determined engineering specifications, and evaluated relative to alternative brainstormed ideas.

Other designs given significant consideration were gear pumps, centrifugal pumps, and rope pumps. Concerning feasibility, piston pumps are a clear winner over all others because they are easier to make, and require less complicated parts. With respect to effectiveness, according to the Pump Handbook [13], different types of pumps are best suited to different applications (typically based on the speed of the pump), and at low speeds the best type of pump to use is the piston-cylinder. With respect to cost, the piston-cylinder is also the cheapest. Gear pumps and centrifugal pumps require precisely machined interior parts (whether it is the gears or the impeller). Additionally, the piston-cylinder can be as low at 1/10 of the cost of a rope pump. Furthermore, our conclusion is supported by what is in use today. Bicycle pumps, treadle (stair-stepper) pumps, rower pumps and lever pumps all actuate a piston to move water. What changes within each design is not the type of pump, but the user interface used to capture input mechanical energy and convert it to the linear reciprocating motion required to actuate a piston in a cylinder.

Alpha Design Description:

Our alpha design consists of six main components: a pre-filter, an inlet hose, a pump, a user interface, a pressure relief valve, and piping to the filter. The water from the swamp will enter the inlet hose and through the pre-filter, then enter the pumping chamber where energy will be added to the water through human input, then pass through the piping which will include a relief valve to regulate pressure, and then enter the Clean Water for the World filtration system. The entire system can be seen in Figure 3 on page 9.

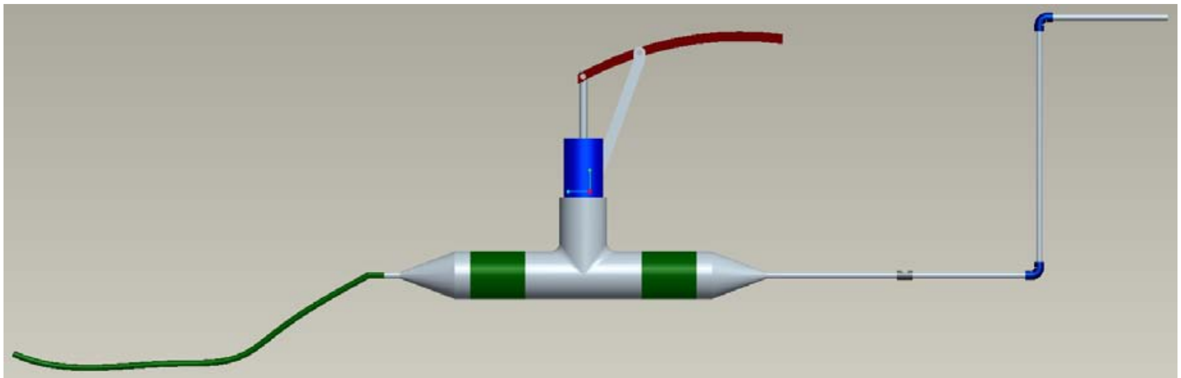

FIGURE 3
CAD MODEL OF ALPHA DESIGN

The biggest problem with our alpha design was that it was not detailed enough to actually create a prototype. However, it was a good foundation for creating our final design.

FINAL DESIGN DESCRIPTION

Since our prototype was intended to be brought to, and installed in Ghana upon completion of the project, our final design was nearly identical to our prototype. Therefore, throughout the final design description it can be assumed that each component was identical to the prototype unless stated otherwise. The final pump design includes several subsystems: a pre-filter, tubing, two identical one way valves, two piston seals, and a handle.

Subsystems Description:

To construct a pre-filter a wire mesh was wrapped around the inlet opening on the end of the inlet hose that is submerged in the swamp. A simplified CAD model of the mesh placement before wrapping can be seen in Figure 4 below. Not pictured was a large PVC end cap attached to the end of the hose. Several 0.5 inch diameter holes were drilled in the cap and the inlet hose was pushed through one in the center. The purpose of the cap is to keep the opening of the inlet hose from sinking into the mud at the bottom of the swamp and therefore preventing flow.

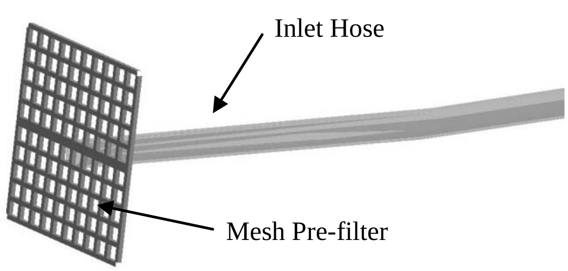

FIGURE 4
PRE-FILTER

Each one way valve includes a 0.75 to 0.50 inch PVC reducer, a 0.625 inch diameter glass marble, a 0.75 inch PVC adapter, a 0.625 inch PVC retainer, a compression spring, and a 0.50 inch PVC adapter. All the PVC parts are attached by PVC glue. The marble is glued with waterproof, non-toxic glue to one end of the spring, and the other end of the spring is glued to the 0.50 inch PVC adapter. As the water enters the inlet side, the water pressure pushes the marble to the right and compresses the spring allowing water to enter. When the flow reverses direction, the marble is forced to the left where the neck of the reducer stops the marble. This contact between the marble and the reducer prevents any water from flowing out through the inlet end. A side view with hidden lines is shown in Figure 5 below.

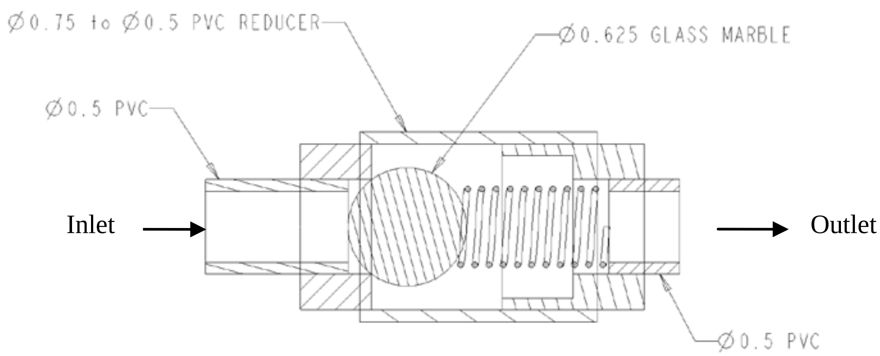

FIGURE 5
ONE WAY VALVE

The piston seals are located on the end of the 0.50 inch diameter aluminum piston rod. The rod is threaded on both ends with at least 3 inches of size 13 UNC threads. The material chosen for the seals was rubber because it is a material commonly used in seals and is available in Ghana. Since the piston chamber is 1.50 inch in diameter, the 0.125 inch thick seals were cut to have a 1.50 inch outer diameter and 0.50 inch inner diameter. Washers with 1.25 inch outer diameter and 0.50 inch inner diameter were positioned on both sides of the seal to help the seal keep its shape and stay in contact with the inner piston housing wall. To constrain the seal and washers along the rod, two 0.50 inch 13 UNC nuts were screwed onto the piston rod as shown in Figure 6. The same configuration as was previously described will be duplicated and positioned just below the first seal. This second seal is used for a number of reasons: 1) it will provide a more robust seal, 2) it is used as a backup in the event that one seal fails, and 3) it helps constrains the rod along the axis of the piston housing.

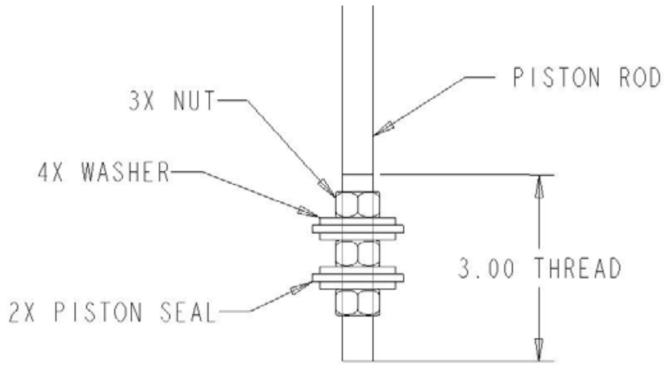

FIGURE 6
PISTON SEAL

The user interface will be a simple handle bar that the user will move up and down in the vertical direction to displace the piston. The handle is 14 inches in length and made out of a 0.75 inch aluminum pipe with a wall thickness of 0.065 inches. Aluminum was chosen because it is a material that is readily available in Ghana, and is relatively lightweight and is strong enough to not fail during pump use. The handle is located on the end of the piston rod with 2.00 inches of 13UNC threads. Nuts are positioned both above and below the handle to prevent displacement of the handle. Figure 22 below shows the positioning of the handle and nuts on the piston rod.

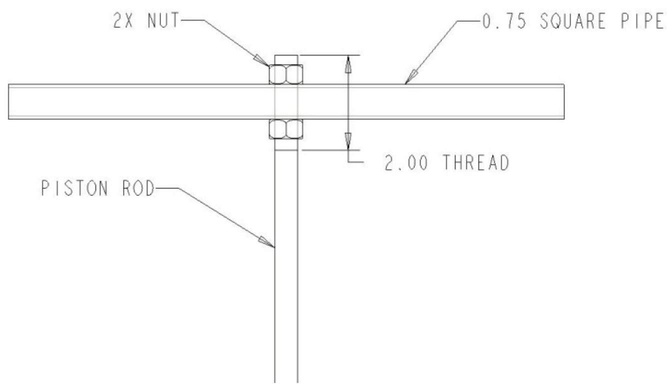

FIGURE 7
HANDLE POSITIONING

Complete System Description:

All of the subsystems are connected using the following components: 1) 25 foot long, 0.5 inch inner diameter clear PVC hose, 2) three 1.5 inch diameter threaded clean out caps, 3) 1.5 inch three-way t-joint, 4) 2 foot long 1.5 inch diameter PVC pipe, 5) 10 foot long, 0.5 inch inner diameter clear PVC hose, and 6) 1.5 inch PVC pipe 2.5 inches in length. Each of these components can be seen in Figure 8.

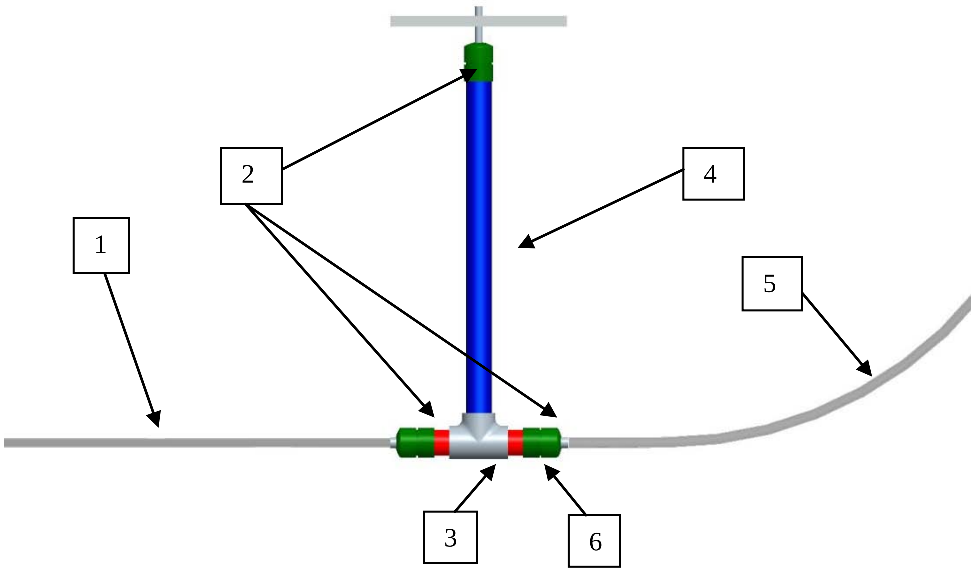

FIGURE 8
TOTAL ASSEMBLY

A 25 foot long, 0.5 inch inner diameter clear, flexible PVC is used as the inlet hose (1). The PVC hose was chosen because it is cheap and flexible. Additionally, clear hose was chosen so that during testing we can see how much dirty accumulates in the tubing. The pre-filter wire mesh is attached to one end with a hose clamp, and the other end is connected to the inlet one-way valve, also with a hose clamp.

Three 1.5 inch two piece threaded clean out caps (2) are used to cap the t-joint and cylinder. They were chosen because they can be unscrewed and removed to facilitate cleaning of the system. Holes drilled in the caps (5/8" diameter holes in the two t-joint caps, and ½" diameter hole in the cylinder cap) allow for the attachment of the one-way valves and insertion of the piston.

The three-way t-joint (3) was chosen to facilitate the connection of one-way valves to the piston-cylinder. Without the use of the t-joint, the one-way valves would have to be attached to the cylinder which would add complexity to the manufacturing process. The piston housing (4) consists of a 2 foot long 1.5" diameter PVC pipe.

A 10 foot long, 0.5 inch inner diameter clear, flexible PVC is used as the outlet hose (5). The PVC hose was chosen because it is cheap and flexible. Additionally, clear hose was chosen so that during testing we can see how much dirty accumulates in the tubing. The hose will be connected to the outlet one-way valve and Clean Water for the World inlet nozzle using hose clamps.

The PVC adapters (6) are necessary to create the marble based one-way valves, and their size is dictated by the diameter of both the marbles to be used and the inlet and outlet hose.

PARAMETER ANALYSIS OF FINAL DESIGN

Pump Dimensions:

In order to determine the diameter of the piston chamber of the pump energy conservation equations must be applied to the entire system. Bernoulli's principle, shown in equation 1 describes the energy considerations for incompressible, inviscid, laminar flow between two locations. The principle states that for an inviscid flow, an increase in the velocity of the fluid occurs simultaneously with a decrease in pressure.

Although a pump cannot actually create continuous steady flow, energy equations can be used to model the times when fluid is flowing through the system. In addition we made the assumption that the system is laminar flow because the relationship between fluid motion and shear stress is very complex for turbulent flow. However, the shear stress in turbulent flow is much larger than that of laminar flow because of the irregular random motion.

It has been experimentally determined that the filter provided by Clean Water for the World is able to produce an output flow rate of 4 gal/min when the input pressure is 10 feet of head. Based on these given quantities and equation 2 we were able to determine the coefficient, C for the filter. This coefficient accounts for all the non-idealities through the filter including friction losses, the input and output ratio of cross sectional areas, and the Reynolds number. The equation can then be used to calculate the pressure drop across the filter for the desired output flow rate of 5 gal/min

We calculated the pressure inside the piston chamber to be 13.874 psi. The combination of this pressure and the desired user input force of 20 lbs from out engineering specifications allows us to calculate the diameter of the piston chamber to be 1.35 in. We chose 1.5 inch diameter PVC pipe because it was the closest to our desired area without requiring too much additional input force.

Piston assembly:

A force analysis was performed on the metal components in the piston to design against failure. The force acting on the parts was assumed to be ten times larger than the expected user input force.

In order to determine the strength of the piston rod material strength equations were used. The yield stress of Aluminum-6061 is 55 MPa which is 7.83 times larger than our calculated yield stress of 7.02 MPa. Therefore, the piston rod will not fail within normal operation of the pump.

We also calculated the stress applied to the handle because should it fail the entire system would become unusable. A moment equation was applied along with the material strength equation. The handle is also made out of Aluminum-6061 which has a yield stress 6.07 times higher than our calculated yield stress of 9.066 MPa. This ensures that failure will not occur when normal operational forces are applied to the piston handle.

An equation used to determine the strength of the nuts holding both the handle and the seals onto the threaded rod determined the failure strength of the nuts. The nuts are made out of zinc-plated steel which has a yield stress of 1200 MPa. This is 15800 times larger than our calculated yield stress of 0.076 MPa which allows us to predict with certainty that the nuts on the piston assembly will not fail.

VALIDATION TESTING OF FINAL DESIGN

Due to the uncertainties involved with the theoretical model of our pump the device was tested extensively once it was constructed. Through testing we were able to gain a better understanding of the actual performance and verify that the pump met our engineering requirements.

There are three main subcomponents of the pump, the piston/cylinder (handle, rubber seal and PVC), the one-way valves, and the pre-filter. Each subcomponent underwent testing before being combined with the other subsystems to create the complete design.

Piston/Cylinder:

The piston cylinder was tested to determine the forces required to operate it, and how effectively the piston seals work. To determine the force we attempted to actuate the piston using a force gauge to measure the forces required to overcome the friction between the seal and PVC cylinder. The pump needed to operate with a force less than 20 lbs to meet the engineering specification. This target was verified and we were able to operate the pump normally without exceeding 20 lbs. During this test we discovered that the down stroke of the pump only required approximately 75% of the force required for the upstroke when performed at approximately the same speeds.

To determine how effectively the piston seals work we observed the region in the cylinder above the seal while performing the force test. We also tried out a number of different seals using varying diameters of leather and rubber and different sized washers. We were able to improve the performance of the seal on these tests, and further reduce the force required to operate while ensuring only limited leakage past the seal. We found that variations in the thousandths of an inch in either the diameter of the seal material or the washers being used had a significant effect on the performance of the seal. Once adjustments had been made, we found the force required to operate the piston to be less than 20 lbs, without a significantly greater amount of leakage occurring.

One-Way Valves:

The one-way valves were tested to determine how effectively they sealed against backflow. They were tested by running water through the valves in both directions. In one direction the water flowed freely while in the other direction the water was blocked. This testing validated that the valves work, and allowed us to compare the constructed valves to each other as well as to a pair of purchased valves. We found that all of our constructed valves allowed a slow drip of water through in the blocked direction while the purchased valves allowed no water to trickle through in the blocked direction. This problem was deemed insignificant due to the fact that the constructed valves are much more cost effective than the purchased valves.

Pre-Filter:

The pre-filter was tested to verify that it does not unduly impede the flow of water into the tubing. This was tested by attaching the pre-filter to a section of tubing, filling the tubing with water, and capping the opposite end of the tubing. We then lifted the capped end of the tube vertically, over the pre-filter covered end of the tubing and simultaneously uncapped the tubing. Without actually measuring the flow, we were able to clearly see that the fine mesh did not have a visible effect on the flow rate when compared to open piping.

Complete System:

Once each subcomponent was tested we were able to validate that the pump met all of the targeted engineering specifications.

The pump must be operable by one user in order to meet the target specified. Each team member took turns using the pump in addition to fellow students. The pump was able to be used without assistance.

To make sure that the pump did not underutilize the Clean Water for the World filter we filled a container with approximately 5 gallons of water pumped water from the container with 5 gallons into another container for 1 minute. We were only able to move 2 gallons of water per minute but with a larger diameter piston cylinder and larger diameter inlet hose the pump would be able to meet the target. However, we did not have time to build another iteration of the pump to test this.

To test that the pressure leaving the pump met the engineering specification of 10 feet of head we raised the pumps outlet hose 10 feet above the pump and attempted to actuate the pump. We are able to pump water out of the top of the hose using less than 20 lbs of force which meets the target.

In order to make the repair and maintenance of the pump easier a user construction manual was created. The manual is entirely pictographic and will be sent with the pump to Ghana. Another engineering specification was that the pump be made entirely out of locally available materials. Mr. Kofi Gyan was able to verify that the materials we had chosen to use would be available in Ghana. We also asked five med students from Ghana and they believed all the material we listed to be readily available with the exception of the marbles. This is not a problematic issue because the design is adaptable enough that any small ball would work in place of a marble.

DESIGN CRITIQUE

Each subsystem is relatively independent of the others and can be analyzed individually in addition to the system as a whole.

Piston/Handle:

The problem with the piston / handle is that we are uncertain of what the best diameter is for the washers or the seal material. Consequently, the seal may be allowing more water to leak past the seal than it should, or it may be creating too much friction inside the PVC cylinder and unnecessarily driving up the required operating force. Finally, we have no idea how long the lifetime of a given seal may be. Given additional time, we would extensively test the effect of varying these parameters. Using this data, we could better select a suggested diameter for both the seal and the washer.

One-Way Valves:

The main critique of the one-way valves is that we don't have a good understanding of how the use of different springs (varying the stiffness) would affect the performance of the valves. Additionally, we were not able to build functioning valves based on rubber balls (instead of marbles) despite multiple attempts. Given additional time we would rebuild the rubber ball valves under the belief that they could seal better than marbles given that rubber would deform more than glass when pressed into a PVC opening.

Tubing:

The tubing initially used (soft clear PVC) collapsed under significant suction. We then had to replace that inlet tubing with reinforced tubing, and we are unsure how long this reinforced tubing will last. Additionally, this reinforced tubing is significantly more expensive than the other tubing. We would recommend experimenting with the inlet tubing used. Both the type of tubing and its diameter could be varied.

Complete System:

The main critiques with respect to the system as a whole are whether it is user-friendly its inability to pump 5 gallons per minute. The prototype created was oriented vertically and may be uncomfortable for shorter users to operate. With respect to the volume flow rate, our final prototype was only able to pump 2 gallons per minute. With continued testing alternative orientations of the pump and larger diameter pipes could be evaluated in order to make the pump more useable and efficient.

RECOMMENDATIONS

The pump was designed specifically to interface with the Clean Water for the World filter. We recommend attaching the pump to a metal or wood stake driven into the ground near the filter. The attachment can be made with any sort of rope or tie. This will help keep the pump upright and hold it steady during operation. The pump also needs to be attached at the base. We recommend clamping the pump to a piece of wood that the user can stand on. If the pump does not appear to be operating at maximum performance the one-way valves can be unscrewed from the pump and cleaned. By running water through them that is free of debris they should begin functioning again. If a part of the valve or seal becomes damaged the parts can be replaced. The construction manual will help the user to rebuild the components that have failed.

Since we were only able to conduct short term testing on the pump, lifetime tracking is recommended. With more information and knowledge of the wear characteristics, a more robust design as well as a more refined maintenance schedule could be determined. Additionally, if we had more time for testing the one way valves could have been improved. Testing is the only way to determine the optimum spring stiffness and ball material to make the valves operate better. Finally, we also recommend refining the construction manual. The pictures are currently difficult to follow and understand.

CONCLUSION

Our major objective was to provide the Kyeamekrom community in the Brong-Ahafo region of Ghana with a clean, safe, drinkable water source. We aim to help prevent a portion of the 5000 deaths each day that result from diseases related to the consumption of contaminated water. In order to do this our goal was to create a surface water pump made entirely out of locally available materials that can interface with the Clean Water for the World filtration system.

Through an extensive literature review we determined that the prototype would be similar to a bilge pump and would include a pre-filter to extend the life of the pump and filter. With the help of our sponsor and mentors we were able to revise our list of customer requirements and engineering specifications in order to get very specific targets with which to evaluate our prototype. From there we were able to begin generating concepts, narrowing down our options, and eventually choose an alpha design.

Our alpha design transformed into our final design through rigorous testing and engineering analysis. Our final pump design includes several subsystems: a pre-filter, tubing, two identical one way valves, two piston seals, and a handle. We selected materials and dimensions based on the engineering specifications and validated the prototype against these specifications.

There are several areas of our design that require further consideration, testing and refinement. We have recommended plans for implementing the current prototype as well as goals for future work.

ACKNOWLEDGMENT

We would like to thank several people for their help and support throughout this project. Professor Kathleen Sienko, Professor Nikos Chronis, Professor Steven Skerlos, Paul Flickinger and the Clean Water for the World organization, Dan Johnson, Domitilla Debpuur, Alex Harrington, Joseph Perosky, Bob Coury, and Marv Cressey

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APPENDIX A

1 INTRODUCTION

Worldwide there are 1.1 billion people who do not have a way to get clean drinking water. Every year, 1.8 million people die from diarrheal disease, and it is estimated that 88% can be attributed to the lack of clean drinking water [1]. This project will partner with the non-profit organization Clean Water for the World which provides simple water filtration systems to communities in need of clean water. Our major objective is to provide the Kyeamekrom community in the Brong-Ahafo region of Ghana with a clean, safe, drinkable water source. In order to do this our goal is to create a surface water pump made completely from locally available materials that will interface with the Clean Water for the World filtration system.

1.1 Sponsors and Mentors

Professor Kathleen Sienko, Ph.D., is the main sponsor for this project. She will be helping us determine the scope in addition to advising us throughout the project as well as providing funding. Paul Flickinger is the Executive Director of Clean Water for the World and will help the project as a mentor. Alex Harrington, a student at the University of Michigan, will assist the project as a student mentor. Professor Steve Skerlos, Ph.D., co-founder and faculty advisor for BLUElab, will act as another mentor to this project.

2 BACKGROUND

To understand the scope of this project, we must understand each individual aspect involved. This section provides information on the target region, current water sources, the consequences of unsafe drinking water, the Clean Water for the World organization, and background of pumps, pre-filters, and pressure relief valves.

2.1 Target Region

Ghana is a country in West Africa known for its agriculture as well as for its gold coast. It is approximately 238, 500 square kilometers. Ghana has a population of approximately 20 million people, divided into 10 regions [20]. Kyeamekrom is our target community and it has a population of approximately 9,000 [21]. Kyeamekrom is located in the Sene district which is one of nineteen districts in the Brong-Ahafo region of Ghana. This region has extremely limited usable electricity as well as almost no clean, drinkable water sources. The climate is tropical with the major rainfall occurring between the months of April and July and the mean annual recorded rainfall is 1191.2 mm. [27]

2.2 Water Sources Currently Used

Through a survey [3] conducted by the GIEU students we know that there are three water sources in the region that most community members utilize. They currently use one or some combination of hand dug wells, bore holes, and a dam. Hand dug wells are manually dug shafts generally less than 65 feet deep [4]. Bore holes are narrow shafts drilled in the ground for the extraction of water [5]. The final source which becomes the main water source for the region in the winter months, is the swamp area created by the dam. A graphical representation of these water sources can be seen in Figure 01. 32% of the community uses only surface water from the dam area, 25% uses only hand dug wells, 11% uses only boreholes, 5% use both a borehole and the dam, 1% use both a borehole and a well, and 27% use a hand dug well, a borehole, and the dam.

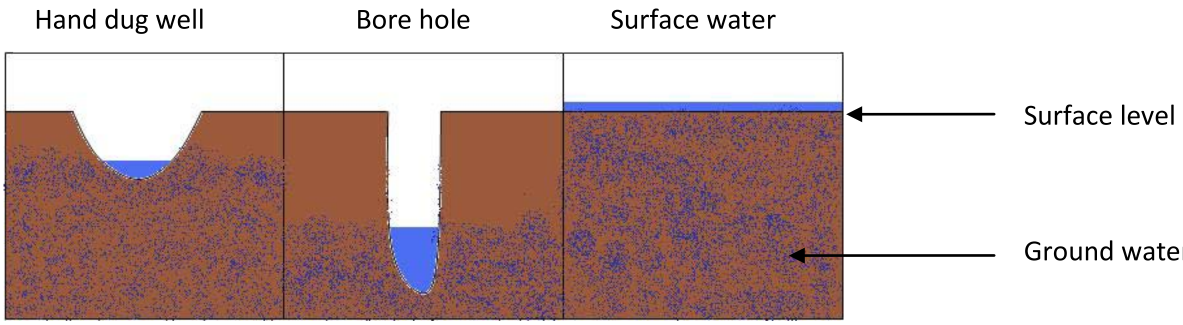


Figure 01: Water sources currently used

Surface water is susceptible to a lot of contaminants from organisms in the environment, elements in the atmosphere and elements in the bedrock. Micro organisms are also present due to the waste products produced by humans in the area and animals which may live around or in the water [10,12]. These pathogens may cause a vast number of diseases some of which are fatal. Another source of disease is found in the soil and bedrock below the surface water. Additionally, elements like nitrogen and fluoride can be found in the environment around surface water locations and mix with the water due to the reactions catalyzed by micro-organisms. Although substances like fluoride are safe to ingest in small quantities [10,12], if ingested in large quantities it can affect the calcium in the body and cause fluoride poisoning. There could also be the heavier elements present in the environment such as arsenic, which is unsafe to drink even in small quantities. Our project will focus on creating a pump to transport surface water to a filtration device.

2.3 Consequences of Unsafe Drinking Water

Ingesting contaminated water causes waterborne diseases. Water is contaminated by viruses, bacteria, parasites and other micro organisms that live in the water. These organisms flourish in surface water and swamp water [25]. Once contaminated water is ingested there are numerous possible illnesses to which the drinker becomes susceptible [25]. Some illnesses associated with the consumption of contaminated water are Gastroenteritis which is caused by E coli, Cholera which is caused by the bacteria vibrio cholera, Hepatitis A which is caused by the Hepatitis A virus and polio which is caused by an Enterovirus [25]. One common symptom of these diseases is diarrhea. Diarrhea is an increase in the frequency of bowel movements or an increase in the looseness of stool. This can lead to dehydration because of the excessive loss of fluids and minerals from the body [24].

A list of the waterborne contaminants as well as their health risks and sources can as be found in Appendix [C] as identified by the EPA.

2.4 Clean Water for the World

Clean Water for the World (CWftW) is a 501c3 organization whose goal is to provide "simple adaptable water purification systems at no charge to communities without access to clean water." The organization has previously supplied and installed filtration systems to communities in El Salvador, Honduras, Guatemala, Nicaragua, Haiti, Ghana, Kenya, and Ecuador. The system costs approximately $750, with CWftW relying on donations to cover manufacturing and installation costs [2].

2.4.1 Clean Water for the World Filtration System

The CWftW filtration system consists of two filters and an electrical tracking subsystem attached to a solenoid valve, all contained inside a wooden box. This system can be seen in Figure 02. The first filter is a simple cotton paper filter used to remove particles, and the second is a stainless steel ultra-violet light chamber, which sterilizes any pathogens [2].

Figure 02: Clean Water for the World filtration system

The electrical subsystem tracks the usage of the UV light and indicates when the UV bulb needs to be replaced. The subsystem includes a LED display that counts down from 365 – decreasing by 1 for every 24 hours of operation – and controls the solenoid valve. The solenoid valve separates the paper filter from the UV chamber and it closes when the tracking subsystem counter reaches 0, indicating that the UV bulb needs to be replaced. When the subsystem first reaches 0, the counter can be reset twice (each give 10 additional 'days'). After the second reset expires, the solenoid closes until the filter is replaced [6].

Typical filter usage ranges from four to ten hours per day. This would imply possible UV bulb-life of up to 6 years; however, it is recommended that the bulb be changed every two years regardless of the number of 'days' remaining. As previously stated the UV bulb requires 24 Watts to operate, while the solenoid valve draws 3 Watts [6].

When working properly, the system requires minor maintenance [2]:

- Paper filter must be replaced every 1-2 months
- UV bulb must be replaced after two years or ~8,760 hours of use (365 days * 24 hours/day)
- Glass sleeve (separating the UV bulb from the water) must be cleaned when the paper filter is changed (every 1-2 months)

Additionally, a two year supply of filters is provided with installation, and resupplied every two years [2].

2.4.2 Relevant Experience with Target Region

Last year, CWftW provided a filtration system to Professor Sienko, to be taken to and installed in the Kyaemekrom community in Brong-Ahafo Region of Ghana. While the system was successfully installed and tested, the installation team faced a number of challenges. Additionally, shortly after installation, a power surge fried the electrical tracking subsystem rendering the system inoperable. It was subsequently returned to the United States with Professor Sienko.

The current system requires power and had to be co-located at an available electrical source. After much debate, it was ultimately decided to place the filter at the community Chief's house and use his electricity. This presented two problems: 1) the Chief's house is not near the community's main surface water source, a local swamp, and 2) it was unclear whose responsibility it would be to pay for the electricity used by the system[7].

There was an initial concern among the installation team that many community members would not use the filter system because of its inconvenient location: the Chief's house is approximately 1 km from the swamp. Furthermore, many community members are located opposite of the Chief's house, from the swamp. Due the power surge, the installation team was not able to see this concern validated; however, it remains a large concern [7].

2.5 Background on Relevant Components

Due to our limited incoming knowledge of the three relevant components for this project: pumps, pre-filters, and pressure relief valves, we performed an extensive literature review on each. The review has included searches of U.S. patents, journal articles, and websites. The information presented below is a distillation of information we felt was relevant within the context of our project. As the project, progresses we will continue to seek out new information and will be reaching out to our sources.

2.5.1 Pumps

We will be designing a pump integrated to the Clean Water for the World filtration system. To build our knowledge base, we researched both the driving principles behind relevant pump designs, as well as an overview of pump designs currently being used to solve similar problems. In order to pump surface water, we must consider the following: viscosity of the fluid, the pressure of the fluid, and whether the fluid is moving. Shallow water pumps rely on atmospheric pressure to work. Shallow surface water pumps can pull water up to 20 feet and push water up 900 feet [3]. The presence of a vacuum is necessary in order to create the pressure difference necessary to move the water.

2.5.1.1 Types of Pumps

At their most basic level, pumps do one thing: provide energy to move water. However, there is an extremely wide range of methods by which pumps accomplish this transfer of energy to water movement. Water pumps into two major groups: positive displacement pumps and dynamic pumps [1]:

1. **Dynamic** –cause fluid to move under its own momentum, meaning that there needs to be moving fluid [2]. They are based on bladed impellers which rotate within the fluid to increase the fluid energy and cause acceleration. Dynamic pumps have lower efficiency than but work well at lower viscosities and have lower maintenance requirements [4].

2. **Displacement** – moveable boundaries (e.g. pistons) are used to trap a specified volume of liquid then increase pressure and push fluid through one valve, followed by a complementary decrease of pressure which draws fluid through a second valve.

These pump types can be further categorized into groups based on the mechanism used to move the fluid. [1]:

1. **Dynamic**
    a. **Dynamic Reciprocating or Linear pumps** operate by using a thin jet of moving fluid ejected perpendicular to the surface of the ambient fluid dragging it along. (e.g. Steam Ejectors)[2]
    b. **Centrifugal or Rotary pumps** use a rotating mechanism to increase fluid velocities as they flow through the pump. Unlike Displacement pumps, in Centrifugal pumps the outlet is not walled off from the inlet (see Figure 03 on page 6). Examples include any impeller based pump [1].

2. **Displacement**
    a. **Reciprocating pumps** operate the principle that a solid will displace an equal cross-sectional area of liquid along a cylinder with a pressure equal to the force exerted on the liquid by the solid along the length. Combining this with a pair of one-way valves completes the pump (see Figure 04). When the plunger moves in, it increases the fluid pressure and pushing the fluid to flow out through the discharge valve. When the plunger moves out it decreases the fluid pressure, pulling fluid through the suction valve. Examples include piston/plunger pumps (e.g. bike tire pump, hand-lever well pump) [1].
    b. **Rotary pumps** similar to Centrifugal pumps in that they utilize rotating parts to move fluid, but unlike Centrifugal pumps, they separate the fluid inlet from the fluid outlet and do not move the fluid by increasing its velocity. Examples include gear and screw based pumps [1].

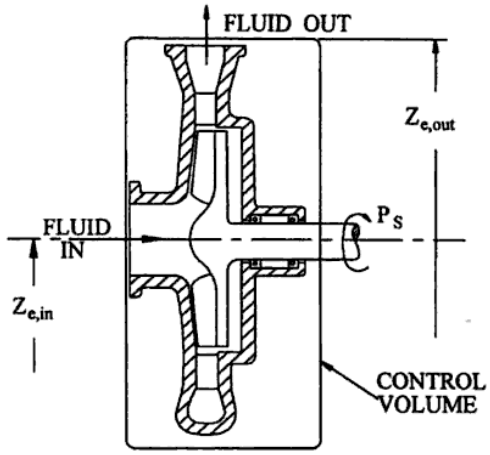


Figure 03 Centrifugal Pump [1]

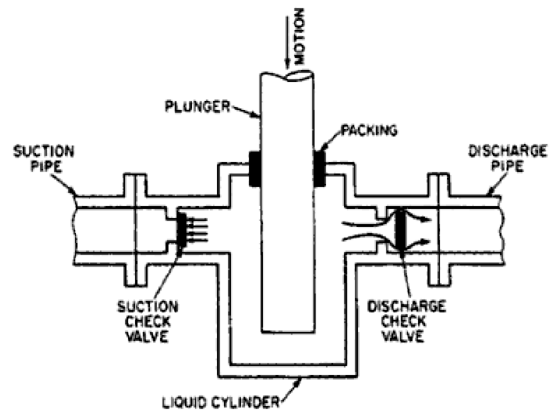


Figure 04 Reciprocating Pump [1]

Within the context of this project the provided energy is going to be limited to the mechanical energy that can be provided by a single person. We assume that the water is stationary, which eliminates the use of Dynamic pumps. Furthermore, the volume flows (typically < 5 gal/min) and the consequently low pump speeds that we will likely be dealing with favor the use of Displacement pumps over Centrifugal pumps, and more specifically Reciprocating pumps. This is due to their higher efficiencies in low volume, low speed applications: see Figure 05.

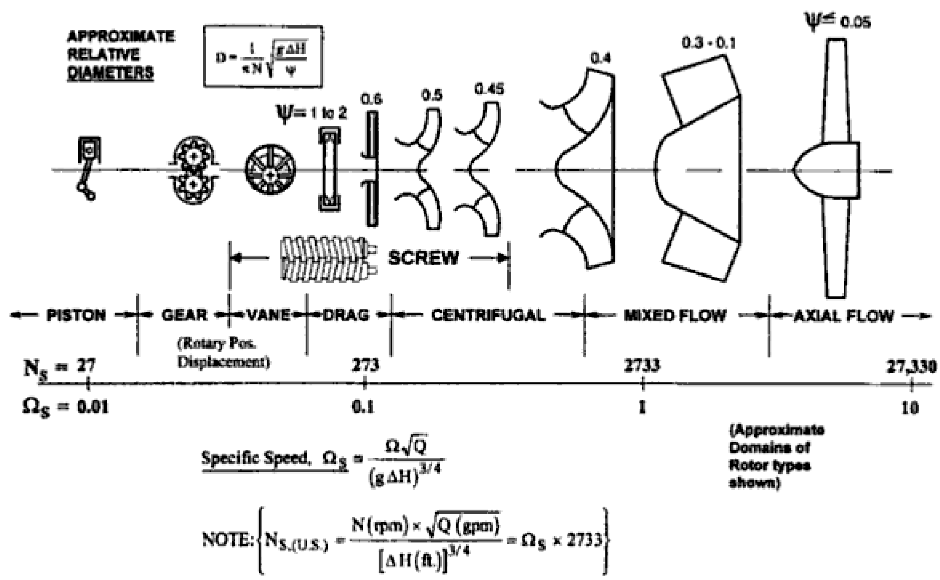


Figure 05: Optimum pump geometry as a function of pump speed [1]

Figure 5 above shows that the higher your pump speed, the further to the right you need to go when it comes to selecting the optimum pump types [1].While displacement pumps rely on very basic design principles to move the water, the forces used to drive the piston can come from a wide variety of sources depending on the most available form of energy for input.

2.5.2.1 *Current Pumps Used in Similar Situations*

Research of current pumps used in rural communities in developing nations tends to confirm the above theory: most pumps used are Reciprocating pumps of some form with a piston. However, there is a wide variety of methods through which energy is supplied to piston. These various methods, along with novel, alternative pump designs, will be the focus of this section.

Three of the most common pump drivers in this situation are simply using the plunge as is (rower pumps), an attached lever, and a flywheel. At their most basic, all mechanisms (see Figures 06 and 07 below) can be hand-powered by a single person. And when constructed properly, they can remain functional with limited to no maintenance for 15+ years [5].

Figure 06 Afripump [6]

Figure 07 Volanta pump [5]

More complicated drivers include:

- Wind power to rotate a flywheel which in turn drives the piston
- Flowing water to drive a flywheel
- Rotational energy from a stationary bicycle in lieu of a flywheel
- Mechanical energy from a stair-stepper device
- Children’s playground equipment (e.g. carousels)

Another option which does not rely on the one-way valves of displacement pumps is the rope pump, which has been used extensively when facing challenges similar to ours. These pumps rely on pushing water through piping by way of a “knotted rope.” The “knots” (which could be attached discs, spheres, or actual knots) achieve complete or near complete blockage of the pipe. As they are drawn through the pipe by the rope, they force water up through the pipe. A schematice of such a pump can be seen below in Figure 08 [6]

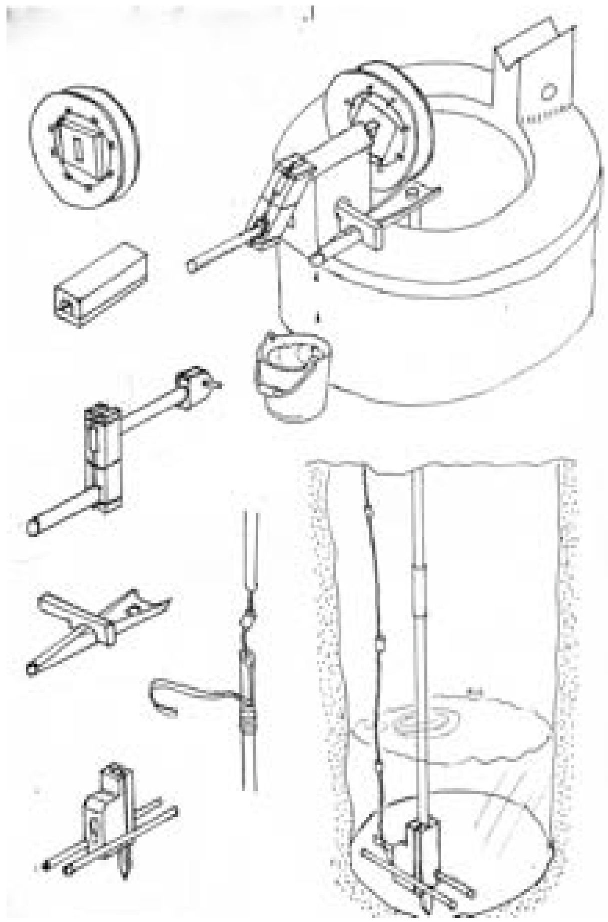


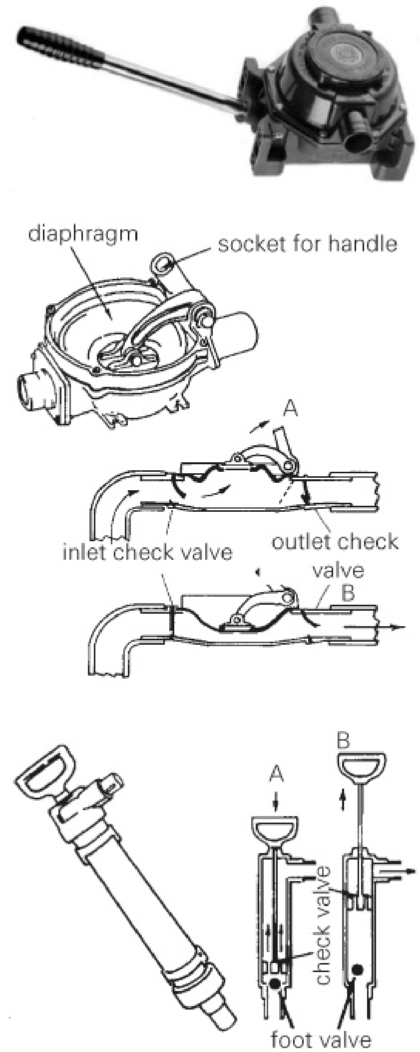
Figure 08 Diagram of a rope pump [6]

One simple and applicable example of the novel pump designs is a string with tennis balls attached at regular intervals being pulled through a PVC pipe with an inner diameter slightly larger than the tennis balls. One end of the PVC is submerged in water – as the string is pulled a tennis ball enters and blocks the bottom opening and pushing the trapped water up the PVC pipe. By attaching a number of balls onto a loop of string, a very simple pump can be created that can continuously move water. Paul Flickinger mentioned a community in India used exactly this design to very effectively meet their pumping needs [7].

2.5.2.2 *Bilge Pumps*

A bilge pump is a type of displacement, reciprocating pump typically used in marine applications to remove excess water that does not drain off the side of the deck [1]. These pumps can either be powered by electricity or by hand. Most bilge pumps that are powered by hand are diaphragm pumps, meaning the top of the main chamber is a flexible diaphragm. This diaphragm is attached to a hand lever, and the rotary motion of the lever causes the diaphragm to move up and down. This motion causes a volume change, and therefore a pressure difference which "pulls" the water into the chamber and "pushes" the water out of the chamber. The other type of bilge pump uses a piston enclosed in a tube. As the user pulls the handle out, the pressure difference sucks up the water through a foot valve. When the handle is pushed back in, it forces the water out through the check valve and out through a tube. Both the diaphragm and piston pumps can be seen in figure 09 on page 9 [28].

Figure 09 Manual Bilge Pumps – Diaphragm and Piston [2]



2.5.2 Pre-Filters

We will desire a pre-filtration system that will be placed before the pump in order to increase the lifetime of the pump as well as the Clean Water for the World filtration system. To build our knowledge base, we researched relevant types of pre-filtration devices. We focused on mechanical Pre-filters because all other types would be too difficult to implement.

2.5.2.1 Types of Pre-Filters

Pre-filters are installed on the intake side of your pump to protect it from debris and large particles that could damage its impeller or clog your pipes. Sediments are kept out of the pipe and water is allowed to flow through the pipes. The selection of the pre-filter depends on the size of the sediments in the water which we are assuming to be as small as 0.05 mm. There are two major categories of pre-filters depth type and membrane type.

1. **Membrane type** pre-filters are sheets of very fine membrane that allows water to pass through but no particles. These are easily cleaned and inexpensive but they clog often. It can be as simple as a wire mesh over the end of the pipe. This type of pre-filter is easier to maintain and easier to replace (Figure 10) [13].

2. **Depth type** per-filters use a block of polyester or carbon material. The water is forced through the block which traps particles. The porous pad is contained in a flat housing that rests on the bottom of the water [13].

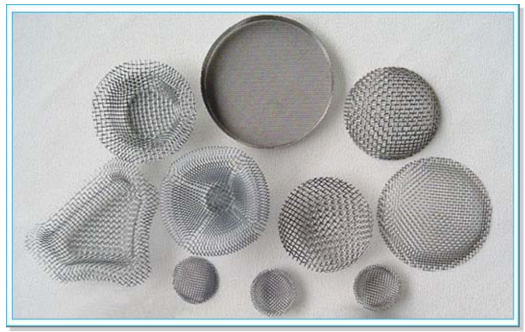


Figure 10 Wire Mesh filters [11]

2.5.3 Pressure Relief Valves

Pressure Relief Valves are safety devices used to manage pressure in a system. They alleviate pressure when a pipe or vessel has too much pressure preventing dangerous build ups [9]. The pressure is released by allowing some of the pressurized fluid to flow from the system through the valve. Pressure valves can be set to relieve at a pre-designated pressure and will reseal once the pressure returns to a level below the designated pressure [9]. Our aim is to maintain a pressure to the filter between 5 psi and 80 psi.

2.6 Financial Constraints

As with nearly every project attempting to make a large impact on the quality of life in communities of developing nations, this project faces strong financial constraints. Clean Water for the World will be providing a new (repaired) filtration system in addition to solar panels to power it. We have a budget of $400 to build our prototype, however we are working towards manufacturing a design that is less than $50.

We will try to minimize cost of the final product in the hopes that it can reach as many additional communities as possible. In addition, we will attempt to limit the cost of designing, testing, and producing the system, in order to mitigate the cost to our sponsor.

3 PROJECT OUTCOME

The outcome of this project will be a surface water pump that will interface with the Clean Water for the World purification system. The entire integrated system will be implemented in the rural Kyeamekrom community in the Brong-Ahafo region of Ghana. The surface water pump will include cleaning instructions as well as enough back up supplies to maintain the pump for at least two years. It will include a pre-filter, pressure relief valve, and tubing to connect it both to the water source and to the filtration system. In addition, the pump will be located near the water source and be easy and safe to use. It will ideally be able to produce enough water to satisfy the community's water volume demand and it will be easy to both maintain and repair. The entire system will be durable and environment proof since it will be located outside. Finally, the prototype will be within our budget in order to remain competitive with comparable products.

4 USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

In order to quickly and effectively generate concepts, all of the following were necessary:

- Clear definition of **user requirements**
- Translation of the requirements into **engineering specifications** with specific numerical targets
- Completion of a QFD diagram [Appendix A] to quantify the importance of our user requirements
- Review of what is currently available

These four steps will be discussed in the sections below and were used to guide our concept generation and selection.

4.1 User Requirements

The first step to better understanding our project is to clearly define the user requirements based on the needs of the Kyeamekrom community in Ghana. These user requirements were generated through team brainstorming, discussions with our sponsors (specifically, Paul Flickinger and Professor Sienko), and a discussion with Domitilla Debpuur, a representative for the Kyeamekrom region, via Skype.

Once we had a final list, each team member (individually) ranked each requirement and we averaged our rankings. We then surveyed a group of GIEU (Global Intercultural Experience for Undergraduates) students who had previously visited the region and incorporated their feedback into our rankings. This process yielded the prioritized list of user requirements that can be seen below:

1. Easy to use
2. Safe to use
3. Efficient
4. Durable
5. Easy to maintain
6. Easy to repair
7. Transportable
8. Low cost
9. Includes pre-filter

The team initially assembled 20+ user requirements. We then consolidated requirements where possible and eliminated requirements identified as insignificant or extraneous (e.g. "The system should not be embarrassing to operate").

Each user requirement stems from a specific need that future users will have of the final system:

Easy to use: The system will ultimately be used by the residents of the Kyeamekrom community, and it is neither feasible nor logical to think that we could train all of them to use a complicated system. This system needs to be something anyone – man, woman, or child – can walk up to, 1) turn on, 2) operate through one simple repetitive motion, and 3) turn off. It should be obvious how it should be operated, and it should operate as expected. If usage gets much more complicated than that, users will likely become frustrated and may not continue to use the system.

Safe to use: The point of this system is to make life easier and safer for the residents of Kymeamekrom, by providing them with accessible clean water. Essentially, the goal is to make the users better off, and any system that injures its users leaves them much worse off. Furthermore, the pump is located at a swamp – if someone were severely injured there, who knows how much time might pass before help arrives.

Efficient: Due to the size of the community (9,000 members), for this system to have a significant impact, it needs to provide as much water as possible.

Durable: The system will be located at a swamp, exposed to the elements. If it cannot withstand the environment, it will soon fail and be of little use to the community.

Easy to maintain: Through discussions with a community representative, we discovered that maintenance requirements (e.g. removal of accumulated dirt in the piping and pump) beyond an hour every other week would be unsustainable. Therefore the system needs to 1) be able to last at least 2 weeks without maintenance, and 2) require a limited amount of time to maintain (< 1 hour).

Easy to repair: A community member with a limited amount of directions and training (provided primarily in a pictographic instruction manual) will have to repair the pump should it fail, therefore, the system needs to be simple enough to be easily understood, deconstructed and rebuilt. Furthermore, since the repairing community member cannot order replacement parts, a significant portion of the system needs to be constructed from locally available materials. Back-ups will be required for those materials that cannot be easily replaced.

Transportable: Because we will be constructing this pump in Ann Arbor, it will need to be transported to Ghana. To facilitate this, it needs to be designed to be as portable as possible, and as small/light as possible (to reduce the cost of checking it on an airplane flight).

Low cost: Because this project is being financially sponsored by Professor Sienko, and repair parts will likely need to be purchased by the community, the entire system needs to be as low cost as possible.

Includes pre-filter: In order to extend the life of the pump and the time between required cleanings, a pre-filter can be used, limiting the amount of dirt and debris that may enter from the swamp. Additionally, Paul Flickinger mentioned that effective pre-filters can extend the life of paper filters in the Clean Water for the World filtration system. It is for this reason that we've included the pre-filter in its own category, as opposed to including it under "Easy to maintain."

Any system we design must meet the above user requirements to effectively address the needs of the Kyeamekrom community (as well as those who are sponsoring this project). These requirements can be seen in the left hand column of Table [1] on page 14. However, in their current form, these user requirements are of limited help when it comes to creating an actual design, nor can they be used to evaluate potential designs. Therefore, we must translate them into engineering specifications with numerical targets

4.2 Engineering Specifications

Through discussion with our sponsors, Dan Johnson (the ME 450 Graduate Student Instructor) and Domitilla Debpuur, we indentified the engineering specifications that correspond to each of the above user requirements. For each engineering specification, we determined a specific, logical numerical target based on input from our mentors as well as through our literature review. Initially, we will design our system to meet these targets, and ultimately we will evaluate our prototype/final design against them. The complete table of user requirements, engineering specifications, and specific numerical targets can be seen in Table [1] 14.

Table 1: Customer requirements and engineering specifications

Customer Requirements	Engineering Specifications	Targets
Easy to use	Number of users at a time Number of simultaneous actions Number of total actions required Co-located at water source Force required for operation	1 user/ time 1 action/time ≤ 4 actions total ≤ 20 feet ≤30 lbs of force
Safe to use	Angle pump can withstand without tipping Force pump can withstand without failing	30 degrees ≥ 200 lbs
Efficient	Does not underutilize filter Pressure required to draw in water Pressure leaving pump Pressure relief valve Max pump can be above water level	≥ 5 gallons/minute < P_{amb}-15 kPa 10 ft. of head Relieves pressures > 10 ft. of head 5 feet
Durable	Environment proof materials Lifetime	Weather and wild-life resistant ≥ 2 years
Easy to maintain	Number of components Number of steps to clean pump Connects to filter	< 20 < 5 0.515 inch diameter hose
Easy to repair	Pictographic explanations % of locally available materials Provide backup kit	Located on pump + Manual 100 % Back up of least durable materials
Transportable	Packed volume (L+W+H) Dry weight	< 45 inches < 50 lbs
Low cost	Comparable to similar products	< $ 50
Includes pre-filter	Keeps out large particles Depth of intake water required for operation	20 mm (40 mesh) > 4 inches

Easy to Use: Five specifications were identified for this user requirement: 1) Number of users at a time, 2) Number of simultaneous actions, 3) Number of total actions required, 4) Co-located at the water source, and 5) Max force required during operation.

1. *Number of users at a time:* From our discussion with Domitilla, we learned that a number of people will make their trip to the swamp solo, consequently we will ensure that our design can be operated by 1 user to create a flow rate (5 gal/min) that will utilize 100% of the Clean Water for the World filter capacity.
2. *Number of simultaneous actions:* Because we hope to ensure this system is as simple to operate as possible, we will design the system such that no more than 1 action is required at any given moment (1 action at a time).
3. *Number of total actions required:* In order to ensure that operating the system is as simple as possible for the user, from start to finish they will only be required to perform a total of 4 actions. These four actions are 1) placing the input piping in the swamp (if it isn't already), 2)

turning on the Clean Water for the World filter, 3) operating the pump, and 4) turning off the clean water for the world filter.

4. *Co-location at the water source:* In order to ensure that people do not have to carry dirty water to the system, the system will be located next to the local swamp. Additionally, from the pictures of the swamp that we have, there is clearly a small drop-off to the swamp, from the surrounding terrain, a drop of up to 5 ft over a lateral distance of as much as 15 ft. To ensure the pump is as close to the swamp as possible while still on level ground, we will plan to locate it no more than 20 ft from the edge of the swamp.
5. *Max force required during operation:* Because the most common operators of this pump system will be women and children, the maximum force required to operate the pump needs to be reasonably low, which we estimate to be approximately 30 lbs. This was determined from the weight of 3 gallons of water (~25 lbs for US gallons and 30 lbs for Imperial gallons), which is the amount of water the Kyeamekrom residents typically carry to and from their normal water sources every day (as verified during our conversation with Domitilla). Since they handle this much weight so frequently, we feel it is reasonable to expect that they would be capable and willing to provide this much force to operate the pump.

Safe to Use: Two specifications were identified for this user requirement: 1) Max angle of tilt without tipping, and 2) Force pump can withstand in any direction without failing.

1. *Max angle of tilt without tipping:*
2. Force pump can withstand in any direction without failing:

Efficient: Five specifications were identified for this user requirement: 1) Does not underutilize filter, 2) Pressure required to draw in water, 3) Pressure leaving pump, 4) Pressure relief valve, 5) Max height pump can be above water level.

1. *Does not underutilize filter:* It is estimated that less than 1000 people use the swamp daily as their primary water source. If each of them requires approximately 1 gallon of purified drinking water per day our system needs to be able to produce 1,000 gallons per day. The filtration system can provide a maximum flow rate of 5 gal/min, or 300 gal/hr. Assuming 10 hours of sunlight for the solar panels which will power the filter that is 3,000 gallons of water per day, which is more than the expected demand. Nevertheless, in order to create an efficient system that provides the user with clean water as quickly as possible it is important that we don't underutilize the filter. This means that our pump will need to produce an output flow rate of 5 gal/min.
2. *Pressure required to draw in water:* In order for the system to draw water from the swamp, it must be able to create suction. At the very least, the pump will have to create a pressure less than the ambient minus 5 ft of head (approximately 15 kPa).
3. *Pressure leaving pump:* To achieve the maximum flow rate through the filter at least 10 ft of head is required (from discussions with Paul Flickinger), which equates to 30 kPa of pressure over the ambient.

4. *Pressure relief valve:* To protect the system from a catastrophic failure resulting from a pressure buildup above the necessary pressure, a pressure relief valve will be used that relieves any pressure over
5. *Max height pump can be above water level:* To maximize the efficiency of the pump, it needs to be located as close to water level as possible; however, as has been previously discussed, the swamp is located an estimated 5 ft (from available photos) below the surrounding terrain. Therefore, the pump will have to be located at least 5 ft above the swamp water level, but ideally no further.

Durable: Two specifications were identified for this user requirement: 1) Environment proof materials, and 2) Lifetime.

1. *Environment proof materials:* In order to ensure the pump can withstand the moisture, dirt, insects, etc…, of the swamp, it will need to be constructed of materials that are both weather and wild-life resistant. This will extend the life-time of the system and allow it to operate effectively for its entire lifetime.
2. *Lifetime:* The Clean Water for the World filtration system is provided with the materials (e.g. replacement filters) necessary to pump water for 2 years. That includes a UV bulb that costs $75, in addition to a number of paper filters. If our pump costs less than $50, we believe it is reasonable to replace it every 2 years as well. Furthermore, as long as it lasts two years, its replacement could be shipped with the additional filtration materials (UV bulb, paper filters…), which could potential reduce total shipping costs.

Easy to Maintain: Three specifications were identified for this user requirement: 1) Number of components, 2) Number of steps to clean pump, 3) Connects to filter.

1. *Number of components:* In order to ensure the system is simple enough to deconstruct if necessary, we'll limit the number of total components to less than or equal to 20 main parts (this excludes fasteners). This is based off of the ~20 unique major parts in the BLUElap treadle design. The number of parts in the EMAS pump has 23 major parts.
2. *Number of steps to clean pump:* In order to ensure the pump can be easily clean, we'll limit the total number of steps required to clean it to 5. 1) disassemble main components (e.g. disconnect input hose), 2) remove large debris, 3) rinse to remove dirt and silt, 4) reassemble, and 5) test.
3. *Connects to filter:* In order to interface with the filter, the piping from the pump must securely connect to the filter's 0.515 inch diameter inlet.

Easy to Repair: Three specifications were identified for this user requirement: 1) Pictographic explanations, 2) Percent of locally available materials, 3) Provided backup kit.

1. *Pictographic explanations:* In order to ensure that our instructions are as easy to read and clear as possible, they must be pictographic, instead of written. Furthermore, to ensure they are readily available, the instructions for how to repair (and maintain) the system must be detailed in an instruction manual, but more importantly, they must also be viewable on the exterior of the pump.

2. Percent of locally available materials: Based on discussions with Dan Johnson, we estimate >10% to be a reasonable target for this specification.
3. Provided backup kit: Because not all of the materials will be attainable locally, replacements will be provided for those materials/parts not readily available, and also not particularly durable.

Transportable: Two specifications were identified for this user requirement: 1) Packed volume (L+W+H), and 2) Dry weight.

1. *Packed volume (L+W+H):* The pump will need to be transported to Ghana via airplane and will need to be capable of being checked as a piece of luggage. In order to avoid incurring additional charges and meet airline luggage restrictions for most airlines the entire pump assembly must be contained within 62 linear inches. This means that the length+width+height of the container must be less than or equal to 62 inches.
2. *Dry weight:* In order to be checked on a plane as a single luggage item (without incurring additional fees), the system must have a dry weight of less than 50 lbs.

Low Cost: One specification was identified for this user requirement: 1) Comparable price to similar products.

1. *Comparable price to similar products:* Any proposed design must not be more expensive than similar designs already available; otherwise, we should just use the available design. Comparable designs were found to range in price from approximately $20 (for lower volume / shorter lifetime pumps) to over $100 for more solid designs (i.e. more sturdy and consequently longer lasting materials).

Includes Pre-Filter: Two specifications were identified for this user requirement: 1) Keeps out large particles, and 2) Depth of intake water required for operation.

1. *Keeps out large particles:* In order to prolong the time between maintenance and repair, as well as extend the lifetime of the pump, the pre-filter must screen large particles. Ideally the mesh would screen as small of particles as possible, but our initial requirement is set at 20 mm – sufficient to catch most small pebbles but not necessarily fine dirt and silt.
2. *Depth of intake water required for operation:* In order to minimize the amount of air pulled into the system with intake water (which negatively impacts performance), we've decided to require a minimum intake depth of at least 4 inches (most garden hoses are ½ inch dia., this requirement would keep that hose below the water a distance of 8 times its width).

4.3 Benchmarking Relevant Components

This section analyzes the advantages and disadvantages of different types of pumps. These findings allow us to compare and contrast possible system components and help to quantify various components that are being used today.

4.3.1 Pumps

As discussed in the background section on pumps, there are a handful of solutions currently receiving widespread use to pump water in rural communities in developing nations. Each solution brings with it various advantages and disadvantages. These are highlighted in the table below. Since pumps are scalable, the volume flow rates have been excluded and the cost of the pumps relative to each other has been included.

Table 2: Benchmarking Pumps

Pump Type	Cost	Cost	Pros	Cons
Rower	$10	Very Low	Extremely simple to build and use, cheap	No mechanical advantage for the user
Lever	$15	Low	Simple to build and use, mechanical advantage, cheap	Requires one-way valves
Flywheel	$15	Low	Easy to use, cheap, can be made with locally available materials	Complicated plunger driving mechanism (whether plunger or rope based)
Bicycle	$50	Moderate	Significant mechanical advantage	Complicated to build
Stair-stepper	Unknown	Unknown	Easy to use	Complicated system
Wind	$100	High	Free input power, no user work necessary	Requires wind
PlayPump (Carousel)	$100	High	"Free" input power	Requires kids to use it Complicated and labor intensive to install

As you may see from the chart, there are a few obvious trade-offs: the lower the cost, the more work required by the user. As cost increases, so does the mechanical advantage provided to the user to the point of "free" power at the high. Additionally, the lower cost options are also the simplest and easiest to install, while installations requirements for the higher cost options are more elaborate and labor intensive. For example, the PlayPump pumping components must be buried under the carousel, requiring significant excavation during installation [8].

4.3.1.1 *Manual Bilge Pumps*

As discussed in the previous section on manual bilge pumps, there are two main types: Diaphragm and Piston. Table [3] below compares some of the most important features of both types of pumps.

Table 3: Benchmarking Bilge Pumps

Pump Type	Cost	Flow Rate	Ease of Use	Mountable
Diaphragm	$30-150	10-15 gal/min	Easiest	Yes
Piston	$15-50	3-5 gal/min	Easy	No

As you can see from the chart, the diaphragm pump outperforms the piston pump in each category except cost. Both pumps are relatively easy to use, but the diaphragm pump has a much higher flow rate and can be mounted to a surface. The piston pump is a more cost effective alternative, but has a lower flow rate which may not be sufficient for the given application. Overall, there is an obvious tradeoff between the two pumps: high performance and usability for a higher cost, or lower performance and usability for a lower cost.

5 FUNCTIONAL DECOMPOSITION

This section explains our functional decomposition which helped us generate concepts and create a final design.

Before proceeding with the concept generation and design selection, our team first performed a functional decomposition to allow us to better focus our efforts. The goals of the functional decomposition were two-fold: 1) to break our complete system down into mutually exclusive subsystems, such that overlap between components was minimized, and 2) ensure that the subsystems are collectively exhaustive, once components are chosen for each subsystem, the compilation of those components should yield a complete system design.

Our functional decomposition (Figure 11) was created in a team discussion, during which we reviewed the user requirements and engineering specifications, then identified the components necessitated by those requirements and specifications. The decomposition includes those necessary components (dark blue boxes), the flow of materials through the system (wide arrows), and the flow of energy through the system (skinny arrows):

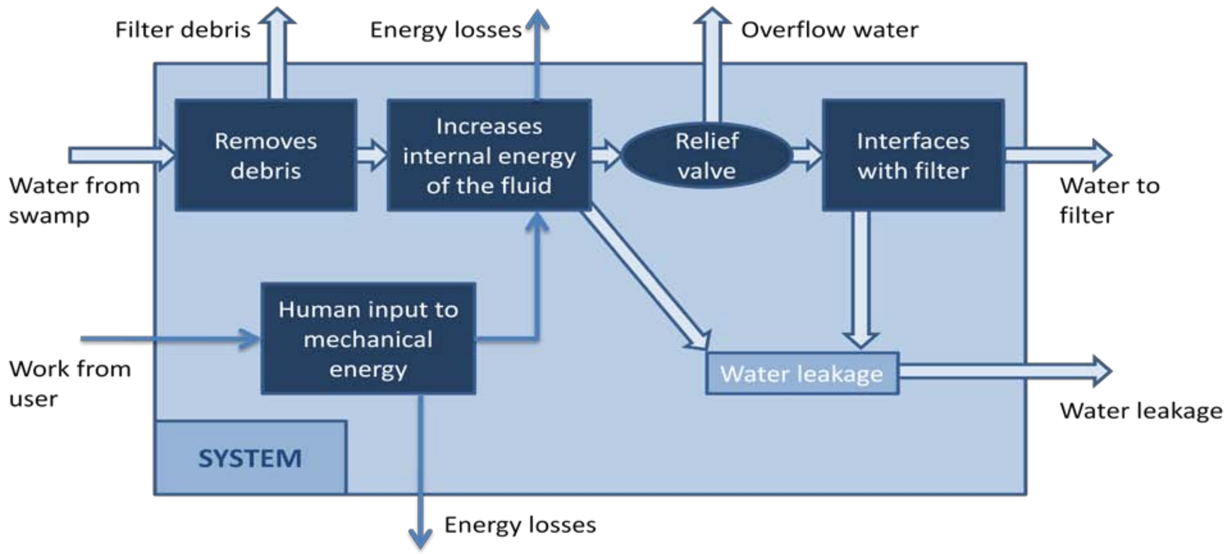


Figure 11: Functional Decomposition

The notable take-away from this decomposition is that there are a total of six subsystems, as can be seen in the adjust chart below. The usefulness of this decomposition lies in the fact that we can research, brainstorm, and select each subsystem (mostly) independent of the other subsystems. Those six subsystems are: 1) Pump, 2) User Interface, 3) Relief Valve, 4) Pre-Filter, 5) Tubing to Pump, 6) Piping to Filter.

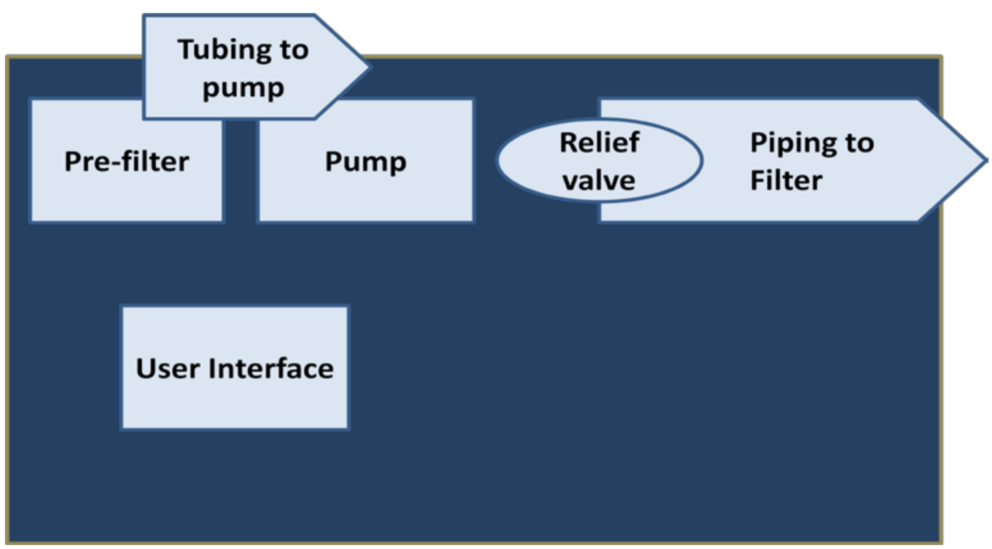


Figure 12: Simplified Functional Decomposition

5.1 Pump: this subsystem is required to provide energy to the water such that the water can be moved from the swamp to the filter, and reach the filter with sufficient pressure to pass through the filter at 5 gal/min. The pump receives energy from the user interface and uses that energy to pull water from the swamp (through the pre-filter and tubing to the pump), and push water to the filter (through the relief valve and piping to the filter).

5.2 User Interface: this subsystem is required to capture input energy from the user and convert that energy into a form that could be used to power the pump. For example, if the user input is spinning a wheel (rotational energy), which is converted through gears to move a piston-cylinder pump, then the user interface would include the input wheel to be spun by the user, and the linkage that translates that energy into straight-line translational motion, used to move the piston. However, this subsystem ends at that point, and does not include the piston or anything thereafter.

5.3 Relief Valve: this subsystem serves entirely as a safety check on the total system. It consists of some sort of relief in the piping to the filter, such that the pressure in the water exiting the pump and entering the filter never exceeds the determined safe operating range. This will minimize the likelihood of the pump failing catastrophically and potentially injuring the user and/or nearby observers.

5.4 Pre-Filter: this subsystem serves to meet the specific user requirements of a pre-filter. The subsystem will need to screen out large particles to prolong the life of the pump, as well as the duration between required maintenance (such as cleaning) and repair (replacement of parts). The pre-filter will also need to be cleaned from time to time to remove debris, and consequently this must be taken into account in the design and material selection.

5.5 Tubing to Pump: this simple subsystem will link the swamp to the pump. A pre-filter will be located on the end of the tubing that is in the swamp.

5.6 Piping to Filter: this simple subsystem will link the pump to the Clean Water for the World filtration system, interfacing with the 0.515 inch input nozzle on the filter.

6 CONCEPT GENERATION AND ALPHA DESIGN SELECTION

With our user requirements, engineering specifications, specification targets, and functional decomposition clearly defined, we were able to move on to the next phase of our design process: concept generation and design selection. Generally speaking, our process of concept generation and design selection consisted of the following four step process, where individual work alternates with group discussion:

1. ***Individual work: Initial research and brainstorming.*** The findings of our initial research are discussed in detail in prior sections of this report. Our research process included extensive literature reviews on what is currently out there, numerous conversations with sponsors and experts, as well as a discussion with a representative of the Kyaemekrom community. The outcome of this research included the customer requirements and engineering specifications discussed above. Additionally, the research brought our team up to speed on how pumps work in general and how they've been used in the past to address similar problems. Building on what

we learned, in our initial brainstorming we translated that knowledge into design ideas specific to our system and our engineering requirements.

2. ***Group discussion: Presentation of ideas and brainstorming.*** Following our initial, individual brainstorming, we had group meetings during which we presented and explained our designs (along with how they worked, their advantages, and disadvantages). The majority of these concepts can be seen in Appendix D. This led to additional team brainstorming, which included a discussion of what problems we are specifically solving for with each design, and how each design attempts to address the relevant user requirements and engineering specifications.

3. ***Individual work: Additional research and brainstorming.*** Following the first group discussion, we allowed for a few days for people to digest what had been presented in the meeting, possibly incorporate other team member's ideas into their designs, and perform additional research to better understand a specific topic, if necessary.

4. ***Group discussion: Group design consolidation and selection.*** A final group meeting was set aside for design consolidation and selection. At this meeting, we first performed a sanity check on each proposal: "Can we do this in 3 months?" If the answer was, "No way," then we threw it out. The remaining designs were then inspected to determine if they could be improved by incorporating superior features from another design. To select top designs, evaluation criteria were identified and each design was evaluated on its potential ability to meet those criteria.

This process was applied to the six identified subsystems (Pump, User Interface, Relief Valve, Pre-Filter, Piping to Pump, and Piping to Filter). Because those subsystems were chosen to be as mutually exclusive and collectively exhaustive as possible with respect to the total design, as well as modular (i.e. if you change one, it does not usually necessitate a major change in the others), the compilation of the selected designs for each of the six subsystems yields a complete design concept.

Throughout the process, we kept in mind the engineering specifications and their targets, using them as points of discussion during group brainstorming, selection and consolidation. In the end, each component was chosen based on its ability to meet the determined engineering specifications, evaluated relative to alternative brainstormed ideas.

Our concept generation was a multi-step, reiterative process consisting of: initial research, brainstorming (both individually and as a group), and design selection. The outcome of our concept generation process is the lever pump discussed in the alpha design section that follows.

6.1 Pump

The first subsystem we tackled was the pump. This was due to the fact that the pump is unique among the other subsystems in that changing the pump could significantly impact selection of the other subsystems. Ultimately, we chose a reciprocating positive displacement pump (i.e. a piston-cylinder paired with two one-way valves). This decision was made taking a combination of the following into account: feasibility, effectiveness, and cost ("can we do it, how well will it work, and how much will it cost?").

Our selected system will require a piston, cylinder, 2 one-way valves which will need to connect with the tubing from the swamp and the piping to the filter. Additionally, a connection between the piston and the user interface will be required. The specifics of these components will be finalized and analyzed by Design Review 3, and are discussed below, in the Alpha Design section below.

Other designs given significant consideration were gear pumps, centrifugal pumps, and rope pumps. Concerning feasibility, piston pumps are a clear winner over all others, they are just easier to make, and require less complicated parts. With respect to effectiveness, according to the Pump Handbook [13], different types of pumps are best suited to different applications (typically based on the speed of the pump), and at low speeds, the best type of pump to use is the piston-cylinder. With respect to cost, the piston-cylinder is also the cheapest. Gear pumps and centrifugal pumps require precisely machined interior parts (whether it is the gears or the impeller). Additionally, the piston-cylinder can be as low at 1/10 of the cost of a rope pump.

Furthermore, we believe our conclusion is supported by what is in use today. Bicycle pumps, treadle (stair-stepper) pumps, rower pumps and lever pumps – they all actuate a piston to move water. What change within each design is not the type of pump, but the user interface used to capture input mechanical energy and convert it to the linear, reciprocating motion require to actuate a piston in a cylinder. Even the famous Gaviotas sleeve pump is nothing more than a piston-cylinder pump, the only difference is that the user moves the cylinder with each stroke, instead of the "piston," (or at least what is acting as the piston) which remains stationary.

We believe this proven track record of cheap, affordable, and easy to build and maintain is one of the most beneficial aspects of the piston-cylinder, because in this situation, the most important

6.2 User Interface

With our pump type settled on a piston-cylinder, the next big decision was, "How to actuate the piston?" This is the subsystem we spent the most time on – from research, to brainstorming, to concept gen, to concept selection – we invested more time on each of these steps than we did on the entire process for any of the other subsystems.

Possible solutions (i.e. pump designs) were created and evaluated based on the user requirements. In fact, we went so far as to use a Pugh chart (see below) to aid in the selection process. To revisit the outline of our concept generation and design selection: we initially brainstormed individually, this was followed by a group discussion to share all our ideas. We generated over 20 unique options pulling in ideas we'd discovered online during research and benchmarking, in addition to new creative designs. After sharing ideas we then took additional individual time to digest what was shared, combine and refine our initial ideas, and flesh out any additional concepts. This was followed again by group discussion, where we further refined and combined our ideas down to a set of approximately 10 different designs, eliminating designs that were obviously infeasible given our combination of limited resources and time. A number of the initial sketches from this stage of our design generation can be seen in Appendix D.

To help facilitate brainstorming, Professor Sienko provided each design team in her section time (four in total) with class time (~30 minutes) during which they could brainstorm with the entire class on an issue pertinent to their project. To ensure (to the best of our abilities) that we were not missing feasible and creative ways to actuate a piston, we used our brainstorming time with our section to try to identify additional ways to actuate a piston. This yielded a handful of additional creative designs that we had not yet considered, such as a utilizing the energy from a child swinging on a playground swing. However, these designs were eliminated from serious consideration due to their infeasibility (e.g. we could not identify an effective and more importantly practical way to convert the energy in the motion of the swing into a form that could run a simple pump).

We then used a Pugh chart to identify and highlight our best options. For the Pugh chart, we used a piston hand pump as the datum and the relevant user requirements as the categories that we scored each design on. Because "Easy to use" is the most important design feature it was triple weighted in the Pugh chart. "Includes a pre-filter" was left off due to its irrelevance, while "Efficient" was also exclude because any of the proposed designs to be scaled to provide the necessary flow rate, the difference being that some would be able to meet that flow rate while requiring less user input. Thus "Efficient" was effectively rolled into the "Easy to use" category. An additional category ("Easy to fabricate") was included to allow us to assess the feasibility of each design.

To populate the Pugh chart, each group member rated each design in each category on a -3 to 3 integer scale. These scores were then totaled to yield the final score for each design in each category (with the "Easy to use" score being tripled). A positive score means that we believe that design is better able to meet that specific use requirement than a hand pump (the higher the better). While a lower score means that we believe that design is not as capable of meeting that user requirement as a hand pump (more negative numbers correlating to increasingly unfavorable opinions of the design within that category). Scores for each design were then totaled and compared. The results from this process can be seen in Figure 13 on page 25.

	DATUM Hand Pump	1 Bicycle	2 Merry-go-round	3 Stair-Stepper	4 Spring bouncer	**5 Hand lever**	6 See-saw	7 Hand crank	8 Spring seat	9 Hand-held
Easy to use	*0*	23	12	15	-3	**15**	-6	-3	-24	-36
Durable	*0*	-4	-4	-7	-3	**0**	-4	-2	-5	0
Safe to use	*0*	-7	-4	-3	-7	**0**	-4	-3	-1	2
Maintainable	*0*	-8	1	-6	-1	**0**	0	-3	-7	-2
Repairable	*0*	-5	-7	-6	-2	**0**	-1	-4	-5	-3
Low cost	*0*	-7	-7	-3	-3	**0**	-2	-3	-5	0
Transportable	*0*	-6	-8	-4	-2	**0**	-4	0	-6	4
Easy to fabricate	*0*	-6	-7	-5	-2	**0**	-3	-6	-7	-2
Number better:	***0***	**+21**	**+17**	**+12**	**+0**	**+15**	**+0**	**+0**	**+0**	**+6**
Number worse:	***0***	**-42**	**-37**	**-35**	**-23**	**+0**	**-23**	**-21**	**-60**	**-43**
Total	***0***	***-20***	***-24***	***-19***	***-23***	***15***	***-24***	***-24***	***-60***	***-37***

Figure 13 Pugh Chart

As you can see from the results from the Pugh chart above, the overall winner is the hand lever pump. Despite many of the designs having the advantage in the triple weighted "Easy to use" category (which accounts for 30% of the possible total score), designs such as the bicycle require several additional complicated components, which would make it much harder to maintain and repair, as well as increase cost. Since the hand lever is essentially a hand pump with one extra attachment used to give the user a mechanical advantage, the hand lever is easier to use but is not notably less maintainable or more costly than a hand pump. The stair-stepper and bicycle came in second and third respectively, as both designs are very easy to use but suffer in every other category.

6.3 Relief Valve

With the two previous subsystems selected, we next focused on the relief valve. As mentioned in previous sections, this valve is required to increase the safety and lifetime of the system. It accomplishes this by ensuring the internal system pressure stays within safe operating limits, thus minimizing the likelihood of catastrophic system failures.

Brainstormed ideas included simply purchasing a relief valve for the our required pressure limit, a 10-15 ft vertical pipe section exposed to the ambient at the top, or a elevated reservoir into which the pump would send water, and from which water would drain into the filter. In the second two options, the height of the exposed portion of the system would determine the max pressure for the system.

First and foremost, all proposed systems could be designed to provide relief at the required pressure. However, the elevated reservoir would require a large tank and this could not be easily transported to the region and would require some significant structural support. While this option would have the added benefit of potentially being used as a reservoir, both of the previous challenges disqualify the option due to its infeasibility. Furthermore, A valve can simply be bought for <$15, which is comparable to the cost of the length of PVC piping required to create the open vertical pipe option. Additionally, the purchased valve would require neither the construction of a support, nor a cover to ensure that debris does not enter system through the relief opening. Therefore, we have currently settled on purchasing a simple relief valve.

6.4 Pre-Filter

The final major subsystem to be selected was the pre-filter. As described in the above, the pre-filter effectively extends the lifetime of the system, as well as increasing the time between required maintenance and repair. It accomplishes this by screening large debris from the swamp water entering the pump, consequently minimizing wear and tear, specifically on the piston's seal with the surrounding cylinder, where small particles can produce wear results similar to taking sand-paper to the material – an effect identified through discussion with Professor Skerlos.

Main options were indentified and considered for this subsystem, some more off-the-wall than others. One example was to bury a large reservoir tank in the swamp, filled with sand, with a hole in the top that would allow swamp water to enter, and a hope in the bottom, from which sand-filtered water could be drawn by the pump. This design however, could obviously not fit in a carry-on bag.

A more, realistic option that we quickly settled on is using a screen that could be made from various materials that can attached to the end of the tubing, and possibly removed for cleaning. If cheap enough, they could simply be replaced at the end of their functional lifetime. Materials that were considered include: paper/wood pulp based materials, cloth, and wire mesh. Ultimately, we decided a wire mesh would prove to be the best option based on a combination of its durability and lifetime, as well as reasonable cost.

6.5 Tubing to Pump

Some sort of tubing will be required for the water to be pulled through by the pump, and from the swamp. Beyond that, the tubing will need to house the pre-filter on the swamp end and attach to the pump at the other. Brainstormed options include rigid or flexible tubing that could be either buried/submerged or lay on the open the ground and float (in the swamp). We decided that flexible tubing would be significantly more useful than rigid tubing, because it could be moved to draw water from the holes the Kyeamekrom residents dig in the dry season. Furthermore, the tubing will be exposed, and not buried, so that it will be more accessible for cleaning and replacement, as well as easily to move, if necessary. However, the disadvantage in leaving the tubing exposed is that it will be less protected from the elements, thus decreasing its lifetime.

6.6 Piping to Filter

The process for identifying and selecting options for this design closely paralleled the selection of the piping to carry water from the swamp to the pump. Additionally, the relief valve has to inserted in-line with the piping. As above, options include rigid or flexible tubing that could be either buried or lay on the open the ground. Ultimately, we decided the easiest and cheapest solution would be to use flexible tubing that would run above ground to the filter. This will make the overall system more flexible – it will be able to be moved around the Clean Water for the World filter, so long as the piping is long enough – and easier to maintain and repair – the piping could more easily be removed from the system to be cleaned or replaced. As mentioned about, the disadvantage in leaving the tubing exposed is that it will be less protected from the elements, thus decreasing its lifetime.

7 ALPHA DESIGN DESCRIPTION

Our alpha design consists of six main components: a pre-filter, an inlet hose, a pump, a user interface, a pressure relief valve, and piping to the filter. The water from the swamp will enter the inlet hose and through the pre-filter, then enter the pumping chamber where energy will be added to the water through human input, then pass through the piping which will include a relief valve to regulate pressure, and then enter the Clean Water for the World filtration system. Each of these six main components and their functions are described in more detail in the following sections and are shown in Figure 14 on page 27.

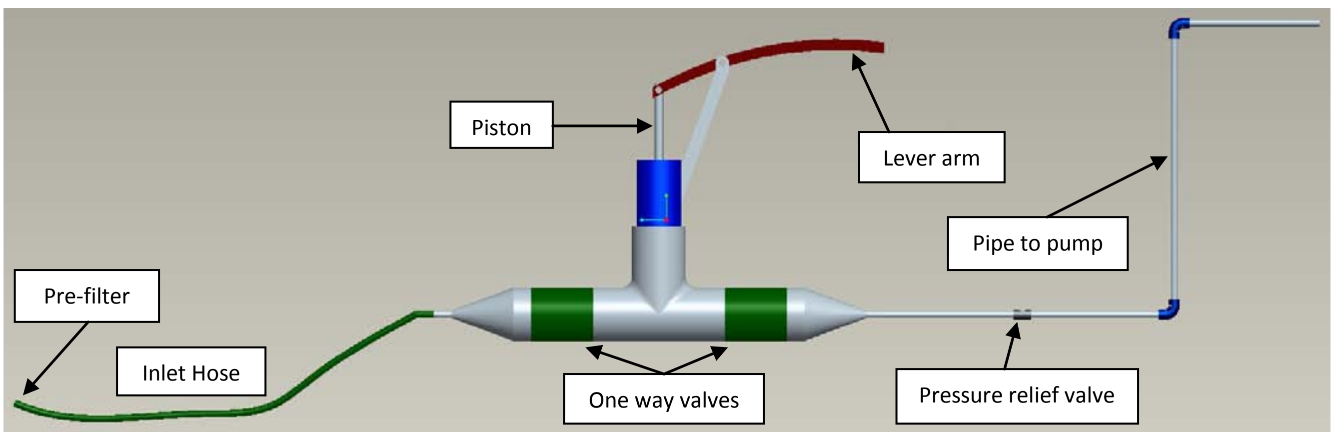


Figure 14: CAD model of alpha design

7.1 Pre-filter

The pre-filter will be a woven mesh screen located at the end of the inlet hose. The size of the opening in the mesh will be 1 micrometer, which is small enough to block silt and sand from entering the pump chamber. This will increase the life expectancy of our system and not require as much routine maintenance. A CAD model of the pre-filter can be seen in Figure 15 on page 28.

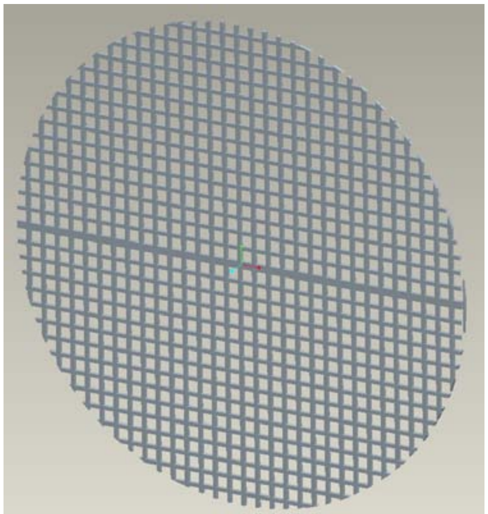


Figure 15: CAD model of pre-filter

7.2 Inlet Hose

A standard garden hose will be used to connect the pump to the water source, and can be seen in Figure 16 on page 28. This hose will be 50 feet long and made of a flexible material to allow the user to reposition the intake if the available swamp water moves, or place the intake in a hand dug hole during the dry season. Also, typical garden hoses are design to withstand the elements. A cheap ($9) PVC hose from a home improvement store has a warranty of two years, which meets the minimum lifetime expectancy of the pump [1].

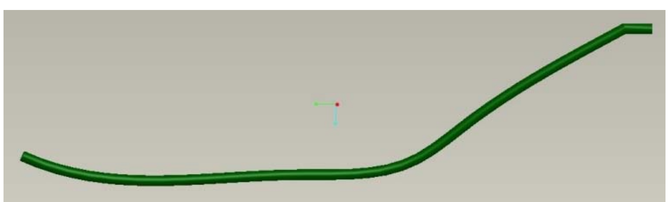


Figure 16: CAD model of inlet hose

7.3 Pump

The pump component will consist of a piston inside of a cylinder that will displace water in through the inlet one way valve on the upstroke, and then out through the outlet one way valve on the down stroke. The piston and cylinder sizes can easily be scaled to produce the required flow rate and pressure difference to sufficiently move the water to the pump. This pump can be seen in Figure 17 below.

7.4 User Interface

The user interface is a lever attached to the piston with a support that allows the lever to rotate about the joint. The motion of the lever will translate to motion of the piston and create pressure differences that will move the water through the system. The length of the lever gives the user a mechanical advantage are will require less input force from the user, and will be determined based on some simple calculations using the engineering specification target for maximum input force required. This user interface can be seen in Figure 17 below.

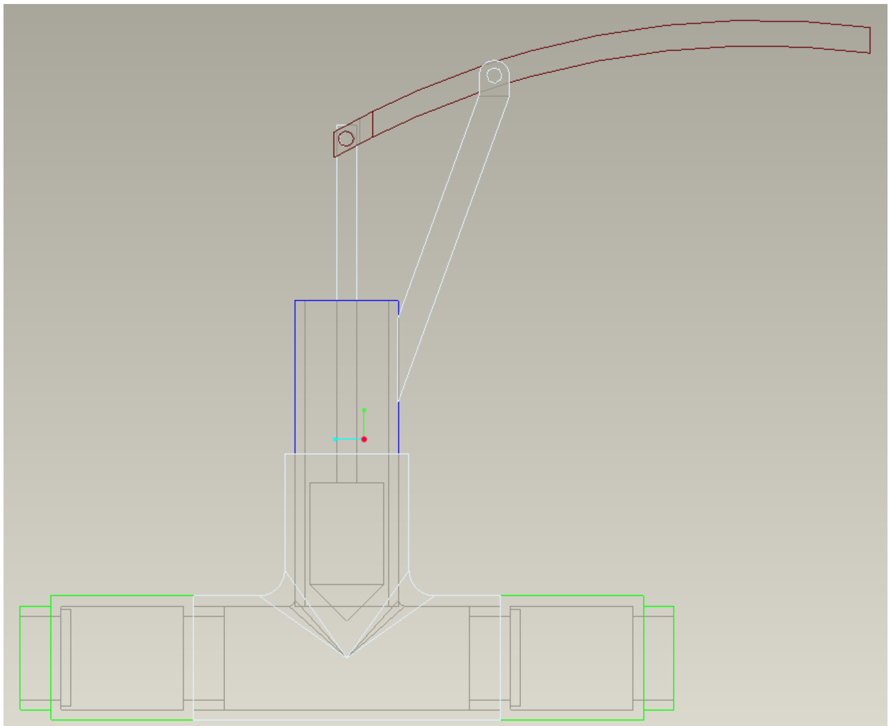


Figure 17: CAD model of pump and user interface

7.4 Pressure Relief Valve

Between the pump and the filter there will be a pressure relief valve as shown in Figure 17 on page 28. From discussions with our Sponsor Paul Flickinger, the filtration system can only handle pressures of up to approximately 50 psi. Therefore, the relief valve chosen will have a threshold pressure of 50 psi and will be located in the piping to the filtration system.

7.5 Piping to Filter

A PVC pipe will connect the pump output to the inlet of the filtration system. The inside diameter of the pipe will be 0.5 inches so that it can connect to the inlet nozzle of the filtration system without extra components. Included in the piping are two PVC corner fittings. These are required to change direction of the flow to the vertical direction then back to horizontal in order to connect to the inlet nozzle of the filtration system. The piping along with the corner fittings can be seen in Figure 18 below.

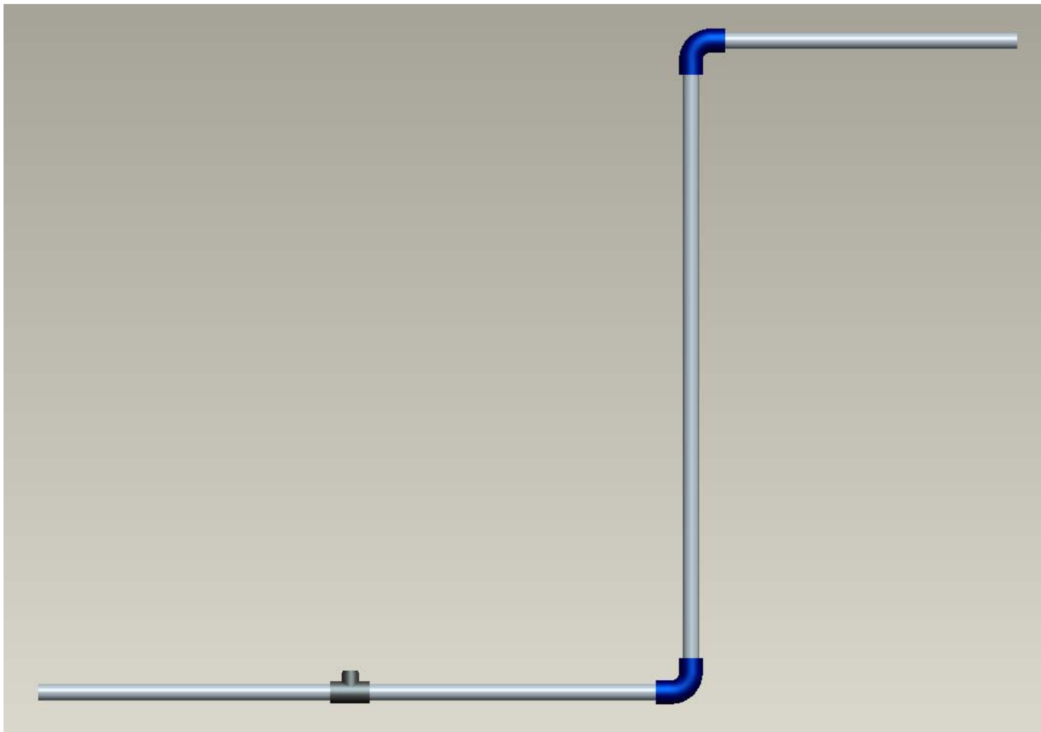


Figure 18: CAD model of piping from pump to filter

7.6 Evaluation against Engineering Specification Targets

Further initial analysis of our selected design can be done by evaluating its ability to meet the engineering specification targets for each user requirement (see table of user requirements above for targeted values if necessary):

1. ***Easy to use:*** The proposed design will only require one user at a time, performing one action at a time with less than four actions total (1: adjust input hose if necessary, 2: turn on filter, 3: operate pump, 4: turn off filter)). It will be located within 20 ft of the swamp, and we believe it can be constructed to require less than 30 lbs of input force to operate.
2. ***Safe to use:*** Mounting the pump on a flat base plate of scrap material available in Ghana as a preventative measure against tipping; furthermore, as we finalize the subsystems we will use statics to ensure our pump can withstand the necessary forces, and will test the prototype and reinforce it where necessary.
3. ***Efficient:*** The pump can be scaled to produce the necessary flow rate, and input and output pressure. Since the required values are so low in comparison to similar low cost pump designs which also require a very limited amount of force (the EMAS pump can pull from a depth of up to 20 meters and push up to a height of 20 meters), we believe we will be able to produce those targeted values without requiring unmanageable input forces. Furthermore, the pressure relief valve will maintain a safe water pressure inside the system.
4. ***Durable:*** We expect that our design will only require basic materials such as PVC and steel, which can typically withstand the elements for our expected lifetime of two years. If necessary,

weatherproofing coatings could potentially be used to extend the lifetime of those components most susceptible to the elements (e.g. PVC's increasing brittleness following prolonged exposure to sunlight).

5. ***Easy to maintain:*** The proposed system requires less than 20 unique parts, and the connections for the subsystems will be easily attachable and detachable. The piping to the filter will have a final diameter of 0.515 to interface with the filter.
6. ***Easy to repair:*** We will create pictographic instructions for maintenance and repair and will mount those instructions on the pump. We have not selected final materials but the design requires mainly basic construction materials. We will attempt to follow up with Domitilla to determine what is available, but believe we will be able to meet the requirement of >10% locally available materials. We plan to provide a backup kit of those materials not easily available and most likely to fail.
7. ***Transportable:*** We are currently unsure of the final size of our pump – we still need to calculate the final diameter and height of the pump (this will also depend on the materials we plan to use). However, we are optimistic that we can meet the dimension and weight requirements. Additionally, the selection of this design provides us with the best possible chance at meeting these requirements as all the other designs required a piston-cylinder pump (just like the one we have chosen), and a complicated, and likely bulky user interface.
8. ***Low-cost:*** We do not have a refined estimate of the cost, because we have not chosen final materials. However, if you estimate the mesh to be $5, the valves $5 a piece, and relief valve at $10, that leaves an additional $25 dollars to purchase the remaining construction materials (which include basic inexpensive items, potentially PVC tubing and hose)
9. ***Includes pre-filter:*** The system will include a mesh pre-filter that will, at a bare minimum, remove particles that are at least 20 mm diameter.

8 PARAMETER ANALYSIS

The shape of our system was based on our benchmarking of other types of surface water pumps such as bilge pumps. The materials we selected were chosen based on their inexpensive costs and ability to be purchased in rural regions of Ghana. We were able to confirm that the materials were purchasable in these regions through contact with Dr. Kofi Gyan as well as several Ghanaian medical students.

Once our alpha design was determined we conducted a parameter analysis on the components of the system that we believed most susceptible to failure. This helped us revise our alpha design and converge on final design parameters. All calculations performed for the analysis can be seen in Appendix E. We did not perform any calculations for the PVC piping, the vinyl hosing, the PVC glued connections, or the hose clamped connections. All of these things were deemed very low risk for failure based on their material and mechanical properties provided by the manufacturer.

In addition, we did not perform any calculations for the rubber seal or pre-filter mesh despite the fact that they do pose some concerns. The rubber seal will be scraped repeatedly through the inside of the

PVC piston chamber with high friction. We are unable to model the wear on the rubber seal theoretically and therefore plan to test its durability purely through experimentation. If given more time for experimentation, we could perform a lifetime test on the seal by creating a test rig which would move the piston up and down the piston chamber. We could then check the performance of the seal after a number of iterations equivalent to several weeks of use, and determine the seal's lifetime. The pre-filter mesh will be in constant contact with water as well as rocks, sand, and various other forms of debris commonly found in swamps. Like the piston seal, we are unable to perform a calculation to model the wear on the wire mesh and consequently intend to conduct further investigation through experimentation. Also, given more time we could set up a similar lifetime test to determine the lifetime of the mesh.

The analysis performed, although thorough, may not be a very accurate description of the actual performance of our pump. We were forced to model elements such as the loss coefficient through the one way valve based on manufacturers specifications for a globe valve due to the fact that our valves will be hand-made. In addition, since the pump is going to be completely manufactured by students with limited machining knowledge the final prototype will probably yield slightly different results than our analysis predicts. This is why experimental validation will be extremely important when verifying the performance of the pump.

8.1 Pump Dimensions

In order to determine the diameter of the piston chamber of the pump energy conservation equations must be applied to the entire system. Bernoulli's principle, shown in equation 1 describes the energy considerations for incompressible, inviscid, laminar flow between two locations. The principle states that for an inviscid flow, an increase in the velocity of the fluid occurs simultaneously with a decrease in pressure.

$$\frac{P_1}{\gamma} + \frac{{V_1}^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{{V_2}^2}{2g} + z_2 + h_L \qquad \text{[Eq. 1]}$$

P, V, and z are the pressure, velocity, and height differences respectively, at either end of the area being analyzed, γ is the specific weight of the fluid, g is the gravitational constant, and h_L is the head loss in the system. The head loss is the summation of the major and minor losses due to the dissipation of kinetic energy of the velocity. Major losses are calculated by using the friction factor for long, straight sections of pipe. The friction factors for the materials used in our pump are extremely close to zero because the inside texture of PVC and vinyl tubing are very smooth. Minor losses are a result of additional components such as valves, bends, or tees.

Although a pump cannot actually create continuous steady flow, this equation can be used to model the times when fluid is flowing through the system. In addition we made the assumption that the system is laminar flow because the relationship between fluid motion and shear stress is very complex for turbulent flow. However, the shear stress in turbulent flow is much larger than that of laminar flow because of the irregular random motion. A new branch of mathematical physics called chaos theory may eventually provide a deeper understanding of turbulence but until then laminar flow is a close approximation.

It has been experimentally determined that the filter provided by Clean Water for the World is able to produce an output flow rate of 4 gal/min when the input pressure is 10 feet of head. Based on these given quantities and equation 2 we were able to determine the coefficient, C for the filter. This coefficient accounts for all the non-idealities through the filter including friction losses, the input and output ratio of cross sectional areas, and the Reynolds number. The equation can then be used to calculate the pressure drop across the filter for the desired output flow rate of 5 gal/min

$$Q = C\sqrt{\frac{2(P_2 - P_1)}{\rho}} \qquad \text{[Eq. 2]}$$

Once the pressure into the filter has been determined equation 1 can be used to work backwards from the filter to the pump and calculate the pressure drop across the vinyl hose and one way valve in order to determine the pressure in the piston chamber. We calculated this pressure to be 13.874 psi.

The linear relationship between force, pressure, and area is shown in equation 3. The combination of the calculated pressure in the piston chamber and the desired user input force of 20 lbs from out engineering specifications allows us to calculate the diameter of the piston chamber to be 1.35 in. We chose 1.5 inch diameter PVC pipe because it was the closest to our desired area without requiring too much additional input force.

$$F = AP \qquad \text{[Eq. 3]}$$

8.2 One way valves

In order to determine whether the marble would function inside the one-way valve as it was intended to, we performed a force analysis in two directions. Using the volume, V and density, ρ of a standard glass marble along with the gravitational constant, g we found that the marble would have a force of 0.053 N acting on it in the downward direction. This relationship is shown in equation 4.

$$F = W = V\rho g \qquad \text{[Eq. 4]}$$

We then calculated the force that would be exerted sideways on the marble, [Eq. 3] pushing it into the PVC reducer and stopping flow through the one way valve to be 1.21 N. Due to the fact that the force acting sideways on the marble is 21 times larger than the force acting downwards the marble should perform as expected.

We are not taking into account how much the marble will spin inside the chamber because it is unable to be modeled analytically. Due to this shortcoming, our analysis is only an approximation and experimental validation of performance will be crucial.

8.3 Piston assembly

A force analysis was performed on the metal components in the piston to design against failure. The force acting on the parts was assumed to be ten times larger than the expected user input force.

In order to determine the strength of the piston rod, equation 5 was used. In this equation σ is the yield stress, F is ten times the force applied in the tensile direction, and A is the cross sectional area of the rod. The yield stress of Aluminum-6061 is 55 MPa which is 7.83 times larger than our calculated yield stress of 7.02 MPa. Therefore, the piston rod will not fail within normal operation of the pump.

$$\sigma = \frac{F}{A} \qquad \text{[Eq. 5]}$$

We also calculated the stress applied to the handle because should it fail the entire system would become unusable. Equation 6 was used after the moment, M and second moment of area, I had been calculated for the appropriate forces acting on the handle and the distance from the center to the edge most susceptible to fracture, y had been determined. The handle is also made out of Aluminum-6061 which has a yield stress 6.07 times higher than our calculated yield stress of 9.066 MPa. This ensures that failure will not occur when normal operational forces are applied to the piston handle.

$$\sigma = \frac{M * y}{I} \qquad \text{[Eq. 6]}$$

Equation 7 [29] was then used to determine the strength of the nuts holding both the handle and the seals onto the threaded rod.

$$\sigma = \frac{F}{\frac{\pi}{4}(D - \frac{0.9743}{n})} \qquad \text{[Eq. 7]}$$

In this equation σ is the yield stress, F is the force applied in the tensile direction, D is the inner diameter of the nut, and n is the number of threads. The nuts are made out of zinc-plated steel which has a yield stress of 1200 MPa. This is 15800 times larger than our calculated yield stress of 0.076 MPa which allows us to predict with certainty that the nuts on the piston assembly will not fail.

We did not take into account the added force created by the friction from the piston seal in our force calculations. We are unable to accurately determine this force theoretically which is why measuring the force experimentally will be important when evaluating the performance of the piston assembly.

9 FINAL DESIGN DESCRIPTION

Since our prototype will be brought to and installed in Ghana upon completion of the project, our final design will be nearly identical to our prototype. Therefore, throughout the final design description it can be assumed that each component will be identical unless stated otherwise.

The final pump design includes several subsystems: a pre-filter, tubing, two identical one way valves, two piston seals, and a handle.

Pre-filter: A wire mesh will be wrapped around the inlet opening on the end of the inlet hose that is submerged in the swamp. Since modeling the fluid dynamics of water flowing through small wire mesh would require advanced expertise outside of our current knowledge level, three different sizes of wire mesh will be purchased and tested. The three sizes of mesh we will be testing are 0.0055 inches, 0.020 inches, and 0.054 inches, where each dimension corresponds to the size of the opening in the mesh. To prevent the hose from coiling into the bottom of the water source, a 3 inch PVC cap will be attached to the end of the hose. Several holes will be drilled in the cap for water to enter through in the event the cap is oriented with the open surface blocked off from the water source. For each size of wire mesh, a 4 inch by 4 inch section is wrapped around the end of the hose and clamped down using a hose clamp. A simplified CAD model of the mesh placement before wrapping can be seen in Figure 19 below.

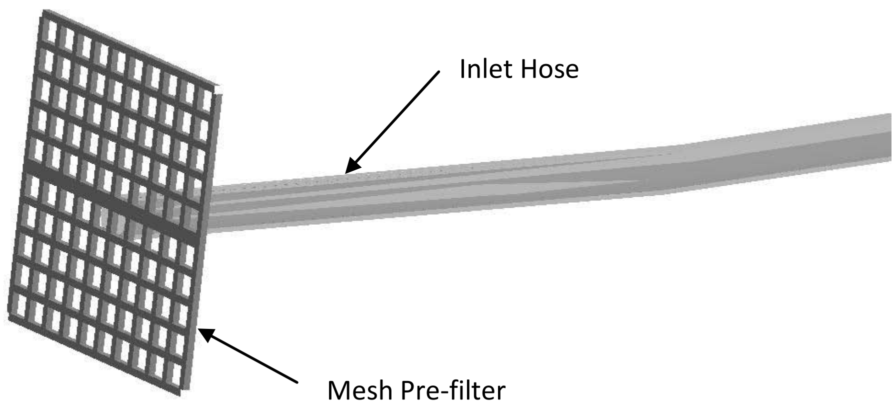


Figure 19 Pre-filter

One Way Valve: Each one way valve includes a 0.75 to 0.50 inch PVC reducer, a 0.625 inch diameter glass marble, a 0.75 inch PVC adapter, a 0.625 inch PVC retainer, a compression spring, and a 0.50 inch PVC adapter. All the PVC parts are attached by PVC glue. The marble is glued to one end of the spring, and the other end of the spring is glued to the 0.50 inch PVC adapter. As the water enters the inlet side, the water pressure pushes the marble to the right and compresses the spring allowing water to enter. When the flow reverses direction, the marble is forced to the left where the neck of the reducer stops the marble. This contact between the marble and the reducer prevents any water from flowing out through the inlet end. A side view with hidden lines is shown in Figure 20 below.

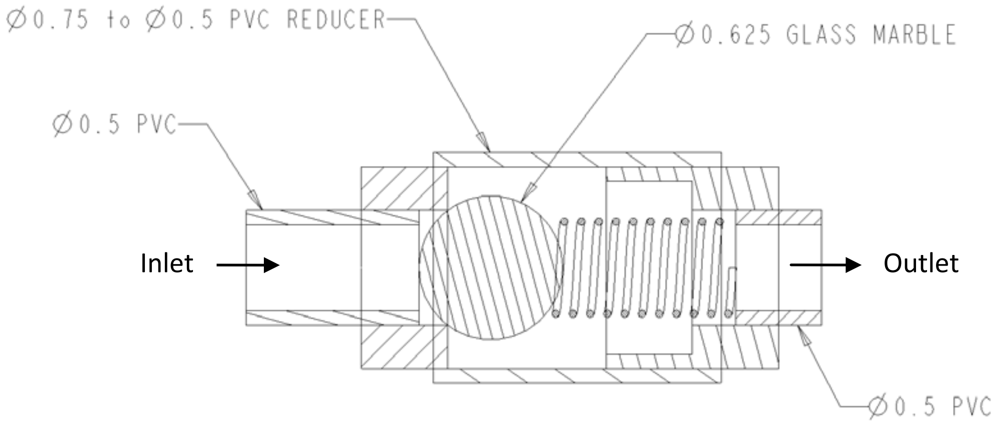


Figure 20 One Way Valve

Piston Seals: The piston seals are located on the end of the 0.50 inch aluminum piston rod with at least 3 inches of size 13 UNC threads. The material of the seals will be either leather or rubber since these materials are currently being used as seals in developing countries and are readily available in Ghana. Final material selection will happen after testing is completed for both materials based on the material performance. Since the piston 1.50 inch in diameter, the 0.125 inch thick seals will be a minimum 1.50 inch outer diameter and 0.50 inch inner diameter to allow the seal to be attached to the piston rod. Washers with 1.25 inch outer diameter and 0.50 inch inner diameter are positioned on both sides of the seal to help the seal keep its shape and stay in contact with the inner piston housing wall. To constrain the seal and washers along the rod, two 0.50 inch 13UNC nuts will screw onto the piston rod as shown in Figure 21 on page 36. The same configuration as was previously described will be duplicated and positioned just below the first seal. This second seal is used for a number of reasons: 1) it will provide a more robust seal, 2) used as a backup in the event that one seal fails, and 3) constrains the rod along the axis of the piston housing.

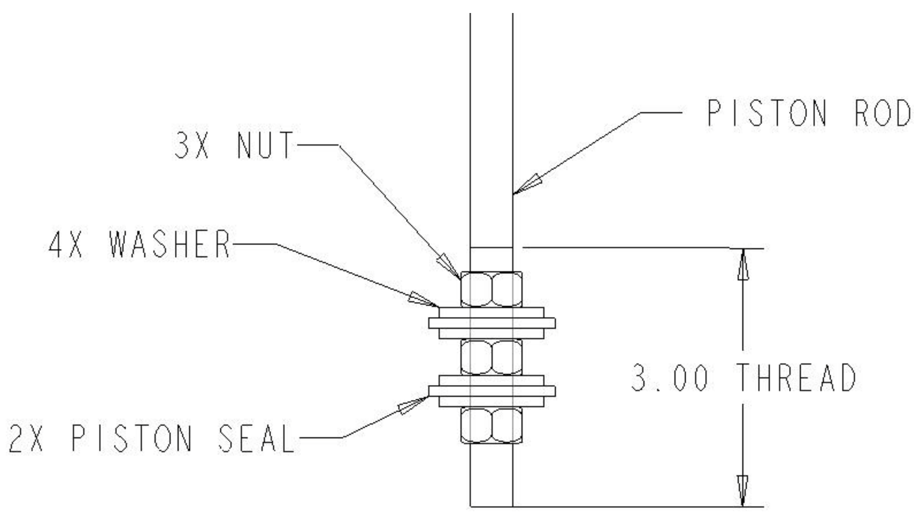


Figure 21 Piston Seal

Handle: The user interface will be a simple handle bar that the user will move up and down in the vertical direction to displace the piston. The handle is 14 inches in length and made out of a 0.75 inch aluminum pipe with a wall thickness of 0.065 inches. Aluminum was chosen because it is a material that is readily available in Ghana, and is relatively lightweight and is strong enough to not fail during pump use. The handle is located on the end of the piston rod with 2.00 inches of 13UNC threads. Nuts are positioned both above and below the handle to prevent displacement of the handle. Figure 22 below shows the positioning of the handle and nuts on the piston rod.

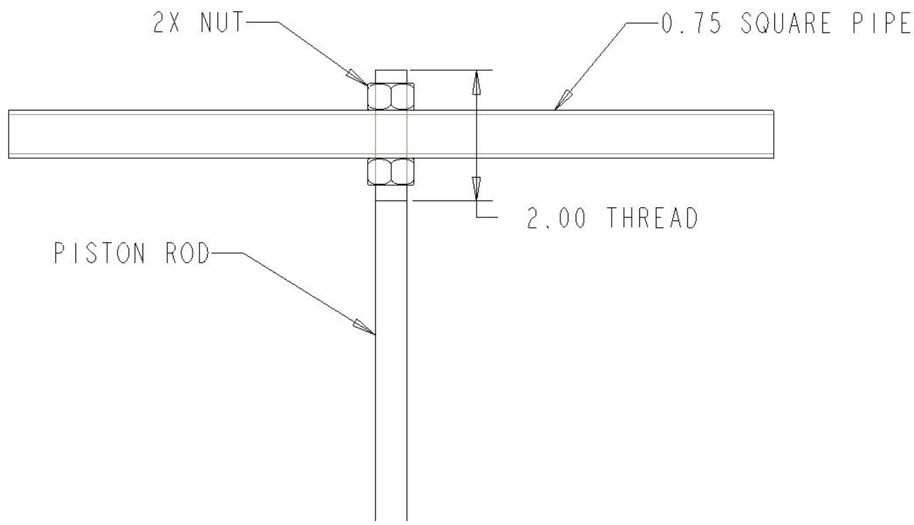


Figure 22 Handle Positioning

All of the aforementioned subsystems are connected using the following components: 1) 25 foot long, 0.5 inch inner diameter clear PVC hose, 2) three 1.5 inch diameter threaded clean out caps, 3) 1.5 inch three-way t-joint, 4) 2 foot long 1.5 inch diameter PVC pipe, 5) 10 foot long, 0.5 inch inner diameter clear PVC hose, and 6) 1.5 inch PVC pipe 2.5 inches in length. Each of these components can be seen in Figure 23 below.

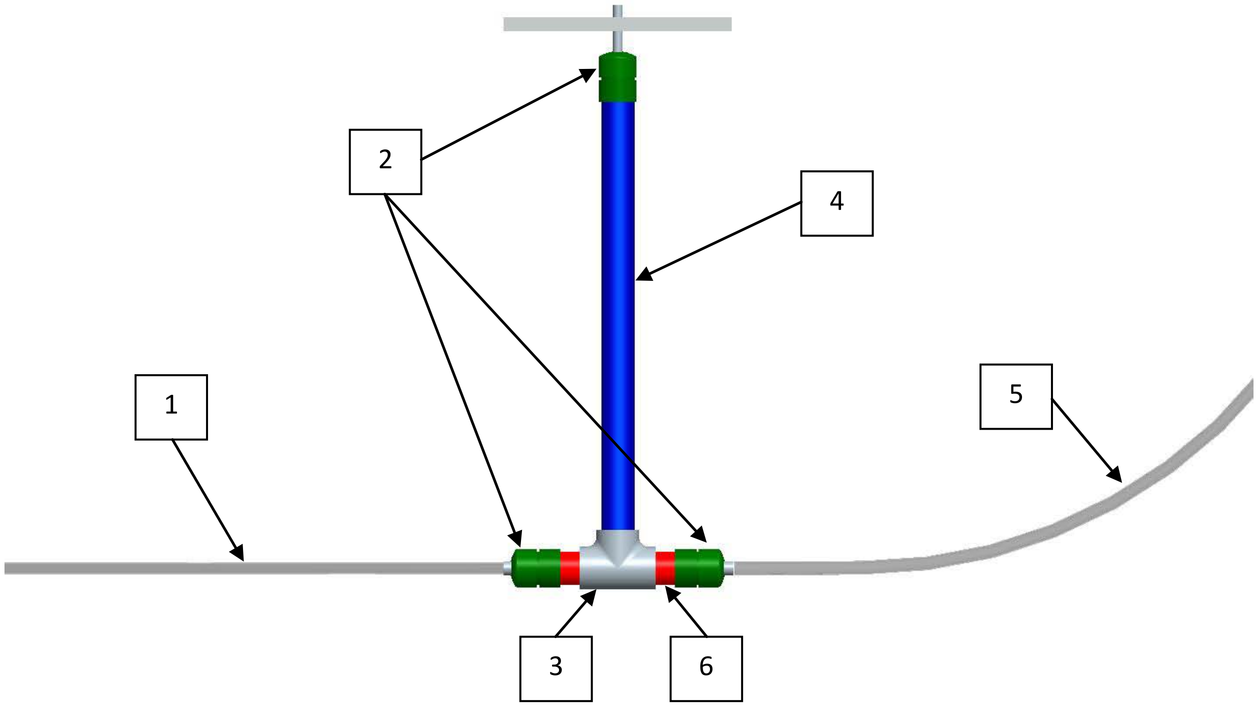


Figure 23: Total assembly

Inlet Hose: A 25 foot long, 0.5 inch inner diameter clear, flexible PVC is used as the inlet hose. The PVC hose was chosen because it is cheap and flexible. Additionally, clear hose was chosen so that during testing we can see how much dirty accumulates in the tubing. The pre-filter wire mesh is attached to one end with a hose clamp, and the other end is connected to the inlet one-way valve, also with a hose clamp.

Threaded Clean Out Caps: Three 1.5 inch two piece threaded clean out caps are used to cap the t-joint and cylinder. They were chosen because they can be unscrewed and removed to facilitate cleaning of the system. Holes drilled in the caps (5/8" diameter holes in the two t-joint caps, and ½" diameter hole in the cylinder cap) allow for the attachment of the one-way valves and insertion of the piston.

Three-way t-joint: The three-way t-joint was chosen to facilitate the connection of one-way valves to the piston-cylinder. Without the use of the t-joint, the one-way valves would have to be attached to the cylinder which would add complexity to the manufacturing process.

Piston Housing: The piston hosing consists of a 2 foot long 1.5" diameter PVC pipe.

Outlet Hose: A 10 foot long, 0.5 inch inner diameter clear, flexible PVC is used as the outlet hose. The PVC hose was chosen because it is cheap and flexible. Additionally, clear hose was chosen so that during testing we can see how much dirty accumulates in the tubing. The hose will be connected to the outlet one-way valve and Clean Water for the World inlet nozzle using hose clamps.

PVC adapter: The PVC adapters are necessary to create the marble based one-way valves, and their size is dictated by the diameter of both the marbles to be used and the inlet and outlet hose.

10 FABRICATION PLAN

The plan for the fabrication of our prototype will consist of two major stages – (1) construction of subsystems and (2) assembly of complete system – separated by functional testing of the pump's subsystems. While that functional testing is described in the validation testing section below, the construction and assembly of the pump is discussed in this section.

Our initial prototype will be built in the ME 450 machine shop using whichever tools and process will allow us to complete a pump as quickly as possible so we can begin testing; however, for our final report we will also develop a production plan for a pump to be made in rural Ghana, using tools available in the region. See Appendix F for the complete list of materials used.

10.1 Construction of subsystems

Each subsystem will be constructed independent of the other subsystems, which include: PVC cylinder and T-joint, handle and piston, one-way valves, and tubing + pre-filter. Once all of these subsystems are created, they will be tested for functionality (as described in the validation testing section below) and modified if necessary. Then they will be assembled into the final system.

The machines and tools used in the construction of the subsystems below include. As the system will ultimately be cemented together with PVC cement, the only case in which fine tolerances matter is the construction of the rubber seal, which must be cut to fit the PVC cylinder and prevent water flow past the seal, without creating excess friction with that PVC cylinder.

- **Lathe and die tool** (to thread a metal rod)
- **Powered hand drill** (to drill holes in PVC)
- **Powered stand drill** (to drill a hole through handle bar)
- **Band saw** (to cut PVC and metal rod to length)
- **Box cuter and scissors** (to cut rubber seal)
- **File** (to smooth PVC after cuts)
- **PVC cement** (to cement PVC)

10.1.1 PVC cylinder and T-joint

To create the Pump body, the following material is required: two 1 ½ in PVC 2 ft L tubes, one 1 ½ in PVC t-joint, PVC glue and three 1 ½ in PVC Caps. Tools required include: hacksaw or band saw, a drill and PVC glue.

The pump body will be made out of PVC that will be purchased from Lowe's in Ann Arbor, Michigan. A 1 ½ in inner diameter T-joint will be purchased as well as PVC tubing, which will be capable of fitting in the

T-joint as shown in section 4. A PVC tube will be cut into two pieces: inlet and outlet to the pump at the dimension shown in section 4. The PVC will be cut using a hacksaw. The piston cylinder will be made using the stock 2ft piece of PVC tubing. Caps will be placed on the ends of each tube with attached one way valves. (See One-way Valve).

In order to construct the pump cylinder casing 1 PVC tubing must be cut into two pieces. The uncut 2ft piece will be the piston housing. The piece will be attached to the T-joint using PVC. The piston is then placed inside this cylinder and a cap placed on the top of the cylinder to secure the piston in place (See Piston and handle). Next, two cylinders will be cut to a length of 3 inches. The one way valves are then placed inside this cylinder and a cap placed on the end of the cylinder (See One Way Valve). These cylinders will be attached to the T-joint using PVC cement.

10.1.2 Piston, Seal, and Handle

To create the piston and handle, the following materials are required: 2 ½ feet of ½”diameter aluminum rod, a 12” section of 1” round aluminum pipe, a 1/8” thick sheet of rubber, four 1 ¼” steel washers, and six ½” steel fasteners. Required tools include: a band saw, a drill, a threading die, and a rubber punch.

We will initially secure the 2 ½’ rod into a lathe and use a threading die to thread approximately 3” down the rod on one end and 2” down the rod on the other end. These lengths are not rigid requirements since the exact placement of the piston seal and handle within one inch in either direction do not affect the precision or accuracy of the system. Once the rod has been threaded we can use a punch to cut the rubber sheet into two 1 ½” outer diameter, ½” inner diameter circles. To manufacture the handle we will cut a 12” section of 1” round steel pipe on the band saw and then drill a ½” diameter hole through two parallel surfaces in the center of the pipe.

To assemble the piston we will begin with the seal end. We will screw one nut onto the 3” threaded end of the rod, slide a washer onto the rod behind the nut, followed by a rubber disc, and then another nut. On the other end of the rod we will screw on a nut, followed by the round aluminum pipe, and then another nut.

10.1.3 PVC end caps

We chose to purchase threaded end caps to close off the PVC pipe in 3 places because they will be easy to remove and clean when necessary. The only tool required to machine the end caps is a drill.

We will clamp one end cap to the drill plate and use a ½” diameter drill bit to drill a hole through the center of the cap. This process will be repeated three times for each of the three caps.

To attach the end cap to the entire system we will glue the male end of the cap onto the 1 ½” PVC pipe and screw the female end to the male end. This process will be repeated three times for each of the three caps.

10.1.4 One-way valves

To create the two one-valve, the following material is required: two ¾” PVC connectors, two ¾” to ½” PVC couplers, PVC cement, two marbles, one compression spring, and approximately 8 inches of the ½” PVC piping. Tools required include: hacksaw or band saw and a rounded file.

The first step is to cut the ½” PVC piping into two sections, each 2 inches in length. Next, insert one of the ½” PVC piping sections into the ½” end of the PVC coupler and glue components together using PVC cement. Next, insert the ¾” PVC connector into the ¾” end of the PVC coupler and together. Then glue the marble to one end of the spring, and glue the other end of the spring to one end of another section of ½” PVC piping. Finally, insert the ½” PVC piping with the attached spring and marble into the ¾” PVC connector and glue the piping to the connector. The valves will be functional when the glue has fully dried.

For each valve, one end cap with a ½” hole drilled in the center will be used to attach to the system. For the inlet valve, the inlet side of the one way valve will be inserted into the hole of the end cap and glued together. For the outlet valve, the outlet side of the one way valve will be inserted into the hole of the end cap and glued together.

10.1.5 Pre-filter

To create the pre-filter, the following materials are required: wire mesh, three hose clamps, and a 3” PVC end cap. Tools required include: wire cutters.

The pre-filter will be made of a wire mesh that will be purchased from Mcmaster.com. The wire mesh will be cut into a 2x2 inch square using wire cutters. The tubing will be purchased from Home Depot in Ann Arbor, Michigan. The tubing will be cut using wire cutters. The filter attachment will be a fitting purchased from Home Depot Ann Arbor, Michigan.

First, cut a 5/8” hole in the center of the PVC cap for the hose to fit through, and several (≥6) holes spaced throughout the cap. The cap will be held in place using two hose clamps, one on each side of the cap. Next, cut a 2” x 2” section of wire mesh. The cut out of the wire mesh is then to be bent over the end of the hose. Once the wire mesh is in place the hose clamp will be used to secure the wire mesh in place on the end of the hose.

Due to the size of the inlet nozzle to the filter and the size of the available hose a fitting is needed to increase the size of the nozzle so that is can be securely connected to the hose. The hose will be attached to the filter by placing the fitting on the nozzle. The hose clamp will be placed on the hose. Once the fitting is attached the filtration system the hose clamp will be used to secure the hose on the fitting.

10.2 Assembly of complete system

Once each subsystem has passed it functionality testing, the systems will be assembled into the final pump. This will be accomplished by first inserting the piston into the cylinder and using PVC cement to attach the caps to the ends of the PVC cylinder and T-joint. Next, hose clamps will be used to secure the

PVC hoses to the inlet and outlet one-way valves and to attach the outlet hose to the Clean Water for the World filtration system. As you can see, assembly of the complete system requires only a handful of steps – we expect it should take no more than 30 minutes in the shop. Once the complete system is assembled, we will begin the system validation described in the validation section below.

11 VALIDATION TESTING

Because of the uncertainties involved with the theoretical model of our pump, once we completed construction of our prototype, we needed to extensively test the device to 1) gain a better understanding of its actual performance, and 2) verify that it meets our engineering requirements. Consequently, the testing we performed can be grouped into two categories: 1) tests targeting each subsystem of the pump, so that we could identify which components worked and which required improvement, and 2) tests targeting engineering requirements, so that we could verify that the pump meets the established targets. In many cases, requirements did not require physical testing (such as the number of unique components, or the number of actions required to operate). In some cases, proper testing was not possible due to time and monetary constraints.

11.1 Testing of Subcomponents

To reiterate, the main subcomponents of the pump are the user input (handle), piston/cylinder (rubber seal and PVC), one-way valves, tubing, and pre-filter. Each of these systems (with the exception of the tubing) underwent testing before being combined with the other subsystems to create the complete design. Because the handle is connected to the piston, at this point, we treated the handle as part of the piston/cylinder subsystem. The testing that was performed on each subsystem is described in the sections below:

- **Piston/cylinder:** The piston cylinder was tested to determine two things: 1) the forces required to operate it, and 2) how effectively the piston seals work. For (1), we submerged one end of the cylinder (the open end, not the end the handle sticks out from) and allowed the rubber seals to become wet. We then attempted to actuate the piston using a force gauge to measure the forces required to overcome the friction between the seal and PVC cylinder. If the force was above 20 lbs, we knew the piston-cylinder design needs to be modified (or that we were pumping too fast). For (2), we observed the region in the cylinder above the seal while performing the test for (1). While some water moved past the seal when the piston is moved up and down, the volume of water leaking past the seal was limited enough that at the time we did not feel it was a significant problem. By trying out a number of different seals (using varying diameters of leather and rubber) and different sized washers, we were able to improve the performance of the seal on these tests, and further reduce the force required to operate while ensuring only limited leakage past the seal. We found that variations in the thousandths of an inch in either the diameter of the seal material or the washers being used had a significant effect on the performance of the seal. Initially the force required to actuate the piston was greater than 50 lbs of force (our force gauge only read up to 50 lbs). to solve this issue, we cut a slight smaller seal and filed off a few thousandths of an inch from the washers we were using. Once these adjustments had been made, we found the force required to operate the piston to be less than 20 lbs, without a significantly greater amount of leakage occurring.

- **One-way valves:** The one-way valves were tested to determine how effectively they sealed against backflow. They were tested by attempting to run water through the valves in both directions. In one direction, water should – and did – flow freely, while in the other direction the water should be – and was – blocked. This testing 1) validated that the valves work, and 2) allowed us to compare the constructed valves to each other and to a pair of purchased valve. We found that all of our constructed valves allowed a slow drip of water through in the blocked direction while the purchased valves allowed no water to trickle through in the blocked direction. However, the marble-spring valves were significantly more effective at preventing backflow when compared to the marble valves (without springs) – water trickled from the marble-spring valves at approximately half the rate that it trickled from the marble only valves.

- **Pre-filter:** The pre-filter was tested to verify that it does not unduly impede the flow of water into the tubing. This was tested by attaching the pre-filter to a section of tubing, filling the tubing with water, and capping the opposite end of the tubing. We will then lift the capped end of the tube vertically, over the pre-filter covered end of the tubing and simultaneously uncap the tubing. Without actually measuring the flow, we were able to clearly see that the filter material with the smallest openings did not have a significant effect on the flow rate, even when compared to an open piping. Thus we decided to use the material with the smallest opening.

Once our subsystems passed these tests successfully we combined them into the completed pump and performed the next stage of testing – testing to verify that the system meets the engineering specifications.

11.2 Testing against Engineering Specifications

To determine what system-level testing is required, we first looked at each engineering specification and determined if it would require experimental testing to verify that our pump met the identified target. See the complete list of engineering requirements in Table 4 below for those identified to require testing:

Table 4: Testing of System

Engineering Specifications	Targets	Testing?
Number of users at a time	1 user/ time	No
Number of simultaneous actions	1 action/time	No
Number of total actions required	≤ 4 actions total	No
Co-located at water source	≤ 20 feet	No
Force required for operation	**≤20 lbs of force**	**Yes**
Angle pump can withstand without tipping	**30 degrees**	**Yes**
Force pump can withstand without failing	**≥ 200 lbs**	**Yes**
Does not underutilize filter	**≥ 5 gallons/minute**	**Yes**
Pressure required to draw in water	**$< P_{amb}$**	**Yes**
Pressure leaving pump	**10 ft. of head**	**Yes**
Max height pump can be above water level	5 feet	No
Environment proof materials	Water and insect resistant	No
Lifetime	≥ 2 years	No
Number of unique components	≤ 20	No
Number of steps to clean pump	≤ 5	No
Connects to filter	0.515 inch diameter hose	No
Pictographic explanations	Located on pump	No
% of locally available materials	100 %	No

Provide backup kit	Back up of least durable materials	No
Packed volume (L+W+H)	≤ 45 inches	No
Dry weight	**≤ 50 lbs**	**Yes**
Comparable to similar products	< $ 50	No
Keeps out large particles	20 mm radius	No
Depth of intake water required for operation	**> 4 inches**	**Yes**

The validation testing for each engineering specifications indentified as requiring testing is described in the subsections below. The reasoning used to develop the above table can be found in the section in Customer Requirements and Engineering Specifications. A discussion on whether our pump meets the engineering specifications not requiring test follows this section.

- ***Force required for operation:*** The target for this requirement is for the maximum force required to operate the piston to be no more than 20 lbs. This was verified by attaching a force gauge to the pump's handle and holding onto said force gauge (as opposed to the handle) while operating the pump. We are able to operate the pump normally without exceeding 20 lbs, consequently verifying that the pump meets this requirement. An interesting phenomenon we discovered is that the down stroke in the pump only required approximately 75% of the force required for the upstroke (when performed at approximately the same speeds)

- ***Angle pump can withstand without tipping:*** The target for this requirement is 30 degrees. To test that our pump met this target, we tipped it 30 degrees and released it. Since the pump returned to its normal upright position, it was verified that the pump meets this specification.

- ***Force pump can withstand without failing:*** The target for this specification is 200 lbs. To test that the pump can successfully withstand 200 lbs of force, we would push on the pump's handle in all possible directions with 200 lbs of force (measured with a force gauge). If the pump remains functioning (i.e. it still meet all other engineering specifications) after 200 lbs of force has been applied, then we would have verified that the pump meets this specification. However, we did not conduct this test as 1) we lacked a force gauge scaled up to 200 pounds and 2) when we did attempt to push in the pump with significant force while standing on and off of the pump, it began to tip, and we realized that personally pushing on the prototype until it failed was as a safety concern. If the pump or the pump stand failed, the tester may potentially hurt his or herself in the resulting fall. Therefore, we did not test this specification. If we had more time and additional resources, an automated mechanism could be used to test that the system can withstand the required force.

- ***Does not underutilize filter:*** The target for this specification is that the pump is capable of moving at least 5 gallons of water per minute. To test this, we filled a container with approximately 5 gallons of water. Using the pump, we then pumped water from the container with 5 gallons, into another tank for 1 minute. However, we were only able to move 2 gallons per minute with our final prototype. Initially, we were only able to pump 1 gallon per minute. While inspecting the pump while operating it, we noticed the inlet hose was collapsing and preventing water from flowing into the pump. After purchasing a reinforced hose, we were able to attain the aforementioned 2 gallons per minute. We believe that a pump with a larger diameter cylinder (and inlet hose) should be able to meet the 5 gallon per minute target, while still meeting the force requirement. However, in the limited amount of time leading up to the expo, we were unable to complete another iteration of our pump using larger diameter PVC.

- ***Pressure required to draw water:*** In order to draw in water from the swamp, the pump would have to lower the internal pressure of the pump below the ambient air pressure. Because our pump would have to meet this requirement to be able to perform the test described for "Does not underutilize filter" above, if the pump passes the above test, or even is able to move any water at all – and it was – then we will have verified that it has met this requirement.

- ***Pressure leaving the pump:*** The target for this engineering specification is 10 ft of head. In order to test that our pump meets this requirement, we raised the pump's output hose at least 10 ft above the pump and attempt to pump water. We are able to pump water out of the top of the hose (using less than 20 lbs of force, as measured with a force gauge), thus we consider this specification met.

- ***Dry weight:*** After constructing the prototype we found that its weight (not including the stand) is less than 20 lbs, thus meeting the specification of less than 50 lbs.

- ***Depth of intake water required for operation:*** The target for this specification is greater than 4 inches. When we performed the tests to measure volume flow, we kept the inlet submerged in at least 4 inches of water through the entire test and the system was able to successfully pump water, thus we verified that the system meets this requirement.

The verification of those specifications not discussed above is handled in the subsections below. While many of the verifications below are obvious, they are included to demonstrate that we have evaluated our design against our complete list of engineering specifications.

- ***Number of users at a time:*** The target for this engineering specification is that the pump can be fully operated by one user. To verify this, each team member took a turn attempting to operate the pump. All four team members (as well as other ME 450 students in the assembly room) were able to operate the pump without assistance, thus we consider this specification met.

- ***Number of simultaneous actions:*** The target for this engineering specification is no more than one action is required at a time to operate the pump (e.g. you should not need to actuate the piston, while simultaneously turning on the Clean Water for the World filtration system). Our system is designed such that the only thing someone must do to operate it is to actuate the handle. Therefore, the only remaining actions required in order to get clean water will be turning on and off the Clean Water for the World Filtration system, which can be performed before and after the pump is operated. Therefore, our pump meets this specification.

- ***Number of total actions required:*** The target for this engineering specification is no more than 4 actions. Assuming the Clean Water for the World filter is not left on, and consequently must be turned on and off (two actions), the only additional actions required are to place the inlet tubing in the swamp (if it is not there already) and to actuate the piston by pumping the handle. This yields a total of four required actions to retrieve filtered water from the swamp, which meets our target.

- ***Co-located at the water source:*** The target for this specification is for the pump to be located less than 20 ft from the swamp. From the pictures we have of the swamp location, there appears to be flat terrain less than 20 ft from the swamp, which would allow the pump to be located within the required 20 ft, meeting the engineering specification. However, for the pump to draw water from the swamp we would need additional inlet hosing, as our current hosing is on 10 ft in length.

- ***Max height pump can be above water level:*** The target for this engineering specification is less than 5 ft above the water source. From the pictures we have of the swamp location, there appears to be flat terrain less than 5 ft above the swamp, which would allow the pump to be located within the required 5 ft, meeting the engineering specification.

- ***Environment proof materials:*** The target for this engineering specification is for the materials we use to yield a final pump that is both water and insect resistant. We will test the water resistance of our pump by throwing water over the pump (to simulate rain) and then performing the test for volume flow described in the "Does not underutilize filter" subsection above. If the pump continues to function after being doused in water, we will consider it sufficiently water resistant. Additionally, the materials we are constructing the pump out of are all water resistant (with the arguable except of the leather seal, which by design is supposed to soak up water improving its sealing properties), therefore we have no reason to believe that the completed system will not be water resistant. While we will be unable to test to verify that our design is insect resistant, the construction materials used are all inorganic (steel, rubber, plastic, and glass) with the exception of the leather (if it is ultimately chosen over a rubber seal). Furthermore, since the leather will be enclosed in the PVC cylinder with only the upper most layer of leather exposed to any insects, we believe the system is as reasonably insect resistant as we can possibly make it, without using prohibitively expensive or significantly less effective materials (if we end up choosing leather over rubber for the seal material).

- ***Lifetime:*** The target for this engineering specification is for the pump system to have a lifetime of at least 2 years (including the use of replacement parts for the leather/rubber seal). As we lack the time and the resources to attempt to conduct a lifetime test of our device, we will not be able to verify that our design meets this requirement through testing. Furthermore, we lack the technical knowledge required to perform a wear analysis on all the pump's subsystems. To conduct such an analysis, we would need to know how water saturated leather wears when rubbed across PVC, and how PVC tubing may deform and yield resulting from the repeated impacts of the one-way valves' marbles. We also lack the time and resources to test our pump until it fails – to accomplish this we would need access to a single-axis actuator for an extended period of time (potentially months of machine time). However, there are many similar systems constructed from PVC, metal and leather/rubber that are used in similar situations (communities in the rural regions of a developing nation) and these systems' lifetimes are often indefinite given that certain specific components (typically seals and one-way valves) are replaced. The replacement of either of these components on our design should be very cheap, and we feel comfortable saying the lifetime of the pump will meet this specification of 2 years – given the leather/rubber seal and the one-way valves are replaced when necessary.

- ***Number of unique components:*** The target for this specification is less than 20 unique components. While our system requires 35 total components, there are a number of duplicated components. Thus, our system meets this target with only 19 unique components.

- ***Number of steps to clean the pump:*** The target for this specification is no more than 5 steps to clean the pump. Our pump will require only five steps: 1) remove tubing, 2) unscrew one-way valves from PVC caps, 3) rinse and clean pump components (tubing, one-way valves, and cylinder + T-joint), 4) re-screw one-way valves into PVC caps, 5) reattach tubing. Once constructed, we went go through the cleaning procedure mentioned above and verified that there are no other steps that have not been accounted for, and that our pump does meet this specification's target.

- ***Connects to filter:*** The target for this specification is that the pump system will connect to the Clean Water for the World filtration system's input nozzle. As we are using tubing that we have already successfully slid over the input nozzle, we verified that our pump meets this specification.

- ***Pictographic explanations on pump:*** The target for this specification is to have pictographic explanations on how to assemble / disassemble the pump (for cleaning) located on the pump. This target was partially met by the creation of our user manual, which is entirely pictographic; however, it is not located on the pump.

- ***Percent of locally available materials:*** The target for this specification is for the pump to be made out of 100% locally available materials. We contacted Dr. Kofi Gyan (a doctor from Ghana) and he verified that the materials we've chosen to use will be available in Ghana. We have also checked are list of materials with five students from Ghana, and they believed all the material we listed to be readily available, with the exception of the marbles. Consequently we created an alternate one-way valve design that uses a rubber ball and larger PVC tubing in place of the marble-based valve in order to provide a secondary option.

- ***Provide backup kit:*** Our target here is to provide a backup kit of the least durable / least available materials. We will provide additional rubber seals and marbles, as the rubber seals will be the system's first component to wear out and correctly-sized marbles may not be easy to find.

- ***Packed volume:*** The packed volume (L + W + H) of our pump must be less than 45 inches. Our pumps dimensions are as follows (with the valves and piston/handle detached): L = 12, W = 2, H = 30. This meets our packed volume target.

- ***Comparable cost to similar products:*** The target for the pump's total cost is less than $50. All of the components used thus far to construct the prototype have amounted to less than $30, including the cost of the stand.

- ***Keeps out large particles:*** The target for this requirement is for the system mesh to block particles up to a diameter of 20 mm. The mesh we'll be using has openings on the magnitude of less than 0.2 mm and consequently meets this specification. We do not need to test that the system screens out particles down to 20 mm in size, because it is physically impossible for them to move through a mesh with openings of less than 0.2 mm – given that we properly attach the mesh to the tubing. Through the choice of components we have verified that this specification is met. Additionally, during testing we found that the pre-filter did screen out all the larger particles.

12 DESIGN CRITIQUE

As discussed above, the main subsystems are the piston/handle, the PVC cylinder, the one-way valves, the tubing, and the pre-filter. Because each subsystem is relatively independent of the others, they will first be critiqued separately, before the system as a whole is discussed.

- **Piston / handle:** The biggest issue with the piston / handle is that we don't have a very good idea of what the best diameter for the washers or the seal material is. Consequently, the seal may be allowing more water to leak past the seal than it should, or it may be creating too much friction with the PVC cylinder and unnecessarily driving up the required operating force. Finally, as mentioned in previous sections, we have no idea how long the lifetime of a given seal may be.

- **PVC cylinder:** Because of time limitations, we were unable to test our marble-spring valves on any cylinder diameters besides 1.5 inches. While 1.5 inch diameter tubing might be the best option, we just don't know because the only alternative we tested was a 2 inch pump with store bought valves, which makes it difficult to isolate the affect of increasing the cylinder diameter. Instead of changing just one variable (cylinder diameter), we ended up varying two (cylinder diameter and type of one-way valves).

- **One-way valve:** The main critique of the one-way valves is that we don't have a very good understanding of how the use of different springs (varying the stiffness) would affect the performance of the valves. Additionally, we were not able to build functioning valves based on rubber balls (instead of marbles) despite multiple attempts.

- **Tubing:** The tubing initially used (soft clear PVC) collapsed under significant suction. We then had to replace that inlet tubing with reinforced tubing, and we are unsure how long this reinforced tubing would last. Additionally, this reinforced tubing is significantly more expensive than the other tubing.

- **Pre-filter:** There were no major issues or concerns with our pre-filter. It was easy to build and did exactly what we expected of it: screen out large particles. Our biggest concern is how it would fare in water with more silt. While we tested the pump is dirt filled water, the dirt used was the typical coarse dirt you'd find outside in Michigan, and not the clay-based silt that is more common in swamps.

With the main subsystems discussed, we can now address the system as a whole. The main critiques with respect to the system as a whole are: 1) user-friendly orientation, and 2) inability to pump 5 gallons per minutes. The prototype we created was oriented vertically, and while we tested alternatives (such as an inclined installation) and settled on a vertical orientation, it is awkward for shorter users to operate. With respect to the volume flow rate, our final prototype was only able to pump 2 gallons per minute

Given the above critiques, the sections below address potential future work – what the next steps would be in improving our current design. As with the previous section, they are organized by the aforementioned subsystems: the piston/handle, the PVC cylinder, the one-way valves, the tubing, and the pre-filter.

- **Piston / handle:** The largest opportunity for improvement on the current piston/handle lies with the seal and the washers that sit adjacent to the seal. By constructing and testing various seals and washers we found that changing the diameter of either by thousandths of an inch has a very notable impact on the effectiveness of the seal (its ability to prevent water from flowing past it) and the force required to actuate the piston. Given additional time, we would extensively test the effect of varying these diameters on the seal leakage and force requirements. Using this data, we could better select a suggested diameter for both the seal and the washer.

- **PVC cylinder:** While we are satisfied with the design of the PVC cylinder (PVC tubing, T-joint, and end caps), we would suggest experimenting with different tubing diameters, as larger diameters would allow a greater volume of water to be pumped with equal piston displacement. However, we would also need to test to ensure that we don't exceed the force requirement.

- **One-way valve:** The most important function of the one-way valves is that they only allow the flow of water in one direction. The second most important function is for them to allow the pump to self-prime. In designing and adjusting our one-valves, our goals were to produce a valve that would perform both of these functions. Our first generation valves based on a marble and heated/deformed PVC were able to perform the first function, but not the second. Our second attempt at one-way valves used vertical valves using rubber balls that were built in the same fashion as the marble valves (deformed PVC acted as the stopper for the balls). These valves led to a complicated PVC cylinder and T-joint construction with three additional PVC elbows, ultimately yielding a pump that would not self-prime and was extremely difficult to prime by hand (to the point that we never successfully pumped water with the pump). These valves failed to perform either of the aforementioned functions of our desired one-way valve. Our next generation consisted of a sphere supported by a spring, with the spring replacing the deformed PVC as the structure that prevents the sphere from blocking both PVC openings in the PVC chamber in which the sphere is contained. The spring also pressed the sphere against on side of the PVC chamber allowing the sphere to close the valve even when the water pressure within the pump was not pushing the sphere into the opening. This would theoretically allow the valve to seal air as well as water. We attempted to construct a pair of different valves based on this design (one with marbles and one with rubber balls). The marble based valves successfully prevented backflow (as the previous marble based valves had), while also allowing the pump to self-prime. However, we were unable to get the rubber ball based version of these valves functioning, and given additional time, would rebuild these valves, under the belief that they should seal better than the marbles given that the rubber would deform more than the marbles when pressed into a PVC opening.

- **Tubing:** Given our experience with the inlet tubing during testing (the tubing we initially purchased collapsed under suction), we would recommend experimenting with the inlet tubing we used: varying both 1) the type of tubing, and 2) the diameter of the tubing. With respect to varying the type of tubing, we would experiment with different levels of reinforcement, to determine what level of reinforcement is required to avoid collapse during intake. This is important because the more reinforcement required, the more expensive and more difficult to find the hose will be. With respect to the diameter of the intake tubing, increasing diameter would allow the pump to draw more water, using less force, from greater depths. However, increasing the diameter of the tubing would also increase its price. Through experimentation a compromise between performance and price could be found.

- **Pre-filter:** While we were extremely satisfied with our pre-filter, we would like to experiment with even finer mesh, because the more we could reduce the amount of particle matter that passes into the filter, the more the addition of our pump would extend the life of the paper filter.

For the pump as a whole, we would further experiment with alternative ways to orient the pump to make it easier to operate. As mentioned above, we would also experiment with larger diameter cylinders to attempt to reach the 5 gallon per minute target flow rate.

13 RECOMMENDATIONS

The pump was designed specifically to interface with the Clean Water for the World filter. We recommend attaching the pump to a metal or wood stake driven into the ground near the filter. The attachment can be made with any sort of rope or tie. This will help keep the pump upright and hold it steady during operation. The pump also needs to be attached at the base. We recommend clamping the pump to a piece of wood that the user can stand on. If the pump does not appear to be operating at maximum performance the one way valves can be unscrewed from the pump and cleaned. By running water through them that is free of debris they should begin functioning again. If a part of the valve or seal becomes damaged the parts can be replaced. The construction manual will help the user to rebuild the components that have failed.

Since we were only able to conduct short term testing on the pump, lifetime tracking is recommended. With more information and knowledge of the wear characteristics, a more robust design as well as a more refined maintenance schedule could be determined. Additionally, if we had more time for testing the one way valves could have been improved. Testing is the only way to determine the optimum spring stiffness and ball material to make the valves operate better. Finally, we also recommend refining the construction manual. The pictures are currently difficult to follow and understand.

14 CONCLUSION AND SUMMARY

Our major objective was to provide the Kyeamekrom community in the Brong-Ahafo region of Ghana with a clean, safe, drinkable water source. We aim to help prevent a portion of the 5000 deaths each day that result from diseases related to the consumption of contaminated water. In order to do this our goal was to create a surface water pump made entirely out of locally available materials that can interface with the Clean Water for the World filtration system.

Through an extensive literature review we determined that the prototype would be similar to a bilge pump and would include a pre-filter to extend the life of the pump and filter. With the help of our sponsor and mentors we were able to revise our list of customer requirements and engineering specifications in order to get very specific targets with which to evaluate our prototype. From there we were able to begin generating concepts, narrowing down our options, and eventually choose an alpha design.

Our alpha design transformed into our final design through rigorous testing and engineering analysis. Our final pump design includes several subsystems: a pre-filter, tubing, two identical one way valves, two piston seals, and a handle. We selected materials and dimensions based on the engineering specifications and validated the prototype against these specifications.

There are several areas of our design that require further consideration, testing and refinement. We have recommended plans for implementing the current prototype as well as goals for future work.

15 ACKNOWLEDGEMENTS

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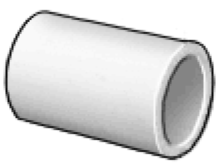
APPENDIX B: Bill of Materials

Plastic Pipe Fittings and Pipe



Part Number: 4880K71	$0.21 Each
Shape	Coupling
Coupling Type	Straight Coupling
Pipe to Pipe Connection	Socket-Weld x Socket-Weld
System of Measurement	Inch
Schedule	40
Pipe/Thread Size	1/2"
Material	PVC
Color	White
Temperature Range	Up to 140° F
Specifications Met	American Society for Testing and Materials (ASTM), National Sanitation Foundation (NSF)
ASTM Specification	ASTM D1784, ASTM D2466
NSF Specification	NSF 61
WARNING	Never use plastic pipe fittings with compressed air or gas.

Tubing

This product matches all of your selections.

Part Number: [5231K227]	1-99 Ft. $0.57 per Ft. 100 or more $0.46 per Ft.
Type	Chemical-Resistant Clear PVC Tubing
Material	PVC
Shape	Single Line
Outside Dia.	5/8" (.625")
Inside Dia.	1/2" (.5")
Wall Thickness	1/16" (.0625")
Available Lengths	25, 50, and 100 feet
Reinforcement	Unreinforced
Color	Clear
Maximum Pressure	20 psi @ 73º F
Operating Temperature Range	-25° to +160° F
Bend Radius	2-1/2" (2.5")
Durometer	60A (Soft)
Tensile Strength	1,650 psi
For Use With	Air, Beverage, Bleach, Food, Water
Sterilize With	Chemical, Gas, Steam (autoclave)
Specifications Met	United States Food and Drug Administration (FDA), United States Department of Agriculture (USDA)

FDA Specification	CFR21 175.300
USDA Specification	USDA Approved
Compatible Fittings	Barbed
Chemical Compatibility Link	5231KAC
Caution	McMaster-Carr does not guarantee chemical compatibility because many variables can affect the tubing. Ultimately, the consumer must determine chemical compatibility based on the conditions in which the product is being used.

Hose and Tube Clamps

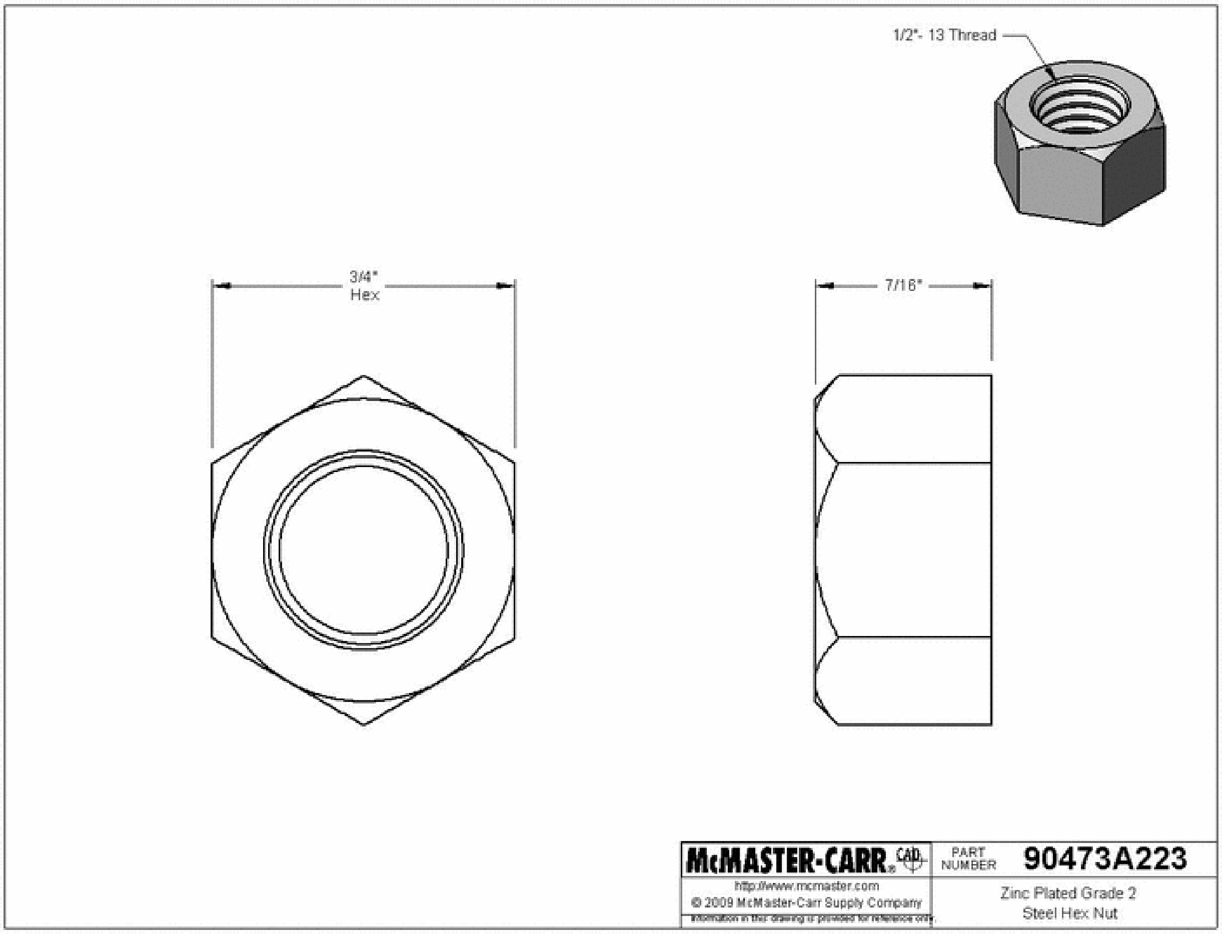
This product matches all of your selections.

Part Number: 54195K14	$7.29 per Pack of 10
Clamp ID Range, mm	5.6 to 16
Clamp Type	Worm Drive
Worm Drive Clamp Type	Standard
Band Material	Stainless Steel
Stainless Steel Band Material	Type 301 Stainless Steel
Screw/Bolt Material	Stainless Steel
Stainless Steel Screw/Bolt Material	Type 305 Stainless Steel
Clamp ID Range, In.	7/32" to 5/8"
SAE No.	4
Operating Temperature Range	-50° to +250° F
Band Width	5/16"
Band Thickness	.023"
Torque, in.-lbs.	15
Reusable?	Yes
Specifications Met	Society of Automotive Engineers (SAE)
SAE Specification	SAE J1508
Note	Not recommended for use with silicone hose and tube.
Installation Instructions	Tighten with a wrench, slotted screwdriver, or 1/4" hex nutdriver.

Nuts

This product matches all of your selections.

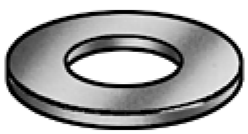
Part Number: 90473A223	$9.96 per Pack of 100
Nut Type	Machine Screw and Hex Nuts
Machine Screw and Hex Nut Type	Hex
Material Type	Steel
Finish	Zinc-Plated
Grade/Class	Grade 2
Steel Type	Plain Steel
System of Measurement	Inch
Inch Thread Size	1/2"-13
Thread Type	Standard Threads
Thread Direction	Right-Hand Thread
Width	3/4"
Height	7/16"
Rockwell Hardness	Maximum C32
Specifications Met	American National Standards Institute (ANSI), American Society of Mechanical Engineers (ASME)
ANSI Specification	ANSI B18.2.2
ASME Specification	ASME B18.2.2



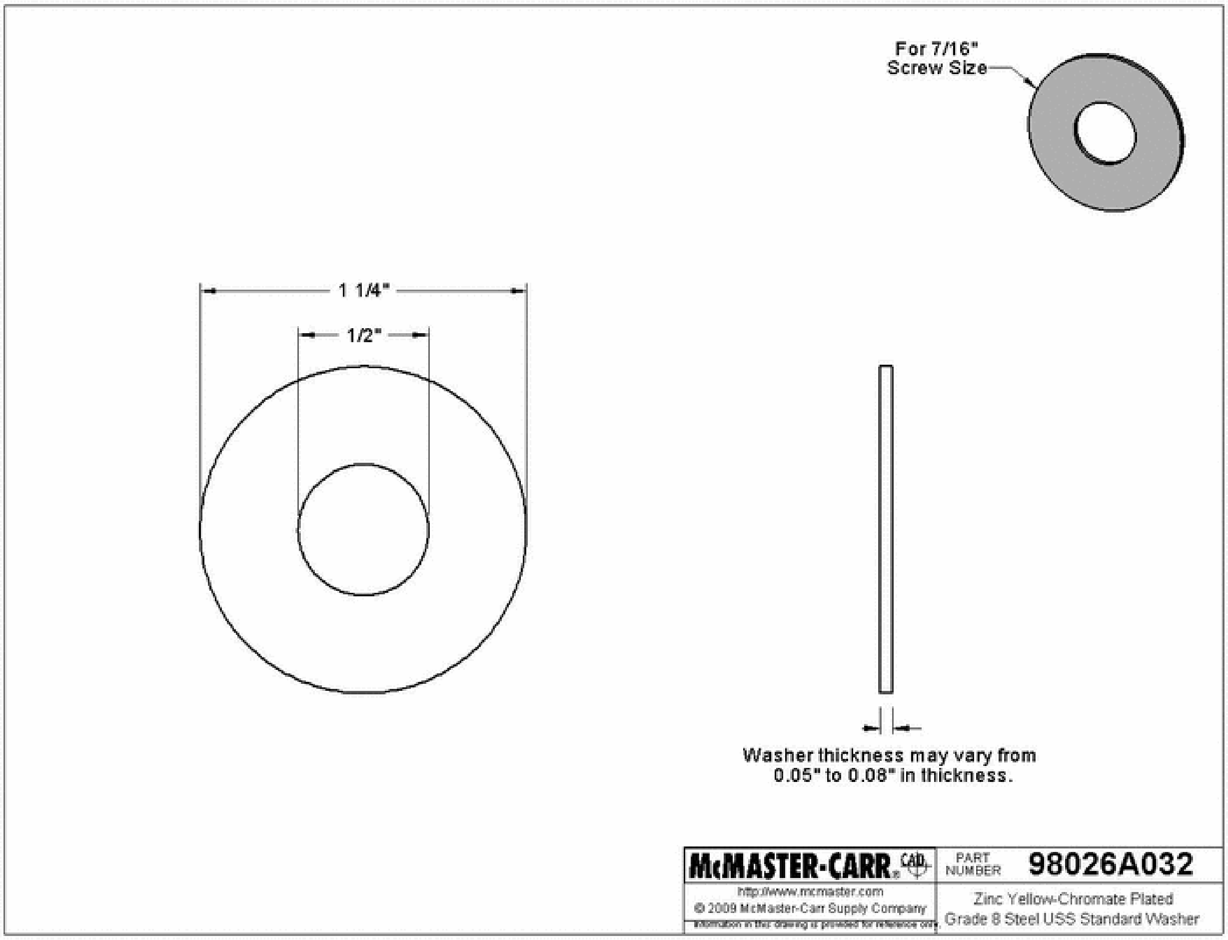
1/2"- 13 Thread
3/4"
Hex
7/16"
McMASTER-CARR
PART NUMBER
90473A223
http://www.mcmaster.com
© 2009 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Zinc Plated Grade 2
Steel Hex Nut

Washers

This product matches all of your selections.

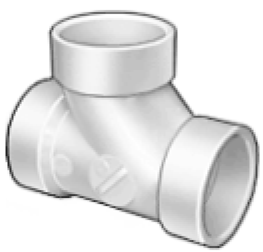


Part Number: 98026A032		$5.38 per Pack of 25
Shape	Round Hole	
For Screw Size	7/16"	
Material Type	Steel	
Finish	Zinc-Plated	
Steel Type	High Strength Steel	
Inside Diameter	.5" (1/2")	
Outside Diameter	1.25" (1-1/4")	
Minimum Thickness	.05"	
Maximum Thickness	.08"	
Rockwell Hardness	Minimum C38	
Specifications Met	American Society of Mechanical Engineers (ASME), United States Standard (USS)	
ASME Specification	ASME B18.22.1	
Note	Also known as Type A washer.	


For 7/16"
Screw Size
1 1/4"
1/2"
Washer thickness may vary from
0.05" to 0.08" in thickness.
McMASTER-CARR
CAD
PART NUMBER
98026A032
http://www.mcmaster.com
© 2009 McMaster-Carr Supply Company
Zinc Yellow-Chromate Plated
Grade 8 Steel USS Standard Washer

Plastic Pipe Fittings and Pipe

This product matches all of your selections.



Part Number: 2389K22	$2.37 Each
Shape	Tee
Tee Type Pipe to Pipe	Sanitary Tee
Non-Pressure Type	Gravity-Flow Drain, Waste and Vent
Pipe to Pipe Connection	Socket-Weld x Socket-Weld
System of Measurement	Inch
Schedule	40
Pipe/Thread Size	1-1/2"
Material	PVC
Color	White
Maximum Pressure	0 psi (Gravity Flow)
Temperature Range	Up to 140° F
Specifications Met	American Society for Testing and Materials (ASTM)
ASTM Specification	ASTM D1784, ASTM D2665, ASTM D3311
Note	Not for use with hot water or pressure-rated applications.
WARNING	Never use plastic pipe fittings with compressed air or gas.

Plastic Pipe

Purchased from Lowe's

Part Number: **23966**	$1.20 Each
Shape	Coupling
Coupling Type	Straight Coupling
Pipe to Pipe Connection	Socket-Weld x Socket-Weld
System of Measurement	Inch
Schedule	40
Pipe/Thread Size	½"
Material	PVC
Color	White
Specifications Met	American Society for Testing and Materials (ASTM), National Sanitation Foundation (NSF)
ASTM Specification	ASTM-D-2241

Plastic Pipe

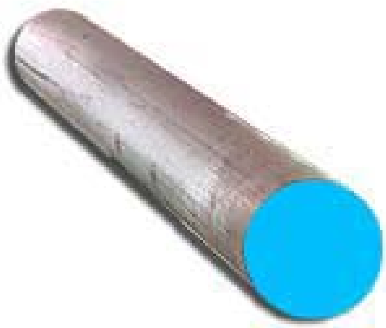
Purchased from Lowe’s

Part Number: **23966** $1.48 Each

Shape	Coupling
Coupling Type	Straight Coupling
Pipe to Pipe Connection	Socket-Weld x Socket-Weld
System of Measurement	Inch
Schedule	40
Pipe/Thread Size	3/4"
Material	PVC
Color	White
Specifications Met	American Society for Testing and Materials (ASTM), National Sanitation Foundation (NSF)
ASTM Specification	ASTM-D-2241, SDR-21, SDR26

Piston Rod

Metalsdepot.com



Stock Number: **R312**	$4.96 Each
Product Type	6061-T6 Aluminum Round
Length	4 feet
System of Measurement	Inch
Rod Diameter	1/2"
Material	Aluminum

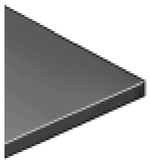
Handle

Metalsdepot.com

Stock Number: T334	$5.86 Each
Product Type	3/4 SCH 40 (1.05 OD X .113W) Aluminum Structural Pipe
Length	2 feet
System of Measurement	Inch
Material	Aluminum
Wall Thickness	0.113”

Rubber

This product matches all of your selections.



Part Number: 8635K644 $10.40 Each

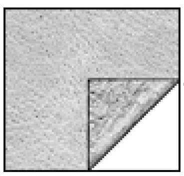
Material Type	Medium-Strength Oil-Resistant Buna-N Rubber
Shape	Sheet
Backing	No Backing
Thickness	1/8"
Thickness Tolerance	±.020"
Length	12"
Length Tolerance	±1/2"
Width	12"
Width Tolerance	±1/2"
Durometer	Medium Soft, Medium Hard
Durometer Rating	50A
Durometer Hardness Tolerance	±5
Temperature Range	-20° to +170° F
Adhesive Temperature Range	-20° to +170° F
Tensile Strength	800 psi
Compression Recovery	Not Rated
Color	Black
Finish	Smooth
Tolerance	Standard

Specifications Met	American Society for Testing and Materials (ASTM)
ASTM Specification	ASTM D2000 BF
Properties	Oil Resistant

Cow Leather

Rubber

This product matches all of your selections.



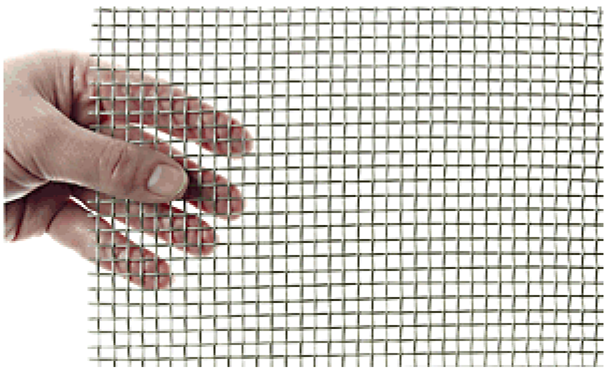
Part Number: 8706k16 $19.87 Each

Material Type	Vegetable Tanned
Shape	Sheet
Thickness	1/8"
Thickness Tolerance	±.020"
Length	12"
Length Tolerance	±1/2"
Width	12"
Width Tolerance	±1/2"
Max Temperature	150° F

Wire Meshes

Wire Cloth, Mesh, and Perforated Sheets

This product matches all of your selections.



Part Number: 85385T137	$14.37 Each
Material Type	Stainless Steel
Stainless Steel Type	Type 304
Form	Woven Wire Cloth
Shape	Sheets
Woven Wire Cloth Tolerance	General Purpose
Mesh Size Range	Coarse Mesh
Mesh Size	4 x 4
Square/Rectangle Size	.196"
Wire Diameter	.054"
Percentage of Open Area	61.5
Sheet Width	12"
Sheet Length	12"

Wire Cloth, Mesh, and Perforated Sheets

This product matches all of your selections.

Part Number: 9238T524	$6.72 Each
Material Type	Stainless Steel
Stainless Steel Type	Type 304
Form	Woven Wire Cloth
Shape	Sheets
Grade/Type of Woven Wire Cloth	Milling Grade

Mesh Size Range	Coarse Mesh
Mesh Size	10 x 10
Square/Rectangle Size	.08"
Wire Diameter	.02"
Sheet Width	12"
Sheet Length	12"

Wire Cloth, Mesh, and Perforated Sheets

This product matches all of your selections.

Part Number: [85385T871]	$6.37 Each
Material Type	Stainless Steel
Stainless Steel Type	Type 304
Form	Woven Wire Cloth
Shape	Sheets
Woven Wire Cloth Tolerance	General Purpose
Mesh Size Range	Fine Mesh
Mesh Size	90 x 90
Square/Rectangle Size	.006"
Wire Diameter	.0055"
Percentage of Open Area	25.4
Sheet Width	12"
Sheet Length	12"

(3) 1.5 inch threaded end caps

0.75 inch PVC coupling

0.75x0.50 PVC reducer

PVC glue/cement

(2) 5/8” Glass Marbles

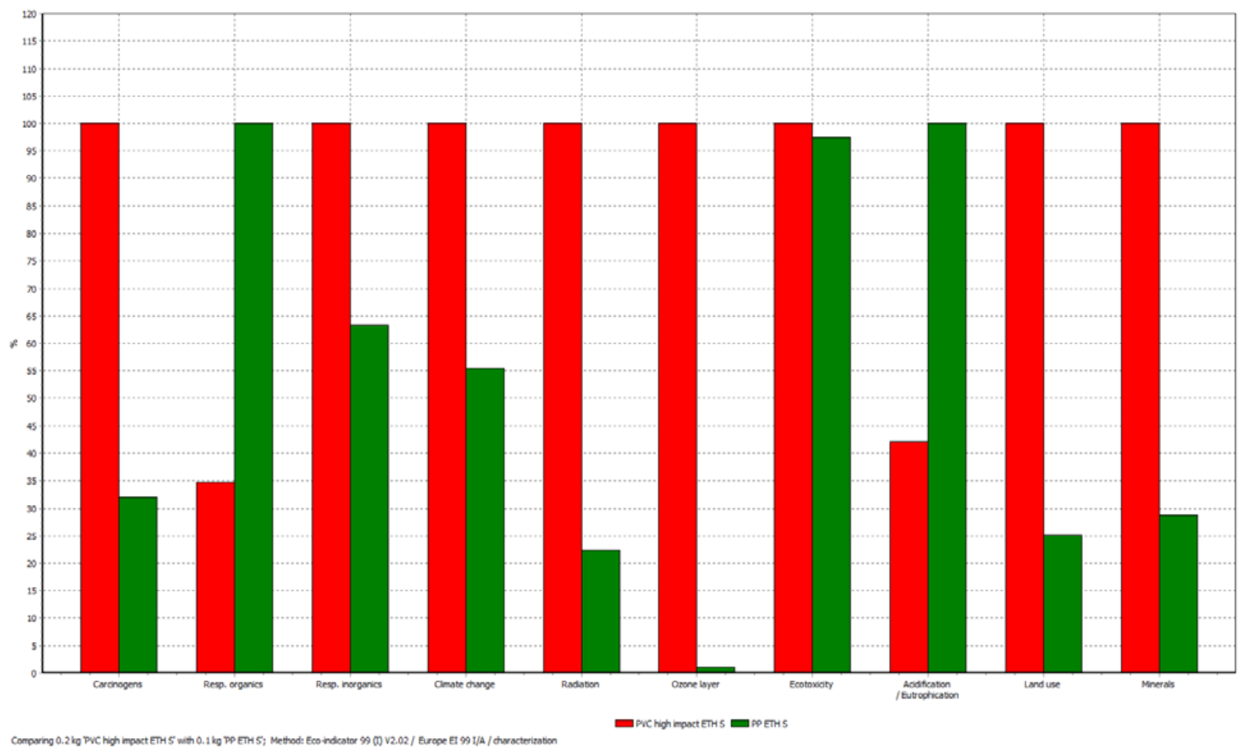
APPENDIX C: Description of Engineering Changes Since Design Review #3

There have been a number of changes to our design since DR3, but the easiest way to discuss them is with respect to the different subsystems of the pump: the piston/handle, the PVC cylinder, the one-way valves, the tubing, and the pre-filter.

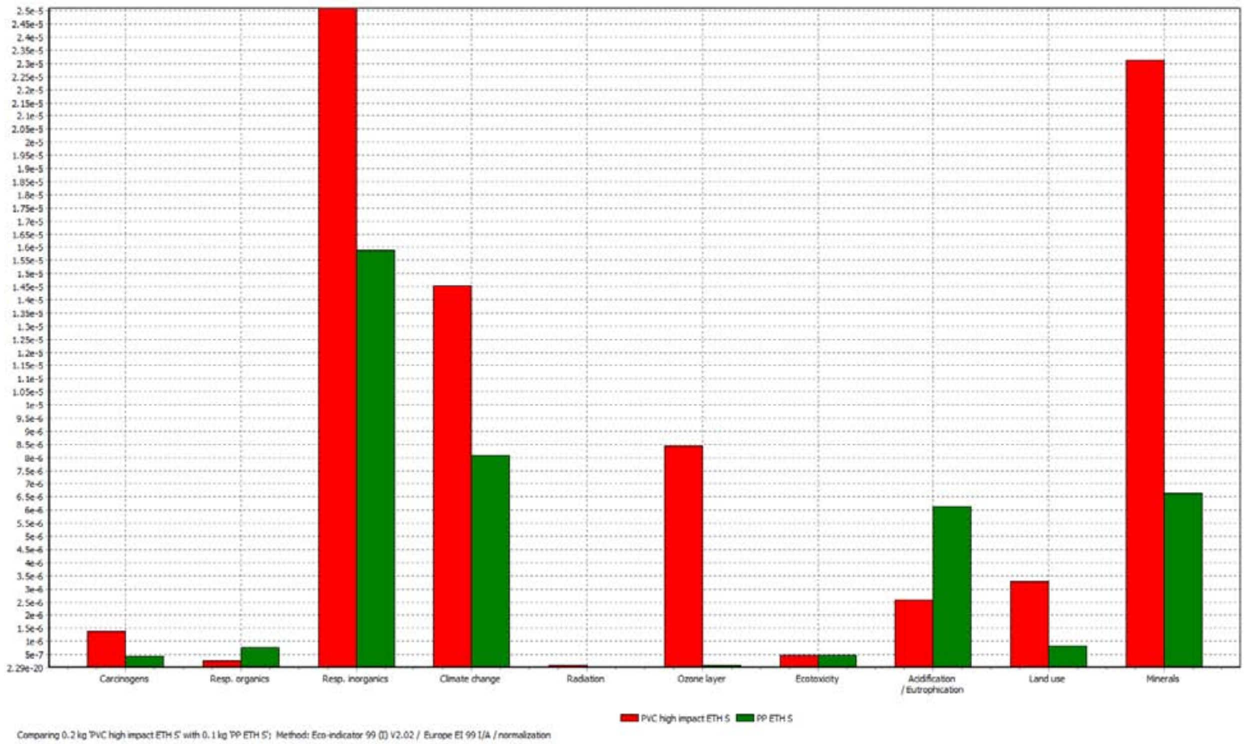
- **Piston / handle:** In DR3, the user interface was a lever. After team discussions, the decision was made to change this to a simple handle attached at the top of the piston. This accomplished a number of things, reducing the complexity of the design, which makes the pump easier to make, maintain and transport.
- **PVC cylinder:** While we experimented with both 1.5 and 2 inch diameter PVC cylinders, there were no significant changes to the PVC cylinder.
- **One-way valve:** Our initial valve design called for a marble located in a PVC chamber, and on one end of the chamber the PVC was to be heated and reformed so that it would prevent the marble from blocking water flow in that direction. In our second generation one-way valves we replaced this heated PVC with a spring. This spring also presses the marble into the other end of the PVC chamber such that it will (attempt to) seal in the absence of water pressure in the pump. I use the words "attempt to" because it does not seal perfectly. In search of a better seal we used rubber balls, however we were unable to get valves based on rubber balls functioning in time to be used in the final design.
- **Tubing:** Initially we assumed any tubing would work and purchased a flexible, clear PVC hose; however, we found that this hose would collapse under suction and replaced it with a reinforced hose, which was able to withstand the pump's suction.
- **Pre-filter:** The pre-filter did not change.

APPENDIX D: Design Analysis Assignment

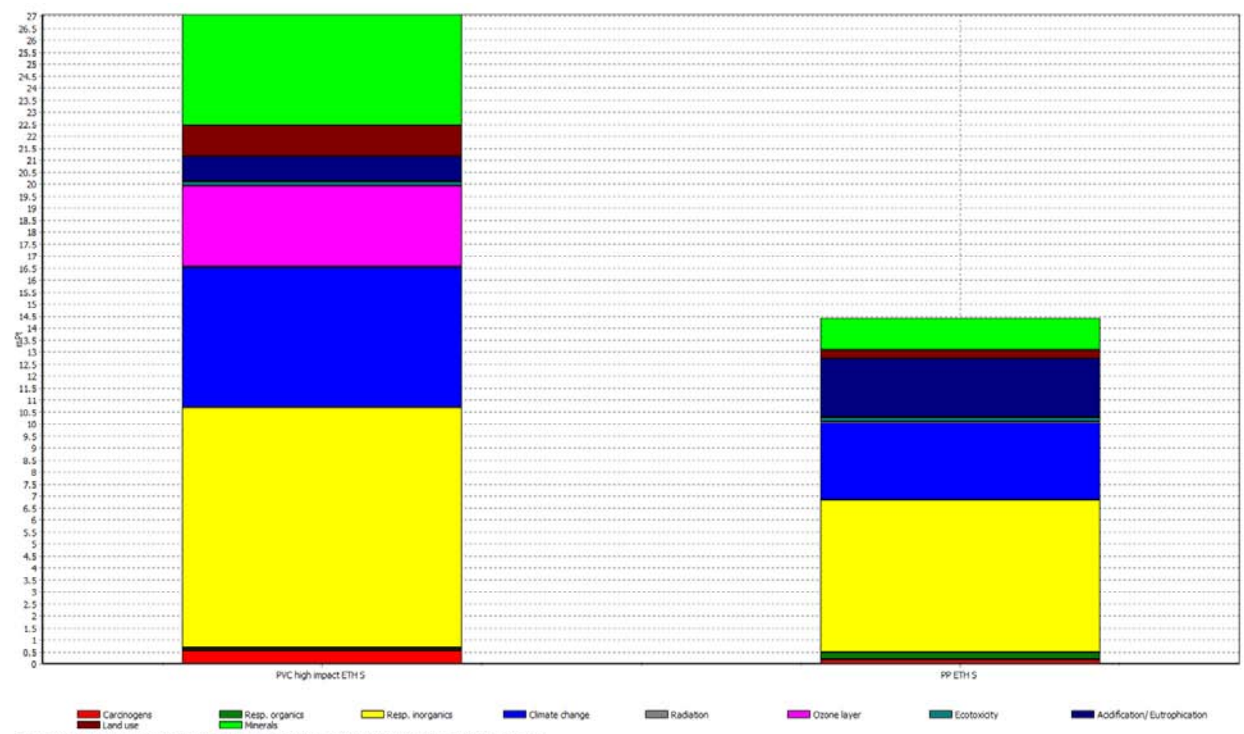
Materials used will be PVC (chlorinated, molding and extrusion) with a mass of 0.532 lb and PP (copolymer, impact low flow) had a mass of 0.31 lb. We were unable to find these exact materials in SimaPro and so we compared PVC high impact ETH S and PP ETH S at the same masses. The total air emissions was found to be 665.576 g for the PVC high impact ETH S and 324.1101g for the PP ETH S. The total raw materials was found to be 16510.28 g for the PVC high impact ETH S and 4451.11g for the PP ETH S. The total water emissions The total raw materials was found to be 15.36122 g for the PVC high impact ETH S and 10.64769g for the PP ETH S. The total soil or solid waste The total raw materials was found to be 0.145499 g for the PVC high impact ETH S and 0.121841g for the PP ETH S. The most important meta-categories are Resp. inorganics, Climate change, Ozone layer and Minerals. Based on the graphs the PVC has a bigger impact on the environment. This would also have the higher EcoIndicator 99 "point value" and would also have a bigger impact over the lifetime of the device. The graphs from SimaPro are shown below.



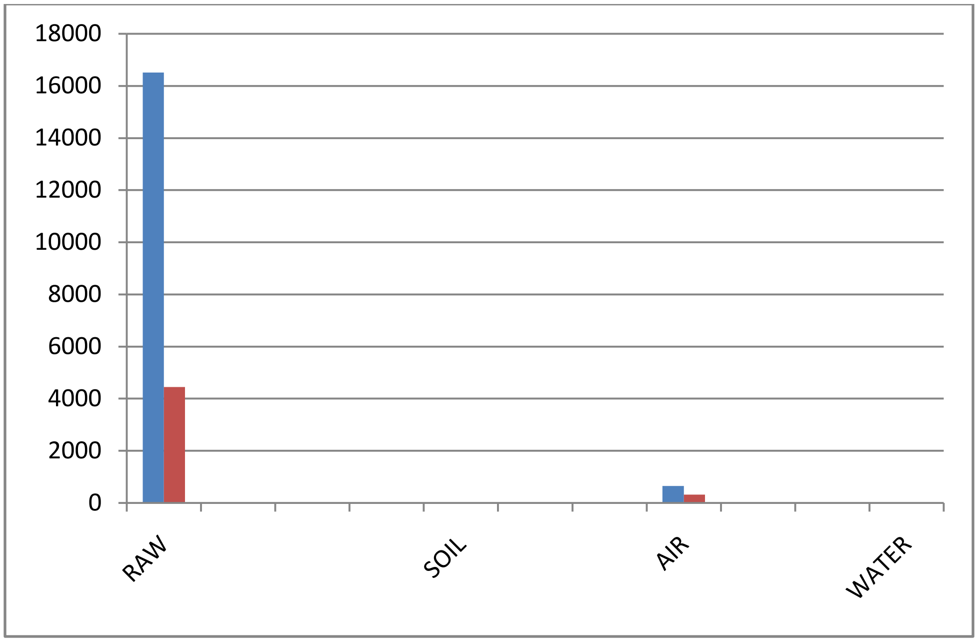
Characterization of PVC high impact ETH S and PP ETH S



Normalization of PVC high impact ETH S and PP ETH S



Meta-categories for PVC high impact ETH S and PP ETH S



Total emissions of Raw materials, Air, Soil and Water through production of PVC high impact ETH S and PP ETH S

APPENDIX E: QFD

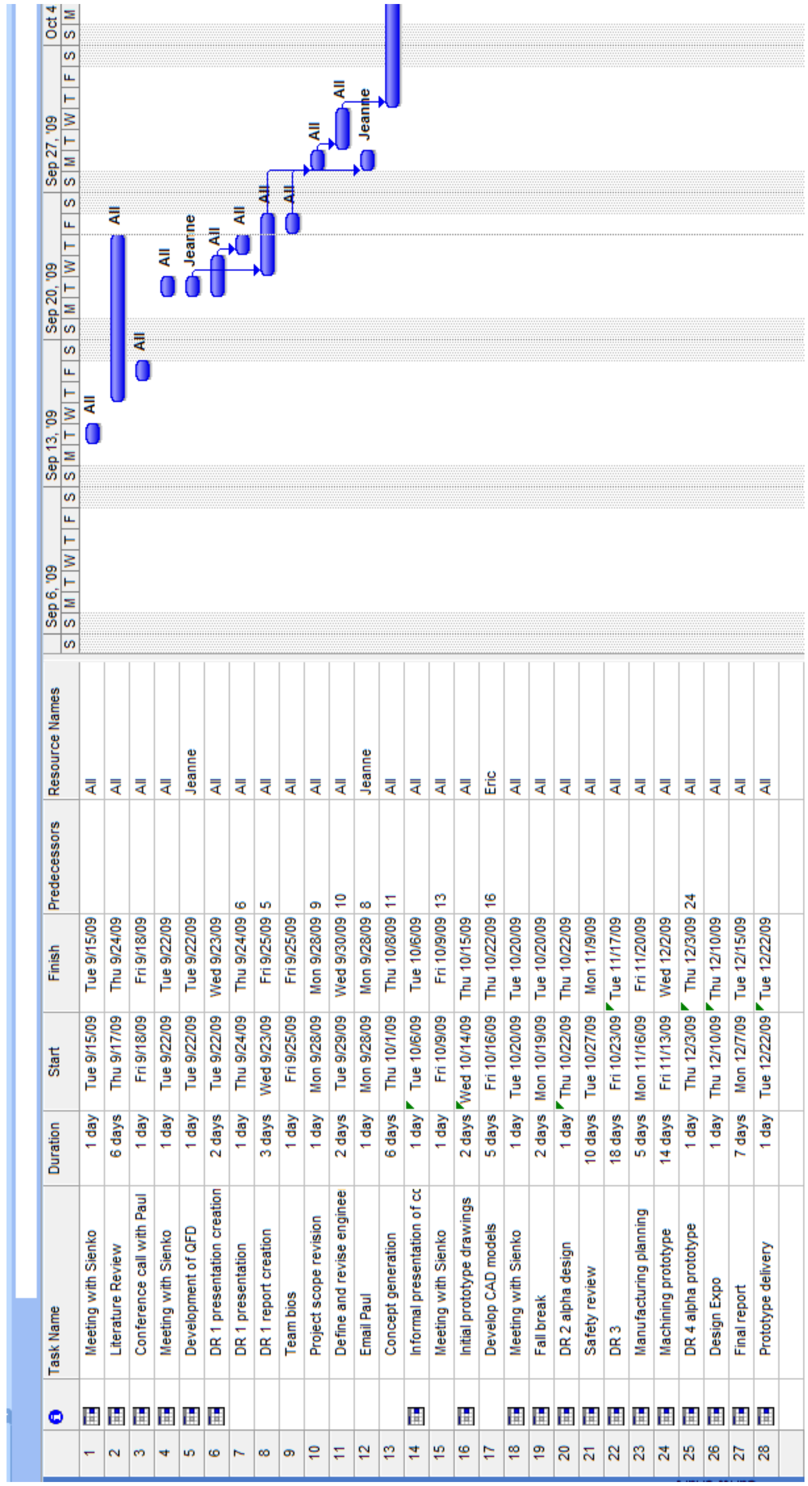
System QFD

#	Technical Requirement
1	Simple user interface
2	Meets volume demand
3	Co-located near water source
4	Easy to install
5	Robust
6	Materials
7	Transportable
8	Safe
9	Securable
10	
11	
12	
13	
14	
15	
16	
17	
18	
19	
20	

			Technical Requirements									Customer Opinion Survey				
	Customer Needs	Customer Weights	Simple user interface	Meets volume demand	Co-located near water source	Easy to install	Robust	Materials	Transportable	Safe	Securable	1 Poor	2	3 Acceptable	4	5 Excellent
1	Water is purified to a potable level	11	3	9	3		9			3						
	Co-located at water source	10	1	1	9	3	1	1		3	9					
2	Easy and safe to use	9	9		3	9	9	3	1	9	1					
3	Satisifies community demand	8		9	9		3			3						
4	Easy to maintain / repair	7	9		3	3	9	3	1	3	3					
5	Easy to interchange operators	6	9	3			1			3						
6	Not physically taxing to operate	5	9	3			1	3		3	1					
7	Durable / environment proof	4			9		9	9	9	1	1					
8	Secure	3	3		9		3	9	9	1	9					
9	Portable water input	2	3	9	9											
10	Replaceable cheap components	1	3			9	9	9	3							
		Raw score	304	232	324	141	342	145	82	229	156					
		Scaled	0.889	0.678	0.947	0.412	1	0.424	0.24	0.67	0.456					
		Relative Weight	16%	12%	17%	7%	17%	7%	4%	12%	8%					
		Rank	3	4	2	8	1	7	9	5	6					

www.robuststrategy.com
kevin_n_otto@yahoo.com
http://www.kevinotto.com/RSS/templates/QFD Template.xls
Modified from a template from Design4X Inc.

APPENDIX F: Gantt Chart



		Task Name	Duration	Start	Finish	Predecessors	Resource Names
1		Meeting with Sienko	1 day	Tue 9/15/09	Tue 9/15/09		All
2		Literature Review	6 days	Thu 9/17/09	Thu 9/24/09		All
3		Conference call with Paul	1 day	Fri 9/18/09	Fri 9/18/09		All
4		Meeting with Sienko	1 day	Tue 9/22/09	Tue 9/22/09		All
5		Development of QFD	1 day	Tue 9/22/09	Tue 9/22/09		Jeanne
6		DR 1 presentation creation	2 days	Tue 9/22/09	Wed 9/23/09		All
7		DR 1 presentation	1 day	Thu 9/24/09	Thu 9/24/09	6	All
8		DR 1 report creation	3 days	Wed 9/23/09	Fri 9/25/09	5	All
9		Team bios	1 day	Fri 9/25/09	Fri 9/25/09		All
10		Project scope revision	1 day	Mon 9/28/09	Mon 9/28/09	9	All
11		Define and revise enginee	2 days	Tue 9/29/09	Wed 9/30/09	10	All
12		Email Paul	1 day	Mon 9/28/09	Mon 9/28/09	8	Jeanne
13		Concept generation	6 days	Thu 10/1/09	Thu 10/8/09	11	All
14		Informal presentation of cc	1 day	Tue 10/6/09	Tue 10/6/09		All
15		Meeting with Sienko	1 day	Fri 10/9/09	Fri 10/9/09	13	All
16		Initial prototype drawings	2 days	Wed 10/14/09	Thu 10/15/09		All
17		Develop CAD models	5 days	Fri 10/16/09	Thu 10/22/09	16	Eric
18		Meeting with Sienko	1 day	Tue 10/20/09	Tue 10/20/09		All
19		Fall break	2 days	Mon 10/19/09	Tue 10/20/09		All
20		DR 2 alpha design	1 day	Thu 10/22/09	Thu 10/22/09		All
21		Safety review	10 days	Tue 10/27/09	Mon 11/9/09		All
22		DR 3	18 days	Fri 10/23/09	Tue 11/17/09		All
23		Manufacturing planning	5 days	Mon 11/16/09	Fri 11/20/09		All
24		Machining prototype	14 days	Fri 11/13/09	Wed 12/2/09		All
25		DR 4 alpha prototype	1 day	Thu 12/3/09	Thu 12/3/09	24	All
26		Design Expo	1 day	Thu 12/10/09	Thu 12/10/09		All
27		Final report	7 days	Mon 12/7/09	Tue 12/15/09		All
28		Prototype delivery	1 day	Tue 12/22/09	Tue 12/22/09		All

APPENDIX G: EPA waterborne contaminants as well as their health risks and sources

Microorganisms

Contaminant	Potential Health Effects	Sources of Contaminant in Drinking Water
Cryptosporidium	Gastrointestinal illness (diarrhea)	Human and animal fecal
Legionella	Legionnaire's Disease, a type of pneumonia	Found naturally in water; multiplies in heating systems
Total Coliforms (including fecal coliform and *E. Coli*)	Not a health threat in itself; it is used to indicate whether other potentially harmful bacteria may be present [5]	Coliforms are naturally present in the environment; as well as feces; fecal coliforms and *E. coli* only come from human and animal fecal waste.
Turbidity	Turbidity is a measure of the cloudiness of water. It is used to indicate water quality and filtration effectiveness (e.g., whether disease-causing organisms are present). Higher turbidity levels are often associated with higher levels of disease-causing microorganisms such as viruses, parasites and some bacteria. These organisms can cause symptoms such as nausea, cramps, diarrhea, and associated headaches.	Soil runoff

Disinfection Byproducts

Contaminant	Potential Health Effects	Sources of Contaminant in Drinking Water
Bromate	Increased risk of cancer	Byproduct of drinking water disinfection
Chlorite	Anemia; infants & young children: nervous system effects	Byproduct of drinking water disinfection

Disinfectants

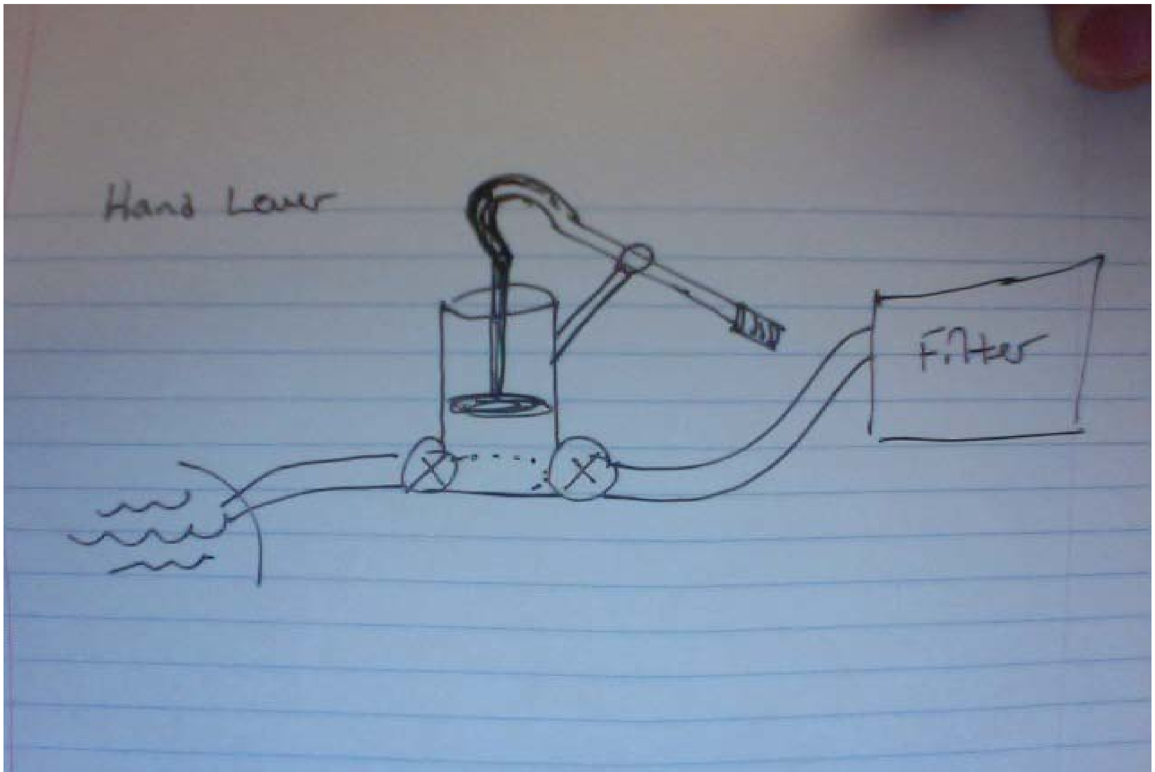
Contaminant	Potential Health Effects	Sources of Contaminant in Drinking Water
Chloramines (as Cl_2)	Eye/nose irritation; stomach discomfort, anemia	Water additive used to control microbes
Chlorine (as Cl_2)	Eye/nose irritation; stomach discomfort	Water additive used to control microbes
Chlorine dioxide (as ClO_2)	Anemia; infants & young children: nervous system effects	Water additive used to control microbes

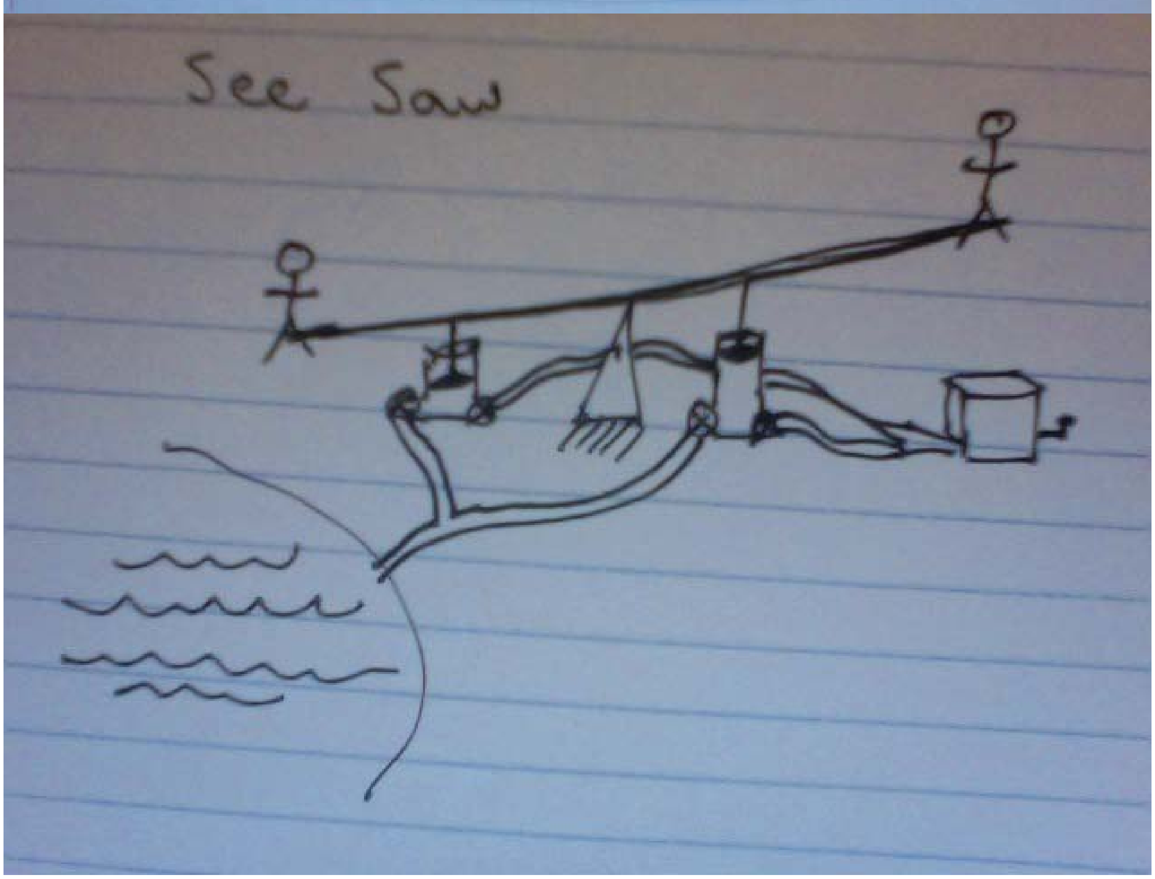
Inorganic Chemicals

Contaminant	Potential Health Effects	Sources of Contaminant in Drinking Water
Arsenic	Skin damage or problems with circulatory systems, and may have increased risk of getting cancer	Erosion of natural deposits; runoff from orchards, runoff from glass & electronicsproduction wastes
Asbestos (fiber >10 micrometers)	Increased risk of developing benign intestinal polyps	Decay of asbestos cement in water mains; erosion of natural deposits
Fluoride	Bone disease (pain and tenderness of the bones); Children may get mottled teeth	Water additive which promotes strong teeth; erosion of natural deposits; discharge from fertilizer and aluminum factories
Lead	Infants and children: Delays in physical or mental development; children could show slight deficits in attention span and learning abilities Adults: Kidney problems; high blood pressure	Corrosion of household plumbing systems; erosion of natural deposits
Mercury (inorganic)	Kidney damage	Erosion of natural deposits; discharge from refineries and factories; runoff from landfills and croplands

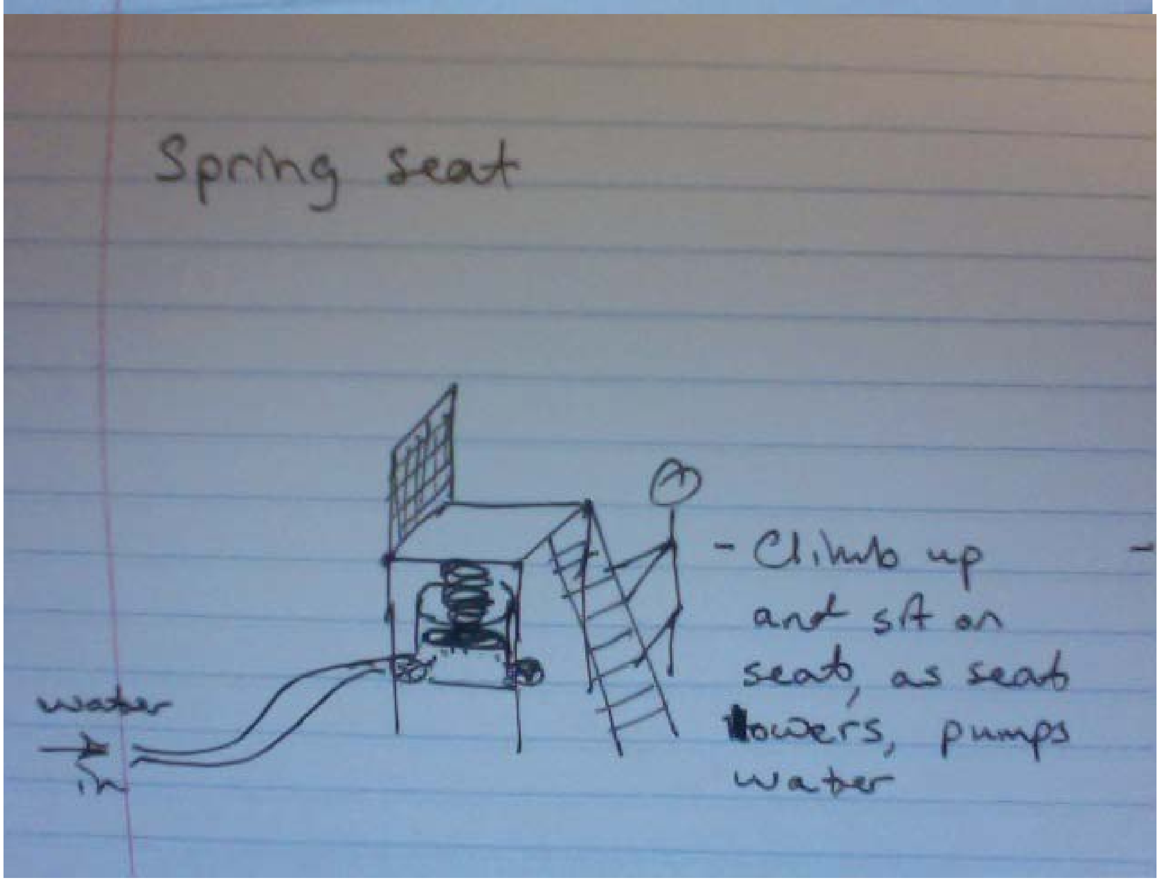
Nitrate (measured as Nitrogen)	Infants below the age of six months who drink water containing nitrate could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome.	Runoff from fertilizer use; leaching from septic tanks, sewage; erosion of natural deposits

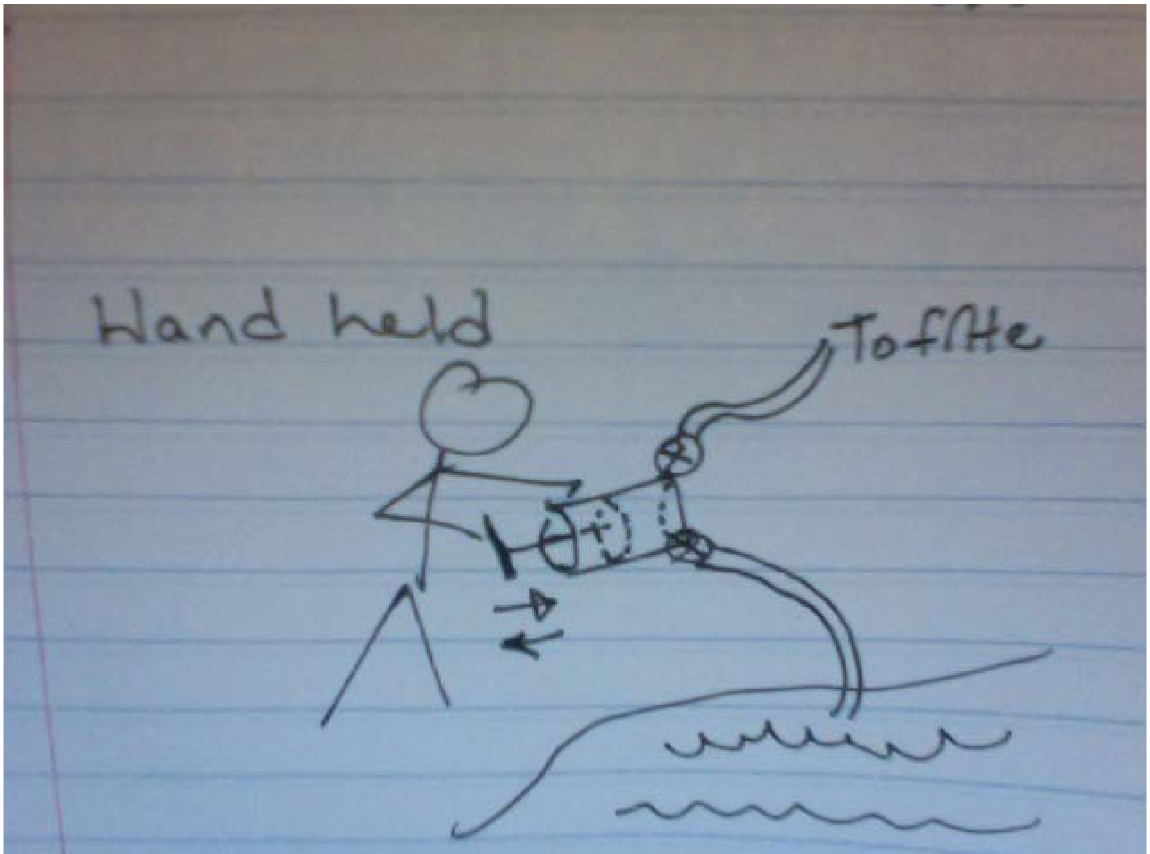
APPENDIX H: Concepts Generated in initial brainstorming session

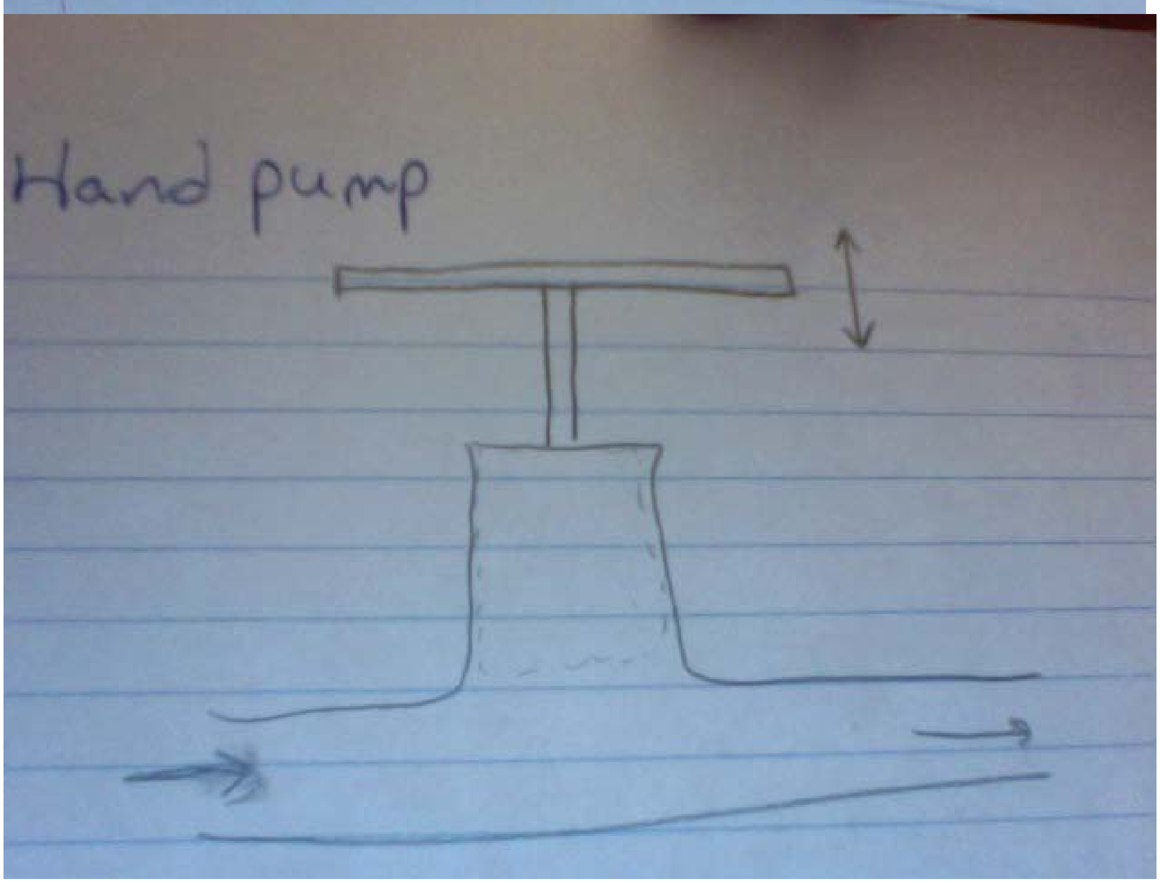




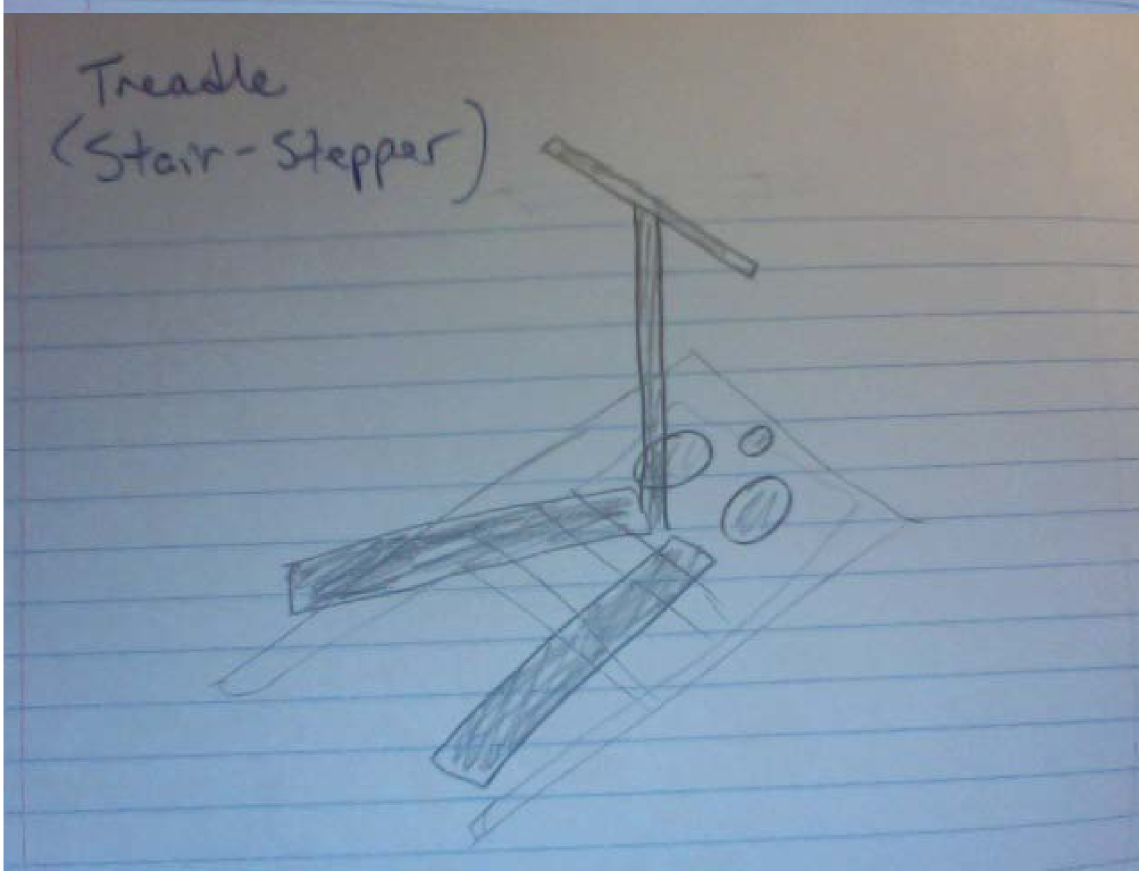

Hand crank


Spring seat
- Climb up and sit on seat, as seat lowers, pumps water
water
in


Hand held
TofAte


Hand pump


Merry-go-round


Treadle
(Stair-Stepper)

APPENDIX I: Parameter analysis calculations

ONE WAY VALVES

$$F = W = V \cdot \rho \cdot g = \left(\frac{4\pi (0.00794\, m)^3}{3}\right)\left(2563 \frac{kg}{m^3}\right)\left(9.8 \frac{m}{s}\right)$$

$$W = 0.0527\ N$$

$$F = P \cdot A = (95658.5\, Pa)(\pi (0.00794 m)^2)$$

$$F = 1.121\ N$$

PISTON ASSEMBLY

ROD

$\sigma = F/A = (10)88.964N / (\pi(0.0127/2)^2) = 7022940 Pa$

$\sigma = 7.02 MPa$

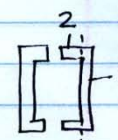
$\sigma_y(Al\text{-}6061) = 55 MPa$

$\frac{55}{7.02} = 7.83$ times difference

$\therefore$ No Failure

HANDLE

$M_y = (10 lb)(10)(6) = \frac{600 lbin}{12 in} = 50 lb \cdot ft$



$I_1 = \frac{b_1 h_1^3}{12} = \frac{(0.065)(0.75)}{12} = 0.0004406$

$I_2 = \frac{b_2 h_2^3}{12} + Ad^2 = \frac{(0.06)(0.065)}{12} + (0.06)(0.065)(0.3425)^2$

$= 0.000782$

$I_T = I_1 + I_2 = 0.001188$

$\sigma = \frac{M \cdot y}{I} = \frac{50 lb \cdot ft \cdot (3/8)(1/12)}{0.001188} = 1315 Psi$

$\sigma = 9.066 MPa$

$\sigma_y(Al\text{-}6061) = 55 MPa$

$\frac{55}{9.066} = 6.07$ times difference

$\therefore$ No Failure

NUT

$\sigma = \frac{F}{\pi/4 (D - 0.9748/n)} = \frac{10(88.964N)}{(\pi/4(0.0127 - 0.9748/6))}$

$\sigma = 0.07563 MPa$

$\sigma_y(steel) = 1200 MPa$ } $\therefore$ No failure

PUMP DIMENSIONS

$Q = C\sqrt{\frac{2\Delta P}{\rho}}$ $\quad$ $Q = 4\,gal/min = 0.01514\,m^3/min$

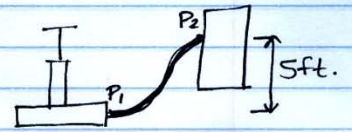
$0.01514\,\frac{m^3}{min} = C\sqrt{\frac{2(29891\,Pa)}{998.2}}$

$C = 0.001956$

$Q = 5\,gal/min = 0.01893\,m^3/min$

$0.01893\,\frac{m^3}{min} = 0.001956\sqrt{\frac{2\,\Delta P}{998.2}}$

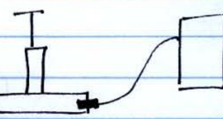
$\Delta P_{FILTER} = 46746.7\,Pa$



$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_L$ ← (hose)

$P_1 = \left(\frac{46746.7}{9782.36} + 5\,ft.\right)(9782.36)$

$P_1 = 95658.5\,Pa$



$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_L$ ← (valve)

$P_1 = \left(\frac{95658.5}{9782.36} + \frac{((1.439)(10^{-4}))^2}{2(9.8)} - \frac{(1.295(10^{-3}))^2}{2(9.8)} + \frac{10(1.295(10^{-3}))^2}{2(9.8)}\right)(9782.36)$

*$K_L = 10$ fully open globe valve

$P_1 = 95658.5\,Pa \rightarrow 13.8741\,Psi$

$F = P \cdot A \rightarrow A = F/P$

$A = 20\,lbs / 13.8741\,Psi = 1.442\,in^2$

$A = \frac{\pi D^2}{4} \rightarrow D = \sqrt{\frac{4A}{\pi}} \rightarrow D = 1.35\,in.$