Multi-Disciplinary Senior Design Conference
Kate Gleason College of Engineering
Rochester Institute of Technology
Rochester, New York 14623

Project Number: 11412

CLEAN WATER UV TREATMENT

Heather Hussain / Mechanical Engineer

Robert Zwecker / Mechanical Engineer

Andrew Baglio / Mechanical Engineer

Andrew Sullivan / Project Lead (ISE)

Daniel Lopez / Electrical Engineer

Sarah Brownell / Advisor

ABSTRACT

The primary goal of this project is to provide a cost efficient water treatment system using Ultra Violet (UV) disinfection technologies to supply drinking water to rural communities in developing countries. We are aiming to lower the overall cost of the original system and improve upon design to increase maintainability and efficiency. The project specifically focused on two main objectives: increasing system efficiency of manual power generation system by inertial increase to rotating driveshaft of B-9 Better Water Maker (BWM) Ultraviolet Water Treatment System, and secondly, increasing durability and optimize the original design to prevent wear and/or damage by environmental conditions to Clean Water for the World's (CW) UV Water Treatment System. In this paper, the design, process, fabrication, experimentation, testing processes and results relating to accomplishing these goals will be described in detail.

NOMENCLATURE

B-9 – The name of one of the not-for-profit customers
BWM – Abbreviation for Better Water Maker, the name of the original crank made by B-9
CW – Abbreviation for Clean Water for the World
CW4TW - Abbreviation for Clean Water for the World
gpm – Abbreviation for gallon per minute
Kg - Abbreviation for Kilogram
Km - Abbreviation for Kilometer
LED - Abbreviation for Light Emitting Diode
LB/LBS- Abbreviation for Pound/Pounds respectively
MOSFIT- Abbreviation for metal oxide semi-conductor field-effect transistor
PCB - Abbreviation for printed circuit board
PZ9- Model of enclosure purchased for CW4TW
RER – Abbreviation for Respiratory Exchange Ratio
RPM – Abbreviation for revolutions per minute
USB - Abbreviation for Universal Serial Bus
UV – Abbreviation for Ultra Violet light
VCO2 – Abbreviation for Volume of Carbon Dioxide
VO2 – Abbreviation for Volume of Oxygen

INTRODUCTION

For millions of people around the world, clean water isn't readily available. In developing countries, women and children spend several hours day collecting water from rivers, lakes and open wells. With limited infrastructure, the task of getting water is an everyday challenge that requires an average walk of 5Km. [1]. After this walk, they then face the rigorous task of trying to eliminate the many contaminates in the untreated water. For many, this task is impossible or is not done thoroughly, and water borne illnesses result.

Every year 1.8 million people die from diarrheal diseases including cholera and E coli [1]. That translates to 4,900 people dying each day, with 90% of those being children under the age of five, mostly in developing countries. For children under the age of five, water-related diseases are the leading cause of death. This mean **a child dies every 15 seconds due to contaminated water.**

According to the World Health Organization (WHO), 1.1 billion people worldwide lack access to clean water, that's approximately one in six people on earth. Furthermore, less than 1% of the world's fresh water is readily accessible for human use. Human use of water has increased by more than 35 times over the past three centuries. The average American uses 80-100 gallons of water at home each day, compared to the average African family, which uses about five gallons per day. Most of our water use is attributed to flushing toilets and bathing. Americans run dishwashers, washing machines, and faucets, often oblivious to how much water we use while taking for granted how easily accessible it is.

The first customer for this project is a not-for-profit organization called Clean Water for the World (CW).

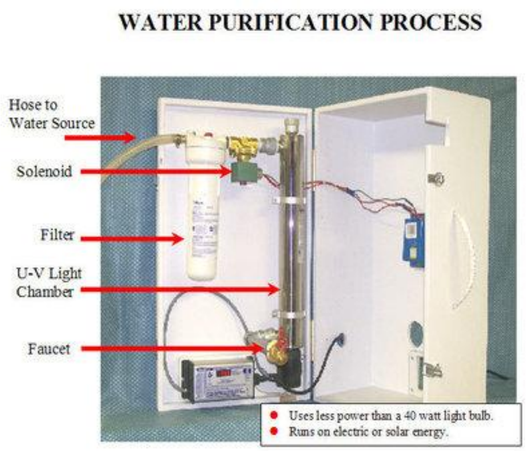


Figure 1: Original Clean Water for the World System

They have developed a solar powered UV water treatment system that can be used in areas without electricity to treat water using a UV bulb. The original system can be seen in **Figure 1.** The team was assigned to improve the enclosure that houses the system and to add an incentive for an individual to operate and maintain the system. Often, nobody maintains the system and it ends up in a state of disrepair. By providing an incentive to maintain it, such as auxiliary power to charge cell phones as a business, we ensure someone will maintain the water system so that they can use the excess power to generate income. The original enclosure was wood and deteriorated over time; therefore the team will implement a cost beneficial solution to counteract this problem.

Our second customer for this project is a not-for-profit organization called B-9 Plastics. The B-9 BWM water treatment system includes a pump and UV disinfection chamber which is manually powered by use of the hand crank, shown in **Figure 2**. The hand crank, however, requires strenuous muscle use, such that the consumer remains at an anaerobic activity level throughout operation of the BWM. Anaerobic activity is not sustainable and therefore is not desirable in this application. The team has redesigned this manual power generation system to make it a more sustainable activity, allowing the user to continuously operate the device and make water for the community.

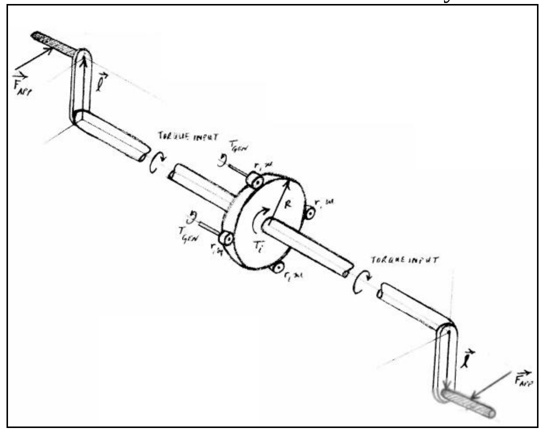


Figure 2: Original Better Water Maker

DESIGN PROCESS (CW)

Mechanical
The design process for the mechanical portion of the CW device was driven by the customer needs obtained through customer interviews. The primary needs of focus were that the redesigned enclosure shall be weather and insect resistant, not weight more than the original enclosure, serve as a shipping container and not cost more than the original enclosure. Environmental effects have played a major role in reducing the useful life of the CW device. The original wood used disintegrates, allowing insects to enter the device and interfere with both mechanical and electrical components. Many options for the enclosure material were available to combat this problem, including untreated wood, pressure treated wood, plastic, metal, and a metal frame with a canvas. Research of these options lead to the formation of a Pugh Diagram which allowed the options to be compared against each other over the critical selection criteria mentioned above. The plastic option had the highest score and was subsequently ranked as the best option

Electrical
The underlying need for the CW electrical system is safety. The user needs to have assurance that the water exiting the system is in fact clean. To achieve this goal, it is necessary to ensure that the UV lamp and ballast are operating correctly during use of the system. To accomplish this, a current sensing circuit was designed and calibrated to provide logic high if the expected current was flowing through the system. Second, it was determined that no water must flow through the system until the UV lamp is fully energized and warmed up. As a result, a timing circuit was added to provide logic high after approximately

20 seconds. The timing circuit combined with the current sensor is used as inputs to control a power MOSFET for the solenoid. This system effectively delayed the flow of water until the system was able perform its germicidal function.
To further provide functionality, feedback to the end user the logic high from the current sensors and timing circuits will then determine if a green LED or red LED are illuminated, indicating the status of the CW system.

To add an incentive to the consumer, a cell phone charging system was added via a buck circuit that efficiently reduces the voltage to five volts, allowing for USB items to be charged. In order to ensure that the operator could only charge USB items when the system was operational, a MOSFET was added to only provide power to the USB power rail when the green safety light is illuminated.

PRELIMINARY DESIGN (CW)

Mechanical

The preliminary design of the CW enclosure encompasses many safety features which will prevent untreated water from exiting the system. The flow of water through the UV chamber was reversed so that untreated water enters the bottom of the chamber and treated water exits at the top. In conjunction with this, the outlet nozzle is located higher than the inlet nozzle. These two features, combined with a solenoid that will close in the event that the UV lamp is de-energized while the system is in operation, will prevent untreated or only partially treated water from exiting the system. Also, the inlet and outlets of water to the enclosure are on opposite sides of the system. This will prevent the inadvertent contamination of the already treated water from spillage associated with pouring untreated water into the inlet bucket of the system.

All mechanical components will be mounted within the enclosure on a plywood backing. This backing serves two purposes; it provides rigidity to the enclosure and ensures that no penetrations through the enclosure will be needed to mount components. Also, the components are arranged in such a way to allow for ease of maintenance. The UV chamber is not recessed within the enclosure, ensuring that when the enclosure is open, the UV bulb can be replaced without having to remove the entire UV chamber from the enclosure. Also, the filter housing is located so that removal of the filter is also permitted without any disassembly of the system. Lastly, the arrangement of mounted components within the enclosure has been optimized to allow for maximum spare filters and UV bulbs to be shipped within the enclosure, supplying between 1.5 and 2 years of equipment to operate the Clean Water for the World device.

A prefabricated plastic enclosure with sturdy hinges, latches and handles was selected. This type of enclosure, PZ9, weighs 9lbs (4.08kg) less than the original design, functions as a shippable enclosure and most importantly, is sealed from the outside environment.

Electrical

When determining the feasibility of the preliminary design, a vector board was used. By using a vector board, the circuits for both water treatment systems could be built with the advantage of ease of modification. This provided critical results in determining points for optimization and improvement before a final PCB would be created. The vector board allowed for identification of critical issues with the timing circuitry that would have required a new PCB to be constructed, costing additional resources if those issues were not found with the vector board. Originally, a 555 timer was planned to provide a one shot after 20 seconds that would feed into a D type Flip-Flop providing a permanent logic high. Unfortunately, the 555 timer requires a trigger other than the initial power supply to provide a one shot, adding circuitry to the system. The system was then modified to use a simple RC circuit to provide logic high after 20 seconds, simplifying the circuit and reducing the cost of the system.

ENGINEERING MODEL (CW)

Figure 3 – Redesigned Enclosure

The solid model in **Figure 3** shows the inside of the redesigned enclosure. As shown, the flow has been modified to provide a safety feature that prevents recontamination, discussed in the Preliminary Design section above. Also, the enclosure is smaller, requiring the components to be optimally arranged and allow easier access to the filter and UV lamp.

Electrical

Please see **Appendix 1 & 2** for original and redesigned electrical system circuits.

TESTING AND DATA ANALYSIS (CW)

Mechanical

The CW device underwent two mechanical tests, a verification of system flow rate test and an endurance and durability of system enclosure test.

The verification of flow rate test was required because of the reversal of water flow through the UV chamber as water will now enter the UV chamber at the bottom and exit at the top. This required the flow rate to be measured to ensure that the system is not impacted adversely, most notably, the flow rate being too great. Too high of a flow rate will cause the water to not be treated properly by the UV lamp. The target flow rate was less than or equal to 5gpm. The flow rate of the system was tested by energizing the system for two minutes and measuring the amount of clean water produced. The test required a stopwatch, water, and two buckets and resulted in a system flow rate of 1gpm, well within the acceptable range.

The endurance and durability of the system enclosure test was designed to verify the customer's needs for a redesigned enclosure. The enclosure needed to be resistant to the environment and durable to shipping hazards. To verify that these needs were met, the strength and clearance of protruding components were measured. Failure of the enclosure occurs when fracture or crack propagation occurs prior to 200lbs (90.72kg) being statically loaded onto the enclosure. To test this, a sheet of plywood was placed onto the test enclosure and weight was added incrementally. The plywood sheet helped to distribute the load evenly, as would be experienced during shipping. The test required a plywood sheet, a test enclosure and masses and resulted in 600lbs (272.16kg) of weight statically loaded onto the enclosure with no fracture or crack formation, well above the minimum acceptable loading.

Electrical

The CW system underwent three electrical tests, a test of the LED circuits, test of the time delay for phone charging and a test of the cell phone charging system.

In order to test the CW system LED circuits, water is placed in the input valve and the system is energized, allowing water to flow. The green LED must be illuminated approximately 20 seconds after the system is turned energized. Afterwards, the power supplied to the solenoid is removed and the red LED must illuminate and no water should flow. When the final PCB for the CW system was connected to the system and activated, the current sensors provided the correct logic high when applicable and the timing circuit provided logic high after 7 seconds.

Power to the USB ports should only be available when the green light is illuminated. This will be tested by connecting a cell phone to each USB port and observing the charging behavior of all cell phones when the LED is both green and red. Furthermore, all USB ports will be connect to a cell phone to ensure that the system is capable of charging all cell phones simultaneously.
During testing, 4.8 volts was supplied to each USB port. In order to confirm that the system was capable of charging cell phones, two phones were connected to the system and both cell Phones provided indication of charging, verifying that that the USB ports perform as expected.

DISCUSSION (CW)

The redesigned enclosure cost $40.97 to purchase whereas the original enclosure cost $35.74 to fabricate. A cost-benefit analysis, see **Table 1** below, estimating the shipping costs due to the reduced weight was performed and it was revealed that in spite of the redesigned enclosure being more expensive, the redesigned enclosure yielded a net savings of $31.77 when shipping was included. This cost-benefit analysis does not take into account the anticipated increased enclosure lifetime for the redesigned system. The original enclosure has a lifetime of about 1.5 years before needing to be replaced, whereas the redesigned enclosure is anticipated to have a longer lifetime due its resistance to the environment.

	Original Enclosure	Redesigned Enclosure
Cost to fabricate / purchase (USD)	35.74	40.97
Increase in price/ cost of enclosure for redesign (USD)		5.23
Loaded Weight (lbs)	35	26
Estimated Shipping Costs (USD)	332	295
Reduction in shipping costs for redesign (USD)		37
Net Savings for Enclosure Redesign (USD)		31.77

Table 1: Cost-Benefit Analysis of CW Enclosure Design

After testing the water flow, it was found that the CW system produced 1gpm. Although this is less than the original 5gpm, the 1gpm flow is acceptable because it ensures the water is exposed to the UV bulb long enough to ensure adequate treatment. Also, the flow rate could be increased by placing the inlet bucket higher above the system, allowing for more head to be produced.

DESIGN PROCESS (B-9 BWM)

Mechanical

Various concepts were considered throughout the manual power generation design process for the B-9 BWM. The design process was driven by two simple concepts presented by the customer: novel and cost-constrained. Three detailed concepts were preliminarily designed including a see-saw, spring floor, and drive-shaft flywheel. An intelligent system improvement that fit closest to the cost constraints detailed by the customer proved to be the flywheel based on preliminary design analysis and cost calculations.

Flywheel Theoretical Analysis

$$\left\{I_R + 4\left(\frac{R}{r}\right)^2 I_r\right\}\mathring{\varpi}_R + \left\{B_R + 4\left(\frac{R}{r}\right)^2 B_r\right\}\varpi_R = T_i - 4\left(\frac{R}{r}\right)T_L$$

Equation 1: First Order Mechanical System Response

$$\frac{\Omega(s)}{T_i(s)} = \frac{L_2 s + R_2 + R_{load}}{[den]}$$

$$[den] = \left(I_R + 4\left(\frac{R}{r}\right)^2 I_r\right)L_2 s^2$$

$$+\left[\left(I_R + 4\left(\frac{R}{r}\right)^2 I_r\right)(R_2 + R_{load}) + \left(B_R + 4\left(\frac{R}{r}\right)^2 I_r\right)L_2\right]s$$

$$+\left[\left(B_R + 4\left(\frac{R}{r}\right)^2 I_r\right)(R_2 + R_{load}) + A^2 k_{tach}\left(\frac{R}{r}\right)\right]$$

Equation 2: Transfer function of Overall Manual Power Generation System, includes electrical and mechanical component interaction

The above equations were derived using the system response of components within the current B-9 system.

Electrical

The BWM originally had safeties built into the system, however, better indication to the user on the appropriate crank speed was required. Speed is proportional to voltage in a DC permanent magnet motor, and in many cases, the user of the original model was cranking too fast and thus wasting energy. Unfortunately, due to limitations on the cost of the total system, a sophisticated feedback to the user could not be implemented effectively, therefore requiring a simpler and cost effective method to be used. Several voltage comparators were placed at the output voltage of the generators to monitor the rotational speed of the hand crank. When the voltage reaches a set voltage, an LED will illuminate indicating the speed to the user. Three LED's were implemented to supply feedback to the user; a red LED to signify the rotational speed is too slow, a green LED to indicate that the rotational speed is appropriate and therefore supplying adequate voltage to the system, and a yellow LED to indicate that the rotational speed is too fast and that the user is wasting energy. This provides the user with a better understanding of the voltage that is supplied to the system and allows the user to adjust accordingly. A voltage regulator for the system was added to further regulate the generator voltage to the 12 volts required for the UV water treatment system.

PRELIMINARY DESIGN

Mechanical

To enhance the current system, we have decided to add a flywheel to the driveshaft as shown in **Figure 4**. The additional moment of inertia supplied by the flywheel acts as a source of rotational energy storage, so that when torque input on the drive shaft goes to zero, the energy stored in the flywheel will be absorbed by the load, essentially adding momentum to the system. The current torque input seems to resemble a rectified sine wave as the operator applies a "push-pull" type of motion to the handles of the power generation system. There is also an almost instantaneous deceleration to zero of angular speed due to significant damping within the system. The flywheel should serve two purposes in this application: "smooth" out torque input to avoid rectified sine input and increase inertia of the system to decrease negative angular acceleration. These two improvements should allow the consumer to more efficiently treat their water for potable and consumption purposes.

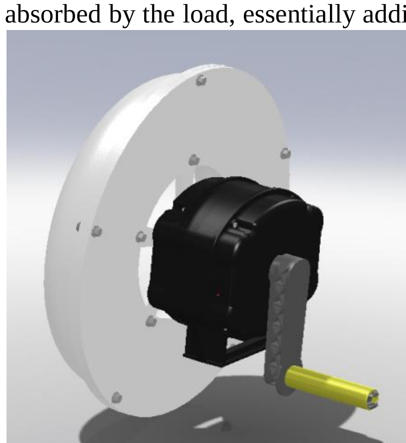


Figure 4 - Rear View of BWM with Flywheel Installed

To determine flywheel design characteristics, the current system parameters and behavior needed to be modeled such that system performance improvements could be simulated. As shown in **Equation 1** and **Equation 2**, moments of inertia and damping coefficients need to be determined to define the mechanical system. Inductance, resistance, and generator characteristics need to be determined for the electrical system. The transfer function shown in **Equation 2** relates the mechanical and electrical systems with angular speed as the output and torque as the input. Parameters were determined through experimental investigation and tested against the system model.

Electrical

By first implementing a vector board, a key implementation flaw of the voltage comparator was exposed. The voltage comparator supplied an output high when the inputs were equal, not low as expected. To ensure proper operation, a voltage dividing system was created, reducing the input voltage experienced by the comparator. The zener diodes used as a reference voltage for the comparator voltage behaved nonlinearly and did not function as expected. This was a result of the size of the resistor supplying current to the zener diode. When the resistor was reduce to 1KΩ from 1MΩ, the diode performed as expected, providing proper functionality for the comparators.

ENGINEERING MODEL (B-9)

STRESS MODELING

The stress analysis of the flywheel assumes a rotational velocity of 120 rpm (25.13 rad/sec), which is based on rotational velocity of the system while in use. Also, a pressure load of 3.5 psi (24,131.65 Pa) is applied to the inner edge of the outer wall of the flywheel. This pressure load is based on the centrifugal force applied to the outer wall from the material loaded within the flywheel. The outer wall is the area of most concern for stress because of the centrifugal forces.

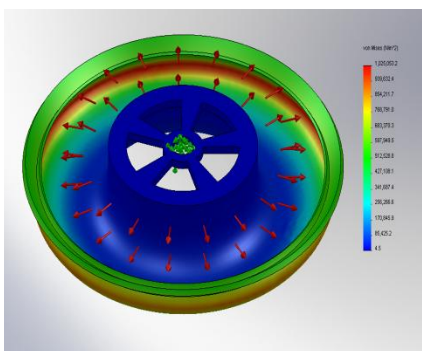


Figure 5: Von Mises Stresses of Flywheel

A finite element analysis was conducted within the SolidWorks package. The maximum stress that the flywheel experienced is 1.03 MPa and as anticipated, it occurs on the outer wall. This maximum stress is far below the ultimate stress limit of 20.00 MPa for ABS plastic, indicating that the flywheel is sufficiently designed to withstand the forces it will experience.

SYSTEM MODEL

A simulink model of the BWM unit was made, and the effect of adding inertia to the system was investigated. Simulation results for an arbitrary inertia gain are shown in the **Figure 6** and **Figure 7** below. The blue curves represent a first cut analysis of the original

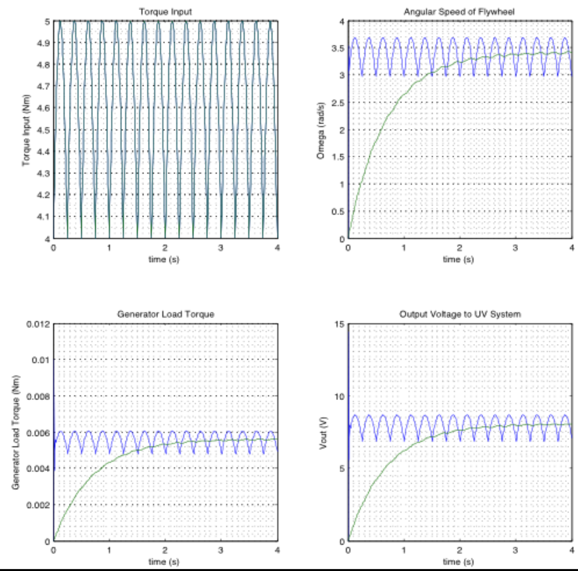


Figure 6: B-9 Manual Power Generation System Response with Rectified Sine Wave Torque Input- Rise Time

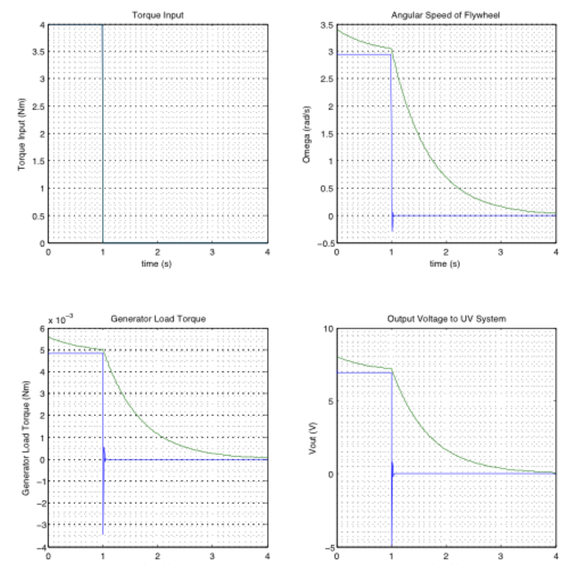


Figure 7: B-9 Manual Power Generation System Response with Rectified Sine Wave Torque Input- Decay Time

BWM system, and adding inertia to the system producing a system response detailed by the green curves. The addition of the flywheel, mechanical energy storage element, shows a much smoother output in terms of angular speed, torque, and output voltage in **Figure 6**. The decay time also increases significantly with increased inertia as shown in **Figure 7**. When the torque input goes to zero on the original unit, the damping in the system forces the drive shaft to decelerate drastically. With an additional energy storage component, the energy stored within the flywheel will take over when the torque input goes to zero, and the system will remain in motion longer

ELECTRICAL MODEL

The final engineering model requires a heat sink for the buck circuit. The voltage regulator has a built in shutoff that disables the system when the heat of the circuit exceeds a preset threshold.

TESTING AND DATA ANALYSIS (B9-BWM)

ERGONOMIC TESTING

A VO2 test is used to see how much oxygen is required to do a certain task. This data can then be extrapolated to find the users respiratory exchange ratio (RER), calorie usage, and overall ability to make water with the device. The test consists of being hooked up to a breathing tube that captures all of your oxygen and CO_2 production. The user's nose is plugged and they wear a heart rate monitor which feeds data directly into a computer. The time is recorded as the user reaches every 1/8 gallon increment. The VO2 and VCO2 data was graphed and when the VCO2 surpassed the VO2, it is clear that the user will soon tire. This allows the team to see how long it takes to make a gallon of water and it also shows how much water can be made before the user reaches exhaustion.

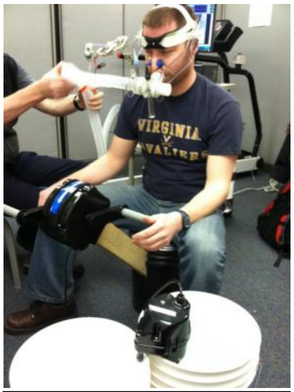


Figure 8: Ergonomic Test

During the ergonomic testing, it was observed that the system operated as expected mechanically; no vibrations and the system maintained structural integrity.

ELECTRICAL TESTING VALIDATION

When testing the B9 BWM, a voltage meter is placed at the generator output. Each LED should only illuminate when the voltage comparators input voltage is greater than the reference voltage. The red LED illuminated at 11.9V, the green at 13V and the yellow at 16V.

DISCUSSION

ERGONOMIC RESULTS

Data for the ergonomic testing is shown in **Figure 9** and **Figure 10**. When comparing the original configuration to the redesigned BWM with the flywheel, it is clear that the user is capable of both producing more treated water and operating the system for a longer period of time. Robert Zwecker and Andrew Baglio both doubled the amount of water they produced before tiring, while also increasing operation time tiring by 150% and 400% respectively. Heather Hussain also experienced improvement by increasing the amount of water produced and operation time before tiring by 50%. Also, when examining the VO2 output, it is noticeable that users took longer to get to the point where their VCO2 surpassed VO2. This indicates that the user can sustain the activity for a longer period of time.

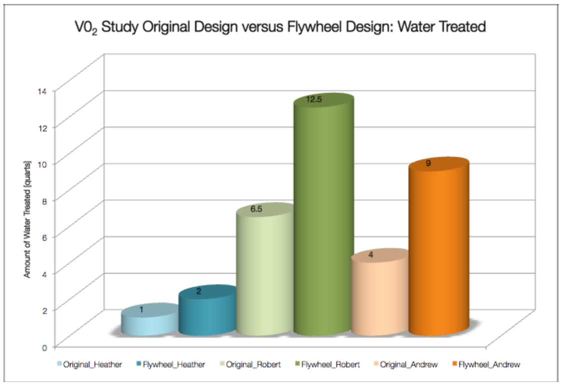


Figure 9: Ergonomic Test Results of Production of Treated Water

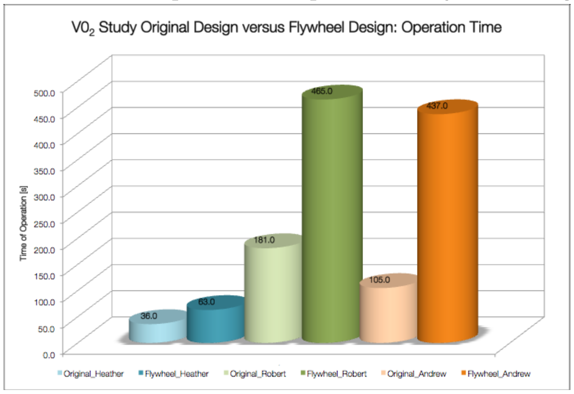


Figure 10: Ergonomic Test Results of Operation Time of BWM

ELECTRICAL TESTING

The Final B9 circuit was able to perform as expected, the voltage regulator supplied power to the BWM. Also, the LED's providing user feedback performed as expected, allowing the operator of the redesigned

BWM to exert less energy by maintaining the appropriate rotational velocity.

CONCLUSIONS AND RECOMMENDATIONS

CW

The cost-benefit analysis with consideration of reduced shipping costs due to reduced weight of the overall system was performed and revealed a net savings of $31.77/unit. The significant increase in enclosure life should also be considered when examining net savings for the CW system. The original enclosure has a lifetime of about 1.5 years before needing to be replaced, whereas the redesigned enclosure is anticipated to have a much longer life. Also, due its resistance to the environment because of its plastic construction with rubber grommets sealing all penetrations, the system will be able to withstand severe weather, direct sunlight, and prevent insect tampering. The functionality of the cell-phone charging system has added incentive for individuals to operate and maintain the system. All primary customer needs for the CW system have successfully been met. It is recommended that the UV chamber be studied next to reduce cost further.

B-9 BWM

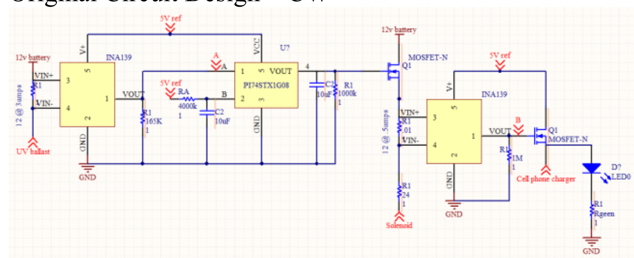
It has been observed that the high required rotational speed is a major contributor to the operator discomfort. If the speed was decreased, and the flywheel remained part of the assembly, easy of system use would increase even further. Future explorations would investigate different generators to obtain better efficiencies at the operating speed, and also, gear the drive shaft to reduce the rotational speed the operator must maintain. Also, the flywheel increases the weight of the BWM system by approximately 25 lbs. The system needs a much heavier base to keep the unit upright and stable during operation. It would be recommended to add an additional structural member to the wood mounting of the BWM, much like a truss member. All primary customer needs for the BWM system were successfully met.

REFERENCES

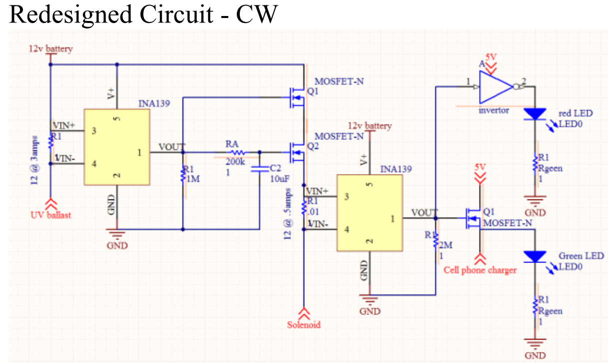
[1] http://www.cleanwaterfortheworld.org/

APPENDIX

1.
Original Circuit Design – CW



2.
Redesigned Circuit - CW



ACKNOWLEDGMENTS

The team would like to give a special thanks to the following individuals:
Harbec Plastics, Bob Bechtold, Kate Pilletteri, Clean Water for the World, Sarah Brownell, Gerry Garavuso, ME Machine Shop Team, Dr. Stephen Boedo, Dr. Mark Kempski, Mr. John Wellin, Dr. William Brewer, Dr. Robert Bowman, Dr. Chris Hoople. The team appreciates all the help given and could not have completed the project without your continued support.