Multidisciplinary Senior Design Conference
Kate Gleason College of Engineering
Rochester Institute of Technology
Rochester, New York 14623

# Project Number: P18461

## SOLAR-POWERED ULTRAVIOLET WATER PURIFIER

**Erik Messier**
Biomedical Engineering

**Justin Morris**
Electrical Engineering

**Ryan Ortiz**
Electrical Engineering

**Aaron Spinney**
Electrical Engineering

**Graham Ardner**
Mechanical Engineering

**Alexander Kessler**
Mechanical Engineering

**Phil Sammon**
Mechanical Engineering

## Abstract

The solar-powered ultraviolet (UV) water purifier allows people without access to improved water sources to produce potable water. The device consists of two filters, a UV light, and a solar panel that charges the system. When the device is placed near a water source, a pump will draw water from the source and force it through the filters where particulates and harmful materials are removed. The water then collects in a chamber where the UV light neuters any bacteria in the water. The system then outputs the potable water to a receptacle of the user's choice.


## Introduction

Our customer wants a unified system that combines features of multiple products that they use to produce potable water. To achieve this function, they require a small, light product that is rugged enough to withstand the pressure and current of the water, but also provides clear, clean, palatable water from the filthiest of samples. The device needs automated capabilities and a simple design for easy use. We defined all these requirements and their priority in order to identify the feasibility of meeting the initial constraints. Table 1-1 identifies all the requirements and their priority for potential flexibility.

| Customer Requirement # | Description | Priority | Category |
|---|---|---|---|
| CR1 | Backpack transportable | 9 | Portable |
| CR2 | Lightweight (can be carried by one adult) | 3 | Portable |
| CR3 | Non-battery powered (no disposable batteries) | 9 | Functional |
| CR4 | Rugged design to handle harsh surroundings | 9 | Durable |
| CR5 | High flow rate through water purification sys | 3 | Functional |
| CR6 | Clean drinkable water | 9 | Functional |
| CR7 | Automated system, not human powered | 9 | Functional |
| CR8 | Simple design, minimal seperate components | 3 | Durable |
| CR9 | Low final-unit cost | 3 | Project |

*Table 1-1 A table of the customer requirements sorted by priority*

From these requirements comes the motivation for a small, fully functioning, multi-faceted system with the functionality of all the simple products in circulation at the time. These products include the Sawyer Squeeze and SteriPEN which use filtration and ultraviolet light respectively to filter or purify the water for safe consumption wherever used. For practical purposes, we need the filter to clean the water and reduce its turbidity for the ultraviolet light to be fully effective. After benchmarking and functional analysis, it's clear that the system requires a prefilter for the carbon block filter since the carbon block filter only safely intakes clear water. The carbon block filter in turn provides the cleanest water possible for the ultraviolet light to neuter any remaining bacterial contaminants and viruses. A solar panel generates the power needed to run the automated system including the pump, circuitry and ultraviolet lamp. A battery is included as a back-up plan for when the natural energy of the sun is insufficient for proper operation. Thus the hybrid-integrated portable purification operation, affectionately named the HIPPO, comes to be.

## 1-1 Mechanical Schematics

The customer requirements, benchmarking, and functional decomposition, leads to the preliminary model. The initial design uses gravity and a pump in order to push water through the filtration system. This system is broken down into 3 chambers, the first chamber being a coarse micro filter, catching mostly particulates and larger bacteria. The following chamber has the fine ultra filter carbon filter which removes any smaller viruses or bacteria as well as chemicals or trace heavy metals that could be in the water such as lead. The final chamber contains the UV lamp which sterilizes any remaining bacteria in the water. The entire system is modular because the chambers can be fitted with different types of filters to meet any customer's specific needs.

The section view of the initial design shown here in Figure 1-1 shows the three chambers with the electrical housing beneath the entire system in order to connect to the bulb. The chambers are threaded into each other for durability and ease of assembly, making this a portable design as well. Figure 1-2 shows the design of a custom part to connect the filter chambers.

*Figure 1-2 The initial design for a connecting piece in between filter chambers.*

After discussing the manufacturing side of this system, we decided to pivot the design. Instead of using the column style design, we determined it was better to use cheaper, standardized housings already designed to withstand pressure and already meeting standard sized filter requirements.

This did however create the necessity for a more powerful pump. Additionally, a UV bulb of this size requires connections on both ends, which created another risk of water leakage. We finally decided on standardized filters, with adesigned UV chamber using 3D printed end caps sized to the dimensions of a quartz sleeve.

The design in Figure 1-3 displays the UV purification chamber with two open ends for the quartz sleeve and bulb. The sleeve protects the bulb from the water inside the chamber. We added two solenoid valves to the ends of this chamber in order to control the water flow; we threaded these solenoids into the 3D printed end caps. After adjusting the fit for the end caps and adding O-rings along the outside, the chamber became watertight.

This the final design shown in Figure 1-4 includes the standardized filters, the UV Chamber, the support structures and the electronics housing. The pump, solar panel, solenoid valves and tubing between the housings are not displayed. The barb fittings used between all of the connections are also not displayed. The support structure in between the housings is plywood in the center and 3D printed elbows at the base to hold the entire structure up. 3D printed clamps are used around the filters and UV chamber in order to hold the items in place, but the filters can still easily be removed.

*Figure 1-4 The final design of the HIPPO*

For the final construction of the UV chamber system, we used several techniques with the 3D-printed parts to allow them to perform functions that no other part on the market could provide. Additionally, the printed parts were used in ways that 3D-printed parts are not typically used.

First, we used a double-gasket design with two embedded O-rings to provide waterproofing between the printed end cap parts and the white schedule 40 PVC tube. One challenge was getting the exact O-ring channel depth and effective O-ring compression as a percentage of its total volume for optimum waterproofing. With a few iterations we were able to arrive on a final design that held water.

Second, we needed to interface the 3D-printed part with NPT tapered pipe threads. The solenoid valves were designed for fitment with typical plumbing threads and needed a secure connection to the UV chamber end caps. While printed threads are not terribly difficult in CAD and 3D printing, it becomes much more difficult when you move from standard, non-tapered machine screw threads (i.e. 8-32, ¼-20, etc) to tapered pipe threads. The solution was to use the average diameters of the starting and ending threads and using the best estimated threads per inch and manually revolving the threads in Solidworks. The result was a good thread fit that mated well with the solenoids and provided a good watertight fit.

## 1-2 Mechanical Construction

*Figure 1-5 Initial build* *Figure 1-6 Side view of initial build*

The final build design displayed in Figures 1-5 and 1-6 shows the tubing and solenoid valves. The filters are easily accessible by removing the housings from the clamps, and the support structure in the middle has a handle for portability. The UV chamber is held in place with two 3D printed clamps. The underside of the chamber and support structure has a cutout where the second solenoid valve is attached. The housing for the electronics will be mounted underneath the structure. The quartz sleeve with the bulb will go through the center slot of the UV chamber.

## 2-1 Electrical Schematics

For the electrical portion of this project the major requirement was that the device be solar powered while still remaining portable. This limited the design because solar panels which would be able to supply the required power are not portable. For this, we selected a smaller solar panel to be used in conjunction with a 12V SLA battery to meet the power and budget requirements of the project. The system required a boost regulator charging circuit since SLA batteries need to be charged at 14V while the solar panel only supplied 12V. We used the LMR61428 to meet the power requirements of the solar panel. Equation 2-1 obtains the required $V_{OUT}$ to select the required resistor values.

$$RF2 = RF1/[(VOUT/1.24)-1] \qquad (2\text{-}1)$$
$$VOUT = 14V\ ,\ RF1 = 150k\Omega,\ RF2 = 147k\Omega$$

From the requirements the resulting circuit was designed and shown in Figure 2-1.

*Figure 2-1 The boost regulator charging circuit design*

Concerning electromechanical devices, the project requires a pump to move the water and two solenoids to isolate the UV chamber and control outflow. To adhere to standards and ensure safe water a flow sensor was added to count processed gallons, memory to track total runtime, an ADC to track current battery level, and an LCD control panel for user interaction. The system additionally requires a microcontroller to process the sensor data; we selected the ATtiny85 for its small profile, low cost, and familiarity. Due to lack of pins on the ATtiny85, we used two ATtiny85's communicating to each other through i2c because it was more cost effective than purchasing a larger microcontroller. The main communication protocol used for the microcontrollers to the sensors is i2c since it only requires 2 pins for the microcontrollers to communicate with the sensors. For the main controller, we used a custom bootloader to bit-bang USB communication to allow for easier programming and debugging. Figure 2-2 and 2-3 show the resulting sensors and circuit.

*Figure 2-2 Dual microcontroller setup*

*Figure 2-3 Peripheral sensors setup*

## 2-2 Electrical Construction

After the initial design process and calculations for the boost regulator, the system was reconstructed on a protoboard. The first step of this process was to procure the proper components required to construct the regulator. Originally, the board was to be professionally printed on a PCB, however the budget constraint would not be able to cover the costs. The original components selected for use in the system were all surface mounted components with a power rating of 1W each to ensure that none of the components would burn in the worst-case scenario. Unfortunately, due to the size of certain surface mounted components, in this case the TI boost regulator chip, the footpads were impossible to solder directly onto the protoboard. To bypass this issue, we soldered the regulator chip onto a breakout board which we then inserted into the protoboard with the rest of the circuit.

When dealing with surface mounted components, the process of soldering the chips onto the board is much different than when dealing with through hole components. Since surface mounted components are not meant for use on protoboards some alterations to the protoboard was required to ensure proper connection. To avoid extra connections that could potentially short out the components, an Exacto knife was required to scrape out the plating in the holes between the placement of the chips. By doing so, the solder when applied to the foot pads on the chip will not flow to other areas causing shorts in the circuit. The use of tweezers and optics to check for strong connections was also necessary due to the size of the components and connections. The first iteration of this circuit is shown in the figure above. Due to the size of the 1st iteration of this circuit, a second iteration using through hole components to simplify the process was constructed to save space in the electrical enclosure. With the boost regulator circuit completed, the only step left in the construction process was to select a proper electronic enclosure to house the buck converter, ATTINY microcontroller circuit, and the boost converter circuits along with the battery. In this case, there were many different methods of selecting an enclosure. To save time, instead of 3D printing a custom enclosure, a prebuilt NEMA 4X rated enclosure with internal PCB mounting plates and an easily accessible hinged lid was selected. Since NEMA 4X rated enclosures are built to withstand a variety of weather conditions including snow, hail and rain, the enclosure suits the needs of this design.

## 2-3 Electrical Testing

We ran a monitored charging test to record the battery charging characteristics. We attached the battery to a regulated power supply which gave 14V and was current-limited to 0.7A for safety precautions. Both the current and voltage were then manually recorded every two minutes until the charging current dropped to 0.1A to ensure the battery was charged. The results in Figure 2-6 showed that the battery was acceptable to use and had a total charge time of around six hours.

*Figure 2-6 A graph of the battery charging characteristics*

## 3-1 Ultraviolet Treatment

Although there are many methods to remove microbiological contaminants from water, the method that we decided to implement in our system is ultraviolet (UV) treatment. Our customer is looking for a portable, sustainable system that is microbiologically effective that still produces visually appealing and palatable water. The collusion between upstream carbon block filtration and downstream UV filtration should provide a moderately priced optimization between water quality and flow rate. The carbon block filter that we are using in our system is a CFBC series Pentair Pentek; it uses both size exclusion through 0.5 micrometer pores and ionic interactions between water contaminants and its matrix of powdered activated carbon and thermoplastic binders [2.C.1]. The carbon block filter is able to remove odor causing bacteria, fungus, and spores through size exclusion, and odor causing chemicals such as pesticides or hydrogen sulfides from the water through ionic interactions. Therefore, the effluent stream from the carbon block filter in our system should be clear water containing viruses and smaller bacteria, which is a perfect scenario for UV treatment implementation.

In exposing microbiological contaminants to UVC (100-280 nm wavelengths) irradiation, the UV light is absorbed by the nucleic acids (building blocks of DNA or RNA) of the contaminants. If an appropriate fluence or dose (measured in $mJ/cm^2$) of UV radiation is administered, the contaminants can be rendered sterile and effectively inactivated [2.C.2]. According to NSF/ANSI standard 55 for Ultraviolet Microbiological Water Treatment Systems the minimum dosage to produce an about log 4 reduction in common waterborne pathogens is 40 $mJ/cm^2$ in clear (<= 1 NTU) previously unpurified water [2.C.3]. In order find the time required to treat the water in our UV reactor (or module) we implemented computational models of UV irradiation (dose rate) for the specific geometry of our system, and we also performed wet lab work in order to validate this model.

## 3-2 Ultraviolet Modeling

There are many accurate numerical UV irradiance modeling techniques, however the technique used here is the Modified (or integral or Line Segment Integral (LSI)) Multi-Point Source Summation (MPSS) model. MPSS assumes that the emission of a linear lamp is equivalent to n point sources equally spaced along the longitudinal axis of the lamp [2.C.4]. In using the optical properties of light at the 3 different mediums through which light passes within the system (air between the bulb and quartz sleeve, quartz sleeve, water) the contribution of a UV power from a point source to a cross sectional surface area within the water medium can be calculated, as shown in Figure 3-1 [2.C.4]. The total irradiance at a specified surface area is the summation of all contributions from the point sources [2.C.4]. If refraction and reflection are ignored between the different mediums, an analytical solution to this model exists as the number of point sources approaches infinity, which is the LSI MPSS [2.C.4]. This model is less difficult to implement, and can be just as accurate as the traditional implementation of MPSS with the inclusion of an attenuation factor, which accounts for reflection and refraction at all mediums. The attenuation factor is simply a ratio between the LSI MPSS and the traditional MPSS for a specific point that the irradiance is being calculated for; however as opposed to using thousands of point sources which can be computationally inefficient, the attenuation factor can be accurately calculated with 5 or 10 point sources along the bulb [2.C.5]. This allows for efficient and easier calculation of irradiance at a desired point. For more detailed information (i.e. equations, methodology, etc.) refer to the UV modeling documentation on P18461 EDGE page.

Furthermore since our system is static, we will not need to include particle tracking, or computational fluid dynamic analyses, therefore we can just look at the average irradiance in the system since we are concerned with the total concentration of microbiological contaminants receiving a log 4 reduction. The average irradiance is proportional to the surface area of water being treated; therefore, once the irradiance is calculated at multiple points longitudinally across the lamp, the radial irradiance at a given point can be calculated as the weighted average of irradiance relative to radius [2.C.6]. For example, if you are calculating the irradiance from the center of the bulb at radial increments of 0.01 cm to the wall of the reactor, the average irradiance will be the irradiance at each 0.01 cm increment weighted by the normal distance between the center of the bulb and the radius.

The results of our modeling are shown in Figures 3-2 and 3-3. We will conservatively be dosing water within our reactor to about 60 mJ/cm$^2$ to account for any assumptions within the model, therefore the amount of time required to treat water within our UV reactor will be about 20 seconds. Also, considering the dimensions of the inlet and outlet connections to the UV reactor, it is possible to model the amount of time for a single cycle of treatment --- water entering the reactor, being treated, and being emptied from the reactor --- to occur. Since we know the dimensions of our reactor we can model the time required for water to leave the reactor as a 1$^{st}$ order ordinary differential equation when only hydrostatic force is used to empty water from the chamber --- as shown in EDGE documentation --- which will take about 25 seconds. Since we will likely have variable inlet flow into the UV reactor based on the pumping and upstream filter conditions, we can look at variable inlet flow into the reactor to find the time required for the reactor to fill with water. Using the total cycle time --- fill up, treat, and empty --- we can approximate the pulsatile flow rate through our system as the amount of water treated per cycle divided by cycle time. These flow rates are shown in the right graph of Figure 3-3.

*Figure 2.C.1: Figure from [2.C.4] showing the path of light from point source A to destination B for the MPSS model. Thetas represent the angles of incidence at the borders between the 3 mediums. The variables $d_1$, $d_2$, and $d_3$ represent the path length that light travels through a specified medium; air, quartz, and water, respectively. The variables $r_1$, $r_2$, and $r_3$ represent the thicknesses of each medium, and r represents the normal distance between the point source A and destination B. h represents the longitudinal distance along the bulb between the destination and the source. The variables $n_a$, $n_q$, and $n_w$ represent the refractive indices of air, quartz, and water, respectively. $T_q$ and $T_w$ represent the 1 cm transmittance of UV light through quartz and water, respectively.*

*Figure 3-2 Average Longitudinal intensity within reactor weighted by radius*

*Figure 3-3 LEFT: Dosage with respect to time of our UV reactor with an average calculated intensity (dosage rate) of 3.191 mW/cm$^2$. Dotted lines represent reference dosages in mJ/cm$^2$. 60, 40, 10, and 5 mJ/cm$^2$ represent the dosage that we are treating to, minimum dosage noted by NSF/ANSI 55, and two dosages along the T7 inactivation curve, respectively. Circles note intersections between reactor dosage and references. RIGHT: Approximated flowrate through the system when treating to 60 mJ/cm$^2$.*

## 3-3 Ultraviolet Testing

One of our customer requirements is to validate the microbiological purification of our system. We will accomplish this by spiking water with viable viruses and running the water through our UV batch treatment subsystem alongside a control sample of the spiked water. We will then enumerate the viruses in the test and control water by serial dilution and culturing on plates containing E. Coli. Living viruses will form plaques with the E. Coli, which in conjunction with the dilution of the viruses allows for the quantification of E. Coli in the form of plaque forming units (pfu) [2.C.7]. By comparing the plaque forming units per volume of tested solution for both the test and control waters we can calculate the log reduction as the reduction of pfu/mL from the control to test solution. The formal name for the enumeration of viruses with bacteria is called Bacteriophage Plaque Assay, and more in depth descriptions of this procedure can be found online, specifically the USEPA's Method 1602 is used as a reference here.

Conventionally --- as can be seen in Method 1602 --- Bacteriophage Plaque Assays are carried out with MS2 Coliphage (phage (virus) that infects E. Coli), however since no one on campus has experience in propagating and using MS2, and since it is not available on campus, we will be using T7 Coliphage. The log inactivation of both viruses when subjected to UV radiation can be seen in Figure 3-4 and 3-5 [2.C.8][2.C.9]. At minimum according to NSF/ANSI 55 we are required to administer 40 mJ/cm2 at the alarm set point of the system, and this is the normal dosage administered by other portable UV purifiers such as the SteriPEN Ultra. Since our system does not agitate water we will shoot for applying about 60 mJ/cm2 of UV radiation to make sure that we are destroying some of the more resilient viruses such as adenovirus. The time required to reach this dosage is approximated by our MPSS LSI model of UV dosage rate at the wall of our UV Batch Treatment subsystem. This model calculates the Dosage rate at the wall of the reactor, which essentially the dosage/time with units mW/cm2 or mJ/sec*cm2 . Unfortunately T7 inactivates relatively quickly, so we will not test the effectiveness of our model directly by applying what we think is 60 mJ/cm2 , because T7 inactivation saturates at about 10 mJ/cm2 . Therefore we will compare our system to the SteriPEN Ultra, which has a known dosage rate at the wall of a 500 mL beaker as shown in the experiment from SteriPEN [2.C.8]. Since dosage is linearly related to time we can calculate dosage rate, for the SteriPEN and control the dosage of the SteriPEN to hit points before inactivation saturation of T7. We will then compare these points to our reactors performance with our model predictions. If we get the same results as the SteriPEN then our model accurately calculated our Dosage rate and we can assume that the model holds true at 60+ mJ/cm2 dosages as well.

The SteriPEN applied about 97 mJ/cm2 with a 48 second dose in a 500 mL pyrex beaker [2.C.8]. Therefore the dosage rate of the SteriPEN in this situation was about 2 mW/cm2 . Therefore in order to apply 5 and 10 mJ/cm2 dosages for the T7 --- associated with about log 2 and log 3 inactivation of T7, respectively --- in a 500 mL pyrex beaker we will need to allow for about 2.5 and 5 seconds of radiation, respectively. Our UV reactor has an average dosage rate of about 3.2 mW/cm2, therefore we will need to treat water for about 1.6 and 3.2 seconds to attain 5 and 10 mJ/cm2 doses, respectively, as shown in the left graph of Figure 3-3.

*Figure 3-4 Log Inactivation of MS2 in response to 253.7 nm UV radiation [2.C.8].*

*Figure 3-5 Log Inactivation of T7 in response to multiple wavelengths of light, as indicated in the legend of the graph [2.C.9]. Our bulb is graded for 253.7 nm wavelength.*

## 4-1 Results

## 4-2 Performance

## 4-3 Budget

# Conclusion

## References

[2.B.2] NEMA Standards Publication 250-2003, “Enclosures for Electrical Equipment (1000 Volts Maximum)”.

[2.C.1]: Aboytes, Ramon. "Long Term Enhanced Surface Water Treatment Rule (LT2ESWTR) and the Water Industry in the USA: Perspective on Cryptosporidiosis and Drinking Water Sanitation."

[2.C.2]: USEPA 820-R-15-098: REVIEW OF COLIPHAGES AS POSSIBLE INDICATORS OF FECAL CONTAMINATION FOR AMBIENT WATER QUALITY, EPA Office of Water Office of Science and Technology Health and Ecological Criteria Division, April 17, 2015

[2.C.3]: NSF/ANSI 55: Ultraviolet Microbiological Water Treatment Systems

[2.C.4]: Ducoste, Joel, and Karl Linden. *Hydrodynamic characterization of UV reactors*. AWWA Research Foundation, 2006.

[2.C.5]: Ducoste, Joel J., Dong Liu, and Karl Linden. "Alternative approaches to modeling fluence distribution and microbial inactivation in ultraviolet reactors: Lagrangian versus Eulerian." *Journal of Environmental Engineering* 131.10 (2005): 1393-1403.

[2.C.6]: Bolton, James R. "Calculation of ultraviolet fluence rate distributions in an annular reactor: significance of refraction and reflection." *Water research* 34.13 (2000): 3315-3324

[2.C.7]: Office of Water, Environmental Protection Agency and United States. Method 1602: Male-specific (F+) and somatic coliphage in water by single agar layer (SAL) procedure. United States Environmental Protection Agency, Office of Water. Washington, D.C. 2001.

[2.C.8]: Linden, Karl. “Laboratory MS-2 Coliphage Testing of the SteriPEN Pure+”. University of Colorado, Boulder, February 19, 2016.

[2.C.9]: Beck, Sara E., et al. "Action spectra for validation of pathogen disinfection in medium-pressure ultraviolet (UV) systems." *water research* 70 (2015): 27-37.