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REDESIGN OF A LOW-COST, POINT-OF-USE UV WATER DISINFECTION DEVICE (THE UV TUBE)

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ABSTRACT

This paper describes the design development, construction, and testing of a point-of-use ultraviolet (UV) disinfection device targeted at household users in the developing world. It builds upon a current design platform developed at UC Berkeley, but introduces improvements such as an integrated safety switch, filter, and a removable lid for easier serviceability. An optional solar power system is also presented as an alternative to the standard grid-powered method. Biological assay testing using the MS2 coliphage resulted in an average UV dosage of 1300 J/m^2 at a flow rate of 3.7 liters/minute. Long-term UV exposure testing of aluminum and water resulted in very high levels of aluminum present, indicating that aluminum is not an ideal choice for the tube material. The device can be built for around $100 US, where all materials are available locally in Venezuela and other parts of the world. All subjects tested say that it is easy to use, and 85% say that it is at least a medium difficulty to construct using the provided construction manual. The environmental impacts of the system are quantified through a lifecycle assessment as 2.22 eco points. Based on this design process and testing, it is concluded that the device is an appropriate technology to be implemented in rural areas of developing nations such as Venezuela.

PROJECT BACKGROUND

Clean drinking water is taken for granted in the United States, yet many people in the world lack access to basic sanitary needs, including safe water. One of every six people worldwide (1.1 billion people) does not have access to an improved drinking water source [1], and even when there are treated water distribution systems, the water is often contaminated by the time it reaches its point of use. The lack of this basic necessity affects the health, life expectancy, education, and social development of much of the world. Especially at risk are children; dehydration from diarrhea is the leading cause of death in children under the age of five, and it claims the lives of 5000 children every day [1]. In addition to deaths, children suffer from malnutrition and other water-borne illnesses.

There are many options for obtaining drinking water in developing countries, including solar pasteurization, slow sand filtration, boiling, chlorination, purchasing bottled water, and ultraviolet disinfection [2]. UV disinfection has many advantages over the other options, yet still faces some challenges. It is effective in inactivating pathogens including bacteria, viruses, and cyst-forming organisms such as Giardia and Cryptosporidium. In addition, it requires only a short contact time, has no known byproducts, avoids the transportation of hazardous chemicals, and presents no danger of overdosing [3]. One of the largest challenges with UV disinfection is that until recently, only expensive commercial systems have been available. There is also a danger of pathogen reactivation, it requires a power source, and UV is less effective when the water is turbid [3].

Ultraviolet Disinfection. UV disinfection is a process that inactivates pathogens in the water by exposing them to radiation from ultraviolet light. Ultraviolet light consists of UVA, UVB, and UVC light, which occur at different wavelengths. In sunlight, UVC is almost entirely filtered out by the atmosphere, and it is this range that shows germicidal effectiveness [2]. In UV disinfection, the wavelength must be in the range of 250 nm to 270 nm, and a special germicidal bulb is used to produce light with a wavelength of 253.7 nm. The ultraviolet light penetrates the cell walls of the organisms and disrupts the cell's genetic material, thus making it impossible for the organisms to reproduce. This makes the water safe for consumption [3].

UV Tube History. The UV Tube project dates back to the early 1990s when Dr. Ashok Gadgil (Senior Staff Scientist at Lawrence Berkeley National Laboratory) developed a high-capacity, low-cost system to be implemented in hospitals, clinics, and communities, called UV Waterworks. While working with these systems in Mexico, Dr. Lloyd Connelly of UC Berkeley saw a need for a lower capacity, simplified household system, and that project has since been known as the "UV Tube." There have been several different design iterations of the UV Tube. It was first made from a four-inch PVC pipe, and since has been PVC lined with stainless steel or just stainless steel tubes, as well as ferro-cement and clay troughs [2]. The UV Tube has also been field-tested in Mexico, Haiti, and Sri Lanka. Most of the emphasis in these past projects has been placed on verifying the germicidal effectiveness of the design and the bulb, and not as much on the mechanical design or construction methods.

Objective. The mission of this student team was to redesign and further develop a series of point-of-use Ultraviolet (UV) water disinfection devices suitable for use in rural areas of developing nations where other water treatment methods cannot be applied because of their cost, inconvenience, limited availability, or energy requirements. The focus was on South American countries where 45% of the population is below the poverty line and 36% live in rural settings where safe water and power may not be available [4]. The intent was to enhance a proven concept and make it easier to manufacture, easier to service, more robust in operation, compatible with a variety of regionally available power sources, and more environmentally benign. The team focused on the design and manufacture of the device, instead of verification of the disinfection technology.

DESIGN PROCESS

Customer Needs. The team developed an extensive list of customer needs after reading about similar projects that have been completed at other universities, and speaking with various individuals about their experiences and insight into the project. The needs were categorized into three tiers of importance, and the top two are summarized in Table 1.

FIRST TIER

The device is easy to build, install, and use. The user should know when the device is on and the water is flowing.
The device is easy to take apart, clean, and repair.
The device is safe against electric shock and UV exposure. It is effective at sterilizing water, and is "child-proof."
The device is inexpensive to build and maintain.

SECOND TIER

The device can utilize the power grid and have an alternative power source available.
The device has an adaptable fluid input and appropriate accessories.
The device is reliable; it doesn't leak or clog.
The device lasts a long time and is sturdy.
The device is easy to build and repair with locally available materials.
The device is environmentally benign.

Table 1: Tiered Customer Needs

Specifications. From the customer needs, engineering specifications were developed to quantify the needs and guide the design process. Target values were identified after competitive benchmarking of the baseline design and similar commercial systems. Those specifications can be found in Table 2 below, and they represent the metrics against which the design was verified.

Metric	Units	Marginal Value	Ideal Value
Number of installation steps	Number	50	30
Usability test-Ease of use	%	90%	95%
Number of total parts	Number	50	20
Water flow rate	L/Min	3	6
Filter Output Size	Microns	10	5
Filter Turbidity output	FTU	10	5
Usability test- construction	%	90%	95%
Time to disassemble	Minutes	10	1

Cost of Materials	USD	100	40
Power Consumed per year	KWhr	50	5
Cost to operate per year	USD	20	2
UV Dose	J/m^2	400	800
Weight	Kg	10	7
Volume	m^3	0.1	0.075
Max footprint	m^2	1	0.3
User is not exposed to UV radiation	Binary	Yes	Yes
Enclosure of core components (ballast, bulb)	Binary	Yes	Yes
Device Indicates On/Off	Binary	Yes	Yes

Table 2: Target Specifications

Concept Development. The operation of the UV Tube was divided into three main subsystems: water input/filtration, the tube cavity, and the power system. The team developed several concepts for each of these sub-functions. These were narrowed down and combined using a series of Pugh's Matrices which weighted such criteria as cost, ease of use, ease of construction and repair, durability, reliability, and use of local materials. The final concept is shown in Figure 1 below. This concept employs a terracotta sand filter atop a water reservoir with a commercial bag filter. The water is gravity fed into a U-shaped sheet metal trough with a removable lid, where the water is disinfected. The wooden lid allows for easier access to the tube interior, and for the bulb to be mounted to the cover instead of directly to the stainless steel. In addition to a grid-powered version, the device can be run by a human-powered flywheel/generator system. This generator was later replaced by a solar system, which provided a similar service with less complexity at a comparable cost to the generator setup.

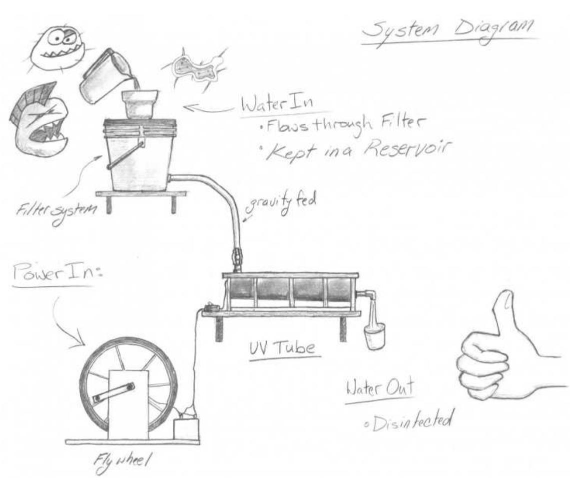

Figure 1: Final system concept

THEORETICAL ANALYSIS

Throughout the design process, several tools were used to design and verify decisions. A summary of the theoretical engineering analysis includes a mathematical model of the UV dosage, flow rate determination, life cycle assessment, design for assembly, and solar system sizing.

Calculated UV Dose. The germicidal power of the bulb is reported as dosage (or fluence), which is a function of the irradiance from the bulb and the residence time of the water in the tube. A mathematical model using the point source summation method was used to characterize this dosage based on the geometry of the system. For this design where the bulb is suspended over the water, the irradiance is defined by Eq. (1) below [5,6], and based on the factors illustrated in
Figure 2.

$$I_{i,j} = \frac{P_\lambda}{4n\pi\rho_{i,j}^{\;2}} \exp\left[-\left((\alpha \ln(10))(R - r_{air})\frac{\rho_{i,j}}{R}\right)\right] \quad (1)$$

where

- $I_{i,j}$ = irradiance at point *j* due to side *i* in point source (mW/cm^2)
- P_λ = bulb power at 254 nm (mW)
- n = number of point sources
- $\rho_{i,j}$ = distance separating site *i* in point source and site *j* in receptor source (cm)
- α = absorption coefficient of water (cm^{-1})
- R = radial distance from bulb t receptor site (cm)
- r_{air} = distance from bulb to surface of water (cm)

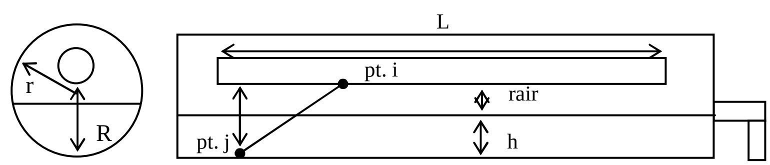

Figure 2: Definition of variables for irradiance model

This is a conservative estimate which does not consider any irradiance beyond the length of the bulb in the tube, or any reflectance in the inside of the tube. It was assumed to be plug flow, and the tube residence time is based on the water volume and flow rate. It was calculated as a numerical solution with step size of 0.5 cm. The fluence was calculated for the "worst case scenario," where the water remains at the bottom of the tube for its entire residence time. From this calculation, the maximum safe flow rate could be determined, based on the results shown below in Figure 33. It should be noted that the minimum required fluence by the National Sanitation Federation and ANSI is 400 J/m^2 [7], which requires that this device maintain a flow rate less than 7 L/min to be safe.

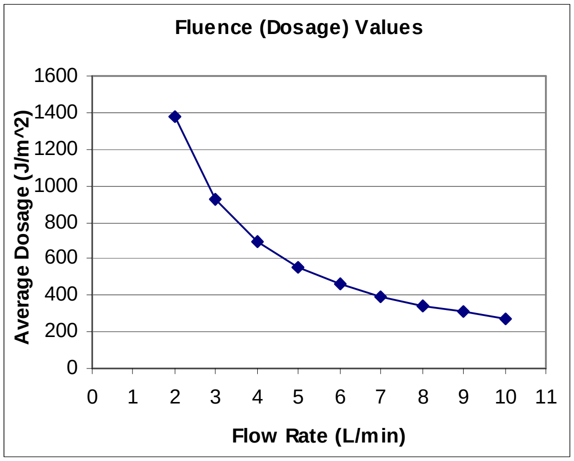

Figure 3: Conservative model of UV dosage at varying flow rates

Flow Rate. As stated above, the flow rate must remain under 7 L/min, yet should be as fast as possible to keep the system working quickly and efficiently. The decided range of flow rates was 3-6 L/min, which is controlled by the hole size drilled in an orifice plate at the water inlet. It was assumed that the piping was standard garden hose and that the height of the water in the bucket was 30 cm (this is the maximum height of water possible assuming the end user's water has low turbidity and does not need to use a filter). Head losses for the ball valve, inlet and outlet, tubing, elbows, and orifice plate were then calculated and plugged into the equation:

$$Height_{BucketOutlet} + Height_{WaterInBucket} = Headloss_{Total} \quad (2)$$

From Eq. (2), given the known heights of the outlet and the water, the orifice plate diameter could be adjusted to find an equal total head loss. Using a conservative flow rate of 3 L/min, the required orifice diameter was found to be 6.39 mm. A 1/4" (size E, 6.35 mm) drill bit was determined to be the closest available size to use for this hole.

Life Cycle Assessment. A life cycle assessment was performed on this product to quantify the environmental impacts of its entire lifecycle, from material extraction through disposal. The analysis was done with the software package, SimaPro 7, and the impacts were measured on the EcoIndicator 99 scale using the Heuristic Method, as it is the most egalitarian. The functional unit is one year's worth of disinfected water for one family. This means that it provides 20 liters per day for one year. Transportation of components was neglected, to indicate that the materials and assembly are occurring locally as well as to be able to compare the various products simply on their respective composition. The electricity needed to power the device was added within the product use phase. As for the disposal scenario, the unit is assumed to be disposed of by landfilling, although many parts are reused from previous applications, others can be used for more than one year and also other parts are recyclable.

As a comparison, a life cycle assessment was also performed on the UC Berkeley baseline design from which the team started. This design reported an impact of 2.06 eco points, where one eco point is equal to the environmental impacts of one European resident over the course of one year. Most of the impacts from this device arise from the production of the copper wire (0.50 eco points), and the HDPE reservoir bucket (0.55 eco points). The analysis on the new design resulted in impacts of 2.22 eco points. Again, the copper wire and reservoir bucket are major contributors, along with the electrical components (0.743 eco points). The team assumed that the bucket would ideally be reused from another application, and the filter was designed so that it could be made from reused denim jeans, or other thick cotton fabric. The reusing of these materials would essentially decrease the overall impact, which had increased from the added design features and material.

As another comparison, the life cycle impacts were quantified for purchasing bottled water for a family for a year, to show the difference between purchasing water in 1 liter bottles and using the UV Tube. For the bottled water, the assumptions were that no transportation was included, 20 one-liter bottles were delivered each day in a standard packaging of PET and a cardboard box, and that all components were landfilled. The impacts associated with bottled water are 149 eco points. Therefore, it seems clear that comparing simply between products, that the UV tube is a much more environmentally-friendly option as well as simply much cheaper over time.

Design for Assembly. An important consideration in this project is the ease of assembly, because a local entrepreneur or the end user will build the device. One project goal was to make this design easier to assemble and service than the baseline, in addition to providing a more robust product. Given the overall project goals and constraints, the trade-off between the two goals leaned towards developing a robust design. Design for Assembly and manufacturing guidelines given by Boothroyd and Dewhurst [8] were followed in order to achieve the lowest assembly difficulty level without compromising the other project goals. As a result of following these guidelines, the assembly complexity, as perceived by the user, was kept to it lowest. Reducing the individual step complexity compensated for the increase in assembly steps and parts from the baseline. The complexity reduction can be seen in converting operations such as the water inlet fastening, among others, into top-down operations. There are some improvement opportunities, especially in reducing the number of parts and fasteners, only if some of the available resource and processes constraints are relaxed (e.g. manufacturing custom components).

Solar System Sizing. Using information and data provided from Stand Alone Photovoltaic Systems [9], the appropriate solar panel and battery could be sized. It is assumed that the UV Tube will be used for an average of 30 minutes per day with a load consisting of a 15 Watt germicidal bulb & magnetic ballast. Taking into account power conversion efficiency, wire efficiency and battery efficiency factors, the corrected amp hour load is 0.8858 AH/day. Using data for the peak sun hours in Caracas, Venezuela (which ranges from 4.76 to 6.47 hours per day [9]), the minimum required design current for the solar panel is 0.1861 A. This corresponds to the needs of May, which is the month with the lowest average daily sunlight. To calculate the battery size required, the corrected amp-hour load was again used. Assuming that the system can accommodate three full days without sun and maximum depth of discharge is 30%, the required battery capacity needed is 8.86 AH.

PRODUCT TESTING

A first-generation alpha prototype was constructed for testing purposes, with the intent of implementing further changes to the design, and constructing a final beta prototype. The prototype was constructed using similar tools and procedures as is intended for the end use. Testing was performed to verify the theoretical analysis in terms of germicidal and filter effectiveness, flow rate consistency, solar system sizing, usability in constructing and using the device, and material degradation.

Biological Assay. In order to validate the germicidal effectiveness of the UV disinfection and verify the theoretical calculated dosage, the system was tested with the MS2 coliphage, which is e. coli that is particularly resistant to UVC radiation [6]. Two samples of MS2 were prepared and diluted into approximately 5 gallons of deionozed water. The complete system minus the filter assembly was used for the testing. The UV bulb had been conditioned for over 100 hours prior to the testing, and had approximately 10 minutes to warm up before testing began. The water flowed through the system, and samples were taken once at the inlet and once at the outlet for each trial, while the UV Tube was running at full capacity with a flow rate of 3.7 L/min. The concentrations of MS2 before and after are listed in Table 3 below. The log reduction was calculated by taking the logarithm of the ratio of the influent and effluent concentrations. The fluence was solved from the log reduction using the linear regression from the experimental dose response curves by Brownell et al. [5]. The experimental fluence values for each trial were 1335 and 1265 J/m^2, which is well above the National Sanitation Federation (NSF/ANSI) required minimum fluence of 400 J/m^2 [7].

	Concentration (cells/mL)			
	Influent	Effluent	Log Reduction	Fluence (J/m^2)
Trial 1	2.8E+07	< 100	5.45	1334.64
Trial 2	2.8E+07	200	5.15	1264.63

Table 3: Bioassay Results

Figure 44 below is a log inactivation chart showing common pathogens of concern to drinking water. The three lines correspond to the NSF minimum required UV dose (400 J/m^2), the theoretical minimum calculated dose (748 J/m^2), and the average experimental dose (1300 J/m^2).

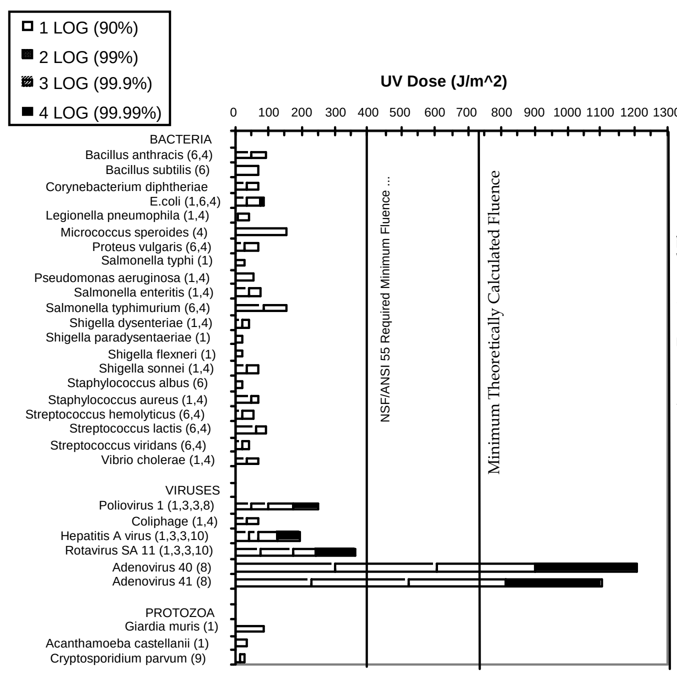

Figure 4: Log inactivation of pathogens based on theoretical and experimental fluence [10].

While there were only a few samples run through the device, it does demonstrate the germicidal effectiveness of the system as designed. Other similarly tested systems have been proven to produce a fluence of 900 +- 80 J/m^2 (95% CI) [5] and this design seems to even improved upon that. Reasons for this increase in dosage are that the flow rate was slowed from 5 to 3.7 L/min, and the diameter of the tube was decreased slightly. Based on these results, the device could safely support a faster flow rate, and would be safeguarded against the user not allowing the bulb to warm up for two minutes before use. It has been shown by Peletz, et al. that when first turned on, the bulb is only at 60% of its maximum output, but this reaches 90% within 2 minutes, and 100% of maximum within 5 minutes [11]. It is also important to note that as turbidity or absorbance of the water increases, the dose will decrease dramatically.

Filter Testing. UV disinfection is much less effective with turbid water because large particles may shield pathogens from exposure. The recommended turbidity is 5 FTU (Formazin Turbidity Units) [2]. Several materials including sand, felt, and canvas were tested for their ability to reduce turbidity. To create turbid water, a half a tablespoon of flour was added to one liter of water; this resulted in an average turbidity of 300 FTU, as measured by a spectrophotometer (Hach DR/2000 Spectrophotometer). This turbid water was then run through the filter system and measured for turbidity again.

The first testing was done visually, and showed that canvas fabric performed much better than felt in removing turbidity. Next, a sand filter was constructed from washed play sand, and it was "conditioned" by running three gallons of water through before testing. It was determined that the sand filter performed better when it was not disturbed between testing, and the turbidity tended to decrease as the filter was used more and more. In repeated trials with five inches of sand, the turbidity decreased from about 300 FTU to 15-20 FTU, as seen in Figure 55. A filter made from several layers of canvas was also constructed, and performance increased with added layers of cloth. As shown in Figure 5, four layers is sufficient to reduce turbidity from 300 to 3 FTU. The fabric is more reliable and lighter weight than the sand, and can be washed when it is visually dirty. The filter may also be constructed from old pairs of denim jeans or other thick cotton fabric.

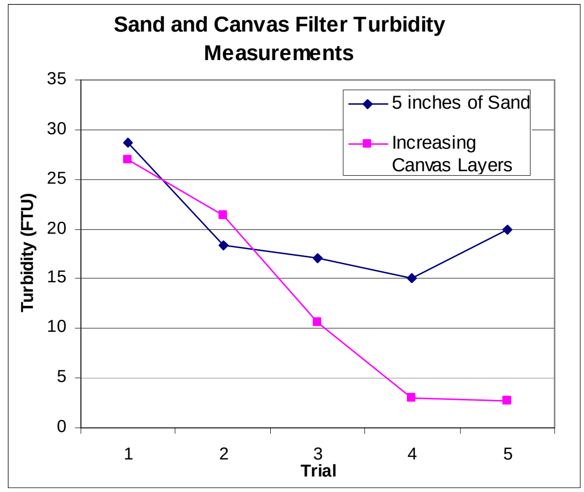

Figure 5: Turbidity results for sand and canvas testing

Flow Rate Testing. Testing to verify the theoretical flow rate was done by flowing the water into a graduated container and timing it with a stopwatch. Three different orifice conditions were used corresponding to possible construction variations that may occur. The first was a roughly cut 1/4" hole that represented a hole in which the user could not securely hold the bottle cap down and quickly gave up. The second was a cleanly cut hole; this represented a bottle cap that was cut correctly. The final condition was a cleanly cut and countersunk hole. This represented a bottle cap that the end user tried to clean up additionally and gave the edges a chamfer. The roughly cut hole flowed the slowest, at 2.16 liters/min. The next was the cleanly cut hole. This hole flowed at 2.9 liters/min if the container was placed under the outlet and the system was then turned on. If the system was allowed to flow for half a minute, giving it time to reach full flow, the cleanly cut hole was found to flow at 3.7 liters/min. The final condition was the countersunk hole. This hole flowed at 4.1 liters/min which is still less than the maximum design flow rate of 6 L/min. Based on this it was determined that all conditions for a 1/4" hole were successful and could be relied on to produce safe results. While there is a significant percent difference between the calculated flow, 3 liters/min, and the experimental flow, 3.7 liters/min, the results are still close given the number of assumptions that needed to be made to model the system, particularly the head loss across the orifice cap.

Solar Testing. The chosen solar panel and battery were both tested for performance in this application. The batteries tested were an 8AH 12V DC industrial sealed lead acid (SLA) battery, and a standard "Lawn and Garden" 12V DC SLA battery. These two batteries were used to power the G15T8 germicidal bulb, and their charge losses were noted. Again assuming a 30 minute daily usage of the device, the results showed that the 8AH battery would be drained by 20.46%, and the Lawn and Garden battery by 18.72% per day. This means that if there were 3 consecutive days of no charge supplied by the solar panel, the batteries charge would be reduced by 61.38% and 56.16% respectively. While this is a reasonable charge loss and can still accomplish the primary goals of the device, the setup could be improved by introducing a larger battery at an additional cost. A car battery could also be utilized.

The solar panel setup was tested using 2 commercially available panels designed to charge a 12V SLA battery. The first was a Sunforce 50022, 350mA, 5W panel and the second was a Coleman CL-300, 300mA 4.5W panel. The panels were set up on the roof of the James E. Gleason Building at RIT and were charged during the day with multiple trials taking place over 2 weeks, and at an orientation consistent with the latitude of Rochester, New York. The results showed that, given the average daily charge time in Venezuela of 300 minutes [9], the panels would be able to charge the 8AH battery by about 74% and 82% respectively. For every minute of use by the UV tube, the solar panel would have to be charging the battery for 3 minutes, meaning that if the average daily usage of the UV tube is 30 minutes, then the solar panel would have to charge the battery for at least 90 minutes daily. It is then possible to conclude from these tests that the 4.5W, 300mA solar panel is commensurate to the task of supplying power to the battery, and that therefore the larger panel is not needed, and unwanted from a price comparison perspective. Choosing a larger battery would in no way affect the performance of the solar panel, but once again would be preferable for the overall system.

Solar intensity data was collected and provided by RIT Multidisciplinary Senior Design Team P07401 (EPA Water Disinfection Project). It was obtained from a data acquisition system on the Gleason Building roof at the same location as this system's solar tests, and was run from around 9AM to 6PM over 3-4 days coinciding with this team's solar testing. The results showed that during the peak hours of 10AM to 4PM the solar intensity was an average of 990 W/m^2. This corresponds well to the anticipated solar intensity values from Venezuela which ranged from 4.76 to 6.47 hours per day of one kW intensity per square meter [9]. This means that it will take the same or less time to charge the battery in Venezuela versus in Rochester, NY.

Usability Testing. The usability testing was two-fold, where independent tests were done to determine both the ease of construction and the ease of use of the device.

For the ease of construction testing, subjects assembled the device by following a detailed construction manual. The subjects were divided into two groups, those experienced with common constructing techniques, and those inexperienced. For manufacturing operations such as cutting and drilling, the subjects merely indicated where they would complete the action, but did not actually do the activity. For assembly testing, each subject was supplied with the proper tools and materials to build the unit. The number of mistakes and questions by each subject was recorded, along with the total time to complete the tasks.

The average assembly time for the experienced group was 1.6 hours, and was 1.9 for the inexperienced. There was however, no significant difference between the two groups. For all subjects, 85% perceived the assembly and following the manual to be at least a medium difficulty level. Seventy percent of the subjects said that it was easy to complete the manufacturing steps (cutting and drilling). Data and observations were also used to further develop and improve the construction manual following testing.

For ease of use, twelve subjects tested the intuitive operation of the UV Tube. The subjects were briefed with the basic purpose of the device, but were not given any instructions regarding operation. They were presented with two buckets; one that contained imaginary infected water, and one to be used for collecting the water, and then were instructed to operate the device to obtain safe water.

The subjects were asked to rate the difficulty of operating the device, based on a scale from 1-9, where one is "very easy," and nine is "very difficult." Twelve out of twelve subjects indicated that the device was "easy" or "very easy" to use. The largest source of confusion was what the second outlet hose was intended to do, and the most common suggestions were to have some instructions integrated into the design via labels, numbers, or schematics.

Materials Degradation Testing. Several alternative materials were considered for the UV Tube cavity itself. Previous designs have implemented ferro-cement troughs, PVC piping, and a rolled stainless steel sheet [2]. It was determined by Brownell et al. [5] that long-term exposure of an entire PVC pipe to UV light produced high levels of chlorinated organics. Similar tests with ABS and galvanized steel have also revealed undesirable reactions with UVC radiation [5].

Aluminum appeared to be a viable option for the tube material because it is ductile, inexpensive, and readily available around the world. Unfortunately, not much research has been conducted concerning the reaction of aluminum when exposed to UVC radiation, and there is little conclusive evidence about aluminum's effects on human health. In very high concentrations, it is believed that aluminum may adversely affect the nervous system and is loosely linked to Alzheimer's, Lou Gehrig's, and Parkinson's diseases [12]. Aluminum is absorbed more readily into the body through drinking water, but there are currently no regulations limiting the concentration of aluminum in drinking water. The EPA, however, recommends a maximum contaminant level of 0.05 mg/L based on taste, odor, and color [13].

A testing apparatus was set up with a rolled sheet of 5052 aluminum, which was sealed and filled approximately halfway with water. It was left exposed to the germicidal bulb for ten days. The water sample was collected and tested for aluminum concentration at the Monroe County Environmental Lab in Rochester, NY. The sample showed levels of 3.18 mg/L of aluminum present, which is well over the recommended limit.

Another material exposed to UV light in the design is the garden hose. To test the reaction of the hose with UV light, the tube was set up and the bulb was left on for seven days with a 15 cm piece of hose inside the empty tube. At the end of a week of continuous exposure the hose showed signs of age and discoloration. It became slightly more brittle and dry, but did not lose its integrity.

Although the PVC end caps showed signs of degradation over the seven day tests, this amount of exposure was tested by Brownell et al. and proven to be safe [5]. In a seven-day test of a PVC pipe lined with stainless steel, there was no evidence of chlorinated organics and VOCs present in the water except for bromomethane and butanone, which are both unregulated. Based on this information, the stainless steel with PVC end caps is safe for use with the UV Tube [5].

FINAL DESIGN

The final design is pictured below in Figure 66. To operate the device, contaminated water is poured into the filter bucket. Flipping a toggle switch to the "on" position turns on the bulb, and the water flow is controlled by the ball valve. These two components have an interference fit so that the valve may not open without the light bulb being switched on. There is also a viewing window in the top of the box so that the user can see whether or not the bulb is on before running water through the device. It is recommended that the bulb warm up for at least 2 minutes before water flows through the system [11]. The outside structure and bucket stand are wood, and the tubing is all pieces of common garden hose.

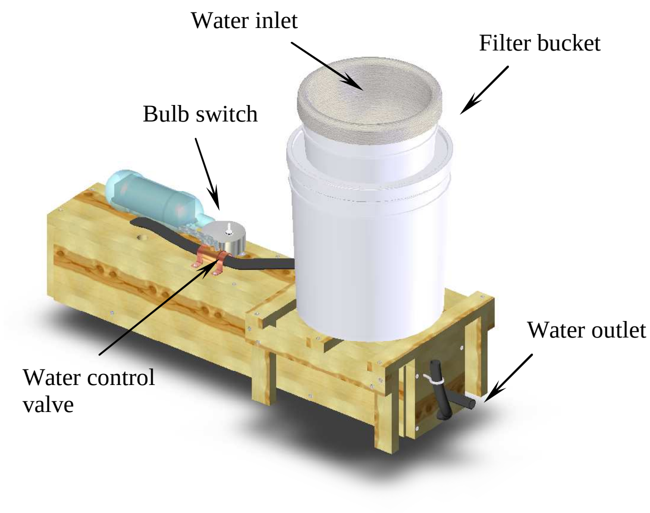

Figure 6: The UV Tube final design

The inner workings of the device can be seen below in Figure 77. When the water enters the system it flows through a four-layer canvas filter, and then through a commercial bag filter to reduce the turbidity. It is then stored in a reservoir. The water then flows into a stainless steel tube and underneath the G15T8 germicidal bulb where it is disinfected. The water exits through the outlet hose. When the user has finished collecting water, he or she unhooks the drain hose from the end board and drains any remaining water from the tube.

The power system consists of a magnetic ballast with starter included, a one amp fuse, and toggle switch. Both the ballast and the fixture (stainless steel tube) must be grounded in order to operate correctly. In addition, an alternative solar panel setup is provided with a 4.5 watt, 300 mA solar panel (Coleman CL 300) attached to an 8 AH, 12 volt battery, and an inverter ballast.

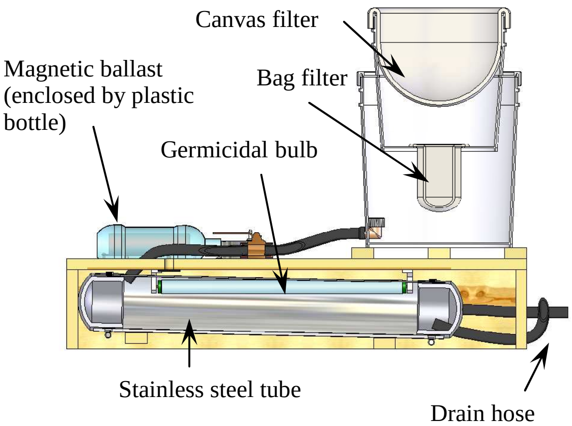

Figure 7: Section view of the UV Tube

CONCLUSIONS

From the analysis and testing on this device, it can be concluded that it is an appropriate technology for disinfecting drinking water in developing nations. The main improvements to the system over previous designs are the addition of the safety switch, integrated filter system, and a removable lid for easy access to the bulb and inside tube. Other advantages are the elimination of many PVC parts and a simplification of the electrical system. The inlet and outlet hoses were standardized to the same part, and several components may be found around the house (e.g. a plastic drink bottle and tin can).

One hundred percent of people tested say that it is easy to use, and 85% say that it is at least a medium difficulty level to construct. The device is effective at disinfecting water; the calculated UV dose was 748 J/m^2, and the experimental dosage is 1300 J/m^2, which is more than three times the NSF/ANSI standard. The flow rate of the device is currently set at 3.7 L/min, but this could also be safely increased to approximately 6 L/min by drilling a larger hole in the orifice cap.

All of the components can be located in the target country (Venezuela). In the United States, the base design can be built for $103.25, where all parts except for the germicidal bulb, bag filter, and stainless steel sheet were obtained locally to Rochester, New York. The solar panel setup calls for an additional $78. The yearly cost for operating and maintaining the device is approximately $11, which includes the cost of replacing the bulb and electricity to run the device.

Testing of aluminum revealed that when exposed to UVC radiation, very high levels of aluminum leached into the water. Interaction between UV light and plastic components, including the garden hose, PVC end caps, and wire casings, caused discoloration and slight brittleness in the plastic, but is not detrimental to the device performance.

Depending on the user's needs and accessibility of the power grid, there is an option of an AC system with a magnetic ballast, as well as a solar panel setup to run the device. With the current solar panel and battery, the panel must have three minutes of sun for every one minute of bulb use. Given the average daily amount of sunlight in Caracas, the system will be able to operate for three days without sun, although a larger battery would be more ideal for this amount of storage.

The environmental impacts of the current design are slightly higher than those of the baseline UV Tube design, as measured by EcoIndicator 99. The design has an impact of 2.22 eco points, versus 149 eco points that are associated with providing an equivalent amount of bottled water.

The design meets all defined specifications with the exception of the number of installation steps, and the ease of construction data. The user manual contains many detailed steps to describe the installation, thus making the number very high. The construction is a series of fairly simple steps, but is a very long process overall.

FUTURE WORK

Although some significant improvements have been made to the UV Tube design, there are always additional considerations. A few improvements in materials could be made; for instance, although the amount of PVC was reduced, it would ideally be eliminated completely. Testing on the interaction between UV-C radiation with other materials (such as more aluminum testing) should be further investigated to reduce the dependence on expensive stainless steel. An alternate outside "box" material could be used to enclose the tube, and the lid could be more easily removed without the use of tools. There could also be better solutions to water and light sealing in the unit, which could reduce the amount of adhesives used. Finally, the water input could also be made more adaptable. Early in the design process the team went towards a batch approach, but it could be fitted to a pressurized water distribution system.

Approaching the problem from a mass-manufacturing standpoint could alleviate many of these design issues such as the material selection, because it would not be limited to part availability on an individual basis. It could reduce the total number of components, dependence on fasteners, and allow more snap fits and thus simpler assembly operations. With appropriate volume of manufacture the cost could also be substantially lowered.

Although there has been some testing done, the product would benefit from long-term field testing to analyze where it will fail and when. This could also be done as accelerated life testing by running water continuously through it and repeatedly cycling the system on and off. It is anticipated that the seals created by epoxy and silicon will fail first. Finally, ultraviolet germicidal LEDs have recently been developed, but they are still very expensive. If the cost of these becomes more reasonable, there could be a great opportunity for the future of water disinfection.

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