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UV WATER TREATMENT SAFETY MECHANISM

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ABSTRACT

The purpose of this project is to expand on an existing UV water treatment system design for Mexico by adding in a safety feature to prevent water contamination during UV bulb failure and power outages. The current system being used in kiosks in Mexico has large reservoir of contaminated water on the roof and gravity-feeds water down through two ultraviolet light-emitting chambers to sanitize the water before passing it into a clean reservoir. Being gravity fed, if the power goes out or if a bulb failure occurs, untreated water flows into the clean reservoir requiring the kiosk operator to completely drain and re-clean it. Our customer wants a system to sense these failures and stop the water flow. To do this we created a system that monitors the UV radiation output inside the sterilization chambers using UV-sensitive photodiodes. In the event of insufficient UV output, a fail-close safety valve is triggered to prevent contaminated water from entering the chambers. Concurrently with the triggering signal, both audible and visual alarms will activate to inform the operator of this failure. When sufficient UV output returns, the system will open the safety mechanism to allow normal water flow.

NOMENCLATURE

L: Length [m]

P: Pressure [Pa]

V': Volumetric Flow Rate [l/min]

VDC: Volts DC

Bi: Binary

UV: Ultraviolet

Kiosk: Building which houses UV water treatment system for a village in Mexico

PCB: Printed Circuit Board

BACKGROUND

There currently exists a low cost UV Water Treatment system developed by students at UC Berkeley. The system allows for rural communities in Mexico and Sri Lanka to obtain clean, safe water at a low cost for families. However a system that stops contaminated water from coming in contact with the decontaminated water when certain failures occur does not exist. The major goal of this project is to implement this function into existing UV treatment kiosks, as well as into kiosks that will be built in the future. The failures which can occur include power outage, UV bulb failure, broken filament, and power brown out. The design must include few consumable parts, and must be easy and inexpensive to install and maintain. The mechanism designed should be able to be retrofitted into existing water treatment kiosks as well as used in newly built kiosks.

CUSTOMER NEEDS & ENGINEERING SPECIFICATIONS

From our project readiness package and our first teleconference with the customer, Fermin Reyegadas, we gathered a set of requirements that he was looking for us to achieve. Figure 1 shows the customer needs listed out along with our interpretation of their importance to the customer. This was an important step to help quantify and order the needs of the customer. The primary objective was to prevent the contamination of the clean storage tank during the given failure modes which included power outages, bulb breakage, brownout condition and potentially worn UV bulbs. Other important aspects included using either long lasting components or components that were available in a local Mexican hardware store. To coincide with this, Fermin asked that the design be repairable with basic hand tools and require few consumable parts since some of the kiosks were fairly remote in Mexico and lacked access to stores. Fermin also asked that our system incorporate both visual and audible warnings to the operator of the kiosk to inform them when a failure occurs.

During later customer meetings, we also gathered that integration with the current kiosk layout was not as important to Fermin as he was willing to modify his designs to include ours. He requested in a later interview that the chambers be capable of working independently as well. This way if one bulb blew, the kiosk could still function on one UV chamber. One of the final customer needs that was added in was that in rapid on-off-on power fluctuation situations, Fermin preferred that the system not shut down immediately but rather have a few second delay.

CN #	Customer Requirements	Customer Importance
1	prevent storage tank contamination during at least given failure modes	9
2	allows normal operation in non-failure situations	3
3	works with all pressures generated from elevated water tank	3
4	provides feedback to operator when failure occurs	9
5	can be installed by one person	1
6	integrates with existing kiosk structure, electric and plumbing	9
7	made from materials and parts available in Mexico	9
8	easy to repair with basic hand tools	9
9	requires few/no consumable parts	3
10	inexpensive to purchase and use	3
11	protects human safety	9
12	resists environmental damage from dust, insects and water	3

Figure 1. Customer needs and importance.

From these customer requirements, our team developed a set of engineering specifications that we would seek to meet by the end of the project. Figure 2 shows these specifications along with their respective nominal and marginal values that we set to achieve. The importance values were calculated using a house of quality and comparing how each engineering spec meet various customer needs. From this, we obtained that our most important specs were the amount of contaminated water allowed to flow into the storage tank, the photodiode threshold to trigger failure, sensing power loss and the time between failure occurrence and flow cut off. From a constraints perspective, the key spec we needed to meet was the independence of the chambers and notifying the operator of a failure.

Engineering Specifications	Importance Totals	Nominal Spec Value	Marginal Spec Value	Spec Units
Limits Contaminated Water flow entering Storage Tank	204	0	<200	mL/tank
Allows flow rate of 5L/min	57	5	1	L/min
Solenoid Voltage	81	24	2	VDC
Operating Voltage	81	24	2	VDC
Time for Operator Reset	52	<5	<10	min
Materials/Labor Cost to Customer	144	<100	<150	$/unit
Total Cost for expected year of life	54	<10	<20	$
Frequency of consumable parts replacement	90	0	<5	~/yr/kiosk
Largest Hole Diam. In electical Housing	36	<2	<5	mm
Weight	39	<5	<10	kg
Photo diode output for failure trigger	198	1.68	0.1	VDC
Water leaked on floor per hour	60	0	<0.5	L
Sense Power Loss	201	y	y	Bi
Time between failure occurance and flow cut-off	201	<4	<6	sec
Audible Warning Decibels	120	95	10	dB
Visual Warning Gets operator attention from distance	117	>8	>4	m
Warn operator duration	93	>150	>60	min
Delay for rapid power on-off	171	3	1	secs
Withstands spray for 1 minute	108	>1	>0.5	min

Figure 2. Engineering Specifications with importance, nominal and marginal values.

The biggest and arguably most important assumption we needed to make was what level to set as the threshold of the photodiode to indicate low UV output and trigger the safety mechanism. This value was estimated based on the data in Figure 3 gathered from UV bulb tests done by Peletz et al. From this graph we estimated that about 80% of the maximum UV output would correlate to a good threshold value. Since we did not have data to correlate UV irradiance to the voltage read by the photodiodes we would be using, we had to test the maximum voltage the photodiode would read with a new bulb and set our threshold based on 80% of that voltage.

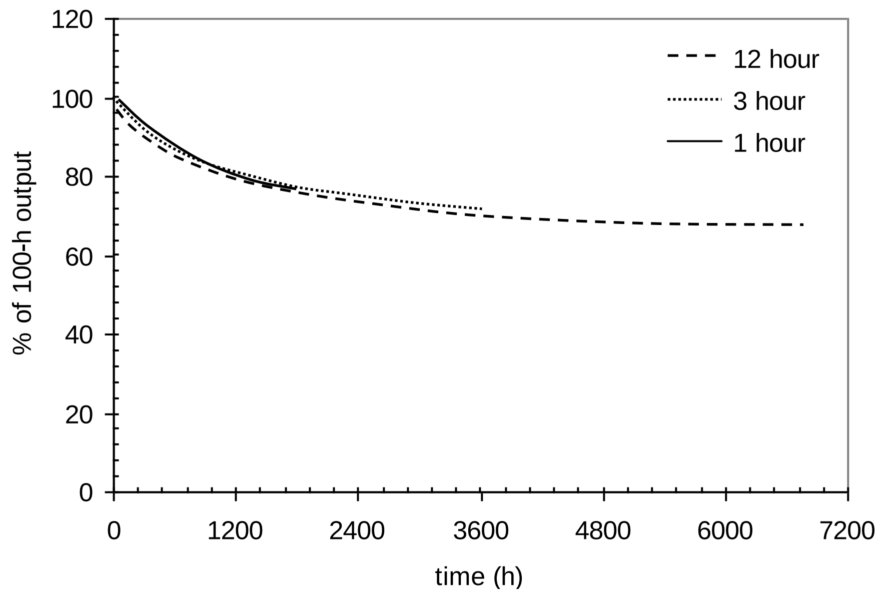

Figure 3. UV bulb output over time. Graph from Peletz et al. paper.

CONCEPT DEVELOPMENT & FINAL DESIGN SELECTION

Since this project had a very direct customer, Fermin Reyegadas, we were able to have a phone conference with him early in the design process so that we could assemble his needs from the project. He was looking for a unit that could sense power failure, brown-outs, and UV bulb blowouts and trigger a safety mechanism which would stop the flow of contaminated water into the clean reservoir. Since the flow rate of the current system was given as 5L/min for optimum water sterilization, we were asked to try to maintain this spec. Fermin wanted the system to be able to warn the operator of a power failure since they would need to drain the UV chambers prior to restarting the system. He requested we use both audible and visual warnings. He was adamant that the parts used be easily serviceable with basic hand tools and have replacement parts be available at a local hardware store. The exception to this was if the parts could be expected to last for at least a year or two in the field so that he could leave several replacement parts and not have to worry about them breaking frequently. As an optional target he asked that we try to incorporate functionality that would allow for rapid power on-off cycles without shutting the flow of water off. In this case we would need to build a lag into the electrical circuit to prevent the system from shutting off flow if the power was to go out and come back within a few seconds. Knowing the environment the system would be used in, it was suggested that we make the system fairly water tight and have no large holes in which bugs could crawl into easily. Finally, since the unit we were to design was going to be both installed in new kiosks as well as retrofitted into existing kiosks, Fermin wanted our system to be capable of integrating into the existing setup without major modifications.

In order to detect the various failures which could occur with the UV bulb, a photodiode which is sensitive to UV light is used. The photodiode is placed in the middle of the UV chamber with leads being run to the circuit board. A current to voltage operational amplifier is used to convert the current produced by the photodiode to a working voltage. This voltage is then compared to a reference voltage using a comparator. This reference voltage is created using a voltage divider. When the op amp output voltage drops below the reference voltage, the output of the comparator will become low, otherwise the output is at 5V. A double pole double throw relay is used to hold the solenoid valve in the open position when the comparator output is at 5V. When the comparator output is low, the relay coil will de-energize causing the solenoid to the lose power and the valve to shut, thus cutting off the water flow through the UV chamber. At the same time, the alarm system turns on.

The alarm system consists of two parts. The first is to warn the operator of a failure. This part consists of a 555 timer configured in astable mode and designed to oscillate its output at a frequency of 1 kilohertz. This output is connected to a red LED and a small speaker. The speaker is resonant at 1kilohertz and outputs a high pitched tone. At 1kilohertz the LED appears solid on to the human eye and the speaker makes a noise that is noticeable from about 30 to 40 feet away. When the operator notices there has been a failure, he can flip a switch to disable the speaker and red LED. By flipping this switch, the second part of the alarm system is activated. This part is simply a green LED that will turn on when power is restored, if the issue was a power failure, or when another possible issue has been resolved, letting the operator know that the system is ready. The operator then flips the switch back to its original position, enabling the alarm to sound when there is another failure.

The process of picking a valve mechanism which would cut off the gravity fed water flow from the roof of the kiosk when failure is detected involved a bilateral design tree. From very early stages in the design process we were relatively confident that we could use a simple off-the-shelf solution which was an irrigation valve. During the early stages of the project, it was suggested by the customer that we look into the adaptation of washing machine solenoid valves as they were readily available in Mexico. After some brief research however, we concluded that modifying these valves to meet the needs of the project was nearly impossible. They were designed for high flow, high pressure situations and would not be capable of opening properly with the given flow conditions within the kiosk. This is where the irrigation valve fit in well. Being designed for low flow, low pressure applications, its diaphragm would function properly for our needs.

This valve functions by having a solenoid open and close a pressure relief in the diaphragm such that when power is applied, it opens the pressure relief on the back side of the diaphragm and allows the front and backside pressures to equalize. Once equalized, the pressure of the water pushes the diaphragm open and water flows through the valve. When power to the solenoid is lost, the pressure hole is plugged and the spring within the valve forces the diaphragm shut, sealing off flow.

This valve was a good fit for our system not only for its flow characteristics and its fail-closed operation but it also draws significantly lower power than a washing machine solenoid since this solenoid does not need to hold back the force of high pressured water. This was an ideal situation for powering through relay logic on the PCB.

The only downfall to the irrigation valve was it was relatively expensive considering we would need two of them to maintain the customer's requirement of individual shut off operation in the case of say, a blown UV lamp. Considering the cost issue and the minimal work required to implement the irrigation valve, we decided to investigate other alternatives. While the irrigation valve seemed to fit our needs quite well, our goal was to see if we could build a cheaper yet equally effective "valve" for the project. After a lot of brainstorming and several abandoned concepts, we decided we would try to use a mouse trap and a piece of flat hose to act as a pinching device to cut off water flow.

This design was cheaper than the irrigation valve and pretty simple to build. It consisted of attaching a short section of PVC pipe to one side of the kill bar on the mouse trap which had the flat hose running underneath it. There was a hole cut out under the trigger mechanism which we were to place a simple solenoid. This would act as our firing mechanism since when the power was lost, the spring-loaded solenoid would hit the trigger of the mouse trap, swinging the PVC pipe onto the flat hose and hopefully pinching off the water flow.

After some brief calculations, we determined that given the water pressure within the hose and the strength of the kill bar spring, we should have close to enough force to seal off flow. So considering the materials were cheap, we went out and purchased everything we needed to do some preliminary testing.

Preliminary testing revealed a handful of problems that would eventually lead us to scrap the idea entirely. First off, the mouse traps were prone to breaking. We destroyed several during our tests where either the staples holding the spring to the base plate would come detached or the base plate would fracture after multiple uses. Since the PVC pipe was not intended to be used on the kill bar, we found it put a lot of strain on the components of the mousetrap and the only way we could get it to sit flush on the base plate without putting a torque on the kill bar was to carve out the edge of the base plate. This was unpractical and not an exact science. Once we got a mouse trap to last more than a handful of swings, we encountered another problem with the design. The flat hose we were using had thick enough walls that when pinched flat, the edges would not seal. This caused significant leaked in our preliminary tests of the unit and we concluded that the mouse trap would not have enough force to seal the edges of the hose. We then began to look into using a Steel pipe rather than PVC so that we could incorporate a magnet into the base plate to aid in sealing. However, after a lot of discussion amongst our group and with the customer, we decided that the robustness of this option was no longer suitable for our needs. Given that the units were going to be put in kiosks that potentially wouldn't have the materials for frequent replacement of parts, our group decided the concept would not hold up to the demands of the customer.

By this point, the use of the magnets and other parts to try to improve the seal quality had brought the price of the unit close to the irrigation valve. The customer had expressed concerns about the aesthetics of using a mouse trap as a water purification safety mechanism as well. When all the options were laid out, using the irrigation valve became the clear choice. It would be much more robust and reliable for nearly the same cost.

RESULTS AND DISCUSSION

Testing revealed that when both photodiodes are used on the same circuit board, issues were seen that caused one valve to close even if a failure was not observed in that particular UV chamber. When only one photodiode was connected to the circuit board, this problem goes away. After troubleshooting problems which may cause the two photodiode circuits to not properly behave properly in parallel, it was determined that the root cause may be the grounding system used on the circuit board. Isolated grounds may be necessary for both to behave separately. One system alone works with no issues over many tests. No accidental closures or openings of the valve were observed.

The operator warning circuit behaves properly. As soon as a failure is observed, the speaker sounds and red LED turns on. The speaker, however, does not quite meet the spec for loudness (85dB). The speaker can be heard from a distance of greater than 8 meters. The LED can also be seen from this distance. Therefore the operator should have no problems identifying if there is an issue.

As for the valve portion of testing, our primary focus was making sure they sealed completely in the fail position and that the flow rate of 5L/min was preserved. The valves sealed well initially but due to large amounts of debris from our test rig construction (primarily sawdust), the diaphragms lost their seal characteristics and would slowly leak. It was noticeable because when they leaked, the flow rate would drop off considerably when one chamber was open and one was closed. This issue was fixed by simply unbolting the halves of the valve and cleaning off the diaphragm. Once this was done and the valve was put back together, it held pressure well. This should not be an issue in the kiosks because the water is run through carbon filters prior to the valves.

To test the flow rate, we ran one chamber at steady state for one minute and measured the water that collected in a beaker. We found the height differential between the reservoirs at the top and the outlet of the chambers had a considerable effect on the flow rate and when we moved the chambers down approximately one foot, the flow rate jumped from 3L/min to 4.5/min. At 4.5L/min, the height differential was exactly 4 feet (measured from the exit of the chamber to the *bottom* of the reservoir tank). The reservoir tanks were both full at approximately 12 gallons of water total for this test as well. The pressure reading on our gauge, which was 2.5 inches above the valve level, was 2.2 PSI.

The entirety of our test results can be seen below in figure 4. In the pass/fail column, those marked with an "x" were passing scores while those with "-" were failed results.

ES #	Engineering Specifications	Nominal Spec Value	Marginal Spec Value	Spec Units	Measured Value	Pass/ Fail	Comments
1	Limits contaminated water flow entering storage tank	0	<200	mL/tank	7.7	X	Average for 2 valves for 30 minutes of closed time (6.5 mL and 9mL leakage).*Leakage collected at entrance to chamber
2	Allows flow rate of 5L/min	5	1	L/min	4.5	X	*per chamber with 4 foot inlet/outlet differential
3	Solenoid Voltage	24	2	VDC	15	X	15V used so on board voltage converter behaves more efficiently, solenoid operates well at 15V.
4	Operating Voltage	5	0.2	VDC	5	X	
5	Time for operator reset	<5	<10	min	0	X	Automatic reset except for if operator shuts ball valve
6	Materials/Labor cost to customer	<100	<150	$/unit	$202	-	For initial install
7	Total cost for expected year of life	<10	<20	$	$5	X	(x2) 9V battery cost
8	Frequency of consumable/replacement parts	0	<5	~/yr/kiosk	2	X	9V battery replacement 6 months
9	Largest hole diam. in electrical housing	<2	<5	mm	0	X	No non-sealed holes in housing
10	Weight	<5	<10	kg	0.42	X	This is the heaviest part of the project
11	Photo diode output for failure trigger			VDC	2.8	N/A	
12	Water leaked on floor per hour	0	<0.5	L	0	X	
13	Sense power loss	y	y	Bi	y	X	one chamber at a time
14	Time between failure occurrence and flow cut-off	<4	<6	sec	10.3	-	Due to water momentum in chamber. Valve shutoff is instantaneous
15	Audible warning decibels	95	10	dB	47	-	had to limit current to not blow small speaker
16	Visual warning gets operator attention from distance	>8	>4	m	>16	X	
17	Warn operator duration	>150	>60	min	~17 hours	X	At full load (speaker running constantly) the battery lasts approximately 17 hours. This can depend on type of 9V battery used (some can hold more charge than others).
18	Delay for rapid power on-off	3	1	secs	0	-	Couldn't get board to operate properly with delay
19	Withstands spray for 1	>1	>0.5	min	>1	X	Water-tight electrical housing

	minute						
C1	Maintenance time to change bulb	<20	<60	min	NA	X	Our additions don't effect change time
C2	Space Required above UV tube	<0.5	<1	m	0	X	Not effected
C3	Notifies Operator of Failure	y	y	Bi	Y	X	
C4	UL Criteria for Elect. Components	y	y	Bi	Y	X	
C5	Operates in rain-leaking kiosk	Y	y	Bi	Y	X	
C6	Safe Materials for Drinking Water	y	y	Bi	Y	X	irrigation valve is only thing in contact with water
C7	Parts/material available in Mexico	y	n	Bi	N	?	Parts that need to be purchased and brought into Mexico are long lasting which meets customer needs
C8	Connect to Kiosk Plumbing	y	y	Bi	Y	X	
C9	Serviceable with basic Hand tools	y	y	Bi	Y	X	Except electrical circuit board
C10	Cuts chamber flow independently	y	y	Bi	N	-	Chamber independence not working on single electrical board. They would need to be on 2 separate circuits

Figure 4. Testing Checklist and data sheet.

Testing revealed that when both photodiodes are used on the same circuit board, issues were seen that caused one valve to close even if a failure was not observed in that particular UV chamber. When only one photodiode was connected to the circuit board, this problem goes away. After troubleshooting problems which may cause the two photodiode circuits to not behave properly in parallel, it was determined that the root cause may be the grounding system used on the circuit board. Isolated grounds may be necessary for both to behave separately. One system alone works with no issues over many tests. No accidental closures or openings of the valve were observed.

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CONCLUSIONS AND RECOMMENDATIONS

The end result of the system is not exactly what was originally anticipated for the safety system. The original idea was to have a single control board with a single power supply to control the two UV chambers in a normal kiosk. The end result is more of a modular design. This means that a single board can only control a single UV treatment system. A UV treatment system in this context involves a UV chamber / bulb, valve system power supply, and control system (PCB). There are benefits and flaws to this end result. The major flaw is the additional cost of multiple power supplies, PCB's and wiring. The major benefit of this more modular design is that there is a greater flexibility in the number of UV chambers inside a kiosk. The system is flexible enough to be able to be used in a single unit system, which is optimal for a residential setting, to several units for more rural to even urban environments. With the end result design for theses larger kiosks the only major constraint besides costs and space is the number of outlets that are available for the UV chambers and control PCB's.

The Test Plan covers the basic dynamics and constraints of the engineering specifications for this project. The Test Plan does not need generic modifications, since each kiosk is assumed to have some variability in between them. However some tests should be performed and repeated throughout installation to modify the safety system to allow for consistent performance. These tests have to include both mechanical and electrical components of the project.

For the electrical control system, the overall dynamics of the board should be tested. This includes that all the operator interface features work as intended and that system is capable of detecting and notifying the operator of system failure.

For the mechanical safety system the valve system dynamics should be tested. Prior to installation in the UV water treatment system all valves should be tested to see if they are functional. After system integration the flow rate and leak tests for each system should be performed. If either of these tests fail, the valve system has been installed in an incorrect location and should be relocated to the specified location, (closer to the UV chamber).

It is recommended that two circuit boards should be used in the final product, one for each UV chamber and photodiode. This adds a few parts, which includes a second external power supply, extra 5V DC-DC LDO on board supply, and extra bare board PCB. However, the cost addition of adding these extra components isn't too high compared to the overall cost of the kiosks. The extra cost is about $50 more.

Testing still needs to be done in correlating UV output to the threshold voltage at which the valve will close. A UV spectrometer should be used to determine the percentage of the initial UV output at which the water will be properly treated. The threshold can then be changed by switching out a couple of resistors (R1 and R2). The photodiode output is effectively linear. Therefore a simple percentage can be used for the threshold voltage at which the solenoid valve closes. The following equation can be used to determine proper resistor values. The maximum output voltage is 3.6V (maximum UV output). $V_{threshold}$ is determined by taking the UV output percentage and multiplying by 3.6.

$$V_{out} = V_{threshold}\left(\frac{R2}{R1 + R2}\right)$$

Overall, this project can be considered a success. We have come up with a means to meet most of the customer's needs and we will have a full documentation package to assist the customer is setting up our system in the kiosks. If the customer chooses not to want to pay a premium for the two PCB design, the system can also be fairly easily set up to plug the valves directly into the PCB's power supply. With this setup, the only failure mode that will be detected is a power outage and will potentially run the risk of contaminating clean tank when the power comes back on until the bulb warms up. Our group is also recommending that ball valves be installed before each irrigation valve so that the operator has manual control of water flow for times like cleaning the diaphragm.

REFERENCES

Peletz, Rachel L., Amy J. Pickering, Alicia R. Chakrabarti, and Kara L. Nelson. *Performance Testing of Ultraviolet Lamps for Point-of-use Water Disinfection*. Tech. 2010. Print.