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Chlorine Generation: The Do-it-Yourself Approach

Background:

Almost one in 6 people lack access to clean drinking water. This results in over 1.5 million deaths each year. Most of these deaths are children under the age of 5. Bleach is a low cost way of disinfecting water. Unfortunately, it becomes more expensive to transport and thus is not always accessible to those with extremely low income. This makes local chlorine generation a viable means of ensuring people in all areas can have access to bleach for clean drinking water.

Previous Work:

In past years this project has not been a d-lab project. Thus we are the first d-lab group to be working on it. However, much research has been done in this field by other groups, including at IDDS 2010, where one group project was local chlorine generation. Primarily which have done previous work in this area are companies. Many companies have found ways to run electrolysis locally in order to produce chlorine.

One of these companies is Miox. Miox produces, among other things, a very small pen-like device which can treat up to a gallon of water at a time. This pen is very easy to use, all the operator has to do is press a button and the chlorine solution is promptly produced. There are downsides to this product, though. It is costly, and thus unaffordable to the poor, and it operates on batteries, making it even more inaccessible to those living on very low incomes.

Another company is Antenna Technologies, the makers of the WATA devices. Antenna's smallest device, the Mini-WATA, produces enough chlorine in 12 hours to treat 4,800 liters of water. It is a very sleek device which can just be placed into the top of any standard plastic water bottle. It consists of two electrodes (made of unknown materials) encased by a plastic tube. The Mini-WATA is then connected to a power source (standard model uses 110 or 220V power source, but it can be adapted to use solar power). This product's simplicity makes it attractive, but it costs over $50. This would be too significant an investment for the extremely poor to purchase on their own. It would have to be a community investment, which then brings about the issue of ownership within the community. Furthermore, while the product does make use of some locally available materials, the bulk of it is not local.

The next place which has done a lot of previous research is waterpot.org. Waterpot is non-profit which has worked on developing a chlorine generator which can be assembled completely locally. The system requires graphite rods, a used car battery, and car battery cables. The cost of this system is approximately $20. However, to truly power the system a bicycle, alternator, and v-belt are also needed. In tests done in Kenya these added up to almost an additional $200. This organization, however, does a good job of making all of its materials locally available and locally producible. They make readily available the exact specifications on how to build their system.

Finally, Paul Polak's organization, International Development Enterprises (IDE), has been rumored to be working with Windhorse International on project which uses local electrolysis to clean water. Almost no information is available on this project, but the project was confirmed by Polak when he visited MIT this spring. His system is a community based system which uses solar power to run electrolysis.

Figure 1 shows a comparison of the specs for all of these previous products. The last column is where we initially saw our specs fitting into the market.

	MIOX Pen	Mini-WATA Regular	Mini-WATA Solar	Water Pot	Us
Cost	$120.00	$55.00	$69 + solar panel (~$100)	$220.00	< $55
Input power Source	2 Li-ion batteries	AC outlet	Solar panel	Pedal power	Renewable energy source
Number of people served	1	240	240	1000-1500	> 200
Store energy or feed-in?	stored	feed-in	feed-in	stored	?
Work time	0	0	0	1 hour	< 1 hour
Production time	seconds	12 hours	12 hours	1 hour	< 1 hour
Materials needed	manufactured	manufactured	Manufactured & sun needed	Locally available	?

Figure 1

Initial Design Concepts and Decisions:

We decided to set our problem statement and from that go about brainstorming and then creating a device. Our problem statement was as follows: Many people in the world lack both potable water and access to chlorine, an effective disinfectant. A device that produces chlorine on site without access to the electrical grid is needed. Our goal is to design an affordable solution that satisfies a person's need for 2L of potable water per day, assuming the user has access to salt, a necessary component in chlorine generation, and the water has no chemical contaminants, e.g., arsenic and pesticides.

Initially we focused out brainstorming around our source of power. After hours of brainstorming we narrowed down our ideas to 6 primary possible sources to look into. A Pugh chart was then made for these 6. The chart is shown in Figure 2.

	Datum (hand crank)	Thermal Energy	Hand Pump	Solar Energy	Traveling Bike	Stationary Bike
Cost	0	- -	+	- - -	+	+
Work Time	0	+ +	+ +	+ +	+ +	+
Production Time	0	-	- - -	+ +	+ + +	+ + +
Ease of Maintenance	0	-	- -	- - - -	+	+
Cool Factor	0	+ +	+ +	+	+ +	+
TOTAL	**0**	**0**	**0**	**-2**	**9**	**7**

Figure 2

Each criterion in the Pugh chart was carefully evaluated with an appropriate method. Our cost evaluation was done via research. Each option's individual components were looked into and prices were found and compared. The evaluation of production time was done via a simple calculation. Essentially, the amount of charge needed to produce a given amount of chlorine is known. Since we also know the Amps we can obtain from each power source we can then calculate the production time by dividing the amount of charge by the amps.

The work time could then be found based upon these calculations. For methods which require no use of human power outside of daily tasks which are already performed (such as a traveling bike) the work time is 0. However, if a method does require extra effort from a human the work time is equal to the production time. Ease of maintenance was another factor which could be measured via research. It was based upon the locality of materials used and expertise on each of the methods. Finally, the "cool factor" was our team's way of weighing in upon which design we thought was most interesting. After considering all of these factors we choose the traveling bike as our method of power for chlorine generation.

Later Design Concepts and Decisions:

After we presented our initial findings to our mentors we had to under-go a complete project change. From the on-set of the project our team had decided that finding a viable replacement for batteries in running electrolysis was our focus. However, after the second design review we were urged by our mentors to abandon that focus. We were essentially told to go back to the basics, our design specifications (shown in figure 3), and start considering designing aspects which would chemically effect our electrolysis. Previous to this we had assumed that since electrolysis had been run many times before that it would be a moot point to experiment on these things. As the mentors pointed out, and as we quickly learned, it was far from moot.

User Need	*Design Specifications*	*Acceptable Value*	*Ideal Value*
Affordable	Cost	$80.00	<$10
Ease of use	Work time	<5 min/L	< 30 sec/L
	Interface	Explanation/expertise required	Self-explanatory, intuitive
Ease of transport	Size	40mL hypochlorite solution	100mL hypochlorite solution
	Weight	< 30 lbs	< 10 lbs
Access to disinfected water	Chlorine concentration	3-5% hypochlorite	3-5% hypochlorite
	Daily chlorine output	50g NaClO	125g NaClO
	Daily capacity	Treat 200L water	Treat 500L water
Durability	Lifetime	1 year	> 5 years
Safety	Toxic output	None	None
	Electrical output	No risk	No risk

Figure 3

Thus we changed the entire focus of our project at this time to fully characterizing electrolysis and coming up with a system which can accurately produce predictable amounts of chlorine solution. This includes the material for the electrodes, the container shape and material, method used to limit the amount of chlorine produced in the reaction, and amount of salt used. To determine each of these we looked to our goal design specifications and went about testing.

For material of electrodes we researched which materials had been proven to work. We found that graphite rods and tungsten both would work. We did test runs of electrolysis using both and found that though the graphite rods are less sturdy than the tungsten ones they make the reaction occur more quickly and thus could potentially lower our work time. Additionally, the graphite rods are far cheaper and more locally available. Thus we chose to use graphite rods.

We realized that our reaction container could be any size so long as it is large enough to fit the electrodes. We considered manufacturing clear containers made of Plexiglas. However, we realized that if instead our container is a used water bottle the cost dramatically decreases. Additionally, the product is then even more locally available.

Due to both of these reasons we chose to use a 1.5 liter water bottle which the user then cuts so that only the bottom third of it remains.

To limit the reaction we considered measuring hydrogen production, limiting salt put it, and measuring time of reaction. We tested each of these options. Limiting the reaction based upon the amount of salt put it posed some serious issues. First, the amount of salt to limit the reactions accordingly was far too small to measure and required that double dilution be done to procure it. Additionally, it proved to be unreliable. This most likely is due to other types of salt already being in the water and reacting along with the salt we put in.

Both the hydrogen and time methods showed promise, though. In the hydrogen method the amount of hydrogen produced during the reaction is used to limit the length of the reaction. Since this amount of hydrogen correlates to the amount of chlorine produced it is a way to measure how much chlorine has been generated. The hydrogen method can be used to build pressure in the reaction chamber. This pressure can push the brine up a siphon so that once the brine reaches the peak of the siphon the siphon is triggered and all the brine rushes out of the reaction chamber. We did tests on the method and found that it allows for a fairly accurate measure of chlorine production. It also automatically stops the reaction by moving the brine out of the reaction chamber.

However, the time method is much simpler for the average person to understand. It also requires a much less complex system. Since the amount of chlorine produced is also related to the time the reaction has run for the reaction can just be timed and stopped appropriately. After many experimental tests our team was able to determine that this method is also accurate enough to use. However, it is not quite as accurate (since different types of water contain different compounds and thus the reactions vary slightly and unpredictably) and it requires that the operator shut off the reaction.

In the end we chose to focus on the time method. We chose this because it involves the least complex system and thus does not increase our costs. It also can be used in conjunction with the water bottle container, where as the water bottle would be more difficult to adapt to use with the hydrogen pressure system.

Finally, we had to look into the amount of salt to use in our reactions. Since we had already eliminated using very small amounts due to the difficulty in measuring we needed to look into either using a saturated solution or an easily measureable amount. After calculations were done we found that the amount of salt needed to saturate 1 liter of water is approximately 360 grams. This is compared to only approximately 35 grams in 1 liter of sea water. This amount is clearly far above the taste threshold and even if it were diluted in 10 liters of water it would still be taste able. Due to this we decided to use a spoonful of salt. It is an easily measured amount and is not above the taste threshold when mixed into 10 liters of water (our eventually chosen volume).

Experimentation and Results:

Our initial methods were aimed at exploiting the concentration of chlorine over time. The amount of chlorine, produced through electrolysis, varies over time, increasing linearly until a certain point at which it decreases to reach equilibrium. We wanted to take advantage of the equilibrium point, tweaking variables (e.g., salt concentration, cell size, electrodes) so the chlorine concentration at equilibrium could purify a desired amount of water. The linear portion of the chlorine profile would also produce the right amount a some point in time, but waiting until equilibrium allows more leeway in time. Specifically, a slight error in timing during the linear portion could have terrible repercussions from producing the wrong amount of chlorine whereas at equilibrium the same amount of chlorine would nonetheless be produced.

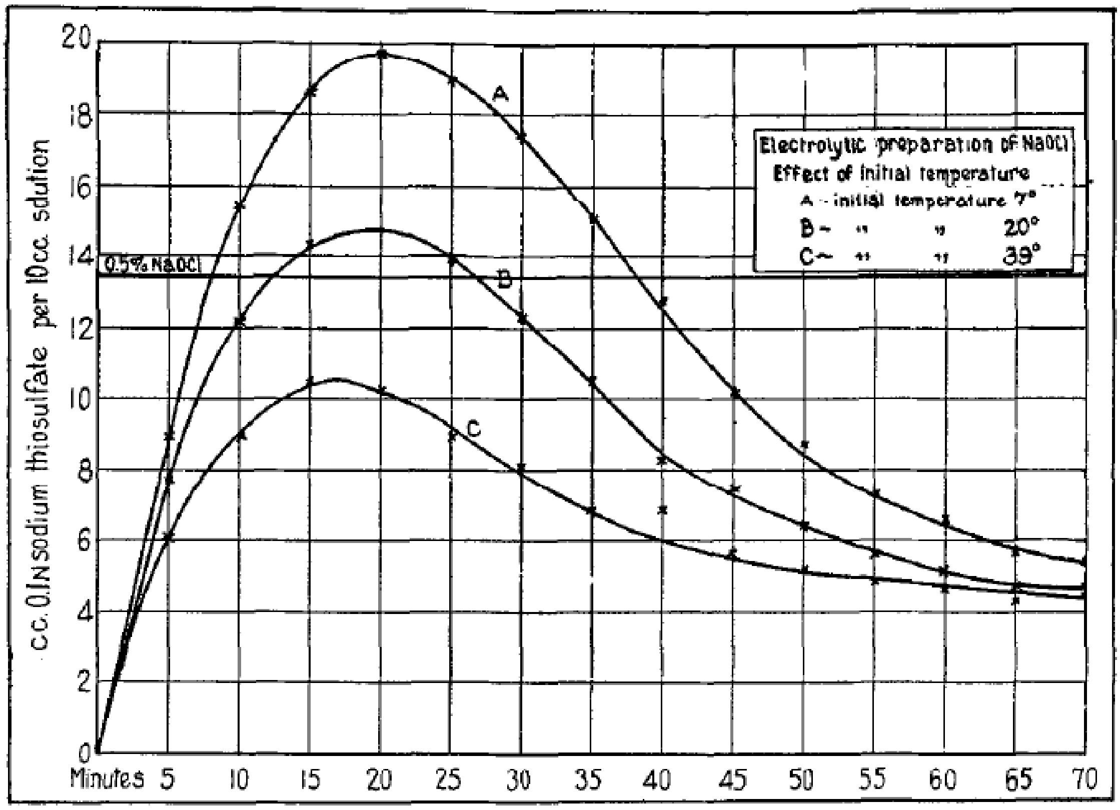


Figure 4: Behavior of Chlorine over Time

We decided to test with a saturated salt solution with the intention of making measuring easy for the user (the user could be instructed to mix salt in water until no more can dissolve). Testing proved that saturation provided far too much salt for chlorine to reach equilibrium within a realistic span of time. Running electrolysis at about 20V and 0.5A (or, the maximum our power supply could provide), the chlorine concentration was still increasing linearly after ten minutes. Extending the result to more realistic voltages (i.e., around 5V) implied that the reaction would take much longer. Therefore, we ruled out saturated salt solution as a realistic approach in reaching equilibrium. Testing was done with a makeshift cell made from tupperware and eight electrodes cannibalized from D-cell zinc-chloride batteries designed solely for purposes of testing.

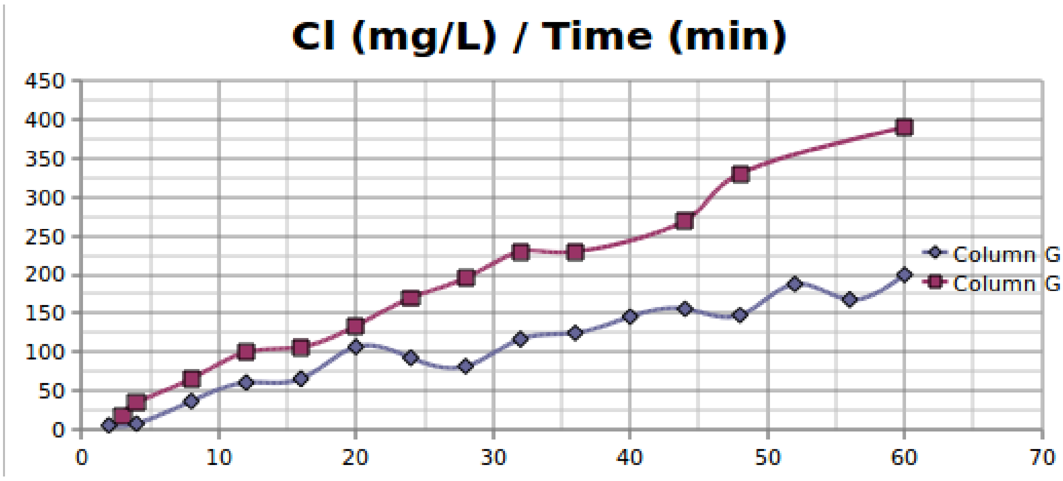


Figure 5: Two iterations of Clorine production in saturated salt solution. Y-axis corresponds to chlorine concentration (mg/L), x-axis corresponds to time (min)

Using saturated salt solution would have also affected the taste of the water. Ultimately, once the water has been dosed with the correct amount of chlorine (produced from our saturated salt solutions), it would consist of about 1% salt. Seawater consists of about 3.5% salt. The amount would certainly be tasted and possibly have negative effects on the human system over time.

We decided to use a spoonful of salt, which would be enough to produce the desired amount of chlorine while eliminating the taste of salt. Again, using the maximum power our power supply could provide to increase the rate of reaction, we found that the chlorine profile would still not reach equilibrium within a reasonable amount of time. Therefore, our remaining option was to focus on the linear behavior, stopping the reaction once enough chlorine has been produced.

We purposely kept “spoonful” fairly vague, hoping we would not need to standardize the spoon size so the user could use any medium-sized spoon. Initial tests with a common teaspoon proved that enough chlorine could be produced within fifteen minutes with an input voltage of 5V. We varied the spoon size and enough chlorine, within an acceptable range, was still produced. This proved that the user could use variations of a medium-sized spoon and still obtain the right amount of chlorine within a certain amount of time.

Next, we tested chlorine production in various types of water. We used tap, bottled, and Charles River water and found that the chlorine concentration was still within the desired range after fifteen minutes of electrolysis. Inspired by the approximate “spoonful,” our cell had evolved into what became our final design, incorporating common materials that can be assembled without much accuracy. This is the cell we used in all tests that involved a spoonful of salt.

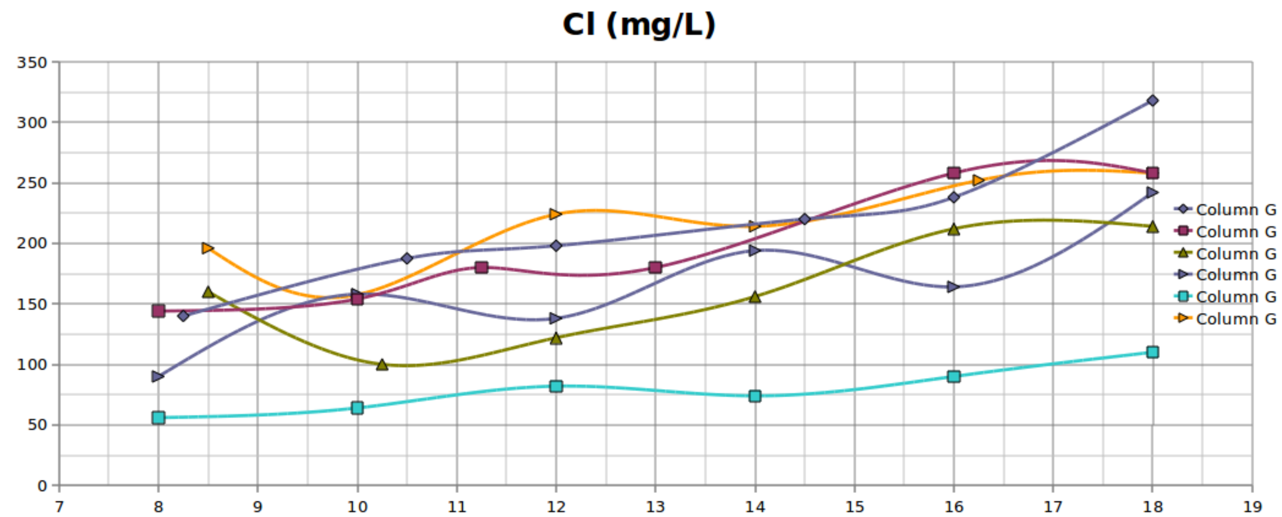


Figure 6 : Chlorine concentration from various spoon sizes. Each color corresponds to a spoon size, y-axis corresponds to Chlorine concentration (mg/L), x-axis corresponds to time (min)

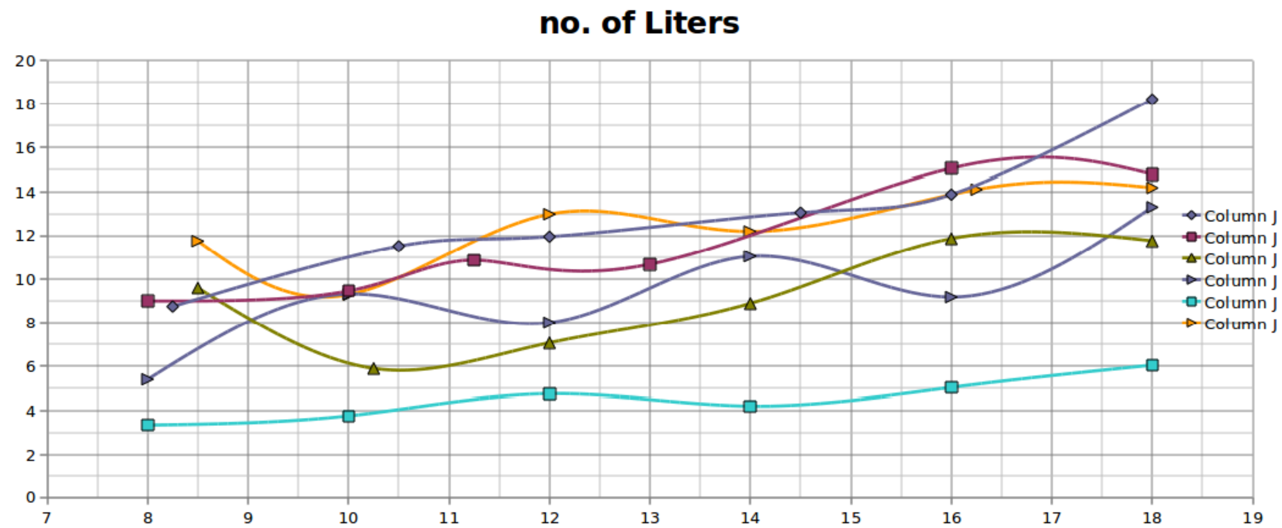
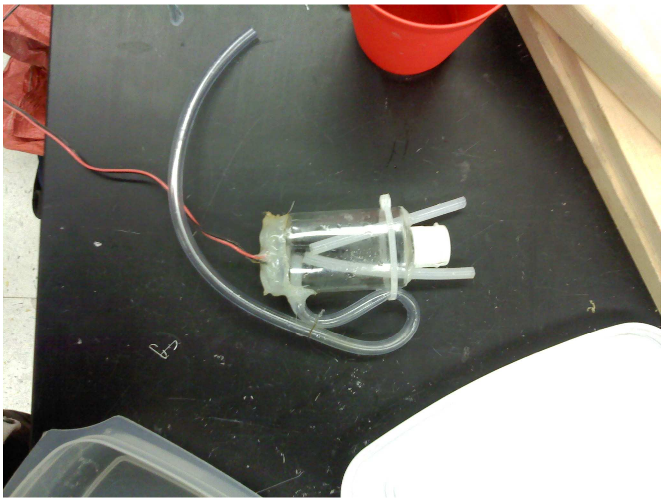


Figure 7 : The number of liters of water corresponding to points in Figure 6 can treat

A spoonful of salt, which ranges from 7-14 g, provides far more salt than necessary to purify 10L of water, our target amount. Only 78.5 mg of salt is required to produce enough chlorine to purify 10L of water. We based our dosage on recommendations made by the World Health Organization, which is four drops of 5% household bleach added to 1L of water (or 4.8 mg/L). Because we want enough to purify 10L, we need to produce 48 mg of chlorine.

Our Prototypes:

Our first prototype was made of a hand sanitizer bottle and used hydrogen gas production to trigger a siphon. When triggered, the siphon would rush the chlorine solution out of the bottle and thus stop the reaction. This was a good first prototype for us to learn from.



Prototype 1

Our second prototype was a means for us to test various electron types. It use two water bottles connected to one another via tube. Each water bottle's cap had an electrode in it. We could then replace the caps with caps holding a different material electrode and run the reaction again. This prototype also worked fairly well, but was too complicated for a person to make on their own and not well enough designed to be considered for manufacturing.

Prototype 2

Our third prototype continued to use two connected water bottles. We did this because by separating the electrodes into different bottles we were able to measure hydrogen gas output and oxygen gas output separately. Though this was a design we liked, we eventually decided that measuring hydrogen output was not the best way to limit the production of the chlorine and thus moved away from this model.

Prototype 3

In our fourth prototype we began to make use of carbon electrodes from cannibalized batteries. In it we decided to try using 8 electrodes wired in parallel to see if it speed up our reaction time significantly. Though it did help a bit, we found that the circuit in this design was often shorting and decided that it was more complex than necessary.

Prototype 4

In our fifth prototype we wanted to keep the used battery electrode idea from the 4th, but move to a simpler container which we did not have to manufacture ourselves and which would be widely available. Thus, we decided on a used peanut butter jar due to its reasonable size, removable lid, and accessibility. This prototype really seemed to be a good idea to us after doing testing on it. However, we wanted to try out a design which allowed us to move around the electrodes.

Prototype 5

In our sixth prototype we keep most things the same as with the fifth, but added in the element of moveable electrodes. We did this by replacing the peanut butter lid with a string mesh top. Though this was interesting, we found that giving the users the ability to vary the electrode separation only decreased our ability to properly control the amount of chlorine produced. Thus we decided that moveable electrodes are not the direction to go, but that allowing electrode to be easily added and removed is a good idea.

Prototype 6

Final Design:

For our final design we chose a do-it-yourself method. The steps are as follows:

1) Gather your materials. You will need 2 D-cell zinc-chloride batteries, an empty bottle, a sheet of plastic, a bike dynamo, some salt, and a bit of water.

2) Remove your electrodes from the batteries and cut-off the bottom third of the bottle, as in shown in Figures 8 and 9 respectively.

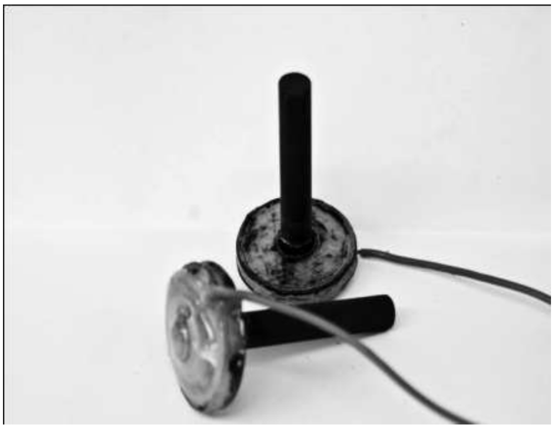


Figure 8

Figure 9

3) Position the electrodes so their edges are almost touching and then push them through the plastic sheet as is shown in Figure 10.

Figure 10

4) Fill the cut bottle with water and mix in 1 medium sized spoonful of salt.

5) Place the plastic sheet with the electrodes on top of the water bottle as is shown in Figure 11.

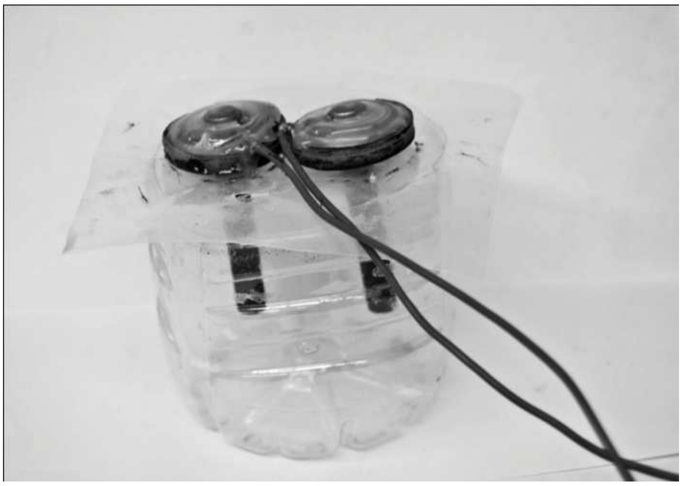


Figure 11

6) Connect the electrodes to the bicycle dynamo (or any other low voltage power source available).
7) Run the power source at 5 volts for 15 minutes. This will produce a concentrated bleach solution in the bottle
8) Dilute the solution in the bottle into 10 liters of water. Now these 10 liters are safely treated water for drinking!

Each of these steps was determined initially based upon the reasoning and testing explained in the design concepts and decisions portion of this paper. However, the time the device is run was determined experimentally (the experiments done are described in the experimentation section above). This had to be done this way because the separation of the electrodes, the length of electrodes, amount of salt, size of container, and voltage all affect the amount of chlorine produced in any given period of time. Thus we decided to set each of those parameters and the amount of chlorine we wanted to produce. Then we experimentally determined the time to get that amount of chlorine with our given system.

Design Discussion:

Here we will briefly discuss how our final design takes into account many aspects and where it has shortcomings.

Usability- Our design is extremely simple, which makes it highly intuitive and thus easily used. The fact that the user puts it together his/her self means that it is a highly transparent design. This also aids in its ease of use.

Affordability- The majority of the design requires only recycled materials. This means it is extremely low cost. However, in our design we are assuming that people would have access to low cost bicycle dynamos or other low-voltage power source. This could actually be quite expensive in some areas, so our design is really only extremely cheap for areas which have easy access to those items.

Re-Usability- The design is not really focused upon re-usability. Most of the parts are already recycled materials and reach the end of their life cycle in this product.

Sustainability- Sustainability was not a huge factor in our design. Many of the materials used in it are frail (such as the water bottle and electrodes) and may wear out fairly quickly. However, since these are locally available recycled materials they will be very easy and cheap to replace.

Failure- The places the design will fail first are either in the wearing-out of the electrodes or in the degradation of the bottle or plastic sheet’s structure. Since all of these places of failure are very easily fixable, due to the readily available nature of their materials, they are optimal places for failure if failure must occur.

Manufacturability- The design requires no specially manufacture materials. This means all the materials are very readily available and low-cost because they rely upon large scale manufacturing systems. Our design was carefully done so as to not really depend upon or deal with manufacturing. It deals more heavily with assembly instead.

Assembly- The product is assembled by the user. This makes it less expensive, but is more of a hassle for the user. The design, however, is extremely simple and requires very few parts, thus making it easy to assemble for the user.

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Appendix A

Chlorine Team Final Paper Summary

Problem Statement: Many people in the world lack both potable water and access to chlorine, an effective disinfectant. A device that produces chlorine on site without access to the electrical grid is needed. Our goal is to design an affordable solution that satisfies a person's need for 2L of potable water per day, assuming the user has access to salt, a necessary component in chlorine generation, and the water has no chemical contaminants, e.g., arsenic and pesticides.

Design Specifications:

User Need	*Design Specifications*	*Acceptable Value*	*Ideal Value*
Affordable	Cost	$80.00	<$10
Ease of use	Work time	<5 min/L	< 30 sec/L
	Interface	Explanation/expertise required	Self-explanatory, intuitive
Ease of transport	Size	40mL hypochlorite solution	100mL hypochlorite solution
	Weight	< 30 lbs	< 10 lbs
Access to disinfected water	Chlorine concentration	3-5% hypochlorite	3-5% hypochlorite
	Daily chlorine output	50g NaClO	125g NaClO
	Daily capacity	Treat 200L water	Treat 500L water
Durability	Lifetime	1 year	> 5 years
Safety	Toxic output	None	None
	Electrical output	No risk	No risk

- *Affordable*. The total cost of our solution should cost no more than $80, and the ideal cost should be less than $10.
- *Ease of use*. "Work time" refers to the amount of time a user needs to use the device in order to produce enough chlorine to purify one liter of water. "Interface" refers to how easy it is to use our device, whether it requires instruction or is completely intuitive.
- *Ease of transport*. "Size" refers to the amount of hypochlorite solution (assuming constant concentration) the device produces. "Weight" is self-explanatory.
- *Access to disinfected water*. The chlorine should be 3-5% solution and enough should be produced to treat 200-500L water per day.
- *Durability*. The device should last at least one year, and ideally more than five years.
- *Safety*. The device should not output any toxic substances, nor pose any electrical threat.

Prior Work:
Most prior work has been done by companies who also wish to create local chlorine generation. Below is a summary of the products which have been produced by these companies. The far left column is how we expected our product to compare to these previous works. l

	MIOX Pen	Mini-WATA Regular	Mini-WATA Solar	Water Pot	Us
Cost	$120.00	$55.00	$69 + solar panel (~$100)	$220.00	< $55
Input power Source	2 Li-ion batteries	AC outlet	Solar panel	Pedal power	Renewable energy source
Number of people served	1	240	240	1000-1500	> 200
Store energy or feed-in?	stored	feed-in	feed-in	stored	?
Work time	0	0	0	1 hour	< 1 hour
Production time	seconds	12 hours	12 hours	1 hour	< 1 hour
Materials needed	manufactured	manufactured	Manufactured & sun needed	Locally available	?

Concept Evaluation:
We began by focusing on finding a proper power source. We did this by brainstorming ideas, selecting the best ones, and creating a Pugh chart for those. From the testing done for this chart we chose a traveling bicycle as our power source.

After making this design decision we evaluated methods for dosing, including limiting salt input, measuring hydrogen output, and tracking length of reaction. We also evaluated electrode materials, such as carbon rods and tungsten, and amount of salt to put to use to create the brine solution. After testing we chose the focus on limiting the reaction by timing it, using carbon electrodes, and using an easily measured amount of salt.

Proposed Solution:
The comprehensive solution we developed is a do-it-yourself solution. It aims to use primarily recycled materials which are readily available to people in most regions. Here are the steps to building and running our solution:
1) Gather your materials. You will need 2 D-cell zinc-chloride batteries, an empty bottle, a sheet of plastic, a bike dynamo, some salt, and a bit of water.
2) Remove your electrodes from the batteries and cut-off the bottom third of the bottle.
3) Position the electrodes so their edges are almost touching and then push them through the plastic sheet.

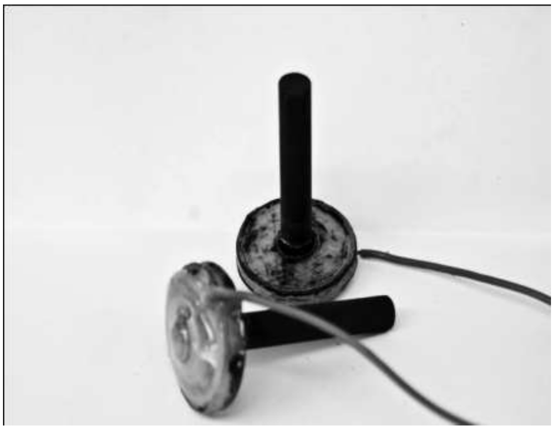
4) Fill the cut bottle with water and mix in 1 medium sized spoonful of salt.
5) Place the plastic sheet with the electrodes on top of the water bottle.
6) Connect the electrodes to the bicycle dynamo (or any other low voltage power source available).
7) Run the power source at 5 volts for 15 minutes. This will produce a concentrated bleach solution in the bottle
8) Dilute the solution in the bottle into 10 liters of water. Now these 10 liters are safely treated water for drinking!

Future Work:

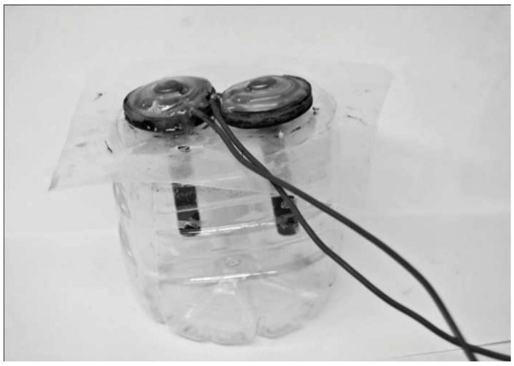
In the future there are a few primary things we would like to do. The first is start comprehensively testing the water we chlorinate for bacteria. This would help us make sure that the concentrations of chlorine our generator is producing are actually sufficiently cleaning the water.

The second thing we would like to do is continuing developing another system we created. This secondary system is more complex than our do-it-yourself model. It requires more components and would need some manufactured pieces. However, it doses based upon hydrogen production, which appears to be a more accurate method. Though this product would be more costly than the do-it-yourself product, it has the potential to be another viable solution and as such we would like experiment with it further.

Photos of Final Product:




On the left are electrodes removed from batteries and on the right is a properly cut water bottle.

On the left is a photo of the electrodes inserted into the plastic sheet. On the right is the assembled product.