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Design And Evaluation Of A Home- Scale Arsenic Removal System

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UNDER MY SUPERVISION BY

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ENTITLED

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DESIGN AND EVALUATION OF A HOME – SCALE ARSENIC REMOVAL SYSTEM

By

Megan Alferness and Alexandria Casares

SENIOR DESIGN PROJECT REPORT

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ABSTRACT

The problem of arsenic contamination affects millions of people worldwide. A home-scale arsenic removal system could provide families in Nepal access to clean drinking water. It would also reduce the risk of adverse health issues that are associated with ingesting arsenic contaminated water. Our experiments show that using electrocoagulation is an effective method of removing arsenic from water. We were able to get the level of arsenic below 10 ppb in 60 minutes of treatment using various system configurations. We identified several parameters that affect the treatment process, the most important being the charge loading, or the amount of charge that passes through the solution during treatment. The more current supplied, the faster the treatment, but too much current is inefficient. We identified an effective range for charge loading to be between 150 and 180 C/L. For a home-scale arsenic removal system to be used in Nepal, we recommend using a 6V rechargeable battery supplying 170 C/L of charge to a 3.5 gallon bucket (13L) and a electrochemical cell which consists of five 4"x4" steel plates. Water treated in the first stage then moves to a sand filter containing 10 inches of fine sand and a simple underdrain nozzle. The water will then be stored in a large container. With the battery constraint reduced or removed, the system can be upgraded to a larger treatment system or even an automated semi-continuous flow system. The design of this removal system is manufacturable, but is dependent upon the identification of a local manufacturer to maintain low cost. A manufacturer can be identified after field testing to observe the system's performance in the intended environment is completed.

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1 INTRODUCTION

Arsenic contamination in groundwater is a problem affecting approximately 137 million people around the world and in 70 different countries (Ravenscroft, 6). **Figure 1** highlights known areas affected by arsenic poisoning in groundwater.

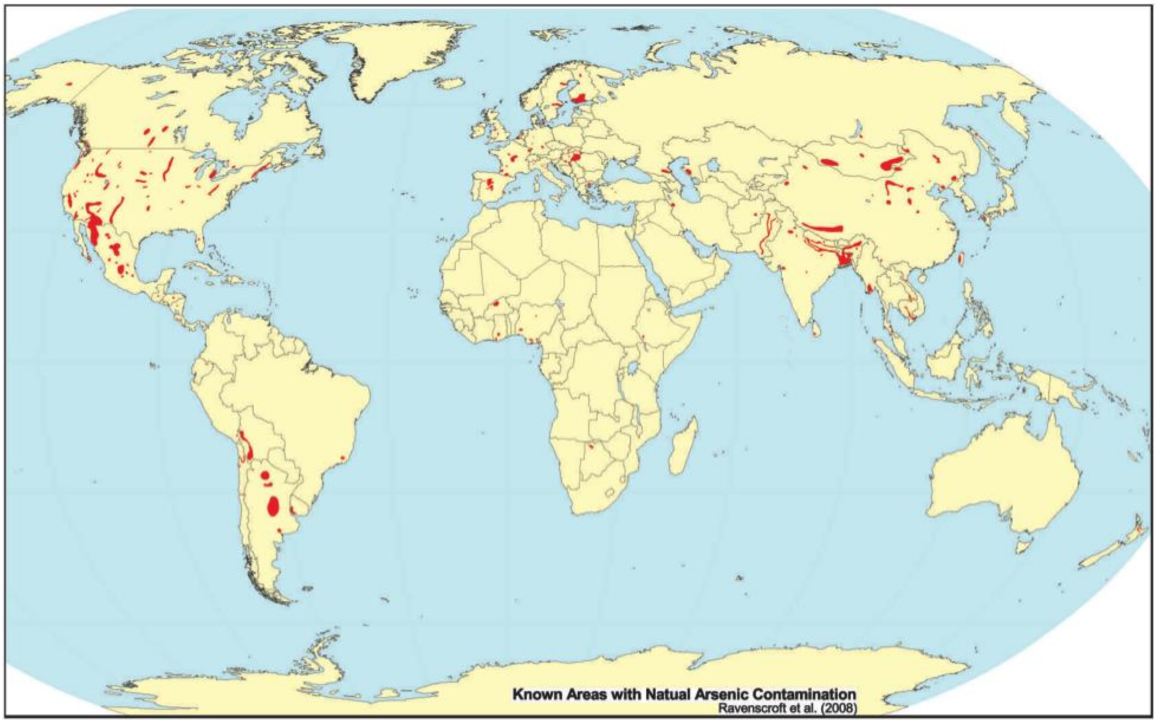


Figure 1: **Known areas of Arsenic Groundwater Contamination (Source: London Arsenic Group, 2008)**

Figure 2 displays areas that have a higher potential to be affected by excessive levels of arsenic contamination. Red indicated a high probability and orange is a lower probability. The widespread nature of areas susceptible to high levels of arsenic, as shown in **Figure 2**, demonstrates the positive global impact that an arsenic removal technology can have.

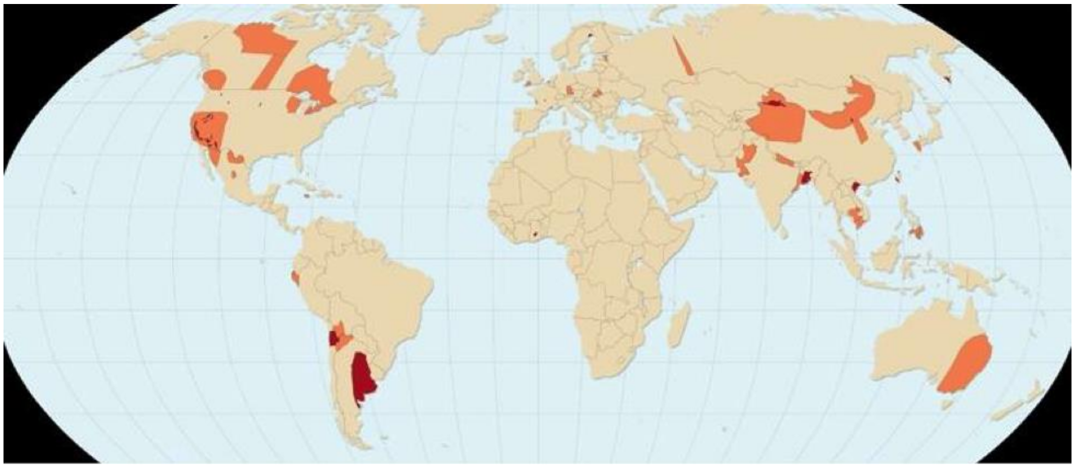


Figure 2: **Potential Regions with Excessive Arsenic Levels in Groundwater. (Source: National Academy of Sciences, 2008)**

This project focused on the people affected in South Asia, where arsenic levels can be as high as 200 ppb. Levels this high can cause a serious risk to health. The World Heath Organization states that potential health issues include skin damage, shown in **Figure 3**, problems with circulatory systems, an increased risk of cancer, and higher infant mortality rates.

Figure 3: Skin Damage Caused by Arsenic Poisoning (Source: Gross, Lisa. *Arsenic and Old Wells*)

As a result of these health hazards, the Nepalese government recommends an MCL (Maximum Contaminant Level) of 50 ppb, and the U.S. Environmental Protection Agency as well as the World Health Organization consider safe arsenic levels to be less than 10 ppb. These values are compared below in **Table 1**. The system was designed to reach the WHO and USEPA MCL of 10 ppb.

Table 1: Standards by Agency for Arsenic in Drinking Water (World Health Organization)

Agency	Maximum Contaminate Level
World Health Organizations	10 ppb
Environmental Protection Agency	10 ppb
Government of Nepal	50 ppb

The ultimate goal of the project was to design, test, and implement a home-scale arsenic removal system in Nepal. Because this project is being designed for use in a developing country there were certain design limitations and criteria. The main limitation was the size of the battery. The removal system had to be designed to provide adequate treatment using a small 6 V rechargeable battery. Other design criteria were that the product must be affordable and user friendly, as many of the families in Nepal have limited resources and knowledge of technology.

2 TECHNOLOGY SELECTION

Various technologies are available for arsenic removal. However, not all techniques are feasible for developing nations, like Nepal. This section evaluates removal technologies based on their applicability in Nepal.

2.1 Alternative Technologies Considered

Nepal is a developing nation with limited access to resources. Resource limitation combined with the need for a home-scale product a number of systems for arsenic removal were eliminated. Given the limited resources and small scale of the product, published scientific reports suggest coagulation techniques as the most effective solution for arsenic removal (Powell, 2001).

The simplest coagulation techniques have been identified as electrocoagulation, chemical coagulation, as well as the use of rusty iron nails. These techniques have been compared in several studies (Powell, 2001; Ngai et al., 2005). A brief comparison of efficiency, system scale, cost, and quality control is summarized in **Table 2**.

Table 2: **Comparison of Common Arsenic Removal Technologies (Source: Powell Water Systems, Inc.)**

Removal Technology	**Home – Scale Treatment**	
	Advantages	Disadvantages
Electrocoagulation with Steel Plates	• Low cost • Removal efficiency (95-99%) • Small scale batch treatment • High quality control	• Requires user maintenance
Chemical Coagulation	• Removal efficiency (80-90%) • High quality control	• High cost • Larger batch treatment
Electrocoagulation with Bucket of Nails	• Low cost • Small scale batch treatment	• Poor quality control

2.2 Selection Process

Electrocoagulation with steel plates was selected as the removal technology for the home-scale arsenic removal system. Electrocoagulation is inexpensive compared to chemical coagulation, and offers high quality control when compared to applying the same process of electrocoagulation with a bucket of nails. Electrocoagulation also removes the arsenic at a higher rate than the other two techniques. This technology is also ideal for home-scale removal systems because it is easier to manage, as the family would not be required to add chemicals to the water for each batch.

2.3 Electrocoagulation

2.3.1 Theory

The design of an arsenic removal system provides "semi-batch" treatment with the use of electrocoagulation and flocculation. Electrocoagulation utilizes electricity from a battery source to create insoluble iron hydroxides that will attract arsenic, forming larger filterable particles. To begin the process, untreated water is poured into a large bucket where an electrical charge is applied to two or more iron plate electrodes.

Anode reactions:

This electrical charge will create the insoluble ferric hydroxides.

$$Fe \rightarrow Fe^{+2} + 2e- \tag{1}$$
$$Fe^{+2}{}_{(s)} \rightarrow Fe^{3+}{}_{(aq)} + e- \tag{2}$$

The iron anode releases the insoluble ferric hydroxides, more commonly referred to as rust.

$$Fe^{3+} + 3OH^{-} \rightarrow Fe(OH)_{3\,(s)} \tag{3}$$

The ferric hydroxides in the water then attract arsenic and form coagulants.

$$Fe(OH)_{3\,(s)} + AsO_4^{3-}{}_{(aq)} \rightarrow [Fe(OH)_3 * AsO_4^{3-}]_{(s)} \tag{4}$$

Cathode Reactions:

The iron cathode plate releases oxygen gas in the form of bubbles.

$$2H_2O + 2e- \rightarrow 2H + 2OH^{-}{}_{(g)} \tag{5}$$

This process is illustrated in **Figure 4**.

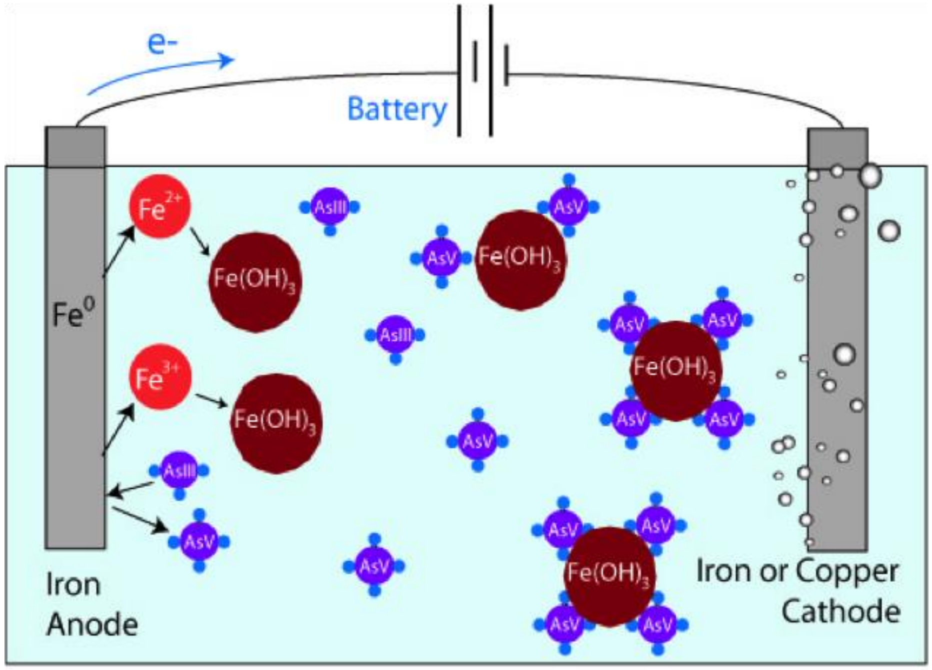


Figure 4: Electrocoagulation Process. (Source: University of California Berkeley, Gadgil Lab)

The larger particles that form are then filtered out as the water passes through a sand filter creating treated water. **Figure 5** shows a time-lapse image of iron generation in the water. After 20 minutes a noticeable amount of iron can be seen in the bucket. This means the system is operating correctly.

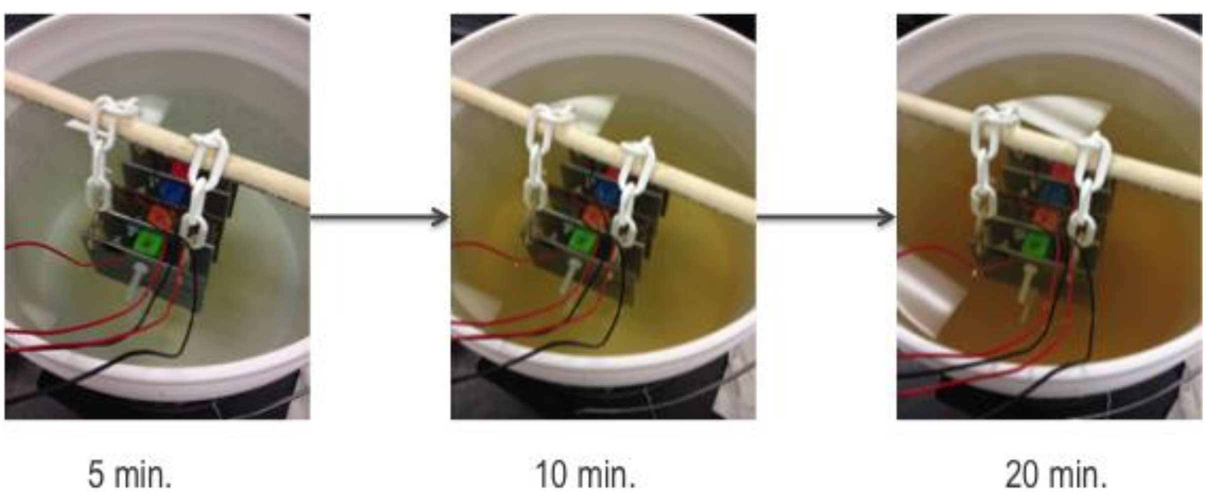


Figure 5: Time-lapse Image of Iron Generation in Water

3 GENERAL SYSTEM PARAMETERS

The system was optimized to function in developing nations. For this reason, certain performance and design parameters were established.

3.1 Module Configuration

Design began with the configuration of the electrochemical cell or module. The initial design utilized four steel plates, two anodes and two cathodes. This worked well, but was improved by adding an anode to the configuration causing current to be passed on both sides of the cathode generating more bubbles than having just one anode. Adding another plate also supplies the system with additional iron.

3.2 System Process

The arsenic removal system works in three stages. The first stage is where the electrocoagulation takes place. Large iron particles are released into the water where they bond with the smaller arsenic particles. The water is then released from the first stage into the second stage, the granular media (sand) filter. When passing through the sand filter, the particles of iron and arsenic are removed from the water. From the sand filter, the water moves into stage three, the collection vessel. This process is illustrated in **Figure 6**.

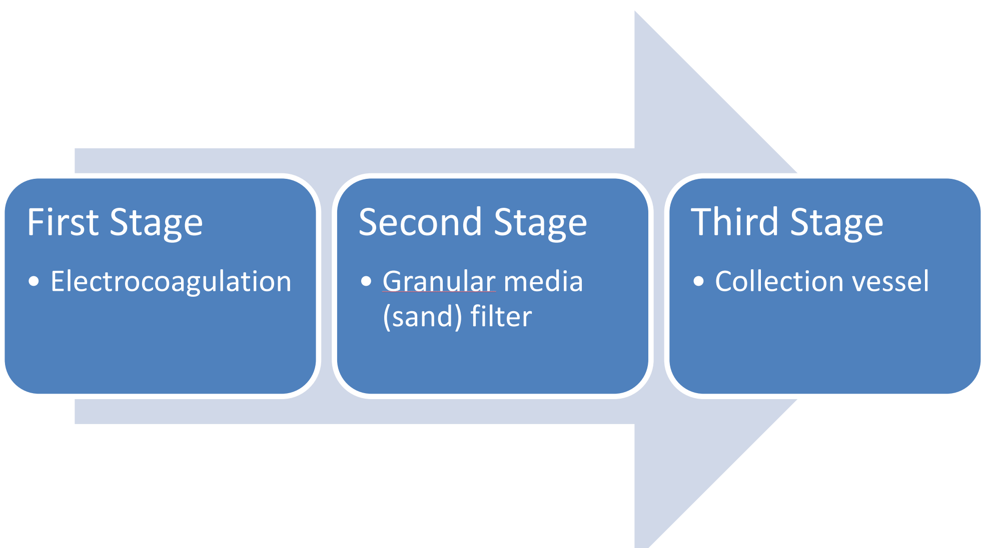


Figure 6: Schematic of Arsenic Removal Process

3.3 System Performance Requirements

Specific system performance requirements focus on how the system operates. These requirements were established to ensure that the system provides the families with a sufficient amount of clean drinking and cooking water per day as well as considering the limitations of living in a developing country. **Table 3** summarizes these requirements.

Table 3: Summary of Performance Requirements

Performance Requirement	**Quantitative Limit**	**Purpose for Requirement**
Production Rate (L/day)	100	• WHO recommends 20 L/capita/day of water for consumption purposes (WHO, 9.1) • The average family size in Nepal is 4.88 people. (National Report, 2011)
Arsenic Level (ppb)	≤ 10	• Aimed to follow the WHO and USEPA standards
Charge Loading (C/L)	150 – 180	• If charge loading is less than 150 C/L treatment will take an extended amount of time to reach 10 ppb • If charge loading is more than 180 C/L then the current being supplied is excessive and not being used efficiently

The World Health Organization recommends 20 liters of water per day per capita. 100 L of water per day would supply a family of five with treated water specifically for drinking and cooking. While the Nepalese Government considers 50 ppb of arsenic to be safe for ingestion, the performance requirement for this removal system follows the WHO and EPA MCL of 10 ppb.

An article published by Lawrence Berkeley National Laboratory (Amrose, *et al.*, 2012) suggested that charge loading has a greater effect on treatment effectiveness and efficiency than current density which is the applied current per square centimeter of steel. Charge loading is the total amount of current that passes through the solution by the current and is measured in coulombs per liter. Charge loading is a function of the charge dosage rate, which has the most effect on removal capacity (microgram Arsenic removed/ Coulomb). The equations used to determine charge loading are as follows:

$$Charge\ Loading = \int Charge\ Dosage\ Rate * dt \quad (6)$$

$$Charge\ Loading = \int \frac{I}{V} dt = \frac{I*t}{V} \quad (7)$$

where

I = current (amperage)
V = volume of batch (liters)
t = time of treatment per batch (seconds)

3.4 System Design Requirements

The removal system design requirements focus on the physical design and overall cost of the system. These requirements are summarized in **Table 4**.

Table 4: Summary of System Design Requirements

Design Requirement	Quantitative Limit	Purpose for Requirement
Height (ft.)	≤ 4	Allows small children to operate the system
Footprint (sq. ft.)	≤4	Families have small homes and limited floor space
Collection Vessel (L)	100	Ability to store all water treated per day. Can be divided into two 50-liter vessels
Batch Size (L)	13 and 18	Reduces cost by using commercially available 3.5 and 5 gallon buckets
Available Power (Battery Supply)	6 Volts	Readily available and inexpensive in Nepal
Cost ($)	≤ 60 per family	Families have limited resources and every family should have the ability to purchase the filter

The system has specific dimensional limitations in order to accommodate the user. In South Asia, young children are often times responsible for fetching and treating the water. For this reason the system does not exceed four feet. The overall footprint of the system does not exceed four square feet due to space limitations in families' homes.

The system will supply the family with 100 liters per day; therefore, the collection vessel we need to store 100 liters of water. This can be divided into two 50-liter buckets that the family rotates as they fill.

The batch size was selected by using commercially available buckets, 3.5 gallons and 5 gallons, to reduce the cost of the system. This corresponds to approximately 13-liter and 18-liter batch sizes.

Most families do not have access to electrical power; therefore, a rechargeable battery is needed to provide the power for treatment. A SUNCA 6 Volt, 4.5 amp-hour rechargeable battery is readily available in the area. This battery will be recharged using solar power and may also supply power to other areas of the homes. It may be required to have two of these batteries per family in order to operate both the arsenic removal system as well as LED lights and cell phones.

Finally, the initial overall cost of the system does not exceed $60 per family. This cost was identified by the NGO, VillageTech Solutions, as the maximum value the families in Nepal would be willing or able to pay for this technology. Occasional parts including the steel plates, the coffee filters, and sand will need to be replaced after a certain amount of use to insure that the removal system operates efficiently. This cost of maintenance should not exceed $10 per year.

4 FIRST STAGE TESTING METHODOLOGY

Designing a multi-stage arsenic removal system required separate testing for each stage. The efficient production of ferric hydroxides and their ability to bond with arsenic particles were requirements of the first stage of removal.

4.1 First Stage Testing Parameters

In the first stage, where electrocoagulation takes place, specific variables were controlled to satisfy both site limitations and desired treatment levels. A summary of these parameters is provided in **Table 5.**

Table 5: First Stage Testing Parameters

Required Charge Loading	150 – 180 C/L
Plate Size	4”x4” and 6”x6” module
Batch Size	3.5 gallon (13L) or 5 gallon (18 L)
Mechanical Mixing	Reduce Treatment Time

Each of these parameters was tested and evaluated to ensure the best method of arsenic removal was being applied. We tested four system configurations for their efficiency (150 – 180 C/L), total treatment time, and ability to reach 10 ppb. Mechanical mixing was also evaluated as an extra component that potentially could reduce total treatment time.

4.2 Synthetic Groundwater

Tap water at Santa Clara University draws from three wells in Santa Clara County. Depending on the day the University may be receiving water from any of these wells. As each well draws from different locations, daily water composition varies affecting the pH and conductivity. In order to eliminate inconsistencies and better mimic the groundwater conditions of South Asia, a formulaic synthetic groundwater was utilized during testing. “Arsenic removal from Groundwater using iron electrocoagulation: Effect of charge dosage rate”, by Amrose, S. et al, discusses the groundwater composition in Bangladesh. Amrose’s analysis of common ions found in Bangladesh groundwater served as a guide in establishing the components of this synthetic groundwater, summarized below in **Table 6.**

Table 6: Bangladesh Synthetic Groundwater Recipe

Ingredient	13L	18L
Arsenic	3.5 mL	4.75 mL
Sodium Phosphate	0.169	0.234
Sodium Bicarbonate	4.92	6.81
Magnesium Chloride	2.31	3.20
Gypsum	3.08	4.27
Tap Water	1.0	1.40
Distilled Water	12.0	16.6

4.3 First Stage Sampling Protocol

In order to reduce sources of error a protocol for sampling was developed and followed for each batch that was run. During each batch, 10 mL samples were collected out of the system using a pipet every 15 minutes starting at time zero and continuing through 60 minutes. Each sample was placed in a glass test tube and immediately filtered through a 0.7 μm micro glass filter. When testing the effectiveness of each sand filter, each batch of water was run through each sand filter after 60 minutes of treatment. Once all samples had been filtered, they were placed in labeled plastic containers with the date of the test, the time the sample was taken, and any specific parameters that were being tested. The details of each test were collected on an excel spreadsheet in order to keep track of all tests. These results can be found in Appendix A.

4.4 Testing Protocol

In order to determine the amount of arsenic remaining in the water after treatment, a method utilizing wet chemistry was followed. This method of arsenic determination is outlined in the paper, "Colorimetric Method For Determining Arsenic Levels" by Omi Agrawal, et al.

Wet Chemistry generally refers to chemistry performed on samples in liquid phase. Determining levels of arsenic in water of liquid phase is significant as consumption takes place during liquid phase. Wet chemistry manipulates a sample in order to identify a specific element or spectrum of elements, in this case arsenic. For this method, four reagents were used:

1. 1% aqueous solution of potassium iodate
2. 0.5 M solution of hydrochloric acid
3. Leucocrystal violet solution
4. 2 M solution of sodium hydroxide

The reaction between potassium iodate and arsenic is used to generate color. Depending upon the level of arsenic in a sample, color absorption varies. A spectrophotometer was used to identify the absorption of samples at a specific wavelength. The observed absorption values were then compared to a standard curve of absorption values of known arsenic concentration levels.

The following **Table 7** outlines the steps taken to reach an absorbance value.

Table 7: Testing Protocol for Determining Arsenic Concentration

Steps	Direction
1	Added specified amount of four reagents and distilled water to filtered sample
2	Placed sample in warm water bath for 10 minutes to accelerate reaction
3	Used spectrophotometer to measure color absorbance
4	Compared absorbance value to standard curve developed using known arsenic concentrations

The equation used to determine arsenic concentration of a given absorbance was generated from a standard curve of samples of known arsenic concentrations, where absorbance values were found using the method outlined in **Table 7**, and plotting the data. The standard curve and corresponding equation are shown below in **Figure 7**.

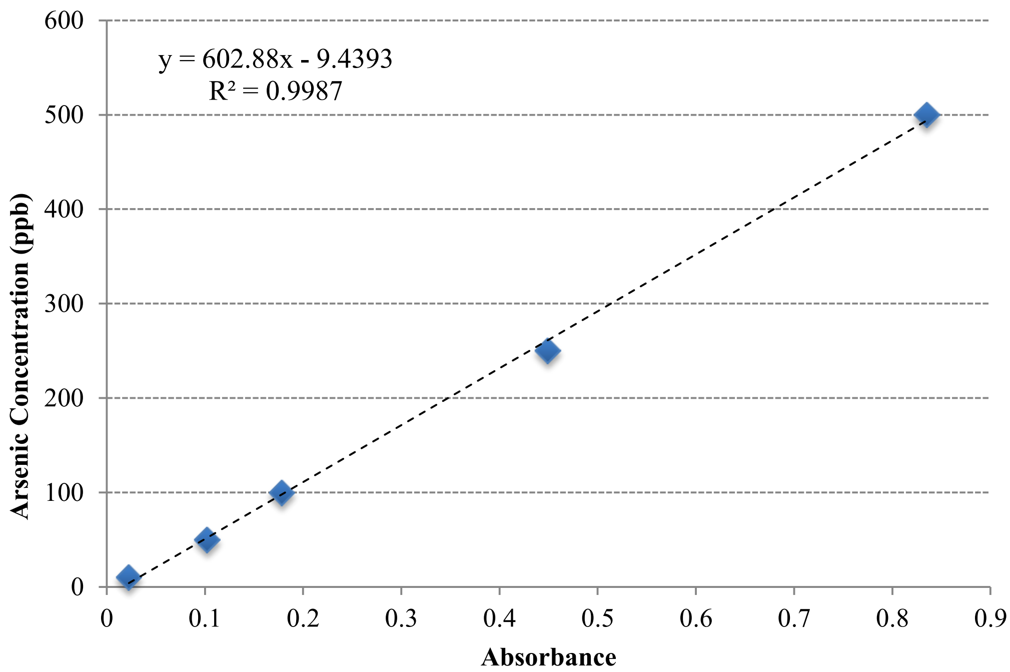


Figure 7: Standard Curve used for Determining Arsenic Concentration

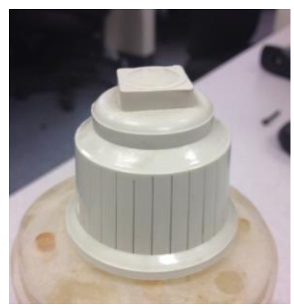
5 STAGE TWO TESTING METHODOLOGY

The second stage of arsenic removal required the filtration of the combined ferric hydroxide and arsenic particles.

5.1 Second Stage Parameters

Two sand filter configurations were compared for stage two. Both configurations used 10 inches of total media depth but varied in media grain size and underdrain system. These configurations are summarized in **Table 8**.

Table 8: Stage Two Sand Filter Configurations

Variable	Configuration 1	Configuration 2
Total Media Depth	10 in.	10 in.
Filter Media Variation	5 in. fine sand 2 in. course sand; 3 in. pea gravel;	10 in. fine sand
Underdrain	Perforated PVC piping 	Plastic underdrain filter nozzle 

5.2 Stage Two Sampling Protocol

After 60 minutes of first stage treatment each filter received half of the treated batch of water, and samples were collected approximately half way through filtration. The purpose of collecting samples half way through filtration rather than at the beginning, was to ensure that any water remaining in the filter from previous batches had entirely passed through the filter and would not affect the arsenic levels of the current batch. A 10 mL sample of the first stage treated water was also filtered through a micro-fiber filter. All samples were stored in labeled plastic containers for later determination of arsenic concentration.

6 RESULTS

The results from each stage of testing are summarized below. These results were the basis for determining the most efficient and reliable design for each stage.

6.1 First Stage

For the first stage testing three main parameters were examined. The first was the total amount of charge loading at various operating conditions. **Figure 8** demonstrates that for the majority of the operating conditions the charge loading fell in the range of 150 – 180 C/L. The outlier shows that there are certain operating conditions, such as using the larger plates, that are not utilizing the current efficiently and untimely wasting energy. A more detailed table summarizing all the testing results can be found in Appendix A.

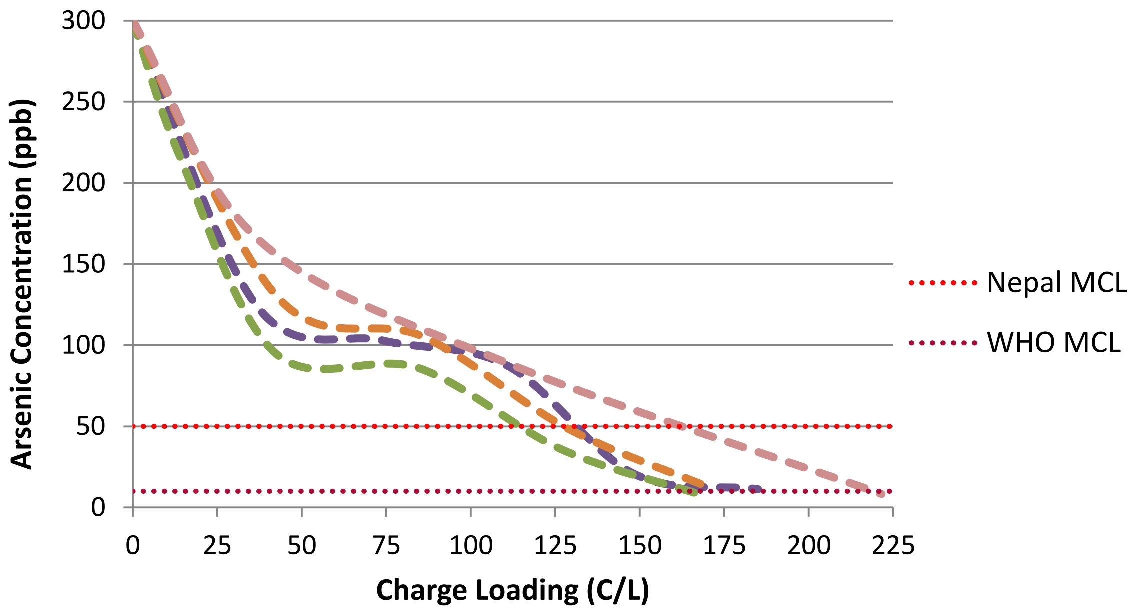


Figure 8: Graph of Arsenic Concentration vs. Charge Loading for Various Operating Conditions

Another parameter that was tested was the size of the plates being used. Two different plate sizes were tested, 4” x 4” and 6” x 6”. **Figure 9** shows that treatment time will take approximately 60 minutes to reach 10 ppb using the smaller plates, while using the larger plates would take 30 minutes.

It is important to note that when the smaller plates are used, they are drawing 0.6 amps while the larger plates draw over twice that amount, 2 amps. The smaller plates also fall in the 150 – 180 C/L range while the larger plates fall outside the range, at approximately

225 C/L. While the larger plates can treat the water faster, they do so less efficiently than the smaller plates.

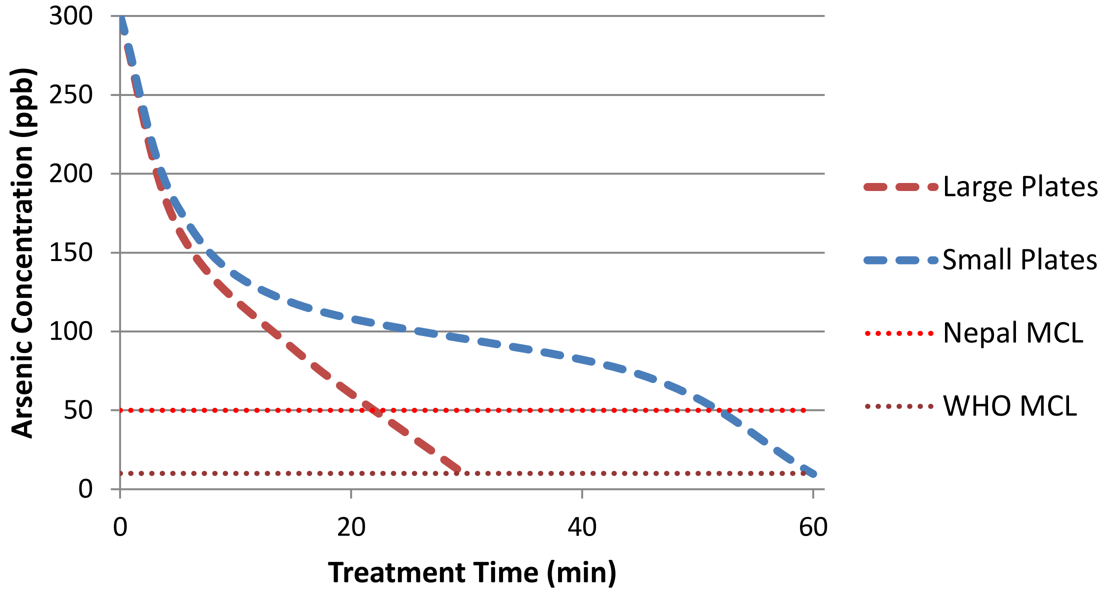


Figure 9: Graph of Arsenic Concentration vs. Treatment Time Comparing the Large and Small Plates

Finally the necessity for mechanical mixing was tested. It was theorized that adding mixing to the system may decrease the total treatment time while using minimal extra energy. Using identical testing conditions the first batch was run for 60 minutes using no mixing. A second batch was then run using a magnetic stirrer operating continuously on speed 2 for 60 minutes. The results of the test, as seen in **Figure 10,** indicate that mechanical mixing is not necessary as both batches took 60 minutes to reach 10 ppb. Most likely the cathode plates are providing enough gas bubbles in the system for the necessary circulation.

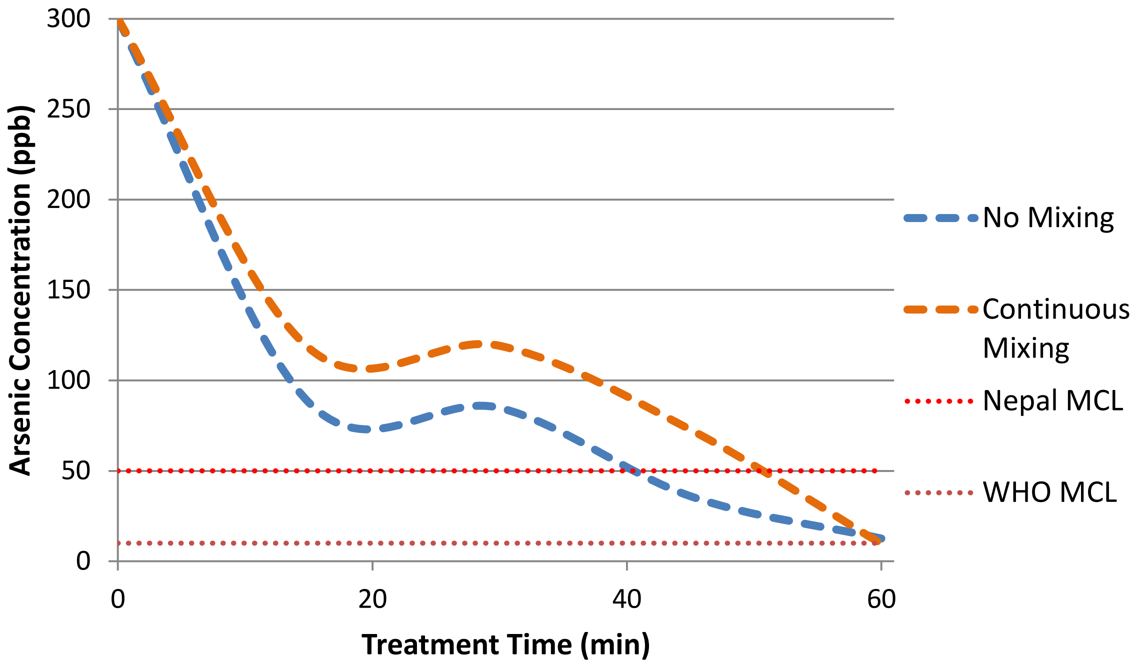


Figure 10: Graph of Arsenic Concentration vs. Treatment Time Comparing No Mixing and Continuous Mixing of the System

6.2 Second Stage

For the second stage, removal efficiency was the basis of comparison of the filters. The two sand filter configurations performed, on average within 5 ppb of each other, as shown in **Table 9**.

Table 9: Testing Results Comparing Sand Filter Configurations

Test #	Arsenic Concentration (ppb)	
	Configuration 1 with Perforated PVC Piping	Configuration 2 with Plastic Underdrain filter nozzle
1	10.5	8.9
2	20.5	21.2
3	23.9	16.9

7 DESIGN RECOMMENDATIONS

Electrocoagulation as an arsenic removal technology is applicable in various scale systems. We aimed to provide the most efficient removal system for use in Nepal, accounting for design constraints that may not be as restrictive in more developed countries, such as the United States. We have a total of three design recommendations. The first and most detailed design is for a home-scale removal system in Nepal. Second is a larger home-scale removal system for use in more developed countries with access to larger power sources. Finally, we detail how this technology can be used with minimal or no design constrains, operating as an automated semi-continuous flow system.

7.1 Final Design for Nepal

While Nepal was the target region of this project, we recognize that arsenic contamination in groundwater is a global issue. Electrocoagulation removal techniques can be applied to any region, with the design changing slightly based on regional resource accessibility and power availability. Below are three different designs based upon general regional restrictions.

7.1.1 Overall System Design

The design recommended for use in Nepal is a 6V rechargeable battery for power supply, a 3.5 gallon bucket for 13 L of treatment per batch, 5 4”x4” steel plates, a 10 inch fine sand filter, a final collection basin, a polishing filter in the form of a coffee filter, and a simple control system for automated shut off. This design, as shown below in **Figure 11**, provides a charge dosage of 170 C/L, which allows the 6V rechargeable battery to supply the needed daily treatment for each Nepalese family.

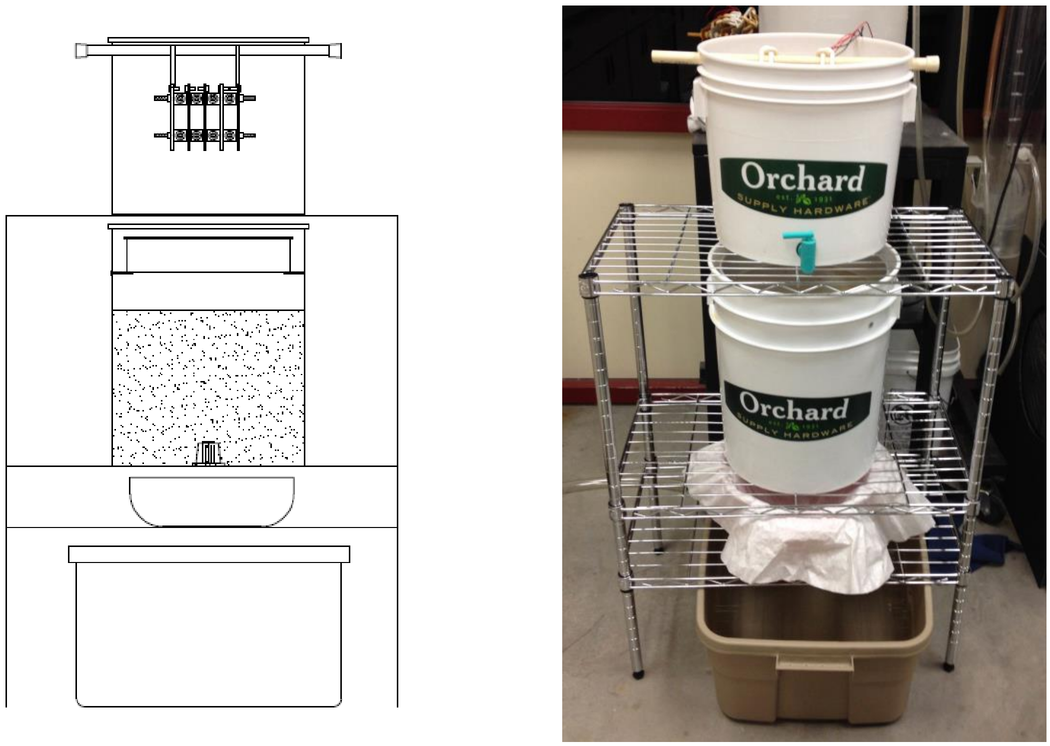


Figure 11: Design for Nepal System Configuration

7.1.2 Simple Control System

The simple control system is shown below in **Figure 12.** This is a prototype that is used in the system to automatically shut the system off when the proper treatment is applied in order to conserve battery life.

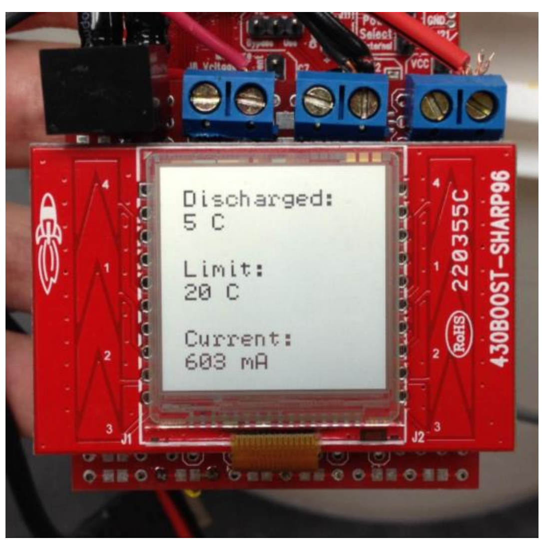


Figure 12: Simple Control System

This control system connects to the battery, measures the current passing into the system, and keeps track of the total amount of coulombs that have been discharged into the system. The limit is a programmable set point that should be set based off knowledge of initial arsenic concentration in the water source as well as the amount of current supplied by the battery source.

7.2 Less Restrictive Design Restraints

Less restrictive battery supplies will result in greater available current. For regions where battery constraint is lowered, we suggest using a five gallon bucket for the first stage and the 6”x6” plates to deliver treatment in fewer batches. The filter and automated shut off control should remain in place.

7.3 Minimal or No Design Constraints

With sufficient funding, the project scope could be expanded to incorporate additional purification that would reliably meet the maximum contaminant levels for developed nations, such as the U.S. The intention behind these enhancements is to provide a product that can be used independent of the site location and recognizes the economic resources of nations beyond those of Nepal. Removal of a battery constraint entirely would result in our suggestion of an automated semi-continuous system. The system would utilize the same technology, only on a larger scale. The system should be connected to a well source where two solenoid vales would be necessary for automated flow control into and out of the first stage of treatment. The system should also be connected to an electrical grid for power and delivery of treated water to a tap connected to households.

8 ENGINEERS' OPINION OF MOST PROBABLE COST

Table 10 below summarizes the engineers' opinion of most probable cost for all three design recommendations. The table outlines the cost of each stage of the system. Appendix B contains an itemized cost analysis of the design recommendations.

Table 10: Summary of Engineers' Opinion of Most Probable Cost for Three Design Recommendations

	First Stage Cost	**Second Stage Cost**	**Third Stage Cost**	**Overall Cost**
System for Nepal	$24	$7	$9	$40
Reduced Design Constraint	$31	$8	$9	$48
Minimal Design Constraint *	$225	$20	$20	$265

*subject to site specific constraints

The system in Nepal is the most inexpensive at $40. Using slightly larger plates and battery, the reduced design constraint recommendation costs $48. With minimal design constraints the cost of the system rises due to the cost of two solenoid valves. The overall cost of the system will fluctuate greatly depending on the specific site location of each system.

There are also certain maintenance costs associated with the removal system. It is expected that approximately every 5 months the steel plates will degrade (See Appendix C for sample calculations). The plates will cost approximately $4 to replace.

9 NON-TECHNICAL ISSUES

There are a variety of non-technical issues associated with this project. These issues played a role in the design parameters as well as the final design selection. A summary of these issues are outlined below in **Table 11**.

Table 11: Summary of Non-Technical Issues

Non-Technical Issue	Description in relation to project
Ethics	Overall project aimed to address the basic human right to clean drinking water
Social Justice	System would be affordable to all community members
Environmental	Disposal of arsenic-iron complexes - studies confirmed that particles are non-toxic Develop a method for disposal of lead acid batteries
Health and Safety	System will reduce the risk of cardiovascular disease, cancer, infant mortality, and sores on skin by removing arsenic from drinking water
Manufacturability	Used commercially available products to keep the cost of the system low and VillageTech Solutions is confident that it can identify a manufacturer in South Asia to mass produce the system.

9.1 Ethics

In creating an arsenic removal system we are affirming every person's right to clean water. Every human, regardless of economic or social standing, has certain unalienable rights as a dignified and valued being. The United Nations Universal Declaration of Human Rights outlines these rights. Article 25 of this declaration states, "Everyone has the right to a standard of living adequate for the health and well-being of him and his family." Contaminant free drinking water is a basic necessity in protecting the rights of the individual, as good health precedes every human right. Without health, rights to education, employment, community participation, property (to name a few) become meaningless.

9.2 Social Justice

As every person has the right to clean water, it is important that every person has access to the removal system necessary to provide clean water. Any removal system needs to be affordable to all members of the community. In order to accomplish this goal a maximum price for the system was set at $60 per family.

9.3 Environmental

Developing an arsenic removal system raises a couple of environmental concerns. The first is the disposal of the arsenic-iron complexes. Studies have shown that arsenic is inactive once coagulated to iron particles (Amrose *et. al*, 2013). This means that the arsenic-iron complexes found in the filter media can be returned to the ground without any potential of re-entering groundwater.

A second concern is the disposal of the lead acid batteries used to deliver treatment in the system's first stage. In order to properly dispose of these batteries, a standard protocol will need to be developed eliminating any risks to the environment.

9.4 Health and Safety

When designing a home-scale arsenic removal system two subjects are of particular significance: risk to the public and informed consent of the public. The public is comprised of the system users who, in this case, are assumed to have limited knowledge of the technology used. Education of this public is important in both matters.

The communication of risk to the public directly shapes informed consent. The public must be told the associated risk of this technology as relative to their health. The use of a home-scale arsenic removal system does not adversely affect the health of its users, but to avoid health risks the user must maintain the system. This means the user must be properly educated on the requirements for maintenance as well as have access to the required equipment and supplies.

9.5 Manufacturability

This issue of maintenance and supply directly related to the choice of products locally available. Local availability raises the question of distribution. Who or what organization is responsible for distribution of these systems and their parts is one of the most important questions raised. VillageTech Solutions is confident that once it is in Nepal, a local manufacturer can be identified to serve the community.

10 FUTURE WORK

VillageTech Solutions plans to take our removal system for field-testing in Nepal. Field-testing will modify the system's function to account for circumstances not producible in a lab. VillageTech Solutions has also stated that it plans to find a manufacturer in the region of Nepal that would be interested in mass-producing the systems.

In order for this project to be successfully implemented the initial arsenic concentration in the region must be identified as well as the groundwater composition, as these will affect the system performance.

It is also essential that the communities accept the system and trust that it works. VillageTech Solutions plans to implement a community education of the filters if they work successfully in the field.

While we will not be traveling to Nepal with VillageTech Solutions, we will serve as a resource for any questions on design and operation of the system. With feedback from field testing, we would be able to modify our design to better fit the targeted region.

11 CONCLUSION

This project outlines a manufacturable, affordable home-scale arsenic removal system for use in Nepal. Because the project was designed for use in a developing country certain system limitations were in place. The parameters that were tested included the total amount of charge loading required, the plate size, and the necessity of mechanical mixing. Consistency was developed between tests through the use of a testing protocol and the use of a synthetic groundwater. After all of these parameters were examined, the final design recommended using a 6 V rechargeable battery, 3.5 gallon bucket, and five 4” x 4” steel plates. This system can treat water to approximately 10 ppb in 60 minutes.

This technology can also be applied to areas with access to bigger batteries or an electrical grid. Using a semi-automated system, the technology can be used to supply water to a home’s tap.

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APPENDIX A – TEST RESULTS

Table A-1: Details of Each Test Run

Test #	Date	Initial Arsenic Concentration (ppb)	Water Type (Tap or Synthetic)	Power Source	Plate Size	Batch Size (L)	Amperage	Mechanical Mixing	Filtration Method	Total Treatment Time (minutes)	Final ppb	Charge Loading (C/L)
1	25-Feb	300	Tap	Power Supply (6V)	4"x4"	13	0.61	No	Micro glass	60	7.3	169
2	4-Mar	300	Tap	Power Supply (6V)	4"x4"	13	0.62	Yes - every 15 minutes	Micro-glass	60	11.4	172
3	6-Mar	300	Tap	Power Supply (6V)	6"x6"	13	1.6	No	Micro glass	30	8.3	221
4	7-Mar	300	Tap	Power Supply (6V)	4"x4"	13	0.72	Yes - 1" on 1" off	Micro glass	60	26	199
5	14-Mar	300	Synthetic	Power Supply (6V)	4"x4"	13	1.02	No	Micro glass	60	12.6	282
6	14-Mar	300	Synthetic	Power Supply (6V)	4"x4"	13	1.02	Yes - continuous (speed 2)	Micro glass	60	9.7	282
7	19-Mar	300	Synthetic	Power Supply (6V)	4"x4"	13	0.94	No	Micro glass	60	10.7	260
									Coffee filter		15	
8	4-Apr	300	Synthetic	Power Supply (6V)	4"x4"	13	0.89	No	Micro glass	60	15	246
									Sand filter (configuration 1)		23	
9	9-Apr	300	Synthetic	Power Supply (6V)	6"x6"	13	2.23	No	Micro glass	60	9.3	308
									Sand filter (configuration 1)		12.6	

Test #	Date	Initial Arsenic Concentration (ppb)	Water Type (Tap or Synthetic)	Power Source	Plate Size	Batch Size (L)	Amperage	Mechanical Mixing	Filtration Method	Total Treatment Time (minutes)	Final ppb	Charge Loading (C/L)
10	10-Apr	300	Tap	Power Supply (6V)	4"x4"	13	0.62	Yes - continuous (speed 2)	Micro glass	60	5	174.5
								No			5.6	
11	11-Apr	300	Synthetic	Battery Supply (6V)	4"x4"	13	0.50 - 0.62	No	Micro glass	60	18	171
									Sand filter (configuration 1)		16	
12	14-Apr	300	Synthetic	Power Supply (6V)	4"x4"	18	0.74	No	Micro glass	75	11.2	185
									Sand filter (configuration 1)		10.5	
									Sand filter (configuration 2)		8.9	
13.1 (First Test of Back-to-Back Test)	16-Apr	300	Synthetic	Battery Supply (6V)	4"x4"	13	0.59	No	Sand filter (configuration 1)	60	20.5	161
									Sand filter (configuration 2)		21.3	
13.2 (Second Test of Back-to-Back Test)	16-Apr	300	Synthetic	Battery Supply (6V)	4"x4"	13	0.55	No	Sand filter (configuration 1)	60	23.9	158
									Sand filter (configuration 2)		16.9	
14	23-Apr	300	Synthetic	Power Supply (6V)	6"x6"	18	2.08	No	Sand filter (configuration 2)	30	16.9	208

Test #	Date	Initial Arsenic Concentration (ppb)	Water Type (Tap or Synthetic)	Power Source	Plate Size	Batch Size (L)	Amperage	Mechanical Mixing	Filtration Method	Total Treatment Time (minutes)	Final ppb	Charge Loading (C/L)
15	23-Apr	300	Synthetic	Power Supply (6V)	4"x4"	13	2.18	No	Sand filter (configuration 2)	20	40	145
16	25-Apr	200	Synthetic	Power Supply (6V)	4"x4"	13	0.67	No	Sand filter (configuration 2)	50	16	185
17	26-Apr	100	Synthetic	Power Supply (6V)	4"x4"	13	0.63	No	Sand filter (configuration 2)	35	7.5	174
18	28-Apr	300	Synthetic	Battery Supply (6V)	4"x4"	13	0.5	No	Sand filter (configuration 2)	60	18	138

APPENDIX B – COST ANALYSIS

Table B-1: Cost Analysis for System in Nepal

	Item	**Price ($) Per Unit**	**# Of units**	**Total**
Tier 1	3.5 gallon bucket	$1.00	1	$1.00
	Steel plates (per square in.)	$0.05	80	$4.06
	Control system	$10.00	1	$10.00
	Plastic chain	$0.05	2	$0.10
	Wires	$0.10	7	$0.70
	Battery	$4.00	1	$2.00
	PVC pipe	$0.50	1	$0.50
	Terminal block	$2.00	1	$2.00
	Plastic blots and nuts	$0.06	10	$0.61
	Spacers	$0.05	8	$0.40
	Threaded rod	$1.00	2	$2.00
	Liquid electrical tape	$0.17	1	$0.17
Tier 2	5 gallon bucket	$1.50	1	$1.50
	Sand	$-	1	$-
	Fine sand underdrain	$2.00	1	$2.00
	Distribution plate	$2.00	1	$2.00
	Colander	$2.00	1	$2.00
	Spigot	$0.10	1	$0.10
Tier 3	Bucket	$4.00	1	$4.00
Other	Stand	$5.00	1	$5.00
Total Cost				$40.13

Table B-2: Cost Analysis for Recommendation with Minimal Design Constraints

	Item	Price ($) Per Unit	# Of units	Total
Tier 1	5 gallon bucket	$1.50	1	$1.50
	Steel plates (per square in.)	$0.05	180	$9.13
	Control system	$10.00	1	$10.00
	Plastic chain	$0.05	2	$0.10
	Wires	$0.10	7	$0.70
	Battery	$4.00	1	$4.00
	PVC pipe	$0.50	1	$0.50
	Terminal block	$2.00	1	$2.00
	Plastic blots and nuts	$0.06	10	$0.61
	Spacers	$0.05	8	$0.40
	Threaded rod	$1.00	2	$2.00
	Liquid electrical tape	$0.17	1	$0.17
Tier 2	5 gallon bucket	$1.50	1	$1.50
	Sand	$-	1	$-
	Filter nozzle	$2.00	1	$2.00
	Distribution plate	$2.00	1	$2.00
	Colander	$2.00	1	$2.00
	Spigot	$0.10	1	$0.10
Tier 3	Bucket	$4.00	1	$4.00
Other	Stand	$5.00	1	$5.00
	Total Cost			$47.70

Table B-3: Cost Analysis for Recommendation with Minimal Design Constraints

	Item	Price ($) Per Unit	# Of units	Total
Tier 1	Large bucket*	$3.00	1	$3.00
	Steel plates (per square in.)*	$0.05	220	$11.15
	Control system	$10.00	1	$10.00
	Plastic chain	$0.05	2	$0.10
	Wires	$0.10	7	$0.70
	PVC pipe	$0.50	1	$0.50
	Terminal block	$2.00	1	$2.00
	Plastic blots and nuts	$0.06	10	$0.61
	Spacers	$0.05	8	$0.40
	Threaded rod	$1.00	2	$2.00
	Liquid electrical tape	$0.17	1	$0.17
Tier 2	Large bucket*	$3.00	1	$3.00
	Sand	$-		$-
	Filter nozzle	$2.00	1	$2.00
	Distribution plate	$2.00	1	$2.00
	Colander	$2.00	1	$2.00
	Spigot	$0.10	1	$0.10
Tier 3	Storage container	$7.00	1	$7.00
Other	Solenoid valve	$100.00	2	$200.00
	PVC piping*	$20.00	1	$20.00
	Total Cost			$266.73

* Quantity and cost depend on specific site

APPENDIX C – SAMPLE CALCULATIONS

Plate maintenance Calculation

Cathode Reaction: $Fe^{+2} + 2\ e^{-} \rightarrow Fe(s)$

# of moles of electrons

$$0.6\ amps\ x\ 3600\ seconds\ =\ 2160\ C$$

$$2160\ C\ x\ \frac{1F}{96485\ C}\ =\ 0.0224\ F$$

$$0.0224\ x\ \frac{1\ mole\ e}{1\ F}\ =\ 0.0224\ mole\ e$$

# of moles of iron produced:

$$0.0224\ mole\ e\ x\ \frac{1\ mole\ Fe}{2\ moles\ e}\ =\ 0.011\ mole\ Fe$$

Mass of iron produced

$0.011\ mole\ Fe\ x\ \frac{55.847\ g\ Fe}{1\ mole}\ =\ 0.625\ g\ Fe$ produced per hour of treatment

Useful Life

Assume 7 hours of treatment per day $=\ 0.625\ x\ 7\ =\ 4.37\ g\ Fe\ produced\ per\ day$
Three Steel plates weighing 230 grams each = 690 grams

$$\frac{690\ g\ Fe}{4.37\ g\ Fe\ produced\ per\ day} =\ 158\ days$$

Synthetic Groundwater Calculation

Chemical Compound: Bicarbonate, HCO_3

From Source Compound: Sodium Bicarbonate, $NaHCO_3$

HCO_3 Formula Weight	61 grams
$NaHCO_3$ Formula Weight	84 grams
Batch Size	13 liters
Desired Concentration	275 mg/l

General equation:

$$Concentration \times Batch\ Size \times \frac{FW\ Source\ Compound}{FW\ Chemical\ Compound}$$

In the case of bicarbonate:

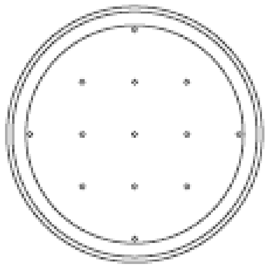
$$275\ \frac{mg}{l} \times 13\ l \times \frac{84\ g}{61\ g} == 4{,}922.95\ mg$$

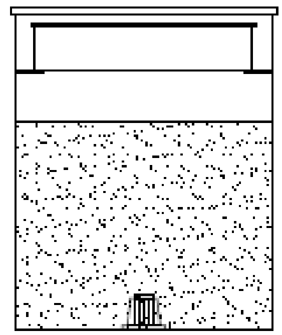
Result:

Insert 4.92 grams of Sodium Bicarbonate into each batch

APPENDIX D – DRAWINGS

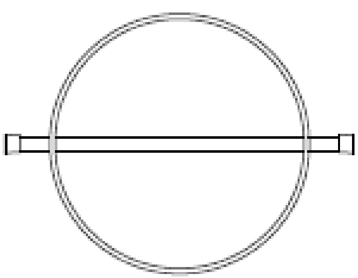
1st Tier Plan and Profile Views:

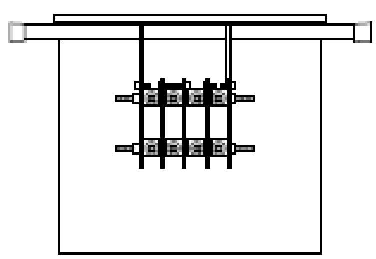




5 gallon bucket

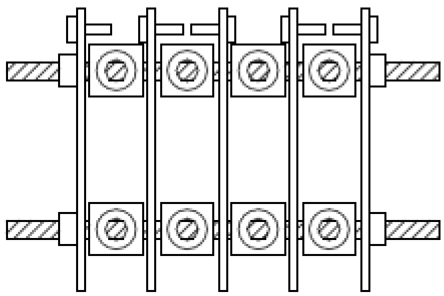
2nd Tier Plan and Profile Views:

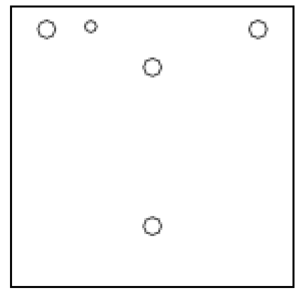




3.5 gallon bucket

Electrochemical Cell:





Scale: 1” = 2”