Chemical Engineering for Good Challenge

2017 Competition Submission

How Chemical Engineering Can Be Applied to Solve World Problems on a Micro Scale

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University Name & Location: _University of California Berkeley_______________

Team Leads: [redacted]

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Title of Submission: Underutilized Simple Iron Matrix filter for use in arsenic remediation.

Submission Type: __X_ underutilized technology ___technology toolkit

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Contest entries must address '**How chemical engineering can be applied to solve world problems on a micro scale**". Three prizes of $3000, $2000, and $1000 will be awarded as unrestricted grants to the winning chapters. If judges determine that there are less than three submissions worthy of award than fewer prizes will be awarded. Submissions are directed toward problems that could be implemented by engineering service organizations in partnership with communities (often small and rural) in the developing world. Typically these partners have limited technical sophistication, capital, and funds to cover operating expenses. Utilizing appropriate, sustainable (in the broadest sense) technology is critical. The competition is open to all AIChE student chapters, and entrants are encouraged to partner with other organizations experienced in doing this kind of work. Teams may be of any size, and may include students, faculty and professional engineers.

Submissions should utilize chemical engineering technology and skills (beyond the hydraulics calculations commonly used in designing water systems). Entries will either focus on one chemical engineering-based technology that is currently underutilized by teams working on international service projects (**ISP**) ***or*** provide a useful toolkit for ISP teams to identify, select, and utilize existing chemical engineering-based technologies to solve specific problems.

Attach to this cover page the information requested below for your type of submission. All submissions to be in electronic format. *Only materials in English language will be considered.*

1. Recommendation of the application of a specific technology, available today, that is not currently utilized in ISP projects.

   A. Define the specific community problem being addressed
   B. Describe the specific technology and how it is based on chemical engineering principles; provide electronic copies of or public links to references (papers, descriptions of commercial applications & offerings, patents, other supporting material)
   C. Describe what kind of data would be required to design / customize this technology for ISP projects
   D. Describe why this technology would be appropriate for implementation in partner communities. . Include consideration of technical, maintenance, financial, and cultural sustainability. Provide estimated typical costs for initial installation, maintenance, and operation.

1. **Recommendation of the application of a specific technology, available today, that is not currently utilized in ISP projects**

A. **Define the specific community problem being addressed**

From drinking to agricultural development, water is essential to our daily lives. Yet, despite its vital necessity to life and stable society, ten percent of the world's population still does not have access to clean water.[1] Even more concerning, lack of access to a sustainable clean water source many times also leads to contamination. Pollutants—pathogens and heavy metals—can lead to waterborne illness and even death. It is estimated that nearly 80% of all illnesses in developing countries are linked to poor water and sanitation conditions, with 3.4 million deaths reported annually according to the World Health Organization.[2]

Beyond the impacts on health, lack of clean water access is debilitating to economic growth and societal development. The UN reports that Sub-Saharan Africans spend nearly 40 billion hours a year acquiring clean water.[1] Many developing countries share similar statistics. According to the UN Sustainable Development Goal, the first step to take in the fight against global poverty is to ensure easy access to clean water sources.[3] This will allow those countless hours to be spent on education and developing a sustainable economy and job market.

Clearly, the lack of access to clean water in many developing countries impacts not just the physical health of citizens of a country, but also the socioeconomic health of a country. Chemical engineering principles are extremely important in solving this global problem. By implementing and designing technologies that combine aspects of filtration, separations, fluid mechanics, and kinetics, chemical engineers in humanitarian engineering can pave the way to universal clean water access. This is essentially what the UC Berkeley Chapter of Engineers Without Borders has been doing in Peru.

In September 2007, a meteorite struck the community of Carancas on the Peruvian Altiplano.[4] After rising reports of illnesses in the area, the World Health Organization was brought in to assess the situation. Test results indicated that the people in the community had ingested a large amount of arsenic. They concluded that the meteor had caused naturally occurring arsenic in the water table to vaporize. Wells tested across the Altiplano also revealed extremely high levels of arsenic, ranging from 60 to 900 ppb.[4] In comparison, the Environmental Protection Agency's standard for drinking water allows a maximum arsenic content of 10 ppb.[5]

Arsenic has many effects on the body, including hyperpigmentation, skin lesions, cardiovascular disease, and cancer.[6] Over 150 million people ingest arsenic contaminated water a day.[7] To combat the crisis in Carancas, the Engineers Without Borders (EWB) Student Chapter at UC Berkeley was deployed to assess the situation and develop a solution. Working in conjunction with campus professors and professional engineers, EWB student members designed and implemented a Simple Iron Matrix (SIM) filter.[4] Here, we outline the development of the filter and its implementation, as well as provide examples of future experiments utilizing chemical engineering principles to improve upon the design for use in widespread ISP projects.

B. Describe the specific technology and how it is based on chemical engineering principles; provide electronic copies of or public links to references (papers, descriptions of commercial applications & offerings, patents, other supporting material)

The technology to be utilized in ISP projects is a Simple Iron Matrix filter. The technology is similar to a Composite Iron Matrix (CIM) filter technology currently used in Bangladesh and follows the 3-kalshi filter design.[8,9] However, while CIM filters require a manufactured composite iron matrix, our model has replaced the matrix with rusty iron scraps instead for increased sustainability in remote communities.

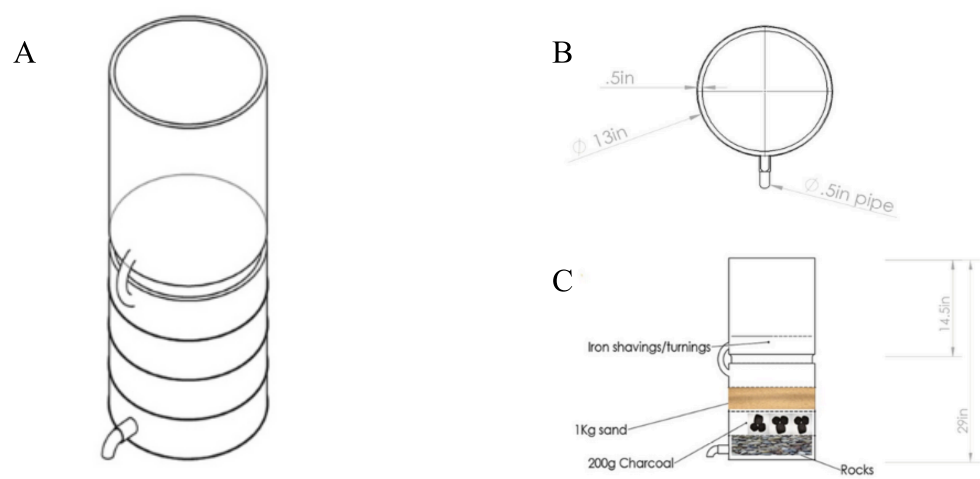

Figure 1: The design uses two 5 gallon buckets, connected via an intermediary spigot (1A). A spigot at the bottom is used to control flow. The cross section depicted is for a 40% scale model (1B). The full prototype has a capacity of 20L. The first bucket holds rusted iron shavings and the second holds a layer of sand, one of charcoal, and finally a layer of rocks (1C). Layers are measured on a mass basis.

The design resembles a heterogeneous packed bed reactor or contactor, a hallmark of chemical engineering design and processes. The top bucket contains 750-1500g of rusted iron turnings or shavings. When water is added, the shavings become suspended, which delineates from the standard packed bed model. It is known that rusted iron shavings in water form positively charged ferric hydroxide. As(III) is also known to adsorb to these rust particles.[10] Yet, the more oxidized arsenate ion is known to adsorb the ferric hydroxide complex better due to the strong attraction between oppositely charged metallic ions. To oxidize the As(III) to As(V), bleach (sodium hypochlorite) is added to the feed water. Furthermore, the rust layer also helps trap bacteria in the water.[4]

After a certain period of time, a spigot between the first and second bucket is opened, and the contents of bucket one enter bucket two, consisting of sand, charcoal, stones, and a spigot at the bottom to control the flow rate. The densely packed sand layer selectively removes any incoming coagulated arsenic-rust particles by size. In the experimental model, the sand layer is approximately 1kg in weight.

200g of charcoal form the next layer. The charcoal is meant to adsorb organic materials and also removes byproducts of the reaction with bleach.[4] This will help with taste, appearance and chlorine removal. Lastly, a section of pebbles helps to remove any charcoal or sand bits from escaping into the filtrate.[4]

Adsorptivity, a property exploited by chemical engineers for separation processes, is used to a large extent here. As described, arsenic adheres to the surface of the rust particles in the iron shavings causing coagulation of the arsenate ion. Also, the small pores in charcoal create an immense amount of surface area and are used to adsorb unwanted organic materials.

The design also relies heavily on mass transport principles. The majority of the diffusion or external transport of the arsenic in its many oxidation states to the rust surface is by Brownian motion, as there is little to no convective flow in the rust-water suspension.

Reaction kinetics are also integral to both the oxidation of the arsenic and the coagulation of the As(V) to the rust. The time scales and the rate laws for the As(III) oxidation to As(V) as well as the chemical coagulation that leads to charge neutralization could be used to improve upon this design. For instance, if the rate of oxidation is limiting, possibly a stronger oxidant should be used.

Lastly, the principles of fluid mechanics and general mass balances are applied. The efficiency of arsenic removal relies on the contact time or residence time between the rusted iron and the arsenic contaminated water. Experiments conducted so far on the filter examine contact time between the iron and the arsenic contaminated water vs the arsenic removal percentage.

C. Describe what kind of data would be required to design/customize this technology for ISP projects

To begin this discussion, we present data already collected by EWB UC Berkeley with the help of our partner community in Peru.[4] The experiments conducted move to optimize the contact time between the contaminated water and the iron rust layer. Furthermore, experiments to advance the performance of the filter are described.

The following data reflects the data collection and analysis involved in Simple Iron Matrix (SIM) testing on Engineers Without Borders' January 2014 trip to Carancas, Peru. This model was made of a plastic San Luis bottle, approximately 1L in capacity using water from a well called the IEP Shallow Well.[4]

The IEP Shallow Well water had an initial concentration of arsenic of 100 ppb and was filtered using Berkeley Steel of hardness 120 mg/L with short, thin iron pieces weighing 225 g total.[4] The dimensions of the bottle have roughly the same length to diameter ratio (~5) as the full-scale 20L prototype that was tested at UC Berkeley in the Dracup Laboratory using arsenic standards. The final prototype was sent abroad to Peru in August of 2014.

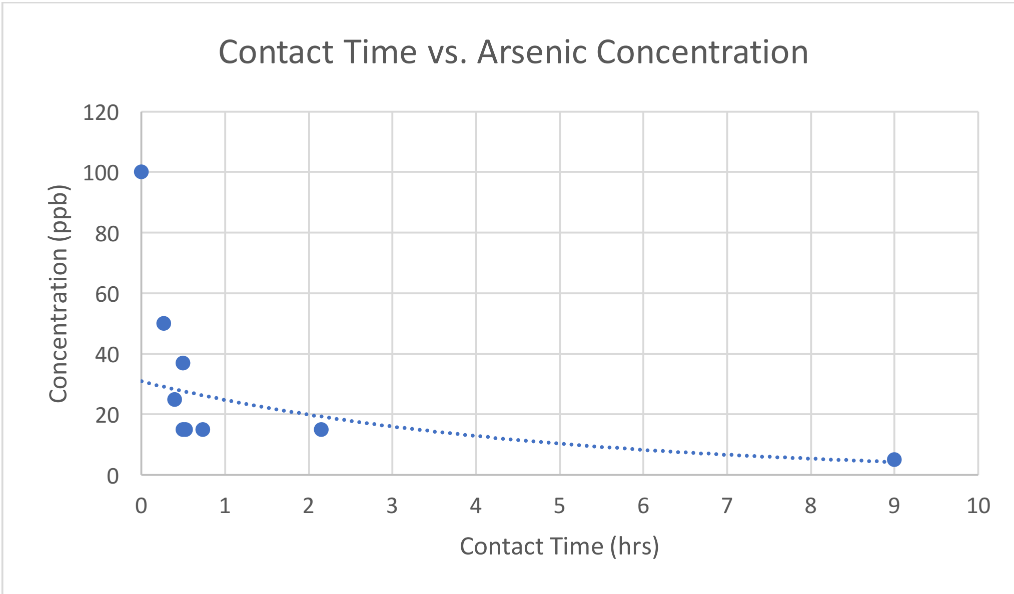

Figure 2: It is clear there is an exponential decrease in arsenic concentration with respect to contact time. As this was expected, more data points were taken in the first hour. At around 4 hours, arsenic concentration reaches about 10ppb and is considered potable.[4] The filter operates at STP and under isothermal conditions.

To control the contact time between the water and the rusted iron, a spigot was inserted to control the flow from the top bucket of rusted iron to the second bucket containing the sand, charcoal and rocks. Below is data collected from one of the first trial experiments for the filter at UC Berkeley.

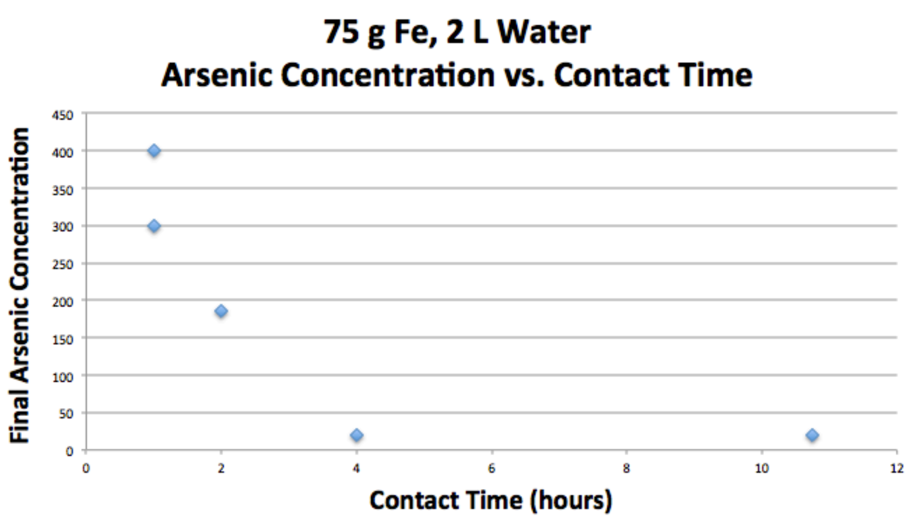

Figure 3: The above graph is from an original laboratory test completed in 2013 in Dracup's Laboratory on the UC Berkeley campus. The test began with 2L of water with arsenic concentration of 400ppb. It should be noted that the first data point should read 400ppb at time 0 and not at time 1 hour. The data could not be altered at this time to reflect

this. Readings were taken often in the first 2 hours and then reduced at long times as exponential decay behavior was expected.[4] Additional data sets are available in Appendix H of source 4 in the works cited. Here we present only two.

From this data and others like it, it was determined that increasing the contact time between the feed and the iron rust shavings does indeed exponentially increase the amount of arsenic removal.

To improve upon this design in the future, the distribution of water entering the second tank could be improved by adding a make shift distributor. As the water enters the second tank, it flows in, but doesn't quite flow over the entire filter. This would cause certain paths or channels in the filter in tank two to form. With continued use, these channels would lose their effectiveness, while much of the bed remained unused. To circumvent this issue, a perforated metal distributor plate could be added to the second tank that allows the incoming water to expand over the entire filter surface. The design would be similar to a shower head, splitting the feed stream into many streams to percolate through the filter. To test the efficacy of having a distributor, the filter could be analyzed over a 6-month period and compared to the pilot design used here. Daily samples of arsenic concentration should be taken, and the filter itself should be opened once a month to check for channeling.

Furthermore, to increase adsorptivity of arsenic to the iron, one could grind the rust particles into a fine powder. Increasing the surface area of the iron rust will increase the number of adsorptive sites for the arsenate to be taken up by. Preliminary experiments on this matter attempted to increase the amount of rusted iron added. The results were inconclusive and are not shown. Future experiments could test the efficiency of the filter versus iron-rust particle diameters. For instance, the iron rust could be ground into select sizes. These particles could then be packed densely into a tall sand-like layer. The contact time could be done away with, and water would be allowed to flow continuously from tank one to tank two. Arsenic concentration measurements could be taken every 10 minutes in the first hour and then every 30 mins in the subsequent 2 hours. The particle size that leads to the most arsenic reduction should be implemented. The height of the packing material can then be altered to achieve even further separation efficiency and higher residence times. Here, a tool to grind the iron with ease would need to be fashioned for use in ISP projects.

Temperature effects on the oxidation reaction rate and overall arsenic removal could also be studied. However, heating or cooling the filter would be very difficult in rural communities with little to no electrical infrastructure.

D. Describe why this technology would be appropriate for implementation in partner communities. Include consideration of technical, maintenance, financial, and cultural sustainability. Provide estimated typical costs for initial installation, maintenance, and operation.

The simple iron matrix filter is ideal for implementation in partner communities with high levels of arsenic contamination for its sustainable, straight-forward, and cost-effective design.

Rather than relying on manufactured composite materials, this simple iron matrix filter relies purely on recycled materials from the community, such as thoroughly washed rusted iron turnings or shavings. When the rusted iron shavings in the top bucket of the filter have been used for two years or are found to be ineffective, the iron shavings can be disposed of down the latrine with no major consequence to the environment. New iron shavings can be bought locally from a black smith for an affordable price. The new shavings are wiped down of any grease, treated with bleach, and then let out to rust for 15 hours before use.[4] Calculations for the disposal of the iron shavings are given in Appendix A.1. All other materials—sand, buckets, spigots, charcoal, PVC tubing and rocks—are commonplace throughout Peru and are easy to find in most developing countries.

There is little day-to-day maintenance involved with the operation of the filter. There are two aspects to maintenance: monthly arsenic testing and per-use addition of bleach. The EWB Student Chapter at Berkeley provided the community of Carancas with HACH EZ Arsenic High Range Test Kits that can take over 100 tests and can be found online for as low as fifty dollars.[4] Members of the community take turns testing the water for arsenic once a month using the HACH test kits. When a filter becomes ineffective, it can be disposed of and replaced in the manner described above. To prevent bacteria build-up, community members also take turns adding 2mg/L of bleach to the contaminated feed water (Appendix A.2). Aside from these two tasks, only periodic maintenance to fix leaks is truly needed for the filter to function well. For these tasks and maintenance, an operation manual was translated into Spanish and left onsite so that the filters can be independently used by the community without the help of Engineers Without Borders. Suma

Marka, a non-governmental organization based in Peru that worked alongside EWB at UC Berkeley, will also help the community replace their HACH kits when the tests are completely spent.

The EWB pilot program of this filter also aimed to ingrain the dangers of arsenic contamination and ingestion into the families in Peru. To do this, EWB members created a children's coloring book in Spanish with common landscape features and animals in the region to instruct the children of the community on the dangers of arsenic. The children asked their parents to read the fairly simple book to them causing a cultural shift that made everyone more aware of the dangers of not filtering their ground water. As the filter is easy to use and stands no taller than three feet, even the children were able to use it, with guidance from an adult. Based on the success of EWB's cultural impact on the community, we would recommend a similar system be used in further ISP projects.

The average family size in Peru is around four people and the average water consumption is 3.79 liters per person per day.[4] In total, the average amount of water needed a day for one family is about 15 liters. By using 20 L buckets, a one-time use of the filter can fulfill an entire family's need for water for one day. Below are the expected costs for a filter that would meet this daily requirement based on a 2014 implementation report provided by EWB at UC Berkeley.[4] It should be noted that costs of each item may not be listed individually, but are included in the total cost due to the documentation provided by local vendors onsite.

Table 1: Estimated costs of items based on implementation report provided by EWB Berkeley in 2014.[4]

Item	Cost in soles
General Materials	
Electric Drill	100 soles (excluded in total)
Drill Bits	21.9 soles
Caulking/glue	21.2 soles
Per Filter Materials	
Two 20 L plastic buckets with lids	55 soles
Sand	Provided in total.
Charcoal	~5 soles per filter
Rocks	Provided in total.
0.5" PVC pipe	35 soles
Spigots	Excluded in total.
Washers	1.4 soles
Iron turnings (if no rusted metal can be found)	Excluded in total.
Tubing	Excluded in total.
TOTAL	166 soles=51 USD

Here, we assume items such as an electric drill, spigots, common bleach for disinfection, and tubing can be found within the community. The iron rust in the filter is expected to last two years. For future projects, partner communities should first be asked what materials they have.

The average minimum wage in Peru is 850 soles a month, well above what is needed to build a simple iron matrix filter.[11] In the town of Carancas, where the average house-hold income is slightly below the national minimum, community members pool their money together to help purchase the equipment so no single person has to take on the burden.

The cost of repair and maintenance would differ depending on need, but can be roughly predicted using the estimates from the EWB implementation report.

Overall, we believe the design developed by the Engineers Without Borders at UC Berkeley has been quite successful for the pilot community of Carancas and recommend the design be further perfected for use in widespread ISP projects.

Works Cited

1. The Water Project. Facts About Water: Statistics of the Water Crisis Why Water? By the numbers. https://thewaterproject.org/water-scarcity/water_stats (accessed Nov 18, 2017).
2. Oosterveen, I. R. C. H. Water for Health: Taking Charge. http://www.who.int/water_sanitation_health/takingcharge.html (accessed Nov 21, 2017).
3. Water and Sanitation - United Nations Sustainable Development. http://www.un.org/sustainabledevelopment/water-and-sanitation/ (accessed Nov 21, 2017).
4. Engineers Without Borders - University of California, Berkeley. EWB UCB 525 Implementation Report. https://drive.google.com/drive/u/1/folders/0B91iK7XurVsqUzJVZXV2MWpZTEk (accessed Nov 18, 2017).
5. United States Environmental Protection Agency. (2017, April 27). *Chemical Contaminant Rules.* https://www.epa.gov/dwreginfo/chemical-contaminant-rules (accessed Nov 18, 2017).
6. Agency for Toxic Substances & Disease Registry. (2010, January 15). Environmental Health and Medicine Education What are the Physiologic Effects of Arsenic Exposure? https://www.atsdr.cdc.gov/csem/csem.asp?csem=1&po=11(accessed Nov 18, 2017).
7. George, C. M., Sima, L., Arias, M. J., Mihalic, J., Cabrera, L. Z., Danz, D., … Gilman, R. H. (2013). *Arsenic exposure in drinking water: an unrecognized health threat in Peru.* World Health Organization.
8. Safe Water International Clearing. http://www.safewaterintl.org/clearinghouse/filtration/three/kolshi.html (accessed Nov 21, 2017).
9. Hussam, A., & Munir, A. K. (2007). A simple and effective arsenic filter based on composite iron matrix: Development and deployment studies for groundwater of Bangladesh. *Journal of Environmental Science and Health, Part A*, 1869-1878.
10. Sancha, Ana Maria. Review of Coagulation Technology for Removal of Arsenic. *J Health Popul Nutr.* 2006, 24, 267-272.
11. Trading Economics. (2017). *Peru Average Monthly Wages*. https://tradingeconomics.com/peru/wages (accessed Nov 18, 2017).
12. Water.org. (2017). The Water Crisis. https://water.org/our-impact/water-crisis/ (accessed Nov 18, 2017).

Appendix A

1. **Calculations for sustainable disposal of iron shavings.**

Assuming a worse-case scenario of 500 ppb Arsenic initially, 40 L used every day, a two-year lifetime usage of steel and that ρwater = $\frac{1000g}{1\,L}$:

$$\frac{500 * 10^{-9}\, mol\, As}{mol\, water} * \frac{1\, mol\, water}{18\, g\, water} * \frac{1000\, g\, water}{1\, L\, water} * \frac{40\, L\, water}{day} * \frac{365\, days}{year}$$

We assume the radius from one house latrine to another is approximately 100m. We then create a spherical control volume with unknown depth, d:

$$V = \prod(100m)^2 * d = 31416\ m^2 * d$$

The water of the unconfined aquifer below the household presumably is already arsenic-contaminated. We can determine the minimum depth of water in the unconfined aquifer needed to raise the concentration of arsenic in the water by 1 ppb. We assume a reasonable value for the porosity to be 0.3.

$$0.81\text{ mol As added} * \frac{1\, mol\, water}{10^{-9}\, As} * \frac{18\, g\, water}{1\, mol\, water} * \frac{1\, L\, water}{1000\, g\, water} * \frac{1\, m^3}{1000\, L} * \frac{1\, m^3}{0.3\, m^3\, water\ (in\ pores)} = 48600\, m^3$$

Comparing this volume of water with our control volume above, we obtain:

$$48600\ m^3 = 31416\ m^2 * d$$

$$d = 1.5\ m$$

Thus, for the disposal of a two-year accumulation of arsenic on the iron, to raise the arsenic in the water by 1 pbb, a minimum depth of water needed in the unconfined aquafer water would be 1.5 m. For any depth ≥ 1.5m, we would see an increase in arsenic concentration less than 1ppAb. Considering that a depth of 1.5m is likely in Peru, this disposal method would not have a significant effect on arsenic groundwater contamination.

2. **Calculation of user added bleach. (Image)**

The max dosage of bleach according to the health standard is 4 mg of H-O-Cl per liter. Assuming there is 5% H-O-Cl in bleach we have:

$$maximum\ dosage = \frac{4\ mg\ HOCl}{L} * \frac{1\ g\ bleach}{0.05\ g\ HOCl} = 80\ \frac{mg\ bleach}{L}$$

Considering this, we can assume 40 $\frac{mg\ bleach}{L}$ is the recommended dosage. This is equivalent to $\frac{800\ mg\ bleach}{20\ L\ water}$. Assuming $\rho_{bleach} = 1.11\ g/mL$ and knowing that 1 mL bleach is approximately equivalent to 20 drops bleach:

$$\frac{800\ mg\ bleach}{20\ L} * \frac{1\ g}{1000\ mg} * \frac{1\ mL}{1.11\ g} * \frac{20\ drops}{1\ mL} = 15\ \frac{drops\ bleach}{20\ L\ water}$$

Doing a quick cost estimate, we know cost of a bottle of bleach ~2 sole such that:

$$2\frac{sole}{bottle} * \frac{1\ bottle}{250\ mL\ bleach} * \frac{1\ mL}{20\ drops} * 15\ drops = 0.006\ sole\ per\ run\ through$$

Acknowledgements: The Engineers Without Borders at UC Berkeley would like to recognize student member, Francesca Tinga, for her work in putting together this application.