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Locally affordable and scalable arsenic remediation for South Asia using ECAR

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An estimated 60 million low income people in South Asia are affected by chronic exposure to naturally occurring arsenic in drinking water sources. Few household and community level technologies have proven to be sustainable and scalable. Electro-chemical Arsenic Remediation (ECAR) is a low cost, robust, highly effective and easily scalable technology that has been designed to fit within a scalable and sustainable business model. In this paper, we describe ECAR treatment results from arsenic-contaminated synthetic and real groundwater and field trials of 100L and 600L scale prototype systems operated at rural schools in West Bengal, India. We demonstrate robust and reliable arsenic removal, the low production of waste sludge and the potential for successful sludge stabilization in concrete. We estimate the operating costs and benefits of ECAR based on field results.

Arsenic crisis in South Asian water supplies

In the 1970s and 80s, millions of tube wells accessing groundwater were installed in Bangladesh and India with the well-intentioned aim of improving the microbial quality of water supplies. By the 1980s, people consuming the tube well water were found to have skin lesions characteristic of chronic arsenic poisoning along with accumulating evidence to show that chronic ingestion of low levels of arsenic causes cancer, particularly of the lungs, bladder and kidneys, as well as cardiovascular and reproductive problems, painful skin lesions, and may have a detrimental effect on the IQ of children (Kapaj et al. 2006). In addition to health effects, loss of productivity and income costs poor families $84 per year (Roy 2008).

Today, millions of people in Bangladesh and India (particularly the Ganga river corridor in Bihar, West Bengal, and Uttar Pradesh) drink water from arsenic contaminated wells as their primary source of water; millions more are at risk in Cambodia, Pakistan, Nepal, and Vietnam among other countries. Many household and community scale treatment methods that have been deployed have been quickly abandoned because they are not maintained, repaired, accepted, or affordable (Kabir and Howard 2007; Das 2011).

Electro-chemical Arsenic Remediation (ECAR) is a form of electrocoagulation (EC) that has been developed to meet the needs of an appropriate community scale implementation scheme that is financially viable, locally affordable, and offers long-term sustainable safe water access in rural areas (Addy 2008; Amrose et al. 2013). In ECAR, electrolytic oxidation of a sacrificial iron anode produces Hydrous Ferric Oxide (HFO; also called Fe(III) precipitates) in arsenic-contaminated water. Arsenic complexes with HFO, which then aggregate to form a floc that can be separated from water. As(III) oxidizes to As(V) during the ECAR process due to highly reactive radical species produced by the oxidation of Fe(II) by dissolved oxygen (Li et al. 2012). ECAR is a promising technology for a financially viable community water business due to many advantages over existing technologies - including pH buffering ability, ease of operation, amenability to automation, low maintenance, low sludge production, small system size, the benefit of side reactions like As(III) oxidation, and because it is low cost enough to be locally affordable after mark-ups for labor, quality control, and marketing (Amrose et al. 2013).

The mechanism of arsenic removal in ECAR is closely related to that of chemical co-precipitation with ferrous salts (as opposed to ferric salts) and Zero-Valent Iron (ZVI) filtration. The delivery of Fe(II) ions differs in each case – in co-precipitation, it occurs through rapid dissolution of ferrous salts, in ZVI it occurs through natural corrosion of fine shavings of metallic iron, and in ECAR it occurs through accelerated corrosion of mild steel plates. Despite similarities, the ECAR process is advantageous due to:

- Simplicity of inputs (no need to import, manufacture, deliver, or handle ferrous salts or ZVI),
- Ability to sensitively control the rate of Fe(II) entering solution (allowing for a higher initial arsenic/HFO ratio, enhancing both HFO adsorption capacity and As(III) oxidation (Li et al. 2012), and
- Rapid corrosion compared to ZVI (up to 100x faster, depending on the current).

In this paper, we describe ECAR treatment results from arsenic-contaminated synthetic and real groundwater and field trials of 100L and 600L prototype systems operating at rural schools in West Bengal, India. We demonstrate the low production of waste sludge and the potential for successful sludge stabilization in concrete. Finally we estimate the operating costs and benefits of ECAR based on field results and evaluate potential for use in a scalable and sustainable community-scale kiosk model.

General principles of designing the technology solution

From the experiments in West Bengal several principles for the scaling up of this and other remediation technologies can be discerned (Gadgil et al. 2012). These include:

1. The technology must be robust
By this we mean that the technology will perform its intended task under stressful and difficult environmental and operating conditions encountered in the field (such as power blackouts and brownouts, dust, ambient heat and humidity, and being serviced by individuals with little formal technical training, under weak regulation and missing markets). This constraint of robustness must be applied right from the early stages of conceptualization. Implied in this statement is the desire that the technology must perform at a level that is expected for first-world inhabitants. In other words, we should ensure that we do not provide a lower service level to the poor people in the developing countries.

2. The technology must be locally affordable and culturally acceptable
Only locally affordable technology will allow a sustainable solution that does not require continuous infusion of external subsidy or cash to keep it operational and make it available to millions of people. Furthermore, the technology must not run counter to local culture. In the ideal case, the invention will be adopted, without compromising its technical performance, to suit the culture and habits of the end users.

3. The invention and innovation must be scalable
"Scalability" is the ability for the invention to be replicated and delivered to millions or even hundreds of millions of end users. For an invention to go to scale, its bare cost must be at least four to five times lower than its perceived monetary value (and therefore market price) to the end user. Only then there is a business case to be made for mobilizing finance capital, which is essential for large-scale production and delivery of the innovative product or service. In addition, the invention must not rely on some unique material that is in short supply, it must not produce waste products that are difficult to dispose of, and it must not cause environmental damage that will be unacceptable when deployed on scale. If used on scale, the innovation must not have foreseeable unacceptable consequences in economic or social spheres.

ECAR performance in synthetic and real groundwater

Arsenic removal is known to be highly sensitive to groundwater composition, specifically the presence of phosphate, silicate, natural iron and, to a lesser extent, carbonate, and calcium (Roberts et al. 2004), each of which is present in contaminated groundwater. Co-occurring ions affect arsenic removal by competing with arsenic for sorption sites on HFO, or by affecting the structure and size of HFO formed from Fe(II) oxidation (van Genuchten et al. 2012). Before moving to field trials, ECAR performance was verified by repeatedly reducing initial concentrations up to 3000 μg/L of As(III) and As(V) to below the WHO-MCL (10 μg/L) in synthetically prepared "worst-case scenario" groundwater and real contaminated groundwater samples from Jessore, Narayanganj, and Chandpur districts in Bangladesh and Kandal province in Cambodia (Amrose et al. 2013). In many cases, final arsenic concentration was < 5 μg/L.

Understanding the structure and colloidal stability of ECAR precipitates

Scanning Electron Microscopy (SEM; Figure 1) revealed that the HFO particles are rounded, consisting of aggregated secondary spherical particles of about 25 nm diameter forming larger popcorn-like clumps with a primary aggregate size of 50 - 100 nm. Extended X-Ray Absorption Fine Structure (EXAFS) spectroscopy results revealed that the very small size of HFO particles likely arises from surface poisoning by phosphate and silicate ions found in groundwater (van Genuchten et al. 2012). These ions bind to the surface sites required for attachment by other HFO nanoparticles for particle growth, constraining the final particles to be sub-micron sizes. Figure 2 shows this surface poisoning modeled by CrystalMaker software. As a result, particle separation by settling alone requires 1 – 2.5 days to achieve arsenic removal comparable to membrane filtration. However, we found that addition of a small amount of aluminum sulfate (e.g. alum) achieves rapid settling with turbidity < 5 NTU.

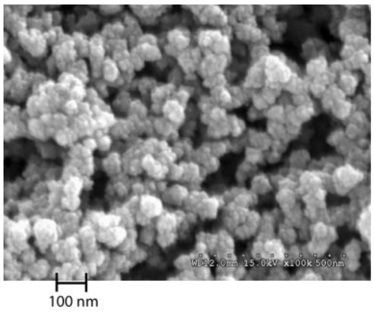

Figure 1. SEM images of HFO produced by ECAR

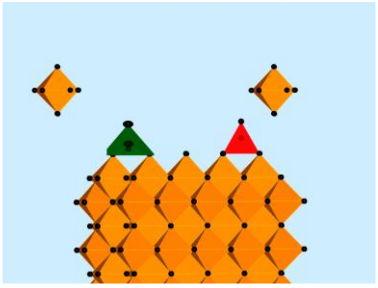

Figure 2. Surface poisoning of HFO (yellow octahedra) by arsenate (red) and phosphate (green). Schematic created in CrystalMaker software

Modelling ECAR performance and As(III) oxidation

Understanding the chemical kinetics of arsenic during electrocoagulation (EC) treatment is essential for a deeper understanding of arsenic removal using EC under a variety of operating conditions and solution compositions. Because EC systems include additional operating parameters, such as the rate of Fe(II) production, the results of previous As(III) oxidation studies in the Fe(II)/O_2 and Fe(II)/H_2O_2 chemical coagulation systems (Hug and Leupin 2003) will not likely provide a complete description of As(III) removal. We developed a highly-constrained, simple chemical dynamic model of As(III) oxidation and As(III,V), Si, and P sorption for the EC system using model parameters extracted from some of our experimental results and previous studies (full details found in Li et al. (2012)). Our model predictions agree well with both our observed experimental data (Figure 3) and data extracted from previous studies and over a broad range of operating conditions (charge dosage rate) and solution chemistry (pH, co-occurring ions) without free model parameters (Li et al. 2012).

The model also demonstrates that charge dosage rate (Coulombs/L/min; distinct from current density and charge loading) controls arsenic removal efficiency in systems containing As(III), a result corroborated with batch tests (Amrose et al. 2013). This is due to operational control over the Fe(II) concentration (and hence the ratio of Fe(II) to As(III) competing for the same oxidants) via the charge dosage rate.

Results from field trials

100L prototype trials at Amirabad Madrasah

In 2010, a 100L batch ECAR reactor was built comprising a cylindrical tank for dosing and mixing connected to a sedimentation tank for coagulant addition (alum) and settling (described in Addy et al. (2011)). The configuration allowed for easy reversal of current to minimize extensive rust build up and passivation. The prototype was transported to West Bengal and used in a successful 6-week field trial (2 weeks of operation) at Amirabad High Madrasah School (Figure 4).

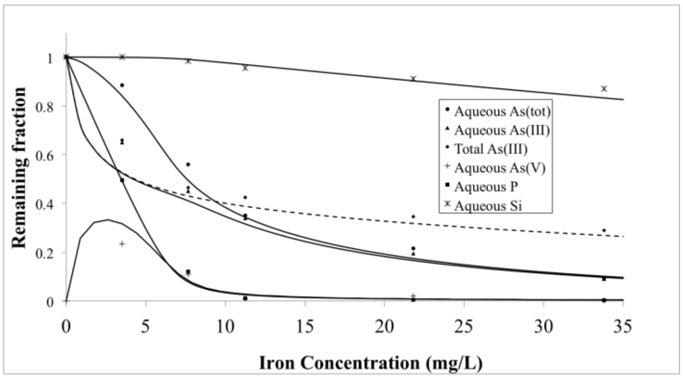

Figure 3. Removal of As(III), As(V), P and Si. The lines represent the output from the model calculation as aqueous (solid) and total (dashed) concentrations. Symbols are experimental data. Initial concentrations: 500 µg/L As(III), 3.0 mg/L P, and 30 mg/L Si

Initial concentrations (except in run 1a of Figure 4) were augmented with additional sodium arsenite to fully stress the ECAR system. The total charge loading (as coulombs passed per liter) was adjusted across runs for each source. ECAR was capable of reducing all sources to a final concentration below 5 µg/L once the appropriate dose was reached. Treated water was visually indistinguishable from commercial bottled mineral water in clarity, and less turbid than the original groundwater. No electrode passivation was seen.

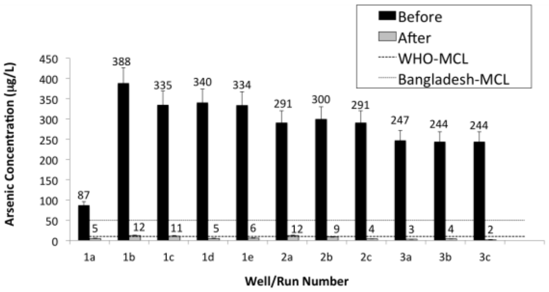

Figure 4. Pre- and Post-ECAR treatment arsenic concentrations during Dec 2010 field trial in West Bengal, India (numbers = unique wells, letters = unique runs). Dotted and dashed lines show the WHO-MCL (10 µg/L) and the India and Bangladesh-MCL (50 µg/L)

Inventing a robust, effective, simple-to-operate, and locally affordable technology is only the first of many steps toward successful implementation (see box). Other steps include efforts to transfer technical knowledge and scientific capacity to local institutions. One crucial development was to replicate the 100L ECAR unit indigenously at Jadavpur University (Kolkata) led by local Professors and students. In 2011, this prototype was successfully field tested and showed comparable performance.

600L prototype trial at Dhopdhopi High School

In spring 2012, a 600L ECAR batch reactor prototype was designed in Berkeley, fabricated in Mumbai, and shipped to Jadavpur University (Photograph 1). The prototype comprised a modular design made of four central "cores" or units of 10 plates each (5 anode, 5 cathode) as seen in Figure 5. This allows for easy scale-up – simply add more cores to a larger tank. The prototype was installed at Dhopdhopi High School near Kolkata in Fall 2012 for four months of daily weekday operation. These longer-term trials demonstrated that ECAR could consistently remediate high levels of arsenic (> 300 µg/L) in real groundwater to less than 5 µg/L when operated by a local trained technician. This was true under several low-cost and low-exertion maintenance scenarios, to be described more fully in a subsequent publication. Final iron concentrations in the treated water were all below the taste threshold for iron of 0.3 mg/L.

Photograph 1. 600L ECAR batch reactor prototype at Jadavpur University

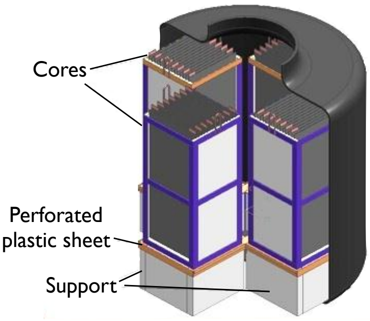

Figure 5. Cutaway of the 600L dosing tank demonstrating the modular cores

Safe disposal of arsenic-laden waste

We previously demonstrated that ECAR waste passes the Toxicity Characteristic Leaching Procedure (and is therefore not considered hazardous waste in the U.S.) and that ECAR sludge is well stabilized in concrete (Addy et al. 2011). Concrete used to stabilize arsenic-laden sludge could potentially be packed into roadways with minimal risk of arsenic leaching.

Estimate of costs

Consumables for EC comprise (1) iron consumed in the sacrificial anode, (2) electrical energy supplied for electrolysis, mixing, and pumping water (e.g. from source to dosing tank, from dosing tank to settling tank, from settling tank to storage, and for sludge removal), and (3) non-ferric commercial alum added to aid settling. Cost estimates are based on average measured power consumption during the 600L prototype field trial with no optimization to reduce energy consumption. Input costs are actual (small-quantity) procurement costs for the field trial (~ \$1/kg for steel plate, \$0.09/kWh for grid electricity, \$ 0.26/kg for commercial non-ferric alum). Using a conservative charge loading shown to reliably achieve < 5 µg/L, estimated consumables costs are \$0.44/m^3. During the field trial, charge loading was reduced for several runs with no performance loss at a consumables cost of \$0.30/m^3. The 100L prototype reached the same level of performance for \$0.20/m^3, suggesting the costs could be pushed lower with some minimal optimization. At current operating conditions, electricity accounts for 48% and materials for 52% of the total cost.

The 600L prototype reactor cost \$5400 to custom make in India, including materials, labor, 20% margin, and retail purchase of all pumps and pipes. Scaling up to 10,000L/day operating 6 days a week (assuming 2 identical reactors) and amortizing over 10 years at 5% (assuming social rate for infrastructure investment) or 15% (assuming commercial rate for business investment) leads to a total cost (amortized capital plus consumables) of \$0.86/m^3 (\$0.0009/L) and \$1.07/ m^3 (\$0.0011/L) respectively. This estimate ignores economies of scale and design optimization to minimize capital cost.

Additional costs for a viable business model must include a civil structure to house the equipment, inventory, marketing, management, quality control, and normal business margins.

A path to scalable Implementation

Ashok Gadgil also invented the technology (“UV Waterworks^{TM}”) licensed to WaterHealth International, a successful social enterprise providing clean water at locally-affordable prices to over 5 million people in India and elsewhere without subsidies. Their build-operate-transfer model overcomes many critical issues that have plagued other interventions, such as lack of maintenance. ECAR has been designed to fit within a similar model, providing a path for scalable and sustainable implementation. Co-locating systems at village schools could additionally educate the customer base while building connections to customer’s aspirations and a better life for their children. School partnerships also offer a strategic advantage to promote scale; Government subsidies focused on improving the children’s health could be leveraged, lowering initial costs and allowing for rapid assessment of demand in a new community before a larger installation is built, reducing expansion risk.

Conclusions

ECAR has been successfully lab tested and undergone a promising first round of field trials. It was found to be highly effective (final arsenic concentrations routinely reaching < 5 µg/L), robust, require little maintenance, and produce small quantities of sludge that can be successfully stabilized in concrete. These qualities combined with an extremely low operating cost make ECAR a promising candidate technology to operate in community scale microutilities offering clean water at a locally affordable price. In addition, ECAR does not need an adsorbent to be imported, manufactured, or regenerated. This reduces large upfront capital investment and the need to set up and maintain chemical supply chains or handle hazardous chemicals, making the technology amenable to rapid scale-up.

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