

BERKELEY
ELECTRO-COAGULATION
ARSENIC
REMEDIATION

ER 291 Sp 08

Debbie Cheng

Jessica Huang

Marianna Kowalczyk

Marc Muller

May 2008

OUTLINE

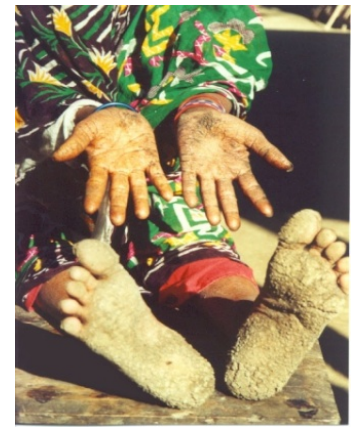
- Project Background
- Proposed Solution
- Design Principles
- Design & Construction (*the birth of a sushi...*)
- Lab Testing
- Market Considerations
- Conclusion & Next Steps



PROJECT BACKGROUND: CONTEXT

○ The Issue: Arsenic contamination in groundwater

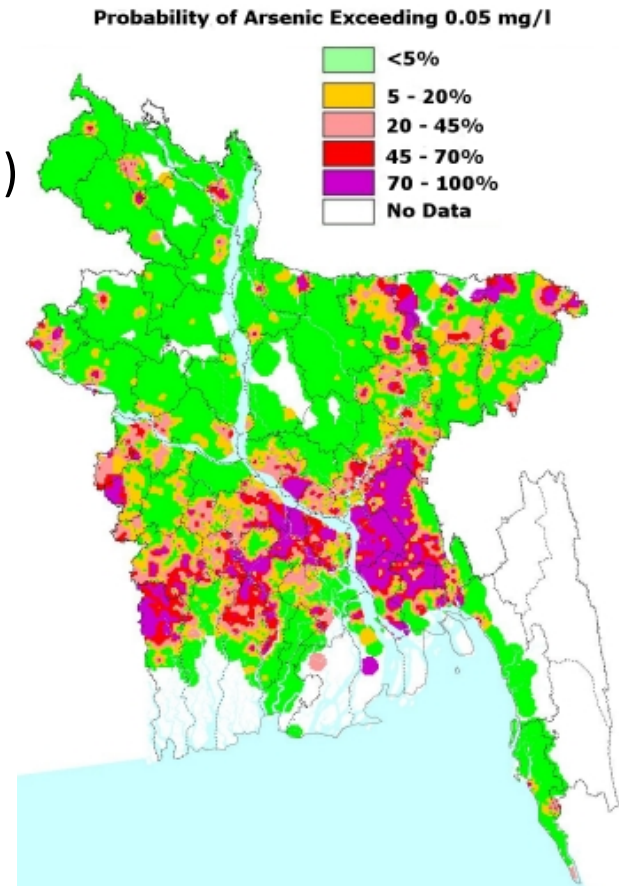
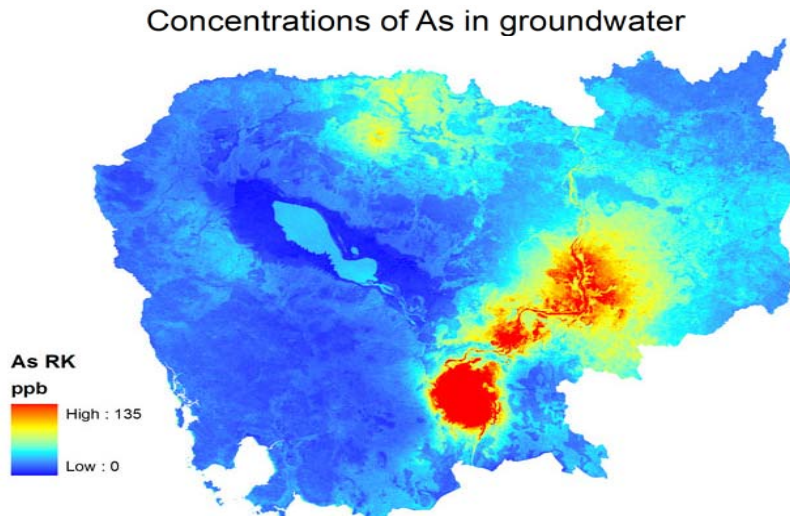
- About **140 million** people worldwide affected
- High convenience and strong incentive to use arsenic-contaminated shallow wells
- Concentrations can exceed WHO standards by up to **100 times**
- Arsenic poisoning can be painful, socially ostracizing, or fatal
- Arsenic is tasteless, colorless, odorless and has no immediate effects
- **“Technological graveyard” situation:** currently available technologies are either inefficient, unaffordable, or not culturally adapted



PROJECT BACKGROUND: REGIONS OF FOCUS

Bangladesh: Estimated **30-77 million** affected

- Berkeley Arsenic Alleviation Group (BAAG)
- Bangladesh University of Engineering and Technology (BUET)



Cambodia: Estimated **2 million** affected

- Resource Development International Cambodia (RDIC)
- *International Development Enterprise (IDE) – Potential Partner*



PROJECT BACKGROUND

○ The Need:

- **Efficiency:** Prevent prolonged contact with arsenic in drinking water
- AND
- **Acceptability:** Ensure financial, time and social burdens are **socially acceptable**



○ Our Motivation:

- **Improve health and livelihood** of millions worldwide
- Emphasize a **sustainable** and **appropriate** technological solution



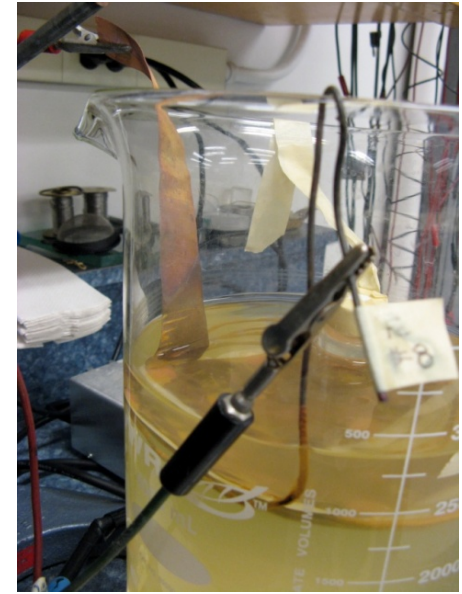
PROPOSED SOLUTION

○ The Technology: Low Cost Electro-Coagulation

- **Known wastewater technology**, yet never applied to drinking water
- Series of 3 distinct processes:
 1. **Dosing:** Formation of Arsenic-Binding Corrosion Products (ABCP) through electrochemical dissolution of iron electrodes
 2. **Mixing:** Coagulation of ABCP with arsenic
 3. **Filtration:** Mechanical removal of the arsenic-laden ABCP

○ The System: Community-Based Center with Full Cost Recovery

- **Sustainable** with built-in incentives for maintenance
- Encourages **local participation**
- **Scalable** and **replicable**



PROPOSED SOLUTION: EXPECTATIONS

○ Expected Benefits:

- **Simple inputs** and supply chain
- Very little waste at **<100 mg/3 L**
- Very **effective** (in lab)
- **Affordable**
- Potential for both **small & large scale** use

○ Principal Challenges:

Design

- Provide **energy** in off-grid rural communities
- Design an efficient, robust, and simple flow-reactor **from scratch**

Lab Testing

- Target and characterize **key parameters** to facilitate fine-tuning during field testing

Implementation

- Meet the low willingness to pay of **\$0.04/person-day**
- **Adapt** to local culture



PROPOSED SOLUTION: REVISED GOALS

-INITIAL-

○ Practical Goals (*minimum*):

- ✓ Design and lab-test a prototype for arsenic removal
- ✓ Create a field-testing protocol
- ✓ Address minimal business aspects

○ Practical Goals (*optimal*):

In addition...

- ✗ Complete a full business plan
- ✓ Identify strategic partnerships & next steps

-REVISED-

○ Practical Goals (*minimum*):

- ✓ Design and lab-test a prototype for arsenic removal
- ✓ Create a field-testing & community survey protocol
- ✓ Address minimal business aspects

○ Practical Goals (*optimal*):

In addition...

- ✓ Secure future funding
- IP Recruit new students
- IP Duplicate prototype
- ✓ Identify strategic partnerships & next steps



DESIGN PRINCIPLES

○ Demand Technical Requirements:

Treatment Capacity

- Serve at least **10 households** per system at **> 500 L/day**

Water Quality

- Removal effectiveness of **< 10 ppb**
- Turbidity of **< 1 NTU**



○ Design Choices:

Size

- Lab friendly and easily scalable at **10 to 100 L/h**

Integration

- **Focus on critical dosing process** after initial design iterations

Operation

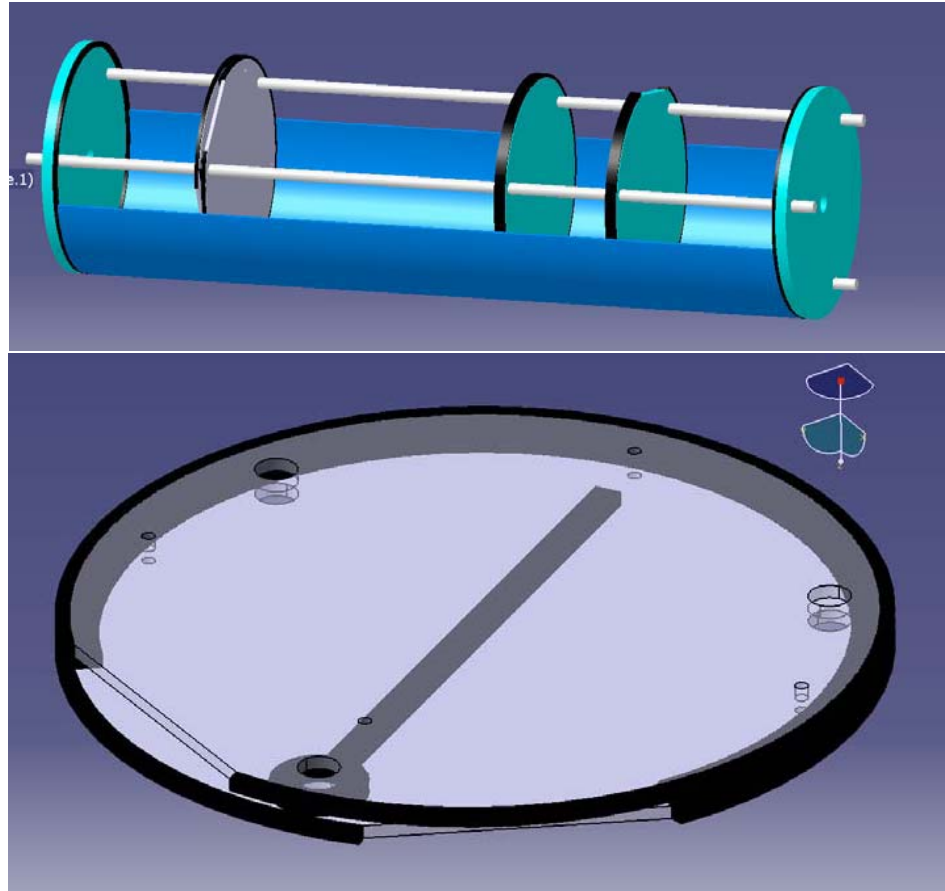
- Allow for a **12 V** car battery input and **gravity flow**
- Optimal “**HOT**” Zone: **150 C/L** and **1.1 mA/cm²**



DESIGN: ADAM

PROTOTYPE 0 FOR DOSING

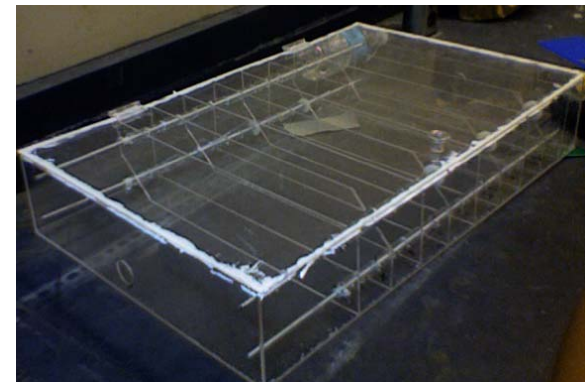
- **The Concept:** Cylindrical Tank for Dosing & Mixing
- **Pros:**
 - One contained unit
 - Standard shapes
 - Pressure-driven flow
 - Longitudinal cut for opening
 - Adjustable electrode spacing allows optimization
- **Cons:**
 - Difficult to build
 - Hinged opening allows leaks
- **Outcome:** ➡ Did not build



DESIGN: CHEX AND BOXER

PROTOTYPE 1 FOR *DOSING & MIXING*

- **The Concept:** Separate Tanks for Dosing & Mixing
- **Pros:**
 - Can characterize and optimize each process separately
 - Materials available at local stores
- **Cons:**
 - Electrode connections not ideal
 - Cascade system, non-homogenous flow
 - Mixing cell is fragile and not leak-proof
 - Also difficult to build!
- **Outcome:** ➡ Built Dosing & Mixing Tanks
 - Improve electrode design
 - Drop mixing cell design



DESIGN: BUILDING CHEX AND BOXER



DESIGN: SUSHI IDEA

CONCEPT FOR *DOSING*

- **The Concept:** Rolled Layers of Carbon Steel Foil Electrodes Separated by Isolating Layers
- **Pros:**
 - More robust and compact for field testing
 - Two continuous electrodes instead of plates connected by rods
 - Parallel homogeneous flow
 - Easy to build without special tools
- **Cons:**
 - Carbon steel foil is expensive
 - Thin foil is easily bent
- **Outcome:** 🗑️ **SELECTED!**



DESIGN: ISOLATING LAYERS BETWEEN ELECTRODES

CONCEPT FOR *DOSING*

- **The Goal:** Simple and Robust Provision of 5 mm Separation Between the Rolled Electrodes Without Impeding Water Flow

- **Neo:** Pattern of **Neoprene Tape**

- **Pros:** Provides good electrode-water contact
- **Cons:** Laborious to build, prone to short-circuiting, fragile

☞ ABORTED

- **Bubble:** Layers of **Bubble Wrap**

- **Pros:** Low risk of short-circuiting, homogenous flow
- **Cons:** Laborious to build, little electrode-water contact, fragile

☞ ABORTED

- **Mesh:** Layers of **Plastic Mesh** From Garden Fence

- **Pros:** Easy to build, homogenous flow, good electrode-water contact
- **Cons:** Potential risk of short-circuiting

☞ SELECTED!



DESIGN: SUSHI 1.0 AND 2.0

PROTOTYPE 2 (WITH REVISION) FOR *DOSING*

- **The Concept:** Modified Off-the-Shelf “Spaghetti Box” Container for Rolled Electrodes and Isolating Layers
- **Sushi Version 1.0:**
 - As initially designed
 - **Pros:** Easy to build
 - **Cons:** Horrible hydraulics!
- **Sushi Version 2.0:**
 - Additional HDPE wrapping and funneling to avoid hydraulic short-circuiting
 - **Pros:** Better hydraulics
 - **Cons:** Not robust, looks amateur
 - **Outcome:** 🍣 **WORKS!**

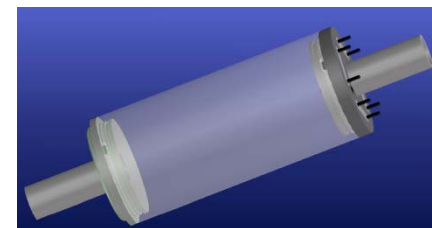
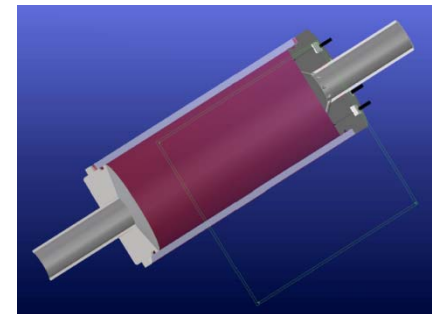
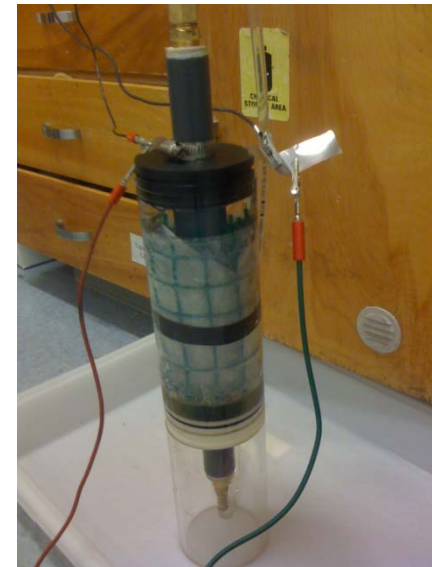
Proof of concept test (w/ synthesized Bangladeshi water): 600 ppb reduced to < 10 ppb



DESIGN: SUSHI 3.0 AND 4.0

PROTOTYPES 3 AND 4 FOR DOSING

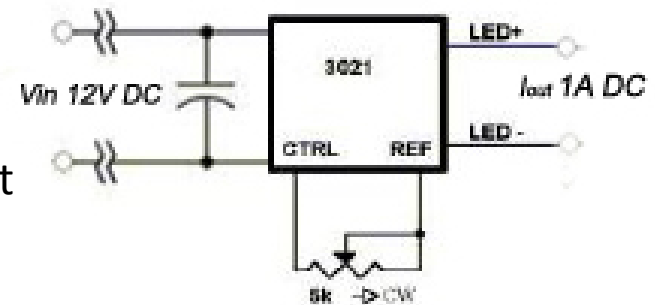
- **The Concept:** Custom-Machined Container for Rolled Electrodes and Isolating Layers
- **Pros:**
 - Adapted leak-free fittings
 - Optimized hydraulics including funnel drainage and homogeneous inflow
 - Compact and robust for adaption to field
 - Looks much more professional
(Thanks Jonathan!)
- **Cons:**
 - Need special equipment to build
- **Outcome:** ➡ Selected!
 - Lab test (Sushi 3.0)
 - Professionally duplicate for field (Sushi 4.0)



DESIGN: WASABI

ELECTRICITY SOURCE FOR *DOSING*

- **The Concept:** Electronic Circuit with a LED Driver to Produce Constant and Adjustable Direct Current Around 1 A
- **Pros:**
 - Cheap
 - Light and Compact
 - Easy to build from basic electronic supplies
 - Provides an adjustable 0.9 to 2 A constant current (though chip is labeled 0 to 1 A), but it's better for our application anyway
- **Outcome:** 🖱️ Selected!
 - More convenient for the field than a lab galvanostat-potentiostat



DESIGN: ROLLING SUSHI



DESIGN: OUTCOMES

○ We completed...

- ✓ A simple, robust, consumable flow-reactor **electrode cartridge** that can be easily built without special tools
- ✓ A robust and hydraulically-optimized permanent **electrode container**
- ✓ A 12 V direct current **car battery input**

○ We are still missing...

- IP A hydraulic **mixing flow-reactor** that requires little additional energy and provides > 20 min of mixing
- IP An adapted **mechanical filter** to remove the arsenic-laden particles
- IP Safe **disposal** procedures for arsenic-laden waste



LAB TESTING: QUESTIONS

○ Proof of Concept:

Will it work at all?

○ Characterization Parameters:

Dosing:

What flow rate?

Current Density:

What current; what power?

Kinetics:

What mixing time?



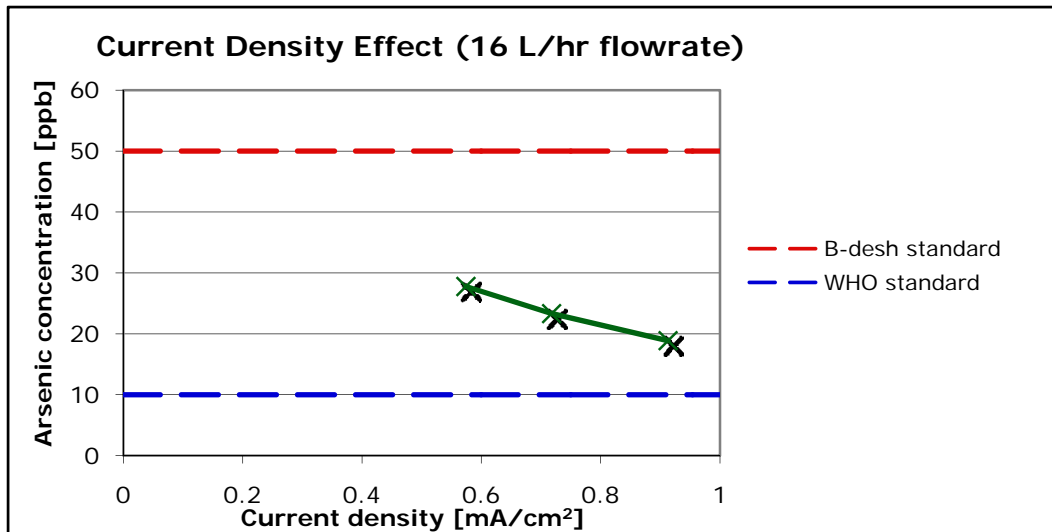
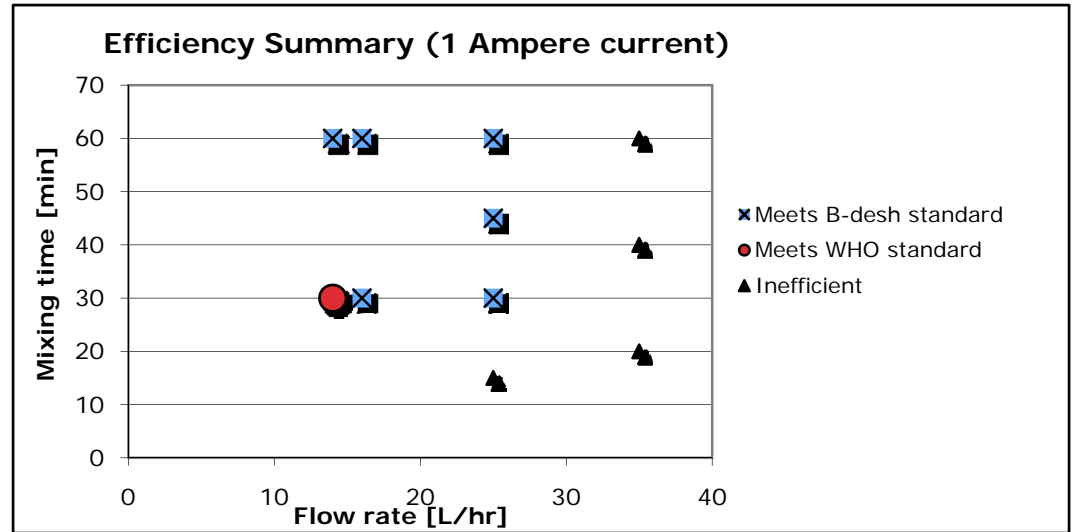
○ Experimental Setting:

- Synthesized Bangladeshi groundwater
 - Replicate pH, DO, principal interfering ions with 600 ppb arsenic
 - 3 hours required per 8 L Batch!
- Controlled flow (valve) and current (galvanostat)
- Batch mixing with magnetic stirrers
- Batch vacuum filtration with 0.1 micrometer membrane
- Quick Test (QT) and ICPMS (more accurate test) results now available



LAB TESTING: ANSWERS

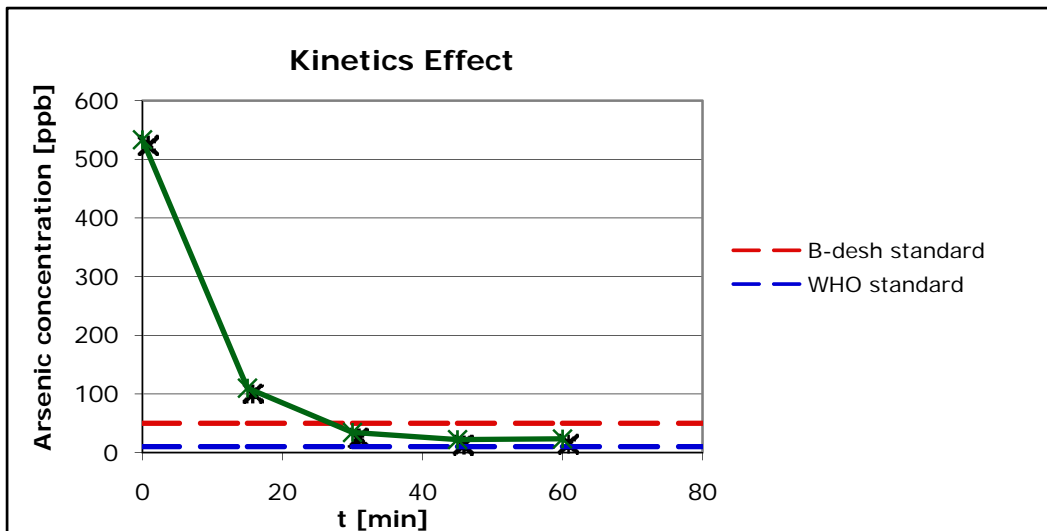
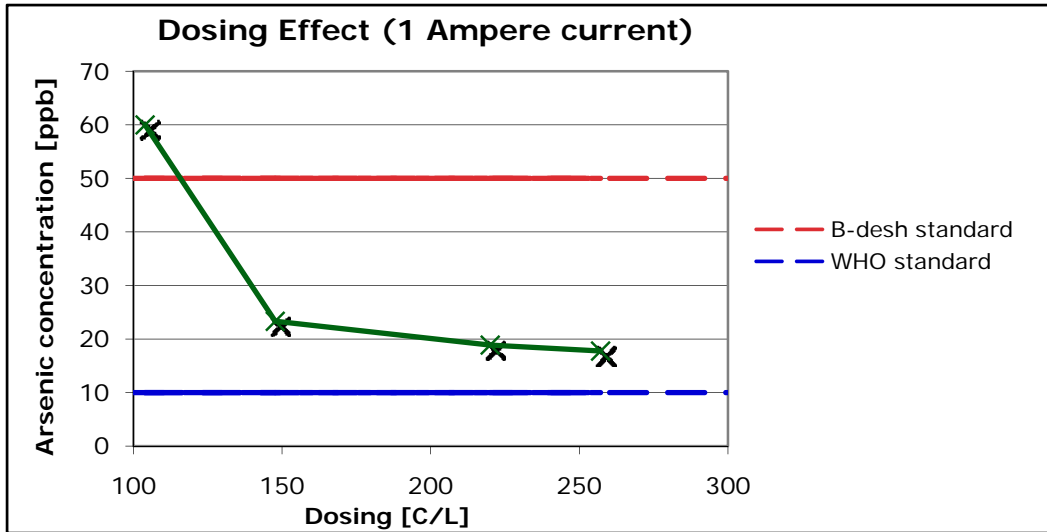
It **does** work!



... at a minimum current density of **0.9 mA/cm²**



LAB TESTING: ANSWERS



...at an optimal flow rate of around **16 L/h**



...and at a minimum mixing time of **30 min**

LAB TESTING: OUTCOMES

○ Working Prototype:

- Consistently meets Bangladeshi standards of **< 50 ppb**
- Requires about **1Wh** (1A*1V) to treat **16 liters**
- Electricity cost of about **\$0.003/L** (assuming \$0.50/kWh with PV)

○ Optimization Needed:

- **Higher current density** of about **1.1 mA/cm²** to consistently meet WHO standards (see trend)
- Slightly **higher flow rate** may be possible
- Minimum mixing time of about **30 minutes**
 - Allow bigger particles to form and facilitate filtration
 - Find optimal mixing speed
- **Adapt** to local field conditions



THE SUSHI MARKET



MARKET CONSIDERATIONS: NEEDS AND CHALLENGES

○ Cost Constraint:

- Satisfy willingness to pay of **< \$0.04/person-day**

○ Qualitative Goals:

- Efficient diffusion of technology (Rogers, 1995)
Relative advantage, compability, trialability, observability, minimal complexity
- Durable, scalable, replicable, environmentally and financially sustainable



○ Challenges:

- High capital **cost** ➤ Reduce cost through **optimization and scale**
- **Electricity** ➤ Provide **adapted electrification**
- Operation and **maintenance** ➤ Provide QA/QC via **professional staff**
- Water **delivery** ➤ Encourage **local initiatives**
- **Cultural acceptance** ➤ Promote a service that is **culturally desirable**
- **Perceived need** ➤ Provide **bound services** to raise the WTP
*Cell phone and appliance charging services
(Example: Uganda computing centers)*



MARKET CONSIDERATIONS: PROJECTED COSTS

○ Cost Estimate:

- **Output:** **Clean Water**

Assumptions: 10 L drinking water consumed daily per person

- **Inputs:** **Electricity** at \$0.0003125/person-day

Assumptions: 1 Wh consumed to clean 16 L of water (Amrose, 2007)
\$0.50/kWh with photovoltaic panel (SELCO, India)

Iron Foil at \$0.02505/person-day

Assumptions: 33 mg iron consumed to clean 1 L of water (Amrose 2007)
\$34.50/lb carbon steel foil (AllFoil, USA)

- **Total Cost:** **Operational cost** at **\$0.025/person-day**

Assumptions: 20% overhead

Retail cost at **\$0.03/person-day** ✓

○ Room for Improvement

- Knowledge **optimization**
- Economies of **scale** with supply and manufacturing



MARKET CONSIDERATIONS: PROJECTED BENEFITS

○ Advantages of Community-Based Model with Full Cost Recovery

- Provides **maintenance** and **quality control** through trained staff
- Provides **electricity** through lease or rent
- **Sustainable** and **replicable** turnkey solution
- Encourages **local participation**
- **Proven success** with WaterHealth International

○ Benefits Estimate:

- **People:** **Avoid 7,800 cancer deaths** and **78,000 cancer cases** within 3 years

Assumptions: 600,000 people served within 3 years of start (WaterHealth)

Average exposure 50 ppb (higher in actuality, British Geological Survey)

Avoid 13/1000 fatal cancer cases, 13/1000 non-fatal cancer cases (Smith et al., 1999)

- **Planet:** **Avoid 2.88 kg arsenic-laden waste/person-year**

Assumptions: 3 kg waste/person-year at 10/L-day consumption with Sono 3-Kolshi Filter (Munir et al., 2001)

120 mg waste/person-year at 10/L-day consumption with electro-coagulation (Amrose, 2007)

- **Prosperity:** **Add \$171 value/household-year**

Assumptions: Welfare cost of \$248/household-year in West Bengal, India (Roy, 2005)

Retail price of \$0.003/L with household of 7 people each consuming 10/L-day



CONCLUSION: PROGRESS UPDATE & NEXT STEPS

-CURRENT STATUS-

○ Technology:

- Duplicated flow prototype for dosing
Robust, simple, adapted to a 12 V battery
- Successful lab tests
Proof of concept, optimization direction

○ Market:

- Cost projection meets WTP
- Business investigation by Haas team

○ Fieldwork:

- Partnership in Cambodia
Research and implementation
- Lab and survey protocol
Working with BAAG

○ Continuity:

- Awarded several grants
- Recruiting new students

-NEXT STEPS-

○ Summer:

- Field test and fine tune prototype
Bangladesh and Cambodia
- Locally adapt and duplicate prototype
- Design mixing and filtration phase
- Market study and WTP assessment
In specific communities
- Implementation Options
Bundled services, manufacturers/suppliers

○ And Beyond:

- EPA and SPS grants
Fundamental research
Prototype characterization
Optimize mixing and filtration
Extended technical trials
- 1 year pilot in Bangladesh
- Business plan
NCIIA I2V, ASME IShow



CONCLUSION: LESSONS LEARNED

- Good intentions may not always lead to good outcomes – Important to take an **integrative approach** linking technology, economics, and culture to solve real world problems
- **Practice makes perfect** – Improve the design through iteration
- Be **humble** and **persevere**
- Not easy to design a **simple** device
- **Reach out** – Collaborate and form partnerships
- Develop **teamwork** and **trust**
- With enough vision, determination, and knowledge, **we can have a real impact**



A BIG BEAR THANKS TO...

Our Mentors

Susan Amrose

Jerry Pugh

Ashok Gadgil

Robert KostECKi

Jonathan Slack

Howdy Goudey

Our Partners

Berkeley Arsenic Alleviation Group

Haas School of Business

Resource Development International Cambodia

And Our Sponsors

Environmental Protection Agency

Richard C. Blum Center for Developing Economies

Sustainable Products and Solutions Program

Ingénieurs du Monde

J. W. Saxe Memorial Fund

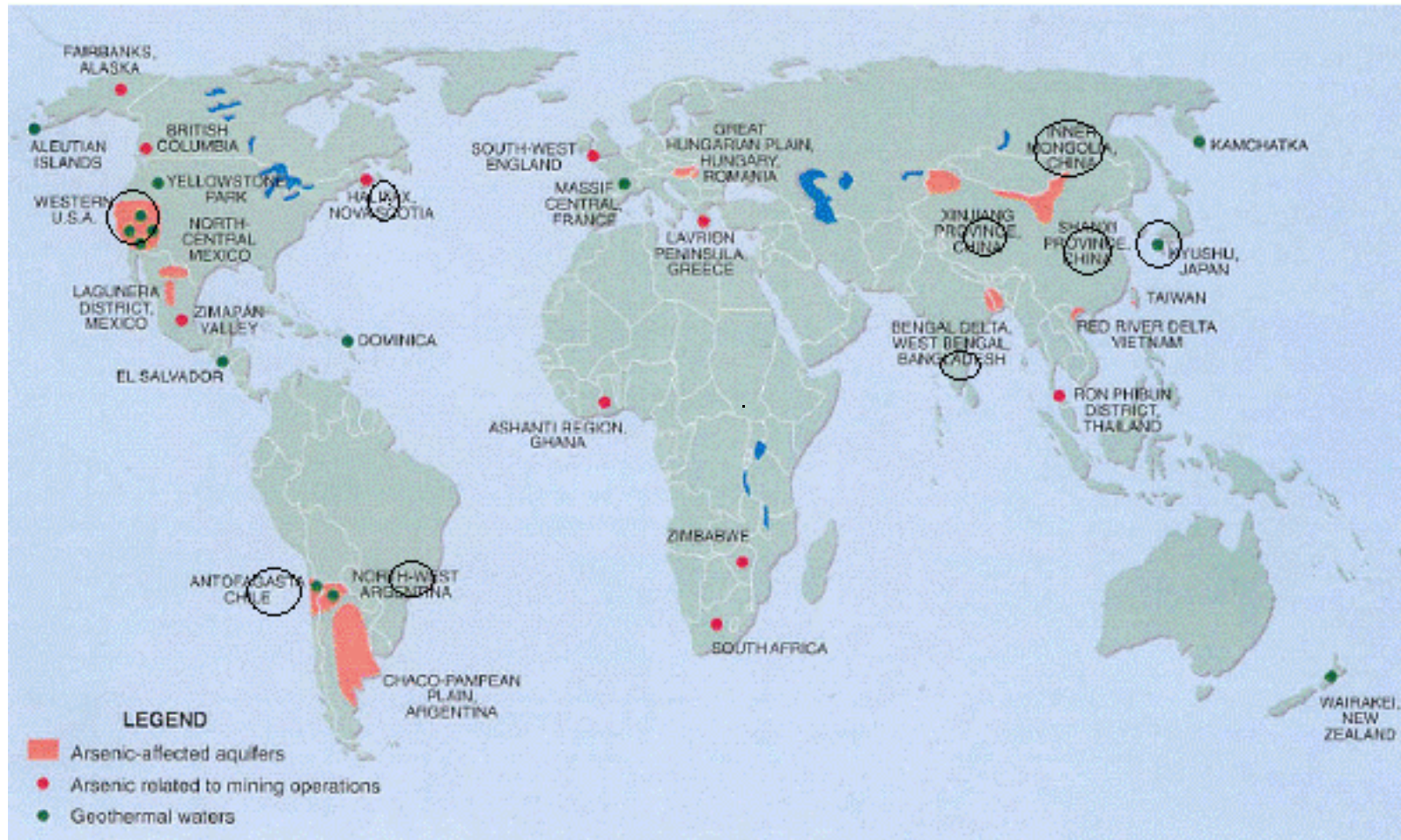
Bears Breaking Boundaries/Big Ideas Marketplace

Associated Students of the University of California



...FOR MAKING OUR WORK POSSIBLE!

QUESTIONS?



YouTube Video: <http://youtube.com/watch?v=OA7vGRHDxYE>

REFERENCES

- Ahmad, J., Goldar, B.N., Misra, S. and Jakariya, M., 2003. Willingness to pay for arsenic-free, safe drinking water in Bangladesh. New Delhi, India: Water and Sanitation Programme–South Asia, The World Bank.
- Ahmed M.F, 2006. Ensuring safe drinking water in Bangladesh. Science.
- Amrose, S., 2008. Personal communication.
- Amrose, S., 2008. Electrochemical arsenic remediation in rural Bangladesh. Environmental Protection Agency Proposal.
- Beck, R., 2007. World facing 'arsenic timebomb', BBC News.
- Berkeley Arsenic Alleviation Group, 2007. Lawrence Berkeley National Laboratory, University of California, Berkeley. <http://arsenic.lbl.gov>.
- Bloch, A., Chary, M., Huang, J., and Oudin, A., 2007. Presentation to the Uganda Ministry of Health on information and communication technologies implementation. Richard C. Blum Center for Developing Economies, University of California, Berkeley.
- Bhattacharya, P., Jacks, G., Ahmed, K.M., Routh, J. and Khan, A.A., 2002. Arsenic in groundwater of the Bengal delta plain aquifers in Bangladesh. Bulletin of Environmental Contamination and Toxicology, 69(4): 538-545.
- Cenkin V.E and A.N. Belevstev, 1985. Electrochemical treatment of industrial wastewater. Eff Water Treat J.
- Chowdhury, U.K. et al., 2000. Groundwater arsenic contamination in Bangladesh and west bengal, India. Environmental Health Perspectives, 108(5): 393-397.
- Government of the People's Republic of Bangladesh, 2004. National policy for arsenic mitigation 2004 & implementation plan for arsenic mitigation in Bangladesh. In: r.d. Ministry of local government, and Co-operatives (Editor).



REFERENCES

Guha Mazumder, D.N., 1996. Treatment of chronic arsenic toxicity as observed in West Bengal. *Journal of the Indian Medical Association*, 94(2): 41-42.

Hansen H.K. et al., 2007. Electro-coagulation in wastewater containing arsenic : Comparing different process designs. *Electrochimica Acta*.

Hansen H.K. et al., 2006. Electro-coagulation as a remediation tool for wastewaters containing arsenic. *Minerals Engineering*.

Hoque, B.A. et al., 2004. Demand-based water options for arsenic mitigation: An experience from rural Bangladesh. *Public Health*, 118(1): 70-7.

Kahn, M., 2007. Arsenic in water a risk to 140 million people. *Reuters*.

Kumar P.R et al., 2004. Removal of arsenic from water by electro-coagulation. *Chemosphere*.

Muller, M., 2007. Participation and arsenic mitigation: Beyond the politically correct. *Energy and Resources Group, University of California, Berkeley*.

Munir, A.K.M. et al., 2001. Evaluation of the performance of sono 3-kolshi filter for arsenic removal from groundwater using zero valent iron through laboratory and field studies. In: M.F. Ahmed, M.A. Ali and Z. Adeel (Editors), *Technologies for arsenic removal from drinking water*. Bangladesh University of Engineering and Technology (Dhaka) and the United Nations University (Tokyo), Dhaka, Bangladesh, pp. 171–189.

Parga J.R. et al., 2005. Arsenic removal via electro-coagulation from heavy metal contaminated groundwater in La Comarca Lagunera, Mexico. *Journal of Hazardous Materials*.

Rahman, M.M. et al., 2005. The magnitude of arsenic contamination in groundwater and its health effects to the inhabitants of the Jalangi; one of the 85 arsenic affected blocks in West Bengal, India. *Science of the Total Environment*, 338(3): 189-200.



REFERENCES

Rogers, E., 1995. Diffusion of innovations, 4th Edition. Free Press.

Rosenboom, J.W., 2004. Arsenic in Asia : A regional overview, 30th WEDC International Conference, Vientiane, Laos PDR.

Roy, J., 2005. Estimating economic benefits from arsenic removal in India: A case study of West Bengal (working paper), Jadavpur University, Kolkata, India.

Sampson, M., 2008. Personal correspondence.

Smith, A.H. et al., 1999. Cancer risks from arsenic in drinking water: Implications for drinking water standards, Proceedings of the third international conference on arsenic exposure and health effects, 12-15 July 1998, San Diego. Elsevier Science, Oxford, pp. 12–15.

Vergara, S.E., 2007. Why do POU's fail? Barriers to the adoption of point of use water treatment technologies. Masters Thesis, UC-Berkeley, Berkeley, CA, pp. 94.

WaterHealth International, 2008. <http://www.waterhealth.org>.

Wilson, R., 2004. Chronic arsenic poisoning: History, study and remediation, <http://phys4.harvard.edu/~wilson>.

World Health Organization, 2006. Arsenic mitigation for safe groundwater. WHO Executive Board.

World Health Organization, 2003. Arsenic, drinking-water and health risk substitution in arsenic mitigation: A discussion paper. WHO Report.

World Health Organization, 2000. Towards an assessment of the socioeconomic impact of arsenic poisoning in Bangladesh. WHO, Geneva.

Yu, W.H., 2003. Socio-hydrologic approaches for managing groundwater contamination problems: Strategies for the arsenic problem in Bangladesh. Harvard University, Cambridge, Massachusetts, pp. 323.

