Affordably removing arsenic from drinking water

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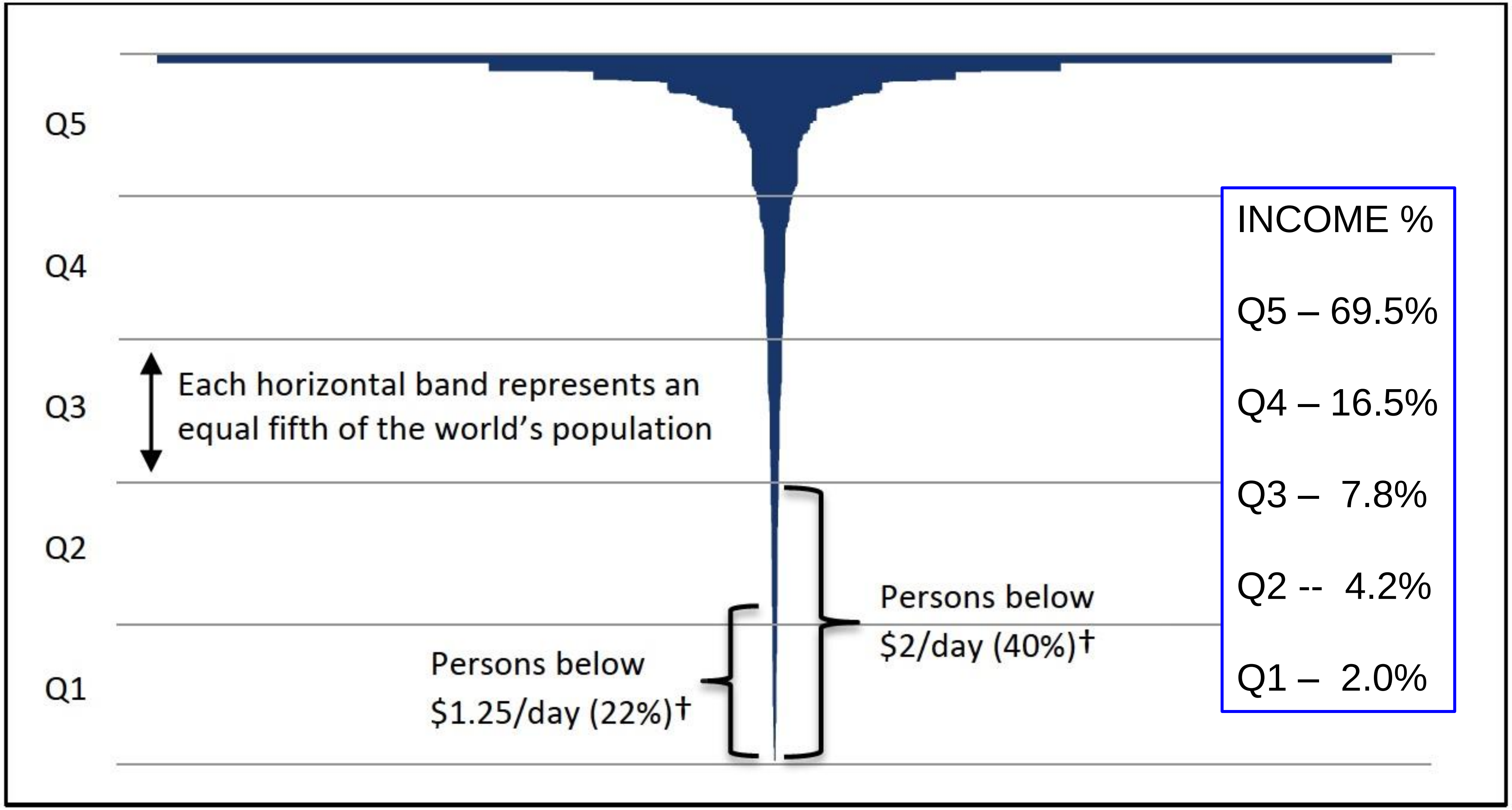
What is “Bottom (or Base) of the Pyramid”?

It is the poorest socio-economic group on the planet (different definitions exist as to cut-off for “poorest”).

So, let’s see what income distribution looks like.



Distribution of Global GDP, by quintiles; richest 20% top (Q5), poorest bottom (Q1).

Figure from: Ortiz and Cummins, "Global Inequality: beyond the poorest billion" UNICEF Working Paper (2011). The superscript † symbol in original figure refers to data sources.

(The wealth distribution is even worse than the income distribution)

On Monday 17 Jan. 2017, Oxfam released a report concluding that the 8 richest individuals on the planet own more wealth than the bottom half of the world's population (3.7 Billion people). That made headlines on CNBC, the Guardian, and many other news media.

The report titled **"An Economy for the 99%"** can be downloaded from the Oxfam UK website. Just Google it.

"For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled."

-- Richard Feynman

PCSSCA (Presidential Commission on Space Shuttle Challenger Accident), Volume 11, Appendix F: Personal Observations on the Reliability of the Shuttle. p. F5 (1986)

Surely correct – but fatally incomplete -- set of principles

To be useful, effective, and scalable, the technology innovation must have each of the following four characteristics

1. Affordable
2. Technically Effective
3. Robust (in relevant operating environment)
4. Culturally Appropriate

Three Lessons Learned

(1) For a new technology to be scalable, <u>design</u> thinking and <u>implementation</u> thinking can not be separated

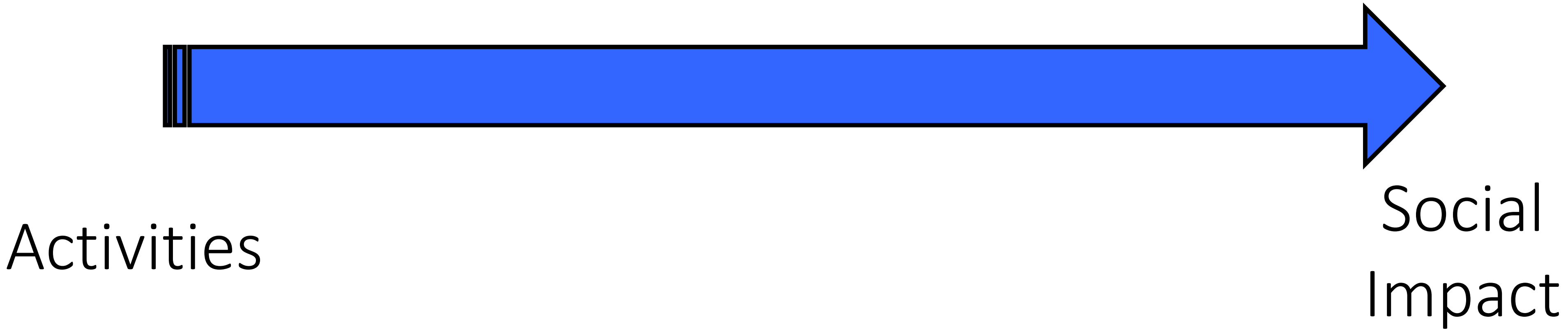
(2) Social factors are as critical for a technology's success as those from engineering-science

(3) Ignoring political economy, behavioral economics, organizational behavior, institutional imperatives, cultural norms and social drivers can prove fatal flaws when the new technology leaves the lab and meets the real world

These three lessons can be summarized in a single requirement

Articulate, and then critically examine, your “Theory of Change”

(“Theory of Change” is an articulation of how and why the intervention will result in a desired positive societal impact.)

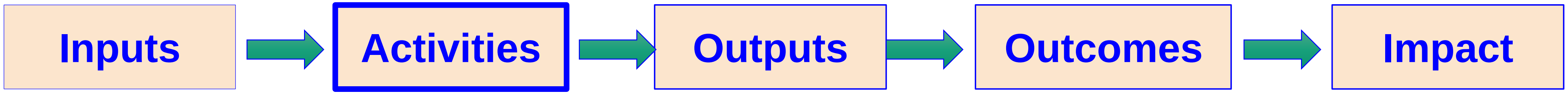


Theory of Change

Why articulate a theory of change?

- Show a **causal relationship** between intervention and desired outcome
- Requires you to **articulate assumptions** that can (possibly) be measured and tested
- Changes point of view from ***what you do*** to ***what you want to achieve***
- Helps you decide ***what not to do***
- Helps you identify necessary factors for your theory to work

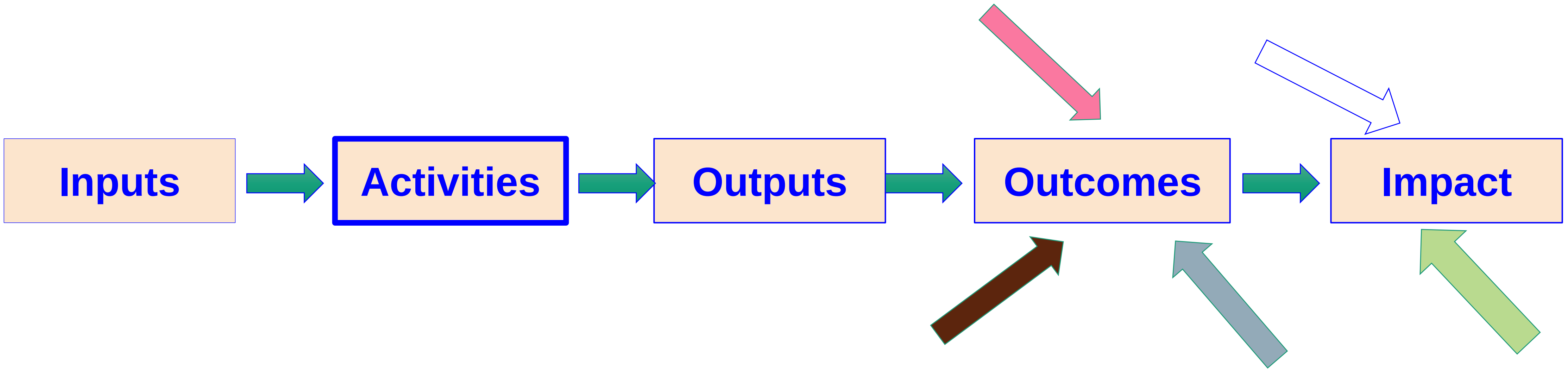
Schematic Components of Theory of Change for societal impact



Each of these boxes needs to be unpacked

In particular, links between the boxes must also be unpacked to understand the *causality* from one box to the other. Each link allows for one or more *metrics* to evaluate the theory of change. See the long Wikipedia entry on “Theory of Change” if you want to get into this deeper.

Schematic Components of Theory of Change for (large scale) societal impact



Theory of Change also forces you to recognize other (positive or negative) drivers that may support or oppose your desirable outcome
– and that might force you to rethink a wishful idea early on.

An illustrative invention and innovation for safe drinking water (and I'll let you guess my Theory of Change as an exercise):

Removing arsenic from drinking water for 200M people that have no alternative but to drink water with high arsenic content

History: A massive successful campaign to switch to handpumps for drinking water in rural B’desh and India in 1980s.

Arsenicosis – ulcers, gangrenes, and cancers -- started appearing in the population from early 1990s.

Access to safe drinking water is recognized by the UN General Assembly as a fundamental human right (UN 28-July-2010). And is also a prominent SDG.

SDG 6: Clean Water and Sanitation

Yet, tens of millions of rural poor have no other water to drink than groundwater contaminated with toxic levels of arsenic.

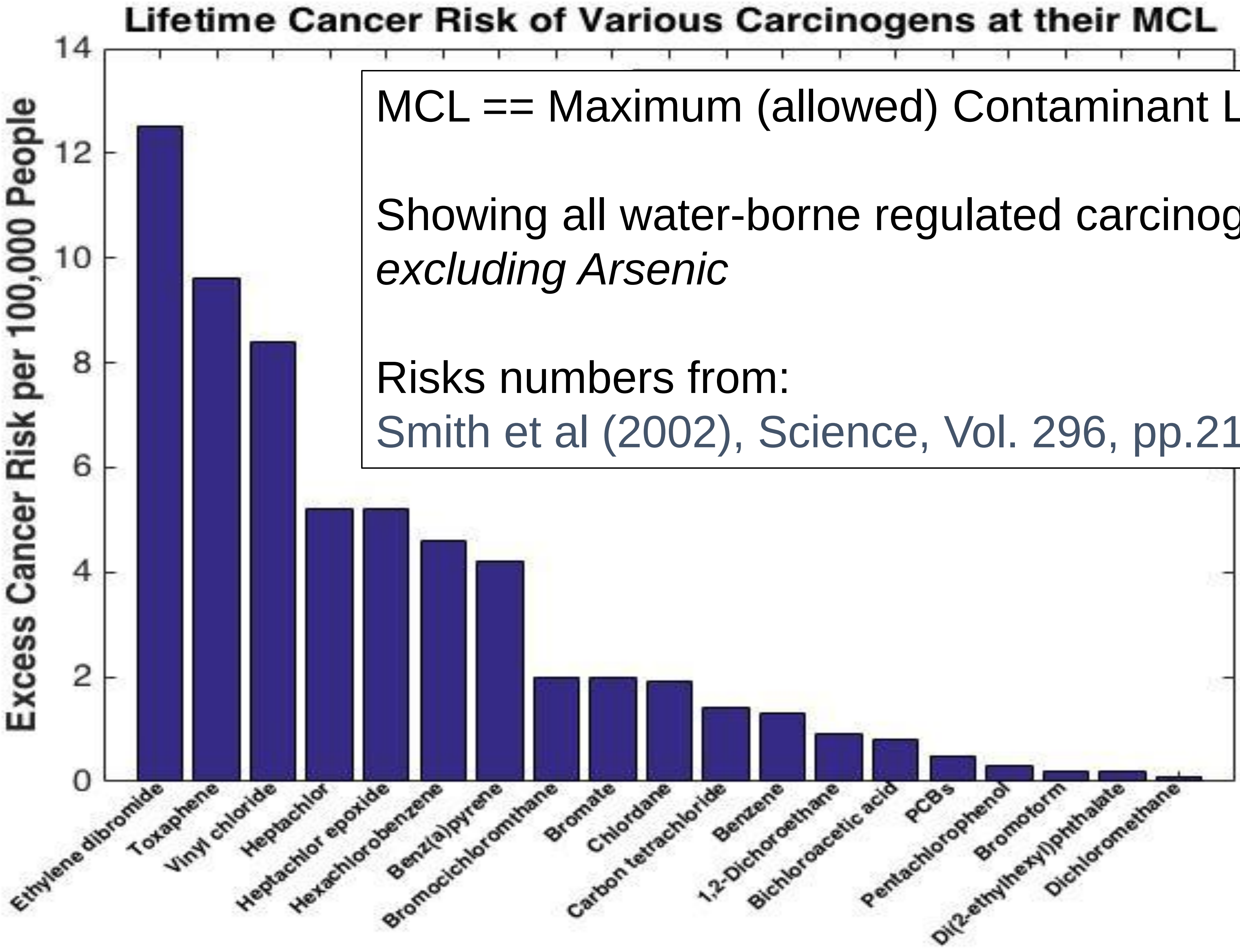
Arsenic is ubiquitous in Earth's crust, but the problem is most severe in Bangladesh, and parts of India. Also in Chile, parts of the US and Mexico, etc.

Chronic exposure to arsenic leads to internal cancers, gangrenes and amputations, neuropathy, skin lesions and painful ulcers. And low IQ in children.

In 2002, the WHO called this the largest mass poisoning in recorded history

Let’s look at only internal cancers, for which there is high quality data and well-tested predictive models.

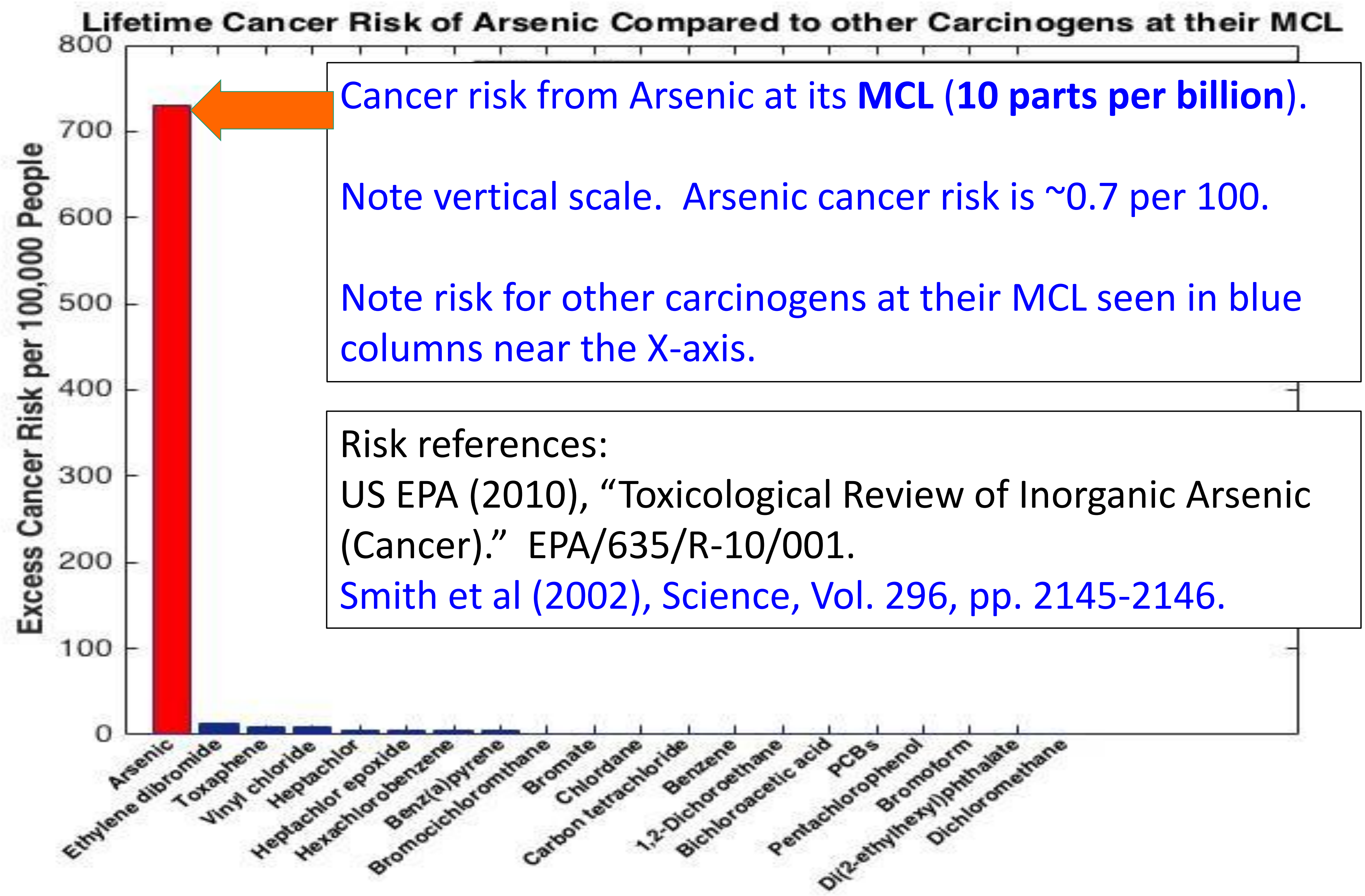
How many internal cancers can be expected in 100,000 people drinking carcinogen-bearing water for a lifetime, at allowed maximum concentration of the carcinogen?



MCL == Maximum (allowed) Contaminant Level.

Showing all water-borne regulated carcinogens, *excluding Arsenic*

Risks numbers from:
Smith et al (2002), Science, Vol. 296, pp.2145-2146.



Cancer risk from Arsenic at its **MCL (10 parts per billion)**.

Note vertical scale. Arsenic cancer risk is ~0.7 per 100.

Note risk for other carcinogens at their MCL seen in blue columns near the X-axis.

Risk references:
US EPA (2010), “Toxicological Review of Inorganic Arsenic (Cancer).” EPA/635/R-10/001.
Smith et al (2002), Science, Vol. 296, pp. 2145-2146.

That risk was at 10 ppb – at arsenic concentration *allowed* by US EPA for drinking water.

Arsenic concentrations of 250, 500, even 1200 ppb are commonly found in groundwaters of West Bengal and Bangladesh

Internal cancer risk rises linearly with arsenic concentration at these values

These pictures show various Arsenic Removal Units (or ARUs) placed in the district of Murshidabad, West Bengal, by NGOs, charitable organizations, Corporate donations via CSR activities, etc.

Photos were taken by Mr. Das in his doctoral study of the functioning of these ARUs after their placement.

The ARUs are usually based on sound technologies, shown to work in the lab, and were expected to work in the field.




>95% of these failed within 1 year*!

*Ph.D. Thesis, Abhijit Das, Jadavpur University, 2012

Need: a Sustainable Technology *System*
= *Effective, Robust, Financially Viable, Locally Affordable, Scalable, and Socially Embedded*

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Photos were taken by Mr. Das in his systematic study of the functioning of these ARUs after their placement.

The ARUs were based on sound technologies, and shown to work in the lab, and were expected to work in the field.

On closer inspection, the Technologies had not failed.

The technologies all indeed removed arsenic just fine in the lab

The Technologists had failed!!

The systems were unsustainable: financially non-viable, not embedded in the societal context, without incentives or structures for their continued maintenance and repair, without knowledge transfer to local community stakeholders

ECAR was designed to fit within a sustainable and scalable technology system

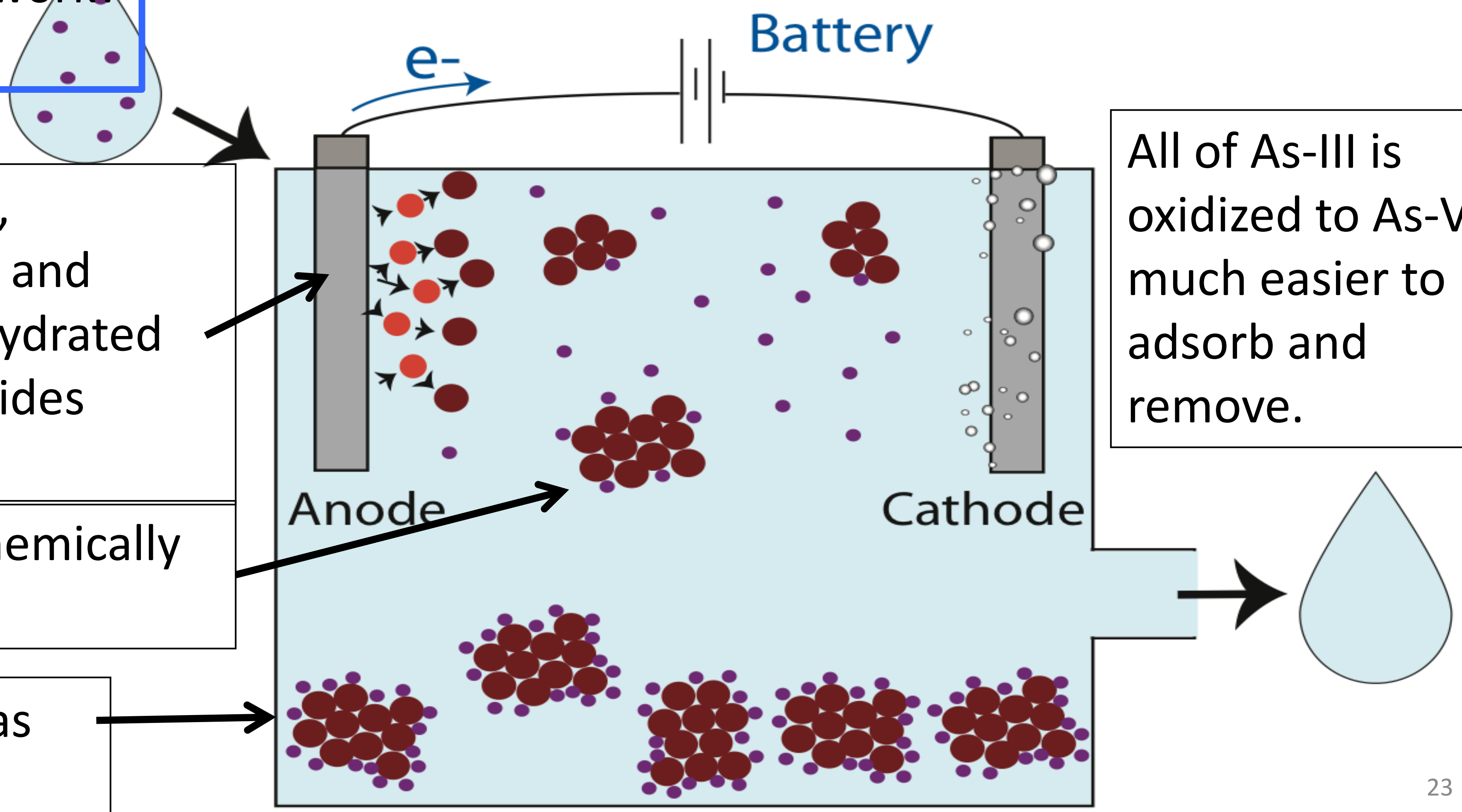
ECAR = Electro-Chemical Arsenic Remediation

How does ECAR work?
The Big Picture

Fe-II is produced, oxidizes to Fe-III, and precipitates as Hydrated Fe-III-OxyHydroxides (“HFO”)

P, Si, and As-V chemically sorb to HFO

Then settle out as sludge



All of As-III is oxidized to As-V; much easier to adsorb and remove.

For 2005-2009 we focused on getting the basic fundamental science right,
And gradually started scaling up the technology.

Berkeley Lab 2006. 0.2L

Amirabad High School 2010. 100L

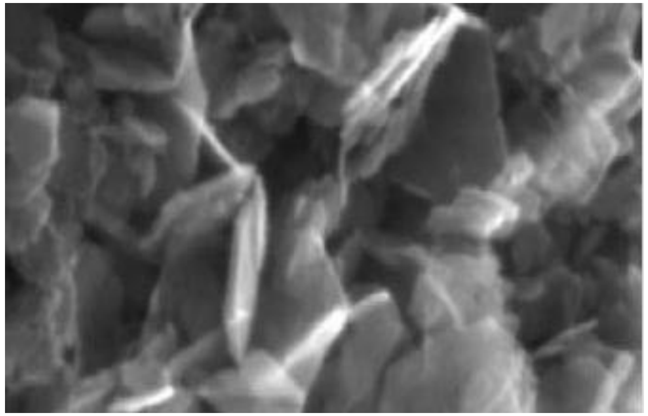
We scaled up the technology carefully, testing each scaled up stage, identifying and overcoming engineering problems and new ones arose at each scale-up.

2012
Jadavpur University
600L

2013
Dhapdhapi High School.
600L

2016.
Dhapdhapi High School.
2800 L

We pursued three tracks in parallel. (1) science research, (2) technology development and testing, and (3) education and outreach for technology adoption, understanding social and institutional priorities



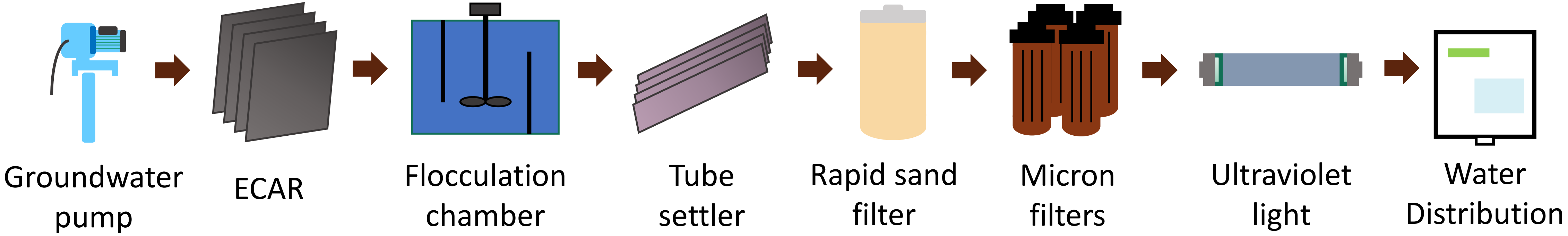
Fundamental Science

Technology Development

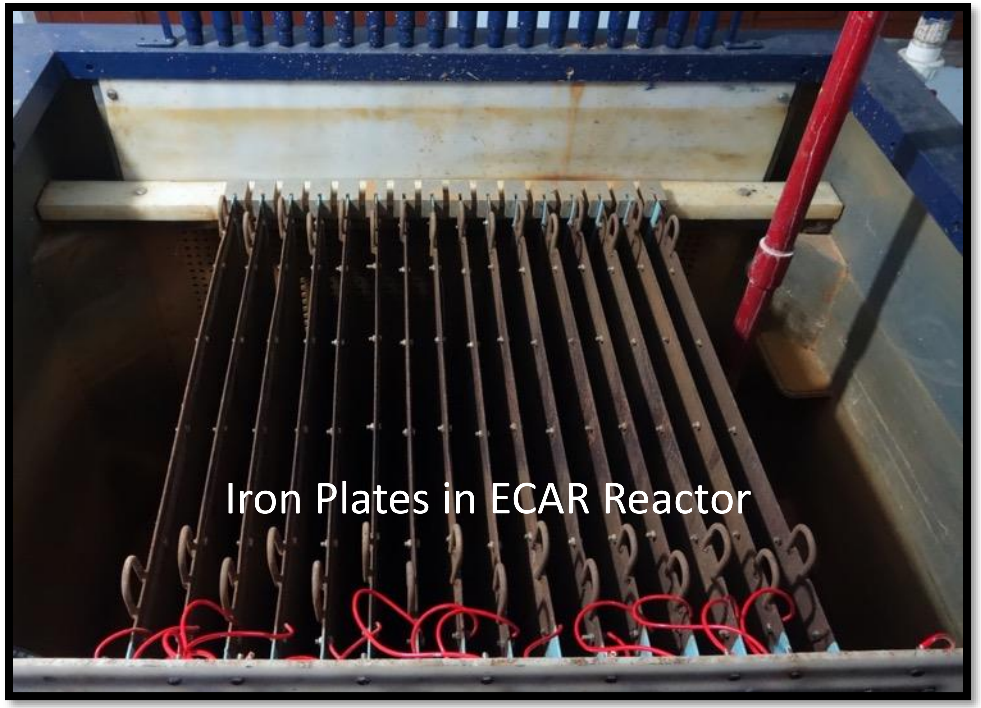
Education and Outreach

ECAR plant in Dhapdhapi

Process flow schematic (below)




ECAR Reactors

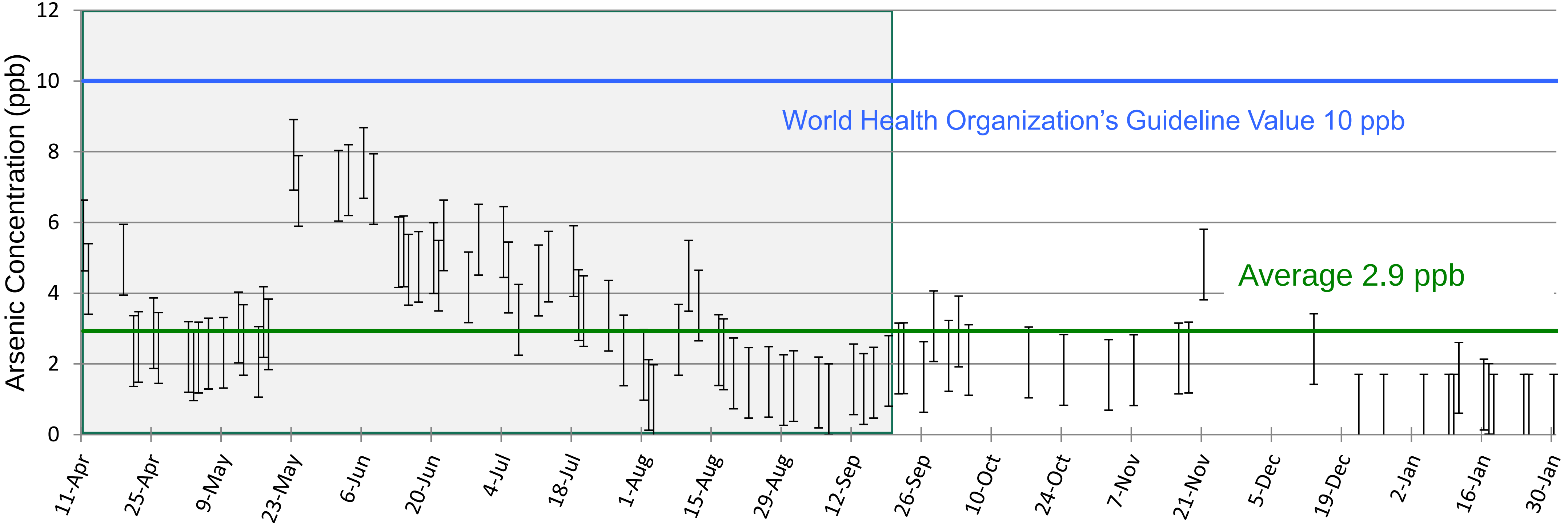

Iron Plates in ECAR Reactor

Field Site is at Dhapdhapi High School, outside Kolkata, India
Pilot Plant designed to treat 10,000 L /day.   Consumables cost: 1/20 cent/L.

2016.
Team photo in front of the two 1400L reactors at the field site in West Bengal.

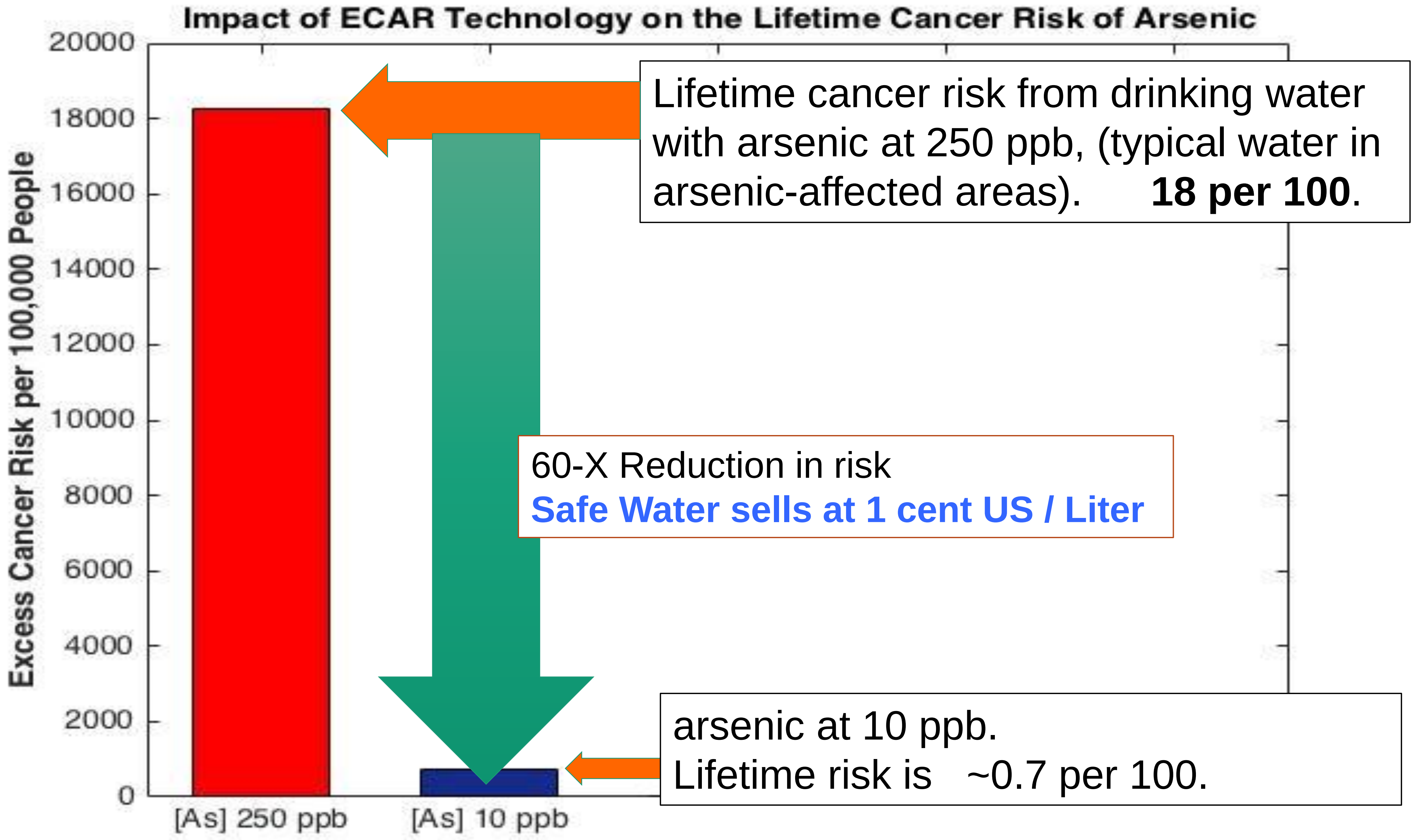
ECAR reduces Arsenic from groundwater to safe levels

Initial Arsenic Concentration **252 ± 29 parts per billion (ppb)**



Arsenic in treated water. April 11, 2016 to January 30, 2017.
Dhapdhapi High School, West Bengal, India

2017. Students and staff use electronic cards to access safe water from water dispensing kiosk



Impact of ECAR Technology on the Lifetime Cancer Risk of Arsenic
Excess Cancer Risk per 100,000 People
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
[As] 250 ppb
[As] 10 ppb
Lifetime cancer risk from drinking water with arsenic at 250 ppb, (typical water in arsenic-affected areas). **18 per 100**.
60-X Reduction in risk
Safe Water sells at 1 cent US / Liter
arsenic at 10 ppb.
Lifetime risk is ~0.7 per 100.

So, again: what is the big picture takeaway for inventing, testing, developing, and maturing **truly new** technologies for the bottom 50% people?
(These NOT some spill-over technologies like Solar-PV, cell phones, and iris-biometrics).

Why are there very few **new** technology inventions that take root for solving the problems of the bottom 50% people?

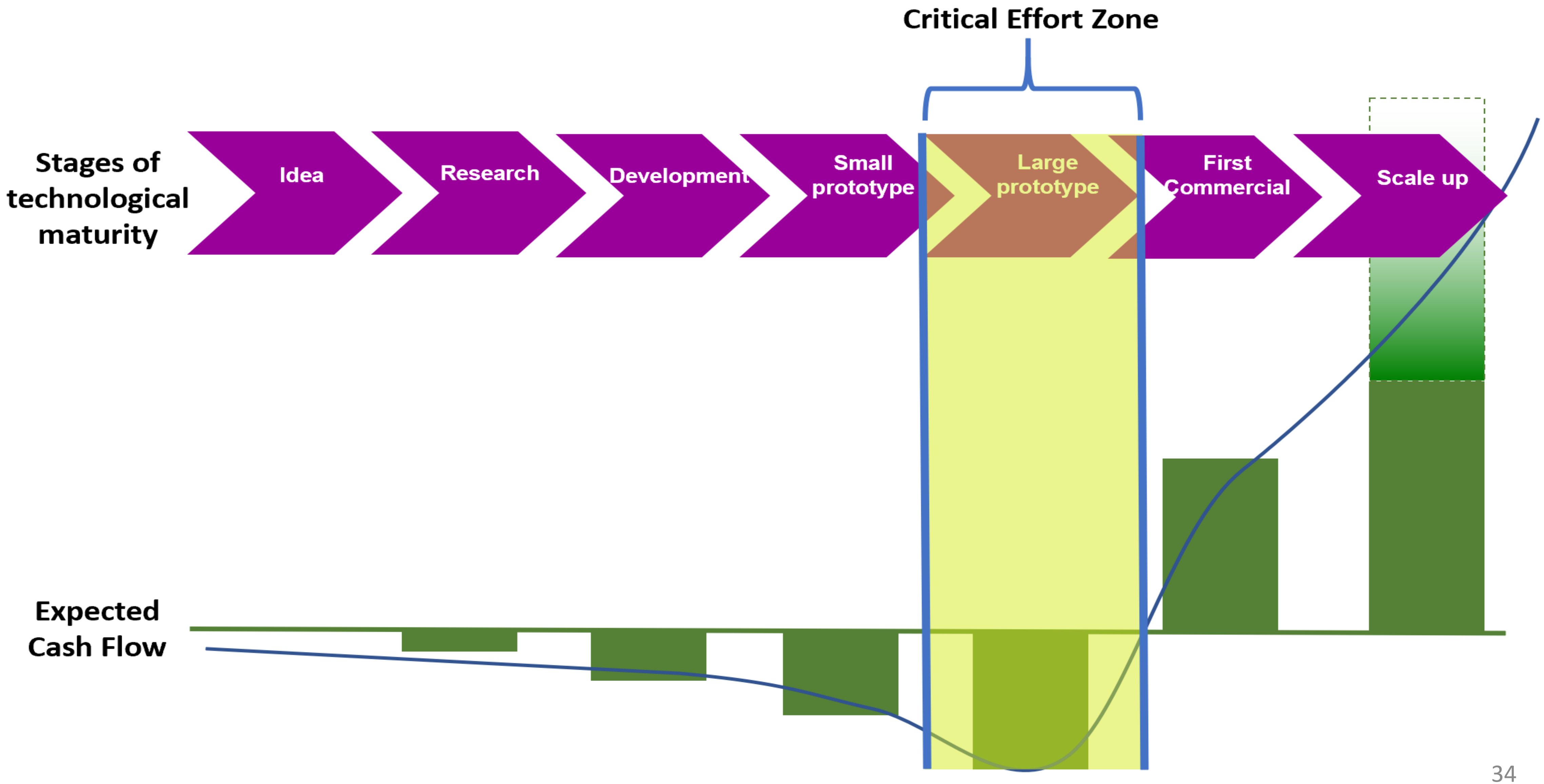
Based on our experience, my colleagues and I hypothesize two major failures and disconnects. (next slide):

TWO major failures and disconnects about developing truly new technologies for the poor majority.

1. Most engineers are left clueless in their formal education about the world outside their deep and narrow discipline. They lack the vocabulary to speak with other disciplines, and are unaware of even the geography of their ignorance.

2. There is inadequate appreciation, and inadequate preparation, for what it takes for crossing the **critical zone** in progression of a new technological solution.

Crossing the critical effort zone requires more than technology efficacy— it requires attention to social placement within the unique social and physical contexts



Strategies we used for crossing the critical zone (Our lessons learned)

(apart from finding funding, and building a high-performing team with high trust, a learning mind-set, and feeling safe about taking risks):

1 Designing a Community-Scale Technology

2 Increasing Economic Opportunity for Community Members

3 Bridging the Knowledge Divide

4 Ensuring Compliance with Local Regulations

Design for “User Experience” or Front End

(a) water-debit cards were distributed to the students and teachers. In Bengali, the cards say, “Let us protect our and our family’s health, by using arsenic-free water from arsenic-safe sources"

(b) a school girl that has just received her own card with spaces for name, grade level, roll number, and water card number,

(c) automatic water dispensing units installed for water delivery

(d) a water queue formed during first water distribution in September 2016.

I will stop here, so we have time for questions and discussion.

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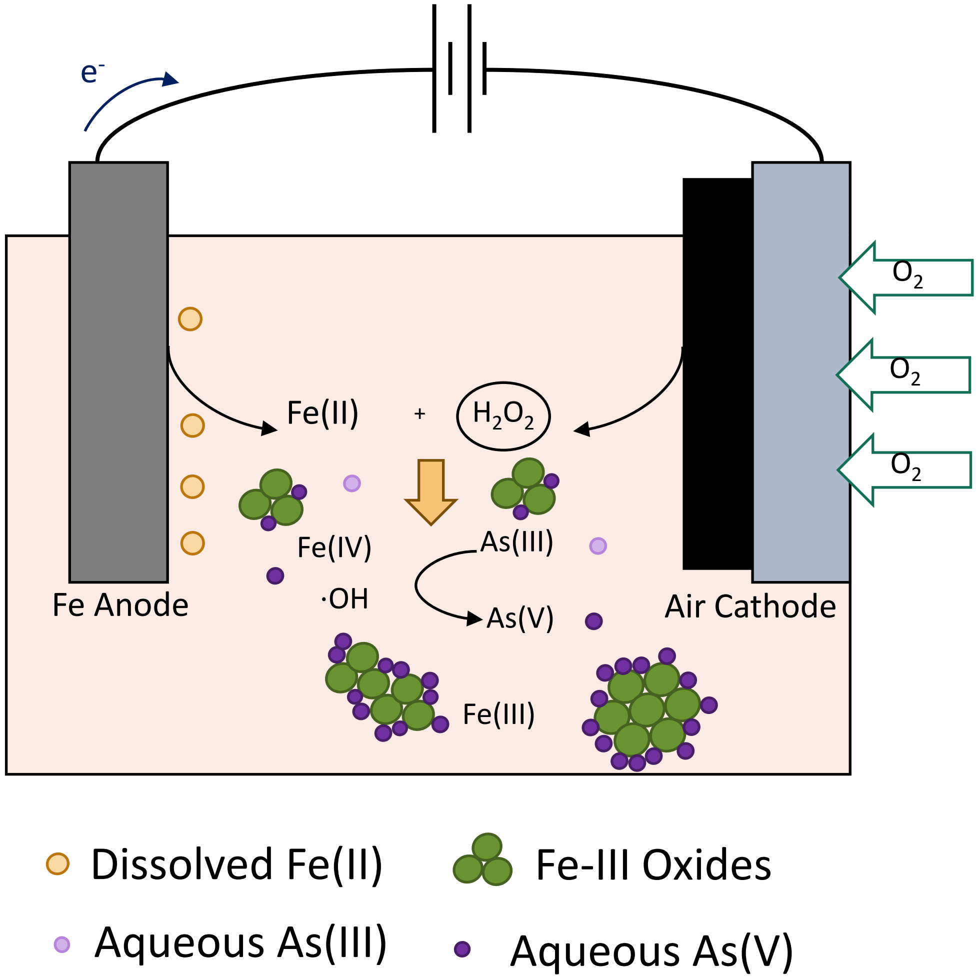
A few slides on our current technology work follow.

Next generation ECAR: Air Cathode **Assisted** Iron Electrocoagulation (ACAIE)



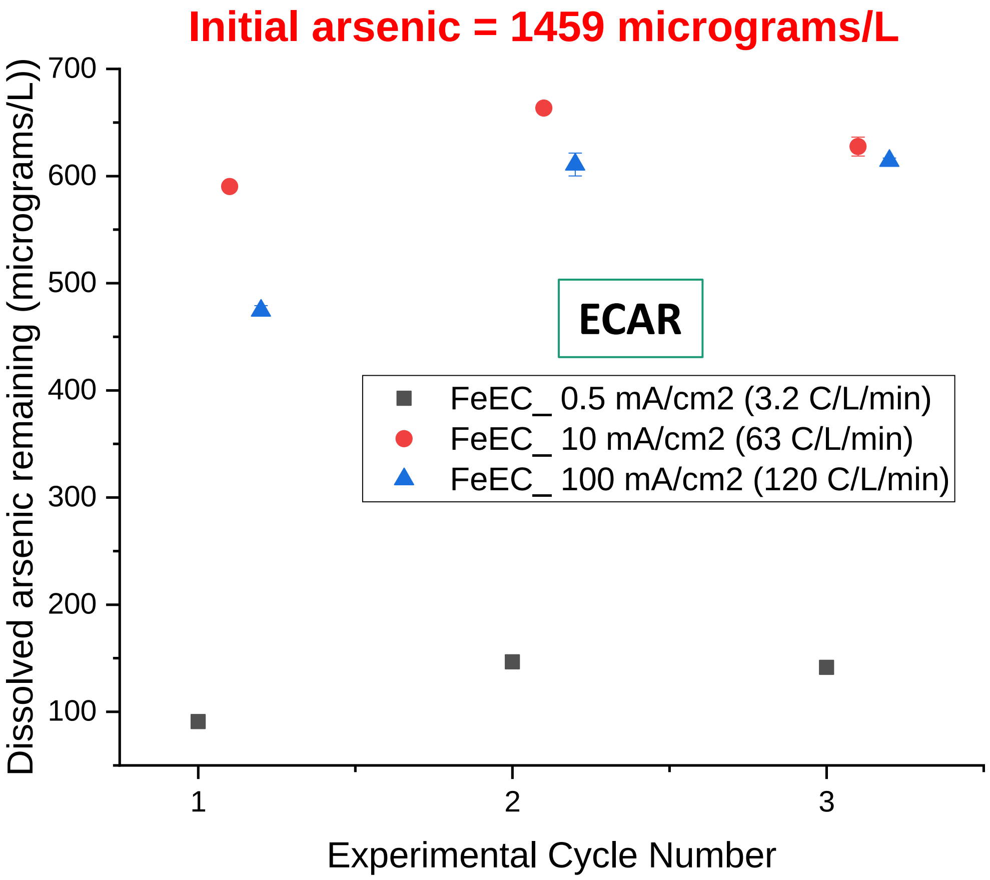
Anode: $\mathrm{Fe(0)} \rightarrow \mathrm{Fe}^{2+} + 2\mathrm{e}^{-}$

Cathode: $2\mathrm{H}^{+} + 2\mathrm{e}^{-} + O_2 \rightarrow \mathrm{H}_2O_2$

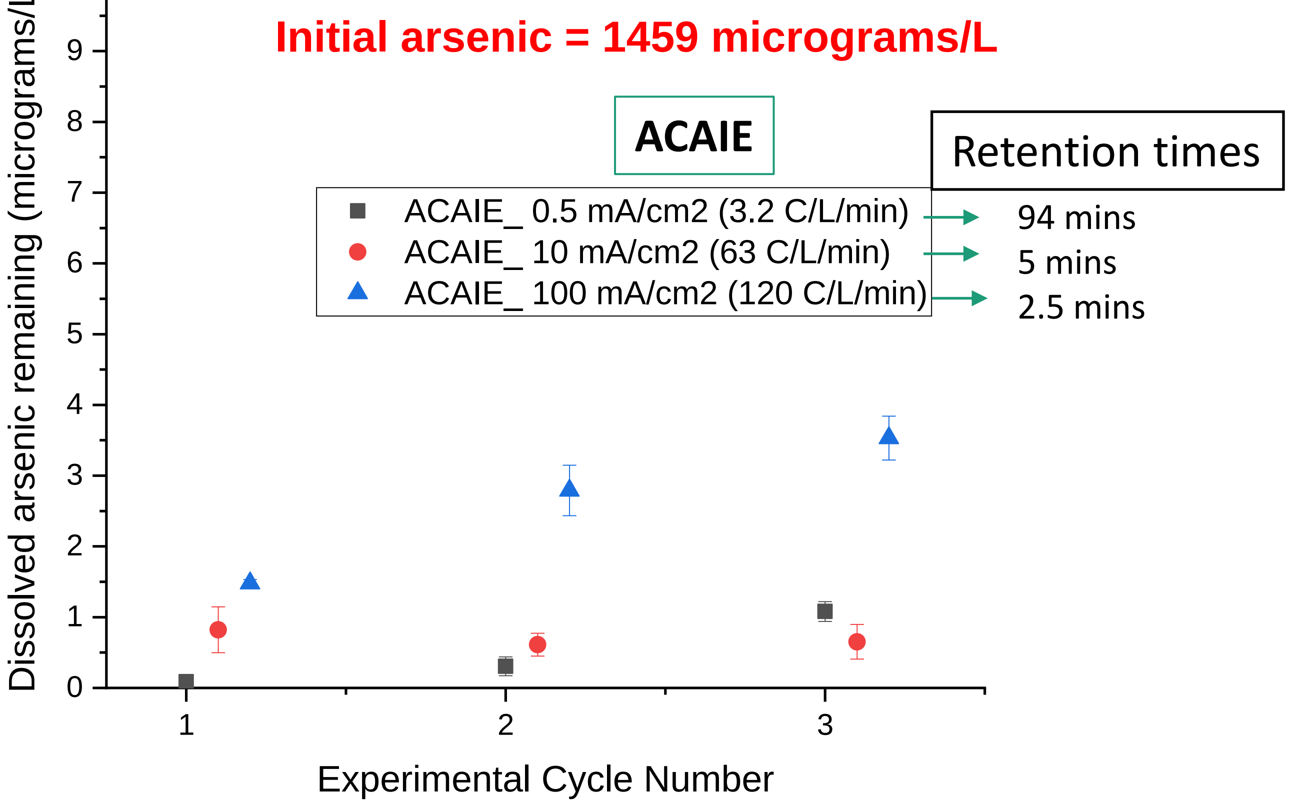
H_2O_2 reacts with Fe(II) ~ 10,000 times faster than O_2, to form Fe-III oxides, and also oxidizes As(III) to As(V)

Much faster reaction kinetics makes possible high flow rates!

Compared to ECAR, Arsenic removal is extremely efficient in ACAIE at identical operating conditions



Note different scales on Y-axes

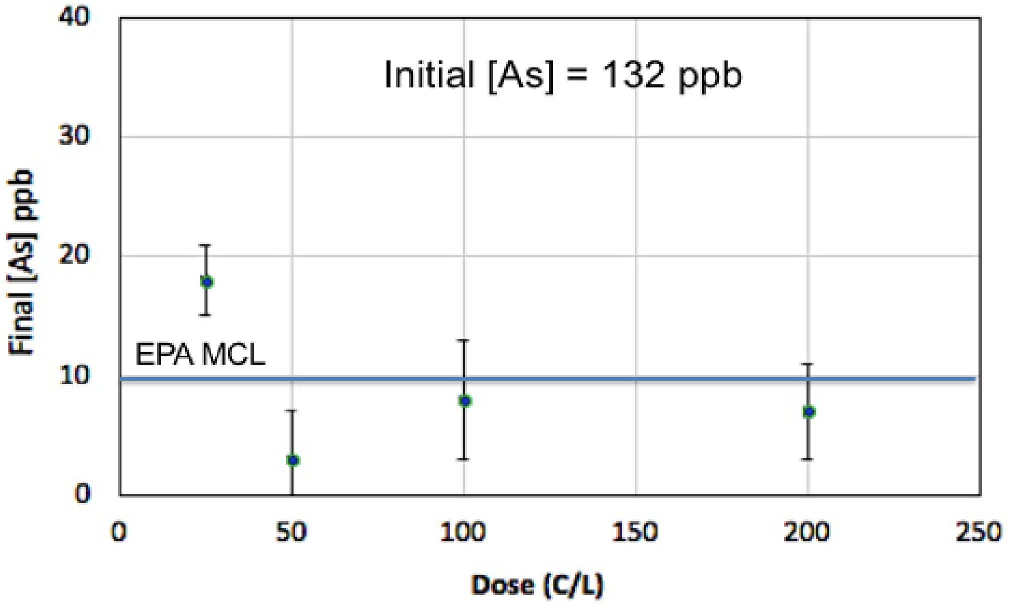


Initial Arsenic (As(III)) = 1460 ± 70 µg/L, Synthetic Bangladesh Groundwater (pH 7), Total Fe dose = 300 C/L or 87 mg/L

Current work: Field test of ACAIE with stackable design at low-income rural California site

Goal: Build and test ACAIE stacks in the field with real CA groundwater containing arsenic

Task 1: Demonstrate successful remediation of arsenic in samples of ash-pond water with our well established ECAR.



Task 2 (ongoing): Design, build, and test a high-throughput ACAIE rack, per industry needs.

60 LPH ACAIE system