Title
Evaluating Different Commercial Forms of Carbon as Cathodes in Air-cathode Assisted Iron Electrocoagulation (ACAIE) of Groundwater for Arsenic Removal

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Stopping Arsenic Poisoning in India

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1. Introduction and Overview

The World Bank defines absolute (i.e., near-destitute) poor as those who earned less than USD $1.90 per day in PPP (Purchasing Power Parity, in 2015) (Katayama and Wadhwa, 2019). At that time, there were 736 million people on the planet in absolute poverty. Of these, 24% lived in India (Sanchez-Paramo, 2020).

It is imperative to address problems that affect the poor by inventing, developing, testing, and scaling up new technologies (elaborated further **in Chapter 2 of this book**). Often these problems are unique or especially intense to those in poverty. Efforts to solve the problems with novel technologies, unless scalable and unless they take root in the local social system, are doomed to remain small one-off examples (see an excellent critique of such approaches in Rybczynski, 1991(Climate & Weather Averages in Kolkata, West Bengal, India, no date)). The technologies to address many of these problems are typically not spill-over technologies (such as solar-PV, or mobile phones), but rather those which are targeted to their specific needs. If the world fails to respond to these needs, new technologies may continue to increase the divide between the rich and poor in the coming years, as suggested by the Human Development Report (Conceição and United Nations Development Programme, 2019).

An effort to solve one urgent problem afflicting hundreds of millions of these people is described in this chapter. The period covered is from its beginning in 2000 up to its status in 2019.

This technology intervention aimed at helping to end the arsenic poisoning of about 200 million people who drink groundwater contaminated with naturally occurring arsenic, at concentrations above its maximum contaminant level (MCL) in drinking water. MCL levels for various contaminants in drinking water are recommended by the World Health Organization (WHO) and set by National Governments. The MCL for arsenic in drinking water is 10 parts per billion (ppb, for water contaminants, 1 ppb is 1µg/L). Millions of people are consuming water with arsenic at 10, 30, or even 60 times that level, resulting in disastrous health consequences due to chronic arsenic poisoning.

The trajectory of this technology intervention has many threads, and a simple way to organize the developing story is to present all the threads in parallel, chronologically. However, the multidisciplinary nature of the intervention, and the parallel nature of the threads, make a simple chronological organization difficult to follow. The authors have therefore tried to balance two perspectives to view the trajectory more comprehensively: chronological and disciplinary. It is imperfect and we authors hope the reader will forgive us for that imperfection.

About 250 individuals, and about 20 organizations have made vitally important contributions to this effort. This chapter is written as viewed through the eyes of only three of these individuals, and we are aware that the other views may be somewhat different, emphasizing different aspects of the work, and with different perspectives. We take responsibility for our inevitable blind spots and distortions that result from our limited viewpoints.

Beyond this chapter, the three most relevant papers for further reading are Gadgil *et al.* 2012, Amrose *et al.*, 2013, and Hernandez *et al.* 2019.

2. Problem Definition

2.1 Arsenic as Development Challenge

The right to clean drinking water was recognized as a basic human right by the United Nations (UN) General Assembly Resolution 64/292, in 2010 ('Human right to water and sanitation', 2020). However, UNICEF and the WHO recently noted that much more progress is certainly needed, given that 2.2 billion people globally still lack access to safe drinking water (*WHO Newsroom*, 2019). As part of the Sustainable Development Goals (SDGs), and specifically SDG 6, the UN has set the target of providing affordable, accessible, and safe drinking water for all by 2030 ('Sustainable Development Goals', 2020).

An estimated 200 million people worldwide are exposed to arsenic contaminated drinking water (Naujokas *et al.*, 2013; Minatel *et al.*, 2018). In the 1980s, much of rural India and Bangladesh switched from surface water, which was causing a high incidence of diarrheal disease, especially among children, to groundwater extracted with hand pumps. To prevent gastrointestinal illness, tens of millions of hand pumps were installed (Nordstrom, 2000).

However, prior to widespread tubewell installations, the groundwater had not been tested for the presence of arsenic. Signs of chronic arsenic poisoning were first discovered in the 1980s in West Bengal, which led to the first diagnosis of arsenicosis in Bangladesh in 1993 (Ghosh and Singh, 2009). Further investigations and measurements in the 1990s led to the discovery that the groundwater in Bangladesh and adjacent parts of India contained concentrations of arsenic far above acceptable levels. In 2000, the WHO called the situation the "largest mass poisoning of a population in history" (Smith, Lingas and Rahman, 2000). Recent studies have pointed to higher levels of arsenic in groundwaters in many parts of the world, particularly the US, Mexico, Argentina, Nepal, Vietnam, Cambodia, the Philippines and China. (Wang and Wai, 2004; Karagas *et al.*, 2015). EAWAG researchers have published a global map highlighting regions of the world with high levels of arsenic in groundwater (Amini *et al.*, 2008).

Chronic exposure to toxic levels of arsenic soon became apparent in the relevant populations, as hyperkeratosis, leading to skin lesions, ulcers, gangrene and amputations, neuropathy, and internal cancers, as well as low IQ in exposed children (Wasserman *et al.*, 2007; Ahmad and Bhattacharya, 2019). Tens of millions of the rural poor in afflicted regions have no viable alternative but to drink groundwater with toxic levels of arsenic.

Arsenic is tasteless, colorless, and odorless, and testing for arsenic is expensive and cumbersome. Arsenic chemistry is complex -- in contaminated waters arsenic occurs in two different oxidation states (As(III), and As(V)), with each oxidation state behaving differently (Smedley and Kinniburgh, 2002). As(III) is more mobile and harder to remove through adsorption mechanisms because of its neutral charge at circumneutral pH. Furthermore, co-contaminant ions commonly found in groundwater (e.g. phosphate) compete for the same binding sites (Roberts *et al.*, 2004) that aim to capture As(III) and As(V), further complicating arsenic removal, particularly because the WHO's recommended MCL of arsenic in drinking water is only 10 ppb. Arsenic concentrations of 250, 500, even 1,200 ppb are found in groundwaters of Bangladesh and Northern India.

Cancer risk assessment models predict that for a population of 100,000 people drinking water at 10 ppb arsenic over their lifetime, there will be 700 cases of excess internal cancers. Internal cancer risk rises linearly with arsenic concentration at these values, so for example, consuming 250 ppb arsenic in drinking water will result in 25-fold increase in excess internal cancers than consuming drinking water with 10 ppb arsenic (National Research Council, 2001; Smith *et al.*, 2002; *U.S. EPA. IRIS Toxicological Review of Inorganic Arsenic*, 2010; *U.S. EPA. 2018 Edition of the Drinking Water Standards and Health Advisories Tables.*, 2018).

Although internal cancers eventually lead to death, there are also high economic costs to households of those who lose arms or legs to amputations from gangrene. This cost is due to loss of their income and the costs of hospitalizations and medical costs. There are also high social and psychological costs for the affected individuals who were considered respected bread-winners but are then perceived as a burden on their family, or socially ostracized (Chakrabarti, 2017; Rahman *et al.*, 2018). An analysis of economic benefits of arsenic removal from groundwater used for drinking has been presented for the Indian state of West Bengal by Prof. Joyashree Roy in 2008 (Roy, 2008).

Even for a community exposed to arsenic in their drinking water, the health burden of arsenic falls disproportionately on the poor. This is due to their lack of access to timely health care, poor nutritional status leading to a higher susceptibility to negative health impacts, lower likelihood to afford treatment, and lower likelihood to be educated about arsenic and its risks. Furthermore, women and girls are the most highly impacted, with instances of women and girls who show signs of arsenicosis being socially ostracized, rejected by their communities and even rejected by their families (Brinkel, Khan and Kraemer, 2009; Das and Roy, 2013).

Technologies that can remove arsenic from drinking water are indeed available. However, resource-poor communities have inadequate technical, managerial, and financial capacity ("TMF Capacity" see US EPA, 2017. Historically, well-intentioned groups, often funded by charitable donations, have installed household or community-scale arsenic-remediation technologies in rural communities. In India, these are called Arsenic Removal Units (ARUs). In almost all cases, the ARUs are installed for free. However, in most cases, the installers leave the community without a clear social organization of responsibility for maintenance and repairs, or in some cases, without even leaving clear instructions. Many times, the consumables and replacement parts were too expensive for the community. Thus, the existence of effective technologies has not translated to solving the arsenic problem. This suggests the need for an effective and affordable arsenic-removal technology that is robust and integrates with its successful social embedding for long-term sustainability. This vision challenged a group of researchers in Berkeley to create an innovation that sustains over the long-term and meets the above criteria.

The Murshidabad district of West Bengal, located on the Indian side of the border with Bangladesh, is one of the poorest and worst arsenic-affected poor regions of West Bengal. In his doctoral research in applied economics, Abhijit Das studied the fate of recently installed ARUs in rural parts of Murshidabad district. Das visited and tracked the ARUs as they were being installed in Murshidabad villages. There was some expectation that some of the ARUs weren't working well in the field -- that is why Das selected this to be his research topic. However, Das found that an astonishingly high fraction (nearly 95%) of ARUs in his study sample failed within one year of installation (Das, Roy and Chakraborti, 2016) (Fig. 5.1). All of the ARUs studied had incorporated sound arsenic removal technologies that were effective at removing arsenic in laboratory settings. However, the failure rate in the field was astonishingly (and embarrassingly) high! Another study, this time focused on the functioning ARU units, found that only 50% were regularly being used by the local population (Inauen *et al.*, 2013).

Fig. 5.1 Arsenic Removal Units (ARUs) in Murshidabad District of West Bengal, India. Panel a), a working ARU, (typical for 5% of installed units at 1-year after installation). And, Panel b), a defunct ARU, (typical of 95% of units at 1-year after installation)

The technologies did not really fail. The *technologists* had failed. The implementing agencies had considered the problem solved as soon as the ARUs were installed (Das and Roy, 2013). The high risks of failure in a purely top down approach to arsenic mitigation are discussed and analyzed in detail by (Chakrabarti, 2017). The systems were unsustainable: financially non-viable, not embedded in the societal context, without incentives or social structures for their continued maintenance and repair, or without knowledge transfer to local community stakeholders about how vital the ARUs were for protecting their health. People didn't know how they worked or why it was important to keep them working. Towards the end of his doctoral research, Das documented and photographed ARUs -- most were used to tie cattle or goats, store hay, -- and had fallen in disrepair within one year. Thus, the fact remains that as more and more of the population in India comes to depend on groundwater aquifers for their drinking water supply, and more areas of India are discovered to have arsenic in their groundwater, the arsenic poisoning of tens of millions of Indians and Bangladeshis continues, almost two generations after the discovery of arsenicosis in populations of rural West Bengal.

3. Approach

3.1 Theory of Change

The Theory of Change describes the eventual long-term goal, and how the proposed activity (with its required inputs and outputs) may lead to outcomes, which in turn lead to the desired impact goals, under certain assumptions and favorable conditions.

The Theory of Change is an excellent way to draw out the assumptions and favorable conditions that may be different for different actors in the "activity", and which may not reflect the real world conditions (out of ignorance, wishful thinking, just hope, etc.). Spelling out the Theory of Change reduces the risk that these assumptions and conditions remain hidden, and challenges the team to come together with a sharper clarity about which assumptions and favorable conditions are necessary to make the desired impact. It also clarifies which activities might be irrelevant, and which could potentially be undertaken to reduce the risk of failure in reaching the ultimate desired goal. Theory of Change is a large domain of intellectual inquiry, primarily from the fields of project evaluation and monitoring. More can be found on the Wikipedia page and the references cited there ('Theory of change', 2020). For brevity, **Fig. 5.2** summarizes the Theory of Change for the project described in this chapter.

Fig. 5.2 The Theory of Change (ToC) that the ECAR team formulated for the project. The Inputs began in 2005 at UC Berkeley and by 2019 the team was continuing to put in efforts to see the project Outcomes.

3.2 Overview of Project Progression from Lab Bench to a Full-Scale Pilot

This section describes the coalition of partners, also called “the team”, that is working with an intention to create a sustainable solution to the arsenic crisis, planning from the start for the solution to have the capacity to achieve a scale commensurate with the immense scope of the problem. From the start, the members that formed the team believed and internalized the idea that this problem is so vast and complicated, that it is outside the abilities of any single narrowly focused group to solve, and that it would require a coalition of partners with high mutual trust and complementary subject-matter strengths. While technology innovation was seen as essential, it had to be undertaken within the narrow parameter space allowed by the requirement of financial viability and scalability of a sustainable solution -- it was critical for the coalition to have a deep understanding of the past failure stories and the cultural, institutional, economic and historical background of the ultimate customers and local community of users of the technology.

Throughout this chapter, the coalition’s funding support is described along with the other aspects of the work. This is because without funding, it is impossible to carry out technology innovation and cover expenses of travel, instruments, measurements, lab experiments, field-surveys, building prototypes, and conducting field tests. Here, only funding support that was successfully obtained is described. The team was always on the lookout for funding, and funding was often thin for impact-driven, highly applied research focused on solving problems of the poor -- and the success rate of proposals, or approaches to funders, was less than 20% overall. So, 80% of persistence and patient effort is not noted here, and will remain undescribed further.

The initial work on an electrochemical approach to solve this problem focused on science, technology, and innovation. That effort was undertaken by a research team at Lawrence Berkeley National Lab, and the Civil and Environmental Engineering Department at the University of California – Berkeley (respectively abbreviated as LBNL and UCB, both at Berkeley, CA, USA), led by Prof. Ashok Gadgil. That period covered the first five years of research, from 2005 to 2010. In these early years, Dr. Susan Amrose, first as a doctoral student and then as a Project Scientist (now a research scientist at MIT), worked closely with Gadgil to test and develop electrochemical approaches to arsenic mitigation. Initially, the team started with a 200 mL glass beaker on a bench top, removing only As(V) spiked in clean deionized water. The effort focused on deepening our understanding systematically until the Berkely team had designed a 100-L batch reactor and tested it successfully with a mixture of equal parts of As(III) and As(V) in a synthetic Bangladesh groundwater matrix, at an arsenic concentration approaching 1,000 ppb. Early research publications show how the Berkeley team gained knowledge little by little as they started (Gadgil *et al.*, 2012; Li *et al.*, 2012; van Genuchten *et al.*, 2012; Amrose *et al.*, 2013).

Funding for this effort first came from LBNL's Laboratory Directed Research and Development ("LDRD") program which provides small limited-duration innovation grants. The Dow Chemicals company had established a funding program at the business school of UC Berkeley called Sustainable Products and Solutions, which funded this work from 2009 to 2012. The Berkeley team also won funding from Phase 1 and Phase 2 of the US EPA's program called "P3" (for People Planet and Prosperity). Gaps and shortfalls were filled with Gadgil's Rudd Chair funds from UC Berkeley Campus. These resources allowed the Berkeley team to take the necessary technical risks that led to a steady increase in knowledge and confidence, to build up to the 100-L reactor.

Current PhD student Dana Hernandez is playing a major role in its ongoing development, along with postdoc and former PhD student Siva Rama Satyam Bandaru, engaged in this project since 2011. Numerous other doctoral students have been involved in the effort at Berkeley, and six of them (Amrose, van Genuchten, Delaire, Bandaru, Glade, and Hernandez) have made this work central to their dissertations, each making a very substantial contribution to advancing our knowledge. NSF doctoral fellowships which funded three of the six doctoral students have been of tremendous financial help in this effort.

The strong focus on creating a sustainable solution that goes to scale led Gadgil to approach Prof. Joyashree Roy, the founder and coordinator of the Global Change Programme at Jadavpur University (GCP-JU; Kolkata, India). Gadgil and Roy had known each other since 1997 - 1998 when Roy spent a year at LBNL as a Ford Foundation Postdoctoral fellow in environmental economics. GCP-JU is an interdisciplinary organizational unit in Jadavpur University and explores Global Change as it manifests itself in India, through the lens of applied social sciences, particularly, applied economics and sociology. In this coalition, UCB contributed technology expertise while GCP-JU provided critical insight into the socio-cultural, economic, and political factors surrounding arsenic mitigation in West Bengal. GCP-JU also provided access to a network of local stakeholders and influential leaders that allowed us to translate our research into impact. Last, but not the least important, GCP-JU brought credibility to the coalition effort, because JU is a highly respected university in India, officially recognized to be in the top ten public Institutions of Eminence, and is seen as a highly credible source of knowledge by the general population. In hindsight, the coalition members acknowledge that this multidisciplinary partnership was essential for the progress that was later achieved.

During 2011-2013, the team conducted field trials first of the 100-L reactor in West Bengal, that led to their increased confidence to design, build, and test an even larger prototype - a 600-L reactor - at a nearby school (Dhapdhapi High School). These field trials were also successful, even as new technical and social-embedding problems surfaced and were successfully dealt with (more on these later). The Berkeley side of the coalition won funding support for this work from UC Berkeley's Blum Center for Developing Economies, and the USAID-funded large multi-campus multi-year program, called the Development Impact Lab, also led from the Blum Center of UC Berkeley. During 2011-2013, the team was forced to change its field site, and start all over (as described later on) owing to unexpected external events. The team's technical and social research in these years is reflected in the corresponding publications (Amrose *et al.*, 2014; Gadgil *et al.*, 2014; van Genuchten *et al.*, 2014).

By 2014, the development of ElectroChemical Arsenic Remediation (ECAR) had reached a key fork in the road. The team had shown successful performance of the ECAR technology at the 600-L scale, both in the lab and in the field, at the Dhapdhapi school. However, they had not yet built or demonstrated the long-term technical effectiveness, commercial viability, and social acceptance of ECAR technology to the scale of a fully functioning demonstration plant. Doing that required more funding support. Most innovative technologies for the poor in the developing world wither on the vine and become obscure memories or dusty curiosities at this point in their development.

The list of the team's failed funding efforts will be skipped to focus on the successful one. The US and India governments jointly established in 2000 an autonomous foundation in India (IUSSTF) which funds and promotes technology transfer and commercialization from the US inventors and innovators to the sectors that India considers of critical importance. Each proposal requires participation from an Indian industrial partner of credible depth of technical, marketing and management expertise. The Berkeley and JU team searched for many months in vain for such a partner through multiple channels, which even included Gadgil giving lectures in India to Indian industry representatives with the help of the Confederation of Indian Industry (CII), all to no avail.

In 2012 January, Gadgil won the Zayed Future Energy Award, for Lifetime Achievement in the Individual category. At the awards ceremony, he met Mr. Jean Pascal Tricoire, the CEO of Schneider Electric who was there to receive the Zayed Energy Award that Schneider Electric had won in the Large Corporate Recognition category. Schneider Electric had just purchased a majority share in an Indian company Luminous Power Technologies, founded by Mr. Rakesh Malhotra. During their interaction, Mr Tricoire offered to introduce Gadgil to Rakesh Malhotra who might be looking to license a novel breakthrough technology to solve a key drinking water problem. It further helped that a VP of Schneider Electric in India, Dr. Satish Kumar, also personally knew Gadgil for over a decade. This entirely fortuitous circumstance led to an introduction of Livpure to the ECAR team. Within the year, in 2012 December, Livpure, JU and Berkeley jointly applied to IUSSTF for funding.

A lot of effort followed the application to refine the proposal to communicate the exact scope of work for meeting the due diligence by IUSSTF. Finally, in July 2014, the collaboration of the three parties was granted the IUSSTF award for a plant that will scale up and demonstrate the technology, to be completed within just two years. This changed the trajectory of ECAR from what otherwise would have been just a dead exhibit in the dusty museum of ignored technical curiosities.

In the meantime, in 2013, the Berkeley-JU team, led by Gadgil, won the top honor of the Prince Sultan bin Abdul Aziz International Prize in Water (www.PSIPW.org) – the Creativity Prize. Winning this top international prize for the ECAR technology innovation increased the team's credibility. Ultimately, the team believes that the recognition was pivotal in raising funds from the IUSSTF to build a demonstration water treatment and distribution unit at a rural school in West Bengal.

Since the team had only two years to design, build, and commission the demonstration plant, the team went back to the same fabricator on whom they had relied for the 600-L smaller project. This fabricator, Shri Hari Industries, is a small engineering company outside Mumbai, and their chief design engineer, with several years of design experience, had been personally interested in contributing to engineering innovation (Fig. 5.3). In close partnership with Berkeley researchers, Shri Hari Industries staff were able to rapidly iterate the design of the ECAR reactors with the Berkeley team to improve ease of manufacture, shipping, and operation, thereby significantly improving reliability and reducing capital costs.

Fig. 5.3 Ashok Gadgil, Narendra Shenoy (Chief Design Engineer of Shri Hari Industries), and Susan Amrose in November 2014, discussing the design details of the water distribution manifold for the two ECAR reactors then under construction.

Fig. 5.8 sketches the progression of the technology over a 12 year span. From 2016 onward, the ECAR full-scale pilot plant has been operating at Dhapdhapi High School in West Bengal India. An automated water dispensing system daily offers 1 L of arsenic-safe drinking water to each of 2,500 students and 400 staff-and-teachers free of cost, and offers the excess water (about 4,000 L) for sale to the surrounding community at a locally affordable price of less than 1 US cent per L.

Fig. 5.8 The progression of ECAR, beginning as a 200-mL beaker, with its development to 100-L and 600-L prototypes, and finally scaled as two ECAR reactors of 1,000 L each. The 2005 photo shows Ashok Gadgil and Susan Amrose at the Berkeley Lab. The 2011 photo shows Ashok Gadgil and Siva Bandaru around the 100-L prototype at Amirabad High School. The 2012 photo shows Siva Rama Satyam Bandaru, Susan Amrose, Caroline Delaire, Ashok Gadgil, Paramitha Chaudhuri, Sudipta Ghosh, Suman Chakraborty, Chandan Bose, Amit Dutta, Peter Kuin, Sayantan Sarkarstanding around the 600-L prototype at Jadavpur University. The 2017 photo shows Susan Amrose standing next to one of the two reactor tanks at Dhapdhapi High School.

The Berkeley-JU team was excited to partner with Livpure. Livpure was a large and vibrant water-treatment company, ranking one of the top three in the booming market of under-the-sink reverse osmosis (RO) units for urban Indian households. Livpure had an excellent understanding of the Indian business and regulatory environment, and a strong marketing team, with thousands of distributors supporting their RO products. The Berkeley-JU team hoped and expected that Livpure would advise and influence the direction of development and maturation of the technology during the demonstration plant stage. If the demonstration plant was successful, then they expected that Livpure would bring capital, sophisticated marketing, and engineering resources to further improve the engineering design and implement a wide-scale solution to the arsenic poisoning problem. This was based on Gadgil's experience with WaterHealth International (more in the following section). Conversely, Livpure expected a prompt flow of funds from the government for building more ECAR plants. For various reasons, these expectations turned out to be misaligned, and the subsequent technology diffusion did not occur as originally hoped.

The outcome was that technology maturation was primarily driven by members of the Berkeley-JU team, who poured their hearts into ensuring that the system worked well technically, economically, and socially, and were pleased to demonstrate its robustness, effectiveness, and market acceptance. However, there has been little interest from the industrial partner in expanding plant capacity, adding additional customers to water delivery, or replicating this plant to other locations. Yet, they did not abandon the plant, and continue to operate and manage it, test the water monthly, and conduct the water sales. They have continued to get the product water tested monthly by a trusted third-party lab, and have posted the results outside the door of the ECAR plant for all interested parties to see. This has been vitally important to maintain the trust of the community members that come daily to purchase water from the plant.

4. Implementing the Approach

This section describes the team's process of understanding and iterating the arsenic problem in West Bengal, creating the ECAR innovation to address it, iteratively implementing the innovation, and adapting the innovation to scale and for other contexts. The iterative nature of the invention innovation process unfolds in primarily three different ways: (1) the technical solution itself is iterated to make it work better, rejecting some aspects of earlier designs, (2) the understanding and framing of the problem and its boundary conditions is adjusted through interactions with potential customers, iteratively improving the problem definition, and lastly, (3) the demands placed on translating the scientific understanding into a specific hardware and operating protocols also become better understood, and are iteratively improved during the field experiments and field testing. In all this effort, the core strength of the team comes from integrity, candor, and an attitude of willingness to learn -- a learning mindset.

4.1 Prior Experience

4.1.1 Water Health International

The team's conceptualization of the arsenic problem was shaped, from the start, by Gadgil's experience in microbial drinking water treatment, particularly in India. In 1995, Gadgil had invented UVWaterWorks, a device that used UV light to disinfect drinking water at a rate of 15 L per minute, at a cost of USD 0.05 / 1000 L, suitable for small community-scale deployment. Although the technology was low cost, robust, low maintenance, and had a high positive impact on health, creating real impact had required a market-based business model in which clean water was sold at a locally affordable price.

A startup company, WaterHealth International (WHI), was able to leverage the extremely low cost of water production from the technology to maintain a locally affordable price point while making a profit. Other good practices of WHI included ensuring good quality control, spending the necessary funds for media outreach, marketing, and getting support of local village-level non-profit organizations for local health education about diarrheal disease and microbial pathogens in water.

Furthermore, achieving a high volume of sale of the purified drinking water was tied to their financial viability. Therefore, the company was incentivized to continue with relevant public health education, and to continue to gain the public's trust that the water was high quality (through monthly third-party testing of the water they sold, and publicly posting and disseminating the resulting certified data). Gadgil knew from this experience in India that if someone's livelihood and profit depended on the continuous provision of arsenic-safe drinking water on a day-to-day basis, then that person (or organization) would not let the technology fail for lack of proper maintenance. This shaped the team's framing of the technology innovation to focus, not just on something that could produce arsenic-safe water, but on something that could do so inexpensively enough to generate a small profit while selling the arsenic-safe water at a locally affordable price.

4.1.2 Arsenic in Bangladesh

Gadgil had started research on affordably removing arsenic from drinking water at Berkeley in 2000. The team initially focused on an innovative approach to build a core-and-shell particulate adsorbent for arsenic, called Arsenic Removal Using Bottom Ash (ARUBA). The ARUBA's core was based on extremely low-cost bottom ash particles (10 micron diameter) from coal-fired power plants, which Gadgil obtained from India, and invented a process to coat them with ferric hydroxide. The powder did remove arsenic successfully from contaminated groundwater and the waste passed the US EPA's Toxic Characteristic Leachate Protocol (TCLP; a test to determine if waste is acceptable for disposal in municipal landfills in the US). However, the adsorbent proved to be inexpensive only when it was deployed at large scales, on the order of tons per day. In 2005, the team had started to explore another technology pathway that could be affordable and profitable at both small and large scales, while enabling a company to survive and grow through the expected slow growth of the arsenic-safe water market.

The ARUBA research and field tests continued through 2008, and the team later published their findings (Mathieu *et al.*, 2010). Switching directions from ARUBA to a new electrochemical technology was the first pivot in the research direction. This new technology, called ECAR (Electro-Chemical Arsenic Remediation) (Fig. 5.4) used a small amount of electricity to remove arsenic from diverse groundwaters in a way that is highly effective, low-cost, produces little arsenic-laden waste, and requires minimal supply chain development of readily available materials, among other factors.

Fig. 5.4 Schematic of ECAR process with iron electrodes. Anodic dissolution of Fe(0) from the iron anode releases Fe(II) in the bulk solution. This Fe(II) reacts with dissolved oxygen (O_2) to form insoluble Fe(III), and simultaneously generates reactive intermediates (like Fe(IV) and *OH), that oxidize arsenite, As(III), to arsenate As(V). The Fe(III) captures the As(V) and then the aggregated precipitates settle out of solution. The letters "ZLD" on the outlet water highlight that this process is Zero Liquid Discharge, a coveted goal of process engineering.

There was another important shift in the team's thinking in the period from 2008 to 2010. Throughout the development and field testing of ARUBA, it had seemed logical to conduct field tests in the country most severely afflicted with arsenic: Bangladesh. The team members reached out to the premier engineering University in Bangladesh (BUET) which continues to offer excellent education in engineering. Team members met several times with UNICEF officers in Dhaka who oversaw UNICEF's programs to improve water quality, and with various officers of BRAC, the world's largest NGO, famous for its breadth and depth of work in Bangladesh. The team also met with the senior echelons of BRAC University and BRAC Bank. The most important and the most consistent take-away from all these meetings was that the arsenic problem in Bangladesh was intensely politicized. External agencies (UN, World Bank, British Geological Survey, and others) were blamed for the arsenic disaster, and they were expected to pay for arsenic-free water. There was a highly politicized division of public opinion, with a large group of opinion leaders who were hostile to any suggestion that arsenic-remediation should ever be part of a commercially viable enterprise. Thus, the only way to reach scale would be to work through a delivery model fully supported by either the government and / or an external aid agency. The team tried many times to obtain this support, or to find alternatives, but it was clear that this could not be achieved with the time and resources at the team's disposal. Right across the border, in the State of West Bengal, the problem was equally grievous, but there was no angry political battle being fought over who would pay, and no blame game. The team decided in 2010 to move all future work to India so it could fight on one front -- against arsenic -- and did not also have to fight on a second front -- the political front -- to get things done. Team members believe this was another key and important pivot that led to the success at Dhapdhapi in West Bengal six years later, in 2016. They believe this could not have been achieved in the highly contentious political atmosphere of Bangladesh.

4.2 The Amirabad Experience

With leadership from JU, the Berkeley-JU team reached out to numerous key stakeholders in India, and West Bengal in particular, to inform them of their planned work and to obtain advice and feedback. This included multiple levels of office-holders and experts in numerous organizations. Two key lessons the team learned through the process were (1) the critical importance of proper handling and disposal of arsenic bearing waste, and (2) the absolute necessity of reaching out to the local public through multiple channels of communication and contact over an extended period until members of the public became familiar with, and socially "normalized" to using the technology.

In 2010, the team selected a field site with the help of a local college teacher and his NGO contacts from the JU team, in the small town of Amirabad, in the district (roughly equivalent to a county in the US) of Murshidabad. This was the same district where, earlier, Das had conducted his doctoral research. Amirabad is a 6-hour drive from JU, so short trips and day-visits were impractical. Nevertheless, via a small local NGO known to the JU team-members, the team leaders approached the local high school (actually the Amirabad High Madrassa, or High Religious School), and were offered a classroom with electricity for conducting the field tests of the 100-L ECAR reactor, with plans for testing successively larger ECAR reactors. The 100-L reactor was first designed, built, and tested in Berkeley, then duplicated and tested in JU, and finally transported to Amirabad. For local outreach, the team held public community meetings and multiple meetings and discussions with school teachers explaining to them what the team was doing and why. This included explaining how mature technologies emerge from science (the progression in Technology Readiness Level (TRL)), since technology maturation research is an unfamiliar activity to most people (even in the US), and expectations of speedy progress continued to run far ahead of what the team could humanly deliver.

As a good faith effort to provide near-term relief, the team paid for a US-based NGO ("Project Well") to dig a protected dug-well on the school grounds. Project Well had given assurance that the well would be a good interim solution. It turned out that very quickly the well ran dry and no operational problem was addressed by the NGO or its local representatives. However, that was only the beginning of the team's troubles at Amirabad.

Although the team had moved the field research work from Bangladesh to West Bengal in favor of finding a less politicized situation, the team discovered the truism that "politics is everywhere -- once there are more than two people involved"! In 2011, elections were imminent. Various political factions and leaders who look for opportunities to strengthen support from their base, are often eager to promise a quick-fix technological solution to win the adulation and endorsement of their local constituencies. So, while the team was field-testing just a prototype, the leaders and communities expected immediate continuous flow of water service delivered to them by the research team. To counter these high expectations, the research team held various public meetings, and clearly stated their short term goals. They also met with multiple administrators to discuss the way forward for a long term solution. However, these efforts had limited impact. Given the past experience of multiple failed technology trials, the community was looking for quick and assured solutions. Meeting this expectation was not only scientifically unfounded, but also beyond the resources and capacity of the research team.

By the Fall of 2011, the field trials of the 100-L ECAR at the Amirabad school reactor had been a technical success (the background work and field test results are described, along with cost estimates, in Amrose *et al.*, 2013). Work was soon completed in Berkeley on the design of the next-iteration larger reactor, now 600-L, based on the technical lessons learned. By the Spring of 2012, the 600-L reactor, the 600-L settling tank, the gantry (a small mobile crane), and all related equipment had been moved to JU and tested successfully. It was time to find a large indoor space in the Amirabad school to accommodate all the equipment.

Initially the fieldwork was conducted with encouragement and support from the Amirabad school's administration led by the Headmaster, who was carefully neutral, pro-science and pro-research. Additionally, the Headmaster lived in Amirabad, and saw the beneficial implications for the community if the novel ECAR technology were to be successful. Unexpectedly (for the team), the Department of Education instituted their normal "rotation" of Headmasters from one school to another, which happens every few years, and our supportive Headmaster was rotated out. The new Headmaster lived out of town, in an area with safe drinking water. He was, from the start, a bit equivocal about allowing ECAR fieldwork in the school’s classroom. He was inclined to support the faction in the school teachers that began to vocally oppose the presence of the team on the school grounds in the absence the team offering a guarantee for providing safe drinking water supply. With increasing virulence, this group attacked the team’s honesty of purpose, and suggested that the team represented outsiders collaborating with others from a wealthy western superpower (the US), who were “exploiting” the school for their research. Some insight of this activity came, but too late, from the local NGO and their contacts at the JU side of the team. In hindsight, the team feels that the large distance (almost 7 hours each way by car from JU), led to inadequate communication from the team to dispel rumours. This all ended badly. In an extremely tense meeting in the summer of 2012 with the school Headmaster and a group of teachers whose screaming accusations he acquiesced in, the team announced its decision to pull out, leave the school site, restore the classroom to its original state and return it to the school. The team felt disappointed and angry, including at themselves. Much work to build social and political capital had been lost.

This led to two immediate consequences for the team.

The first and immediate consequence was the beginning of an internal process of reflection, discussion and review to try to understand what went wrong, what the team could have done differently, and what safeguards could have been put in place to avoid such a major setback. Team members were sure that given the intensity of the verbal exchange at the meeting, and the political situation at the school, the damage was beyond repair and pulling out was absolutely the right decision. In a few short years, after news of the success at Dhapdhapi reached the Amirabad school, the Headmaster and NGO there telephoned the team leader at JU several times asking the team to restart the work at Amirabad. However, given his complete lack of support for the field test in 2012, the team asked for the invitation to be made in writing before it would be even considered (he never wrote).

4.2.1 Assessing Failure

One reason the team’s effort fell victim to the local socio-political division and acrimony was the inadequate two-way formal communication between the team, the community, and the school’s opinion leaders. This communication was hampered by the long distance from JU to Amirabad, and absence of a formal mechanism for two-way communication. As a result, the impressions and expectations from the opposing faction of teachers did not surface and get corrected promptly. They operated under the growing belief that the research team was performing the work for some future financial gain from unseemly business profit, and that the school should see a mature technology delivering safe drinking water to the school within weeks or at most months from the start of the field test. This comprehension led to two major shifts in the team’s thinking: (1) the team must formalize agreements with fieldsite owners by creating a signed Memorandum of Understanding (MOU) that (although not legally non-binding) spells out the roles, responsibilities, and mutual expectations from all sides, and (2) the team needed to pay a lot more attention, and invest more effort in "managing expectations" of the field-site influencers and opinion leaders. When MOUs were created, a copy of the MOU would be given to each signee, so that it could be referenced in future discussions, and if further adjustments are made these would also be in writing and signed by all parties.

A second consequence of the blow up at Amirabad was the urgent requirement to find another field site to continue our work. The team decided to be more systematic than just finding friends of friends of friends to find the next field-site. A more rational and systematic approach was needed and implemented. The team followed the example of Harvey MacKay searching for a bank lender for his start up business, described in his well-known book "How to swim with the sharks without being eaten alive" (Mackay, 2005). Two team members were charged with visiting every school within concentric circles drawn with the JU Campus at its center; starting with the shortest travel radius (30 minutes), they kept on increasing the radius of the search after exhausting the schools in circles of successively increasing travel-time radii (30, 60, 90, 120 minutes, etc.). Their goal was to come back with a list of three different potential schools that each met the following criteria:

(1) Strong interest and support from the school administration in the effort
(2) Availability of infrastructure at the school (room, water, electricity)
(3) Presence of arsenic in the local water being used at the school
(4) Reasonable travel time from JU to the School

Table 5.1 The data for top three schools for selecting site for the demonstration of the ECAR technology**.**

Fig. 5.6 Map with central location being Jadavpur University and its relative distance to promising school sites. As the bird flies, the distance from JU to Amirabad (the first school partner) is 195 km as the straight-line distance, but time to travel is 6 hours and 45 minutes by car. The travel time to Dhapdhapi is only about 2 hours and 15 minutes.

In about a month, the team (of Das and Bandaru) brought a list of three strong candidate schools (Table 5.1), which the team discussed and ranked. The highest weight was given to strong support from the school administration. The top ranked school, Dhapdhapi High School, was a mere ~2 hour drive from JU (Fig. 5.6), well connected also by railways/public buses, had 2,500 students and about 250 ppb arsenic in the local groundwater that supplied the school. A small municipal pipe delivered a small amount of potable water intermittently; but the daily delivered volume was completely inadequate for the daily needs of 2,500 students (in the age group of 11-19 years) and 400 teachers and staff. Another nearby school ranked equally well; however, it was a girls-only school. After burning their fingers at Amirabad with accusations of unethical motivation, the team favored the co-ed school at Dhapdhapi. There was less risk of another messy accusation, particularly because the field engineers who would spend many months at the school would include both men and women. Thus, after following a systematic and rational approach, the team found the second field site within just a few weeks, and the work was able to proceed.

4.3 The 600-L Prototype

Prof. Joyashree Roy, leader of the JU team, reached out to the Dhapdhapi higher secondary school administration and was warmly received by the Headmaster. This time the team took care to have a clearly written MOU with the school administration, which was countersigned and approved by the Secretary of the School's Governing Board. This MOU proved to be a lifesaver during the few occasions of misunderstandings and differing mutual expectations that inevitably arose. This is an important point. In a community-scale technology trial, not only the official hosting agency but also the community get involved, often with incomplete or incorrect information. Therefore, careful attention to managing community expectations becomes very important. The team went through the process of holding community outreach meetings, including open-mike meetings with school teachers and staff, as well as meetings with a pair of student representatives from each class. In parallel, the Berkeley team had completed the design of the 600-L reactor. This reactor, along with its settling tank and gantry (a kind of small crane on tracks) was fabricated at Shri Hari Industries, in the presence of field engineers from Berkeley. Then the reactor, gantry, and settling tank were all shipped to JU for re-assembly and testing by JU's faculty members in Environmental Engineering, who joined the JU team in 2011.

After successful testing at JU Environmental Engineering Lab in the summer of 2012, the 600-L system (which was previously meant to go to Amirabad), was then moved to Dhapdhapi High School, where the administration provided a dedicated classroom for the field test (Fig. 5.7). While 600-L was too small to serve an entire community, or even the school, it was a good step up from the small 100-L device (about the size of a large trash can) previously tested at Amirabad. The next step would be a device that would deliver approximately 6,000 to 10,000 L/day. This capacity was seen as optimal, based on prior experience and calculations, for the sweet spot to obtain good economies of scale while meeting the demand of the local community members who would have to walk to the plant to pick up the water. For larger throughputs, the coverage territory becomes too large, and potential customers are generally unwilling to walk the long distances back to their households carrying water. This was another lesson from Gadgil's WaterHeath work.

Fig. 5.7 Professor Gadgil discussing the chemistry of ECAR with Siva Bandaru, at that time a field engineer in the Berkeley team. Dr. Susan Amrose is on the right. This is in the classroom of Dhapdhapi High School allocated for the 600-L prototype trial in 2012.

The field test of the 600-L device ended successfully (results were published as a journal paper (Amrose *et al.*, 2014)). Soon the team received the exciting news that the IUSSTF grant was being released in July 2014 to enable demonstration of a full-scale pilot of a community ECAR plant.

The team took a calculated risk by significantly changing the design of the 2,000-L reactors compared to the 600-L reactor without going through another pilot study at the 600-L scale with the new design. The 2,000-L reactors incorporated completely changed hydraulics, and a more sophisticated train for processing the product water. This was based on the team's confidence in their scientific understanding, and also the very limited window of available time (2 years).

4.4 Scaling Up and Commissioning the Demonstration Plant

Learning from weaknesses observed during long-term performance of the 600-L reactor, the electrode layout and hydraulics of the reactors for the 10,000 L per day (LPD) demonstration plant changed again, though the core chemistry remained the same. The reactors were again designed in Berkeley and built in Mumbai by the same trusted small fabricator, Shri Hari Industries. The Berkeley team placed two of their engineers in Mumbai for daily supervision and participation during the fabrication. The 10,000 LPD design comprises two identical reactors, each capable of treating 1,000 L of arsenic-contaminated groundwater per batch. The transfer of water from each reactor tank to the settling phase occurs alternately, operating as a semi-batch process (Fig. 5.10). As the water in the second tank is transferred, raw water fills in the first reactor tank for the next batch of treatment. There was no possibility of testing the reactors in Mumbai or at JU due to the size. However, by then the Berkeley team had developed high confidence in their understanding of ECAR reactor designs, so the reactors were transported by truck directly to Dhapdhapi.

Fig. 5.10 Treatment train at the Dhapdhapi Plant. Water treatment begins at 1) the ECAR reactors where electrolysis occurs of pumped up groundwater, followed by 2) flocculation and settling, 3) tertiary treatment consisting of a rapid sand filter, micron filters, and a UV light. An activated carbon filter is also seen in panel 3, but is not in use (nor necessary to ensure safe-drinking water, but was part of the pilot testing phase). Water is then distributed to students, teachers, and staff through 4) the water kiosk that contains four automatic dispensing units.

In March 2015, the two 1,000-L reactors arrived and were installed at Dhapdhapi High School. Civil work was also completed by Livpure on an external shed, built adjacent to the school, to house part of the system. Electrical upgrades were also completed for the school power supply to receive the additional 10 kW power needed by the ECAR plant.

The team worked with officers of the State Pollution Control Board, and a reputed hazardous waste collection company to establish and get approval of the plan for safe sludge management and disposal. Livpure and the team coordinated to complete wiring, plumbing, and tertiary treatment systems for the full plant integration, as well as to conduct initial testing and troubleshooting. The first local operator was hired and trained. Maintenance equipment for the electrode plates was fabricated and tested.

Clean, arsenic-safe drinking water was first produced intermittently in mid-2015. However, no water was allowed for human consumption until the team had developed very high confidence in the plant operation. This confidence emerged by mid-September 2016, six months after plant operations began on a daily basis. During that time, the produced arsenic-safe water was discarded into the soak pit, much to the distress of some of the local stakeholders, who were left drinking arsenic-contaminated water while the team completed all testing.

The Government of India had certified several commercial labs (under the accreditation scheme "National Accreditation Board Labs" (NABL)) for conducting tests -- but not all NABL-labs were equally reliable, as the team discovered by paying them to test blind samples of calibrated arsenic solutions of known strengths. Throughout this period, raw and finished product water samples were air shipped to Berkeley for analysis, in addition to water quality analysis being conducted by a local Indian NABL-certified lab, which the team had independently verified to be trustworthy. Sending the samples all the way to the US was a way to overcome some of the limitations of the technical environment faced in the team's field research. Another research group in JU had a highly accurate instrument (inductively coupled plasma - mass spectrometer or ICP-MS) for measuring water quality, including arsenic. However, that ICP-MS remained inaccessible to the team. Another sensitive instrument at JU had been functioning, but the essential supply of Argon for its operation had run out, and the empty cylinder of Argon was not being replaced or refilled over many months. These are some small examples of the numerous difficulties of conducting high quality scientific research in developing countries without a steady flow of adequate funds to support research infrastructure.

The leaders of the Berkeley team visited the completed pilot plant for commissioning (Fig. 5.17), and met with the leadership of Livpure, relevant officers of the Ministry of Drinking Water and Sanitation, and USAID staff in Delhi, to discuss progress and steps forward. Progress at the demonstration site was reported in India's prominent daily newspaper the Times of India.

Fig. 5.17 Plant inauguration on July 8, 2016. Picture shows teachers and staff of Dhapdhapi High School, as well as researchers from UCB and GCP-JU. This picture was taken right after a meeting with teachers and staff where Prof. Gadgil and Prof. Roy explained project efforts and answered questions of students, teachers and staff. Sustained support and advice from the headmaster, Mr. Biswas, (in center, in white shirt sleeves) was crucial for overall project success.

After the technical challenges (described in Sect. 4.5) were identified and overcome, water production from the full treatment plant (Fig. 5.10) began to reliably meet all chemical and biological aspects of the Indian drinking water quality standard IS:10,500:2012, including exceeding the international standards for arsenic corresponding to the WHO-recommended MCL; the initial arsenic concentration of approximately 250 ppb was reliably reduced to < 5 ppb (Fig. 5.11).

Fig. 5.11 ECAR product water results from April 11, 2016 to January 30, 2017 demonstrate that the Dhapdhapi plant is technically effective in reducing high arsenic concentrations (Average initial: 252 +/- 29 ppb) to concentrations much below the WHO limit of 10 ppb (Average final: 2.9 +/- 1 ppb). The grey shaded region (left half) depicts the time period in which water was treated and arsenic level was carefully measured, but the water was not allowed for consumption. The white region (right half) depicts the time period when water began to be distributed to students, teachers, and staff for consumption. This figure is adapted from Hernandez et al., 2019.

4.5 Technical Challenges

While the deployment of ECAR as a large-scale plant was ultimately successful, there were a number of unanticipated technical challenges that surfaced and were overcome along the way. One of the primary reasons for engaging in field work is to uncover and resolve these kinds of contextual challenges. The major benefit of operating in the field-relevant environmental conditions is the opportunity to see effects that may simply not be anticipated or cannot be replicated in the laboratory. These specific challenges resulted from the field conditions, multi-stake-holder management, and maintenance requirements. It is worthwhile to give a few examples, since the devil is always hiding in the details. As another way to put it: “In theory, there is no difference between theory and practice, but in practice, there is a world of difference between theory and practice”.

Intermittent Power Supply. The pilot plant in rural West Bengal, India, relies on intermittent grid power. Especially during the monsoon season (April – July), power outages occurred almost daily due to storms, damage to transmission lines, or substation breakdowns, etc. When power returned, the ECAR process would simply resume where it had left off (one advantage of the ECAR process is that it does not lose efficiency when operation stops and starts). However, because it operated as a semi-batch process, power outages were sometimes long enough to prevent a single daily batch of 2,000 L from being treated.

Hot and Humid Climate. The summer daytime temperatures in West Bengal, India reach as high as 40 degrees Celsius in the shade, followed by heavy rains and high humidity (average relative humidity of 84% between July and September). Such extreme environmental conditions led to rapid corrosion of bare electrical contacts (due to high humidity); which in turn led to heat build up that was not dissipated under high ambient temperatures, leading to melting and burning of plastic insulation; powdery white precipitates appearing in the product water during summer (later determined to be calcium carbonate); and the water delivered to consumers in intense summer heat being unpleasantly hot. With the onset of winter the team also observed unexplained significant deterioration in the performance of the tube settler process.

4.6 Implementation Challenges

Training of Local Operators. At the start of the field trial, there were no written instructions, either in English or Bengali, on plant operation. Thus, training was "on the job" and based on (sometimes inconsistent) verbal instructions from various team members and partners. Locally trained plant operators heard different instructions from different stakeholders, leading to confusion. This eventually led to the development of an operations manual to remove inconsistencies, and ensure clarity. However, that did not always ensure common-sense operation. In one case, the arsenic concentration strangely spiked in the product water above the target level (though it remained below the recommended WHO MCL of 10 ppb). This is seen in Fig. 5.11 at about mid-June 2016. With a lot of effort, the engineering science team traced it to the recirculation pumps in the ECAR reactors being shut off, mid-processing, by the plant operator. It turned out that the plant operator's action was due to the pump noise interfering with his personal cell phone calls. After identifying the cause, the research team explained the importance of keeping the recirculation pumps on, and that it was an essential and non-negotiable part of his job as an ECAR operator.

Ensuring Continuity of Knowledge Within the Team. As this project involved many researchers, interns, and partners, at certain phases there was insufficient time allocated to training the next incoming team member. The training process requires expenditure of precious time in a time-bound project. However, turnover of some team members is inevitable (e.g., as some graduate) in such multi-year projects. This leads to discontinuity in knowledge whose documentation may be overlooked, or was felt as only supplemental information. The team's stumbling from this problem led to a partial solution -- as far as possible, the team had field staff work in pairs, so if one of them rotated out, the other in the pair had detailed field knowledge that could be useful to train the replacement hire. This patchwork solution seems to have worked well enough.

Revisiting and Correcting Early Mistakes. Some of the initial actions and decisions during the actual construction were suboptimal for the long-term operation of the demonstration plant. This was the result of different priorities between the implementing partners; the industry partner prioritized cost saving via shortcuts and cheaper components and parts, while the research partners preferred the plant to remain robust and resilient (in their future absence) with higher quality parts, and with a layout facilitating easy trouble-shooting, should problems develop later. Some problems emerged very soon -- owing to the initial shortcuts and cheap components right after the pilot plant was commissioned in April 2015. Fortunately, the research partners had committed to support two field engineers at the plant for many months even after commissioning to diagnose and overcome unexpected problems.

First, there were misdirected water jets into one of ECAR reactor tanks. During ECAR treatment, it is important to replenish the dissolved oxygen in the water, which is being depleted by the chemical reactions in the ECAR process. This was done through cleverly engineered water jets integrated into a water recirculation system, which also helped maintain chemical homogeneity in the bulk solution. Without understanding the underlying chemistry, the installers had misdirected these water jets, preventing the recharge of dissolved oxygen. On discovering this mistake, the field engineers inserted a metal spacer in the reactor and ensured that the jets impinged the water surface as intended.

Second, to cut costs, the industrial partner had installed inappropriately rated / falsely labeled, and poorly installed electrical wires. This caused overheating and melting of the plastic insulation on the wire. Furthermore, these wires were buried in a shallow trench in the floor, and covered with concrete. The field engineers, responsible to commission the plant, had to reinstall and replace all of the faulty wiring, and move it to overhead cable trays for future easy access.

Finally, there were large energy-losses and voltage-drops at the power supply. The research team had ordered a custom low-voltage DC power supply that would deliver 80 Amps of DC current to each reactor at a voltage that could be adjusted manually between 5 volts to 15 volts. They discovered that the busbar used for the power supply's output electrical distribution was not electrical grade copper, but just plain aluminum (a poorer and cheaper conductor of electricity). The poorer conductivity could have been compensated with a larger cross-section of the busbar, but was not. So, the reactors kept receiving lower voltage than desired from the power supply because of the significant voltage (and energy) loss in the aluminum busbar. A similar problem arose from not using electrical-grade copper in other parts of current distribution within the ECAR reactors. It took some time and effort to diagnose these problems. The reactor performance improved after the field engineers replaced the busbars of aluminum and poor-grade copper with busbars of electrical-grade copper.

Additional Engineering Work Needed During Commissioning. The demonstration plant included many components (Fig. 5.10) in addition to the ECAR reactor tanks. It was impractical to test and fine tune the performance of the large pieces of equipment (e.g., for particle separation) in a controlled laboratory setting. As a result, the researchers worked on these aspects of the demonstration plant on-site for the first many months. This included tests to calibrate the correct dose of particle coagulant, and flocculation treatment duration, and observe and diagnose any fluctuations in the overall performance of the particle separation equipment. Only then, a maintenance routine could be established to ensure reliable long-term plant performance. For each of the treatment steps, alterations or maintenance requirements were identified. Two examples follow:

The actual implemented tube settler proved much less effective than expected. It was then discovered that the plastic lamella that form the core of the tube settler was incorrectly installed by the overconfident installation expert (who remained in denial!). The mis-assembled lamella assembly was damaged beyond repair and had to be discarded. New lamella were purchased and correctly installed by Berkeley field engineers. Ironically, the field engineers that identified and rectified the problem learned on the job, and found the solution by searching on the internet and watching on YouTube about how to correctly assemble and install the lamella. After the retrofit, the tube settler reliably delivered water with low turbidity (<1 NTU).

Originally the finished treated water was pumped up to the top of the (three story) school building and stored in a dark blue plastic tank. In summer, the tank got quite hot making the water unpleasant to drink, and furthermore, the team engineers figured out that this high temperature was the cause of precipitation of calcite dust floating on the water. The tanks' location was moved to a shaded spot (on top of the water dispensing unit), and the tanks changed to white color. This kept the water cool and avoided calcite precipitates. The reduced height also decreased the excessively high rate of water flow at the dispensing unit.

The team had planned the project timeline such that two technical persons (either field engineers or researchers) were present and engaged full time at the site for the first nine months of the plant operation. They were invaluable in identifying, diagnosing, and solving numerous technical problems, and transferred the knowledge to the industry partner. The field researchers also developed manuals for maintenance, engineering, and plant operation, that were reviewed by the project team lead, and handed over to Livpure, the industrial partner, on January 30, 2017 (Fig. 5.14).

Fig. 5.14 Handoff of Dhapdhapi plant from UCB and GCP-JU to Livpure on January 31st, 2017. From left to right, Joydeep Bhattacharjee (Livpure), Pratik Mukherjee (Livpure), Joyashree Roy (GCP-JU), and Ashok Gadgil (UCB). All manuals were handed over to Livpure after the signing. From this day onward, Livpure has taken over the responsibility for operating and maintaining the plant, while giving access for the researchers to the plant, on an as-needed basis.

Until commissioning and for the first several months of regular operation all the sludge produced was needed by researchers at JU conducting research on safe encapsulation of the sludge in structural concrete blocks (Roy *et al.*, 2019). Doctoral research along similar lines was also conducted earlier by Tara Clancy at University of Michigan, Ann Arbor. See Clancy, Hayes and Raskin, 2013 for a good review of arsenic-bearing waste management. The team arranged for safe handling and storage of the sludge on site (Fig. 5.18), and its periodic pickup and disposal at the Hazardous Chemicals Waste-disposal facility at Haldia, by a licensed chemical waste disposal company, Ramki.

Fig. 5.18 Rathin, one of the locally trained plant operators, is safely storing sludge into the on-site cage, using proper personal protective equipment (PPE)

5. Reaching Scale: Opportunities and Challenges

5.1 Lessons Learned from Innovation, Implementation, Evaluation, and Adaptation

Based on the extensive experience of past efforts to take new technologies to scale, the team came to define the concept of the "Critical Effort Zone" (introduced in the published literature in (Hernandez *et al.*, 2019)). The Critical Effort Zone (Fig. 5.12) is introduced as a part of the commonly defined innovation chain, along with schematic cash-flow for a financially sustainable innovation. As stated in Hernandez et al., 2019, "the Critical Effort Zone matches the period in the innovation chain for which the expected cash flow of a project reaches its largest negative value. In the social embedding process of technology maturation, this zone requires intense efforts for trust building with key social actors, and ultimately, for acceptance of the technology by the society that will use the innovation. These efforts require understanding of human behavior, strategic planning, and deep social science understanding of the local social context. If efforts during this period are unsuccessful, the innovation can stagnate or remain unused and perish. In contrast, if the efforts are successful, the technology may progress towards successful commercialization and scale-up".

Fig. 5.12 A schematic of the Critical Effort Zone for the ECAR project. This zone encompasses the 600-L prototype at Dhapdhapi High School, its first demonstration plant, and short duration after the hand-off to the industry partner. The figure highlights that the greatest financial expenditure falls within the Critical Effort Zone, and if the team does not succeed here, scale-up will not be possible. This figure is adapted from Hernandez et al., 2019. Note that the vertical axis for the cash-flow bar charts is not to scale.

During this critical zone, GCP-JU served as the locally reputed and trusted scientific partner that helped deploy capacity-building strategies beyond the large prototype phase, aiming for long-term sustainability of the project beyond the pilot phase. The duration of the Critical Effort

Zone is different for each project. For the ECAR project it took about four years (Dec. 2012 to Jan. 2017), comprising part of the small prototype, the entire large prototype, and the initial commercial stages of distributing ECAR drinking water to the community. The Critical Effort Zone consists of successful operation of the field pilot, well designed communication to the public by the scientists in field operations, and flexibility towards any technology redesign needed to fit cultural practices. The actions taken during this zone must ensure a good fit of the technology to the market needs, or "Product – Market Fit" (Andreesen, 2007), and must build the technical, management, and financial capacity for a transition to commercialization. During the Critical Effort Zone, the project team deployed and socially embedded the first ever large-scale ECAR pilot plant, and delivered arsenic-safe drinking water to the first few thousand people daily for long-term health security.

5.2 ECAR Business Model

Although a technology is capable of delivering arsenic-safe water, only a technology combined with a viable business model is capable of delivering arsenic-safe water sustainably, day after day for many years. The ECAR team was very aware that many grant-funded projects fail to create impact once the grant resources are spent. Thus, the team worked to build a business model into their early conceptual framing of the long-term sustainable operation of ECAR technology. Although this chapter has focused largely on the technical efforts, parallel efforts led largely by GCP-JU and also by Berkeley, focused on understanding what kind of business model and behavior change strategies would be most appropriate for the arsenic-affected communities of West Bengal. Previously, Prof. Joyashree Roy had published on the household spending on safe drinking water in Kolkata (Roy *et al.*, 2004). A doctoral student in the Gadgil group, Caroline Delaire, also investigated, through rigorous in-person surveys of over 500 households in Murshidabad District of rural West Bengal, the factors that influence consumer's decisions about purchasing arsenic-safe drinking water and alternatives (Delaire *et al.*, 2017). The Berkeley-JU team believed that a technically successful demonstration plant that was also financially viable would reduce the overall risk perceived by the industry partner, and provide it with higher confidence in the financial reward from further scale-up. All this fitted well with the vision of the funding agency (IUSSTF) for the demonstration plant. Partnering with a school such as Dhapdhapi High School, would provide a familiar central location and trusted source of public health information and education, critical to help change behavior.

6. Results/Lessons Learned

Multi-Stakeholder Management Requires Attention. Partnerships are built and matured at all stages of the technology development and deployment process and requires close and consistent attention. This signifies continuously explaining and defining roles among all stakeholders and keeping communication as open as possible. There will be challenges in the project management among partners when hiring new staff members, seeing trained engineers leave, instructing field researchers from abroad, and the given nature of international efforts separated by time zones and varying levels of resources.

The design of the two 1,000-L reactors required the involvement of all three partners: UCB, GCP-JU, and Livpure. UCB provided adequate training about ECAR fundamentals and operation to GCP-JU and Livpure, answering all technical and scientific questions to the full extent of their knowledge. Livpure pushed to have a design that delivered 10,000 LPD.

Thorough and Transparent Documentation Ensures Continuity Despite Unexpected Changes in Stakeholder Leadership. This large-scale, multi-year, international project involved many stakeholders. Unexpected changes in leadership can disrupt the timeline and the anticipated date of completing milestones, causing the cooperation to be halted, or completely altered. A formal documentation signed by key project members (Fig. 5.16) reduces the risk of the new leader, like a new school headmaster questioning the effort and commitment of the organization to project effort. This holds clear accountable expectations among the parties.

Fig. 5.16 Official signing, by the Headmaster, Shubhendu Biswas (center), of the document giving "Consent to Establish" and "Consent to Operate" to the ECAR water treatment plant at Dhapdhapi High School, November 2016. The "Consent to Operate" grants Livpure 10 years of operation of the plant following yearly performance review of an advisory and a working group. Also in the photograph are Abhijit Das (left) and Joyashree Roy (right)

Technology Design and Debugging Requires Your Boots on the Ground. In the laboratory, the innovation of ECAR became well understood by the team. In the field, ECAR also reliably removed arsenic, exactly as designed. However, the remaining aspects of scaled up processes of sludge separation and elements of the water distribution technology encountered unexpected challenges that could be identified, diagnosed and resolved only because of the full involvement of research personnel. Thus, the research team strongly recommend that the first field trials remain research environments, under realistic conditions, in which the system is improved upon after feedback and iterations.

Trust-Building is the Foundation for Social Acceptance of a Technology. The concept of social capital becomes evident in development engineering efforts. Local communities have seen many good-willed researchers come and fail and go away, never to return. They will have doubts in their minds about why this work is being carried out. They may keep these doubts among themselves, or raise questions publicly about the motives of the team. Conscious efforts towards transparency and building mutual trust are a worthwhile and critical investment of time and effort. These efforts can include periodic public meetings with community leaders and open-mike sessions with the community, and making analysis and data fully accessible.

Schools Can be Effective Locations for Addressing a Public Health Concern. A local public school provides an excellent means of transferring information to the students, teachers, staff, and the parents and families of the students. The ECAR team held informational sessions and large inauguration events at the school, inviting questions from community members. They assisted with science fair entries and a student-poster competition about arsenic in drinking water. The water debit cards used to dispense water from the automatic dispensing units carried messaging on the importance of drinking arsenic-safe water. These activities allowed for the diffusion of public health awareness on arsenic, as well as better understanding and acceptance by the community of the team's efforts in providing arsenic safe drinking water.

Plans will Change in the Field. Researchers will face technical problems in the field in resource-poor settings. It is also likely that researchers will not have immediate access to the principal investigators (PIs) or other supervisors and thus will need to either work within their capacities or hold off on certain action items. These experts are also likely to be remote, and will be pressed to diagnose the root cause of the observed problem from incomplete information with very limited or no analytical instruments on-site. Thus, the entire team needs to be resourceful in low-income, rural settings, and be prepared for much slower progress with the same hard effort they may make in a technologically better resourced environment.

6.1 Cost of Reducing Cancer Risk by Removing Arsenic from Drinking Water

The lifetime excess risk of internal cancer from drinking water with arsenic at 250 ppb, is 18 per 100 (Fig. 5.13). Reducing arsenic concentration to 3 ppb, means that the lifetime risk is lowered to 0.23 per 100, signifying a 80-fold reduction in lifetime cancer risk for those drinking water from the Dhapdhapi plant. The safe water sells at 1 cent US per L, (or 6 INR rupees per 10 L), serving about 8,000 people. For a simple estimate (without discounting, etc.), assume 1 L (i.e. 8 cups) of drinking water consumption per person per day, and a 70-year lifespan. So, each person spends a sum of USD 255.50 over a 70-year period. When 100 people spend this much (i.e., spend USD 25,550), 17 of their lives are saved from internal cancers. This works out to be USD 1,500 per life saved. In this calculation, the benefits from avoidance of skin ulcers, gangrene, amputations, neuropathy, diabetes, heart disease, and social ostracization are ignored.

Fig. 5.13 The lifetime excess risk of internal cancer from drinking water with arsenic at 250 ppb, which is typical of groundwater in arsenic-affected areas, is about 18,360 per 100,000 people. The lifetime excess cancer risk of consuming arsenic at 3 ppb is about 230 per 100,000 people. By drinking ECAR water, which sells at 1 cent US per L, there is a 80-X reduction in risk. These numbers are calculated using the EPA risk model, which is based on numerous studies in the scientific literature.

6.2 Looking Back and Adapting to New Contexts

It is worthwhile to briefly revisit the Theory of Change, and where the team ended in India after 14 years of effort (from 2005 to 2019). What worked, what didn't, and why? For sure, the team can say that ECAR performs technically well, is energy efficient, has Zero Liquid Discharge (ZLD is a coveted goal in sustainability engineering design), and removes arsenic easily to concentrations below 10 ppb. ECAR is also economically attractive, financially viable, and socially acceptable to the community at Dhapdhapi. So, the team met three of the four items in the "Outcomes" (Fig. 5.3). The outcome not achieved so far is the interest from companies and from public agencies at the State and Central Government level in replicating the success at Dhapdhapi.

We note that the Central Government of India took the highly unusual step in February 2016 to release INR 800 Crores (INR 8 billion, about USD 120 million) to the States affected by arsenic and fluoride in their groundwater (Feeds, 2017). These are grant funds for capital expenditures to be used by the State PHEDs (Public Health Engineering Departments) only for community-scale safe drinking water systems. So, now the problem, the solution, and the money are all there. Furthermore, the ECAR team spent a very significant time and effort to register ECAR at the website of the Ministry of Drinking Water and Sanitation (MDWS) to invite testing, verification, and certification of the implementation and performance of the ECAR technology at the operating plant at Dhapdhapi. After such testing and visits by independent government-appointed experts, the Mashelkar Committee of the MDWS lists ECAR on its website since August 2019, as an approved technology for arsenic remediation of groundwater for drinking (*List of Recommended Technologies*, 2019). With this approval (posted on the website of MDWS), no individual State PHED needs to undertake its own testing and verification of the ECAR technology, removing another barrier to the technology's dissemination.

The estimated number of Indians drinking water above 10 ppb continues to grow, as more testing data become available. Prof. Chander Kumar Singh and his research group at TERI University, Delhi, estimate that the number of Indians exposed to arsenic above 10 ppb in their water exceeds 100 million (Singh, 2020).

The IUSSTF project ended in 2016. Beyond IUSSTF, what is the funding landscape for further work on ECAR? And where is it headed? A large multi-campus, multi-year project led by UCB on water-energy research, funded by the US Department of Energy, has supported applications of advanced versions of ECAR to remediate arsenic-bearing wastewater from coal-fired power plants in the US. The Philippines has a groundwater arsenic problem in some regions. Since 2018 Gadgil has collaborated with faculty at their top engineering school, University of Philippines, Diliman, to transfer ECAR science and technology from Berkeley to UP Diliman, supported by the Government of Philippines. In 2019, the UCB research group won three-years of research support from the State of California's program to reduce cancer incidence in California populations. This project supports the UCB group to develop an advanced form of ECAR that must work well in the California socio-economic and regulatory environment, and to conduct a short field test in an affected region of rural California.

The requirement of using ECAR chemistry in rural California have led researchers in the Gadgil Lab to invent two more-advanced versions of ECAR. These two versions are able to treat a much higher flow of water for arsenic-removal than ECAR at only marginally higher cost, but with a much smaller footprint and much smaller labor content. They rely on the same ECAR principles, so the team's confidence is high that they will likely function well in the field. Both the advanced technologies have tested well in the laboratory and in very limited field tests in rural California. The first of them, called Air Cathode Assisted Iron Electrocoagulation (ACAIE) has been disclosed and published (Bandaru *et al.*, 2020), and the second, Fe-EC with External Oxidizer (FOX) is being prepared for publication at the time of this writing (August 2020).

7. Summary of Key Actions as Viewed by the Team

- Stay focused from the start of technology invention on strong science based effectiveness, affordability, environmental safety of removing arsenic, and technology's fit to a business model
- Revisit the engineering design often, as the science understanding gets deeper
- Keep a learning mindset -- stay curious about learning everything that might impact the technology, its implementation, and eventual scale up
- Actively seek to identify the team's weaknesses ("holes" in combined organizational skills and goals) and always look to fill them by reaching out to potential partners (e.g., unsuccessful outreach to all major industrial players in India and finally finding Livpure serendipitously through a Zayed Prize connection!)
- Undertake conscious efforts to keep relevant authorities at various levels of the government informed so the team is not treated as strangers, upstarts, or fly-by-night operators
- Ensure, as far as possible, transparency and redundancy of skills, so the work does not collapse owing to one single individual getting removed from the team
- Aim for written signed MOU agreements from all parties on whom the team critically depend for their cooperation to be successful. MOUs are not legally enforceable, but avoid later accusations of who promised what, and help in expectation management
- Undertake outreach effort to the community (e.g., teachers, staff, students, and nearby community) through public meetings every six months or so. Report progress or setbacks,

manage expectations, and answer questions publicly and honestly to suppress rumors and speculations.
- Work to understand all the stakeholder's needs and constraints, which may change throughout the project, and address the issues rationally and through transparent communication.

8. Interpretive Text Boxes

- **A Critical Role for Academia.** Academia brings to the table not just an unusual depth of knowledge, but is also seen as neutral in the sense of not having a long-term financial or political interest in the new social arrangements arising from introduction of the new technology. Thus, academia could act as an mediator and coordinator of stakeholders (e.g., UCB's help to resolve issues between Shri Hari and Livpure, or JU's frequent coordination between Livpure and the community/school/government).
- **Importance of Field Work.** Apart from the technical aspect of iteratively testing in the field and improving the prototypes, field work greatly helps in developing and strengthening relationships with partners who will be essential to scale-up and sustainable implementation.
- **Expectation Management.** It is very important (and difficult) to manage expectations of stakeholders so they are aligned, and timelines are matched. It is important to repeatedly emphasize and convey the purpose of research. This is related to outreach efforts to the community, such as removing rumors, inflated expectations, and misunderstandings.
- **Doing Field Work Early and Often.** Field work can shape the research questions being asked. Our field work led to a focus on designing a large-scale rapid settling stage (based on learning this was the limiting step in 100-L trials), robust waste management (based on feedback from the community), steps to overcome the passivation of electrode plates over long term use (after 100-L trials, 600-L and 2,000-L trials), and the need to look at bacterial contamination in addition to arsenic, among other questions.
- **Development Engineering Research Groups are Unique**. Intense impact-oriented research is facilitated by operating in a slightly different way than how most academic research groups operate. The UCB part of the team included project scientists and staff engineers who worked as equals in the group, along with the PI, graduate and undergraduate students, and a part-time administrative support.

9. Questions for Discussion

1. Was it right for the team leadership to have a protected dug-well installed at the Amirabad school to offer immediate relief (although it did not work out)? Why or why

not? What was the team's responsibility, having installed it, to ensure its successful and continued operation? Was this an example of mission creep?

2. Was the team leadership right in moving their earlier efforts from Bangladesh to West Bengal, India, for the reasons stated? Why or why not?
3. As noted in the narrative, when the team was testing various minor issues in the treatment train after arsenic-removal from the 1,000 L reactors they kept on discarding all treated water into a soak pit for six months, while local people had to continue drinking the local arsenic-contaminated water as was the past practice. Discuss the ethical and legal pros and cons of this decision. Was that the right decision? Why or why not? What would you do?
4. The narrative mentions rejecting a girls-only school for the field trial (after the Amirabad blow up), and selecting a Co-Ed school to avoid another risk of controversy. Was that the right decision? Why or why not? Are there options you think the team should have explored before abandoning the girls-only school for the site of the field trial. The girls-only school is only 45 minutes by car, compared to ~2 hours to Dhapdhapi.
5. Discuss the experience described overall, of attempting technology transfer to what seems like a passive industrial partner. What could have been done differently for ensuring a more energetic commitment and commercial take-off, particularly given that the industrial partner is a non-exclusive licensee of the technology.

10. Acknowledgements

We would like to thank Professor Joyashree Roy and Siva Rama Satyam Bandaru for their invaluable roles in the ECAR project, as well as their careful review of this book chapter for accuracy of the narrative.

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Campus. These resources allowed the Berkeley team to take the necessary technical risks that led to a steady increase in knowledge and confidence, to build up to the 1000-L reactor.

Fig. 5.1 Photographs of arsenic treatment devices in Murshidabad District of West Bengal, India. Panel a), Working arsenic filter, (typical for 5% of installed units at 1-year after installation). And, Panel b), Defunct arsenic treatment unit, (typical of 95% of units at 1-year after installation)

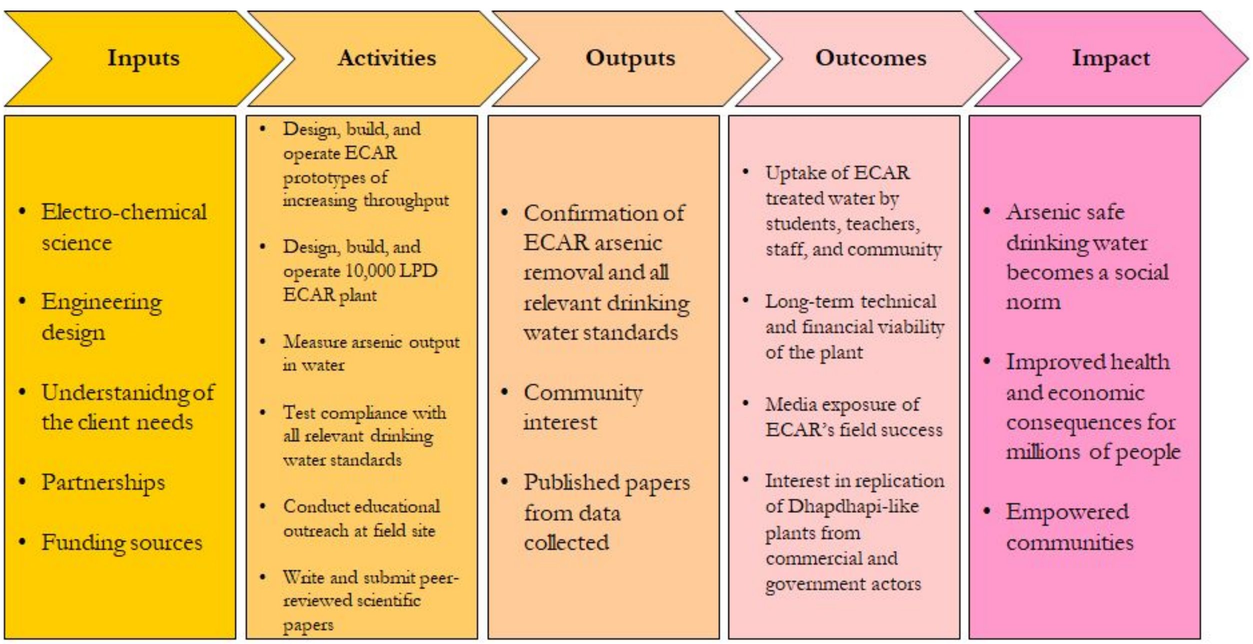

Fig. 5.2 The Theory of Change (ToC) that the ECAR team formulated for the project. The Inputs began in 2005 at UC Berkeley and by 2019 the team was continuing to put in efforts to see the project Outcomes.

Fig. 5.3 Ashok Gadgil, Shri Hari Chief Design Engineer, Narendra Shenoy, and Susan Amrose in November 2014, discussing the design details of the water distribution manifold of the two ECAR reactors then under construction.

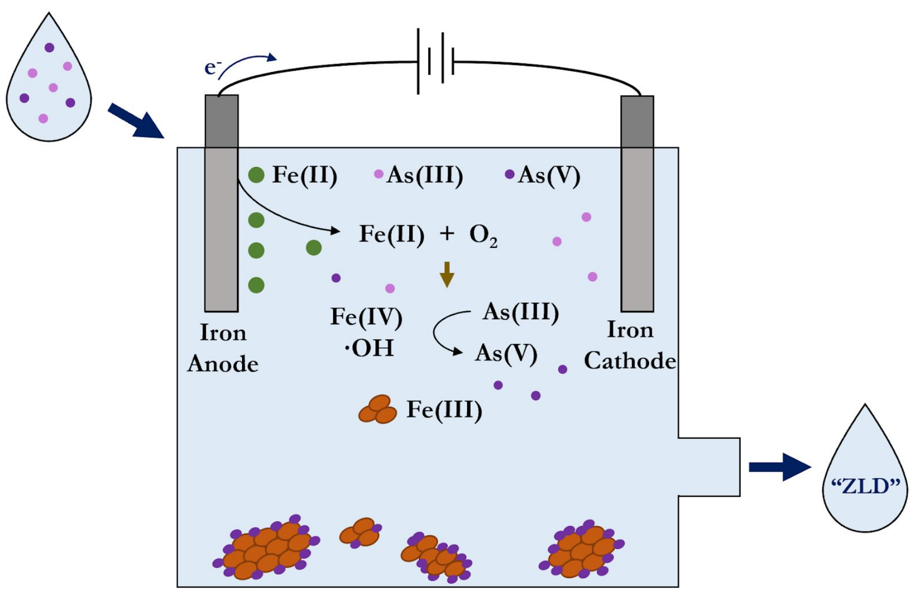

Fig. 5.4 Schematic of ECAR process with iron electrodes. Anodic dissolution of Fe(0) from the iron anode releases Fe(II) in the bulk solution. This Fe(II) reacts with dissolved oxygen (O2) to form insoluble Fe(III), and simultaneously generates reactive intermediates (like Fe(IV) and *OH), that oxidize arsenite, As(III), to arsenate As(V). The Fe(III) captures the As(V) and then the aggregated precipitates settle out

of solution. The letters “ZLD” on the outlet water highlight that this process is Zero Liquid Discharge, a coveted goal of process engineering.

	1. Co-Ed Primary School	2. Co-Ed Dhadhapi High School	3. Girls High School
Arsenic concentration (ppb)	~100 – 200	~225	~200
Water source	Hand pump, shallow tube well	Hand pump, shallow tube well	Shallow tube well attached with submersible pump
Number of students	200 - 250	2,500	510
Suitable space	Adequate	Excellent	Excellent
Travel time from JU	2 hours 15 minutes	2 hours	45 minutes

Table 5.1 The data collected while selecting a school site for the deployment of the ECAR technology.

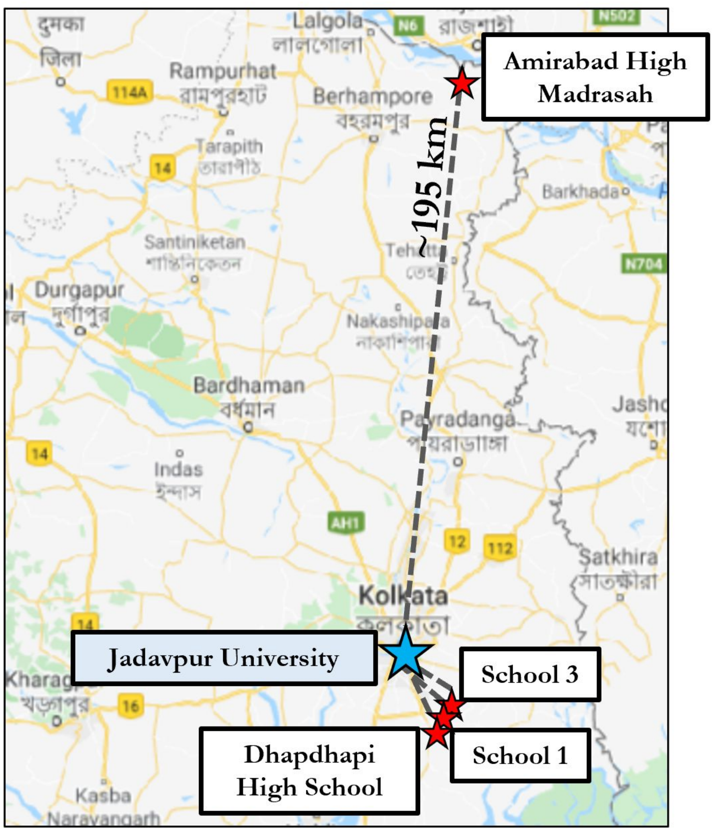

Fig. 5.6 Map with central location being Jadavpur University and its relative distance to promising school sites. As the bird flies, the distance from JU to Amirabad (the first school partner) is 195 km as the straight-line distance, but time to travel is 6 hours and 45 minutes by car. The travel time to Dhapdhapi is only about 2 hours and 15 minute.

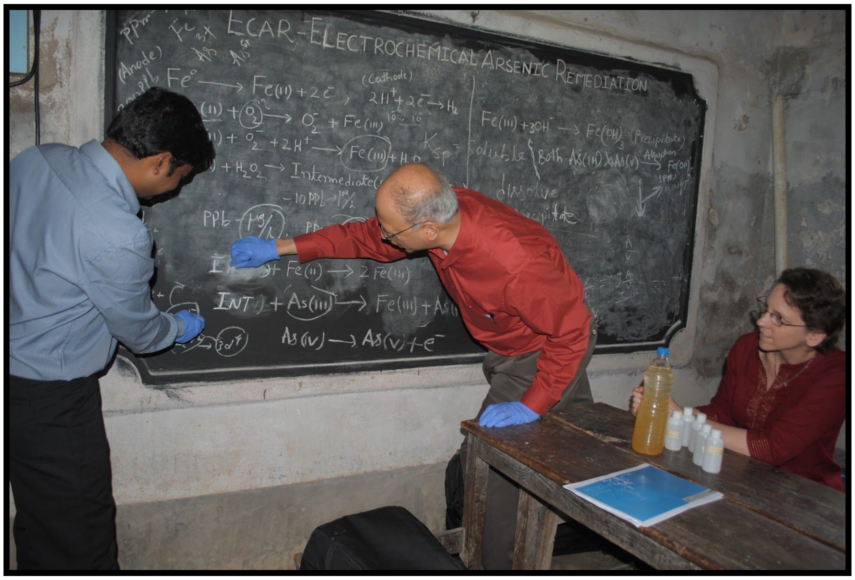

Fig. 5.7 This picture from 2012 shows Professor Gadgil discussing the chemistry of ECAR with Siva Bandaru, at that time a field engineer in the Berkeley team. Dr. Susan Amrose is on the right. This is in the classroom of Dhapdhapi High School that was allocated for the 600-L prototype trial.

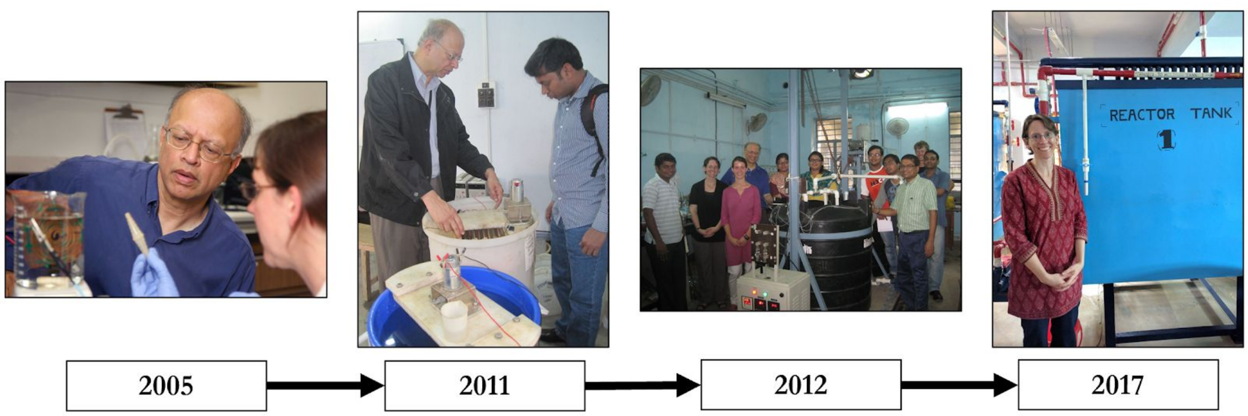

Fig. 5.8 The progression of ECAR, beginning as a 200-mL beaker, with its development to 100-L and 600-L prototypes, and finally scaled as two ECAR reactors of 1,000 L each. The 2005 photo shows Ashok Gadgil and Susan Amrose at the Berkeley Lab. The 2011 photo shows Ashok Gadgil and Siva Bandaru around the 100-L prototype at Amirabad High School. The 2012 photo shows Siva Rama Satyam Bandaru, Susan Amrose, Caroline Delaire, Ashok Gadgil, Paramitha Chaudhuri, Sudipta Ghosh, Suman Chakraborty, Chandan Bose, Amit Dutta, Peter Kuin, Sayantan Sarkarstanding around the 600-L prototype at Jadavpur University. The 2017 photo shows Susan Amrose standing next to one of the two reactor tanks at Dhapdhapi High School.

Fig. 5.10 Treatment train at the Dhapdhapi Plant. Water treatment begins at 1) the ECAR reactors where electrolysis occurs of pumped up groundwater, followed by 2) flocculation and settling, 3) tertiary treatment consisting of a rapid sand filter, micron filters, and a UV light. An activated carbon filter is also seen in panel 3, but is not in use (nor necessary to ensure safe-drinking water, but was part of the pilot testing phase). Water is then distributed to students, teachers, and staff through 4) the water kiosk that contains four automatic dispensing units.

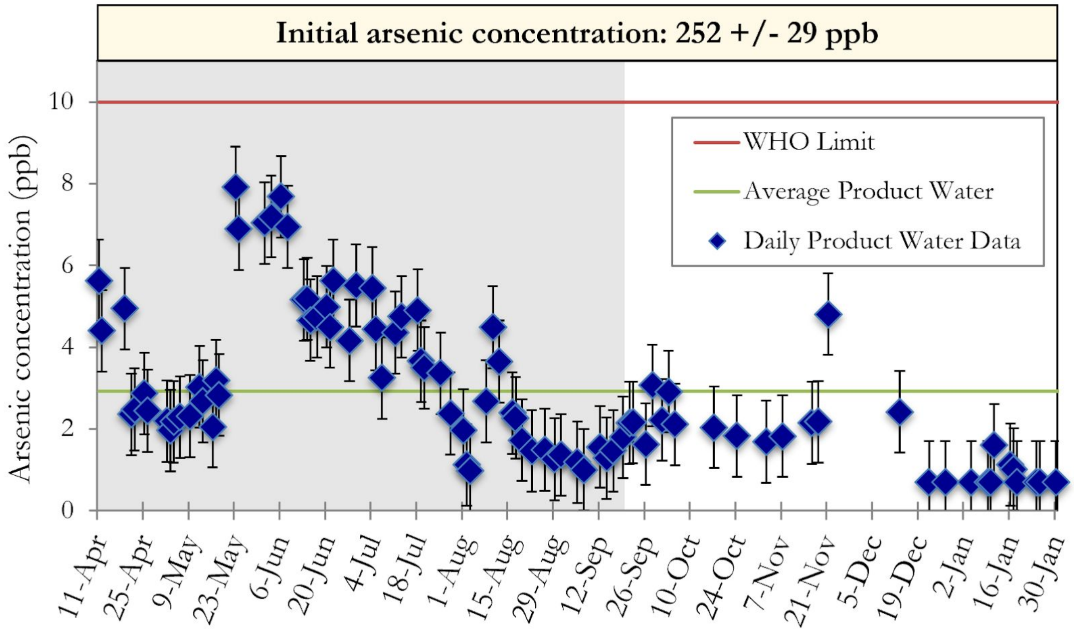

Fig. 5.11 ECAR product water results from April 11, 2016 to January 30, 2017 demonstrate that the Dhapdhapi plant is technically effective in reducing high arsenic concentrations (Average initial: 252 +/- 29 ppb) to concentrations much below the WHO limit of 10 ppb (Average final: 2.9 +/- 1 ppb). The grey shaded region (left half) depicts the time period in which water was only treated and arsenic level was carefully measured , but the water was not allowed for consumption. The white region (right half) depicts the time period when water began to be distributed to students, teachers, and staff for consumption.

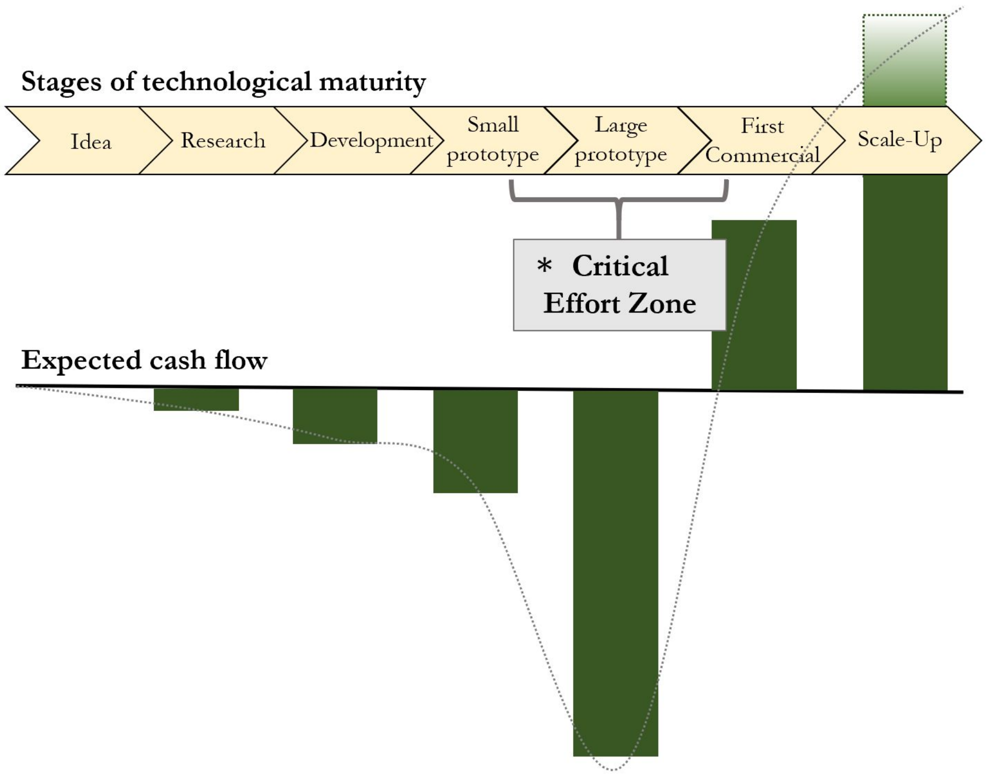

Fig. 5.12 For the ECAR team, the Critical Effort Zone encompasses the first large prototype at Dhapdhapi High School, as well as the 600-L prototyping at Dhapdhapi and shortly after handing-off the plant to the industry partner. The figure highlights that the greatest financial expenditure falls within the Critical Effort zone, and if the team does not succeed here, scale-up will not be possible. This figure is adapted from Hernandez et al., 2019. Note that the vertical axis for the cash-flow bar charts is not to scale.

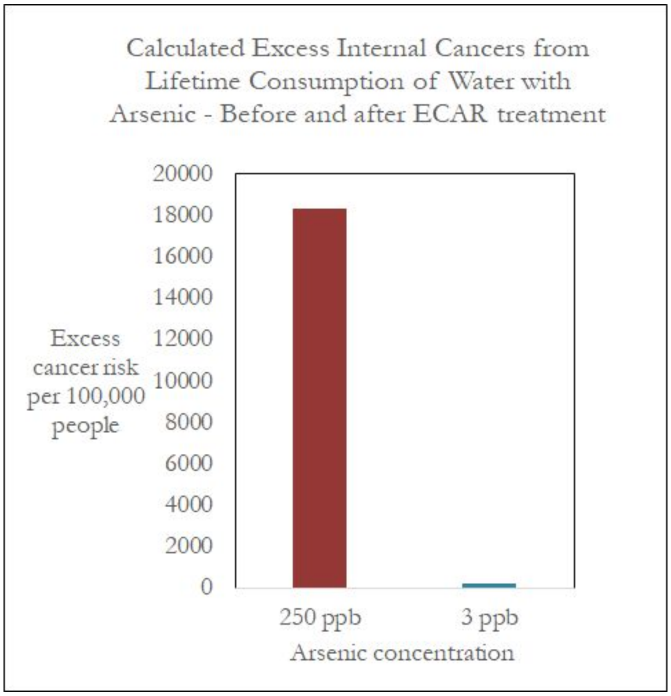

Fig. 5.13 The lifetime excess risk of internal cancer from drinking water with arsenic at 250 ppb, which is typical of groundwater in arsenic-affected areas, is about 18,360 per 100,000 people. The lifetime excess cancer risk of consuming arsenic at 3 ppb is about 230 per 100,000 people. By drinking ECAR water, which sells at 1 cent US per L, there is a 80-X reduction in risk. These numbers are calculated using the EPA risk model, which is based on numerous studies in the scientific literature.

Fig. 5.14 Handoff of Dhapdhapi plant from UCB and GCP-JU to Livpure on January 31st, 2017. The picture shows, from left to right, Joydeep Bhattacharjee (Livpure), Pratik Mukherjee (Livpure), Joyashree Roy (GCP-JU), and Ashok Gadgil (UCB). All manuals were handed over to Livpure after the signing. From this day onward, Livpure has taken over the responsibility for operating and maintaining the plant, while giving access for the researchers to the plant, on an as-needed basis.

Fig. 5.16 Official signing, by the Headmaster, Shubhendu Biswas, of the document giving "Consent to Establish" and "Consent to Operate" the ECAR water treatment plant at Dhapdhapi High School, November 2016. The "Consent to Operate" grants Livpure 10 years of operation

of the plant following yearly performance review of an advisory and a working group. Also in the photograph are Abhijit Das (left) and Joyashree Roy (right).

Fig. 5.17 Plant inauguration on July 8, 2016. Picture shows teachers and staff of Dhapdhapi High School, and researchers from UCB and GCP-JU. This picture was taken right after a meeting with teachers and staff where Prof. Gadgil and Prof. Roy explained project efforts and answered questions of students, teachers and staff. Sustained support and advice from the headmaster, Mr. Biswas, (in center, in white shirt sleeves) was crucial for overall project success.

Fig. 5.18 Rathin, one of the locally trained plant operators, is safely storing sludge into the on-site cage, using proper personal protective equipment (PPE)

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