Feasibility Study of an Electrodialysis System for In-Home Water Desalination and Purification in Urban India

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FEASIBILITY STUDY OF AN ELECTRODIALYSIS SYSTEM FOR IN-HOME WATER DESALINATION AND PURIFICATION IN URBAN INDIA

Kishor G. Nayar* **Prithiviraj Sundararaman*** **Jeffrey D. Schacherl**

Catherine L. O'Connor **Michael L. Heath** **Mario Orozco Gabriel**

Natasha C. Wright **Amos G. Winter, V**

Massachusetts Institute of Technology
Department of Mechanical Engineering
Cambridge, Massachusetts 02139, U.S.A.

ABSTRACT

Desalination of high salinity water is an effective way of improving the aesthetic quality of drinking water and has been demonstrated to be a characteristic valued by consumers. Across India, 60% of the groundwater, the primary water source for millions, is brackish or contains a high salt content with total dissolved solids (TDS) ranging from 500 parts per million (ppm) to 3,000ppm. The government does not provide sufficient desalination treatment before the water reaches the tap of a consumer. Therefore consumers have turned to in-home desalination. However, current products are either expensive or have low recovery, product water output per untreated feed water, (~30%) wasting water resources. Electrodialysis (ED) is a promising technology that desalinates water while maintaining higher recovery (up to 95%) compared to existing consumer reverse osmosis (RO) products. This paper first explores the in-home desalination market to determine critical design requirements for an in-home ED system. A model was then used to evaluate and optimize the performance of an ED stack at this scale and designated salinity range. Additionally, testing was conducted in order to validate the model and demonstrate feasibility. Finally, cost estimates of the proposed in-home ED system and product design concept are presented. The results of this work identified a system design that provides consumers with up to 80% recovery of feed water with cost and size competitive to currently available in-home RO products.

INTRODUCTION

The Indian government has expressed the goal of providing clean drinking water to all of its citizens, but this goal is yet to be achieved [1]. In particular, the challenges of water scarcity and brackish water represent a significant threat to India's future health and water security.

Current State of In-Home Water Treatment

The 2011 Census of India found that piped water is supplied to 71.2% of urban households and 35% of rural households [2]. However, no major Indian city is able to provide a 24-hour water supply, with most supplying only 4-5 hours of water each day [3]. Additionally, quality of the supplied water is an issue. Though 12% of the water supply in urban areas of India is treated before delivery [4], approximately 70% of piped water that was tested was designated as not potable, due to bacterial and chemical contamination [3]. Because current government infrastructure is not able to reliably deliver safe, desalinated, and uncontaminated water to homes, consumers have turned to in-home water purification. Approximately 53% of households in India use at least one form of water purification, which may take the form of straining water though a cloth, boiling, or use of in-home reverse osmosis units [3]. Based on preliminary consumer interviews, people using treatment systems to reduce TDS levels are interested in a product that minimizes the percentage of water wasted.

*Joint first authors

Water scarcity

India holds just 4% of the world's fresh water supply, but houses 16% of the world's population [5]. Across much of the country, there is not sufficient fresh water to meet the needs of the population [6]. This is a primary cause of the intermittent daily supply. Consumers who need clean water for drinking and cooking in the morning and evening face significant uncertainty. Those who can afford it, pump extra water into large in-home storage tanks further exacerbating the shortage [3].

Brackish water

Wright and Winter [6] studied the groundwater salinity distribution across India and the effect of salinity on water usage. Throughout India, 60% of the groundwater [6] which serves as the primary water source for millions is classified as brackish. This means the water contains a high salt content with total dissolved solids (TDS) from 500 parts per million (ppm) to 3,000ppm [6]. This is above the drinking water standard of 500 ppm TDS recommended by the Bureau of Indian Standards (BIS) [21], as well as the taste threshold. It has been hypothesized that water purification methods that reduce levels of TDS, addressing the taste issue, will encourage higher rates of adoption [6]. Additionally, it is important to note that the areas with brackish water tend to also be the areas of water scarcity.

Motivation and Objective

Current in-home water purification systems either do not address the high levels of TDS present in the water or do so but provide low water recovery (as low as 30% [6]), further stressing the limited water resources. Electrodialysis (ED) was identified as a process that could be incorporated as part of a solution to address an unmet consumer need: a cost-competitive, high water recovery (up to 95% [6]) in-home desalination and treatment system. The purpose of this research project was to determine the technical and economic feasibility of implementing ED in an in-home water treatment system for consumers in India.

Approach

In developing an in-home water treatment system, the team adopted a user-centered design approach. Before investigating desalination technologies including ED, user needs were identified and translated into preliminary design requirements. Requirements were then referenced throughout the project to ensure that the design direction aligned with the consumer needs. This approach is crucial to enable future product adoption in the marketplace.

NOMENCLATURE

Acronyms

AEM	Anion Exchange Membrane
BIS	Bureau of Indian Standards
CDI	Capacitive Deionization
CEM	Cation Exchange Membrane
ED	Electrodialysis
EDR	Electrodialysis Reversal
ID	Internal Diameter
INR	Indian Rupee
L	Liter
L/h	Liters per Hour
M	Molarity
PPM	Parts per Million
RO	Reverse Osmosis
RR	Recovery Ratio
TDS	Total Dissolved Solids
UV	Ultraviolet

Symbols

A	Membrane area (m^2)
B_0	Falkenhagen equation constant
B_1	Falkenhagen equation constant
B_2	Falkenhagen equation constant
D	Diffusion coefficient (m^2/s)
F	Faraday constant (C/mol)
i	Current density (A/m^2)
I	Current (A)
l	Thickness of membranes (mm)
L	Gap between membranes (mm)
N	Number of cell pairs
Q	Tank volume (L)
$\dot{Q}$	Internal stack flow rate (L/h)
r	Resistance (Ωcm^2)
R	Gas constant (J/mol-K)
S	Absolute Salinity (g/kg)
t	Time (s)
t_+	Transport number of cation
t_-	Transport number of anion
T	Temperature (K)
v	Flow velocity (cm/s)
Vol	Volume
z	Charge number

Subscripts

a	Anion exchange membrane
c	Cation exchange membrane
ch	Channel
con	Concentrate
dil	Diluate
f	Feed (input water)
p	Product (output water)
w	Wall

Greek

ϕ	Current efficiency
Π	Osmotic pressure

DESIGN REQUIREMENTS

Preliminary design requirements were developed based on a review of existing consumer desalination products and discussions with the project partner, Tata Chemicals Ltd. The preliminary product requirements helped inform decision making related to desalination technology and process architecture selection, as well as product concept development.

Requirements Drawn from Existing Products

There are different types of water purifiers currently available on the market. Table 1 represents the options available to consumers, alongside the concept developed in this paper.

Table 1. Available Product Category Comparison

Technology	Gravity Driven	Reverse Osmosis	Electrodialysis concept
Example	Tata Swach Silver Boost	Tata Swach Ultima Silver RO	N/A
Desalination	No	Yes	Yes
Sediment Filtration	Yes	Yes	Yes
Carbon Filtration	Yes	Yes	Yes
Ultraviolet Treatment	No	Yes	Yes
Recovery Ratio	100%	30%	Up to 95%

Reverse osmosis (RO) is currently the only commercially offered technology that provides desalination for the in-home water purification market. The table below summarizes the features found in current in-home RO units, which influenced the requirements for this project.

Table 2. RO Product Comparison

Manufacturer	Kent	Pureit	Tata
Model	Supreme RO [7]	Marvella RO [8]	Swach Ultima Silver RO[9]
Price (INR)	17,000	15,290	16,999
Dimensions (mm)	L 430 W 270 H 630	L 265 W 360 H 480	L 168 W 420 H 537
Weight (kg)	10.9	7.8	11.05
Flow Rate (L/h)	15	9-12	15
Storage Capacity (L)	9	10	7
Power Consumption (W)	60	36	55
Recovery (%)	50	25	Unknown

Summary of Preliminary Design Requirements

Table 3 summarizes the key requirements compiled for this project.

Table 3. Preliminary Design Requirements

Requirement	**Description**
Water Recovery	The product should be designed to recover at least 80% of the feed as product water. A higher water recovery product is less wasteful and more desirable.
Water Treatment Rate (Time to Desalinate)	The minimum acceptable water treatment rate for the product is 12 liters/hour. Additionally, the product should treat 1 liter in at most 5 minutes. Higher treatment rate is desirable.
Storage Capacity	The product should be capable of storing up to 10 liters of treated water. Storage is needed to provide a safety stock of water for times when water and electricity is otherwise unavailable.
Unit Cost / Sales Price	The product should be designed and constructed at a unit cost that supports a sales price target of less than $270 (16,000 INR). The unit should be priced to compete with existing household desalination products offered in the Indian market.
Input and Output Water Salinities	The product shall be designed to treat input water with salinity up to 3000ppm TDS. The product should produce output water with salinity no greater than 500ppm TDS. An output water salinity of 350ppm should be targeted to provide margin from the 500ppm limit.
Electrically Powered	The product should be capable of operating from standard Indian outlet power (220VAC, 50Hz). The power consumption should be less than 200 W, which is approximately that of a typical Indian home refrigerator.

Alternative Technologies Considered

With the preliminary design requirements in mind, several high water recovery technologies were considered for desalination including electrodialysis (ED), high-pressure closed circuit reverse osmosis (RO), capacitive deionization, as well as thermal technologies ranging from simple boiling to multi-effect distillation. A description of each technology is provided in the appendix. Thermal technologies were eliminated from consideration due to their intensive energy requirements (in excess of 200 W). Capacitive deionization was also eliminated from consideration as an unacceptable technological readiness level exists due to challenges in obtaining commercially feasible electrodes and difficulties in achieving high recovery [10].

Comparison of High-Pressure Closed Circuit RO to ED

Among the desalination technologies evaluated, high-pressure closed circuit RO and ED emerged as the leading candidates. High-pressure closed circuit RO, compared to conventional RO used in commercially available products previously described, operates as a batch process with fluid recirculation at high pressure (in excess of 10 bar). The high-pressure system enables higher water recovery, but results in an increase in cost because of the added complexity from the pressure requirements (pumps, pressure vessels, etc). The cost of a small scale ED system, on the other hand, is currently less understood and may be less expensive than currently available RO units. Furthermore, ED membranes are expected to last longer than RO membranes [6]. Finally, according to Wright and Winter [6], for lower feed salinities (500-3000ppm), ED is expected to be more energy efficient than RO. For these reasons, ED was the selected desalination technology.

ELECTRODIALYSIS STACK DESIGN

Home Use ED System

Electrodialysis only removes charged particles and thus does not disinfect the water if any bacteria or protozoa are present. Therefore, it is important to retain the pre- and post-filtration components of current in-home RO water purifiers for the in-home ED system proposed in this paper. These components include: a sediment filter and carbon filter for pre-filtration, as well as a carbon filter and UV filter for post filtration.

ED Stack Components

An ED stack consists mainly of two (2) electrodes, a cathode and an anode, along with a series of anion and cation exchange membranes separated by spacers that provide two (2) isolated flow paths. Each set of anion and cation exchange membrane constitutes a cell pair. All of these components are packaged in a housing that has inlets and outlets for the feed water, desalinated (diluate) water, reject (concentrate) water, and rinse solution for the electrodes (usually made from Na_2SO_4). The primary components are shown in Figure 1.

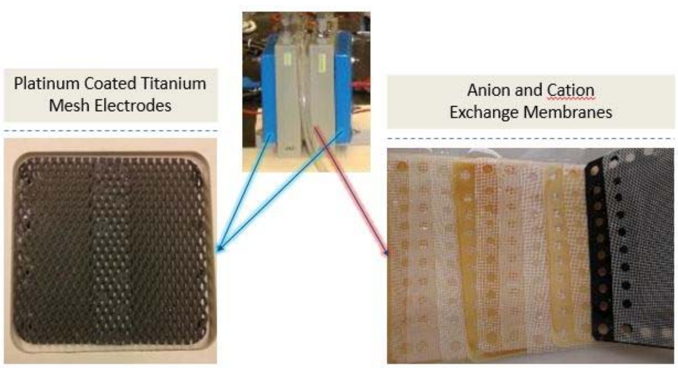

Figure 1. Components of ED test stack (Model: PCCell ED 64002)

Current ED stacks contain mesh electrodes made of titanium and coated with platinum. The use of these electrodes in a small-scale in-home system requires additional consideration. When a voltage potential is applied at the electrodes, water molecules dissociate at the cathode to produce hydroxide (OH^-) ion and hydrogen gas (H_2). At the anode, hydrogen ions (H^+), oxygen (O_2), and chlorine gas (Cl_2) are produced. Gas formation at the electrodes increases the electrical resistance of the stack and the acidic nature of the anode stream, which can cause scaling on that electrode. To avoid these issues, a Na_2SO_4 solution is rinsed over the electrodes. The use of Na_2SO_4 necessitates physical separation from the other flow paths in the stack, which requires the use of an extra tank, pump, and associated plumbing.

A new type of electrode has recently been developed, which is made primarily of carbon [11]. This type of electrode is believed to be cheaper because it uses a lower cost material. Additionally it would not produce chlorine gas and therefore would not require a rinse stream. However, these electrodes can only be used with an Electrodialysis Reversal (EDR) process, not simple ED. EDR involves periodically reversing the polarity of the electrodes. This process increases the life of the exchange membranes as it removes any scaling on the membranes, but it also increases complexity in terms of electronics and plumbing.

Architecture Discussion

When considering electrodialysis, there are two main architectures that can be used: batch and continuous. These architectures function differently but are both capable of treating water with the same level of TDS.

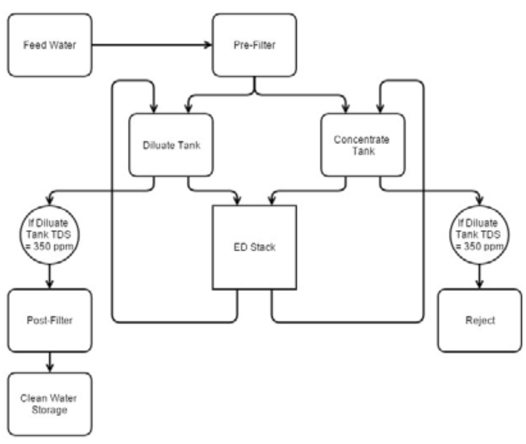

Figure 2. Flow Diagram for Batch ED Process

The batch process involves recirculation of both the diluate and concentrate streams while a voltage is applied across ED stack. The recirculation continues untill the desired level of TDS is achieved in the diluate tank.

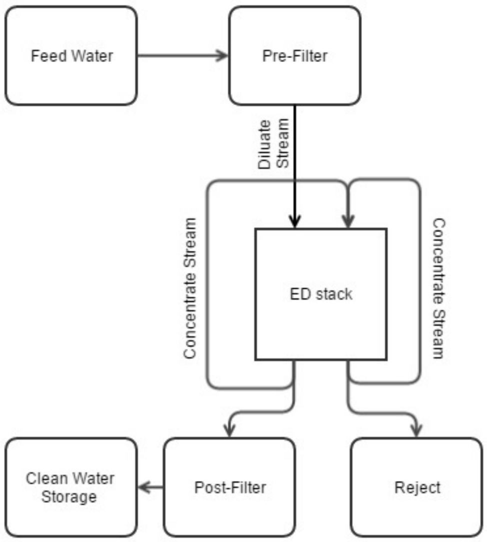

Figure 3. Flow Diagram for Continuous ED Process

The continuous process involves a single pass through of the diluate stream. Through modulation of stack parameters such as voltage and flow rate the diluate reaches the desired level of TDS. Additionally, a small portion of the diluate stream is added to the concentrate stream to prevent its concentration from reaching saturation values of TDS. Table 4 provides a side-by-side comparison of the two architechtures.

Table 4. ED Architecture Comparison

Design Considerations	Batch	Continuous
Diluate Flow	Recirculation	Single pass
Concentrate Flow	Recirculation	Recirculation
Process Tanks	2	1
Transfer Pumps	2	2
Voltage Applied	Fixed	Variable
Flow Control	Simple	Complex
Treatment Capacity	Flexible	Fixed
Membrane Area	Small	Large

Architecture Selection

Although a continuous architecture would allow for instant water desalination and simpler plumbing, the batch architecture is a better fit for this application. In order to desalinate water of varying input salinity, the continuous architecture would require modulation of voltage and/or flow rate. The batch architecture control system, on the other hand, is less complex, relying on recirculation through the stack until the target salinity level is reached. Expensive power electronics, variable flow valves and pumps are therefore avoided for the batch configuration. Additionally, since the feed water in the batch configuration is cycled through multiple times until the target salinity is reached, the stack can be smaller in size, and lower in capital costs.

MODELING

The performance of the batch ED process, in terms of diluate and concentrate concentrations, time to desalinate, power consumption etc. was simulated using a detailed analytical model originally developed by Ortiz et al. [12] and further improved by Wright [6], [13]. The model has been validated by both Ortiz and Wright, with Ortiz having reported deviations between model and experimental data of less than 7 % for power consumption, time to desalinate and stream concentrations. Experimental stack conditions such as stack voltage, number of cell pairs, initial diluate and concentrate salinity were given as inputs to the model. The constants used in modeling are given in Table 5 while the range of model input variables used to design and optimize the ED stack is given in Table 6. Key aspects of the model relevant for design optimization are discussed at length in the 'Optimization' section of this paper.

Table 5. Value of constants used in model described by Ortiz et al. and Wright

Constants	Value	Units	Ref.
A	64	cm^2	
B_0	0.3277		[14]
B_1	0.2271		[14]
B_2	54.164		[14]
D_a (in AEM)	3.28×10^{-11}	m^2/s	[15]
D_c (in CEM)	3.28×10^{-11}	m^2/s	
F	96485	C/mol	
l_a	0.2	mm	[16]
l_c	0.2	mm	[16]
L	0.5	mm	
ϕ	0.92		[13]
r_a	29	Ωcm^2	[6]
r_c	24	Ωcm^2	[6]
R	8.31	J/mol-K	
t_+	0.4		[17]
t_-	0.6		[17]
T	293	K	
V	2.78	cm/s	[6]
V_{el}	0.9, 3	V	[6], [18]

Table 6. Model Input Variables

Parameters varied	Value	Units
V_{cp}	1-2	V
N	0-40	
Q_{dil}	2.2-2.7	L
Q_{con}	0.6-1.1	L
$\dot{Q}$	20-72	L/h

PRELIMINARY EXPERIMENTATION

Two rounds of testing were performed; Phase I testing was based on initial model simulations, and available equipment. Optimization was then performed following the first round of testing using test results, and additional model simulations. Phase II of testing was then performed to validate the optimized design.

ED stack setup

The experimental test configuration consisted of one (1) PCCell ED 64002 lab-scale test unit [16] outfitted with ten (10) anion exchange membrane and cation exchange membrane pairs [19] and the associated spacers, each with an effective area measuring 8 cm x 8 cm, and titanium electrodes with platinum-iridium alloy coating.

This stack is the only commercially available stack which allowed for testing of water treatment capacity in a size similar to that of an in-home water treatment system. Additionally, this stack is representative since it contains parts such as the membranes that would be identical to one used for an in-home system. Through modeling it was found that the form factor of this stack could be incorporated into a similar package as current RO products on the market.

The test solution was split into two (2) 1L beakers, one for each of the diluate and concentrate streams. Two (2) Iwaki centrifugal pumps, model MD-20RZ(T) [20], were used to feed the diluate and concentrate streams into the ED stack, and tubing off of the stack discharge was returned to the beakers, recirculating the two test streams. King 7430 series rotometers with valves [21] were used to vary the flow rate through the stack, and manual-read pressure gauges were installed to monitor pressure upstream and downstream of the stack in the diluate and concentrate streams.

Deionized water was mixed with lab-grade sodium chloride [22] to formulate the 3,000-ppm test solution. During the test, magnetic stirring plates were used to mix the diluate and concentrate beakers, and a Jenco Model 3250 conductivity/salinity/temperature meter [23] was used to monitor conductivity and salinity levels within each beaker throughout the experiment. A separate solution of deionized water and sodium sulfate (0.2M) [24] was formulated for the electrode rinse stream, which was recirculated during each test by a third Iwaki centrifugal pump at a rate of approximately 2.5 LPM.

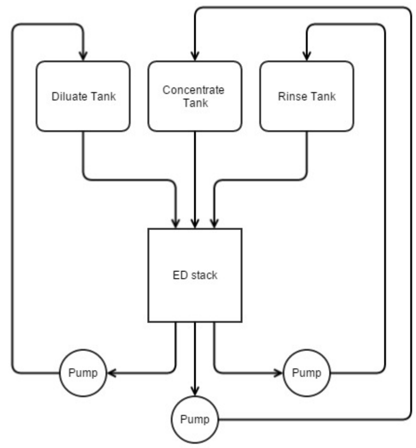

Figure 4. Flow Diagram of Experimental Setup

Testing of ED stack – Phase I

The ED stack was initially tested to verify whether the model was applicable for the test conditions selected and also to evaluate ways to improve the design of the ED stack and the experimental setup. Tests were conducted with 10 cell pairs at an influent salinity of 3,000 ppm. A total of 3.75L (2.62L diluate and 1.13L concentrate) was tested in batch mode. The recovery ratio was set at 70% to maximize recovery given the initial equipment size, and the recirculation rate was operated between 20-25 L/h. To verify the effect of voltage on time to desalinate, two tests were run at different voltage levels: the first test was performed at a total voltage of 16V, or approximately 1.6V/cell pair; the second test was performed with a total of 10V, or approximately 1.0V/cell pair. 1V/cell pair and 1.6V/cell pair were chosen as they were representative of the operating limits set by the manufacturer. A third test was then run on the 10 cell pair stack with a total of 16V, or approximately 1.6V/cell pair, and an increased recirculation rate of 40 L/h. Results from Phase I, experiment 3, are provided below in Figure 5 with error bars reflecting a maximum uncertainty of 13%.

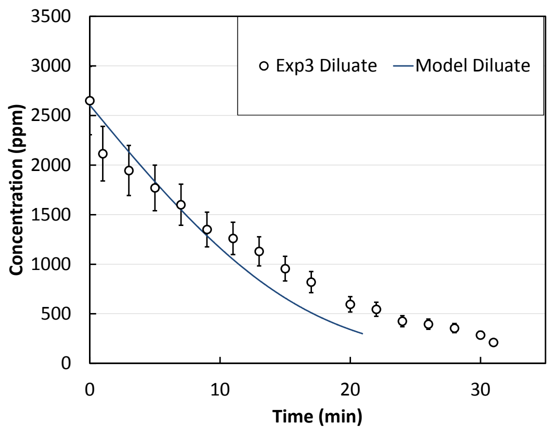

Figure 5. Phase I, Test 3 results (10 cell pairs, 1.6V/cell pair, 40 L/h)

Overall, the first round of testing was found to validate the performance evaluation model. System performance improved with the higher voltage, and higher recirculation rate while the total power consumed was well within the 200 W limit. Additional modeling was then performed to optimize the design for an in-home system, given the identified water quality conditions and design requirements.

Lessons Learned from Experimentation

The team learned several key lessons from the preliminary experimentation. First, the experimental setup and final design will need to minimize volume in the tubing connections between the ED stack and the diluate and concentration tanks; this volume should be reduced in order to maximize and control the water recovery ratio. Second, it was observed that air in the lines significantly affected the performance of the centrifugal pump and thus the water flow rate through the ED stack. This problem could be solved by incorporating air vents in the system, or by using pumps like diaphragm pumps that can handle air in the tubing better than centrifugal pumps. Third, there was difficulty in collecting consistent water salinity readings during testing. Care should be taken to ensure proper mixing in the tanks to reduce the effects of salinity gradients. Lastly, the plumbing of the various water streams could be conceived as confusing for a consumer; as such, service technicians trained and educated in proper system installation and operation would be used for this equipment, much like other in-home water treatment products.

OPTIMIZATION

After preliminary validation, the model previously described was used for optimizing the ED stack design to minimize our objective function of “time to desalinate to 350 ppm”. The physics of the process was used to select key model parameters to be varied with the goal of reducing desalination time. The key aspects of the process physics are described next.

An ED stack can be divided into individual identical functional units known as cell pairs. The voltage across each cell pair is:

$$V_{cp}=\frac{V_t-V_{el}}{N} \qquad (1)$$

where V_t is the total applied voltage in V, V_{el} is the voltage drop across the electrodes in V, while N is the number of cell pairs in the stack. The cell pair voltage can further be expressed as a function of the current density, i, in the stack and the resistance and voltage across the membranes, which are themselves a function of the salt concentration in the diluate and concentrate streams as:

$$V_{cp}=i\times R(C_{dil},C_{con})-E_{mem}(C_{dil},C_{con}) \qquad (2)$$

This is depicted using a circuit diagram in Figure 6.

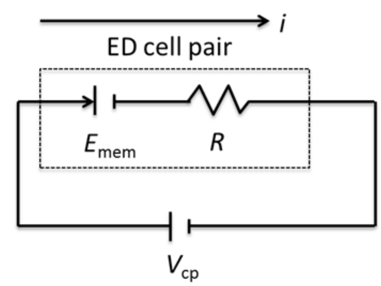

Figure 6. Simplified depiction of the physics of the ED process

The relationship between rate of change of diluate concentration and current is given by:

$$NVol_{ch}\frac{dC_{dil}}{dt}=Q_{dil}(C_{dil,in}-C_{dil})-\frac{N\phi I}{zF}+\frac{NAD_a(C_{conc,a,w}-C_{dil,a,w})}{l_a}+\frac{NAD_c(C_{conc,c,w}-C_{dil,c,w})}{l_c} \qquad (3)$$

where Vol_{ch} is the volume of each channel, $C_{dil,}$ is the concentration of diluate, $C_{dil,in}$ is the concentration of diluate entering the channel, Q_{dil} is the diluate recirculation rate, ϕ is current efficiency, I is current in Ampere, z is the charge number of the ion, l is the membrane thickness, A is membrane area, ($C_{conc,a,w}$ - $C_{dil,a,w}$) and ($C_{conc,c,w}$ - $C_{dil,c,w}$) are the concentration differences of ions across the AEM and CEM respectively.

From Eqs. (2) and (3), the rate of change of concentration in the diluate or concentrate channels was proportional to, the current in the ED stack, the area of the membranes and the recirculation rate in the stack. To reduce the desalination time, each of these terms needed to be optimized.

First, the voltage of the cell pair was optimized with the number of cell pairs set to an increased value of N=25. Figure 7 shows the effect of cell pair voltage on performance. Time required to desalinate decreased with increasing cell pair voltage. The manufacturer had recommended not exceeding 2 V per cell pair due to concerns on membrane degradation. Thus, with an appropriate factor of safety accounting for voltage fluctuations, an optimal value of cell pair voltage of 1.6 V was selected.

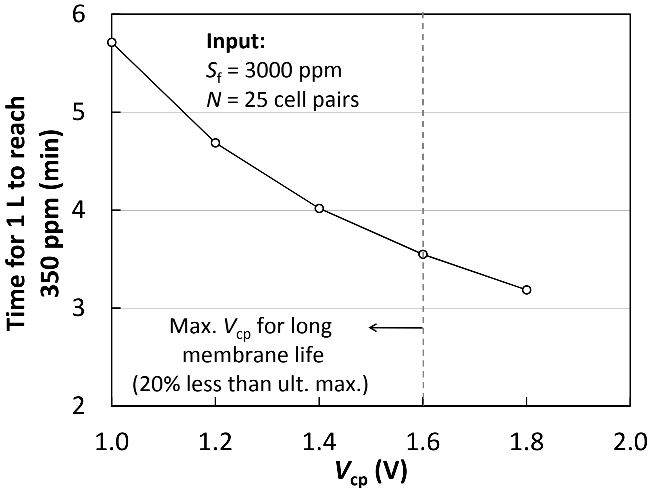

Figure 7. Model results showing variation of time to desalinate 1 L of diluate to 350 ppm from 3000 ppm with voltage across a cell pair with 25 cell pairs in the stack.

Next, keeping V_{cp} = 1.6 V, the area of the membranes in the ED stack was increased by increasing the number of membranes and hence the number of cell pairs. The recirculation rate proportionately increased with the increase in number of cell pairs to maintain a constant flow velocity in the channel. The velocity was an optimal value to maintain a low pressure drop in the stack and to keep the pressure loading on the membrane low. Figure 8 shows how desalination time reduces with increasing number of cell pairs. The resulting total voltage is also shown in the figure. The manufacturer recommended voltage limit was 33 V with a 3 V drop across the electrodes [18]. This limited the peak lab stack performance to just under 5 min of desalination time with 18 cell pairs. This design point predicted by the model, graphically depicted at the intersection of the dashed lines in the figure, was selected for final validation by experimentation. For a commercial in-home ED stack, increasing the number of cell pairs beyond 18 can further reduce desalination time. The final capital costs and required operating margins would determine the maximum number of cell pairs that could be put in a commercial stack. Peak ED stack power consumption at V_{cp} = 1.6 V was low, around 40 W for N = 18 and 90 W for N = 40, equating to electricity consumption (when including 53 W for pumping power) of less than $6 per year, therefore not constraining our design.

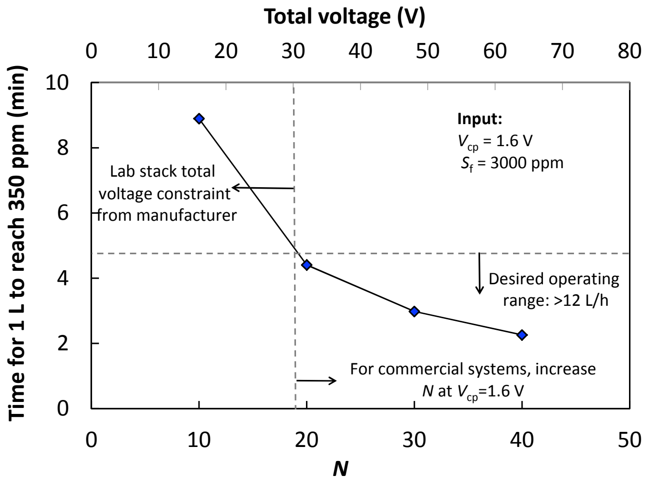

Figure 8. Model results showing variation of time to desalinate 1 L of diluate to 350 ppm from 3000 ppm with total voltage for a cell pair voltage of 1.6 V. Desired operating range and test stack constrains are shown by horizontal and vertical dashed lines respectively.

Testing of ED Stack - Phase II

A final round of testing was conducted to test performance under the optimized conditions of 18 cell pairs and 1.6 V applied per cell pair. In addition to these changes, the tubing and transfer pumps were replaced to make the test configuration more representative of future product conditions. The tubing was downsized from ½-in. ID to ¼-in. ID. The diluate and condensate centrifugal transfer pumps were replaced by KNF Flodos NF300 KPDC diaphragm pumps [25] with a smaller pump chamber compared to the Iwaki centrifugal pumps originally used for testing [20], the ability to operate even with air in the tubes, and a lower capital cost.

A total of 2.96 L (2.41L diluate and 0.55L concentrate) with a salinity of 3000 ppm was created, and recovery was set to 80%. To maintain the flow velocity in the channels, the recirculation flow rate was increased linearly with the increase from 10 membrane cell pairs to 18 membrane cell pairs to a total of approximately 72 L/h. Two tests were performed in succession, with a period of stack flushing with fresh 3000 ppm salinity solution lasting approximately 5 minutes between each test. The peak power consumed in the tests was 88 W: 53 W for three pumps and 35 W for the ED stack. As shown in Figure 9, the tests achieved the target salinity concentration within 13 minutes, which was within 13% of the performance predicted by the model. The error bars shown reflect a maximum uncertainty of 8%. Thus, we have proved that electrodialysis could be used to desalinate feed water of 3000 ppm salinity to 350 ppm at 80% recovery and greater than 12 L/h clean water production rate.

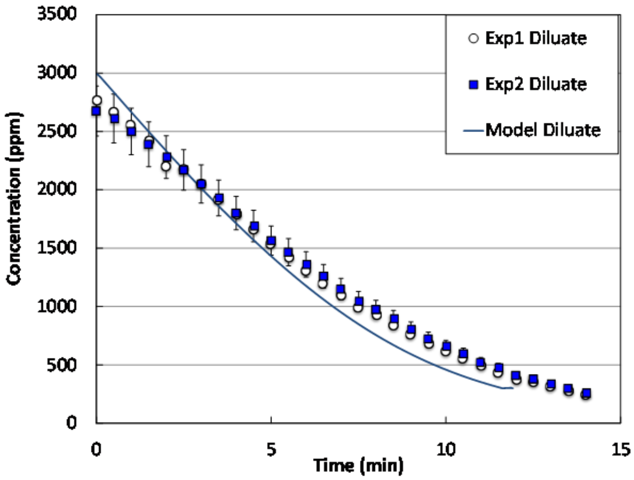

Figure 9. Phase II, Test results (18 cell pairs, 1.6V/cell pair, 72 L/h)

Sources of Error in Testing

Uncertainty in salinity arising from probe uncertainties, salinity gradients and variation during duration of recording (10-15 s) contributed the most to the overall experimental uncertainty; uncertainties in voltage and current measurements and solution preparation were negligibly small in comparison (< 0.1%). For phase I, the total uncertainty in salinity was 9-13% due to issues with the initial salinity probe. For phase II, total uncertainty in salinity was 6-8% primarily due to the variation in salinity within the duration of each measurement.

PRODUCT CONCEPTUALIZATION

An important aspect of demonstrating the feasibility of an in-home ED system is ensuring that all the components can be packaged within a form factor acceptable to the consumer. As users are already accustomed to in-home RO units from a size and functionality perspective, product concepts for an ED system were modeled in a similar form factor for the initial product design. Additional work is recommended to further refine this design so that it can meet consumer needs in the most efficient means possible. Figure 10 shows the complete in-home electrodialysis system along with all of its components and the water flow paths.

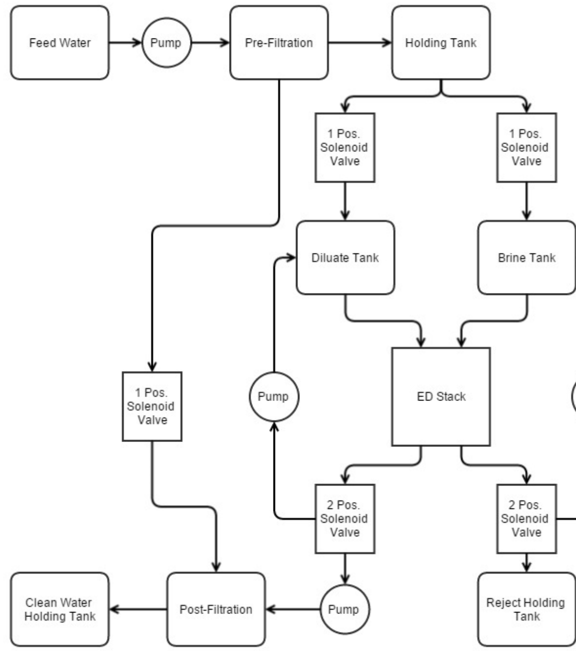

Figure 10. Flow path of a in-home ED system with all components included.

The ED concept shown in Figure 11 matches the form factor of the existing in-home RO units. Although the model does not include all components such as valves and tubing, it serves to demonstrate the general concept. This model represents a preliminary design, therefore, there is room for further optimization which may be in the form of changes to stack dimensions, or use of different pumps. Alterations to the length to width ratio of the stack, while preserving the same area may provide a superior packaging and/or performance solution. However, tests on these parameters was not in the scope of this project. The modeling conducted here utilized the PCCell test unit as the “ED stack”, but at scale an alternative stack may be selected.

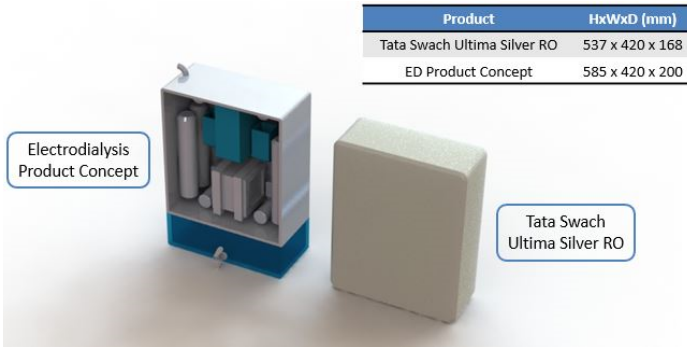

Figure 11. Comparison of ED product dimensions to that of a Tata Swach Ultima Silver RO unit.

All the components used in the model can be found in the exploded view in Figure 12. The two components boxed in red, could be removed if carbon electrodes were to be used in the ED stack rather than titanium electrodes, since carbon electrodes would not require a rinse stream.

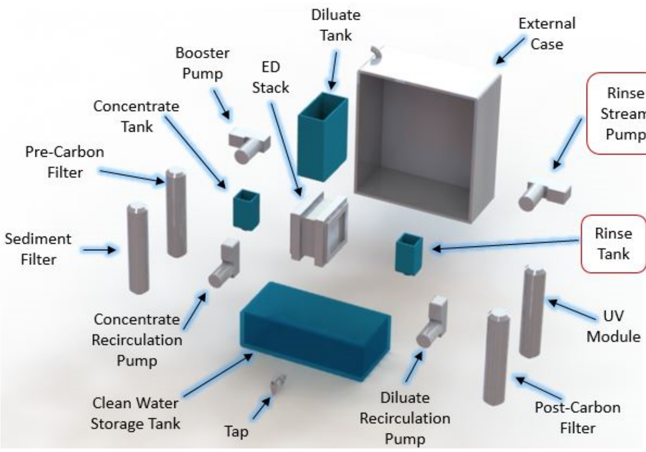

Figure 12. Exploded view of product concept

COST ESTIMATION

One of the principal goals of this system was to achieve cost-competitiveness compared to in-home RO desalination products currently available to consumers in India, while incorporating the high water recovery benefits of ED. The complete system production cost is estimated at $205 and is summarized in Table 7. Assuming a 30% margin, the system sale price of $270 matches competitive RO systems. This meets the product cost requirement and demonstrates the cost feasibility of the ED system.

The system costs of ED can be segmented into two main sections: (1) the stack components specific to the ED technology and (2) other system components found in comparable RO consumer products. The most significant costs of the ED stack arise from the platinum coated titanium electrodes, of which the platinum coating contributes more than 90% of the component cost. Overall, the ED stack accounts for approximately 46% of the manufactured system cost. The additional system costs are largely driven by pumps, filtration, and UV treatment, and account for the remaining 54% of the manufactured system costs.

Cost estimates, summarized in Table *7*, were developed based on supplier quotations and replacement costs of comparable components used in on-market RO systems. Ion exchange membrane specifications were reviewed, and quotations obtained from suppliers including General Electric [26], Membranes International [27], PC Cell [19], and IonTech [28]. These suppliers offered membranes that were larger than required for the smaller household system, and consequently, cost estimates were determined assuming linear scaling with membrane area. Electrode costs were calculated based on supplier quotations [29][30][31][32]; scaling was not required since the electrode size needed for the in-home system was available. The UV system cost was estimated based on the replacement cost of the UV system in a Kent RO device [33]. It is anticipated that future economies of scale would enable additional cost reductions.

Table 7: Cost breakdown of ED product components.

ED Stack Components	**Cost Estimate (USD)**
Cation Exchange Membrane	$11.50
Anion Exchange Membrane	$11.50
Spacers	$3.50
Titanium Electrodes	$64.00
Stack Frame	$5.00
Sub-Total	$95.50
Additional System Components	
Pumps	$50.00
Filter (Sediment, Carbon x2)	$20.00
UV System	$13.00
Housing, Tanks x2	$15.00
Switches, Flow Restrictor, Tubing	$11.50
Sub-Total	$109.50
Grand Total	**$205.00 (12800 INR)**

To consider how system cost can be driven down further, new electrode materials should be considered. Carbon electrode technology has begun to reach the market, and represents a promising avenue to decrease cost of the system significantly, by reducing both electrode costs and part counts [11]. Using a less expensive material that does not require platinum coating reduces electrode costs. If titanium electrodes are no longer used in the system, the transfer pump and storage tank associated with the rinse solution can be eliminated from the system. As the carbon electrode technology matures, adoption will significantly lower costs for the in-home electrodialysis system.

CONCLUSION

A household water treatment product that utilizes electrodialysis desalination technology to achieve high water recovery has the potential to disrupt the marketplace if priced competitively. It is technically feasible to design and incorporate a small-scale electrodialysis stack that can achieve water recovery greater than 80%. With increased production of the key components needed for electrodialysis (notably membranes and electrodes) for the size constraints of an in-home system, economies of scale are expected to reduce prices to levels that enable companies to cost effectively produce household ED products that can directly compete with existing RO systems. As such, it is recommended that further work be undertaken to develop a household water desalination system utilizing ED technology. Potential government subsidies may also lower the price to consumer of ED technology, as the government is motivated to reduce water wastage.

RECOMMENDATIONS FOR FUTURE WORK

Future work could include a comprehensive market study to determine potential consumers' willingness to pay for an in-home desalination product with higher water recovery in urban India. The development of carbon electrodes should be tracked and once available, evaluated for use in replacement of the titanium electrodes with platinum coating. To achieve, quicker desalination, the length of the ED stack could be optimized. Control systems should be integrated into the design, potentially incorporating the use of analog salinity meters. System costs should be refined to reflect the evolution of ED component manufacturers and better define economies of scale. A detailed cost optimization should be done to evaluate an upper limit to the number of cell pairs in a commercial in-home ED stack and the performance possible.

ACKNOWLEDGMENTS

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REFERENCES

[1] M. of W. R. ,Government of India, "National water policy," 2002.

[2] D. P. Sharma, "Serving the Cities: An Indian Scenario," *IOSR J. Humanit. Soc. Sci.*, vol. 19, no. 1, pp. 15–22, 2014.

[3] D. Mckenzie and I. Ray, "Household Water Delivery Options in Urban and Rural India," 224, 2005.

[4] Central Ground Water Board, "Ground Water Quality in Shallow Aquivers of India," Faridabad, 2010.

[5] G. Harris, "Rains or Not, India Is Falling Short on Drinkable Water," *New York Times*, 2013. .

[6] N. C. Wright and A. G. Winter V., "Justification for community-scale photovoltaic-powered electrodialysis desalination systems for inland rural villages in India," *Desalination*, vol. 352, no. 0, pp. 82–91, Nov. 2014.

[7] KENT RO Systems Ltd, *Kent Supreme RO*. Noida 201309, Uttar Pradesh, India.

[8] Hindustan Uniliver Limited - Pureit, *Pureit Marvella RO*. Mumbai, India 400 099, 2014.

[9] Tata Chemicals Limited, *Tata Swach Ultima Silver RO*. Mumbai, India 400 001, 2014.

[10] A. Subramani, M. Badruzzaman, J. Oppenheimer, and J. G. Jacangelo, "Energy minimization strategies and renewable energy utilization for desalination: a review.," *Water Res.*, vol. 45, no. 5, pp. 1907–20, Feb. 2011.

[11] J. Barber, P. Ge, H. Yang, and G. E. Grc, "Electrodialysis Reversal with Capacitive Electrodes," 2013.

[12] J. M. Ortiz, J. a. Sotoca, E. Expósito, F. Gallud, V. García-García, V. Montiel, and A. Aldaz, "Brackish water desalination by electrodialysis: batch recirculation operation modeling," *J. Memb. Sci.*, vol. 252, no. 1–2, pp. 65–75, Apr. 2005.

[13] N. C. Wright, "Justification for community-scale photovoltaic-powered electrodialysis desalination systems for inland rural villages in India," Massachusetts Institute of Technology, 2014.

[14] G. Kortüm, *Treatise on electrochemistry*. Elsevier Pub. Co., 1965.

[15] D. Nwal Amang, S. Alexandrova, and P. Schaetzel, "The determination of diffusion coefficients of counter ion in an ion exchange membrane using electrical conductivity measurement," *Electrochim. Acta*, vol. 48, no. 18, pp. 2563–2569, Aug. 2003.

[16] PCA-Polymerchemie Altmeier GmbH, *Laboratory Scale Electrodialysis Cell 64002*. D-66265 Heusweiler, Germany, 2014.

[17] D. Dobos, "Electrochemical data a handbook for electrochemists in industry and universities." Elsevier Scientific Pub. Co., Amsterdam; New York, 1975.

[18] "PCCell GmbH." Personal Communication.

[19] P. C. GmbH, *PC-SA and PC-SK Ion Exchange Membranes*. Heusweiler, Germany, 2014.

[20] Iwaki America, *Iwaki MD-20RZ(T) pump*. Holliston, Massachusetts 01746, USA, 2014.

[21] King Instrument Co., *King 7430 glass tube flow meter with 65 MM scale flow range, tube 2-34-G-041*. Garden Grove, California 92841, USA, 2014.

[22] Sigma-Aldrich, *Sodium chloride*. St. Louis, Missouri 63103, USA, 2014.

[23] Jenco Instruments Inc., *Jenco Model 3250 Microcomputer based pH/mV/Conductivity/Salinity/Temperature portable meter*. San Diego, California 92126, USA, 2014.

[24] Sigma-Aldrich, *Sodium Sulfate*. St. Louis, Missouri 63103, USA, 2014.

[25] KNF Flodos AG, *KNF Flodos pump*. 6210 Sursee, Switzerland, 2014.

[26] G. E. Corporation, *Ion Exchange Membranes*. Westborough, Massachusetts, USA, 2014.

[27] M. I. Inc, *AMI-7001CRX Continuous Roll: 48" x 120 feet (1.2m x 36.50m) roll*. Ringwood, NJ 07456, USA, 2014.

[28] L. Hangzhou Iontech Environmental Technology Co., *IONSEP Ion Exchange Membrane*. Hangzhou, China, 2014.

[29] G. E. Corporation, *Platinum-coated Titanium Electrodes*. Westborough, Massachusetts, USA, 2014.

[30] B. R. T. I. C. Ltd, *Titanium Ion Mesh, platinum-coated two sides*. Baoji City, Shaanxi, China, 2014.

[31] X. S. S. T. Corporation, *Titanium Electrode*. Xi'an, China, 2014.

[32] B. C. C. T. C. Ltd, *Titanium Mesh Electrode, ASTM B265, GR1*. Baoji City, Shaanxi, China, 2014.

[33] O. W. P. a division of P. W. House, *Kent RO Spare Parts*. Onlinewaterpurifiers.com, 2014.

[34] Census of India, "Houses, Household Amenities and Assets: Drinking Water." 2011.

[35] Census of India, "Population Enumeration Data (Final Population), 2011 Census," 2011. [Online]. Available: http://www.censusindia.gov.in/2011census/population_enumeration.html. [Accessed: 01-Dec-2014].

[36] Census of India, "HH-01 Normal Households by Household Size, 2011 Census," 2011. .

[37] M. Al-Shammiri and M. Safar, "Multi-effect distillation plants: state of the art," *Desalination*, vol. 126, no. 1–3, pp. 45–59, Nov. 1999.

[38] K. S. Spiegler and A. D. K. Laird, *Principles of Desalination, Part B*, 2nd ed., no. pt. 2. Elsevier Science, 1980.

[39] K. H. Mistry, R. K. McGovern, G. P. Thiel, E. K. Summers, S. M. Zubair, and J. H. Lienhard V, "Entropy Generation Analysis of Desalination Technologies," *Entropy*, vol. 13, no. 12, pp. 1829–1864, Sep. 2011.

[40] H.-J. Lee, F. Sarfert, H. Strathmann, and S.-H. Moon, "Designing of an electrodialysis desalination plant," *Desalination*, vol. 142, no. 3, pp. 267–286, Mar. 2002.

ANNEXES

MARKET INTELLIGENCE AND STUDIES

Crowd Sourced Online User Survey

In developing products and technology for emerging markets it is important to understand and immerse oneself in the environment. Often emerging market users can have vastly different needs as well as different preferences, which may be a result of their environments. Due to the limited time and scope of this project such immersion was not possible. Therefore, as a first step an online survey was created using the SurveyMonkey service. The survey consisted of 15 questions aimed to understand user perception and daily usage. Users were recruited for the survey by passing the link along to family, friends, and other contacts. The survey was open for one week after which the data was aggregated for analysis. During that time, the survey was completed by 120 people, including 78 people (a combination of natives and non-natives) living in India at the time of the survey. Results presented below utilized data from the residents of India, unless otherwise noted.

Survey Results

Nearly ½ of the survey respondents had groundwater as their primary or secondary source of water in the home. When asked the amount of water consumed throughout the day, over 40% of respondents indicated that they consumed between 1-4 liters in each the morning, afternoon, and evening. This value compares well with data provided by Tata Chemicals of 12 liters per day per household. It should be noted that all survey participants were assumed to have tap water available in their house, though the 2011 Census indicated this is true for just 71% of urban households [34].

In terms of water used for cooking and drinking, approximately 74% of respondents treated their water in some way for either cooking or drinking or both. Out of the 78 respondents from India, 20 used Reverse Osmosis water treatment systems to treat their water. Of this subset, over 75% of users indicated maintenance was required every 6 or 12 months, and maintenance was performed by others (e.g. through a service contract) for most respondents (80%).

Interesting Observations from Market Survey

A review of the October SurveyMoney survey results highlighted certain inconsistencies with data provided by Tata Chemical and publicly available census information. One inconsistency was related to percent recovery. Survey users appeared to overestimate the recovery associated with their Reverse Osmosis system, with over ⅓ of respondents indicating recovery achieved 60% or higher compared to the average 30% recovery claims from the product vendors themselves [6]. This may indicate that in order to create a successful product with high recovery it is imperative to educate consumers on the true recovery rates of current RO systems so that users would be inclined to switch. Additionally it was found that many users indicated that their current water filtration systems wasted water, which they disliked and often captured for doing dishes or other chores.

Limitations of Market Survey

The October 2014 SurveyMoney survey was used to gain a general understanding of the needs of in-home water treatment system users for people living in India. Nearly 80% of respondents were between the ages of 18 to 34 years old compared to 32% recorded in the 2011 India census (urban areas) [35]. In terms of household size, 91% of survey respondents live in households of 5 or less people compared to 74% of households in urban areas of India containing 5 or less people [36]. Due to these differences, and the means in which the survey was distributed through connections of the study authors, the survey has a potential bias towards young, highly educated people. Additional work is therefore recommended to confirm the applicability of these results in Tata Chemical's targeted service areas.

DESALINATION TECHNOLOGY SELECTION

Technologies Evaluated

The team performed a high-level comparison of desalination technologies including Electrodialysis, High-Pressure Reverse Osmosis, Capacitive Deionization, as well as thermal techniques like Multi-Effect Evaporation. This technology comparison was conducted in order to verify that Electrodialysis is the best small-scale desalination technique given the project objectives and preliminary product requirements.

Overview of Electrodialysis

Electrodialysis (ED) is a desalination technology that uses a series of membranes and electrodes to transport ions from one solution to another. The ED stack is composed of an alternating series of anion and cation exchange membranes that only allow anions or cations to pass through respectively. These membranes are separated by a spacer, through which flow is allowed to pass usually in a designated path. At either end of the stack are electrodes, one positively charged (the anode) and one negatively charged (the cathode). As flow is passed through the channels between the anion and cation exchange membranes the negatively charged ions in the water are attracted towards the anode and positively charged ions are attracted towards the cathode. Due to the alternating layout of the anion and cation exchange membranes the streams between membranes become either a concentrate stream or a diluate stream, meaning there are more salt ions or less respectively. By varying parameters such as voltage applied, residence time between the electrodes, and length of membrane a target concentration in the diluate stream can be achieved.

Overview of High Pressure Reverse Osmosis

Osmosis is the process by which solvent, in this case water, moves from a low solute environment to a high solute environment seeking equilibrium. A semi-permeable membrane commonly divides these two solute environments. Therefore the key component in reverse osmosis is a semi-permeable membrane. Reverse osmosis involves using a positive pressure to counteract the osmotic pressure and drive the solvent, in this case water, through the membrane from the high solute environment to a low solute environment. In order to reach higher recovery ratios it becomes necessary to proportionally increase the pressure applied across the membrane, since concentration scales linearly with pressure. For example to reach 80%, approximately 12 bar of osmotic pressure must be overcome.

Overview of Capacitive Deionization

Capacitive deionization works in a similar fashion to electrodialysis. The key difference is that there are no membranes to separate the ions and create diluate and concentrate streams. Instead the voltage potential draws ions directly to the electrodes and the entire stream is desalinated uniformly. Since the electrodes are exposed to the ions buildup of ions occurs over time reducing the effectiveness of these electrodes.

Overview of Multi-Effect Evaporation

Multi-effect distillation reuses the latent heat multiple times with the best designs being typically around 15 times more energy efficient that simple boiling [37].

Decision Matrix

In order to systematically select the correct desalination technology, a decision matrix (summarized in Table 9 of the Annex) was utilized in which the various technologies were scored and ranked using decision criteria that were weighted (1-5). Criteria included Water Recovery Ratio, Simplicity of Design, Unit Cost (Estimate), Ability to Prototype, and Operating Power. The following is a discussion of the criteria, technology ranking, and results of the decision making process.

Water Recovery Ratio

Water Recovery Ratio is key for market disruption and was given the highest weighting of 5. Recovery ratios possible for each technology were obtained from literature[38]–[40].

Simplicity of Design, Unit Cost, and Ability to Prototype

Technologies were compared considering the simplicity of the components, controls, and assembly. Including a criterion for Simplicity of Design was given a weighting of 4 and provided a means to contrast significantly different technological complexities of, say, Electrodialysis to Multi-effect Evaporation. Unit Cost, given a weighting of 3, considered some of the materials and componentry required. High Pressure RO, for example, requires higher-pressure pumps and a pressure vessel, which would incur a higher cost compared to Electrodialysis. Finally, the Ability to Prototype criterion was given a weighting of 3 and allowed for consideration of available project resources.

Operating Power

Operating Power, although not highly weighted, for desalination was a useful criterion to eliminate several technologies. Operating Power was given a weighting of 3 because target consumers are assumed to already own and operate energetically comparable appliances in the home, such as a refrigerators.

Design requirements for desalination previously discussed were applied to four (4) technologies: simple boiling (as a baseline), Multi-effect Distillation (the most efficient thermal desalination technology in the world), Reverse Osmosis (RO) and Electrodialysis (ED). Since the thermodynamic driving forces are the same in ED and CDI, operating power of CDI was not separately investigated. The equations and relevant inputs used are summarized in Table 8. For boiling, the power required was approximated as the heat input required to vaporize pure water at 12 L/h. Multi-effect distillation reuses the latent heat multiple times with the best designs being typically around 15 times more energy efficient that simple boiling [37]. High-pressure closed-circuit reverse osmosis was thermodynamically modeled by considering an osmotic pressure and a driving pressure difference along with pump efficiency. Osmotic pressure was calculated assuming aqueous sodium chloride feed and Vanthoff's law. Hydraulic pressure was assumed to be 2 bar based on available data for home water RO systems (where typically at 30% recovery, operating pressure was 4-5 bar) while pump efficiency was assumed to be 15% to match a power consumption of 40 W at 30% recovery. The low value is typical of small pumps. Electrodialysis power consumption was calculated using a model from Lee et al. [40]. Figure 13 shows the results of the simple comparison. ED was found to be capable of producing product at high recovery at low operating powers—lower than RO. RO in a simple constant pressure closed circuit configuration could achieve up to 80% recovery without additional operating power from current operating conditions of 30% recovery.

Table 8. Equations and input conditions used to model operating power of various desalination technologies.

Fixed:	**Varied:**
$m_{\mathrm{p}} = 12$ kg/h $S_{\mathrm{f}} = 3000$ ppm	$\mathrm{RR} = \dfrac{m_{\mathrm{permeate}}}{m_{\mathrm{feed}}}$

Output:

Technology	**Power, $P =$**
Boiling	$m_{\mathrm{p}} \times h_{fg}$
Best thermal tech.	$\dfrac{m_{\mathrm{p}} \times h_{fg}}{15}$
RO	$\eta_{\mathrm{p}} \times (\Delta\Pi + \Delta P_{\mathrm{drive}}) \times \mathrm{flow}$ $= \left[iRT\left(\dfrac{kS_{\mathrm{f}}}{1-RR}\right) + \Delta P_{\mathrm{drive}} \right] \times \dfrac{m_{\mathrm{p}}}{RR}$
ED	From, Lee et al. [40]

Tata Chemical Desalination Technology Decision Matrix (Input / Calculation)

Decision criteria weight: 1-5, higher weight = better or lower risk

Technology score: higher score = better or lower risk

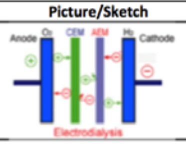
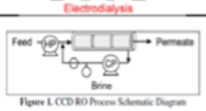
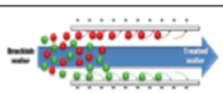
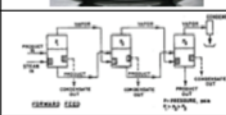
			Decision Criteria & Weight					
			Recovery	Unit Cost	Operating Power	Simplicity of design	Ability to Prototype	
Technology	Picture/Sketch	Description	5	3	3	4	3	Totals
Electrodialysis		Ion conecntration using potential difference. Membranes to isolate cations anions.	70-80% Recovery possible	Higher cost membrane, potential use of titanium	Low for low salinity (<5000 ppm).	Recirculation required. But low pressures, no pressure vessels	Materials available	
		Score - - >	5	3	5	4	5	22
		Weighted Score - - >	25	9	15	16	15	80
High Pressure Reverse Osmosis		Closed ciricuit high pressure reverse osmosis. 90% recovery.	90% recovery possible	Pressure vessel and high pressure pump	Lower than ED for >5000ppm. Better for 90% recovery (3x concentration) but likely needed only 10% of the time.	High pressure pump (20-30 bar) and high pressure recirculatin pump	RO unit could be re-configured	
		Score - - >	5	3	4	3	4	19
		Weighted Score - - >	25	9	12	12	12	70
Capacitative Deionization		Activated carbon electrodes. No membranes. 75% recovery obtained.	75-90% recovery possible	No rare earth elements. Carbon electrode but unknown manufacturing	Operating power comaprable or lower than ED.	Requires switching of polarity and water consumption for cleaning.	Fabricating good electrodes challenging	
		Score - - >	3	4	5	2	1	15
		Weighted Score - - >	15	12	15	8	3	53
Boiling		Simple boiling and condensation	>95% possible	Requires cheap electric or gas heater	High electricity consumption 7.2kW for 12 lph	Simplest design	Easy to test	
		Score - - >	5	5	0	3	4	17
		Weighted Score - - >	25	15	0	12	12	64
Multi-Effect Evaporation (I.e read best thermal technology)		Most efficient thermal technology. Reuses latent heat up to 10-15 times.	>95% possible	Expensive metal heat exchangers	Reasonably high electricity consumtion 340 W for 12ph	Multiple pressure vessels required. Vacuum pump to maintain pressure	Difficult to fabricate for small scale. Not commercially available in small scale	
		Score - - >	5	1	2	0.5	0	8.5
		Weighted Score - - >	25	3	6	2	0	36

Table 9 - Desalination Technology Selection Decision Matrix

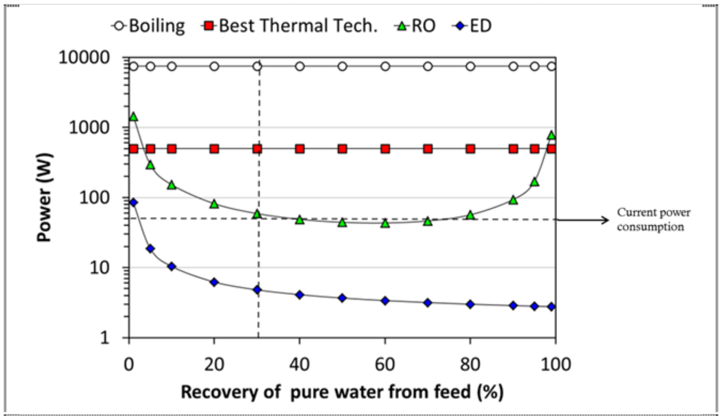


Figure 13. Variation of operating power required to produce 12 L/h of pure water from a feed salinity of 3000 ppm with recovery for different desalination technologies.

ED Test Results – Phase I

Results from the first phase of testing, experiments 1 and 2, are presented below in *Figure 14* and *Figure 15*.

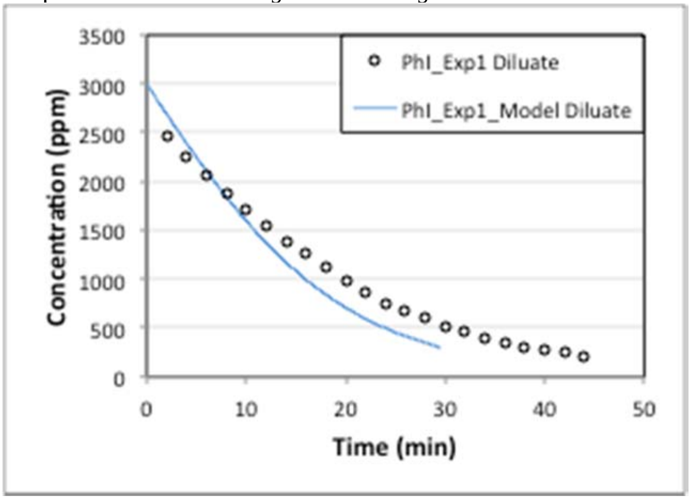


Figure 14. Phase I, Test 1 results (10 cell pairs, 1.6V/cell pair, 20 L/h)

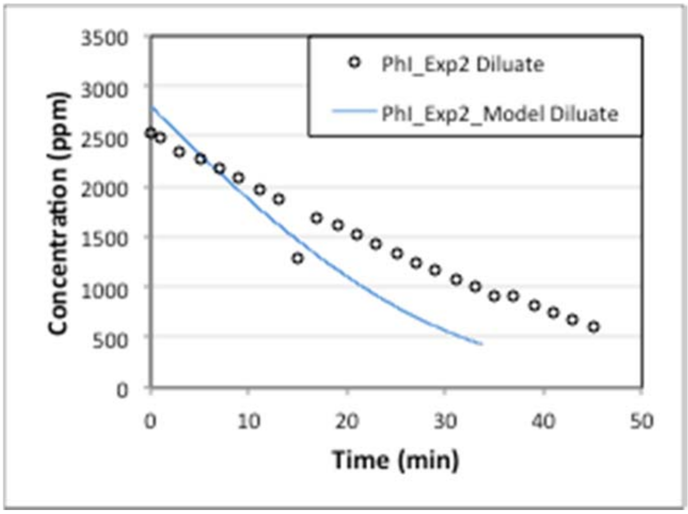


Figure 15. Phase I, Test 2 results (10 cell pairs, 1.0V/cell pair, 25 L/h)