Viability of Ion Concentration Polarization Technology for Creation of a Portable Desalination Unit

by

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ABSTRACT

Ion Concentration Polarization (ICP) is an emerging desalination technology developed by the Han Group of MIT Research Laboratory of Electronics. ICP desalination has significant benefits over conventional desalination technologies, and subsequently, may be well equipped for the creation of a portable desalination unit. Portable desalination units have applications in disaster relief and providing drinking water to remote regions of developing nations without established water infrastructure. In this thesis, the viability of a portable desalination unit based upon ICP is assessed. A number of different system modifications, both theoretical and experimental, are proposed to increase the propensity of ICP to meet the needs of such a portable system.

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i. Introduction

The inaccessibility of clean drinking water is a global humanitarian crisis. According to the World Health Organization, 844 million people still lack access to clean drinking water [24]. Every minute, a newborn baby dies from diseases caused by this deprivation [25]. The inaccessibility of clean drinking water is the biggest obstacle to development throughout much of the lesser developed world. Women's empowerment in these regions is severely hampered because women are disproportionately responsible for collecting drinking water [26]. Water deprivation is worst in rural remote regions and those impacted by natural disaster because they are cut off from water infrastructures; this often leads to the spread of epidemics through contaminated drinking water supplies [27].

Currently, there are two types of water purification systems on the market, individual home water purification systems and large scale industrial purification systems. All of the at-home purification systems currently available are extremely energy intensive making them cost-ineffective or inaccessible for poor, remote regions and those impacted by natural disasters [28]. While large scale industrial systems are far more energy efficient, they are also poorly equipped to service these isolated areas because of the difficultly and expense of transporting the water produced to people in need [29]. In order to better meet the needs of these underserved regions a portable desalination system was proposed. Ion Concentration Polarization (ICP) is a viable technology for the creation of such a portable system.

ICP is a membrane based separation process that utilizes Ion Exchange Membranes (IEMs) to remove ionic charges. The ion selective properties of these IEMs allows the removal of salts from feed water via the application of an electric field. [1] ICP is closely related to electrodialysis; both systems utilize ion exchange membranes and applied current to remove dissolved salts from solution. However conventional electrodialysis, utilizes both Anion Exchange Membranes(AEM) which allow conduction of negatively charged salts, and Cation Exchange Membranes(CEM) which allow conduction of positively charged salts; these membranes are stacked in AEM/CEM pairs and facilitate salt removal via bipolar ion

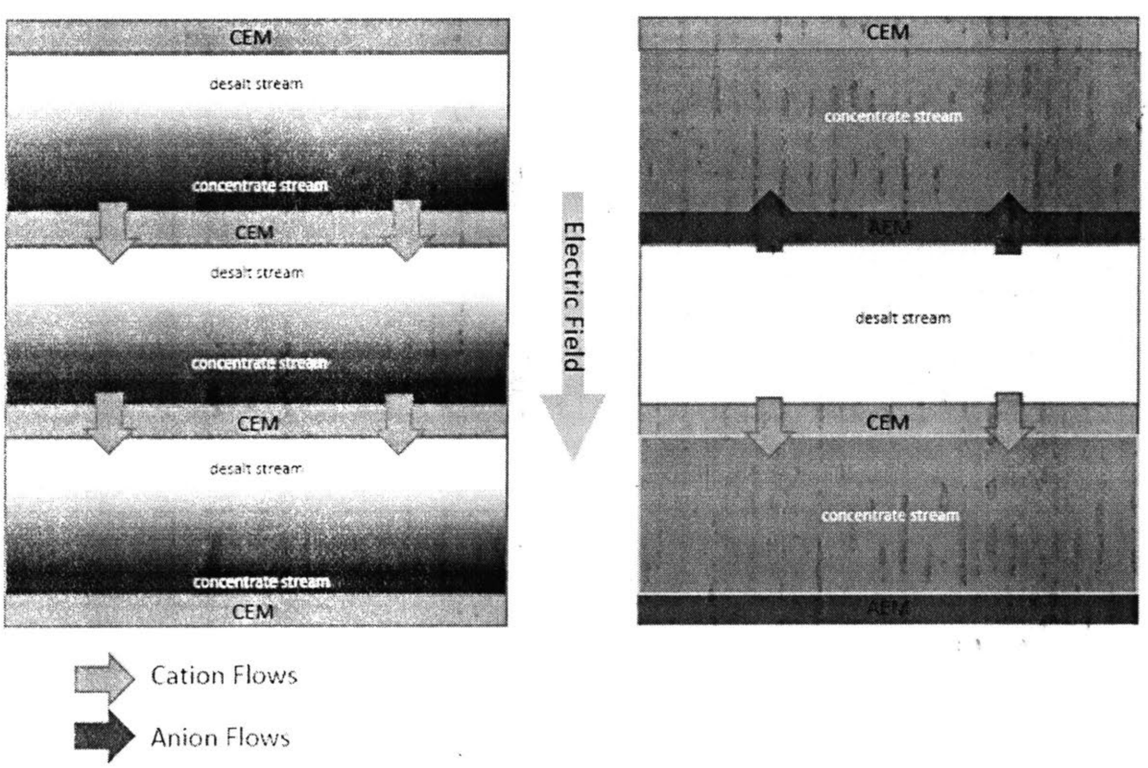


Figure 1- Stack Configurations for ICP and Electrodialysis [1]

In ED desalination, anions and cations migrate in opposite directions under the influence of an applied current, creating alternating channels of desalted and brine waters. In ICP desalination, anions are unable to migrate across the CEMs, causing them to accumulate on the cathode side of the CEM interface. Cations are able to migrate across the CEM and also accumulate on the cathode side of the membrane. This creates separate concentrate and brine streams within each of the channels which need to be separated to achieve purification.

conduction. In contrast, ICP utilizes only one type of Ion Exchange membrane and removes salt via unipolar ion conduction [2]. Structurally, the most significant difference between ICP and ED systems is that ICP purification stacks must facilitate laminar flow in order to prevent mixing of brine and desalt streams within the stack; this is necessary in order to maintain high salt removal and current utilization. In contrast, electrodialysis requires mixing of boundary layers in order to maximize salt removal. Figure 1 above illustrates standard setups for electrodialysis vs. ICP and the flow of ions in each setup.

Although reverse osmosis is currently considered to be the dominant technology in the desalination market, ED and ICP are still considered to be a highly developed water purification technologies and are rising in prominence [2]. Ion exchange purification processes are valuable for a number of ion manipulation applications such as acid and base production, water softening, waste water treatment and energy production via reverse-ED processes [3]. Because of the parallels between ICP and ED systems, they share many of the same benefits: high quality output water, improved ion controllability, scalability and versatility [2].

ICP also has particular benefits as compared to a conventional ED system. Unlike ED, ICP does not requires the simultaneous removal of cations and anions can therefore take advantage of differential migration speeds of ions in solution; in NaCl solution, Chloride ion migrates ~ 52% faster than sodium ion when subject to an electrical current, allowing for significantly faster removal of ions [2].Theoretical analysis illustrated a 20% increase in current utilization (CU) and a 50% decrease in Energy per Ion Removal (EPIR) for CEM-only ICP as compared to electrodialysis with NaCl feed solution [2]. The separation of desalted and brine flows within an ICP channel also makes it possible for cells, colloids and other dissolved solids that cannot cross IEMs to be removed from the solution [2]. The removal of all suspended solids from solution removes the necessity of pretreatment for the system [5]. Additionally, because ICP purification stacks that include porous membranes are capable of withstanding a hydraulic pressure difference, it is possible to manipulate recovery ration by changing the flow ratio in the different channels [2]. This manipulation of flow ratio can be utilized either to achieve ultra-pure output waters or improved recovery ratios [1]. ICP systems can also be quickly implemented for a number of different applications. In many cases it is possible to convert an existing ED unit into an ICP unit simply by replacing all CEMs with AEMs or vice versa [2].

The relative scalability and decreased energy consumption ICP systems makes them theoretically ideal for creation of a portable desalination unit, which can potentially provide drinking water to remote, capital-poor regions. This is an obvious advantage over reverse osmosis, which requires energy intensive, high pressure pumping in order to overcome the significant osmotic pressure gradients in salty water [1]. ICP technology has been shown to be highly effective for purifying high salinity brine because of the high conductivity of the solutions [4,5]. However, little work has been done to assess the effectiveness of ICP for producing drinkable quality water from saline feed water. The focus of this thesis work will be assessing the suitability of ICP for creating drinkable quality water and optimizing the current ICP unit to better meet the requirements of a portable system for drinking water production.

ii. Suitability of ICP System for Creation of a Portable Desalination Unit

In order to determine the suitability of ICP technology for creation of a portable desalination unit, it was necessary to first a set determine of criteria by which to assess the system. Table 1 summarizes the results of this analysis. Based upon this analysis, it was determined that the most critical design constraints were feed water composition, output flow rate and output water quality. As a result, later work will focus on testing and optimization of these particular parameters.

Category	*Qualitative Criteria*	*Quantitative Specification*	*Priority*
Portability	Able to fit into the trunk of a car and be carried by 2 people	Smaller than 1m x 1m x .15m Less than 100lbs	Preferable
Feed Water Composition	Seawater, no bacterial or VOC components	35,000 ppm NaCl [6]	High
Output Water Quality	Drinkable Quality Water	150 < ppm TDS, < 500 [7]	Critical
Output Flow Rate	Must provide water for at least a small family	Minimum 40L/day [8]	Critical (exact amount required is application dependent)
Ease of Use	Intuitive User Interface, Quick setup	Requires less than 30 minutes to setup	Preferable
Energy Source	Able to be powered by a small solar panel	Maximum Power Consumption: 50W[9]**	Preferable (Use of AC power may also be acceptable)

Table 1- Summary of design constraints for portable ICP unit

A set of qualitative criteria were determined based upon end user needs. These end user needs were then converted to quantitative criteria, in order to objectively determine whether ICP was able to satisfy these criteria. Finally, each of the criteria was assigned a priority level to determine what factors to emphasize in later work.

*Assumes that the system will only provide water for short term survival needs (drinking and cooking)

iii. Design Challenges and Proposed System Configurations

There are several foreseeable challenges to utilizing ICP to meet these system requirements. ICP may not be the ideal technology for producing drinkable quality water because it is energy intensive at low salinity levels and the output flow rates may be too low to be usable. Producing drinking water from seawater requires a 99% reduction in salinity [6,7] The required energy per ion removal in this salinity regime is very high, making the process extremely energy intensive [4]. Additionally, in order to achieve such low salinity, the operating current density of the system must be very low to prevent damage of the membranes [2]. As a result of this low current density, ions migrate out of solution very slowly, meaning that the flowrate must be very low in order to achieve the desired levels of purity [9].

In order to attempt to address these challenges, two different potential system configurations were proposed: recirculation systems and hybrid systems. In an ICP recirculation system, partially desalinated water would be recirculated into the ICP unit as feed water to be further purified. In the proposed hybrid system model, two different water purification systems are connected in series, allowing each of the systems to remove a smaller percentage of the total salinity of the feed water. Because the total energy consumption and EPIR of ICP increase at lower levels of salinity, it may be worthwhile to pair ICP with another purification system that is more efficient at lower salinity levels [4]. These hybrid/ recirculation systems would maintain many of the benefits of ICP desalination, such as lower power consumption and pretreatment requirements, but also has the potential to provide more economical drinking water than the current ICP system alone can provide. Several different hybrid/recirculation systems were proposed, each with a unique potential to improve the efficiency of the purification process.

a. ICP Recirculation System

As salt ions are removed from the desalt channel of the ICP system, the limiting current density in the desalt channel decreases [1]. To prevent damage of the IEMs, ICP units should not be operated above 70% of the limiting current density of the least saline water in the system [9]. This is particularly problematic when ICP is used to produce drinkable quality water, because the limiting current density of drinking water is so low. In order to achieve high levels of purity with such a low limiting current density very low flow rates are required [2]. In a recirculation system configuration, a smaller salinity drop across the purification stack would be required; the partially desalted water would be recirculated through the system to be further purified until the desired level of salinity is reached. The voltage would be changed during each circulation cycle to match the limiting current density for that salinity level. One major consideration for this kind of system would be designing a sophisticated enough control system to automatically change the voltage during each of the circulation cycles. A schematic of this system is provided in Figure 2. A recirculation system could increase the speed of the purification process because a higher current density can be used in the early stages of the recirculation process. This system could potentially to achieve higher salt removal, even though less ions are removed at each stage, because the current can be regulated to achieve high removal ratios. Additionally, since the recirculation configuration only requires a single purification unit, it may be best suited to meet the space constraints of a portable system. One drawback of a recirculation design is low recovery rates; every time that water is recirculated through the system, 25% will be lost as waste water discharge. There are also concerns about the time required to recirculate the flow; this could potentially outweigh the benefits of increased flow rate.

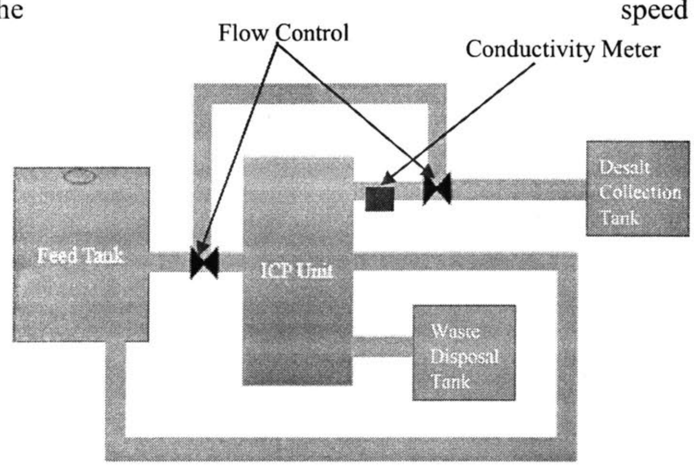


Figure 2- Schematic of fluid flows in ICP recirculation system.

Water flows from the feed tank into the ICP unit, which separates it into concentrate, intermediate and desalt flows. Water from the concentrate channel is collected in a tank for disposal. Water from the intermediate channel is recirculated to the feed tank in order to increase recovery ratios. As the water exits the desalt channel of the ICP unit, the salinity is measured. This water is re-circulated until it's been sufficiently desalted. The current in the ICP unit is altered every cycle to match the limiting current density for that salinity level. When the water has been sufficiently desalted, a valve opens to allow it to enter the desalted water collection tank.

ICP / Capacitive Deionization Hybrid

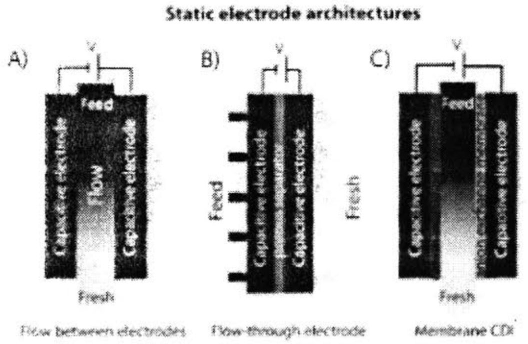


Figure 3 - Summary of CDI Electrode Architectures

CDI produces high salinity feed water through electrosorption of ions on the surface of capacitive electrodes. This technology is particularly effective and energy efficient at achieving high quality output water from brackish feed waters. Flow-through Electrode CDI, Membrane CDI and Standard Flow CDI, three of the most common electrode architectures are shown [11]

Capacitive Deionization (CDI) is an emerging technology in the field of desalination. It is based on ion electrosorption on the surfaces of a pair of electrically charged, porous carbon electrodes [11]. A summary of commonly used CDI system architectures are summarized in Figure 3. CDI is ineffective at high salinity levels because of the limited electrosorption capacity of the carbon electrodes; it has, however, been shown to be highly effective for achieving high levels of purity from low salinity source water. CDI has commonly been used for achieving high levels of purity from ED purified feed water [11]. ICP and CDI could be very compatible technologies for a hybrid system because they are most efficient in complementary operating regimes.

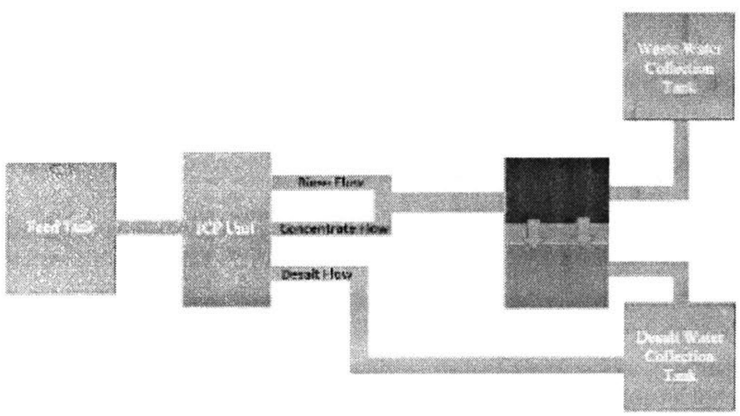


Figure 4- Schematic of fluid flows in the ICP unit.

Water exits the feed tank and enters the input of the ICP unit; rinse and concentrate outflows enter the feed side of the membrane distillation unit while the desalt flow is routed to a desalted water collection tank. Water from the feed side of the MD unit crosses the hydrophobic membrane as water vapor and condenses as distillate water before being mixed into the desalt water tank.

b. ICP/ Membrane Distillation System

Membrane distillation (MD) is a heat-driven membrane desalination process. Feed and distillate waters are separated by a hydrophobic membrane [11]. A high temperature is imposed on the feed side of the membrane, facilitating the creation of a vapor pressure gradient and the movement of water vapor across the membrane, where it eventually condenses as distillate water. This water needs to be re-mineralized before it can be consumed [11]. In a hybrid MD/ ICP system, distilled water from the MD system will be mixed with the ICP desalted water to produce this final output water. By combining these two output waters, less purification is required of the ICP unit and re-mineralization of the distilled water would not be required. Additionally, the heat generated at the electrode of the ICP unit can be utilized to drive the membrane distillation process. This process is illustrated in Figure 4. This hybrid system could potentially help to increase output flow rates and lower the energy requirements of each of the systems. However, the complexity of such a hybrid system may outweigh its benefits and it may not be more efficient than operating the systems individually.

c. *ICP/ Reverse Osmosis Hybrid*

An ICP/ Reverse Osmosis hybrid system could also have significant benefits in terms of increasing flow rates and energy efficiency. Reverse Osmosis is a membrane-driven water purification process in which a high pressure pump is used to facilitate the flow of water through a porous membrane [12]. Salts and other dissolved contaminants are rejected by the membrane, allowing only pure water to pass through the membrane. Reverse osmosis is significantly more energy intensive at higher salinity levels because there is a larger hydrostatic pressure gradient that must be overcome in order to drive water across the membrane [12]. In this hybrid system, the water would first flow through the ICP system at high salinity and then through the RO system at lower salinity, utilizing each of the systems in the salinity regime where they are most efficient. Because less salinity must be removed by each stage of the system the throughput flow rates would be higher than can be achieved by a single-stage system. There are however, significant concerns of sizing constraints for use in a portable system because of expansive pump required by reverse osmosis [12].

d. ICP/ Electrodialysis Hybrid

ICP and Electrodialysis are potentially compatible technologies for a hybrid system. While ICP has significantly improved energy efficiency in high salinity regions, electrodialysis is a well-established technology and has been optimized to maximize recovery ratio and to operate more effectively in high salinity regimes. By utilizing ICP and ED in series, as is shown in Figure 5, it may be possible to achieve higher energy efficiencies than the systems could achieve individually. Because ICP and ED are closely related technologies they require many of the same system components; both systems require a voltage source, ion exchange membranes and circulation pumps. Many of these elements could possibly be shared both systems, making it far more feasible to incorporate this hybrid into a portable system. A 3D rendering of a potential ICP/ED portable system is shown in Figure 6.

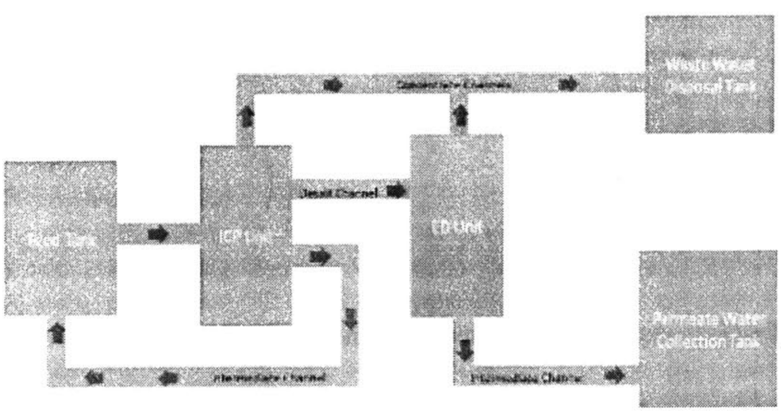


Figure 5- Schematic of ICP/ED system

Water flows from the feed tank into the ICP unit where it is partially desalinated before the desalt waters entering the ED unit to be further purified. The intermediate channel from the ICP unit is recirculated into the feed tank and the concentrate channels from the ED and ICP units are routed to the waste water tank for disposal.

e. Summary of Potential ICP System Configuration

Each of the potential ICP system configurations proposed above has unique features that could potentially increase the output flow rate or energy efficiency of the unit. A summary of each of the system configurations and their comparative advantages and disadvantages are summarized in Table 2 below.

Proposed Technology	Feature	Advantage	Disadvantage
ICP Recirculation System	-Desalt Channel Concentration Monitoring - Recirculation of Output Waters -Limiting current density is changed with each circulation	- Decreases the required energy to produce high quality output water - Faster flow velocities can be utilized	- Low recovery rates due to losses in every circulation cycle - Recirculation could be too time consuming a process
ICP/Capacitive Deionization Hybrid	- Water is treated first with ICP and CDI is used as a secondary treatment method	-Utilizes the most efficient operating regimes of each system	- Both technologies are relatively undeveloped and have not been optimized for maximum efficiency
ICP/Membrane Distillation Hybrid	-Output waters from membrane distillation are mixed to produce drinkable quality water	- Capable of achieving high quality output water - Can increase the energy efficiency of the system	- Not necessarily compatible technologies for a hybrid system due to different purification methods
ICP/ Reverse Osmosis Hybrid	- Input water is treated first with ICP and secondarily by reverse osmosis	-Does not require pretreatment -Utilizes the most efficient operating regimes of each system	- Requires many large system components, may not be compatible with portable system
ICP/Electrodialysis/ Hybrid	- Water is treated first with ICP system and then by the Electrodialysis system	-Utilizes shared system components - ED has been optimized for improved energy efficiency	- Neither of the systems are most efficient in the low salinity operating regime

Table 2- Summary of Proposed Purification System Configurations

Each of the system configurations were proposed because of a compatibility between the systems that could potentially improve the efficiency of the system compared to ICP alone. The defining features, advantages and disadvantages of each system configuration are summarized.

iv. Construction of ICP System for Testing

In order to assess whether ICP is a suitable candidate for creation of a portable desalination unit, and if any of the proposed hybrid /recirculation configurations would be beneficial, it was necessary to understand the challenges faced by the current ICP system. This entailed first observing the construction and operation of the current ICP unit being utilized by the lab. The system was then reconstructed with two significant modifications. First, a bifurcate system design was utilized in place of the trifurcate system currently in use. In a bifurcate system configuration, only desalt and concentrate channels are present in the ICP unit. There are two primary benefits of the bifurcate system configuration. First, it is simpler to fabricate and operate a bifurcate system because it is less complex. In operation of a trifurcate system, the flow rates of the intermediate, desalt and concentrate channels must be controlled separately in order to maximize the efficiency of the system. By removing one of these controls, the system will become easier to build and operate. The second benefit is that removal of the intermediate channel decreases the thickness of the ICP unit; this therefore decreases the amount of voltage and power required to provide a given current density. Additionally, decreasing the thickness of the channel means that more ICP purification stacks are able to be stacked within a particular volume. This could potentially increase the output flow rate that a system of a given system size is capable of providing. Because this project is addressing the viability of portable ICP desalination, the compactness of ICP purification stacks and the size of the power source required to operate the system are important factors to optimize.

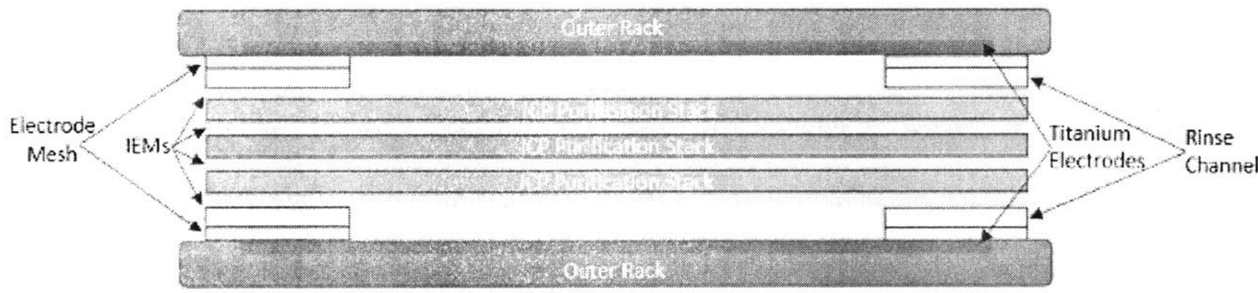


Figure 6- Schematic of ICP Unit Construction

This image shows the placement of all components of the completed ICP unit design. Each of these components are labeled, and these names are referenced later in the explanation of the fabrication process.

One of the drawbacks of the bifurcate system is that it only has a 50% recovery ratio, compared to standard electrodialysis which can achieve as high as 80% recovery ratios [23]. In the current trifurcate system design, water in the intermediate channel does not experience a significant change in salinity, and can therefore be recirculated to the feed tank. However, based upon the specifications laid out in Table 1, it was determined that seawater would serve as the feed water for the system. Because this feed water is available in large quantities at low or no cost, recovery ratio was not an important factor to be considered. Another drawback of the bifurcate design is the potential for increased diffusion of salts from the concentrate to desalt channels. In a trifurcate ICP purification stack design the intermediate channel acts as a buffer between the high salinity concentrate channel and the low salinity desalt region, minimizing the movement of salts into the desalt channel via diffusion and the movement of water from the desalt to the concentrate channel via osmosis [1]. Without the presence of the intermediate channel, these transport processes will likely play a larger role in determining the salinity of the output water of the system. However, before constructing and testing these bifurcate purification stacks, it is difficult to predict how much of an impact that they will have.

The second change made in the modified design was a doubling of the channel length of the ICP unit. All of the other channel geometries for the ICP unit were maintained. Doubling the traveling length of the purification stacks will increase the amount of ions removed for a given current density and flow rate because the ions have more time to migrate out of the desalt channels [4]. In creating a portable system, it is important to weigh the benefits of increased traveling length with considerations of sizing constraints. In the modified system, doubling the channel length did not significantly alter the size of the ICP system relative to other system components such as pumps, power sources and water reservoirs. However, further increases in channel length would require greater consideration of sizing constraints. The modified ICP test unit was fabricated with these two design changes; a schematic of the ICP desalination unit to be constructed is shown in Figure 6. The process of ICP fabrication is detailed in the sections that follow.

Outer Frame Fabrication

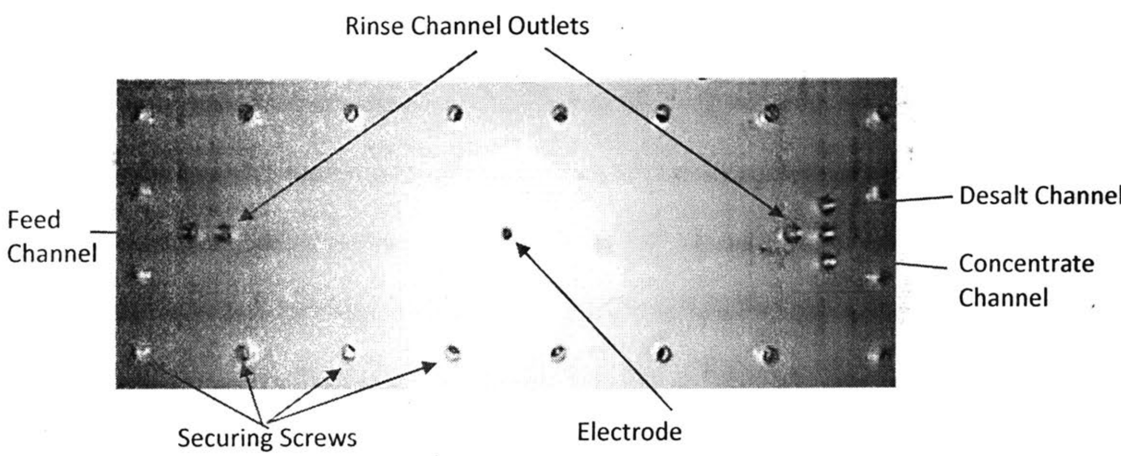


Figure 7- Image of ICP Outer Rack structure

The outer rack structure serves to connect the ICP purification units to the rest of the testing system. They allowed for the connection of the rinse, concentrate and desalt channels on the ICP units to be connected to the rest of the system. The electrode connection allows for the transmission of current into the ICP unit stacks. The outer racks allow the stacking of the ICP units and the securing screws holds the units together to prevent leakage.

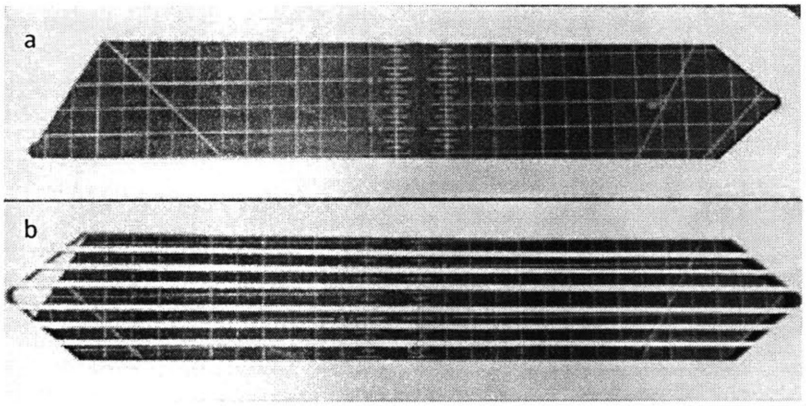


Figure 8- Templates for desalt and intermediate channels for ICP unit fabrication.

Silicon rubber could not be cut with the laser cutter because the heat of the laser melted the silicon material. Instead, these templates were used to precisely cut the silicon into the desired channel shapes.

The top and bottom outer racks were laser cut into 1/2" thick PTFE clear plastic according to the CAD drawings in Appendix 1a and Appendix 1b. The prepared outer rack structure is shown in Figure 7. Templates for the rinse channel and electrode mesh were laser cut into 1/16" thick PTFE plastic according to the CAD drawings in Appendix 1c and Appendix 1d. Two pieces of 1/8" thick adhesive-backed silicon rubber were cut with an x-acto knife according to the electrode mesh templates prepared above and two pieces of 1/16" thick adhesive-backed silicon rubber were cut according to the rinse channel templates were also prepared based on the template prepared above. The silicon rubber electrode meshes were attached to the outer frames using the adhesive backing of the silicon rubber. The copper mesh was cut according to the dimensions specified in Appendix 1e and fitted into the space in the electrode mesh. The titanium electrode was cut to dimensions specified in the drawing of Appendix 1d. A thin layer of epoxy around the edge of the titanium electrode. The titanium electrode was fitted into the space in the mounted rinse channel cutout and pressed down to create adhesion between the electrode and the outer frames. Two pieces of 1/16" thick adhesive-backed silicon rubber were cut with an x-acto knife according to the electrode mesh templates prepared above. The silicon rubber electrode mesh was aligned with the rinse channel and adhered. Rinse, feed, concentrate and desalt channel holes were tapped with a 1/8 NPT pipe and conduit thread tap and electrode connection holes were tapped with a 5/16"-18 general purpose tap. Push-to-Connect Tube Fittings (Adapter for 5/16" Tube OD x 1/8 NPTF Male Pipe) were wrapped in 3 layers of Teflon tape and screwed into the tapped rinse, feed, concentrate and desalt channels. A 3" screw (Super-Corrosion-Resistant 316 Stainless Steel Hex Head Screw 5/16"-18) was wrapped with 3 layers of Teflon tape. Electro-conductive adhesive was applied to the end of the screw to ensure adhesion to the titanium electrode. The screw was rotated into the hole until contact was made with the electrode and the electro-conductive adhesive was dried overnight.

Bifurcate ICP Purification Stacks Fabrication Methods and Results

Several different bifurcate ICP stack designs were constructed according to the designs below and tested to determine their robustness and effectiveness.

Design 1

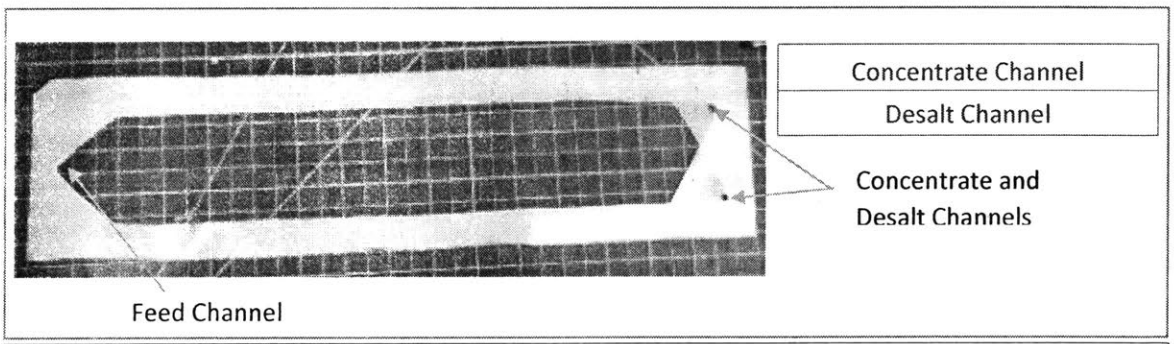


Figure 9 – ICP Unit Design 1

In this design, feed water enters and travels along the channel. The concentrate and desalt streams are separated into their respective channels. This design was not ideal, because it did not contain a support structure or porous membrane to suppress vortex formation.

Templates for the intermediate and concentrate channels were laser cut into 1/16" thick PTFE plastic according to the CAD drawings in Appendix 1f and 1g and are shown in Figure 8a above. Two pieces of 1/32" thick adhesive-backed silicon rubber were cut with an x-acto knife according to the templates prepared. The channels were aligned and adhered each other using the adhesive backing of the silicon rubber.

This design was the thinnest of all the ICP stack designs, meaning that it requires the smallest voltage drop to drive the purification process. However, this design was difficult to fabricate because the silicon rubber used to form the concentrate and desalt channels stretched and deformed easily during fabrication. This also made it difficult to align the stacks when stacking them. Finally, this design also did not have a porous membrane for electro-convective vortex suppression.

Design 2- Rigid Support Structure

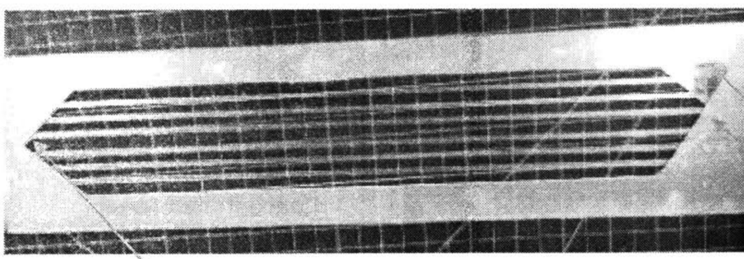


Figure 10 – ICP Stack Design 2

In this design, a silicon rubber desalt channel is mounted atop a PTFE concentrate channel and produces a rigid ICP unit design. The bar support structure was successful in preventing the deflection of the porous membrane but prevented even distribution of water throughout the channels.

An alternate concentrate channel design was laser cut into 1/16" thick PTFE plastic according to the specifications in Appendix 1h and is shown in Figure 8b. A piece of 1/32" thick adhesive-backed silicon rubber was cut with an x-acto knife according to the template prepared for Design 1. The silicon rubber channel was adhered to the PTFE concentrate channel using the adhesive backing of the silicon rubber. The bar structure was beneficial because it provided better support for the CEM's when the stacks were placed on top of each other. The use of the solid PTFE concentrate layer made the system easy to fabricate because there was no stretching or deforming during fabrication. The rigidity of the structure also makes it easier to stack and align multiple purification stacks on top of each other. Despite its benefits, this design would need to be altered because the bar structure prevented even distribution of water across the different ICP unit stacks. Additionally, because the thinnest available acrylic is 1/16", this is the thickest proposed ICP design. Additionally, because the concentrate channel is thicker than the desalt channel in this design, the recovery ratio for this design is lower than that of design 1. Finally, this design also had no porous membrane to suppress electro-convective vortex which could lower the efficiency of the system.

Design 3- Porous Membrane Channel

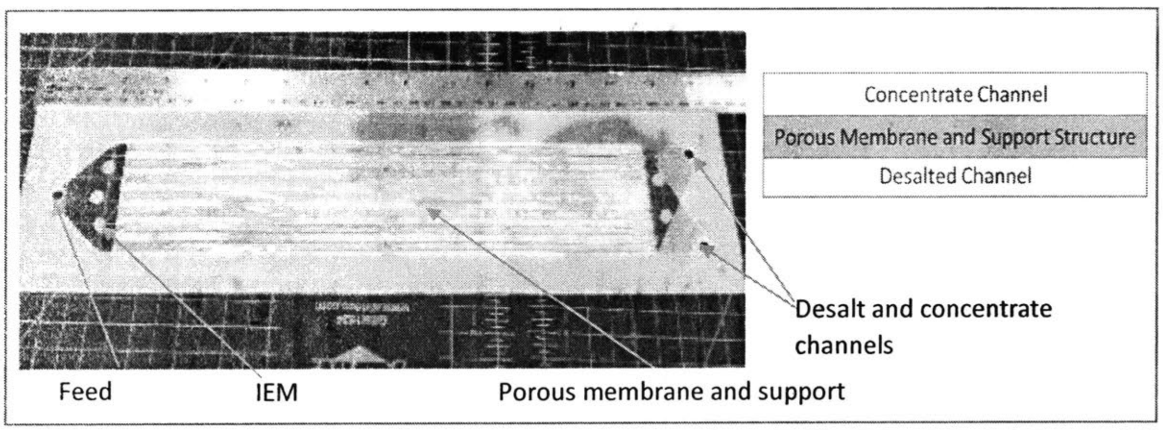


Figure 11- ICP Stack Design 3

Water enters through the feed channel and distributes through the stack through the gap in the thin film structure. The porous membrane allows the movement of salts and water to form concentrate and desalt streams and suppresses electro-convective vortex formation. The concentrate and desalt streams are separated into two channels on either side of the thin film.

A 500 um thick PET thin film sheet was cut to the 320mm x 500mm and one side of the film was covered with 3M 467MP double sided tape. The thin film was laser cut according to the CAD drawing shown in Appendix 1i. The double-sided tape backing was removed 2 mm from the edge of the structure in order to allow for adhesion of porous membrane. The Sterlitech

PCT1020030 porous membrane (1 micron thick, 1 um pore size) was well adhered to the thin film support structure and excess porous membrane was removed from the edges. The 1/32" thick adhesive-backed silicon rubber was cut with an x-acto knife according to the concentrate and permeate channels templates prepared for Design 1. The concentrate and desalt channels were aligned and adhered to opposite sides of the thin film layer support structure. A template for hole placement was laser cut into 1/16" PTFE plastic according to the CAD drawing in Appendix 1j. Holes were punched in desalt and concentrate channels, using this template, to allow for water output flow. The outer edges of the ICP stack were cut according to the template to allow for alignment. The 1/32" silicon rubber was cut into strips 5mm shorter than the length of the channel and 3mm wide. The strips were adhered to thin film in order to provide support for the IEMs.

This design utilized the best elements of the previous designs as well as incorporating new elements. The inclusion of the porous membrane was helpful in suppressing electro-convective vortex formation. The silicon rubber support structure was effective in preventing deflection of the CEMs during system usage. Connecting this support structure to the porous membrane rather than to the outer parts of the channel allowed free movement of the water in the channel and the opening in the thin film structure allowed for even distribution of the water across the different stacks. The thin film did not significantly change the thickness of the stack, but was sufficiently rigid to prevent significant deformation during fabrication. The most significant problem with this design is the difficulty of fabricating the purification stack. There are many pieces that need to be carefully aligned in order for the system to function properly and the porous membrane is very susceptible to tears during the fabrication process.

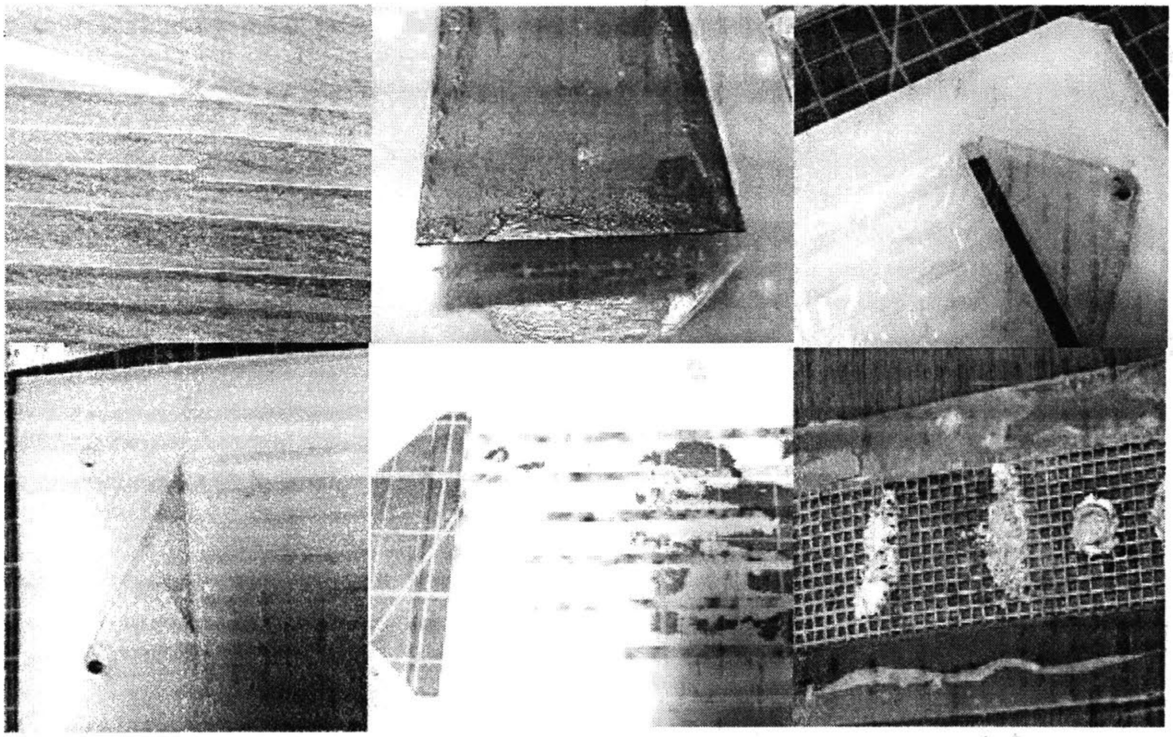


Figure 12- Difficulties fabricating ICP test unit

a. When laser cutting the bar structure, the bars often bent and deformed under the heat of the laser. This deformation led to misshapen and broken bar structures that were not suitable for ICP fabrications. In order to prevent this deformation, two separate cuts were made, each cutting half the thickness of the PTFE. The decreased power produced by these cuts resulted in less heating and deformation of the thin bar structure.

b. Poor adhesion led to separation between the electrode and rinse channels. This malfunction prevented the transmission of current across the ICP unit and led to corrosion of the electrode mesh. In order to prevent this kind of malfunction, the area was carefully cleaned of dust and other particulates that could prevent adhesion. The surface of the electrode was slightly roughed using sandpaper to increase the surface area on the electrode. After the adhesive was applied, weight was placed uniformly over the electrode surface and left overnight to ensure proper contact between the electrode and the rinse channel during drying.

c. Because each of the ICP unit stacks was fabricated by hand, there were slight differences in the way they were each manufactured. The resulting misalignments lead to blockages of water flow and leakages between desalt and concentrate channels. In order to prevent these blockages, the channel inputs and outputs were cut after all of the stacks were fabricated and aligned. This, however, did not fix misalignments in the channels. If these channel designs are effective, it will be important to create a more effective process for producing consistent ICP unit designs.

d. The porous membrane was extremely susceptible to tearing and fouling. Great care needed to be taken both in the fabrication and storage of the ICP stacks to prevent such damage to these membranes.

e. Leakage in the rinse channels led to corrosion of the copper mesh and titanium electrode.

During the early stages of the process, many fabrications failed because of difficulties in carrying out the procedures detailed above or human error in manufacturing. These challenges are summarized in Figure 12.

ICP Test Unit Assembly

Following the successful fabrication of the ICP stacks and outer racks, the entire testing unit was constructed. ICP purification stacks were constructed based upon Design 3, described above. The CEMs were soaked in 35kppm NaCl water overnight. Using the same PTFE template as ICP Unit Design 3 above, the outer edges of the membranes were cut and holes for feed, desalt, and concentrate channels were punched in all but 2 of the CEMs. The outer rack base was placed electrode side up on the table and one of the CEMs, without holes, was stacked to act as a cover for the rinse channel. The first ICP purification stack was placed with the desalt channel facing upwards and a CEM membrane, with holes punched for input, desalt and concentrate channels, was placed atop the stack. Steps f & g were repeated for each of the ICP unit stacks in the test unit. The remaining CEM was stacked atop the ICP units to act as a cover for the upper rinse channel. The flow side of the ICP outer racks was placed atop of the stack and the alignment of the unit was confirmed. Finally, the securing screws were placed through the structure and secured with wingnuts starting at opposite corners and moving towards the center.

Testing Apparatus Construction

A testing apparatus was constructed that contained all of the system elements required for operation of the unit. The testing apparatus is diagramed in Figure 13.

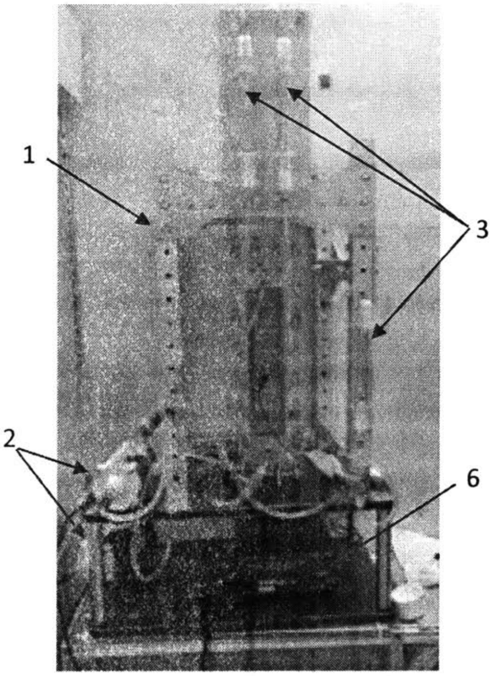


Figure 13- Schematic of ICP unit testing apparatus

1. A frame was constructed to support the ICP unit and testing apparatus.
2. 2 different pumps were sized according to the flow rate and pizeometric head requirements of the rinse and input flow channels.
3. Flow Meters and control valves were installed to monitor the flow rates of the ICP unit's input, output, and rinse channel flows.
4. Tubing was sized according to the necessary flow rates of the unit as well as the pipe sizes of the ICP unit input and outputs
5. Conductivity probes were used to measure the salinity of the output water and determine the salt removal (not shown)
6. The power source was used to create a voltage drop across the system to facilitate the movement of ions

ICP Unit Testing

After fabricating the ICP unit, the operational flow rates for testing were selected based upon previous ICP research. In this work, the salt removal ratio was determined for different combinations of flow velocities and current densities. A summary of the relevant data is

35K TDS		V=0.25mm/sec					35K TDS		V=3.0mm/sec				
SRR(%)	Power(Wh/L)	Current(A)	Voltage(V)	Q(mL/min)	W	W/m^2	SRR(%)	Power(Wh/L)	Current(A)	Voltage(V)	Q(mL/min)	W	W/m^2
10	0.112	0.087	0.029	0.375	0.002523	0.140166667	10	0.342	0.952	0.097	4.5	0.092344	5.130222222
30	0.63	0.3	0.051	0.375	0.0153	0.85	30	5.92	3.44	0.465	4.5	1.5996	88.86666667
50	2.473	0.562	0.099	0.375	0.055638	3.091	50	35.45	7.42	1.29	4.5	9.5718	531.7666667
70	7.89	1.06	0.1675	0.375	0.17755	9.863888889	70	138.1	13.51	2.76	4.5	37.2876	2071.533333
90	20.24	1.822	0.25	0.375	0.4555	25.30555556	90	-	-	-	-	-	-

Table 3-4 - Summary of relevant data from previous work on ICP [5]

In order to determine the optimal combination of flow rate and salt removal current levels for ICP, raw data from Dr. Kim's previous work was used. .25 mm/second was the only flow velocity capable of achieving upwards of 90% salt removal ratio, but the corresponding flow rates are too low to be useable. Alternatively, the 3mm/sec flow rate provides an appropriate flow rate but insufficient salt removal. These factors must be weighed in the design of a portable system.

provided in Tables 3 and 4 above. Because the objective is to produce drinkable quality water from seawater, greater than 90% salt removal will be required [6,7]. From 35kppm feed water, .25mm/sec was the only flow velocity able to achieve 90% salt removal ratios. However, at this flow rate, 100 ICP purification stacks would be required in order to achieve target flow rates laid out in Table 1. Because of the difficulties of aligning the stacks and the large voltage drop that would be required, this system configuration is not feasible. Instead of trying to achieve complete desalination by ICP, a higher flow velocity and lower salt removal ratio were selected. At a flow velocity of 3 mm/sec it was possible to achieve 70% salt removal ratio. At this flow rate only 9 stacks would be required to achieve desired output flow rates, but a secondary method such as electrodialysis or reverse osmosis would be required to achieve drinkable quality water. After selecting this flow rate, the rest of the flow conditions were calculated. A summary of the selected flow conditions can be found in Table 5

Single Stack ICP Testing Methods and Results

System Parameter	***Qualitative Criteria***
Target Output Flow Rate	5 L/h
Input Flow Rate	10 L/h
Target Flow Velocity	3 mm/ second
Input Flow Rate per Stack	20 ml/ min
Number of Stacks required to achieve target flow rates	9

Table 5- Summary of Operating Condition for ICP Unit Testing

The target output flow rate was calculated based upon a required daily output of 40L/day. Because the system has a 50% recovery ratio, the input flow rate must be twice the desired output flow rate. The target flow velocity was selected based upon the above analysis and the per stack flow rate was calculated using the flow velocity and cross sectional area of the channel. The number of required stacks was then determined by dividing the total input flow rate by the per stack flow rate.

A test system was constructed with a single stack according to the ICP system assembly instruction provided above. The single stack system was operated at a 20ml/min flow rate according to the conditions selected in Table 2. The current was set to an initial value of 1A and after a 5-minute equilibration period, the salinity of the output water was measured every 5 minutes for a 30-

minute period. Changes in the salinity of the desalted water were recorded over this period. No further changes in salinity were observed after the 30-minute measurement period. This procedure was repeated with current levels of 2A and 3A. The experiments were repeated 3 times in order to minimize the effects of confounding variables and experimental errors. The average data across each of these trials is reported in Figure 13 below.

The results of these experiments indicate that the single stack bifurcate ICP unit was not capable of achieving the same salt removal ratios as the results in Figure 12 would indicate. With 2 Amps of current and the corresponding density of 320.5 A/m^2, the system should have been capable of producing greater a 10% salt removal based upon the data in Figure 12. Additionally, the increased traveling length of the system should have increased the removal ratio of the system for the same current density. But even with 3A of current and 1.5x the current density used in previous trials, it was not possible to achieve greater than a 5% salt removal. This result may indicate that the bifurcate ICP stack design is not well equipped to achieve high salinity output waters. Another possible explanation for the high salinities recorded is migration of ions from the rinse channel. This hypothesis is supported by the presence of pronounced fouling on the anode side of the membrane, shown in Figure 14, This ion diffusion could significantly increase the salinity of the

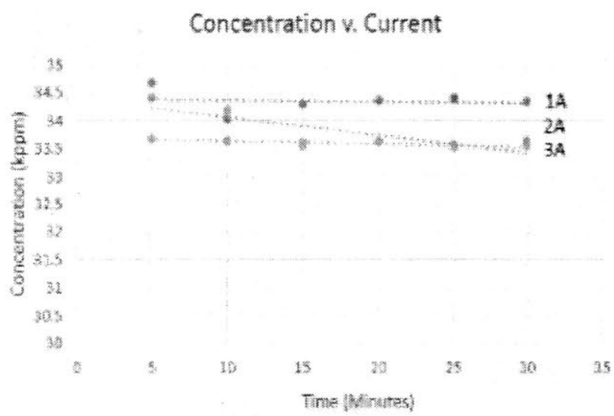


Figure 13- Single Stack ICP Unit Testing Results

The conductivity of the output feed water was measured for various current levels with a single stack was plotted. A line of best fit was drawn to allow trends to be more easily identified. These results were not consistent with the previous work summarized in Figure 12.

desalt channel. In order to determine whether this ion migration is the dominant factor in the elevated ion concentrations, a 5 stack ICP unit test was performed.

5 Stack ICP Testing Methods and Results

The test unit was assembled utilizing the same methodology as above, but with 5 ICP unit stacks instead of 1. All of the operating conditions were the same as the single stack test conditions detailed in Table 5. The 5 stack ICP unit test produced very similar results to the single stack ICP unit test, as is shown in Figure 15 This suggests that diffusion from the rinse channel is not the dominant cause of poor salt removals. If diffusion from the rinse channel were the dominant factor in the low salt removal ratios, the effect of this migration should be reduced by 80% in the 5-stack system, since only the nearest desalt channel should be effected by ion migration from the rinse channel. Instead, it is possible that this bifurcate ICP unit design is not well equipped to achieve drinkable quality output waters. In a bifurcate ICP unit, the concentrate and desalt channels are directly adjacent because there is no intermediate channel to act as a buffer region. This has two effects that serve to decrease the salt removal of the unit. First, this unit layout

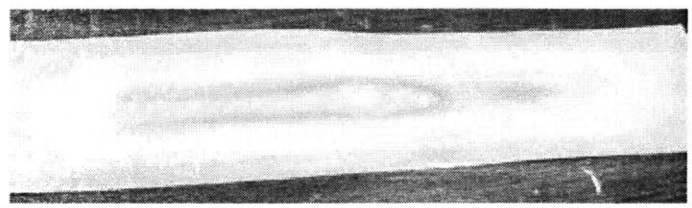


Figure 14- Fouling of Ion Exchange Membrane

Pronounced fouling was observed on the anode side of the CEM closest to the rinse channel. This fouling was not observed on any of the other CEMs, suggesting that it may be caused by mass migration of ions from the rinse channel.

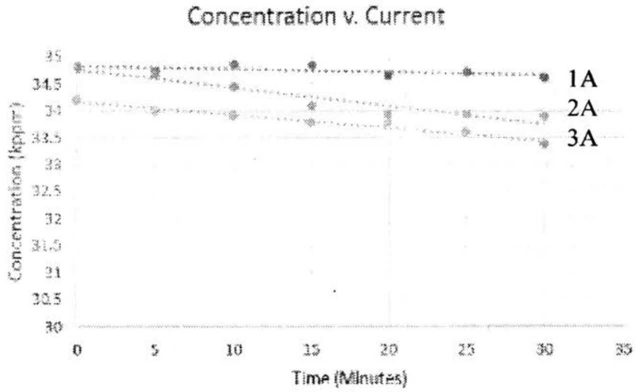


Figure 15- 5 Stack ICP Unit Testing Results

The conductivity of the output feed water for the 5 purification stack system was measured for various current levels and plotted. A line of best fit was drawn to allow trends to be more easily identified. These results were not consistent with the previous work summarized in Figure 12. They were however, very similar to the single stack ICP unit results presented in Figure 13.

creates a much more drastic concentration gradient than in the trifurcate unit design; leading to greater resistance to ion migration via diffusive forces. Second, the direct contact between the concentrate and desalt water could lead to leakage of concentrate water into the desalt channel. In an optimally designed ICP unit, the depletion layer produced by current application would be the same thickness as the desalt channel [1]. However, the depletion layer is not necessarily as thick as the physical desalt channel. When the desalt channel is larger than the depletion layer, water from the adjacent layer is mixed with the purified water as it exits the desalt channel, increasing the salinity of the output water. The effects of this mixing are likely more pronounced in a bifurcate ICP unit than they are in a trifurcate unit because more concentrated water is mixed in the desalt channel. Theoretically, this mixing could be eliminated by altering the current density to increase the thickness of the depletion layer. However, significant energy expenditures are required to increase the thickness of the depletion layer and the benefits of increased removal ratios must be weighed against the energy requirements [4].

Utilizing an ICP unit design with a thinner desalt channel could allow the production of lower salinity output waters with the same operating current density by decreasing the mixing of unpurified water in the desalt channels. However, this thinner design would require more stacks to achieve the desired output flow rates. None of the existing units can be easily scaled to produce this system. It is difficult to align the unit stacks and not possible to decrease the thickness of the desalt channel using the current materials and manufacturing techniques.

Spacer Structure	• Utilizes mesh structure to act as mixing promoters to decrease energy required in creation of depletion layer [14,15] • Mesh structure can reduce the effects of concentration polarization in the channel by acting as turbulence promoters [16] • Water paths are often snaked in order to increase effective traveling length [17]
Filament Thickness	• Smallest possible to minimize "spacer shadow effect" [16] • Must be thick enough to prevent membrane deflection [15]
Spacer Geometry	• Non-woven mesh is optimal for creating water flow channels [18] • Mesh filaments should not be oriented perpendicular to the direction of water flow [18] • 90° angle between filaments is ideal [15]
Spacer thickness	• Minimizing spacer thickness size as much as possible will improve energy consumption but more stacks will be required to produce same flow rate [4]
Material	• Polypropylene is most widely used for creation of membrane spacers [19]

Table 6- Summary of Literature Review of Spacer Structures for Large Scale ED Systems.

Because of the structural similarities between ICP and ED, spacers for large scale ED systems were used as a model for the creation of a new ICP purification unit design. Data on best design and manufacturing practices was collected from a number of sources in both academia and industry.

Therefore, further work in this thesis focused on designing, manufacturing and testing an optimized ICP unit that was easier to stack and had a thinner desalt channel.

__Alternate ICP Channel Design__

Because of the structural similarities between ICP and ED systems, the design process began with a literature review of current purification unit designs for large stack electrodialysis systems. The findings of this literature review is summarized in Table 6. Based upon the results of the above literature review, a new desalt channel design was implemented. This modified ICP unit was designed so that it can easily incorporated with the existing system; a mesh structure was incorporated in order to promote mixing in the channel and the channel was designed to be as thin as possible.

Optical Adhesive Curing

The first manufacturing technique attempted to fabricate this unit was sealing the edges of an existing mesh structure to create the flow-through channel. The benefit of this design was that the pre-existing mesh structures were already available in the desired geometry and materials. They are also more cost-effective because their design has been optimized to be manufactured more efficiently. Finding a suitable adhesive was the biggest challenge in this manufacturing process. The adhesive needed to be fluid enough to flow into and completely fill all of the spaces in the mesh structure. This will prevent leakage out of the edges of the mesh structure once the adhesive has cured. However, the adhesive also needed to allow precise placement to form a flow-through channel. Optical adhesives, such as those shown in Figure 16, were an ideal

Figure 16- Optical Adhesive used in Modified ICP Stack Manufacturing Technique 1

This adhesive came in a variety of viscosities and was able to be selectively cured by blocking UV curing in certain regions; this made them a prime candidate for desalt channel fabrication.

adhesive to meet these criteria because they are fluid enough to mold to the shape of the mesh structure but also capable of being selectively cured in the desired region. Because UV light serves as the curing agent, regions can be left uncured by preventing exposure to UV light during the curing process. Uncured optical adhesive can be easily removed with running water.

Black reflective paper was used to block the passage of the UV light and prevent the curing of the optical adhesive. In order to determine the accuracy with which this optical adhesive would be cured, small test pieces were created. A $4in^2$ square piece of polypropylene mesh was placed in a clear petri dish. The bottom of the petri dish was covered in black reflective paper and a 1 in^2 diamond was cut into the reflective paper to allow for penetration of UV light in this region. Optical adhesive was poured into the petri dish so that it completely covered the mesh structure and was cured by placing the petri dish on a UV lamp. This procedure was repeated with different layers of reflective paper. The experimental setup is illustrated in Figure 17 below.

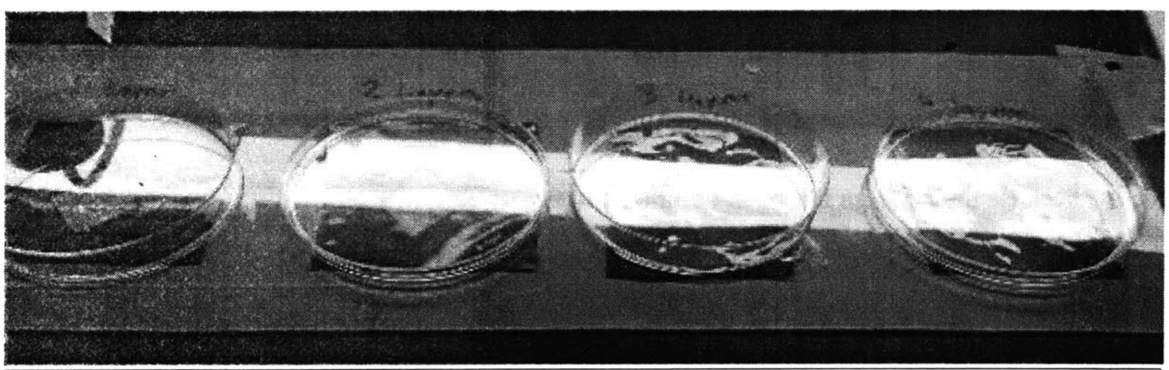


Figure 17- Experimental Setup to Test Selective Curing of Optical Adhesive using Reflective Paper

Different layers of black UV reflective paper were used to prevent the curing of optical adhesive. Only the small diamond shaped region in the system was directly to the UV light and should have been cured. However, none of the setups above were able to achieve the precise curing of the optical adhesive that would be required for creation of a flow through channel.

If the reflective paper was able to effectively prevent the curing of the UV glue, only the diamond-shaped uncovered regions should be cured. But even with 4 layers of UV reflective paper, other regions of the UV adhesive were cured. This result indicates that it is not possible to cure the UV glue precisely enough to be used for creation of a flow-through channel using this method. Alternative manufacturing methods needed to be considered.

3D Printing

3D printing was the next method considered for the fabrication of the ICP channels. The benefits of 3D printing are that it is easy to customize the structural properties of the channel, such as the thickness and orientation of the filaments, and that there is a high degree of repeatability in the manufacturing process. The main drawback of this manufacturing method is that it cost and time intensive. If this design were to be produced at scale, it would likely be necessary to switch to another manufacturing method such as injection molding to produce the channels.

Property	***ABSplus- P430 [20]***	***Polypropylene[21]***
Tensile Strength @ Yield (psi)	6,500	5,400
Tensile Modulus (psi)	340,000	195,000
Tensile Elongation at Yield(%)	25	12
Coefficient of Thermal Expansion(in/°F)	$5.3*10^{-5}$	Negligible
Volume Resistivity (Ω-cm)	1015	$8.5x10^{14}$
Max Operating Temperature (°F)	140	N/A

Table 7- Comparison Relevant Mechanical, Thermal and Electrical Properties of ABSplus and Propylene

Both materials have similar tensile strengths and thermal expansion coefficients. ABSplus has a greater tensile modulus which is beneficial because it will prevent deflection of the Ion Exchange Membranes. It also has significantly less volume resistivity than Polypropylene; this will, however, likely have minimal effect because significantly more of the current will be transmitted through the spaces between the filaments. The biggest drawbacks of the ABSplus material is that they have a maximum operating temperature that must be considered and are susceptible to thermal expansion.

In order to determine whether 3D printing would be a suitable technology, the available materials and precision of the printing process were the most important factors to be considered. Figure 18 compares the mechanical and electrical properties of ABSplus, the thermoplastic printed by the 3D printer, and polypropylene, the industry standard material for creation of mesh

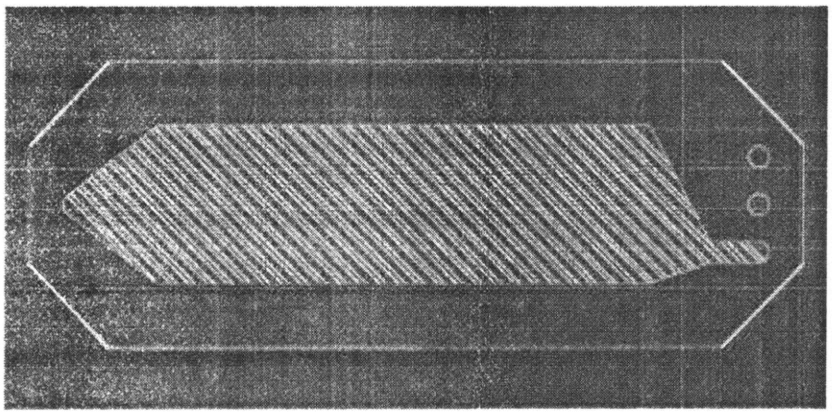


Figure 18 – 2D CAD drawing of ICP desalt channel design

The thickness and orientation of the filaments were designed according to the results of the literature review above. The channel structure was fitted to the existing ICP unit design. The corners of the structure were clipped in order to allow the structure to fit in the bed of the 3D printer.

spacer. The results, shown in Table 7, of this analysis indicate that ABSplus is to be a viable option for creation of a mesh desalt channel. After determining that ABSplus was a suitable candidate for creation of the mesh channel design, a 2D model of the channel geometry was created in AutoCAD and is shown below in Figure 18. A non-woven mesh structure with 90 degree angled filaments was selected to act as a mixing promoter in the channel. Two separate layers of crisscrossing mesh filaments were used to allow space for water to flow through the filaments in the channel. In order to assess the viability of

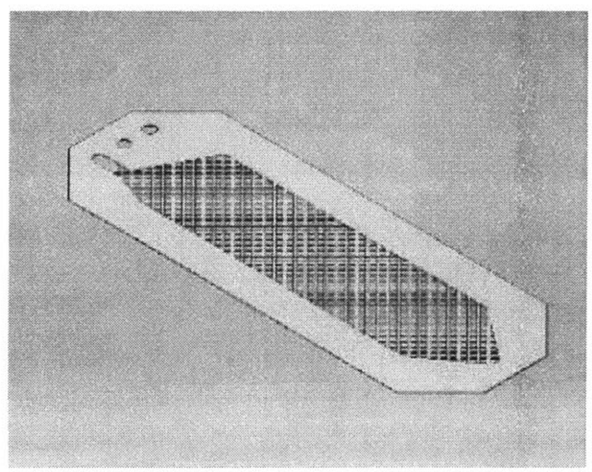


Figure 19- 3D AutoCAD Inventor drawing used for 3D printing.

The 2D CAD drawing provided in Figure 18 above was extruded in both directions in order to create the 3D channel with a non-woven mesh structure. All desalt channels were printed based on this design

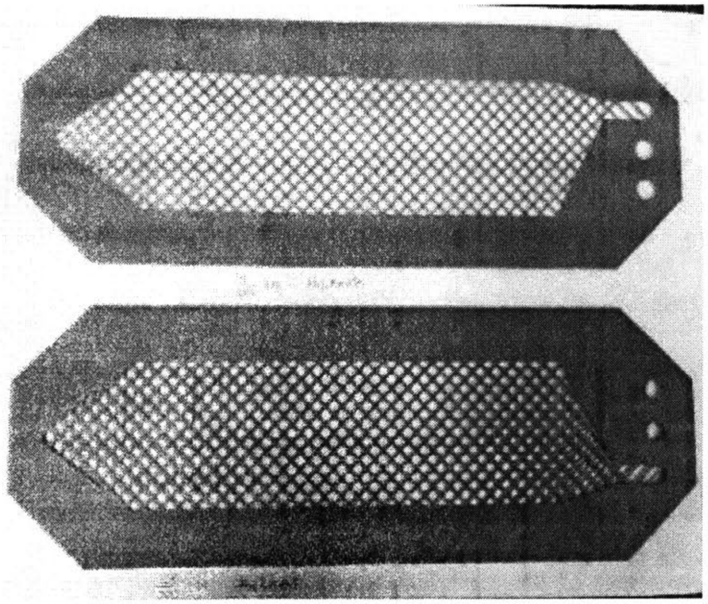


Figure 20- 3D printed model of desalt channels (.014 in and .028 thick)

Both channels were successfully fabricated with no deformities in either of the structures. Both channels had similar mechanical such as stiffness, hardness, and elasticity. The thickness of the channel appears to have no significant impact on the effectiveness of the fabrication process.

manufacturing and utilizing this channel in ICP unit, 2 test pieces were fabricated. The 2D CAD model was extruded using AutoCAD Inventor software in order to create a model that could be used for printing and is shown in Figure 19. Two different extrusion thicknesses were examined. Because the desalt channel design is a 2-layer structure, the channel must be at least 2 print layers (.014 inches) thick; this is half the thickness of the current design. A 4-layer (.028 inch) thick ICP unit was also fabricated, in order to determine if they were both viable print thicknesses and to assess any differences in properties between these two units. Both designs were successfully printed and are shown in Figure 20. There were no significant differences in the surface structures or mechanical properties. Since both of these channels had similar properties, the thinner design was chosen in order to decrease the current density required to create a suitable depletion layer and the required voltage drop across each unit.

In an ICP spacer design the filament thickness should be minimized in order to prevent the "spacer shadow effect"; due to limited electro-conductivity of the ABSplus materials, the presence of the filaments in the channel resists the transmission of current in the regions. Thinner filaments will limit the effect of this "spacer shadow effect" and allow for less resisted flow of fluid through the channel [16]. In order to determine the minimum filament thickness that could be fabricated for this channel thickness, 1 cm^2 test pieces were printed with the same mesh structure as would be used in the channel design and filament thicknesses of .25mm, .5mm, 1mm, 1.5mm as is shown in Figure 21.

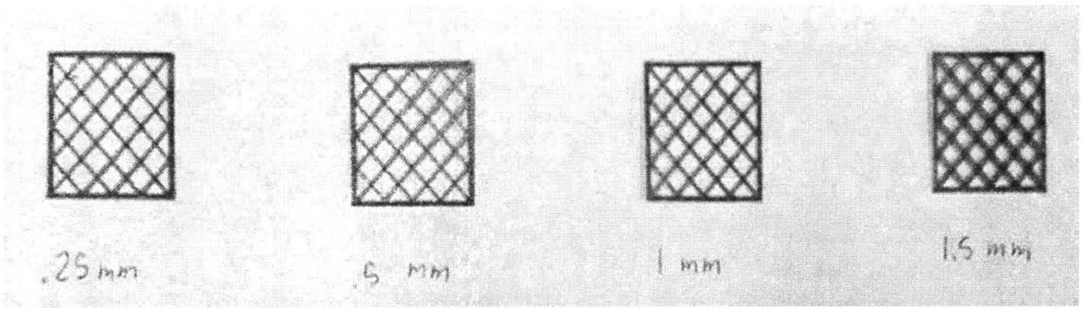


Figure 21- 3D Printer Filament Thickness Testing

1 cm^2 test pieces were built minimum filament thickness printable by 3D printer. It was determined that the minimum printable filament thickness was .5mm, which is the minimum resolution of the 3D printer in the XY plane All thicknesses less than .5mm print as .5mm. However, the .5mm filaments had breaks and deformities in the print layers, making them unsuitable for use in ICP purification stack fabrication. 1mm filaments were selected because they were the minimum filament thickness that produced a stable structure.

.5mm filaments were the thinnest that were able of being printed. However, since they are only a single print layer thick, they are extremely susceptible to bending and breakages. Instead, 1 mm filaments were selected because of their increased structural stability.

ICP Stack Fabrication - Methods and Results

After determining the optimal fabricating conditions, desalt and concentrate channels were 3D printed based on the designs in Figure 19 and 20 with a .014in channel height and .05 mm filament thicknesses. Spray adhesive was used to join the 3D printed desalt and concentrate channels. However, because both of the structures were rigid, they were unable to be effectively joined. Even when extensive pressure was applied during the adhesion process, a pronounced gap remained between the channels, creating space for leakage in the stack. A more pliable concentrate channel structure was required to allow for proper adhesion with the rigid 3D printed desalt channel.

Instead, an alternate ICP concentrate channel was fabricated using 1/32" silicon rubber. The same procedure was followed as Design 3 above, except the 3D printed desalt channel was used in place of a silicon rubber channel. This modified ICP purification stack design is shown in Figure 22. The biggest drawback of this design is the increased unit thickness; because the thinnest silicon rubber available is 1/32", the height of the concentrate channel was required to be at least twice the height of the desalt channel. This decreases the recovery ratio of the unit from 50% to 33.33% and increases the required voltage drop across the stack by 1/3. However, the thinner desalt layer does still require a smaller depletion layer, which could still increase the energy efficiency and salt removal ratios of the unit.

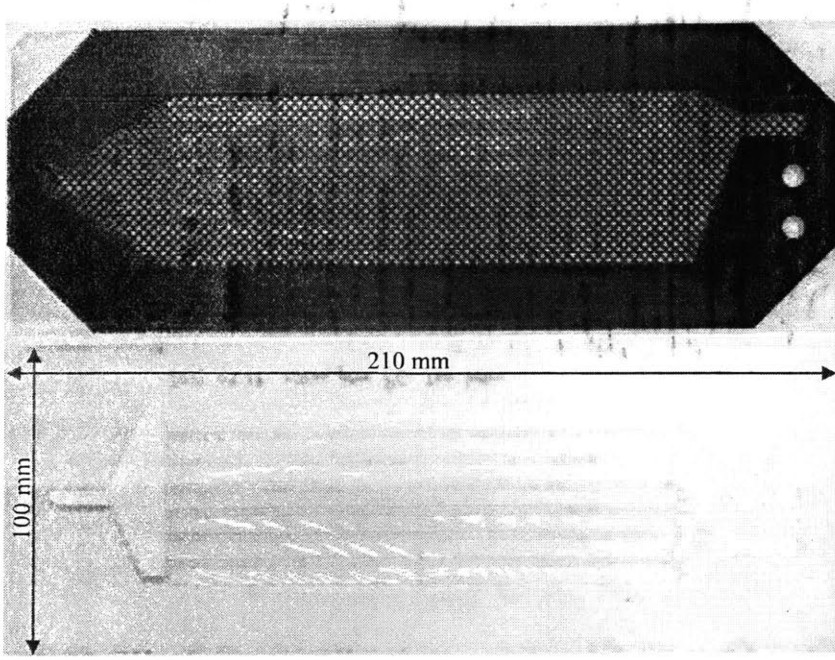


Figure 22- Front and Rear Views of Modified ICP Stack

The use of silicon rubber to fabricate the concentrate channel allowed for firm adhesion between the channels. There was however a height difference at the edges of the unit because of the clipped corners of the desalt channel. This design promotes mixing in the desalt channel which should improve the salt removal and current utilization in this region; however, a design with a thinner concentrate channel is preferable.

While the channels in this design were well adhered in this design, there was still significant leakage between the ICP unit stacks as is shown in Figure 23. The stacks were checked for defects in manufacturing and assembly. There were no visible breaks in adhesion between the channels of the ICP units, all of the stacks were pressed together tightly to prevent leakage. Because the 3D printer utilized an extrusion process, it is possible that the printer produced a porous rather than completely solid structure. The small gaps between the extrusion layers were not perceptible to human to the human eye, but could be sufficiently large to allow leakage between the layers of the structure. Potential solutions include post-treating the edges of the channels with a hydrophobic coating or determining a method of 3D printing that does not produce a porous structure.

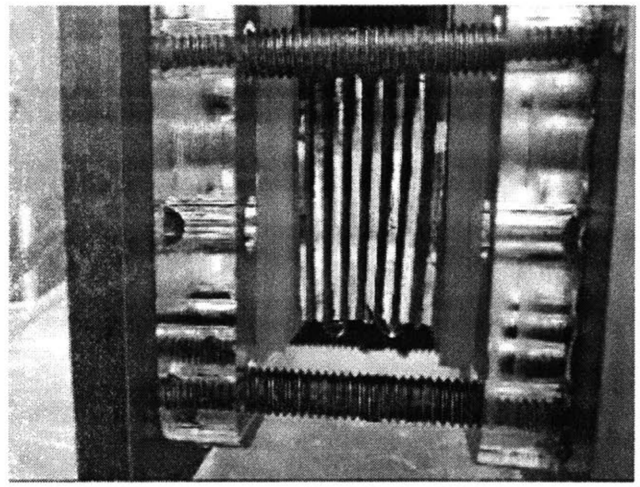


Figure 23- Leakage in ICP unit design with

When this leakage was observed the ICP unit was first checked to ensure proper adhesion between the flow through channels. From examination of the structure, it appeared that the leakage is from within the desalt channel itself rather than between the layers. Therefore, the leakage is likely due to deformation of the purification stacks or a flaw in the 3D printed desalt structure.

Another possible explanation is that it is not possible to properly secure the stacks together; the current ICP outer rack is designed to evenly distribute pressure along the surface of flat, rectangular units. The clipped corners of the 3D printed desalt channel prevent the even distribution of pressure in the channels causing the units to bend and leakage between the units. It was hypothesized that this bending, which is illustrated in Figure 23, was caused by the uneven height of the ICP unit in different areas. In order to test this theory, the uncovered corners of the ICP unit were removed so that the entire unit was of uniform height. Unfortunately, this made the units difficult to align and secure in the system and the leakage problem continued. This suggests that the current ICP outer rack design was best suited to secure rectangular ICP units. In order to address this problem, one solution is to find a larger 3D printer that is capable of printing a rectangular unit of the appropriate size. However, since most 3D printers experience a tradeoff between print size and resolution, printing a larger ICP unit may not be viable. Another possible solution is to modify the placement of support screws on the outer rack so that it can better secure an irregularly shaped ICP unit. However, this solution is not ideal because it requires the modification of all of the structural components of the ICP unit, rather than just the modification of the ICP purification stack.

Future Work

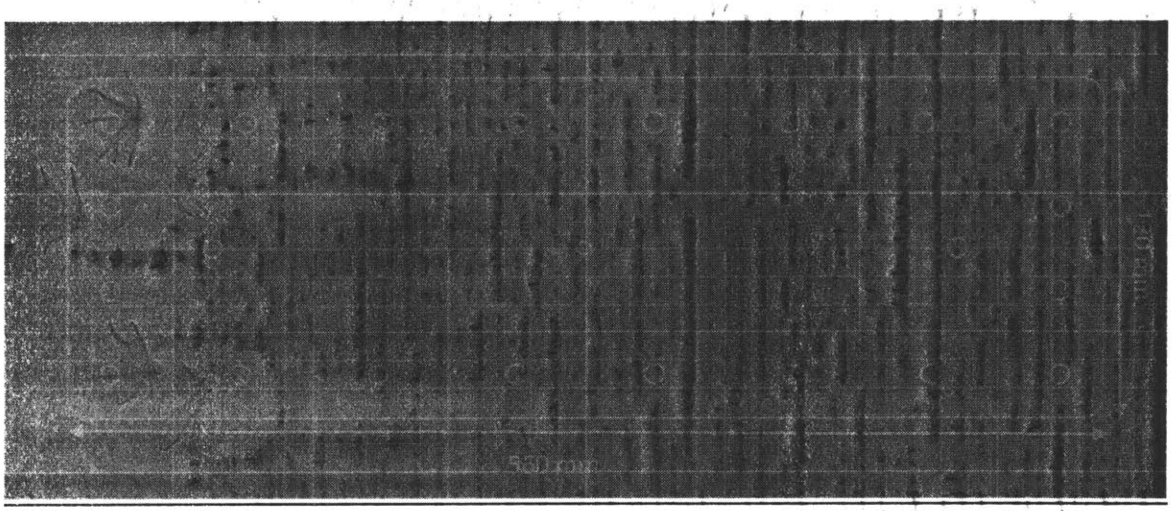
Future work will focus on further development of the thinner ICP stack design; with particular emphasis on utilizing a thinner desalt channel. This is extremely important in the production of drinkable quality water because a thinner desalt channel can both increase the salt removal ratios of the stack and decrease the energy requirements to create a depletion layer. Further testing would be conducted in order to assess the viability of 3D printing as a manufacturing method to produce these thinner desalt channels. Despite the current problems with leakage, 3D printing is a promising manufacturing technique, because it allows the creation of a mesh structure to act as a mixing promoter and the thickness of the channel to be decreased by half. Additionally, further changes to the channel structure can be easily made without requiring changes in the manufacturing process.

Conclusion

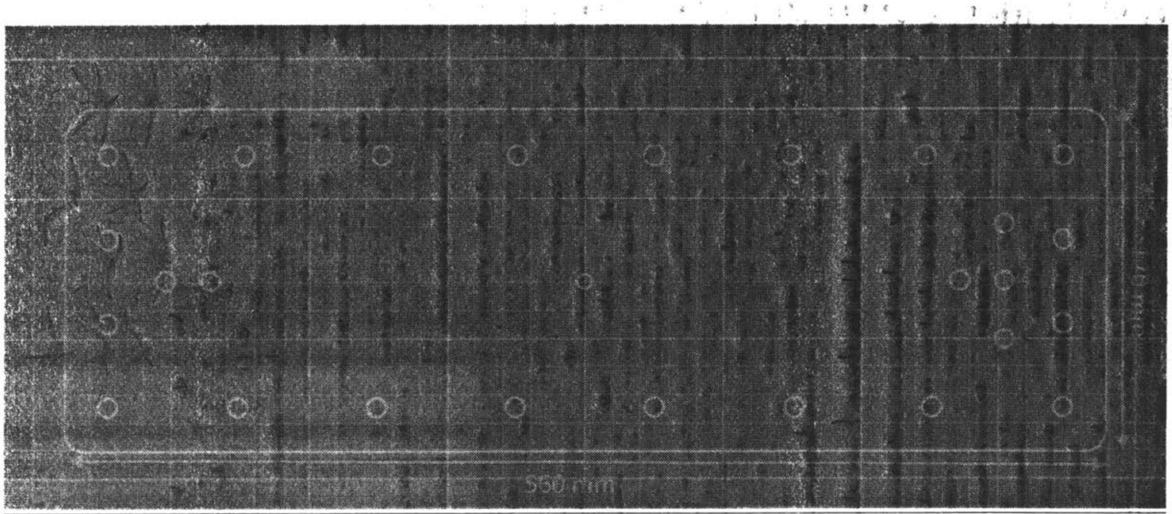
In this thesis, the viability of ICP for the creation of portable desalination unit was assessed. It was determined that increasing flow rates and decreasing desalted water salinity were the most important obstacles before the current ICP system configuration could be utilized in a viable portable desalination unit. A number of different theoretical system configurations, including recirculation and ICP-hybrid systems were proposed to address these challenges. A modified ICP unit with an increased traveling length and various bifurcate ICP purification units were fabricated to test whether these would be able to achieve higher salt removals than previous designs. Because these modifications were unsuccessful, further literature review was conducted to determine an optimal ICP channel design based on analogies to high throughput ED systems. Based on this literature review, a new desalt channel was designed and manufacturing was attempted via curing of optical adhesive and 3D printing. While these manufacturing techniques were not capable of producing a suitable desalt channel design, the viability and challenges of using various methods of manufacturing for future production of ICP purification stacks was able to be assessed. Overall, the data and expertise collected in this thesis is beneficial in understanding the affinity and challenges of converting the existing ICP unit into a portable desalination unit.

Appendix 1- CAD Drawings used in Fabrication

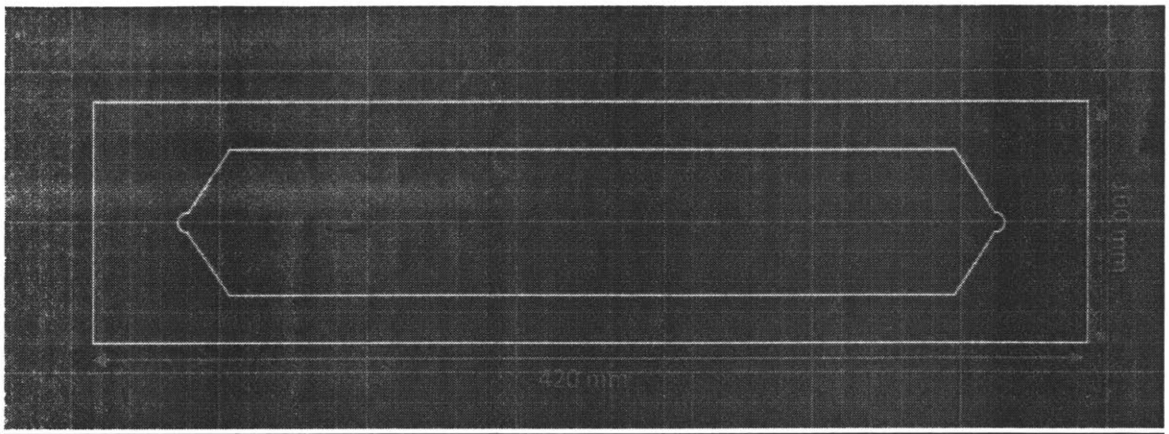
Appendix 1a- ICP Outer Rack Base



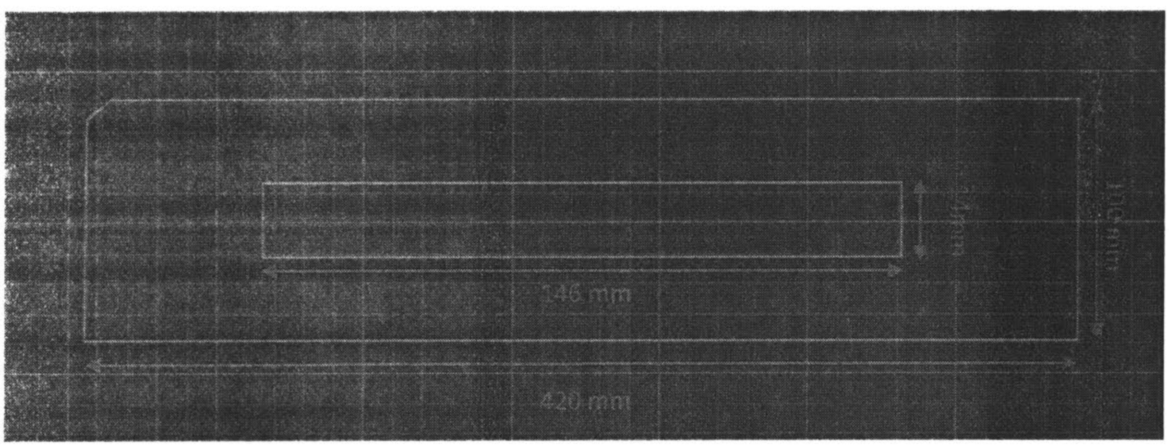
Appendix 1b. - Outer Rack Top



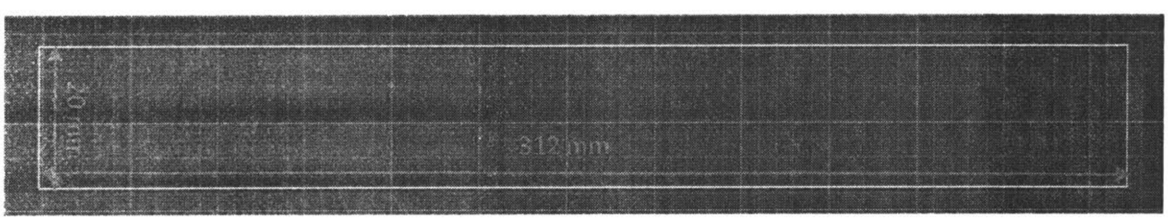
Appendix 1c. – Rinse Channel Template



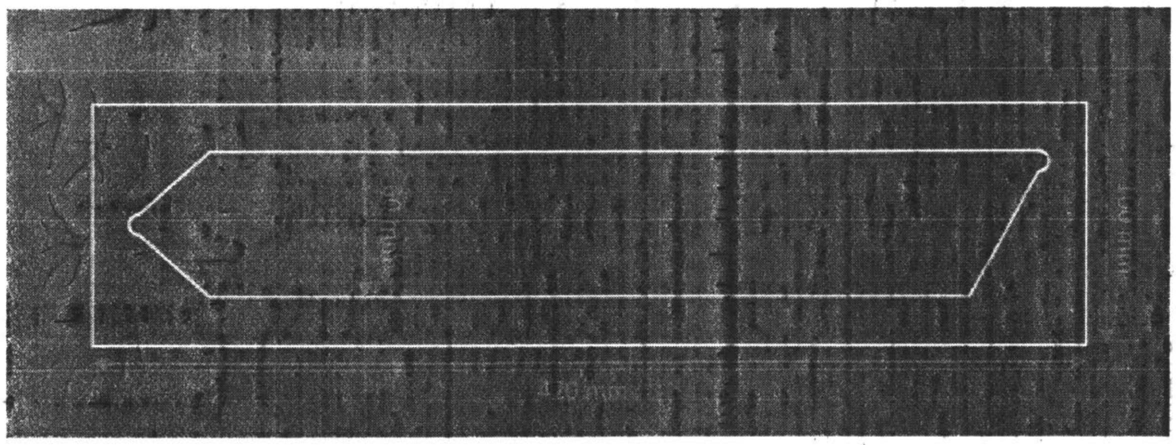
Appendix 1d. - Electrode Mesh Template



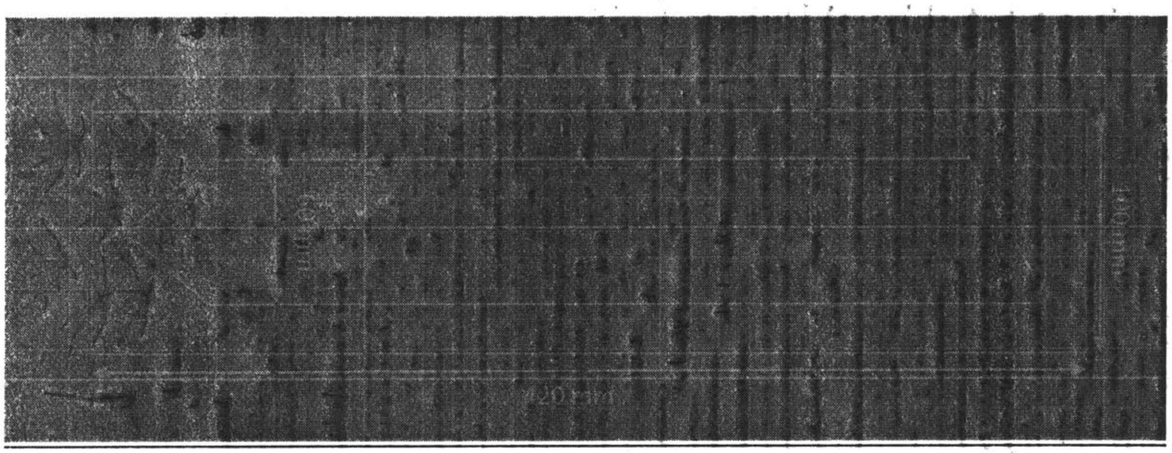
Appendix 1e- Copper Mesh Template



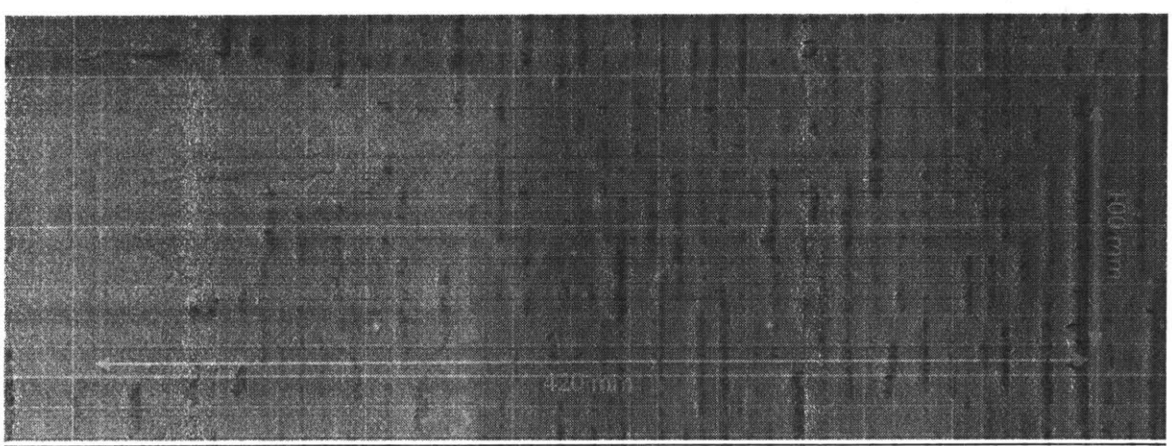
Appendix 1f- Desalt Channel Design



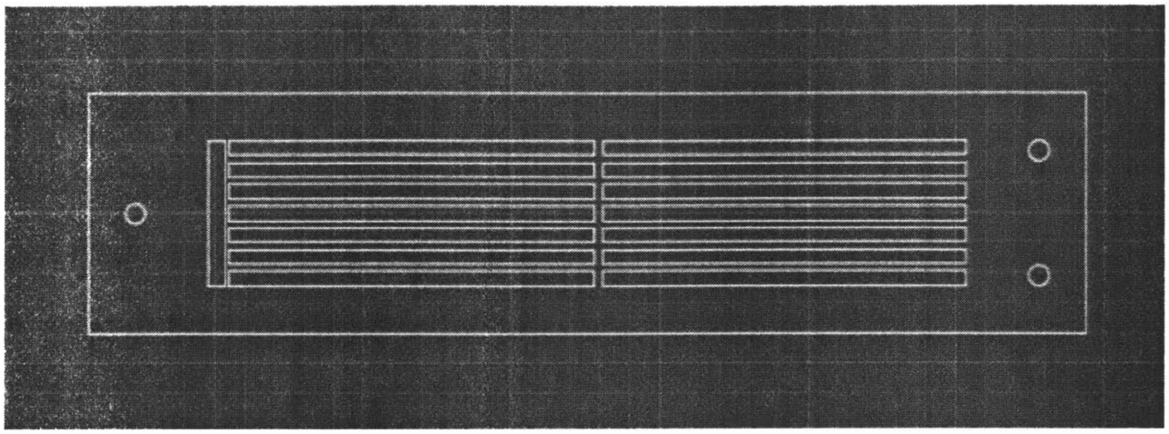
Appendix 1g.- Concentrate Channel Design 1



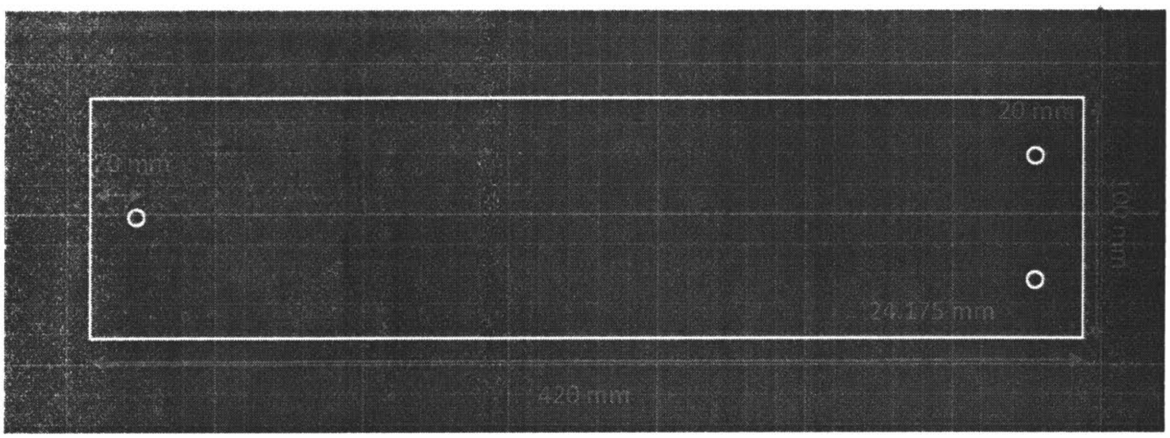
Appendix 1h- Concentrate Channel Design 2



Appendix 1i- Porous Membrane Support Structure



Appendix 1j- Template for Hole Cutting



Bibliography

[1] Kwak, Rhokyuan, et al. "Microscale Electrodialysis: Concentration Profiling and Vortex Visualization." Desalination, Elsevier, 8 Aug. 2012, www.sciencedirect.com/science/article/pii/S0011916412003888.

[2] Kwak, Rhokyun, et al. "Enhanced Salt Removal by Unipolar Ion Conduction in Ion Concentration Polarization Desalination." Nature News, Nature Publishing Group, 9 May 2016, www.nature.com/articles/srep25349.

[3] Strathmann, H. Ion-Exchange Membrane Separation Processes. 1st ed, Elsevier Science, 2004. EBook collection,search.ebscohost.com/login.aspx?direct=true&db=nlebk&AN=249114&site=eds-live&scope=site. Accessed 24 Apr. 2018.

[4] Kim, Bumjoo, et al. "Partial Desalination of Hypersaline Brine by Lab-Scale Ion Concentration Polarization Device." Desalination, Elsevier, 7 Mar. 2017, www.sciencedirect.com/science/article/pii/S001191641631517X.

[5] Kim, Bumjoo, et al. " Purification of High Salinity Brine by Multi-Stage Ion Concentration Polarization Desalination." Scientific Reports, vol. 6, no. 1, 2016, doi:10.1038/srep33775.

[6] Harris, G. "Salinity." Encyclopedia of Inland Waters, 2009, pp. 79–84., doi:10.1016/b978-012370626-3.00103-4.

[7] Scheelbeek, Pauline F.d., et al. "Drinking Water Salinity and Raised Blood Pressure: Evidence from a Cohort Study in Coastal Bangladesh." Environmental Health Perspectives, vol. 125, no. 5, 2017, doi:10.1289/ehp659.

[8] "How Much Water Is Needed in Emergencies." TECHNICAL NOTES ON DRINKING-WATER, SANITATION AND HYGIENE IN EMERGENCIES 9.1 TECHNICAL NOTES ON DRINKING-WATER, SANITATION AND HYGIENE IN EMERGENCIES, vol. 1, no. 9, 2011.

[9] "Solar Panel Power Per Square Foot." The Renewable Energy Hub, vol. 1, no. 1.

[10] Chehayeb, Karim M., et al. "Optimal Design and Operation of Electrodialysis for Brackish-Water Desalination and for High-Salinity Brine Concentration." Desalination, vol. 420, 2017, pp. 167–182., doi:10.1016/j.desal.2017.07.003.

[11] E. Suss, M., et al. "Water Desalination via Capacitive Deionization: What Is It and What Can We Expect from It?" *RSC Advances*, The Royal Society of Chemistry, 5 May 2015, pubs.rsc.org/en/content/articlehtml/2015/ee/c5ee00519a.

[12] Pangarkar, B.l., et al. "Review of Membrane Distillation Process for Water Purification." Desalination and Water Treatment, vol. 57, no. 7, 2014, pp. 2959–2981., doi:10.1080/19443994.2014.985728.

[13] Soltanieh, Mohammad, and William N. Gill'. "Review Of Reverse Osmosis Membranes And Transport Models." Chemical Engineering Communications, vol. 12, no. 4-6, 1981, pp. 279–363., doi:10.1080/00986448108910843.

[14] Chiapello JM, Bernard M. Improved spacer design and cost reduction in an electrodialysis system. Journal of Membrane Science. 1993;80(1):251-256. doi:10.1016/0376-7388(93)85149-q.

[15]Balster J, PUNT I, STAMATIALIS D, Wessling M. Multi-layer spacer geometries with improved mass transport. Journal of Membrane Science. 2006;282(1-2):351-361. doi:10.1016/j.memsci.2006.05.039.

[16] Balster J, Stamatialis DF, Wessling M. Membrane with integrated spacer. Journal of Membrane Science. 2010;360(1-2):185-189. doi:10.1016/j.memsci.2010.05.011.

[17] Wright, Natasha C., et al. "Justification, Design, and Analysis of a Village-Scale Photovoltaic-Powered Electrodialysis Reversal System for Rural India." Volume 2A: 41st Design Automation Conference, 2015, doi:10.1115/detc2015-46521.

[18] S. Geissler, H. Heits, U. Werner Description of fluid flow through spacers in flat channel filtration systems Filtration & Separation, 32 (1995), pp. 538-544

[19] Electrodialysis- Technical Data of ED Stacks. GmbH- PCCEll, 2014, p. 1, Electrodialysis- Technical Data of ED Stacks.

[20] Technical Data Sheets (ABS) Vanderveer Industrial Plastics, 2018, pp. 1–2, Technical Data Sheets (ABS).

[21] Technical Data Sheets (Polypropylene). Vanderveer Industrial Plastics, 2018, pp. 1–2, Technical Data Sheets (Polypropylene).

[22] Kim B, Kwak R, Kwon HJ, et al. Purification of High Salinity Brine by Multi-Stage Ion Concentration Polarization Desalination. Sci Rep. 2016;6:31850. doi:10.1038/srep31850.

[23] "Feasibility Study of an Electrodialysis System for in-Home Water Desalination in Urban India:" Egyptian Journal of Medical Human Genetics, Elsevier, 18 Dec. 2016, www.sciencedirect.com/science/article/pii/S2352728516300045.

[24] "Drinking-Water." World Health Organization, World Health Organization, www.who.int/news-room/fact-sheets/detail/drinking-water.

[25] "WHO World Water Day Report." World Health Organization, World Health Organization, www.who.int/water_sanitation_health/takingcharge.html

[26] "Sustainable, Development, United Nations, Rio+20, Decade, Water for Life, 2015, UN-Water, United Nations, MDG, Water, Sanitation, Financing, Gender, IWRM, Human Right, Transboundary, Cities, Quality, Food Security." United Nations, United Nations, www.un.org/waterforlifedecade/water_and_sustainable_development.shtml.

[27] Watson, John T., et al. "Epidemics after Natural Disasters." Advances in Pediatrics., U.S. National Library of Medicine, Jan. 2007, www.ncbi.nlm.nih.gov/pmc/articles/PMC2725828/.

[28] "Small-Scale of Water Production Using Renewable Energy: Economic Evaluation." Egyptian Journal of Medical Human Genetics, Elsevier, 28 Aug. 2015, www.sciencedirect.com/science/article/pii/S1876610215010553.

[29] Zhou, Yuan, and Richard S. J. Tol. "Evaluating the Costs of Desalination and Water Transport." Journal of Geophysical Research: Atmospheres, Wiley-Blackwell, 2 Mar. 2005, agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2004WR003749.