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Wastewater Brine Purification and Recovery through Electrodialysis Ion Exchange

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Reutilizing resources onboard the International Space Station (ISS) and for future deep space missions are critical for mission longevity and sustainability. Wastewater brine produced from water recovery systems contain chemical species that could be processed into a potential fertilizer for future plant systems. This can be achieved through a process called electrodialysis ion exchange. Wastewater containing inorganic salt components are fed through a series of ion exchange membranes to produce fertilizer (a phosphate rich stream), electrolysis-grade water, and other useful commodities. Electrodialysis cells consisting of anion and cation exchange membranes, monovalent anion exchange membranes, and bipolar membranes were utilized to achieve selective ion exchange. The use of the electrodialysis cells were effective for both water extraction and ion separation. Ions successfully diffused across their respective membranes into the concentrate, acid, and base streams. This resulted in pure water, a phosphate rich stream, and a separate anion/hydrogen and cation/hydroxide stream. However, sulfate and some phosphate ions were able to diffuse through the monovalent anion exchange membrane into the acid stream. This resulted in predominantly phosphate ions remaining in the concentrate. Optimization of the process was accomplished by altering flowrates of each stream and initial volumes, adjusting the power input and resulting current through each cell, and varying the starting parameters by splitting the inorganic waste input into the diluate and the concentrate. As expected, increasing the flowrate and the power input to each cell reduced the overall time of the process. However, mission constraints may require a longer duration process in order to reduce the power consumption. Further analysis will be required to determine the power input necessary to achieve ion diffusion effectively and in a timely manner.

Nomenclature

A = ampere
A60 = monovalent anion exchange membrane
AC = acid
BA = base
BPM = bipolar membrane
cm = centimeter
CT = concentrate
DC = direct current

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DI = deionized
DL = diluate
ED = electrodialysis
EDBM = electrodialysis bipolar membrane
EDR = electrodialysis polarity reversal
EL = electrolyte
ESM = equivalent system mass
g = gram
IC = ion chromatography
ISRU = in-situ resource utilization
ISS = International Space Station
JSC = Johnson Space Center
KSC = Kennedy Space Center
L = liter
LEO = Low-Earth Orbit
mg = milligram
min = minute
mL = milliliter
mS = millisiemen
MSFC = Marshall Spce Flight Center
ppm = parts per million
PVC = polyvinyl chloride
SA = anion exchange membrane
SC = end cation exchange membrane
SK = cation exchange membrane
V = volt

I. Introduction

AS human exploration of space continues, long duration missions and extraterrestrial habitats will become more commonplace. Two problems facing such missions are a lack of available resources and the disposal of waste products. One key solution which addresses both of these is in-situ resource utilization (ISRU) – including finding ways to obtain necessary commodities from existing waste streams.

On any crewed space mission, one unavoidable waste stream is urine. Fortunately, urine contains many components which can be recycled and reused. Among these are potable water and chemicals that can be processed into plant fertilizers, such as phosphate, sulfate, and potassium.

In previous NASA studies, Anthony et al.[1] used electrodialysis to purify waste water and Lunn et al.[2] used ion exchange beds to isolate components of waste water. The goal of this project is to build on past efforts and determine the efficacy of separating urine into usable materials for the purpose of in-situ resource utilization through electrodialysis.

Here, two electrodialysis cells were selected which would allow inorganic urine brine simulant, to be separated into potable water and additional solutions which prove more readily usable than a simple, concentrated brine. In particular, this project had a goal of separating phosphate and sulfate, which could be used for plant fertilizer, out of the concentrated brine. The electrodialysis cell and membranes chosen separated the concentrated brine into three parts, removing chloride ions into the acid solution, removing all cations into the base solution, and leaving the sulfate and phosphate ions in the concentrate solution.

To fully understand the electrodialysis process and prepare for future optimization efforts, this project began by using two electrodialysis cells separately, first removing ions from the urine simulant to produce potable water and concentrated brine, then using that concentrated brine as the input solution for the second electrodialysis cell which would separate the brine into its various ionic components. Then, the two cells were combined in series, as a continuous system, in order to simplify operation for future use in space.

II. Methods & Materials

The test methods, setup, and operational conditions are described below.

A. Inorganic Urine Simulant

The urine simulant chosen for this research is referred to as the JSC hybrid ersatz formulation. This recipe is based on Verostko's 2009 urine ersatz,[3] but updated based on more recent urine data collected from the ISS. Because of the goals of this project, only the inorganic portion of the JSC hybrid ersatz formula was used. The recipe for JSC hybrid ersatz is given in Table 1.

Table 1. JSC hybrid ersatz inorganic formulation.[3]

Compound Name	Chemical Formula	mg/L
Sodium Chloride	$NaCl$	4876
Potassium Chloride	KCl	1261
Potassium Monobasic Phosphate	KH_2PO_4	4772
Magnesium Chloride Hexahydrate	$MgCl_2 \cdot 6H_2O$	703
Ammonium Chloride	NH_4Cl	2895
Calcium Chloride	$CaCl_2$	637
Sodium Sulfate	Na_2SO_4	3253

B. Water Extraction

The first phase of testing used electrodialysis to extract potable water from the urine simulant. To accomplish this, a *PCCell 64002* electrodialysis cell was used. This electrodialysis cell is designed for the flow of three solutions, each with an inlet and outlet: electrolyte (EL), concentrate (CT), and diluate (DL). Using peristaltic pumps, each of the three solutions were circulated from their respective beakers, through the cell, back to their beakers. The overall setup of this system is shown in Figure 1.

Three fluids were circulated through this electrodialysis cell: electrolyte, which provided conductivity to the membranes, diluate, which began as urine simulant and became potable water as ions were removed, and concentrate, which began as DI water and became concentrated brine as it collected the ions removed from the diluate.

While passing through the electrodialysis cell membranes, ions were moved from the diluate solution into the concentrate solution as shown in Figure 2. The stack consists of 10 cell pairs of alternating anion and cation exchange membranes, 110 x 110 mm cell size, an active surface area of 64 cm^2 per membrane, and 0.5 mm cell thickness. The diluate and concentrate streams could be reversed to run electrodialysis with polarity reversal (EDR), thus the electrodes are both made of iridium mixed metal oxide coated titanium-stretched metal.

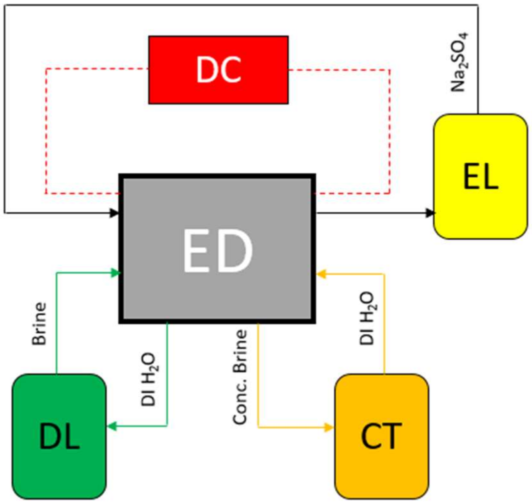

Figure 1. Water extraction test setup. *The electrodialysis cell (ED) had power applied to its membranes from a power supply (DC). Three solutions were circulated through the cell: electrolyte (EL), which provided conductivity to the membranes, diluate (DL) which began as a urine simulant and became potable water as ions were transported out, and concentrate (CT), which collected the ions removed from the diluate, becoming concentrated brine.*

Flow of each of the solutions was controlled by Cole-Parmer Masterflex peristaltic pumps. Different flowrates were used to determine the effects on the ion exchange rates.

The electrodialysis cells have ports designed to connect to manufacturer-provided PVC tubing. Short segments of this tubing were connected to the Masterflex peristaltic pump tubing, in sizes coordinated with the pump heads, using compatible hose barbs, securing both tubes in place with hose clamps.

Power was provided to the electrodialysis cells using a BK Precision power supply which was capable of operating at constant voltage or current. During initial testing (water extraction, ion separation, and continuous system tests), a constant voltage set to 10.0 V was used. Other voltages were used during optimization with additional testing to evaluate the impact of voltage on ion exchange.

During the tests, each solution was placed in a one liter beaker with tubing and sensor probes inserted. The electrolyte solution, which provided conductivity needed for the function of the electrodialysis cell, was a 0.25 M Na_2SO_4 solution, as recommended by the manufacturer, PCCell. The manufacturer-recommended flowrate was 2 L/min, but a flowrate of 1 1/3 L/min was used in the majority of testing due to the equipment constraints.

In this initial testing, at the start of each test, 1 L of urine simulant was used for diluate, and 0.5 L of DI water was used for the concentrate. The electrodialysis cell manufacturer recommended flowrates ranging from 2/3 L/min to 1

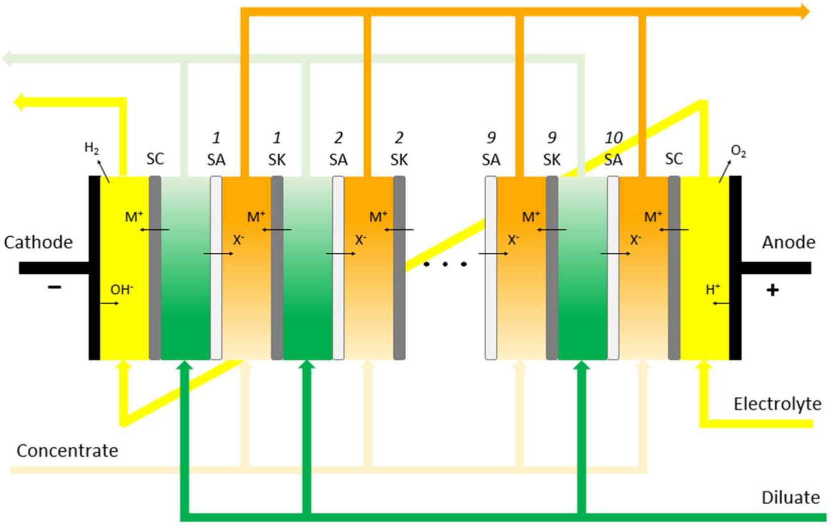

Figure 2. Ion transport through ED water extraction cell membranes. *Anions diffuse towards the anode across the anion exchange membranes (SA), and cations towards the cathode across the cation exchange membranes (SK). The end cation exchange membranes (SC) are manufactured to withstand the pressures exerted by the electrolyte. Membranes manufactured by PCCell.*

1/3 L/min for the cell and membrane combination used. To evaluate the impact of flowrate of the ion transport, two flowrates were chosen for the diluate and concentrate: 2/3 L/min and 1 L/min. To ensure repeatability, three complete test runs were performed for each flowrate.

Conductivity probes were used to monitor ion exchange throughout each run. To accommodate both the lower and higher conductivity values expected, probes with conductivity constants of both 0.1 and 1.0 were used.

Samples of each solution were also collected periodically for use in ion chromatograph analysis. Samples were collected using an Eppendorf pipette to extract a known sample volume each time. The mass of each sample was also measured, allowing a total mass and volume balance to be determined for each test run.

Between test runs, the cell was flushed repeatedly with DI water to prevent cross-contamination from one run to the next.

C. Ion Separation

In the next phase of testing, the concentrated brine output from the water extraction process was separated into various components using another electrodialysis cell, the *PCCell 64004*. This electrodialysis cell has four inlets and outlets for the circulation of solutions that the manufacturer refers to as electrolyte, acid, base, and salt. As with the *PCCell 64002* used in water extraction, each solution is circulated from its beaker, through the electrodialysis cell, and back to its beaker using a peristaltic pump. Flow of each solution, power to the electrodialysis cell, and sampling of solutions used the same equipment and methods as the water extraction setup. The overall setup for this phase of testing is shown in Figure 3. Once again, the electrolyte provided conductivity to the cell membranes. While passing through the cell membranes, ions were moved from the concentrate solution, which the PCCell labeled "salt," in this case, concentrated brine, into either the acid or base solution. Ion flow through this membrane stack is shown in Figure 4. Cations, sodium, potassium,

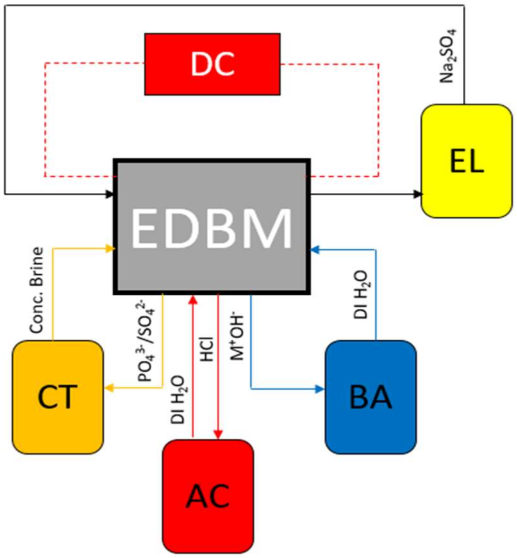

Figure 3. Ion separation test setup. *The electrodialysis cell with bipolar membrane (EDBM) had power to its membranes provided by a power supply (DC). Four solutions are circulated through the cell: electrolyte (EL), which provided conductivity to the membranes, concentrate (CT), which began as the concentrated brine resultant from water extraction in the previous test phase and retained its phosphate and sulfate as other ions were removed, acid (AC), which began as water and collected the chlorides removed from the concentrate, and base (BA), which began as water and collected the cations removed from the concentrate.*

magnesium, calcium, and ammonium, were moved from the concentrate solution into the base solution. Monovalent anions, chlorides, were moved from the concentrate solution into the acid solution. The remaining divalent and trivalent anions, sulfate and phosphate, remained in the concentrate solution because they were unable to pass through the monovalent membrane. Thus, the concentrated brine simulant resulting from the water extraction was separated into three solutions. The stack consists of 5 cell triplicates of alternating monovalent anion, cation exchange, and bipolar membranes. The anode is made of platinum/iridium mixed metal oxide coated titanium-stretched metal and the cathode, V4A stainless steel.

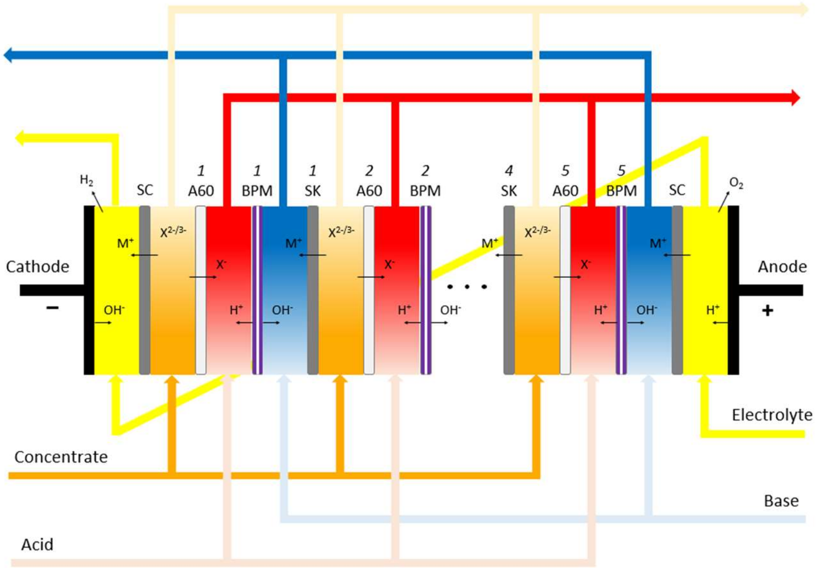

Figure 4. Ion transport through EDBM ion separation cell membranes. *Monovalent anion exchange membranes (A60), in theory only allow anions with a valence of 1 to diffuse across. The bipolar membranes (BPM) contain both an anion and cation exchange layer. Hydrogen ions diffuse into the acid stream, and hydroxyl ions into the base. Cations diffuse towards the cathode across the cation exchange membranes (SK). The end cation exchange membranes (SC) are manufactured to withstand the pressures exerted by the electrolyte. Membranes manufactured by PCCell.*

Throughout the test, the concentrate was monitored using a conductivity probe. The acid and base solutions were monitored using pH probes.

At the start of the test, the concentrate output from a previous water extraction run was used as the concentrate solution. Acid and base solutions were each initially 0.5 L of DI water. Electrolyte remained the same as the water extraction tests, 1 L of 0.25 M Na_2SO_4.

For this portion of testing, 2/3 L/min was chosen as the flowrate for the concentrate, acid, and base solutions. Because the water extraction testing showed little impact between the two flowrates, only the lower flowrate was used for ion separation testing.

Again, three complete test runs were performed to ensure repeatability. Between test runs, the cell was flushed repeatedly with DI water to prevent cross-contamination from one run to the next.

D. Continuous System

In initial testing, urine simulant was processed into potable water and concentrated brine, then the concentrated brine was used as the input salt for the ion separation electrodialysis cell to be segregated into its various components. In order to test the process as a continuous system, the electrodialysis cells were used in the same method and general setup as before, but with a single beaker serving as both the concentrate feed for the water extraction cell and the ion separation cell simultaneously, as shown in Figure 5. A photo of the setup is shown in Figure 6.

Initially, a flowrate of 2/3 L/min for all three test runs was chosen; however, flowrates were reduced to 1/2 L/min for the last two runs to accommodate backpressure build up in the base stream. Because the results for conductivity and pH were similar between the 2/3 L/min trial and the 1/2 L/min trials, the process was deemed to be repeatable and, therefore, a third run at 1/2 L/min was not performed.

Between test runs, the cell was flushed repeatedly with DI water to prevent cross-contamination from one run to the next. Rinses with a 12% nitric acid were also incorporated between runs to reduce membrane clogging, which seemed to be the result of a precipitate, possibly $Mg(OH)_2$, within the membranes of the base stream.

E. Sample Collection and Analysis

Opto 22 data analysis software was incorporated to collect conductivity, pH, and current measurements in real time. Conductivity probes with a cell constant of 0.1 was used in the diluate and 1.0 in the concentrate. pH probes were recording the pH of the acid and base streams. The current through each membrane cell was also recorded.

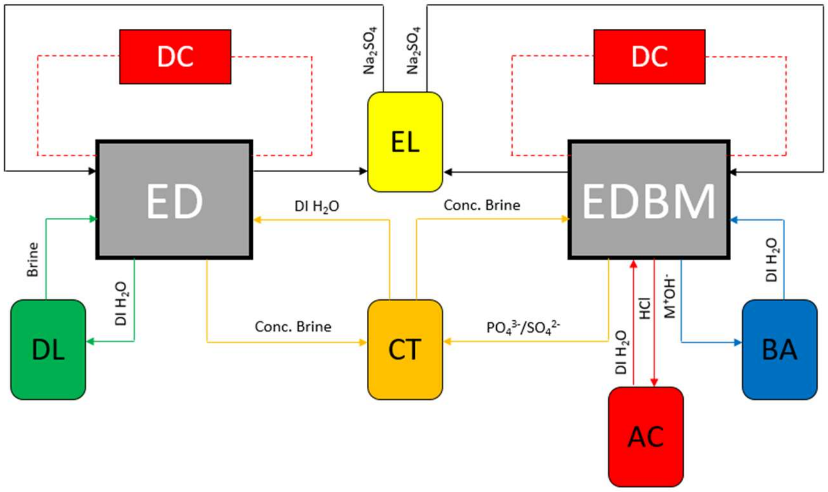

Figure 5. Continuous system test setup. *Each electrodialysis cell and its solutions were configured as in previous testing. For the continuous system test, however, the electrolyte and concentrate solutions were shared between the two cells.*

Throughout each electrodialysis test run for water extraction, ion separation, and continuous system testing, samples of known volume were collected from the various solutions using Eppendorf pipettes. Samples were stored in vials whose empty masses had been measured prior to testing. Masses of extracted samples in their vials were determined following sample collection so that sample mass could be calculated. This allowed for a mass balance to be calculated for each test run.

The collected samples underwent ion chromatography (IC) evaluation to determine the concentrations of each ion species in each solution as a function of time during the test run. Ion chromatography was performed using a Dionex ICS 3000. This instrument was calibrated periodically throughout the timeframe of the project. Check standards were also run intermittently along with samples to ensure that calibrations remained accurate.

In order to get each of the ion species concentrations within the calibrated range for each sample, multiple dilutions were required for each sample. Dilutions were made in high-purity, deionized water using Eppendorf pipettes.

F. Optimization and Additional Testing

Once the initial tests were completed, further experimentation was required to determine the optimum conditions in order to achieve the desired product streams. A set of ten extra experiments were completed that will test one of four questions: 1) Can the starting volumes be altered? 2) Can the flowrates be lowered and if so, what will change? 3) What will happen if the voltage is increased or decreased? 4) Can the initial diluate stream also be used as the initial concentrate stream instead of DI water?

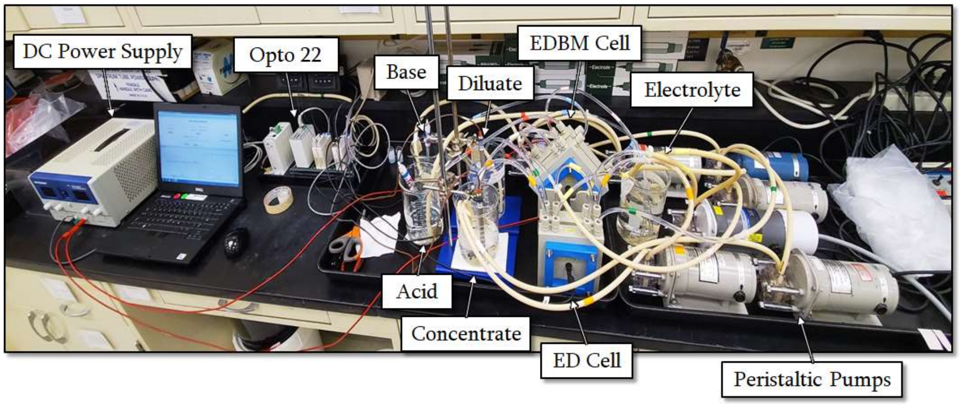

Figure 6. Continuous system test setup.

In order to answer these four questions, multiple tests would need to be completed adjusting a single constraint, while keeping everything else constant. For example, in order to test if the starting volumes can be altered, the voltage and flowrates would need to remain constant.

Overall, two flowrates were chosen (1/2 and 1/4 L/min), three starting volumes (250, 500, and 1000 mL), and three voltages (5, 10, and 15 V). The flowrates were consistent across all streams (diluate, concentrate, acid, and base). The flowrate and starting volume for the electrolyte remained constant at 1 L/min and 1000 mL. The starting volumes were consistent across all streams, except the diluate which remained constant at 1000 mL.

Additional runs were completed in which the diluate stream was split with the concentrate stream. In this case, the diluate and concentrate streams were both initially 500 mL of inorganic waste. This would negate the need for DI water input to the concentrate stream. However, DI water will still be needed for the acid and base stream.

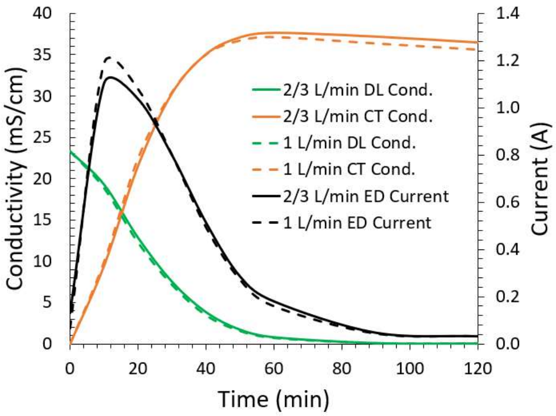

Figure 7. Conductivity of diluate and concentrate, and ED cell current in water extraction runs with a flowrate of 2/3 and 1 L/min.

III. Results & Discussion

Overall test results are discussed here.

A. Water Extraction

The water extraction segment of testing was successful. Results from six runs (three for each flowrate) were averaged, up to 120 minutes. Conductivity values measured for the diluate solution match the expected conductivity of potable water by the end of each test run, approximately 3.5E-2 mS/cm. The ending concentrate conductivity (36.2 mS/cm) increases to well above the starting conductivity of the diluate (23.3 mS/cm), which is expected due to the 500 mL starting concentrate volume as compared to the 1000 mL starting diluate volume. In addition, ion chromatography results show that a vast majority of the ions present in the urine simulant were moved into the concentrate solution. The current of the cell peaked at 1.1 A (2/3 L/min) and 1.2 A (1 L/min) at approximately the 15 minute mark.

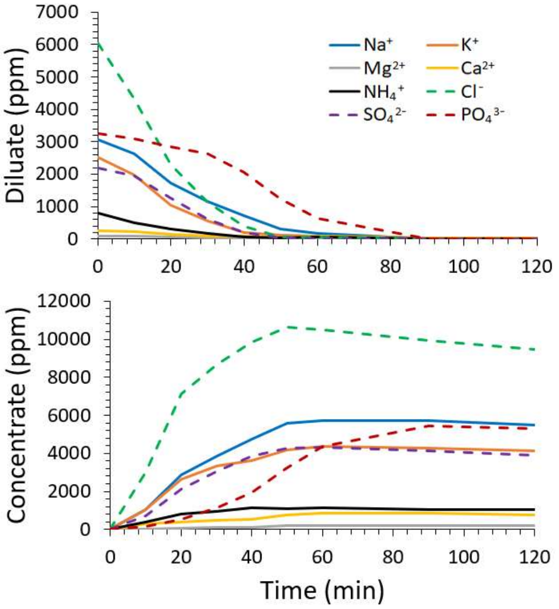

Figure 8. Diluate and concentrate ion concentrations as a function of time during a 2/3 L/min flowrate water extraction run.

Figure 7 shows the average conductivity of the concentrate and diluate solutions, and the current throughout each of the three water extraction runs for a flowrate of 2/3 and 1 L/min.

Figure 8 shows the concentration of each ion in the diluate and concentrate solutions over time for the three, repeated, test runs at a flowrate of 2/3 L/min. The diluate, which began as urine simulant, showed a rapid decrease in ion concentration early on, leveling off with minimal ion concentrations after two hours. The ion concentrations in the concentrate solution rose as expected relative to their decrease in the diluate.

It is notable that not all ions are transferred from the diluate to the concentrate at the same rate. In particular, phosphate was the slowest, while chloride was the fastest. This could be due to ion size, charge, or charge-to-mass ratio.

Results for the 1 L/min flowrate were similar to the 2/3 L/min tests, with a slight increase in ion transport rate as expected for the higher flowrate.

B. Ion Separation

Ion separation was also successful. pH data acquired during each run showed strong acid and base solutions forming quickly. IC results also showed that phosphate was effectively separated from the other ions in the concentrated brine. Results from three runs were averaged, up to 180 minutes, each with a flowrate of 2/3 L/min.

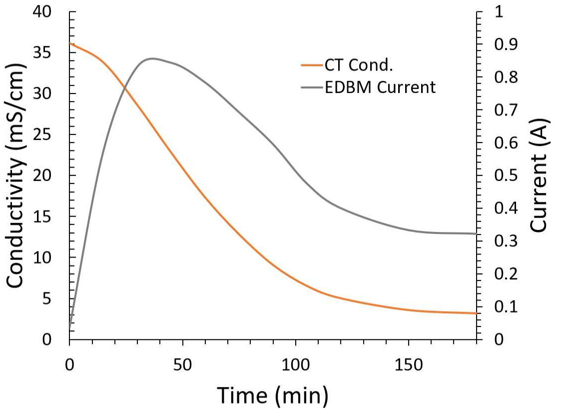

Figure 9. Conductivity of concentrate and EDBM cell current in a ion separation run with a flowrate of 2/3 L/min.

The current for this cell peaked at 0.85 A around the 40 minute mark. The concentrate conductivity decreased over time to approximately 3 mS/cm. This is expected since the phosphate and sulfate ions should remain in the concentrate stream. The pH curves also behaved as expected, the pH dropped in the acid, due to hydrogen ions and anions, and the pH increased in the base due to hydroxide ions and cations. Figure 9 shows the cell current recorded and the conductivity of the concentrate solution during the ion separation run.

Figure 10 shows the ion concentrations in the concentrate, acid, and base solutions during one of the three test runs. Most notable in the concentrate is that, as the other ions were transported to the acid and base solutions, phosphate remained at a fairly steady concentration. In the acid solution, chloride concentration increased dramatically as expected; however, the increase in sulfate in this solution was unanticipated. Sulfate should have been blocked by the monovalent membrane in this electrodialysis cell, causing it to remain in the concentrate rather than travelling into the acid solution. Ion concentrations in the base solution showed cations accumulating in that solution over time.

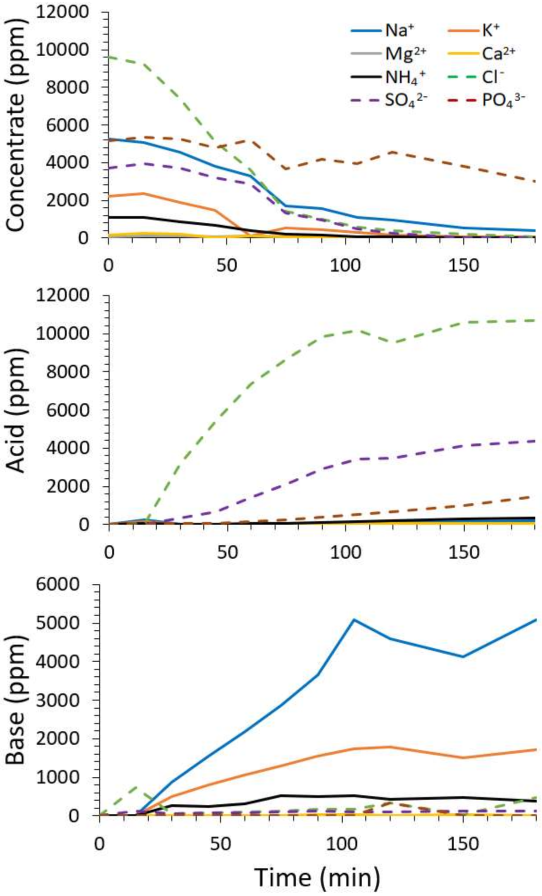

Figure 10. Concentrate, acid, and base ion concentrations as a function of time during a 2/3 L/min flowrate ion separation run.

C. Continuous System

When run as a continuous system, rather than two back-to-back processes, the electrodialysis cells were once again successful in producing potable water as well as an isolated phosphate solution, acid, and base. Results from two of three runs were averaged, up to 240 minutes, at a flowrate of 1/2 L/min.

Similar to the previous tests, the current for the ED cell peaked at 1.1 A, while at 0.8 A for the EDBM cell. The diluate conductivity decreased to that of potable water, and the concentrate conductivity peaked at 26 mS/cm at approximately 45 minutes before decreasing to 3 mS/cm by the end of the run. Again, the pH curves behaved as expected, the pH dropped in the acid, due to hydrogen ions and anions, and the pH increased in the base due to hydroxide ions and cations. Figure 11 shows the cell currents for continuous system runs and the conductivities of the diluate and concentrate solutions during continuous system runs.

IC results for this test are shown in Figure 12. These results mimicked the results of the water extraction and ion separation testing, showing that running as a continuous system does not significantly change the efficacy of the overall process.

Ion concentrations in the diluate were minimal after about 90 minutes, leaving behind the desired clean water. As seen in the water extraction test, ion transport rates varied, with chloride being the fastest and phosphate being the slowest.

The concentrate quickly gained ions early in the test, as shown by the rise in concentration of all ions early on. As expected, a majority of the ions were transported into the acid and base solutions, leaving phosphate behind in the concentrate. The drop in the concentration of phosphate later in the test run is due, in part, to some phosphate transport to other solutions over time, but is also due to water migration into the concentrate reducing the concentrations of all ions present.

The chloride concentration shown here was somewhat erratic, but this appeared to be primarily due to difficulty obtaining consistent results at very high dilution levels required for IC analysis, as the ion levels of chloride were more stable in all other solutions, indicating that the chloride was not being transported back and forth. In future testing, adjustments should be made to accommodate for challenges in accurately evaluating such samples.

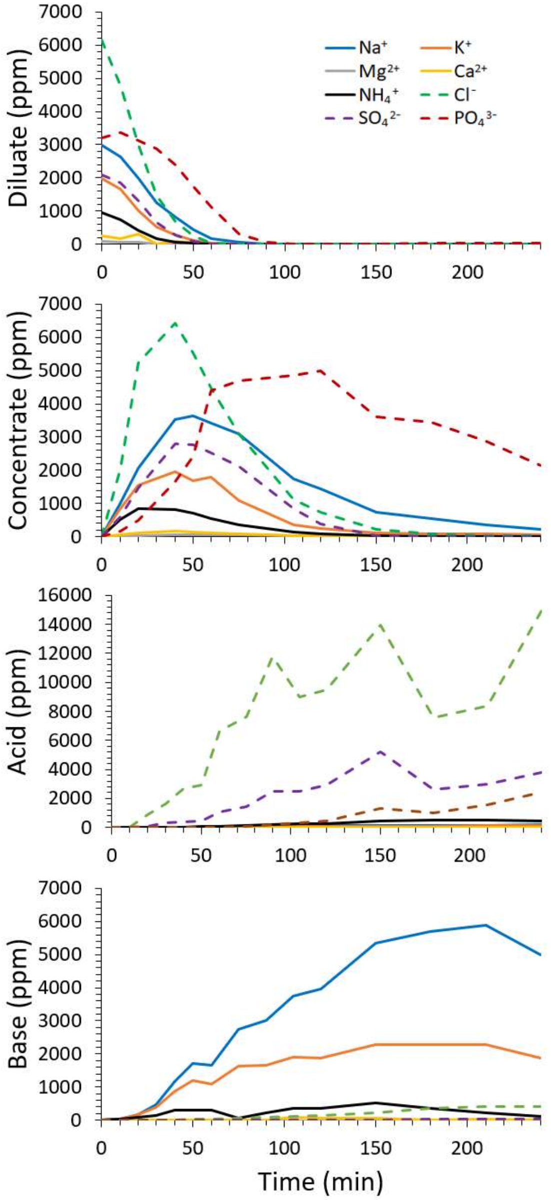

Figure 12. Diluate, concentrate, acid, and base ion concentrations as a function of time during a 1/2 L/min flowrate continuous system run.

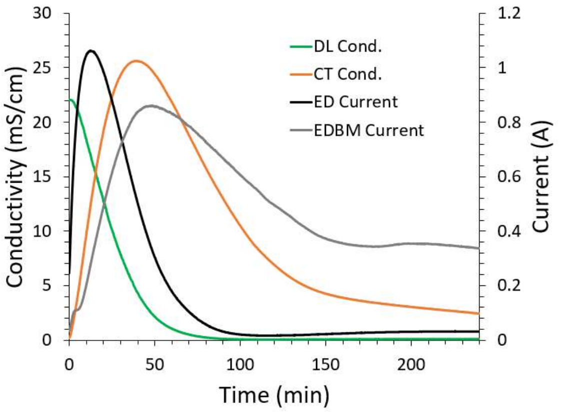

Figure 11. Conductivity of diluate and concentrate, and ED and EDBM cell current in a continuous system run with a flowrate of 1/2 L/min.

Also notable in the acid solution was the presence of sulfate. Sulfate was expected to remain in the concentrate solution, blocked from transport by the monovalent membrane in the electrodialysis cell. While that membrane was more effective for phosphate, it did not effectively block sulfate.

The base solution showed the expected increase in cation concentration throughout the test. The decrease in concentration near the end of the test was primarily due to water migration through the membrane diluting the concentrations of all ions present.

D. Optimization Testing

Table 2 shows the run matrix for this portion of the testing. The continuous system setup was used for all runs, except for S3 and S9 which used the water extraction setup. Most runs were stopped at 240 minutes, except S10 which was completed at 210 minutes, S7 at 120 minutes, and S3/S9 both at 70 minutes. For the majority of the runs, the diluate volume decreased while that of the concentrate, acid, and base increased.

Figure 13 shows the results for Runs S1 and S2. The only difference between these two runs was the flowrate for the diluate, concentrate, acid, and base, which was 1/2 and 1/4 L/min, respectively. Run S1 was slightly faster than Run S2. The conductivity of the diluate decreased to that of potable water at a greater rate than at the slower flowrate. The current peaked at about a 0.2 A difference for the ED cell and a 0.1 A difference for the EDBM cell. This means that the power input to each cell, and the power requirement to the pumps, were lower for the 1/4 L/min flowrate than the 1/2 L/min. The pH of the acid and base streams for each flowrate was nearly identical.

Table 2. Optimization testing run matrix. **Split DL so that 500 mL starts in DL and 500 mL in CT.*

	Voltage	Initial Volumes (mL)					Flowrates (L/min)				
ID	**(V)**	**DL**	**CT**	**AC**	**BA**	**EL**	**DL**	**CT**	**AC**	**BA**	**EL**
S1	10	1000	500	500	500	1000	½	½	½	½	1
S2	10	1000	500	500	500	1000	¼	¼	¼	¼	1
S3	10	1000*	-	0	0	1000	½	½	0	0	1
S4	10	1000	250	250	250	1000	½	½	½	½	1
S5	10	1000	250	250	250	1000	¼	¼	¼	¼	1
S6	10	1000	1000	1000	1000	1000	¼	¼	¼	¼	1
S7	15	1000	500	500	500	1000	¼	¼	¼	¼	1
S8	5	1000	500	500	500	1000	¼	¼	¼	¼	1
S9	10	1000*	-	0	0	1000	¼	¼	0	0	1
S10	10	1000*	-	500	500	1000	¼	¼	¼	¼	1

Figure 14 shows the results for Runs S3 and S9. These runs used only the ED cell and the 1000 mL inorganic waste stream was split evenly between the diluate and concentrate. Therefore, no DI water was initially added to the system. The only difference between these two runs was the flowrate for the diluate and concentrate, which was 1/2 and 1/4 L/min, respectively. Again, Run S3 was slightly faster than Run S9 due to the larger flowrate. The current initially started high and slowly decreased over the course of the experiment. Potable water was produced in about an hour of run time, quicker than any other run.

Figure 15 shows the results for Runs S5, S2, and S6. The difference between these three runs was the starting volumes of the concentrate, acid, and base, which was 250, 500, and 1000 mL for Runs S5, S2, and S6, respectively. The conductivity of the diluate remained unaffected, this is expected because the diluate volume remained constant at 1000 mL for each of the three runs. The conductivity of the concentrate peaked at about 50 minutes for all three runs, each at different values, due to the differing volumes increasing the ion concentration. The same is true for the pH of the acid and base, since the volumes are different and the pH will be altered based on the increasing ion concentration. The current through each membrane decreased slightly as the volume increased. This is due to the changing concentration since the lower volume, and resulting higher ion concentration, would conduct better than those with lower ion concentrations. The main takeaway from this result is that the cells still functioned

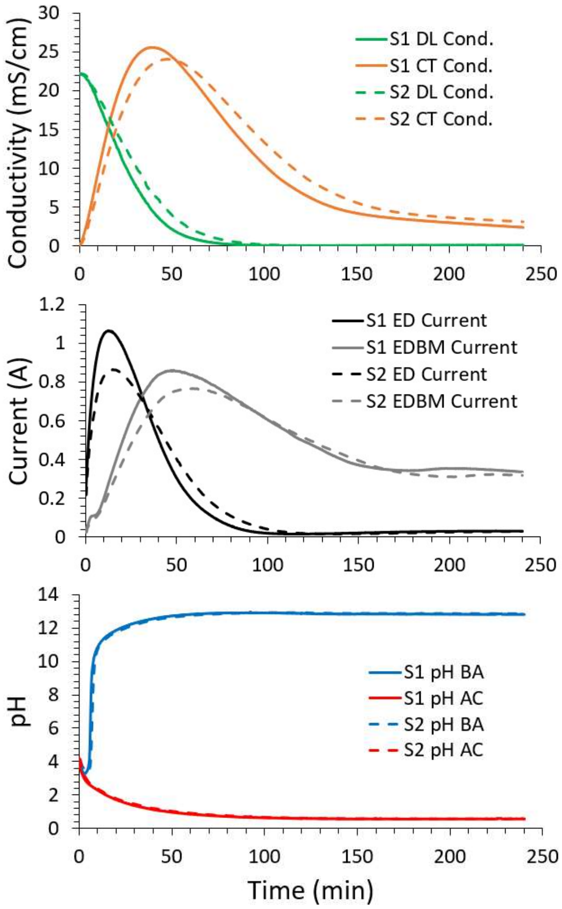

Figure 13. S1/S2 conductivity, current, and pH over time. *S1: 1/2 L/min flowrate, S2: 1/4 L/min flowrate.*

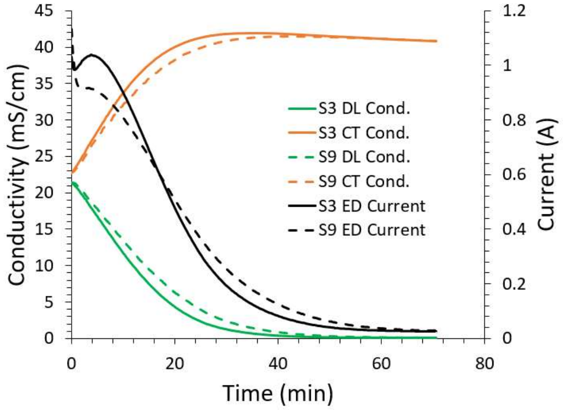

Figure 14. S3/S9 conductivity and current over time. *S3: 1/2 L/min flowrate, S9: 1/4 L/min flowrate. 1000 mL inorganic waste distributed evenly between the diluate and concentrate.*

properly when dropping the starting volumes. As long as the solubility limit is not reached, it appears that the starting volumes can be further decreased.

Figure 16 shows the results for Runs S7, S2, and S8. The difference between these three runs was the supplied voltage, which was 15, 10, and 5 V, respectively. Altering the voltage had the greatest effect on the overall results. Supplying 15 V, the concentrate conductivity peaked at 17 mS/cm at 20 minutes, and the whole run was completed by 120 minutes. At 10 V, the concentrate conductivity peaked at 24 mS/cm at 50 minutes and the run was doubled in length (240 minutes). At 5 V, the run never reached completion within the allotted time of 240 minutes. The peak current for the ED cell increased by about 0.4 A, while that of the EDBM cell increased by 1 A between the 10 and 15 V tests. While running at high voltage appears to drastically reduce the overall time, the membranes can only handle so much voltage and current. The manufacturer, PCCell, recommends a maximum of 2 V per cell pair and no more than 5 A per cell. The ED cell has 10 cell pairs so no more than 20 V should be applied. The pH of each run confirms that the higher the supplied voltage, the quicker the ions diffuse through the membranes.

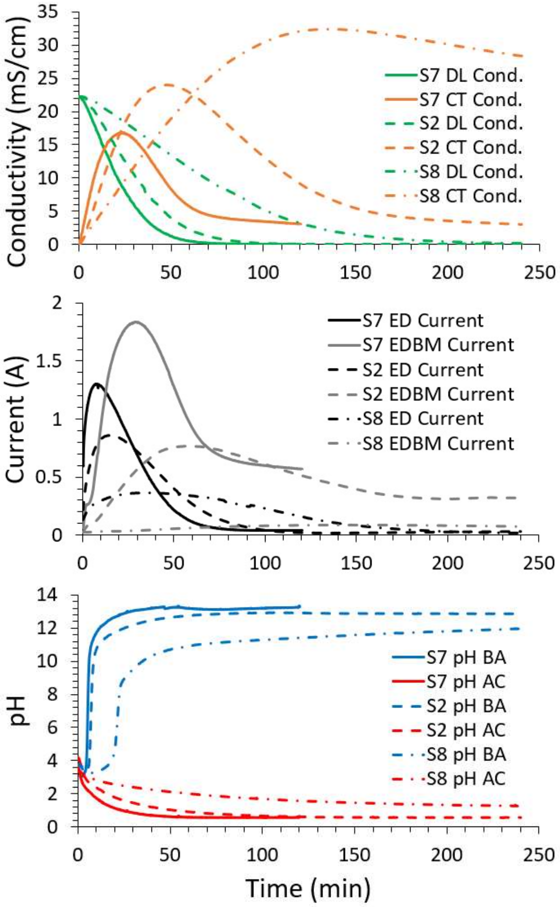

Figure 16. S7/S2/S8 conductivity, current, and pH over time. *S7: 15 V, S2: 10 V, S8: 5 V.*

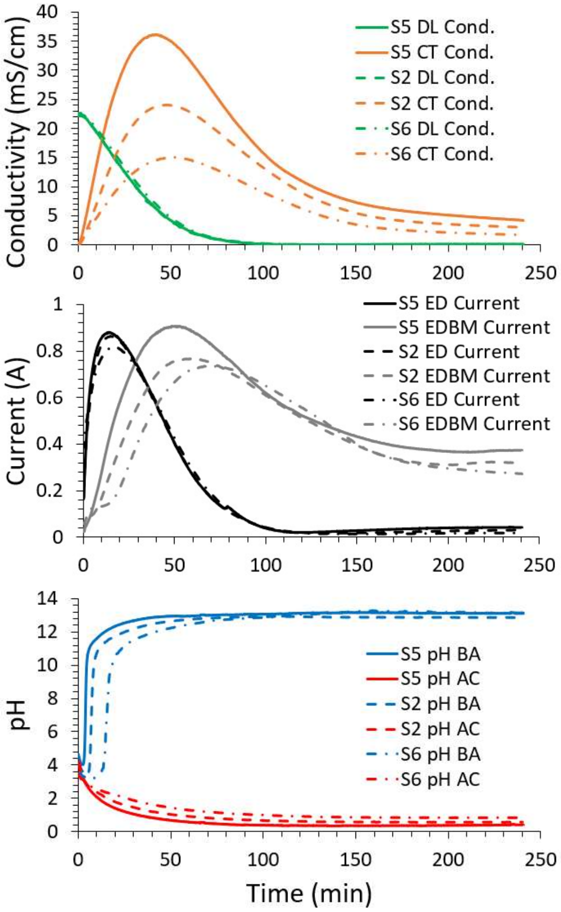

Figure 15. S5/S2/S6 conductivity, current, and pH over time. *S5: 250 mL, S2: 500 mL, S6: 1000 mL starting volumes.*

Figure 17 shows the results for S10 and S2. Run S10 was setup similar to Runs S3 and S9, except that the EDBM cell was also used with 500 mL of DI water initially in the acid and base streams. This run was completed in 210 minutes, as compared to 240 minutes for S2. For S10, the concentrate conductivity peaked at 35 mS/cm at 20 minutes, while that of S2 peaked at 24 mS/cm at 50 minutes. Basically, S10 got a 30 minute head start on S2 and the ions diffused at the same rate.

Ultimately, the amount of extracted water should be equal to or greater than the amount of water input into the system initially. Runs S5, S9, and S10 all exhibited the potential of producing more potable water than the amount that was necessary at the start. Run S5 began with an input of 750 mL of water, not including the amount of water needed in the electrolyte, and produced 168 mL of potable water in addition to retaining the input. Run S9 did not require any water initially since the inorganic waste stream was split between the diluate and concentrate. This

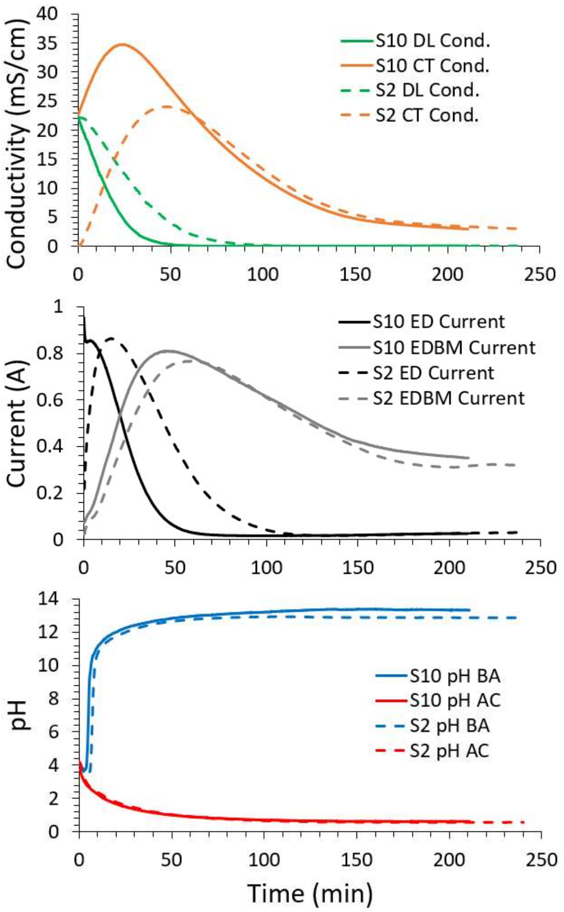

Figure 17. S10/S2 conductivity, current, and pH over time. *S10: 1000 mL inorganic waste distributed evenly between the diluate and concentrate, S2: 1000 mL inorganic waste in the diluate and 500 mL DI water in the concentrate.*

resulted in 455 mL of potable water. Run S10 only required water for the acid and base streams initially. Although this run resulted in an overall loss of 552 mL of water, this run proved that the initial inorganic waste stream can be split between the diluate and concentrate. Repeating this test, but reducing the initial input of water to the acid and base streams, and adjusting the diluate to concentrate ratio could maximize potable water yield.

IV. Conclusions

The use of these two electrodialysis cells was effective for both water extraction and ion separation. Both methods, with the cells used one after the other or together in series, worked well and met the project goals of producing potable water, a phosphate solution, and a separate anion/hydrogen and cation/hydroxide stream. However, sulfate and some phosphate ions were able to diffuse through the monovalent anion exchange membrane into the acid stream, resulting in predominantly phosphate ions remaining in the concentrate.

Optimization of the process was accomplished by altering flowrates of each stream and initial volumes, adjusting the power input to each cell, and splitting the inorganic waste input into the diluate and the concentrate.

The lower flowrate appears to slow down the process, however less power is ultimately required. Dropping the initial volumes of each stream is a good way to reduce the intake of water; however, while we didn't reach it in this project, the volume can only be dropped until the solubility limit is reached. Increasing the power input to each cell drastically reduced the overall time, however the upper voltage limit was nearly attained. Splitting the input waste stream between the diluate and concentrate proved to be advantageous as it reduced the water intake and the overall time. On the other hand, only half the amount of potable water was produced per liter of inorganic waste.

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