Removal Rates of Electrolytes Commonly Found in Brackish Groundwater by Means of Electrodialysis Reversal Desalination

by

Georgia D. Van de Zande

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Bachelor of Science in Mechanical Engineering at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2015

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Abstract

This thesis tested and analyzed the removal rates of six different electrolytes: NaCl, Na₂SO₄, MgCl₂, K₂SO₄, Ca(NO₃)₂, and CaSO₄ when using electrodialysis reversal (EDR) desalination. A bench top EDR set-up was designed and built, and this set-up was used to desalinate feed water with initial concentrations of about 1000 ppm of each of the electrolytes. The tests ran until the diluate stream reached a concentration of 415 ppm. These results were then compared to a mathematical model that predicts the electrolyte removal behavior, and the experimental results did align with the model. When the mathematical model was used to estimate the electrolytes’ behaviors for beginning concentrations of exactly 900 ppm, it was shown that the ranking of electrolytes with highest to lowest removal rates is NaCl (38.8 ppm/min when the diluate concentration is 415 ppm), K₂SO₄ (36.0 ppm/min), CaSO₄ (33.6 ppm/min), Na₂SO₄ (33.4 ppm/min), MgCl₂ (32.7 ppm/min), and Ca(NO₃)₂ (31.8 ppm/min).

Thesis Supervisor: Amos Winter
Title: Assistant Professor of Mechanical Engineering
Acknowledgments

I would like to thank Professor Amos Winter and Natasha Wright for their advice and support throughout this project. Since becoming involved with this research, I’ve had so many incredible opportunities that I couldn’t have expected to have as an undergraduate student. I’d like to thank all other members of the Global Engineering and Research Lab for letting me use their lab while I worked on this project and helping me along the way. I’d like to thank the MIT Undergraduate Research Opportunities Program for first introducing me to research. And finally, I’d like to thank my parents and brother for helping me be where I am today and always supporting me.
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Chapter 1

Introduction

1.1 Motivation

This undergraduate thesis project stemmed from a year and a half long Undergraduate Research Opportunities Program project I have been working on in Professor Amos Winter’s Global Engineering and Research (GEAR) lab under the guidance of Natasha Wright, a doctoral candidate in the lab who heads this project.

The end goal of this project is to design a system that can provide clean drinking water to rural villages in India. Currently, 60% of India’s land area is underlain with brackish water with total dissolved solids (TDS) levels of over 480 ppm (Figure 1-1). Targeting areas with groundwater salinity levels in the range of 1000-3000 ppm, the current system has been designed using electrodialysis reversal (EDR) technology because at these low salinity levels, EDR was shown to be more economical than the reverse osmosis technology currently used in many Indian villages [9].

Further information on the background of this project can be found in Wright and Winter’s journal article [9] and Wright’s master’s thesis [7].
1.2 Electrodialysis Reversal

This desalination system uses EDR to remove ions from saline water and ultra-violet desinfection for treatment of biological contaminants. There are a number of different ions that commonly compose the groundwater found in India, and this thesis explores the removal rates of electrolytes containing these ions when using EDR, comparing the results to predicted rates using a mathematical model developed by Wright.

EDR removes ions from water by applying a voltage to two electrodes that have pairs of ion-selective membranes between them (Figure 1-2). A single cell pair consists of one cation exchange membrane (CEM) and one anion exchange membrane (AEM). As saline water is pumped through channels between these membranes, the electric
field from the applied voltage causes cations to move toward the cathode and anions to move toward the anode. In a stack of membranes, the CEMs and the AEMs alternate. When a cation moves through a CEM due to the electric field pulling it that way, the cation is then blocked by the next membrane, an AEM. It stays in that channel. Similarly, when an anion moves through an AEM due to the electric field pulling it the other way, the anion is then blocked by the next membrane, a CEM, and it stays in that channel. The alternating CEMs and AEMs cause the water exiting every other channel to have a lower ion concentration than when it entered (referred to as the diluate stream) while the water exiting the remaining channels to have a higher ion concentration (referred to as the concentrate stream).

![Diagram of a two cell pair EDR stack with ions moving in the electric field through ion-selective membranes](image)

Figure 1-2: A schematic of a two cell pair EDR stack with ions moving in the electric field through ion-selective membranes [9].

A rinse solution flows over each electrode to clear away any gas bubbles or residue that may build up on the electrode during operation. In addition, to clean the scale that may build up on the membranes during operation and to extend the lifetime of the membranes, the voltage applied to the electrodes can be reversed. This will reverse the direction that the ions will migrate as well as flip which streams of outlet water are diluate or concentrate streams.
The performance of an EDR stack is a result of a number of parameters including the voltage applied across the electrodes, the resistances of the membranes, the changing resistances of the concentrate and diluate streams, the beginning concentration of feed water, the desired end concentration of dilute stream, the active membrane area, the flow rate of water through the stack, the quality of the membranes, the design of spacers placed between the membranes that allow for mixing in the channels, and the chemical composition of the feed water. This thesis investigates the removal rate of different electrolytes while keeping other parameters constant.
Chapter 2

Experimental Set-Up

In order to test the removal rates of various electrolytes, a benchtop EDR system was constructed. A PCCell ED 64 0 02 stack with 18 cell pairs, each with an active membrane area of 64 cm², was used. These membranes were designed to select both monovalent and divalent ions, and these tests incorporate electrolytes that dissociate into both monovalent and divalent ions. A Jenco 3250 salinity/conductivity/temperature meter with a Conductivity Cell 106 probe was used for the temperature and conductivity measurements taken during these tests. For conductivity measurements, this meter and probe combination have an accuracy of ±0.5%. The dilute and concentrate streams were pumped with KAG pumps m48x28/1, and the rinse stream was pumped with an Iwaki WMD-20RZ-115 pump. Magnetic stirrers were placed under the concentrate and diluate beakers to ensure uniform mixing within each beaker.

2.1 Electrodialysis Reversal Batch Set-Up

For these tests, a batch set-up was used in which the water recirculates through the EDR multiple times (as opposed to passing through the membrane channels just once) in order to become desalinated (Figure 2-1). For example, the water in the diluate stream is pumped from a beaker, through a valve and pressure gauge, through the
ED stack, and back into the diluate beaker. This cycle continues for both streams until the diluate cycle reaches the desired concentration. To simulate the reversal of the EDR system, the voltage applied over the stack was flipped between tests. A flow diagram of the batch set-up is shown in Figure 2-2.

![Flow diagram of EDR batch set-up](image)

Figure 2-1: The experimental set-up for an EDR batch set-up.

### 2.2 Testing Procedure

Two tests were run for each of six different electrolytes: NaCl, Na$_2$SO$_4$, MgCl$_2$, K$_2$SO$_4$, Ca(NO$_3$)$_2$, and CaSO$_4$. In a test, salt crystals were dissociated in diluted water to give the water an initial TDS level of about 1000 ppm. Exact initial TDS levels are given in Table 2.1, which were calculated from the measured conductivity measurements using the parameters in Table 2.2. These factors were calculated using mass composition of the electrolytes and ion conductivity factors [3]. Both the diluate
and the concentrate streams began with 2 L of saline feed water. Before voltage was applied to the stack, both the diluate and concentrate streams were flushed with feed water. Initial measurements that were taken for each stream were the water temperature, the pressure drop across the stack, the flow rate, and the conductivity. Temperature, pressure, and flow rate measurements can be seen in Table 2.3.

Once the stack was flushed and both streams were running at 0.18 GPM, a constant 12V was applied to the stack. Every 30 seconds, measurements were taken of the conductivity in both streams. The test ran until the diluate stream reached a total
Table 2.1: Measured initial TDS levels for the twelve tests run.

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>Test 1</th>
<th>Test 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Concentrate (ppm)</td>
<td>Diluate (ppm)</td>
</tr>
<tr>
<td>NaCl</td>
<td>954</td>
<td>939</td>
</tr>
<tr>
<td>Na$_2$SO$_4$</td>
<td>1229</td>
<td>1248</td>
</tr>
<tr>
<td>MgCl$_2$</td>
<td>809</td>
<td>847</td>
</tr>
<tr>
<td>K$_2$SO$_4$</td>
<td>1135</td>
<td>1187</td>
</tr>
<tr>
<td>Ca(NO$_3$)$_2$</td>
<td>1245</td>
<td>1295</td>
</tr>
<tr>
<td>CaSO$_4$</td>
<td>1131</td>
<td>1088</td>
</tr>
</tbody>
</table>

dissolved solid (TDS) level of 415 ppm, which meets the World Health Organization drinking water standards [6].

When the test was complete, final water temperature readings (also presented in Table 2.3) were taken for each stream to ensure that the temperature had not increased enough to affect the conductivity measurements. Between the two tests that were run for each electrolyte, the polarity of the electrodes was reversed to simulate the reversal function that occurs in an EDR system.
Table 2.2: Factors used to convert conductivity measurements to TDS measurements.

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>Factor (mg/L per μS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>0.47</td>
</tr>
<tr>
<td>Na₂SO₄</td>
<td>0.58</td>
</tr>
<tr>
<td>MgCl₂</td>
<td>0.39</td>
</tr>
<tr>
<td>K₂SO₄</td>
<td>0.60</td>
</tr>
<tr>
<td>Ca(NO₃)₂</td>
<td>0.66</td>
</tr>
<tr>
<td>CaSO₄</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Table 2.3: Measured test parameters of initial and final water temperature (°C), pressure drop across the stack (psi), and water flow rate in the streams (GPM).

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>Test</th>
<th>Initial Temp. (°C)</th>
<th>Final Temp. (°C)</th>
<th>Pressure (psi)</th>
<th>Flow Rate (GPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>1</td>
<td>20.2</td>
<td>20.2</td>
<td>20.5</td>
<td>20.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>21.6</td>
<td>21.5</td>
<td>21.6</td>
<td>21.5</td>
</tr>
<tr>
<td>Na₂SO₄</td>
<td>1</td>
<td>25.5</td>
<td>25.6</td>
<td>25.6</td>
<td>25.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>18.8</td>
<td>18.8</td>
<td>19.5</td>
<td>19.5</td>
</tr>
<tr>
<td>MgCl₂</td>
<td>1</td>
<td>23.4</td>
<td>23.6</td>
<td>23.4</td>
<td>23.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>23.6</td>
<td>23.6</td>
<td>23.8</td>
<td>23.8</td>
</tr>
<tr>
<td>K₂SO₄</td>
<td>1</td>
<td>22.3</td>
<td>22.3</td>
<td>22.8</td>
<td>22.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>22.9</td>
<td>22.8</td>
<td>23.3</td>
<td>23.3</td>
</tr>
<tr>
<td>Ca(NO₃)₂</td>
<td>1</td>
<td>25</td>
<td>24.1</td>
<td>24.5</td>
<td>24.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>24.7</td>
<td>24.7</td>
<td>24.8</td>
<td>24.8</td>
</tr>
<tr>
<td>CaSO₄</td>
<td>1</td>
<td>24.9</td>
<td>24.7</td>
<td>24.9</td>
<td>24.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>25.3</td>
<td>25.2</td>
<td>25.3</td>
<td>25.3</td>
</tr>
</tbody>
</table>
Chapter 3

Mathematical Model

The mathematical model to which the experimental results were compared is described in detail in Wright’s master’s thesis [7]. This model uses the Falkenhagen Equation

\[ \Lambda_c = \Lambda_0 - (B_1 \Lambda_0 + B_2) \frac{\sqrt{c}}{1 + B_a \sqrt{c}} \]  

(3.1)

which gives the conductivity of a solution for a specific electrolyte at a specific concentration [4]. Parameters for the Falkenhagen Equation (\( \Lambda_0, B, B_1, \) and \( B_2 \)) differ for each electrolyte to find the molarity, \( c \). Parameters for NaCl, Na\(_2\)SO\(_4\), and MgCl\(_2\) are given in J.M. Ortiz’s article [5]. For the remaining electrolytes, the parameters were determined by fitting the Falkenhagen Equation to sets of standard equivalent conductivity data [2]. These sets of data cover the same ranges of conductivities measured in the tests discussed in this thesis. The parameters used are presented in Table 3.1. For all electrolytes used, \( a \), the mean atomic diameter, is 4.0 Å.

The model also uses the relationship between current traveling through the stack and the total applied voltage over the stack

\[ V_{total} = V_{elec} + N V_{potential} + Ni(R_{dil} + R_{cone} + R_{AEM} + R_{CEM}), \]  

(3.2)
Table 3.1: Parameters used for the Falkenhagen Equation.

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>$A_0$</th>
<th>$B$</th>
<th>$B_1$</th>
<th>$B_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{NaCl}$</td>
<td>126.45</td>
<td>0.358</td>
<td>0.240</td>
<td>60.32</td>
</tr>
<tr>
<td>$\text{Na}_2\text{SO}_4$</td>
<td>129.8</td>
<td>0.505</td>
<td>1.1346</td>
<td>60.324</td>
</tr>
<tr>
<td>$\text{MgCl}_2$</td>
<td>133.4</td>
<td>0.678</td>
<td>0.9867</td>
<td>60.32</td>
</tr>
<tr>
<td>$\text{K}_2\text{SO}_4$</td>
<td>113.6</td>
<td>0.8124</td>
<td>0.4577</td>
<td>0.02133</td>
</tr>
<tr>
<td>$\text{Ca(NO}_3)_2$</td>
<td>123.1</td>
<td>1.253</td>
<td>0.5162</td>
<td>0.01682</td>
</tr>
<tr>
<td>$\text{CaSO}_4$</td>
<td>123.1</td>
<td>1.253</td>
<td>0.5162</td>
<td>0.06292</td>
</tr>
</tbody>
</table>

which gives the relationship between the applied voltage and the instantaneous resistance through the stack. $V_{\text{total}}$ is the total voltage applied over the stack, $V_{\text{elec}}$ is the electrode potential, $N$ is the number of cell pairs in the stack, $V_{\text{potential}}$ is the concentration potential, and $i$ is the current density ($A/m^2$). $R_{\text{dil}}$, $R_{\text{conc}}$, $R_{\text{AEM}}$, and $R_{\text{CEM}}$ are the area resistances of the diluate stream, concentrate stream, AEM, and CEM, respectively.

Finally, the model uses the mass balances for the diluate tank, concentrate tank, diluate cells, and concentrate cells

$$
\frac{dC_{\text{dil}}^{\text{in}}}{dt} = \frac{1}{V_{\text{dil}}^{\text{tank}}}[Q_{\text{dil}}C_{\text{dil}}^{\text{out}} - Q_{\text{dil}}C_{\text{dil}}^{\text{in}}],
$$

(3.3)

$$
\frac{dC_{\text{conc}}^{\text{in}}}{dt} = \frac{1}{V_{\text{conc}}^{\text{tank}}}[Q_{\text{conc}}C_{\text{conc}}^{\text{out}} - Q_{\text{conc}}C_{\text{conc}}^{\text{in}}],
$$

(3.4)

$$
\frac{dC_{\text{dil}}^{\text{out}}}{dt} = \frac{1}{NV_{\text{cell}}}[Q_{\text{dil}}(C_{\text{dil}}^{\text{in}} - C_{\text{dil}}^{\text{out}}) + \frac{N\phi I}{zF} + \frac{NAD_a(C_{\text{AEM}} - C_{\text{AEM}}^{\text{EM}})}{l_a} + \frac{NAD_c(C_{\text{CEM}} - C_{\text{CEM}}^{\text{EM}})}{l_c}],
$$

(3.5)
and

\[
\frac{dC_{\text{conc}}}{dt} = \frac{1}{N V_{\text{cell}}} \left[ Q_{\text{conc}} (C_{\text{conc}}^{\text{in}} - C_{\text{conc}}^{\text{out}}) + \frac{N \phi I}{z F} \left( \frac{NAD_a(C_{\text{conc}}^{\text{AEM}} - C_{\text{dil}}^{\text{AEM}})}{l_a} - \frac{NAD_c(C_{\text{conc}}^{\text{CEM}} - C_{\text{dil}}^{\text{CEM}})}{l_c} \right) \right].
\]

(3.6)

where \(C_{\text{dil}}^{\text{in}}, C_{\text{conc}}^{\text{in}}, C_{\text{dil}}^{\text{out}}, \) and \(C_{\text{conc}}^{\text{out}}\) are the concentrations of the diluate and concentrate streams at the inlet and outlet of the ED stack, respectively. \(V_{\text{dil}}^{\text{tank}}\) and \(V_{\text{conc}}^{\text{tank}}\) are the volumes of water in the diluate and concentrate beakers. \(Q_{\text{dil}}\) and \(Q_{\text{conc}}\) are the flow rates in the diluate and concentrate streams. \(\phi\) is the current efficiency, \(z\) is the ion charge, \(F\) is the Faraday constant (C/mol), \(A\) is the active membrane area of a single membrane, \(D_c\) and \(D_a\) are the diffusion coefficients of the given solution in the anion and cation exchange membranes, and \(l_a\) and \(l_c\) are the thicknesses of the anion and cation exchange membranes. \(C_{\text{dil}}^{\text{AEM}}, C_{\text{conc}}^{\text{AEM}}, C_{\text{dil}}^{\text{CEM}}, \) and \(C_{\text{conc}}^{\text{CEM}}\) are the concentrations of the diluate and concentrate streams at the interface with the anion or cation exchange membranes.
Chapter 4

Analysis of Electrolyte Removal Rates

Figures 4-1 to 4-6 show the results of the twelve tests compared to the corresponding mathematical models. From these graphs, it can be seen that the experimental results reflected the behavior predicted by the model. The salt with the furthest deviation from the model was CaSO$_4$. This could be caused because the model did not account for the ions’ concentrations reaching the salt’s solubility in water. Although no precipitate was observed during the tests, the solubility of anhydrous CaSO$_4$ in water is 2550 ppm, so the concentrate stream approached this limit as the test was conducted.

4.1 Linearizing the Experimental Results

First, the experimental results were linearized, and an average electrolyte removal rate was calculated for each test by dividing the difference between the initial and final TDS levels in the diluate streams by the amount of time it took to reach the final level. The linearized electrolyte removal rates are presented in Table 4.1. These rates give an idea of the time it took to desalinate the water under the given conditions:
Figure 4-1: The results and model for the NaCl tests.

Figure 4-2: The results and model for the Na$_2$SO$_4$ tests.
Figure 4-3: The results and model for the MgCl$_2$ tests.

Figure 4-4: The results and model for the K$_2$SO$_4$ tests.
Figure 4-5: The results and model for the Ca(NO₃)₂ tests.

Figure 4-6: The results and model for the CaSO₄ tests.
initial and final concentrations, voltage applied, and membrane type and size. These rates will change for different conditions but were calculated for these tests to give a sense of the relative removal rates between different electrolytes.

The initial and final concentrations and the times used to calculate the removal rates are also presented in the table. These concentrations were calculated using the conductivity measurements taken with the Jenco meter and the conversion factors found in Table 2.2 These data are helpful when the feed water is comprised of a single, known electrolyte. It should be noted that the electrolyte removal for any given test is not a linear relationship, but instead follows the model given in Chapter 3, so the results stated in Table 4.1 are averaged over the course of a test desalinating until the diluate stream reached a TDS measurement of 415 ppt.

Error in these tests could have come from the conductivity measurements taken with the conductivity meter and probe which have a ±0.5% error associated with conductivity readings. However, when this error is taken into account, it is too small to show on Figures 4-1 to 4-6 or to significantly change the data.

A larger error that occurred during these tests that introduces difficulty when comparing one electrolyte to another is the range of starting TDS levels for the initial feed water. All feed water TDS levels (shown in Table 2.1) were in the range of 786 to 1294 ppm with an average of 1048 ppm and a standard deviation of 255.6 ppm. This range in starting TDS levels does not change the overall trends seen in Figures 4-1 to 4-6, but it does affect the values presented in Table 4.1. Even with this error, some conclusions can still be drawn. For example, looking at a given electrolyte, it would take more time to desalinate a higher initial TDS level to a set final TDS level than it does to desalinate a lower initial TDS level to that same set final TDS level. However, K₂SO₄ had a high initial TDS level and still reached the final 415 ppm in less time than it took for MgCl₂ to reach 415 ppm from a much lower initial TDS level. Further tests with more similar initial feed water TDS levels would need to be conducted to produce an accurate ranking of removal rates for the various electrolytes.
Table 4.1: Results of the linearized electrolyte removal rates and averages for six electrolytes over the course of twelve tests. The removal rates were linearized by dividing the difference between the initial and final concentrations by the time it took to reach the final concentration.

<table>
<thead>
<tr>
<th>Electro.</th>
<th>Test</th>
<th>Initial Conc. (ppm)</th>
<th>Final Conc. (ppm)</th>
<th>Time (min)</th>
<th>ERR (ppm/min)</th>
<th>Avg. ERR (ppm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>1</td>
<td>939</td>
<td>422.8</td>
<td>10.0</td>
<td>51.6</td>
<td>54.7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>956</td>
<td>408.3</td>
<td>9.5</td>
<td>57.7</td>
<td></td>
</tr>
<tr>
<td>Na₂SO₄</td>
<td>1</td>
<td>1248</td>
<td>415.0</td>
<td>12.0</td>
<td>69.4</td>
<td>68.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1254</td>
<td>419.2</td>
<td>12.5</td>
<td>66.8</td>
<td></td>
</tr>
<tr>
<td>MgCl₂</td>
<td>1</td>
<td>847</td>
<td>409.5</td>
<td>9.0</td>
<td>48.6</td>
<td>47.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>854</td>
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<td>K₂SO₄</td>
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<td>406.0</td>
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<td>74.4</td>
<td>72.8</td>
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<tr>
<td>Ca(NO₃)₂</td>
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<td>1295</td>
<td>415.9</td>
<td>13.0</td>
<td>67.6</td>
<td>67.9</td>
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<tr>
<td></td>
<td>2</td>
<td>1268</td>
<td>417.7</td>
<td>12.5</td>
<td>68.1</td>
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<tr>
<td>CaSO₄</td>
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<td>17.5</td>
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<td>1125</td>
<td>417.5</td>
<td>15.0</td>
<td>47.2</td>
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</table>

4.2 Further Analysis Using the Mathematical Model

To account for the error in varying initial TDS levels as well as to provide more information than the linearized estimation, the mathematical model was used to compare the predicted behavior for electrolyte removal rates if all feed waters had an initial TDS level of 900 ppm for each of the six electrolytes. The comparison of the diluate streams for all six electrolytes can be seen in Figure 4-7. Figures 4-8 and 4-8 show closer views of the diluate streams' behaviors when the concentrations are at 750 ppm and 415 ppm. The removal rates of the six electrolytes at these two concentrations are presented in Table 4.2. These values were determined from the
model by taking the instantaneous change in TDS level at 750 ppm and at 415 ppm. At lower TDS levels in the diluate stream, the electrolyte removal rate was lower than when the diluate stream had a higher TDS level. This is due to the increasing resistance of the diluate stream as it becomes desalinated which changes the stack’s current density calculated in Equation 3.2. From this analysis of the model, it can be shown that the ranking of electrolytes with highest to lowest removal rates at both 750 ppm and 415 ppm is NaCl, K2SO4, CaSO4, Na2SO4, MgCl2, and Ca(NO3)2.

Table 4.2: Electrolyte removal rates at 750 ppm and 415 ppm calculated using the mathematical model.

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>IRR at 750 ppm (ppm/min)</th>
<th>IRR at 415 ppm (ppm/min)</th>
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</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>59.5</td>
<td>36.8</td>
</tr>
<tr>
<td>Na2SO4</td>
<td>53.8</td>
<td>33.4</td>
</tr>
<tr>
<td>MgCl2</td>
<td>52.3</td>
<td>32.7</td>
</tr>
<tr>
<td>K2SO4</td>
<td>59.4</td>
<td>36.0</td>
</tr>
<tr>
<td>Ca(NO3)2</td>
<td>52.0</td>
<td>31.8</td>
</tr>
<tr>
<td>CaSO4</td>
<td>54.9</td>
<td>33.6</td>
</tr>
</tbody>
</table>

An error that leads to inaccuracies in the model is the unknown exact volume of water in the diluate and concentrate streams. The volumes of water in the beakers were known, but the volumes of water in the tubes, flow meters, and ED stack were estimated to be 0.2 L for each stream. If incorrect, this estimated total volume, used in the model, could be a factor in why the model and experimental results were not better aligned with the model.
Figure 4-7: The results when the mathematical model was used to compare predicted concentration behavior if all feed waters had an initial TDS level of 900 ppm for each of the six electrolytes. For reference, 750 ppm and 415 ppm are marked in blue and red, respectively. Figures 4-8 and 4-9 zoom in on the times when the concentrations of the diluate streams reach these reference TDS levels.
Figure 4-8: A closer look at when the diluate streams from the mathematical model in Figure 4-7 reach 750 ppm. Note that the concentrations of K$_2$SO$_4$ and NaCl overlap, as do the concentrations of MgCl$_2$ and Ca(NO)$_3$)$_2$.

Figure 4-9: A closer look at when the diluate streams from the mathematical model in Figure 4-7 reach 415 ppm.
Chapter 5

Conclusion and Future Work

5.1 Conclusion

For this thesis, an electrodialysis reversal (EDR) test set-up was designed and built. This set-up was used to run two tests for each of six different electrolytes: NaCl, Na$_2$SO$_4$, MgCl$_2$, K$_2$SO$_4$, Ca(NO$_3$)$_2$, and CaSO$_4$. During the tests, feed water starting at about 1000 ppm of each electrolyte was run though the ED test set-up until the diluate stream reached 415 ppm. Conductivity measurements were taken at 30 second intervals, and these data were compared to and validated a mathematical model developed in Wright's master's thesis. When the mathematical model was run for each electrolyte beginning at exactly 900 ppm, it was shown that the ranking of electrolytes with highest to lowest removal rates is NaCl (38.8 ppm/min when the diluate concentration is 415 ppm), K$_2$SO$_4$ (36.0 ppm/min), CaSO$_4$ (33.6 ppm/min), Na$_2$SO$_4$ (33.4 ppm/min), MgCl$_2$ (32.7 ppm/min), and Ca(NO$_3$)$_2$ (31.8 ppm/min).

5.2 Future Work

The findings of this model along with the results of these tests were applied to a full-scale prototype of the EDR system in April of 2015 [8]. This full-scale proto-
type was tested at the Desal Prize, a competition hosted by the U.S. Agency for International Development (USAID) and the Bureau of Reclamation, in partnership with the Swedish International Development Cooperation Agency and the Ministry of Foreign Affairs of the Kingdom of The Netherlands. In the semi-final round of the competition held at the Bureau of Reclamation’s Brackish Groundwater National Desalination Research Facility (BGNDRF) in Alamogordo, NM, the EDR prototype developed by the MIT GEAR Lab and Jain Irrigation Systems placed first among five teams. In one 24-hour competition run, the MIT/Jain system was tested with 8.73 m³ of groundwater that had an initial TDS level of 3470 ppm. This groundwater was desalinated into 0.303 m³ of water suitable to drink with a TDS level of 172 ppm and 8.427 m³ of water suitable for agricultural uses with a TDS level of 462.

The next steps of testing for this project are to further optimize the power settings of the entire system, including the voltages applied to the stacks electrodes. Additional tests using the same procedure outlined in this undergraduate thesis could be run to reduce error. Additional testing relating to electrolyte removal rates by means of electrodialysis reversal could incorporate starting the initial feed water at higher salinities, applying higher voltages to the stack, replacing the current stack’s membranes with membranes rated to remove select ions, and running similar tests on the full-scale prototype tested at BGNDRF in the spring of 2015. Additionally, running tests with mixtures of different electrolytes (as opposed to dissolving a single electrolyte for one test) to introduce more than two different ions would better simulate what one would typically find in groundwater.

By the fall of 2015, the MIT/Jain system prototype will have been improved as a result of these future tests and other considerations. In September of 2015, the system will be tested abroad in the final round of the USAID competition.
Bibliography


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nation in India. In The International Desalination Association World Congress on Desalination and Water Reuse 2015, San Diego, CA, 2015.