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Evaluation of Reverse Osmosis Membrane Performance Indicators for Desalination in a Changing World

A Major Qualifying Project
Submitted to the faculty of

WORCESTER POLYTECHNIC INSTITUTE

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Submitted by:
Zoe Mahoney
&
Kiersten Potts

Advised by:
John Bergendahl

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Abstract

The United Arab Emirates is one of the largest producers of desalinated water in the world. Reverse osmosis is a growing desalination technology being implemented worldwide. As the populations increase and urbanization continues, it is expected that seawater quality will be affected through rises in temperature, increase in salinity, and presence of human-derived contaminants, like particulate material. Through literature review and experimental study, implications of increasing salinity, temperature, and TiO_2 on reverse osmosis performance indicators were explored in this work. The increase of salinity was found to have the most notable effect in amount of permeate the reverse osmosis membrane could produce.

Acknowledgments

First, we would like to personally thank the university in collaboration with this project - the American University of Sharjah (AUS) (located in the United Arab Emirates (UAE)) for providing our team with time and input used to achieve the goal of our project. Specifically, we would like to thank students Fatima Alblooshi and Fatima Al Nabouda and Professor Maruf Mortula and Tarig Ali for taking the time to attend occasional meetings to discuss our project work. The meetings we had with the AUS team were critical times to receive feedback on how our project work can be correlated with their work in the UAE and applicable in the real world. We have immense gratitude for the time and resources that the AUS team has contributed to our project.

We would also like to thank Professor John Bergendahl for being our advisor throughout our project work throughout WPI’s 2021 B term and 2022 C term. His guidance prior to the start of our project work in B term, throughout B and C term, during team meetings, and regular feedback on our project approach was essential to meeting and exceeding the objectives and goals for our project. We are grateful for his guidance in steering our project in a reasonable and purposeful direction despite all of the unexpectedness along the way.

Capstone Design Statement

The Major Qualifying Project (MQP) is an integral part of the WPI degree requirements and project-based educational philosophy. The MQP is a team-based capstone project experience. This MQP was completed by Zoe Mahoney (CE) and Kiersten Potts (CE, INGS) on campus. The team intended to travel to the American University of Sharjah in the United Arab Emirates to complete their project. Due to COVID-19 restrictions, the team instead remotely collaborated with students and advisors from the UAE working on a similar project.

This MQP investigated the effects of salinity, temperature, and TiO_2 increase in desalination feedwater on reverse osmosis membrane performance indicators by evaluating the reverse osmosis membrane's fouling, freshwater production quantities/recovery rate, membrane salt rejection, and temperature changes. The testing required the design, development, and construction of a bench-scale reverse osmosis apparatus. The Aquatic Life RO Buddie was the reverse osmosis system chosen because it was inexpensive and quick and easy to obtain. As discussed in section 3.0 and 3.1, the reverse osmosis membrane in the system was isolated and several components were necessary to plumb the bench-scale apparatus together including a pump, polyethylene tubing, and many fittings. Literature review and evaluation of the membrane helped determine the size and type of pump sufficient for the apparatus, the tubing, the fittings, other components, and the design testing protocol. Calculations were performed according to existing literature and manufacturer provided equations to make predictions about the reverse osmosis membrane's performance under certain variables. Multiple variations of the apparatus were developed before the apparatus achieved the needs for the project, but the final apparatus that was settled on is discussed in the paper and used in the laboratory work performed.

Professional Licensure Statement

The primary purpose of a Professional Engineer (PE) is to protect the health, safety, and welfare of its community. A PE may have the responsibilities of preparing, signing, sealing, and submitting engineering plans for clients of both the public and private sector. A PE is required to be competent in their field, and their competency is ensured by the several steps required to obtain a PE license. A four-year degree in engineering must first be obtained from an accredited program. The next step is to pass the Fundamentals of Engineering (FE) exam. Once the FE exam has been passed, the individual becomes an Engineer in Training (EIT). As an EIT, one must complete four years of engineering related work under a PE. The requirements for PE licensure varies by state. Regardless, the individual has to prepare, complete, and pass the PE exam to receive their PE license. Once acquiring the PE license, the individual is expected to uphold the requirements for retaining their license and the aspects of professional practice. Most states have a continuing education or professional development requirement.

Authorship

Section	**Primary Author**
1.0 Introduction	ZM, KP
2.0 Background	KP
2.1 Seawater - An Alternate Drinking Water Source	ZM
2.1.1a Total Dissolved Solids	ZM
2.1.1b Brine	ZM
2.2 Importance of Desalination	KP
2.2.1 The UAE’s Reliance on Desalination	KP
2.2.2 Threats to Seawater	ZM
2.2.2a Algae	KP
2.2.2b Microplastics	ZM
2.2.2c Sunscreen	ZM
2.2.2d Desalination	ZM
2.3 Desalination Processes	ZM
2.3.1 Thermal Desalination	ZM
2.3.1a Multistage Flash Desalination	ZM
2.3.1b Multi Effect Desalination	ZM
2.3.2 Membrane Desalination & Reverse Osmosis	ZM
2.3.2a Pretreatment	ZM
2.3.2b Reverse Osmosis Filters	ZM
2.3.2c Desalination Efficiencies	ZM
2.3.2d Reverse Osmosis Fouling	ZM
2.3.2e Membrane Transport Models	ZM

2.3.2f Reverse Osmosis Operating Conditions	ZM
2.3.2g Reverse Osmosis Prediction Calculations	ZM
2.3.2g.1 Recovery	ZM, KP
2.3.2g.2 Flux	ZM, KP
2.3.2g.3 Salt Rejection	ZM, KP
2.4 Bench Scale Reverse Osmosis System	KP
2.5 Hypotheses	ZM, KP
2.6 Project Objectives	ZM, KP
3.0 Design of Apparatus	ZM
3.1 Plumbing & Pumping Feedwater	ZM
4.0 Methodology	ZM
4.1 Variables	ZM
4.1.1 Salinity	ZM
4.1.2 Temperature	ZM
4.1.3 Titanium Dioxide	ZM
4.2 Evaluation of Membrane Fouling	KP
4.3 Evaluation of Freshwater Production	KP
4.4 Evaluation of Membrane Salt Rejection	KP
4.5 Evaluation of Temperature Change	ZM
5.0 Findings & Results	ZM
5.1 Baseline Testing	ZM
5.2 Increasing Salinity Trials	ZM
5.2.1 Membrane Salt Rejection	ZM
5.2.2 Recovery Rate & Feedwater:Permeate	ZM
5.2.3 Temperature Change	ZM

5.2.4 Membrane	KP
5.3 Increasing Temperature Trials	KP
5.3.1 Membrane Salt Rejection	KP
5.3.2 Recovery Rate & Feedwater:Permeate	KP
5.3.3 Temperature Change	KP
5.4 Increasing TiO_2 Trials	KP
5.4.1 Membrane Salt Rejection	KP
5.4.2 Recovery Rate & Feedwater:Permeate	KP
5.4.3 Temperature Change	KP
5.5 Possible Errors in Trials	KP
5.5.1 Cavitation	KP
5.5.1.a Overheating	KP
5.5.2 Flushing	KP
5.6 Improvements for Future Experiments	ZM

Executive Summary

Background

There are limited freshwater sources available on Earth as a potable water supply. In fact, only 3% of the Earth's water sources are freshwater. Provided that water is a necessary resource that supports the perpetual existence of life, coastal, arid regions have had no other option than to adopt desalination technologies to make potable water from seawater, the most abundant water source on Earth. Seawater is water with high salinity, exceeding 35,000 ppm, while freshwater is typically less than 1,000 ppm. The Middle East holds approximately 50% of the world's desalination units. Among other Middle Eastern nations, the United Arab Emirates (UAE) has one of the largest desalination capacities in the world, extracting water from the Persian Gulf.

There are two main types of desalination technologies: 1) thermal desalination and 2) membrane desalination. Common approaches to thermal desalination include multistage flash desalination (MSF) and multi-effect desalination (MED). Membrane desalination is most commonly executed through reverse osmosis. Compared to thermal desalination, reverse osmosis plants are more energy efficient, and consequently cheaper due, in part, to them only requiring electrical energy. Reverse osmosis is a process driven by a vapor pressure differential across the membrane, meaning that the concentrated solution will travel from the high pressure side of the membrane to the low pressure side of the membrane against the natural, spontaneous direction of osmosis, resulting in usable freshwater while leaving brine behind. The reverse osmosis treatment step is typically preceded by a pretreatment process to remove larger particles and to protect the membranes from premature fouling and damage. Conventionally, pretreatment consists of coagulation and flocculation. Non-conventionally, the pretreatment process can include ultrafiltration, microfiltration, and nanofiltration.

Threats to seawater quality can impact the design or function of a desalination plant. Seawater quality, overtime, is being affected by urbanization. The oceans are increasingly at risk for contamination. Oil spills, raw sewage discharge, algae, microplastics, uv-blocking nanoparticles, and brine from desalination itself are all affecting the quality of seawater. Changes in temperature and salinity of the seawater can also affect the desalination process. If seawater of damaging quality surpasses pretreatment and enters the reverse osmosis membrane, it can cause fouling. There are several types of fouling including organic fouling, inorganic fouling, biofouling, and colloidal fouling.

Seawater reverse osmosis membranes are expected to treat feedwater with TDS of 10,000 ppm to 60,000 ppm and can reject more than 99% of salt coming in with a feed pressure of 6000 to 8000 kPa (Greenlee et al., 2009). Based on existing literature and reverse osmosis membrane performance theory, several hypotheses can be made. It is likely that higher feedwater temperatures at a constant pressure will result in a higher salinity in the permeate and a lower recovery rate. In general, higher feed pressure will increase freshwater production quantities, have a higher recovery rate, and increase salt rejection in the permeate. Higher salinity will decrease freshwater production by decreasing the flow rate of the permeate and will result in higher salinity concentration in the permeate. Higher concentrations of particles will cause membrane fouling, higher salinity in the permeate, and will decrease freshwater production. Membrane fouling, overtime, will decrease the quality of the permeate and an increase in differential pressure indicates that, indeed, the membrane is fouling. Within these hypotheses there are several reverse osmosis performance indicators present: recovery rate, feedwater:permeate volume ratio, membrane salt rejection, and temperature changes in the brine and the permeate

Small-scale reverse osmosis membrane units are available, and useful for investigating the hypotheses mentioned above. The capacity of these units are much smaller than the large industrialized units used to serve larger populations, but can be used in a bench-scale apparatus. The unit purchased for this project was the Aquatic Life RO Buddie which includes a thin-film composite reverse osmosis membrane. Several objectives were addressed within this project:

1. Evaluate how increases in salinity, temperature, and titanium dioxide (TiO_2) affect fouling of the reverse osmosis membrane
2. Determine the effect of increases in salinity, temperature, and TiO_2 concentration on permeate production of the reverse osmosis membrane
3. Measure membrane salt rejection changes due to increases in salinity, temperature, and TiO_2 concentration
4. Evaluate how increases in salinity, temperature, and TiO_2 affect temperature change from the feedwater to the brine and permeate
5. Discuss the implications of the results on large industrial scale reverse osmosis plants

Apparatus Design & Methodology

The Aquatic Life RO Buddie was received as a three-stage system. The reverse osmosis membrane was isolated and plumbed. A shallow well jet pump was used to pressurize and supply the feedwater to the membrane. Pressure gauges and ball valves were plumbed into the feedwater, brine, and permeate line. Trials for salinity, temperature, and TiO_2 dosing tests were performed at high (65 psi) and low (40 psi) pressures. As these variables were altered throughout their trials, all other variables remained constant. To achieve the aforementioned objectives, several measurements were taken. Membrane fouling was evaluated by performing baseline tests at the beginning and the end of each set of trials. Freshwater production quantities were evaluated by calculating the recovery rate and the feedwater:permeate ratio. To calculate these quantities, the cumulative volume of the feedwater, brine, and permeate was measured and recorded as well as the time of the flow. The membrane salt rejection was calculated based on electrical conductivity measurements taken in the feedwater, brine, and permeate and converted to TDS in ppm. The temperature change from the feedwater to the brine and the permeate was calculated based on temperature readings taken.

Results & Discussion

Based on the laboratory work performed, several findings have presented themselves. The observation of freshwater production/recovery rates, membrane salt rejection, and temperature changes has helped develop an understanding on the effect of increasing salinity, temperature, and titanium dioxide (TiO_2) in feedwater on reverse osmosis membrane fouling and performance. The trends of the results have been discussed based on reverse osmosis membrane performance theory and a comparison with existing literature has been made for each of the variables. A set of baseline trials was performed prior to the execution of the salinity, temperature, and TiO_2 trials to confirm that the membrane was functioning properly according to the hypotheses generated. The baseline trials did confirm the hypotheses, but left an interesting question as to why constant salinity still resulted in decreased permeate quality overtime (increased salinity in the permeate).

In the salinity trials, trials were performed at both low and high pressure of increasing salinity until the membrane was no longer capable of producing an adequate amount of permeate. As the salinity of the feedwater increased, the salinity of the permeate and brine increased affecting the membrane salt rejection. The reverse osmosis membrane's ability to reject salt decreased throughout both the low and pressure trials. The reverse osmosis membrane during the high pressure trials performed significantly better, surviving salinities almost ten times greater than the salinities of the low pressure trials and reaching the low pressure's minimum membrane salt rejection at a greater salinity. Over the salinity trials, the salinity of the feedwater was increased in uneven increments. It is likely that a better measure of salinity is the amount of salt that is passed through the reverse osmosis membrane. Evaluating the membrane salt rejection via salt exposure produces more realistic results provided that the membrane salt rejection for the high pressure salinity trials is greater than the low pressure trials. A higher recovery rate can indicate that the permeate is less concentrated. Throughout the salinity trials, lower feedwater salinity resulted in higher recovery rates. Based on the results of the membrane salt rejection, it is obvious that the higher recovery rates are also associated with lower concentration in the permeate. Higher recovery rates can also be the result of higher feed pressures which is confirmed by the recovery rates in the high pressure trials being significantly greater than the low pressure trials. Additionally, the feedwater:permeate ratio increased over the salinity trials as the salinity of the feedwater was increased. As the salinity increased, there was less permeate produced for every milliliter of feedwater that was run through the reverse osmosis membrane. In regard to the salinity trials temperature changes, throughout the low pressure salinity trials, the brine temperature change remained relatively constant as the salinity of the feedwater was increased. The permeate temperature change decreased as the salinity of the feedwater was increased. Throughout the high pressure salinity trials, the brine temperature change primarily increased as the salinity of the feedwater was increased, while the permeate temperature change decreased.

In the temperature trials, trials were performed at both low and high pressure of increasing temperature from 20 to 45℃ in increments of 5℃. The salt rejection at low pressure and high pressure acted very similarly. As the temperature increased over the trials, the membrane salt rejection slightly decreased. It was expected that as the temperature of the feedwater increased, the permeate salinity also increased, meaning that an increase in salt passage or a decrease in membrane salt rejection would be observed. Throughout the trials, the recovery rate was constant. For the low pressure trials, the recovery rate did not exceed 10%, while the high pressure trials exhibited a recovery rate greater than 90% relatively consistently. The feedwater:permeate ratio remained relatively constant throughout the low and high pressure trials, with more variation in the low pressure trials. Variation in the low pressure trials may indicate that, at a lower pressure, the reverse osmosis membrane's feedwater:permeate ratio is more susceptible to temperature change. As the temperature increased during the low pressure trials, there was more permeate produced for every milliter of feedwater that was run through the reverse osmosis membrane. The difference in temperature drop between brine and permeate was more notable in the high pressure tests. The data collected throughout the trials indicates that the temperature of the water tends to change once run through the membrane and the output temperatures continually decrease as the input temperature increases.

In the TiO_2 trials, trials were performed at both low and high pressure with TiO_2 concentrations ranging from 500 to 2,500 ppm. The membrane salt rejection during the low and pressure trials acted very similarly. As the concentration of the TiO_2 was increased over the five trials, the membrane salt rejection was relatively constant with a slight decrease. Despite the slight decrease in the membrane salt rejection, the reverse osmosis membrane performed well in all of the TiO_2 trials. Throughout the trials, the recovery rate was constant. For the low pressure trials, the recovery rate did not exceed 10%, while the high pressure trials exhibited a recovery rate greater than 94% consistently. While it appears that the TiO_2 did not affect the recovery rate across the trials, it is apparent that the pressure of the pump greatly affected the recovery rate. The feedwater:permeate ratio remained relatively constant throughout the high pressure trials. There was a slight increase in the low pressure trials. The general trend throughout the trials was an increase in temperature change with an increase in TiO_2 concentration. The exception to the trend is the permeate temperature change during the low pressure trials, where the temperature change was relatively constant throughout the trials with a slight decrease.

List of Figures

List of Tables

Table of Contents

1.0 Introduction

A major factor contributing to the support of human life and health is water quantity. High quality freshwater is the only form of water that humans should consume, but it is a limited resource especially in arid regions of the world like the Middle East. Arid regions near sourcesof seawater have adopted desalination technology to help solve their potable water supply crises and further investigation is needed to ensure a sustainable water supply.

Desalination can be performed via several different processes. The two main types of desalination processes are 1) thermal desalination and 2) membrane desalination. One of the most significant approaches to purifying water extracted from the ocean is through the widely used membrane desalination technology known as reverse osmosis. Reverse osmosis uses pressure to drive purified water across the membrane, in the reverse direction to osmotic tendency, producing potable water and keeping brackish water on the opposite side of the membrane. There are several variables that can affect seawater quality and adversely affect the reverse osmosis treatment effectiveness. Some performance degrading variables include increases in salinity, increases in temperature, or the presence of particles like algae or microplastics.

The performance of a membrane can be indicated by a variety of outputs, but the most common performance indicators are recovery rate, feedwater:permeate ratio and membrane salt rejection. The recovery rate of the membrane compares the flow rate of the feedwater versus the flow rate of the permeate. Therefore, the recovery rate and feedwater:permeate ratio can determine efficiency of the membrane in terms of how much feedwater needs to be pumped into the system to generate a desired amount of permeate. Membrane salt rejection can be calculated by comparing the feedwater salt concentration with the permeate salt concentration. All of these performance indicators can be affected by increases in salinity, increases in temperature, or increases in titanium dioxide (TiO_2) concentration in the feedwater.

The goal of this project was to investigate the effect of salinity, temperature, and TiO_2 concentration increase in feedwater on reverse osmosis membrane performance by evaluating the reverse osmosis membrane's fouling, freshwater production quantities/recovery rate, membrane salt rejection, and temperature changes. The implications of our results on large industrial scale reverse osmosis plants have also been discussed. While countries like the United Arab Emirates (UAE) have large scale plants that can purify up to 200 million gallons per day, an affordable, experimental study cannot be conducted on a plant of that size. To better understand the relationship between salinity and temperature with the three performance indicators, this project conducted several trials on a bench-scale reverse osmosis system. The variables of interest were modified while keeping all other variables constant. Desalination is the main process for producing potable water for many arid, coastal countries. Acquiring an understanding of the effects of increased temperature and salinity is important for desalination plants to prepare for sudden or long term changes in the marine environment.

The report contains five main sections beyond the introduction - background, design of apparatus, methodology, results & discussion, and conclusion. The background section includes research about desalination, the reverse osmosis process, and the UAE’s current use of desalination to provide the potable water needs. The design of the apparatus section and methodology describe the apparatus and procedure used to test desalination variables. The results and discussion section presents the findings from the trials and analyzes the implications of the results.

2.0 Background

While water is an abundant resource on Earth, covering approximately 71% of the Earth's surface, 97% of the Earth's water is oceans, leaving only 3% of the Earth's water sources as freshwater (*Water Facts - Worldwide Water Supply*, 2020). Freshwater is primarily obtained from groundwater, but can also be found in surface-water runoff, snow, or unavailable for use trapped in glaciers and icecaps. Groundwater is not only critical in supplying various agricultural, industrial, and environmental pursuits, but is essential in providing 25-40% of humans' potable water supply (*Safe Drinking Water Is Essential*, 2007). The scarcity of freshwater is concerning when considering that freshwater is used for humans' potable water, a resource that is vital in supporting the perpetual existence of humankind.

2.1 Seawater - An Alternate Drinkable Water Source

Seawater is the most plentiful water source on Earth, as oceans encapsulate nearly the entirety of Earth. What makes seawater different from freshwater is that it has a high concentration of ionic species. Water's "salinity" is often measured by the concentration of ions by weight in the water source and is expressed in parts per million (ppm). The ocean's salinity comes from land rock erosion. As rain falls, it carries dissolved carbon dioxide which is acidic due to its composition that includes carbonic acid. Consequently, the rocks are physically and chemically eroded by the rain and the acids, respectively. As primarily chloride and sodium ions, the salts and minerals are carried from streams or rivers into the ocean resulting in a seawater salinity of approximately 35,000 ppm (*Why Is the Ocean Salty?*, n.d.).

The salinity of freshwater is typically less than 1,000 ppm. The high salinity of seawater makes seawater unusable for a human potable water supply. Human consumption of seawater can lead to eventual death via dehydration. While a small amount of salt is a necessary component to human survival, the salinity of seawater is too high for potable water, exceeding the salinity of human blood by a fourfold (*Why Don't We Drink Saltwater?*, n.d.). When too much salt is ingested, the kidneys must get rid of it through urination, so when saltwater is ingested, there is not enough freshwater to dilute the salt to pass through the kidneys (*Water Q&A: Why Can't People Drink Seawater?*, n.d.).

2.1.1 Introduction to Desalination

With proper treatment, high saline water can be converted into freshwater by extracting the salt. The process by which salt is removed from water is known as desalination. Desalination allows communities to be provided with potable water from seawater in the case where water treatment is uneconomical or environmentally destructive or where, geographically, freshwater sources are scarce (Mechell & Lesikar, n.d.). The major components driving the design of desalination plants are total dissolved solids and brine, respectively these components are the concentration of dissolved matter within untreated water and the byproduct of desalination.

2.1.1a Total Dissolved Solids

The ionic species, or salts, in water that do not evaporate or the total concentration of substances that are dissolved in water are known as ‘total dissolved solids’ (TDS) (Masten & Davis, 2020). TDS is composed of inorganic matter and some small amounts of organic matter. The primary components of TDS found in water are typically “calcium, magnesium, sodium, and potassium cations and carbonate, hydrogen carbonate, chloride, sulfate, and nitrate anions” (*Total Dissolved Solids in Drinking-Water*, 2003). The TDS of freshwater sources is typically low, while the TDS for seawater or brackish water is much higher.

High concentrations of TDS can negatively affect the palatability of potable water and lead to mineral deposition, excessive hardness, and corrosion. Low concentrations of TDS can also affect palatability. A panel of tasters have rated the palatability of water according to its TDS concentration. It was found that samples with less than 300 ppm were excellent and samples between 300 and 600 ppm were good (*Guidelines for Canadian Drinking Water Quality*, 1991). Above 1000 ppm, water is generally unsuitable for drinking due to its corrosivity, color, taste, and odor.

$$\boldsymbol{TDS}\ (\frac{\boldsymbol{mg}}{\boldsymbol{L}}) = k * \boldsymbol{EC}\ (\frac{\boldsymbol{\mu S}}{\boldsymbol{cm}})$$

A way to readily measure the TDS of a water sample is through an electrical conductivity (EC) probe. TDS and EC are both water quality parameters used to measure salinity and they have a mathematical correlation. The EC, “the measure of liquid capacity to conduct an electric charge”, can be used to calculate the TDS, via the formula above where k is dependent on the ion average activity and ionic strength (Rusydi, 2018).

Table 1. *Relating Electrical Conductivity to Constant k*, adapted from (Rusydi, 2018).

Type of Water	**EC in 25℃ (µS/cm)**	**k**
Natural water	500-3,000	0.55-0.75
Distillate water	1-10	0.5
Freshwater	300-800	0.55
Seawater	45,000-60,000	0.7
Brine water	65,000-85,000	0.75

The constant k’s value can change with the amount of ions present in the water as seen in Table 1 above. It also relates conductivity and TDS to one another, however, several studies have revealed that their relationship is not entirely linear. Because of the nonlinear relationship, conductivity meters in the United States typically use a 500 ppm conversion factor, meaning to convert a conductivity meter reading in mS/cm to ppm, it must be multiplied by 500 ppm. However, as a solution becomes concentrated past the point of a TDS of 1,000 ppm, the k constant can reach upwards of 0.9. Conclusively, determining the TDS of a water sample from an EC reading can be increasingly difficult and inaccurate as the sample becomes more concentrated. The most accurate approach in determining the k constant relating TDS and EC would be to mix a known concentration of salt in deionized water and measure the EC with a conductivity meter.

2.1.1b Brine

While processing seawater through desalination can beneficially be a freshwater resource for arid coastal regions around the world, it leaves a concentrated discharge behind called “brine”, which is typically discharged back to the ocean. In the average desalination process, 1.5 liters of polluted liquid twice as saline as seawater is generated with every liter of potable water produced by the desalination plant (*Five Things to Know about Desalination*, 2021). While desalination is a beneficial technology for these arid coastal regions, the rejection of brine back into the ocean is likely to cause an increase in ocean salinity overtime.

Untreated brine is capable of causing destruction and pollution to marine and coastal ecosystems because it can contain a high amount of nutrients, like phosphorus and nitrogen, and has a much higher salinity than that of the ocean. Specifically, brine can decrease the amount of oxygen in the water, known as the dissolved oxygen (DO). Ultimately, concentrated brine creates “dead” or anoxic zones in the ocean that are unable to support almost all forms of marine life.

2.2 Importance of Desalination

Since water is such a necessary resource for human life, a society with access to clean water has a higher chance of thriving. With about half of the population currently residing in cities, there is a large need to provide an adequate amount of clean water (*International Decade for Action “Water for Life” 2005-2015. Focus Areas*, n.d.).

As the world population increases, so do urban populations. Cities are struggling to provide water for this growth with limited freshwater sources. Approximately half of all cities with a population over 100,000 have very limited, if any, easy access to a freshwater basin (Richter et al., 2013). The easiest way to provide needed freshwater resources to a population is through a natural source, like rivers, lakes, or groundwater (*Water Q&A: Why Can’t People Drink Seawater?*, n.d.). However, in dry regions, these natural resources are in short supply. Figure 1 shows different nation's accessibility to freshwater.

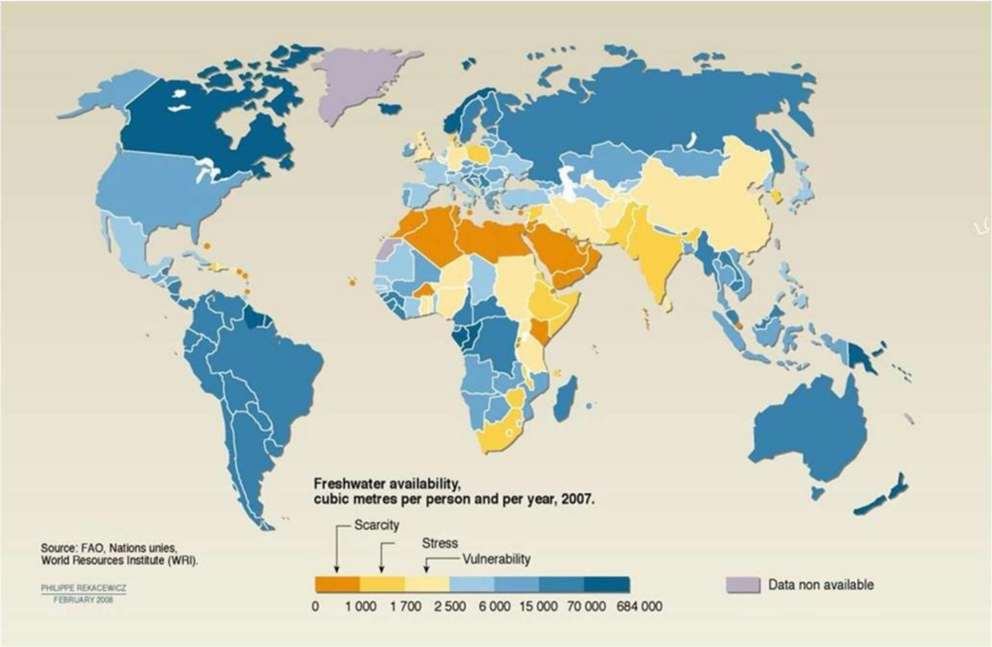

Figure 1. *Freshwater Availability* (*Freshwater Availability*, 2008).

Arid countries with limited water supply have had to turn to other resources to supply water, like extracting salt from water through desalination. It is not a new idea and is made up of varying methods to efficiently remove certain elements. Water from desalination is the potable source for approximately 300 million people worldwide in 150 different countries (Bienkowski, 2015). The Middle East holds less than 3% of the world's population but approximately 50% of the world's desalination units (Greenlee et al., 2009). A common negative of desalination methods is a large amount of energy used. Energy is expensive and creates increased carbon emissions. It is a cycle of trying to solve the water problem and worsening it through the effects of climate change. With rapid industrial and population growth, desalination demands are going to increase. However, as desalination plants continue to be implemented and brine is released into the ocean, the ocean is at risk of marine life damage and increased salinity. These arid areas, like the Middle East, face a different problem that needs to be solved quickly (Richter et al., 2013).

2.2.1 The UAE's Reliance on Desalination

The United Arab Emirates (UAE) is an example of a country in the Middle East which is addressing their water quantity problems with desalination. While it is bordered by a body of water (the Persian Gulf as seen in Figure 2), this body of water is a mixing spot for freshwater and saltwater. The Strait of Hormuz is a passageway linking the gulf to the open ocean. The inflow from the strait to the gulf is 33.7 meters per year and is a lower salinity surface current known as the Indian Ocean Surface Water. The outflow into the ocean is approximately 32.1 meters per year along the southern part of the strait. The Shatt-al Arab River brings freshwater into the gulf at approximately 0.2 meters per year (Chow et al., 2019).

The Persian Gulf is also shallow and in a hot temperate area, leading to a large amount of evaporation of water, thus leaving the salty brine behind and creating hypersaline conditions. Because of the density difference between the dense brine and the water inflowing into the strait, a subsurface gravity current is created. The dense, salty seawater sinks while the lighter, more fresh water rises to the surface. The evaporation flow is measured to be removed at about 1.8 meters per year, while rainfall is only about 0.09 meters per year. The large amount of evaporation and little rainfall is both a cause and effect of the gulf's shallowness (Chow et al., 2019). Ultimately, all of these qualities of the Persian Gulf make it an undrinkable water source on its own.

Figure 2. *The Persian Gulf* (*Persblu2.Gif (1100×900)*, n.d.).

The Persian Gulf fluctuates in temperature between 15 and 30°C between the hot and cool months (February and August). The salinity also changes throughout the year. The gulf has a minimum amount of salt in early summer and the maximum occurs in late fall/winter andpeaks at about 40% throughout the year (National Oceanographic Data Center (U.S.), n.d.). The extremely high salinity concentration is largely correlated with a shallow gulf and high evaporation rates. Around the coasts of the UAE, the salinity can exceed 40,000 ppm (Smith et al., 2006). Typically, the Persian Gulf ranges from 42,000 to 45,000 ppm (Greenlee et al., 2009).

Due to these conditions in the UAE, they are a leading country utilizing desalination plants. As can be seen in Appendix A, there are 35 different desalination plants in the UAE. They average around 290,000 m^3/day (Mogielnicki, 2020). Across the UAE, in 2018, the total installed capacity was 7.5 million m^3/day (*UAE: Desalination Water Plant Capacity 2018*, n.d.). Some UAE desalination plants include Shuweihat S2 power and water plant in Abu Dhabi. It can produce 1510 MW of electricity and 454,609 m^3/day of water. The Jebel Ali power station is the largest power and desalination plant in the UAE. Its six gas turbines can produce 2060 MW of electricity along with 636,452.6 m^3/day of water. The F2 Plant is located in Fujairah and has a power capacity of 2850 MW and can produce 590,991.7 m^3/day of water. It is also a greenfield power and seawater desalination plant (*Water - The Official Portal of the UAE Government*, n.d.) Another production unit is a solar-powered water pumping and desalination station at the Mohammed bin Rashid Al Maktoum Solar Park. The solar panels installed are photovoltaic and desalinate the water with reverse osmosis technology. The capacity is 50 m³/day (*Water Desalination Plant*, n.d.).

As desalination has become more utilized around the Persian Gulf coast, excess brine is deposited back into the gulf. With 95 million cubic meters of potable water produced every day by desalination plants around the world, it is estimated that 142 million cubic meters of brine is released per day, 55% of which is produced by Saudi Arabia, the UAE, Kuwait, and Qatar(Jones et al., 2019). This product of the desalination process tends to be 10 to 15°C warmer than the seawater and can contain up to 35,000 ppm more salinity than normal seawater. Different areas of the gulf have differing levels of salinity. The northern end of the gulf bordering Kuwait and Iran contains water with a lower salinity concentration, usually 0-1 g/kg. However, in the southern region of the gulf, especially near the Strait of Hormuz, the salt buildup jumps to almost 7 g/kg (Ibrahim & Eltahir, 2019). This drastic inconsistency in salinity is largely due to brine being ejected to the southern border of the gulf, which is “a shallow, reverse tidal estuary with only one outlet available for exchange flow” (Chow et al., 2019). With such a small outlet, any excess nutrients, materials, or constituents deposited in the water build up and do not properly mix with a large volume of water. The lack of mixing results in an increase in salinity which creates an environment fit for only certain living things, and is deleterious for many life forms.

While the UAE is a leading country in the use of desalination, not all of the information on the UAE’s desalination units and production is made publicly available. The UAE has a modest culture, especially compared to countries like the United States (Southan, 2013). Culture plays a large role in how a nation is run because things like culture, beliefs, and morals are an important part of people’s lives. Hence, the UAE government restricts online content (Ververis et al., 2020). Due to some restriction on information accessible from the UAE, statistics on some components of the UAE’s desalination units couldn’t be retrieved.

2.2.2 Threats to Seawater

There are threats to seawater and desalination in the Persian Gulf that are important to address and explore. Almost every aspect of human life can affect the oceans. From oil spills from oil transport accidents to pollution through air deposition to raw sewage discharges, seawater quality is adversely impacted. Seawater quality can affect the desalination process. As urbanization continues to rapidly develop, the oceans become increasingly at risk for contamination. This section will explore several factors that may affect the quality of seawater including algae, microplastics, sunscreen, and the desalination process itself.

2.2.2a Algae

Phytoplankton are an example of a living creature that can live through aquatic environment changes, unlike lots of other underwater life forms (Alemzadeh et al., 2014). Phytoplankton are a good indicator of adverse climate conditions. They thrive due to their flexibility in living through environmental stress (Alemzadeh et al., 2014). When some phytoplankton release harmful toxins at a certain level that can result in adverse effects on marine life, aquatic ecosystems, and human health; these growths become known as harmful algal blooms (Gholami et al., 2019). Some types of algae and their particle size can be found in Table 2 below.

Table 2. *Seawater Algae Particle Sizes*, adapted from (*Dinoflagellate*, n.d.); (Jordan, 2009); (Wiśniewska et al., 2019); (Postgraduate Unit of Micropalaeontology, 2002)**.**

Algae	**Particle Diameter (µm)**
Coccolithophores	2.0 – 75.0
Cyanobacteria	0.2 – 100
Diatoms	20 – 200
Dinoflagellates	5 – 2000

Worldwide, in the past few decades, algal blooms have increased. Harmful algal blooms can take on different forms and have various adverse effects to the environment around them. They are a major contributor to increased mortality rates in fish. Harmful algal blooms can discolor water, dissipate dissolved oxygen, and block fish gills (Gholami et al., 2019). There are several types of algae that may bloom in seawater including coccolithophores, cyanobacteria, diatoms, and dinoflagellates. Their particle size can range from 0.2 to 2000 µm.

Any large natural water body requires a balanced pH and nutrient inflow for a livable environment. An indicator of nutrient dense water is an increased concentration of chlorophyll. Chlorophyll can indicate “eutrophication in aquatic systems, which is associated with low biodiversity and hence deprives the aquatic environment of sufficient ecosystem services” (Sharifina et al., 2015).

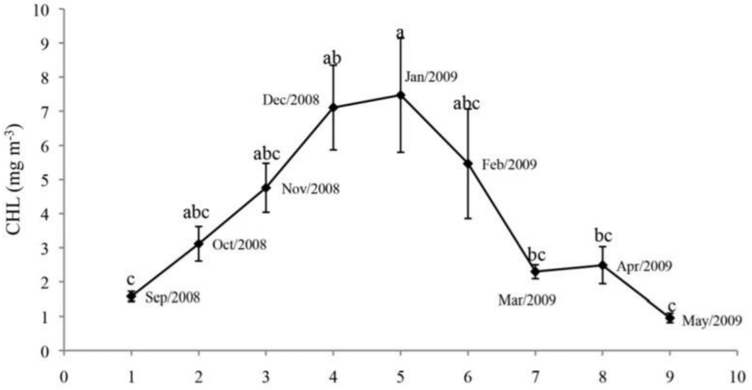

FIGURE 2. Monthly chlorophyll-α concentration (Mean ± SE) of the Persian Gulf from September 2008 to May 2009

Figure 3. *Monthly Chlorophyll a Concentration* (Sharifina et al., 2015).

Since the Persian Gulf is a warm, shallow environment, it does experience levels of chlorophyll that affect the environment. The relationship between the time of year and level of chlorophyll can be seen in Figure 3. According to the graph in Figure 3, September 2008 had the lowest value at about 1.57 ± 0.14 mg-m^{-3} while January 2009 had the highest value 7.47 ± 1.67 mg-m^{-3} (Sharifina et al., 2015).

2.2.2b Microplastics

With the highest particulate matter pollution (80 μg/m^3) in the World as of 2015, the UAE is at risk for particulate matter deposits into the sea (Paleologos et al., 2018). In the Gulf Region, microplastics with a diameter between 1 μm and 5 mm and a composition primarily of polyethylene, polypropylene, and polystyrene have been entering seawater (Aslam et al., 2019). Via the region's air currents and desert dust from "aquaculture and fisheries, agriculture, construction, cosmetics, textiles, packaging, land transportation and shipping" or degraded from larger plastics, these particles have been making their way to the Persian Gulf's waters (Paleologos et al., 2018). Due to the lack of mixing in the Persian Gulf, its low energy areas have the ideal conditions for microplastic accumulation. Over time, these microplastics can degrade in the water releasing harmful contaminants, be mistaken as prey and ingested by marine life leading to poison or death, cause detriment to marine ecosystems in general, or be ingested by humans through potable water resulting in DNA damage, inflammation, or the formation of lesions (Uddin et al., 2020); (Skuse et al., 2021).

The bulk of research on the effects of plastic litter on the marine environment have been conducted using consumer plastics. These homogenous post-production plastics are not suitable for replicating marine litter which is physically and chemically different. Plastics that are collected from beaches and coastal areas can be ground or cryo-milled down into a microplastic mixture (Kuhn et al., 2018). Using a microplastic mixture composed of marine weathered litter is an approach that more accurately can assess plastic litter's effect on the marine environment. This approach is known as bulk sampling and is used in the case where microplastics cannot be easily attained or identified in the field. Specifically, bulk sampling, the samples collected in the field are taken without being reduced in the sampling process (Hildago-Ruz et al., 2012).

In 2020, a study called *Evaluation of microplastics in beach sediments along the coast of Dubai, UAE* was conducted along the coastline of Dubai, UAE. Samples of sand were collected along sixteen beaches and were sampled for their concentration of microplastics. Per kg of dry sediment, 59.71 microplastic items were found, with the average weight of microplastic being 0.33 mg per g of dry sediment (Aslam et al., 2019). Therefore, for every kg of dry sediment, there would be 330 mg of microplastic or 330 ppm with each microplastic item weighing approximately 3.68 mg. As of 2012, 68 studies had been conducted on the identification and quantification of microplastics in the marine environment and overall indicated a range of microplastics concentration in seawater to be 0.022 to 8,654 items per m^3 at the sea surface and 0.014 to 12.51 items per m^3 in the water column (Hildago-Ruz et al., 2012). In the 2018 journal article *Marine Microplastics: Abundance, Distribution, and Composition*, results from 73 papers/reports and 61 studies were extracted. It was found that the "mean abundance of microplastics in seawater reported worldwide ranged from $4.8 * 10^{-6}$ n/m^3 [...to…] $8.6 * 10^3$ n/m^3" (Shim et al., 2018). In a 2017 study, *Microplastics in coastal environments of the Arabian Gulf*, several locations along the Qatar coastline were surveyed for microplastics. It was found that the microplastics in the sea surface samples were mainly composed of polyethylene and polypropylene with 67.4% of the microplastics being 1 to 5 mm and with 93.8% of particles being fibers, 4.7% being film, and 1.5% being fragments (Abayomi et al., 2017). Similarly, in the 2020 study *Neustonic microplastic pollution in the Persian Gulf*, neustonic samples were collected along the Persian Gulf. The samples indicated that 76% of the microplastics analyzed were polyethylene and polypropylene and 44.1% of the particles were fibers, 29% fragments, 14.7% film, and 12.2% pellets (Kor & Mehdinia, 2020). Globally, over 90% of microplastic concentrations are fibers.

These previously mentioned studies are mostly concerned in investigating both categories of microplastics: primary microplastics and secondary microplastics. Secondary microplastics are the plastic particles that are the result of the degradation and breakdown of larger plastics due to chemical and physical weathering. Primary microplastics are plastic particles that are manufactured; they are oftentimes referred to as microbeads. They are often made out of polyethylene plastic and are used in cosmetic or personal care products like facial cleansers or toothpastes as a scrubbing agent. Polypropylene, polystyrene, and polyethylene terephthalate are also common plastics used to manufacture microbeads. Microbeads, when washed down the sink, can easily enter waterways into the ocean. The Netherlands was the first country to ban the use of microbeads in rinse-off cosmetic products. Since then, several countries, including the United States, have implemented similar bans (*OECD Ocean - Microbeads in Cosmetics*, n.d.). While distinguishing the difference between primary and secondary microplastics is important, they cause the same problems.

2.2.2c Sunscreen

Sunscreen is used by humans to protect the skin from the damaging effects of ultraviolet (UV) radiation. A main ingredient used in sunscreen lotions as a nanoparticulate, mineral UV-blocker is titanium dioxide (TiO_2). It is a fine, bright white powder and is also used in a wide range of consumer products as a pigment. TiO_2 has the ability to absorb or reflect UV radiation, preventing the skin from sunburn and decreasing the risk of developing skin cancer. The particle size of TiO_2 is generally less than 100 nanometers (Labille, Catalano, et al., 2020). Another common mineral UV-blocker used in sunscreen is zinc oxide (ZnO). After being rinsed from the skin, mineral UV-blockers can be released into waterways and, eventually, into the oceans. Provided that sunscreen is oftentimes used in a beach setting, coastal seawater is more at risk to direct exposure to sunscreen release.

Boxall et al., in the 2007 study *Current and Future Predicted Exposure to Engineered Nanoparticles,* found concentrations of TiO_2 and ZnO in water, obtaining values of 24 to 245 µg/L and 76 to 760 µg/L, respectively (Boxall et al., 2007). Labille, Slomberg, et al. carried out a study at three beaches in Marseille, France. Through surveys, they found that, on average, 52 kg of sunscreen per day are likely released into the beaches' bathing water provided 3,000 people attend the beach per day and 68% of that population applying sunscreen 2.6 times on average (Labille, Slomberg, et al., 2020). Under these conditions, Labille, Slomberg et al. found 20 to 50 µg/L of TiO_2 in the water column.

TiO_2 can be harmful as a runoff in any body of water for many reasons. A study conducted at Shandong Key Laboratory of Water Pollution Control and Resource Reuse by Yingjie Meng et all found that it can enhance the degradation of dissolved organic matter, ultimately possibly changing the structure of the organic matter or molecular characteristics (Meng et al., 2016). The creatures have evolved to the current chemical makeup of the water body they're inhabiting. By changing the matter, it may kill off some species that cannot adapt as fast to the changing water. Another reason it can be harmful to humans is it can cause immune problems (Vijayaraghavan et al., 2012) and allergic reactions (Pigatto et al., 2011). When consumed, these risk of these problems can become more evident than just a skin exposure since it takes time for the body to emit the titanium.

2.2.2d Desalination

Not only can desalination processes be affected by poor seawater quality, but desalination processes themselves can cause detriment to the marine environment. Because the Persian Gulf is responsible for approximately 50% of the world's desalination capacity, it is a mecca for desalination activity and the adverse effects that come along with it. The Persian Gulf has to rely on desalination because of the extremely arid climate conditions that cause water scarcity in the region. The construction of desalination plants, the extraction of seawater, and deposition of brine back into the ocean are the main consequences of desalination.

While desalination is another technological process created by mankind to support mankind, it is also another technological process created by mankind that is capable of destroying other forms of life. As populations continue to increase, more construction of desalination plants is bound to occur to supply a larger demand. With more construction, the use of open space, the use of fossil fuels, and the implementation of impervious surfaces will increase, spewing several other categories of adverse impacts on the environment.

According to Hosseini et al., the “effect of desalination activities on the marine environment has not been widely studied” (Hosseini et al., 2021). However, the effect of desalination activities on the marine environment are generally discussed on seawater intake and brine discharge. As large amounts of water are needed for desalination to produce a fraction of potable water, the marine environment can be disturbed as seawater is pumped into a desalination plant. Organisms in the marine environment are at risk of being taken into the desalination process and, ultimately, can end up facing injuries or fatalities. As previously discussed in section 2.1.1b, brine can be severely detrimental to the marine environment. Not only can it discharge water back into the ocean of extreme salinities and temperatures, but it can also contain chemicals used in the desalination process, especially pretreatment. Brine can disrupt the marine environment to the point of causing organisms to experience dehydration or death due to decreased concentrations of dissolved oxygen (Hosseini et al., 2021). Because the Persian Gulf is shallow and has limited water circulation, the impact of brine is significant in the marine environment.

2.3 Desalination Processes

While desalination is a centuries old technology, over the last few decades it has been rapidly growing and has been adopted in various regions worldwide, especially in arid, seaside regions like the Middle East and North Africa. A major consideration when designing and implementing a desalination plant are the costs associated with it, related to capital and energy. Desalination forms a relationship between capital and energy as, generally, desalination is an expensive pursuit *because* it requires a great deal of energy (Fountain & Smith, 2019). Due to the high capital cost, desalination is primarily limited to high-income countries with plentiful access to fossil fuels and seawater, leaving low-income countries relatively unexposed to the technology - a technology that could drastically alter the way that they approach their potable water supply.

Due to the great deal of energy required to desalinate seawater, desalination plants face greater environmental costs due to climate change through the release of greenhouse gases. Compared to traditional freshwater costing about $0.50 per cubic meter, the cost to produce one cubic meter of freshwater from desalinated seawater can range from $0.50 up to $1.50 (Toth, 2020). As urbanization and populations continue to expand, efficiency and reducing commercial processes' effects are important in a world that is dominated by industrial processes. There are two main types of desalination processes: 1) thermal desalination and 2) membrane desalination.

2.3.1 Thermal Desalination

Thermal desalination is a dominant desalination process in the Arab states of the Persian Gulf, however, due to the rapid development of reverse osmosis membrane technology, reverse osmosis is being heavily adopted. There are several thermal processes for treating salinated water, including, but not limited to, multistage flash desalination (MSF) and multieffect desalination (MED).

2.3.1a Multistage Flash Desalination

As seen in Figure 4, MSF plants contain a series of chambers to separate pure water from mixed seawater and recycled brine by evaporation. The salinated feedwater is fed through a series of stages where there is a continuous decrease in pressure and temperature (Al-Sahali & Ettouney, 2007). First, the feedwater is heated to approximately 90 to 110℃ to pass through the MSF's first stage heat exchanger. The first stage is pressurized to a pressure less than the pressure of the heated feedwater's pressure at equilibrium, allowing the mixture to become partially vaporized (Toth, 2020). The vapor cools, condenses, condensates, and accumulates as the product of pure water. The saline water remaining after the first stage proceeds into the secondary stage, where a lower pressure is exerted, indemnifying the loss of energy/temperature and increased salinity of the saline water. The saline water can be partially flash evaporated through several stages until it is rejected back into the ocean as brine.

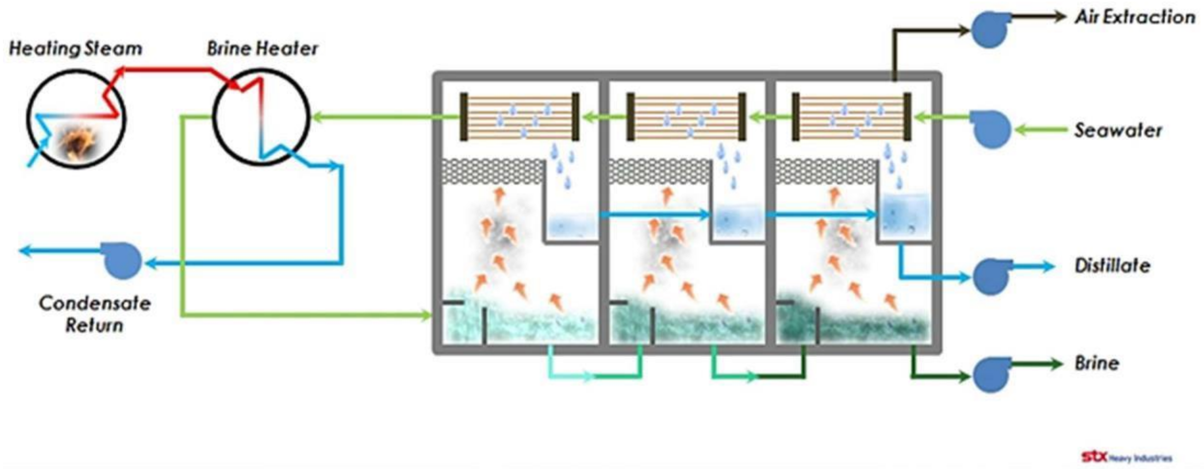

Figure 4. *Multistage Flash Desalination Process*, (*Desalination Plant*, n.d.).

Making up 3 out of every 4 thermal desalination plants used in the world, the electrical energy usage, thermal energy usage, and the investment cost of a MFS plant is approximately 2.5 to 4 kWh/m³, 7.5 to 12 kWh/m³, and $1200 to $2500 per m³/day, respectively (Toth, 2020). Per cubic meter, the total cost of water is $0.80 to $1.50. MSF desalination is the most inefficient and expensive desalination process used today.

2.3.1 b Multi Effect Desalination

As seen in Figure 5, MED plants contain a series of chambers that are used to evaporate seawater and recover the vapor to obtain freshwater. Each subsequent chamber in a MED plant operates at a lower pressure and lower temperature than the previous chamber. Throughout the MED plant, heated steam is flowing from the vapor compressor. In the first chamber, seawater is sprayed onto the tubes where the steam is flowing. Partial evaporation of the seawater occurs and the remaining seawater is the feedwater for the next chamber. In this part of the process, the vapor produced by the first chamber is used as the heating source. The process continues into subsequent chambers at lower pressures and temperatures and the freshwater is collected through condensate. The seawater can be partially evaporated through several more chambers to increase the efficiency of the plant. Brine is then ejected back into the ocean.

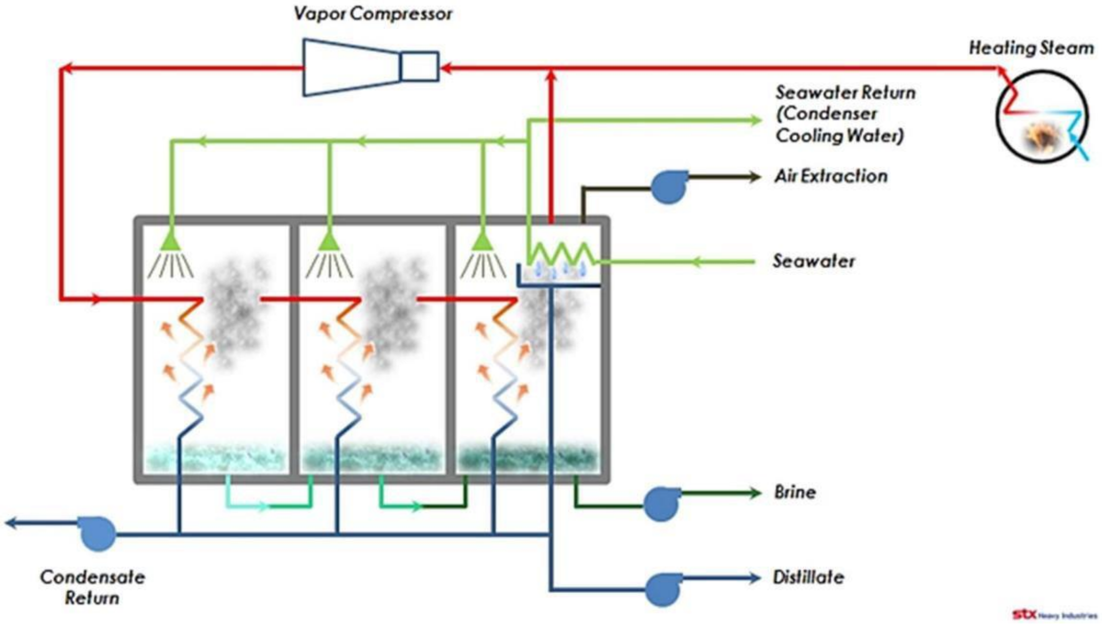

Figure 5. *Multi Effect Desalination Process*, (*Desalination Plant*, n.d.)

Making up only 1 out of every 4 thermal desalination plants used in the world, electrical energy usage, thermal energy usage, and the investment cost of a MED plant is approximately 1.5 to 2 kWh/m³, 4 to 7 kWh/m³, and \$900 to \$2500 per m³/day, respectively (Toth, 2020). Per cubic meter, the total cost of water is \$0.70 to \$1.20. Although MED plants are a more thermodynamically efficient choice over MSF plants, they consume more energy overall and cost more in investment in comparison to their capacity.

2.3.2 Membrane Desalination & Reverse Osmosis

There are several membrane processes for treating salinated water, including reverse osmosis, nanofiltration, ultrafiltration, and microfiltration - just to name a few. Simply, in membrane desalination, water containing salts, minerals, and organic chemicals is passed through a semipermeable barrier or membrane. The membrane separates the freshwater/permeate from the contaminated water by allowing only certain particles to pass through.

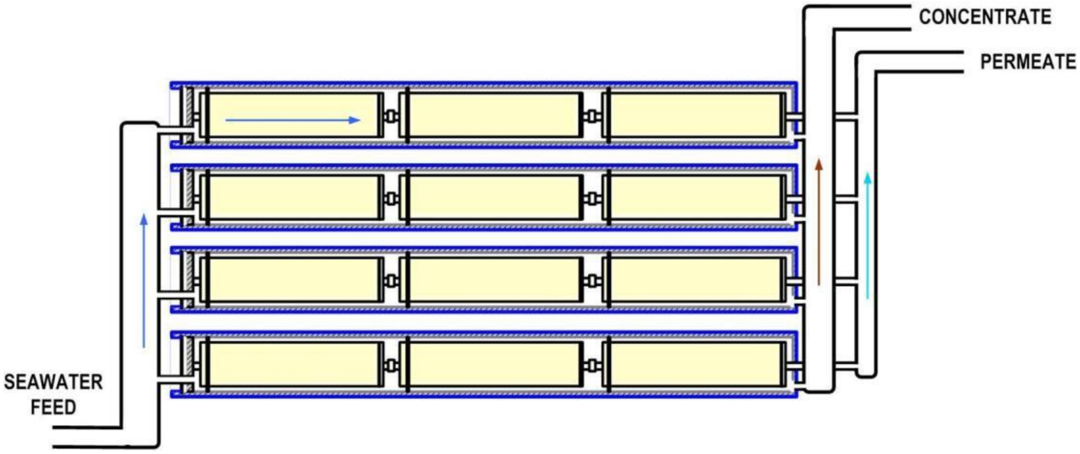

Figure 6. *Spiral Wound Reverse Osmosis Membrane Process* (*Reverse Osmosis Desalination Process*, n.d.)

Reverse osmosis is the most widely used membrane desalination technology as it is used in treating seawater, brackish water, and wastewater, and used to produce quality potable water, however, this project primarily focuses on seawater reverse osmosis. Reverse osmosis is possible because it is driven by a vapor pressure differential across the membrane, meaning that the concentrated solution will travel from the high pressure side of the membrane to the low pressure side of the membrane against the natural, spontaneous direction of osmosis, resulting in usable freshwater while leaving brine behind. Specifically, the hydrostatic pressure must be greater than the osmotic pressure of the concentrated solution. The journey of the seawater feed can be seen in Figure 6.

Table 3. *Advantages of Thermal and Membrane Desalination Processes*, adapted from (Li & Li, 2017)

Process	Advantages	Disadvantages
Thermal Desalination	Relatively unreliant on feedwater quality, effective salt-water separation effect, automated, stable operation	High investment, large land occupation, dependent on fuel cost, large energy input
Membrane Desalination	High water quality, high water recovery, technical maturity, small land occupation, advancing membrane technology, reduced energy input	High investment, dependent on feedwater, frequent membrane cleaning, slow filtration rate, extensive pretreatment

2.3.2a Pretreatment

At the commercial level, there are several steps involved in converting seawater to quality potable water through reverse osmosis. Typically, the seawater goes through a pretreatment process in which a series of filters remove particles like seaweed, clay, and sand before the seawater enters the reverse osmosis system, ultimately to prevent fouling viabacteria, particles, algae, organic material, minerals, or oxidants. Conventionally, the pretreatment process consists of coagulation and flocculation. Non-conventionally, the pretreatment process may include ultrafiltration (UF), microfiltration (MF), and nanofiltration (NF). Coagulation is a chemical process preceding sedimentation. Chemicals like aluminum sulfate, ferric sulfate, or sodium aluminate combine smaller particles suspended in the seawater into larger solids known as floc (*Coagulation and Flocculation*, n.d.). Coagulation is carried out through a rapid mixing stage and a slow mixing stage, known as flocculation. In the rapid mixing stage, the coagulants are dispersed throughout the water to complete a chemical reaction. Flocculation allows particles to collide and for floc to grow, ultimately leading the water to flow into sedimentation tanks (*Coagulation and Flocculation*, n.d.). UF, MF, and NF filters have pore sizes of 0.01 µm, 0.1 µm, and 0.001 µm, respectively (*Ultrafiltration, Nanofiltration and Reverse Osmosis*, n.d.). UF can remove plastics and viruses from incoming seawater. MF can remove algae, sediment, and bacteria. NF can remove microbes, organic matter, and natural minerals.

The Ghalilah desalination plant located in Ras Al Khaimah, United Arab Emirates (UAE) uses a pretreatment process including media and cartridge filters preceded by chemical treatment via “chlorine, ferric chloride bisulfate coagulant, sulfuric acid, sodium metabisulfite, and antiscalant” (Stover et al., 2005). The Al Zawra desalination plant in Ajman uses dual-stage media filters and cartridge filtration (Jacangelo et al., 2018). The Jebel Ali desalination plant in Dubai (WCN Editorial Team, 2019) and Fujairah F2 Plant in Fujairah (Jacangelo et al., 2018) both use dissolved air flotation (DAF) and gravity filters to pretreat the reverse osmosis feedwater. Similarly, the Layyah desalination plant in Sharjah uses dual-stage media filters preceded by DAF (International, 2009). The Hamriyah desalination plant in Sharjah also utilizes a DAF pretreatment system as well as an ultra-filtration unit (*Hamriyah SWRO Desalination Plant, Sharjah - Water Technology*, n.d.). One of the largest desalination plants in the world and the largest in the UAE, Al Taweelah located in Abu Dhabi, also uses DAF (*DAF for Largest Desalination Plant in the World*, n.d.).

Single media filters and multimedia filters can remove particles ranging in size of 0.1 to 500 µm and 5 to 10 µm, respectively (Mehner, 2010). In the unconventional pretreatment process DAF, pressurized air saturates a liquid stream and mixes with incoming feedwater. Small bubbles bring small particles with them to the surface to be removed via a skimmer as the pressure returns to the atmosphere (Show et al., 2019, p. 7). The bubbles’ diameter in DAF generally ranges from 10 to 100 µm (Esteves et al., 2020, p. 10). Ultimately, although UAE data is limited as discussed in section 2.2.1, the most common pretreatment in the UAE appears to be a combination of DAF and some other filtration system, removing particles of sizes in a range anywhere from 0.1 to 100 µm. By the time that the seawater has passed through pretreatment, virtually all particles except dissolved salts and minerals will remain. Generally, although depending on the pretreatment system in place, water entering the reverse osmosis membrane has been filtered to remove particles larger than 1 to 5 μm (*Particle Filtration in Desalination Systems*, 2014).

2.3.2b Reverse Osmosis Filters

After pretreatment, the reverse osmosis system then removes the salt from the pressurized seawater being fed in from a high pressure pump. In a pressure vessel, several membranes can be connected in series and, then, in parallel with other pressure vessels (*Reverse Osmosis Desalination Process*, n.d.). Desalinated, pure water exits the reverse osmosis system through the membrane's inner tube and enters posttreatment where it is exposed to chemicals to prepare it for human consumption. Highly salinated, highly pressurized concentrated water leaving the membranes generally enters an energy recovery device that helps transfer energy and pressurize incoming seawater. Energy recovery devices can reduce the cost of the desalination plant operation by utilizing the high energy from the system's byproduct. The concentrated water, or brine, produced by the plant is then sent back into the ocean. There are some devices that collect brine to remediate its otherwise adverse effects on marine life.

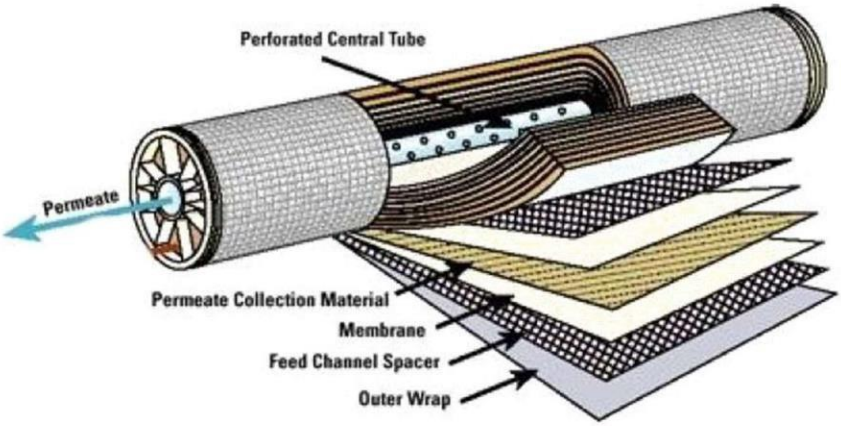

Figure 7. *Spiral Wound Seawater Reverse Osmosis Module* (*Reverse Osmosis Desalination Process*, n.d.).

Most reverse osmosis membranes, as seen in Figure 7, are constructed as a spiral wound module made up of a polymer material forming a "layered, web-like structure" forcing water to follow a "tortuous pathway to reach the permeate side" as the membrane rejects the concentrate water containing monovalent ions and miniscule contaminants to the opposite end of the feed (Greenlee et al., 2009). The product water collects in the membrane's inner tube. The most common reverse osmosis membranes used in industrial processes are FilmTec membranes.

Hollow fiber and tubular reverse osmosis membranes are also used to process high TDS feedwater streams. Hollow fiber modules have fibers 0.1-1mm diameter in size and a space inside that is hollow. The feedwater enters the module either through the inside or outside of the hollow fiber. Through the fiber wall, the permeate passes through to the other side. The fiber wall is constructed as an asymmetric membrane and a "bundle of hollow fibers is mounted in a pressure vessel" (Ismail & Matsuura, 2019). Tubular modules have an inner membrane tube and an outer shell tube. The feedwater passes through the membrane tube and permeate is ejected into the shell tube (*Tubular Membranes*, 2014). These tubular modules are constructed with porous walls.

2.3.2c Desalination Efficiencies

Table 4. *Comparison of the Energy and Capital Efficiencies of Desalination Technologies*, adapted from (Toth, 2020)

Desalination Process	Thermal/ Membrane	Investment Cost ($/m³/day)	Water Cost ($/m³)	Thermal Energy (kWh/m³)	Electrical Energy (kWh/m³)	Total Energy (kWh/m³)
MSF	Thermal	1200-1500	0.8-1.5	7.5-12	2.5-4	10-16
MED	Thermal	900-2500	0.7-1.2	4-7	1.5-2	5.5-9
RO	Membrane	900-2500	0.5-1.2	N/A	3-4	3-4

As seen in Table 4, reverse osmosis plants are more efficient, and consequently cheaper, than thermal desalination processes, which can require an energy demand two to four times greater than reverse osmosis plants (Toth, 2020). The cost efficiency of reverse osmosis plants is due, in part, to them only demanding electrical energy, unlike thermal desalination plants that require thermal energy. The electrical energy usage and the investment cost of a reverse osmosis plant is approximately 3 to 4 kWh/m³ and $900 to $2500 per m³/day, respectively (Toth, 2020). The total cost for water is $0.50 to $1.20 per cubic meter. As seawater reverse osmosis technology becomes more efficient and technologically advanced possibly via the use of renewable energy, it is expected to decrease the capital and energy cost of desalination, become a more economically attractive resource for freshwater, and even become competitive with traditional water treatment processes.

2.3.2d Reverse Osmosis Fouling

While seawater reverse osmosis has the advantage of high water permeability and salt rejection, a major cost efficiency and desalination process efficiency concern for all membrane desalination technology is membrane fouling. Membrane fouling is the "accumulation of undesired deposits on the membrane surface or inside the membrane pores, causing decrease of permeation flux and salt rejection" (Jiang et al., 2017). The degradation in the performance of the reverse osmosis membrane overtime can be affected by salinity, temperature, and cleaning procedures. A membrane is expected to have a total membrane life up to 7 years, but the aging of reverse osmosis membranes is expected to increase salt passage by 10% each year, ultimately adversely affecting the quality of the product water (Greenlee et al., 2009). Increased membrane fouling can affect several other factors involved in the operation and maintenance of a reverse osmosis desalination plant such as requiring higher feed pressure, resulting in an increase in energy costs to operate the plant and a reduction in productivity. It may also cause an increase in chemical use and may require more frequent cleaning, resulting in an additional cost and more system downtime. Eventually, as the membrane fouls past the point of reversibility, the membrane will have to be replaced, resulting in a higher cost of materials to operate the plant (Villacorte et al., 2015). There are several types of fouling including organic fouling, inorganic fouling, biofouling, and colloidal fouling. Colloidal fouling occurs as the result of particle accumulation on the reverse osmosis membrane. Colloidal particles are typically 1 to 1000 nm in size, the size range between suspended solids and true dissolved solids. Their size ultimately allows them to surpass pretreatment but still accumulate on the surface of the reverse osmosis membrane. The majority of colloidal particles are aluminosilicates of size 0.3 to 1.0 μm (Matin et al., 2021).

To limit the fouling of a membrane, the membrane's cleanliness should be kept in mind. There are differing ways to keep a membrane clean depending on the size of the membrane and the concentration of particles like NaCl, Ca^{2+}, Ba^{2+}, and Sr^{2+}. Small or medium sized brackish water plants can use a strong acid cation exchange method to soften the water running through the membrane. Large seawater plants mainly use dealkalization with a weak acid cation exchange. This method minimizes the consumption of regenerate chemicals. A weak acid exchange removes Ca^{2+}, Ba^{2+}, and Sr^{2+} and replaces them with H^{+} to lower the pH to between four and five. Because only the cations that are bound to bicarbonate are removed, it's ideal for water with high levels of bicarbonate, which occurs naturally since circulating water dissolves carbon dioxide into bicarbonate and carbonate ions. The equation below is an example of this relationship (*DOW Water & Process Solutions FILMTEC Reverse Osmosis Technical Manual*, n.d.).

$$HCO_{3^-} + H^+ \leftrightarrow H_2O + CO_2$$

At smaller units, like single element plants, scaling can be controlled by cleaning the membrane. This method does not soften the water and doesn't use any dosage of chemicals. According to the DOW reverse osmosis units, the "simplest way of cleaning is a forward flush at low pressure by opening the concentrate valve. Short cleaning intervals are more effective than long cleaning times (e.g., 30 seconds every 30 minutes)" (*DOW Water & Process Solutions FILMTEC Reverse Osmosis Technical Manual*, n.d.). On this scale, it is a common practice to clean after every batch. However, even with a low pressure forward flush, it is important to notice that a scaling layer does not develop over time.

2.3.2e Membrane Transport Models

Throughout the development of membranes, several models mathematically describing the behavior of mass transporting through a reverse osmosis membrane have been discussed. The ideal transport model is the solution-diffusion model. It is dependent on assuming that the membrane of interest is free of defects and is nonporous. However, in the solution-diffusion model, the solvent and solute's transportation through the membrane are treated independently of one another. The flux of the solvent can be calculated as follows:

$$J_w = A(\Delta P - \Delta \Pi)$$

In this equation, J_w is the flux of the solvent, A is the permeability coefficient of water, ΔP is the applied pressure driving force, and $\Delta \Pi$ is the solution's osmotic pressure (Kucera, 2015). The flux of the solute can be calculated as follows:

$$J_S = K(C_{A2} - C_{A3})$$

In this equation, J_c is the flux of the solute, K is the salt permeability coefficient, C_{A2} is the molar concentration of the solute at the boundary layer, and C_{A3} is the molar concentration of the solute in the permeate (Kucera, 2015). These two equations demonstrate that as the applied pressure is increased, the concentration of salt in the permeate decreases because of the greater water to salt ratio. They are also the set of design equations used to describe the water and salt flux provided in the Dupont FilmTec Reverse Osmosis Membranes Technical Manual.

Another model used to describe mass transport through a membrane is the solution-diffusion imperfection model. This model accounts for the imperfections in industrial membranes that occur during manufacturing and can affect the membrane's indicators for performance. The flux of the solvent can be calculated as follows:

$$N_W = J_W + K_3 \Delta P C_W$$

Similar to the solution-diffusion model, this equation adds an additional term to the solution-diffusion model solvent flux to account for the aforementioned imperfections. In this equation, N_W is the total water flux, K_3 is the coupling coefficient, and C_W is the feed solvent concentration (Kucera, 2015). The flux of the solute can be calculated as follows:

$$N_C = J_C + K_3 \Delta P C_R$$

Similar to the solution-diffusion model, this equation adds an additional term to the solution-diffusion model solute flux to account for the aforementioned imperfections. In this equation, N_C is the total solute flux and C_R is the feed solute concentration.

A third model used to describe mass transport through a membrane is the finely-porous model. This model accounts for friction, membrane thickness, and fractional pore area. Friction can occur 1) between the solute and the solvent and 2) between the solute and the reverse osmosis membrane (Kucera, 2015). A final model used to describe mass transport through a membrane is the preferential sorption - capillary flow model. This model accounts for the viscous flow of water and pore diffusion. The calculation of solvent flux is the same equation used to solve for solvent flux in the solution-diffusion model. The flux of the solute, however, can be calculated as follows:

$$N_C = (D_{AM} K / T)(C_{A2} - C_{A3})$$

In this equation, D_{AM} is the diffusivity of the solute in the membrane and T is the effective thickness of the membrane.

2.3.2f Reverse Osmosis Operating Conditions

Seawater reverse osmosis membranes are expected to treat feedwater with TDS of 10,000 ppm to 60,000 ppm and can reject more than 99% of salt coming in with a feed pressure of 6000 to 8000 kPa to override the osmotic pressure of seawater typically ranging from 2300 kPa to 3500 kPa (Greenlee et al., 2009). Designed for high salt rejection, seawater reverse osmosis membranes tend to have “lower permeate fluxes [...and…] must operate at higher pressures to compensate for the higher osmotic pressure of seawater” (Greenlee et al., 2009). As the salinity of a concentrated solution (i.e. seawater) is increased, salt is expected to pass through the membrane, osmotic pressure increases, and permeate flow decreases. When the pressure of the feedwater remains constant and salt concentration is increased, the permeate flux is expected to decrease. Generally, the increase in temperature of a concentrated solution at a constant pressure has a near linear relationship with the permeate flux of the membrane due to a higher rate of diffusion. However, temperatures below 30°C can allow lower feed pressures, while increases in temperature increase the osmotic pressure requiring an increase in feed pressure. In a seawater reverse osmosis system operated at a constant pressure, it can be expected to see that permeate salinity increases with temperature, meaning an increase in salt passage or a decrease in salt rejection.

An important factor that affects reverse osmosis membranes is the presence of particles in seawater. For example, concentration increases of particle chlorophyll *a* in seawater has been associated with increased rates of membrane fouling because pretreatment processes are typically inadequate in reducing the concentration of chlorophyll *a* in the feedwater (Ozair et al., 2018). As microplastic particle sizes exceed 100 nm in seawater, the performance of the reverse osmosis membrane is bound to be negatively affected through fouling, decrease membrane salt rejection, or decrease freshwater production. Microplastic particle sizes less than 100 nm can also “penetrate the membrane and contaminate the drinking water” (Skuse et al., 2021). Microplastics ranging in size from <5 to 5,000 μm have been found in potable water and freshwater, meaning despite pretreatment processes, microplastics can still surpass pretreatment and the reverse osmosis membrane (Tang & Hadibarata, 2021). An indicator of particles, and, consequently, membrane fouling is an increase in differential pressure - a measure of theamount of pressure lost due to friction within the reverse osmosis membrane. The differential pressure of a reverse osmosis membrane is calculated as the difference between the pressure of the feedwater and the pressure of the permeate. Observing particles in reverse osmosis plants is important because it can cause increased rates in membrane fouling, an increase in chemical consumption, and, possibly, outage of the plant (Ozair et al., 2018).

2.3.2g Reverse Osmosis Prediction Calculations

Important components involved in determining the performance of a seawater reverse osmosis membrane are the recovery, the membrane salt rejection, and the permeate flux. These performance indicators can be used to predict the impact of increasing salinity and temperature of feedwater on the performance of the reverse osmosis membrane. Therefore, desalination plants can more easily be prepared to adapt and modify their reverse osmosis system to account for changes in the marine environment. Changes in salinity and temperature in seawater could occur suddenly or overtime. It is important for desalination plants to be cognizant of the impacts in the event that a sudden change occurs.

2.3.2g.1 Recovery

The recovery, varying from 35% to 85% depending on the composition, salinity, and pretreatment of the feedwater, can be found by dividing the permeate volumetric flow rate by the feed volumetric flow rate (Greenlee et al., 2009). If the recovery rate value is high then thewater discharged is less concentrated. Higher recovery rates may be dependent on higher feed pressures, membrane area, and permeate flux because salinity is decreased by increasing dilution. Recovery can be calculated as follows:

$$\frac{Q_{permeate}}{Q_{feed}}$$

Table 5 shows an example of the range that can be found in one area of recovery rates. All of the desalination units in Table 3 are located in the UAE. The average of these plants' recovery rate is 46.125%. The average rate being below 50% is most likely due to how concentrated water from the Persian Gulf is.

Table 5. *UAE Desalination Plants Recovery Rates*, adapted from (Ahmed et al., 2001)

UAE Desalination Unit	**Recovery Rate**
Qidfa I Plant	40%
Qidfa II RO Plant	35%
Kalba Plant	67%
Umm Al-Qwain Plant	75%
Jabal Al-Dhana Plant	30%
Hamriyah Plant	70%
Al-Aryam Plant	30%
Al-Rafeek Plant	22%

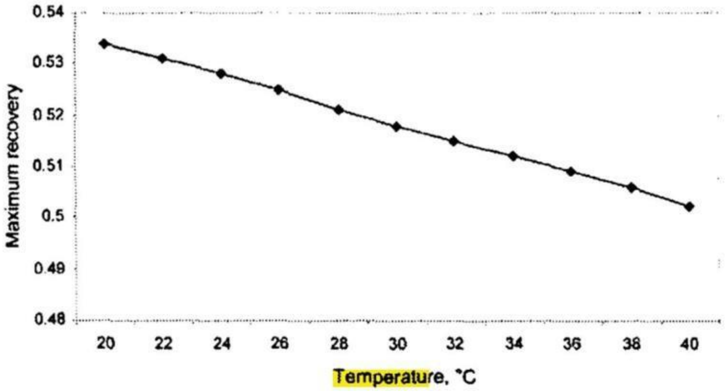

Figure 8. *Temperature versus Recovery* (Agashichev & Lootahb, 2003).

A research center in the UAE conducted a study on temperature and permeate recoveryon a reverse osmosis system. They found that an increase in temperature leads to a decrease inrecovery (Agashichev & Lootahb, 2003). The slope of the line on the graph is approximately -1/600 since an increase of 20 degrees celsius of temperature leads to a decrease in maximum recovery of 0.033. The indirect relationship shows that too warm of a temperature impacts the concentration of discharged water and thus is not as successful as a desalination process. This linear relationship is shown graphically in Figure 8. Due to the relationship between feedwatertemperature and recovery rate, it can be predicted that as seawater temperature increases, the reverse osmosis system will have a lower recovery rate.

2.3.2g.2 Flux

The flux of the membrane can be affected by several variables such as temperature, feed pressure, and temperature. Because the flux is directly proportional to temperature, the temperature correction factor (TCF) for flux can be calculated as follows, where T is the temperature of the water in degrees Celsius:

$$TCF = exp(2640(\frac{1}{298} - \frac{1}{273.15 + T})); \quad T \geq 25℃$$

$$TCF = exp(3020(\frac{1}{298} - \frac{1}{273.15 + T})); \quad T \leq 25℃$$

Generally, the flux changes by 3% for every 1℃ change in temperature (Kucera, 2010). Therefore, if seawater temperature increases over time and, consequently, a reverse osmosis system's feedwater increases, the percent increase in flux can be predicted.

Table 6. *Temperature Correction Factor for Increasing Seawater Temperature*

Temperature (℃)	TCF	% Change in Flux
15	0.71	-29
20	0.85	-15
25	1	0
30	1.16	16
35	1.34	34
40	1.54	54

In Table 6 above, the TCF for temperatures ranging from 15 to 40℃ were calculated using a reference point of 25℃. Feedwater entering the reverse osmosis membrane at a temperature over 45℃ can anneal the membrane and make it difficult for water to pass through, resulting in a decrease of flux (Kucera, 2010). If seawater temperature increases in the future, reverse osmosis plants can expect an increase in flux and can predict efforts to remediate any plant issues that may arise out of it. A 2002 study *Effect of Feed Temperature on Permeate Flux and Mass Transfer Coefficient in Spiral-Wound Reverse Osmosis Systems* found a 60% increase in permeate flux of a spiral-wound membrane while increasing the feed temperature from 20 to 40*℃* (Goosen et al., 2002). At constant feed pressures and NaCl feed concentrations, it appeared that, in this study, there was minimum at an intermediate temperature (30*℃*) found where then, from 30*℃* to 40*℃*, the permeate flux virtually doubled. Goosen et al. conducted several trials at varying temperatures, transmembrane pressures, and NaCl feed concentrations.

Table 7. *Effect of Feed Temperature on Permeate Flux*, adapted from (Goosen et al., 2002)

NaCl Feed Concentration (%)	**Temperature (℃)**	**Transmembrane Pressure (bar)**	**Permeate Flux (L/m^{2}h)**
1	20	9.1	15.6
1	30	9.6	14.18
1	40	9.1	25.3

As seen in Table 7 above, it can be observed that while the NaCl feed concentration percentage and transmembrane pressure were held relatively constant and the temperature varied, the permeate flux increased from 20*℃* to 40*℃*. These types of trials from 20*℃* to 40*℃* were repeated for NaCl feed concentration percentages ranging from 0 to 5% (0 to 50,000 ppm) and transmembrane pressures ranging from approximately 9 bar to 49 bar.

Table 8. *Effect of Salinity on Permeate Flux*, adapted from (Goosen et al., 2002)

NaCl Feed Concentration (%)	**Temperature (℃)**	**Transmembrane Pressure (bar)**	**Permeate Flux (L/m^{2}h)**
0	40	19.0	48.1
1	40	18.8	44.6
2	40	18.6	42.3
3	40	18.7	39.1
4	40	18.5	36.3

As seen in Table 8 above, the partial results from Goosen et al. varying NaCl feed concentration percentage while keeping temperature constant at 40*℃* and transmembrane pressure constant at approximately 19 bar resulted in an decrease of permeate flux. Across all of the trials performed there was a significant decrease in permeate flux with an increase in feed salinity especially at high temperatures and pressures. Ladner et al. also supports this hypothesis through experimental study at a higher pressure. The 2010 study, *Bench-scale evaluation of seawater desalination by reverse osmosis*, indicated that if pure water is passed through the system at 6900 kPa, its flux would be around 50 liters per meter-squared per hour (lmh) compared to 32,000 ppm seawater with a flux of 30 lmh at the same pressure (Ladner et al., 2010).

2.3.2g.3 Salt Rejection

Membrane salt rejection can be found by subtracting the dividend of the concentration of the permeate and the concentration of the feed from 1. Bartels et al. conducted a study, *The effect of feed ionic strength on salt passage through reverse osmosis membranes*, in 2005 on the effect of increased salinity on reverse osmosis membrane salt rejection and found feedwater concentrations of 1,000 ppm upwards to 10,000 ppm experienced increasing salt passage(Bartels et al., 2005).

$$\left(1-\frac{C_{\mathrm{permeate}}}{C_{\mathbf{feed}}}\right) * 100\%$$

As mentioned previously, an increase in temperature can increase salt passage through the membrane. Specifically, a 1℃ increase in temperature can increase the salt passage by 6%. Therefore, based on a desalination plant’s current feed temperature and salt passage, a desalination plant can predict how much salt passage would increase based on a temperature increase. For example, if a desalination plant’s feed temperature is typically 25℃, it can expect to see salt passage increase by 30% at 30℃, 60% at 35℃, and 90% at 40.

Regarding changes in feed concentration, salt rejection will likely increase until a maximum value of rejection at 300 to 500 ppm (*Principles of Reverse Osmosis Membrane Separation*, n.d.). Past the maximum salt rejection, it is expected as the feed concentration increases, the salt rejection of the membrane will decrease.

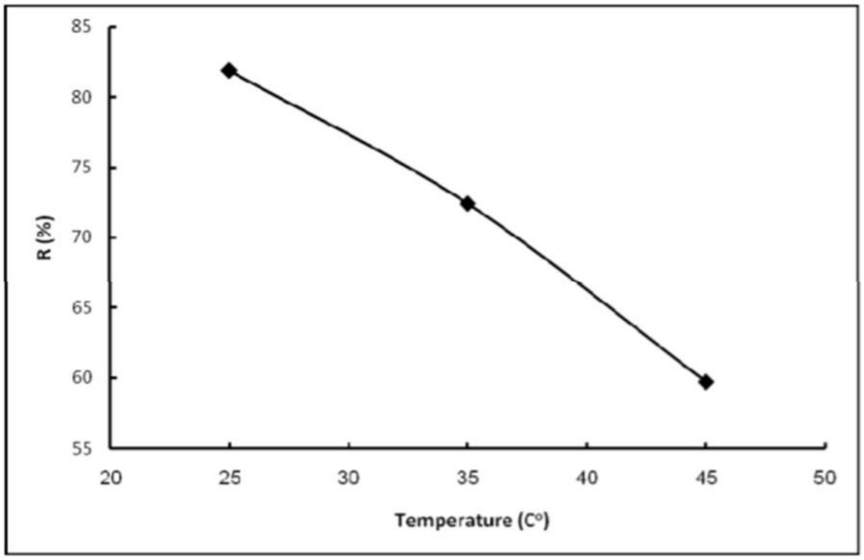

Figure 9. *Effect of Temperature on Salt Rejection @ 15,000 ppm and 1 bar* (Abdulmuttaleb et al., 2014)

Abulmuttaleb et al. explored the effects of increasing salinity, pressure, and temperature on reverse osmosis performance, specifically, the membrane's salt rejection and permeation flux. The 2014 study, *Effect of Operating Conditions on Reverse Osmosis (RO) Membrane Performance* found that salt rejection decreased when increasing the feedwater temperature from 25 to 45℃.

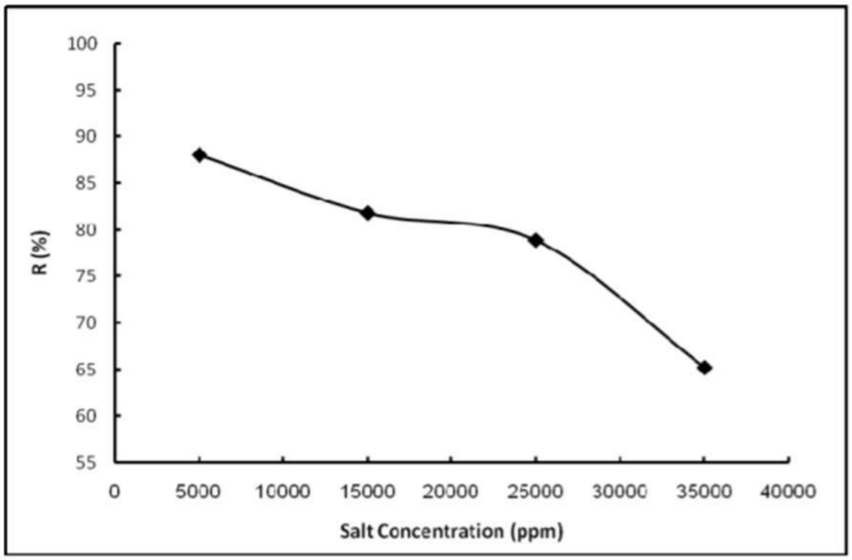

Figure 10. *Effect of Salt Concentration on Salt Rejection @ 25℃ and 1 bar* (Abdulmuttaleb et al., 2014)

Abdulmuttaleb et al. also found that salt rejection decreased from 88% to 65% when running a feed concentration of 5,000 and 35,000 ppm of Na_2CO_3 through a reverse osmosis membrane (Abdulmuttaleb et al., 2014). Although not entirely linear, assumption of a linear relationship can be used to predict salt rejection for higher salinities. With such an assumption, the slope of this function would be -0.00076667. The y-intercept would be 91.833. The linear equation relating these results is:

$$y = -0.00076667x + 91.833$$

Therefore, the salt rejection at 45,000 ppm, 55,000 ppm, 65,000 ppm, and 75,000 ppm would be 57.33%, 49.67%, 41.99%, and 34.33%, respectively.

Yale University studied the relationship salt rejection holds with the other important components. The study, titled *Influence of colloidal fouling and feed water recovery on salt rejection of RO and NF membranes*, was conducted by Sangyoup Lee, Jaeweon Cho, and Menachem Elimelech. Lee et al. concluded that "an increase in feed water recovery (or concentration factor) does not affect salt rejection despite the continuous decline in permeate flux". For feedwater containing colloidal particles, the salt rejection of both the reverse osmosis and nanofiltration membranes decreases continuously as fouling progresses (Lee et al., 2004).

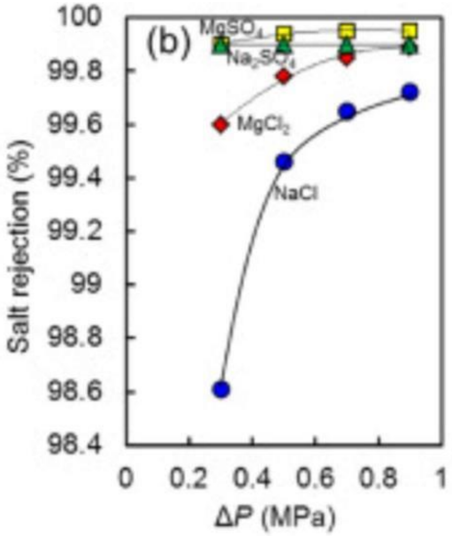

Figure 11. *Effect of Transmembrane Pressure on Salt Rejection for 0.2 wt% of NaCl,* $MgCl_2$*,* $MgSO_4$ *and* Na_2SO_4 *aqueous solutions* (Takeuchi et al., 2018)

In a 2018 study, *Salt rejection behavior of carbon nanotube-polyamide nanocomposite reverse osmosis membranes in several salt solutions*, Takeuchi et al. evaluated a relationship between salt rejection and pressure and found that when pressure increased, so did the salt rejection. In fact, when the pressure first increased by only 0.2 MPa, the salt rejection jumped up almost 1% whereas in the final 0.2 MPa increase, salt rejection only increased by 0.1%. The relationship can be seen in Figure 11 above.

According to the Dupont FilmTec Reverse Osmosis Membranes Manual, the salt concentration in the permeate can be calculated as follows:

$$C_p = BC_{fc}\underline{pf}(TCF)(\frac{N_E S_E}{Q})$$

In this equation, C_p is the permeate concentration, B is the salt diffusivity coefficient, C_{fc} is the average concentrate-side concentration, $\underline{pf}$ is the concentration polarization factor, N_E is the number of elements in the reverse osmosis system, S_E is the surface area of each membrane element, and Q is the system's permeate flow. The $\underline{pf}$ of a system composed of 8" elements can also be calculated as follows:

$$\underline{pf} = EXP[0.7\underline{Y_i}]$$

In this equation, $\underline{Y_i}$ is the average recovery rate across all elements. It can be found by dividing the permeate flow by the feed flow.

As seen in the permeate concentration equation, there are several variables dependent on the membranes used in the reverse osmosis system. The impact of increased salinity in feedwater or increased feedwater temperature can simply be seen as a function dependent on the rest of these variables. For instance, if an increase in salinity from 35,000 to 40,000 ppm at a constant temperature of 25℃ were to be predicted using this equation, the equation could only be simplified to:

$$C_p = 35{,}000B\underline{pf}\left(\frac{N_E S_E}{Q}\right);\ @\ 35{,}000\ ppm$$

$$C_p = 40{,}000B\underline{pf}\left(\frac{N_E S_E}{Q}\right);\ @\ 40{,}000\ ppm$$

$$C_p @\ 40{,}000\ ppm - C_p @\ 35{,}000\ ppm = 5{,}000B\underline{pf}\left(\frac{N_E S_E}{Q}\right)$$

Similar behavior of this equation would occur for temperature. For instance, if an increase in temperature from 25℃ to 30℃ (using previously calculated TCF) at a constant salinity of 35,000 ppm were to be predicted using this equation, the equation could only be simplified to:

$$C_p = 35{,}000B\underline{pf}\left(\frac{N_E S_E}{Q}\right);\ @\ 25℃$$

$$C_p = 35{,}000(1.16)B\underline{pf}\left(\frac{N_E S_E}{Q}\right) = 40{,}600B\underline{pf}\left(\frac{N_E S_E}{Q}\right);\ @\ 30℃$$

$$C_p @\ 30℃ - C_p @\ 25℃ = 5{,}600B\underline{pf}\left(\frac{N_E S_E}{Q}\right)$$

Both temperature and salinity scale this equation. Limited implications can be made about this mathematical relationship without the specifications of a desalination plant's reverse osmosis membranes. Provided that data on desalination plant's specifications is limited, a theoretical desalination plant could be discussed to simplify the equation. Assume that a desalination plant uses 10,000 FilmTec Seamaxx - 440 Elements. At standard testing conditions of 32,000 ppm NaCl, 800 psi or approximately 5,500 kPa, 25℃, and 8% recovery, the membrane achieves a permeate flow rate of 17,000 GPD. The membrane also has an active area of 440 cubic feet. With 10,000 elements with a permeate flow rate of 17,000 GPD each, this theoretical reverse osmosis plant would produce 170,000,000 GPD of permeate. With this information, the concentration in the permeate can be calculated as a function of the salt diffusivity coefficient, B-value. Not only is the B-value a function of a membrane's diffusivity and thickness, but it is "specific to different membrane types and is arrived at by analytical methods" (Bartels et al., 2005).

$$C_p = 32{,}000(0.08)\left(\frac{10{,}000 * 440}{17{,}000}\right)B = 662{,}588B$$

If this theoretical desalination plant experiences an increase in feedwater concentration to 40,000 ppm while all other variables remain constant, the permeate concentration will be:

$$C_p = 40{,}000(0.08)\left(\frac{10{,}000 * 440}{17{,}000}\right)B = 828{,}235B$$

If this theoretical desalination plant experiences an increase in temperature to 30℃ while all other variables remain constant, the permeate concentration will be:

$$C_p = 32{,}000(0.08)(1.16)\left(\frac{10{,}000 * 440}{17{,}000}\right)B = 768{,}602B$$

Although these calculations are a function of the B-value, they do indicate that when all other variables remain constant, an increase in temperature or an increase in salinity increases the permeate concentration or, in other words, allows greater salt passage.

2.4 Bench-Scale Reverse Osmosis Systems

While the implementation of large-scale desalination operations has increased for dry and arid areas where freshwater sources are strained, smaller reverse osmosis units are available for use on a smaller scale. The size and flow rate capacities of these machines are much smaller than the large industrialized units serving a large population.

There are a variety of these systems with differing numbers of stages available for purchase. Multi-stage units separate the processes that extract separate elements and tend to be more efficient (*APEC Water Systems Essence Premium Quality 5-Stage Under-Sink Reverse Osmosis Drinking Water Filter System-ROES-50*, n.d.). Multiple stages means one small error or fouling of a filter can be fixed easily by replacing a filter without having to change any other working parts of the machine. For most multi-stage units, the first stages filter out large particulates to prepare for and to protect the reverse osmosis membrane from elements that may affect its lifespan, which uses higher pressure to separate the ionic species as discussed in section 2.3.2.

For ease of use, most of these bench-scale reverse osmosis systems are alreadyassembled and require very little maintenance and upkeep. A benefit of upkeep of the small system is each stage can be bought separately if a membrane is fouled. Keeping it at a constant temperature is easier in a location already temperature controlled. Since it is a smaller unit though in comparison to industrialized units, its output is significantly smaller.

In this project, experiments were performed with a bench-scale reverse osmosis unit. The unit was available at a relatively inexpensive cost, and was easily manipulated to evaluate critical variables involved in desalination. The unit purchased was an Aquatic Life RO Buddie. It is a three-stage system that can produce 100 gallons of freshwater per day. It comes equipped with a carbon, sediment, and reverse osmosis membrane. It does not include a pump because the water system in a house is already pressurized enough to flow through the tubes. The water supply connects the sediment cartridge first, then is directed to the carbon cartridge, and finally runs through the reverse osmosis membrane. The reverse osmosis membrane is a thin-film composite membrane (TFC). TFC membranes tend to consist of a non-selective macro-porous layer that is thick and porous which supports an ultra-thin selective layer. Sub-nanometer pores between the polymer matrix's molecular chains allows for permeation across the membrane. This type of membrane has been picking up popularity for use in bench-scale reverse osmosis units (He et al., 2015). The reverse osmosis membrane has two outputs: a waste (or brine) tube and a fresh filtered water tube. This unit is 7.25 x 4 x 13.75 inches.

Table 9. *Aquatic Life RO Buddie Temperature and Pressure Corrections*, adapted from (*RO Buddie® Installation & Maintenance Guide*, n.d.)

Temperature (Celsius)	**Correction Factor**	**Pressure (psi)**	**Correction Factor**
10	0.58	10	0.17
16	0.73	20	0.33
21	0.87	30	0.50
25	1.00	40	0.67
27	1.06	50	0.83
32	1.23	60	1.00
38	1.45	70	1.17
-	-	80	1.33

The recommended temperature range for this unit is 39 to 100℉ and the recommended pressure range is 35 psi to 80 psi. The optimal temperature and pressure for the unit where the full potential of the unit is achieved at 100 gallons per day are 25 ℃ and 65 psi, respectively. Using a temperature other than 25℃ is said to adversely affect the effectiveness of the membrane's filtration and can accelerate its degradation. The specifications of the system also indicate that water hardness exceeding 170 ppm can shorten the life of the membrane. At optimal conditions, the membrane is expected to last two years, remove up to 95% of the TDS from water, and produce one gallon of freshwater for every 4.5 gallons passed through the membrane (3.5 gallons rejected). In Table 9 above are the expected temperature and pressure correction factors for this specific membrane's performance in the case that there is deviation from the optimal temperature and pressure. Clearly, higher temperatures and pressures can increase the production of the unit, while lower temperatures and pressure decrease the production of the unit. In fact, the specifications indicate that water temperatures over 100℉ and TDS over 1,800 ppm cannot be handled by the membrane.

2.5 Hypotheses

Based on existing literature addressing the effects of temperature, salinity, andparticle size on reverse osmosis membranes, several hypotheses have been developed for this project. The following relationships are expected to develop as research is conducted:

1. Higher temperatures at a constant pressure will result in higher salinity in the permeate and a lower recovery rate.
2. Higher feed pressure will increase freshwater production, have a higher recovery rate, and increase salt rejection in the permeate.

3. Higher salinity will decrease freshwater production by decreasing the flow rate of the permeate and will result in higher salinity concentration in the permeate.
4. Higher concentrations of TiO_2 particles will cause membrane fouling, higher salinity in the permeate, and will decrease freshwater production.
5. Membrane fouling will decrease the quality of freshwater produced (will increase salinity in permeate). An increase in differential pressure over time will indicate membrane fouling.

2.6 Project Objectives

The following objectives were addressed with this project:

1. Evaluate how increases in salinity, temperature, and titanium dioxide (TiO_2) affect fouling of the reverse osmosis membrane
2. Determine the effect of increases in salinity, temperature, and TiO_2 concentration on permeate production of the reverse osmosis membrane
3. Measure membrane salt rejection changes due to increases in salinity, temperature, and TiO_2 concentration
4. Evaluate how increases in salinity, temperature, and TiO_2 affect temperature change from the feedwater to the brine and permeate
5. Discuss the implications of the results on large industrial scale reverse osmosis plants

3.0 Design of Apparatus

To conduct trials, a bench-scale reverse osmosis membrane system was purchased: the Aquatic Life RO Buddie. To properly test the reverse osmosis membrane, it needed to be isolated; the carbon and sediment filters were removed so that the membrane could be challenged with the changing conditions without the prefilters. The three-stage system now became a one-stage system, allowing the feedwater to only pass through the reverse osmosis membrane. The water flowed through polyethylene tubing provided with the system. The polyethylene tubing has an outer diameter of ¼” and an inner diameter of 0.142”. It is rated for 120 psi at $70℉$ or 60 psi at $150℉$. The new system had a line entering the reverse osmosis membrane for feedwater and two lines exiting the membrane - one for the freshwater and one for the brine. Because these bench-scale units are generally attached to a wall, a ring stand and two clamps were used to hold the unit and levitate it above the work bench. The reverse osmosis membrane contains a preservative to keep it sterile, therefore, the membrane was flushed while testing its function and setting up the apparatus. All materials used in the apparatus are shown below.

Table 10. *Materials Used In Lab*

Item	**Quantity**
Aquatic Life RO Buddie	2
Everbilt ¾ HP Shallow Well Jet Pump	1
Wrench	1
1 ¼” x 1” PVC reducer	1
1” x ½” PVC reducer	2
John Guest ¼” x ½” NPTF male adapter	2
¼” O.D. 0.142” I.D. polyethylene tubing	1
Ring stand	1
Ring stand clamp	2
1 liter beaker	1
1000 mL graduated cylinder	1
2 L Erlenmeyer Flask	2
DI water	-
Isotemp 110 Fisher Scientific water bath	1
Mettler Toledo analytical balance	1
Extech Instruments RTD Thermometer	3
Orion 150 electrical conductivity probe	1
Magnetic stirring bar retriever	1
Teflon stir bar	1
Husky ¼” brass full port ball valve	3
Husky ¼” brass tee fitting	3
Everbilt 100 psi ¼” connection pressure gauge	3
15 lb Instant Ocean marine aquarium salt	1
Teflon thread sealant tape roll	1

Pantai Chemical USA Inc. Titanium Dioxide PTR-620 0.5 lb	1
John Guest ¼” x ¼” NPTF male to push-to-connect adapter	9
John Guest ¼” x ¼” NPTF female to push-to-connect adapter	3
Everbilt ¼” brass female coupling	3

3.1 Plumbing & Pumping Feedwater

A pump was used to pressurize the water to around 40 and 65 psi. The reverse osmosis system’s optimal feedwater pressure is 65 psi. By keeping the pressure of the system relatively constant throughout all of our trials, it can be decided how much the water is pressurized when being pumped into the membrane and ultimately allow an easier derivation and accurate relationship between the variables and indicators for the membrane’s performance. The pump used was the Everbilt ¾ HP Shallow Well Jet Pump as can be seen in Figure 12. It is originally designed to pump water from a shallow well up to 25’ deep. With a flow rate of about nine gallons per minute and 3/4 HP, the maximum advised pressure of the pump is 65 psi. A pressure switch on the pump prevented the system pressure from exceeding 50 psi, therefore, it had to be modified to exceed 50 psi and reach the desired 65 psi. A wrench was used to turn the nut clockwise until the desired cut off pressure was achieved. An initial challenge in configuring the apparatus was downsizing the inlet and outlet of the pump to the ¼” tubing required to be used with the reverse osmosis membrane. The inlet of the pump is 1 ¼” FNPT and the outlet of the pump is 1” FNPT. PVC reducers of 1 ¼” x 1” and 1” x ½” were used on the inlet along with a John Guest ¼” x ½” NPTF male adapter. A 1” x ½” PVC reducer along with a John Guest ¼” x ½” NPTF male adapter was used for the outlet.

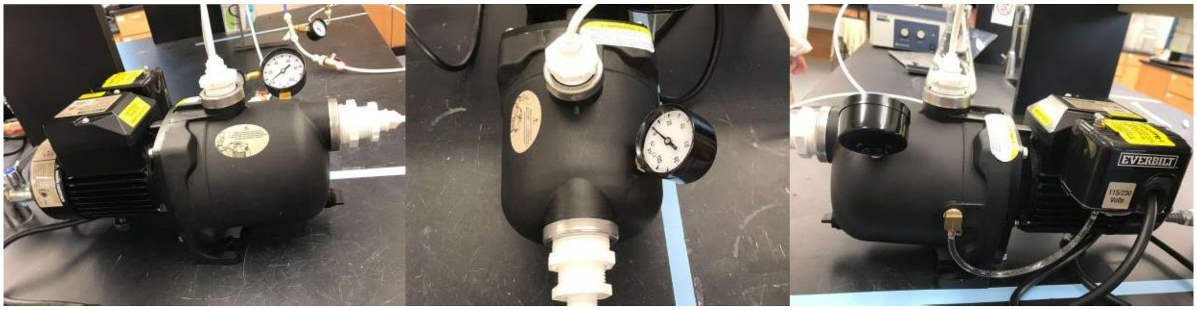

Figure 12. *Everbilt ¾ HP Shallow Well Jet Pump*

A pressure gauge was plumbed into the polyethylene tubing at the feed inlet, permeate outlet, and brine outlet to be able to read the pressures at each location. The pressure gauge being used was the Everbilt ¼” NPT 100 psi pressure gauge. To plumb into the polyethylene tubing, a tee fitting was necessary. The tee fitting used was the Husky ¼” brass tee fitting.

Because the two outlets of the tee fitting are female threaded, a John Guest ¼” x ¼” NPTF male to push-to-connect adapter was attached to each outlet. An Everbilt brass pipe ¼” female coupling was used to connect the male threaded main connection line to the pressure gauge. The male threads of the pressure gauge were wrapped in teflon tape prior to threading into the coupling to prevent leakage. The polyethylene tubing was then inserted into the adapter on each end of the tee fitting. A ball valve was plumbed into the polyethylene tubing at the feed, brine, and permeate to have the control to throttle the flow of water. The ball valve used was the Husky ¼” full port ball valve. Because the ball valve has a female threaded end and a male threaded end, a John Guest ¼” x ¼” NPTF male to push-to-connect adapter was used on the female threaded end and a John Guest ¼” x ¼” NPTF female to push-to-connect adapter was used on the male threaded end. The polyethylene tubing was then inserted into the adapter on each of the ball valves. The ball valves were added to adjust the flow and, consequently, the pressure. During the trials, the ball valve between the pump and the membrane at the feed line was throttled primarily. If this did not slow down the flow and increase the pressure enough, a ball valve between the pump and the membrane was also throttled carefully.

Figure 13. *Bench-Scale Reverse Osmosis Apparatus*

For each trial run, two liters of DI water was fed into the system. At 25°C and 65 psi, the Aquatic Life RO Buddie’s specifications indicate that 4.5 gallons of feedwater shall, ideally, result in 1 gallon of permeate. Therefore, for every two liters of feedwater, 437 mL of permeate should be produced. As the variables are changed, this value was expected to change. Provided that the Aquatic Life RO Buddie is capable of producing 100 gallons per day of freshwater, it should theoretically produce 1 gallon of freshwater in 14 minutes and 24 seconds if pumped in at a rate of 450 GPD. Provided that the pump can pump 9 GPM, throttling the ball valves was imperative to dropping to flow rate and increasing the pressure of the feedwater. The apparatus set up can be seen in Figure 13 above and a diagram of the apparatus can be seen below. In the diagram, the Erlenmeyer flask held the feedwater, the beaker to the left held the brine, and the beaker to the far right held the permeate.

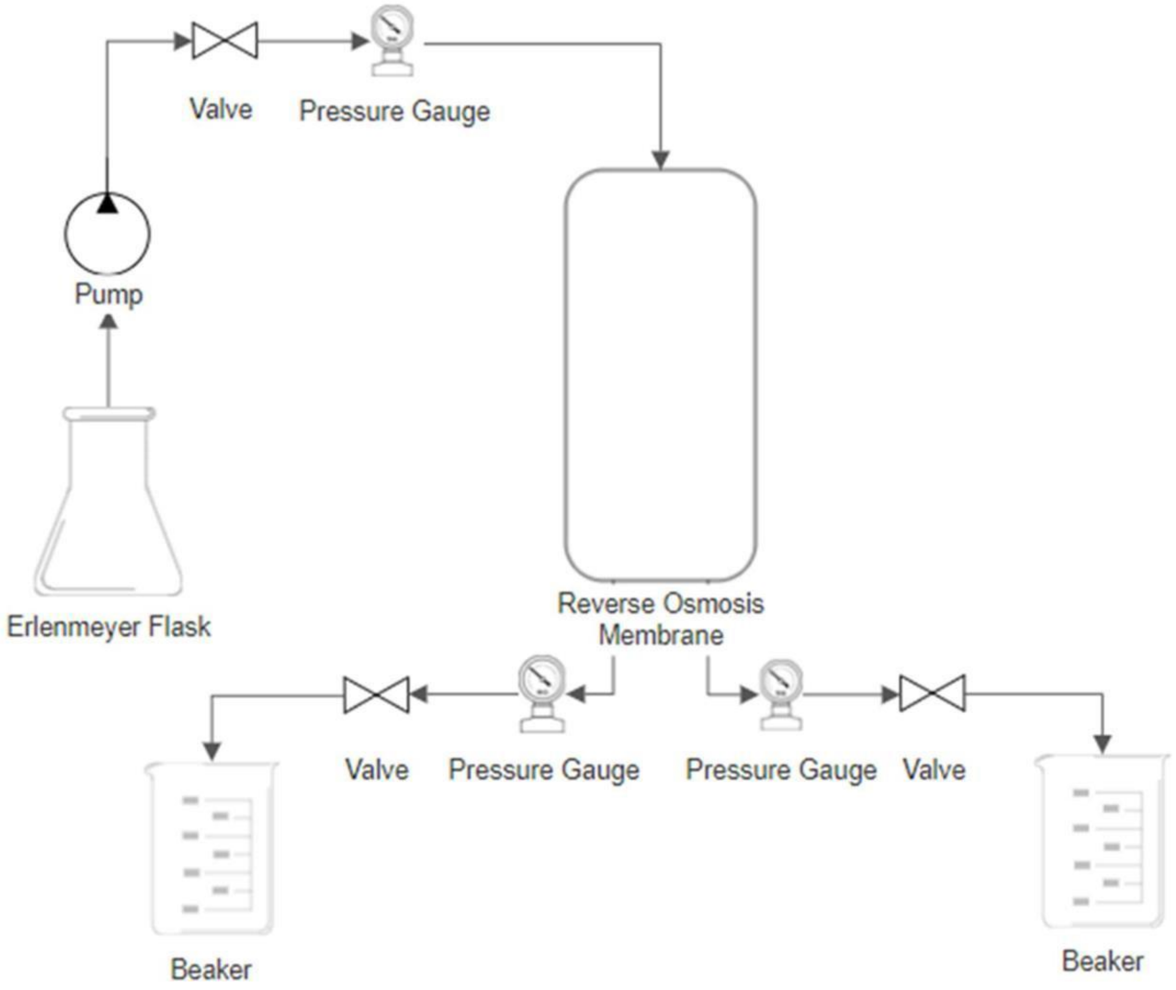

Figure 14. *Bench-Scale Reverse Osmosis System Schematic*

The plastic outer coating of the RO Buddie holds the membrane in place and adds support. The membrane on the inside is composed of multiple layers. The innermost layer looks like a thin netting and acts as the feed channel spacer.. Then, there are two layers of membrane and permeate collection material stuck together that make up a thicker layer. The outermost layer is a plastic outer wrap to keep it all together. These different layers can be seen below.

Figure 15. *Layers of RO Membrane*

4.0 Methodology

The goal of this project was to challenge a bench-scale RO membrane system by increasing salinity, temperature, and titanium dioxide (TiO_2) concentration in the feedwater to observe how it affects the membrane performance. Parameters evaluated in the testing included: membrane salt rejection, permeate production quantities/recovery rate, temperature changes in permeate and brine, and membrane fouling.

Through research on existing related literature and laboratory work, several implications can be made about the reverse osmosis process on a large industrial scale, especially in the United Arab Emirates (UAE) where desalination is a necessary component of their potable water supply. Although thermal desalination has been a primary desalination technology used in the UAE, in the past few years, the implementation of membrane technologies like reverse osmosis have been rapidly expanding as membranes are continuing to be improved to be more efficient and to handle more extreme conditions. Because of the expansion of reverse osmosis desalination and the effects of urbanization and human activities on water quality, it is important to know how changes in salinity, temperature, and TiO_2 presence in seawater feed may affect the membrane process. It is plausible that urbanization and global human activities may cause increases in these three water quality parameters over the next few decades by impacting climate change and increasing sunscreen use. Knowledge of how reverse osmosis membranes operate under extreme conditions is imperative in assuring that plants can serve their populations with potable water. The following sections discuss the methodology for this project.

4.1 Variables

As mentioned previously, the effects of increased salinity concentration, increased temperature, and increased TiO_2 concentration on the reverse osmosis membrane were evaluated at both a low and high pressure.

4.1.1 Salinity

First, the salinity trials were conducted. A set of trials was conducted at a low pressure of approximately 40 psi before a set of trials conducted at a higher pressure of 65 psi. For the low pressure trials, the salinity of feedwater ranged from 250 ppm to 3,000 ppm over twelve trials. For the high pressure trials, the salinity of the feedwater ranged from 500 ppm to 35,000 ppm over eight trials. Trials were run until the reverse osmosis membrane produced enough permeate to measure, which was 30 mL with the EC used in this experiment. Before and after each set of trials, a baseline test was run through the membrane with a salinity of 0 ppm.

For each trial, two liters of DI water was measured using a 1000 mL graduated cylinder and carefully poured into a two liter Erlenmeyer flask. The salinity of the feedwater was altered by adding Instant Ocean sea salt. Instant Ocean sea salt is used in water to simulate the marine environment and is commonly used in aquariums and research facilities. It is made up of over 99% sodium chloride, with less than 1% containing magnesium chloride, sodium sulfate, calcium chloride, and potassium chloride. The salt was weighed on a digital analytical balance and added to the feedwater. The digital analytical balance used was a Mettler Toledo model.

This analytical balance has an accuracy up to 0.0001 g and maximum weight of 120 g. The feedwater was then stirred using a stir bar and a magnetic stirring bar retriever until the particles appeared to be suspended and the mixture appeared to be homogeneous. The temperature for the feedwater for the salinity trials was held constant at room temperature. After the solution was prepared for each trial, the feedwater line was inserted into the Erlenmeyer flask. The pump was started by plugging it into an outlet and timers were started immediately to track the flow of the feedwater, brine, and permeate. This was repeated for solutions of increasing salinity until the reverse osmosis membrane could not produce enough permeate. At the end of each trial, several measurements were taken as discussed in sections 4.2 to 4.4 and all glassware was cleaned for the next trial. After each set of trials, 10 to 15 liters of water was flushed through the membrane.

4.1.2 Temperature

Next, the temperature trials were conducted on a separate reverse osmosis membrane. Trials of increasing temperature were conducted at 20, 25, 30, 35, 40, and 45°C. Before and after each set of trials, a baseline test was run through the membrane with a salinity of 0 ppm. As previously stated, the feedwater was pumped into the system at approximately 40 and 65 psi for the low and high pressure trials, respectively.

For each trial, two liters of DI water was measured using a 1000 mL graduated cylinder and carefully poured into a two liter Erlenmeyer flask. The salinity for the feedwater for the temperature trials was held constant at 1,000 ppm. The Instant Ocean sea salt was weighed on a digital analytical balance and added to the feedwater. The feedwater was then stirred using a stir bar and a magnetic stirring bar retriever until the particles appeared to be suspended and the mixture appeared to be homogeneous. The temperature of the feedwater was altered by placing a 2 liter Erlenmeyer flask of feedwater into the water bath. The water bath used was the Isotemp 110 by Fisher Scientific. Prior to filling the water bath, the filled Erlenmeyer flask was placed in the water bath. The water bath was then filled to approximately 1 to 1.5" from the top. The water bath was then turned on and the temperature of the feedwater was closely monitored using a thermometer. The probe of the thermometer was inserted into the feedwater. The thermometer used was the Extech Instruments RTD Thermometer. After the solution was prepared for each trial, the feedwater line was inserted into the Erlenmeyer flask. The pump was started by plugging it into an outlet and timers were started immediately to track the flow of the feedwater, brine, and permeate. This was repeated for solutions of increasing temperature until 45°C. At the end of each trial, several measurements were taken as discussed in sections 4.2 to 4.4 and all glassware was cleaned for the next trial. After each set of trials, 10 to 15 liters of water was flushed through the membrane.

4.1.3 Titanium Dioxide

In the final sets of trials, TiO_2 increasing in concentration was added to the feedwater. While most small particles are removed from seawater before entering the reverse osmosis membrane to prevent fouling, TiO_2 particles are small enough to surpass most pretreatment processes, enter the membrane, and potentially cause colloidal fouling. TiO_2 particles in the form of a fine powder will be added to the feedwater to mimic nanoparticulate, mineral UV-blockers suspended in seawater. The concentrations of TiO2 ranged between 500 and 2,500 ppm. Before and after each set of trials, a baseline test was run through the membrane with a salinity of 0 ppm. As previously stated, the feedwater was pumped into the system at approximately 40 and 65 psi for the low and high pressure trials, respectively.

For each trial, two liters of DI water was measured using a 1000 mL graduated cylinder and carefully poured into a two liter Erlenmeyer flask. The salinity of the feedwater for the TiO_2 trials was held constant at 1,000 ppm. The temperature of the feedwater for the TiO_2 trials was held constant at room temperature. The TiO_2 and the Instant Ocean sea salt was weighed on a digital analytical balance and added to the feedwater. The feedwater was then stirred using a stir bar and a magnetic stirring bar retriever until the particles appeared to be suspended and the mixture appeared to be homogeneous. After the solution was prepared for each trial, the feedwater line was inserted into the Erlenmeyer flask. The pump was energized and timers were started immediately to track the flow of the feedwater, brine, and permeate. This was repeated for solutions of increasing TiO_2 concentration until 2,500 ppm. At the end of each trial, several measurements were taken as discussed in sections 4.2 to 4.4 and all glassware was cleaned for the next trial. After each set of trials, 10 to 15 liters of water was flushed through themembrane.

4.2 Evaluation of Membrane Fouling

As mentioned in section 3.1, water was supplied through the reverse osmosis membrane with a shallow well jet pump. As mentioned in section 2.3.2, an increase in differential pressure can indicate membrane fouling. To minimize errors in membrane fouling, in between tests for salinity, temperature, and TiO_2 , the membrane was flushed with water. An indication of membrane fouling is the determination of the differential pressure, requiring 1) the feedwater pressure and 2) the permeate pressure. Differential pressure is the difference between two pressures: the feedwater pressure and permeate pressure. The pressure of the brine stream was also observed via a pressure gauge and recorded. Unfortunately, the water coming through the permeate line did not achieve a pressure reading high enough to be detectable by the pressure gauge. Another way to determine membrane fouling is through baseline tests. As previously mentioned, a baseline test was run through the membrane at the start and end of a set of trials. This baseline test had constant temperature and pressure with a feedwater salinity of 0 ppm. Comparing the performance indicators at the baseline start test and baseline end test could indicate the presence of fouling or not.

4.3 Evaluation of Freshwater Production

To quantify the amount of permeate water produced, the volume of the feedwater was first measured and recorded prior to running each trial (approximately 2 liters). A 1000 mL graduated cylinder was filled to a liter and transferred to the 2 liter Erlenmeyer flask. The remaining liter was measured in the same graduated cylinder and transferred to the same 2 liter Erlenmeyer flask. Then, the feedwater was run through the reverse osmosis system. While the water was being pumped out of the feedwater beaker submerged in the water bath, the time for the feedwater to enter the reverse osmosis membrane was recorded to determine the feedwater flow rate. Another timer was started when the permeate began to flow and ended when the ejection of permeate appeared to be complete to determine the flow rate of the permeate. A third timer was started when the brine began to flow and ended when the ejection of the brine appeared to be complete to determine the flow rate of the brine. Once the trial appeared to be complete, all excess water remaining in the tubing was carefully transferred to another beaker so that more accurate feedwater volumes could be obtained. The excess water was then transferred from the beaker to a graduated cylinder to accurately measure the volume.

The recovery rate of the membrane was then calculated provided that the flow rate of the feedwater and the flow rate of the permeate were obtained. As discussed in section 2.3.2, the recovery rate is found by dividing the permeate flow rate by the feedwater flow rate:

$$\frac{Q_{permeate}}{Q_{feed}}$$

The feedwater:permeate ratio was also calculated. The ratio is found by dividing the volume of feedwater that entered the reverse osmosis membrane by the volume of permeate produced. Once the recovery rates were found through division, the recovery rates and feedwater:permeate salinity of salinity, temperature, and TiO_2 were compared in tabular and graphical form.

4.4 Evaluation of Membrane Salt Rejection

After the Instant Ocean sea salt was added to the feedwater, an electrical conductivity meter was used to obtain a reading for the feedwater's electrical conductivity. It was also used after running each trial to measure the electrical conductivity of the permeate and the brine. The conductivity meter used is an Orion 150. When using the unit, it was, first, plugged in and turned on. Then, the probe was inserted into the water set to the appropriate unit and setting. This laboratory work used Siemens/cm, therefore, a conversion was made to TDS ppm. As discussed in 2.1.1a, mS/cm value is generally multiplied by 500 to get a salinity value in units of ppm. The temperature is an important aspect of conductivity. Temperature and conductivity are related. A high temperature may lead the conductivity meter to read an incorrect value. The Orion 150 Conductivity probe also measures the temperature of the water, so the temperature trial conductivity value did not have to be recalculated to accommodate for the change. All other variables changed did not have to be accommodated on the conductivity meter.

As discussed in section 2.3.2, the membrane salt rejection can be found by subtracting the dividend of the concentration of the permeate and the concentration of the feed from 1:

$$(1 - \frac{C_{permeate}}{C_{feed}}) * 100\%$$

Once the membrane salt rejections were found, the membrane salt rejections specific to the variables of salinity, temperature, and TiO_2 were compared in tabular and graphical form.

4.5 Evaluation of Temperature Change

During each trial, a thermometer was used to measure the temperature of the feedwater, brine, and permeate. The thermometer was inserted into the water until the thermometer held a steady value. Each temperature was recorded. The temperature change from the feedwater to the brine and from the feedwater to the permeate was calculated. The temperature changes were calculated by subtracted the brine temperature from the feedwater temperature and subtracting the permeate temperature from the feedwater temperature. Once the temperature changes were found, the temperature changes specific to the variables of salinity, temperature, and TiO_2 were compared in tabular and graphical form.

5.0 Results & Discussion

In the aforementioned methodology section, the laboratory work performed was discussed and described. Based on the experiments conducted, several findings have presented themselves. The observation of freshwater production/recovery rates, membrane salt rejection, and temperature changes has helped develop an understanding of the effect of increasing salinity, temperature, and titanium dioxide (TiO_2) from normal to extreme conditions on reverse osmosis membrane performance. The analysis and comparison of the data collected has allowed for understanding the effects of several variables on membrane performance indicators. The analyses also have provided insight on how the effect on membrane performance indicators can be applicable to industrial scale desalination plants using reverse osmosis technologies. The examination of the findings through the laboratory work of this project have resulted in the determination of multiple mathematical relationships between variables and membrane performance indicators that can possibly be considered by industrial desalination plants to ease the prediction of increasing variables and extreme conditions. In this chapter, the findings pertinent to increasing salinity, temperature, and TiO_2 are presented. Throughout the laboratory work for this project, all measurements were recorded and tabulated and can be found throughout this section and appendices D to G.

5.1 Baseline Testing

The relationship between changing parameters (salinity, temperature, and TiO_2) on membrane performance indicators is essential when trying to predict the maintenance steps required to maintain sufficient desalination plant operations. In the baseline trials (BLL1 to BLL3 and BLH1 to BLH3), all variables were held constant to confirm how the membrane should behave under constant conditions. The relationship between constant variables and the performance indicators of the membrane are imperative to observe when analyzing the effects of changing variables on the membrane’s performance indicators. To evaluate the effects of other variables on the membrane, mathematical relationships need to be developed and compared. If the performance indicators change in the varying salinity, temperature, and TiO_2 trials (compared to the baseline trials), then implications about their effects on membrane performance can be made. If there is no change in the performance indicators, then there is likely no change in the performance of the membrane due to that variable. The raw data can be found in Appendix E. The baseline trials were conducted at a pressure below the optimal operating pressure of the reverse osmosis membrane (40 psi) and at the optimal operating pressure (65 psi). Throughout the trials, all controllable variables were held constant. The controllable variables included the salinity of the feedwater, the temperature of the feedwater, the system pressure of the pump, and the volume of the feedwater. The following section describes the calculations for the data collected for the baseline trials conducted at both the lower pressure of 40 psi and the higher pressure of 65 psi. Four performance indicators are explored: 1) membrane salt rejection, 2) recovery rate, 3) feedwater:permeate volume ratio, and 4) temperature change.

The calculation of membrane salt rejection is dependent on salinity measurements of the feedwater and permeate. The electrical conductivity (EC) of the feedwater, brine, and permeate waters were measured with an EC probe/meter. Electrical conductivity can be converted to a salinity TDS measurement in parts per million. The TDS was calculated on a parts per million 500 scale as it is commonly used in the United States. The membrane salt rejection was calculated by subtracting the dividend of the concentration of the permeate and the concentration of the feed from 1. The intended salinity for the feedwater was 1,000 ppm. The feedwater salinity was closer to 1,500 ppm and remained constant along with all other variables throughout the three trials at low pressure. The results of these calculations can be seen in Appendix E.

Over the three trials conducted at both low and high pressure, the quality of the permeate water slightly changed. The salinity of the permeate and the brine water increased throughout the trials. The membrane salt rejection was greater during the high pressure trials than during the low pressure trials. The degradation in permeate water quality was unexpected. It was expected that the permeate salinity would be constant provided that the feedwater salinity was constant. The water quality impairment indicates that the permeate water quality may not be affected not only by the salinity of the feedwater, but rather by the amount of the salt that the membrane has been exposed to. After trial BLL1, the membrane had been exposed to 2 grams of salt. After trial BLL2, the membrane had been exposed to 4 grams of salt. After trial BLL3, the membrane had been exposed to 6 grams of salt in total. Therefore, the baseline trials may indicate an increase in salinity (or other variables) in feedwater will likely expedite poor performance ofthe membrane in regard to permeate water quality.

The flow rate for the feedwater, brine, and permeate were calculated along with the recovery rate. As mentioned in the methodology section, the time elapsed in which water was flowing and the volume was recorded for each of the flows. Therefore, the flow rate for the feedwater, brine, and permeate was calculated by simply converting the mL volume to L and dividing it by the time elapsed in minutes. The results of these calculations can be seen in Appendix E. The pressure was held constant throughout the trials. The flow rate for the feedwater, brine, and permeate throughout both the low and high pressure trials was relatively constant as well as there is little variation from one trial to the next. The recovery rate was calculated by dividing the permeate flow rate by the feedwater flow rate. The recovery rate was greater during the high pressure trials than during the low pressure trials.

The feedwater:permeate ratio describes the efficiency of the membrane as it determines how many milliliters of feedwater are needed to produce one milliliter of permeate. The feedwater:permeate ratio was calculated by dividing the feedwater used by the permeate produced in each trial. The results of the calculations can be seen in Appendix E. Throughout both the low and high pressure baseline trials, the feedwater:permeate ratio was also relatively constant. There was little variation in permeate produced from one trial to the next. The feedwater:permeate ratio was greater during the low pressure trials than during the high pressure trials, meaning that more feedwater was required to produce 1 mL of permeate. Although the reverse osmosis membrane apparatus was significantly smaller than community-scale reverse osmosis plants, the equation can be used to predict the effects of constant conditions on the feedwater to permeate ratio.

The temperature change from the feedwater to the brine and permeate was calculated. To calculate the brine temperature change, the temperature of the feedwater was subtracted from the temperature of the brine. Similarly, to calculate the permeate temperature change, the temperature of the feedwater was subtracted from the temperature of the permeate. The results of these calculations can be seen in Appendix E. The permeate and brine temperature change was relatively constant throughout both the low and high pressure trials. The temperature change was greater during the high pressure trials than during the low pressure trials. The temperature change of the brine is important to discuss because, in an industrial setting, the brine is going to be discharged back into the ocean. If the temperature of the brine is different from the surrounding seawater, it may have an effect on the marine environment. The polynomial equation for the permeate and brine temperature change could be used to predict how the temperature of the permeate and brine may change with constant conditions.

5.2 Increasing Salinity Trials

One of the variables that were explored throughout the project was salinity. The effects of increasing feedwater salinity on reverse osmosis membrane performance indicators were specifically developed. On a bench-scale system, feedwater with increasing salinity was pumped through a reverse osmosis membrane at a low pressure and a high pressure. The relationship between increasing salinity and membrane performance indicators are essential when trying to predict the maintenance steps required to maintain sufficient desalination plant operation conditions. In the salinity trials (SL1 to SL12 and SH1 to SH8), the salinity of the feedwater was increased from low salinity to extreme salinity, challenging the membrane until no permeate was produced. A large range of salinity values to extremes provided data necessary to make predictions if the salinity of seawater used for desalination were to increase drastically and to collect data points to develop a mathematical relationship between increasing salinity and membrane performance indicators. The raw data can be found in Appendix B. As mentioned in the methodology, the effects of increasing salinity on the reverse osmosis process were explored. Trials were conducted at a pressure below the optimal operating pressure of the reverse osmosis membrane (40 psi) and at the optimal operating pressure (65 psi). Several measurements were recorded throughout the trials and several calculations followed to determine the reverse osmosis membrane’s performance indicators: membrane salt rejection, recovery rate and feedwater:permeate ratio, temperature change, and membrane fouling via baseline tests. Throughout the trials, all controllable variables were held constant as the salinity of the feedwater was increased. The following section describes the calculations for the data collected for the salinity trials conducted at the lower pressure of 40 psi and the higher pressure of 65 psi and discusses how the data collected throughout the laboratory work compares to existing literature and what the data may imply about the effects of increasing salinity in seawater on industrial size desalination plants.

5.2.1 Membrane Salt Rejection

From the data collected in the laboratory work, the membrane salt rejection for the high and low pressure trials was calculated and graphed as seen below in Figure 16. All calculations can be found in Appendix B. Generally, as the salinity of the feedwater was increased, the salinity of the permeate and the brine increased affecting the membrane salt rejection. The reverse osmosis membrane's ability to reject salt decreased throughout both the low and pressure trials. Ultimately, the quality of the permeate water drastically decreased. Considering that water is palatable only until 1,000 ppm, the low pressure trials exceeded palatability at its maximum of SL11 with a feedwater salinity of 3,580 ppm. The high pressure trials exceeded palatability much sooner at SH4 but at a much higher feedwater salinity of 11,750 ppm.

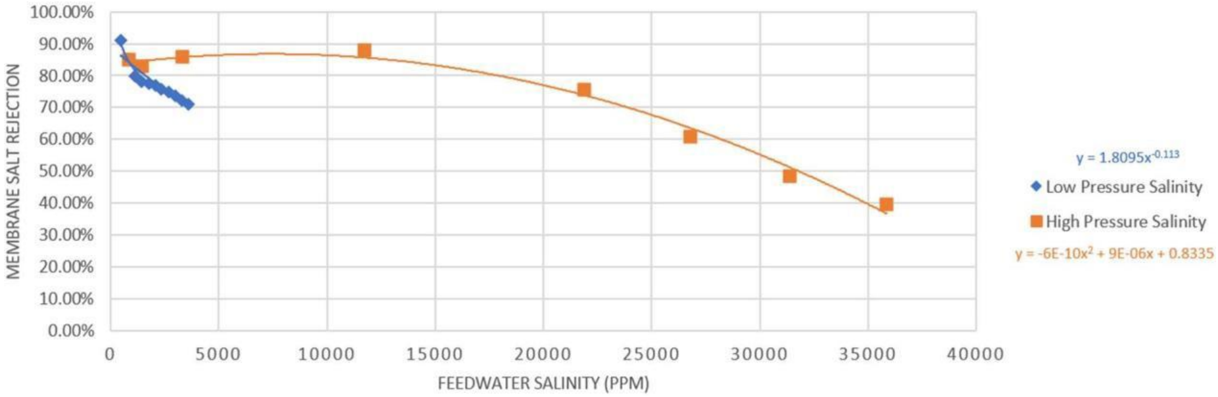

Figure 16. *Membrane Salt Rejection vs. Feedwater Salinity (T = 25℃, P = 40, 65 psi, V = 2 L)*

During trial SL12 of the low pressure trials, at 3,915 ppm salinity, the membrane could not produce enough permeate to measure its electrical conductivity. During trial SH8 of the high pressure trials, At 35,850 ppm salinity (SH8), the membrane produced just enough permeate to measure its electrical conductivity. Another trial would result in not enough permeate. All of these trials were conducted on a bench-scale level. Therefore, it was expected that the reverse osmosis membrane would not perform well at high salinities. The operating pressure of the pump can affect the performance of the reverse osmosis membrane. The reverse osmosis membrane during the high pressure trials performed significantly better, surviving salinities almost ten times greater than the salinities of the low pressure trials and reaching the low pressure's minimum membrane salt rejection at a greater salinity.

Throughout the salinity trials, the electrical conductivity of the feedwater, brine, and permeate were measured and recorded. The data collected during the trials allowed the development of a mathematical relationship between increasing feedwater salinity and the resulting brine and permeate salinites. At low pressure, the mathematical relationship exhibited between the feedwater salinity and membrane salt rejection was represented by a power function of $y = 1.8095x^{-0.113}$. At a high pressure, the mathematical relationship was represented $y = -0.0000000006x^2 + 0.000009x + 0.8335$. The mathematical relationships developed between increasing feedwater salinity and membrane salt rejection can be used to predict how membrane salt rejection would be affected by feedwater of even higher salinities. Membrane salt rejection is a main indicator of membrane performance. Therefore, the results of the calculations can be compared to determine the effect of higher pressure on membrane salt rejection and can also be compared against existing literature to determine if the results of the lab work confirm or deny reverse osmosis performance theory. Although the existing literature on evaluating the effects of increasing salinity on reverse osmosis membrane performance indicators is limited, membrane salt rejection is the most widely discussed performance indicator.

Generally, it is expected that the membrane salt rejection will increase until a maximum value of rejection at approximately 300 to 500 ppm. Past the value of maximum, it is expected that increases in feed concentration will then cause the salt rejection to decrease. In the low pressure trials, this is confirmed from the baseline start trial to SL2. The baseline start trial at a feedwater salinity of 131 ppm had a 86.95% membrane salt rejection. SL1 at a feedwater salinity of 468.5 ppm had a 91.04% membrane salt rejection and SL2 at a feedwater salinity of 805.5 ppm exceeding 500 ppm had a 85.23% membrane salt rejection. A similar trend occurred in the high pressure trials from the baseline start trial to SH5, although with a greater maximum before rejection decline. The baseline start trial at a feedwater salinity of 157.5 ppm had a 80.92% membrane salt rejection. SH4 at a feedwater salinity of 11,750 ppm had a 87.91% membrane salt rejection and SH5 at a feedwater salinity 21,900 ppm had a 75.57% membrane salt rejection.

Abdulmuttaleb et al. found that salt rejection decreased from 88% to 65% when running a feed concentration of 5,000 and 35,000 ppm of Na_2CO_3 at 1 bar (~14.5 psi) through a reverse osmosis membrane. As discussed in the background section, assumption of a linear relationship of the data from this study would produced a linear equation of $y = -0.00076667x + 91.833$. However, it is important to note that a different mathematical function may better represent the data presented in this study like a polynomial function. The results of the study can be compared to the results of the work of this project. The low and high pressure equations describing the membrane salt rejection in terms of feedwater salinity can be used to calculate the membrane salt rejection at extreme salinities. The equation derived from the data from Abdulmuttaleb et al. can be used to calculate membrane salt rejection at the same feedwater salinities.

Table 11. *Comparing Lab Work with Existing Literature on Membrane Salt Rejection*

Feedwater Salinity (ppm)	SL Salt Rejection	SH Salt Rejection	Abdulmattaleb et al. Salt Rejection
35,000	55.47	41.35	64.99
45,000	53.92	2.35	57.33
55,000	52.71	-48.65	49.67
65,000	51.72	-111.65	41.99
75,000	50.90	-186.65	34.33

Based on Table 10. above comparing the laboratory work done in this project with the results of Abdulmuttaleb et al., it is clear that there is a significant difference. Provided that the membrane used by Abdulmuttaleb et al. was comparable to the membrane used in this project, the difference in the results is surprising and unexpected. The salt rejection from 35,000 to 75,000 ppm drops 4.57% based on the low pressure salinity model developed. The salt rejection drops 228% based on the high pressure salinity model developed. The decrease in the salt rejection is 30.66% for Abdulmuttaleb et al. The difference in the results may lie in the methodologies used with the possibility of flushing and cleaning the reverse osmosis membrane between each trial of increasing salinity or using a different salt composition.

As previously mentioned in the background chapter, Takeuchi et al. evaluated a relationship between salt rejection and pressure and found that when pressure increased, so did the salt rejection. Specifically, Takeuchi et al. found that when the pressure first increased by only 0.2 MPa, the salt rejection jumped up almost 1% whereas in the final 0.2 MPa increase, salt rejection only increased by 0.1%. Comparing the salt rejection of the low pressure and high pressure models developed, it appears that as the pressure is increased from 40 to 65 psi, the salt rejection significantly decreases at projected high salinities of 35,000 to 75,000 ppm. At the salinities tested in the laboratory work, the reverse osmosis membrane was able to sustain the same membrane salt rejection at low pressure and salinity as high pressure and higher salinities. The minimum low pressure membrane salt rejection was 70.87% at 3,580 ppm. Using the mathematical model for high pressure membrane salt rejection, at high pressure, the reverse osmosis membrane would reach the same membrane salt rejection of 70.87% at 23,755 ppm. The fact that the results from this project's laboratory work do not support the findings of Takeuchi et al. and Abdulmuttaleb et al. at high salinities brings into question the validity of using these mathematical models to make predictions about reverse osmosis performance at extreme salinity levels. Flushing and cleaning the membrane may be essential in developing a perfect, ideal model of increasing salinity. The laboratory work performed in this project can be discussed via a different approach. The membrane salt rejection can be discussed based on the amount of salt that the membrane has been exposed to.

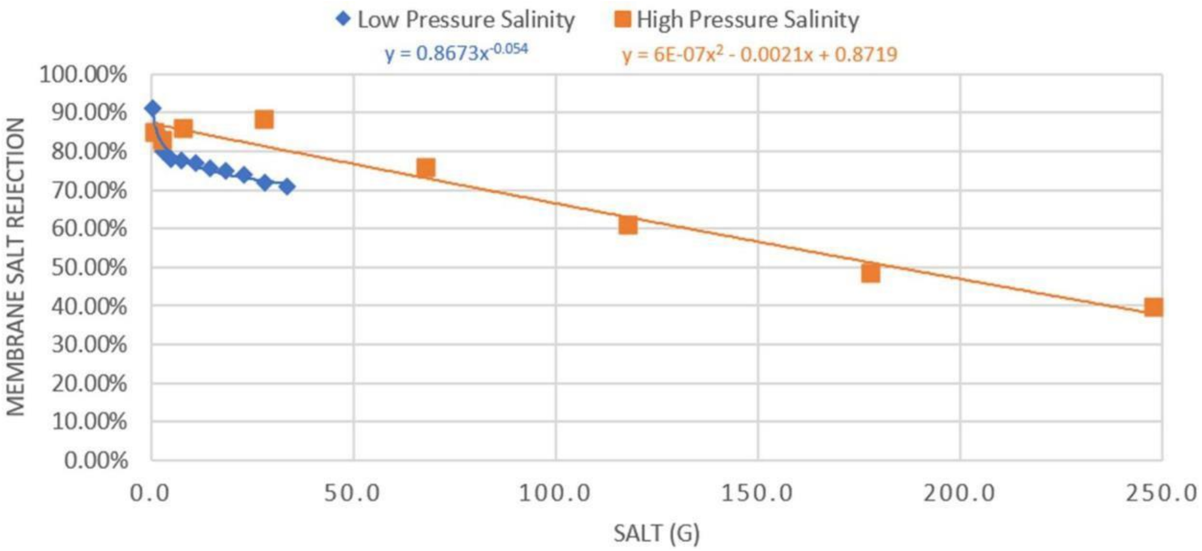

Figure 17. *Membrane Salt Rejection vs. Salt Exposure (T = 25℃, P = 40, 65 psi)*

Over the range of salinity trials, the salinity of the feedwater was increased in uneven increments. Based on the baseline trials that indicate that constant salinity still results in decreased permeate quality (increased salinity overtime), it is likely that a better measure of salinity is the amount of salt that is passed through the reverse osmosis membrane. Assuming that 1 L of water is passed through the reverse osmosis membrane at 35,000 ppm, it will be exposed to 35 g of salt. Such an assumption can be used to make predictions on the membrane salt rejection at high salinities based on salt exposure in grams. At low pressure, the mathematical relationship exhibited between the feedwater salinity and membrane salt rejection was represented by a power function. At a high pressure, the mathematical relationship was represented by a polynomial function.

Table 12. *Comparing Membrane Salt Rejection based on Feedwater Salinity & Salt Exposure*

Feedwater Salinity (ppm, g)	SL Salt Rejection	SH Salt Rejection	SL Salt Rejection based on Salt Exposure	SH Salt Rejection based on Salt Exposure
35,000, 35	55.47	41.35	71.58	79.91
45,000, 45	53.92	2.35	70.61	77.86
55,000, 55	52.71	-48.65	69.85	75.82
65,000, 65	51.72	-111.65	69.22	73.79
75,000, 75	50.90	-186.65	68.69	71.78

Evaluating the membrane salt rejection via salt exposure produces more realistic results provided that the membrane salt rejection for the high pressure salinity trials is greater than the low pressure trials. The high pressure membrane salt rejection also decreases less than when measured via feedwater salinity. The salt rejection from 35,000 to 75,000 ppm drops 2.89% based on the low pressure salinity model developed. The salt rejection drops 8.13% based on the high pressure salinity model developed. The data does confirm that as the salinity of the feedwater increases, the membrane salt rejection rate decreases.

5.2.2 Recovery Rate & Feedwater:Permeate

From the data collected in the laboratory work, the recovery rate and feedwater:permeate ratio was calculated for each of the salinity trials. The data collected during the trials allowed the development of mathematical relationships between feedwater salinity and the recovery rate and feedwater:permeate ratio. The polynomial functions representing the recovery rate and feedwater:permeate ratio can be found in Figures 18 and 19 below. Recovery rate is an important indicator of membrane performance. Therefore, the results of the calculations can be compared to determine the effect of higher pressure on recovery rate and can also be compared against existing literature on recovery rate to determine if the results of the lab work support or deny reverse osmosis performance theory. Although, it is important to note that existing literature on the effects of increasing salinity on recovery rate or feedwater:permeate ratio is limited. The feedwater:permeate ratio was also calculated as it describes the efficiency of the membrane in terms of how many milliliters of feedwater are needed to produce one milliliter of permeate.

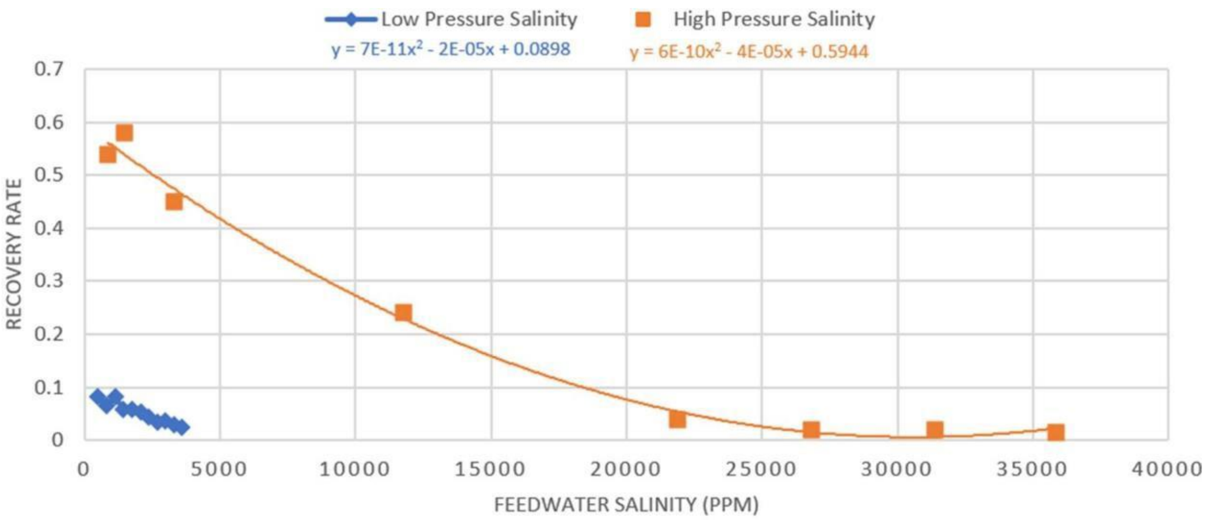

Figure 18. *Recovery Rate vs. Feedwater Salinity (T = 25℃, P = 40, 65 psi, V = 2 L)*

The recovery rate was calculated by dividing the permeate flow rate by the feedwater flow rate. As discussed in section 2.3.2g.1, the recovery rate typically varies from 35% to 85%. Although, this value is highly dependent on the composition of the feedwater, especially the salinity and pretreatment. A higher recovery rate can indicate that the permeate is less concentrated. In Figure 18 above, the trendlines confirm this hypothesis. Throughout the trials, lower feedwater salinity resulted in higher recovery rates. Based on the results of the membrane salt rejection, it is obvious that the higher recovery rates are also associated with lower concentration in the permeate. Higher recovery rates can also be the result of higher feed pressures. Figure 18 also confirms this as the recovery rates in the high pressure trials was significantly greater than the low pressure trials. The results of the recovery rate graphed against the membrane salt exposure was not significantly different from the results of the recovery rate graphed against the increasing feedwater salinity. The brine and feedwater flow rates were relatively constant throughout the salinity trials. The permeate flow rate decreased slightly with increasing salinity, ultimately affecting the recovery rate results.

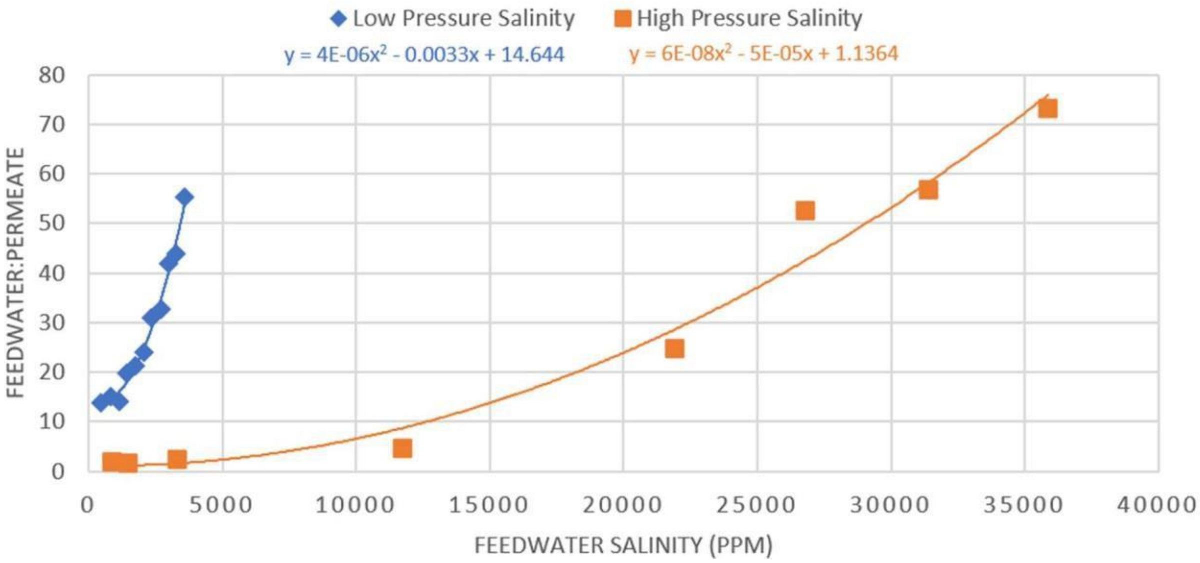

Figure 19. *Feedwater:Permeate Ratio vs. Feedwater Salinity (T = 25℃, P = 40, 65 psi, V = 2 L)*

The feedwater:permeate ratio increased over the salinity trials as the salinity of the feedwater was increased. As the salinity increased, there was less permeate produced for every milliliter of feedwater that was run through the reverse osmosis membrane. The feedwater:permeate ratio was graphed against the feedwater salinity as seen in Figure 17 above. In other words, the reverse osmosis membrane required more feedwater at higher salinities to produce the same amount of permeate produced at feedwaters with lower salinities. The results of the feedwater:permeate ratio graphed against the membrane salt exposure was not significantly different from the results of the feedwater:permeate ratio graphed against the increasing feedwater salinity.

5.2.3 Increasing Temperature Change

The temperature for the feedwater, brine, and permeate was measured and recorded for each of the salinity trials performed. The temperature difference between the brine or permeate with the feedwater was then calculated. The data collected during the trials allowed the development of a mathematical relationship between increasing feedwater salinity and the temperature changes experienced by the brine and permeate produced, as seen in the polynomial functions in Figure 20 below. The mathematical relationships developed can be used to calculate temperature changes in the brine and permeate due to increasing feedwater salinity. Existing literature on reverse osmosis membrane discharge temperature change is limited. However, it is important to discuss the implications of the data collected in this laboratory work because it may indicate some effect on seawater and the marine environment.

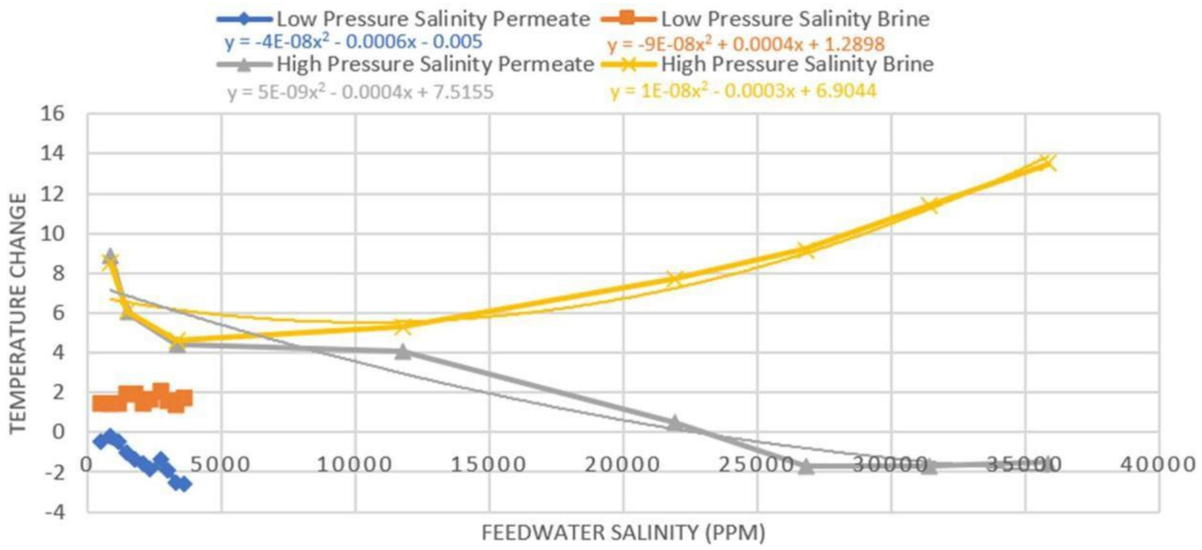

Figure 20. *Temperature Change vs. Feedwater Salinity (T = 25℃, P = 40, 65 psi, V = 2 L)*

The temperature change from the feedwater to the brine and permeate was calculated. To calculate the brine temperature change, the temperature of the feedwater was subtracted from the temperature of the brine. Similarly, to calculate the permeate temperature change, the temperature of the feedwater was subtracted from the temperature of the permeate. The results of these calculations can be seen in Appendix B. Throughout the low pressure salinity trials, the brine temperature change remained relatively constant as the salinity of the feedwater was increased. The permeate temperature change decreased as the salinity of the feedwater was increased. Throughout the high pressure salinity trials, the brine temperature change primarily increased as the salinity of the feedwater was increased, while the permeate temperature change decreased.

Table 13. *Brine Temperature Change Predictions, High Pressure*

Salinity (ppm)	High Pressure Brine Temperature Change
35,000	8.65
45,000	13.65
55,000	20.65
65,000	29.65
75,000	40.65

The temperature change of the brine is especially important to discuss because, in an industrial setting, the brine is going to be discharged back into the ocean. If the temperature of the brine is different from the surrounding seawater, it may have an effect on the marine environment. The polynomial functions in Figure 18 can be used to predict the brine temperature change at high pressure. The results of the calculations are located in Table 12 above. It is evident that as the salinity of the feedwater increases, the temperature of the brine will be affected. The temperature of the brine will increase and will likely be released back into the ocean at this higher temperature. Not only will brine be at a higher temperature, but it will, knowingly, be at a higher salinity than the seawater as well. Such a discrepancy can disrupt the marine environment and may create anoxic zones. The brine being released into the ocean may also eventually adversely affect the reverse osmosis system operation conditions if the seawater entering the system is higher concentrated and warmer. As desalination continues to support human life, it may be at the cost of destroying marine life.

To evaluate the possibility of membrane fouling, a baseline test was run at the beginning and end of each set of the trials. A baseline test consists of running pure water through the reverse osmosis membrane. The indicators of reverse osmosis membrane performance were measured for the baseline start and end trials as they were for all other trials. A degradation in any of the performance indicators would indicate that the membrane had experienced some degree of membrane fouling. Therefore, the membrane salt rejection, recovery rate, and feedwater:permeate ratio are critical in evaluating the membrane fouling.

For the low pressure salinity trials, the baseline start membrane salt rejection was 86.95% and the baseline end membrane salt rejection was -710.90%. The baseline start feedwater had a salinity of 131 ppm and a permeate salinity of 17.1 ppm. The baseline end feedwater had a salinity of 156 ppm and a permeate salinity of 1,265 ppm. Clearly, throughout the low pressure trials, the reverse osmosis membrane’s ability to reject salt drastically decreased. The recovery rate for the baseline start was 0.087 and the recovery rate for the baseline end was 0.035. While the feedwater flow rate was relatively constant throughout the trials, the permeate flow rate drastically decreased affecting the recovery rate of the baseline end. The feedwater:permeate ratio increased from 14.05 at the baseline start to 37.08 at the baseline end.

For the high pressure salinity trials, the baseline start membrane salt rejection was 80.92% and the baseline end membrane salt rejection was -11,169.8%. The baseline start feedwater had a salinity of 157.5 ppm and a permeate salinity of 30.05 ppm. The baseline end feedwater had a salinity of 157.5 ppm and a permeate salinity of 17,750 ppm. Clearly, throughout the high pressure trials, the reverse osmosis membrane’s ability to reject salt drastically decreased, even more than the low pressure trials. The recovery rate for the baseline start was 0.69 and the recovery rate for the baseline end was 0.071. In this case, both the feedwater and the permeate flow rates drastically decreased affecting the recovery rate of the baseline end. The feedwater:permeate ratio increased from 1.49 at the baseline start to 16.35 at the baseline end. During the high pressure trials, the reverse osmosis membrane had the ability to be exposed to much higher feedwater salinities. Compared to the largest salinity tested in the low pressure trials (3,915 ppm), SH3 falls closest to this salinity at 3,315 ppm. SH3 had a recovery rate of 0.45 and membrane salt rejection of 85.67%. If a baseline test was run after

SH3, it would not exhibit the degree of detriment that the low pressure trials have. Therefore, this data is also an indicator that the increase in pressure helped the performance of the membrane.

Ultimately, the drastic changes in all of the performance indicators indicate that an increase in salinity can negatively impact the performance of the membrane by creating colloidal fouling. It is likely that the amount of salt the membrane was exposed was past its operational capacity for quality permeate water.

5.2.4 Membrane

As mentioned in section 4.1.2, a membrane was used for salinity and a separate membrane was used for temperature and TiO_2. The two membranes were taken apart after running trials and the only difference was visible on the top. As can be seen in Figure 16, there are blue dots on top of the permeate collection material. These dots were not found on the temperature and TiO_2 membrane.

Figure 21: *Visible salt on top of Salinity RO Membrane*

5.3 Increasing Temperature Trials

Another variable that was explored in this project was influent temperature. The effects of increasing feedwater temperature on reverse osmosis membrane performance indicators were specifically developed. On this bench-scale system, feedwater with increasing temperature was pumped through a reverse osmosis membrane at a low pressure and a high pressure. The relationship between increasing temperature and membrane performance indicators are essential when trying to predict the maintenance steps required to maintain sufficient desalination plant operation conditions. In the temperature trials (TL1 to TL6 and TH1 to TH6), the temperature of the feedwater was increased from low to high temperature, challenging the membrane. A large range of temperature values provided data necessary to make predictions if the temperature of seawater used for desalination were to increase drastically and to collect data points to develop a mathematical relationship between increasing temperature and membrane performance indicators. The raw data can be found in Appendix C. As mentioned in the methodology, the effects of increasing temperature on the reverse osmosis process were explored. Trials were conducted at a pressure below the optimal operating pressure of the reverse osmosis membrane (40 psi) and at the optimal operating pressure (65 psi). Several measurements were recorded throughout the trials and several calculations followed to determine the reverse osmosis membrane’s performance indicators: membrane salt rejection, flow rate and feedwater:permeate ratio, temperature change, and membrane fouling via baseline tests. Throughout the trials, all controllable variables were held constant as the temperature of the feedwater was increased. The following section describes the calculations for the data collected for the temperature trials conducted at the lower pressure of 40 psi and the higher pressure of 65 psi and discusses how the data collected throughout the laboratory work compares to existing literature and what the data may imply about the effects of increasing temperature in seawater on large size desalination plants.

5.3.1 Membrane Salt Rejection

From the data collected in the laboratory work, the membrane salt rejection for the high and low pressure trials was calculated and graphed as seen below in Figure 22. The feedwater salinity was held constant at 1,000 ppm. The membrane salt rejection percentage was calculated as indicated in section 2.3.2: by subtracting the dividend of the concentration of the permeateand the concentration of the feed from 1, then multiplying by 100%. The salt rejection at low pressure and high pressure acted very similarly. As the temperature increased over the trials, the membrane salt rejection slightly decreased, following a polynomial function for the low pressure trials and a logarithmic function for the high pressure trials.

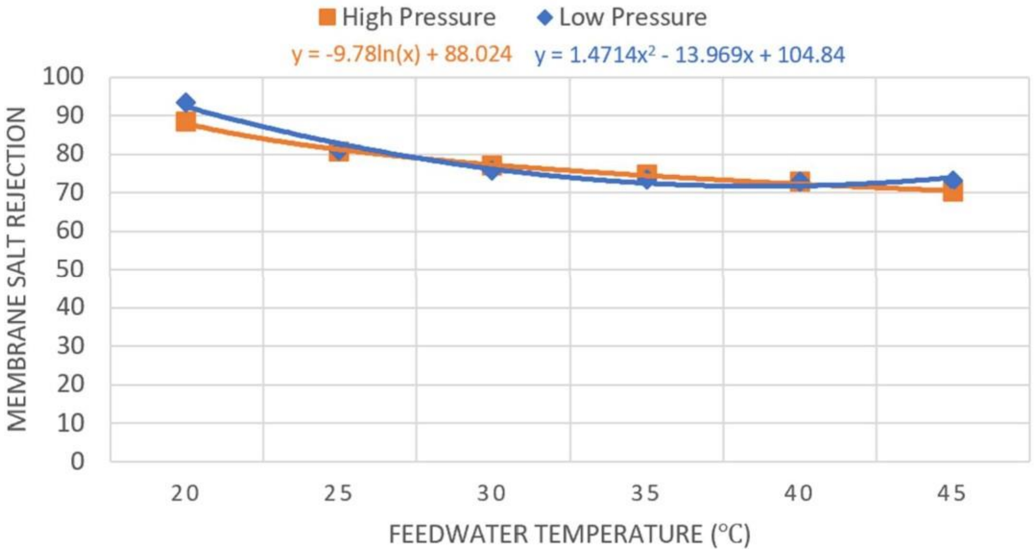

Figure 22. *Membrane Salt Rejection Percentage vs. Salt Exposure (S = 1,000 ppm, P = 40, 65 psi, V = 2 L)*

The reverse osmosis membrane performed well in all of increasing the temperature trials. The operating pressure of the pump did not affect the performance of the reverse osmosis membrane. The mathematical relationships developed between increasing feedwater temperature and membrane salt rejection can be used to predict how membrane salt rejection would be affected by feedwater of even higher temperatures. The results of the calculations can be compared against existing literature to determine if the results of the lab work confirm ordeny reverse osmosis performance theory. Although the existing literature evaluating the effects of increasing temperature on reverse osmosis membrane performance indicators is limited, it is still important to discuss its implications.

Abulmuttaleb et al. explored the effects of increasing temperature (25 to 45℃) on membrane salt rejection at a pressure of 1 bar. At 25℃, the membrane salt rejection was approximately 82%, while at 45℃ the membrane salt rejection was around 60%. Abdulmuttleb et al. also evaluated membrane salt rejection at a variable pressure (1 bar to 5 bar) with constant salinity and temperature. They found that the membrane salt rejection increased with pressure from 82% to 94%. This project work explored variable pressures of much less discrepancy and found that the membrane salt rejection was very similar despite the difference in pressure. At 25℃, the membrane salt rejection ranged from 88.4% to 93.5%. At 45℃, the membrane salt rejection ranged from 70.2% to 73.1%. The results of the temperature trials confirm reverse osmosis theory. It is expected that as the temperature of the feedwater increases, the permeate salinity also increases, meaning that an increase in salt passage or a decrease in membrane salt rejection will be observed.

5.3.2 Recovery Rate & Feedwater:Permeate

From the data collected in the laboratory work, the recovery rate and feedwater:permeate ratio was calculated for each of the temperature trials. The data collected during the trials allowed the development of mathematical relationships between feedwater temperature and the recovery rate and feedwater:permeate ratio. The polynomial functions representing the recovery rate and feedwater:permeate ratio can be found in Figures 23 and 24 below. As mentioned previously, recovery rate is a main indicator of membrane performance. Therefore, the results of the calculations can be compared to determine the effect of higher pressure on recovery rate and can also be compared against existing literature on recovery rate to determine if the results of the lab work support or deny reverse osmosis performance theory. Although, it is important to note that existing literature on the effects of increasing temperature on recovery rate or feedwater:permeate ratio is limited. The feedwater:permeate ratio was also calculated as it describes the efficiency of the membrane in terms of how many milliliters of feedwater are needed to produce one milliliter of permeate.

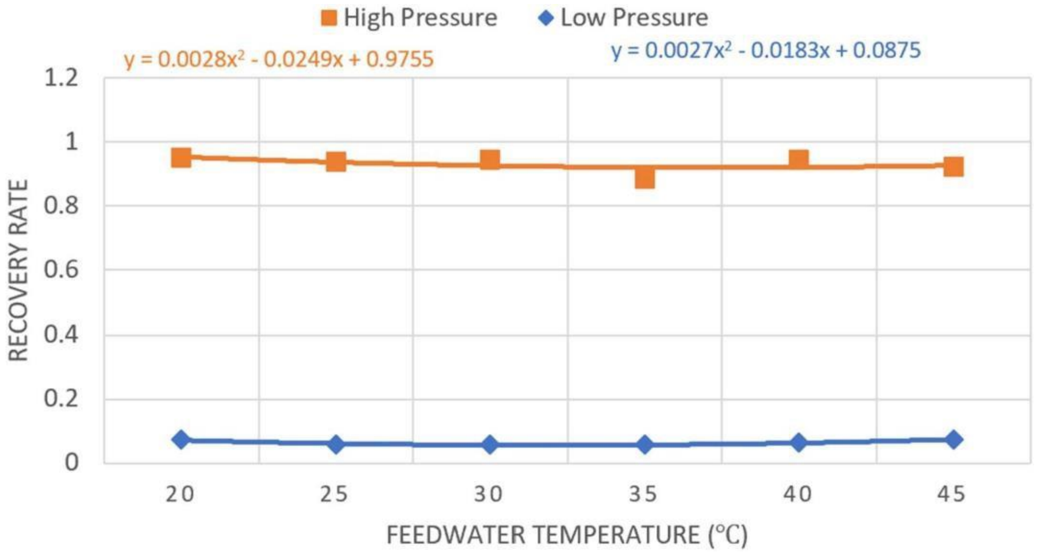

Figure 23. *Recovery Rate vs. Feedwater Temperature (S = 1,000 ppm, P = 40, 65 psi, V = 2 L).*

The recovery rate was calculated by dividing the permeate flow rate by the feedwater flow rate. As seen in Figure 23, the recovery rate was graphed against the increasing temperature of the feedwater for the six trials. The recovery rate is known to typically vary from 35% to 85%, as discussed in section 5.2.2. Throughout the trials, the recovery rate was constant. For the low pressure trials, the recovery rate did not exceed 10%, while the high pressure trials exhibited a recovery rate greater than 90% relatively consistently. Agashichev & Lootahb found that as the temperature of the feedwater increased from 20 to 40℃, the recovery rate would decrease approximately 0.033 for every degree of increase. At such a small rate of decrease, the results of their work was nearly constant. The data collected in this project work did not exemplify the same mathematical decrease that was found in the work of Agashichev & Lootahb, but did have a similar unvarying recovery rate throughout the trials.

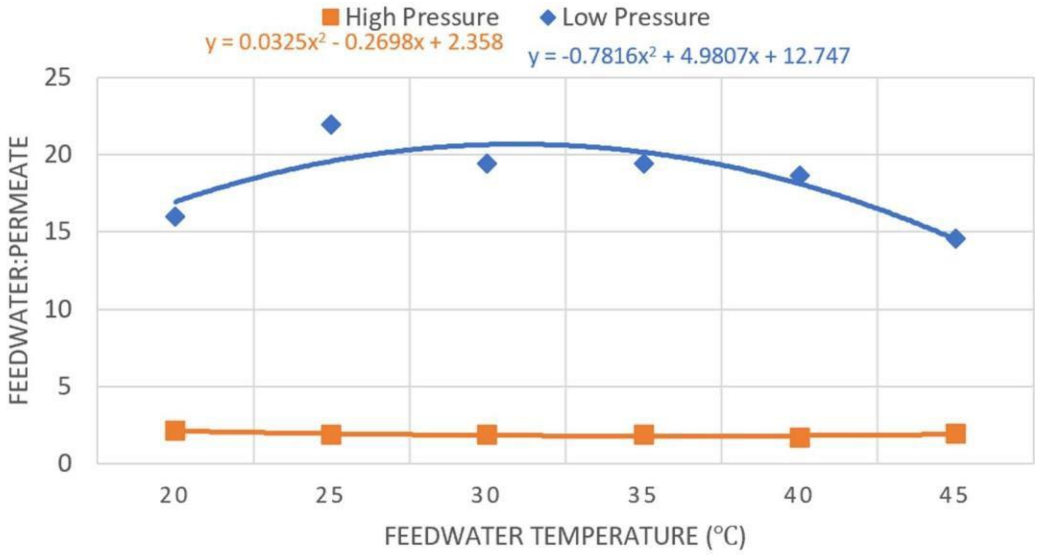

Figure 24. *Feedwater:Permeate vs. Feedwater Temperature (S = 1,000 ppm, P = 40, 65 psi, V = 2 L)*

In Figure 24 above, the feedwater:permeate ratio was graphed against the feedwater temperature. The feedwater:permeate ratio remained relatively constant throughout the low and high pressure trials, with more variation in the low pressure trials. Variation in the low pressure trials may indicate that, at a lower pressure, the reverse osmosis membrane's feedwater:permeate ratio is more susceptible to temperature change. As the temperature increased during the low pressure trials, there was more permeate produced for every milliter of feedwater that was run through the reverse osmosis membrane. In other words, the reverse osmosis membrane would require more feedwater at a lower pressure to produce the same amount of permeate produced at a higher pressure.

5.3.3 Temperature Change

The temperature for the feedwater, brine, and permeate was measured and recorded for each of the temperature trials performed. The temperature difference between the brine and permeate with the feedwater was then calculated. The temperature change from the feedwater to the brine and permeate was calculated. To calculate the brine temperature change, the temperature of the feedwater was subtracted from the temperature of the brine. Similarly, to calculate the permeate temperature change, the temperature of the feedwater was subtracted from the temperature of the permeate. The data calculated during the trials allowed the development of a mathematical relationship between increasing feedwater temperature and the temperature changes experienced by the brine and permeate produced, as seen in the polynomial functions in Figure 25 below. The calculations of temperature change can be found in Appendix C. As can be seen by the temperature data collected throughout these trials, the temperature of the water tends to change once run through the membrane. The trend of the brine and permeate is that the change in temperature decreases as the feedwater temperature increases.

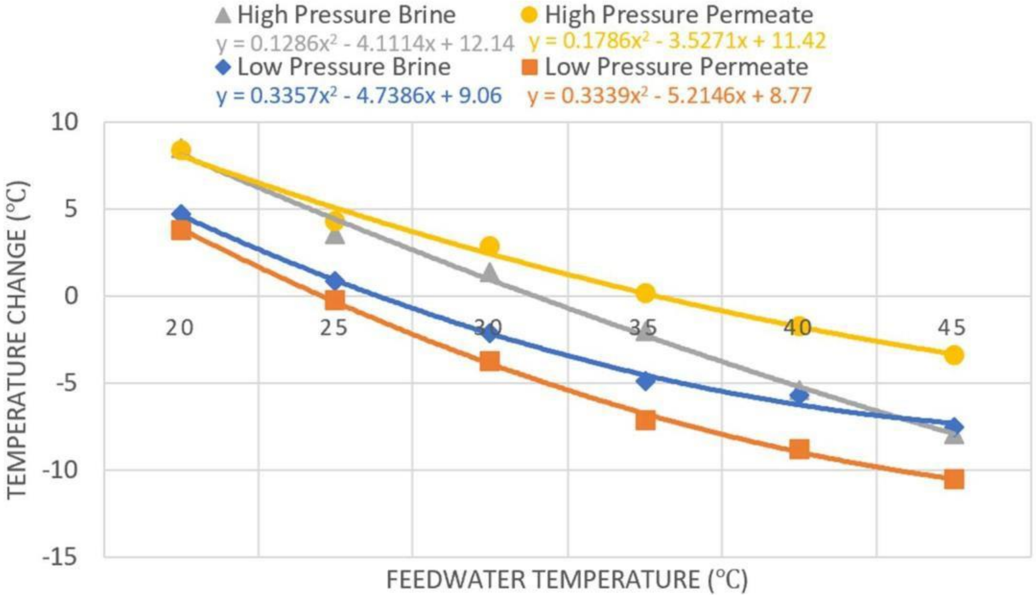

Figure 25. *Temperature Change vs. Feedwater Temperature (S = 1,000 ppm, P = 40, 65 psi, V = 2 L)*

The difference in temperature drop between brine and permeate was more notable in the high pressure tests. The data collected throughout the trials indicates that the temperature of the water tends to change once run through the membrane and the output temperatures continually decrease as the input temperature increases. The mathematical relationships developed can be used to calculate temperature changes in the brine and permeate due to increasing feedwater temperature. Existing literature on reverse osmosis membrane discharge temperature is limited, however. The temperature change of the brine is important to predict. The polynomial function in Figure 25 can be used to predict the brine temperature change at high pressure. It is evident that as the feedwater temperature increases, the temperature of the brine will be affected. The temperature of the brine will decrease more at a higher feedwater temperature than at a lower feedwater temperature.

5.4 Increasing TiO_2 Particles Trials

Another variable that was explored in this work was the presence of TiO_2 particles in the feedwater. The effects of increasing feedwater TiO_2 concentration on reverse osmosis membrane performance indicators were specifically developed. On a bench-scale system, feedwater with increasing TiO_2 concentration was pumped through a reverse osmosis membrane at a low pressure and a high pressure. The relationship between increasing TiO_2 concentration and membrane performance indicators are discussion points for the effects of increased sunscreen use on the reverse osmosis process. In the TiO_2 trials (OL1 to OL5 and OH1to OH5), the TiO_2 concentration of the feedwater was increased from 500 ppm to 2,500 ppm. An adequate range of TiO_2 concentration values provided data necessary to make predictions if the TiO_2 concentration of seawater used for desalination were to increase drastically and to collect data points to develop a mathematical relationship between increasing TiO_2 concentration and membrane performance indicators. The raw data can be found in Appendix D. As mentioned in the methodology, the effects of increasing TiO_2 concentration on the reverse osmosis process were explored. Trials were conducted at a pressure below the optimal operating pressure of the reverse osmosis membrane (40 psi) and at the optimal operating pressure (65 psi). Several measurements were recorded throughout the trials and several calculations followed to determine the reverse osmosis membrane's performance indicators: membrane salt rejection, flow rate and feedwater:permeate ratio, temperature change, and membrane fouling via baseline tests. Throughout the trials, all controllable variables were held constant as the TiO_2 concentration of the feedwater was increased. The following section describes the calculations for the data collected for the TiO_2 trials conducted at the lower pressure of 40 psi and the higher pressure of 65 psi and discusses how the data collected throughout the laboratory work compares to existing literature and what the data may imply about the effects of increasing TiO_2 concentration in seawater on industrial size desalination plants.

One of the properties of TiO_2 is its concentrated white color in solution, explaining why it is often used as a pigment in consumer products. The feedwater turned a milky white once the TiO_2 was mixed in. The membrane did a visibly notable job of clearing out the white pigment, as seen in Figure 26 below. The clear liquid on the right is the permeate and the milky white liquid on the left is the brine after running the feedwater through the membrane.

Figure 26. *Brine vs. Permeate on a* TiO_2 *Trial*

Once the pump was turned off, the brine usually ran for a few extra seconds throughout all of the trials. However, when running the TiO_2 trials, the brine ran considerably longer than the salinity and temperature trials and is important to discuss. The average runoff of brine was about 8 minutes and 170 mL. The excess brine deposited after the pump was turned off likely is related to the addition of TiO_2. The buildup could slow down the flow rate and lengthen the time it takes to output brine. Therefore, it can be devised that the membrane may experience a different rate or type of fouling than with the salt.

5.4.1 Membrane Salt Rejection

From the data collected in the laboratory work, the membrane salt rejection for the high and low pressure trials was calculated and graphed as seen below in Figure 27. The feedwater salinity was held constant at 1,000 ppm. The temperature of the feedwater was held constant at room temperature. The membrane salt rejection percentage was calculated. The membrane salt rejection during the low and pressure trials acted very similarly. As the concentration of the TiO_2 was increased over the five trials, the membrane salt rejection was relatively constant with a slight decrease, but following a polynomial function in both the low and high pressure trials. The slight decrease in membrane salt rejection may indicate that an increase in TiO_2 can adversely affect the membrane salt rejection

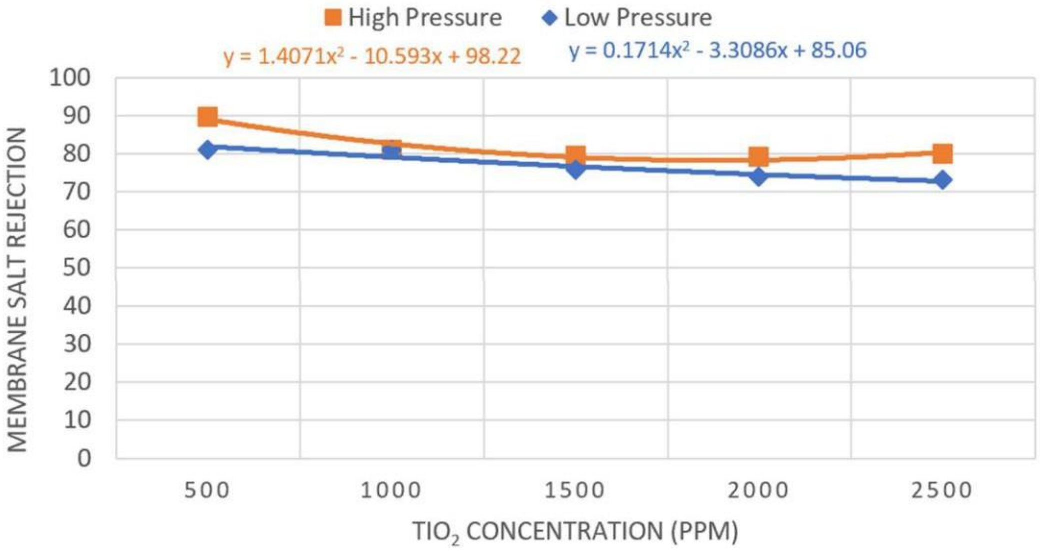

Figure 27. *Membrane Salt Rejection Vs. Feedwater* TiO_2 *Concentration (S = 1,000 ppm, P = 40, 65 psi, T = 25℃)*

Despite the slight decrease in the membrane salt rejection, the reverse osmosis membrane performed well in all of the TiO_2 trials. The operating pressure of the pump affected the membrane salt rejection moderately. For the high pressure trials, the membrane salt rejection barely fell below 80%. In the low pressure trials, the membrane salt rejection achieves a drop closer to 70%. The mathematical relationships developed between increasing TiO_2 concentration and membrane salt rejection can be used to predict how membrane salt rejection would be affected by even higher concentrations of TiO_2. Unfortunately, there appears to be no existing literature evaluating the effects of TiO_2 on reverse osmosis membrane performance indicators, therefore, the results of the laboratory work in this project cannot be compared against any existing literature or research. However, it is still important to discuss the implications of TiO_2 on the reverse osmosis process and the results of this laboratory work.

5.4.2 Recovery Rate & Feedwater:Permeate

From the data collected in the laboratory work, the recovery rate and feedwater:permeate ratio was calculated for each of the TiO_2 trials. The data collected during the trials allowed the development of mathematical relationships between TiO_2 concentration and the recovery rate and feedwater:permeate ratio: The polynomial functions representing the recovery rate and feedwater:permeate ratio can be found in Figures 25 and 26 below. As mentioned previously, recovery rate is a main indicator of membrane performance, however, there is no existing literature discussing the effects of TiO_2 concentration on these reverse osmosis performance indicators. The feedwater:permeate ratio was also calculated as it describes the efficiency of the membrane in terms of how many milliliters of feedwater are needed to produce one milliliter of permeate.

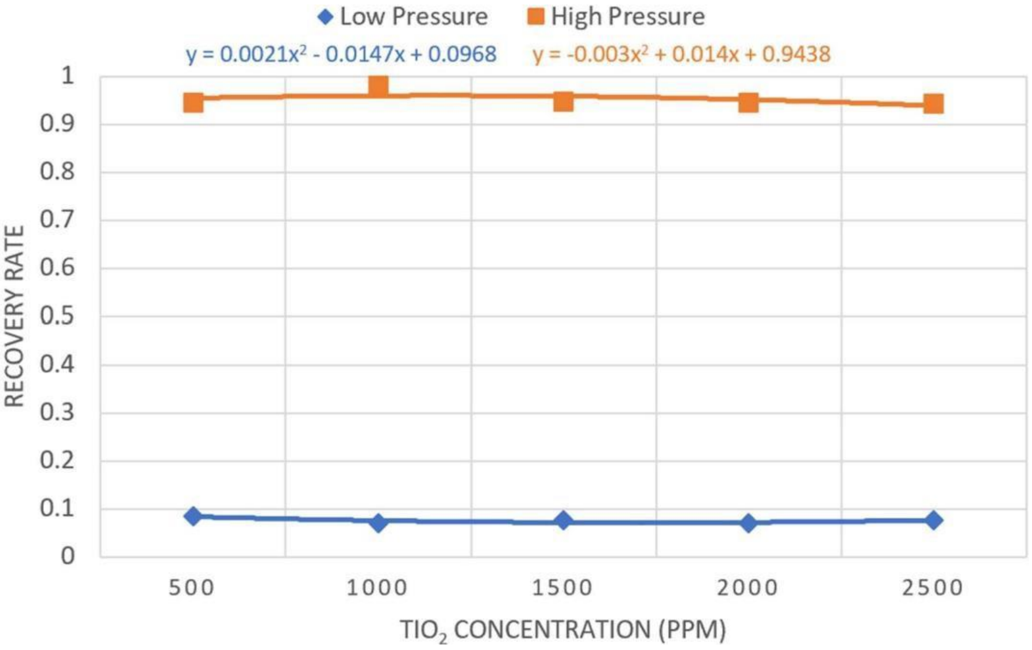

Figure 28. *Recovery Rate Vs. Feedwater* TiO_2 *Concentration (S = 1,000 ppm, P = 40, 65 psi, T = 25℃)*

The recovery rate was calculated by dividing the permeate flow rate by the feedwater flow rate. As seen in Figure 28, the recovery rate was graphed against the increasing TiO_2 concentration for the five trials. Throughout the trials, the recovery rate was constant. For the low pressure trials, the recovery rate did not exceed 10%, while the high pressure trials exhibited a recovery rate greater than 94% consistently. While it appears that the TiO_2 did not affect the recovery rate across the trials, it is apparent that the pressure of the pump greatly affected the recovery rate.

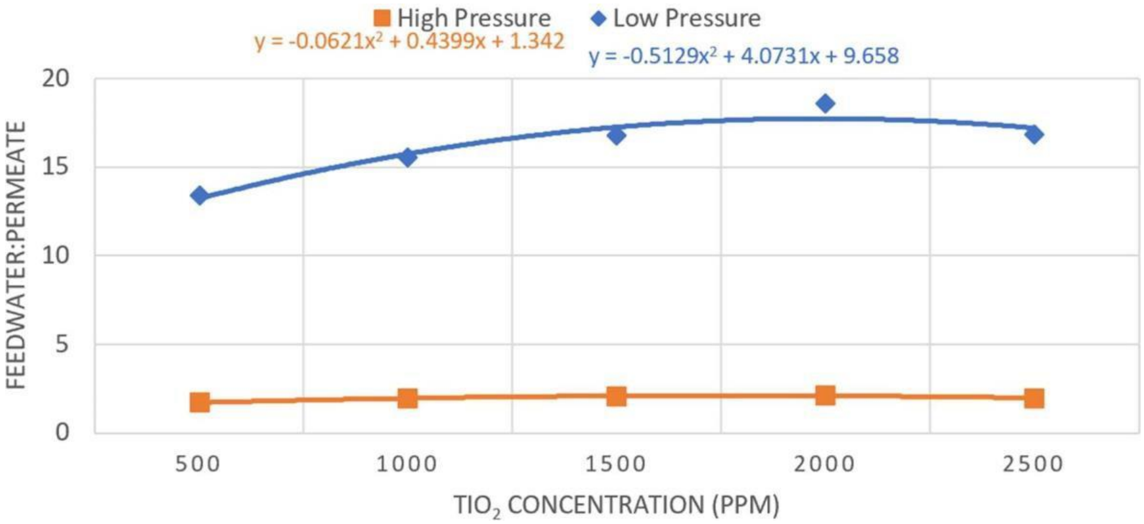

Figure 29. *Feedwater:Permeate Vs. Feedwater* TiO_2 *Concentration (S = 1,000 ppm, P = 40, 65 psi, T = 25℃)*

In Figure 29 above, the feedwater:permeate ratio was graphed against the feedwater TiO_2 concentration. The feedwater:permeate ratio remained relatively constant throughout the high pressure trials. There was a slight increase in the low pressure trials. The mathematical relationships described by polynomial functions can be found in Figure 26. Variation in the low pressure trials may indicate that, at a lower pressure, the reverse osmosis membrane's feedwater:permeate ratio is more susceptible to TiO_2 concentration change. As the TiO_2 concentration increased during the low pressure trials, there was less permeate produced for every milliliter of feedwater that was run through the reverse osmosis membrane. In other words, the reverse osmosis membrane would require more feedwater at a lower pressure to produce the same amount of permeate produced at a higher pressure.

5.3.3 Temperature Change

The temperature for the feedwater, brine, and permeate was measured and recorded for each of the TiO_2 trials performed. The temperature difference between the brine and permeate with the feedwater was then calculated. The temperature change from the feedwater to the brine and permeate was calculated. To calculate the brine temperature change, the temperature of the feedwater was subtracted from the temperature of the brine. Similarly, to calculate the permeate temperature change, the temperature of the feedwater was subtracted from the temperature of the permeate. The data calculated during the trials allowed the development of a mathematical relationship between increasing feedwater TiO_2 concentration and the temperature changes experienced by the brine and permeate produced, as seen in the polynomial functions in Figure 30 below. The calculations of temperature change can be found in Appendix D. As can be seen by the temperature data collected throughout these trials, the temperature of the water tends to change once run through the membrane. The general trend throughout the trials was an increase in temperature change with an increase in TiO_2 concentration. The exception to the trend is the permeate temperature change during the low pressure trials, where the temperature change was relatively constant throughout the trials with a slight decrease.

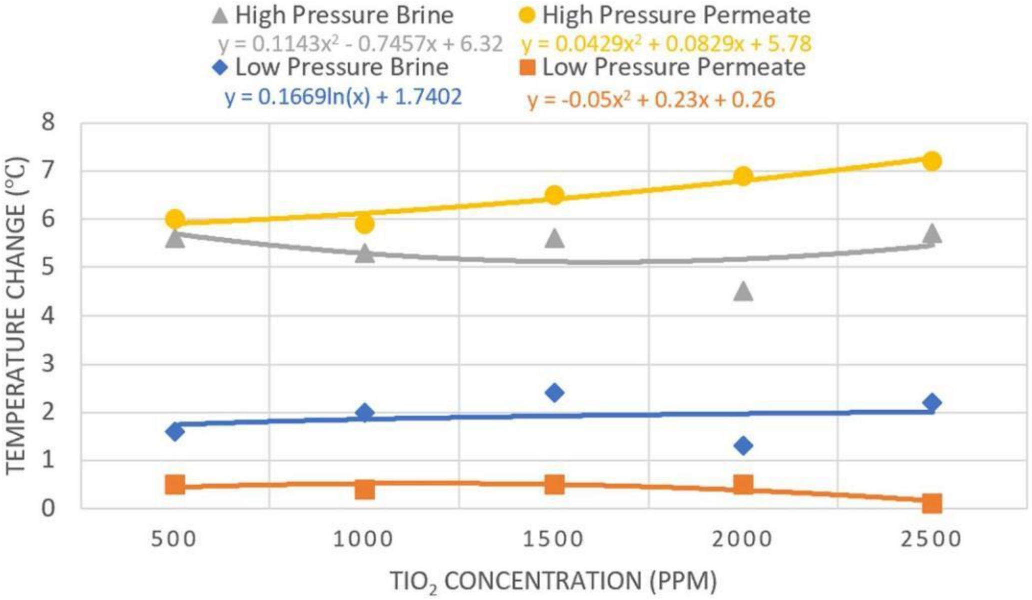

Figure 30. *Temperature Change Vs. Feedwater TiO_2 Concentration (S = 1,000 ppm, P = 40, 65 psi, T = 25°C)*

The mathematical relationships developed can be used to calculate temperature changes in the brine and permeate due to increasing TiO_2 concentrations in the feedwater. The temperature of brine is important to discuss and predict because of its adverse effect on the marine environment. The data here indicates that increased TiO_2 concentration may increase the temperature of the brine. Because there is no existing literature on TiO_2 concentration and reverse osmosis performance theory, more trials should be run in a wider range ofconcentrations to obtain more conclusive data.

5.5 Possible Errors in Trials

There are multiple possible sources of errors in this experimental work. This section evaluates some of the most likely errors and how future experiments can be done to further avoid these errors.

5.5.1 Cavitation

Cavitation occurs when air bubbles, or cavities, are formed on a metallic surface such as an impeller of a water pump. Bernoulli’s equation demonstrates the inverse relationship between flow velocity and pressure. If local pressure falls below the pressure at which the liquid is vaporized, the liquid “boils” and small vapor bubbles are formed. The bubbles formed by low pressure are transported to higher pressure. The higher pressure zones condense the vapors to liquid, causing them to suddenly collapse. A cavity forms and is instantly filled with the surrounding liquid. The rushing liquid from all sides causes collision at the center, leading to a very high local pressure that could be up to 7000 atm in some hydraulic turbines. This creation and collapse of cavities happen repeatedly, hundred or even thousands of times a second. This phenomenon causes fatigue and possible failure because of the pitting on the metallic surface of blades or the tubing. The high stress and damage ultimately can erode the tubing as well (Kumar & Saini, 2010).

One observation made while running the higher pressure tests was that the pressure dropped from its original 65 to below 60. It usually took a few minutes for the drop to begin, but it consistently occurred. A pressure drop was not seen during the lower pressure trials so the slow descent of pressure in the higher pressure trials is likely due to cavitation. While cavitation cannot be fully avoided, it can be minimized. Design changes in moving parts would be the best way to accomplish a lower amount of cavitation. For this experiment, a different pump design to avoid cavitation would be best for future experiments (Kumar & Saini, 2010).

5.5.1.a Overheating

While cavitation occurs because of the pressure change from an originally high pressure liquid flowing over a metallic surface, temperature change affects the process as well. Higher temperature creates the cavities earlier and speeds up the collapse (Hajnayeb, 2021).

Since a cause of error for cavitation is overheating of the pump, letting the pump sit and cool down in between trials would help prevent this issue. For the increasing temperature trials, this would not make a difference since warm water is being pumped into the machine. Another way to help avoid cavitation is to have larger-sized tubing on the suction side of the pump.

5.5.2 Flushing

When the first few trials were run, it quickly became obvious that prior trials' salinity levels were affecting future trials. The team decided to flush the system occasionally to reduce fouling and eliminate extra salinity or other minerals. The salinity trials were always run from lowest salinity to higher salinity so any leftover salt would not drastically increase the salinity level of a low salinity feedwater test.

However, while flushing the system is a helpful way to clear out any previous trials, it does not guarantee perfectly clean equipment. Therefore, from trial to trial and variables that shared a membrane (TiO_2 particles and temperature trials) results could have been affected by the previous trials. To avoid this error in future experiments, each variable should utilize its own membrane. For maximum purity, a new membrane should be used for each trial, since the only way to truly have a clean and non-fouled membrane is to use a new one.

5.6 Improvements for Future Experiments

This project work ran multiple tests with multiple variables involved. To further expand upon the work of this project, more tests would need to be run. Consistent trends over more tests would better confirm the trends present in this laboratory work. An important consideration is the range of the variable of interest being tested. Considering a larger range would provide more insight as to how the variable affects the reverse osmosis membrane’s performance at all possible stages. It is also important to consider the rate of increase of the variable. More trials run in smaller increments may provide better data and a clearer trendline to represent the behavior of the variable and its effect on the reverse osmosis membrane performance. Specifically, if testing salinity, more accurate data may be drawn if the salinity of the feedwater from trial to trial is increased in equal increments. The trials performed in the salinity trials of this work did not do that and it appeared that some reverse osmosis membrane performance indicators may be more dependent on the salt exposure overtime on the reverse osmosis membrane rather than just the salinity of the feedwater. Extending the work of this project may also include running trials at a higher pressure. The pump used in this project was limited to 65 psi. Provided that membranes in community-sized plants run at a transmembrane pressure much higher than this, the higher the pressure achieved, the more applicable the results would be to full-scale plants. Although this project used a salt composition that is used to mimic seawater, another extension of this project would be to test salts of different compositions.

At the beginning of this project, when the project's direction was being determined, several other variables to test were discussed beyond increasing salinity, temperature, and TiO_2 concentration. Implementing the same methodology discussed in this project with other variables could provide more insight as to how other threats to seawater can impact the reverse osmosis membrane performance. Other possible variables discussed included challenging the membrane with microplastics and algae, two variables that are also increasing with population growth and climate change and have particle sizes small enough to surpass pretreatment and penetrate a reverse osmosis membrane.

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Appendix A: UAE Desalination Plants

Adapted from (Mogielnicki, 2020).

Operational Date	Plant	Emirate	Desalination Process	Capacity (MIGD)	Capacity (m³/day)
1995	Al Taweelah B	Abu Dhabi	MSF	75	340909
1996	Jebel Dhanna	Abu Dhabi	MSF	4	18182
2001	Al Taweelah A2	Abu Dhabi	MSF	50	227273
2003	Al Taweelah A1	Abu Dhabi	MED/MSF	84	381818
2004	Shuweihat S1	Abu Dhabi	MSF	100	454545
2005	Jebel Ali L-Station, Phase 1	Dubai	MSF	70	318182
2007	Umm Al Nar IWPP	Abu Dhabi	MED/MSF	145	659091
2007	Layyah Desalination Plant	Sharjah	MED/MSF/RO	63.5	288636
2008	Al Taweelah B Extension	Abu Dhabi	MSF	98	445455
2008	Khor Fakkan Desalination Plant	Sharjah	RO	3	13636

2009	Al Rahmaniya (Sajaa)	Sharjah	RO	5	22727
2011	Fujairah F2 Plant	Fujairah	MED/RO	130	590909
2011	Ajman Power and Desalination Plant Phase 1	Ajman	RO	30	136364
2011	Ajman Desalination Plant	Ajman	RO	10	45455
2012	Shuweihat S2	Abu Dhabi	MSF	100	454545
2013	Jebel Ali M-Station	Dubai	MSF	140	636364
2014	Hamriyah	Sharjah	RO	20	90909
2015	Fujairah F1 IWPPF	Fujairah	MSF/RO	130	590909
2015	Ghalilah	Ras Al Khaimah	RO	15	68182
2017	Mirfa IWPP	Abu Dhabi	RO	53	240909
2020	Ras Al Khaimah IWP	Ras Al Khaimah	RO	22	100000
2021	Umm Al Quwain IWP	Umm Al Quwain	Unknown	150	681818

2022	Al Taweelah IWP	Abu Dhabi	RO	200	909091
2023	Hassyan Power and Desalination Plant	Dubai	RO	120	545455
On Hold	Al Zawra IWP	Ajman	RO	30	136364
On Hold	Ras Al Khaimah Desalination Plant	Ras Al Khaimah	RO	30	136364
Ongoing	Kalba Desalination Plant	Sharjah	RO	6	27273
Unknown	Jebel Ali RO Plant	Dubai	RO	40	181818
Unknown	Jebel Ali	Dubai	MSF	27	122727
Unknown	Jebel Ali D-Station	Dubai	MSF	35	159091
Unknown	Jebel Ali E-Station	Dubai	MSF	25	113636
Unknown	Jebel Ali G-Station	Dubai	MSF	60	272727
Unknown	Jebel Ali K-Station, Phase 1	Dubai	MSF	60	272727

Unknown	Jebel Ali K-Station, Phase 2	Dubai	MSF	40	181818
Unknown	Jebel Ali L-Station, Phase 2	Dubai	MSF	55	250000

Appendix B: Salinity Trials

Low Pressure Trials

Target Salinity Values vs. Actual Measured Values for Salinity Trials

Trial #	Target Value (ppm)	Target Volume (L)	Salt (g)
Baseline Start	0	2	0
SL1	250	2	0.5
SL2	500	2	1
SL3	750	2	1.5
SL4	1,000	2	2
SL5	1,250	2	2.5
SL6	1,500	2	3
SL7	1,750	2	3.5
SL8	2,000	2	4
SL9	2,250	2	4.5
SL10	2,500	2	5
SL11	2,750	2	5.5
SL12	3,000	2	6
Baseline End	0	2	0

Salinity Trials Feedwater Temperature

Trial #	Feedwater Temperature (℃)	Brine Temperature (℃)	Permeate Temperature (℃)
Baseline Start	25.3	27.1	24.5
SL1	25.0	26.5	24.5
SL2	24.8	26.3	24.6
SL3	24.8	26.3	24.3
SL4	24.7	26.6	23.7

SL5	24.5	26.4	23.1
SL6	24.6	26.1	23.1
SL7	24.3	26.0	22.5
SL8	24.0	26.1	22.6
SL9	24.2	25.8	22.3
SL10	24.2	25.6	21.7
SL11	24.2	26.0	21.6
SL12	20.3	24.6	22.9
Baseline End	22.2	23.6	22.4

Salinity Trials Pressure Measurement

Trial #	Feedwater Pressure (psi)	Brine Pressure (psi)
Baseline Start	41	31
SL1	41	31
SL2	41	31
SL3	41	31
SL4	41	31
SL5	41	31
SL6	41	31
SL7	41	31
SL8	41	31
SL9	41	31
SL10	41	31
SL11	41	31
SL12	41	31
Baseline End	41	31

Salinity Trials Volume Measurement

Trial #	Feedwater Volume (mL)	Brine Volume (mL)	Permeate Volume (mL)
Baseline Start	1,840	1,740	131
SL1	1,836	1,690	132
SL2	1,830	1,705	121
SL3	1,828	1,715	130
SL4	1,864	1,725	94
SL5	1,865	1,755	88
SL6	1,820	1,760	76
SL7	1,857	1,745	60
SL8	1,838	1,780	56
SL9	1,841	1,745	44
SL10	1,840	1,785	42
SL11	1,826	1,775	33
SL12	1,874	1,775	13
Baseline End	1,843	1,780	48

Salinity Trials Time Elapsed for Flow Rate Calculation

Trial #	Feedwater Time	Brine Time	Permeate Time
Baseline Start	00:53.18	00:51.53	00:44.90
SL1	00:53.27	00:49.38	00:45.93
SL2	00:52.06	00:51.29	00:51.11
SL3	00:52.32	00:51.26	00:45.23
SL4	00:54.40	00:52.53	00:46.65
SL5	00:55.08	00:52.07	00:44.05
SL6	00:53.16	00:53.87	00:42.73
SL7	00:55.00	00:52.44	00:41.40

SL8	00:54.00	00:53.59	00:45.77
SL9	00:54.89	00:52.72	00:39.28
SL10	00:54.21	00:53.28	00:42.81
SL11	00:54.22	00:52.84	00:40.08
SL12	00:56.33	00:48.53	00:40.09
Baseline End	00:55.40	00:50.82	00:39.25

Salinity Trials Electrical Conductivity Measurement

Trial #	Feedwater EC	Brine EC	Permeate EC
Baseline Start	262 µS	190.6 µS	34.2 µS
SL1	937 µS	519 µS	84.0 µS
SL2	1,611 µS	1118 µS	283 µS
SL3	2.28 mS	1774 µS	457 µS
SL4	2.86 mS	2.42 mS	629 µS
SL5	3.53 mS	3.05 mS	790 µS
SL6	4.15 mS	3.70 mS	960 µS
SL7	4.70 mS	4.29 mS	1146 µS
SL8	5.40 mS	4.91 mS	1351 µS
SL9	5.97 mS	5.54 mS	1565 µS
SL10	6.57 mS	6.16 mS	1836 µS
SL11	7.16 mS	6.74 mS	2.09 mS
SL12	7.83 mS	7.34 mS	-
Baseline End	312 µS	4.84 mS	2.53 mS

Salinity Trials Salinities Converted from Electrical Conductivity

Trial #	Feedwater Salinity (ppm)	Brine Salinity (ppm)	Permeate Salinity (ppm)	Membrane Salt Rejection

Baseline Start	131	95.3	17.1	86.95%
SL1	468.5	259.5	42	91.04%
SL2	805.5	559	119	85.23%
SL3	1,140	887	228.5	79.96%
SL4	1,430	1,210	314.5	78.01%
SL5	1,765	1,525	395	77.62%
SL6	2,075	1,850	480	76.87%
SL7	2,350	2,145	573	75.62%
SL8	2,700	2,455	675.5	74.98%
SL9	2,985	2,770	782.5	73.79%
SL10	3,285	3,080	918	72.05%
SL11	3,580	3,370	1,045	70.87%
SL12	3,915	3,670	-	-
Baseline End	156	2,420	1,265	-710.90%

Salinity Trials Flow Rates Converted from Times Elapsed and Volumes

Trial #	Feedwater Flow Rate (L/min)	Brine Brine Flow Rate (L/min)	Permeate Flow Rate (L/min)	Recovery Rate
Baseline Start	2.08	2.03	0.18	0.087
SL1	2.07	2.05	0.17	0.082
SL2	2.11	1.99	0.14	0.066
SL3	2.10	2.01	0.17	0.081
SL4	2.06	1.97	0.12	0.058
SL5	2.03	2.02	0.12	0.059
SL6	2.05	1.96	0.11	0.054
SL7	2.03	2.00	0.09	0.044

SL8	2.04	1.99	0.07	0.034
SL9	2.01	1.99	0.07	0.035
SL10	2.04	2.01	0.06	0.029
SL11	2.02	2.02	0.05	0.025
SL12	2.00	2.19	0.02	0.01
Baseline End	2.00	2.10	0.07	0.035

Salinity Trials Ratio of Feedwater to Permeate

Trial #	Feedwater:Permeate (mL:mL)
Baseline Start	13.28:1
SL1	13.91:1
SL2	15.12:1
SL3	14.06:1
SL4	19.83:1
SL5	21.19:1
SL6	23.95:1
SL7	30.95:1
SL8	32.82:1
SL9	41.84:1
SL10	43.81:1
SL11	55.33:1
SL12	136.54:1
Baseline End	37.08:1

Salinity Trials Changes in Temperature from Feedwater to Brine and Permeate

Trial #	Brine Temperature Change	Permeate Temperature Change

Baseline Start	1.8	-0.8
SL1	1.5	-0.5
SL2	1.5	-0.2
SL3	1.5	-0.5
SL4	1.9	-1.0
SL5	1.9	-1.4
SL6	1.5	-1.5
SL7	1.7	-1.8
SL8	2.1	-1.4
SL9	1.6	-1.9
SL10	1.4	-2.5
SL11	1.8	-2.6
SL12	4.3	2.6
Baseline End	1.4	0.2

High Pressure Trials

Target Salinity Values vs. Actual Measured Values for Salinity Trials

Trial #	Target Value (ppm)	Target Volume (L)	Salt (g)
Baseline Start	0	2	0
SH1	500	2	1
SH2	1,000	2	2
SH3	2,500	2	5
SH4	10,000	2	20
SH5	20,000	2	40
SH6	25,000	2	50
SH7	30,000	2	60
SH8	35,000	2	70

Baseline End	0	2	0

Salinity Trials Feedwater Temperature

Trial #	Feedwater Temperature (℃)	Brine Temperature (℃)	Permeate Temperature (℃)
Baseline Start	23.8	34.0	34.4
SH1	22.4	30.9	31.3
SH2	23.7	29.8	29.7
SH3	25.2	29.8	29.6
SH4	25.0	30.3	29.1
SH5	24.7	32.4	25.2
SH6	25.5	34.7	23.8
SH7	24.9	36.3	23.2
SH8	24.5	38.0	23.0
Baseline End	25.0	39.3	29.5

Salinity Trials Pressure Measurement

Trial #	Feedwater Pressure (psi)	Brine Pressure (psi)
Baseline Start	61	61
SH1	61	61
SH2	61	61
SH3	61	61
SH4	63	63
SH5	65	65
SH6	66	66
SH7	66	66
SH8	67	67

Baseline End	66	66

Salinity Trials Volume Measurement

Trial #	Feedwater Volume (mL)	Brine Volume (mL)	Permeate Volume (mL)
Baseline Start	1,576	620	1,055
SH1	1,636	555	870
SH2	1,532	660	860
SH3	1,590	610	665
SH4	1,590	1,215	350
SH5	1,530	1,470	62
SH6	1,580	1,330	30
SH7	1,590	1,375	28
SH8	1,610	1,390	22
Baseline End	1,635	1,290	100

Salinity Trials Time Elapsed for Flow Rate Calculation

Trial #	Feedwater Time	Brine Time	Permeate Time
Baseline Start	02:35.83	02:32.98	02:29.34
SH1	02:27.40	02:24.83	02:22.76
SH2	02:52.21	02:48.85	02:45.14
SH3	02:59.29	02:57.09	02:48.56
SH4	04:37.18	04:32.01	04:21.23
SH5	05:52.84	05:52.45	05:44.32
SH6	05:54.33	05:49.78	05:40.13
SH7	06:12.15	06:13.24	06:04.29
SH8	06:16.24	06:06.59	06:03.48

Baseline End	05:56.35	05:44.09	05:44.34

Salinity Trials Electrical Conductivity Measurement

Trial #	Feedwater EC	Brine EC	Permeate EC
Baseline Start	315 µS	922 µS	60.1 µS
SH1	1700 µS	1627 µS	259 µS
SH2	2.97 mS	3.39 mS	511 µS
SH3	6.63 mS	6.90 mS	950 µS
SH4	23.5 mS	15.62 mS	2.84 mS
SH5	43.8 mS	29.7 mS	10.7 mS
SH6	53.6 mS	43.3 mS	21.1 mS
SH7	62.8 mS	54.6 mS	32.4 mS
SH8	71.7 mS	63.7 mS	43.3 mS
Baseline End	315 µS	45.1 mS	35.5 mS

High Pressure Calculations

Salinity Trials Salinities Converted from Electrical Conductivity

Trial #	Feedwater Salinity (ppm)	Brine Salinity (ppm)	Permeate Salinity (ppm)	Membrane Salt Rejection
Baseline Start	157.5	461	30.05	80.92%
SH1	850	813.5	129.5	84.76%
SH2	1,485	1,695	255.5	82.79%
SH3	3,315	3,450	475	85.67%
SH4	11,750	7,810	1,420	87.91%
SH5	21,900	14,850	5,350	75.57%
SH6	26,800	21,650	10,550	60.63%
SH7	31,400	27,300	16,200	48.41%
SH8	35,850	31,850	21,650	39.61%

Baseline End	157.5	22,550	17,750	-11,169.8%

Salinity Trials Flow Rates Converted from Times Elapsed and Volumes

Trial #	Feedwater Flow Rate (L/min)	Brine Brine Flow Rate (L/min)	Permeate Flow Rate (L/min)	Recovery Rate
Baseline Start	0.61	0.24	0.42	0.69
SH1	0.67	0.23	0.36	0.54
SH2	0.53	0.23	0.31	0.58
SH3	0.53	0.21	0.24	0.45
SH4	0.34	0.27	0.08	0.24
SH5	0.26	0.25	0.01	0.038
SH6	0.27	0.23	0.005	0.019
SH7	0.26	0.22	0.005	0.019
SH8	0.26	0.23	0.004	0.015
Baseline End	0.28	0.22	0.02	0.071

Salinity Trials Ratio of Feedwater to Permeate

Trial #	Feedwater:Permeate (mL:mL)
Baseline Start	1.49:1
SH1	1.88:1
SH2	1.78:1
SH3	2.39:1
SH4	4.54:1
SH5	24.68:1
SH6	52.67:1
SH7	56.79:1
SH8	73.18:1

Baseline End	16.35:1

Salinity Trials Changes in Temperature from Feedwater to Brine and Permeate

Trial #	Brine Temperature Change	Permeate Temperature Change
Baseline Start	10.2	10.6
SH1	8.5	8.9
SH2	6.1	6.0
SH3	4.6	4.4
SH4	5.3	4.1
SH5	7.7	0.5
SH6	9.2	-1.7
SH7	11.4	-1.7
SH8	13.5	-1.5
Baseline End	14.3	4.5

Appendix C: Temperature Trials

Low Pressure Trials

Target Salinity Values vs. Actual Measured Values for Temperature Trials

Trial #	Target Value (ppm)	Target Volume (L)	Salt (g)
Baseline Start	0	2	0
TL1	1,000	2	2
TL2	1,000	2	2
TL3	1,000	2	2
TL4	1,000	2	2
TL5	1,000	2	2
TL6	1,000	2	2
Baseline End	0	2	0

Temperature Trials Feedwater Temperature

Trial #	Target Feedwater Temperature (℃)	Feedwater Temperature (℃)	Brine Temperature (℃)	Permeate Temperature (℃)
Baseline Start	Room Temp.	24.2	26.7	25.5
TL1	20	21.5	26.2	25.3
TL2	25	25.3	26.2	25.1
TL3	30	30.5	28.4	26.8
TL4	35	36.0	31.1	28.9
TL5	40	39.7	34.0	30.9
TL6	45	45.3	37.8	34.8
Baseline End	Room Temp.	24.9	36.3	32.8

Temperature Trials Pressure Measurement

Trial #	Feedwater Pressure (psi)	Brine Pressure (psi)

Baseline Start	41	31
TL1	41	31
TL2	40	30
TL3	40	30
TL4	41	31
TL5	41	31
TL6	41	32
Baseline End	41	31

Temperature Trials Volume Measurement

Trial #	Feedwater Volume (mL)	Brine Volume (mL)	Permeate Volume (mL)
Baseline Start	1,830	1,695	130
TL1	1,867	1,750	117
TL2	1,868	1,750	85
TL3	1,827	1,730	94
TL4	1,827	1,690	96
TL5	1,826	1,700	98
TL6	1,888	1,685	130
Baseline End	1,848	1,715	136

Temperature Trials Time Elapsed for Flow Rate Calculation

Trial #	Feedwater Time	Brine Time	Permeate Time
Baseline Start	00:54.29	00:49.50	00:44.92
TL1	00:55.23	00:51.65	00:48.49
TL2	00:54.33	00:51.90	00:41.45
TL3	00:52.77	00:52.17	00:47.58

TL4	00:53.65	00:49.47	00:47.81
TL5	00:52.96	00:48.12	00:44.58
TL6	00:51.98	00:49.31	00:48.98
Baseline End	00:51.68	00:53.57	00:49.41

Temperature Trials Electrical Conductivity Measurement

Trial #	Feedwater EC	Brine EC	Permeate EC
Baseline Start	258 µS	242 µS	93.4 µS
TL1	2.90 mS	1401 µS	187.2 µS
TL2	2.93 mS	2.49 mS	560 µS
TL3	2.93 mS	2.86 mS	710 µS
TL4	2.90 mS	2.97 mS	771 µS
TL5	2.88 mS	2.99 mS	780 µS
TL6	2.87 mS	3.02 mS	772 µS
Baseline End	265 µS	1.96 mS	676 µS

Low Pressure Calculations

Temperature Trials Salinities Converted from Electrical Conductivity

Trial #	Feedwater Salinity (ppm)	Brine Salinity (ppm)	Permeate Salinity (ppm)	Membrane Salt Rejection
Baseline Start	129	121	46.7	63.7
TL1	1450	700.5	93.6	93.5
TL2	1465	1245	280	80.9
TL3	1465	1430	355	75.8
TL4	1450	1485	385.5	73.4
TL5	1440	1495	390	72.9
TL6	1435	1510	386	73.1
Baseline End	132.5	980	338	-155.1

Temperature Trials Flow Rates Converted from Times Elapsed and Volumes

Trial #	Feedwater Flow Rate (L/min)	Brine Flow Rate (L/min)	Permeate Flow Rate (L/min)	Recovery Rate
Baseline Start	2.03	2.08	0.18	0.089
TL1	2.03	2.06	0.15	0.074
TL2	2.08	2.06	0.12	0.058
TL3	2.11	2.00	0.12	0.057
TL4	2.07	2.07	0.12	0.058
TL5	2.11	2.12	0.14	0.066
TL6	2.22	2.06	0.16	0.073
Baseline End	2.17	1.94	0.17	0.078

Temperature Trials Ratio of Feedwater to Permeate

Trial #	Feedwater:Permeate (mL:mL)
Baseline Start	14.08:1
TL1	15.95:1
TL2	21.97:1
TL3	19.44:1
TL4	19.44:1
TL5	18.63:1
TL6	14.52:1
Baseline End	13.59:1

Temperature Trials Changes in Temperature from Feedwater to Brine and Permeate

Trial #	Brine Temperature Change	Permeate Temperature Change
Baseline Start	2.5	1.3

TL1	4.7	3.8
TL2	0.9	-0.2
TL3	-2.1	-3.7
TL4	-4.9	-7.1
TL5	-5.7	-8.8
TL6	-7.5	-10.5
Baseline End	11.4	7.9

High Pressure Trials

Target Salinity Values vs. Actual Measured Values for Temperature Trials

Trial #	Target Value (ppm)	Target Volume (L)	Salt (g)
Baseline Start	0	2	0
TH1	1,000	2	2
TH2	1,000	2	2
TH3	1,000	2	2
TH4	1,000	2	2
TH5	1,000	2	2
TH6	1,000	2	2
Baseline End	0	2	0

Temperature Trials Feedwater Temperature

Trial #	Target Feedwater Temperature (℃)	Feedwater Temperature (℃)	Brine Temperature (℃)	Permeate Temperature (℃)
Baseline Start	Room Temp.	24.3	30.0	30.0

TH1	20	20.3	28.8	28.7
TH2	25	25.6	29.2	29.9
TH3	30	29.7	31.1	32.6
TH4	35	35.1	33.1	35.3
TH5	40	40.1	34.7	38.4
TH6	45	45.1	37.2	41.7
Baseline End	Room Temp.	25.1	38.5	38.9

Temperature Trials Pressure Measurement

Trial #	Feedwater Pressure (psi)	Brine Pressure (psi)
Baseline Start	63	63
TH1	63	63
TH2	63	63
TH3	62	62
TH4	62	62
TH5	65	65
TH6	65	65
Baseline End	65	65

Temperature Trials Volume Measurement

Trial #	Feedwater Volume (mL)	Brine Volume (mL)	Permeate Volume (mL)
Baseline Start	1,495	515	795
TH1	1,630	510	765
TH2	1,615	595	850
TH3	1,600	600	850
TH4	1,600	540	850

TH5	1,590	525	940
TH6	1,650	430	840
Baseline End	1,580	535	1040

Temperature Trials Time Elapsed for Flow Rate Calculation

Trial #	Feedwater Time	Brine Time	Permeate Time
Baseline Start	02:17.80	02:05.81	02:02.86
TH1	02:27.83	02:20.54	02:20.97
TH2	02:46.34	02:46.56	02:36.44
TH3	02:44.41	02:42.47	02:35.14
TH4	02:34.37	02:32.50	02:14.49
TH5	02:31.70	02:27.78	02:23.72
TH6	02:10.77	02:06.81	02:00.57
Baseline End	02:27.46	02:23.24	02:19.96

Temperature Trials Electrical Conductivity Measurement

Trial #	Feedwater EC	Brine EC	Permeate EC
Baseline Start	312 µS	883 µS	106.5 µS
TH1	2.98 mS	2.85 mS	345 µS
TH2	2.96 mS	4.57 mS	575 µS
TH3	2.95 mS	5.20 mS	679 µS
TH4	2.94 mS	5.64 mS	740 µS
TH5	2.94 mS	5.94 mS	800 µS
TH6	2.95 mS	6.00 mS	880 µS
Baseline End	308 µS	4.40 mS	595 µS

High Pressure Calculations

Temperature Trials Salinities Converted from Electrical Conductivity

Trial #	Feedwater Salinity (ppm)	Brine Salinity (ppm)	Permeate Salinity (ppm)	Membrane Salt Rejection
Baseline Start	156	441.5	53.25	65.9
TH1	1490	1425	172.5	88.4
TH2	1480	2285	287.5	80.6
TH3	1475	2600	339.5	77.0
TH4	1470	2820	370	74.8
TH5	1470	2970	400	72.8
TH6	1475	3000	440	70.2
Baseline End	154	2200	297.5	-93.2

Temperature Trials Flow Rates Converted from Times Elapsed and Volumes

Trial #	Feedwater Flow Rate (L/min)	Brine Brine Flow Rate (L/min)	Permeate Flow Rate (L/min)	Recovery Rate
Baseline Start	2.28	2.08	2.03	0.89
TH1	2.45	2.33	2.35	0.95
TH2	2.77	2.43	2.60	0.939
TH3	2.73	2.7	2.58	0.945
TH4	2.52	2.53	2.23	0.885
TH5	2.52	2.45	2.38	0.944
TH6	2.17	2.1	2	0.922
Baseline End	2.45	2.38	2.33	0.951

Temperature Trials Ratio of Feedwater to Permeate

Trial #	Feedwater:Permeate (mL:mL)
Baseline Start	1.88:1
TH1	2.13:1

TH2	1.9:1
TH3	1.88:1
TH4	1.88:1
TH5	1.69:1
TH6	1.96:1
Baseline End	1.52:1

Temperature Trials Changes in Temperature from Feedwater to Brine and Permeate

Trial #	Brine Temperature Change	Permeate Temperature Change
Baseline Start	5.7	5.7
TH1	8.5	8.4
TH2	3.6	4.3
TH3	1.4	2.9
TH4	-2	0.2
TH5	-5.4	-1.7
TH6	-7.9	-3.4
Baseline End	13.4	13.8

Appendix D: TiO_2 Trials

Low Pressure Trials

Target TiO_2 Concentration vs. Actual Measured Values for TiO_2 Trials

Trial #	TiO_2 Target Value (g/L)	Target Volume (L)	TiO_2 (g)
Baseline Start	0	2	0
OL1	0.5	2	1
OL2	1	2	2
OL3	1.5	2	3
OL4	2	2	4
OL5	2.5	2	5
Baseline End	0	2	0

Target Salinity Values vs. Actual Measured Values for TiO_2 Trials

Trial #	Target Value (ppm)	Target Volume (L)	Salt (g)
Baseline Start	0	2	0
OL1	1,000	2	2
OL2	1,000	2	2
OL3	1,000	2	2
OL4	1,000	2	2
OL5	1,000	2	2
Baseline End	0	2	0

TiO_2 Trials Feedwater Temperature

Trial #	Feedwater Temperature (℃)	Brine Temperature (℃)	Permeate Temperature (℃)
Baseline Start	22.1	23.0	21.9
OL1	22.0	23.6	22.5
OL2	22.0	24.0	22.4

OL3	21.8	24.2	22.3
OL4	21.9	23.2	22.4
OL5	22.1	24.3	22.2
Baseline End	22.2	24.5	22.9

TiO_2 Trials Pressure Measurement

Trial #	Feedwater Pressure (psi)	Brine Pressure (psi)
Baseline Start	41	31
OL1	41	31
OL2	41	31
OL3	41	31
OL4	42	32
OL5	42	32
Baseline End	41	31

TiO_2 Trials Volume Measurement

Trial #	Feedwater Volume (mL)	Brine Volume (mL)	Permeate Volume (mL)
Baseline Start	1,765	1690	145
OL1	1,810	1,650	135
OL2	1,785	1,700	115
OL3	1,765	1,665	105
OL4	1,765	1,650	95
OL5	1,770	1,660	105
Baseline End	1,765	1,640	115

TiO_2 Trials Electrical Conductivity Measurement

Trial #	Feedwater EC	Brine EC	Permeate EC

Baseline Start	361 µS	206 µS	36.5 µS
OL1	2.99 mS	1500 µS	160.8 µS
OL2	2.98 mS	2.57 mS	563 µS
OL3	2.98 mS	2.91 mS	725 µS
OL4	2.98 mS	3.04 mS	779 µS
OL5	2.96 mS	3.03 mS	789 µS
Baseline End	362 µS	1934 µS	706 µS

TiO_2 Trials Time Elapsed for Flow Rate Calculation

Trial #	Feedwater Time	Brine Time	Permeate Time
Baseline Start	00:52.73	00:50.64	00:45.89
OL1	00:55.60	00:54.85	00:47.30
OL2	00:54.81	00:54.84	00:47.80
OL3	00:54.57	00:56.03	00:42.63
OL4	00:54.13	00:55.57	00:40.41
OL5	00:54.57	00:55.21	00:41.62
Baseline End	00:53.36	00:55.38	00:40.78

Low Pressure Calculations

TiO_2 Trials Salinities Converted from Electrical Conductivity

Trial #	Feedwater Salinity (ppm)	Brine Salinity (ppm)	Permeate Salinity (ppm)	Membrane Salt Rejection
Baseline Start	180.5	103	18.25	89.9
OL1	1,495	750	281.5	81.1
OL2	1,490	1,285	281.5	81.1
OL3	1,490	1,455	362.5	75.7
OL4	1,490	1,520	389.5	73.9
OL5	1,480	1,515	394.5	73.3

Baseline End	181	967	353	-95.0

TiO_2 Trials Flow Rates Converted from Times Elapsed and Volumes

Trial #	Feedwater Flow Rate (L/min)	Brine Brine Flow Rate (L/min)	Permeate Flow Rate (L/min)	Recovery Rate
Baseline Start	2.04	2.03	0.19	0.093
OL1	1.97	1.83	0.17	0.086
OL2	1.98	1.89	0.14	0.071
OL3	1.96	1.78	0.15	0.077
OL4	1.96	1.8	0.14	0.071
OL5	1.96	1.81	0.15	0.077
Baseline End	1.99	1.79	0.17	0.085

TiO_2 Trials Ratio of Feedwater to Permeate

Trial #	Feedwater:Permeate (mL:mL)
Baseline Start	12.17:1
OL1	13.41:1
OL2	15.52:1
OL3	16.81:1
OL4	18.58:1
OL5	16.86:1
Baseline End	15.35:1

TiO_2 Trials Changes in Temperature from Feedwater to Brine and Permeate

Trial #	Brine Temperature Change	Permeate Temperature Change
Baseline Start	0.9	-0.2

OL1	1.6	0.5
OL2	2	0.4
OL3	2.4	0.5
OL4	1.3	0.5
OL5	2.2	0.1
Baseline End	2.3	0.7

High Pressure Trials

Target TiO_2 *Concentration vs. Actual Measured Values for* TiO_2 *Trials*

Trial #	TiO_2 Target Value (g/L)	Target Volume (L)	TiO_2 (g)
Baseline Start	0	2	0
OH1	0.5	2	1
OH2	1	2	2
OH3	1.5	2	3
OH4	2	2	4
OH5	2.5	2	5
Baseline End	0	2	0

Target Salinity Values vs. Actual Measured Values for TiO_2 *Trials*

Trial #	Target Value (ppm)	Target Volume (L)	Salt (g)
Baseline Start	0	2	0
OH1	1,000	2	2
OH2	1,000	2	2
OH3	1,000	2	2
OH4	1,000	2	2

OH5	1,000	2	2
Baseline End	0	2	0

TiO_2 Trials Feedwater Temperature

Trial #	Feedwater Temperature (℃)	Brine Temperature (℃)	Permeate Temperature (℃)
Baseline Start	24.4	29.0	30.9
OH1	24.1	29.7	30.1
OH2	24.4	29.7	30.3
OH3	24.2	29.8	30.7
OH4	24.4	28.9	31.3
OH5	24.4	30.1	31.6
Baseline End	24.3	29.1	31.0

TiO_2 Trials Pressure Measurement

Trial #	Feedwater Pressure (psi)	Brine Pressure (psi)
Baseline Start	63	63
OH1	62	62
OH2	62	62
OH3	62	62
OH4	63	63
OH5	63	63
Baseline End	63	63

TiO_2 Trials Volume Measurement

Trial #	Feedwater Volume (mL)	Brine Volume (mL)	Permeate Volume (mL)
Baseline Start	1,610	415	810

OH1	1,550	560	900
OH2	1,585	550	800
OH3	1,600	610	770
OH4	1,695	615	795
OH5	1,630	650	825
Baseline End	1,700	575	850

TiO_2 Trials Electrical Conductivity Measurement

Trial #	Feedwater EC	Brine EC	Permeate EC
Baseline Start	310 µS	437 µS	41.2 µS
OH1	2.93 mS	2.6 mS	303 µS
OH2	2.92 mS	4.59 mS	550 µS
OH3	2.94 mS	4.96 mS	603 µS
OH4	2.90 mS	5.09 mS	601 µS
OH5	2.89 mS	5.17 mS	581 µS
Baseline End	303 µS	3.63 mS	439 µS

TiO_2 Trials Time Elapsed for Flow Rate Calculation

Trial #	Feedwater Time	Brine Time	Permeate Time
Baseline Start	02:08.14	01:53.12	01:45.31
OH1	02:34.28	02:22.13	02:26.89
OH2	02:39.95	02:35.06	02:36.97
OH3	02:40.87	02:37.43	02:32.55
OH4	02:42.96	02:33.81	02:34.32
OH5	02:53.34	02:43.60	02:43.09
Baseline End	02:31.65	02:22.09	02:20.58

High Pressure Calculations

TiO_2 Trials Salinities Converted from Electrical Conductivity

Trial #	Feedwater Salinity (ppm)	Brine Salinity (ppm)	Permeate Salinity (ppm)	Membrane Salt Rejection
Baseline Start	155	218.5	20.6	86.7
OH1	1,465	1,300	151.5	89.7
OH2	1,460	2,295	275	81.2
OH3	1,470	2,480	301.5	79.5
OH4	1,450	2,545	300.5	79.3
OH5	1,445	2,585	290.5	79.9
Baseline End	151.5	1,815	219.5	-44.9

TiO_2 Trials Flow Rates Converted from Times Elapsed and Volumes

Trial #	Feedwater Flow Rate (L/min)	Brine Brine Flow Rate (L/min)	Permeate Flow Rate (L/min)	Recovery Rate
Baseline Start	2.13	1.88	1.75	0.822
OH1	2.57	2.37	2.43	0.946
OH2	2.67	2.58	2.62	0.981
OH3	2.67	2.62	2.53	0.948
OH4	2.72	2.55	2.57	0.945
OH5	2.88	2.72	2.72	0.944
Baseline End	2.52	2.37	2.33	0.925

TiO_2 Trials Ratio of Feedwater to Permeate

Trial #	Feedwater:Permeate (mL:mL)
Baseline Start	1.99:1
OH1	1.72:1
OH2	1.98:1
OH3	2.08:1

OH4	2.13:1
OH5	1.98:1
Baseline End	2:1

TiO_2 Trials Changes in Temperature from Feedwater to Brine and Permeate

Trial #	Brine Temperature Change	Permeate Temperature Change
Baseline Start	4.6	6.5
OH1	5.6	6
OH2	5.3	5.9
OH3	5.6	6.5
OH4	4.5	6.9
OH5	5.7	7.2
Baseline End	4.8	6.7

Appendix E: Baseline Trials

Low Pressure Trials

Target Salinity Values vs. Actual Measured Values for Baseline Trials

Trial #	Target Value (ppm)	Target Volume (L)	Salt (g)
BLL1	1,000	2	2
BLL2	1,000	2	2
BLL3	1,000	2	2

Baseline Trials Feedwater Temperature

Trial #	Feedwater Temperature (℃)	Brine Temperature (℃)	Permeate Temperature (℃)
BLL1	21.5	23.8	21.9
BLL2	21.6	23.5	22.0
BLL3	21.7	24.1	22.3

Baseline Trials Pressure Measurement

Trial #	Feedwater Pressure (psi)	Brine Pressure (psi)
BLL1	41	31
BLL2	41	31
BLL3	41	31

Baseline Trials Volume Measurement

Trial #	Feedwater Volume (mL)	Brine Volume (mL)	Permeate Volume (mL)
BLL1	1,765	1,860	80
BLL2	1,760	1,700	105
BLL3	1,780	1,710	100

Baseline Trials Electrical Conductivity Measurement

Trial #	Feedwater EC	Brine EC	Permeate EC

BLL1	2.99 mS	1270 µS	55.4 µS
BLL2	2.99 mS	2.54 mS	457 µS
BLL3	3.00 mS	2.91 mS	712 µS

Baseline Trials Time Elapsed for Flow Rate Calculation

Trial #	Feedwater Time	Brine Time	Permeate Time
BLL1	00:50.56	00:57.94	00:46.81
BLL2	00:54.91	00:57.41	00:43.65
BLL3	00:54.36	00:56.37	00:43.93

Low Pressure Calculations

Baseline Trials Salinities Converted from Electrical Conductivity

Trial #	Feedwater Salinity (ppm)	Brine Salinity (ppm)	Permeate Salinity (ppm)	Membrane Salt Rejection
BLL1	1,495	635	27.7	98.15%
BLL2	1,495	1,270	228.5	84.72%
BLL3	1,500	1,455	356	76.27%

Baseline Trials Flow Rates Converted from Times Elapsed and Volumes

Trial #	Feedwater Flow Rate (L/min)	Brine Brine Flow Rate (L/min)	Permeate Flow Rate (L/min)	Recovery Rate
BLL1	2.09	1.93	0.10	0.048
BLL2	1.92	1.78	0.14	0.073
BLL3	1.96	1.82	0.14	0.071

Baseline Trials Changes in Temperature from Feedwater to Brine and Permeate

Trial #	Brine Temperature Change	Permeate Temperature Change
BLL1	2.3	0.4

BLL2	1.9	0.4
BLL3	2.4	0.6

High Pressure Trials

Target Salinity Values vs. Actual Measured Values for Baseline Trials

Trial #	Target Value (ppm)	Target Volume (L)	Salt (g)
BLH1	1,000	2	2
BLH2	1,000	2	2
BLH3	1,000	2	2

Baseline Trials Feedwater Temperature

Trial #	Feedwater Temperature (℃)	Brine Temperature (℃)	Permeate Temperature (℃)
BLH1	21.6	25.8	25.5
BLH2	21.7	26.2	26.0
BLH3	21.8	26.3	26.0

Baseline Trials Pressure Measurement

Trial #	Feedwater Pressure (psi)	Brine Pressure (psi)
BLH1	61	61
BLH2	61	61
BLH3	61	61

Baseline Trials Volume Measurement

Trial #	Feedwater Volume (mL)	Brine Volume (mL)	Permeate Volume (mL)
BLH1	1,700	1,150	580
BLH2	1,760	1,170	520
BLH3	1,730	1,190	510

Baseline Trials Electrical Conductivity Measurement

Trial #	Feedwater EC	Brine EC	Permeate EC
BLH1	2.98 mS	1787 µS	112.3 µS
BLH2	3.04 mS	3.24 mS	456 µS
BLH3	2.98 mS	4.06 mS	589 µS

Baseline Trials Time Elapsed for Flow Rate Calculation

Trial #	Feedwater Time	Brine Time	Permeate Time
BLH1	02:03.25	02:06.28	01:59.02
BLH2	01:59.87	01:52.19	01:50.54
BLH3	02:07.61	02:01.63	01:55.62

High Pressure Calculations

Baseline Trials Salinities Converted from Electrical Conductivity

Trial #	Feedwater Salinity (ppm)	Brine Salinity (ppm)	Permeate Salinity (ppm)	Membrane Salt Rejection
BLH1	1,490	893.5	56.15	96.23%
BLH2	1,520	1,620	228	85.00%
BLH3	1,490	2,030	294.5	80.24%

Baseline Trials Flow Rates Converted from Times Elapsed and Volumes

Trial #	Feedwater Flow Rate (L/min)	Brine Brine Flow Rate (L/min)	Permeate Flow Rate (L/min)	Recovery Rate
BLH1	0.83	0.55	0.29	0.35
BLH2	0.88	0.63	0.28	0.32
BLH3	0.81	0.59	0.26	0.32

Baseline Trials Ratio of Feedwater to Permeate

Trial #	Feedwater:Permeate (mL:mL)

BLH1	2.93:1
BLH2	3.38:1
BLH3	3.39:1

Baseline Trials Changes in Temperature from Feedwater to Brine and Permeate

Trial #	Brine Temperature Change	Permeate Temperature Change
BLH1	4.2	3.9
BLH2	4.5	4.3
BLH3	4.5	4.2