Team 13: H₂Osmosis

Project Proposal and Feasibility Study

8 December 2014
Executive Summary

This project investigates the feasibility of designing a green (optimizing use of renewable energy sources) desalination plant. This topic was chosen because currently desalination is an expensive process, particularly for countries that cannot afford to run such a plant on the traditional power sources. This summer, in Jamaica, there was a terrible drought, reinforcing the need for alternative methods of obtaining potable drinking water. The successful design of a sustainable desalination plant has remarkable implications for the future of the desalination industry.

The key variables that the team considered include method of desalination, energy source, durability, reparability and sustainability of plant, removal of waste, power source, and production capacity. The team ultimately decided on a design which uses a forward osmosis desalination process with a solar thermal separation unit to output seven million gallons of water per day over the three months (per year) of operation. This volume is expected to adequately supplement current drinking water supplies for Kingston’s 900,000 inhabitants.
# Table of Contents

© 2014 Emma Camilleri, Brianna Neil, Toyin Ogunsanya, Josh Schalk, Calvin College ........................................ 2

Executive Summary ................................................................................................................................. 3

Table of Contents .......................................................................................................................................... i

Table of Figures ........................................................................................................................................... iii

Table of Tables ........................................................................................................................................... iii

List of Abbreviations ................................................................................................................................... iv

1 Introduction ............................................................................................................................................... 1

2 Project Management .................................................................................................................................. 2

   2.1 Team Organization ............................................................................................................................... 2

   2.2 Schedule ............................................................................................................................................... 2

   2.3 Budget ................................................................................................................................................... 2

   2.4 Approach ............................................................................................................................................. 2

3 Requirements .............................................................................................................................................. 3

   3.1 Volume .................................................................................................................................................. 3

   3.2 Seawater Feed ...................................................................................................................................... 3

   3.3 Salt Content of Seawater ....................................................................................................................... 3

   3.4 Filtration and Pretreatments .................................................................................................................. 3

      3.4.1 Filtration ........................................................................................................................................ 4

      3.4.2 Pretreatments ................................................................................................................................. 4

   3.5 Post-Separation ................................................................................................................................... 5

      3.5.1 Salt Content .................................................................................................................................. 5

      3.5.2 Additional Purification .................................................................................................................. 5

      3.5.3 Brine Disposal ............................................................................................................................... 5

4 Design Alternatives .................................................................................................................................... 6

   4.1 Multi Stage Flash Distillation (MSF) .................................................................................................... 6

      4.1.1 Process Description ......................................................................................................................... 6

      4.1.2 Capacity ......................................................................................................................................... 6

      4.1.3 Energy Requirements .................................................................................................................... 6

      4.1.4 Water Inlet and Outlet Conditions ................................................................................................. 7

      6.2.1.5 Economics .................................................................................................................................. 7

   4.2 Multi-Effect Distillation (MED) .......................................................................................................... 7

      4.2.1 Process Description ......................................................................................................................... 7

      4.2.2 Capacity ......................................................................................................................................... 7
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.3</td>
<td>Energy Requirements</td>
<td>8</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Water Inlet and Outlet Conditions</td>
<td>8</td>
</tr>
<tr>
<td>4.2.5</td>
<td>Economics</td>
<td>8</td>
</tr>
<tr>
<td>4.3</td>
<td>Reverse Osmosis (RO)</td>
<td>8</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Process Description</td>
<td>8</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Capacity</td>
<td>9</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Energy Requirements</td>
<td>9</td>
</tr>
<tr>
<td>4.3.4</td>
<td>Economics</td>
<td>9</td>
</tr>
<tr>
<td>4.4</td>
<td>Forward Osmosis (FO)</td>
<td>9</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Process Description</td>
<td>9</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Energy Requirements</td>
<td>9</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Economics</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>Design</td>
<td>12</td>
</tr>
<tr>
<td>5.1</td>
<td>Design Norms</td>
<td>12</td>
</tr>
<tr>
<td>5.1.1</td>
<td>Justice</td>
<td>12</td>
</tr>
<tr>
<td>5.1.2</td>
<td>Caring</td>
<td>12</td>
</tr>
<tr>
<td>5.1.3</td>
<td>Stewardship</td>
<td>12</td>
</tr>
<tr>
<td>5.2</td>
<td>Design Criteria</td>
<td>12</td>
</tr>
<tr>
<td>5.3</td>
<td>Decision Matrix</td>
<td>13</td>
</tr>
<tr>
<td>5.4</td>
<td>Design Decisions</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>System Architecture</td>
<td>14</td>
</tr>
<tr>
<td>6.1</td>
<td>Proposed Process</td>
<td>14</td>
</tr>
<tr>
<td>6.2</td>
<td>Process Alternatives</td>
<td>14</td>
</tr>
<tr>
<td>6.2.1</td>
<td>Membranes</td>
<td>14</td>
</tr>
<tr>
<td>6.2.2</td>
<td>Osmotic Agents</td>
<td>15</td>
</tr>
<tr>
<td>6.2.3</td>
<td>Separation Units</td>
<td>17</td>
</tr>
<tr>
<td>6.2.4</td>
<td>Solar Energy</td>
<td>18</td>
</tr>
<tr>
<td>7</td>
<td>Testing</td>
<td>21</td>
</tr>
<tr>
<td>8</td>
<td>Conclusion</td>
<td>22</td>
</tr>
<tr>
<td>9</td>
<td>Acknowledgements</td>
<td>23</td>
</tr>
<tr>
<td>10</td>
<td>References</td>
<td>24</td>
</tr>
<tr>
<td>11</td>
<td>Appendices</td>
<td>28</td>
</tr>
<tr>
<td>11.1</td>
<td>Gantt Chart for PPFS</td>
<td>29</td>
</tr>
<tr>
<td>11.2</td>
<td>Separation Process Simulation using UNISIM</td>
<td>32</td>
</tr>
<tr>
<td>11.3</td>
<td>Output Calculation</td>
<td>33</td>
</tr>
</tbody>
</table>
Table of Figures
Figure 1: Salts present in seawater [3] ........................................................................................................ 3
Figure 2: Process flow diagram for multi-stage flash distillation (MSF) [13] .................................................. 6
Figure 3: Process flow diagram for multi-effect distillation (MED) [19] ......................................................... 7
Figure 4: Mechanism of osmosis and reverse osmosis [21] ......................................................................... 8
Figure 5: Capital Cost comparison between RO and FO at different capacities [23] ................................. 10
Figure 6: Comparison of a FO membrane system and a RO membrane system operating on a common feed water. [24] ................................................................................................................................. 11
Figure 7: Block diagram of the proposed FO process ................................................................................... 14
Figure 8: Photovoltaic Cell [48] .................................................................................................................. 19
Figure 9: Components of thermal solar energy collection method [46] .......................................................... 20

Table of Tables
Table 1: Comparison of energy consumption and desalination costs for different desalination processes [22] ................................................................................................................................................. 9
Table 2: Decision matrix for desalination method ......................................................................................... 13
Table 3: Characteristics of various Osomotic agents .................................................................................... 16
List of Abbreviations

AL-DS – Active Layer facing Draw Solution
AL-FS – Active Layer facing Feed Solution
CNT – Carbon Nanotube
CP – Concentration polarization
CTA – Cellulose Triacetate
DS – Draw Solution
EPA – Environmental Protection Agency
FO – Forward Osmosis
HTI – Hydration Technology Innovations
ICP – Internal Concentration Polarization
IOP – Internal Osmotic Pressure
MED – Multi Effect Distillation
MED/TVC – Multi Effect Distillation and Thermal Vapor Compression hybrid
MIGD – Million Imperial Gallons per Day
MSF – Multi Stage Flash Distillation
NF – Nanofiltration
OA – Osmotic Agent
OPEX – Operating Expenditure
PRO – Pressure Retarded Osmosis
RO – Reverse Osmosis
TDS – Total Dissolved Solids
TFC – Thin Film Composite
1 Introduction

This project attempts to address one of the fastest growing issues in the world today: availability of safe drinking water. On a planet that is 70% water, desalination of ocean water is not a new technological concept. However, currently used methods have proven to be very energy intensive, which poses a problem to smaller, poorer countries that find it too expensive to run such a plant. With the advent of exploitation of renewable energy sources and advancements made in increasing the efficiency of renewable energy processes, there is potential for the two concepts to be combined to create a process that is significantly more affordable.

This thought process coupled with our compassion for our fellow man as influenced by our Christian faith, nurtured and encouraged at Calvin College, forms the basis of our team’s desire to undertake this project.
2

Project Management

2.1 Team Organization

The work has been divided evenly among the team members. The team advisor is Dr. Jeremy VanAntwerp, and the industrial consultant is Mr. Randy Elenbaas. Meetings will be held twice a week, in which upcoming deadlines will be assessed, and tasks and research will be delegated to individual team members. Meeting minutes will be kept and sent to each team member via email after each meeting.

2.2 Schedule

A Gantt Chart has been the team’s primary method of scheduling, as it effectively breaks down the tasks that need to be completed in a visual manner, which is helpful in ensuring that we do not fall behind. This can be found in section 11.1 of the appendix. In addition, each week, short-term goals and deadlines are set, designating a task to each team member which they commit to completing within the span of a week. When schedule issues arise, the team maintains some amount of flexibility to compensate for the interruption but makes it a priority to get back on track as soon as possible.

2.3 Budget

The team’s project is entirely design-based, so allocating funds to construction will not be an issue. However, it is our hope to build a bench-top model of the forward osmosis process, and the membrane will have to be purchased. The team’s budget is $500 and it is expected that a bench-scale model could be created using most of that budget. No other expenses should be required for this project.

2.4 Approach

The team began by identifying the problem and potential solutions. There are two major components of our proposed solution, namely the desalination process and solar energy utilization. The team then went on to research several currently used desalination processes and compiled a list of 10 potential alternatives. A preliminary process of elimination was used to discard those alternatives which, for whatever very obvious reasons, would not be suitable for our problem. A secondary process of elimination rejected those alternatives that could not fulfill the output capacity requirements. This second process left the team with a list of four viable alternatives for our problem. Through the determination of design criteria and the construction of a decision matrix (explained in a later section), the team was able to select a final process on which to focus. Research then began on various solar energy collection methods and is currently on-going.
3 Requirements

3.1 Volume
Initial volume calculations were completed to estimate the volume of water needed per day. A local consultant estimated that residents of Kingston, Jamaica use 45 L/person-day. The population of Kingston is 937,700 according to the 2011 census [1]. Assuming that the plant will produce 25% of the total resident water consumption and that the plant will operate for 300 days/year, the total water output per day of the plant will be 12,800 m³/day.

3.2 Seawater Feed
Each desalination process requires an ocean water feed. This feed will come from a large pipe whose inlet is approximately one mile offshore. The pipe will be approximately 1.0 m in diameter based off a system of similar size [2]. Pumps will be required to bring the seawater from the ocean into the plant. Seawater is very corrosive, so all pipes and holding tanks must be constructed from materials which are not easily corroded.

3.3 Salt Content of Seawater
Seawater is approximately 3.5% salts by weight. The salts in seawater are mainly sodium, chlorine, sulfate, calcium, and potassium. Figure 1 below shows the approximate salt compositions.

Figure 1: Salts present in seawater [3].

3.4 Filtration and Pretreatments
Initially, the seawater will need to be pre-treated before desalination. The first step will be multiple filtrations. The pretreatment step depends on the type of desalination. While distillation processes require little pretreatment, membrane processes require more extensive treatment to prevent membrane fouling.
3.4.1 Filtration
Filtrations of the initial seawater feed are required before the seawater is desalinated. The seawater feed will likely contain algae, bacteria, sand, and other large solid particles such as small rocks, plants, and sticks. The four different types of filters that may be used are bed filters, rotary filters, plate-and-frame filters, and leaf filters [4].

3.4.1.1 Bed Filters
Bed filters are the simplest type of filter. It is comprised of layers of solid particles with the largest particles on the bottom and finer particles on top. Water flows from the top of the bed and out through slots in the bottom plate. This type of filter is most often used when small amounts of solids need to be removed [4].

3.4.1.2 Rotary Filters
This type of filter is a continuous process. Slurry enters a rotating drum that undergoes drying, washing and the cake remaining on the drum is sliced off every rotation. This type of filter may only be used if the cake is compressible [4].

3.4.1.3 Plate-and-Frame Filters
This type of filter uses a piece of cloth (plate) stretched across a frame. The slurry flows across the plate and filtrate flows through while particulates collect on the plate. This type of filter has disadvantages similar to batch processes. The plate must regularly be removed, cleaned, and replaced [4].

3.4.1.4 Leaf Filters
Leaf filters were developed for larger volumes of slurry but cannot handle large volumes of sludge. Leaves, which are hollow wire frameworks covered by a filter cloth, are hung in parallel in a tank. The slurry enters the tank and is forced through the leaves by pressure differences. Leaf filters often require a large volume of wash water [4].

The large solid particles are incompressible, which limits the types of filters that may be used in the initial filtration. Bed filters and rotary filters are not suitable for these filters. Leaf filters include an unnecessary washing step; therefore, plate-and-frame filters are likely the optimal type of filter for the initial solid filtration.

Further filtration of algae and smaller solid particles such as sand may be accomplished in bed filters. Rotary filters still may not be used due to the incompressible nature of sand particles and the washing step included in the leaf filtration process is not necessary. Either bed filters or plate-and-frame filters are likely the best design for the secondary filtration steps. Once all solid particles have been removed, pretreatment of the seawater must occur to prevent fouling of the membrane.

3.4.2 Pretreatments
For membrane desalination processes, pretreatment must include purification steps to rid the seawater of microbes, algae, organic compounds, inorganic minerals, and oxidants. This will prevent fouling of the membrane. The typical pre-treatment process for reverse osmosis membranes involves three main steps: coagulation to remove colloidal matter, precipitation to remove slightly soluble salts, and granular media packed-bed filtration to remove particles larger than a few micrometers or smaller than 0.1 μm [5].

During coagulation, an inorganic coagulant, such as iron salts, is introduced to the water, and it binds to small suspended solid particles by neutralizing the charges which cause the particles to repel each other. The water is then slowly stirred to allow the coagulated bits to stick together and form larger chunks called flocs, which fall to the bottom of the sedimentation tank and are removed by basic filtration [6]. During the precipitation step, calcium carbonate or calcium sulfate is added to the water in small
quantities, and when done in conjunction with pH control, slightly soluble salts will precipitate out of solution. The filtration step involves passing the water through a packed bed of sand, anthracite, pumice, gravel or garnet, and removes the last of the particulates in the water [5]. As a final step, the water may be disinfected by chlorination or ultraviolet (UV) light to remove microbes and bacteria. However, since most membranes are sensitive to chlorine, UV disinfection is the more appropriate choice. It involves introducing a UV light source to a stream of water, and as the UV rays are absorbed by the microbes, it rearranges their DNA, making them incapable of further reproduction and thus rendering them effectively dead [7].

3.5 Post-Separation
3.5.1 Salt Content
The desalination product must be below the safe limit for the salinity of drinking water, which is 1000 ppm, but the process will comply with the voluntary EPA standard of 500 ppm. [8]

3.5.2 Additional Purification
The desalination process will require large holding tanks for the desalinated ocean water. This water will need to undergo further treatments to be used by the municipality. For this treatment, the desalinated water will be transported to one of the current water purification reservoirs in Jamaica. A pH balance may be required at the end of the desalination process to safely add the water to the reservoir. From these reservoirs, the water will undergo a purification process and be distributed to the municipality. This purification process must meet Jamaica’s federal drinking water standards.

3.5.3 Brine Disposal
Brine must be disposed of properly for each process. Holding tanks for the brine will be required until it can properly be disposed of or sold. Brine is very corrosive; therefore, metals which are not easily corroded must be used.

In the Middle East, where desalination is common, the majority of brine is disposed of in the sea [9]. This can be harmful to the natural aquatic ecosystem, affecting coral species, mollusks, and echinoderms [9]. An alternative to marine disposal is inland disposal, where brine is either evaporated by open exposure to the air or injected into the ground below the water table through deep well injection [9]. However, deep well injection requires an intensive study of nearby aquifers and careful construction. Evaporation requires a large amount of land area and can cause environmental concerns if done directly on land.

An alternative to disposing the brine is selling the brine to the Morton Salt facility in Inagua, Bahamas [10]. Though there is no reliable source about the size of the plant, the company’s website lists this as a solar salt plant [11]. Solar salt is produced by evaporating brine in open ponds. Selling the brine to Morton would reduce the environmental impact of the plant, and it could make the plant more economically feasible for Jamaica.
4 Design Alternatives

4.1 Multi Stage Flash Distillation (MSF)

4.1.1 Process Description

The system uses a series of evaporators. Seawater is pumped into the system from the sea and enters at the top of the nth stage (the rightmost stage). This cool sea water then is preheated as it flows through condensing coils (which also condenses the flashed steam in the evaporators). The preheated seawater then exists the top of the 1st stage (the leftmost stage) to be heated to between 90-110°C [12] in a heater. This vapor is then sent to the bottom of the same first stage to be flashed. The water vapor rises and is condensed into a collector at the top while the concentrated brine settles at the bottom. Both the vapor and the concentrated brine are both sent to the next stage. This continues until the nth stage as shown in Figure 2 below. The distillate (fresh water) is collected at the top of the nth stage and the bottoms (brine) is collected at the bottom.

Figure 2: Process flow diagram for multi-stage flash distillation (MSF) [13].

4.1.2 Capacity

MSF is known to have very large capacity per unit (20 MIGD); however, MSF plants cannot operate below 70% capacity [14].

4.1.3 Energy Requirements

MSF is very energy intensive and requires energy in two forms/stages:

1. About 3-4kWh/m³ of electrical energy for processes such as pumping of water and pulling a vacuum in subsequent flash stages.
2. About 70kWh/m³ of thermal (fuel) energy for thermal processes such as heating the brine [14].

The thermal energy requirements far outweigh the electrical energy requirements. The main energy problem therefore, would be trying to efficiently use solar energy to mitigate the use of conventional energy sources especially with the thermal energy requirements since solar energy is more efficiently converted to thermal energy than electrical energy??
4.1.4 Water Inlet and Outlet Conditions
The MSF process is insensitive to initial feed concentrations and the presence of suspended solids; therefore, pretreatment not as important. The main major process involved is just heating to get pure water. Because of this, pretreatment units for filtration or chlorination are not required [14]. On the other end of the system, MSF is known to produce pure water at its outlet. The Total Dissolved Solids (TDS) at the outlet is recorded to be between 5 to 50 ppm [14].

6.2.1.5 Economics
MSF is very expensive due to a high initial capital cost and energy cost, especially electrical energy. The cost per volume of desalinated water is approximately between $0.8-1.5/m³ of desalinated water [14]. However, this number is on a decline and is expected to be as low $0.3/m³ in 2025. This decline in cost is due to better and more efficient MSF processes due to advancement in technology. In terms of capital and investment, this cost is still high compared to other desalination methods. The process requires between $1200 – 1500 /m³/day investments [14].

4.2 Multi-Effect Distillation (MED)
4.2.1 Process Description
This process is very similar to the MSF process in that it consists of a series of evaporators. However, MED is known to be more energy efficient than MSF and requires fewer effects (stages) to desalinate sea water [16]. Evaporation in the first effect is driven by heat steam extracted from cogeneration boilers. The vapor formed in the first effect is used to drive evaporation in the second effect. This process continues in subsequent effects until the vapor temperature drops to about 30–40°C [17]. This operates on the principle of decreasing the ambient pressure at each stage so boiling can occur at the different effects without having to supply additional heat to each effect [18]. This process is illustrated below in Figure 3:

![Figure 3: Process flow diagram for multi-effect distillation (MED) [19].](image)

4.2.2 Capacity
MED is known to have medium to large capacity and can produce up to 15 MIGD. However, MED plants also cannot operate below 70% capacity [14].
4.2.3 Energy Requirements
MED, like other thermal desalination techniques (MSF) is very energy intensive. To decrease energy consumption MED is usually combined with vapor compression. These are called MED/TVC. Energy is required as electrical and thermal in this case. It requires 38kWh/m³ in form of thermal energy and 1.5kWh/m³ in form of electrical energy [14].

4.2.4 Water Inlet and Outlet Conditions
The MED process is also insensitive to initial feed concentrations since it also just involves boiling of the sea water to get pure water. However, the presence of suspended solids is to mitigated [14]. At the outlet, the TDS is similar to that of MSF – i.e. between 5 to 50 ppm [14].

4.2.5 Economics
MED is thermodynamically more efficient than MSF and therefore not as expensive. MED requires a capital cost of about $3.5-4.5 per installed gallon/day with a cost per volume of desalinated water of approximately between $0.8-1.5/m³ of desalinated water [15]. In terms of capital and investment, the process requires between $900 – 1000 /m³/day investments [15].

4.3 Reverse Osmosis (RO)
4.3.1 Process Description
RO operates by forcing pressurized seawater across a semi-permeable membrane that only allows water to pass through, leaving the salt and other impurities behind. The natural process of osmosis is that water flows from high salt concentrations to low. The seawater must be pressurized to overcome the osmotic pressure created by this natural process of osmosis (see Figure 4). The amount of applied pressure to overcome the osmotic pressure typically ranges from 55 to 75 bar. The recovery ratio of fresh water created to seawater fed ranges from 40% to 45% for RO [20]. Aside from the heat required for disinfecting, there are no thermal processing steps required for RO, making it rely solely on electrical energy. One advantage that reverse osmosis has over the distillation processes is that the energy required for desalination is a function of salinity, which is advantageous for treating seawater with low salinity [9]. However, RO requires more pretreatment to prevent membrane fouling and scaling. This additional purification step makes RO require larger plants than MSF or MED.

![Figure 4: Mechanism of osmosis and reverse osmosis [21].](image-url)
4.3.2 Capacity
While the current capacity for RO technology is 200,000 m³/day [20], there are plants that use a hybrid of RO and MSF that can produce of 455,000 m³/day [9].

4.3.3 Energy Requirements
The energy requirement for RO plants ranges from 3.5 kWh/m³ to 4.3 kWh/m³, depending on the salt content of the water [20].

4.3.4 Economics
While RO doesn’t require heat, the membranes are usually replaced once every 4 years due to membrane fouling. The operating expenditures (OPEX) for a typical RO plant is 0.47 US$/m³, which is lower than those of MSF ($0.54/m³) or MED ($0.65/m³). However, the capital cost is comparable to the distillation methods [20].

4.4 Forward Osmosis (FO)
4.4.1 Process Description
Forward osmosis (FO) utilizes the natural process of osmosis (Figure 4) to facilitate the travel of water across a semi-permeable membrane. In desalination, the feed seawater is exposed to the surface of a membrane that has a more concentrated solution, called the draw solution (DS), contacting its opposite surface. This concentration gradient causes water to flow from the seawater to the DS to shift the solutions towards equilibrium with each other. The solute in the DS is called the osmotic agent (OA), which is chosen with the criterion that it is more easily separated from water than the salts in seawater. Once the water is transferred, it can be separated from the OA through various separation processes that depend on the OA chosen. The advantage to FO is that the energy required to separate the water from seawater is negligible, making the majority of the energy required to produce freshwater dependent on the OA and separation process chosen. This provides flexibility for optimization. The primary disadvantage of FO is that it is a new process that is still under development, making few resources available for industrial applications.

4.4.2 Energy Requirements
As stated previously, the energy requirement of a FO system is considerably lower than other traditional desalination methods because the energy to separate the seawater contents from water is effectively negligible. The bulk energy requirement of the system would be to separate the freshwater from the OA of choice which is easier to achieve than separating freshwater from seawater directly. This reasoning is portrayed by Table 1 below.

Table 1: Comparison of energy consumption and desalination costs for different desalination processes [22]

<table>
<thead>
<tr>
<th>Process</th>
<th>Energy consumption [kW/m³ freshwater]</th>
<th>Desalination cost [$/m³ freshwater]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSF</td>
<td>26.4-80</td>
<td>0.7-5.4</td>
</tr>
<tr>
<td>MED</td>
<td>26.4-76.4</td>
<td>0.3-1.5</td>
</tr>
<tr>
<td>RO(seawater)</td>
<td>2.4-8.3</td>
<td>0.4-6.6</td>
</tr>
<tr>
<td>FO</td>
<td>0.8-1.6</td>
<td>0.4-0.7</td>
</tr>
</tbody>
</table>
4.4.3 Economics

According to tests performed by a current FO company, Trevi Systems, FO systems excel at large capacities. This is depicted in Figure 5 below. The capital cost is consistently lower than that of RO systems. Also, the overall cost per volume of freshwater produced is less for FO than that of RO systems as shown in Table 1: Comparison of energy consumption and desalination costs for different desalination processes [22] above.

![Capital Cost vs System Size](image)

Figure 5: Capital Cost comparison between RO and FO at different capacities [23]

Another contributor to the cost is membrane replacement. Results of a comparison between RO and FO membrane systems to a common feed water source is shown in figure 6 below and from this plots, it is clear that FO has lower fouling than RO [24]. This makes it more practicable to use FO for purifying a more concentrated water source (seawater as opposed to brackish water). This also shows that it is more economically viable to use a FO system than an RO system which would require more membrane replacement.
Figure 6: Comparison of a FO membrane system and a RO membrane system operating on a common feed water. [24]
5 Design

5.1 Design Norms

5.1.1 Justice
Access to drinking water is a basic human right [25]. However, in a recent study by UNISEF and WHO, it was found that there are over 780 million people worldwide without access to an improved water source, meaning something other than a natural body of water [26]. In Jamaica, it was found that 7% of the population lacks access to an improved water source. This number excludes the lack of water due to the yearly droughts that the country experiences. This project aims to create an improved water source for those without access and also to provide water for those who lose access to water in droughts.

5.1.2 Caring
While the majority of the US doesn’t experience this need for freshwater, this project demonstrates caring for the wellbeing of other countries. This project will meet a physical human need, and aims to promote socio-economic development through the creation of jobs and by providing water for industries that currently have to halt production during a drought.

5.1.3 Stewardship
Most desalination processes require large amounts of energy to achieve the separation of salt from seawater. Current renewable energy technologies are unable to provide the energy required by these processes, making desalination rely heavily on traditional energy sources. Two of the primary goals of the project have been to find a process that requires less energy than current processes and one that can utilize renewable energy. This will aid in the conservation of natural resources and reduce harmful emissions that are a result of fossil fuel use. Additionally, the brine created from the process will be disposed of in a manner that does not negatively affect the environment.

5.2 Design Criteria

Energy Requirements: This is the amount of energy each method requires. On the design matrix (Table 2) this was given a high rating of 10 because one of the primary focuses of the project is to design an energy efficient process. Each method was rated from 1 to 10 with higher ratings requiring the less energy and lower ratings requiring more energy.

Capacity: This is the known amount of freshwater output each method can produce. On the design matrix, this was given a rating of 5 because the population of the case study (Kingston, Jamaica) is not too high and so therefore would not require that much output. Each method was rated from 1 to 10 with higher ratings having more capacity than lower ratings.

Innovation: This describes the possibility for expansion on existing research. On the design matrix, this was given a rating of 5. Though not a primary criteria, this was decided on based on team’s personal preference rather than technical need. Each method was rated from 1 to 10 with high ratings indicating more possibility for expansion and lower ratings indicating less.

Existing Research: This is the availability of research and data from existing desalination technologies. On the design matrix, this was given a rating of 4. This is also not a primary criteria, however, this project is more theoretical than experimental, and therefore, our results and conclusions would be based on existing research. Each method was rated from 1 to 10 with high ratings indicating the method with more research and data available and lower ratings indicating less availability.

Operating Cost: This includes annual costs primarily membrane replacement costs for membrane processes (FO and RO). On the design matrix, this was given a rating of 9. Once again, the design must
be affordable for municipalities like Kingston, Jamaica as per the project definition. Each method was rated from 1 to 10. Higher ratings indicate less operating cost and lower ratings indicate more operating cost.

**Capital Cost:** This is the initial investment required to build and start up the plant. On the design matrix, this was given a rating of 6. This is because, though we want it to be affordable, we still recognize that the cost would be considerably high no matter the method that was picked. Each method was rated from 1 to 10. In this case, higher ratings indicate less investment and lower ratings indicate more investment.

**Possibility for Solar:** This is the possibility of the combination of a desalination technology to solar energy. This is mostly based on the fact that solar energy is not very efficiently converted to electrical energy. On the design matrix, this was given a rating of 10 as the project definition requires solar energy incorporated in the design. Each method was rated from 1 to 10 with higher numbers indicating methods with the more possibility of solar energy incorporated and less numbers indicating less possibility.

**Feed Conditions:** This ranks how well each method handles different ocean water inlet compositions. It indicates how independent each method is of the inlet conditions. On the design matrix, this was given a rating of 7. Each method was rated from 1 to 10 with higher numbers indicating methods whose function depends on the inlet water conditions while lower ratings indicates methods whose function do not depend on inlet water conditions. In other words, highly rated methods require more pretreatment processes than lower rated methods.

### 5.3 Decision Matrix

Table 2: Decision matrix for desalination method.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>FO</th>
<th>RO</th>
<th>MED</th>
<th>MSF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>10</td>
<td>9</td>
<td>5</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td><strong>Capacity</strong></td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td><strong>Innovation</strong></td>
<td>5</td>
<td>10</td>
<td>7</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td><strong>Existing Research</strong></td>
<td>4</td>
<td>3</td>
<td>8</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td><strong>Operating Cost</strong></td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td><strong>Capital Cost</strong></td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td><strong>Possibility for Solar</strong></td>
<td>10</td>
<td>9</td>
<td>6</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>Feed Conditions</strong></td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>-</td>
<td>374</td>
<td>294</td>
<td>241</td>
<td>206</td>
</tr>
</tbody>
</table>

### 5.4 Design Decisions

Due to the scope of this project, each of the desalination processes were researched in detail before a decision was made. From the criteria above, FO was chosen. FO was particularly attractive due to its low energy requirements and potential for expansion. Section 6 System Architecture lists the proposed FO process, and alternatives to be considered for the final design. Further research and calculations will be done to determine the optimal OA, membrane design, and processes to separate the OA from water.
6 System Architecture
6.1 Proposed Process
While various separation units can be used to separate the OA from the fresh water, the general process for desalination using FO is below in Figure 7. Pretreated seawater is fed to a membrane contactor where it comes into contact with the DS, which is at a higher concentration of solute-to-water than the seawater. Through the natural processes of osmosis, the water from the feed seawater will travel across the membrane to the DS, leaving behind NaCl and other impurities in the leftover brine, which can be disposed of or processed to be sold. The diluted DS is then fed to a separation unit, where the properties of the OA can be manipulated so that the freshwater can be separated from the OA with a relatively small amount of energy. The resulting DS is then returned to the membrane contactor. A detailed equipment list can be found in section 11.4 of the appendix.

Figure 7: Block diagram of the proposed FO process.

6.2 Process Alternatives
6.2.1 Membranes
One of the main challenges facing forward osmosis is lack of membrane technology, but studies are being performed to find a membrane that will improve FO to make it competitive with RO on the industrial scale [27]. While the science behind FO membranes is similar to that of RO membranes, RO membranes cannot be used in FO operations because they are built to withstand the high operating pressures of RO, which increases the effects of internal concentration polarization (ICP) [28]. ICP describes the resistance to diffusion caused by the accumulation of solutes close to the DS side of the membrane. While both osmosis processes experience concentration polarization (CP), ICP is unique to FO because of the presence of solutes on both sides of the membrane. Thus alternative materials and structures have been researched to create a membrane suitable for FO use that minimizes the effects of CP and promotes natural water flux.

6.2.1.1 Symmetricity
Symmetric membranes are membranes that consist of a dense, porous layer of material that is selectively permeable to the feed solvent. Since this material actively promotes osmosis, it is referred to the active layer. Asymmetric membranes consist of an active layer in addition to a support layer, which provides physical support to the membrane. Due to the high pressures required in industrial applications, asymmetric membranes are preferred to symmetric membranes because of the support layer [29]. Symmetric membranes, however, experience greater flux because the support layer blocks some of the pores in the active layer. Thus, asymmetric membranes with minimal support layers are preferred.

6.2.1.2 Orientation
The orientation of the active layer also plays a role in the flux across a membrane. The active layer facing the feed solution (AL-FS) or FO mode is preferred for desalination, because the feed water foulants are
deposited on the active layer, where they can be removed more easily [30]. This orientation usually results in a lower flux across the membrane than if the active layer were facing the draw solution (AL-DS), which is also referred to as pressure retarded osmosis (PRO) mode, but AL-FS mode is justified due to its ease of cleaning and anti-fouling characteristics [30].

6.2.1.3 Hydrophilicity
Hydrophobic membranes have the advantage of high salt-rejection. The only way water can transport across a hydrophobic membrane is if it vaporizes, leaving the solute behind. This is accomplished though a partial pressure gradient created by a maintained temperature gradient across a membrane. However, the primary disadvantage of hydrophobic membranes is the low water fluxes caused by [31]. Hydrophilic membranes produce better water fluxes, since they allow water to freely flow through the membrane [32]. However, the pores must be specially designed to prevent solute flow.

6.2.1.4 Common Types
Early commercialized FO membranes were cellulose triacetate (CTA) membranes [31]. These membranes work well with water containing chlorine dioxide, which is a common disinfectant in the pretreatment of water. However, advancements in thin-film composite (TFC) membrane technology have made CTA membranes obsolete for FO desalination, due to the relatively low pure water permeability and the sensitivity to certain draw solutions of CTA membranes [28]. TFC membranes are asymmetric polymer-based membranes that are generally composed of multiple polymers, because membranes composed of a single polymer usually have low permeability and selectivity [33]. While TFC membranes generally have a longer life, are more selective, and are compatible with a wide range of draw solutions, chlorine dioxide degrades TFC membranes, thus limiting the pretreatment process.

6.2.1.5 Other Types
At the time of this study, the highest observed water flux across a FO membrane has been observed in a TFC membrane containing immobilized counter ions, which create an internal osmotic pressure (IOP) that reduces the effects of ICP [30]. One study found that a coating of Ag and TiO₂ particles reduces membrane fouling and eases the membrane cleaning process [34]. While flat sheet membranes are common, a hollow-fiber TFC membrane has been tested, showing comparable flux to the flat sheets [35]. Other membrane alternatives include Biomimetic and Carbon Nanotube (CNT) membranes. These membranes have high selectivity, demonstrate relatively high flux, and do not require the use of a draw solution [31]; however, such membranes are expensive due to their complex structure [36].

6.2.2 Osmotic Agents
Desirable properties for a DS are high osmotic pressure, high molecular weight, high solubility in water, and large changes in solubility with temperature or pH [37]. Undesirable properties for a DS are toxicity, membrane corrosivity, polymerization, and high potential for inductively coupled plasma (ICP). Potential species for OAs are represented in Table 3: Characteristics of various Osmotic agents. [O7] [38]. While ionic salts are commonly used due to their high osmotic potential, the separation processes are limited and similar to those used for traditional desalination. Thus, multiple OA species will be studied.
Table 3: Characteristics of various Osmotic agents.

<table>
<thead>
<tr>
<th>Osmotic Agent</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic compounds</td>
<td>Multiple liquid phases for extraction</td>
<td>Possible toxicity, flammability, or membrane permeation</td>
</tr>
<tr>
<td>Polymer Surfactants</td>
<td>High osmotic pressures, large changes in solubility with temperature</td>
<td>Possible precipitation as coagel</td>
</tr>
<tr>
<td>Ammonium Bicarbonate</td>
<td>High salt rejection, easy separation from water</td>
<td>Decomposition of OA during separation, produces CO2 gas</td>
</tr>
<tr>
<td>Ionic salts</td>
<td>High osmotic potential</td>
<td>Properties similar to NaCl, costly consumables, toxic byproducts</td>
</tr>
<tr>
<td>Thermosensitive polyelectrolytes</td>
<td>Easy, high water recovery</td>
<td>High operating cost unless low grade heat is used</td>
</tr>
<tr>
<td>Magnetic/Functionalized nanoparticles</td>
<td>Easy separation, energy efficient, environmentally friendly</td>
<td>Expensive</td>
</tr>
<tr>
<td>Polymer hydrogels</td>
<td>Energy efficient, environmentally friendly</td>
<td>Poor water recovery, unsuitable for continuous FO processes</td>
</tr>
<tr>
<td>Divalent salts</td>
<td>Low operating cost, high water recovery rate, high salt rejection</td>
<td>Limited to divalent salts with multivalent ions</td>
</tr>
</tbody>
</table>

6.2.2.1 Organic Compounds
Organic compounds that are hydrophilic can be used as an OA in FO desalination. Most often, these organic compounds are polymer chains such as polymer surfactants and hydrogels. These organics are separated by physical means and not thermal means [12].

6.2.2.2 Polymer Surfactants
Surfactants are chemicals added to a system to reduce surface tension. Surfactants assist in creating emulsions, which are mixtures of two immiscible fluids, of organic agents and water. The separation of surfactants from water is very difficult and leads to the formation of coagels, which are toxic.

6.2.2.3 Ammonium Bicarbonate
Ammonium Bicarbonate was another OA considered for this process. According to lab-scale experiments, ammonium bicarbonate solutions have a high rejection rate from the semipermeable membranes used by FO processes. The DS is separated from water via thermal separation, during which the ammonium salts decompose into ammonia and carbon dioxide gas [39]. The cost of the consumables of this separation increases the cost of desalination by $0.4 per 100 L of fresh water produced [40].

6.2.2.4 Ionic salts
Aluminum, Magnesium, and Cupric salts can be used as OAs as well. These salts are energy efficient, but the salts can only be separated by precipitation with hydroxides. The consumables can be very costly. Also, the reaction with the hydroxides can produce coagulant byproducts. These byproducts are toxic [38].

6.2.2.5 Thermosensitive Polyelectrolytes
Thermosensitive polyelectrolytes are another possible OA. Polyelectrolytes are a group of cross-linked hydrophilic polymers, similar to polymer hydrogels. The absorption capacity of these polymers groups is temperature-sensitive; therefore, these polymer groups are more easily separated from water than polymer
hydrogels [41]. This separation is accomplished through hot ultrafiltration. However, a high operating cost is required for the separation unless low grade heat is used [38].

6.2.2.6 Magnetic/Functionalized Nanoparticles
Nanoparticles may also be used for FO desalination. Magnetic nanoparticles are separated from water through the use of magnets. Functionalized nanoparticles are very reusable and very energy efficient [38]. However, both types of nanoparticles are very expensive and are not widely available.

6.2.2.7 Polymer Hydrogels
Polymer hydrogel agents were one of the OAs considered for this process. Hydrogels are created by crosslinking hydrophilic polymer groups together. Because of the hydrophilic nature of the polymer groups, hydrogels can absorb large amounts of water without dissolving. This ability makes polymer hydrogels ideal to use as an OA [42]. Hydrogels are energy efficient when used in FO processes and they are environmentally friendly. However, the separation of water from the polymer hydrogels is very difficult. There is conflicting evidence about whether or not hydrogels are useful for continuous FO processes. Some studies indicate that the water recovery is low during the separation of hydrogels from water [38].

6.2.2.8 Divalent Salts
Divalent salts, when used as an OA, can be separated from water via nanofiltration. This OA creates a high salt rejection during the desalination process, which causes this OA to have a low operating cost. Divalent salts also have a high recovery rate during their separation from water. However, only salts with multivalent ions will be effective for FO separation [38].

6.2.2.9 Design Criteria for OAs
Design criteria for OAs include toxicity, cost of raw materials, cost of separation of the OA from water, availability of the OA, purity of output water, membrane sensitivity, and the lifetime of the OA.

6.2.3 Separation Units
In order to justify the use of FO to achieve the goal of lowering the cost of desalination, it is important to choose a separation step that consumes little or no OA. The type of separation unit depends on the OA used. Various distillation techniques could be used for most OAs; however, this step would require nearly the same energy as treating the seawater directly with distillation would, making the FO step impractical. For OAs with solubilities that change significantly with temperature, a crystallizer with a solar-powered refrigeration cycle can be used.

While a thermal separation unit would be preferred because it would use solar thermal energy, other separation units are a possibility as well. For example, an air stripper could be used to separate highly volatile OAs from the fresh water. However, this could require a large amount of energy, because it will involve circulating large volumes of air [43]. Additionally, a nanofiltration (NF) or RO unit could be used to separate solid OAs from the fresh water. This approach is known as a manipulated osmosis process [37].

Ion exchange is another very effective process for desalting water. However, for desalination, the applicability of ion exchange is generally limited to polishing. The reason for this is that the consumption of expensive acid and base during the regeneration of the exchanger scales directly with concentration of salt to be removed, and the process soon becomes cost prohibitive [43]. This then leaves us with either chemical precipitation or crystallization.
6.2.3.1 Chemical Precipitation
Chemical precipitation involves the addition of a different chemical (e.g. ethanol or H₂SO₄) to react with the OA and form a precipitate so that freshwater can then be obtained. This process however, is dependent on the type of OA used. Two different scenarios (based on the OA chosen) would need to be investigated. The first scenario would be the formation of a precipitate that could have some market value. The second scenario would be where the reaction resulting in precipitation is readily reversible in a different separation unit.

6.2.3.2 Crystallizer
A crystallizer can be used to separate OAs when the solubility for the OA is highly temperature dependent. This process can therefore incorporate solar thermal energy for either evaporative crystallization or cooling crystallization.

6.2.3.3 Simulation
This process was simulated on UNISIM with a component splitter as the separation unit. NaCl was modeled as the OA and was entered as a hypothetical component with constants and properties deduced from [44] while solubility values were derived from [45]. Though not very accurate, this gives a ball-park estimate of energy requirement for the crystallizer (6.4 * 10¹⁰ kW). A report of this results is attached in the section 11.2 of the appendix. Based on the 50% recovery rate of RO and the best observed flux across a FO membrane, a preliminary calculation for the seawater input was performed (Appendix 11.3). The amount of seawater feed needed was calculated to be 6.16 * 10⁵ m³/hr.

6.2.4 Solar Energy
There are two main methods of capturing solar energy: solar thermal and photovoltaic energy. The solar thermal method uses a heat transfer medium to collect heat from solar radiation. This heat can then be converted to electrical energy. The photovoltaic method uses semiconductors to convert solar radiation directly into electrical energy [46]. For this project solar thermal will be focused; however, photovoltaic will also be considered.

The photovoltaic method begins by exposing a radiation collection cell to sunlight. The photons are absorbed onto the negative (n-type) surface of the cell. When a certain amount of photons have been absorbed, electrons are released from the semiconductor. These electrons migrate to the positive (p-type) surface of the cell and this creates a voltage drop across the cell. The voltage drop across the cell then can be thought of as a battery. When a load is attached to the cell, the electrons will be free to move through the system and electrical current will be created. The system will then be able to provide electrical power [47]. Figure 8 shows this process.
There are different types of units that are used to collect solar radiation for solar thermal processes [46]. One type of solar radiation collection is a solar panel. The solar panel includes a mirror on which radiation is captured and concentrated. Various shapes of solar panels mirrors are flat, curved, and parabolic dish-shaped. Other collection units include solar ponds, evacuated tubes, solar chimneys, linear Fresnel reflectors, parabolic troughs, and heliostat field collectors [46].

This radiation then is transmitted to a receiver. Types of receivers include tubular receivers, volumetric receivers, heat-pipe receivers, and solid-state receivers. Tubular and volumetric receivers involve contacting radiation with a circulating working fluid. These types of receivers are used to convert radiation to usable thermal energy. Heat-pipe receivers use a liquid-vapor mixture at its boiling point. When radiation heats areas of this mixture, the liquid will evaporate. This creates a high conductivity, which can be used to generate electrical energy. Solid-state receivers use semiconductor materials to directly produce low voltage, direct current electric power. Both heat-pipe and solid-state receivers are used to convert radiation to electrical energy [46].

This radiation is then converted to a different form of energy. If the process is a solar thermal process, the radiation is converted to thermal energy. Heat transport media include oil, steam, air, molten salt, or chemical systems as heat transfer mediums. In some processes, the thermal energy is then converted to electrical energy by a Rankine cycle, a Stirling engine, or a Brayton cycle [46]. Figure 9 shows the general process for solar energy collection and conversion.
Solar ponds are another type of solar thermal collection. Solar ponds use a small pond instead of a solar panel as the radiation concentrator. The rest of the process is very similar to the solar panel collection method. This type of radiation collection is good for using solar thermal energy to generate electricity [49].
Testing

Hydration Technology Innovations (HTI) sells FO membrane samples for the purposes of advancing research in the technology [50]. They offer a Basic FO membrane kit that includes 9 CTA membranes or 6 TFC membranes in 1 ft² sheets for $200. With this and a draw solution, we should be able to simulate the process on the bench scale. While a flow process scale model would be ideal, this may not be feasible with the equipment available and the project budget. Thus the process may have to be simulated with individual unit process. Simulations of this plant design will be also performed using UNISIM with created hypothetical components for the salts.
8 Conclusion

It was determined by the group that FO presents a possible solution to the high operating cost of desalination facilities. By using FO technology instead of RO, MSF, or MED processes, the power and thermal energy required for desalination are greatly reduced. And by using solar-thermal energy, energy costs are reduced as well.

In February, the team will begin the design and modeling of various forward osmosis desalination processes using combinations of the process alternatives mentioned above. These processes will be evaluated upon energy requirements, operating and capital costs, and environmental impact.
9 Acknowledgements
The team would like to thank Professor Jeremy VanAntwerp and Randy Elenbaas for their guidance throughout this design process. The team would also like to thank Calvin College for providing the resources to make the research required for this project possible.
10 References


[30] Zhengzhong Zhou, Jim Yang Lee, Tai-Shung Chung, “Thin film composite forward-osmosis membranes with enhanced internal osmotic pressure for internal concentration polarization reduction”,


11 Appendices
11.1 Gantt Chart for PPFS ................................................................. 29
11.2 Separation Process Simulation using UNISIM ...................... 32
11.3 Output Calculation ................................................................. 33
11.4 Equipment List for Proposed Process ................................. 34
11.1 Gantt Chart for PPFS
# 11.2 Separation Process Simulation using UNISIM

![Diagram of separation process](image)

<table>
<thead>
<tr>
<th>Streams</th>
<th>Dilute Draw Solution</th>
<th>Fresh water</th>
<th>Draw solution</th>
<th>energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapour Fraction</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>&lt;empty&gt;</td>
</tr>
<tr>
<td>Temperature</td>
<td>C</td>
<td>30.00</td>
<td>100.0</td>
<td>99.99</td>
</tr>
<tr>
<td>Pressure</td>
<td>kPa</td>
<td>4.247</td>
<td>101.3</td>
<td>101.3</td>
</tr>
<tr>
<td>Molar Flow</td>
<td>kg/mole/h</td>
<td>1.243e+007</td>
<td>3.696e+006</td>
<td>8.734e+006</td>
</tr>
<tr>
<td>Mass Flow</td>
<td>kg/h</td>
<td>2.737e+008</td>
<td>6.658e+007</td>
<td>2.071e+008</td>
</tr>
<tr>
<td>Std Ideal Liq Vol Flow</td>
<td>m³/h</td>
<td>2.356e+005</td>
<td>6.672e+004</td>
<td>1.687e+005</td>
</tr>
<tr>
<td>Heat Flow</td>
<td>kJ/h</td>
<td>-3.692e+012</td>
<td>-1.032e+012</td>
<td>-2.596e+012</td>
</tr>
<tr>
<td>Molar Enthalpy</td>
<td>kJ/kg/mole</td>
<td>-2.970e+005</td>
<td>-2.752e+005</td>
<td>-2.973e+005</td>
</tr>
</tbody>
</table>
11.3 Output Calculation

<table>
<thead>
<tr>
<th>Literature Value</th>
<th>T = 295 K</th>
<th>Source:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux</td>
<td>19 L/m²-h</td>
<td>Zhengzhong Zhou, Jim Yang Lee, Tai-Shung Chung, “Thin film composite forward-osmosis membranes with enhanced internal osmotic pressure for internal concentration polarization reduction”, Chemical Engineering Journal, Volume 249, 1 August 2014, Pages 236-245, ISSN 1385-8947</td>
</tr>
<tr>
<td>Filter Size</td>
<td>2 cm²</td>
<td></td>
</tr>
<tr>
<td>Period</td>
<td>15 min</td>
<td></td>
</tr>
<tr>
<td>ΔV</td>
<td>0.00095 L</td>
<td></td>
</tr>
<tr>
<td>Source:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water needed</td>
</tr>
<tr>
<td>Population (2011)</td>
</tr>
<tr>
<td>Percent of Supply</td>
</tr>
<tr>
<td>Days of Operation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Feed SW</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
</tr>
<tr>
<td>CNaCl</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Brine</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
</tr>
<tr>
<td>CNaCl</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Membrane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane Area:</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dilute DS</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
</tr>
<tr>
<td>CNaCl</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Concentrated DS</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
</tr>
<tr>
<td>CNaCl</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fresh Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
</tr>
<tr>
<td>CNaCl</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qin</td>
</tr>
<tr>
<td>UNSIM Value</td>
</tr>
</tbody>
</table>
11.4 Equipment List for Proposed Process

*Process Units*

**Heat Exchanger**
- Pumps
- Valves
- Heat exchanger

**Membrane Separation**
- Membrane
- Pumps
- Valves
- FO membrane vessel

**Thermal Separation- Crystallizer/Precipitation**
- Solar energy collection apparatus
- Pumps
- Vessel
- Valves
- Storage tank

**Pre-Treatment**
- Large suspended solids filter
- Pumps
- Packed-bed filter
- Sedimentation tank
- Storage Tank
- Valves
- Mixing tank