Reverse Osmosis System for Small-Scale Maple Syrup Production

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Abstract

Maple syrup production has become not only a popular hobby but also a small business venture for many home producers throughout the world. Maple syrup production involves the collection of sap from maple trees, followed by a relatively simple processing operation to increase the sugar concentration of the substance. Costs for home producers are relatively high due to high capital and energy costs. In an effort to reduce these costs, reverse osmosis systems have been incorporated to concentrate the sap before boiling. This process reduces the necessary boiling time, thereby reducing labor and energy costs. However, these reverse osmosis systems are typically too expensive for home producers to afford. Therefore, it is the aim of this design project to develop a low-cost, medium-capacity reverse osmosis system. Building off the work from MME 448, the team is now working towards model verification and prototype system production.

Introduction

The aim of this design project is to design a reverse osmosis (RO) system for the production of maple syrup. To fill a current market void this system should cater to the needs of the small-scale maple syrup producer. Currently there are a number of commercially available systems but these systems tend to fall short in meeting the needs of small-scale producers who commonly produce between 20 - 100 gallons of syrup per season. Chief among these needs is the cost of the system. In addition, this system should aim to provide functionalities that are appropriate for a home producer of maple syrup, with consideration given to such factors as processing capacity and power consumption. Throughout the remainder of this project both the operation and initial capital costs will be given much attention as a major goal of the final design. Additionally, the team needs to be mindful of trying to create not only a functional product, but also one that could potentially be marketed to consumers in the future. The team plans to test the final system during this year's syrup season and will then determine the feasibility of the design as a marketable product to the maple syrup community.

Approach to the Problem

During the course of this project, the team will follow a conventional engineering design process as illustrated by the graphic in Figure 1. Because the engineering design process is iterative in nature, it is expected that many of the steps will be

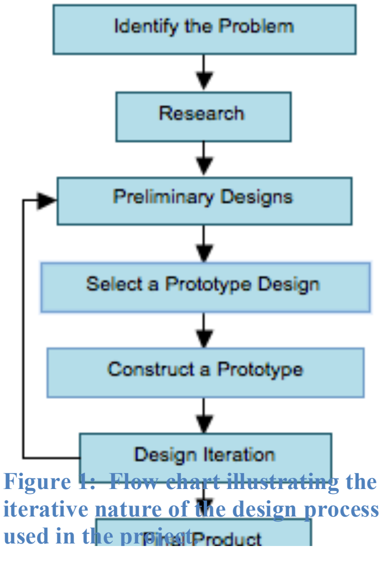


Figure 1: Flow chart illustrating the iterative nature of the design process used in the project.

repeated throughout the project in order to develop the best possible design solution and effectively address any challenges that might be encountered. Up to this point in the design process the team has been primarily focused on conducting background research in order to gain a better understanding of the current technology as well as developing preliminary designs and potential prototype design. The following report details the progress made on the project throughout the first semester of the course.

A heavy emphasis is placed on the project background in this report, which further explains some of the motivation for developing this design. The team has also conducted extensive preliminary research into current solutions, the science behind the process, and many other areas that will assist the team in developing future designs. Four main areas of research are presented in this report: commercially available reverse osmosis systems, costs associated with the boiling of sap, patents related to reverse osmosis and sap production, and the science and engineering behind reverse osmosis. Further, some of the initial engineering analysis that has been conducted in order to start brainstorming preliminary designs has been included. This preliminary engineering analysis has included the development of a multi-parameter research tool for cost analysis and system optimization in order to start evaluating the economic qualities of the design. Further, analysis has been conducted on reverse osmosis membranes using Reverse Osmosis System Analysis (ROSA) software developed by Dow Scientific Inc. Using the results of these analyses, the team has begun developing and selecting a preliminary design capable of meeting the necessary design requirements for the project. In parallel with the development of preliminary designs, specific components have been researched more extensively and a number of different options have been gathered. Finally, the team will present the plans it has developed for future work next semester to ensure the project is completed in a timely and effective manner.

Project Background

Before a new reverse osmosis system for the production of maple syrup could be developed the team had to learn about current ways in which maple syrup is being produced. By doing so the team was able to familiarize themselves with the industry as a whole and understand the motivation for why there is a current void in the market for this type of design. The following overview on the background of the maple syrup industry has allowed the team to identify the problems associated with current techniques for the collection and processing of sap. While the team is focused on designing a system for small-scale maple syrup producers, processing and collection techniques employed by a wide variety of producers were explored in order to understand the basic principles of the maple syrup production process.

Defining Maple Syrup

The concentration of sugar in the sap collected from maple trees can range anywhere from 1% to 4% but is typically between 2% to 2.5%. In order for this sap to be successfully made into syrup and also be legally classified as syrup, this concentration needs to be at least 66%. Typically, the sugar percentage within syrup or sap is measured in degrees Brix, a unit derived by [2]. A Brix is actually a very intuitive unit of measurement as 1° Brix corresponds to a concentration of one gram of solute per 100 grams of solution. Using this measurement system, for a solution to be classified as maple syrup the substance must have a measurement of at least 66° Brix. Using these concentrations, this implies that approximately 50 gallons of sap are need to produce one gallon of syrup, with this ratio depending on the initial concentration of sugar in the sap. Equation (1) is used to calculate the amount of sap needed to yield one gallon of syrup [2]:

$$\frac{86}{\%\ Concentration\ of\ Sugar\ in\ Sap} = Gallons\ of\ sap\ per\ one\ gallon\ of\ syrup \qquad \textbf{(1)}$$

For example, if a certain sample of sap has a 2% sugar concentration, the number of gallons of sap required for processing to yield one gallon of syrup would be 43 gallons. This calculation is shown below in Eq. (2):

$$\frac{86}{2\%} = 43\ gallons\ of\ sap\ required \qquad \textbf{(2)}$$

Maple syrup is classified into grades based on the color. As shown in Figure 2, the syrup is classified as follows: Grade A (Light Amber), Grade A (Medium Amber), Grade A (Dark Amber) and Grade B. This color is directly proportional to the "mapley" flavor of the syrup and the darker the syrup (Grade B is the darkest currently produced), the stronger the maple flavor. With this in mind, the grades do not necessarily make the syrup better, but rather can make it more appealing depending on the desired color and flavor.

Figure 2: Grades of maple syrup indicating the clear difference in color for different grades as well as their qualitative classification.

Sap Collection

Maple syrup is processed from a sap that flows from different species of maple trees. The sap is stored within the tree's xylem layer in the trunk and used as an energy source for the tree since it is essentially a sugar-water with a viscosity slightly greater than that of pure water. However, the tree only needs about 10% of the sap that it produces to remain healthy, which explains why sap can be collected without detriment to the overall health of the tree. This sap flows during a freeze, thaw, and flow cycle and can be collected at this time. When temperatures rise above a certain point, a positive pressure is developed within the tree that causes the sap to flow out of any opening in the tree bark (whether it be a wound or intentional tap). In order for the sap to be replenished, the temperatures must drop below a certain point so that a suction pressure develops and the tree can take in more water to replenish the amount of sap within the tree. The ideal times of year for these type of temperature fluctuations, and consequently for sap collection, are late winter/early spring before buds have formed on the tree. Although it will continue to flow after the buds on the trees are formed in the springtime, the sap will then acquire an abnormal taste that is tart and undesirable [3].

The first step in the production of maple syrup is to tap maple trees to collect this sap as it flows due to the positive pressure developed. The number of taps a tree can have is dependent on the diameter of the tree measured approximately 4-5 feet from the base of the tree, so as to avoid measuring at the crown of the tree where the roots protrude. A tree diameter between 10-17 inches corresponds to one tap, 18-24 inches corresponds to two taps, and a diameter greater than 25 inches can accommodate three taps. These conventions are used so that the collection process will not extract too much sap from a tree, and, thereby, allow it to remain healthy. The taps are simply holes that are drilled at a slight upward angle about 2.5 inches into the tree where the xylem, or sapwood, of the tree is located. In terms of the expected yield of each tap, historical practice has shown that approximately 15 gallons of sap per season can be collected from each tap. However, this flow rate is highly dependent on various environmental factors including the health of the tree and length of the sap season [2].

There are three different conventional collection methods employed for the gathering of sap: hooks and buckets, gravity lines, and vacuum lines. While each collection method serves to remove sap from the tree, the process of transporting the sap to a central storage unit is what differs in each method. The hook and bucket method is the original collection method and many syrup producers still use this method because of its simplistic nature and the associated low cost. However, this is a time consuming method because each bucket of sap must be manually transported from the tree to a central storage tank. Looking to improve on the collection efficiency, the gravity line collection method requires that all of the taps be positioned above a central storage tank. The sap then flows down these lines into the collection tank due to gravity. This method eliminates the labor involved with the collection of the buckets, but is time consuming to setup and requires extensive planning to position all of the taps above the tank, as well as a suitable plot of land. The last collection method used is the vacuum line system. The vacuum system uses the same set-up as the gravity line method, but additionally introduces a vacuum into the collection lines of the system. This is done by utilizing pumps that automatically sense when the sap is flowing via a gravity line and a sensor. Once the sensor has been triggered, the pump is activated and applies a vacuum on the lines of the system to promote increased sap flow from the trees. Ultimately, this vacuum pressure tends to pull the sap through the lines and out of the tree, leading to a higher yield of sap than the two previously mentioned methods [2].

The storage of the extracted sap is the most difficult part of the collection process. This is because sap spoils in a similar manner as milk, thus requiring that the sap remain chilled. This chilling is necessary to prevent a buildup of yeast and bacteria developed during the storage period before the sap is actually processed into syrup. The buildup of yeast and bacteria will not only cause the sap to be potentially unsafe to consume and produce a poor taste in the finished product, but will also accelerate the clogging of filters and other equipment in the processing operations of the sap. To help combat this problem the sap should be processed relatively soon after it has been collected. A maximum time lapse of 7 days between sap collection and processing is highly recommended since this is the commonly accepted spoilage rate of milk. This is difficult for small-scale producers to follow because they are typically unable to build-up a collection of sap large enough to make processing efficient in terms of the associated energy costs. An alternative to processing the sap so quickly after it has been collected is to expose the sap to ultraviolet light before storage. Exposure of the sap to ultraviolet light destroys harmful bacteria and/or yeast found in the sap, thereby, increasing the shelf life of the sap. Through the method of pre-treatment with ultraviolet light, a higher efficiency of production is acquired by enabling the producer to conduct bulk processing of the sap into syrup [3].

The Processing of Maple Syrup: Boiling

The next step after the collection of sap is to remove the water from the sap until it reaches a concentration of at least 66º Brix as discussed above. The traditional method of processing sap involves boiling off the water until the concentration of sugar is at the desired level as typically measured by a refractometer. During the boiling process water will evaporate from the sap solution and the sugar molecules will remain. The boiling process is completed by placing the sap in a pan above an oven called an arch. The arch supplies the heat to the pan which has been specifically designed to allow the sap to flow and boil effectively. Many different fuels are used for heating the arch and include natural gas, coal, wood, propane, kerosene and fuel oil. Figure 3 shows a picture of a typical evaporator used in this boiling process consisting of both the arch (black) and the pan on top. There are two different types of pans which are commonly used as a part of the boiling process, the flat pan and the flue pan. The traditional pan, primarily used by hobbyists, is a flat pan. The flat pan is less efficient than its counterpart, the flue pan, which is widely used in commercial applications. The flue pan is more efficient because it provides a larger surface area, thereby allowing increased contact between heat and sap, leading to a quicker increase in the temperature of the sap. For a capacity comparison, the typical pan size for commercial maple syrup production is roughly 160 square feet, and the typical hobbyist pan is only about 9 square feet. One of the disadvantages of using these smaller systems is that the hobbyist will be able to boil off approximately 10-30 gallons of water per hour. This number could be increased with the use of a more efficient system; however, components with increased efficiency, such as the flue pan, are often too expensive for many hobbyists. The high initial capital costs of such components along with high fuel costs are one of the primary reasons some improvement is necessary over these conventional solutions [2].

Figure 3: Evaporator commonly used for the boiling of sap.

The Processing of Maple Syrup: Reverse Osmosis

In a recent effort to increase the efficiency of maple syrup production and consequently reduce costs, the process of reverse osmosis has been introduced to the maple syrup community. It has been found that sap can be pretreated with reverse osmosis to extract up to 2/3 of the water present in sap before the boiling process. By removing a majority of the water the overall boiling time necessary for the sap is reduced so energy costs can be minimized. Reverse osmosis is commonly used today for water purification as well as other production processes like that of maple syrup. Some of the large producers of commercially available maple syrup reverse osmosis systems include Springtech, Dominion and Grimm, and Lapiere and have been offering commercial systems available to consumers for many years. These systems typically have a high initial cost (greater than $5000) and their processing rates are much too high for a small-scale home producer. In addition, the amount of energy that these systems require is extremely high due to the large flow rate and high pressures required. Therefore, there is a current void in the market for a low cost, medium-capacity reverse osmosis system to aid in the processing of maple sap for the small-scale home-producer [4,5,6].

The scope of this report is to examine the progress which has been made thus far in the semester in the development of a reverse osmosis system for the small-scale production of maple syrup. Last semester, system analysis to identify the optimal operating parameters was completed which guided component selection for the model verification prototype. Since then the necessary components have been acquired and an initial prototype has been constructed. Currently the team is working to get the model verification prototype running properly and move into the testing stage of the project since the uncharacteristically warm winter has already prompted the sap to flow earlier in the season than anticipated. Following the completion of testing the system operating parameters will be optimized through a design revision and a final marketable system will be developed.

Proposals

Once the team had completed extensive background research and system analysis, attention was shifted towards developing a number of proposals to address the given design problem. Developing these proposals involved a number of different stages beginning with the development of preliminary designs for a reverse osmosis system that met the desired characteristics. Since this was such a complex system the design of the system was focused more on the layout of the entire system and what types of components would be needed. Once the team had decided upon a basic idea for the overall design, candidate components to be included in the system were identified that met the necessary design criteria. These components were broken up into four general categories: pumps, membranes, plumbing materials, and valves and measurements devices.

Pumps

The pump component selection for the prototype is crucial for specifying operating parameters, as well as maintaining the low cost of the system. The decision to select a positive displacement vane pump was made because the pump required by the team needed to have low flow rate and high-pressure capabilities at a low cost. As a result of the team's research, an extensive list of potential pump suppliers was generated. From this list of positive displacement pumps, the team selected Procon as the most appropriate pump supplier for this application. Procon was chosen because they carry a large selection of rotary vane pumps which can operate at 25-660 gallons per hour, maintain a maximum pressure of 250 psi, and include a built-in adjustable pressure relief valve. Based on the results of the preliminary analysis these features provided operating characteristics that were in the appropriate range of parameters for optimal performance of the reverse osmosis system [1,2,3,4,5].

Reverse Osmosis Membranes

Reverse osmosis membranes are defined by the operating parameters of the system and rated for a certain range of temperatures, pressures, and flow rates. Although the membranes can be used outside of these ranges, the manufacturers indicate that performance can degrade and failure can possibly occur. The chemical formulation of the actual membrane element is one of the most important parameters in defining the performance. However, most companies do not readily disclose this information and simply provide the membrane contained within a housing without any additional information on the make-up of the material. Most of the preliminary analysis conducted last semester focused on the performance of the membrane in the system as it is in fact one of the most crucial components in the systems. Using the results of this analysis the team began to research a number of potential membranes from a number of suppliers including

Dow Filmtec, GE, Axeon Water, and Hydranautics. When comparing membranes between these companies, the team realized that price and performance were fairly consistent for all suppliers. Therefore, the team decided that Dow Filmtec would be the most appropriate supplier because their software had been utilized to analyze the preliminary system as well as having the least expensive membrane [6,7,8,9].

Valve Selection

One of the main decisions that needed to be made in regards to valves was whether to implement a manual or automatic system. In order to choose between these two options for the RO system the team had to weigh the increased ease of use of the automated system versus the cost savings for the manual system. At this point in the project the team has decided to pursue the manual controls in order to best meet the problem definition. However, because this system is being designed with the intent of constructing a marketable system the automation components may be considered in the future as an extra feature available on a specialized version of the system. The selection of these valves was primarily driven by the operating parameters of the system and desired features the team wished to implement. The team attempted to acquire a donation of these components from Swagelok through engineering alumni connections due to the superior quality their products are known for. However, after meeting with a representative the team was informed that a 15% discount off the retail price was the largest donation that they could make at the time. The team then decided to purchase the necessary valves and fittings through Grainger and McMaster due to the low cost and short lead time on these products [10,11].

Plumbing Material

The selected plumbing material, PEX, which is cross-linked polyethylene, is a new material being implemented in the plumbing market. It is very low cost, estimated at only $0.22 per foot, and can handle the process temperatures and pressures that the system will be experiencing. Also, PEX is easily reconfigurable due to its partially cross-linked structure allowing for the team to create a modifiable layout. On account of these properties the team has chosen to utilize PEX for the primary plumbing system material for the prototype design. The supplier was not as crucial as it was for other components due to the high availability, so cost was the driving factor in the purchasing decision [12,13,14].

Inline Heating Element

The purpose of the heating element is to raise the temperature of the sap before it enters the reverse osmosis membrane. As shown by the team's modeling efforts, this increased temperature serves to increase the operating efficiency of the membrane so that it can achieve a higher output concentration. A basic heating element from a hot-water heater is the most viable option because these elements are inexpensive and are already commonly used for heating potable water. For this heating element, the team also needed to acquire a thermostat used for open loop control of the heating element.

Envisioned Final Design and Objectives

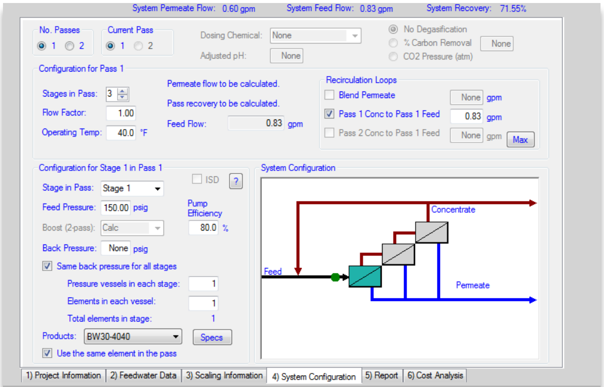
The ultimate goal of this project is to have a fully marketable system which will meet all the design requirements which the team has developed including price, operating parameters, and commercial appeal. After selecting the components, as presented above, the team utilized the reverse osmosis system layout shown in Appendix A to develop the model verification prototype. Components for the system have been purchased and the prototype constructed allowing the team to now focus on the testing and development stage as discussed in the following sections of this report. If the prototype performs as modeled, the team plans on further optimizing the system and designing a marketable packaging for the system as the final end product for the course.

Progress of the Final Design and Results

In MME 448 the course and project focused heavily on preliminary background research to better understand the design problem and objectives as well as developing candidate design solutions. These candidate design solutions were developed using a combination of patent research, evaluation of current design solutions as well as modeling using commercial reverse osmosis system analysis software. With a final candidate solution chosen the focus of MME 449 is further testing and evaluation of this design in order to identify the best possible system configuration for the final marketable product. The following sections of the report detail the work of the team thus far towards these efforts. The team has included further discussion of the preliminary model results from last semester and its applicability to the testing to be conducted with the current model verification prototype. Further a testing plan has been developed that will be used with the constructed prototype to both validate the model results using ROSA software and also optimize the system parameters for the highest possible output concentration. The following sections of the report summarize the current modeling efforts, the proposed testing plan, construction of the model verification prototype, as well as the results of the initial testing the team has conducted this semester.

Membrane Performance Analysis

One of the main outcomes for the group during the course of MME 448 was to gain a fundamental understanding of what types of operating parameters were important in determining the overall performance of the reverse osmosis system. In order to analyze the system, the team looked into what types of governing equations were needed to characterize and evaluate reverse osmosis systems. During this research, the team discovered a number of well documented and commonly implemented equations that are used to analyze reverse osmosis systems involving parameters such as flow rates, pressures, number of filters in the system, flow path of the system, etc. Instead of trying to develop a new computer simulation tool that incorporated all of these equations, such as a MATLAB m-file, the team was able to locate the Reverse Osmosis System Analysis (ROSA) software distributed by Dow Scientific Inc., one of the leading producers of reverse osmosis membranes. The team has previously discussed the functionality of this software in a previous report, however, screenshots of the software are provided below in Figure 1 and Figure 2 for the reader's reference.



System Permeate Flow: 0.60 gpm   System Feed Flow: 0.83 gpm   System Recovery: 71.55%

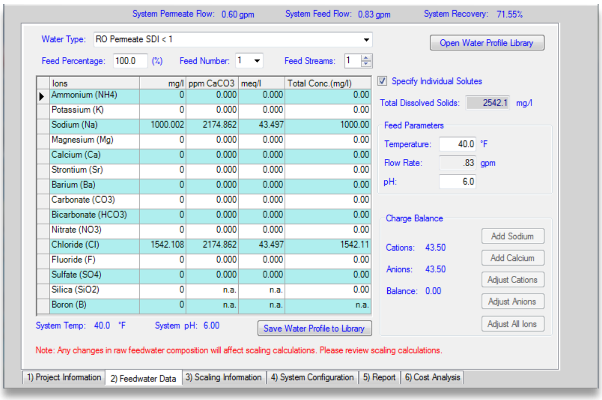
No. Passes: ● 1 ○ 2
Current Pass: ● 1 ○ 2
Dosing Chemical: None
Adjusted pH: None
● No Degasification
○ % Carbon Removal: None
○ CO2 Pressure (atm)

Configuration for Pass 1
Stages in Pass: 3
Flow Factor: 1.00
Operating Temp: 40.0 °F
Permeate flow to be calculated.
Pass recovery to be calculated.
Feed Flow: 0.83 gpm

Recirculation Loops
☐ Blend Permeate: None gpm
☑ Pass 1 Conc to Pass 1 Feed: 0.83 gpm
☐ Pass 2 Conc to Pass 1 Feed: None gpm

Configuration for Stage 1 in Pass 1
☐ ISD
Stage in Pass: Stage 1
Feed Pressure: 150.00 psig
Pump Efficiency: 80.0 %
Boost (2-pass): Calc
Back Pressure: None psig
☑ Same back pressure for all stages
Pressure vessels in each stage: 1
Elements in each vessel: 1
Total elements in stage: 1
Products: BW30-4040
☑ Use the same element in the pass

System Configuration



System Permeate Flow: 0.60 gpm   System Feed Flow: 0.83 gpm   System Recovery: 71.55%

Water Type: RO Permeate SDI < 1
Feed Percentage: 100.0 (%)   Feed Number: 1   Feed Streams: 1

Ions	mg/l	ppm CaCO3	meq/l	Total Conc.(mg/l)
Ammonium (NH4)	0	0.000	0.000	0.00
Potassium (K)	0	0.000	0.000	0.00
Sodium (Na)	1000.002	2174.862	43.497	1000.00
Magnesium (Mg)	0	0.000	0.000	0.00
Calcium (Ca)	0	0.000	0.000	0.00
Strontium (Sr)	0	0.000	0.000	0.00
Barium (Ba)	0	0.000	0.000	0.00
Carbonate (CO3)	0	0.000	0.000	0.00
Bicarbonate (HCO3)	0	0.000	0.000	0.00
Nitrate (NO3)	0	0.000	0.000	0.00
Chloride (Cl)	1542.108	2174.862	43.497	1542.11
Fluoride (F)	0	0.000	0.000	0.00
Sulfate (SO4)	0	0.000	0.000	0.00
Silica (SiO2)	0	n.a.	n.a.	0.00
Boron (B)	0	n.a.	n.a.	n.a.

☑ Specify Individual Solutes
Total Dissolved Solids: 2542.1 mg/l

Feed Parameters
Temperature: 40.0 °F
Flow Rate: .83 gpm
pH: 6.0

Charge Balance
Cations: 43.50
Anions: 43.50
Balance: 0.00

System Temp: 40.0 °F   System pH: 6.00

Note: Any changes in raw feedwater composition will affect scaling calculations. Please review scaling calculations.

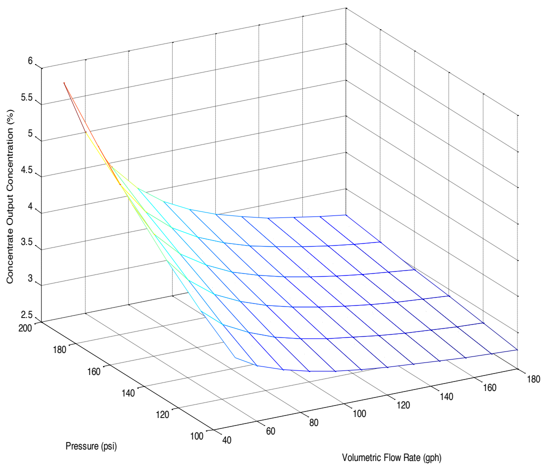
Figure 2: Screenshot of feedwater properties input in the

Figure 1: Screenshot of system configuration input in the ROSA software from DOW Scientific, Inc.

Parameter Analysis

After the team had gained a working knowledge of the ROSA software, the team decided to investigate the effect of different operating parameters on the performance of the system. These simulations were run in order to gain a qualitative understanding of what trends could be observed for a number of different parameters such as temperature, pressure, flow rates, number of stages, and filter type in order to guide component selection during the preliminary design phase of the system. In order to quantitatively measure the output of the system, the team looked at the concentration percentage of the sap after it had passed through the membrane with a higher value being more desirable. It should be noted that in each of these simulations an initial sap concentration of 2.5% sucrose was utilized with sodium chloride molecules being used to approximate the characteristics of a normal sucrose molecule.

The simulations that the team initially ran were quite extensive and documented within the analysis appendix and final report for MME 448. The three most important operating parameters that were analyzed were the volumetric flow rate of sap through the system, the pressure of the sap passing through the membrane, as well as the temperature of the sap. The results of these simulations for one particular filter are shown below in Figures 3 and 4. In looking at the surface in Figure 3 it is clear that the concentration of the sap at the output of the reverse osmosis membrane increases with decreasing flow rate and increasing pressure. It is also important to note that the range of pressures and flow rates tested in this simulation are realistic for a home-producer, therefore verifying that these results would be applicable for the scope of this project. Figure 4 illustrates how the output concentration of the reverse osmosis changes as the input temperature of the sap is increased. These results demonstrate that the warmer the sap is that is passed through the system, the more effective the system performance would be.



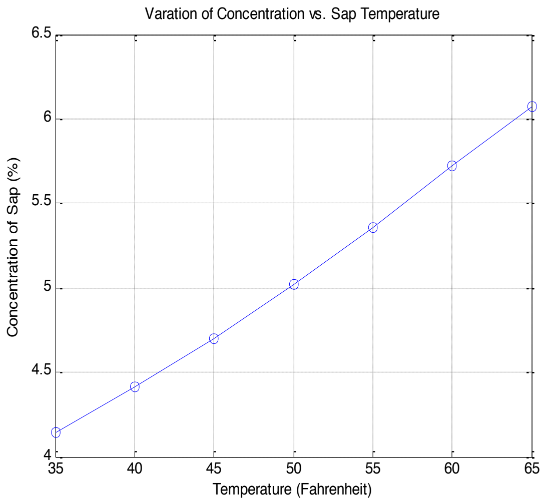


Figure 3: Surface plot summarizing the results of the simulation in which pressure and volumetric flow rate through the membrane are varied.

Figure 4: Simulation results showing the effect of increasing temperature on the output concentration of the sap.

Additional simulations were conducted using the ROSA software in order to assess the performance of different membranes as well as the effect of increasing the number of membranes throughout the system. The team found that using a higher number of membranes is more desirable as well as the higher end membranes. However, these simulations were only important from the point of view that they gave the team a better understanding of the operating principles of the system and not really practical to implement. The increased cost of adding additional membranes and higher end products was not feasible for the project budget, and also conflicted with the overall project goal of a low cost system, despite the improved predicted performance.

Model Verification Techniques

The results presented above were crucial for the team as they provided the team an initial qualitative understanding of the trends of the system performance as the different model parameters are varied. Initially, these results help the team in the initial design of the system (the decision to inlcude components such as preheaters and a recirculation loop) and component selection for the appropriate range of pressures, flow rates and temperatures.

At this point of the project, the primary goal of the team is to try and verify the above results of the modeling with experimental data to ensure the system is functioning as intended. The team has constructed a prototype system, as will be discussed shortly, for model verification based on the initial designs presented previously in this report. This system not only serves as a functioning reverse osmosis system, but also was designed for testing so that the team can measure the operating parameters experimentally while running the system. The team has included a number of pressure gauges, thermocouples, and flow meters to properly measure these quantities. The locations of each of these measurement devices are pictured/labeled in the model verification prototype photo in Appendix B with their functionalities and reason for inclusion as follows:

- **Thermocouple 1 (Type T):** the purpose of the first thermocouple is to measure the temperature of the sap after it has passed through the heating element. This value can be compared to the entrance temperature of the sap, as measured with a Thermapen$^{\text{TM}}$ (essentially a handheld Type K Thermocouple), to determine how much the sap is being heated when passed through the heating element housing.
- **Thermocouple 2 (Type T):** the purpose of the second thermocouple is to measure the temperature of the sap right before it passes through the membrane. This allows for the team to determine how much the temperature of the sap is increasing as it passes through the pumps, as well as accurately determine the temperature at which the sap will be passing through the membrane (and ensure it does not exceed the specification).
- **Pressure Gauge 1:** the purpose of this pressure gauge is to measure the inlet pressure of the sap going into the membrane for the reverse osmosis process. Additionally, this gauge can be used to check the pressure of each of the pumps within the system since this value is set by blindly turning the pressure adjustment screw.

- **Pressure Gauge 2:** the purpose of this pressure gauge is to measure the outlet pressure of the permeate and determine the pressure drop across the membrane.
- **Pressure Gauge 3:** the purpose of this pressure gauge is to measure the outlet pressure of the concentrate and determine the difference in pressures between the permeate and concentrate, if any.
- **Flow Meter 1:** the purpose of this flow meter is to measure the amount of input flow into the system and also allows the operator to ensure sap is flowing through the system. Ideally, the team would place this flow meter right before the entrance to the membrane. However, since this is at a pressure of 250 PSI, the flow meter required for this pressure is much too high cost for this application.
- **Flow Meter 2:** the purpose of this flow meter is to measure the amount of output permeate flow out of the reverse osmosis membrane. This flow can be used to determine the concentrate flow out of the membrane as well using a simple conservation of volume calculation with the input flow into the system.

Testing Plan

Once the model verification prototype had been constructed, the team was ready to begin testing the system with collected sap in order to verify the above models. However, before starting testing, the team needed to establish a testing plan that could be used during operation in order to properly assess the validity of the model to this system. There are a number of different experiments that will need to be conducted for the system in order to evaluate a number of different features/aspects of the system. For each of the experiments, however, the ultimate output variable that is being measured is the output concentration of the permeate and concentrate. The concentration of these two different solutions will be measured using a handheld refractometer, which measures the refractive index of the liquid which is directly correlated to the amount of sugar (soluble solids) within the solution. The tests that the team planned to conduct with the initial testing are summarized as follows:

1. **Varying Temperature of the Sap**: In order to verify that increasing the temperature of the sap will increase the output concentration, the team will need to run the sap through the system at varying temperatures. The heating element that has been included in the system is an open-loop component with no feedback control, so it is difficult and impractical to try and control the temperature. Rather, this test focuses on testing the sap using a "hot" and "cold" condition. In the "hot" condition the preheater will be turned on and the sap will be input at its storage temperature. In the "cold" condition the sap will simply be processed at its storage temperature with the preheater turned off and completely cooled. In each of the cases, the pressure and flow rate through the system will be held constant.

2. **Varying Pressure and Flow Rate:** In order to verify that higher pressures and lower flow rates are desirable, the team will need to vary the flow rates and pressures through the system. The pumps that were chosen have adjustable flow rates and pressures, so the team is able to vary each of these parameters rather simply. A number of different combinations of inlet pressures and inlet flow rates will be varied using the feed pump, and the output concentration of the concentrate will be measured as the output variable.

In this test, the temperature of the sap will be consistent, with either the heating element being constantly turned on or off.

3. **Varying Number of Times through the Recirculation Loop:** Another parameter of interest to the team is the number of times the sap should be passed through the recirculation loop before the concentrate should be drawn off. It is hypothesized that the more the sap is passed through the recirculation loop, the higher the concentration of the concentrate will be when it is drawn off through the gate valve. In order to conduct this experiment, the team will need to turn on the system and wait set amounts of time before drawing off any concentrated sap. The amount of time to wait after turning the system on will be 1 minute, 2 minutes, 3 minutes, and 5 minutes, while measuring the output concentration of the sap after each time interval.

Once the previous experiments have been completed and the model has been verified, the team will switch its testing focus from model validation to system optimization. Using methods described in *Design and Analysis of Experiments* by Montgomery [15], the team has designed a factorial experiment where the temperature, volumetric flow rate, and pressure will be varied within set ranges to determine which combination of system parameters are significantly higher. It is important to distinguish between significantly higher and simply higher because if there is not a significant difference between certain pressures, flow rates, or temperatures, then it may be possible for the team to optimize the performance, while also minimizing cost by using smaller pumps or other components. The significant differences between output concentrations of sap will be assessed using standard statistical models for a three factor factorial design and the use of SAS statistical software. The different levels of each factor that will be evaluated are summarized as follows:

- **Volumetric Flow Rate:** 50 gph-70 gph in increments of 5 gph
- **Pressure:** 100 psi-200 psi in increments of 20 psi
- **Temperature:** Although it might be beneficial to try a number of different temperatures, this factor would be difficult to control with the open loop hot water heating element. For this factor the levels are simply outdoor/room temperature sap and heated sap.

Model Verification Prototype Bill of Materials

The final design used to create the model verification reverse osmosis system was derived from one of the preliminary designs that was created during the first half of the project (Appendix A). This design included all components necessary to construct the prototype system. It was decided that the prototype system would be assembled on a sheet of plywood to create a model verification, or proof-of-concept, system that would allow easy monitoring of all of the components of the system as well as allow the team to detect any issues, such as leaks, that may arise during testing.

The first step in the fabrication process was to create a detailed bill of materials (BOM), included in Appendix C, to determine what the team would need to purchase and what could be obtained from the Mechanical and Manufacturing Engineering Department shop. After creating the BOM, it was decided that the team would be able to use two motors from the shop, which would need to be modified to accompany the pumps, as well as three pressure gauges, two T-type thermocouples, twelve hose clamps, one flow meter, and aluminum and mild steel stock to create a membrane housing as well as the motor mounts and adapters. Additionally, Karl Reiff donated a pre-filter housing for use in the system. The remaining items shown in the BOM were purchased using funding provided from the Mechanical and Manufacturing Engineering Department. The items were selected with the budget as the highest priority, resulting in a focus on low cost, while still searching for high quality components.

Component Fabrication for Model Verification Prototype

Before system construction began, the various items to be fabricated were designed and machined. The fabricated components needed to complete the model verification prototype included the membrane housing, the motor mounts and adapter, and the inline heater.

Membrane Housing

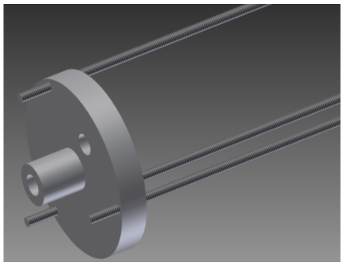


Figure 5: CAD drawing of the membrane housing.

The membrane housing/pressure vessel, as shown in Figure 5, was designed as two separate caps machined from two pieces of 5” round Aluminum 6061-T6 stock. The machining of these caps was programmed using FeatureCAM and the component was fabricated on the Haas CNC mill. Included in the design of the caps were features to accommodate the plastic end pieces on the membrane. The caps also had three holes located around the perimeter through which steel rods would be inserted to clamp the two end caps together. These solid connecting rods were made from mild carbon steel and were threaded on each end with external ¼”-20 threads. The caps were then installed on each end of the membrane with custom O-rings around the outer edge of the membrane and were secured using Nylon lock nuts. Each rod was then torqued to a capacity of 45 in-lbs in a circular pattern, each time increasing the torque by five in-lbs on each rod so as not to apply too much pressure to one side of the membrane.

Motor Mounts and Adapters

Following the manufacturing of the membrane housing, the motor mounts and adapters were fabricated. Two mounts, one for the front of each motor, were fabricated out of flat aluminum 6061-T6 plates. These plates were cut in half, drilled and tapped and then reassembled into a single plate. The purpose of this was to create a way for the plate to encapsulate the round motor mount on the face of the motor. This mount was then placed in the Haas CNC mill where the corresponding hole was machined in the plate. This hole was positioned so that it was centered on the line separating the two plates. Finally, four mounting holes for the pump adapter were also drilled and tapped using the Haas CNC mill.

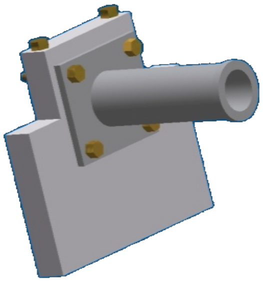


Figure 6: CAD drawing of motor mount and adapter

Next, the adapter for the pump, which allowed the pump to be attached to the motor with a V-band clamp, was machined out of a piece of 2” mild steel round stock. This machining was done on the manual lathe and required about 4 hours of machining time, due to the precision necessary for this component and the type of material being machined. The plate that the V-band adapter was attached to was cut out on the plasma cutter. This piece was then sanded and filed to the proper size for the V-band adapter to fit in. Once this fit was made, the two pieces were welded together, using a number of clamps to ensure that no deformation occurred during welding.

The final piece for the motor-pump assembly was the shaft adapter. This adapter had to allow a round, male shaft on the motor to attach to a flat, male shaft on the pump. The part was made from ¾” mild steel round stock. The manual lathe was again used to turn the piece down to the proper size and to drill the hole for the round motor shaft. The manual mill was then used to make the slot for the flat male pump shaft and to drill and tap the set screw holes for securing the round shaft in the adapter. These three components work together to attach the pumps to the motors as pictured in Figure 6. The construction of each part was necessary to utilize the motors that the shop had in supply. Adaptation was the alternative to purchasing the accompanying motors for the pumps from the pump supplier. Since funding was a large concern during this project, the less expensive method of adaptation was pursued.

Inline Heater

The next major component that required machining was the inline heater. This component was created from 2-¾” OD, 2-¼” ID aluminum 6061-T6 round tubing. The tubing was then cut to the proper size to accommodate the purchased heating element. Internal threads were then machined into each end of the tube. The tube was cut on the horizontal band saw, and the threads were cut on the manual lathe using a power-feed setting that cut the threads at 13 TPI (threads per inch).

Two caps for the tube were machined from 2-¾” 6061-T6 aluminum round stock. The external threads were cut on the Storm CNC lathe using a program created in FeatureCAM. These threads were also cut to 13 TPI to match the tube. Following the thread cutting operation, the caps were placed in the Haas CNC mill, which was used to machined flat faces on either side of the caps to allow a wrench to grip the caps for tightening purposes. Custom O-rings were then made to seal both ends of the tube and were placed on the outer diameter of the threaded portion of the caps.

Assembly of the Model Verification Prototype

Following the fabrication of these parts, the assembly of the system was all that remained. This process involved installing 3/8” NPT hose barbs on each of the valves, the ports on the membrane pressure vessel, the ports on the inline heater, and on the ports on the pre-filter. Prior to instillation, the threads of the hose barbs were wrapped in PTFE tape to prevent leaks from occurring.

Once each element had hose barbs on each of the ports being utilized, the final task was to run PEX tubing to and from each element. This semi-rigid tubing can be easily deformed and shaped if heat is applied. The team used a heat gun, set to 720 °F, to heat up the ends of the tube until they were able to be slipped over the hose barbs and to heat the sides of the tube to create bends. Hose clamps were used to secure the PEX around the hose barbs in high pressure areas. In other areas, the PEX solidified well enough around the hose barbs to create an effective seal. Additional PEX tubing was run from the system to the sap tank for input, to a water tank for back flush input, and to buckets to collect the concentrate, permeate and back flush waste water.

Preliminary Testing

Although the team initially had the lofty goal of following the testing plan presented above exactly and the system functioning perfectly, there were some problems that were encountered. However, these problems were both beneficial in helping to improve the overall layout and design of the system, while still causing delays in our testing plan. Upon finishing the construction of the model verification prototype, the team began to check the system for leaks to determine if the method of construction was adequate. The team determined that simply heating the PEX tubing and placing it around the hose barbs provided a sufficient seal from water escaping in most locations. However, at the high pressure areas of the systems, hose clamps were still needed to prevent leaks from the membrane.

The initial run of the system focused on simply determining if there was a difference in the sugar concentration of the concentrate and permeate to verify that the membrane and fabricated caps were functioning effectively. Upon running the system, it was observed that there was no significant difference between the concentrations of the concentrate or permeate, leading the team to believe that there was some problem with the membrane caps that had been fabricated. The membrane caps were fabricated as pictured in Figure 7 to be press fit on the ends of the membrane itself, relying on the press fit only to provide a seal between the concentrate and permeate. However, it was evident based on the results of testing that this was not a tight enough seal for this application, so the team needed to change the design of the end caps. Instead of relying on a press fit, the team decided to implement O-Rings within the design to provide a seal between the permeate flow and concentrate flow as illustrated in Figure 8. The O-Ring grooves were fabricated according to standards in the Machinery Handbook 25th Edition [16] and provided an effective solution that solved this problem.

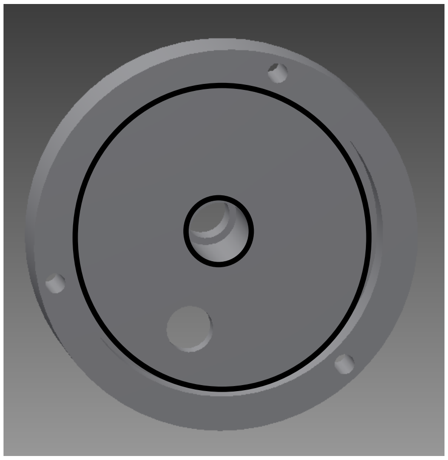


Figure 7: CAD model of membrane cap with the O-Rings shown in black.

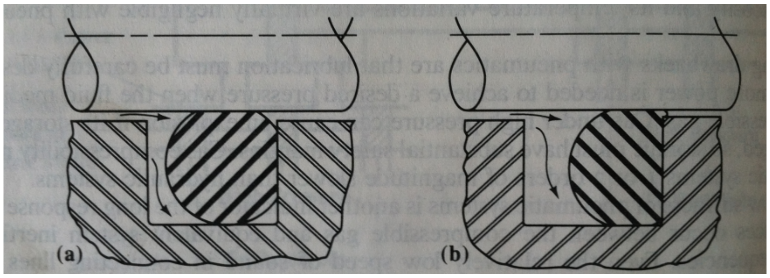


Figure 8: Illustration showing O-Ring seal used in membrane cap

Another problem that was encountered during preliminary testing was the ability to control the flow of the output permeate and concentrate appropriately. Initially a gate valve had been used to control the output of the concentrate which seemed to be an effective means for regulating the flow. The team had assumed that the flow of permeate would only need to be shut completely on or off and no type of regulation would be needed for this output. However, in order to establish an appropriate pressure drop across the membrane, this output needed to be adjusted which proved difficult to accomplish with a simple ball valve. This ball valve was therefore replaced with a gate valve to enhance flow control for the user. Additionally, brass restrictor valves were also included in line with each of these gate valves. These restrictor valves changed the diameter the fluid passed through from 3/8” to 1/32” in order to give the operator better control of the output flow of the system.

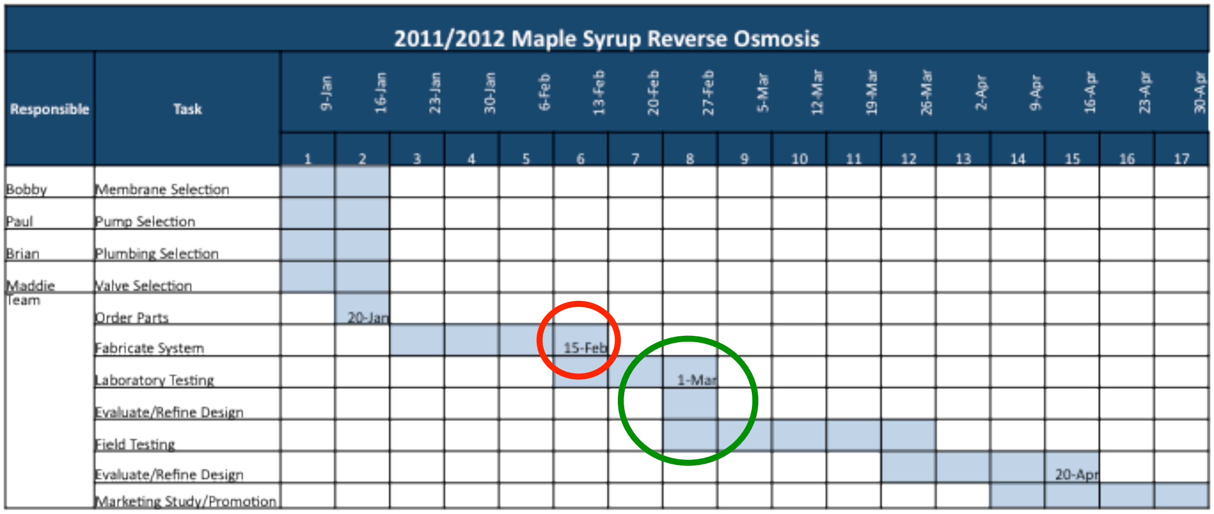
Further, a concern that was evident during testing was the temperature control of the sap being processed through the system using the water heating element. Upon using the heating element for the first time, it was clear that there would be some problem using simply the open loop thermostat for the system, as it continued to heat the sap continually without adjusting to the temperature of the sap. The heating element raised the temperature of the sap from around 45 °F to nearly 130 °F instantly. However, in heating the sap, the housing for the heating element became extremely hot and the heating element continued to increase the temperature of the sap even higher without stopping. It was clear that some sort of feedback control needs to be added to the system in order to control when the heating element is turned on or off in order to regulate the temperature of the sap. The team also noted that the temperature of the sap was increased even further by approximately 10 °F after being run through the pumps.

Finally, the team had planned on continuing testing and proceeding with the testing plans when some mechanical problems and breakage happened with the membrane. When trying to tighten the fabricated caps to the membrane, one of the NPT fittings on the cap was placed on one of the plastic radial supports of the membrane. As the caps were tightened together using a torque wrench, an unanticipated force was placed on the membrane by the NPT fitting, causing the membrane to buckle and form a crack in the fiberglass exterior. Despite a number of attempts to repair the crack in the external fiberglass housing, the water began to seep between the layers of the fiberglass and began to delaminate. Upon testing with the broken membrane it was determined that this delamination was detrimental to the performance of the membrane and rendered it ineffective and in fact useless. The team has secured additional funding to order a new membrane and commercial housing in order to begin testing again in the next few weeks.

Conclusions and Future Work

At this point in the project the team has experienced multiple events which have both set back and brought forward key project deadlines. However, consistent progress continues to be made in regards to the verification and eventual optimization of the system. To verify the team’s final design a thorough testing plan has been developed and is ready to be carried out as soon as an appropriate prototype is ready. With the exception of the damaged membrane, the successful assembly of the model verification prototype has been completed. Additionally, preliminary testing has identified system issues including leaks, touchy flow control, heater stability, and motor/pump operation. With these issues remedied, and a new membrane and housing ordered, the team expects to complete the testing plan outlined above following spring break.

The Gantt chart constructed at the end of last semester has been provided in Figure 9. The red circle in Figure 9 highlights the deadline for the completion of the model verification prototype. Initially, this deadline was in jeopardy due to the lengthy lead time associated with the procurement of the ProCon pumps. Aside from this concern, the deadline for assembly of this prototype was met and the team was on schedule until the membrane was cracked, thereby delaying the schedule. As of now, the deadline has officially been passed since the team has had to order a new membrane and housing. Another scheduling complication currently being dealt with is the current sap availability. For the successful completion of this project, the model must be verified using real sap in field testing. The original plan, shown in green, was to first test the prototype in the laboratory and follow-up with field testing after spring break. However, a mild winter has caused the freeze/thaw cycle which leads to sap flow to occur early. Instead of sap flow in early March, sap has been flowing since mid-February. Because of sap's short shelf life, attempts to field test the system were advanced by two weeks.



2011/2012 Maple Syrup Reverse Osmosis

Responsible	Task	9-Jan	16-Jan	23-Jan	30-Jan	6-Feb	13-Feb	20-Feb	27-Feb	5-Mar	12-Mar	19-Mar	26-Mar	2-Apr	9-Apr	16-Apr	23-Apr	30-Apr
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Bobby	Membrane Selection	🟦	🟦															
Paul	Pump Selection	🟦	🟦															
Brian	Plumbing Selection	🟦	🟦															
Maddie	Valve Selection	🟦	🟦															
Team	Order Parts		🟦 20-Jan															
	Fabricate System			🟦	🟦	🟦	🟦 15-Feb											
	Laboratory Testing						🟦	🟦	🟦 1-Mar									
	Evaluate/Refine Design								🟦									
	Field Testing								🟦	🟦	🟦	🟦	🟦					
	Evaluate/Refine Design												🟦	🟦	🟦	🟦 20-Apr		
	Marketing Study/Promotion														🟦	🟦	🟦	🟦

Figure 7: Gantt chart for the completion of the project

The speedy completion of the testing plan is crucial to the success of the project. To finish field testing, sap will be collected and stored in a refrigerator to prevent spoiling over spring break. This sap will then be used to complete the testing plan. Following the completion of testing, the design will be evaluated and refined. A final design iteration will then be created using the results of testing, and the final cost of this marketable system will be determined. Lastly, the feasibility of the system as a marketable product will be evaluated through a comprehensive marketing study. The team is looking forward to the completion of the project through further testing and design refinement in order to create the best possible solution to the stated design problem.

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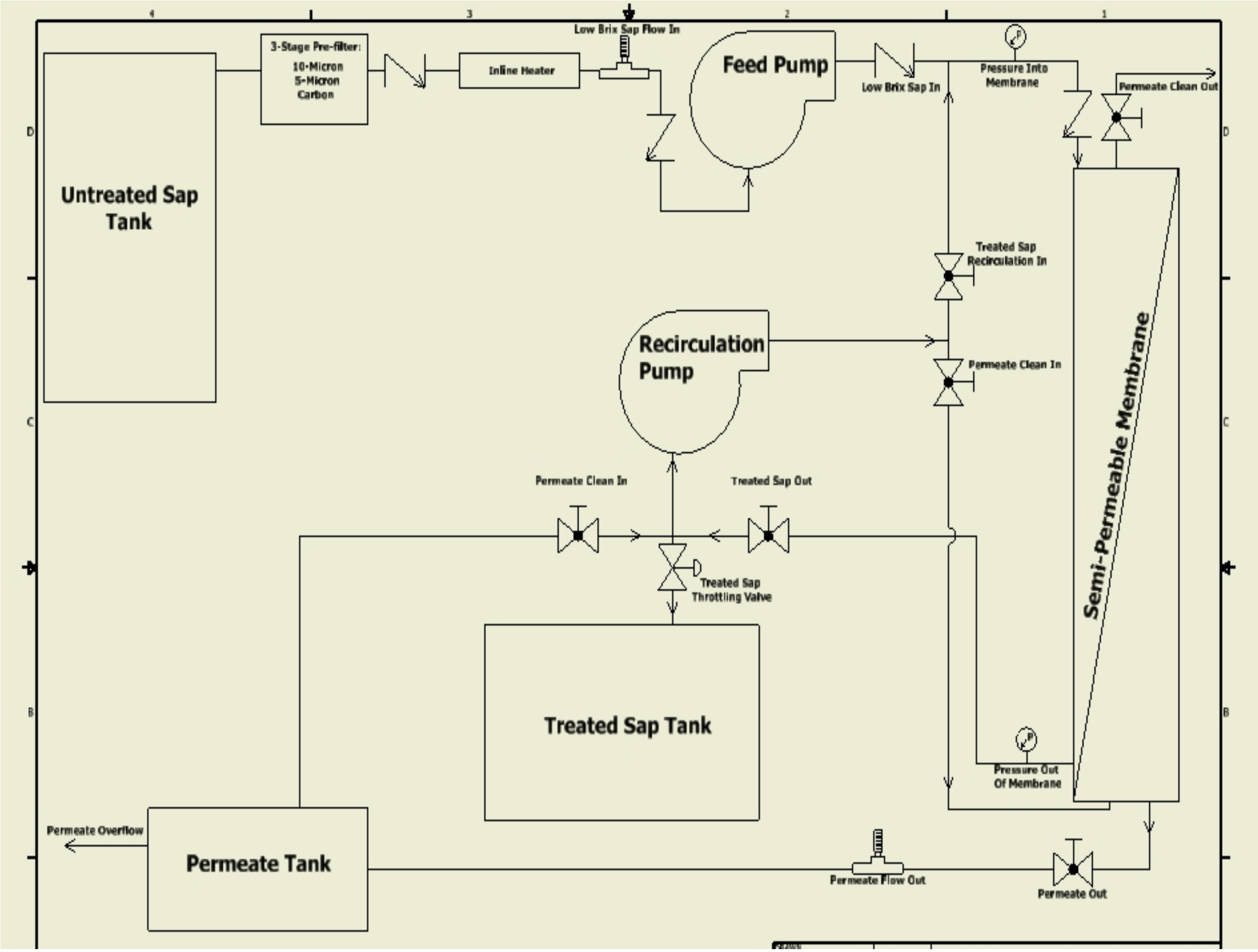
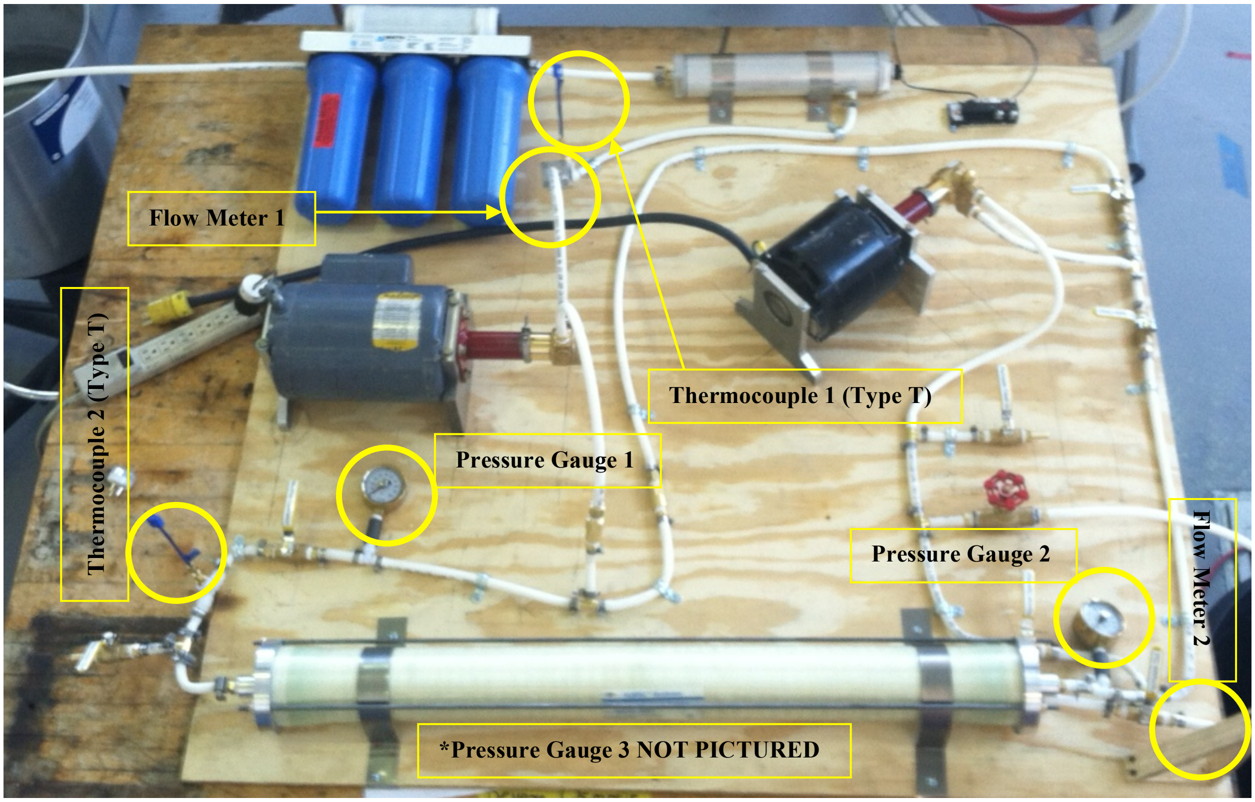
Appendix A-Preliminary Design Diagram



Appendix B-Model Verification Prototype Diagram



Appendix C-Prototype Bill of Materials

Component/ Part #	Component Description	Quantity	Retail Price ($)	Total Price ($)	Purchase Price ($)
Procon 112A080F11xA250	Feed Pump	1	74.84	74.84	66.44
Procon 112A050F11xD50	Recirculating Pump	1	74.84	74.84	66.44
1113	Clamps (Motor-Pump)	2	6.5	13	13
41279	Red Pex Tubing (3/8 ID x 100ft)	1	30	30	30.14
PV4040SSAW-316	Membrane Pressure Vessel	1	100	100	0
BW30-4040	Membrane	1	229	229	239.8
	Water Heater Element	1	15	15	11.78
	Water Heater Thermostat	1	20	20	18.78
GE 5KH36MNA445X	Feed Pump Motor (.5HP)	1	155.43	155.43	0 (1-1/2 hp shop motor)
GE 5KH32DN5587X	Recirculating Pump Motor (.25HP)	1	119.99	119.99	0 (1/3 hp shop motor)
94A10201	Brass Ball Valves (3/8 NPT)	7	10.31	72.17	72.17
CHKBRS610-6M6F-B	Brass Check Valves (3/8 NPT)	4	15.29	61.16	61.16
5WZ57	Pressure Gauge (1/4npt 2.5" dial 0-300psi)	3	6.5	19.5	0
	T-Type Thermocouple	2	19.33	38.66	0
5346K21	Brass Barbed Hose Fittings - Male (3/8 ID, 3/8 NPT)	23	1.52	34.96	45.48
5346K55	Brass Barbed Hose Fittings -Female (3/8 ID, 3/8 NPT)	2	1.786	3.572	8.93
5388K14	SS Hose Clamps (1/2" x 7/16-25/32")	20	0.641	12.82	11.4
4400K64	Flow Meter (.5-5gpm 3/8npt)	1	46.71	46.71	46.71
	Flow Meter (.5-5gpm 3/8npt)	1	95.5	95.5	0
5372K636	Hose Barb Tee for Pressure Gage	10	0.746	7.46	7.46

	Carbon Block Filter Kit	1	24	24	24
t61r2.75x.25-36	Aluminum Tube for Heating Element Housing	1	41.06	41.06	41.06
NIBCO TI8 3/8	Brass Gate Valve	1	6.02	6.02	6.02
BW30-4040	Membrane #2	1	229.99	229.99	242.7
EPSS440	Membrane Housing	1	105.5	105.5	105.5
				Shipping	67.48
				Spent:	**1186.45**
				Cash Left:	88.55