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Xanthan Gum Isolation Alternative via Ultrafiltration

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May 8, 2023

Dr. Sankar V. Raghavan
437 Dougherty Engineering Building
1512 Middle Drive
Knoxville, TN 37996

Dear Dr. Raghavan,

We are submitting our report entitled "Xanthan Gum Isolation Alternative via Ultrafiltration" as fulfillment of the final report requirement in the chemical engineering senior design course (CBE 488/490).

This report will present the evaluation of implementing an ultrafiltration unit in a xanthan gum production plant to decrease both capital and manufacturing costs. As a foundation for assessment, a new production layout was designed and then subsequently valued. The details of the equipment design and economic feasibility will be justified through application of concepts from our chemical engineering education.

Sincerely,

Jeffrey Greer
Anna Beth Malone
Lucy Moore
Lareesa Thomas

CBE 488/490

Final Report

Xanthan Gum Isolation Alternative via Ultrafiltration

Submitted to:

Dr. Sankar Raghavan

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University of Tennessee, Knoxville

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Jeffrey Greer

Anna Beth Malone

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Abstract

The cost of a xanthan gum production facility was compared with and without an ultrafiltration step to determine if this new set up is more profitable. The calculated capital cost is $4.2 million with ultrafiltration and $9.4 million without ultrafiltration, which is a 55% decrease in cost. In addition, the utility, raw materials, and wastewater costs differ since there is a higher volume of liquid to process in the system that lacks the ultrafiltration unit. The annual utility, raw material, and wastewater treatment costs are $8.5 million with ultrafiltration and $24.5 million without ultrafiltration, which is a 65% decrease in cost. In a 12 year financial analysis for this new system, the price for Xanthan gum can remain priced at $7.61 per kg and generate $35 million in revenue a year. Overall, the process with the ultrafiltration step is recommended since the company can become profitable by year 3 as opposed to year 12 without ultrafiltration.

Introduction

This project investigates the economic impacts of adding an ultrafiltration unit to a prospective xanthan gum production process. In theory, adding the ultrafiltration unit will help minimize the liquid volume in the downstream processes. Ultrafiltration is a filtration process driven by a pressure differential. This pressure differential is known as transmembrane pressure (TMP). Xanthan Gum is also a shear thinning fluid, this means that the viscosity of the fluid decreases with an increase in shear rate. This unique flow characteristic was capitalized on in the design of the ultrafiltration unit proposed herein.

The addition of an ultrafiltration system will decrease the sizes of columns, tanks, heaters, and other vessels which will decrease their costs. In addition, less raw materials, utilities, and wastewater treatment will be required in the process, resulting in a decrease in these annual costs. An economic analysis for the current system without the ultrafiltration unit and the new proposed system with an ultrafiltration unit will be performed to compare the differences in profitability over a 12 year period.

Block Flow Diagram

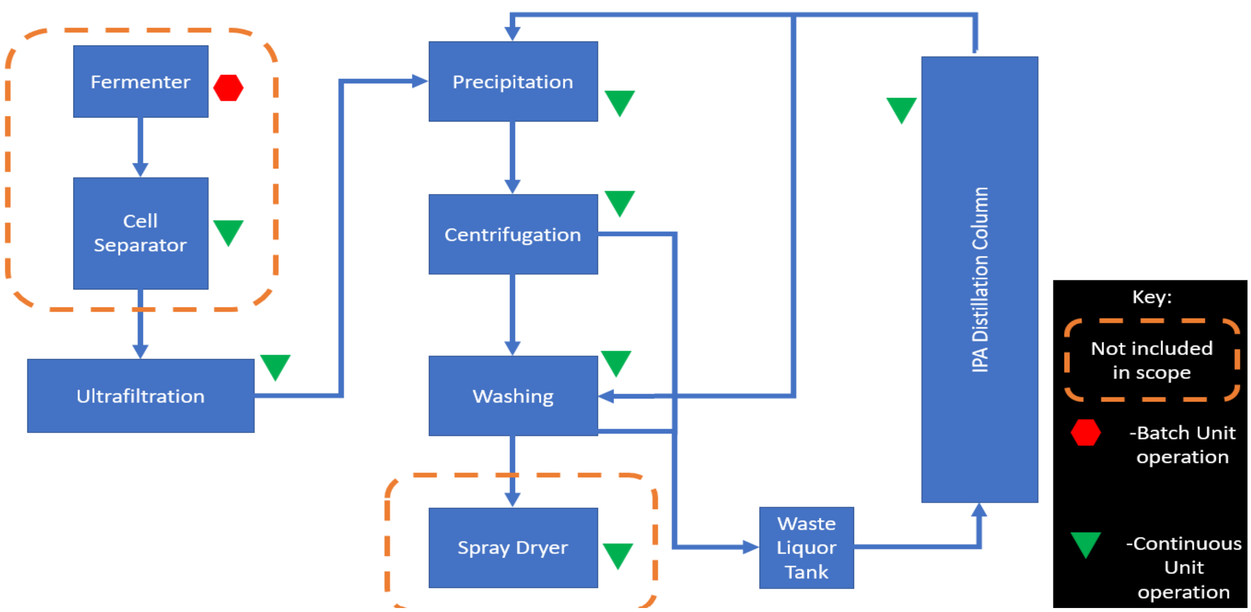

Figure 1. Block Flow Diagram 1 for Xanthan Gum Production with Ultrafiltration

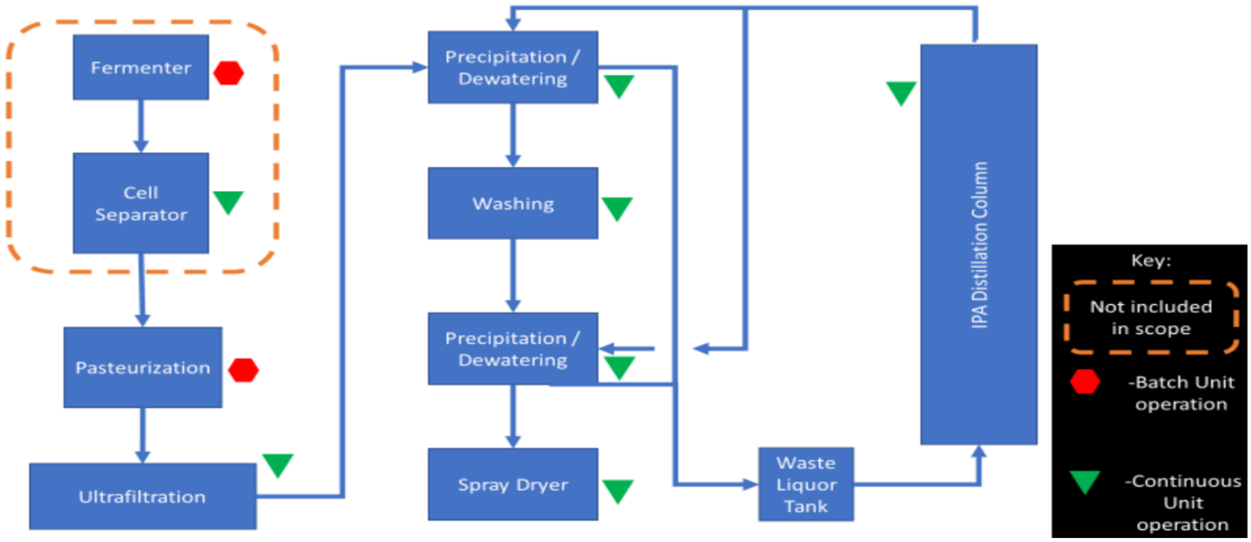

Figure 2. Block Flow Diagram 2 with batch pasteurization

The block flow diagrams display whether each unit operation will run continuously or as batch. Continuous operation was chosen when possible to more efficiently produce xanthan gum and continuously operate at steady state opposed to facing difficulties more frequently during startup for batch operation. The blocks outlined by the orange dotted indicate processing steps that are deemed out of scope of our original assignment. These steps would not be impacted positively or negatively due to the addition of an ultrafiltration processing step. Figure 1 was the selected block diagram for design purposes given that all operations in scope would be continuous and reduce the number of large intermediate tanks. To note, pasteurization was included as a potential sterilization step in the initialization process flow provided to the team but was later determined to also be out of scope for a similar reason as the previously mentioned processes.

Process Flow Diagram and Material Balances

Process Flow Diagram

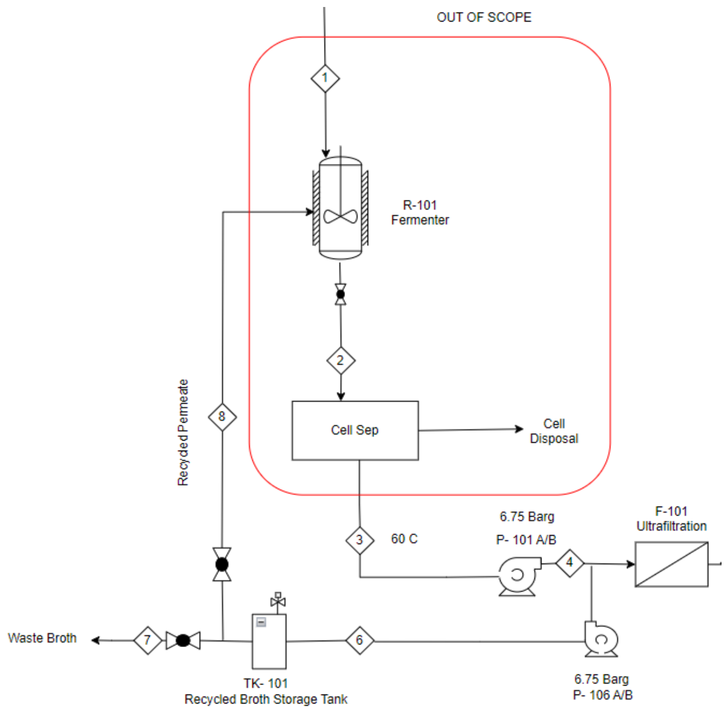

Figure 3. Process Flow Diagram – Fermentation and Ultrafiltration

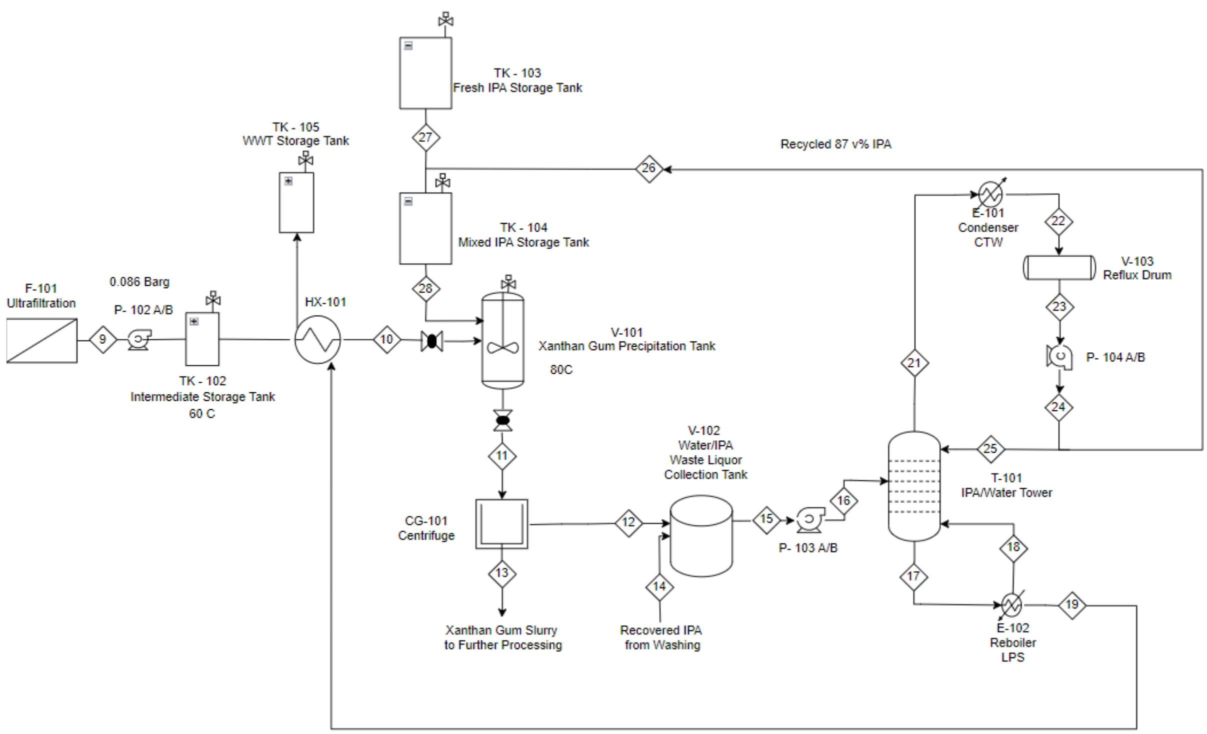

Figure 4. Process Flow Diagram – Precipitation and Recovery

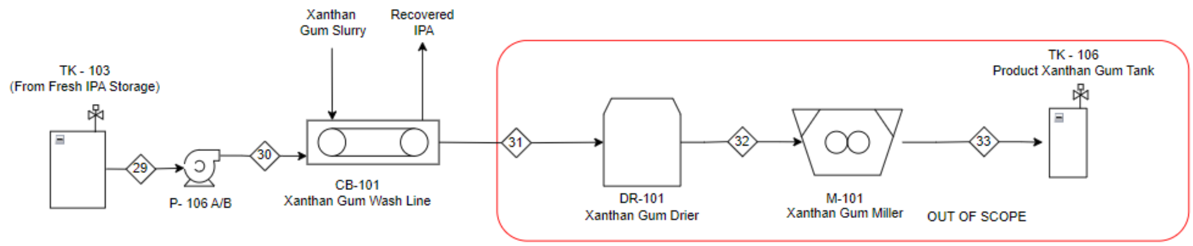

Figure 5. Process Flow Diagram – Final Processing

Assumptions for Material Balance

The foundation of equipment design, safety review, and financial analysis require a comprehensive stream table. The yearly xanthan gum production requirement is 5,000 metric tons. To find the hourly production of xanthan gum, the plant is assumed to be a 24 hour facility that is operational 333 days in a calendar year. Using those assumptions, the average hourly xanthan gum production is 625.53 kg/hr. Given the concentration out of fermentation is 2.5 w/v%, the volumetric flow rate of post fermentation broth can be calculated. This broth is mostly water but a residual amount of the fermentation substrate, sucrose, remains. The concentration of sucrose out of fermentation is 6.5g/L.[9] Due to water being the primary constituent, the density of the broth is assumed to be that of water at 60℃ (0.999 kg/L). Using the required volume needed to produce a 2.5w/v% of xanthan gum and the density, the ultrafiltrated inlet mass flow can be determined. Using a similar methodology, the outlet mass flow can be calculated with a 7.5 % w/v%. The balance of these mass flows is the permeate of ultrafiltration of which 50% is recycled back to the fermenter. The retentate volume is used to determine the needed isopropyl alcohol volume by the ratio of 1 volume broth to 4 volumes IPA. Using the density of 87v% isopropyl alcohol (0.820 kg/L), the mass flow can be determined. Through centrifugation it is assumed 95% of the liquid and 5% of the xanthan gum is removed and sent to distillation recovery. The distillation separation was designed in ASPEN using the UNIQUAC property method. This column was designed to produce 87 v% (84w%) isopropyl alcohol in the distillate and to minimize isopropyl alcohol losses in the bottoms. The last assumption key to the material balance was a ratio 1 volume of isopropyl alcohol to 1 volume xanthan gum in the wash line. With the above assumptions and conservation of mass, the mass balance was performed in an attached spreadsheet.

Material Balance with Ultrafiltration

Table 1. Stream 1 through Stream 12 – With Ultrafiltration

	S-1	S-2	S-3	S-4	S-6	S-7	S-8	S-9	S-10	S-11	S-12
Mass Flows (kg/hr)											
Total	25502.25	25852.60	25852.60	25852.60	15937.46	7968.73	7968.73	9915.14	9915.14	37560.28	35062.89
Xanthan Gum	0.00	688.19	688.19	688.19	0.00	0.00	0.00	688.19	688.19	688.19	34.41
Sucrose	500.50	162.66	162.66	162.66	103.02	51.51	51.51	59.64	59.64	59.64	56.66
Water	25001.75	25001.75	25001.75	25001.75	15834.44	7917.22	7917.22	9167.31	9167.31	13590.53	12911.00
Isopropyl Alcohol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	23221.91	22060.82
Mass Fractions											
Xanthan Gum	0.00	0.03	0.03	0.03	0.00	0.00	0.00	0.07	0.07	0.02	0.00
Sucrose	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00
Water	0.98	0.97	0.97	0.97	0.99	0.99	0.99	0.92	0.92	0.36	0.37
Isopropyl Alcohol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.62	0.63
Temperature (C)			60.00	60.00	60.00	60.00	60.00	60.00	80.00	80.00	90.00
Pressure (Barg)			1.01	6.74	0.09	0.09	0.09	0.09	0.20	0.11	2.00

Table 2. Stream 13 through Stream 23 – With Ultrafiltration

	S-13	S-14	S-15	S-16	S-19	S-20	S-21	S-22	S-23
Mass Flows (kg/hr)									
Total	2497.38	4680.27	39743.17	39743.17	8799.92	8799.92	61886	61886	61886
Xanthan Gum	653.78	0.00	34.41	34.41	34.41	34.41	0	0	0
Sucrose	2.98	0.00	56.66	56.66	56.66	56.66	0	0	0
Water	679.53	748.84	13659.85	13659.85	8708.84	8708.84	9902.02	9902.02	9902.02
Isopropyl Alcohol	1161.10	3931.43	25992.25	25992.25	0.01	0.01	51983.98	51983.98	51983.98
Mass Fractions									
Xanthan Gum	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sucrose	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00
Water	0.27	0.16	0.34	0.34	0.99	0.99	0.16	0.16	0.16
Isopropyl Alcohol	0.46	0.84	0.65	0.65	0.00	0.00	0.84	0.84	0.84
Temperature (C)	90.00	30.00	70.00	70.00	103.00	103.00	80.00	79.60	79.60
Pressure (Barg)	2.00	0.20	0.00	0.09	0.11	0.20	0.01	0.01	0.00

Table 3. Stream 24 through Stream 33 – With Ultrafiltration

	S-24	S-25	S-26	S-27	S-28	S-29	S-30	S-31	S-32	S-33
Mass Flows (kg/hr)										
Total	61886	30943.00	30943.00	69.12	27645.14	4727.55	4727.55	745.81	653.78	653.78
Xanthan Gum	0	0.00	0.00	0.00	0.00	0.00	0.00	653.78	653.78	653.78
Sucrose	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water	9902.02	4951.01	4951.01	11.06	4423.22	756.41	756.41	33.98	0.00	0.00
Isopropyl Alcohol	51983.98	25991.99	25991.99	58.06	23221.91	3971.14	3971.14	58.05	0.00	0.00
Mass Fractions										
Xanthan Gum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.88	1.00	1.00
Sucrose	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.05	0.00	0.00
Isopropyl Alcohol	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.08	0.00	0.00
Temperature (C)	79.60	79.60	79.60	25.00	80.00	25.00	25.00	25.00	25.00	25.00
Pressure (Barg)	0.00	0.00	0.00	0.20	0.20	0.00	0.20	-	-	-

Material Balance without Ultrafiltration

Table 4. Stream 1 through Stream 15 – Without Ultrafiltration

	S-1	S-2	S-3	S-4	S-9	S-10	S-11	S-12	S-13	S-14	S-15
Mass Flows (kg/hr)											
Total	25502.3	25852.6	25852.6	25852.6	25852.6	25852.6	111765.2	105557.6	6207.6	4680.3	110237.9
Xanthan Gum	0.0	688.2	688.2	688.2	688.2	688.2	688.2	34.4	653.8	0.0	34.4
Sucrose	500.5	162.7	162.7	162.7	162.7	162.7	162.7	154.5	8.1	0.0	154.5
Water	25001.8	25001.8	25001.8	25001.8	25001.8	25001.8	38747.8	36810.4	1937.4	748.8	37559.2
Isopropyl Alcohol	0.0	0.0	0.0	0.0	0.0	0.0	72166.6	68558.3	3608.3	3931.4	72489.7
Mass Fractions											
Xanthan Gum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Sucrose	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water	1.0	1.0	1.0	1.0	1.0	1.0	0.3	0.3	0.3	0.2	0.3
Isopropyl Alcohol	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.6	0.6	0.8	0.7
Temperature (C)	-	-	60.0	60.0	60.0	80.0	80.0	80.0	80.0	30.0	70.0
Pressure (Barg)	-	-	1.0	6.7	0.1	0.2	0.3	2.0	2.0	0.2	0.0

Table 5. Stream 16 through Stream 23 – Without Ultrafiltration

	S-16	S-17	S-18	S-19	S-20	S-21	S-22	S-23
Mass Flows (kg/hr)								
Total	110237.9	97009.5	73257.8	23940.6	23940.6	172594.7	172594.7	172594.7
Xanthan Gum	34.4	34.4	34.4	34.4	34.4	0.0	0.0	0.0
Sucrose	154.5	154.5	154.5	154.5	154.5	0.0	0.0	0.0
Water	37559.2	96820.5	73068.9	23751.6	23751.6	27615.2	27615.2	27615.2
Isopropyl Alcohol	72489.7	0.1	0.0	0.0	0.0	144979.5	144979.5	144979.5
Mass Fractions								
Xanthan Gum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sucrose	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water	0.3	1.0	1.0	1.0	1.0	0.2	0.2	0.2
Isopropyl Alcohol	0.7	0.0	0.0	0.0	0.0	0.8	0.8	0.8
Temperature (C)	70.0	102.5	103.0	103.0	103.0	80.0	79.6	79.6
Pressure (Barg)	0.1	0.1	0.1	0.1	0.2	0.0	0.0	0.0

Table 6. Stream 24 through Stream 33 – Without Ultrafiltration

	S-24	S-25	S-26	S-27	S-28	S-29	S-30	S-31	S-32	S-33
Mass Flows (kg/hr)										
Total	172594.7	86297.4	86297.4	429.6	85912.6	4727.6	4727.6	1208.4	653.8	653.8
Xanthan Gum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	653.8	653.8	653.8
Sucrose	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water	27615.2	13807.6	13807.6	68.7	13746.0	756.4	756.4	193.7	0.0	0.0
Isopropyl Alcohol	144979.5	72489.8	72489.8	360.8	72166.6	3971.1	3971.1	360.8	0.0	0.0
Mass Fractions										
Xanthan Gum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	1.0
Sucrose	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.
Isopropyl Alcohol	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.3	0.0	0.0
Temperature (C)	79.6	79.6	79.6	25.0	80.0	25.0	25.0	25.0	25.0	25.0
Pressure (Barg)	0.0	0.0	0.0	0.2	0.2	0.0	0.2	-	-	-

Process Description

Xanthan gum is produced at an industrial scale via the fermentation of Xanthomonas campestris in a broth which consists of sucrose and water. Following this fermentation process, the bacterial cells are separated out. The aqueous xanthan gum is concentrated using the ultrafiltration process, thus reducing the volume of flow that goes to the rest of the process. The permeate of ultrafiltration consists of sucrose and water, 50% of which is recycled to fermentation, and the rest is sent to waste water processing. The retentate, a concentrated xanthan gum solution, is precipitated in a continuous stirred tank reactor with four times its volume of isopropyl alcohol. The alcohol affects the solubility of the xanthan gum solution and causes the xanthan gum to precipitate out as a solid. This allows for centrifugation to next produce a thick slurry of xanthan gum precipitant. This xanthan gum solution is washed with isopropyl alcohol, dried, and milled to final product. The supernatant of centrifugation is a solution of isopropyl alcohol, sucrose, residual xanthan gum, and water. This solution, along with the wash liquor from xanthan gum washing, is collected and separated. Separation occurs in a distillation column where the distillate is 87 v% (84 wt%) isopropyl alcohol, and the bottoms product is the remaining water, residual xanthan gum, and sucrose. The distillate is recycled back to precipitation and xanthan gum washing. The bottoms product is sent to waste water processing. The distillation process was modeled using aspen as seen in the figure below.

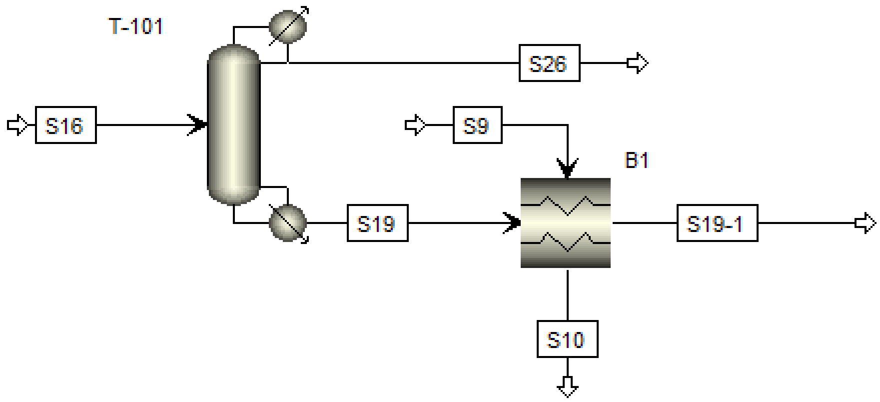

Figure 6. Aspen Distillation Model

Energy Balance and Utility Requirements

The energy balance was evaluated by examining the major energy transfers and consumers in the system. For this system, that includes the column condenser (E-101), the column reboiler (E-102), and the precipitation preheater (E-103). The heat transfer rate (Q) in watts was found using Aspen. E-101 is an open air condenser, so there is no utility required. E-103 uses heat integration to transfer heat from two process streams. Because of this there are no utility requirements in E-103. Finally for the E-102, the column reboiler, the following equation was used to calculate the required utility rate.

$$Q = \dot{m}c_p\Delta T + \dot{m}\lambda \qquad (1)$$

Low pressure steam (1.5 barg) has a saturation temperature of 127.6℃ and a latent heat of vaporization of 2180650 kJ/kg. These values are sufficient enough to produce the required temperature change in the column bottoms. Since reboilers utilize the latent heat of steam to produce the needed heat transfer, the equation simplifies to the following equation.

$$Q = \dot{m}\lambda \qquad (2)$$

Table 7. Low Pressure Steam Usage

	Usage (kg/hr)
Plant with Ultrafiltration	31171
Plant without Ultrafiltration	76289

Table 8. Heat Transfer Rates of Heat Exchangers – Plant with Ultrafiltration

Equipment Number	Equipment Description	Q (Watts)
E-101	Column Air Condenser	15,854,176.24
E-102	Column Reboiler	18,881,410.25
E-103	Bottoms to Precipitation Exchanger	156,117.2745

Table 9. Heat Transfer Rates of Heat Exchangers – Plant without Ultrafiltration

Equipment Number	Equipment Description	Q (Watts)
E-101	Column Air Condenser	44,188,414.15752
E-102	Column Reboiler	46,211,411.02212
E-103	Bottoms to Precipitation Exchanger	382,090.083

The other required utility in the process is electricity. Electricity is used in pumps and in the precipitation tank agitator. For pumps the electricity requirement is found by finding the shaft work required to produce the needed pressure change.

$$W_s = \frac{\dot{m}\Delta P}{\eta\rho} \qquad (3)$$

Table 10. Pump Electricity Requirements – Plant with Ultrafiltration

Equipment Number	Equipment Description	Mass Flow (kg/hr)	Density (kg/m^3)	deltaP (Pa)	Efficiency	Power (kW)
P-101 A/B	UF Feed Pump	28228	997.7	575000	0.87	5.05
P-102 A/B	Precipitation Feed Pump	9915	980.6	11381.6	0.75	0.0426
P-103 A/B	Column Feed Pump	38942	854.6	8675	0.75	0.1464
P-104 A/B	Column Reflux Pumps	61886	752.8	1333	0.75	0.04059
P-106 A/B	UF Recirculation Pump	684000	997.7	665690	0.87	150.2

Table 11. Pump Electricity Requirements – Plant without Ultrafiltration

Equipment Number	Equipment Description	Mass Flow (kg/hr)	Density (kg/m^3)	deltaP (Pa)	Efficiency	Power (kW)
P-104 A/B	Column Reflux Pumps	172595	752.8	1333	0.75	0.1132
P-102 A/B	Precipitation Feed Pump	25853	980.6	11381.6	0.75	0.1111
P-103 A/B	Into Column	110238	854.6	8675	0.75	0.4145

The last electricity draw is the agitator (M-101) in the precipitation tank. The required power was found by using a scale up lab data. In this lab scale performance of xanthan gum precipitation, the power requirement was 2 W, and the volume of the tank was 5.9 L. The volume is determined by using the dimensions of the tank and liquid level provided.[2] Scaling up to a tank size of 46,508 L, the power required for the agitator will be 15.7 kW. These values can be taken as a power to volume ratio which would be kept constant from a lab scale to an industrial scale and was found to be 2.96.

$$MP = 2.96 * V \qquad (4)$$

Table 12. Mixer (M-101) Electricity Requirements

	Tank Size (m^3)	Power Requirement (kW)
Plant with Ultrafiltration	58.1	15.75
Plant without Ultrafiltration	139.8	37.90

Equipment List and Unit Descriptions

T-101 Isopropyl Alcohol and Water Separation Distillation Column

This column recovers the isopropyl alcohol used in the precipitation and washing steps. This column consists of 14 sieve trays. This column is designed to have 87 w/v% isopropyl alcohol in the distillate and the remaining water, sucrose, and xanthan gum in the bottoms.

V-101 CSTR Precipitation of Xanthan Gum and Isopropyl Alcohol

This vessel will precipitate the xanthan gum using 4 equivalent volumes of IPA. A mechanical seal agitator will mix the tank to allow for the xanthan gum to precipitate out of solution.

V-102 Waste Liquor Collection

This tank will act as a collection vessel for the liquid product out of the centrifuge and the wash line. This liquid consists of isopropyl alcohol, residual sucrose, and residual xanthan gum. This tank will feed the distillation process which recovers the isopropyl alcohol.

V-103 Reflux Drum for Column T-101

This process vessel collects the condensed reflux and distillate product before it is pumped back to the column and storage, respectively.

TK -101 Tank for Recycled Broth Stream

The recycled broth stream will be pumped into this tank. Half of the permeate will be recycled back to the fermentation step, and half will be sent to wastewater processing.

TK-102 Tank for Post Ultrafiltration Stream

This will serve as an intermediate storage tank after the ultrafiltration unit before it goes into the preheater for the precipitation. This tank's main purpose is to allow mid-process storage in the event of a process upset.

TK-103 Tank for Fresh Isopropyl Alcohol

This tank will store approximately a year's supply of IPA.

TK-104 Tank for Fresh and Recycled Isopropyl Alcohol

The recycled IPA and fresh IPA will both flow into this tank before going into V-101.

TK-105 Tank for Wastewater Stream

This tank will hold some of the wastewater stream as it is sent to wastewater treatment.

TK-106 Tank for Xanthan Gum

This tank will hold the accumulating xanthan gum.

E-101 Condenser for Column T-101

This air-cooled (fin-fan) exchanger operates at the top of the distillation column to condense a liquid stream to supply the top tray. This condenser operates at a pressure of 1 atm.

E-102 Reboiler for Column T-101

This kettle reboiler operates at the bottom of the distillation column to generate vapor flow for the bottom tray. This reboiler operates at a pressure of 0.02 barg. The needed heat duty is supplied by low pressure steam.

E-103 Preheater for Precipitation Reaction

The preheater will use the bottoms of T-101 to preheat the solution to 80℃ before going into V-101.

P-101 A/B Feed Pump for Ultrafiltration

This pump will feed the solution into the Ultrafiltration unit.

P-102 A/B Feed Pump for Precipitation

This pump will feed the solution from the ultrafiltration unit into the precipitation tank.

P-103 A/B Feed Into Column

This pump will feed the solution in the waste liquor tank into column T-101.

P-104 A/B Column Reflux Pump

This pump provides the needed pressure to pump the condensed liquid back to the column and the liquid product to storage.

P-106 A/B Fresh Isopropyl Alcohol Pump

This pump will feed fresh isopropyl alcohol from TK-103 to the xanthan gum wash line CB-101.

M-101 Mixer for V-101

The mixer will agitate the solution in V-101.

CG-101 Centrifuge

The centrifuge “dewaters” the xanthan gum slurry to separate the precipitated gum from water, isopropyl alcohol, and residuals.

F-101 Ultrafiltration Unit

Transmembrane pressure driven unit that retains the xanthan gum and specified amount of fermentation broth while removing excessive broth to recycle or send to waste handling.

Equipment Specification Sheets

Tanks and vessels are sized using Equation 5 assuming an 80% fill volume.

$$V = \frac{\dot{m} * \tau}{\rho * level\ set\ point} \qquad (5)$$

Table 13. Sizing Specifications of Tanks and Vessels

Unit	Temp (C)	MoC	Orientation	Type	Volume (m^3)	Height (m)	Diameter (m)
TK-101	N/A	Carbon Steel	Vertical	Cone Roof	19.921825	N/A	N/A
Tk-102	N/A	Carbon Steel	Vertical	Cone Roof	12.393925	N/A	N/A
TK-103	N/A	Carbon Steel	Vertical	Floating Roof	0.10875	N/A	N/A
TK-104	N/A	Carbon Steel	Vertical	Floating Roof	53.7053625	N/A	N/A
TK-105	N/A	Carbon Steel	Vertical	Cone Roof	10.99875	N/A	N/A
TK-106	N/A	Carbon Steel	Vertical	Cone Roof	0.81625	N/A	N/A
V-101	80	Carbon Steel	Vertical	CSTR	58.134625	9	3
V-102	90	Carbon Steel	Vertical	N/A	49.67895	7	3
V-103	80	Carbon Steel	Vertical	Reflux Drum	38.2975	5.5	3

Heat exchangers are assumed to be counter-current flow with all components made out of carbon steel. The required heat transfer area was found using Equation 6.

$$Q = U * A * \Delta T_{LM} \qquad (6)$$

The overall heat transfer coefficient (U) was found from heuristics.[2]

Table 14. Common Overall Heat Transfer Coefficients

Exchanger Type	U ($\frac{W}{m^2K}$)
Reboiler	1140
Condenser	850
Liquid to Gas	60

Table 15. Heat Exchangers Equipment Specification – With Ultrafiltration

Equipment Number	Equipment Description	$T_{cold,\ in}$ (℃)	$T_{cold,\ out}$ (℃)	$T_{hot,\ in}$ (℃)	$T_{hot,\ out}$ (℃)	Q (Watts)	U ($\frac{W}{m^2K}$)	ΔT_{LM}	A (m^2)
E-101	Column Air Condenser	25	35	79.97	79.5911	15854176.24	60	49.63	5324.55
E-102	Column Reboiler	102.507	102.864	127.59	127.588	18881410.25	1140	24.90	665.11
E-103	Bottoms to Precipitation Exchanger	60	80	100	94.7	156117.27	850	26.68	6.88

Table 16. Heat Exchangers Equipment Specification – Without Ultrafiltration

Equipment Number	Equipment Description	$T_{cold,\ in}$ (℃)	$T_{cold,\ out}$ (℃)	$T_{hot,\ in}$ (℃)	$T_{hot,\ out}$ (℃)	Q (Watts)	U ($\frac{W}{m^2K}$)	ΔT_{LM}	A (m^2)
E-101	Column Air Condenser	25	35	79.64	79.59	44188414.16	60	49.45	14893.2
E-102	Column Reboiler	100.013	100.018	127.58	127.58	46211411.02	1140	27.57	1470.17
E-103	Bottoms to Precipitation Exchanger	60	80	100	94.7	382090.07	850	26.68	16.85

The ultrafiltration unit was sized using two equations provided to the team at the beginning of the project. These equations below identify the effectiveness of the theoretical ultrafiltration system. In order to take the stream from the feed 2.5 w/v% (25 g/L) to the specified target of 7.5 w/v% (75 g/L) it was calculated that 5.1 L/s of broth had to be removed to maintain the target production rate. The filter specification and separation efficiency can be seen in Table 17. The size of the filter cross section and the amount of active area was determined based on commercially available units.

$$J,\ \frac{m^3}{m^2 s} = 3 * 10^{-8} * TMP^{0.4} * C^{-0.25} * \gamma^{0.5} \qquad (7)$$

$$\Delta p = 220 * C * \gamma^{0.5} \qquad (8)$$

Table 17. Ultrafiltration Filter Specification

Filter	deltaP (Pa)	Y (gama) (1/S)	J (Permeate Flux) L/(s*m^2)	Q (L/S)	Area (m^2)	TMP Pa	Average C (g/L)	Y (1/S)	Exit C [redacted]
1	48208.64	58.78868	0.013304864	0.731768	55	206842.8	28.579548	58.78868	32.1591
2	59863.02	58.56312	0.012573569	0.691546	55	206842.8	35.556894	58.56312	38.95469
3	70930.4	58.34996	0.012024037	0.661322	55	206842.8	42.207484	58.34996	45.46028
4	81518.91	58.14611	0.011587611	0.637319	55	206842.8	48.593183	58.14611	51.72609
5	91704.35	57.94966	0.011227742	0.617526	55	206842.8	54.75727	57.94966	57.78845
6	101542.6	57.75931	0.010922819	0.600755	55	206842.8	60.731595	57.75931	63.67474
7	111076.6	57.57413	0.010659078	0.586249	55	206842.8	66.540495	57.57413	69.40625
8	120339.9	57.39343	0.010427243	0.573498	55	206842.8	72.203126	57.39343	75

This system was also designed to include two additional backup filters incase of plugging or maintenance that could potentially occur. These additional filters would provide continued processing without the need to shutdown the whole system. The TMP within each filter would be controlled with a controller strategy based on the pressure indicators shown in the detailed design figure below.

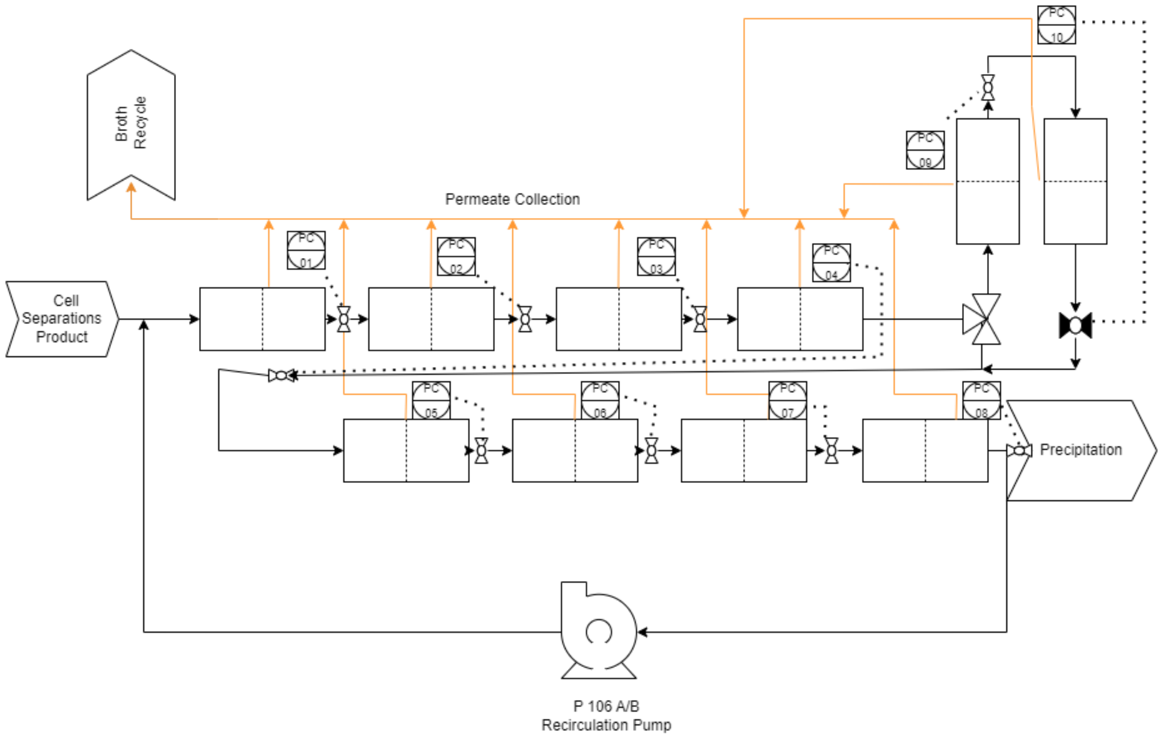

Figure 7. Detailed design image of Ultrafiltration Unit.

The distillation column was modeled as a RadFrac unit in ASPEN, and the diameter was found using the sizing functionality with an 80% approach to flood. A standard 50% tray efficiency was used as an early conservative design approximation. The trays themself are sieve trays constructed of stainless steel. A two foot tray spacing was chosen to allow for enough room during tray inspections during regular maintenance shutdowns. An additional 20 feet of space is added to the height of the column to allow for proper vapor liquid disengagement. The column itself is constructed of carbon steel.

Table 18. Distillation Equipment Specifications – With Ultrafiltration

Equipment Number	Equipment Description	Number of Aspen Equilibrium Stages	Tray Efficiency	Number of Trays	Tray Spacing (m)	Vapor Liquid Disengagement Space (m)	Column Height (m)	Column Diameter (m)
T-101	IPA Recovery Column	9	0.5	14	0.6096	6.096	11.5824	3

Table 19. Distillation Equipment Specifications – Without Ultrafiltration

Equipment Number	Equipment Description	Number of Aspen Equilibrium Stages	Tray Efficiency	Number of Trays	Tray Spacing (m)	Vapor Liquid Disengagement Space (m)	Column Height (m)	Column Diameter (m)
T-101	IPA Recovery Column	9	0.5	14	0.6096	6.096	11.5824	5

Equipment Cost Summary

All equipment costs were estimated using the capital costing packet provided during CBE 480.[2] An inflation rate of 831/400 was used in the calculations.

The tanks and vessels were costed with carbon steel as the material of construction and vertical configuration. Using the cubic meters calculated from the flow rates, Table 5.61 for tanks and 5.44 for vessels is used from the costing guide.[2]

Table 20. Summary of Tanks and Vessel Equipment Costs

	Equipment Number	Total (with UF)	Total (without UF)
	V-101	$519,375.00	$2,077,500.00
	TK-101	$32,762.18	$32,762.18
	TK-102	$31,578.00	$31,578.00
	TK-103	$31,578.00	$197,362.50
	TK-104	$134,206.50	$134,206.50
	TK-105	$27,630.75	$27,630.75
	TK-106	$19,736.25	$19,736.25
	V-102	$130,259.25	$78,945.00
	V-103	$251,169.75	$251,169.75
Total Tank/Vessel Costs:		$1,178,295.68	$2,850,890.93

All components of each heat exchanger are constructed of carbon steel. The column condenser (E-101) was cost using the air-cooled (fin-fan) pricing data (Figure 5.40).[2] The column reboiler (E-102) and precipitation preheater (E-103) were costed using the shell and tube heat exchanger pricing data (Figure 5.36).[2] The column reboiler was cost as a kettle reboiler and the preheater as a fixed tube sheet type.

Table 21. Summary of Heat Exchanger Equipment Costs

Equipment Number	Equipment Description	Total (with UF)	Total (Without UF)
E-101	Column Condenser	$708,427.50	$1,223,647.50
E-102	Column Reboiler	$32,201.25	$1,288,050.00
E-103	Precipitation Preheater	$18,697.50	$28,981.13
	Total:	$759,326.25	$2,511,697.50

The pumps were cost using their required shaft power which was calculated earlier in the "Energy Balance and Utility Requirements" section. All pumps are centrifugal pumps. Pumps P-101A/B and P-105 A/B are constructed of cast iron. All other pumps are of stainless steel construction.

Table 22. Summary of Pump Equipment Costs

Equipment Number	Equipment Description	Total (with UF)	Total (without UF)
P-101 A/B	UF Feed Pump	$81,022.50	-
P-102 A/B	Precipitation Feed Pump	$32,575.20	$40,719.00
P-103 A/B	Column Feed Pump	$122,157.00	$61,078.50
P-104 A/B	Column Reflux Pumps	$30,539.25	$40,719.00
P-106 A/B	UF Recirculation Pump	$336,555.00	-
	Total:	$602,848.95	$142,516.50

The column was cost as two parts: the exterior vessel and the internal trays. The external vessel was cost using the same methodology as the process vessels described above. The trays were cost using their diameter and Figure 5.48 in the costing data.[2] The vessel is carbon steel, and the trays are stainless steel sieve trays. A quantity factor of 1.11 was used.

Table 23. Summary of Distillation Column Equipment Costs

Equipment Number	Equipment Description	Total (with UF)	Total (without UF)
T-101	External Vessel	$1,142,625.00	$1,038,750.00
T-101	14 Sieve Trays	$355,127.85	$1,065,383.55
	Total:	$1,497,752.85	$2,104,133.55

The mixer was cost using Figure 5.42 and the power consumption calculated in the "Energy Balance and Utility Requirements" section.[2] The mixer was assumed to be an agitator with a mechanical seal constructed of carbon steel. The ultrafiltration unit filters were cost using the provided theoretical Equation 7 and Equation 8. This determined the concentration leaving each filter and the amount of permeate removed. The information was put into a spreadsheet and determined eight filters would be required for the separation at a pressure condition of 30 psig transmembrane pressure (TMP). Two additional filters were included in the design and cost, as well as in-line spare units. The value of these filters with the required area were found online at DWS Advantage.

For the centrifuge, Stokes' Law was applied to determine the sedimentation velocity and relative centrifugal force. With these values, an approximate estimate of the sigma factor was calculated to be 3,688,162 m^2. With the particle diameter of approximately 10 micron and separation of solid and liquid, a vertical sedimentation centrifuge is most common. Evaluating industrial centrifuge purchasing options, Alfa Laval separators were compared by the machine specifications and the process needs. To meet the process demands of flow and viscosity, in addition to the calculations described, the Clara 601H model centrifuge was chosen with advising from an Alfa Laval sales representative.[8] More specifically, this is a disc-stacked, vertical, solids-ejecting centrifuge system frequently used in the food and beverage industry. The Alfa Laval sales representative drafted a quote for the machine. From this research, the comparison for centrifugation without ultrafiltration was completed in a similar manner, and the Alfa Laval representative confirmed that a second or even third unit may have been necessary to the process without the alterations adding ultrafiltration resulted in.

Table 24. Summary of Miscellaneous Equipment Costs

Equipment Number	Equipment Description	Total (with UF)	Total (without UF)
M-101	Precipitation Tank Mixer	$124,650.00	$228,525.00
CG-101	Centrifuge	$800,000.00	$1,600,000.00
F-101	Ultrafiltration Filters	$27,562.50	-
	Total:	$952,212.50	$1,828,525.00

Table 25. Summary of All Equipment Costs

	Plant With Ultrafiltration	Plant Without Ultrafiltration
Tanks and Vessels	$1,178,295.68	$2,850,890.93
Heat Exchangers	$759,326.25	$2,511,697.50
Pumps	$602,848.95	$142,516.50
Distillation Column	$1,497,752.85	$2,104,133.55
Miscellaneous	$952,212.50	$1,828,525.00
Total	$4,990,436.23	$9,437,763.48

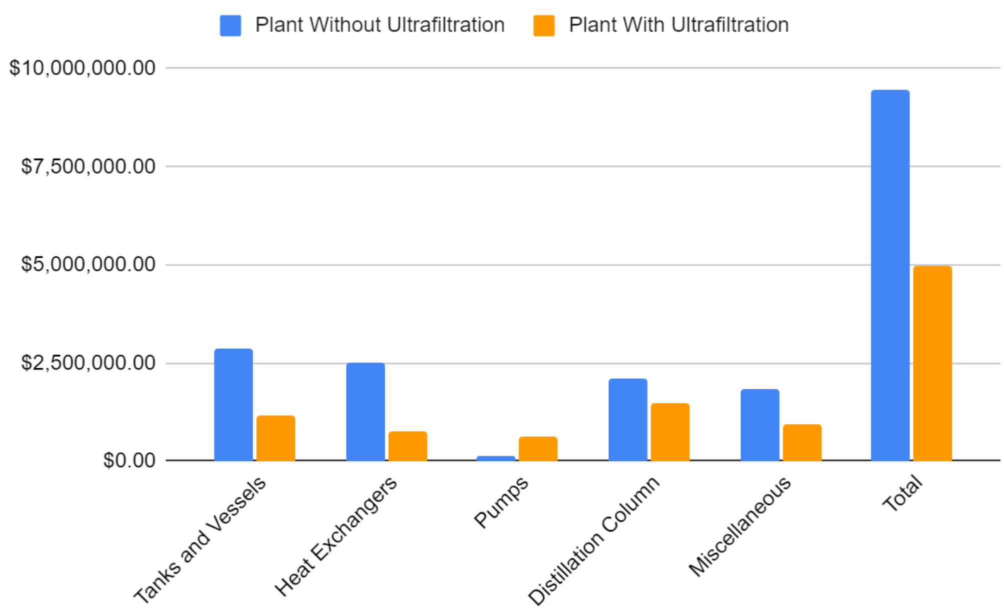

Figure 8. Comparison of Equipment Costs With and Without Ultrafiltration

Fixed Capital Investment Summary

The capital investments considered in this project were focused on those incurred by the purchase of equipment. For comprehensive detail on the equipment sizing considerations please reference the equipment cost summary section. An additional 10% of this cost was assumed to be the cost for purchasing the land this plant would be located on in the United States.

Safety, Health, and Environmental Considerations

All relevant MSDS information was considered for applicable health, safety, and environmental concerns.[11] [12] All MSDS will be located onsite and available to all employees or contractors in proximity of the process. Xanthan gum can occasionally be an irritant to humans, and inhalation of dust may cause respiratory tract irritation. If needed, remove from exposure and move to fresh air immediately and flush eyes and/or mouth with plenty of water for at least 15 minutes. "If irritation develops, get medical aid. Get medical aid if irritation develops or persists, but no specific treatment is necessary, since this material is not likely to be hazardous."[11] No exposure limits are recommended for xanthan gum, but avoid dust generation and use adequate ventilation to keep airborne concentrations low.

Isopropyl alcohol is quite dangerous to inhale or ingest. If contacted, remove from exposure and move to fresh air immediately. As needed, flush eyes and/or skin with plenty of water for at least 15 minutes, or "give conscious victim 2-4 cups of milk or water. Never give anything by mouth to an unconscious person. Get medical aid at once."[12] The chemical has an OSHA recommended maximum exposure limit of 400 ppm TWA or 980 mg/m^3 TWA.

Through proper wastewater treatment, all organic compounds are broken down into carbon dioxide and water. The primary organics consumed in this process are sucrose and xanthan gum. The consumed oxygen and released carbon dioxide can be estimated by the balanced cellular respiration reaction.

$$\text{Sucrose: } C_{12}H_{22}O_{11} + 12O_2 \rightarrow 12CO_2 + 11H_2O$$

$$\text{Xanthan Gum: } 4C_{35}H_{49}O_{29} + 131O_2 \rightarrow 140CO_2 + 98H_2O$$

Oxygen is consumed through chemical and biological means. The chemical oxygen demand (COD) is the required amount of oxygen to complete the cellular respiration which is calculated through stoichiometry. The biological oxygen demand (BOD)is the amount of oxygen required to keep the cells alive. The BOD is typically about 50% of the COD.

Table 26. Wastewater Oxygen Demand

	Plant With Ultrafiltration	Plant Without Ultrafiltration
BOD (kg/hr)	38.4	52.95
COD (kg/hr)	76.8	105.9

Similar to the chemical oxygen demand, the carbon dioxide released can be found through stoichiometry.

Table 27. Annual Carbon Dioxide Emissions due to Wastewater Processing

	Plant With Ultrafiltration	Plant Without Ultrafiltration
CO_2 (MTon/year)	1716	2359

The failure mode and effects analysis submitted with this report estimates the continuous operation of distillation leading to decreased reboiler efficiency as the highest risk priority number. This would result in less efficient use of isopropyl alcohol and a decrease in profit or increase in product price. Because the scenario is likely caused by the gradual fouling of equipment, regular cleaning and maintenance would be maintained. Additionally, regular laboratory analysis of the distillate would be conducted to monitor tower efficiency. To decrease adverse effects of fouling, blowdown could also be implemented in the reboiler. By instilling these process checks, the potential for fouling is decreased.

Safety for the vessels and tanks includes adding floating roofs to tanks with IPA. In addition, level sensors and pressure sensors will be used to monitor and control flow rates, activate any pressure relief systems, and alert personnel to unfavorable conditions in these units. The failure mode and effects analysis also determined the overpressure of tanks, centrifuge, and other vessels to have high risk priority numbers. In addition to the controls previously described, sensors, alarms, and pressure relief devices will be installed on the centrifuge, all tanks, and other applicable vessels.

Manufacturing and Operations Costs

The manufacturing and operational costs include the cost of operation labor, raw materials, waste treatment and utilities. The cost of operation labor (C_{OL}) is found by Equation 10 . First to find the number of operators (N_{OL}) per shift, use Equation 9.

$$N_{OL} = (6.29 + 31.7P^2 + 0.23N_{np})^{0.5} \qquad (9)$$

Where P is the total number of processing steps handling solids and Nnp is the total number of nonparticulate processing steps, which excludes pumps and tanks. The Nnp is determined to be 9 and P is 0. This number is multiplied by 4.5 to find the operating labor. Then, Equation 10 is used assuming an annual salary of $55,000.

$$C_{OL} = N_{OL} * (annual\ salary) \qquad (10)$$

The C_{OL} is $715,000.

The cost of raw materials (C_{RM}) was found by using $3.77 per kilogram for IPA. Air is free for the air condenser, and the water needed for the fermentation was a process not included in our scope as there would be no change with the inclusion of ultrafiltration

Table 28. Annual Raw Material Cost

	IPA Usage (kg/hr)	Unit Cost ($/kg)	Annual Cost ($/year)
Plant with Ultrafiltration	69.12	3.77	$2,081,834.23
Plant without Ultrafiltration	429.58	3.77	$12,938,740.66

The cost of utilities (C_{UT}) was found by adding together the annual cost of low pressure steam and electricity. To find the cost of low pressure steam, the yearly usage was multiplied by the provided unit price.

Table 29. Low Pressure Steam Annual Costs

	Usage (kg/hr)	Unit Cost ($/MT)	Annual Cost ($/year)
Plant with Ultrafiltration	31171	15.00	$3,736,781.44
Plant without Ultrafiltration	76289	15.00	$9,145,551.55

The cost of electricity was found by taking each power drawing piece of equipment and determining the annual electricity amount. That usage was then multiplied by the unit price of electricity.

Table 30. Annual Electricity Costs

Equipment Number	Equipment Description	Unit Cost ($/kWh)	Annual Cost- with UF	Annual Cost- without UF
M-101	CSTR Stirring	0.07	$87,832.08	$212,027.76
P-105 A/B	UF Recirculation pump	0.07	$840,278.88	0
P-101 A/B	UF Feed Pump	0.07	$28,251.72	0
P-104 A/B	Column Reflux Pumps	0.07	$227.07	$633.27
P-103 A/B	Into Column	0.07	$819.10	$2,318.73

P-102 A/B	Into Precipitation	0.07	$238.46	$621.75
		Total:	$957,647.31	$215,601.51

Table 31. Summary of Annual Utility Costs

	Plant with UF	Plant without UF
Low Pressure Steam	$3,736,781.44	$9,145,551.55
Electricity	$957,647.31	$215,601.51
Total:	$4,694,428.75	$9,361,153.05

The cost of waste processing is determined by the cost of processing the waste streams as well as the organics within the streams. The two waste streams involved come from the ultrafiltration permeate that is unable (S-7) to be recycled and the bottoms of the distillation column (S-20). The cost of processing the streams is found by multiplying the annual waste stream production by the unit cost of wastewater processing.

Table 32. Annual Cost of Wastewater Stream Processing

	Volumetric Flow Rate– With UF ($Mgal/hr$)	Volumetric Flow Rate– Without UF	Cost of Wastewater Processing ($/Mgal)	Annual Cost– With UF	Annual Cost– Without UF
Stream 7	2.239	0	1.00	$17,734.69	$0.00
Stream 20	6.465	6.833	1.00	$51,204.35	$54,116.95
			Total:	$68,939.05	$54,116.95

To find the cost of treating the organics in the waste streams, the mass of the organics (xanthan gum, sucrose, and isopropyl alcohol) in each stream is multiplied by the unit cost of organic compound treatment.

Table 33. Annual Cost of Treatment of Organics in Wastewater – With Ultrafiltration

	Mass Flow of Xanthan Gum in Stream (kg/hr)	Mass Flow of Sucrose in Stream (kg/hr)	Mass Flow of Isopropyl Alcohol in Stream (kg/hr)	Cost of TOC Processing ($/kg)	Annual Cost
Stream 7	0	54.22	0	1.54	$668,734.73
Stream 20	31.28	51.51e3	0	1.54	$1,021,106.50
				Total:	$1,689,841.23

Table 34. Annual Cost of Treatment of Organics in Wastewater – Without Ultrafiltration

	Mass Flow of Xanthan Gum in Stream (kg/hr)	Mass Flow of Sucrose in Stream (kg/hr)	Mass Flow of Isopropyl Alcohol in Stream (kg/hr)	Cost of TOC Processing ($/kg)	Annual Cost
Stream 7	-	-	-	-	-
Stream 20	34.41	154.53	0.0148	1.54	$2,330,466.10
				Total:	$2,330,466.10

Table 35. Total Cost of Wastewater

	Plant with Ultrafiltration	Plant without Ultrafiltration
Annual Cost of Waste Stream Processing	$68,939.05	$54,116.95
Annual Cost of Organic Treatment	$1,689,841.23	$2,330,466.10
Total:	$1,758,780.28	$2,384,583.05

The total manufacturing and operating costs is the summation of the operating labor, raw material, utility, and wastewater costs.

Table 36. Summary of Operating and Manufacturing Costs

	Plant with Ultrafiltration	Plant without Ultrafiltration
Operating Labor	$715,000	$715,000
Raw Material	$2,081,834.23	$12,938,740.66
Utility	$4,694,428.75	$9,361,153.05
Waste Water	$1,758,780.28	$2,384,583.05
Total:	$9,250,043	$25,399,477

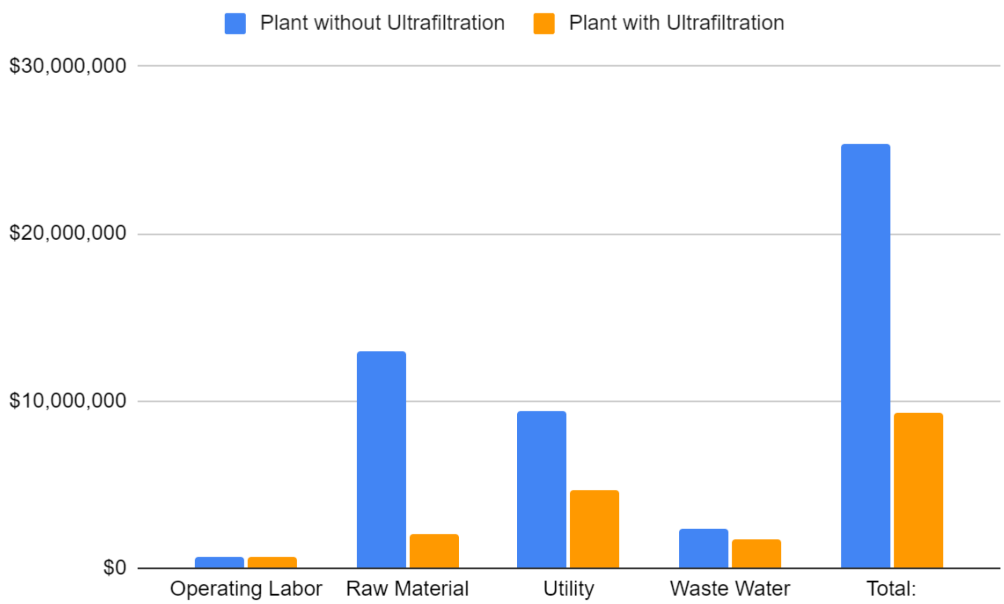

Figure 9. Comparison of Operating and Manufacturing Costs With and Without Ultrafiltration

Economic Analysis

The total capital and manufacturing costs are found by Equation 11.

$$COM_D = 0.18FCI_L + 2.73C_{OL} + 1.23(C_{UT} + C_{WT} + C_{RM}) \qquad (11)$$

Table 37. Summary of Total Cost of Manufacturing before Depreciation

	Plant with Ultrafiltration	Plant without Ultrafiltration
COM_D	$13,208,999.67	$33,859,893.15

The total cost of operation and initial capital investment for both operating systems with and without an ultrafiltration unit were analyzed to determine the appropriate route for investment strategy. These different costs were compared using an analysis that evaluated the net present value of the two investment routes and revenue streams. For all financial analysis, the MACRS method of depreciation was applied and a standard 21% tax rate was applied as well. This analysis assumed that if an investment occurred today that it would break even or meet its designated return requirement 12 years after initial investment, 10 years after start up. For the proven operational method of a refining process without ultrafiltration, a second analytical method evaluating only a 15% internal rate of return (IRR) would be required to pursue this investment. The process of designing a commercial operation without piloting is inherently more risky. Therefore, the expected IRR was increased to 30% for the comparative financial analysis. All of these methods determined an annual revenue which was then divided by the designed production rate to identify a market price per kilogram. It is apparent that, even with the higher return on investment requirement of the riskier xanthan gum refining strategy, the addition of the ultrafiltration unit is highly advantageous.

Table 38. Financial evaluation of required revenue for different financial scenarios of xanthan gum refining.

Financial Evaluation			
		Revenue/Year	**$/Kg**
Without UF	Break even	$35,812,938.08	$7.16
	15% I.R.R	$38,396,670.97	$7.68
With UF	Break even	$16,625,197.25	$3.33
	30% I.R.R	$18,062,380.85	$3.61

These results appeared to be quite conclusive, but in order to evaluate how effective this new configuration of xanthan gum refining could be further analysis was conducted. As a company actively competing in this market, a significant drop in selling price just to make a similar return is not the most viable business strategy. Instead, with a competitive manufacturing alternative the more likely result is that the company would continue to sell at a market price as before, potentially slightly reduced, and use the significantly lower capital investment and operating costs to recover the investment more quickly with a higher margin. To demonstrate this, a comparison was done to evaluate the investment return by evaluating the profitability of selling xanthan gum at $7.16/kg, the breakeven price for the without ultrafiltration configuration. This indicates that not only do you have a significantly higher rate of return at the end of the 12 year period after the initial investment in the ultrafiltration system, but the rate at which the investment recovers the cost of the investment is much more rapid. This analysis also indicated that refining xanthan gum with ultrafiltration is profitable within the first year.

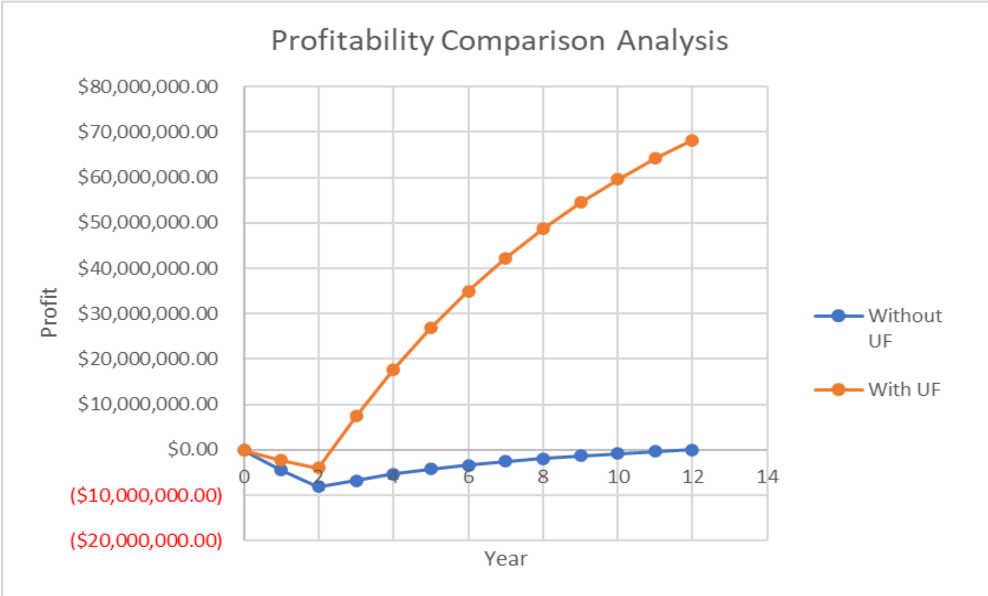

Figure 10. Profitability Comparison of xanthan gum refining with and without ultrafiltration (UF).

The accelerated rate of investment recovery and profitability is highly dependent on the significant reduction in operational costs that was explained in the previous section. This allows more of the revenue to reside as profits than to be consumed by covering operating expenses.

Conclusions and Recommendations

The potential competitive advantage this design could have over the existing market by investing in refining xanthan gum using ultrafiltration is strong. With a 55% decrease in capital cost and 65% decrease in annual utility, raw material, and wastewater treatment costs, introducing ultrafiltration into this process is estimated to be the superior option, especially because it is estimated the company would be profitable by year 3 instead of year 12 without ultrafiltration.

Investing in refining xanthan gum using ultrafiltration would allow the manufacturer to respond quickly to market swings in demand and pricing without jeopardizing profitability due to a significantly higher profit margin. It is our recommendation that this is a highly viable option and would be strongly recommended. There is significant risk that is difficult to quantify for applying a lab scale model and directly scaling to industrial application. At the very least, these results indicate that investing in a piloting scale system would be strongly advised. The significant impact this system has on reducing operational cost is not only a strong financial factor but also environmentally beneficial. This system would reduce the amount of energy required to produce this product and minimize the amount of organic material needing to be processed further in a wastewater treatment facility.

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Appendix A: Equation Notation

$\dot{m}$	mass flow rate
c_p	specific heat capacity
T	temperature
λ	latent heat of vaporization
Q	heat transfer rate
η	efficiency
ρ	density
MP	mixing power
V	volume
C	Concentration
TMP	Transmembrane Pressure
γ	Shear Stress
Δp	pressure drop
J	Permeate Flux
C_{OL}	Cost of Operating Labor
N_{OL}	Number of Operators per shift
P	Number of processing steps handling solids
N_{np}	Number of processing steps handling non particulates
FCI_L	Fixed Capital Investment without Land
COM_D	Total Cost of Manufacturing without Depreciation