Frozen Yogurt Manufacturing

Yogurina Frozen Yogurt

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Executive Summary

The goal of this project was to design a manufacturing facility to produce 7.4 million containers of vanilla frozen yogurt annually with each container holding 1.75 quarts. Pennsylvania was chosen as the building site because of the demand for frozen yogurt in the region. In today's market there are many reasons to market more low-fat and more healthful foods based on recent diet and health trends. In 2006, the market for frozen yogurt in the United States was $200 million, and 30% of this market is concentrated in the northeastern US alone (Parker, 2005). While Yogurina will supply a small percentage of that, 5%, we feel that the region has a strong demand for the low-fat frozen yogurt product we are offering.

Frozen yogurt has several key ingredients, starting with ultrafiltered skim milk. A sweet mix is made by adding cream, sugar, and stabilizers to a third of the milk, and yogurt is made by fermenting the other two thirds of the milk. Next, the sweet mix and yogurt are combined, aged, and then flavored. In the most important step, the frozen yogurt mix is sent through an ammonia-cooled scraped surface heat exchanger, where initial freezing takes place and air is injected to give the frozen yogurt a light, creamy texture. Finally, the frozen yogurt is packaged, hardened, and finally sent to a storage freezer to await shipping.

In order to be environmentally friendly and economical, the design was optimized at various stages of the process. The primary optimization involves the refrigeration cycle needed to freeze the frozen yogurt. Wherever possible, energy was recycled to reduce the amount of utilities needed. Also, ambient air was used as a coolant to reduce cooling water needs. A cooling tower was also used, not only to prevent disposal of hot water into the environment, but also to recycle cooling water. Because ultrafiltering the milk leaves 78% of the milk as waste

filtrate, some filtrate was reused as the growth medium for the yogurt culture. In addition, insulated pipes are used in order to reduce energy losses.

While designing the process, safety was also considered. Within the refrigeration cycle, temperatures and pressures were kept as ambient as possible while still freezing the frozen yogurt. Excepting ammonia, the coolants water, brine, and air were used because they are both economical and safe to handle. The main safety hazard in the plant is an ammonia leak. Though the process has relatively few hazards, proper protective equipment requirements and safety training are necessary to maintain a safe working environment. Finally, to ensure food safety, a quality control lab is necessary to prevent microbiological or other product contamination.

A 30 year cost analysis for this project was performed. The overall bare module cost for the equipment is $7.9 million. Estimated annual sales total $29.7 million at a selling price of $4 per container based on current market values. The net present value of the investment after 30 years is $9.9 million. An initial total capital investment of $22.99 million is required with an annual operating cost of $22.6 million. At a 20% interest rate, the payback period is 2.8 years. The investor's rate of return or discounted cash flow rate of return is calculated to be 34.4%.

Yogurina is producing a product that is similar to other frozen yogurt products on the market. However, Yogurina produces frozen yogurt with added health benefits, such as lower fat, higher calcium, live probiotics, higher protein, lower lactose, and added prebiotics. Although Yogurina is a premium frozen yogurt, it will still be offered at a midrange price so that when the market price of raw materials, such as milk, fluctuates, Yogurina would be able to adjust the selling price accordingly to maintain profits. After producing and evaluating this design, Yogurina concludes that this process to produce hard-packed frozen yogurt is economically feasible and recommends that further work to build this plant go forward.

Table of Contents

1.0 Introduction

1.1 Overall Goal

The objective of the present study is to design a dairy facility in rural Pennsylvania with a minimum manufacturing capacity of 7.43 million (1.75 quart) units of vanilla flavored frozen yogurt annually. The annual production rate is intended to meet about 5% of the demand for frozen yogurt in the northeastern United States. This region includes New York City, Philadelphia, Baltimore, and Washington DC (Parker, 2005). The process starts with the milk and other raw ingredients and ends with hard-packed frozen yogurt ready for shipping. Given current trends towards low-fat foods, techniques to keep a creamy product while lowering the fat content are incorporated into this process (Stogo, 1998). Regular ice cream is 10-16% milk fat, but the goal is to make this frozen yogurt 2% milk fat and still tasty (Arbuckle, 1977). Also, probiotic bacteria are included along with the normal yogurt cultures to provide added digestive benefits (Teitelbaum and Walker, 2002).

1.2 Current Market Information

With consumers becoming more concerned about their health, frozen yogurt is becoming an increasingly popular alternative to ice cream (Stogo, 1998). While the whole market for frozen desserts is growing, frozen yogurt is experiencing the strongest growth (Pszczola, 2008). In 2006, consumption of frozen yogurt in the United States was $200 million with 30% of this consumption concentrated in the northeast region alone. China had the second highest consumption of frozen yogurt in 2006 with $92 million in latent demand. New York City consumes the most frozen yogurt in the world: 5.3% of the world's frozen yogurt and 22.8% of the United States' frozen yogurt is consumed by New Yorkers (Parker, 2005). In order to situate the plant in close proximity to the east coast market, one of the leading states in dairy production, Pennsylvania, was chosen for the plant's location (Environmental Protection Agency, Dairy Production, 2008).

Vanilla was chosen as the flavor to be produced because it is the most popular ice cream and frozen yogurt flavor. Vanilla also forms the base for many other frozen yogurt flavors (Stogo, 1998).

The main focus of Yogurina is to provide consumers with a product that will have additional health benefits in comparison to current frozen yogurt and ice cream products. There are many options in frozen yogurt for adding health benefits that will attract customers. The key, however, is to add the health benefits while maintaining similar sensory attributes to the original version. Sensory factors which are important to consumer perception include creaminess, hardness, flavor, acidity and melting (El-Nagar, et al., 2002). With frozen yogurt, this often means tasting more like ice cream and less like yogurt (Stogo, 1998).

The most attractive health promotion is lower fat. The challenge with low-fat frozen yogurt, however, is achieving the same creamy texture that the full fat version has (Hartel, 1996). Thus, the low-fat frozen yogurt this process will produce must retain the properties and texture of traditional ice cream.

Another popular health claim is the inclusion of probiotic bacteria. According to recent research, these bacteria likely support immune system function and gastrointestinal health (Teitelbaum and Walker, 2002). It is also imperative that a sufficient percentage of probiotic bacteria are present in the final product for optimum digestive benefits (Ordonez, et al., 2000). One marketplace example of probiotics is Danone's Activia yogurt, which is a conventional yogurt with claims to help "naturally regulate your slow intestinal transit" (Danone Activia, 2008). Currently, sales of dairy foods with probiotics are increasing dramatically: about 20% annually (Pszczola, 2008). Given the trend towards probiotics, incorporating some in Yogurina would be an added selling point for customers.

Claims of higher calcium or lower lactose content may also attract customers concerned about their bones or lactose intolerance. Using ultrafiltered milk can achieve both these ends while improving the frozen yogurt's texture at the same time (Ordonez, et al., 2000).

Fiber is also attractive to consumers, particularly when it is advertised as prebiotics, which promote the growth of probiotic bacteria in the intestines (Teitelbaum and Walker, 2002). A study by El-Nagar, et al. (2002) showed that the addition of inulin, a soluble dietary fiber, to the low-fat frozen yogurt mix improved the texture comparable to a high fat content frozen yogurt while adding the health benefit characteristic of dietary fibers.

Yogurina believes the incorporation of these findings into a new product will appeal to a wide range of consumers. It is assumed that Yogurina will capture approximately 5% of the east coast's current market based on regional demand and annual production for the facility. Due to all of the health benefits and the intended rich and creamy taste, Yogurina is intended to be a premium frozen yogurt, which will command a higher selling price. In 2007, the monthly average selling price of ice cream varied between $1.897 and $2.113 per quart (University of Wisconsin, Madison, 2008). Currently grocery stores are selling Häagen Dazs frozen yogurt for $7.00/qt ($3.74/lb) and Food Club frozen yogurt for $1.75/qt ($1.37/lb) (Safeway, 2008; Coborn's, 2008). Yogurina intends to sell its product to grocery stores for $2.29/qt ($1.46/lb or $4 per 1.75 qt). This is the wholesale price to the grocery stores. To stay competitive with other brands, Yogurina could be sold for $3.43/qt, $6 per container, in grocery stores.

1.3 Project Premises and Assumptions

The process to make frozen yogurt is nearly identical to the ice-cream-making process, with the exception that yogurt is added to the mix. There is no federal standard of identity for frozen yogurt, so composition can vary between brands (Guinard, et al., 1994; Univ. of Guelph, 2008). A typical frozen yogurt mix contains milk, cream, sugar, stabilizers, and emulsifiers. Once the mix is prepared, it is initially frozen in a scraped surface heat exchanger, where about 50% of the water is frozen (Adapa, et al., 2000). A drawing of a typical scraped surface heat exchanger is shown in Fig. 1.3.1. Air is also injected into the product in the freezer. The product is still soft at this point, so it is packaged and then hardened. As the ice crystallizes, the remaining water contains more and more sugar, which depresses the freezing point so that in the final, hardened product, about 75% of the water is frozen (Hartel, 1996). The product is both an emulsion and a foam. The emulsion consists primarily of milk fat dispersed in an aqueous phase containing sugar, acid, and the dry matter contents (Adapa, et al., 2000; Güven and Karaca, 2002). The foam is formed by pockets of air being dispersed throughout the emulsion and is stabilized by coalesced fat globules (Univ. of Guelph, 2008).

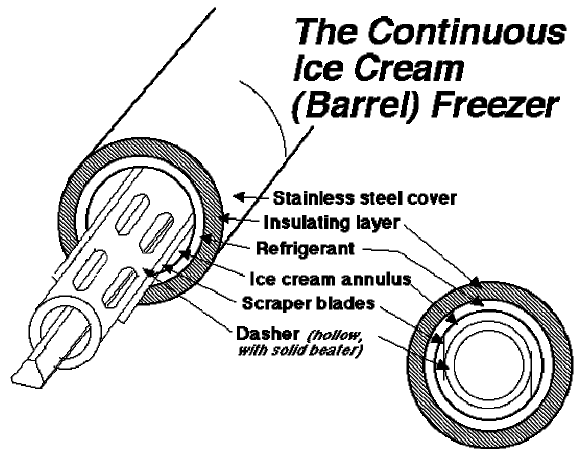

Fig. 1.3.1: Schematic of a scraped surface heat exchanger for initial frozen yogurt freezing (Univ. of Guelph, 2008)

One key quality issue in frozen yogurt and ice cream manufacture is the size of the ice crystals in the final product (Drewett and Hartel, 2007). The best ice creams on the market have a smooth and creamy texture, along with a delicious flavor. That creamy texture, often associated with a high fat content, is determined, in large part, by the average size of the ice crystals. Larger crystals (greater than 50 μm) impart a grainy texture on the ice cream, while smaller crystals (around 10-20 μm) give ice cream the desired creaminess (Drewett and Hartel, 2007). This means that if the ice crystal size can be kept small, less fat can be added to the product. The challenge with low fat ice cream, however, is achieving the same creamy texture that the full fat ice cream has. The source of this challenge is that when ice cream contains more fat, it, most commonly, contains less water, and thus the crystals that are formed are smaller (Hartel, 1996).

Processing conditions and the mix formulation can both affect ice crystal size. A shorter residence time in the scraped surface heat exchanger has been found to correlate with smaller crystal size since heat is removed faster from the freezer (Drewett and Hartel, 2007). Higher overrun, the percent increase in volume due to air injection, also correlates with slightly smaller crystal size. It is believed that the air pockets act as barriers to crystal growth (Sofjan and Hartel, 2004). However, lower overrun is characteristic of a premium ice cream. A super-premium brand may have between 25-50% overrun, while an economy brand can have up to 120% overrun (Univ. of Guelph, 2008). Since Yogurina is intended to be a premium frozen yogurt, the overrun will be 50%. Stabilizers are added to slow down undesirable recrystallization during storage. Carrageenan was found to be one of the best stabilizers for slowing recrystallization (Adapa, et al., 2000). The type of sweetener used can also affect crystallization and recrystallization. The lowest rates of recrystallization were seen in ice creams made with 20 dextrose-equivalent corn syrup, and the highest with high fructose corn syrup (Adapa, et al., 2000). In another study, the type of sweetener was found not to significantly affect ice crystallization provided that an appropriate draw temperature was selected based on the freezing point depression (Drewett and Hartel, 2007).

Lactose crystallization, which can cause a sandy texture, is another issue in ice cream quality. Lactose is not highly soluble in milk's serum phase, and thus it is known to precipitate out (Arbuckle, 1977). Low storage temperatures and a viscous serum phase can help minimize the possibility of lactose crystallization (Nickerson, 1962). Less lactose would also logically lead to less lactose crystallization.

In yogurt manufacture, milk is fermented until the desired acidity is reached. The thermophilic lactic acid bacteria used to ferment the product must include *Lactobacillus bulgaricus* and *Streptococcus thermophilus* for the yogurt portion to be considered yogurt (Chandan, 2006). In addition to these bacteria, probiotic bacteria, such as *Bifidobacterium bifidum* and *Lactobacillus acidophilus*, can also be incorporated (Ordonez, et al., 2000; Saarela, et al., 2000). Yogurt is formed when the acidity reaches such a level that the milk coagulates (Spreer, 1998). For frozen yogurt, a lower titratable acidity, 0.23% to 0.29% lactic acid, correlates with a higher degree of liking, irrespective of sugar content. For comparison, a plain, unfrozen yogurt may have a titratable acidity of 0.95% (Guinard, et al., 1994).

Frozen yogurt manufacturing is a rigorous and complex process. Therefore, several assumptions were made in order to develop an operational design. First of all, it is assumed that Yogurina products have enough consumer demand in the east coast to capture about 5% of the current market. Secondly, this preliminary design lacks research and development facilities and pilot plants for flavor development and quality testing. As a result, Yogurina is assuming that the developed formulations will yield a high quality product. Pilot plant trials could be carried out to assess whether any modifications to the process or formulation are needed to make Yogurina frozen yogurt taste as delicious as intended.

2.0 Process Description, Rationale, and Optimization

2.1 Written Description of Process

The process to make frozen yogurt is described in this section. A block flow diagram of the process can be found in section 2.2, Figs. 2.2.1 and 2.2.2, and the process flow diagram can be found in section 2.3, Figs. 2.3.1 through 2.3.5. The stream tables are given by Tables 2.4.1 and 2.4.4. The equipment tables, material requirements, and utility requirements are located in sections 2.5, 2.6, and 2.7 respectively. A mass and energy balance for this process can be found in Appendix A, and the detailed process calculations are located in Appendix B.

The frozen yogurt making process begins with milk and cream receiving. This step involves metering the milk or cream from a truck into a silo. A quality control lab can also determine at this point if the milk is acceptable with regards to temperature, taste, and bacteria. Milk and cream enter the plant by truck and are delivered at 4 °C. The milk is skim milk and the cream is 38% milk fat. When a milk tanker arrives at the plant, the quantity of milk delivered is determined by sending the milk through volumetric flow meter ST-101 on its way to silo SL-101 in stream 2. The density of the milk is then used to calculate the mass delivered. The cream is received in the same fashion and transferred to silo SL-102 via stream 22. The plant requires 175,136 lb/day of skim milk and 2,880 lb/day of cream when it operates for 16 hr/day.

To concentrate the milk, ultrafiltration is used. The reasons for ultrafiltration are addressed in section 2.8. Stream 3 takes the skim milk from the silo, through pump P-101A/B to increase the pressure, and then through membrane MB-101. The filtrate, which contains mostly water and lactose along with some protein and other minerals, leaves the membrane in stream 5. The retentate, ultrafiltered (UF) milk, leaves the membrane in stream 6. While most of the filtrate is a waste product, 1,616 lb/day, about 1.2%, can be reused in preparing the bulk culture, a batch process described later. The UF milk is split into two streams. Stream 8, containing 1,548 lb/hr UF milk, is used to make the yogurt portion of the frozen yogurt mix. Stream 7, containing 860 lb/hr UF milk, is used to prepare the ice cream mix portion.

To prepare the ice cream mix portion of the frozen yogurt mix, several ingredients must be mixed together, pasteurized, and homogenized. Stream 7 takes the UF milk to mixer M-101. Also coming into M-101 are cream from SL-102 in stream 24, mono- and diglycerides in stream 25, carrageenan in stream 26, cane sugar in stream 27, water in stream 28, inulin fiber in stream 29, and corn syrup solids in stream 30. The raw ice cream mixture proceeds to the pasteurizer, E-201 through 204, after leaving the mixer in stream 31 at 4 °C, a conservative temperature estimate since colder product takes more energy to pasteurize. The pasteurizer has four sections, the regenerator, the heater, the water cooler, and the brine cooler. Stream 31 first takes the ice cream mix to the regenerator, E-201, which uses already hot mix to heat the incoming mix in stream 44. Stream 44 is then sent through the homogenizer, HG-201, which breaks apart large fat globules producing a better emulsion. Stream 45 takes the ice cream mix from the homogenizer to E-202, the heater. The heater uses saturated steam to heat the ice cream mix to 90 °C in stream 46. This hot ice cream mix passes through the regenerator, heating up the incoming ice cream mix and getting cooled down in stream 47. Water in E-203 further cools the ice cream mix. The ice cream mix is finally cooled down to 3 °C in stream 54 after passing through E-204, where brine is the coolant. The brine heats up through E-204 in stream 53 and then goes to E-208 where it cools the water in stream 51 to its original temperature in stream 49.

Before the yogurt can be made, the culture which is used to ferment the UF milk into yogurt must be prepared in batch. Table 2.4.4 presents the stream information for the batch process streams, and area 500 of the process flow diagram visually describes the batch process. The medium used to grow the yogurt culture is the filtrate from membrane MB-101. Once every day, stream 113 diverts 1616 lb of filtrate from stream 80. Heat exchanger E-501 uses saturated steam to heat the filtrate. Cooling water then cools the filtrate in stream 115 through E-502. The culture can now be grown in three stages: the initial mother culture is used to make the intermediate culture, which is used to make the bulk culture, which is finally used to ferment the UF milk into yogurt. The mother culture is normally prepared on a laboratory scale. For each run, 6.08 lb of pasteurized filtrate, stream 116, is combined with 6 grains (0.000857 lb) of concentrated freeze-dried culture, stream 119. This mixture is grown at 40 °C in a flask, R-501, for about 5.5 hr, or until the pH is 5.5. The finished mother culture, stream 120, is mixed with the pasteurized filtrate, stream 117, in the intermediate culture tank, R-502. The intermediate culture is incubated the same as the mother culture. Stream 121 takes the finished intermediate culture to the bulk culture tank, R-503, where it is mixed with the last of the pasteurized filtrate, stream 118. Again, the culture is incubated for 5.5 hours or until the pH reaches 5.5.

Preparing the yogurt portion of the frozen yogurt mix requires pasteurizing and homogenizing the UF milk, fermenting the UF milk into yogurt, and cooling the yogurt to stop fermentation. To pasteurize the UF milk in stream 8, the stream is sent to E-101, the regenerator stage of the pasteurizer, where hot UF milk heats the incoming UF milk, stream 9. Stream 9 then passes through homogenizer HG-101, which improves the stability of the emulsion (although the UF milk is from skim milk, it is still about 0.5% fat) (Premaratne and Cousin, 1991). Stream 10 takes the UF milk from the homogenizer to the heater section of the pasteurizer, E-102, from which the UF milk exits at 90 °C in stream 11. The hot fluid is superheated compressed ammonia (this stream is part of the ammonia refrigeration loop, detailed later). Stream 11 takes the hot UF milk through the regenerator, E-101, where it cools down in stream 13. Heat exchanger E-103 then cools the UF milk down to the incubation temperature. The cold fluid is cooling water. Brine returns the cooling water to its original temperature in E-104. The UF milk in stream 14 is then sent to the continuous fermentation tank, R-101, where it is mixed with the bulk culture from stream 33. The milk is incubated at 40 °C in R-101 with a 4 hour residence time or until the total (titratable) acidity reaches 0.30%. Yogurt leaves the fermentation tank in stream 20 and heads to E-205 and E-206 where refrigerated water and brine cool it respectively. The brine then goes into E-207 where it cools the refrigerated water to its original temperature. This brine stream and the brine from E-104 are mixed together into stream 57. Ammonia then cools the brine back to its original temperature in stream 64 through E-302. This stream is then split to send brine to E-204 and E-206 again.

Now that the ice cream mix and the yogurt are prepared, they can be mixed together, aged, and flavored. Stream 54 carries ice cream mix to mixing tank M-201 where it is joined by yogurt. Stream 55 takes the frozen yogurt mix to an insulated tank, JT-201, where the mix ages for four hours as explained in section 2.8. Stream 56 then takes the frozen yogurt mix from the jacketed tank to mixer M-301 where it is joined by vanilla extract from stream 81. If flavors other than vanilla frozen yogurt were to be made, the appropriate ingredients would be added into M-301 in place of the vanilla.

To turn the frozen yogurt mix into hard-packed frozen yogurt, the mix is sent through a scraped surface heat exchanger, filled into the 1.75 qt cartons the product is to be sold in, sent through a hardening tunnel to further chill the product, and finally put into a storage freezer.

Stream 82 takes the vanilla frozen yogurt mix at 3 °C and sends it through the scraped surface freezers, ES-301-308 (there are 8 identical freezers in parallel due to the size of each freezer), while injecting compressed air into the mix via stream 84 to give 50% overrun (a 50% increase in volume). Soft frozen yogurt exits the scraped surface freezer at -7 °C in stream 70 and goes to the filler, FL-301, to be packaged. The packaged frozen yogurt is taken in stream 71 to the hardening tunnel, HT-301. Ammonia from stream 68 keeps the air in the hardening tunnel at -40 °C, and the frozen yogurt leaves the tunnel in stream 72 at -18 °C after a 1.75 hour residence time. This final product is sent to the storage freezer, SF-301, at 3613 lb/hr to await shipping.

The refrigeration for the scraped surface heat exchangers, the hardening tunnel, the storage freezer, and the brine in the pasteurizer is achieved using ammonia, with air as the final heat sink. The ammonia loop begins with the refrigerant in stream 62 being isentropically expanded through valve V-301 and to -16.7 °C in stream 63. Stream 63 then cools off the brine in E-302. The ammonia is then passed through a second valve, V-302, and expanded to -33.7 °C in stream 66. This stream is then split into streams 67, 68, and 69 which carry ammonia to the ES-301-308, HT-301, and SF-301 respectively. The streams are divided so that each warm stream (streams 74, 75, and 76) is at -33.7 °C and 99.1% vapor when the three streams reconnect into stream 77. The ammonia is then compressed in C-401 and C-402 and aftercooled by ambient air being blown across the heat exchanger in E-403 and E-402. The ammonia is compressed one more time in C-403 in stream 110. The hot compressed ammonia then passes through E-102 to heat the UF milk. Cooling water cools the ammonia in stream 59 through E-401. Filtrate from MB-101 then cools the ammonia in E-303. Finally, E-301 uses ambient air to cool the ammonia to its original state in stream 62.

The cooling water used to cool off the compressed ammonia, stream 88, and the pasteurized filtrate, stream 87, is cooled back to its original temperature through a cooling tower, CT-401. These two streams are combined into stream 89 and enter the cooling tower. Through CT-401, water evaporates out with the air being blown through the tower. The air enters in stream 97 at ambient conditions and exits with 100% relative humidity. Stream 85 replenishes the cooling water and connects with stream 90. The water is then split into streams 93 and 94 to be sent to cool the compressed ammonia in E-401 and the pasteurized filtrate in E-502.

2.2 Block Flow Diagram

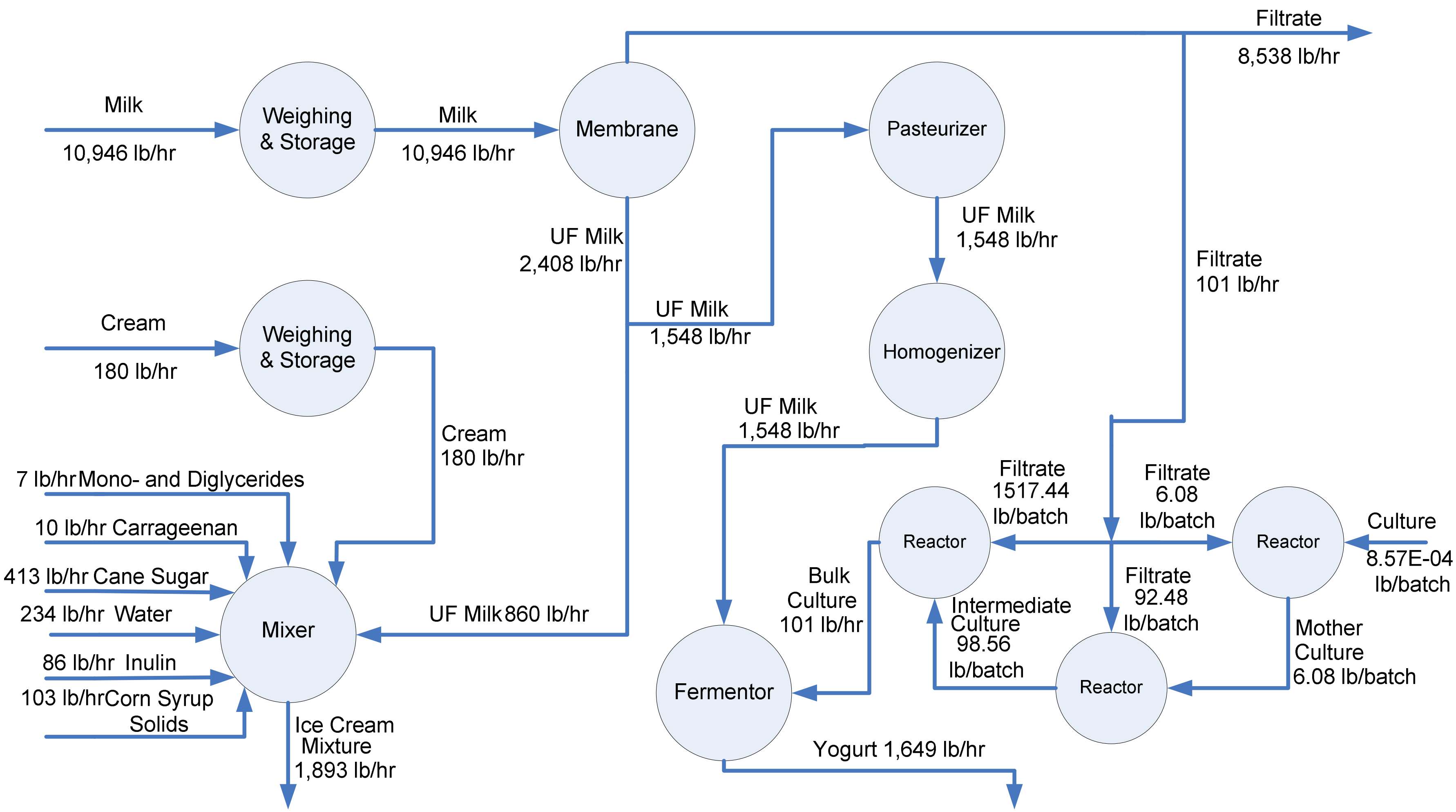

Fig. 2.2.1: First half of block flow diagram for frozen yogurt manufacture

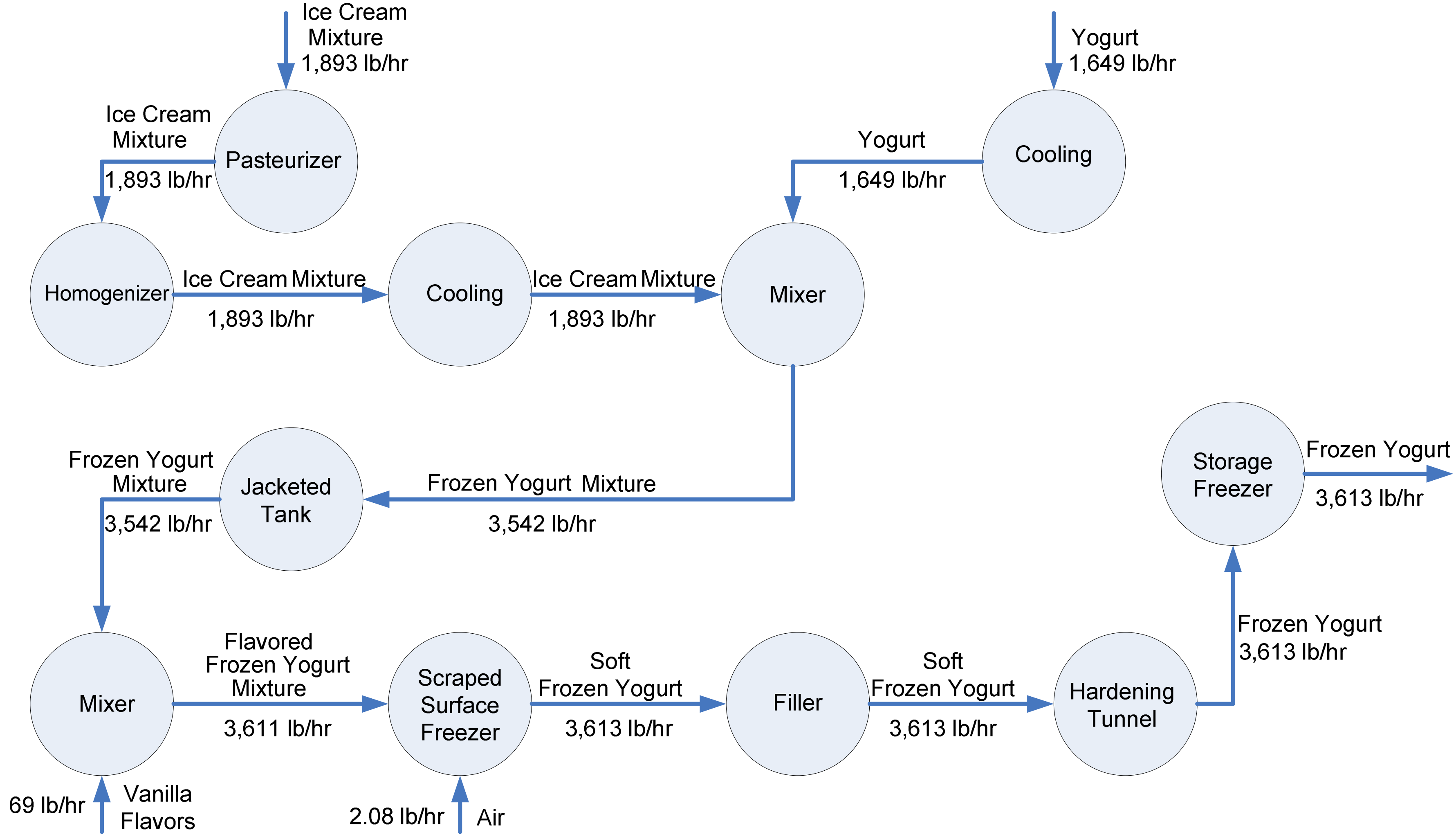

Fig. 2.2.2: Second half of block flow diagram for frozen yogurt manufacture

2.3 Process Flow Diagram

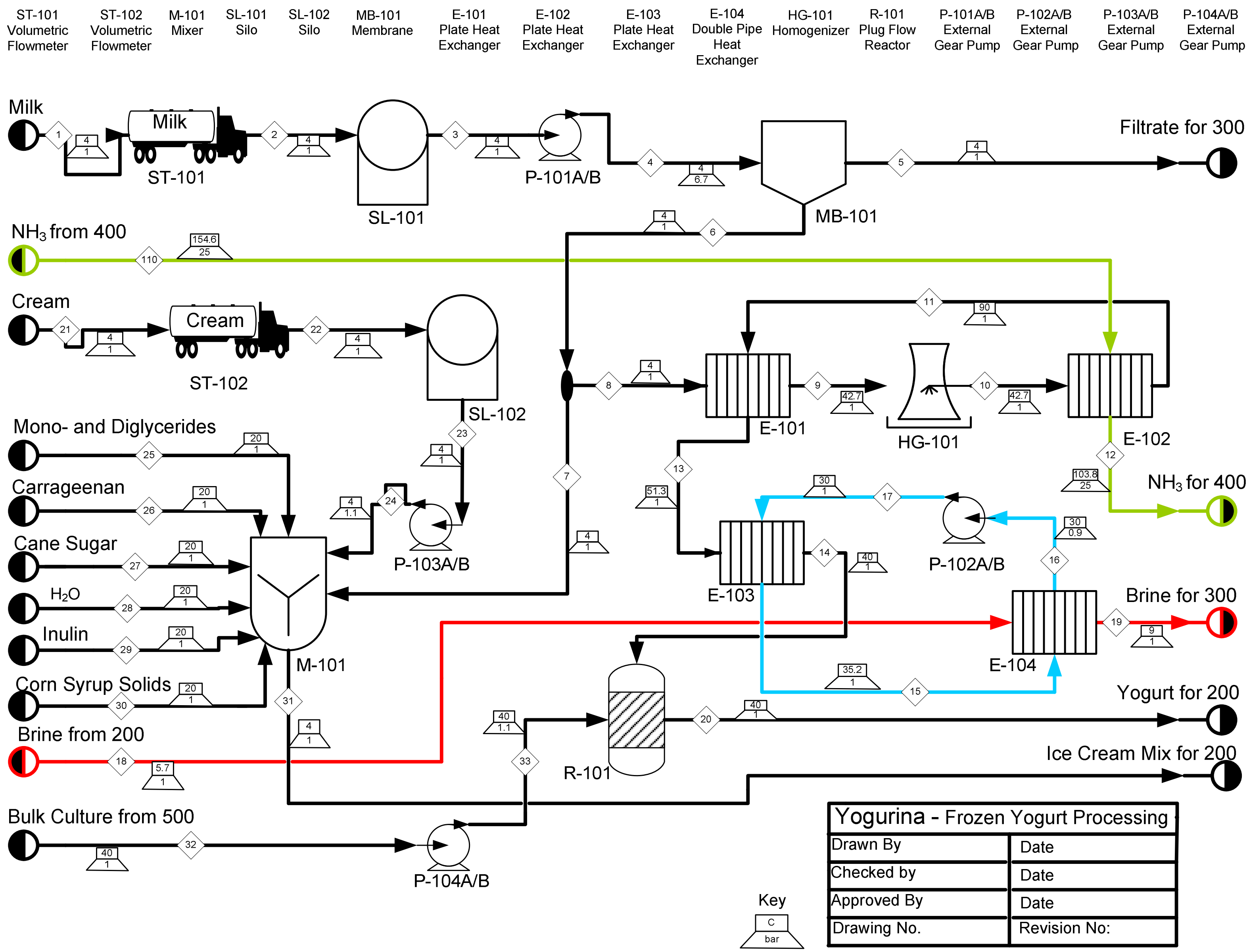

Fig. 2.3.1: Process flow diagram for area 100 of frozen yogurt manufacture

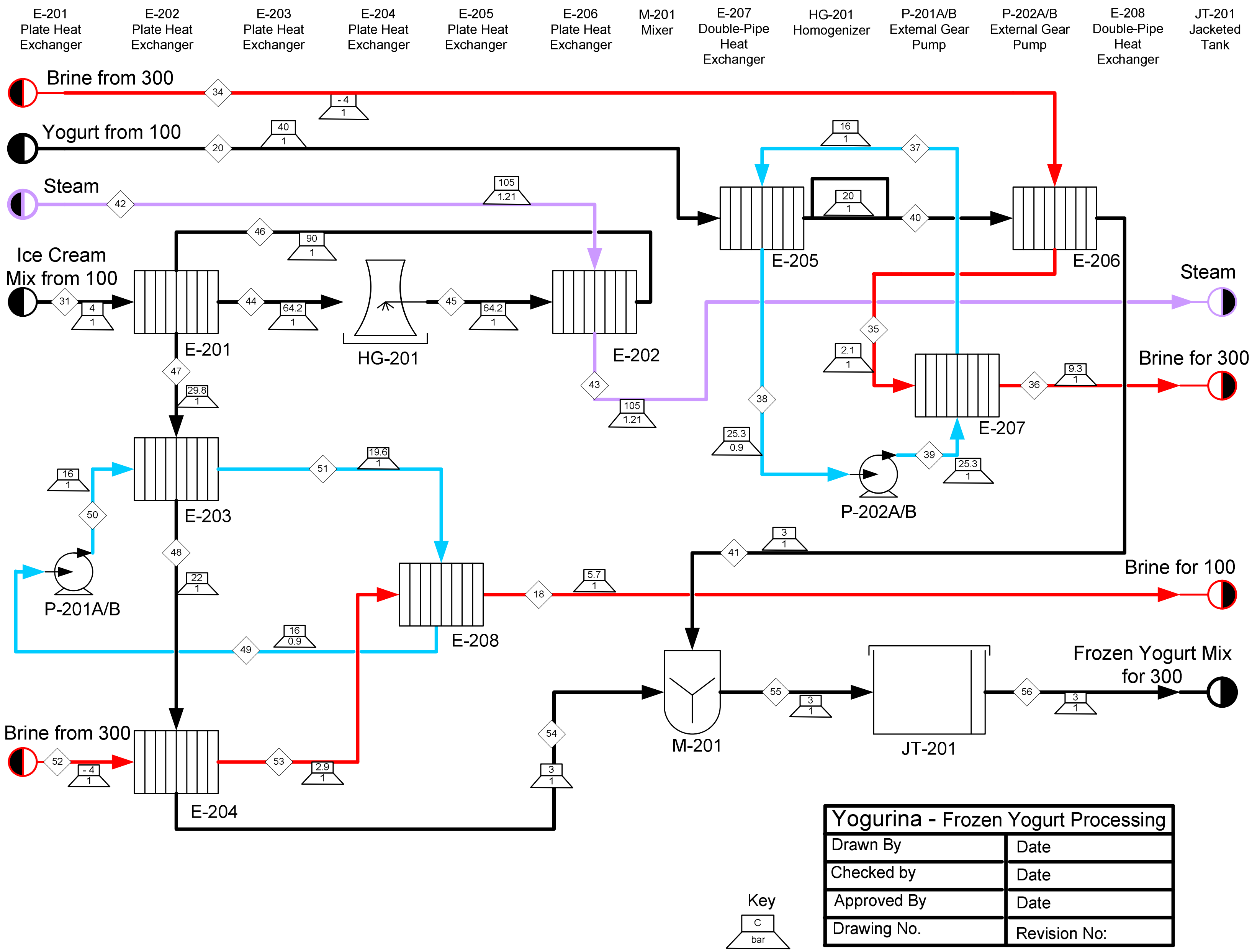

Fig. 2.3.2: Process flow diagram for area 200 of frozen yogurt manufacture

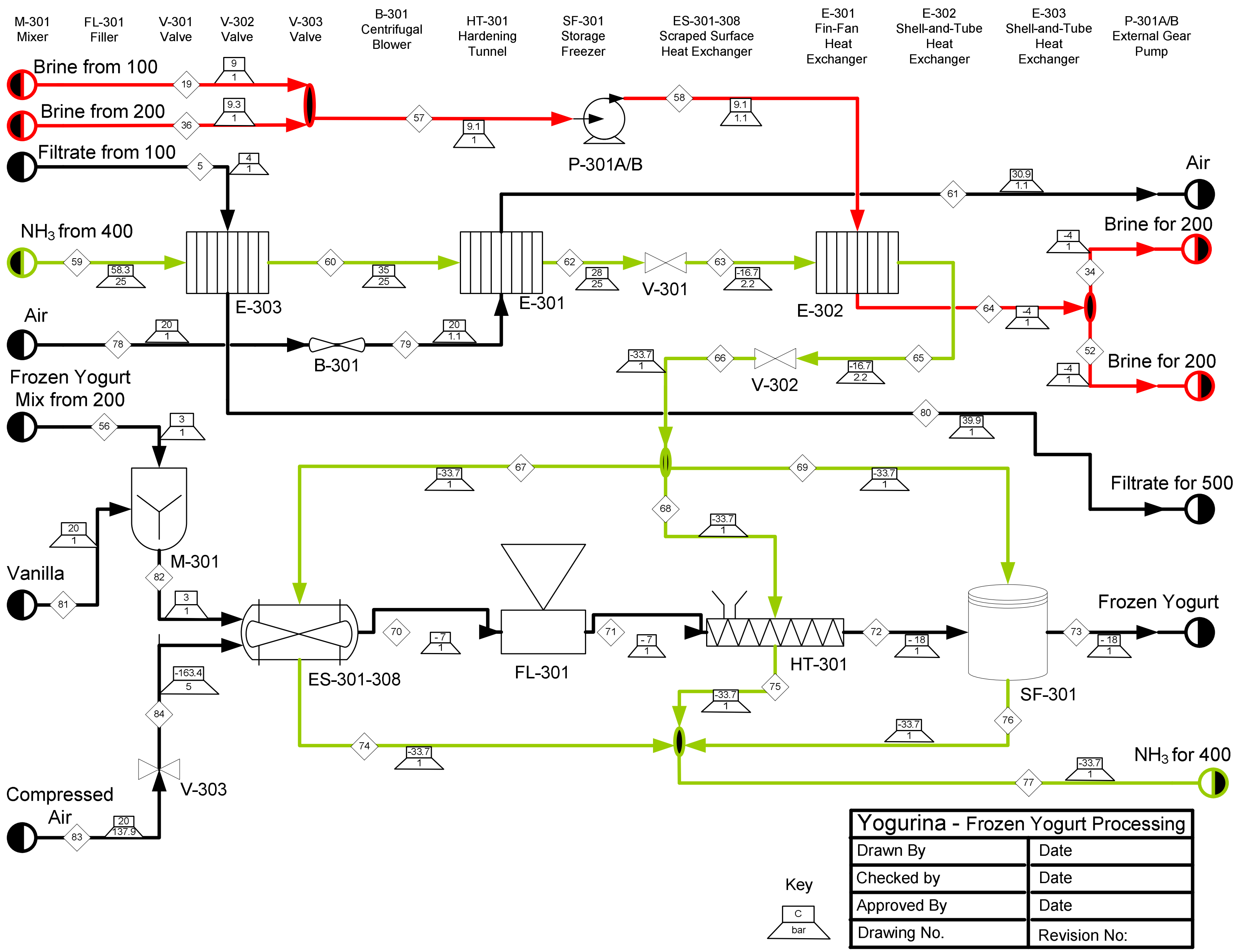

Fig. 2.3.3: Process flow diagram for area 300 of frozen yogurt manufacture

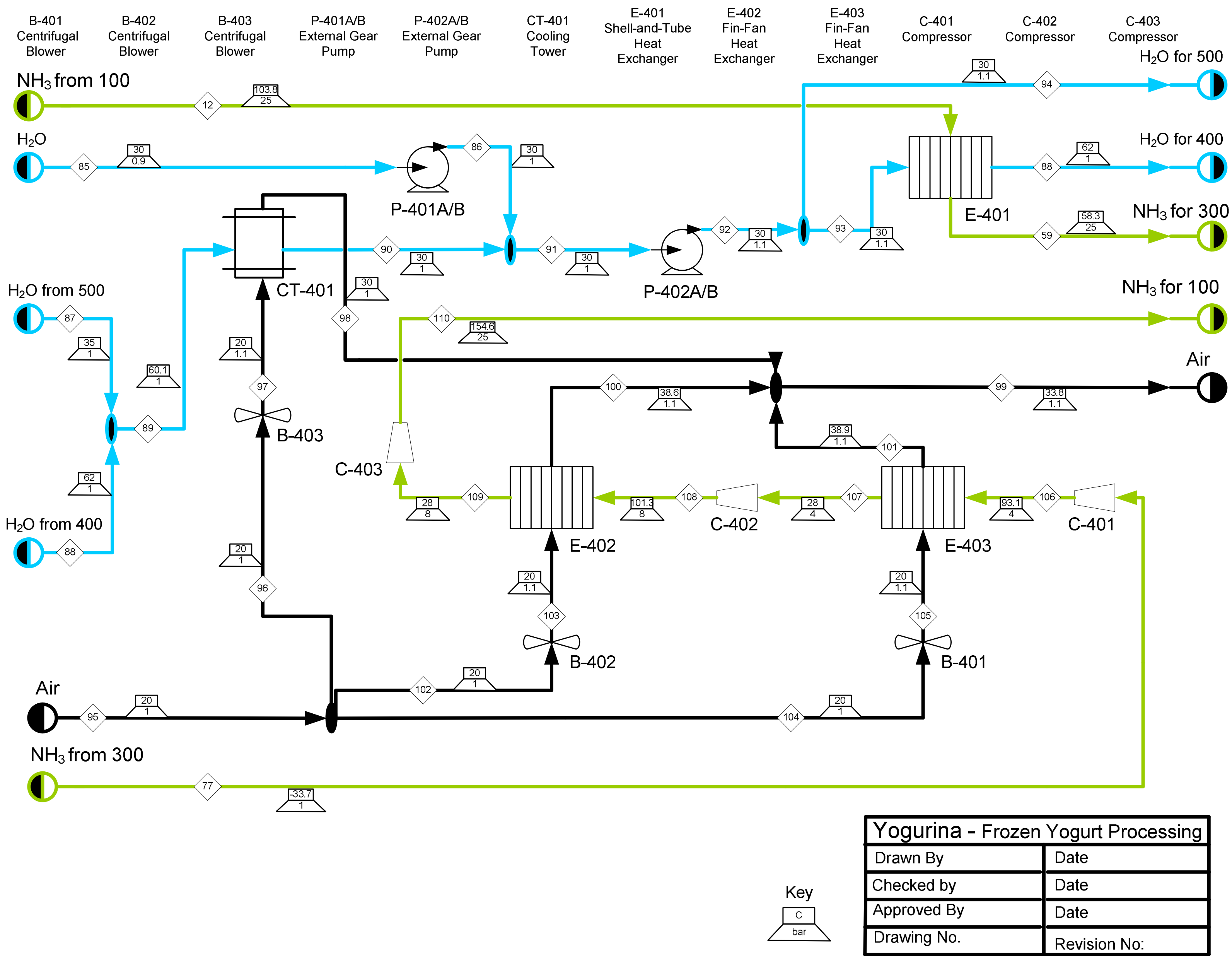

Fig. 2.3.4: Process flow diagram for area 400 of frozen yogurt manufacture

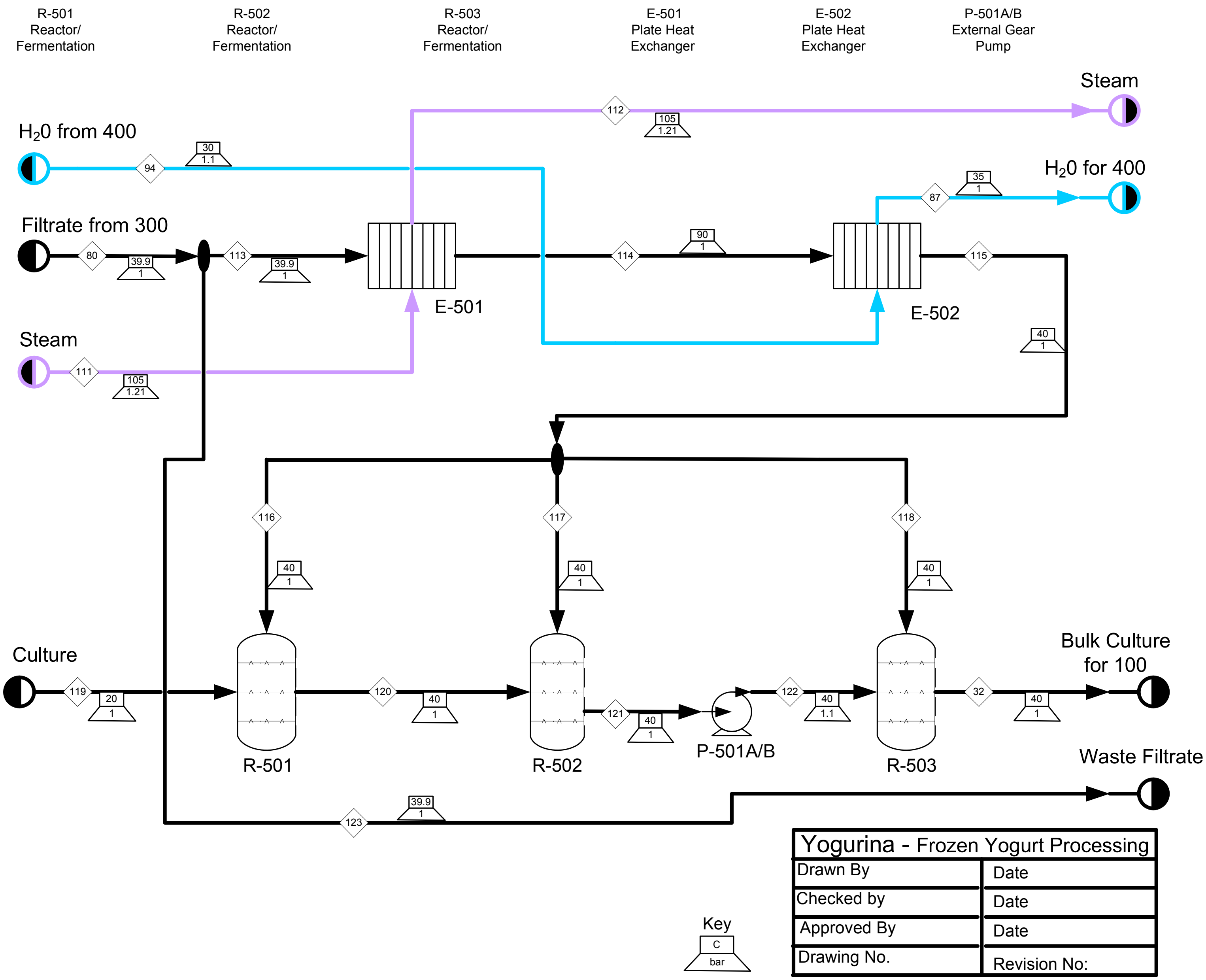

Fig. 2.3.5: Process flow diagram for area 500 of frozen yogurt manufacture

2.4 Stream Tables

Table 2.4.1: Stream table for continuous processing of frozen yogurt, streams 1-37

Stream	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Temperature (ºC)	4	4	4	4	4	4	4	4	42.7	42.7
Pressure (bar)	1	1	1	6.7	1	1	1	1	1	1
Total Mass Flow (lb/hr)	10,946	10,946	10,946	10,946	8,538	2,408	860	1,548	1,548	1,548
Volumetric Flow Rate (gpm)	21.21	21.21	21.21	21.21	17.04	4.45	1.59	2.86	2.86	2.86
Component	Milk	Milk	Milk	Milk	Filtrate	UF Milk	UF Milk	UF Milk	UF Milk	UF Milk
Vapor Fraction	0	0	0	0	0	0	0	0	0	0

Stream	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Temperature (ºC)	90	103.8	51.3	40	35.2	30	30	5.7	9
Pressure (bar)	1	25	1	1	1	0.9	1	1	1
Total Mass Flow (lb/hr)	1,548	2,250	1,548	1,548	3,096	3,096	3,096	5,679	5,679
Volumetric Flow Rate (gpm)	2.86	291.90	2.86	2.86	6.18	6.18	6.18	10.28	10.28
Component	UF Milk	Ammonia	UF Milk	UF Milk	Water	Water	Water	Brine	Brine
Vapor Fraction	0	1	0	0	0	0	0	0	0

Stream	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Temperature (ºC)	40	4	4	4	4	20	20	20	20
Pressure (bar)	1	1	1	1	1.1	1	1	1	1
Total Mass Flow (lb/hr)	1,649	180	180	180	180	7	10	413	234
Volumetric Flow Rate (gpm)	3.05	0.36	0.36	0.36	0.36	0.02	0.03	0.52	0.47
Component	Yogurt	Cream	Cream	Cream	Cream	Mono- and Diglycerides	Carrageenan	Cane Sugar	Water
Vapor Fraction	0	0	0	0	0	0	0	0	0

Stream	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**
Temperature (ºC)	20	20	4	40	40	-4	2 1	9.3	16
Pressure (bar)	1	1	1	1	1.1	1	1	1	1
Total Mass Flow (lb/hr)	86	103	1,893	101	101	4,947	4,947	4,947	3,298
Volumetric Flow Rate (gpm)	0.13	0.34	3.44	0.20	0.20	8.95	8.95	8.95	6.58
Component	Inulin	Corn Syrup Solids	Ice Cream Mix	Bulk Culture	Bulk Culture	Brine	Brine	Brine	Water
Vapor Fraction	0	0	0	0	0	0	0	0	0

Table 2.4.2: Stream table for continuous processing of frozen yogurt, streams 38-73

Stream	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**
Temperature (ºC)	25.3	25.3	20	3	105	105	64.2	64.2	90
Pressure (bar)	0.9	1	1	1	1.21	1.21	1	1	1
Total Mass Flow (lb/hr)	3,298	3,298	1,649	1,649	84.4	84.4	1,893	1,893	1,893
Volumetric Flow Rate (gpm)	6.58	6.58	3.05	3.05	246.8	0.18	3.44	3.44	3.44
Component	Water	Water	Yogurt	Yogurt	Saturated Steam	Saturated Water	Ice Cream Mix	Ice Cream Mix	Ice Cream Mix
Vapor Fraction	0	0	0	0	1	0	0	0	0
Stream	**47**	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**
Temperature (ºC)	29.8	22	16	16	19.6	-4	2.9	3	3
Pressure (bar)	1	1	0.9	1	1	1	1	1	1
Total Mass Flow (lb/hr)	1,893	1,893	3,786	3,786	3,786	5,679	5,679	1,893	3,542
Volumetric Flow Rate (gpm)	3.44	3.44	7.56	7.56	7.56	10.28	10.28	3.44	6.26
Component	Ice Cream Mix	Ice Cream Mix	Water	Water	Water	Brine	Brine	Ice Cream Mix	Frozen Yogurt Mix
Vapor Fraction	0	0	0	0	0	0	0	0	0
Stream	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**
Temperature (ºC)	3	9.1	9.1	58.3	35	30.9	28	-16.7	-4
Pressure (bar)	1	1	1.1	25	25	1.1	25	2.2	1
Total Mass Flow (lb/hr)	3,542	10,626	10,626	2,250	2,250	8,000	2,250	2,250	10,626
Volumetric Flow Rate (gpm)	6.26	19.23	19.23	96.37	7.67	12,221	7.53	446.44	19.23
Ammonia **Component**	Frozen Yogurt Mix	Brine	Brine	Ammonia	Ammonia	Air	Ammonia	Ammonia	Brine
Vapor Fraction	0	0	0	0.369	0	1	0	0.177	0
Stream	**65**	**66**	**67**	**68**	**69**	**70**	**71**	**72**	**73**
Temperature (ºC)	-16.7	-33.7	-33.7	-33.7	-33.7	-7	-7	-18	-18
Pressure (bar)	2.2	1	1	1	1	1	1	1	1
Total Mass Flow (lb/hr)	2,250	2,250	1,864	332.9	53.1	3,613	3,613	3,613	3,613
Volumetric Flow Rate (gpm)	866.9	2,038.7	1,688.9	301.63	48.11	9.62	9.62	9.62	9.62
Component	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Soft Frozen Yogurt	Soft Frozen Yogurt	Frozen Yogurt	Frozen Yogurt
Vapor Fraction	0.346	0.392	0.392	0.392	0.392	0	0	0	0

Table 2.4.3: Stream table for continuous processing of frozen yogurt, streams 74-123

Stream	**74**	**75**	**76**	**77**	**78**	**79**	**80**	**81**	**82**
Temperature (ºC)	-33.7	-33.7	-33.7	-33.7	20	20	39.9	20	3
Pressure (bar)	1	1	1	1	1	1.1	1	1	1
Total Mass Flow (lb/hr)	1,864	332.9	53.1	2,250	8,000	8,000	8,538	69	3,611
Volumetric Flow Rate (gpm)	4,259	761	121.3	5,141	12,221	12,221	17.04	0.15	6.38
Component	Ammonia	Ammonia	Ammonia	Ammonia	Air	Air	Filtrate	Vanilla	Flavored Frozen Yogurt
Vapor Fraction	0.991	0.991	0.991	0.991	1	1	0	0	0
Stream	**83**	**84**	**85**	**86**	**88**	**89**	**90**	**91**	**92**
Temperature (ºC)	20	-163.4	30	30	62	60.1	30	30	30
Pressure (bar)	137.9	5	0.9	1	1	1	1	1	1.1
Total Mass Flow (lb/hr)	2.08	2.08	744	744	13,000	14,010	13,266	14,010	14,010
Volumetric Flow Rate (gpm)	0.03	0.27	1.49	1.49	25.95	27.96	26.48	27.96	27.96
Component	Compressed Air	Compressed Air	Water	Water	Water	Water	Water	Water	Water
Vapor Fraction	1	1	0	0	0	0	0	0	0
Stream	**93**	**95**	**96**	**97**	**98**	**99**	**100**	**101**	**102**
Temperature (ºC)	30	20	20	20	30	33.8	38.6	38.9	20
Pressure (bar)	1.1	1	1	1.1	1	1.1	1.1	1.1	1
Total Mass Flow (lb/hr)	13,000	81,202	44,202	44,202	44,946	81,946	20,000	17,000	20,000
Volumetric Flow Rate (gpm)	25.95	134,866	73,414	66,740	77,782	138,489	30,553	25,970	33,670
Component	Water	Air, 70% R.H.	Air, 70% R.H.	Air, 70% R.H.	Air, 100% R.H.	Air, 86% R.H.	Air	Air	Air
Vapor Fraction	0	1	1	1	1	1	1	1	1
Stream	**103**	**104**	**105**	**106**	**107**	**108**	**109**	**110**	**123**
Temperature (ºC)	20	20	20	93.1	28	101.3	28	154.6	39.9
Pressure (bar)	1.1	1	1.1	4	4	8	8	25	1
Total Mass Flow (lb/hr)	20,000	17,000	17,000	2,250	2,250	2,250	2,250	2,250	8,437
Volumetric Flow Rate (gpm)	30,553	28,620	25,970	1,935	1,605	989	778	345	16.84
Component	Air	Air	Air	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Filtrate
Vapor Fraction	1	1	1	1	1	1	1	1	0

Table 2.4.4: Stream table for batch processing of frozen yogurt, streams 87-122

Stream	**87**	**94**	**111**	**112**	**113**	**114**	**115**
Temperature (ºC)	35	30	105	105	39.9	90	40
Pressure (bar)	1	1.1	1.21	1.21	1	1	1
Total Mass Flow (lb/batch)	1,010	1,010	152	152	101	101	101
Volumetric Flow Rate (gal/batch)	121	121	444	0.32	11.74	11.74	11.74
Component	Water	Water	Saturated Steam	Saturated Water	Filtrate	Filtrate	Filtrate
Vapor Fraction	0	0	1	0	0	0	0

Stream	**116**	**117**	**118**	**119**	**120**	**121**	**122**
Temperature (ºC)	40	40	40	20	40	40	40
Pressure (bar)	1	1	1	1	1	1	1.1
Total Mass Flow (lb/batch)	6.08	92.5	1517	8.57×10^{-04}	6.08	98.56	98.56
Volumetric Flow Rate (gal/batch)	0.71	10.75	176	1.56×10^{-04}	0.71	11.46	11.46
Component	Filtrate	Filtrate	Filtrate	Dry Culture	Mother Culture	Intermediate Culture	Intermediate Culture
Vapor Fraction	0	0	0	0	0	0	0

2.5 Equipment Tables

Table 2.5.1: Equipment table for volumetric flowmeters

Volumetric Flowmeter	ST-101	ST-102
MOC*	SS	SS
Type	Magnetic inductive	Magnetic inductive
Component	Milk	Cream
Inlet Temperature (°C)	4	4
Inlet Pressure (bar)	1	1
Mass Flow (lb/hr)	10,946	180

*Stainless steel is abbreviated SS

Table 2.5.2: Equipment table for silos

Silo	SL-101	SL-102
MOC	SS	SS
Type	Cone Roof	Cone Roof
Component	Milk	Cream
Inlet Temperature (°C)	4	4
Inlet Pressure (bar)	1	1
Volume (ft^3)	2,804	46.62
Mass Flow (lb/hr)	10,946	180

Table 2.5.3: Equipment table for reactors (fermentors)

Reactor	R-101	R-501	R-502	R-503
MOC	SS	SS	SS	SS
Type	Plug Flow	Batch	Batch	Batch
Component	UF Milk and Bulk Culture	Filtrate and Culture	Filtrate and Culture	Filtrate and Culture
Incubation Temperature (°C)	40	40	40	40
Operating Pressure (bar)	1	1	1	1
Mass	1,649 lb/hr	6.08 lb/batch	98.56 lb/batch	1,616 lb/batch
Volume (ft^3)	133.28	negligible	1.99	32.66
Residence Time (hr)	4	5.5	5.5	5.5

Table 2.5.4: Equipment table for membrane

Membrane	MB-101
MOC	SS
Type	Ultrafiltration, 5 kDa molecular weight cut-off
Component	Milk
Target Retentate Composition	20% solids
Inlet Temperature (°C)	4
Inlet Pressure (bar)	6.7
Outlet Pressure (bar)	1
Filtrate Flux (gal/ft^2/hr)	3.49
Mass Flow (lb/hr)	10,946
Area (ft^2)	297.4
Transmembrane Pressure (bar)	5.7

Table 2.5.5: Equipment table for mixers

Mixer	M-101	M-201	M-301
MOC	SS	SS	SS
Type	Closed vessel with agitator	Closed vessel with agitator	Closed vessel with agitator
Inlet Temperature (°C)	4	3	3
Inlet Pressure (bar)	1	1	1
Mass Flow (lb/hr)	1,893	3,542	3,611
Mixing Time (hr)	0.5	0.5	0.5
Volume (ft^3)	35.87	32.64	32.64

Table 2.5.6: Equipment table for homogenizers

Homogenizer	HG-101	HG-201
MOC	SS	SS
Type	Single Stage	Two Stage
Component	UF Milk	Ice Cream Mix
Inlet Temperature (°C)	42.7	64.2
Inlet Pressure (bar)	1	1
Mass Flow (lb/hr)	1,548	1,893
Homogenized Pressure (bar), first stage	100	140
Homogenized Pressure (bar), second stage	-	35

Table 2.5.7: Equipment table for filler

Filler	FL-301
MOC	SS
Type	Rotary
Component	Soft Frozen Yogurt
Inlet Temperature (°C)	-7
Inlet Pressure (bar)	1
Mass Flow (lb/hr)	3,613
Carton size (qt)	1.75
Cartons per minute	22

Table 2.5.8: Equipment table for heat exchangers

Heat Exchanger	E-101	E-102	E-103	E-104	E-201	E-202
Type	Plate & Frame	Plate & Frame	Plate & Frame	Double pipe	Plate & Frame	Plate & Frame
Area (ft^2)	5.8	4.7	4.5	3.9	19.4	5.7
Heat Duty (kW)	30.6	36.1	8.6	8.6	55.6	23.9
Cold Side						
Stream, inlet	8	10	17	18	31	45
Stream, outlet	9	11	15	19	44	46
Component	UF Milk	UF Milk	Water	Brine	Ice Cream Mix	Ice Cream Mix
Mass Flow (lb/hr)	1,548	1,548	3,096	5,679	1,893	1,893
Temperature (°C), Inlet	4	42.7	30	5.7	4	64.2
Temperature (°C), Outlet	42.7	90	35.2	9	64.2	90
Pressure (bar)	1	1	1	1	1	1
Phase	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid
MOC	SS	SS	SS	Nickel alloy	SS	SS
Hot Side						
Stream, inlet	11	110	13	15	46	42
Stream, outlet	13	12	14	16	47	43
Component	UF Milk	Ammonia	UF Milk	Water	Ice Cream Mix	Steam
Mass Flow (lb/hr)	1,548	2,250	1,548	3,096	1,893	84.4
Temperature (°C), Inlet	90	154.6	51.3	35.2	90	105
Temperature (°C), Outlet	51.3	103.8	40	30	29.8	105
Pressure (bar)	1	25	1	1	1	1.21
Phase	Liquid	Vapor	Liquid	Liquid	Liquid	Condensing
MOC	SS	SS	SS	SS	SS	SS

Table 2.5.9: Equipment table for heat exchangers

Heat Exchanger	E-203	E-204	E-205	E-206	E-207	E-208
Type	Plate & Frame	Plate & Frame	Plate & Frame	Plate & Frame	Double pipe	Double pipe
Area (ft^2)	9.8	17.2	21.2	14.2	12.9	6.0
Heat Duty (kW)	7.2	17.8	16.2	13.8	16.2	7.2
Cold Side						
Stream, inlet	50	52	37	34	35	53
Stream, outlet	51	53	38	35	36	18
Component	Water	Brine	Water	Brine	Brine	Brine
Mass Flow (lb/hr)	3,786	5,679	3,298	4,947	4,947	5,679
Temperature (°C), Inlet	16	-4	16	-4	2.1	2.9
Temperature (°C), Outlet	19.6	2.9	25.3	2.1	9.3	5.7
Pressure (bar)	1	1	1	1	1	1
Phase	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid
MOC	SS	Nickel alloy	SS	Nickel alloy	Nickel alloy	Nickel alloy
Hot Side						
Stream, inlet	47	48	20	40	39	51
Stream, outlet	48	54	40	41	37	49
Component	Ice Cream Mix	Ice Cream Mix	Yogurt	Yogurt	Water	Water
Mass Flow (lb/hr)	1,893	1,893	1,649	1,649	3,298	3,786
Temperature (°C), Inlet	29.8	22	40	20	25.3	19.6
Temperature (°C), Outlet	22	3	20	3	16	16
Pressure (bar)	1	1	1	1	1	1
Phase	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid
MOC	SS	SS	SS	SS	SS	SS

Table 2.5.10: Equipment table for heat exchangers

Heat Exchanger	E-301	E-302	E-303	E-401	E-402	E-403	E-501	E-502
Type	Fin-Fan	Fixed Head Shell & Tube	Fixed Head Shell & Tube	Fixed Head Shell & Tube	Fin-Fan	Fin-Fan	Plate & Frame	Plate & Frame
Area (ft^2)	355.2	216.4	271.7	1,848.1	669.5	637.2	23.1	31.2
Heat Duty (kW)	10.98	63.14	147.7	208.9	46.94	40.58	154.2 MJ	153.9 MJ
Cold Side								
Stream, inlet	79	63	5	93	103	105	113	94
Stream, outlet	61	65	80	88	100	101	114	87
Component	Air	Ammonia	Filtrate	Water	Air	Air	Filtrate	Water
Mass Flow (lb/hr)	8,000	2,250	8,538	13,000	20,000	17,000	1,616 lb/batch	16,160 lb/batch
Temperature (°C), Inlet	20	-16.7	4	30	20	20	39.9	30
Temperature (°C), Outlet	30.9	-16.7	39.9	62	38.6	38.9	90	35
Pressure (bar)	1	2.2	1	1	1.1	1.1	1	1
Phase	Gas	Vaporizing	Liquid	Liquid	Gas	Gas	Liquid	Liquid
MOC	SS	SS	SS	SS	SS	SS	SS	SS
Hot Side								
Stream, inlet	60	58	59	12	108	106	111	114
Stream, outlet	62	64	60	59	109	107	112	115
Component	Ammonia	Brine	Ammonia	Ammonia	Ammonia	Ammonia	Steam	Filtrate
Mass Flow (lb/hr)	2,250	10,626	2,250	2,250	2,250	2,250	152 lb/batch	1616 lb/batch
Temperature (°C), Inlet	35	9.1	58.3	103.8	101.3	93.1	105	90
Temperature (°C), Outlet	28	-4	35	58.3	28	28	105	40
Pressure (bar)	25	1	25	25	8	4	1.21	1
Phase	Liquid	Liquid	Condensing	Condensing	Vapor	Vapor	Condensing	Liquid
MOC	SS	Nickel alloy	SS	SS	SS	SS	SS	SS

Table 2.5.11: Equipment table for pumps

Pump	P-101A/B	P-102A/B	P-103A/B	P-104A/B	P-201A/B
MOC	SS	SS	SS	SS	SS
Type	External Gear	External Gear	External Gear	External Gear	External Gear
Temperature (°C)	4	30	4	40	16
Inlet Pressure (bar)	1	0.9	1	1	0.9
Outlet Pressure (bar)	6.7	1	1.1	1.1	1
Power (shaft) (hp)	1.8	0.0091	0.0005	0.0003	0.011
Power (kW)	1.32	0.0068	0.0004	0.0002	0.008
Efficiency	0.8	0.8	0.8	0.8	0.8
Mass Flow (lb/hr)	10,946	3,096	180	101	3,786
Component	Milk	Water	Cream	Bulk Culture	Water

Table 2.5.12: Equipment table for pumps

Pump	P-202A/B	P-301A/B	P-401A/B	P-402A/B	P-501A/B
MOC	SS	SS	SS	SS	SS
Type	External Gear	External Gear	External Gear	External Gear	External Gear
Temperature (°C)	25.3	9.1	30	30	40
Inlet Pressure (bar)	0.9	1	0.9	1	1
Outlet Pressure (bar)	0.9	1.1	1	1.1	1.1
Power (shaft) (hp)	0.0094	0.027	0.0023	0.044	0.00002
Power (kW)	0.007	0.02	0.0017	0.033	0.000013
Efficiency	0.8	0.8	0.8	0.8	0.8
Mass Flow (lb/hr)	3,298	10,626	744	14,010	6.16
Component	Water	Brine	Water	Water	Intermediate Culture

Table 2.5.13: Equipment table for scraped surface heat exchangers

Heat Exchanger	ES-301 to ES-308
MOC	SS
Type	Scraped Surface
Inlet Temperature (°C)	3
Outlet Temperature (°C)	-7
Pressure (bar)	1
Mass Flow (lb/hr)	3,613
Heat Duty (kW)	126
Coolant	Ammonia
Volume (ft^3)	0.67
Dasher Speed (rpm)	500
Residence Time (hr)	0.063

Table 2.5.14: Equipment table for hardening tunnel

Hardening Tunnel	HT-301
MOC	SS
Type	Spiral
Component	Soft Frozen Yogurt
Inlet Temperature (°C)	-7
Outlet Temperature (°C)	-18
Pressure (bar)	1
Mass Flow (lb/hr)	3,613
Heat Duty (kW)	34.43
Hardening Time (hr)	1.75

Table 2.5.15: Equipment table for storage freezer

Storage Freezer	SF-301
MOC	SS
Component	Frozen Yogurt
Inlet Temperature (°C)	-18
Outlet Temperature (°C)	-18
Pressure (bar)	1
Mass Flow (lb/hr)	3,613
Heat Duty (kW)	5.49
Volume (ft^3)	19,300

Table 2.5.16: Equipment table for jacketed tank used in aging

Jacketed Tank	JT-201
MOC	SS
Component	Frozen Yogurt Mix
Inlet Temperature (°C)	3
Inlet Pressure (bar)	1
Mass Flow (lb/hr)	3,542
Holding Time (hour)	4
Volume (ft^3)	261.08

Table 2.5.17: Equipment table for cooling tower

Cooling Tower	CT-401
MOC	Various
Component	Water
Inlet Temperature (°C)	60.1
Outlet Temperature (°C)	30.0
Pressure (bar)	1
Inlet Air Relative Humidity	70%
Inlet Air Temperature (°C)	20
Inlet Air Volumetric Flow Rate (ft^3/min)	9,814
Inlet Mass Flow (lb/hr)	14,010
Mass Evaporated (lb/hr)	744
Heat Duty (kW)	211.6

Table 2.5.18: Equipment table for compressors

Compressors	C-401	C-402	C-403
MOC	SS	SS	SS
Type	Centrifugal	Centrifugal	Centrifugal
Component	Ammonia	Ammonia	Ammonia
Inlet Temperature (°C)	-33.7	28	28
Inlet Pressure (bar)	1	4	8
Outlet Temperature (°C)	93	101.3	154.6
Outlet Pressure (bar)	4	8	25
Efficiency	72%	72%	72%
Mass Flow (lb/hr)	2,250	2,250	2,250
Power (shaft) (hp)	104	58	99
Power (kW)	77.63	43.52	74.19

Table 2.5.19: Equipment table for expansion valves

Expansion Valves	V-301	V-302	V-303
MOC	SS	SS	SS
Type	Isentropic	Isentropic	Isentropic
Component	Ammonia	Ammonia	Compressed Air
Inlet Temperature (°C)	28	-16.7	20
Inlet Pressure (bar)	25	2.2	137.9
Outlet Temperature (°C)	-16.7	-33.7	-163.4
Outlet Pressure (bar)	2.2	1	5
Mass Flow (lb/hr)	2,250	2,250	2.08

Table 2.5.20: Equipment table for blowers

Blowers	B-301	B-401	B-402	B-403
MOC	SS	SS	SS	SS
Type	Centrifugal	Centrifugal	Centrifugal	Centrifugal
Component	Air	Air	Air	Air
Inlet Temperature (°C)	20	20	20	20
Inlet Pressure (bar)	1	1	1	1
Outlet Temperature (°C)	20	20	20	20
Outlet Pressure (bar)	1.1	1.1	1.1	1.1
Mass Flow (lb/hr)	8,000	17,000	20,000	46,520
Power (hp)	28.3	13.5	33.2	1.5
Power (kW)	21.08	10.04	24.79	1.12

2.6 Production and Raw Material Requirements

Raw material requirements for the manufacture of frozen yogurt include ingredients and containers. Containers of 1.75 quart volume are needed, along with lids. The raw ingredients include: inulin, culture, milk, cream, vanilla, mono- and diglycerides, cane sugar, carrageenan, corn syrup solids, compressed air, and water. Table 2.6.1 outlines the assortment of raw materials and relative amounts needed for the process. An overall material balance is given in Appendix A.

Table 2.6.1: Raw material requirements

Raw Material	**Unit Price per lb**	**Flow rate lb/hr**	**First Year Cost**	**Annual Cost**
Inulin	$0.45	86	$217,920	$217,920
Concentrated Freeze Dried Culture	$40.82	5.4×10^{-5}	$13	$13
Milk	$0.11	10,946	$6,927,990	$6,927,990
Heavy Cream, 38% fat	$0.57	180	$574,396	$574,396
Vanilla	$5.73	69	$2,230,155	$2,230,155
Mono and Diglycerides	$0.15	7	$5,913	$5,913
Cane Sugar	$0.24	413	$558,145	$558,145
Carrageenan	$5.50	10	$309,705	$309,705
Corn Syrup Solids	$0.95	103	$550,993	$550,993
Compressed Air	$0.25	480	$6,732	$6,732
Ice Cream Containers	(a)$0.10	(b)7,428,571	$728,000	$728,000
Process Water	6.0×10^{-5}	234	negligible	negligible
		Total	**$12,109,962**	**$12,109,962**

(a) price per container
(b) containers per year

2.7 Utility Requirements

There are many utility requirements for the production of frozen yogurt. Table 2.7.1 outlines the assortment of utilities and their annual costs. Ammonia, brine, cooling water, and steam are all used in the refrigeration cycles for the various phases of heating and cooling. It is assumed that the coolants will not leak, so no extra coolant is purchased to make up for leaks. Due to the safety hazard an ammonia leak poses, it is assumed that suitable safety precautions will prevent an ammonia leak during typical operation. The electricity needs come from the following equipment used in the process: compressors, homogenizers, mixers, pumps, filler, blowers, and scraped surface heat exchangers. The total electricity usage is 3 million kWh per year for the entire process. A breakdown of the electricity use by piece of equipment is given in Table 5.1.2. The sulfuric acid and sodium hydroxide are used in the cleaning in place procedures along with the process water to rinse after each acid or base flush of the system. Liquid water disposal is the cost to dispose of the cleaning in place materials after use. The compressed air used to operate the filler is considered a utility; the compressed air in Table 2.6.1 is injected into the scraped surface heat exchangers. An overall energy balance for the whole process in shown in Appendix A.

Table 2.7.1: Utility requirements

Utilities	**Unit Price (per gal)**	**Flow rate (gal/hr)**	**First Year Cost**	**Annual Cost**
Brine	$0.05	(a)577	$29	None
Ammonia	(b)$0.09	(c)1,125	$135	$14
Cooling water	$\$5.0\times10^{-5}$	528,349	$35	$35
Electricity	(d)$0.04	(e)419	$159,331	$159,331
Sulfuric Acid	$0.12	2.66	$2,380	$2,380
Sodium Hydroxide	$0.30	2.66	$6,010	$6,010
Liquid Water Disposal	$\$3.0\times10^{-3}$	13.28	$299	$299
Process Water	$\$5.0\times10^{-4}$	36.00	$30	$30
Steam	(f)$\$2.5\times10^{-3}$	(g)236.4	$1,768	$1,768
Compressed Air	(h)$0.25	(i)2.08	$300	$300
		Total	**$170,317**	**$170,167**

(b) price per pound
(c) pounds in loop
(d) cost per kilowatt-hr
(e) power consumption in kW of equipment
(f) cost per pound of steam
(g) pounds of steam per hour
(h) price per pound
(i) flow in pounds per hour

2.8 Rationale for Process Choice

Since frozen yogurt is not a new product in the supermarket, there is already a well established process for making it. However, as with every process, there is room for variations and improvements. The basic process to make frozen yogurt involves making the yogurt; adding in sugar, cream, other additives, and flavors; freezing the mixture while incorporating air; and hardening the product (University of Guelph, 2008). Aside from the yogurt, this process is identical to making ice cream, where milk replaces the yogurt (Stogo, 1998). The process elements with room for variation were the ratio of yogurt to milk, the ingredients, culture addition, the aging time, and the hardening stage. The elements of this process that make it unique are the ultrafiltration membrane, the added inulin fiber, and the probiotic bacteria.

The process begins with fluid skim milk and cream arriving at the plant and weighed into storage silos. By starting with minimally processed raw materials and making the yogurt on-site, a greater degree of control can be maintained over the process. It is well accepted in frozen yogurt processes to begin with milk and make the yogurt at the plant (Knight, 2008; Ordonez, et al., 2000; El-Nagar, et al., 2002). Also, since yogurt is about 55 times more viscous than milk, milk would be the easier component to transport (Prentice, 1992).

The next step for the skim milk is ultrafiltration, which increases the total solids in the milk from 9% to 20%. This is not a normal unit operation for frozen yogurt production, but it does provide several benefits. Ultrafiltered milk and the products produced from it are higher in protein and calcium and lower in lactose than their conventional counterparts, which are made from milk with added milk solids non fat (MSNF include milk proteins, lactose, and minerals) (Ordonez, et al., 2000). Furthermore, lactose crystallization is a cause of the “sandy” texture of some ice creams. The more lactose in the product, the more likely it will crystallize out the water phase (Arbuckle, 1977). Most ice creams or frozen yogurts use milk (5% lactose) plus nonfat dry milk (54% lactose) to increase the solids content. The UF milk, however, only contains about 4% lactose and does not need added MSNF (Premaratne and Cousin, 1991). Once a portion of the UF milk has been made into yogurt, the lactose content will be even lower because the yogurt culture contains lactic acid bacteria, which consume lactose (Spreer, 1998). Since the lactose content of this product will be 42% lower than that of skim milk, significant lactose crystallization is not expected, which will contribute to a premium texture. Also, the calcium content of the final product is expected to be 2.5 times higher than that of skim milk (pg. A-7). UF milk also provides higher flavor and higher consistency scores in sensory tests than products made with milk and nonfat dry milk. Since flavor and consistency are common complaints in low fat ice cream and frozen yogurt, higher sensory scores makes UF milk a good option for low fat frozen yogurt (Ordonez, et al., 2000).

Next, the ice cream mix is prepared. This consists of the UF milk, cream, mono- and diglycerides, carrageenan, cane sugar, corn syrup solids, water, and inulin fiber. The cream is added to increase the fat content of the finished product to 2% (Univ. of Guelph, 2008). The mono- and diglycerides are added because they are emulsifiers, which keep the water and fat phases together (Kessler, 1981). Carrageenan is the chosen stabilizer because it is one of the best tested products for slowing recrystallization, the joining of ice crystals or the melting and reformation of ice crystals (Adapa, et al., 2000). Cane sugar (sucrose) was chosen as the primary sweetener because of its general acceptability to customers. Some corn syrup solids are used as well because they aid in preventing recrystallization (Adapa, et al., 2000). High fructose corn syrup is not used because ice creams made with it have the highest recrystallization rates and because it lowers the freezing point of the ice cream mix relative to sucrose, making nucleation more difficult (Adapa, et al., 2000; Drewett and Hartel, 2007). Also, ice cream made with sucrose is softer, therefore easier to scoop, than ice cream made with corn syrup (Muse and Hartel, 2004). Water is added based on the frozen yogurt formulation in Ordonez, et al. (2000). Lastly, inulin is an ingredient not normally added to frozen yogurt. This ingredient was chosen because, not only is it a fiber with metabolic benefits, but it can be a fat replacer. Inulin increases the creaminess and viscosity of the frozen yogurt while decreasing the meltdown rate (El-Nagar, et al., 2002). The ice cream mix is also pasteurized to kill potentially dangerous microorganisms and homogenized, as shown in Fig. 2.8.1, to distribute the fat phase within the water phase more evenly and to keep the two phases more stably emulsified (Spreer, 1998). The method of pasteurization used is higher-heat shorter time (HHST) pasteurization, which requires that the milk be brought up to 90 °C and held there for at least 0.5 seconds and then cooled again (International Dairy Foods Association, 2008). HHST pasteurization was chosen because the holding time is so short that no holding tank will be needed to maintain 90 °C for the required time.

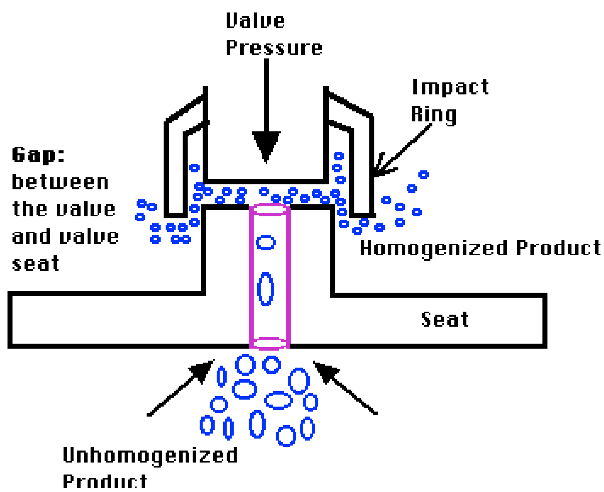

Fig. 2.8.1: Diagram of the homogenization process (Univ. of Guelph, 2008)

When making yogurt, the culture must contain the lactic acid bacteria *Lactobacillus bulgaricus* and *Streptococcus thermophilus* (Chandan, 2006). Since it is desirable for the frozen yogurt to have the benefits of probiotic bacteria (improved digestive health), *Bifidobacterium bifidum* and *Lactobacillus acidophilus* are also included in the culture (Ordonez, et al., 2000;

Saarela, et al., 2000). The cultures used in this product, Yo-flex (yogurt culture) and Nu-trish (probiotic culture) from Chr. Hansen, were chosen because Yo-flex requires fewer milk solids to grow and because Nu-trish has good survival characteristics, the importance of which is explained below (Chr. Hansen, Nu-trish, 2004; Chr. Hansen, Yo-flex, 2004). One technological challenge in incorporating probiotics into food is keeping the probiotic bacteria alive. Some techniques for the survival of probiotic bacteria are using oxygen-impermeable containers, micro-encapsulating the bacteria, incorporating micro-nutrients (peptides or amino acids) into the product, and selecting acid- or bile-resistant strains (Shah, 2000). The probiotic bacteria used in this product are tolerant to gastric acids and bile (Chr. Hansen, Nu-trish, 2004). Incorporating any of the other techniques would be areas for future improvement. Before the culture is added to the UF milk, it is pre-grown as "bulk culture." Normally, the growth medium is water with 10% nonfat dry milk, NFDM (Ordonez, et al., 2000). The Yo-flex culture, however, does not require as high a milk solids content to grow (Chr. Hansen, Yo-flex, 2004). Therefore, since lactic acid bacteria eat lactose, it was assumed that as long as the growth medium has as much lactose as the 10% NFDM solution, 5.3% lactose, the culture will grow. Lactose concentrations over 15% can begin to inhibit growth of the yogurt culture (Ozen and Ozilgen, 1992). The filtrate from the membrane meets the lactose requirement, and is therefore used to grow the bulk culture without added solids (pg. B-2).

There are three common choices regarding the form of culture used: liquid culture, deep-frozen culture or concentrated culture, and concentrated freeze-dried culture. Liquid culture is good for about eight days and must be kept refrigerated, and deep-frozen culture, though having a shelf life of several years, must be kept at -25 °C. Concentrated freeze-dried culture (CFDC), on the other hand, can be kept at room temperature and has a moderate shelf life of about 5 months (Spreer, 1998). The chosen cultures are CFDC, though the manufacturer recommends storing them at -18 °C for up to 24 months (Chr. Hansen, Yo-flex, 2004). Since the process requires a large storage freezer at -18 °C for the final product and since the CFDCs do not take up much space, storing the cultures will not require special refrigeration.

Before making the yogurt portion, the yogurt culture must be prepared for inoculation. The culture can be added to the milk either by direct inoculation (which would require much more culture, and is more common in cheese manufacture) or through a bulk starter culture (which requires little culture). Making the bulk culture involves adding the CFDC to a pasteurized growth medium, the filtrate, and letting it incubate. After incubation, this becomes the mother culture, which is used to inoculate more filtrate at a rate of 6.1% to make an intermediate culture (Ordonez, et al., 2000). This inoculation rate means that intermediate culture, before fermentation, is 6.1 wt% mother culture and 93.9% filtrate. The intermediate culture is used to inoculate even more filtrate at the same rate to make the bulk culture, which is used to inoculate the milk and make yogurt (Spreer, 1998; Food and Agriculture Organization, 2004). Since 2 grains of culture are added per liter of milk or filtrate, direct addition would use 2.973 lb of culture per run while making a bulk culture uses 6 grains (0.0009 lb) of culture per run (Food and Agriculture Organization, 2004; pg. B-27).

The process to make the yogurt is quite standard: lactic acid bacteria ferment milk. First, the UF milk is pasteurized and homogenized to stabilize the emulsion. The bulk culture is then added to the milk at an inoculation rate of 6.1% and fermented at 40 °C until the total acidity reaches 0.30%, about four hours, as suggested by Ordonez, et al. (Ordonez, et al., 2000; Food and Agriculture Organization, 2004). This acidity level is low enough to be acceptable to customers (Guinard, et al., 1994). Once the yogurt is fermented, it must be cooled as fast as possible to prevent further acidification (Spreer, 1998).

Next, the ice cream and the yogurt portions are mixed together. The ratio of yogurt to ice cream mix is nearly half and half (Ordonez, et al., 2000; Univ. of Guelph, 2008). Using only half yogurt ensures a less yogurt-like and more ice-cream-like flavor. The mixture is then aged for fours hours at 3 °C (How Products are Made, 2007). The aging process allows the "hydrocolloids to swell, the casein to become hydrated, the viscosity to increase, the whippability to improve, fats to crystallize out and aroma to develop uniformly throughout" (Kessler, 1981). The vanilla flavor is mixed in after aging (How Products are Made, 2007; Kessler, 1981).

The mix is now ready to be frozen. During the freezing process, the mix is rapidly cooled, about 50% of the water is frozen, and air is incorporated into the product (Adapa, et al., 2000). This results in a three-phase system that is both an emulsion and a foam: the milk fat and the air are dispersed within a serum phase. The fat was previously dispersed by the homogenizer, but the air is dispersed by the rotating blade inside an ice cream freezer and is stabilized by the fat and emulsifiers (Univ. of Guelph, 2008). By far, the most common way to freeze ice cream or frozen yogurt is with a scraped surface heat exchanger (Hartel, 1996). Common refrigerants in an ice cream freezer are ammonia or Freon (Kessler, 1981). Ammonia was chosen for this process because, while Freon refrigerants (hydrochlorofluorocarbons) are nontoxic, ammonia is more environmentally friendly. Also, Freon products are currently being phased out from industry (DuPont, 2007). The frozen yogurt's draw temperature, the temperature at which it comes out of the scraped surface freezer, was chosen to be -7 °C. A lower draw temperature helps more ice crystals to nucleate in the freezer, which will help keep the size of the ice crystals small in the final product (Drewett and Hartel, 2007).

The product that leaves the scraped surface heat exchanger is more like soft-serve ice cream than hard-packed ice cream, so the next step is to freeze the frozen yogurt further. Before hardening, however, the frozen yogurt is packaged while it is still soft and easy to flow (Knight, 2008; How Products are Made, 2007). The hardening step is carried out in a hardening tunnel—akin to a blast freezer—where the temperature of the frozen yogurt is lowered to -18 °C over 1.75 hours. A schematic of a spiral hardening tunnel is shown in Fig. 2.8.2. During this step, the ice crystals formed in the scraped surface heat exchanger grow to about 45-50 μm, at which point 75-80% of the water from the original serum phase has been frozen (Hartel, 1996). The hard frozen yogurt can now be kept in a storage freezer at -18 °C until it is ready to ship out.

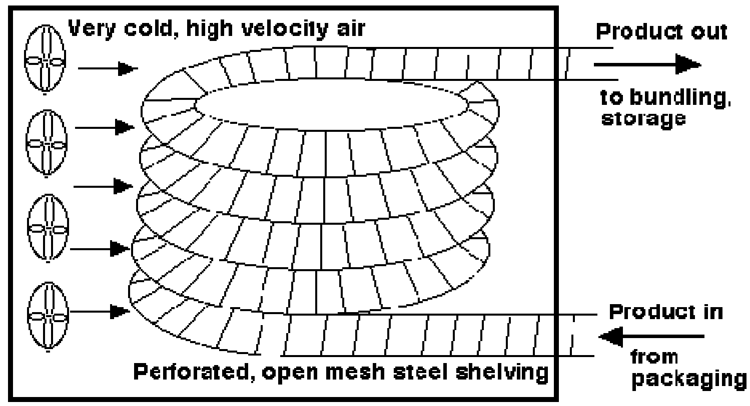

Fig. 2.8.2: Drawing of a spiral hardening tunnel (Univ. of Guelph, 2008)

A classic refrigeration cycle (expansion valve, heat exchanger, compressor, and condenser) is used to take heat out of the process (Koretsky, 2004; pg. B-19 – B-20). The main refrigerant for the process is ammonia, as mentioned above, which cools the brine, the scraped surface freezer, the hardening tunnel, and the storage freezer. The ammonia is expanded twice, instead of once, so that the ammonia is at -16.7 °C and 2.2 bar when cooling the brine (whose freezing point is -21 °C) and is then at -33.7 °C and 1 bar when cooling the freezers and the tunnel (Lide, 2007; pg. B-20 – B-24). Cooling water and air are used to cool and condense the ammonia along with the filtrate and a stream of UF milk. These last two trade heat with ammonia for energy recycling. The cooling water is cooled to its original temperature by a cooling tower, which avoids sending hot water down the drain and reduces the mass flow of incoming cooling water by 94.7% (Felder and Rousseau, 2000; pg. B-25). An intermediate refrigerant between ammonia and the cooling water or the air was not used to avoid extra process equipment and because ambient air is free and at a low enough temperature to cool the ammonia. Brine and water are also used as coolants for the product; however, they always remain liquid because of their high boiling points. The heat exchangers that use brine or water do so instead of using ammonia, whose normal boiling point is -33.7 °C, in order to avoid freezing the product prematurely (pg. B-20 – B-24).

2.9 Equipment Description, Rationale, and Optimization

The following section discusses and rationalizes the pieces of equipment used to make frozen yogurt in this process. All of the equipment specifications can be found in the equipment tables, Tables 2.5.1 through 2.5.20 in section 2.5, and the detailed calculations for equipment size and cost can be found in Appendix C.

When the milk and cream are brought to the plant, they are paid for by weight. Since the density of milk is known, a volumetric flowmeter is a cheap and accurate way to measure how much milk is being received. Magnetic-inductive flowmeters were chosen because they are easy to manipulate during cleaning (Spreer, 1998). Another option considered was to have a truck scale, but given the size of such a scale and the accuracy needed, it was considered more economical to use a flow meter (Warner, 1976). Once the milk and cream are received, they are not used all at once, so two silos (storage tanks, SL-101 and SL-102) are needed to hold the milk and cream until use. The silos are made of stainless steel and are equipped with a stirring system for cleaning (Spreer, 1998). All the equipment that contacts the product is made of stainless steel because it is resistant to corrosion and bacteriological contamination. In practice, stainless steel is the material of choice for food processing equipment (Krishna Industries, 2008). Since milk and cream are delivered daily, the silos were designed to hold 100% of the daily milk supply and 100% of the daily cream supply (Spreer, 1998; pg. C-30).

The idea to ultrafilter the skim milk was incorporated into the design based on a paper by Ordonez, et al., which, as described in the previous section, will increase the creaminess of the frozen yogurt, increase the amount of protein and calcium in the product, and decrease the amount of lactose (2000). The membrane specifications, as listed in Table 2.5.4, indicated a molecular weight cut-off of 5 kDa and a retentate that is 20% total solids (Ordonez, et al., 2000). To achieve this percentage of total solids, a volume reduction factor of 4.55 is needed (Premaratne and Cousin, 1991; pg. B-2). This means that 78% of the incoming skim milk is filtrate, and only 22% of the skim milk becomes UF milk. The waste is recycled as much as possible. Since the filtrate is cold, it can be recycled to cool the compressed ammonia, some filtrate is used to grow the bulk culture, and the rest can be sold as pig feed (Knight, 2008). The ultrafiltration membrane to be used will be provided by Koch Membrane Systems and it will be a spiral membrane with a molecular weight cut-off of 5 kDa. A flux of 25 L/m^2/hr/bar (0.614 gal/ft^2/hr/bar) and a membrane area of 27.2 m^2 (292.8 ft^2) were selected (Koch, 2007). Using the volumetric flow of the filtrate, a flux of 142.3 L/m^2/hr was found, which made the transmembrane pressure 5.7 bar (Sáez, 2007). The membrane chosen has a larger area than other 5 kDa cut-off membranes by Koch, which increases the flux while allowing the pressure to remain relatively low (Koch, 2007). To increase the pressure of the skim milk before the membrane a rotary (external gear) pump was selected because the liquid is at a low flow rate, about 22 gpm, and is being pumped to a low pressure, 6.7 bar (Seider, et al., 2005; PDH Engineer, 2008). All the other pumps in this process, except for the homogenizers, are also rotary pumps for the same reasons. Pump details are found in Tables 2.5.11 and 2.5.12.

Preparing the ice cream mix is the next step. The ingredients for the ice cream mix come together in a closed vessel with a propeller-type agitator, M-101. This vessel, along with all the other vessels in the process (except for the silos), are oversized by 30%, in case any unit operations take longer than expected. To get the cream from its silo to the mixer, a rotary pump is used just as for the skim milk. The mono- and diglycerides, carrageenan, cane sugar, water, inulin fiber, and corn syrup solids are all added to the process by the operators. During a tour of the Phoenix Ice Cream Plant, it was noted that most of the additives were manually added to the process (Knight, 2008). To pasteurize the ice cream mix, a plate-and-frame heat exchanger is used. This type of heat exchanger, as shown in Fig. 2.9.1, was selected because it is the most common type of heat exchanger used for milk pasteurization (Univ. of Guelph, 2008; Spreer, 1998). Also, the ice cream mix will be somewhat viscous, and plate-and-frame heat exchangers are considered ideal for viscous flows (Seider, et al., 2005). The pasteurizer consists of four sections: a regenerator, E-201; a heater, E-202; a water cooler, E-203; and a brine cooler, E-204 (pgs. B-3–B-4). The specifications for these heat

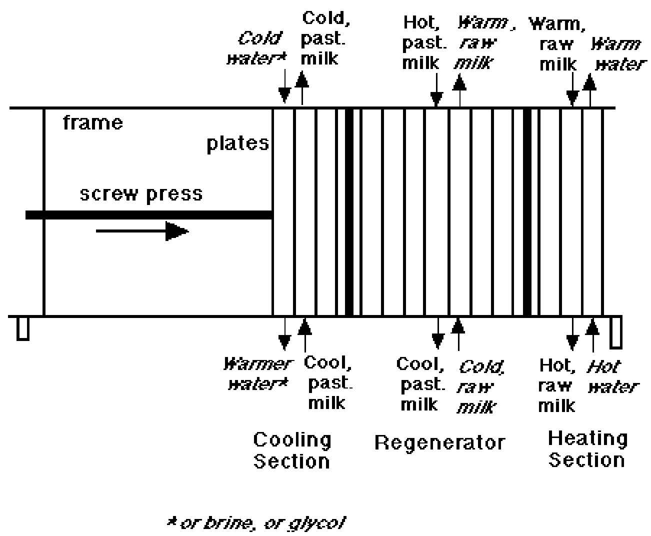

Fig. 2.9.1: General schematic of a plate-and-frame milk pasteurizer (Univ. of Guelph, 2008)

exchanger sections can be found in Tables 2.5.8 and 2.5.9. Since the mix must be both heated and cooled, the regenerator is an excellent way to save energy. In this section the hot, pasteurized ice cream mix is cooled from 90 °C to 29.8 °C by heating the incoming ice cream mix from 4 °C to 64.2 °C (Kessler, 1981). Between the regenerator and the heater, the ice cream mix is at the right temperature for homogenization, so the mix is diverted to the homogenizer, HG-201, Table 2.5.6, after the regenerator (Ordonez, et al., 2000; Kessler, 1981). The homogenizer is a type of reciprocating pump that subjects the liquid to very high pressures while passing between a valve and valve seat, which causes the fat globules to be torn apart and creates a better emulsion (Warner, 1976; Univ. of Guelph, 2008). This homogenizer has two stages since the ice cream mix will be thick due to the inulin and carrageenan. It operates at 140 bar in the first stage and 35 bar in the second stage. These specifications are based on research into making frozen yogurt with added inulin (El-Nagar, et al., 2002). In the heating section of the pasteurizer, saturated steam is used to heat the mix to 90 °C, HHST pasteurization temperature (Kessler, 1981; International Dairy Foods Association, 2008). The water cooler uses refrigerated water, 16 °C, to bring the temperature of the ice cream mix down to 22 °C, and the brine cooler brings the ice cream mix the rest of the way to target temperature of 3 °C (Kessler, 1981). Brine is used to make sure that the coolant temperatures can be high enough to avoid freezing the coolant in the pipes. Water is used in addition to brine because it usually leads to slightly higher overall heat transfer coefficients than brine, it is less corrosive than brine, and it is cheaper than brine (Kessler, 1981; Iowa Department of Transportation, 2008; Seider, et al., 2005). After the brine cools the ice cream mix, it is used to bring the water back to its original temperature in a double-pipe heat exchanger, E-208. This model was chosen because double-pipe heat exchangers are more appropriate than shell-and-tube heat exchangers for heat transfer areas between 2 ft^2 and 200 ft^2 (Seider, et al., 2005). This heat exchanger falls within that range at 6.0 ft^2 (pg. B-10). Also, the brine side of E-208 is made of nickel alloy to avoid corrosion from the brine (Turton, et al., 2003). For the other heat exchangers in the plant, all the surfaces contacting brine use nickel alloy, too. A rotary pump, P-201A/B, keeps the refrigerated water moving (Seider, et al., 2005).

To make the bulk culture, the culture's growth medium, the filtrate from the milk ultrafiltration process, is pasteurized and the culture is grown in the three stages described in sections 2.1 and 2.8: mother culture, intermediate culture, and bulk culture. The pasteurizer used on the filtrate only consists of a heater, E-501, and a water cooler, E-502; both are described in Table 2.5.10. No brine is used because the filtrate is exiting the pasteurizer at the incubation temperature, 40 °C. While a regenerator could have been added to the pasteurizer, the savings, about $108 per year in steam and cooling water costs, would take about 15 years to outweigh the cost of a larger heat exchanger (Seider, et al., 2005; Kessler, 1981; pg. B-28). Since this is a pasteurization process, plate-and-frame heat exchangers are used as described earlier. The mother culture can be grown in a lab because of the small quantities produced. A 4-L flask incubated at 40 °C will be sufficient to grow the mother culture. To make the intermediate culture, the mother culture is poured into a 14.9 gal tank, R-502, and incubated at 40 °C. The tank must have a port so that periodic samples can be taken to check the pH of the culture. Also, since the intermediate culture must be kept warm for several hours, insulation on the tank will prevent heat loss. A rotary pump transfers the intermediate culture into the bulk culture tank. The bulk culture tank, R-503, is the same as the R-502, but larger; it holds 32.66 ft^3. R-503 also requires a rotary pump to take the bulk culture to the fermentor, R-101.

To prepare the UF milk for fermentation, it is pasteurized in a three-stage plate-and-frame pasteurizer (regenerator, heater, and water cooler; E-101 through 103) with a homogenizer again between the regenerator and the heater. Since the UF milk only needs to be cooled to 40 °C, the fermentation temperature, cooling water at 30 °C can be used alone instead of refrigerated water and brine. The other three stages are used based on typical pasteurizer operation, as for the ice cream mix pasteurizer (Kessler, 1981; pg. B-5). Since the UF milk is thinner than the ice cream mix, it is homogenized in a single-stage homogenizer, HG-101, operated at 100 bar (Ordonez, et al., 2000). To cool off the water from the water cooler, brine is used in E-104. The heat transfer area is very small, 3.9 ft^2, so a double-pipe heat exchanger is used (Seider, et al., 2005; pg. B-10). A rotary pump keeps the cooling water circulating at 6.2 gal/min.

Fermentation is carried out in R-101. This reactor is intended to operate continuously, so it must operate as a plug flow reactor. While a continuous stirred tank reactor is possible, to go from a pH of 6.5 (the approximate pH of milk) to 5.5 would require a CSTR ten times larger than a comparable PFR (Levenspiel, 2004). In order to ferment the yogurt continuously, the unfermented UF milk and bulk culture must be added in such a way that there is no back mixing. The residence time for the reactor is about four hours, which should allow the yogurt to reach a total acidity of 0.30% (Ordonez, et al., 2000). After fermentation, the yogurt is taken directly to be cooled by refrigerated water at 16 °C, E-205, then by brine at -4 °C, E-206, to stop acidification and bring the yogurt to 3 °C (pg. B-6). Because yogurt is much more viscous than milk, a plate-and-frame heat exchanger is best suited for cooling the yogurt (Prentice, 1992; Seider, et al., 2005). The water for E-205 is cooled by the brine in E-207. Because of the small area of this heat exchanger, 12.3 ft^2 (pg. B-6), and the corrosive nature of brine, a nickel-alloy double-pipe heat exchanger was selected (Seider, et al., 2005; Turton, et al., 2003). As with the other water coolers, a rotary pump is used to keep the water moving.

The yogurt and the ice cream mix are mixed together in a closed vessel with an agitator, M-201. The vessel is closed to prevent contamination, and the agitator is necessary to ensure mixing. The mix is intended to remain in the mixer for a short amount of time, maximum 30 minutes. To age the frozen yogurt mix, it sits in a tank, JT-201, for fours hours while the flavors develop as described earlier. The tank must be insulated since the mix is at 3 °C. As with the fermentor, a plug flow through the tank will ensure that all the mix has been aged for four hours. Since aging is not as critical a process as fermentation, limited back mixing is acceptable. To add vanilla to the frozen yogurt mix, another closed vessel with an agitator is used, M-301. This vessel was designed using the same rationale as M-201.

For the initial freezing process, the vanilla frozen yogurt mix is sent through a scraped surface heat exchanger with compressed air at 5 bar being added directly into the mix (Warner, 1976; Adapa, et al., 2000). Table 2.5.13 details the freezer specifications. A scraped surface heat exchanger is the most common type of freezer used to make ice cream, as mentioned in section 2.8. During the freezing process, the majority of the ice crystals are nucleated on the wall of the heat exchanger where a large temperature gradient drives nucleation. To maintain efficient heat transfer and maximize ice crystal nucleation, the ice layer must be frequently scraped off. Furthermore, to obtain a smooth frozen yogurt, the ice crystals must be kept as small as possible. This makes it desirable to nucleate as many crystals as possible during initial freezing. In general, no new crystals nucleate during the hardening stage. The more existing crystals there are from initial freezing, the smaller these crystals can grow during the hardening stage—there is less room to grow. Thus, having the scraper, called a dasher, in the heat exchanger removes the growing ice crystals and allows more to nucleate. The dasher cannot revolve too quickly, however, because heat liberated by viscous dissipation will cause small ice crystals to melt, thus increasing the final size of the ice crystals (Hartel, 1996). A moderate dasher speed, 500 rpm, was chosen based on a study on ice crystallization in ice cream in a scraped surface heat exchanger. This study also found that a shorter residence time resulted in smaller ice crystals because of necessarily faster heat removal (Drewett and Hartel, 2007). The ice cream freezer chosen has a volume of five gallons, which results in a very short residence time, about four minutes (Anco-Eaglin Inc, 2008). The heat transfer area of the freezer also means that eight scraped surface freezers in parallel are needed (pg. B-13). To calculate the amount of heat generated by viscous dissipation, several estimations had to be used, but the viscous heat calculated was similar to values found by Russell, et al. (1999).

Between the initial freezing and hardening, the product is packaged while it can flow readily. The piece of equipment used for packaging is an ice cream filler. The model chosen can fill up to 60 1.75 qt containers per minute, though the process only requires 22 cartons per minute. It fills each 1.75 qt container with the product and sends it off to the hardening tunnel. To prevent tubs that are only partially full, the filling line can include a scale with a control to automatically reject containers that are less than the target weight using compressed air. Also, in the filling line, a metal detector can be installed to ensure that no metallic foreign objects have wound up in the product.

To harden the frozen yogurt, the options were either a hardening room or a hardening tunnel (Arbuckle, 1977). Since this process is continuous, a hardening tunnel was selected. Also, a hardening tunnel will cool the frozen yogurt faster than a hardening room would. Faster hardening is important to prevent warm spots in the soft frozen yogurt from melting the ice crystals formed in the freezer (Warner, 1976). The containers of frozen yogurt are conveyed from the filler to the hardening tunnel and then off to the storage freezer. Due to the presence of the conveyor belt, a spiral hardening tunnel was chosen. The conveyor belt takes the frozen yogurt to be hardened into a chamber with air at -40 °C. The belt then takes the frozen yogurt on a spiral path in the chamber for about 2 hours and then conveys the hardened frozen yogurt on to the storage freezer (Knight, 2008; pg. B-15).

The storage freezer keeps the frozen yogurt stored until it is shipped. The storage freezer is kept at -18 °C, which is the target core temperature of the frozen yogurt when it leaves the hardening tunnel. The freezer was designed to hold one week's worth of product and to allow space to move around in.

The ammonia refrigeration cycle is the key to providing temperatures low enough to make frozen yogurt. As described in section 2.1, the refrigeration cycle consists of expansion valves, compressors, and heat exchangers. While a turbine could have been used, it would not have generated much work, and it would have cost more than a valve (Koretsky, 2004). The three compressors used are centrifugal because that type delivers a smooth flow rate, has low maintenance costs, and is small in size (Seider, et al., 2005). The highest compression ratio used is 4, which is the maximum recommended compression ratio according to the heuristics in Seider, et al. (2005). Based on the precedent set by the home refrigerator, blowing air will provide some of the cooling for the hot, compressed ammonia (Marshall, et al., 2003). These heat exchangers, E-402, E-403, and E-301, were selected to be air-cooled fin-fan heat exchangers. The air is conservatively assumed to be at 20 °C, based on Pennsylvania climate data (Pennsylvania State Climatologist, 2008). To keep a decent temperature approach, the air cools the ammonia to 28 °C. The air is brought in with centrifugal blowers, B-301, 401, 402, and 403, because chemical plants commonly use centrifugal blowers to supply air (Seider, et al., 2005). The ammonia/brine heat exchanger, E-302, is a shell-and-tube heat exchanger because its heat transfer area is over 200 ft^2 (pg. B-11). The style of shell-and-tube chosen is a fixed head because of the low price (Seider, et al., 2005). The brine loop is kept flowing with a rotary pump, P-301A/B. The filtrate/ammonia and the cooling water/ammonia heat exchangers are also fixed-head shell-and-tube heat exchangers because of their size (pg. B-19). Cooling water is used in addition to filtrate, air, and UF milk to cool off the compressed ammonia because not using cooling water would have required the air/ammonia heat exchanger to have a prohibitively large area (aspenONE, 2005).

Hot cooling water is cooled back to its original temperature, 30 °C, using a cooling tower. Because the cooling water that cools off the ammonia reaches 62 °C, it would not be environmentally friendly to return hot water to the environment. Also, adding the cooling tower saves nearly 8.95 million gallons of water each year (pg. B-25). Rotary pumps are used to bring new cooling water into the process and to keep the cooling water circulating.

3.0 Safety

3.1 Safety Statement

There are three major safety hazards associated with frozen yogurt manufacturing: microbiological, chemical, and physical. The greatest hazard is microbiological, which is a serious concern to human health (van Schothorst and Kleiss, 1994). Potential risks for the presence of pathogens can occur throughout the process from milk receiving to storage and transportation if the design parameters are not strictly controlled. Chemical hazards are a concern due to the presence of large quantities of toxic, highly corrosive compounds, on-site.

The last potential hazard is physical and can result in human injury or fatality. This hazard has a direct impact on the personnel working at the facility during the operational phase. Process hazard analyses were completed for the manufacturing of frozen yogurt and are given in Tables 3.2.1 to 3.2.12.

This assessment identifies specific hazards in the microbiological, chemical and physical areas. At the same time, each hazard is analyzed to determine how it can be controlled or eliminated. Lastly, a safety risk assessment was developed using a potential hazard analysis (PHA) around different pieces of equipment throughout the process.

Microbiological Hazards

In order to minimize the hazard of food borne illnesses, the Food and Drug Administration adopted a program known as Hazard Analysis and Critical Control Point (HACCP) in different areas of the food industry. A critical control point is a step, such as pasteurization, that eliminates or acceptably reduces food safety hazards. Currently, the FDA does not require the use of HACCP as the food safety standard in the dairy industry (FDA, 2001). However, there is a dairy voluntary HACCP in place that was used as a model in this safety assessment.

Since frozen yogurt is a milk-based product, it is a good medium for growth of microbes at different stages of the process due to the high nutrient content, favorable pH range (6-7) and long storage period (van Schothorst and Kleiss, 1994). The FDA has identified the following hazardous pathogens in milk products (FDA, 2001):

- *Salmonella*
- *Listeria monocytogenes*
- *Staphylococcus aureus*
- Enterohemorrhagic *Escherichia coli*

- *Campylobacter jejuni*
- *Clostridium botulinum*
- *Bacillus cereus*

Most of these pathogens have the potential to grow in frozen yogurt, at any stage of the process, unless the environmental conditions inhibit the growth. The three areas within manufacturing that restrict the growth of pathogens are: pasteurization, fermentation and hardening. However, the processing facility must have an automated system in place to assign lot numbers to each product, in case of a recall, should any of the control points fail.

Pasteurization is the most commonly applied heat treatment in milk products (van Schothorst and Kleiss, 1994). The parameters used to accomplish an effective pasteurization are time and temperature. In this process, the raw ice cream mixture, the ultrafiltered milk for making yogurt, and the filtrate for growing the bulk culture are heated to 90 °C for a period of 0.5 seconds. After reaching this temperature and maintaining it for the specified time, 99.9% of pathogenic bacteria have been destroyed (International Dairy Foods Association, 2008; Spreer, 1998). This process is known as higher-heat shorter time (HHST) pasteurization, and it is one of several types of pasteurization methods. This is a critical control point since it reduces potential hazards in milk to acceptable levels by the International Dairy Foods Association.

The fermentation of yogurt is also used as a critical control point to eliminate the presence of undesired bacteria. During fermentation, bulk culture made of lactic acid bacteria (benign bacteria to humans) is added to pasteurized UF milk which drops the total acidity of the mixture to 0.30%. This acidic environment makes it unlikely for pathogens to survive (Adams and Nicolaides, 1997). In addition, the rapid growth of the lactic acid bacterial population restricts the growth of other organisms by competing for available space and uptake of nutrients

(Adams and Nicolaides, 1997). Therefore, the fermentation serves as an additional control point for any pathogens that may have survived pasteurization.

Frozen yogurt hardening is the last step within the process that reduces microbiological hazards. The frozen yogurt is cooled down to -18°C in the hardening tunnel, and it is kept at this temperature during storage and transportation. While some bacteria may survive the freezing and hardening processes, the low temperatures are not conducive to bacterial growth, so no new bacteria is expected to grow in the system. Any pathogens that happen to survive the pasteurization, fermentation, and freezing steps, may become active again after consumption due to the warm temperatures of the human body (Rahman, 2007).

Setting control points to avoid contamination from the process equipment is more difficult because contaminants can arise from many sources (van Schothorst and Kleiss, 1994). This includes buildup of microorganisms in cracks, void spaces, dead ends, etc. Good manufacturing practice is a good measure of control. Therefore, frequent cleaning of conveyor belts, product lines and flow pipes is required. This is performed by flushing with water, caustic, acid and water once again into the systems. Another way to detect unforeseen sources of contamination is to collect samples on the microbiology of the plant's soil and its environment (Kleiss, et al., 1994). This process allows identification of microorganisms that can be found in drains, air handling units, insulation around tanks and pipes. In addition, the possibility of pests entering production, or storage can be determined (Kleiss, et al., 1994).

In the case of control failure and/or suspicion of product contamination, the product must be recalled. Yogurina must identify the lot number associated with the contaminated products, and notify the nearest FDA office. This will assure that the product will be quickly removed from the market to avoid consumer harm (FDA, 2002).

The final frozen yogurt product has the potential to become contaminated even after leaving the manufacturing facility through transportation and shipping if good manufacturing practice is not followed or proper temperatures are not maintained. Keeping the temperature in shipping trucks below freezing will prevent microbial growth, though the temperature ought to be kept near -18 °C to maintain product quality. In addition, the following actions can support safety assurance:

- Use hygienic and sanitatary practices when loading, unloading, and inspecting the product
- Inspect transportation vehicles for cleanliness, odors, and dirt before loading

Table 3.1.1 below summarizes process hazards and describes each particular control point.

Table 3.1.1: Hazard identification and prevention in frozen yogurt manufacturing

Process	Hazard	Action to Prevent Hazard
Milk receiving	Presence of pathogens	-Purchase materials from certified sources -Conduct testing to assure milk temperature is no higher than 4°C -Conduct microbiological testing for presence of pathogens
Pasteurization	Survival of pathogens	-Adjust residence time and temperature control -Equipment disinfection -Install valves to divert milk back to silos when temperature falls below the set point (90°C)
Fermentation	Survival of pathogens	-Good hygienic practices -Monitor pH of culture mixture by taking samples from tank ports
Aging	Contamination	-Good manufacturing practices -Regular cleaning
	Growth of microorganisms	-Maintain low temperatures (less than 4 °C) to inhibit growth
Packaging	Contamination	-Use of automated equipment -Regular cleaning
Additional ingredients: iInulin, vanilla flavoring, mono- and diglycerides, carrageenan, cane sugar and corn syrup	Contamination	-Purchase materials from certified sources -Maintain storage areas regularly clean -Maximum storage temperature of 25 °C
Hardening	Contamination	-Cleaning and disinfection of equipment
Storage and transportation	Growth of microbes	-Maintain a freezing temperature -Discard product exposed to temperatures > 0°C

Chemical Hazards

There are three chemicals used in this process that are toxic to human health: ammonia, sodium hydroxide and sulfuric acid. Exposure to these chemicals involves chemical handling during cleaning operations, maintenance of cooling systems, and equipment failure. The primary method to avoid exposure to chemicals is the use of personal protective equipment (OSHA, 2003).

Cleaning and washing the equipment/pipelines in preparation for maintenance can create problems. Sulfuric acid, used as a cleaning agent in the plant, is a strong irritant causing severe skin burns and respiratory tract irritation (Kegley, et al., 2007). Similarly, sodium hydroxide can also cause severe skin burns, shortness of breath, and collapse (Kegley, et al., 2007). Respirators, lab coats, appropriate gloves, and shoes should be required while handling this agent. Employees with appropriate technical training should be considered for this stage of the manufacturing process. Additional safety sessions should be presented to all employees every 6 to 8 months to enrich their knowledge and safety awareness about the plant (OSHA, 1992).

Maintenance of cooling systems is one area where many accidents have occurred. For example, an ice cream plant manager was killed by an explosion while replacing a leaking drain valve on an oil trap as a part of an ammonia refrigeration system (Sanders, 1999). In 1994, an employee was killed when disconnecting a line from an ammonia valve. The line had not been adequately isolated, causing the release of liquid ammonia which struck the worker's face and body (OSHA, 1996). The OSHA Permissible Exposure Limit for ammonia in general industry is 50 ppm. Ammonia can be harmful and additional safety features must be implemented throughout the refrigeration cycle to ensure a safe working environment. This highly hazardous refrigerant can be protected by safety valves or pressure-relief devices discharging to a surge tank, flare or other safer place for storage. Leak detectors are also recommended in order to avoid further complications and ensure hazard prevention (OSHA, 1996).

Physical Hazards

Many safety considerations are related to physical hazards in the working environment during manufacturing of frozen yogurt. In recent years, the total recordable cases of safety incidents in the food industry are about 3 to 5 times higher than the chemical industry according to the U.S. National Safety Council (Sanders, 1999). The potential for employee injury arises from performing repetitive activities in the production lines, exposure to cold in refrigerated areas, and performing maintenance on process equipment.

Dairy operations require employees to perform heavy lifting, carrying, and repetitive work. The following guidelines can be used as a prevention method to avoid injuries (International Finance Corporation, 2007):

- Use mechanical equipment when possible.
- Provide employees ergonomic awareness education to avoid work-related repetitive motion injuries.
- Train employees within the first week of employment in effective lifting and stretching techniques that place minimum stress on the lower back.
- Assign different job tasks to each employee on a weekly basis to reduce the outlined hazards and improve overall labor efficiency.

The working environment in frozen yogurt manufacturing process can also pose a hazard to employees. The main area of concern is exposure to noise and vibrations from heavy machinery like the homogenizer, fillers, and packing lines (IFC, 2007). In order to minimize exposure, ear plugs must be worn at all times in the operation floor. In addition, the hardening tunnel and storage freezer can expose employees to extremely low temperatures over long periods of time. Employee activities in these areas should be replaced by automated equipment, if possible. Otherwise, the employees must wear a thermal suit to prevent frostbite and other related damages. Lastly, a proper drainage system must be in place to minimize the volume of liquids on the floors. Employees must wear slip-resistant footwear to prevent slips and falls.

Overall, frozen yogurt manufacturing is a safe process. This study indicated that the major safety hazard, specific to the equipment, is the ammonia refrigeration. Ammonia is a highly toxic compound, and any type of failure can lead to human fatalities. In addition, the process hazard analysis (PHA) indicated that another major hazard is the compressed air lines flowing into the scraped surface heat exchanger due to the extreme high pressures. This type of incident can potentially lead to upsets in downstream units, which would magnify the effects of the event. Appropriate installation of automatic control in combination with daily inspections can reduce the potential hazards significantly. Microbiological hazards, on the other side, are not specific to one piece of equipment, and can occur at any stage of the process. Good manufacturing practices, regular equipment cleaning, equipment monitoring, and sample testing are essential to reduce the presence of pathogens in the milk or frozen yogurt. By implementing the recommendations stated in this safety study, the safety performance for this facility should increase to a level that will protect human health and the working environment.

3.2 Process Hazard Analyses

Table 3.2.1: Process hazard analysis on E-202

Company: University of Arizona-Tucson April 13, 2008	**Plant:** Yogurina	**Site:** Rural Pennsylvania	**Unit:** 200	**System:** Frozen Yogurt Manufacturing
Method: What-if	**Type:** Heat Exchanger	**Design Intent:** Pasteurize incoming raw milk		
Number: Unit 200				
Team Members: Yirla Morehead, Stefka Ormsby, Kathryn Cook, Dena Moline				

No.: 1	**Description: E-202 Plate and Frame Pasteurizer (Heater)**				
Item	**What if...?**	**Root Causes/Related Questions**	**Responses**	**Safeguards**	**Action Items**
1.1	What if the pasteurizer plates fail due to stress corrosion?	Use of cleaning in place (CIP) chemicals during equipment cleaning	Pressure drop across the plates and loss of heat transfer occurs	Monitor equipment with temperature and pressure gauges to and compare to normal operating conditions to detect any corrosion Consider duplex stainless steel as MOC	Consider ultrasonic monitoring for wall thickness Close outlet of mixer M-101 to prevent more ice cream mix from coming into pasteurizer Shut off P-101 to prevent M-101 from overfilling
1.2	What if the pasteurizer plates become clogged with burned milk solids?	Equipment is not properly maintained or cleaned	Milk pathogens will contaminate the final product Inefficient heat transfer across plates Product loss and production delay	Divert unpasteurized milk back to E-202 Product recall in worst case scenario	Consider installation of valves to divert milk back to E-202 Clean pasteurizer (would need to stop process and run CIP)
1.3	What if the contents of the pasteurizer are overheated by steam causing the vapor pressure to rise?	Excess steam flow Steam pressure is too high	Over-pressurization in E-202, HG-201 Fire or explosion Fatalities	Pressure relief system Use of flowmeters to monitor flow of steam	Install temperature and pressure alarms or interlocks to stop steam flow

Table 3.2.2: Process hazard analysis on ES-301-308

Company: University of Arizona-Tucson April 13, 2008	**Plant:** Yogurina	**Site:** Rural Pennsylvania	**Unit:** 300	**System:** Frozen Yogurt Manufacturing
Method: What-if	**Type:** Heat Exchanger	**Design Intent:** Remove growing ice crystals from the wall of the scraped surface heat exchanger		
Number: Unit 300				
Team Members: Yirla Morehead, Stefka Ormsby, Kathryn Cook, Dena Moline				

No.: 2	**Description: ES-301-308 Scraped Surface Heat Exchanger with Dasher**				
Item	**What if...?**	**Root Causes/Related Questions**	**Responses**	**Safeguards**	**Action Items**
2.1	What if the dasher blades become dull?	Equipment use An error in vendor specifications Lack of maintenance	Overgrowth and oversized ice formation used in frozen yogurt mix Filler failure or clogging Inefficient heat transfer Icy frozen yogurt with poor consistency	Replace dasher blades based on supplier recommendation Sharpen blades periodically Perform maintenance and inspection	Sharpen or replace blades when needed Sampling of product before sending to fillers
2.2	What if the compressed air flowing into the heat exchanger is over pressurized?	V-303 failure to control flow of compressed air	Product contains too much air; overrun specification is not met Pressure drop across ES-301-308 Plant explosion due to over-pressurized heat exchanger plates in contact with ammonia refrigeration cycle Casualties Failure of downstream process units	Pressure relief system Periodic valve testing	Consider installation of a safety valve after V-303 Close flow of frozen yogurt mix from M-301 and close flow of air from compressed air tank (before stream 83) Replace or repair V-303

Table 3.2.3: Process hazard analysis on R-503

Company: University of Arizona-Tucson April 13, 2008	**Plant:** Yogurina	**Site:** Rural Pennsylvania	**Unit:** 500	**System:** Frozen Yogurt Manufacturing
Method: What-if	**Type:** Reactor	**Design Intent:** To ferment the ultrafiltered milk into yogurt		
Number: Unit 500				
Team Members: Yirla Morehead, Stefka Ormsby, Kathryn Cook, Dena Moline				

No.: 3	**Description: R-503 Bulk Culture Batch Reactor**				
Item	**What if...?**	**Root Causes/Related Questions**	**Responses**	**Safeguards**	**Action Items**
3.1	What if the target pH (5.5) is not reached during fermentation?	Growth medium for bacteria is below 5.3% lactose (not enough lactose to feed culture) Incubation temperature too high or too low Lower percentage of live bacteria in culture	pH control loss Viscosity of mixture will decrease Product loss and production delay	High/low pH alarm Test pH regularly during batch culture growth	Extend fermentation time until pH reaches set point Grow culture ahead of time to keep a good production schedule
3.2	What if the starter culture is not active?	Supplier error Inappropriate culture storage (i.e. at the wrong temperature)	Fermentation will not be achieved Product loss and production delay	Perform fermentation ahead of time Test pH regularly during batch culture growth	Grow culture ahead of time to keep a good production schedule Start a new batch of culture

Table 3.2.4: Process hazard analysis on compressed air lines

Company: University of Arizona-Tucson April 13, 2008	**Plant:** Yogurina	**Site:** Rural Pennsylvania	**Unit:** 300	**System:** Frozen Yogurt Manufacturing
Method: What-if	**Type:** Line/Pipe	**Design Intent:** Carry compressed air to scraped surface heat exchanger		
Number: Unit 300				
Team Members: Yirla Morehead, Stefka Ormsby, Kathryn Cook, Dena Moline				

No.: 4	**Description: Compressed air lines before and after V-303**				
Item	**What if...?**	**Root Causes/Related Questions**	**Responses**	**Safeguards**	**Action Items**
4.1	What if the line leaked or ruptured?	Supplier error Corrosion Air line accidentally punctured Overpressurization	Plant explosion if near ignition sources or in proximity to ammonia Casualties Process delay and production loss Final overrun too low (i.e. frozen yogurt is too dense; not enough air in product)	Daily inspection of pipelines and flowmeters	Close flow of frozen yogurt mix from M-301 and close flow of air from compressed air tank (before stream 83) Repair or replace compressed air lines
4.3	What if the valve failed to control flow of compressed air?	Control failure Maintenance error Supplier error	Pressure drop in ES-301-308 Final product does not meet quality standard (overrun)	Daily valve testing Product quality testing schedule to check overrun Install automatic turn-off control for compressed air flow	Close flow of frozen yogurt mix from M-301 and close flow of air from compressed air tank (before stream 83) Repair or replace V-303

Table 3.2.5: Process hazard analysis on JT-201

Company: University of Arizona-Tucson April 13, 2008	**Plant:** Yogurina	**Site:** Rural Pennsylvania	**Unit:** 200	**System:** Frozen Yogurt Manufacturing
Method: What-if	**Type:** Tank/Vessel	**Design Intent:** Aging of frozen yogurt mix		
Number: Unit 200				
Team Members: Yirla Morehead, Stefka Ormsby, Kathryn Cook, Dena Moline				

No.: 5	**Description: JT-201 Jacketed Tank**

Item	What if...?	Root Causes/Related Questions	Responses	Safeguards	Action Items
5.1	What if microbes are present in cracks, void spaces inside the tank after cleaning?	Flow of chemicals was not maintained during cleaning Void spaces and crack due to supplier error Geometry of equipment may result in difficult to clean corners	Potential pathogens present in final product If pathogens are not detected, it can lead to consumer harm	Quality control lab tests for pathogens Eliminate corners in equipment Have clean welds and rounded surfaces Conduct periodic testing for pathogens in vessel	Product recall in worst case scenario Perform extra CIP (stop process) Replace tank
5.2	What if the tank deteriorates?	Internal corrosion and decomposition Internal reactions between the stainless steel and cleaning chemicals CIP chemicals	Tank rupture Process delay and production loss Contaminated product	Daily inspection of equipment Appropriate material of construction Product recall possible	Replace tank

Table 3.2.6: Process hazard analysis on HT-301

Company: University of Arizona-Tucson April 13, 2008	**Plant:** Yogurina	**Site:** Rural Pennsylvania	**Unit:** 300	**System:** Frozen Yogurt Manufacturing
Method: What-if	**Type:** Hardening Tunnel	**Design Intent:** Hardening of soft frozen yogurt with anhydrous ammonia as refrigerant		
Number: Unit 300				
Team Members: Yirla Morehead, Stefka Ormsby, Kathryn Cook, Dena Moline				

No.: 6	**Description: HT-301 Spiral Hardening Tunnel**				
Item	**What if...?**	**Root Causes/Related Questions**	**Responses**	**Safeguards**	**Action Items**
6.1	What if there is ammonia leak during refrigeration in the hardening tunnel HT-301?	Pipe/ joint/ seal leak or eruption Chemical and physical wear Supplier error	Fire or explosion if ammonia comes into contact with lubricant oil or ignition source Process upset and production loss	Air monitoring device Leak detectors Daily inspection Excess flow valve to detect a sudden drop of pressure due to the release of ammonia Automatic shut-off control for ammonia flow	Fire protection Emergency evacuation plan Call Hazmat team and shut off ammonia flow in event of leak Stop process and evacuate plant Fix leak if reasonable to do so
6.2	What if employees are exposed to ammonia?	Caused by ammonia leak in the system	Frostbite from evaporating ammonia 20 ppm for five minutes is maximum exposure Fatalities occur at 30,000 ppm for five minutes Potential law suit	Leak detectors Daily inspection Install ammonia alarm detectors Have safety shower and eye wash nearby	Fire protection Emergency evacuation plan Call Hazmat team and shut off ammonia flow in event of leak Stop process and evacuate plant Fix leak if reasonable to do so
6.3	What if the product containers are not properly sealed and the product gets contaminated with ammonia?	Caused by ammonia leak in the system	Process upset and production loss Health threat (poisoning) to consumers Potential law suit	Inspection of product before hardening Quality testing	Inspect product seal Contact Department of Health Product recall possible

Table 3.2.7: Process hazard analysis on pipelines

Company: University of Arizona-Tucson April 13, 2008	**Plant:** Yogurina	**Site:** Rural Pennsylvania	**Unit:** Pipes	**System:** Frozen Yogurt Manufacturing
Method: What-if	**Type:** Pipelines	**Design Intent:** Transportation of reactants, products and refrigerants		
Number:				
Team Members: Yirla Morehead, Stefka Ormsby, Kathryn Cook, Dena Moline				

No.: 7	**Description: Pipelines**

Item	What if...?	Root Causes/Related Questions	Responses	Safeguards	Action Items
7.1	What if some of the stainless steel pipes are corroded?	Caused by overall breakdown of the passivation layer formed on the stainless steel due to CIP chemicals Physical damage to the passivation layer of the pipe surface	Contamination of product Pipe fracture/rupture Loss of product and production delays	Daily inspection Ultrasonic monitoring for wall thickness Duplex stainless steel as MOC	Replace pipes when needed
7.2	What if some of the Ni-alloy pipes are corroded?	Chemical wear	Contamination of product Pipe fracture/rupture Loss of product and production delays	Daily inspection	Replace pipes when needed
7.3	What if the corroded pipe carries ammonia?	Caused by overall breakdown of the passivation layer formed on the stainless steel due to CIP chemicals Physical damage to the passivation layer of the pipe surface	Reaction of ammonia with oxidizing or reducing agents in corroded material Process upset and production loss	Microprocessor leak detectors Daily inspection	Consider Emergency Evacuation Plan Consider duplex stainless steel as MOC

Table 3.2.8: Process hazard analysis on V-301

Company: University of Arizona-Tucson April 13, 2008	**Plant:** Yogurina	**Site:** Rural Pennsylvania	**Unit:** 300	**System:** Frozen Yogurt Manufacturing
Method: What-if	**Type: Valve**	**Design Intent:** Expansion and decrease of ammonia temperature and pressure		
Number: Unit 300				
Team Members: Yirla Morehead, Stefka Ormsby, Kathryn Cook, Dena Moline				

No. 8	**Description: V-301 Isentropic Expansion valve**				
Item	**What if...?**	**Root Causes/Related Questions**	**Responses**	**Safeguards**	**Action Items**
8.1	What if the valve V-301 is malfunctioning and fails to relieve pressure?	Supplier error Maintenance error	Pipeline overpressure Pressure drop across E-302 Insufficient refrigeration in the ammonia cycle Production delay Poor product quality	Pressure relief system Periodic valve testing Perform maintenance and inspection	Replace valve when needed Stop ammonia flow and process flow until valve is fixed
8.2	What if the valve is leaking?	Supplier error Pipe/ joint/ seal leak or eruption Chemical and physical ware Maintenance error	Fire or explosion if ammonia comes into contact with lubricant oil or ignition source Process upset and production loss	Air monitoring with direct reading device Leak detectors Daily inspection Excess flow valve to detect a sudden drop of pressure due to the release of ammonia	Automatic shut-off control for ammonia flow Replace valve when needed Shut off flow of ammonia in case of leak Use emergency action plan

Table 3.2.9: Process hazard analysis on B-301

Company: University of Arizona-Tucson April 13, 2008	**Plant:** Yogurina	**Site:** Rural Pennsylvania	**Unit:** 300	**System:** Frozen Yogurt Manufacturing
Method: What-if	**Type:** Blower	**Design Intent:** Air transportation to heat exchanger		
Number: Unit 300				
Team Members: Yirla Morehead, Stefka Ormsby, Kathryn Cook, Dena Moline				

No. 9	**Description: B-301 Centrifugal Blower**

Item	What if...?	Root Causes/Related Questions	Responses	Safeguards	Action Items
9.1	What if the blower B-301 failed and the air is not passing through E-301?	Electric short-circuit Supplier error	Lack of air cooling supply for ammonia Insufficient refrigeration to produce product Potential for explosion due to rise in temperature of ammonia	Daily inspection Temperature monitoring throughout process Install temperature alarms or interlocks	Replace blower Shut off compressors to stop ammonia flow, and stop process
9.2	What if during maintenance, the power supply is turned on?	Miscommunication Supplier error	Severe injury/death Process delay and production loss	Safety locks Lock out tag out	Continue safety education for employees to avoid miscommunication Turn power supply to blower off

Table 3.2.10: Process hazard analysis on P-401A/B

Company: University of Arizona-Tucson April 13, 2008	**Plant:** Yogurina	**Site:** Rural Pennsylvania	**Unit:** 200	**System:** Frozen Yogurt Manufacturing
Method: What-if	**Type:** Pump	**Design Intent:** Pumping additional water to cooling tower		
Number: Unit 200				
Team Members: Yirla Morehead, Stefka Ormsby, Kathryn Cook, Dena Moline				

No. 10	**Description: P-401A/B External Gear Pump**				
Item	**What if...?**	**Root Causes/Related Questions**	**Responses**	**Safeguards**	**Action Items**
10.1	What if pump P-401A/B failed and water is not added back to stream 90 after the cooling tower?	Supplier error Build up of minerals due to water hardness Mechanical failure	Will result in decrease of water flow in cooling cycle After 20 cycles, cooling tower will be dry, which will result in insufficient heat transfer in downstream units Process delay and production loss Will result in failure to cool the ammonia in E-401 Ammonia will overheat the filtrate in E-303 above 39.9 C Filtrate used for fermentation will be above the required temperature leading to lack of bacteria growth	Measure flow rates in stream 86 Filter water if water hardness is high Daily inspection	Regular readings of the flow meter on stream 86 to detect malfunctioning in early stage Replace pump and switch to backup pump in even of pump failure
10.2	What if some of the pump's parts have fretting corrosion (common on the pump shaft or sleeve)?	Supplier error (MOC of pump's parts) Chemical oxidation	External fire if lubricant oil from pump is mixed with released ammonia Resulting in seal leakage	Avoid pumps containing carbon steel parts Regular maintenance and inspection	Assure pump is made of correct materials of construction Replace pump if corrosion is found Switch to P-401B

Table 3.2.11: Process hazard analysis on C-401

Company: University of Arizona-Tucson April 13, 2008	**Plant:** Yogurina	**Site:** Rural Pennsylvania	**Unit:** 400	**System:** Frozen Yogurt Manufacturing
Method: What-if	**Type:** Compressor	**Design Intent:** Ammonia compression during refrigeration		
Number: Unit 400				
Team Members: Yirla Morehead, Stefka Ormsby, Kathryn Cook, Dena Moline				

No. 11	**Description: C-401 Centrifugal Compressor**				
Item	**What if...?**	**Root Causes/Related Questions**	**Responses**	**Safeguards**	**Action Items**
11.1	What if the compressor C-401 failed to compress the ammonia going into E-403?	Supplier error Maintenance error	Process upset Insufficient heat removal during freezing and hardening Temperature of storage freezer rises, product could melt Unpasteurized ultrafiltered milk Presence of pathogens in yogurt mix	Backup compressor in case of failure; install parallel compressors C-401 A/B	Fix or replace C-401 Stop process since refrigeration is required to produce product
11.2	What if there was ammonia release?	Supplier error Pipe, seal leak, or eruption Chemical and physical ware	Fire or explosion in proximity to ignition sources Process upset and production loss	Air monitoring with direct reading device Leak detectors Daily inspection Excess flow valve to detect a sudden drop of pressure due to the release of ammonia Automatic shut-off control for ammonia flow	Fire protection Use emergency evacuation plan Call Hazmat team and shut off ammonia flow in event of leak Stop process and evacuate plant Fix leak if safe to do so

Table 3.2.12: Process hazard analysis on P-101A/B

Company: University of Arizona-Tucson April 13, 2008	**Plant:** Yogurina	**Site:** Rural Pennsylvania	**Unit:** 100	**System:** Frozen Yogurt Manufacturing

Method: What-if	**Type:** Pump	**Design Intent:** Milk pressurizing before ultrafiltration in membrane
Number: Unit 100		
Team Members: Yirla Morehead, Stefka Ormsby, Kathryn Cook, Dena Moline		

No. 12	**Description: P-101A/B External Gear Pump**				
Item	**What if...?**	**Root Causes/Related Questions**	**Responses**	**Safeguards**	**Action Items**
12.1	What if there is pump malfunctioning and the pressure is too low for MB-101?	Supplier error Pump- internal corrosion Pump malfunctioning	Poor separation of UF milk and filtrate UF milk contains less than 20% milk solids nonfat, which would diminish product quality UF milk with high content of lactose Fermentation failure due to lack of lactose Product loss and production delay	Daily inspection Install pressure gauges Flow meters to check ratio of filtrate to retentate	Switch to backup pump in case of malfunction and replace or repair broken pump
12.2	What if the milk pressure is too high?	Pump malfunctioning Operator error	Pipe eruption Membrane failure and milk spill If pressure is too high, but not high enough to cause failures, the UF milk will have the wrong composition	Pressure regulator Install pressure relief system Automatic shut-off control to stop flow from SL-101	Shut off pump and switch to backup if malfunctioning Reduce pump speed if operator is at fault

4.0 Environmental Impact Statement

Yogurina frozen yogurt performed a gate to gate life cycle assessment (LCA) to identify potential environmental impacts arising from production, material use, and disposal associated with frozen yogurt manufacturing. The results of this study are based on the plant's delivery of 20.4 million lb/yr of frozen yogurt to market. The overall study was broken down into different sections to evaluate environmental performance: contributions by impact category, regulations, impact from utilities, and process improvements to reduce environmental burdens.

Impact Categories

In the first part of the analysis, the following environmental impact categories were used to estimate the percentage contribution from raw materials, cooling fluids, and on-site chemicals (cleaning agents).

- Human toxicity
- Ecotoxicity
- Depletion of non-renewable resources
- Ozone layer depletion
- Global warming potential

In order to determine human toxicity from each material, material safety data sheets were used (ScienceLab.com, 2005). Ecotoxicity data (terrestrial and aquatic) was not found for any of the raw materials or steam using both the Environmental Protection Agency website and online search engines. Ecotoxicity data on the impacts to aquatic life was found for ammonia, sulfuric acid, and sodium hydroxide. The latter chemicals have highly toxic effects in aquatic organisms (ScienceLab.com, 2005). The brine solution was considered to be benign to aquatic life (Nova Chemicals, 2007).

The remaining categories were found to have a favorable outlook on the environment. The global warming potentials were determined to be low or nonexistent for all the chemicals based on the EPA inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006 (EPA, 2008). The processing materials were considered to be non-ozone depleting since no emissions were recorded on the EPA Global Anthropogenic non-CO_2 Greenhouse Emissions: 1990-2020 (EPA, 2006). Lastly, all materials are renewable because they are either produced from livestock, or industrial chemical reactions. A summary of all environmental burdens by category is shown in Table 4.0.1.

Table 4.0.1: Summary of environmental burdens by category from raw materials, cooling fluids and on-site chemicals during one year of operation.

	Quantity used annually (lb)	Human Toxicity	Ecotoxicity	Depletion of non-renewables	Ozone layer depletion	Global warming potential
Raw Materials						
Inulin	484,266	Low	No	No	No	No
Freeze dried culture	0.30	No	No	No	No	No
Milk	61,636,926	No	No	No	No	No
Heavy cream	1,013,580	Low	No	No	No	No
Vanilla	388,539	Low	No	No	No	No
Mono- & Diglycerides	39,417	Low	No	No	No	No
Cane Sugar	2,325,603	Low	No	No	No	No
Carrageenan	56,310	Low	No	No	No	No
Corn Syrup Solids	528,751	Low	No	No	No	No
Cooling Fluids						
Ammonia	2,250*	High	Slight	No	No	No
Brine	5,313*	Low	No	No	No	No
Steam	528,751	No	No	No	No	No
**On-site chemicals						
Sulfuric acid	177,843	High	High	No	No	No
Sodium hydroxide	150,022	High	High	No	No	No

* Close loop, one-time inputs

** Storage period for on-site chemicals is three weeks; raw materials is one week.

Regulations

The EPA's consolidated list of chemicals subject to the Emergency Planning and Community Right to Know Act (EPCRA) and section 112 (r) of the Clean Air Act was used to determine the rules and regulations pertaining to frozen yogurt manufacturing (EPA, 2001). For the most part, the raw materials consist of solid chemicals except for milk, heavy cream, and vanilla. The threshold planning quantity (TPQ) for solids is 10,000 pounds. Most of the raw materials are stored for one week. Milk and heavy cream arrive daily, so they are stored for one day or less. The storage amount is under the TPQ, except for cane sugar which is not regulated at all. Therefore, these substances are not subject to state or local reporting. The remaining chemicals, with the exception of brine and steam, fall under the extremely hazardous category and are thus regulated.

Ammonia, sodium hydroxide, and sulfuric acid are considered extremely hazardous substances (EHS) under the EPCRA sections 302 and 304, and the Comprehensive Environmental Response Compensation and Liability Act of 1980 (CERCLA) (EPA, 2001). Since these substances will be present on-site in amounts above the TPQ, the following actions must be taken:

1) Obtain an emergency response plan from the Local Emergency Planning Committee (LEPC)
2) Notify the State Emergency Response Commission (SERC) of the presence of such substances
3) Provide a list of material safety data sheets or a list of the chemicals to the SERC, LEPC and the local fire department.

Table 4.0.2 shows a summary of the chemicals that are regulated with the corresponding TPQ values and release reportable quantities (RQ) in pounds.

Table 4.0.2: Regulated chemicals under the EPCRA and CERCLA (EPA, 2001)

Hazardous Substance	Registry Number	EPCRA Section 302 TPQ	EPCRA Section 304 RQ	CERCLA RQ	Yogurina storage amount, 3-week period
Ammonia	1310-73-2	500	100	100	
Sulfuric acid	7664-93-9	1000	1000	1000	6400
Sodium hydroxide	7664-41-7			1000	6400

Impact from utilities

The major environmental burden for this facility results from electricity usage during manufacturing. The primary energy source in the state of Pennsylvania is coal (Energy Information Administration, 2006). Based on statistics from the Energy Information Administration, 2006, the following emissions to air in Table 4.0.3 were calculated for a facility with similar electricity requirements of 3 million kWh:

Table 4.0.3: Greenhouse gas emissions from electricity requirements

Emissions	Unit	Value
Sulfur Dioxide	lb	25,368
Carbon Dioxide	lb	3,784,257
Nitrogen Oxide	lb	5,372

Using the US average, per capita electricity use in 2001 (13,000 kWh), it is estimated that the electricity use from this facility is equivalent to the electricity use of 230 citizens (California Energy Commission, 2005). During process design, the required electricity was minimized by recycling energy, reducing materials used, and making use of pre-insulated pipes.

The total average water consumption for the facility is 500,000 gal per year. This value is equivalent to the average water consumption of 12 citizens living in Arizona in 2004 (Tucson Water, 2008).

Process improvements to reduce environmental burdens

In recognizing the importance of protecting the environment, several actions were implemented into the overall process to reduce material use, utilities (electricity), and waste products. The modifications are listed below:

- Membrane filtrate (4°C) is used to cool down ammonia at 58.3 °C down to 35 °C in E-303, reducing the amount of cooling water needed.
- The membrane concentration ratio was increased making the filtrate suitable for culture growth in terms of lactose content and eliminating the use of non fat dry milk (NFDM).
- The pasteurization of ultrafiltered milk (for making yogurt) uses hot ammonia at 154.6 °C instead of steam, reducing utilities.
- Cooling water is also used to cool off ammonia and pasteurized filtrate (for culture growth) before sending it to a cooling tower to save energy and materials used.
- A cooling tower was incorporated into the process to reduce water use and avoid sending hot water back into the environment.
- Brine, ammonia, and cooling water are recycled throughout the heat exchanger network
- Frequency converters are incorporated to control the speed of pumps and thus reduce consumption of electrical power.
- Tanks and pipes are designed to be insulated to reduce heat losses.
- Warm milk reused in pasteurizer to warm incoming milk
- Any filtrate waste sold (for minimal price) to a pig farm as pig feed, instead of going to waste.
- Brine was used in place of another non-environmentally friendly refrigerant to minimize environmental impact

Figure 4.1 summarizes the overall environmental impact statement.

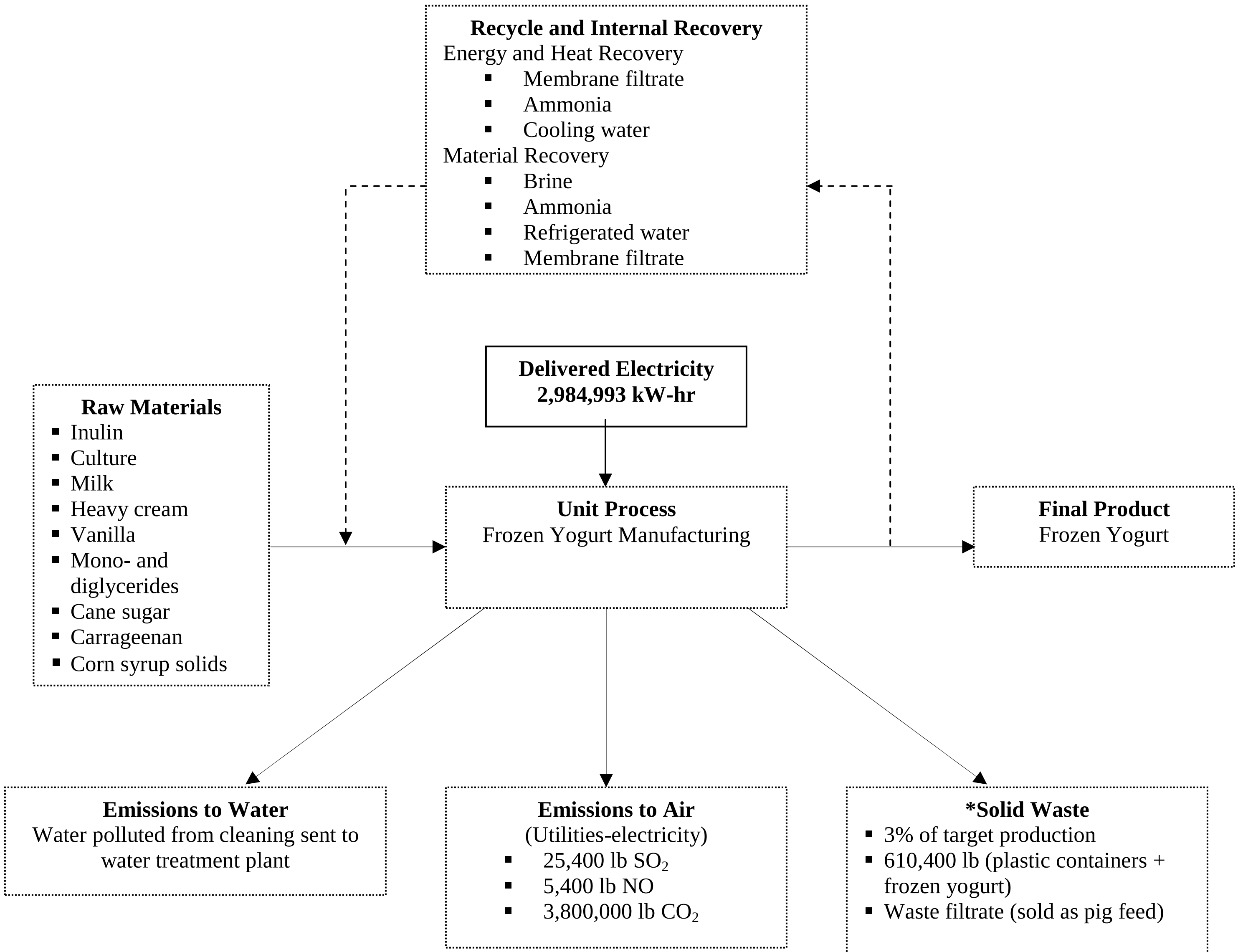

Fig. 4.1: Frozen yogurt environmental impact for a delivery of 20,344,803 lb/yr to market

* Solid waste amount typical of an average frozen yogurt/ice cream manufacturing facility (Knight, 2008)

5.0 Economics

5.1 Economic Analysis

The theoretical selling price of the frozen yogurt at $4.00 per container was determined from market research, as described in the introduction. A profitability analysis of the selling price of $4.00 per container of frozen yogurt was completed (Table C.5). Income from selling the frozen yogurt at $4.00 per container amounts to $29.7 million per year, while operating costs are $22.6 million per year as summarized in Table 5.1.1. At a 20% rate of return, the payback period is 2.82 years. With a 15 year MACRS depreciation schedule, the net present value (NPV) after thirty years is $9.91 million and the investor's rate of return is 34.4%. A summary of this information is shown in Table C.6.

The net present value was determined by utilizing the calculated bare equipment cost, annual production costs, and total capital investment. The overall bare module cost for all equipment is $7.87 million (Table C.1), and the total capital investment (TCI) comes to $22.99 million (Table C.2). The total feedstocks cost totals $12.28 million. For utilities including electricity, cooling water, brine, sulfuric acid, sodium hydroxide, liquid water disposal, process water, compressed air and steam, the costs sum to $170,317. The annual cost for milk, the main raw material, is $6.9 million, as shown in Table 2.6.1. The total cost for raw materials totals $12.11 million. Electricity usage (Table 5.1.2) is the electricity required by the pump, compressor, filler, blowers, scraped surface heat exchanger, mixers, and homogenizers. The total electricity usage is 3 million kWh per year for the entire process. In addition to utility and material costs, the annual cost of production, which totaled $22.6 million (Table C.4), includes the cost of maintenance, operations, employee wages, and benefits.

Table 5.1.1: Summary of annual sales

Product	Production Rate	Selling Price	Annual Sales
Frozen Yogurt	7,428,571 containers/year	$4.00/container	**$29,714,286**
	Total Annual Sales		**$29,714,286**

Table 5.1.2: Energy requirements breakdown by equipment

Equipment	Electricity Consumption (kW)	Equipment	Electricity Consumption (kW)
P-101	1.3	M-101	1.0×10^{-1}
P-102	6.8×10^{-3}	M-201	9.0×10^{-2}
P-103	4.0×10^{-4}	M-301	9.0×10^{-2}
P-104	2.0×10^{-3}	R-502	5.6×10^{-3}
P-201	8.0×10^{-3}	R-503	9.0×10^{-2}
P-202	7.0×10^{-3}	R-501	negligible
P-301	2.0×10^{-2}	B-401	10.0
P-401	2.0×10^{-3}	B-402	24.8
P-402	4.0×10^{-2}	B-403	1.5
P-501	1.3×10^{-4}	B-301[b]	21.1
ES-301 to ES-308[a]	125.6	HG-101	74.6
*C-401	77.6	HG-201	74.6
*C-402	43.5	FL-301	1.2
*C-403	74.2		
		Total	**530.10**

* Compressors' electricity needs were taken from Aspen simulations with process-specific inputs. All others determined by hand calculations shown in Appendix C. These values are used for annual plant operating costs.
(a) From Anco-Eaglin Inc., 2008
(a) From American Cooling Tower, 2008

5.2 Economic Hazards

The profitability of this plant depends primarily on the economic hazards. In order to compete with other large frozen yogurt manufacturers, it is imperative to provide a superior product at a similar price to the consumer. Without high-quality advertising, consumers will not be persuaded from the reputation of a recognized vendor such as Dreyer's.

The demand for frozen yogurt will increase with time as the population grows and as the importance of healthy food products increases. Since market prices fluctuate, it is important to have enough financial backing to cover losses and maintain operation while consumption ebbs.

However, frozen yogurt is experiencing very strong growth and sales of dairy foods with probiotics are increasing 20% annually (Pszcola, 2008). As is the case with many food sales, frozen treats, such as frozen yogurt sales are influenced by the economy. Constant innovation in the frozen desserts sector is very important, both with improving current products to developing brand new products (PRWeb, 2008). Every company will experience weak economic periods, but with appropriate risk management, companies are able to recover. When sales are strong, it is important to put away money in preparation for the inevitable downfall. The market will grow in the long run and business ventures will profit if they invest wisely.

The largest financial risk to this plant is the fact that operating costs are quite large, if these costs rise 32% or more, the annual sales will only equal the annual operating costs. If the plant were to produce more frozen yogurt, it is likely that sales would increase moderately faster than the operating and capital costs. The raw materials are by far the largest part of the annual operating cost. Future work to lower the cost of these materials would be beneficial to Yogurina's production.

A sensitivity analysis was performed on the process to determine which factors would affect the process the most if they were to change. The results are shown in Table 5.2.1 and the calculations can be found in Appendix C. The most important factors to Yogurina's profitability include the cost of milk and the annual sales. If the annual sales were to decrease by 25% the NPV after 30 years would be reduced by 208%. If the cost of milk were to double the NPV would decrease by 220% and the TCI would increase by 5%. Thus by Yogurina selling the frozen yogurt at a relatively low price, this allows the selling price to increase as the price of milk increases or if annual sales were to decrease.

Table 5.2.1: Sensitivity analysis summary

Changing Cost	**Change in TCI**	**Change in 30 Year NPV**
Equipment costs increased by 25%	18.6%	-53.7%
Feedstocks cost increased by 25%	2.2%	-97.1%
Production costs increased by 25%	0.0%	-179.0%
Annual sales decreased by 25%	-3.3%	-208.0%
Price of milk doubles	5.0%	-220.0%
Price of vanilla doubles	1.6%	-70.5%
Cost of electricity increases by 25%	2.9×10^{-4}%	-1.3%

In summary, it is possible for the plant to be profitable with a selling price of $4.00 per container. Therefore, Yogurina recommends the construction of this plant to produce frozen yogurt. From the sensitivity analysis, it is clear that decreasing sales and doubling the cost of milk are the factors that most dramatically affect the NPV after thirty years. Another factor to consider is the production costs for the process. If the costs were to increase significantly, it would affect the NPV dramatically as well.

6.0 Conclusions and Recommendations

After creating and evaluating this design, Yogurina concludes that this process to produce hard-packed frozen yogurt is economically feasible and recommends that further work to produce this plant go forward. With a projected investor's rate of return of 34.4% and a net present value of $9.9 million after 30 years, the plant is expected to be profitable. The selling price to achieve this profit is $4 per 1.75 qt container and is based on current commodity prices. As with all commodities, however, the price of milk and the other ingredients fluctuates, and, if needed, the selling price can be adjusted to maintain such profits.

Given the large number of unit operations involved in making Yogurina frozen yogurt, there are several areas that room for future work and improvement. The most important recommendation is to test making this product in a pilot plant. While Yogurina believes it has developed a delicious frozen yogurt with a superior flavor and texture, pilot plant testing would ensure that the frozen yogurt does, in fact, taste great and meet Yogurina's quality standards. Based on the results of these test runs, or even of bench-top tests, the recipe for the product can be adjusted where needed. Pilot plant testing would also expose physical problems in making the frozen yogurt. For example, as mentioned in the process rationale, section 2.8, the product is intended to become viscous due to the inulin, carrageenan, and fermentation. For laminar flow, viscosity is directly proportional to the power required to pump a fluid, so any sharp increases in viscosity—such as can happen during fermentation—will result in a proportionally sharp increase in pump power (McCabe and Smith, 2004). In this case the ingredients or fermentation end points could be adjusted to lower viscosity or more powerful pumps could be required.

This design produces vanilla-flavored frozen yogurt specifically. However, consumers as a whole buy many flavors, so others should be developed and produced, too. Yogurina suggests flavors such as strawberry shortcake, chocolate chip cookie dough, and mint chocolate brownie.

The focus of this report is manufacturing the frozen yogurt and providing refrigeration for the process. Sanitation, via cleaning in place, is an important process in ensuring a safe product, however. Basic ideas for sanitation are mentioned in this report, but further research into a CIP process should be done in order to better quantify the process. Also, steam for pasteurization is currently obtained from an off-site source. The process would be less dependent on others if a boiler were added to make the steam on-site.

As mentioned in the process rationale, there are a few areas for improvement related to the culture. Further research can be done into keeping a maximal number of probiotic bacteria alive by the time the frozen yogurt reaches the consumer's intestines. Processing improvements, such as micro-encapsulation of bacteria or two-step fermentation, have the potential to keep the probiotics alive long enough to yield the intended health benefits. Also, obtaining stress-adapted and acid-resistant culture strains from the supplier can help the bacteria survive processing and passage through the consumer's gut respectively (Shah, 2000). Also, if the culture strains do not grow well when cultured together, they may need to be grown separately in the mother culture through bulk culture stages or the equipment could be redesigned to optimize bacteria growth based on experiment.

Other areas for improvement include reducing the amount of filtrate produced, finding a more profitable use for the waste filtrate, increasing the efficiency of the pasteurizers, and further optimizing the scraped-surface freezers. It may also be beneficial to do future research around plant profitability and product quality with less or no ultrafiltration. Reducing the amount of waste filtrate produced would then reduce the amount of milk needed as a raw material and should therefore increase the plant's profitability. Any improvement to reduce costs while keeping a quality product would be beneficial.

The plant, with its many recycle streams, is already designed with the environment in mind. An entirely self-sufficient plant in terms of energy would be ideal for environmental friendliness. More practically, maximizing energy recycle and minimizing wasted energy would not only benefit the environment, but would also save the plant money. In conclusion, Yogurina has developed an economically feasible design for producing hard-packed frozen yogurt and recommends that the plant be built.

Appendix A – Overall Mass and Energy Balances

Tables A.1 and A.2 tabulate the inlet and outlet mass flow rates for the ingredient streams.

Table A.1: Mass balance on ingredients entering plant

Component	Flow rate (lb/hr)
Skim milk	10,946
Cream (38% fat)	180
Mono- and diglycerides	7
Carrageenan	10
Cane sugar	413
Water	234
Inulin	86
Corn syrup solids	103
Vanilla	69
Air	2
Dried culture	8.6×10^{-4}
Total	12,050

Table A.2: Mass balance on ingredients leaving plant

Component	Flow rate (lb/hr)
Filtrate	8,437
Frozen yogurt	3,613
Total	12,050

The following pages detail the calculations for the flow rates in each stream and the calculations for the density of the ingredient and product streams. Also included is a calculation of how much lactose and calcium is expected to be in the finished product.

Table A.3 presents the overall energy balance on the plant. It shows that the amount of energy lost from the product and waste (the frozen yogurt and the waste filtrate) is equal to the rate of energy gain in the utilities. Table A.4 through A.10 present the energy balances on the various components. The components that circulate in a closed loop (ammonia, water, and brine) balance out to a net energy consumption of 0 kW, or nearly 0 kW in the case of brine.

Table A.3: Overall energy balance

Product	Heat duty (kW)	Energy source	Heat duty (kW)
Frozen yogurt and filtrate	-88.7	Steam	-26.6
		Ammonia	0.0
		Air	310.1
		Electricity	-195.34
		Water	0.0
		Brine	0.5
Total	-88.7	Total	88.7

Table A.4: Energy input and output on frozen yogurt product and by-products

Equipment #	Heat Duty (kW)	Description
E-101	30.6	UF milk regenerator
E-102	36.1	UF milk heater (with NH_3)
E-101	-30.6	UF milk regenerator
E-103	-8.6	UF milk water cooler
E-205	-16.2	yogurt water cooler
E-206	-13.8	yogurt brine cooler
E-201	55.6	ice cream mix regenerator
E-202	23.9	ice cream mix heater (steam)
E-201	-55.6	ice cream mix regenerator
E-203	-7.2	ice cream mix water cooler
E-204	-17.8	ice cream mix brine cooler
ES-301-308	-192.8	initial freezing, with NH_3
HT-301	-34.4	hardening, with NH_3
SF-301	-5.5	storage, with NH_3
E-303	147.7	filtrate cooling NH_3
E-501	2.7	heating filtrate with steam, +154.2 MJ (batch)
E-502	-2.7	cooling filtrate with water, -153.9 MJ (batch)
	-48.9	to NH_3
	-31.6	to brine
	-34.7	to water
	26.6	from steam
Total	-88.7	

Table A.5: Energy balance on steam

Equipment #	Heat Duty (kW)	Description
E-202	-23.9	to ice cream mix
E-501	-2.7	to filtrate, -154.2 MJ (batch)
Total	-26.6	

Table A.6: Energy balance on ammonia

Equipment #	Heat Duty (kW)	Description
E-102	-36.1	UF milk heater
E-303	-147.7	cooled by filtrate
E-301	-11.0	cooled by air
E-302	63.1	cools brine
ES-301-308	192.8	freezes frozen yogurt
HT-301	34.4	hardens product
SF-301	5.5	storage for product
E-401	-208.9	cooled by water
E-402	-46.9	cooled by air
E-403	-40.6	cooled by air
C-401	77.6	compresses NH_3 to 4 bar (using electricity)
C-402	43.5	compresses NH_3 to 8 bar (using electricity)
C-403	74.2	compresses NH_3 to 25 bar (using electricity)
	48.9	from product
	-98.5	to air
	195.3	from electricity
	-208.9	to water
	63.1	to brine
Total	0.0	

Table A.7: Energy balance on air

Equipment #	Heat Duty (kW)	Description
E-301	11.0	cools NH_3 at 25 bar
E-402	46.9	cools NH_3 at 8 bar
E-403	40.6	cools NH_3 at 4 bar
CT-401	211.6	cools water via evaporation
	98.5	from NH_3
	211.6	from water
Total	310.1	

Table A.8: Energy balance on brine

Equipment #	Heat Duty (kW)	Description
E-104	8.6	cools water
E-204	17.8	ice cream mix brine cooler
E-206	13.8	yogurt brine cooler
E-207	16.2	cools water
E-208	7.2	cools water
E-302	-63.1	cooled by NH_3
	32.0	from water
	31.6	from product
	-63.1	to NH_3
Total	0.5*	

*The energy balance on brine does not sum to 0 kW due to rounding errors.

Table A.9: Energy balance on water

Equipment #	Heat Duty (kW)	Description
E-103	8.6	UF milk water cooler
E-104	-8.6	cooled by brine
E-203	7.2	ice cream mix water cooler
E-208	-7.2	cooled by brine
E-205	16.2	yogurt cooler
E-207	-16.2	cooled by brine
E-401	208.9	cools NH_3
CT-401	-211.6	evaporation cools water
E-502	2.7	cools filtrate, +153.9 MJ (batch)
	34.7	from product
	-32	to brine
	208.9	from NH_3
	-211.6	to air
Total	0.0	

Table A.10: Energy balance on electricity

Equipment #	Heat Duty (kW)	Description
C-401	-77.63	to NH_3
C-402	-43.52	to NH_3
C-403	-74.19	to NH_3
Total	-195.34	

Appendix B – Process Calculations

This appendix presents the detailed calculations used around each piece of equipment. The unit operations are organized as follows:

- Ultrafiltration membrane, MB-101
- Ice cream mix pasteurization, E-201 – E-204
- Ultrafiltered milk pasteurization for making yogurt, E-101 – E-103
- Yogurt cooling, E-205 – E-206
- Summary of pasteurizers and yogurt cooling
- Brine cooling, E-104, E-207, E-208, and E-302
- Initial frozen yogurt freezing, ES-301 – ES-308
- Hardening tunnel, HT-301
- Storage freezer, SF-301
- Ammonia refrigeration loop with Aspen diagram and stream table, V-301, V-302, ES-301-308, HT-301, SF-301, C-401 – C-403, E-102, E-301 – E-303, and E-401 – E-403
- Cooling tower, CT-401
- Bulk culture and fermentation, R-101 and R-501 – R-503
- Filtrate pasteurization for growing bulk culture, E-501 and E-502

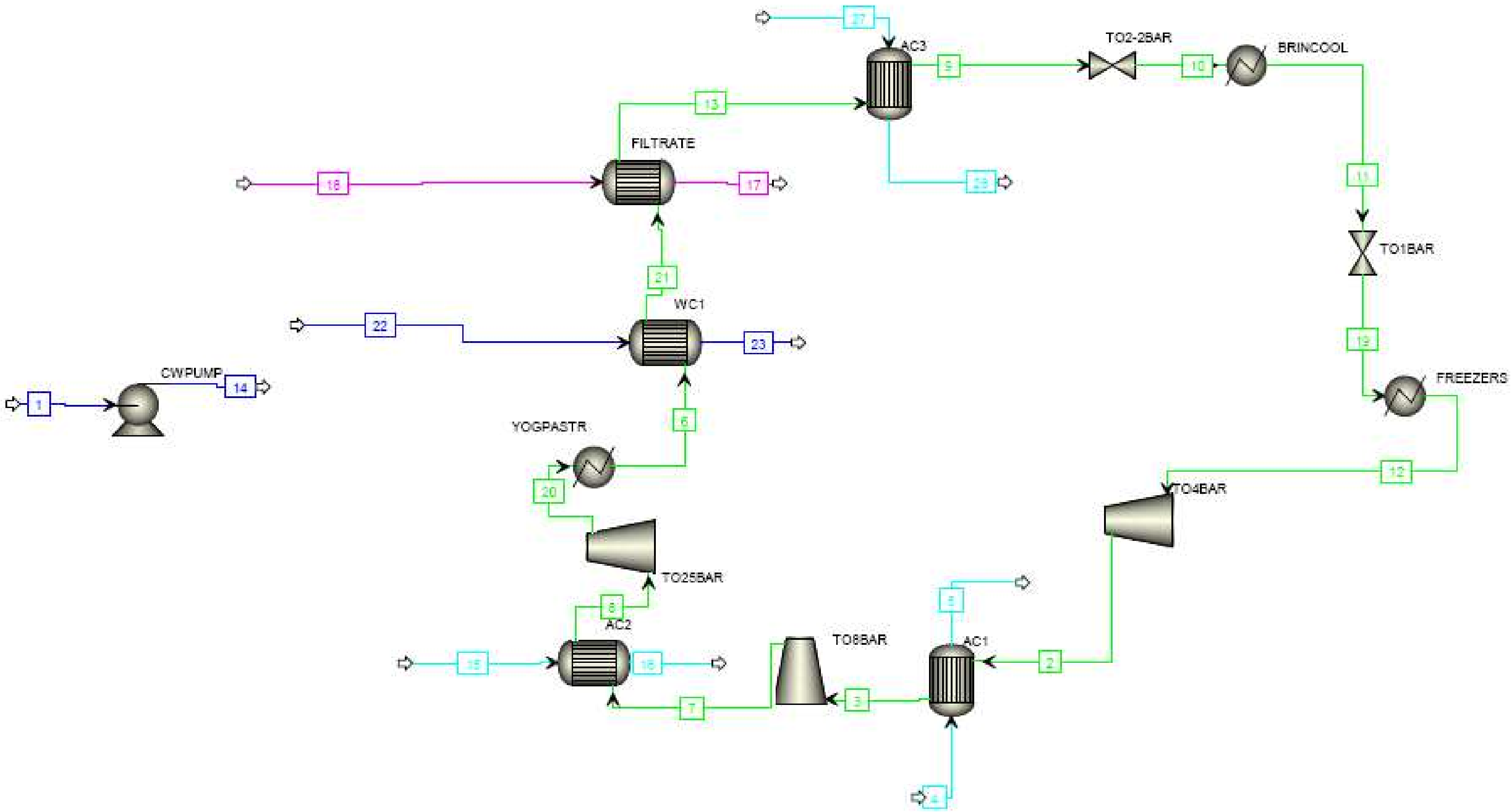

Fig. B.12: Aspen screen shot of ammonia refrigeration loop modeled in Aspen, the stream numbers do not match up to those on the stream table; the cold water pump on the left hand side is P-401

Table B.1: Stream table corresponding to Aspen diagram in Fig. B.12, English units, streams 1-13

Stream ID		1	2	3	4	5	6	7	8	9	10	11	12	13
From			TO4BAR	AC1		AC1	YOGPASTR	TO8BAR	AC2	AC3	TO2-2BAR	BRINCOOL	FREEZERS	FILTRATE
To		CWPUMP	AC1	TO8BAR	AC1		WC1	AC2	TO25BAR	TO2-2BAR	BRINCOOL	TO1BAR	TO4BAR	AC3
Phase		LIQUID	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	LIQUID	MIXED	MIXED	MIXED	LIQUID
Substream:		MIXED												
Mole Flow	lbmol/hr													
WATER		777.6732	0	0	0	0	0	0	0	0	0	0	0	0
AMMON-01		0	132.1154	132.1154	0	0	132.1154	132.1154	132.1154	132.1154	132.1154	132.1154	132.1154	132.1154
AIR		0	0	0	587.0166	587.0166	0	0	0	0	0	0	0	0
Total Flow	lbmol/hr	777.6732	132.1154	132.1154	587.0166	587.0166	132.1154	132.1154	132.1154	132.1154	132.1154	132.1154	132.1154	132.1154
Total Flow	lb/hr	14010	2250	2250	17000	17000	2250	2250	2250	2250	2250	2250	2250	2250
Total Flow	cuft/hr	226.988	15496.67	12870.48	2.08E+05	2.20E+05	2341.267	7931.596	6237.181	60.37037	3580.771	6952.966	41232.06	61.50585
Temperature	F	86.00001	185.6649	82.40001	68.00001	97.89349	209.189	210.5915	82.40001	82.40001	1.995654	1.995654	-28.59532	95.00001
Pressure	psi	14.50377	58.0151	58.0151	15.95415	15.95415	362.5944	116.0302	116.0302	362.5944	31.9083	31.9083	14.50377	362.5944
Vapor Frac		0	1	1	1	1	1	1	1	0	0.1766188	0.3455221	0.9913585	0
Liquid Frac		1	0	0	0	0	0	0	0	1	0.8233812	0.6544779	8.64E-03	1
Solid Frac		0	0	0	0	0	0	0	0	0	0	0	0	0
Enthalpy	Btu/lbmol	-1.23E+05	-18848.74	-19770.23	-65.60036	141.7931	-18973.34	-18681.09	-19858.48	-28368.32	-28368.32	-26737.6	-20727.15	-28084.7
Enthalpy	Btu/lb	-6809.363	-1106.76	-1160.868	-2.265206	4.896171	-1114.076	-1096.916	-1166.05	-1665.73	-1665.73	-1569.978	-1217.056	-1649.076
Enthalpy	Btu/hr	-9.54E+07	-2.49E+06	-2.61E+06	-38508.49	83234.9	-2.51E+06	-2.47E+06	-2.62E+06	-3.75E+06	-3.75E+06	-3.53E+06	-2.74E+06	-3.71E+06
Entropy	Btu/lbmol-R	-38.59221	-24.81547	-26.37067	-0.2853299	0.0969755	-28.46629	-25.9042	-27.85276	-44.164	-43.72865	-40.19637	-25.66965	-43.66472
Entropy	Btu/lb-R	-2.142193	-1.457114	-1.548432	-9.85E-03	3.35E-03	-1.671483	-1.521042	-1.635458	-2.593221	-2.567657	-2.360249	-1.50727	-2.563904
Density	lbmol/cuft	3.426055	8.53E-03	0.010265	2.82E-03	2.67E-03	0.056429	0.0166568	0.0211819	2.188416	0.0368958	0.0190013	3.20E-03	2.148015
Density	lb/cuft	61.72133	0.1451925	0.1748187	0.0816392	0.0772499	0.9610183	0.2836756	0.3607399	37.26994	0.6283564	0.3236029	0.0545691	36.58189
Average MW		18.01528	17.03056	17.03056	28.96	28.96	17.03056	17.03056	17.03056	17.03056	17.03056	17.03056	17.03056	17.03056
Liq Vol 60 F	cuft/hr	224.8512	113.3436	113.3436	309.5003	309.5003	113.3436	113.3436	113.3436	113.3436	113.3436	113.3436	113.3436	113.3436

Table B.2: Stream table corresponding to Aspen diagram in Fig. B.12, English units, streams 14-28

Stream ID		14	15	16	17	18	19	20	21	22	23	27	28
From		CWPUMP		AC2	FILTRATE		TO1BAR	TO25BAR	WC1		WC1		AC3
To			AC2			FILTRATE	FREEZERS	YOGPASTR	FILTRATE	WC1		AC3	
Phase		LIQUID	VAPOR	VAPOR	LIQUID	LIQUID	MIXED	VAPOR	MIXED	LIQUID	LIQUID	VAPOR	VAPOR
Mole Flow	lbmol/hr												
WATER		777.6732	0	0	473.931	473.931	0	0	0	721.6097	721.6097	0	0
AMMON-01		0	0	0	0	0	132.1154	132.1154	132.1154	0	0	0	0
AIR		0	690.6078	690.6078	0	0	0	0	0	0	0	276.2431	276.2431
Total Flow	lbmol/hr	777.6732	690.6078	690.6078	473.931	473.931	132.1154	132.1154	132.1154	721.6097	721.6097	276.2431	276.2431
Total Flow	lb/hr	14010	20000	20000	8538	8538	2250	2250	2250	13000	13000	8000	8000
Total Flow	cuft/hr	226.9891	2.45E+05	2.60E+05	139.5607	134.9387	16351.19	2764.362	772.8939	210.6241	217.5766	97992.08	1.02E+05
Temperature	F	86.00941	68.00001	100.4651	102.0906	39.20001	-28.59532	300.5836	136.9042	86.00001	143.6	68.00001	87.55287
Pressure	psi	15.95415	15.95415	15.95415	15.95415	15.95415	14.50377	362.5944	362.5944	15.95415	15.95415	15.95415	15.95415
Vapor Frac		0	1	1	0	0	0.3923714	1	0.3695253	0	0	1	1
Liquid Frac		1	0	0	1	1	0.6076286	0	0.6304747	1	1	0	0
Solid Frac		0	0	0	0	0	0	0	0	0	0	0	0
Enthalpy	Btu/lbmol	-1.23E+05	-65.60036	159.6379	-1.22E+05	-1.23E+05	-26737.6	-18040.98	-24368.54	-1.23E+05	-1.22E+05	-65.60036	70.0442
Enthalpy	Btu/lb	-6809.351	-2.265206	5.512358	-6794.34	-6851.843	-1569.978	-1059.33	-1430.871	-6809.359	-6754.529	-2.265206	2.418653
Enthalpy	Btu/hr	-9.54E+07	-45304.11	1.10E+05	-5.80E+07	-5.85E+07	-3.53E+06	-2.38E+06	-3.22E+06	-8.85E+07	-8.78E+07	-18121.64	19349.23
Entropy	Btu/lbmol-R	-38.59194	-0.2853299	0.1289069	-38.10505	-40.04456	-39.61274	-27.16068	-37.44	-38.59223	-36.87471	-0.2853299	-0.0329155
Entropy	Btu/lb-R	-2.142178	-9.85E-03	4.45E-03	-2.115152	-2.222811	-2.32598	-1.59482	-2.198401	-2.142194	-2.046858	-9.85E-03	-1.14E-03
Density	lbmol/cuft	3.426037	2.82E-03	2.66E-03	3.395878	3.512195	8.08E-03	0.0477923	0.1709361	3.426055	3.316577	2.82E-03	2.72E-03
Density	lb/cuft	61.72102	0.0816392	0.0768943	61.17769	63.27318	0.1376047	0.813931	2.911137	61.72133	59.74906	0.0816392	0.0787137
Average MW		18.01528	28.96	28.96	18.01528	18.01528	17.03056	17.03056	17.03056	18.01528	18.01528	28.96	28.96
Liq Vol 60 F	cuft/hr	224.8512	364.118	364.118	137.0292	137.0292	113.3436	113.3436	113.3436	208.6414	208.6414	145.6472	145.6472

Table B.3: Stream table corresponding to Aspen diagram in Fig. B.12, metric units, streams 1-13

Stream ID		1	2	3	4	5	6	7	8	9	10	11	12	13
From			TO4BAR	AC1		AC1	YOGPASTR	TO8BAR	AC2	AC3	TO2-2BAR	BRINCOOL	FREEZERS	FILTRATE
To		CWPUMP	AC1	TO8BAR	AC1		WC1	AC2	TO25BAR	TO2-2BAR	BRINCOOL	TO1BAR	TO4BAR	AC3
Phase		LIQUID	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	LIQUID	MIXED	MIXED	MIXED	LIQUID
Substream:		MIXED												
Mole Flow	kmol/hr													
WATER		352.7466	0	0	0	0	0	0	0	0	0	0	0	0
AMMON-01		0	59.92656	59.92656	0	0	59.92656	59.92656	59.92656	59.92656	59.92656	59.92656	59.92656	59.92656
AIR		0	0	0	266.2662	266.2662	0	0	0	0	0	0	0	0
Total Flow	kmol/hr	352.7466	59.92656	59.92656	266.2662	266.2662	59.92656	59.92656	59.92656	59.92656	59.92656	59.92656	59.92656	59.92656
Total Flow	kg/hr	6354.829	1020.583	1020.583	7711.07	7711.07	1020.583	1020.583	1020.583	1020.583	1020.583	1020.583	1020.583	1020.583
Total Flow	l/min	107.1264	7313.614	6074.188	98275.11	1.04E+05	1104.955	3743.296	2943.621	28.49164	1689.936	3281.435	19459.37	29.02753
Temperature	K	303.15	358.5194	301.15	293.15	309.7575	371.5884	372.3675	301.15	301.15	256.4809	256.4809	239.4859	308.15
Pressure	atm	0.9869233	3.947693	3.947693	1.085616	1.085616	24.67308	7.895387	7.895387	24.67308	2.171231	2.171231	0.9869233	24.67308
Vapor Frac		0	1	1	1	1	1	1	1	0	0.1766188	0.3455221	0.9913585	0
Liquid Frac		1	0	0	0	0	0	0	0	1	0.8233812	0.6544779	8.64E-03	1
Solid Frac		0	0	0	0	0	0	0	0	0	0	0	0	0
Enthalpy	cal/mol	-68151.44	-10471.52	-10983.46	-36.44464	78.77395	-10540.74	-10378.38	-11032.49	-15760.18	-15760.18	-14854.22	-11515.08	-15602.61
Enthalpy	cal/gm	-3782.98	-614.8666	-644.9267	-1.258448	2.720095	-618.9311	-609.3976	-647.8053	-925.4057	-925.4057	-872.21	-676.1424	-916.1536
Enthalpy	cal/sec	-6.68E+06	-1.74E+05	-1.83E+05	-2695.549	5826.345	-1.75E+05	-1.73E+05	-1.84E+05	-2.62E+05	-2.62E+05	-2.47E+05	-1.92E+05	-2.60E+05
Entropy	cal/mol-K	-38.59221	-24.81547	-26.37067	- 0.2853299	0.0969755	-28.46629	-25.9042	-27.85276	-44.164	-43.72865	-40.19637	-25.66965	-43.66472
Entropy	cal/gm-K	-2.142193	-1.457114	-1.548432	-9.85E-03	3.35E-03	-1.671483	-1.521042	-1.635458	-2.593221	-2.567657	-2.360249	-1.50727	-2.563904
Density	mol/cc	0.0548801	1.37E-04	1.64E-04	4.52E-05	4.27E-05	9.04E-04	2.67E-04	3.39E-04	0.035055	5.91E-04	3.04E-04	5.13E-05	0.0344078
Density	gm/cc	0.9886809	2.33E-03	2.80E-03	1.31E-03	1.24E-03	0.015394	4.54E-03	5.78E-03	0.5970072	0.0100653	5.18E-03	8.74E-04	0.5859857
Average MW		18.01528	17.03056	17.03056	28.96	28.96	17.03056	17.03056	17.03056	17.03056	17.03056	17.03056	17.03056	17.03056
Liq Vol 60F	l/min	106.1179	53.49224	53.49224	146.0679	146.0679	53.49224	53.49224	53.49224	53.49224	53.49224	53.49224	53.49224	53.49224

Table B.4: Stream table corresponding to Aspen diagram in Fig. B.12, metric units, streams 14-28

Stream ID		14	15	16	17	18	19	20	21	22	23	27	28
From		CWPUMP		AC2	FILTRATE		TO1BAR	TO25BAR	WC1		WC1		AC3
To			AC2			FILTRATE	FREEZERS	YOGPASTR	FILTRATE	WC1		AC3	
Phase		LIQUID	VAPOR	VAPOR	LIQUID	LIQUID	MIXED	VAPOR	MIXED	LIQUID	LIQUID	VAPOR	VAPOR
Substream:													
Mole Flow	kmol/hr												
WATER		352.7466	0	0	214.9715	214.9715	0	0	0	327.3166	327.3166	0	0
AMMON-01		0	0	0	0	0	59.92656	59.92656	59.92656	0	0	0	0
AIR		0	313.2544	313.2544	0	0	0	0	0	0	0	125.3018	125.3018
Total Flow	kmol/hr	352.7466	313.2544	313.2544	214.9715	214.9715	59.92656	59.92656	59.92656	327.3166	327.3166	125.3018	125.3018
Total Flow	kg/hr	6354.829	9071.848	9071.848	3872.772	3872.772	1020.583	1020.583	1020.583	5896.701	5896.701	3628.739	3628.739
Total Flow	l/min	107.1269	1.16E+05	1.23E+05	65.86531	63.68397	7716.901	1304.634	364.7653	99.40351	102.6847	46247.11	47965.97
Temperature	K	303.1552	293.15	311.1862	312.0892	277.15	239.4859	422.3631	331.4301	303.15	335.15	293.15	304.0127
Pressure	atm	1.085616	1.085616	1.085616	1.085616	1.085616	0.9869233	24.67308	24.67308	1.085616	1.085616	1.085616	1.085616
Vapor Frac		0	1	1	0	0	0.3923714	1	0.3695253	0	0	1	1
Liquid Frac		1	0	0	1	1	0.6076286	0	0.6304747	1	1	0	0
Solid Frac		0	0	0	0	0	0	0	0	0	0	0	0
Enthalpy	cal/mol	-68151.32	-36.44464	88.68771	-68001.08	-68576.6	-14854.22	-10022.77	-13538.08	-68151.4	-67602.64	-36.44464	38.91345
Enthalpy	cal/gm	-3782.973	-1.258448	3.062421	-3774.633	-3806.58	-872.21	-588.5167	-794.9285	-3782.978	-3752.517	-1.258448	1.343696
Enthalpy	cal/sec	-6.68E+06	-3171.234	7717.171	-4.06E+06	-4.10E+06	-2.47E+05	-1.67E+05	-2.25E+05	-6.20E+06	-6.15E+06	-1268.494	1354.423
Entropy	cal/mol-K	-38.59194	-0.2853299	0.1289069	-38.10505	-40.04456	-39.61274	-27.16068	-37.44	-38.59223	-36.87471	-0.2853299	-0.0329155
Entropy	cal/gm-K	-2.142178	-9.85E-03	4.45E-03	-2.115152	-2.222811	-2.32598	-1.59482	-2.198401	-2.142194	-2.046858	-9.85E-03	-1.14E-03
Density	mol/cc	0.0548798	4.52E-05	4.25E-05	0.0543967	0.0562599	1.29E-04	7.66E-04	2.74E-03	0.0548801	0.0531264	4.52E-05	4.35E-05
Density	gm/cc	0.9886759	1.31E-03	1.23E-03	0.9799726	1.013539	2.20E-03	0.0130379	0.0466319	0.9886809	0.9570882	1.31E-03	1.26E-03
Average MW		18.01528	28.96	28.96	18.01528	18.01528	17.03056	17.03056	17.03056	18.01528	18.01528	28.96	28.96
Liq Vol 60F	l/min	106.1179	171.8446	171.8446	64.67059	64.67059	53.49224	53.49224	53.49224	98.46775	98.46775	68.73783	68.73783

Appendix C – Economic Calculations

The purchase costs for compressors (Table C.1) were calculated with equation 16.35 (Seider, et al., 2005)

$$C_p = F_D F_M C_B$$

and the base cost equation for centrifugal compressor equation 16.36 (Seider, et al., 2005).

$$C_B = \exp\{7.2223 + 0.80[\ln(P_C)]\}$$

where P_C is power consumption in horsepower which was calculated in Aspen, F_D is the driver factor, and F_M is the material factor. Since the compressors are driven by steam turbine motors in this design the driver factor is 1.15. The material factor is determined from Table 16.21 in Seider, et al. (2005). The material factor for stainless steel is 2.0.

For heat exchangers the f.o.b. purchase cost (Table C.1) and base costs depend on the heater type used. In this design, five types of heat exchangers, shell and tube fixed head, double pipe, scraped surface, plate and frame, and air cooled fin fan are used. The base cost equations and purchase costs, respectively, for shell and tube fixed head and double pipe are 16.40, 16.43, 16.46, and 16.47 (Seider, et al., 2005).

$$\mathrm{C_B} = \exp\{11.0545 - 0.9228\ln[\mathrm{A}] + 0.09861(\ln[\mathrm{A}])^2\}$$

$$C_P = F_P F_M F_L C_B$$

$$\mathrm{C_B} = \exp\{7.1248 + 0.16\ln[\mathrm{A}]\}$$

$$C_P = F_P F_M C_B$$

where A is the area of the heat exchanger in square feet, and the type of heat exchanger selected is based on this area. F_L is the tube length correction and was considered to be 1.00, where the tube length is 20 feet. The pressure factor was also considered to be 1.0 as many of the pressures in the process are atmospheric pressure. Material factors from equation 16.44 and Table 16.25

for fixed head heat exchangers also from Seider, et al. (2005). Stainless steel was chosen for the material to determine a and b.

$$F_M = a + \left(\frac{A}{100}\right)^b$$

Air cooled fin fan heat exchangers, plate and frame heat exchangers, and scraped surface heat exchangers were all costed using Table 16.32 of Seider, et al. (2005)

$$\mathrm{C_B} = 1{,}970[\mathrm{A}]^{0.4}$$

$$\mathrm{C_B} = 7{,}000[\mathrm{A}]^{0.42}$$

$$\mathrm{C_B} = 11{,}400[\mathrm{L}]^{0.67}$$

where L is assumed to be 10 feet for the scraped surface heat exchangers.

External gear pumps purchase cost (Table C.1) calculated from equations 16.15 and 16.20 for pump and its motor,

$$\mathrm{C_P} = \mathrm{F}_M C_B$$

$$C_p = F_T C_B$$

for the pump the size factor was calculated from 16.13,

$$S = Q(H)^{0.5}$$

cost base equation for the motor from 16.19,

$$C_B = \exp\{5.4866 + 0.13141[\ln(P_C)] + 0.053255[\ln(P_C)]^2 + 0.028628[\ln(P_C)]^3 - 0.0035549[\ln(P_C)]^4\}$$

material factor from Table 16.15 and for motor the power consumption was calculated from equation 16.16

$$P_C = \frac{QH\rho}{33{,}000\eta_P\eta_M}$$

where:

$$\eta_P = -0.316 + 0.24015\ln[Q] - 0.01199(\ln[Q])^2$$

$$\eta_M = 0.80 + 0.0319\ln[P_B] - 0.00182(\ln[P_B])^2$$

where Q is the flow rate through the pump in gallons per minute, H is the pump head, ρ is the density in pounds per gallon, η_p is the fractional efficiency, η_M is the fractional efficiency of the electric motor. Pump head is the pressure rise over the liquid density

The motor-type factor was chosen to be F_T=0.90 from Table 16.22 in Seider, et al., and the power was assumed P_B=1Hp (assumed as the minimum) (2005). The base cost for the actual pump from equation 16.21.

$$C_B = \exp\{7.2744 + 0.19861\ln[Q] + 0.0291(\ln[Q])^2\}$$

The jacketed tank was costed using Table 16.32 of Seider, et al., as well for an open storage tank (2005). Its insulation was priced using a vendor quote.

$$C_B = 14[V]^{0.72}$$

The purchase cost for mixers was determined using Table 16.32 of Seider, et al., for a closed vessel agitator and a cone roof storage tank (2005).

$$C_B = 2{,}600[S]^{0.17}$$

$$C_B = 210[V]^{0.51}$$

where S is the motor horsepower for the agitator, S=0.5 Hp per 1,000 gallons of liquid page 557 of Seider, et al. (2005).

The purchase cost of blowers was determined by using Eqn. 16.30 for the brake horsepower, P_B

$$P_B = 0.00436\left(\frac{k}{k-1}\right)\left(\frac{Q_1 P_1}{\eta_B}\right)\left[\left(\frac{P_0}{P_1}\right)^{\frac{k-1}{k}} - 1\right]$$

where Q_1 is the inlet flow rate in cubic feet per minute, P_1 is the inlet pressure in pounds per square inch, P_0 is the outlet pressure in pounds per square inch, k is the specific heat ratio which is dimensionless and 1.4 for air.

The brake horsepower was then used to calculate the purchase cost of the blowers.

$$C_B = \exp\{6.6547 + 0.7900 \ln[P_B]\}$$

The cost of the membrane included the cartridge for the membrane as well as the actual membrane. The membrane cost was quoted by a vendor and the cartridge cost was determined by using Table 16.32 of Seider, et al. (2005)

$$C_B = 14A$$

where A is area of membrane in square feet.

To cost the silos for the cream and milk, they were considered to be cone roof storage tanks from Table 16.32 of Seider, et al. (2005).

$$C_B = 210[V]^{0.51}$$

The cost of the storage freezer was considered to be part of the building cost and the cost of the valves was considered to be negligible.

The following pieces of equipment were costed by vendor quotes: volumetric flow meters, hardening tunnel, filler, membrane, homogenizers, cooling tower, and the insulation for the jacketed tank. Blower B-403 is part of the cooling tower and was included in the cost of the cooling tower.

Bare module costs were scaled to update the cost to current cost index values using the Chemical Engineering (CE) Plant Cost Index from 2007 (527.1) and bare module factor from Table 16.11 (Seider, et al., 2005). The bare module factor, F_{BM}, includes the cost of materials and labor to install the equipment. Each piece of equipment's cost was multiplied by its bare module factor, depending on its type. If there was not a listed bare module factor listed in Seider, et al., an average of the F_{BM}'s was used from Table 16.11, which was calculated to be 2.28. The total bare module cost the equipment, $7.9 million, (Table C.1) is the sum of the individual bare module costs for each piece of equipment. Detailed calculations for each piece of equipment are given on pages C-20 to C-37.

The total capital investment, $23 million (Table C.2), is estimated from pages 493-496 & 504 in Seider, et al. (2005). The direct permanent investment is the sum of the total bare module cost and the site, buildings, and allocation costs. For a grass roots plant (a plant built from the ground up, not an addition on to an existing plant) the site costs are approximately 10-20% of the bare module costs in which the higher end percentage was taken with site costs at 20% to be safe in economic calculations. Building costs are 20% of C_{TBM} and allocation costs are 5%.

Contingencies need to be included as well, which can be between 10-40% of the direct permanent investment depending on how well the process is known and contractors' fees which are approximately 3%. The contingencies will be estimated to be 15% plus 3% for contractor fees, since frozen yogurt production is a relatively well-known process. The sum of the direct permanent investment and the contingencies and contractor fees make up the total depreciable investment (TDC). The other costs involved in the total permanent investment (TCI), include land, royalties, and startup, and do not typically depreciate and thus are calculated separately from the depreciable investment. Land, royalties, and startup costs were calculated as percentages of the total depreciable investment, 2%, 2%, and 10% respectively. Total permanent investment is also dependent upon the location of the plant. For Pennsylvania (the Northeast), the proposed locale of the plant, the correction factor for investment site location is 1.10 from Table 16.13 (Seider, et al., 2005). To attain the final total capital investment the working capital is added to the corrected total permanent investment.

The total feedstocks cost for the process which includes the utilities and raw materials are shown in Table C.3. Raw materials include any ingredient in the frozen yogurt making process. Utilities are any materials used to operate or maintain the process. Process water and compressed air are listed in both tables. Process water is used as a main ingredient as it is mixed into M-101 as an ingredient and it is used during cleaning in place after acid and base rinses. The compressed air is injected into the frozen yogurt as an ingredient and it is also used to operate the filler pneumatically.

Table C.4 shows the total annual productions costs for the frozen yogurt making facility. Table C.4 is put together using Seider, et al., pages 563-581 (2005). The total annual production costs take into account operations, maintenance, overhead, taxes and insurance, and other miscellaneous costs.

The cash flow sheet for 30 years is shown in Table C.5. The investments in the cash flow sheet are the working capital and total depreciable capital (both previously calculated in Table C.2). These values coupled with annual sales, annual costs, and annual depreciation make up the net cash flow. The tax rate used in the cash flow sheet is 37%. Sales in the cash flow sheet were calculated in the following manner. Annually, 7.4 million containers of frozen yogurt are produced and sold for $4.00 per container. Multiplying the annual production of the frozen yogurt by its market prices yields the annual sales for this process.

A summary of the NPV and payback period for the thirty year outlook is presented in Table C.6. Tables C.7 and C.8 show the thirty year outlook when the price of milk and vanilla, respectively, are doubled for the manufacture of frozen yogurt. These two ingredients were part of the economic analysis. Finally, C.9 shows how the IRR (DCFRR, discounted cash flow rate of return) of 34.4% is calculated.

Table C.1: Bare module equipment cost for Yogurina's frozen yogurt making process

Equipment	#	C_p	Total C_p	F_m	F_{bm}	C_{bm}	Yearly Cost
Volumetric Flow meter ST-101	1	$1,544	$1,544	1	2.28	$3,520	N/A
Volumetric Flow meter ST-102	1	$1,544	$1,544	1	2.28	$3,520	N/A
Milk Silo Storage SL-101	1	$33,595	$33,595	2.00	2.28	$204,945	N/A
Cream Silo Storage SL-102	1	$4,119	$4,119	2.00	2.28	$25,128	N/A
Reactor R-501-flask	1	Negligible	Negligible			negligible	N/A
Reactor R-502-CSTR	1	$1,963	$1,963	2.00	4.3	$22,590	N/A
Reactor R-503-CSTR	1	$5,286	$5,286	2.00	4.3	$60,820	N/A
Membrane MB-101	1	$29,332	$29,332	2.00	3.2	$29,332	$2,685
Final Reactor/Mixer-R-101	1	$4,810	$4,810	2.00	4.3	$55,341	N/A
Mixer M-101	1	$5,486	$5,486	2.00	2.28	$33,467	N/A
Mixer M-201	1	$5,285	$5,285	2.00	2.28	$32,242	N/A
Mixer M-301	1	$5,285	$5,285	2.00	2.28	$32,242	N/A
Homogenizer HG-101	1	$300,000	$300,000	1.00	2.28	$684,000	N/A
Homogenizer HG-201	1	$300,000	$300,000	1.00	2.28	$684,000	N/A
Plate and Frame Heat Exchanger E-201 to E-204	4	$36,827	$36,827	1.00	3.3	$162,584	N/A
Plate and Frame Heat Exchanger E-101 to E-103	3	$23,008	$23,008	1.00	3.3	$101,577	N/A
Plate and Frame Heat Exchanger E-501 to E-502	2	$37,473	$37,473	1.00	3.3	$165,436	N/A
Plate and Frame Heat Exchanger E-205	1	$25,244	$25,244	1.00	3.17	$111,447	N/A
Plate and Frame Heat Exchanger E-206	1	$21,333	$21,333	1.125	3.17	$94,182	N/A
Shell and Tube Heat Exchanger E-401	1	$16,193	$16,193	2.721	3.17	$186,858	N/A
Double Pipe Heat Exchanger E-208	1	$1,656	$1,656	2.500	3.17	$17,557	N/A
Double Pipe Heat Exchanger E-104	1	$1,542	$1,542	2.500	3.17	$16,349	N/A
Double Pipe Heat Exchanger E-207	1	$1,869	$1,869	2.500	3.17	$19,816	N/A
Shell and Tube Heat Exchanger E-302	1	$7,659	$7,659	2.721	3.17	$88,381	N/A
Shell and Tube Heat Exchanger E-303	1	$7,942	$7,942	2.721	3.17	$91,646	N/A
Air Cooled Fin Fan Heat Exchanger E-402	1	$26,593	$26,593	2.000	2.17	$154,402	N/A
Air Cooled Fin Fan Heat Exchanger E-403	1	$26,073	$26,073	2.000	2.17	$151,383	N/A
Air Cooled Fin Fan Heat Exchanger E-301	1	$20,637	$20,637	2.000	2.17	$119,821	N/A
External Gear Pump P-101A/B	2	$3,739	$3,739	2.00	3.3	$32,229	N/A
External Gear Pump P-102A/B	2	$2,285	$2,285	2.00	3.3	$20,765	N/A
External Gear Pump P-103AB	2	$1,215	$1,215	2.00	3.3	$11,056	N/A

External Gear Pump P-104A/B	2	$1,128	$1,128	2.00	3.3	$10,258	N/A
External Gear Pump P-201A/B	2	$2,435	$2,435	2.00	3.3	$22,110	N/A
External Gear Pump P-202A/B	2	$2,331	$2,331	2.00	3.3	$21,173	N/A
External Gear Pump P-301A/B	2	$3,393	$3,393	2.00	3.3	$30,560	N/A
External Gear Pump P-401A/B	2	$1,586	$1,586	2.00	3.3	$14,427	N/A
External Gear Pump P-402A/B	2	$4,038	$4,038	2.00	3.3	$36,253	N/A
External Gear Pump P-501A/B	2	$1,060	$1,060	2.00	3.3	$9,639	N/A
Filler FL-301	1	$42,000	$42,000	1.00	2.28	$95,760	N/A
Scraped Surface Heat Exchanger ES-301 to ES-308	8	$53,322	$426,576	1.00	2.06	$1,175,602	N/A
Hardening Tunnel HT-301	1	$770,000	$770,000	1.00	2.28	$1,755,600	N/A
Storage Freezer SF-301	1	assumed to be included in cost of building	assumed to be included in cost of building	2.00	1.00	$0	N/A
Jacketed Tank JT-201	1	$3,477	$3,477	2.00	2.28	$21,211	N/A
Cooling Tower CT-401, B-403 (one unit)	1	$4,872	$4,872	1.00	2.28	$11,108	N/A
Blower B-401	1	$6,054	$6,054	2.50	2.28	$46,165	N/A
Blower B-402	1	$12,368	$12,368	2.50	2.28	$94,313	N/A
Blower B-301	1	$10,880	$10,880	2.50	2.28	$82,966	N/A
Compressor C-401	1	$56,307	$56,307	1.15	4.3	$372,499	N/A
Compressor C-402	1	$35,445	$35,445	1.15	4.3	$234,488	N/A
Compressor C-403	1	$54,308	$54,308	1.15	4.3	$359,275	N/A
Insulation for jacketed tank	1	$3,200	$3,200	1.00	1	$3,200	N/A
Blower, B-403	1	included in cost of cooling Tower	included in cost of cooling tower	1.00	2.28	$0	N/A
Total						**$7,866,224**	

Table C.2: Total capital investment

Total Bare Module Cost for onsite equipment	$7,866,224
Total Bare Module Cost for Spare	$209,610
Total bare module investment, TBM	**$8,075,834**
Cost of site preparation	$1,615,167
Cost of service facilities	$1,615,167
Allocated cost for utility plants and related facilities	$403,792
Total Direct Permanent Investment DPI	**$11,709,959**
Contingencies and contractor's fee	$2,107,793
Total Depreciable Capital, TDC	**$13,817,752**
Cost of Land	$276,355
Cost of Royalties	$276,355
Cost of Plant Startup	$1,381,775
Total Permanent Investment	**$15,752,237**
Adjusted Total Permanent Investment	$17,327,461
Working Capital	$5,663,043
Total Capital Investment	**$22,990,504**

Table C.3: Total feedstocks costs

Feedstocks	**Unit**	**Cost**
Utilities		
Steam	$/yr	$1,768
Electricity	$/yr	$159,331
Cooling Water (CW)	$/yr	$35
Process Water	$/yr	$30
Ammonia	$/yr	$135
Brine	$/yr	$29
Liquid Water Disposal	$/yr	$299
Sodium Hydroxide	$/yr	$6,010
Sulfuric Acid	$/yr	$2,380
Compressed Air	$/yr	$300
Raw Materials		
Inulin	$/yr	$217,920
Concentrated Freeze Dried Culture	$/yr	$13
Milk	$/yr	$6,927,990
Heavy Cream	$/yr	$574,396
Vanilla	$/yr	$2,230,155
Mono- and Diglycerides	$/yr	$5,913
Cane Sugar	$/yr	$558,145
Carrageenan	$/yr	$309,705
Corn Syrup Solids	$/yr	$550,993
Compressed Air	$/yr	$6,732
Ice Cream Containers	$/yr	$728,000
Process Water	$/yr	negligible cost
Total Feedstocks Cost	**$/yr**	**$12,280,278**

Table C.4: Annual expenses

Annual Cost Factor (excluding depreciation)	**Factor**	**Unit**	**Annual Amount**	**Unit**	**Cost**
Feedstocks (raw materials)			$12,280,278	$/yr	$12,280,278
Operations					
Direct Wages & Benefits (DW&B)	$53.51	$/operator hr	$40,000	operator hour/yr	$2,140,508
Direct Salaries & Benefits	15%	% of DW&B	$2,140,508	$/yr	$321,076
Operating Supplies and Services	6%	%of DW&B	$2,140,508	$/yr	$128,430
Technical Assistance to Manufacturing	$69,567	$/operator shift-yr	$5	operators shift	$347,832
Control Laboratory	$76,256	$/operator shift-yr	$5	operators shift	$381,278
Maintenance					
Solid-Fluid Handling Process	4.50%	% of C_{tdc}	$13,817,752	$/yr	$621,799
Salaries and Benefits	25%	% of MW&B	$621,799	$/yr	$155,450
Materials and Services	100%	% of MW&B	$621,799	$/yr	$621,799
Maintenance Overhead	5%	% of MW&B	$621,799	$/yr	$31,090
Operating Overhead					
General Plant Overhead	7.10%	% of M&O-SW&B	$3,238,832	$/yr	$229,957
Mechanical department Overhead	2.40%	% of M&O-SW&B	$3,238,832	$/yr	$77,732
Employee relations department	5.90%	% of M&O-SW&B	$3,238,832	$/yr	$191,091
Business Services	7.40%	% of M&O-SW&B	$3,238,832	$/yr	$239,674
Property taxes and Insurance	2%	% of C_{tdc}	$13,817,752	$/yr	$276,355
Depreciation					
Direct plant	8%	% of (C_{tdc}-1.18C_{alloc})		$/yr	$1,067,302
Allocated plant	6%	% of 1.18C_{alloc}	$403,792	$/yr	$28,588
Annual COST OF MANUFACTURE (COM)					**$19,140,239**
General Expenses					
Selling Expense	3%	% of sales	$29,714,286	$/yr	$891,429
Direct Research	4.80%	% of sales	$29,714,286	$/yr	$1,426,286
Allocated Research	0.50%	% of sales	$29,714,286	$/yr	$148,571
Administrative expense	2%	% of sales	$29,714,286	$/yr	$594,286
Management Incentive Compensation	1.25%	% of sales	$29,714,286	$/yr	$371,429
Annual TOTAL GENERAL EXPENSES (GE)					**$3,432,000**
Annual TOTAL PRODUCTION COST (excluding depreciation)					**$22,572,239**

MW&B: Maintenance, wages, and benefits; M&O: Maintenance and overhead; SW&B: Salaries, wages, and benefits; C_{tdc}: Total depreciable capital; C_{alloc}: Cost of allocation

Table C.5: Thirty year cash flow analysis for frozen yogurt manufacturing at a selling price of $4.00/container

Year	Investment fC_{TDC}	C_{WC}	Depreciation[a]	C excl Dep	Sales	Net Earnings	Cash Flow	Cum PV @ 20% 0.2
1	-$13,817,752	-$5,663,043					-$19,480,795	-$13,817,752
2			$690,888	$22,572,239	$29,714,286	$3,672,497	$4,363,384	-$10,181,598
3			$1,312,686	$22,572,239	$29,714,286	$3,672,497	$4,985,183	-$6,719,685
4			$1,181,418	$22,572,239	$29,714,286	$3,755,196	$4,936,614	-$3,862,828
5			$1,063,967	$22,572,239	$29,714,286	$3,829,190	$4,893,157	-$1,503,088
6			$957,570	$22,572,239	$29,714,286	$3,896,220	$4,853,790	$447,541
7			$860,846	$22,572,239	$29,714,286	$3,957,156	$4,818,002	$2,061,081
8			$815,247	$22,572,239	$29,714,286	$3,985,884	$4,801,131	$3,400,988
9			$815,247	$22,572,239	$29,714,286	$3,985,884	$4,801,131	$4,517,578
10			$816,629	$22,572,239	$29,714,286	$3,985,013	$4,801,642	$5,448,168
11			$815,247	$22,572,239	$29,714,286	$3,985,884	$4,801,131	$6,223,577
12			$816,629	$22,572,239	$29,714,286	$3,985,013	$4,801,642	$6,869,821
13			$816,629	$22,572,239	$29,714,286	$3,985,013	$4,801,642	$7,408,357
14			$815,247	$22,572,239	$29,714,286	$3,985,884	$4,801,131	$7,857,089
15			$816,629	$22,572,239	$29,714,286	$3,985,013	$4,801,642	$8,231,073
16			$407,624	$22,572,239	$29,714,286	$4,242,686	$4,650,310	$8,532,903
17				$22,572,239	$29,714,286	$4,499,489	$4,499,489	$8,776,271
18				$22,572,239	$29,714,286	$4,499,489	$4,499,489	$8,979,078
19				$22,572,239	$29,714,286	$4,499,489	$4,499,489	$9,148,083
20				$22,572,239	$29,714,286	$4,499,489	$4,499,489	$9,288,921
21				$22,572,239	$29,714,286	$4,499,489	$4,499,489	$9,406,286
22				$22,572,239	$29,714,286	$4,499,489	$4,499,489	$9,504,090
23				$22,572,239	$29,714,286	$4,499,489	$4,499,489	$9,585,594
24				$22,572,239	$29,714,286	$4,499,489	$4,499,489	$9,653,513
25				$22,572,239	$29,714,286	$4,499,489	$4,499,489	$9,710,113
26				$22,572,239	$29,714,286	$4,499,489	$4,499,489	$9,757,279
27				$22,572,239	$29,714,286	$4,499,489	$4,499,489	$9,796,584
28				$22,572,239	$29,714,286	$4,499,489	$4,499,489	$9,829,339
29				$22,572,239	$29,714,286	$4,499,489	$4,499,489	$9,856,634
30		$5,664,125		$22,572,239	$29,714,286	$4,499,489	$10,162,533	$9,908,008

[a] Based on a fifteen year class-life MACRS Tax-Basis depreciation schedule

Legend:

fC_{TDC}: fraction of total depreciable capital

C_{WC}: working capital

$C_{excluding\ Dep.}$: costs excluding depreciation

Cum. PV at 20%: cumulative present value with an interest rate of 20%

Table C.6: Payback period and NPV summary

Payback Period	2.82
NPV after 30 years	$9,908,008
IRR (DCFRR)	34.40%

Table C.7: Thirty year cash flow analysis for frozen yogurt manufacturing at a selling price of $4.00/container doubling the milk price

	Investment						**Cash**	**Cum PV @ 20%**
Year	**fC_{TDC}**	**C_{WC}**	**Depreciation**	**C excl Dep**	**Sales**	**Net Earnings**	**Flow**	**0.20**
1	-$13,817,752	-$6,817,246					-$20,634,998	-$13,817,752
2			$690,888	$29,500,229	$29,714,286	-$692,137	-$1,249	-$13,818,793
3			$1,312,686	$29,500,229	$29,714,286	-$692,137	$620,550	-$13,387,855
4			$1,181,418	$29,500,229	$29,714,286	-$609,438	$571,980	-$13,056,848
5			$1,063,967	$29,500,229	$29,714,286	-$535,443	$528,523	-$12,801,966
6			$957,570	$29,500,229	$29,714,286	-$468,414	$489,157	-$12,605,385
7			$860,846	$29,500,229	$29,714,286	-$407,477	$453,369	-$12,453,553
8			$815,247	$29,500,229	$29,714,286	-$378,750	$436,497	-$12,331,735
9			$815,247	$29,500,229	$29,714,286	-$378,750	$436,497	-$12,230,219
10			$816,629	$29,500,229	$29,714,286	-$379,621	$437,008	-$12,145,524
11			$815,247	$29,500,229	$29,714,286	-$378,750	$436,497	-$12,075,027
12			$816,629	$29,500,229	$29,714,286	-$379,621	$437,008	-$12,016,211
13			$816,629	$29,500,229	$29,714,286	-$379,621	$437,008	-$11,967,198
14			$815,247	$29,500,229	$29,714,286	-$378,750	$436,497	-$11,926,401
15			$816,629	$29,500,229	$29,714,286	-$379,621	$437,008	-$11,892,364
16			$407,624	$29,500,229	$29,714,286	-$121,947	$285,676	-$11,873,822
17				$29,500,229	$29,714,286	$134,856	$134,856	-$11,866,528
18				$29,500,229	$29,714,286	$134,856	$134,856	-$11,860,450
19				$29,500,229	$29,714,286	$134,856	$134,856	-$11,855,384
20				$29,500,229	$29,714,286	$134,856	$134,856	-$11,851,163
21				$29,500,229	$29,714,286	$134,856	$134,856	-$11,847,646
22				$29,500,229	$29,714,286	$134,856	$134,856	-$11,844,714
23				$29,500,229	$29,714,286	$134,856	$134,856	-$11,842,272
24				$29,500,229	$29,714,286	$134,856	$134,856	-$11,840,236
25				$29,500,229	$29,714,286	$134,856	$134,856	-$11,838,540
26				$29,500,229	$29,714,286	$134,856	$134,856	-$11,837,126
27				$29,500,229	$29,714,286	$134,856	$134,856	-$11,835,948
28				$29,500,229	$29,714,286	$134,856	$134,856	-$11,834,966
29				$29,500,229	$29,714,286	$134,856	$134,856	-$11,834,148
30		$6,817,246		$29,500,229	$29,714,286	$134,856	$6,952,102	-$11,799,004

Table C.8: Thirty year cash flow analysis for frozen yogurt manufacturing selling at $4.00/container doubling the vanilla price

Year	Investment fC_{TDC}	C_{WC}	Depreciation	C excl Dep	Sales	Net Earnings	Cash Flow	Cum PV @ 20% 0.20
1	-$13,817,752	-$6,034,587					-$19,852,339	-$13,817,752
2			$690,888	$24,802,394	$29,714,286	$2,267,499	$2,958,387	-$11,352,429
3			$1,312,686	$24,802,394	$29,714,286	$2,267,499	$3,580,186	-$8,866,189
4			$1,181,418	$24,802,394	$29,714,286	$2,350,199	$3,531,616	-$6,822,430
5			$1,063,967	$24,802,394	$29,714,286	$2,424,193	$3,488,159	-$5,140,254
6			$957,570	$24,802,394	$29,714,286	$2,491,222	$3,448,793	-$3,754,262
7			$860,846	$24,802,394	$29,714,286	$2,552,159	$3,413,005	-$2,611,253
8			$815,247	$24,802,394	$29,714,286	$2,580,886	$3,396,133	-$1,663,455
9			$815,247	$24,802,394	$29,714,286	$2,580,886	$3,396,133	-$873,623
10			$816,629	$24,802,394	$29,714,286	$2,580,015	$3,396,644	-$215,330
11			$815,247	$24,802,394	$29,714,286	$2,580,886	$3,396,133	$333,164
12			$816,629	$24,802,394	$29,714,286	$2,580,015	$3,396,644	$790,312
13			$816,629	$24,802,394	$29,714,286	$2,580,015	$3,396,644	$1,171,268
14			$815,247	$24,802,394	$29,714,286	$2,580,886	$3,396,133	$1,488,684
15			$816,629	$24,802,394	$29,714,286	$2,580,015	$3,396,644	$1,753,237
16			$407,624	$24,802,394	$29,714,286	$2,837,689	$3,245,312	$1,963,875
17				$24,802,394	$29,714,286	$3,094,492	$3,094,492	$2,131,250
18				$24,802,394	$29,714,286	$3,094,492	$3,094,492	$2,270,728
19				$24,802,394	$29,714,286	$3,094,492	$3,094,492	$2,386,961
20				$24,802,394	$29,714,286	$3,094,492	$3,094,492	$2,483,821
21				$24,802,394	$29,714,286	$3,094,492	$3,094,492	$2,564,538
22				$24,802,394	$29,714,286	$3,094,492	$3,094,492	$2,631,802
23				$24,802,394	$29,714,286	$3,094,492	$3,094,492	$2,687,855
24				$24,802,394	$29,714,286	$3,094,492	$3,094,492	$2,734,567
25				$24,802,394	$29,714,286	$3,094,492	$3,094,492	$2,773,493
26				$24,802,394	$29,714,286	$3,094,492	$3,094,492	$2,805,931
27				$24,802,394	$29,714,286	$3,094,492	$3,094,492	$2,832,963
28				$24,802,394	$29,714,286	$3,094,492	$3,094,492	$2,855,489
29				$24,802,394	$29,714,286	$3,094,492	$3,094,492	$2,874,262
30		$6,034,587		$24,802,394	$29,714,286	$3,094,492	$9,129,079	$2,920,411

Table C.9: Investor's rate of return thirty year outlook

Year	Investment fC_{TDC}	C_{WC}	Depreciation	C excl Dep	Sales	Net Earnings	Cash Flow	Cum PV @ DCFRR% IRR: 0.344
1	-$13,817,752	-$5,663,043					-$19,480,795	-$13,817,752
2			$690,888	$22,572,239	$29,714,286	$3,672,497	$4,363,384	-$10,571,221
3			$1,312,686	$22,572,239	$29,714,286	$3,672,497	$4,985,183	-$7,811,448
4			$1,181,418	$22,572,239	$29,714,286	$3,755,196	$4,936,614	-$5,778,074
5			$1,063,967	$22,572,239	$29,714,286	$3,829,190	$4,893,157	-$4,278,481
6			$957,570	$22,572,239	$29,714,286	$3,896,220	$4,853,790	-$3,171,701
7			$860,846	$22,572,239	$29,714,286	$3,957,156	$4,818,002	-$2,354,284
8			$815,247	$22,572,239	$29,714,286	$3,985,884	$4,801,131	-$1,748,223
9			$815,247	$22,572,239	$29,714,286	$3,985,884	$4,801,131	-$1,297,290
10			$816,629	$22,572,239	$29,714,286	$3,985,013	$4,801,642	-$961,743
11			$815,247	$22,572,239	$29,714,286	$3,985,884	$4,801,131	-$712,108
12			$816,629	$22,572,239	$29,714,286	$3,985,013	$4,801,642	-$526,351
13			$816,629	$22,572,239	$29,714,286	$3,985,013	$4,801,642	-$388,140
14			$815,247	$22,572,239	$29,714,286	$3,985,884	$4,801,131	-$285,316
15			$816,629	$22,572,239	$29,714,286	$3,985,013	$4,801,642	-$208,803
16			$407,624	$22,572,239	$29,714,286	$4,242,686	$4,650,310	-$153,669
17				$22,572,239	$29,714,286	$4,499,489	$4,499,489	-$113,977
18				$22,572,239	$29,714,286	$4,499,489	$4,499,489	-$84,445
19				$22,572,239	$29,714,286	$4,499,489	$4,499,489	-$62,472
20				$22,572,239	$29,714,286	$4,499,489	$4,499,489	-$46,123
21				$22,572,239	$29,714,286	$4,499,489	$4,499,489	-$33,959
22				$22,572,239	$29,714,286	$4,499,489	$4,499,489	-$24,908
23				$22,572,239	$29,714,286	$4,499,489	$4,499,489	-$18,174
24				$22,572,239	$29,714,286	$4,499,489	$4,499,489	-$13,163
25				$22,572,239	$29,714,286	$4,499,489	$4,499,489	-$9,435
26				$22,572,239	$29,714,286	$4,499,489	$4,499,489	-$6,662
27				$22,572,239	$29,714,286	$4,499,489	$4,499,489	-$4,598
28				$22,572,239	$29,714,286	$4,499,489	$4,499,489	-$3,062
29				$22,572,239	$29,714,286	$4,499,489	$4,499,489	-$1,920
30		$5,663,043		$22,572,239	$29,714,286	$4,499,489	$10,162,533	$0

IRR: investor's rate of return

Appendix D – Assumptions

Operation

- 5631 operating hours per year
- 16 hours per day of making product
- 3,250,000 million gallons of frozen yogurt produced per year
- Since no pilot plant tests have been conducted, it is assumed that the product will turn out as intended in terms of texture, flavor, and viscosity by using the ingredients and process detailed in this report.

Densities

- The density of the bulk culture and the filtrate is the same as for skim milk.
- Ultrafiltered milk and yogurt have the same density.
- Assume the concentrated freeze-dried culture has the same density as Grape Nuts Flakes, but is packed 4 times more closely. This assumption was used because both are dried items, but CFDC is in smaller granules than the cereal.
- The mono- and diglycerides have the same density as milk fat.

Environment

- External temperature is constant at 20 °C, which is about the average high in Pennsylvania (Pennsylvania State Climatologist, 2008).
- Average atmospheric relative humidity is constant at 70%, which is around the average annual relative humidity in Pennsylvania (Pennsylvania State Climatologist, 2008).
- Cooling water enters at 30 °C (Seider, et al., 2005).

Ultrafiltration Membrane

- The flux of milk through membrane is 25 $L/m^2/hr/bar$ (Koch, 2007).

- Assume the ultrafiltered milk composition data from Premaratne and Cousin accurately describes the UF milk that will be obtained in this process (1991).
- The culture is assumed to grow in filtrate only because it contains as much lactose (the food of yogurt culture, lactic acid bacteria) as a 10% nonfat dry milk and water solution, which is the normal way to grow culture (pg. B-2).

Pasteurization

- Estimates for the overall heat transfer coefficients and heat capacities were taken from Kessler (1981).
- Since E-102 uses ammonia instead of steam to heat the UF milk, it is assumed that the heat exchanger has safety features preventing the ammonia from entering the milk.
- The overall heat transfer coefficient between UF milk and ammonia is taken to be the same as the coefficient for milk and steam.
- The overall heat transfer coefficient between water and brine was estimated by averaging the water-milk and the brine-milk coefficients in Kessler (1981).

Scraped Surface Freezers

- Assume that with a draw temperature of -7 °C and mostly sucrose as a sweetener, 55 vol% of the frozen yogurt is ice (Drewett and Hartel, 2007).
- The freezing point of the frozen yogurt mix is assumed to be -2.7 °C (Drewett and Hartel, 2007).
- The fraction of water that is frozen in the mix is taken to be a linear function of temperature over the range of the freezer (3 °C to -7 °C) (Kessler, 1981).
- The viscosity of the frozen yogurt is assumed to be constant.
- The distance between the scraper blade and the freezer wall is assumed to be 1 mm.
- The overall heat transfer coefficient in the freezer is assumed to be 1000 $W/m^2/°C$ (Earle, 1983).
- The compressed air being injected into the freezer along with the mix was assumed to provide negligible refrigeration (pg. B-14).

Hardening Tunnel

- The hardening time was calculated using a model for transient heat transfer through an infinite cylinder (pg. B-15). It was assumed that this model is applicable.
- The convective heat transfer coefficient in the tunnel was taken to be 35 $W/m^2/K$ (Amarante and Lanoisellé, 2005).
- The thermal conductivity was estimated at 0.55 W/m/K (Cogné, et al., 2003).
- Heat transfer coefficients for heat loss through the walls, ceiling, and floor of the tunnel were estimated from Warner (1976).

Storage Freezer

- Assume the only heat losses are through the walls, ceiling, and floors. Doors are neglected.
- Sized for one week's capacity of frozen yogurt demand.

Refrigeration Loop with Ammonia

- Calculations were done in Aspen (aspenONE, 2005).
- Overall heat transfer coefficients estimated using heuristics in Turton, et al. (2003).
- Physical properties were estimated in Aspen using the "UNIFAC" property method.
- The filtrate was modeled as water.

Cooling Tower

- Assume that the water will leave the tower at 30 °C.
- The flow rate through the cooling tower is assumed to be constant for the calculation. In practice, because some of the water is coming from a batch process, the amount of water could fluctuate during a run.

Bulk Culture Fermentation

- The different bacteria strains are assumed to all be able to grow together when making the bulk culture.
- It is assumed that 1 granule (grain) of concentrated freeze-dried culture weighs 1 grain.
- Use two grains of culture per liter of filtrate (Food and Agriculture Organization, 2004).
- It is assumed that the culture will grow as expected in the paper by Ordonez, et al. (2000). This means that it is assumed that each stage of culture preparation will take 5.5 hours to reach a pH of 5.5 and that yogurt fermentation will take 4 hours.

- For pasteurizing the filtrate, it was assumed that the filtrate has the same thermodynamic properties as water.

Environmental Impact

- Environmental impact study is based on the plant's delivery of 20,344,803 lb/yr of frozen yogurt to market
- In the environmental impact, material quantities of raw materials and on-site chemicals is an estimate for one year operation but the facility will not store the indicated amount during normal operation.
- Storage period for on-site chemicals is three weeks; raw materials are stored for one week. Milk and heavy cream are stored for one day or less.

Economic Assumptions:

- If cost equations from Seider, et al. were not in correct range, it was assumed that they would still be applicable.
- The plant was taken to produce product 5631 hours per year.
- An average F_{BM} of 2.28 was used, based on Table 16.11 of Seider, et al., for any equipment not in the list.
- All materials of construction in contact with the product are stainless steel.
- It was assumed that F_p equals 1.0 for the double pipe heat exchangers.
- The storage freezer is assumed to be part of building cost.
- Valves costs are considered to be negligible.

- For shell-and-tube fixed-head heat exchangers, the length was assumed to be 20 feet, therefore F_L=1.0.
- A minimum brake horsepower for fractional efficiency of electric motor was assumed, therefore η_M=0.72, which is the standard efficiency in Aspen.
- The jacketed tank will be able to hold 4 hours worth of mix, plus 30% extra volume.
- Mixers will have 30% extra capacity, as well, and be able to hold enough mix for the required holding time.
- The price of a two-stage homogenizer is assumed to be same price as for a one stage homogenizer.
- The silos will be able to hold a whole day's supply of milk and cream.
- Ammonia, brine, cooling water (except for the amount added to make up for evaporation) will be a one time investment to fill each loop.
- The time for one component to complete a full loop is 30 minutes.
- The ammonia, brine, and cooling water are assumed not to leak. Due to the safety hazard an ammonia leak poses, it is assumed that suitable safety precautions will prevent an ammonia leak during typical operation. The cooling water and brine are assumed not to leak because they are both cheap and very easy to replace.
- It was assumed that the electricity needs for a 175 rpm scraped surface heat exchanger can be scaled up to a 500 rpm scraped surface heat exchanger.
- It was assumed that the cleaning in place chemicals were the same relative amounts as those needed by Phoenix Ice Cream (Knight, 2008).
- Heat exchangers, where the majority of the materials of construction were stainless steel, were costed with the stainless steel material factor.

Appendix E – References

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