University of Nevada, Reno

Brewery Design and Experimentation

A thesis submitted in partial fulfillment
of the requirements for the degree of

Bachelor of Science in Chemical Engineering and the Honors Program

by

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We recommend that the thesis
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Tamara Valentine, Ph. D., Director, **Honors Program**

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Abstract

The goal of this project was to design full scale breweries with production capacities of 300, 800, and 3000 barrels per day. A base case is presented with alternative cases for consideration. Further analysis of the effects of malt addition, hops addition, and fermentation temperature on the alcohol production and acidity are presented through the use of a full three factorial analysis.

Acknowledgements

We would like to thank the following people for their expertise and advice on our project: Sierra Nevada Brewery, especially Gil Sanchez, and Dr. Alan Fuchs**.**

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Introduction

Several design objectives were established for the senior design project. The primary objective was to design a full scale large production brewery for three established production rates being 300, 800, and 3,000 bbl/yr. An overview of each unit operation in the brewing process is provided along with basic and alternative designs. An overview of the brewing process is provided in Figure 1.

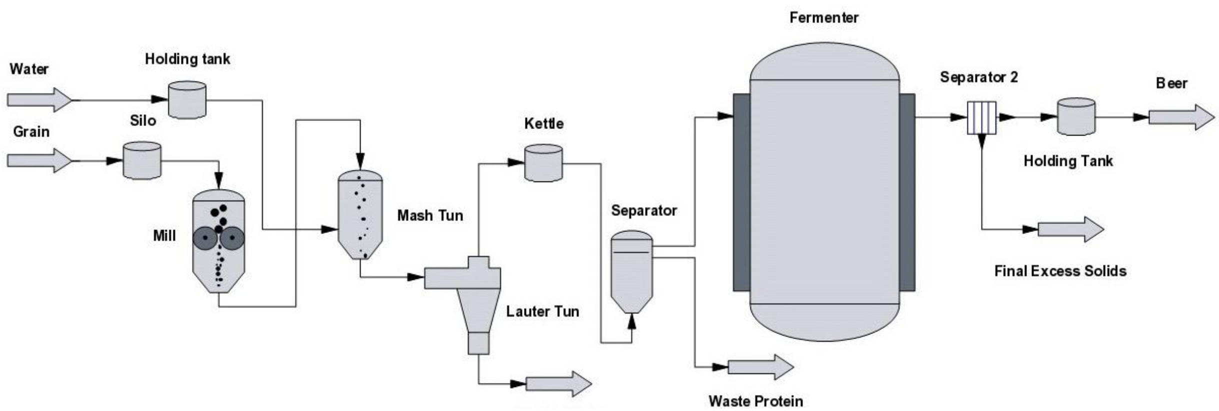

Figure 1: Process Flow Diagram for the Brewing Process

The secondary goal was to design an experiment to examine potential variables affecting beer fermentation and more specifically the specific gravity of the selected amber ale beer. The variables selected for brewing experimentation included malt concentration, fermentation temperature, and hops concentration. These parameters were then analyzed to draw experimental conclusions.

Base Design

Mill

The mill is the unit operation that breaks down the grain and extracts the kernel. The mill uses rollers that crash the husk of the grain, and force out the kernel. The reason as to why this unit operation is so important is because the kernel contains all of the sugars that the yeast will consume in the fermentation process. There are three different types of milling processes. The three different processes were dry milling, wet milling, and hammer milling. Wet milling is the preferred type of milling for Sierra Nevada brewery and malt beverages. The reasons for this are because the wet milling allows for the husk of the grain to remain intact. The grain is the fed into the mill while still in the water and a screen is used to separate the water from the grain. The wet milling process will require a heat exchanger to be added to the mill which will increase the cost of the mill. The heat exchanger is required so that the eater can reach a temperature of 155 degrees (Priest & Stewart, 2006).

The base case as shown in table 1 was designed for 300 bbl/day brewery. The mill has a required capacity to meet the 300bbl/day brewery. This capacity is a little higher than the required capacity to compensate for any disturbances in the system. For this brewery the mill will only require two rollers with a particle gap size of 0.4 mm (Kunze, 2004). This 0.4 mm gap comes from the minimum grain size needed to produce the wort. Also, the mill only requires two rollers as opposed to the scale up models because it has a much smaller required capacity. The heat exchanger will have a volume 0.117m^3, and will need to keep a constant temperature of 155°F. Table 2 will give the costs required to construct and operate the mill. The bare module cost came from a direct quote given by

Pacific Brewery Incorporations. The yearly operating cost and the cost of labor was calculated using the CapCost excel program. The yearly operating costs were the same for each mill because each mill required two operators to run.

Table 1: Design parameters for 300bbl/day brewery

Design Parameters	300 bbl/day
MOC	316 Stainless Steel
Number of Rollers	2
Particle Gap Size	0.4mm
Dimensions of rollers	125mm Diameter by 1 meter in length
RPM	125
heat exchanger size	1.8ftx2.3ftx1ft
Capacity	3,000 lbs/hr

Table 2: Costs for a 2500 lb/hr mill

Construction Costs	$162,000.00
Yearly Operating costs	$2,750.00
Cost of Labor	$105,800.00

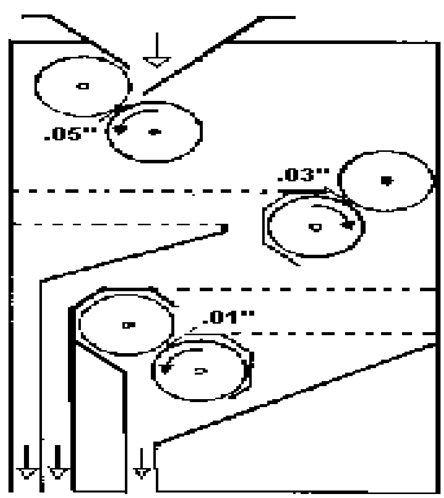

Figure 2: Six roller Mill. www.geabrewerysystems.com

Alternative mills were generated to compensate for higher production breweries. One major change that comes from the scale-up is that to compensate for the higher capacity requirements the mills will require six rollers, as shown in Figure 2. Each set of rollers will have a different gap size to compensate for the larger throughput. Table 3 displays the design parameters for the 800bb/day brewery. The mill design parameters were derived from established brewery heuristics, and by direct quotes from GEA brewery systems (Kunze, 2004). For the 800 bbl/day brewery the first two rollers will have a roll gap of 1.25mm of followed by the middle two having a roll gap of 0.8mm and the final two will have a roll gap of 0.5mm (Kunze, 2004). The heat exchanger for the 800bbl/day will have a volume 0.484m^3, and will need to keep a constant temperature of 155°F. Table 4 will display the construction and operating costs for an 800bbl/day brewery. The bare module cost came from a direct quote given by GEA Brewery Systems shown in Appendix C. The utilities and cost of labor where found using the CapCost excel sheet program.

Table 3: Design parameters for 800bbl/day brewery

Design Parameters	800bbl
MOC	316 Stainless Steel
Number of Rollers	6
Particle Gap Size	0.4-1.25mm
Dimensions of rollers	125mm Diameter by 1 meter in length
RPM	250
heat exchanger size	2ftx1.5ftx1ft
Capacity	7,000 lbs/hr

Table 4: Costs for a 7,000 lbs/hr capacity mill

Construction Costs	$281,00.00
Yearly Operating costs	$4,800
Cost of Labor	$105,800.00

Table 5 displays the design parameter for a mill in a 3000 bbl/day brewery. The 3000bbl/day mill required a much higher capacity, and a much larger heat exchanger from the previous mills. However, like the 800bbl/day mill it will require six rollers each with different gap sizes. The first two rollers will have a roll gap of 1.35mm followed by the middle two having a roll gap of 0.95mm and the final two will have a roll gap of 0.7mm. Table 6 will display the construction and operating costs for a 3000bbl/day brewery. The bare module cost for the 3000bbl/day was found by using equation (1) shown in the Analysis, Synthesis, and Design of Chemical Processes.

$$\frac{C_a}{C_b} = \left(\frac{A_a}{A_b}\right)^n \quad (1)$$

Equation 1 can then be manipulated to give equation (2), or the six-tenths rule. This six-tenths rule gives percent increase of a unit operation based upon the increase in a particular design parameter, which for this case was chosen to be the flow rate of the mill.

$$\left(\frac{A_a}{A_b}\right)^{0.6} = \%increase \quad (2)$$

The percent increase was found to be 76%. The yearly operating costs and the cost of labor were calculated using the CapCost excel sheet program.

Table 5: Design parameters for 3000bbl/day brewery

Design Parameters	3000bbl
MOC	316 Stainless Steel
Number of Rollers	6
Particle Gap Size	0.4-1.75mm
Dimensions of rollers	125mm Diameter by 1 meter in length
RPM	250
heat exchanger size	5ftx3.8ftx2.5ft
Capacity	18,000 lbs/hr

Table 6: Costs for an 18,000 lbs/hr capacity mill

Construction Costs	$495,000.00
Yearly Operating costs	$5,200.00
Cost of Labor	$105,800.00

Mash Tun

Function

The mash tun is a heated mixing tank unit operation. In the mash tun, milled grain is mixed with heated water, which by malt enzymatic conversion, converts complex starches into a fermentable sugar solution with grain husks referred to as the mash (Supply, 2000-2010). This process is known as mashing. From an efficiency point of view, the process of mashing requires that the most starches are extracted and converted to simple sugars, and that heat supplied to the process is kept to a minimum to reduce brewery costs. While the question of considering efficient heating will be addressed under the section labeled “Alternative Mash Tun Lauter Tun Cases,” conversion will be considered here. In order to extract the starches from the milled husks the mashing water must be heated to around 150-158°F (Supply, 2000-2010). It is at this specified range of temperatures that the starch extraction and starch to sugar enzymatic conversion takes place over an infusion mash retention time of approximately 110 min (McKetta & Cunningham, 1977). However, it should be noted that if the mash temperature exceeds temperatures of approximately 168-170°F the enzymes in the malt used to convert starches within the malt grain to fermentable sugars will be destroyed, and the process will have few overall fermentable sugars (Supply, 2000-2010). Further, two methods of mashing exist, decoction and infusion mashing. Decoction mashing, typically utilized by

European breweries, recovers small amounts of partial wort during the mashing process and heats the small portions of partial wort to be place back into the mash for further sugar extraction. The cyclic process of heating small portions of partial wort benefits the wort as more sugars are extracted leading to more concentrated worts. Decoction mashing is highly efficient, but produces distinct European style beers when fermented (Supply, 2000-2010).The other type of mashing, commonly found in American breweries is infusion mashing. In infusion mashing, water is heated to the specified mashing temperature then mixed with the milled grain. The benefit of infusion mashing is that process requires less time, but produces weaker wort, characteristic of many American style beers (Supply, 2000-2010). The basics of mash tun operation have been covered which are further considered for design analysis. To lead into mash tun design, Figure 3 provides a typical mash tun provided by Brew Plants Micro Brewery Equipment.

Figure 3: Typical Mash Tun (Brew Plants Micro Brewery Equipment)

Base Case Design

A single base case mash tun was designed to meet the need for three distinct scaled throughputs. The design parameters include; the size of the vessel determined by a height to diameter ratio of 1:2 (McKetta & Cunningham, 1977), the operating costs determined by an estimated heating duty and equivalent natural gas cost calculated by estimating the necessary amount of energy to heat water to the specified mashing conditions (EIA, 2011), the bare module and purchase estimate costs calculated by the 2006 CapCost equipment design program and estimated to the year 2009 by the Marshall Swift Cost Index (Engineering, 2010), and a scaled cost estimate of each mash tun based on a quote received by Pacific Brewery Systems for a 50 bbl/batch system.. Each of these throughputs and the design parameters for a single mash tun are presented in Table 7. Design parameters not specified in Table 7 include; the retention time of 110 min, where approximately 90 min. is used to infuse the mash and 20 min. are used for agitation (McKetta & Cunningham, 1977), the assumption that the vessel is insulated, an additional boiler is used to heat the mashing water before the onset of mashing infusion, and a variable agitator speed with an estimated range of 0- 28 rpms is used during the 20 min. of agitation (Williamson, 2010). Additionally, sample calculations for the base case mash tun design are located in Appendix A.

Table 7: Mash Tun Single Tank Base Case Design Parameters

For Cylindrical Tank Geometry	300 bbl/day	800 bbl/day	3000 bbl/day
Height (ft)	8.5	11.7	18.1
Inner Diameter (ft)	4.2	5.9	9.0
Volume (hL) (with 20% Void)	45	120	435
Operating Heating Cost ($/yr)	$14,637	$39,032	$146,371
2009 Marshall (Bare Module Cost) ($)	$46,613	$78,431	$156,051
2009 Marshall (Purchase Estimate Cost) ($)	$31,007	$52,287	$104,372
Scaled Equipment Cost Estimate Based on Pacific Brewing Company (50 bbl/batch) ($)	$44,335	$59,503	$88,460

Other information that was specified for the mash tun includes the throughput based on mash compositions, and heating duties and operating costs determined by estimating the necessary amount of energy to heat water to the specified mashing conditions and the cost of natural gas to supply the equivalent amount of heat. This information is supplied in Table 8. Additionally, throughput for the mashing process was based on heuristics such as 1 barrel of water is utilized for every 75-100lbs. of grain, and one barrel of water is used for each 100-125lbs. of malt (McKetta & Cunningham, 1977).

Table 8: Mash Single Tank Base Case Material Throughput

Material/Scale	300 bbl/day	800 bbl/day	3000 bbl/day
Water (lb/day)	50546	134790	505461
Water (hL/day)	306	816	3057
Malt (lb/day)	24035	64093	240348
Grain Husks (lb/day)	165769	442050	1657689
Grain w/Malt (lb/day)	189804	506143	1898037
Mash (lb/day)	240350	640933	2403498
Mash (hL/day)	477	1272	4770
Estimated Heating Duty (J/day)	5.87E+09	1.56E+10	5.87E+10
Estimated Heating Duty (kJ/day)	5.87E+06	1.56E+07	5.87E+07
Estimated Operating Cost ($/day)	40.1	106.9	401.0
Estimated Operating Cost ($/yr)	14637.1	39032.4	146371.2

Scaled Cases

Alternative mash tun tank sizes were generated and scaled to meet the three specific throughputs defined. Further, the cost estimate for each set of scaled tanks was estimated and provided by CapCost. The mash tun tanks scaled to meet the throughput rates were selected as tank sizes of 45hL, 50hL, and 60hL. The size and cost information for each set of scaled mash tun tanks is provided in Table 9, 10, and 11 respectively. Additionally, Table 12 provides a summary of the number of mash tun tanks necessary to meet the desired throughput for the individual mash tun tanks specified.

Table 9: Mash Tun Scaled Tank Analysis (45hL Tanks)

Specifications	300 bbl/day	800 bbl/day	3000 bbl/day
Number of 45hL Tanks	1	3	10
ID (ft)	4	4	4
H (ft)	8	8	8
Total Unit Capcost 2008 $ BMC	$46,000	$138,000	$460,000
2009 Marshall $ BMC	$46,613	$139,838	$466,126
Total Unit Capcost 2008 $ PEC	$30,600	$91,800	$306,000
2009 Marshall $ PEC	$31,007	$93,022	$310,075

Table 10: Mash Tun Scaled Tank Analysis (50hL Tanks)

Specifications	300 bbl/day	800 bbl/day	3000 bbl/day
Number of 50hL Tanks	1	3	9
ID (ft)	4	4	4
H (ft)	9	9	9
Total Unit Capcost 2008 $ BMC	$48,600	$145,800	$437,400
2009 Marshall $ BMC	$49,247	$147,742	$443,225
Total Unit Capcost 2008 Capcost $ PEC	$32,400	$97,200	$291,600
2009 Marshall $ PEC	$32,831	$98,494	$295,483

Table 11: Mash Tun Scaled Tank Analysis (60hL Tanks)

Specifications	300 bbl/day	800 bbl/day	3000 bbl/day
Number of 60hL Tanks	1	2	8
ID (ft)	5	5	5
H (ft)	9	9	9
Total Unit Capcost 2008 $ BMC	$53,600	$107,200	$428,800
2009 Marshall $ BMC	$54,314	$108,628	$434,510
Total Unit Capcost 2008 $ PEC	$35,700	$71,400	$285,600
2009 Marshall $ PEC	$36,175	$72,351	$289,403

Table 12: Mash Tun Size of Tank and Number of Tanks Analysis

Tank Volume	300 bbl/day	800 bbl/day	3000 bbl/day
45 hL	1	3	10
50 hL	1	3	9
60 hL	1	2	8

Lauter Tun

Function

The lauter tun is a liquid solid separator unit operation. More specifically, the liquid wort containing fermentable sugars is separated from the grain husks and other potential errant particulates. The first stage of the lauter tun consists of placing mash from the mash tun into the lauter tun. The mash, at this stage in the process, consists of fully developed wort with fermentable sugars that needs to be separated from the grain husks. The lauter tun facilitates the separation of the wort from the grain husks by the use of a gravity driven false bottom plate that exists as the bottom of the lauter tun. The false bottom plate consists of tiny slots that allow the wort to drain through, but not the larger grain husks. However, this separation is achieved by maintaining a specific pressure differential across the grain bed so as to allow optimal wort permeability and inhibit the grain bed from compacting. It should be noted that this pressure differential is maintained by large knives that slowly rotate through the grain bed which helps prevent grain bed compaction and helps maintain consistent bed pressure (Goode & Arendt, 2003). In many breweries, the lauter tun knives also move in the vertical direction for ease of cleaning and again to help maintain grain bed pressure for effective wort separation. Further, the wort extraction process is driven by the process of sparging in which water heated to 170-175°F is sprayed lightly onto the top of the grain bed during the wort extraction (Supply, 2000-2010). It should be noted that the sparging process requires approximately 50% more water than was originally used for mashing (Palmer J. , 1999). The basics of lauter tun operation have been covered which are further considered for design analysis. To lead into lauter tun design, Figure 4 provides a typical lauter tun provided by Brew Plants Micro Brewery Equipment.

Figure 4: Typical Lauter Tun (Brew Plants Micro Brewery Equipment)

Base Case Design

A single base case lauter tun was designed to meet the need for three distinct scaled throughputs. The design parameters include; the size of the vessel determined by a height to diameter ratio of 1:5 (McKetta & Cunningham, 1977), the number of knives necessary for each tank of 100mm width ,the operating costs determined by an estimated heating duty and equivalent natural gas cost calculated by estimating the necessary amount of energy to heat sparge water to the specified sparging conditions (EIA, 2011), the bare module and purchase estimate costs calculated by the 2006 CapCost equipment design program and estimated to the year 2009 by the Marshall Swift Cost Index (Engineering, 2010), and a scaled cost estimate of each lauter tun based on a quote received by Pacific Brewery Systems for a 50 bbl/batch system.. Each of these throughputs and the design parameters for a single lauter tun are presented in Table 13. Design parameters not specified in Table 13 include; the retention time of 135 min, where the limiting lautering step is sparging coupled with wort extraction, the assumption that the vessel is insulated, a false bottom with plates specified to a slot width of 2.5mm which create an overall opening that is 8-10% of the area of the bottom of the lauter tun tank, a 12-14in. grain bed depth, and a grain bed pressure differential that cannot exceed 0.5 lb/in^2 or 0.5 psig so as to allow optimal wort permeability, and prevent grain bed compaction (McKetta & Cunningham, 1977). Further, sample calculations for the base case lauter tun design are provided in Appendix A.

Table 13: Lauter Tun Single Tank Base Case Design Parameters

For Cylindrical Tank Geometry	300 bbl/day	800 bbl/day	3000 bbl/day
Height (ft)	16.3	23	35.6
Inner Diameter (ft)	3.3	4.6	7.1
Volume (hL) (with 20% Void)	53	144	532
Number of Knives (1 knive = 100 mm width)	3	4	7
Operating Heating Cost ($/yr)	$21,956	$58,549	$219,557
2009 Marshall (Bare Module Cost) ($)	$51,274	$86,031	$161,117
2009 Marshall (Purchase Estimate Cost) ($)	$34,250	$57,354	$107,412
Scaled Equipment Cost Estimate Based on Pacific Brewing Company (50 bbl/batch) ($)	$46,047	$61,800	$91,875

Other information that was specified for the lauter tun includes the throughput based on incoming mash compositions, the additional sparge water necessary to perform separation which is approximately 50% more water required than for the mashing process (Palmer J. , 1999), and heating duties and operating costs determined by estimating the necessary amount of energy to heat sparge water to the specified mashing conditions and the cost of natural gas to supply the equivalent amount of heat. This information is supplied in Table 14.

Table 14: Lauter Tun Single Tank Base Case Throughput

Material/Scale	300 bbl/day	800 bbl/day	3000 bbl/day
Sparge Water (lb/day)	75819	202185	758192
Sparge Water (hL/day)	459	1223	4585
Incoming Mash (lb/day)	240350	640933	2403498
Incoming Mash (hL/day)	477	1272	4770
Wort (hL/day)	937	2498	9362
Estimated Heating Duty (J/day)	8.80E+09	2.35E+10	8.80E+10
Estimated Heating Duty (kJ/day)	8.80E+06	2.35E+07	8.80E+07
Estimated Operating Costs ($/day)	60.2	160.4	601.5
Estimated Operating Costs ($/yr)	21955.6	58548.6	219556.9

Scaled Cases

Alternative lauter tun tank sizes were generated and scaled to meet the three specific throughputs defined. Further, the cost estimate for each set of scaled tanks was estimated and provided by CapCost. The lauter tun tanks scaled to meet the throughput rates were selected as tank sizes of 55hL, 60hL, and 75hL. The size and cost information for each set of scaled lauter tun tanks is provided in Tables 15, 16, and 17 respectively. Additionally, Table 18 provides a summary of the number of latuer tun tanks necessary to meet the desired throughput for the individual lauter tun tanks specified.

Table 15: Lauter Tun Scaled Tank Analysis (55hL Tanks)

Specifications	300 bbl/day	800 bbl/day	3000 bbl/day
Number of 55 hL Tanks	1	3	10
ID (ft)	10	10	10
H (ft)	49	49	49
Total Unit Capcost 2008 $ BMC	$51,100	$153,300	$511,000
2009 Marshall $ BMC	$51,780	$155,341	$517,805
Total Unit Capcost 2008 $ PEC	$34,100	$102,300	$341,000
2009 Marshall $ PEC	$34,554	$103,662	$345,541

Table 16: Lauter Tun Scaled Tank Analysis (60hL Tanks)

Specifications	300 bbl/day	800 bbl/day	3000 bbl/day
Number of 60 hL Tanks	1	3	9
ID (ft)	10	10	10
H (ft)	50	50	50
Total Unit Capcost $ BMC	$53,600	$160,800	$482,400
2009 Marshall $ BMC	$54,314	$162,941	$488,824
Total Unit Capcost $ PEC	$35,700	$107,100	$321,300
2009 Marshall $ PEC	$36,175	$108,526	$325,579

Table 17: Lauter Tun Scaled Tank Analysis (75hL Tanks)

Specifications	300 bbl/day	800 bbl/day	3000 bbl/day
Number of 75 hL Tanks	1	2	8
ID (ft)	11	11	11
H (ft)	54	54	54
Total Unit Capcost $ BMC	$60,300	$120,600	$482,400
2009 Marshall $ BMC	$61,103	$122,206	$488,824
Total Unit Capcost $ PEC	$40,200	$80,400	$321,600
2009 Marshall $ PEC	$40,735	$81,471	$325,883

Table 18: Lauter Tun Size of Tank and Number of Tanks Analysis

Tank Volume	300 bbl/day	800 bbl/day	3000 bbl/day
55 hL	1	3	10
60 hL	1	3	9
75 hL	1	2	8

Kettle

Once the wort has passed through the lauter tun, it is boiled in a wort boiler for one hour. The wort is boiled to make sure all components are thoroughly dissolved and sanitized as it kills any bacteria which may have been present. Hops are also added during the boiling process to stabilize the wort and add its signature bitter taste. Depending on the type of hops used, hops can be added anywhere from five minutes to an hour before the end of the boil. Bittering hops are added earliest to extract most of the alpha acids while boiling off their aromas and other volatiles. Aroma hops are added near the end of the boil to extract the aromas but not let them completely boil off, while leaving the bittering units undissolved (Palmer J. J., 1994). Figure 5 shows a typical design of a wort kettle.

Figure 5: Wort Kettle (Brew Plants Micro Brewery Equipment)

For each production rate, it is assumed the plant will operate on 10 batches per day to meet the desired throughput. A 20% safety factor is assigned to the height to compensate for the hot break, the time at which a vigorous boil begins requiring a large headspace. An original quote from GEA breweries was used and scaled for the required volumes. Table 19 shows the dimensions and costs for the kettles at the required production rates.

Table 19: Kettle Capital Costs

Production Rate (bbl/day)	**Kettle Size (gal)**	**Height (ft)**	**Radius (ft)**	**Cost**
300	1134	6.528	2.72	$39,167
800	3024	9.048	3.77	$70,550
3000	11340	14.064	5.86	$155,925

A batch boiler can be treated as a jacketed vessel with a nonisothermal heating medium where steam will be used to boil the wort. Such a system is described by the equation (3) (Green & Perry, 2008):

$$\ln\left(\frac{T_1 - t_1}{T_1 - t_2}\right) = \frac{WC}{Mc}\left(\frac{K_1 - 1}{K_1}\right)\theta \text{ } and \text{ } K_1 = \exp(UA/WC) \tag{3}$$

where A is the heat-transfer surface, C and c are the specific heats of the hot and cold fluids respectively, M is the mass of the fluid in the tank, T_1 and t_1 are the temperatures of the hot and cold fluid, respectively, at the beginning of the process, t_2 is the temperature of the cold fluid, at the end of the process, U is the overall heat transfer coefficient, W is the rate of steam through the steam jacket, and θ is the residence time in the tank. This equation utilizes multiple assumptions including: (1) U is constant for the process and over the entire surface, (2) liquid flow rates are constant, (3) specific heats are constant for the process, (4) the heating or cooling medium has a constant inlet temperature, (5) agitation produces a uniform batch fluid temperature, (6) no partial phase changes occur, and (7) heat losses are negligible (Perry). Numerical assumptions can be made to approximate the amount of steam required. These are presented in table 20.

Table 20: Assumed Heat Transfer Values

Variable	**Value**	**Units**	**Source**
T_1	406.7	K	Elliott
t_1	349.7	K	Priest
t_2	373.2	K	Priest
C	1918.1	J/kgK	Elliott
c	4224.9	J/kgK	Elliott (average between t_1 and t_2)
U	900	W/m^2K	Green
θ	3600	s	Priest
ρ_{wort}	1040	kg/m^3	Priest

Results from equation (1) are shown in table 3. Turton prices steam at 5 barg and 160°C at $29.29 / 1000 kg. Using this as an over estimation since our conditions are lower than this, the steam costs per day can be found in table 21.

Table 21: Kettle Steam Requirements

Production Rate (bbl/day)	**Kettle Size (gal)**	**Steam Flow Rate (kg/s)**	**Steam used (Mg/day)**	**Cost per day**
300	1134	1.302	46.883	$1373.19
800	3024	3.982	143.347	$4198.62
3000	11340	27.275	981.891	$28,759.58

Fermenter

Background

Fermenters are the staple unit operation of breweries. Fermenters operate by creating an environment in which yeast can grow (aerobic growth) and then ferment the simple sugars (anaerobic growth) extracted from the wheat from earlier in the brewing process. A typical fermenter includes controls for the gas above the wort and yeast mixture, a bottom cone for collection and recycle of yeast, a temperature control jacket, outlets for waste gas, and probes, sensors, and analytical devices for keeping track of process conditions.

Biochemistry

> The ability of yeast cells to convert sugar into Carbon dioxide and Alcohol is down to enzymes. Several enzymes are involved each does its step in the process. The final step is Zymase reduction which takes the end product of the other enzymes (acetaldehyde/glycerol), and turns this into good old ethyl alcohol. Sadly alcohol actually destroys enzymes and kills the yeast cell if in high concentrations. This happens at different levels for different strains of yeast. Brewers' yeast cannot withstand much beyond 5 or 6% Alcohol by volume. Wine yeast is more tolerant at a range of 10-15% Specially cultured strains of yeast with the correct environment can withstand alcohol levels up to 21% alcohol. (Alcoholic Fermentation of Sugar into CO2 and Ethanol)

According to yobrew, most yeast stop fermenting around 5% alcohol. This is consistent with typical beers. That 5% is used as an assumption in the calculation of sugar conversion and heat released per batch. The yeast used in a fermenter is important in determining the optimal fermentation conditions and the final specific gravity. Below is an excerpt which describes the important organic compounds seen in beer after fermenting.

> Alcohols
> Produced from wort carbohydrates via oxo-acids of from transamination and deamination of amino acids in wort. Include both the aromatic alcohol 2-phenylethanol as well as such aliphatic alcohols as butanol, propanol, and hexanol.
> Esters
> Most important group of beer volatiles providing strong fruity flavors. Formed via lipid metabolism by yeast in which acetyl-CoA reacts enzymatically with different alcohols, as shown here for ethyl acetate:
>
> $$\underset{\text{Acetyl-CoA}}{CH_3COCoA} + \underset{\text{Ethanol}}{CH_3CH_2OH} \longrightarrow \underset{\text{Acetyl acetate}}{CH_3COOCH_3CH_2OH} + \underset{\text{Coenzyme A}}{CoA}$$
>
> The amount of esters formed during fermentation depends on the yeast strain, fermentation temperature, and aeration of wort.
> Carbonyl Compounds
> Attribute to the "buttery, honey-or toffee-like, or butterscotch" flavor in beer. Most important formed during fermentation are diketones such as diacetyl and pentane-2,3-dione. Formed from oxidative decarboxylation of oxaloacetate and acetohydroxybutyrate. (Biochemistry in Beer Brewing)

This article and Figure 1 in Appendix D give a summary of flavoring biochemistry and the ethanol production (fermentation) process. The chemicals discussed are the most common chemicals that are analyzed to give the flavor characteristics of a beer. Furthermore, many advanced fermenter designs, bottling processes, etc. are done with particular attention paid to the flavoring chemicals, their reactions, and avoiding any averse decompositions or combinations of chemicals.

Design

The most important basic design criteria of a fermenter are its dimensions. These dimensions determine the ability of yeast to move through the beer and the ease of isolation of the yeast away from the rest of the brew mixture. Table 22 is a summarized table of Appendix A, which gives all of the important necessary design considerations of the fermenter geometry. Furthermore, the design parameters are consistent upon surface analysis with Figure 2 in Appendix D.

Table 22: Design Dimensions

Fermenter Design Dimensions			
Height Total	4.77 m	Volume Cylinder	11.41 m^3
Height Cylinder	2.38 m	Volume Cone	24.58 m^3
Height Cone	0.639 m	Volume Total	35.8 m^3
Radius	4.13 m	Cylinder Angle	60 Degrees

All engineering design must be analyzed for feasibility. The main portion of engineering design analysis for feasibility is costing. Below is the start of my intended, detailed fermenter costing, much of which is based on the design P&ID given as figure 3 in Appendix D. The cooling operating cost and the staffing costs are calculated in Appendix A, while Appendix A gives the capital cost. These costs are summarized in Table 23. Furthermore, the fermenter was parted out and costed, as shown in Table 24.

Table 23: Fermenter Costing

Fermenter Costing Information			
(300 bbl fermenter, 12 day cycle)			
Production Rate	300	800	3000
Operating Cost of Labor Total ($/year)	$158,700		
Operating Cost of Heating ($/fermenter*year)	$4,361		
Number of Fermenters per day	1	2.67	10
Total Number of Fermenters	12	32	120
Total Operating Cost ($)	$211,032	$298,426	$682,020
Capital Cost per Fermenter ($/Fermenter)	$149,000		
Total Capital Cost	$1,788,000	$4,768,000	$17,880,000

Table 24: Detailed Fermenter Design Costing

Object	Number	Cost	Total Cost	Notes
Air Flow Meter	1	281.3	281.3	
Control Valves	12	1051.0	12612.0	Overestimate
Immersed Temperature Probe	2	740.0	1480.0	High Cost
Impeller	1	0.0	0.0	
Motor	1	6000.0	6000.0	Overdesign
Pressure Indicator	1	180.0	180.0	
Air filter	2	2118.5	4237.0	Overdesign
Heat Exchanger	2	1413.0	2826.0	Overdesign
Storage Tank	1	5000.0	5000.0	Averaged
Total			32616.26	

The costing design revealed more important additional information. First, it was necessary to determine the conversion of sugars because the heat of reaction of the glycolysis reaction can be used to figure out the cooling capacity necessary for the fermenter. Furthermore, the heat released per batch would give an easy scale to the yearly cooling costs. The cooling cost index of ~4.3 $/GJ was for refrigeration around 5-15 degrees C, which is consistent with the fact that some yeasts operate best as low as approximately freezing temperature. Yeast is reused at most breweries because using the exact same yeast batch gives a more consistent product. Yeast is stored between batches and then added to each subsequent new batch from an older one. Therefore, the cost of yeast is simply that of the initial value—no more than $25 for the initial brew. Furthermore, the biochemistry article discussed earlier gave more extra important information via the characteristic functional groups for different brew flavoring compounds. The additional important information gained during the fermenter costing and design is listed in Table 25.

Table 25: Important Information

Other Information			
Conversion of Sugars	0.647		
Heat of Reaction	118 kJ/mol	Flavors:	
Heat Released per Batch	$3.03*10^9$ J/batch	Alcohols	Aromatic, Harsh
Cost Heating per Year	$4,895/year	Carbonyls	Buttery
Yeast Cost	Initial Value - $200	Esters	Fruity

Finally, it's important to mention the inputs and outputs of each batch in the fermenter. The input is the wort, while the output is essentially beer. These flows are characterized below in slightly strange units. Each fermenter is designed to hold 300bbl, so that amount goes through the process for each fermenter once every 12 days. Finally, the ethanol content rises from essentially zero to about five percent. Last, yeast enters and leaves the process as a growing catalyst. Because yeast grows aerobically at the beginning of beer production, the yeast amount gains mass before exiting the process. Additionally, due to the carbon dioxide leaving the system, some volume is likely lost during fermentation. These input and output values are shown in Table 26.

Table 26: Inputs and Outputs

Inputs-Outputs			
Wort	~305 bbl/(12 days*fermenter)	Beer	~300 bbl/(12 days*fermenter)
Ethanol %	0%	Ethanol %	5%
Yeast	44 kg	Yeast	~49 kg

Whirlpool

Whirlpool Function

The whirlpool unit operation is a liquid/solid separator that functions to remove the bulk of solids from the wort after the boiling process. Solids typically removed include remaining vegetative material (from grains, barley, and/or hops) and coagulated proteins (McKetta & Cunningham, 1977) (Reynolds, 1996).

The whirlpool functions as a rotational vortex, where the central velocity is zero and increases in the radial direction. The tangential velocity, "v_Θ", of a whirlpool can be determined by equation 4, where "ω" is the angular velocity and "r" is the radial distance. Since whirlpools consider the fluid to move as a continuous body, the fluid vorticity is 2ω at all locations (McKetta & Cunningham, 1977) (Reynolds, 1996).

$$\omega r = v_\Theta \tag{4}$$

Basic Whirlpool Design

Whirlpools are typically cylindrically large tanks where the inlet stream enters tangentially at the bottom of the tank. Typical design criteria consider, and assumed values used for unit operation design, are shown in table 27. Selected values were established from published brewery heuristics (McKetta & Cunningham, 1977) (Reynolds, 1996).

Table 27: The above table shows typical design criteria used for sizing a brewery whirlpool (McKetta & Cunningham, 1977) (Reynolds, 1996).

Design Criteria	Selected Values Used for Design	Selected Value Units
Overall Retention Time	60	min
Average Liquid Density	1060	kg/m^3
Average Particulate Density	800	kg/m^3
Height to Diameter Ratio	1 to 4	
Rotations	40	per min

Base case sizing was produced for an 800 bbl per day brewery. For a 60 minute retention time, a total volume of 33.3 m^3 is required. This requires a height of 1.4 m and a diameter of 5.5m. The fastest tangential velocity is 8.38 m/s, with a maximum loading rate of 0.3 gallons per minute. Two whirlpools are recommended so one can be in active production while the other is undergoing automatic CIP cleaning (McKetta & Cunningham, 1977) (Reynolds, 1996).

Additional Whirlpool Design Parameters, Cost Analysis, and Scale-up Adjustment

All whirlpools should be constructed with 316 Stainless Steel with a minimum wall thickness of 12mm. Overall dimensions for a 300, 800, and 3000 bbl per day brewery are shown in table 28 (McKetta & Cunningham, 1977) (Reynolds, 1996).

Table 28: Table showing required dimensions for the whirlpools of a 300, 800, and 3000 bbl per day brewery.

Total Whirlpool Production (bbl/day)	Total Volume (m^3)	Diameter (m)	Height (m)	Max Loading (gpm)
300	12.6	4	1	0.13
800	32.7	5.5	1.375	0.3
3000	120.6	8.5	2.125	1.2

Costing was performed using the CapCost Excel spreadsheet program for a 800 bbl per day whirlpool. This is shown in table 29.

Table 29: Cost Analysis of the 300, 800, and 3000 bbl per day whirlpool. This was calculated using the CapCost Excel spreadsheet program.

Total Whirlpool Production (bbl/day)	Initial Capitol Cost	Annual Operating Cost
300	$145,450	$51,100
800	$262,000	$92,000
3000	$579,100	$203,000

The primary alternative design implementation would be to include an additional waste stream at the bottom of the whirlpool. Traditional design has a single tangential inlet stream and a single outlet stream. However, since the solids form a cone in the central location of the whirlpool, an additional opening could be used as needed to allow collected solids to exit the whirlpool during the exiting process. The primary impacts would reduce cleaning downtime but also cause wasted wort. When recommended to Sierra Nevada Brewery, this alternative design was denied because this alternative design would still require two whirlpools, in effect only costing the brewery more money without adding any real value (McKetta & Cunningham, 1977) (Reynolds, 1996).

Wort Cooler

After the wort has been sufficiently boiled and solids have been removed from the whirlpool, it must be cooled before it can be added to a fermentor with yeast. While cooling, this sugary solution is the perfect breeding ground for wild bacteria and other airborne organisms; therefore, the wort must be cooled quickly to minimize the risk of contamination. At the same time, heat removed from the wort should be effectively utilized so that energy is not completely wasted. If optimized, the cooling water can be used at the wet mill back at the beginning of the process. Care is taken to meet these parameters.

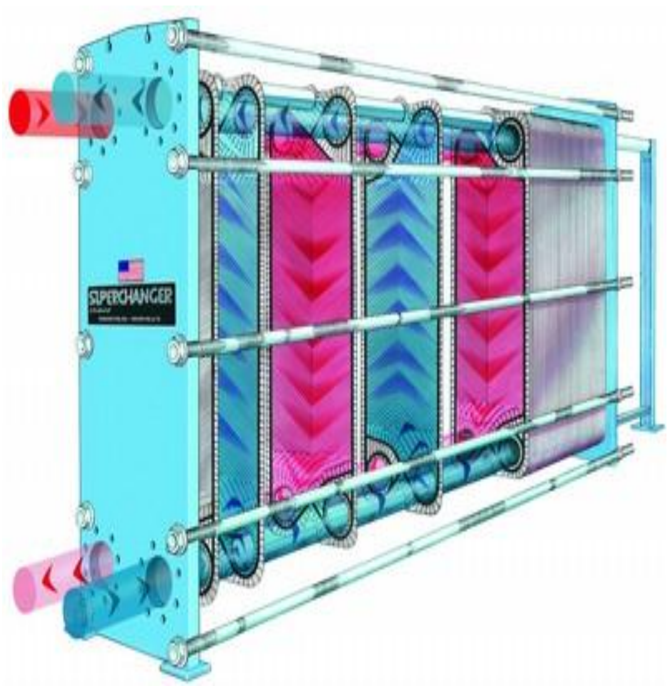

Figure 6: Plate and Frame Heat Exchanger (Tranter, 2011)

Stainless steel plate and frame heat exchangers are typically used to achieve this because they are compact, easy to clean, and require short resonance time (Kunze, 2004). A typical plate and frame heat exchanger is shown in Figure 6. Plates force alternating flows of cold and hot liquids to pass each other, driving heat transfer. Like other heat exchangers, plate and frame heat exchangers follow the general heat transfer equation shown in equation 5 (Geankoplis, 2003):

$$Q = UA\Delta T_{lm} = UA\frac{[(T_{hi} - T_{co}) - (T_{ho} - T_{ci})]}{\ln[(T_{hi} - T_{co})/(T_{ho} - T_{ci})]} \tag{5}$$

where Q is the heat transferred from the hot fluid to the cold fluid, U is the overall heat transfer coefficient, A is the required heating area, and ΔT_{lm} is the log mean temperature difference from the hot and cold fluid, as defined by the right hand side of the equation where T is absolute temperatures specified by the subscripts. Subscript *h* and *c* represent hot and cold fluid, respectively, while the subscript *i* and *o* represent inlet and outlet, respectively. Q can be determined from the energy required to be removed to cool the wart from its boiling temperature of about 98°C to a safe fermentation temperature of about 8°C. This can be done using the mass and heat capacity of the wort as shown in equation (6) (Geankoplis, 2003):

$$Q = m\int_{T_i}^{T_o} C_p dT \tag{6}$$

where Q is the heat transferred, m is the mass of water passing through the heat exchanger, and C_p is the specific heat capacity of water, as defined by Elliot. The inlet and outlet temperatures of the cooling water are be fixed to determine the required heat exchanger area. Water through an ice cooler could be produced at 2°C and then be heated to 80°C by the hot wort to be used at the wet mill or preheated brewing water elsewhere in the brew house. Priest suggests an overall heat transfer coefficient of 4500 W/m^{2}K. Thus, the equation can be rewritten to determine the required area as shown in equation (7):

$$A = \frac{Q}{U\Delta T_{lm}} \tag{7}$$

Table 30 shows the heat transfer area required and cooling water required, assuming all heat removed from the wort is absorbed by the cooling water.

Table 30: Heat Exchanger Calculations

Production Rate (bbl/day)	**Heat Transfer Required (MJ/brew)**	**Heat Transfer Area (ft^2)**	**Cooling Water (Mg/day)**	**Cost per day**	**Capital Cost**
300	1.406	.513	42.99	$0.0011	$5264
800	3.749	1.368	114.64	$0.0029	$8569
3000	14.058	5.131	429.91	$0.0109	$25483

Centrifuge

Centrifuge Function

Continuous centrifuges are used to remove yeast particulates after fermentation. These types of centrifuges are liquid/solid separations that maintain an extremely high throughput rate. Yeast consists of less than 1% by mass, after fermentation, but can greatly affect beer turbidity, flavor, and/or storage behavior. A disk centrifuge maintains multiple rotating plates that rapid spin to separate the beer by content density. An outside vendor was selected for appropriate sizing and cost estimations. Primary design criteria include assumed fluid density, solid density, desired final separation, total production requirements, and desired separation criteria (McKetta & Cunningham, 1977) (Company, 2011) (Geankoplis, 2003) (Brew 700: Hermetic solids-ejecting Brewery polisher with high capacity).

Centrifuge Selection and Costing

Primary material of construction is 316 Stainless Steel. Alfa Laval was consulted for the overall sizing requirements of this process. Alfa Laval happens to produce a line of continuous centrifuges specifically designed for the brewing industry. The Brew 700 model was selected for this process with an initial capital investment of approximately $500,000. This centrifuge is designed to remove suspended solids of 0.4 to 200 μm particulate size. The maximum throughput capacity is 700 hl/h, which is much larger than even the 2000 bbl per day size requirement. The selected continuous centrifuge is completely capable of handling all required brewery sizing. 30 kW of power are required for optimal rotor rotation of 4800 rpm. Since the throughput is so large, actual machine operation only occurs for a fraction of daily production time. Table 31 shows total machine usage and cost estimations. Utility costs were calculated using the CapCost Excel spreadsheet program. (McKetta & Cunningham, 1977) (Company, 2011) (Geankoplis, 2003) (Brew 700: Hermetic solids-ejecting Brewery polisher with high capacity).

Table 31: Table showing continuous centrifuge usage times and estimated operating costs.

Product (BPD)	Total Usage Requirement (Hr/Day) [Includes 9 min. Start-up and 25 min. Stop Time]	Total Energy Consumption (KWHr/Day)	Cooling Water (Gal/Day.)	Quoted Initial Capital ($)	Estimated Operating Cost ($/yr)
300	1.05	78.86	630.91	500000	13548.58
800	1.86	139.47	1115.76	500000	15722.31
3000	5.42	406.14	3249.09	500000	25286.76

Filtration

The general design and type of filter that will be used in the brewery is a Diatomaceous earth (DE) filter with a thickness of 4 cm. For the 2000 barrel per year brewery the filter will have an area $5m^2$ and a thickness of 4 cm. The design parameters for the filter were based off of established and published heuristics, and also came from recommendations from GEA brewery systems.(Priest and Graham, 865) The main design parameter was the area of each filter, but the thickness of the filter is based upon what is recommended by published heuristics for brewing ales. [1] The bare module cost for the 300 barrles per day is $68,0000.00. It will cost of labor of $58,000.00. For the 800 barrel per day it will require an equivalent area of $20m^2$. The bare module cost for the 800 barrel per year filter is $135,000.00, and the cost of labor will be $58,000.00. For the 3000 barrel per day it will require an equivalent area of $45m^2$. The bare module cost for the

3000 barrel per year filter is $213,000.00, and the cost of labor will be $116,000.00. All of the Costs were calculated using The CapCost excel sheet program.

Table 32: CapCost Filter Calculations

User Added Equipment

Filters	Type	Area (square meters)	Purchased Equipment Cost	Bare Module Cost
Fr-101	Plate And Frame	5	$ 45,400	$ 68,000
Fr-102	Plate And Frame	20	$ 90,100	$ 135,000
Fr-103	Plate And Frame	45	$ 142,000	$ 213,000

Total Costs

The capital cost of each unit operation and total cost of the brewery for each scale is listed in table 33. The annual operating cost of each unit operation and total annual operating cost of the brewery for each scale is listed in table 34.

Table 33: Total Capital Costs

Unit Operation	300 bbl/day	800 bbl/day	3000 bbl/day
Mill	$162,000	$281,00.00	$495,000
Mash Tun	$31,007	$52,287	$104,372
Lauter Tun	$21,956	$58,549	$219,557
Kettle	$39,167	$70,550	$155,925
Whirlpool	$145,450	$262,000	$579,100
Heat Exchanger (Wort Cooler)	$5,264	$8,569	$25,483
Fermentation	$1,788,000	$4,768,000	$17,880,000
Filtration	$68,000	$135,000	$213,000
Centrifuge	$500,000	$500,000	$500,000
Total Cost	$2,760,844	$5,854,955	$20,172,437

Table 34: Annual Operating Costs

Unit Operation	300 bbl/day	800 bbl/day	3000 bbl/day
Mill	$2,750	$4,800	$5,200
Mash Tun	$14,637	$39,032	$146,371
Lauter Tun	$21,956	$58,549	$219,557
Kettle	$501,214	$1,532,496	$10,497,247
Whirlpool	$51,100	$92,000	$203,000
Heat Exchanger (Wort Cooler)	$0.40	$1.06	$3.98
Fermentation	$211,032	$298,426	$682,020
Filtration	$58,000	$58,000	$116,000
Centrifuge	$13,549	$15,722	$25,287
Total Cost ($/yr)	$874,238	$2,099,027	$11,894,685

Alternative Cases

Mill

One alternative case for the mill is to implement dry milling. This would nullify the need for a heart exchanger; this would save money on the construction costs of the mill and also save money on the yearly operating costs of the mill. However, the dry milling allows for small particles to interfere with other unit operations further on it the process. The particle could cause failure in many of the different operations, which would result in extremely high costs for repair and replacement of any of the damaged equipment. Another device that could be used instead of the roller mills are hammer mills. The hammer mills would create a more uniformed particle size, and it also handles fibers much better than roller mills. The hammer mills have a much lower initial cost, but will cost more in terms of the yearly operating costs. This means that eventually the cost of the hammer mill will surpass the cost of the roller mill.

Mash Tun and Lauter Tun:

Capturing Waste Heat Energy

Waste heat can be captured from the mashing process. In some facilities, saturated steam, at 340°F, from a boiler can be used to heat the mash vessel. After the mash is heated, to around 150-158˚F, hot water around 200-210°F is leftover which can be used in other areas of the production facility, reducing heating costs. However, the mash vessel has to be fit with a special waste heat capture area that surrounds the mashing vessel, and additional waste recovery piping networks need to be installed (Galitsky, Martin, Worrell, & Lehman, 2003).

Use of Compression Filter in Mashing Process

A compression filter can be used to replace the plate filter found in most breweries. The advantage of using a compression filter over an air filter is that the compression filter is cleaned with air, and the plate filter is cleaned with water. Reducing water use reduces energy consumption which reduces cost. One example of the switch to a compression filter from a plate filter is the Brand Brewery, a 0.9bbl/yr operation. The claimed energy savings for the Brand Brewery using a compression filter amounts to 18.6 kBtu/barrel. The total fixed capital cost was claimed to be $620,000 with a payback period of 2 years. (Galitsky, Martin, Worrell, & Lehman, 2003).

Combined Mash Lauter Tun

A combined mash lauter tun unit operation was considered as an alternative to a separate mash tun and lauter tun system. The idea behind a combined mash lauter tun is that the processes of mashing and lautering occur in the same vessel and therefore the tank needs to be outfitted with components of both processes, a combination of a mixer and a separator. A major drawback of combining the two processes is that less control and efficiency is achieved in the mixing and separation of the wort from the grain bill. This is not ideal for large breweries and as Sierra Nevada Brewery noted, combining the two operations is highly inefficient in a large production brewery. The inefficiency from a combined system stems from the large retention times in mashing and lautering which if combined doubles the amount of process time, which is to say that you can mash and lauter with two separate vessels, but can only perform one of the separations at a time with the combined vessel. However, while the combined vessel is not satisfactory for large production breweries the operation is favorable for smaller brewers such as local craft brewers and home brewers. The benefit for smaller brewers is that the capital cost for purchasing a single combined vessel is far less than if two vessels were purchased to perform the same processes.

Kettle

As previously mentioned, one major aspect of the brew house is heat recovery. There is a significant amount of money spent on generating heat and if it is not properly recovered, money will be wasted generating more heat than necessary. One method to save money on heat generation would be to reprocess the spent grain used to create the wort. The dried grain could be used much like pellets to supplement natural gas used in a water boiler. This is also a great renewable initiative as the carbon dioxide generated would be utilized by growing more grain to be used to brew more beer, a carbon neutral process (Rhodes, 2008).

A major problem with this process is that the spent grain is saturated in a weak wort solution; thus, it is wet and sticky as it is removed from the brewing process. The drying process can be very energy intensive, which may cause the brewery to lose more money than it would gain from the savings in heating cost. Most drying processes involve heating the wet material to remove water, so there does not seem to be a good reason to try and dry the spent grain. This is why most breweries simply pay to send their spent grain to a nearby farm for animal feed.

One way to utilize Nevada's arid climate is to use a fluidized bed to dry the wet grain. This would remove the need for any heating element while minimizing the required area of a green house or solar heating apparatus. Since there are no moving parts, they yield reliable operation and low maintenance (Rhodes, 2008).

Fluidized bed particles are classified by their particle diameter and density as shown in figure 7. While the particle size of the spent grain varies, its diameter is roughly 5 mm and density difference with air of approximately 500 kg/m^3; therefore, biomass would be considered as a group D particle, as indicated by the star in figure 7.

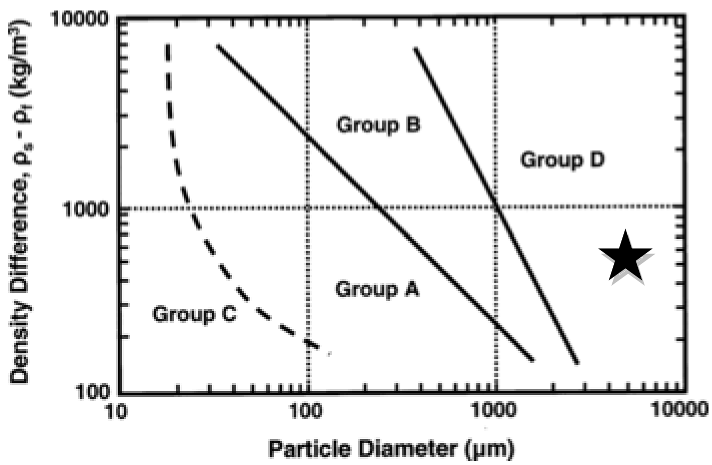

Figure 7: Geldart Particle Classifications (Mak, *et al.*)

Group D particles are characterized by their tendency to create large spouted beds as demonstrated by our previous research posted on YouTube (http://tinyurl.com/GroupDbed). Parry's handbook suggests the using equation (8) to determine the required fluid velocity to fluidized the bed:

$$u = \frac{D_p}{D_c}\left(\frac{D_o}{D_c}\right)^{0.33}\left[\frac{2gL(\rho_s - \rho_f)}{\rho_f}\right]^{0.5} \tag{8}$$

where u is the minimum fluidization velocity, D_p is the particle diameter, D_c is the column diameter, D_o is the air inlet diameter, g is gravitational acceleration, L is the length of the fluidized bed, and ρ_s and ρ_f are the solid and fluid densities, respectively. As an order of magnitude calculation, some approximations can be made as shown:

$$D_p := 5mm \quad D_c := 2in \quad D_o := 1mm \quad L := 2ft \quad \rho_s := 500\frac{kg}{m^3} \quad \rho_f := 1\frac{kg}{m^3}$$

$$u := \frac{D_p}{D_c}\cdot\left(\frac{D_o}{D_c}\right)^{.33}\cdot\left[\frac{2g\cdot L\cdot(\rho_s - \rho_f)}{\rho_f}\right]^{.5} \qquad u = 2.08\frac{m}{s}$$

Once dried, the spent grain can be stored in a silo where a mechanical corkscrew transpiration system will pass spent grain to a burning chamber where natural gas would usually be used to boil water. The natural gas line will still be required but can now act similar to a pilot light used in a conventional home heating system. A depiction of this system is shown in figure 8. When the spent grain is low, natural gas will solely be used to generate steam. The Alaska Brewing Company has reported 70% savings in natural gas usage from a similar system (Alaskan Brewery Company, 2011). At a price of \$4.27/GJ for natural gas as reported by the United States Department of Energy as of April 28th, 2011 (U.S. Energy Information Administration, 2011), the operating costs of the boiler are significantly reduced as shown in table 35.

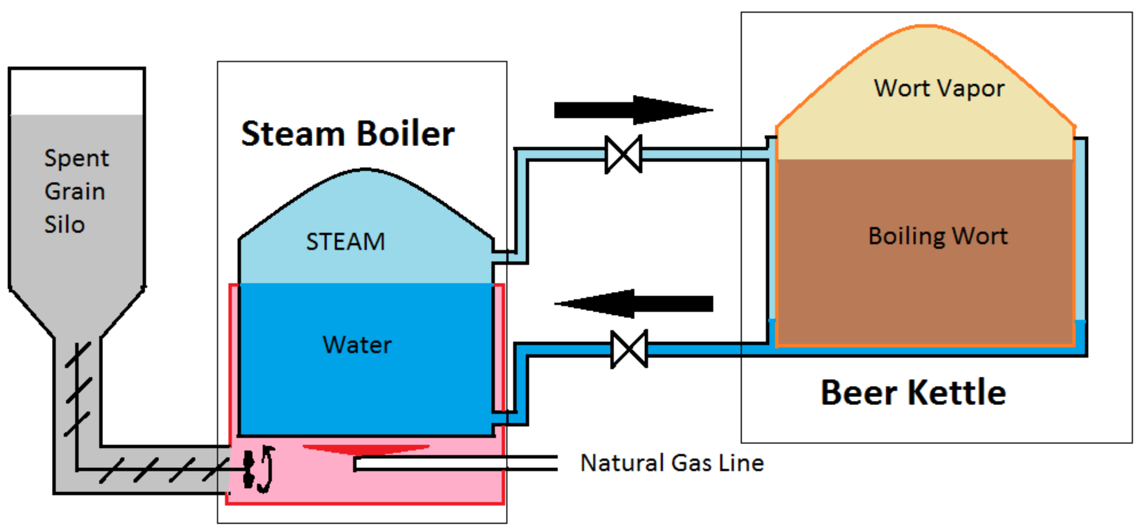

Figure 8: Utilization of Dried Grain

Table 35: Alternative Kettle Operating Costs

Production Rate (bbl/day)	Kettle Size (gal)	Steam used (Mg/day)	Natural Gas Used (kg/day)	Cost per day
300	1134	46.883	2836.86	$451.32
800	3024	143.347	8673.84	$1379.93
3000	11340	981.891	59413.62	$9452.18

Wort Cooler

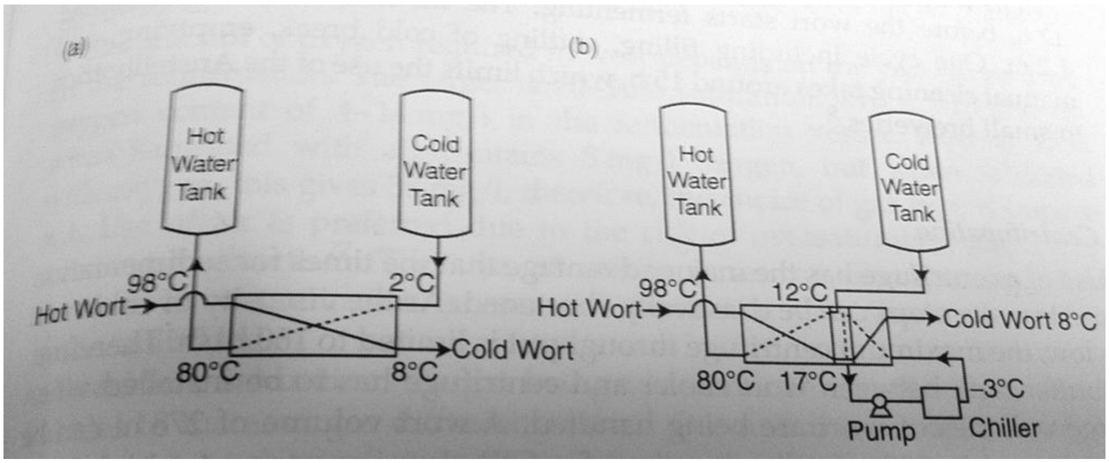

Figure 9: (a) Single Stage and (b) Two Stage Heat Exchangers (Priest & Stewart, 2006).

An alternative case to a one stage heat exchanger, as shown in figure 9, is to separate the cooling into two stages with a multi-stage heat exchanger. Figure 9 from Priest (437) shows these two setups. The idea behind this is to reduce operating costs by using readily available cold water at 12°C and recirculating another refrigerant, such as glycol or ammonia, rather than cooling water and losing it. This requires two separate heat exchangers, and therefore greater capital cost, but slightly reduces operating cost. It also allows for an easier control of the final temperature, important when using specialty yeasts.

Fermenter

Efficacious continuous fermentation is a major goal for beer producers. This is because continuous production makes very large scale production faster and more cost effective. Furthermore, at the large scale, such as in international breweries like Budweiser, only one product needs to be constantly produced, such that the decrease in production options afforded by batch production is not an important concern.

Continuous fermenters theoretically follow several design schemes. The two major design schemes are plug flow reaction and discrete continuous fermentation. Plug flow fermentation is more alike the true definition of continuous production, as it is a constant, uninterrupted flow. However, it is easier and possibly more cost effective to employ discrete fermentation. This setup involves using many smaller fermenters in series with such low residence times that the process approaches continuity from a perspective akin to Newtonian integration.

The alternative case design for this brewery uses 30 fermenters in series. This discrete continuous fermentation design utilizes immobilized yeast bioreactors to reduce fermentation time to 2 days. (I. B. Holcberg) Examples of various immobilized yeast systems are shown in Figure 4 of Appendix D. Appendix A shows the calculations used to find the sizes and costs of the fermenters. Utility costs will be similar to those for the batch fermentation scheme. Table 36 below is a summary of the calculations. CAPCOST, shown in Appendix D was used to determine the fermenter prices.

Table 36: Continuous Discrete Fermenter Design

Continuous Discrete Fermenter Design						
Production Rate	**Size (m^3)**	**Number**	**Cost per Unit($)**	**Total Cost ($)**	**Height (m)**	**Diameter (m)**
300 bbl/day	1.192	30	17600	528000	1.35	1.06
800 bbl/day	3.18	30	29700	891000	1.872	1.47
3000 bbl/day	11.924	30	59800	1794000	2.909	2.285

Centrifuge

Semi-Continuous Centrifuge

An alternative design consideration would be to use a semi-continuous centrifuge. This would require two centrifuges, instead of one, as there is a central holding cell that fills with waste and needs to be cleaned daily. The Western States Machine Company was consulted for base case considerations. A semi-continuous centrifuge greatly increases operating costs, but has a much lower initial capital cost. A 12,000 rpm rotation is required for the semi-continuous centrifuge, with a power requirement of 19kW. Table 37 shows semi-continuous centrifuge sizing and cost estimates. Cost estimates were performed using the CapCost Excel spreadsheet program. (McKetta & Cunningham, 1977) (Company, 2011) (Geankoplis, 2003) (Turton, Bailie, Whiting, & Shaeiwitz, 2009).

Table 37: The above table includes required sizing and cost estimates for the semi-continuous centrifuge.

Semi-Continuous Tubular Centrifuge		
Diameter	[cm]	19
Height	[m]	1.3
Solid holding volume	[L]	25
RPM		12000
Motor	[kW]	19
Estimated Cost Considerations		
Initial Capital Cost	$380,000	
Total Annual Operating Cost	$121,000	

Although the alternative case reduces initial costs, the operational costs are considerably higher. Moreover, Sierra Nevada Brewery advised against the semi-continuous centrifuge because of contamination issues during equipment cleaning.

Filter

An alternative case for the filter is a sheet filter. The sheet filter would require only half of the maintenance, and does not require breathing masks to be worked on. However, is the filter is not properly maintained it can cause a severe loss of pressure, and eventually the pressure build up can become so large as to cause an explosion. The sheet filters are also much more expensive than the DE filter, but are much less complicated to run and maintain.

Experimental Analysis

Hops in Brewing

Hops contain alpha acids. Alpha acids are converted to various isomers, or iso-alpha-acids (cis/trans forms), which provide hopped beer with the characteristic bitter flavor and taste. Additionally, Iso-alpha-acids provide various degrees of foam stability, assist in preserving and creating off-flavors to beer, and contribute to bacteriostatic, or growth limiting, properties within the brewing process. According to Hofta, the most common forms of iso-alpha acids contain normal, co- and ad- R groups which make up about 80% of final bitterness in beers. The isomerization of various alpha acids is provided in Figure 10.

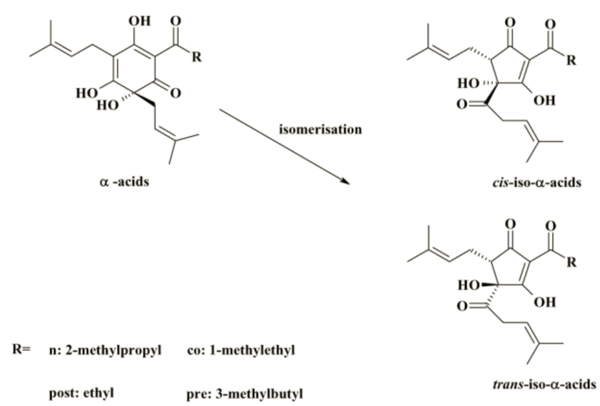

Figure 10: Cis/Trans Isomerization of Alpha Acids with Specific R Groups (Hofta, Dostálek, & Sýkora, 2007)

A suitable separation technique to identify iso-alpha-acids in brewing and chemically, specifically the structural isomers often referred as stereoisomers, is liquid phase chromatography under alkaline conditions (Hofta, Dostálek, & Sýkora, 2007). Further, cis/trans iso-alpha-acids can be differentiated by UV spectra evaluation, or spectroscopy techniques such as a spectrophotometer.

Hops Chemistry for Experimental Consideration

The commonly referred alpha/beta-acid and iso-alpha/beta acid of contained within the hop plant (*Humulus lupulus*) are known to contribute to the bitterness of beer (Wikipedia, 2010). However, the alpha/beta-acid and the isomerizations that are created by thermal decomposition during wort boiling are known by the chemistry community as humulones and iso-humulones (Verzele & De Keukeleire, 1991). Figure 11 provides the chemical decomposition that occurs when humulones are thermally isomerized into their cis/trans configurations.

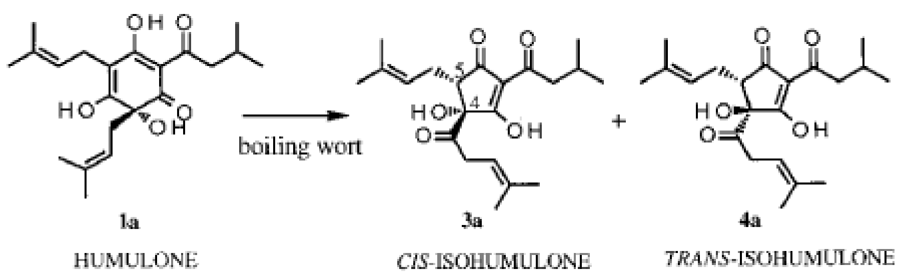

Figure 11: Conversion of the Humulones to the Isohumulones (Verzele & De Keukeleire, 1991)

The importance of identifying the type of acid within the hop is that if experimental analysis were to be instigated on the acidity of the hop, humulones and iso-humulones are the lead. Additionally, the IBU, International Bittering Unit, used to quantify bittering can be translated to the contribution made by the isohumulone by this rule of thumb “one IBU corresponding to 1 part per million of isohumulone.” (Wikipedia, 2010). Concerning the isohumulones effect on micro-organisms, it is known that the isomerized acid has a bacteriostatic effect on a wide variety of gram-positive bacteria (Blanco, Rojas, & Nimubona, 2007). Gram-positive bacteria are classified based on the bacteria’s ability to retain a purple stain in the Gram staining process. The purple stain remains in the bacteria due to the large amount of peptidoglycan (amino acids and disaccharides) within the cell wall. Gram-positive bacteria phylum includes the Firmicutes and Actinobacter which include common bacteria genus such as *Lactobacillus*, *Streptococcus*, and *Staphylococcus*. For experimental purposes it should be noted that yeast cells are Eukaryotic cells and the reported “bacterio-static effect” for bacteria is yet unknown for Eukaryotes and the inhibition threshold will be studied. Reasoning behind the inhibiting effects of hop compounds on bacteria includes the hop compounds ability to cross cytoplasmic membranes undissociated and dissociate in the cytoplasm, internally, which then go on to inhibit the active transport of sugars and amino-acids. (Blanco, Rojas, & Nimubona, 2007). According to the research conducted by Blanco, Rojas, and Nimubona, the conclusion to be drawn is that the iso-beta acid has the best ability to cross the cytoplasmic membrane followed by the iso-alpha acid. However, due to degradation of the iso-beta acid during wort boiling more of the iso-alpha acid is present in the final cooled wort imparting the wort and final beer with potential gram positive bacteriostatic properties.

Laboratory Experiment

In past years, previous Sierra Nevada Brewery projects have determined malt concentration is most influential factor of the final alcohol content in a brew. Malt concentration is used as a standard to compare other potential variables. Hops concentration greatly affects the α-acid concentration within the final product. It has been hypothesized that these acids may affect the yeast growth and therefore alcohol production in the final product. The yeast can also be very temperature specific when it comes to fermentation. The fermentation temperature is studied to see how much it affects the final product. Two outputs are measured in this experiment. The alcohol content is measured via specific gravity. General acidity will be measured by measuring the pH as this relates to the α-acid concentration.

In order to run a full three-factorial experiment, a total of 2^3=8 experiments must be run, each with a different combination of the three variables. The general procedure to produce 1L of beer has been created as a scaled down version of the procedure suggested by Charlie Papazian (Papazian, 2003).

1. 100 grams of malt extract is boiled in 1.25L of water for 1 hour, resulting in 1L of wart.
2. 2.5 grams of hops are added 30 minutes before the end of the boil.
3. Once boiled, the wart will be cooled in a cool water bath, then separated into two 600 mL beakers. Sufficient yeast will be added to each of these beakers.
4. An initial specific gravity measurement is taken.
5. Each beaker will be split into 3 Erlenmeyer flasks, where they will be sealed with an air lock and left to ferment. One of the sets of three will be left in the hood in the Unit Ops lab at room temperature while the other will be place in a small refrigerator.
6. After a week of fermentation, each sample has a final specific gravity and pH value measured.

The procedure produces a triplicate of two data points, one for the two temperatures of interest. These portions were used as the base case for experiment 1 as shown in table 38. The procedure can then be used again while doubling the malt extract added or hops added, or both. Table 38 shows full list of variables for each experiment. The malt added was intended to be 100 g for the first four experiments and 200 g for the final four but measuring precise masses of viscous fluids proved to be a difficult task.

Table 38: 3 Full Factorial Experiment Variables

Experiment	**Malt Added (g)**	**Hops Added (g)**	**Fermentation Temperature (°C)**	**Initial Specific Gravity**
1	104.6	2.5	20	1.029
2	104.6	2.5	5	1.029
3	107.1	5	20	1.031
4	107.1	5	5	1.031
5	203	2.5	20	1.056
6	203	2.5	5	1.056
7	203	5	20	1.073
8	203	5	5	1.073

Alcohol by Volume (ABV) produced can be measured by comparing initial and final specific gravities of a solution using the equation (9) (Papazian, 2003):

$$ABV = \frac{1.05}{0.79}\left(SG_i - SG_f\right) \tag{9}$$

where SG_i and SG_f represent initial and final specific gravity, respectively. 1.05 is a mass ratio of carbon dioxide produce per mass unit of ethanol. 0.79 represents the density of ethanol in grams per mL. Final results are shown in table 39. Full experimental results can be found in Appendix B.

Table 39: Final Experimental Data

Experiment	Average Final SG	Standard Deviation	Change in SG	ABV	Average pH	Standard Deviation
1	1.010	0.001	0.020	2.59%	4.19	0.02
2	1.002	0.001	0.027	3.56%	4.35	0.04
3	1.008	0.001	0.023	2.98%	4.23	0.01
4	1.019	0.003	0.012	1.55%	4.35	0.07
5	1.013	0.000	0.043	5.58%	4.37	0.03
6	1.048	0.002	0.008	1.00%	4.59	0.01
7	1.019	0.003	0.054	7.03%	4.44	0.04
8	1.047	0.003	0.026	3.41%	4.56	0.02

Full analysis of variance (ANOVA) of this data can be found in Appendix B. An augmented view of the ANOVA is presented in table 40. This table notes the effects of malt addition, hops addition, and fermentation temperature on alcohol production and acidity as measured via pH. It is observed that the hops addition statistically has a larger effect than malt addition based on the coefficients; however, for these values to be statistically significant, a P-value of 0.05 or less is desired. Thus, from our data, it cannot be determined with confidence which variable has a stronger effect on either alcohol production or acidity.

Table 40: Augmented ANOVA

	Alcohol Production		**Acidity**	
	Coefficients	*P-value*	*Coefficients*	*P-value*
Malt Added (g)	0.00016	0.28620	0.00220	0.00044
Hops Added (g)	0.00217	0.69262	0.00656	0.46137
Fermentation Temp (K)	0.00144	0.16510	-0.01028	0.00157

Lacking strong correlations from ANOVA, some qualitative trends can be observed from table 39. In three out of four cases, an increase in alcohol content resulted from increased fermentation temperature (exp 3vs4, 5vs6, 7vs8), increased hops concentration (exp 1vs3, 5vs7, 6vs8), and increased malt concentration (exp 1vs5, 3vs7, 4vs8). The degree of these increases varies from experiment to experiment so no strong correlation is observed. This is supported by a large P-value for all three variables. Similarly, qualitative analysis shows in all four cases, pH increases due to a decrease in fermentation temperature and increase in malt concentration, while hops addition had varying affects. The consistency of the fermentation temperature and malt addition effects yield a low P-value, but the large P-value for hops addition leaves its affects inconclusive.

Much of the error with this experiment can be contributed to experimental constraints. The wort production was performed in a waste sludge lab where airborne contaminants are very prevalent. As much care was taken to avoid contamination, it was a likely outcome. Another constraint was a limit on alcohol production. Such constraints limit the accuracy of hydrometer reading which may have cause error in alcohol production readings.

Conclusion

Brewery unit operation sizing and costing was determined for a 300, 800, and 3000 barrel per day brewery. The most affordable brewery, based on production per total costs, was the 3000 barrel per day brewery. Experimentation results were inconclusive overall. When the final project was presented to Sierra Nevada Brewery, several recommendations were made. One recommendation was that the currently limited scale of fermentation should be removed. Sierra Nevada Brewery believes this limitation could be a source of error during experimentation. Other engineering programs that work with the brewery are not hindered by this brewing limitation. Sierra Nevada Brewery also recommended that future teams investigate whirlpool waste heat recovery, improving the whirlpool precoolers, and reducing air leaks that are costing approximately $50,000 annually.

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APPENDIX A

Sample Calculations

Sample Calculations
Designing the Mash Tun, Estimates Using Heuristics and Known Examples

For an assumed cylindrical tank

$H_{mashtun} = 2 \cdot D_{mashtun}$ The heuristic that the the height to diameter ratio is 1:2

$V_{mashtun} = \frac{\pi}{4} \cdot D_{mashtun}^{2} \cdot H_{mashtun}$ Volume of a cylindrical tank

$D_{mashtun} = \text{Needs\_to\_be\_provided}$

Conversions:

$bbl := 31.5 \cdot gal$ US Fluid Barrel

$hL := 0.628981074385 \cdot bbl$

From the known details of a specific mash tun

$M_{malt} := 1600 \cdot kg$ $M_{malt} = 3527.396 \cdot lb$

$M_{grain.water} := \frac{M_{malt}}{.11111}$ According to the heuristic that cereal brew is about 10% Malt

$M_{grain.water} = 31746.883 \cdot lb$

$Malt_{\%} := \frac{M_{malt}}{M_{malt} + M_{grain.water}}$ $Malt_{\%} = 10 \cdot \%$

$Total_{mass.mash} := M_{grain.water} + M_{malt}$ $Total_{mass.mash} = 35274.279 \cdot lb$

The known volume of mash from literature is: $V_{mash} := 70 \cdot hL$

$\rho_{water} := 1000 \cdot \frac{kg}{m^3}$

An average density of the mash can be formulated as: $\rho_{avg.mash} := \frac{Total_{mass.mash}}{V_{mash}}$ $\rho_{avg.mash} = 503.918 \cdot \frac{lb}{hL}$

From the average mash density the mass of the mash can be calculated:

From the heuristic that to determine water mass: $1bbl_{water} = 125lb_{malt}$ The mass water to mass malt ratio follows as:

$M_{r.water} := \frac{1bbl}{125 \cdot lb} \cdot \frac{\rho_{water}}{1}$ $M_{r.water} = 2.103$

Three Rates:

$r_1 := 300 \cdot \frac{bbl}{day}$ $r_2 := 800 \cdot \frac{bbl}{day}$ $r_3 := 3000 \cdot \frac{bbl}{day}$

Mash Mass Rate	Malt Mass Rate	Water Mass Rate	Grain Mass Rate
$Mash_1 := r_1 \cdot \rho_{avg.mash}$	$Malt_1 := Mash_1 \cdot Malt_{\%}$	$Water_1 := Malt_1 \cdot M_{r.water}$	$Grain_1 := Mash_1 - Malt_1 - Water_1$
$Mash_2 := r_2 \cdot \rho_{avg.mash}$	$Malt_2 := Mash_2 \cdot Malt_{\%}$	$Water_2 := Malt_2 \cdot M_{r.water}$	$Grain_2 := Mash_2 - Malt_2 - Water_2$
$Mash_3 := r_3 \cdot \rho_{avg.mash}$	$Malt_3 := Mash_3 \cdot Malt_{\%}$	$Water_3 := Malt_3 \cdot M_{r.water}$	$Grain_3 := Mash_3 - Malt_3 - Water_3$
$Mash_1 = 240349.812 \cdot \frac{lb}{day}$	$Malt_1 = 24034.765 \cdot \frac{lb}{day}$	$Water_1 = 50546.121 \cdot \frac{lb}{day}$	$Grain_1 = 165768.927 \cdot \frac{lb}{day}$
$Mash_2 = 640932.833 \cdot \frac{lb}{day}$	$Malt_2 = 64092.706 \cdot \frac{lb}{day}$	$Water_2 = 134789.655 \cdot \frac{lb}{day}$	$Grain_2 = 442050.471 \cdot \frac{lb}{day}$
$Mash_3 = 2403498.124 \cdot \frac{lb}{day}$	$Malt_3 = 240347.649 \cdot \frac{lb}{day}$	$Water_3 = 505461.207 \cdot \frac{lb}{day}$	$Grain_3 = 1657689.268 \cdot \frac{lb}{day}$

Sample Calculations
Designing the Mash Tun, Estimates Using Heuristics and Known Examples

The preliminary total mash volume rates, for the 3 volumes, through the mash tun can be calculated using the average density provided above.

$Total_{V1} := \rho_{avg.mash}^{-1} \cdot Mash_1$ $\quad Total_{V2} := \rho_{avg.mash}^{-1} \cdot Mash_2$ $\quad Total_{V3} := \rho_{avg.mash}^{-1} \cdot Mash_3$

$Total_{V1} = 476.962 \cdot \frac{hL}{day}$ $\quad Total_{V2} = 1271.898 \cdot \frac{hL}{day}$ $\quad Total_{V3} = 4769.619 \cdot \frac{hL}{day}$

The retention time of the material in the mash tun for one batch is estimated in the literature as a maximum of approximately 1.5 hr to process and 20 min. for agitation. The total for the time comes to:

$T_{ret.mashtun} := 90 \cdot min + 20 \cdot min$

$T_{ret.mashtun} = 110 \cdot min$ This is the maximum mash tun retention time estimate for one batch based on heuristics.

Therefore the volume of mash in the mash tun for any give batch, using the maximum average retention time is calculated as follows:

$V_{mash.1} := Total_{V1} \cdot T_{ret.mashtun}$ $\quad V_{mash.2} := Total_{V2} \cdot T_{ret.mashtun}$ $\quad V_{mash.3} := Total_{V3} \cdot T_{ret.mashtun}$

$V_{mash.1} = 36.435 \cdot hL$ $\quad V_{mash.2} = 97.159 \cdot hL$ $\quad V_{mash.3} = 364.346 \cdot hL$

The dimensions of the mash tun with no void space can be estimated as follows:

$V_{mashtun} = V_{mash} = Base\_Assumption$

$H_{mashtun} = 2 \cdot D_{mashtun}$ $\quad V_{mashtun} = \frac{\pi}{4} \cdot D_{mashtun}^2 \cdot H_{mashtun}$ $\quad \boxed{V_{mashtun} = \frac{\pi}{2} \cdot D_{mashtun}^3}$

Diameter of the Mash Tun

$$D_{mashtun}(V_{mashtun}) := \left(V_{mashtun} \cdot \frac{2}{\pi}\right)^{\frac{1}{3}}$$

Height of the Mash Tun

$$H_{mashtun}(D_{mashtun}) := 2 \cdot D_{mashtun}$$

$D_{mash.1} := D_{mashtun}(V_{mash.1})$ $\quad H_{mash.1} := H_{mashtun}(D_{mash.1})$

$D_{mash.2} := D_{mashtun}(V_{mash.2})$ $\quad H_{mash.2} := H_{mashtun}(D_{mash.2})$

$D_{mash.3} := D_{mashtun}(V_{mash.3})$ $\quad H_{mash.3} := H_{mashtun}(D_{mash.3})$

Diameters of Mash Tun (with assumption)	Heights of Mash Tun (with assumption)	Mash Volume Assuming Mash Volume = Mash Tun Volume
$D_{mash.1} = 3.946 \cdot ft$	$H_{mash.1} = 7.892 \cdot ft$	$V_{mash.1} = 36.435 \cdot hL$
$D_{mash.2} = 5.472 \cdot ft$	$H_{mash.2} = 10.944 \cdot ft$	$V_{mash.2} = 97.159 \cdot hL$
$D_{mash.3} = 8.501 \cdot ft$	$H_{mash.3} = 17.002 \cdot ft$	$V_{mash.3} = 364.346 \cdot hL$

The heights and diameters provided only truly provide the mash volumes and not those of the actual tanks.

Sample Calculations:
Designing the Lauter Tun, Estimates Using Heuristics and Known Examples

For an assumed cylindrical tank

$H_{L.tun} = 5 \cdot D_{L.tun}$ The heuristic that the the height to diameter ratio is 1:5 (Mcketta)

$V_{Ltun} = \frac{\pi}{4} \cdot D_{Ltun}^{2} \cdot H_{Ltun}$ Volume of a cylindrical tank

Conversions:
$bbl := 31.5 \cdot gal$ US Fluid Barrel
$hL := 0.628981074385 \cdot bbl$

$D_{L.tun} = Needs\_to\_be\_provided$

From the known,k, details of a specific Lauter tun (Florian)

$V_{L.k} := 127.11 \cdot hL$ $ID_k := 3400 \cdot mm$ $H_k := \frac{V_{L.k} \cdot \frac{4}{\pi}}{ID_k^{2}}$ $H_k = 1.05 \cdot m$ $Specific_{Load.k} := 176.23 \frac{kg}{m^2}$

$Retention_{time.k} := 135 \cdot min$ $V_{L.wort.k} := 110 \cdot hL$ $Knives_{calc} := 1.65 \cdot \frac{1}{m^2}$

Three Rates:

$r_1 := 300 \cdot \frac{bbl}{day}$ $r_2 := 800 \cdot \frac{bbl}{day}$ $r_3 := 3000 \cdot \frac{bbl}{day}$ $r_k := \frac{V_{L.wort.k}}{Retention_{time.k}}$ $r_k = 738.004 \frac{bbl}{day}$

Where n is approximately 1

$\frac{r_1}{r_k} = \left(\frac{V_{L.1}}{V_{L.k}}\right)^n$ $\frac{r_2}{r_k} = \left(\frac{V_{L.2}}{V_{L.k}}\right)^n$ $\frac{r_3}{r_k} = \left(\frac{V_{L.3}}{V_{L.k}}\right)^n$

$V_{L.1} := \left(\frac{r_1}{r_k}\right) \cdot V_{L.k}$ $V_{L.2} := \left(\frac{r_2}{r_k}\right) \cdot V_{L.k}$ $V_{L.3} := \left(\frac{r_3}{r_k}\right) \cdot V_{L.k}$ $r_1 \cdot Retention_{time.k} = 44.715 \cdot hL$

$\boxed{V_{L.1} = 51.67 \cdot hL}$ $\boxed{V_{L.2} = 137.8 \cdot hL}$ $\boxed{V_{L.3} = 516.7 \cdot hL}$ These are the Lauter tank volumes for the three rates 300, 800, and 3000 bbl.

To determine the volume of wort produced by the lauter tun.

$\frac{r_1}{r_k} = \left(\frac{V_{L.wort.1}}{V_{L.wort.k}}\right)^n$ $\frac{r_2}{r_k} = \left(\frac{V_{L.wort.2}}{V_{L.wort.k}}\right)^n$ $\frac{r_3}{r_k} = \left(\frac{V_{L.wort.3}}{V_{L.wort.k}}\right)^n$

$V_{L.wort.1} := \left(\frac{r_1}{r_k}\right) \cdot V_{L.wort.k}$ $V_{L.wort.2} := \left(\frac{r_2}{r_k}\right) \cdot V_{L.wort.k}$ $V_{L.wort.3} := \left(\frac{r_3}{r_k}\right) \cdot V_{L.wort.k}$

$\boxed{V_{L.wort.1} = 44.7 \cdot hL}$ $\boxed{V_{L.wort.2} = 119.2 \cdot hL}$ $\boxed{V_{L.wort.3} = 447.2 \cdot hL}$

Sample Calculations:
Designing the Lauter Tun, Estimates Using Heuristics and Known Examples

Another way to calculate the wort times, which is essentially the same math as the ratio calculated above is to multiply the rate with the retention time to determine the wort volume in the tank.

$V_{L.wort1} := r_1 \cdot Retention_{time.k}$ $\quad V_{L.wort2} := r_2 \cdot Retention_{time.k}$ $\quad V_{L.wort3} := r_3 \cdot Retention_{time.k}$

$\boxed{V_{L.wort1} = 44.7 \cdot hL}$ $\quad \boxed{V_{L.wort2} = 119.2 \cdot hL}$ $\quad \boxed{V_{L.wort3} = 447.2 \cdot hL}$

Adding an additional 20% void space to the volume of the liquid wort should yeild similar tank volumes to those calculated by ratios above.

$V_{L.1.v} := V_{L.wort1} \cdot 1.2$ $\quad V_{L.2.v} := V_{L.wort2} \cdot 1.2$ $\quad V_{L.3.v} := V_{L.wort3} \cdot 1.2$

$\boxed{V_{L.1.v} = 53.7 \cdot hL}$ $\quad \boxed{V_{L.2.v} = 143.1 \cdot hL}$ $\quad \boxed{V_{L.3.v} = 536.6 \cdot hL}$

The tank volume of the lauter tun for various rates considering a void spaec of around 20% yeilds similar tank volumes to those calculated above. Therefore, the assumption that n = 1 is a valid assumption and the tank volumes used to calculate ratios are assumed more accurate (as 20% was an assumption use to calculate the void space).

The number of rakes can be calculated from the heuristic provided with the known lauter tun. The number of rakes is based on the cross sectional area of the tank. To calculate the cross sectional area, the diameter and height will need to be calculated for each case. The heights and diameters provided are for a 1:5 ratio.

$V_{Ltun} = \frac{\pi}{4} \cdot D_{Ltun}^{2} \cdot H_{Ltun}$ $\quad H_{L.tun} = 5 \cdot D_{L.tun}$ $\quad H_{L.t}(D_{L.t}) := 5 \cdot D_{L.t}$

$ID_{L1} := \left[\left(\frac{4}{5 \cdot \pi}\right) \cdot V_{L.1}\right]^{\left(\frac{1}{3}\right)}$ $\quad ID_{L2} := \left[\left(\frac{4}{5 \cdot \pi}\right) \cdot V_{L.2}\right]^{\left(\frac{1}{3}\right)}$ $\quad ID_{L3} := \left[\left(\frac{4}{5 \cdot \pi}\right) \cdot V_{L.3}\right]^{\left(\frac{1}{3}\right)}$

$\boxed{ID_{L1} = 3.266 \cdot ft}$ $\quad \boxed{ID_{L2} = 4.53 \cdot ft}$ $\quad \boxed{ID_{L3} = 7.037 \cdot ft}$

$H_{L.1} := H_{L.t}(ID_{L1})$ $\quad H_{L.2} := H_{L.t}(ID_{L2})$ $\quad H_{L.3} := H_{L.t}(ID_{L3})$

$\boxed{H_{L.1} = 16.3 \cdot ft}$ $\quad \boxed{H_{L.2} = 22.6 \cdot ft}$ $\quad \boxed{H_{L.3} = 35.2 \cdot ft}$

Sample Calculations:
Designing the Lauter Tun, Estimates Using Heuristics and Known Examples

The number of knives should be calculated via the area of the known tank so that the knives heuristic can be used from an estimated area based on the diameter to height ratio of 1:3.238. A second set of values for tank heights and diameters is provided as follows:

$$ratio_{D.H} := \frac{ID_k}{H_k} \qquad ratio_{D.H} = 3.238$$

$$ID_{L11} := \left[\left[\frac{4}{\left(ratio_{D.H}\right)^{-1}\cdot\pi}\right]\cdot V_{L.1}\right]^{\left(\frac{1}{3}\right)} \qquad ID_{L22} := \left[\left[\frac{4}{\left(ratio_{D.H}\right)^{-1}\cdot\pi}\right]\cdot V_{L.2}\right]^{\left(\frac{1}{3}\right)} \qquad ID_{L33} := \left[\left[\frac{4}{\left(ratio_{D.H}\right)^{-1}\cdot\pi}\right]\cdot V_{L.3}\right]^{\left(\frac{1}{3}\right)}$$

$$\boxed{ID_{L11} = 8.263\cdot ft} \qquad \boxed{ID_{L22} = 11.459\cdot ft} \qquad \boxed{ID_{L33} = 17.803\cdot ft}$$

$$H_{L.11} := \frac{ID_{L11}}{ratio_{D.H}} \qquad H_{L.22} := \frac{ID_{L22}}{ratio_{D.H}} \qquad H_{L.33} := \frac{ID_{L33}}{ratio_{D.H}}$$

$$\boxed{H_{L.11} = 2.6\cdot ft} \qquad \boxed{H_{L.22} = 3.5\cdot ft} \qquad \boxed{H_{L.33} = 5.5\cdot ft}$$

The number of are calculated as follows, from the second set of heights and volumes using the calculated ratio:

$$Knives_1 := Knives_{calc}\cdot\left(\frac{\pi}{4}\cdot ID_{L11}{}^2\right) \qquad Knives_2 := Knives_{calc}\cdot\left(\frac{\pi}{4}\cdot ID_{L22}{}^2\right) \qquad Knives_3 := Knives_{calc}\cdot\left(\frac{\pi}{4}\cdot ID_{L33}{}^2\right)$$

$$\boxed{Knives_1 = 8.2} \qquad \boxed{Knives_2 = 15.8} \qquad \boxed{Knives_3 = 38.2}$$

The volume of the tank and the volume of the liquid wort for the three throughputs of, 300, 800, and 3000 bbl for the lauter tanks appear reasonable. However, the actual height and diameter vary slightly dependent on the the chose height to diameter ratio. The knives heuristic is also reasoanble and is dependent on the cross sectional area of the lauter tun tank.

Kettle Sample Calculations

$T_1 := 406.7K \quad t_1 := 349.7K \quad t_2 := 373.2K \quad C := 1918.1 \frac{J}{kg \cdot K} \quad c := 4224.9 \frac{J}{kg \cdot K} \quad U := 900 \frac{J}{m^2 \cdot s \cdot K}$

$\theta := 3600s \quad \rho := 1040 \frac{kg}{m^3} \quad brew := 1 \quad dollar := 1 \quad Mg := 1000kg$

Kettle Dimensions:

$V_{300} := 945gal \cdot 120\% = 1134 \cdot gal \quad V_{800} := 2520gal \cdot 120\% = 3024 \cdot gal \quad V_{3000} := 9450gal \cdot 120\% = 11340 \cdot gal$

$r_{300} := 2.72ft \quad r_{800} := 3.77ft \quad r_{3000} := 5.86ft$

$h_{300} := 5.44ft \cdot 120\% = 6.528 \cdot ft \quad h_{800} := 7.54ft \cdot 120\% = 9.048 \cdot ft \quad h_{3000} := 11.72ft \cdot 120\% = 14.064 \cdot ft$

$A_{300} := \pi \cdot r_{300}^2 + \pi \cdot r_{300} \cdot h_{300} \quad A_{800} := \pi \cdot r_{800}^2 + \pi \cdot r_{800} \cdot h_{800} \quad A_{3000} := \pi \cdot r_{3000}^2 + \pi \cdot r_{3000} \cdot h_{3000}$

$M_{300} := 945gal \cdot \rho = 3720\,kg \quad M_{800} := 2520gal \cdot \rho = 9921\,kg \quad M_{3000} := 9450gal \cdot \rho = 37203\,kg$

$\ln\left(\frac{T_1 - t_1}{T_1 - t_2}\right) = 0.532 \quad K_1(W, A) := \exp\left(\frac{U \cdot A}{W \cdot C}\right) \quad W_{300g} := 1\frac{kg}{s} \quad W_{800g} := 1\frac{kg}{s} \quad W_{3000g} := 1\frac{kg}{s}$ Given

$$\ln\left(\frac{T_1 - t_1}{T_1 - t_2}\right) = \frac{W_{300g} \cdot C}{M_{300} \cdot c} \cdot \left(\frac{K_1(W_{300g}, A_{300}) - 1}{K_1(W_{300g}, A_{300})}\right) \cdot \theta \quad \ln\left(\frac{T_1 - t_1}{T_1 - t_2}\right) = \frac{W_{800g} \cdot C}{M_{800} \cdot c} \cdot \left(\frac{K_1(W_{800g}, A_{800}) - 1}{K_1(W_{800g}, A_{800})}\right) \cdot \theta$$

$$\ln\left(\frac{T_1 - t_1}{T_1 - t_2}\right) = \frac{W_{3000g} \cdot C}{M_{3000} \cdot c} \cdot \left(\frac{K_1(W_{3000g}, A_{3000}) - 1}{K_1(W_{3000g}, A_{3000})}\right) \cdot \theta$$

$$\begin{pmatrix} W_{300} \\ W_{800} \\ W_{3000} \end{pmatrix} := \text{Find}(W_{300g}, W_{800g}, W_{3000g})$$

$$\begin{pmatrix} W_{300} \\ W_{800} \\ W_{3000} \end{pmatrix} = \begin{pmatrix} 1.302 \\ 3.982 \\ 27.275 \end{pmatrix} \frac{kg}{s} \quad \begin{pmatrix} W_{300} \\ W_{800} \\ W_{3000} \end{pmatrix} \cdot \theta = \begin{pmatrix} 4688.26 \\ 14334.66 \\ 98189.06 \end{pmatrix} \cdot \frac{kg}{brew} \quad \begin{pmatrix} W_{300} \\ W_{800} \\ W_{3000} \end{pmatrix} \cdot \theta \cdot 10 \frac{brew}{day} = \begin{pmatrix} 46.883 \\ 143.347 \\ 981.891 \end{pmatrix} \cdot \frac{Mg}{day}$$

$$\begin{pmatrix} W_{300} \\ W_{800} \\ W_{3000} \end{pmatrix} \cdot \theta \cdot 10 \frac{brew}{day} \cdot \frac{29.29 \cdot dollar}{1000kg} = \begin{pmatrix} 1373.19 \\ 4198.62 \\ 28759.58 \end{pmatrix} \cdot \frac{dollar}{day}$$

$hL := 100L$ $\quad\quad USD := 1$

$Vol := \frac{\pi}{4}\cdot(2.7m)^{2}\cdot 3m \quad Vol = 171.767\cdot hL \quad Cost := 90000USD$

$C(A) := Cost\cdot\left(\frac{A}{Vol}\right)^{.6}$

$$C\left(\begin{pmatrix} V_{300} \\ V_{800} \\ V_{3000} \end{pmatrix}\right) = \begin{pmatrix} 39166.524 \\ 70549.879 \\ 155924.742 \end{pmatrix}$$

Whirl Pool Sample Calculations

300 Barrels per day

1 Barrel = 31 Gallons

$Vfinal := 300 \cdot 31 = 9.3 \times 10^{3}$

$\frac{9300}{7.48} = 1.243 \times 10^{3}$ cfpd

$venter := \frac{9300}{7.48 \cdot 24 \cdot 60 \cdot 60}$

$venter = 0.014$ cfs

$vl := venter \cdot 28.3 = 0.407$ lps

Assume operation 90% of the time = 7884 hours of production

$vt := 7884 \cdot 32.3 = 2.547 \times 10^{5}$ hl per year

$\frac{.407}{1000} = 4.07 \times 10^{-4}$ cmps

Assume entering stream is 15% waste solids to be removed
Assume a particle diameter of 0.8 um

Assume a desired retention time in the vessel of 60 mins (3600 seconds)

Assume a liquid density of 1060 kg per cubic liter for the liquid

Assume a desity of 800 kg per cubic liter

Assume 40 rotations per min

.667 rot per sec

$D := 4m$ $H := 1m$

$C := 3.1415 \cdot D = 12.566\,m$

$Vtot := 3.1414 \cdot \left(\frac{D}{2}\right)^{2} \cdot H = 1.257 \times 10^{4}\,L$

$vtan := C \cdot 0.667 = 8.382\,m$

Heat Exchanger Sample Calculations

$T_{hi} := 98\,°C \quad T_{ho} := 8\,°C \quad T_{ci} := 2\,°C \quad T_{co} := 80\,°C \quad t := 10\text{min} \quad \rho := 1040\,\frac{kg}{m^3} \quad U := 4500\,\frac{W}{m^2 \cdot K}$

$M_{300} := 945\text{gal} \cdot \rho = 3720\,kg \quad M_{800} := 2520\text{gal} \cdot \rho = 9921\,kg \quad M_{3000} := 9450\text{gal} \cdot \rho = 37203\,kg$

$Mw_{water} := 18.02\,\frac{kg}{mol} \quad MJ := 10^6 J \quad Mg := 1000kg$

Water Heat Capacity: $C_p(T) := \left[72.43 + .01039 \cdot \frac{T}{K} - 1.497 \cdot 10^{-6} \cdot \left(\frac{T}{K}\right)^2\right] \cdot \frac{J}{mol \cdot K}$ (Elliot)

$$Q_{wort}(M) := \frac{M}{Mw_{water}} \cdot \int_{T_{ho}}^{T_{hi}} C_p(T)\,dT \qquad \Delta T_{lm} := \frac{\left[\left(T_{hi} - T_{co}\right) - \left(T_{ho} - T_{ci}\right)\right]}{\ln\left[\frac{\left(T_{hi} - T_{co}\right)}{\left(T_{ho} - T_{ci}\right)}\right]}$$

$$A(M) := \frac{Q_{wort}(M)}{U \cdot \Delta T_{lm} \cdot t} \qquad m_{cw}(M) := \frac{Q_{wort}(M) \cdot Mw_{water}}{\int_{T_{ci}}^{T_{co}} C_p(T)\,dT}$$

$$\begin{pmatrix} Q_{300} \\ Q_{800} \\ Q_{3000} \end{pmatrix} := Q_{wort}\left(\begin{pmatrix} M_{300} \\ M_{800} \\ M_{3000} \end{pmatrix}\right) = \begin{pmatrix} 1.406 \\ 3.749 \\ 14.058 \end{pmatrix} \cdot MJ$$

$$\begin{pmatrix} A_{300} \\ A_{800} \\ A_{3000} \end{pmatrix} := A\left(\begin{pmatrix} M_{300} \\ M_{800} \\ M_{3000} \end{pmatrix}\right) = \begin{pmatrix} 0.513 \\ 1.368 \\ 5.131 \end{pmatrix} \cdot ft^2 \qquad \begin{pmatrix} m_{300} \\ m_{800} \\ m_{3000} \end{pmatrix} := m_{cw}\left(\begin{pmatrix} M_{300} \\ M_{800} \\ M_{3000} \end{pmatrix}\right) = \begin{pmatrix} 4.299 \\ 11.464 \\ 42.991 \end{pmatrix} \cdot Mg$$

Refrigerated Water from Turton pg 231 $\quad USD := 1 \quad RW := (0.185 + .067) \cdot \frac{USD}{1000 \cdot kg}$

$$Cost := \begin{pmatrix} m_{300} \\ m_{800} \\ m_{3000} \end{pmatrix} \cdot RW = \begin{pmatrix} 1.08337 \\ 2.88898 \\ 10.83367 \end{pmatrix}$$

Discrete Fermenter Design

$bbl := 31.5gal$

$bpd := \begin{pmatrix} 300 \\ 800 \\ 3000 \end{pmatrix} bbl$

$ncf := 30$

$iybt := 2day$

$barrels_{per.day} := bpd$

$continuous_{discrete.fermenter.number} := ncf$

$immobilized_{yeast.bioreactor.fermentation.time} := iybt$

$$fermentersize := \frac{bpd}{ncf} = \begin{pmatrix} 10 \\ 26.667 \\ 100 \end{pmatrix} \cdot bbl$$

$$retentiontime := \frac{fermentersize}{\left(\frac{bpd}{iybt}\right)} = \begin{pmatrix} 0.067 \\ 0.067 \\ 0.067 \end{pmatrix} \cdot day$$

$$fermentersize = \begin{pmatrix} 1.192 \\ 3.18 \\ 11.924 \end{pmatrix} \cdot m^3$$

$$FermenterCost := \begin{pmatrix} 17600 \\ 29700 \\ 59800 \end{pmatrix}$$

$$TotalCost := FermenterCost \cdot ncf = \begin{pmatrix} 5.28 \times 10^5 \\ 8.91 \times 10^5 \\ 1.794 \times 10^6 \end{pmatrix}$$

$n := 0..2$

$$fermenterdiameter_n := \left(fermentersize_n\right)^{\frac{1}{3}}$$

$$fermenterheight_n := \frac{fermentersize_n}{\left(fermenterdiameter_n\right)^2 \cdot \frac{\pi}{4}}$$

$$fermenterheight = \begin{pmatrix} 1.35 \\ 1.872 \\ 2.909 \end{pmatrix} m$$

$$fermentercheck_n := \left(fermenterdiameter_n\right)^2 \cdot \frac{\pi}{4} \cdot fermenterheight_n$$

$$fermenterdiameter = \begin{pmatrix} 1.06 \\ 1.47 \\ 2.285 \end{pmatrix} m$$

$$fermentercheck = \begin{pmatrix} 1.192 \\ 3.18 \\ 11.924 \end{pmatrix} \cdot m^3$$

Fermenter Costing and Design.

Fermenter Volume

$bbl := 31.5gal$ $300bbl = 35.772 \cdot m^3$

Fermenter Costing

$K1 := 4.1052$

$K2 := -0.4680$

$K3 := -0.0005$

capacity in m^3
minimum size 0.1, maximum 35 $A := 35.8m^3$

$$\log(Cp) = K_1 + K_2 \cdot \log(A) + K_3 \cdot \log(A)^2$$

$$Cp := 10^{K1+K2\cdot\log\left(\frac{A}{m^3}\right)+K3\cdot\log\left(\frac{A}{m^3}\right)^2} = 2.381 \times 10^3$$

$Cp \cdot 4 \cdot 12 = 1.143 \times 10^5$

Derivation of Fermenter Sizing (solve for r)

$h_t = 2 \cdot r$

$cone = \frac{1}{3} \cdot \pi \cdot r^2 \cdot h_c$

$cylinder = \pi \cdot r^2 \cdot h_y$

$h_y + h_c = 2r$

$cone + cylinder = A$

$\tan\left(\frac{\pi}{6}\right) = \frac{r}{h}$ $\tan\left(30 \cdot \frac{\pi}{180}\right) = 0.577$

$A := 36$ $h_c := 1$ $h_y := 2$ $r := 3$

Given

$\frac{1}{3} \cdot \pi \cdot r^2 \cdot h_c + \pi \cdot r^2 \cdot h_y = A$ $\tan\left(\frac{\pi}{6}\right) = \frac{r}{h_c}$ $h_y + h_c = 2r$

$\text{Find}(r, h_y, h_c) = \begin{pmatrix} 2.384 \\ 0.639 \\ 4.13 \end{pmatrix}$ $cylinder := \pi \cdot 2.384^2 \cdot 0.639 = 11.409$ $cone := \pi \cdot \frac{1}{3} \cdot 2.384^2 \cdot 4.13 = 24.581$

Operating Cost of Labor

Because fermenters usually have an associated heat exchanger, we will assume an N.np of 2 for the fermenter (a reactor) and for the heat exchanger.

$$N_{np} := 2$$

$$N_{OL} := \left(6.29 + 0.23 \cdot N_{np}\right)^{0.5} = 2.598$$

This is rounded up to 3, since you can't have 2.6 people. Using an average cost per laborer of $52900 per year...

$$3 \cdot 52900 = 1.587 \times 10^{5}$$

Fermentation of sugar, mostly glucose releases 118 kJ/mol. Wort generally has an SG of 1.2 before fermentation. Most of this weight is due to the dissolved glucose. With an extra .2g sugar / g water, we can do a simple conversion to determine the approximate molar amount of sugar in a typical fermentation vessel. This requires a calculation of the typical brew conversion of sugars. The typical yeast stops converting at about 5% ethanol. 1 mole of glucose yields 2 of ethanol.

$$\rho_{h2o} := 1 \frac{gm}{mL} \qquad mw_{h2o} := 18 \frac{gm}{mol} \qquad kJ := 1000J \qquad GJ := 10^{9} J$$

$$\rho_{etoh} := .79 \frac{gm}{mL} \qquad mw_{etoh} := 46.07 \frac{gm}{mol} \qquad energy_{rxn} := 118 \frac{kJ}{mol}$$

$$mw_{glucose} := 180.16 \frac{gm}{mol}$$

$$V_{ferm} := 35.7m^{3}$$

$$mass_{wort} := V_{ferm} \cdot 1.2 \frac{gm}{mL} = 4.284 \times 10^{4} kg$$

$$mass_{sugar} := \frac{.2}{1.2} \cdot mass_{wort} = 7.14 \times 10^{3} kg$$

$$mol_{sugar} := \frac{mass_{sugar}}{mw_{glucose}} = 3.963 \times 10^{4} mol$$

$$mass_{etoh} := V_{ferm} \cdot 5\% \cdot \rho_{etoh} = 1.41 \times 10^{3} kg$$

$$mol_{etoh} := \frac{mass_{etoh}}{mw_{etoh}} = 3.061 \times 10^{4} mol$$

$$conversion := \frac{\frac{mol_{sugar}}{2}}{mol_{etoh}} = 0.647$$

$$mol_{sugar.converted} := conversion \cdot mol_{sugar} = 2.566 \times 10^4\ mol$$

$$heat_{generated} := mol_{sugar.converted} \cdot energy_{rxn} = 3.028 \times 10^9\ J$$

Refrigration costs to keep the fermenter at the same temperature run at 4.43 $/GJ. The heat generated given above is for an entire fermenter batch. The per annum value is going to be

$$PerAnnumCost := 365 \cdot heat_{generated} \cdot \frac{4.43}{GJ} = 4.895 \times 10^3$$

Therefore, the cooling costs of the fermenter are about $4900 per annum.

Kettle Operating Costs Sample Calculations

$kJ := 1000J$ $Mg := 1000kg$ $MJ := 1000kJ$ $USD := 1$

$\Delta H_w := 2257 \frac{kJ}{kg}$

Steam Demand $SD := \begin{pmatrix} 46.883 \\ 143.347 \\ 981.891 \end{pmatrix} \frac{Mg}{day}$

$NGE := 37.3 \frac{MJ}{kg}$ $Price := \frac{4.5USD}{10^6 BTU}$

$NC := \Delta H_w \cdot SD \cdot Price$ $NC = \begin{pmatrix} 451.32 \\ 1379.93 \\ 9452.18 \end{pmatrix} \cdot \frac{USD}{day}$ $\frac{\Delta H_w \cdot SD}{NGE} = \begin{pmatrix} 2836.86 \\ 8673.84 \\ 59413.62 \end{pmatrix} \cdot \frac{kg}{day}$

$OC := \begin{pmatrix} 1373.19 \\ 4198.62 \\ 28759.58 \end{pmatrix} \frac{USD}{day}$ $n := 0..2$

$\frac{NC_n}{OC_n} =$

0.329
0.329
0.329

APPENDIX B

Experimental Data

Experimental Data

	Experiment	Malt Added (g)	Hops Added (g)	Fermentation Temperature (K)	Fermentation Temperature (°C)	Initial Specific Gravity	Initial SG Temp	Correction Factor	Corrected Initial SG
MHT+	1	104.6	2.5	293	20	1.028	22	0.0013	1.029
MHT-	2	104.6	2.5	278	5	1.028	22	0.0013	1.029
MH+T+	3	107.1	5	293	20	1.03	21	0.0011	1.031
MH+T-	4	107.1	5	278	5	1.03	21	0.0011	1.031
M+HT+	5	203	2.5	293	20	1.054	23	0.0016	1.056
M+HT-	6	203	2.5	278	5	1.054	23	0.0016	1.056
M+H+T+	7	203	5	293	20	1.07	27	0.0026	1.073
M+H+T-	8	203	5	278	5	1.07	27	0.0026	1.073

Sample 1

pH	Final SG	Temp	Correction	Corrected Final SG
4.17	1.008	19.6	0.0008	1.009
4.39	1.002	14.3	-0.0001	1.002
4.23	1.006	20.4	0.0010	1.007
4.37	1.022	13.8	-0.0002	1.022
4.35	1.012	20.8	0.0011	1.013
4.6	1.05	7.8	-0.0007	1.049
4.4	1.019	20.7	0.0010	1.020
4.55	1.048	7.4	-0.0008	1.047

Sample 2

pH	Final SG	Temp	Correction	Corrected Final SG
4.2	1.008	19.6	0.0008	1.009
4.34	1.002	13.5	-0.0002	1.002
4.23	1.008	20.2	0.0009	1.009
4.27	1.016	15.6	0.0001	1.016
4.37	1.012	20.5	0.0010	1.013
4.58	1.05	7.7	-0.0008	1.049
4.48	1.02	20.7	0.0010	1.021
4.56	1.044	8	-0.0007	1.043

pH	Final SG	Temp	Correction	Corrected Final SG
4.17	1.008	19.6	0.0008	1.009
4.2	1.008	19.6	0.0008	1.009
4.21	1.01	21.7	0.0013	1.011
4.39	1.002	14.3	-0.0001	1.002
4.34	1.002	13.5	-0.0002	1.002
4.31	1.003	14.3	-0.0001	1.003
4.23	1.006	20.4	0.0010	1.007
4.23	1.008	20.2	0.0009	1.009
4.22	1.008	21.4	0.0012	1.009
4.37	1.022	13.8	-0.0002	1.022
4.27	1.016	15.6	0.0001	1.016
4.41	1.02	14.5	-0.0001	1.020

Average Final SG	Standard Dev	Change in SG	Average pH	Standard Dev
1.010	0.001	0.020	4.19	0.02
1.002	0.001	0.027	4.35	0.04
1.008	0.001	0.023	4.23	0.01
1.019	0.003	0.012	4.35	0.07

Sample 3

pH	Final SG	Temp	Correction	Corrected Final SG	Average Final SG	Standard Dev	Change in SG	Average pH	Standard Dev	ABV
4.21	1.01	21.7	0.0013	1.011	1.010	0.001	0.020	4.19	0.02	2.59%
4.31	1.003	14.3	-0.0001	1.003	1.002	0.001	0.027	4.35	0.04	3.56%
4.22	1.008	21.4	0.0012	1.009	1.008	0.001	0.023	4.23	0.01	2.98%
4.41	1.02	14.5	-0.0001	1.020	1.019	0.003	0.012	4.35	0.07	1.55%
4.4	1.012	20.6	0.0010	1.013	1.013	0.000	0.043	4.37	0.03	5.58%
4.6	1.046	8.7	-0.0007	1.045	1.048	0.002	0.008	4.59	0.01	1.00%
4.45	1	20.6	0.0010	1.016	1.019	0.003	0.054	4.44	0.04	7.03%
4.58	1.05	7	-0.0008	1.049	1.047	0.003	0.026	4.56	0.02	3.41%

Experiment	Average Final SG	Standard Dev	Change in SG	ABV	Average pH	Standard Dev
1	1.010	0.001	0.020	2.59%	4.19	0.02
2	1.002	0.001	0.027	3.56%	4.35	0.04
3	1.008	0.001	0.023	2.98%	4.23	0.01
4	1.019	0.003	0.012	1.55%	4.35	0.07
5	1.013	0.000	0.043	5.58%	4.37	0.03
6	1.048	0.002	0.008	1.00%	4.59	0.01
7	1.019	0.003	0.054	7.03%	4.44	0.04
8	1.047	0.003	0.026	3.41%	4.56	0.02

Alcohol per Volume

Regression Statistics	
Multiple R	0.730744518
R Square	0.533987551
Adjusted R Square	0.184478215
Standard Error	0.018040554
Observations	8

ANOVA

	df	SS	MS	F	Significance F
Regression	3	0.001491741	0.000497247	1.527820563	0.337028514
Residual	4	0.001301846	0.000325462		
Total	7	0.002793587			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-0.410260937	0.244458844	-1.678241339	0.168602438	-1.088987497	0.268465623
Malt Added (g)	0.000161453	0.000131297	1.22967371	0.286201269	-0.000203087	0.000525993
Hops Added (g)	0.002169463	0.005103061	0.425129665	0.692615083	-0.011998907	0.016337833
Fermentaiton Temp (K)	0.001442466	0.00085044	1.696141547	0.165099862	-0.000918733	0.003803666

pH

Regression Statistics	
Multiple R	0.988582091
R Square	0.97729455
Adjusted R Square	0.960265462
Standard Error	0.028513794
Observations	8

	Alcohol Production		Acidity	
	Coefficients	P-value	Coefficients	P-value
Malt Added (g)	0.00016	0.28620	0.00220	0.00044
Hops Added (g)	0.00217	0.69262	0.00656	0.46137
Fermentaiton Tem	0.00144	0.16510	-0.01028	0.00157

ANOVA

	df	SS	MS	F	Significance F
Regression	3	0.139979799	0.046659933	57.38971882	0.000959285
Residual	4	0.003252146	0.000813036		
Total	7	0.143231944			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	6.955582378	0.38637667	18.00207651	5.59731E-05	5.882828763	8.028335992
Malt Added (g)	0.00220402	0.000207521	10.62072537	0.000444932	0.00162785	0.002780189
Hops Added (g)	0.006564657	0.008065586	0.813909454	0.461372058	-0.015829001	0.028958314
Fermentaiton Temp (K)	-0.010277778	0.001344153	-7.646284864	0.001571746	-0.014009745	-0.00654581

APPENDIX C

Quotation

GEA Brewery Systems				**Quotation**	
Custom Builder to Your Specifications					
				DATE	March 18, 2011
				Quotation #	
Heinrich-Huppmann-Str. 1, 97318 Kitzingen, Germany,				**Customer ID**	
Phone: +49 (0)9321/303-0, Fax: +49 (0)9321/303-124</brlocations:					
800 bbl Malt Mill				*Quotation valid:*	For 30 days
				Prepared by:	Thomas Bachmeier
MILLSTAR™	1	6 adjustable rollers, with 1000 lbs capacity hopper		7,000 lbs/h	281,000.00

APPENDIX D

Fermentation Figures

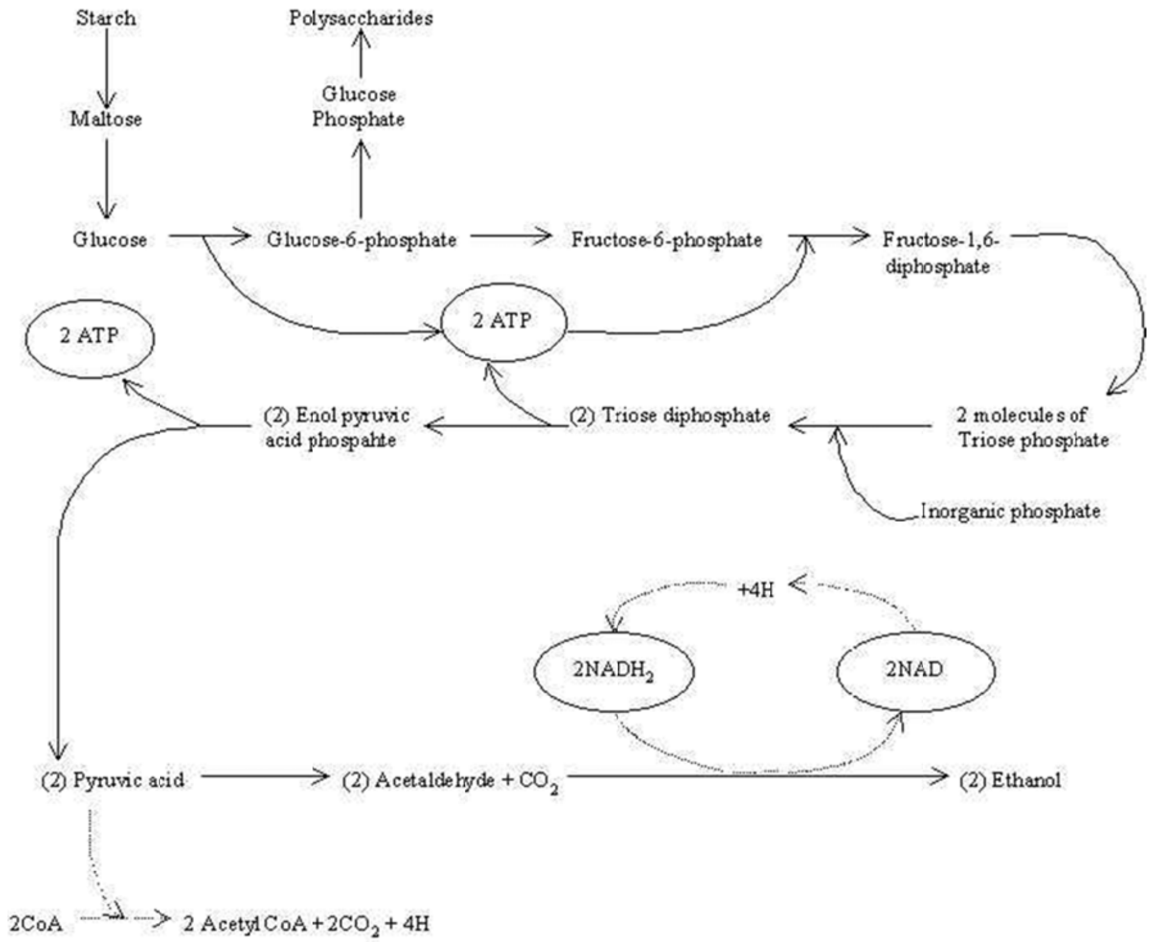

Fig . The glycolytic (Embden-Meyerhof-Parnas) pathway for glucose dissimilation.

Figure 1: Fermentation/Ethanol Production Biochemistry (Biochemistry in Beer Brewing)

Figure 2: Standard Fermenter Design (Brewery Fermenter Picture)

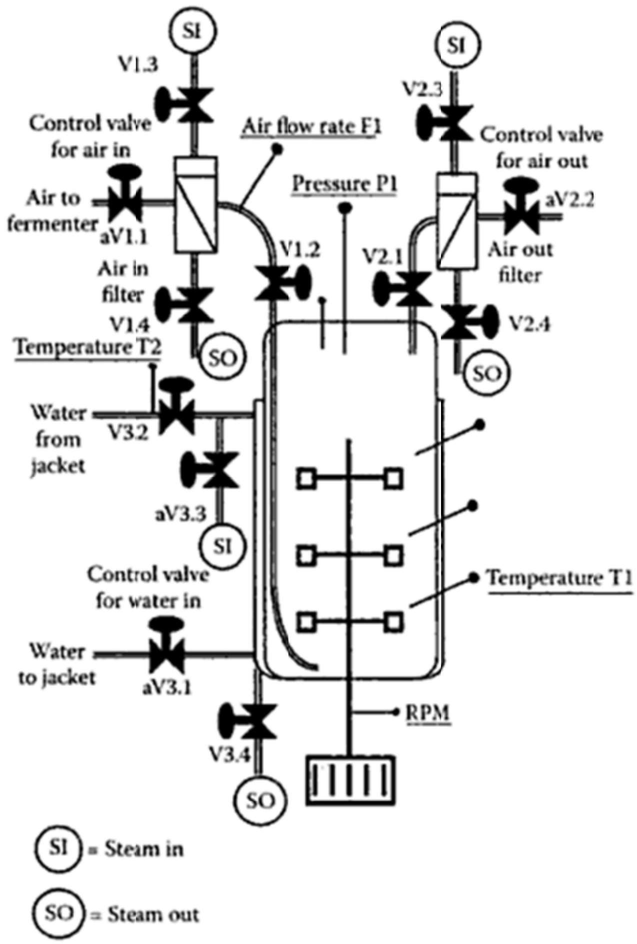

Figure 3: Fermenter P&ID (Mansi El-Mansi)

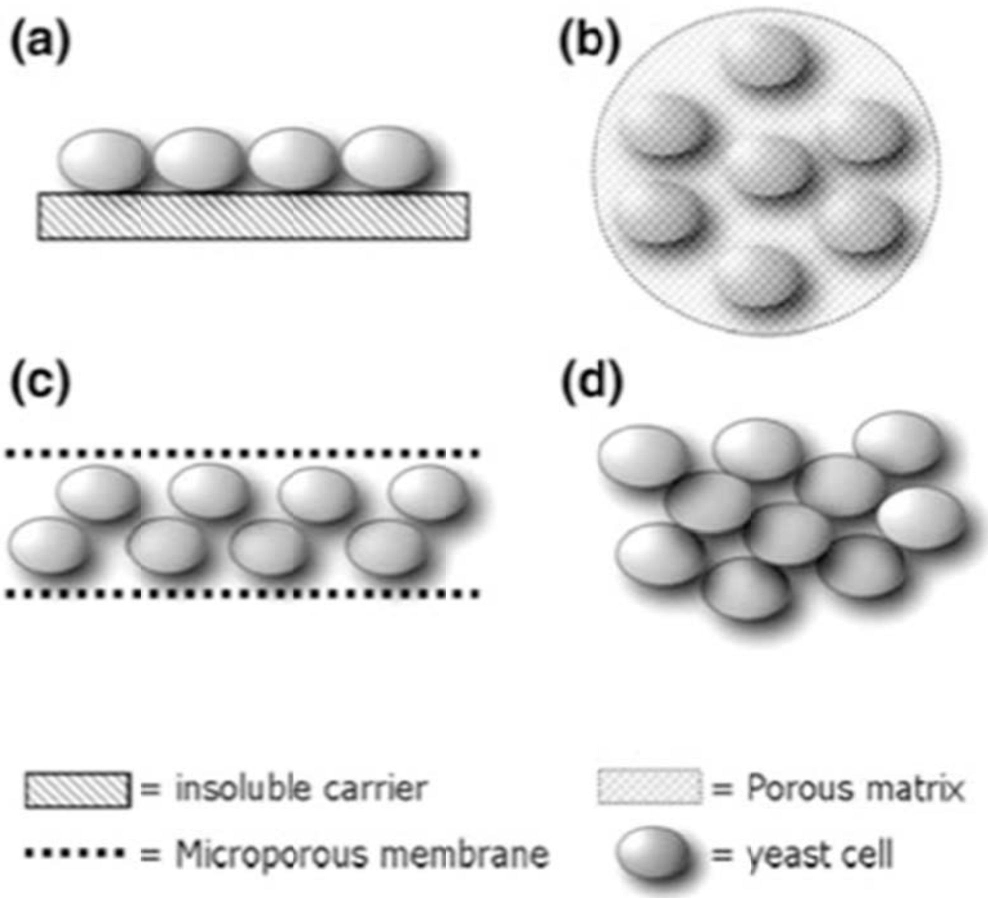

Figure 4: Immobilized Yeast Systems (Pieter J. Verbelen)

User Added Equipment

Reactors	Type	Volume (cubic meters)	Purchased Equipment Cost	Bare Module Cost
R-101	Fermenter	36	$ 149,000	$ 224,000
R-102	Fermenter	1.19	$ 17,600	$ 26,400
R-103	Fermenter	3.18	$ 29,700	$ 44,500
R-104	Fermenter	11.9	$ 59,900	$ 89,900

Figure 5: Capcost Fermenter Capital Costs