MEMORANDUM

Date: March 10th, 2023
To: AIChE, Greg Yeo
From: Jack Aruskevicius, Caleb Astley, and Evan Mills

Subject: AIChE 2023 Design Project

Enclosed is the Oklahoma State University Chemical Engineering AIChE design project for the spring semester of 2023 that was assigned on January 17th.

There was a lot of information collected through a few resources while this project was being completed. The information for this project was collected from notes, textbooks, and online sources.

Part 1 of the project requested the design of a plastic pyrolysis purification unit and determination of its capital costs and fixed and variable operating costs. Detailed safety analysis has also been requested including a distillation control scheme, pressure relief sizing, failure rate analysis, atmospheric detonation analysis, and a HAZOP study.

Part 2 of the project required a creative analysis of three gaps in the plastic “ecosystem”: the quality, quantity, and affordability gap. The project requested that innovative solutions be proposed that close these 3 gaps.

The project was successfully completed as of March 10th, 2023, with economic estimates determined and safety analysis performed.

Sincerely,

Jack Aruskevicius, Caleb Astley, and Evan Mills

Closing Critical Gaps to Enable a Circular Plastics Economy

Group 6

10 March 2023

Executive Summary

The request of a preliminary design of a plastic pyoil separation unit has been requested, downstream from a pyrolysis unit, converting plastic into usable oil, called pyoil. This design is focused on removing trace impurities from the pyoil stream and separating it into four separate cuts: py gas, naphtha, gas oil, and heavy resid. The py gas is used as a downstream fuel and is a vapor. The naphtha and gas oil (also called the light cut and medium cut, respectively) is used downstream in a steam cracker to produce valuable ethylene. The process that has been designed contains a series of adsorption columns, standing 36 ft tall and 6.5 ft in diameter, using PuriCycle H and HP catalysts (adsorbents) to remove trace elements. After these elements are removed, the feed enters a 42 stage, 95 ft tall, 5.5 ft diameter single multi-cut distillation column, charged with the separation into the four aforementioned streams. Once the separation has been performed, the products are cooled and pumped into storage tanks. The medium cut is also used to pre-heat the feed stream to save energy costs.

Economics play a large part in the feasibility of a preliminary design, and capital costs and variable and fixed operating costs have been calculated. Preliminary design estimates vary from -20% to +40%, and the calculated values reflect this. Capital costs are estimated at $3,255,000, fixed operating costs are $340,000 annually, and variable operating costs are $2,087,000 annually.

For general safety, situations where power is lost, pressure increases, and controller failure have been evaluated. For power loss, the control valves have the appropriate orientation, there are pressure relief systems in place on vulnerable equipment, and there are alarms in place for controller failures in order to prevent extreme situations within the process.

In order to close the quantity, quality, and affordability gaps, it is recommended to create collection centers in the community, where citizens can recycle their plastic and get paid. In addition, the installation of a drum separator is highly recommended. The improvements would serve to increase the amount of recyclables collected, reduce the cost of sorting the recyclables, and raise the quality of the recyclables so they could be used in the pyrolysis plant.

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Brief Process Description

The plastic pyrolysis purification process begins with the removal of trace impurities from the pyoil stream including water, chlorides, metals, calcium, and silica. BASF has an excellent selection of adsorbents (PuriCycle H & HP) designed for the removal of these impurities and has been selected for this project's applications.

The process begins with the pyoil feed entering one of the dual PuriCycle H adsorption columns. In this scheme, one column is actively in service, while the other is being regenerated using hot nitrogen gas. After the first set of columns, the feed then enters one of the PuriCycle HP columns, configured in the same manner.

Once these trace impurities have been removed, the feed enters a single, multi-cut distillation column designed to separate all streams by their boiling points, including the py gas, light cut (naphtha), medium cut (gas oil), and heavy cuts specified by the project appendix. A thermosyphon reboiler has been chosen for the bottoms, and a fixed tube heat exchanger for the condenser.

Once streams have been separated, the light and heavy streams are cooled and pumped to their appropriate storage tanks at the specified temperature and pressure. The light and medium cuts are to be used in ethylene processing downstream. The medium cut is used to pre-heat the feed entering the distillation column to reduce operating costs of the associated heat exchangers, and finally cooled further and pumped to the specified temperature and pressure and stored in its storage tank.

Process Detail

The process flow diagram, stream tables, equipment list, and utility consumption can be found below, in Figure 1, Table 1, Table 2, and Table 3. All vessels and equipment were sized and priced according to heuristics and procedures outlined in Turton et al [1]. For the scope of this project, detailed steps, and equations for designing tanks, pumps, and heat exchangers have been excluded, but designs followed standard industry procedures, also outlined in Turton et al [1]. Detailed procedures for the adsorption and distillation units can be found in the adsorption detail and distillation detail sections, respectively. Storage tanks were sized using a 50% full maximum assumption, where one week of process would fill the tank halfway.

V-101	V-102 A/B	V-103 A/B	E-101	T-101	E-102	E-103	V-104	P-101	P-103	P-102	P-104	E-104	E-105	E-106	V-105	V-106	V-107
Feed Storage	PuriCycle H Adsorption Columns	PuriCycle HP Adsorption Columns	Feed Preheater	Pyoil Distillation Column	Reflux Condenser	Thermo-Syphon Reboiler	Reflux Drum	Reflux Pump	Medium Cut Pump	Light Cut Pump	Heavy Cut Pump	Light Cut Cooler	Medium Cut Cooler	Heavy Cut Cooler	Light Cut Storage	Medium Cut Storage	Heavy Cut Storage

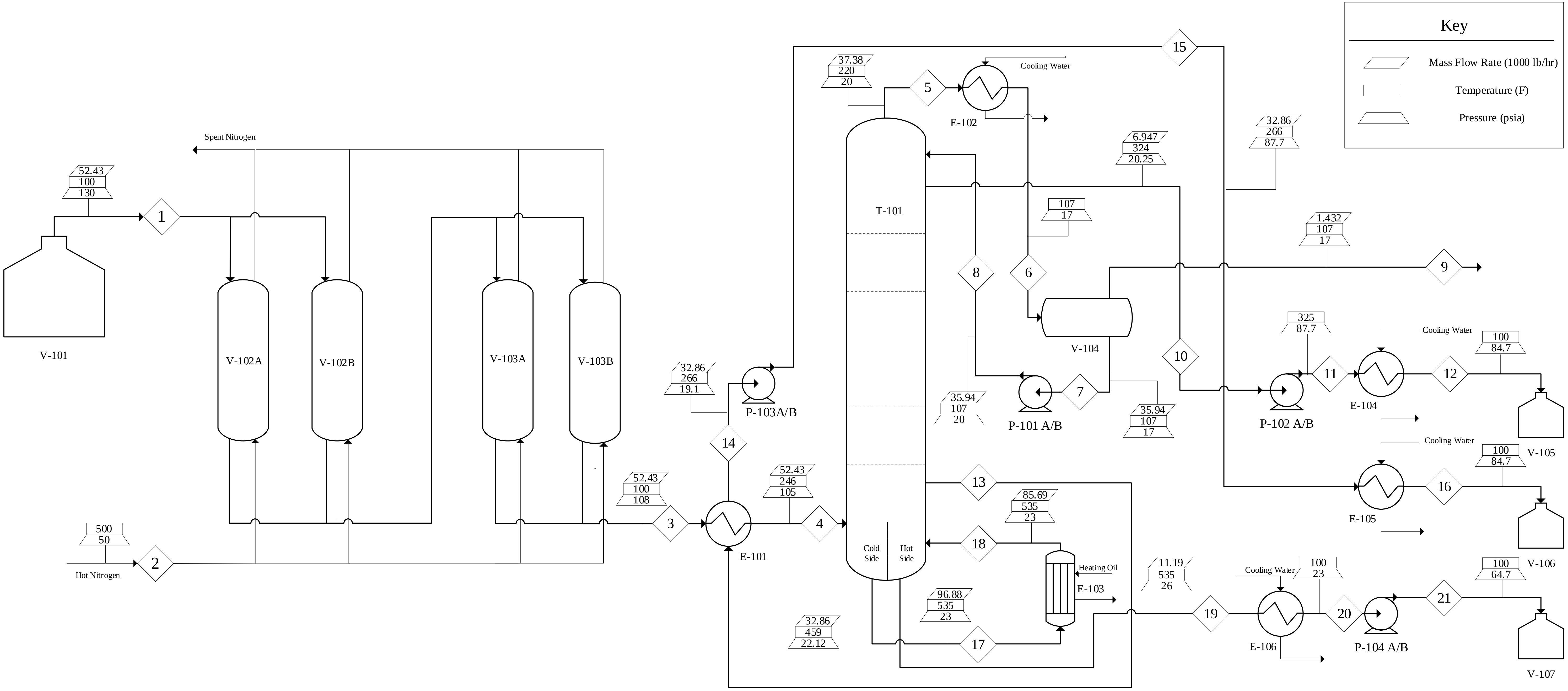


Figure 1: Process Flow Diagram for Pyrolysis Purification

Table 1: PFD Flow Summary Table

Flow Summary Table	Adsorber Feed Stream	Hot Nitrogen Feed Stream	Adsorber Outlet Stream	Column Feed Stream	Distillate Condenser Inlet	Distillate Condenser	Condensed Reflux Outlet	Pressurized Reflux Outlet	Py Gas Outlet	Light Key Side Draw	Pressurized Light Key
Stream Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Temperature (°F)	100	500	100	246	220	107	107	107	107	324	325
Pressure (Psia)	130.00		108.00	105.00	20.00	17.00	17.00	20.00	17	20.25	86.7
Phase	Liquid	Vapor	Liquid	Liquid	Vapor	Two Phase	Liquid	Liquid	Vapor	Liquid	Liquid
Enthalpy (btu/lbmole)	-164,696		-164,696	-150,842	-55,701	-75,098	-75,098	-75,098	-27,715	-105,376	-105,319
Mass Flow Rate (lb/hr)	52,430		52,430	52,430	37,380	37,380	35,940	35,940	1,432	6,947	6,947
Vol. Flow Rate (bbl/day)	4,565		4,565	4,565	3,781	3,781	3,610	3,610	171	638	638
Density (lb/ft^3)	48.0		48.0	48.0	0.2	41.5	41.46	41.5	0.2	39.0	39.0

Flow Summary Table Continued	…	Cooled Storage Ready Light Key	Medium Key Side Draw	Feed Cooled Medium Key	Pressurized Medium Key	Storage Ready Cooled Medium Key	Bottoms Reboiler Inlet	Bottoms Reboiler Vapor Product	Heavy Key Bottoms Product	Cooled Heavy Key	Pressurized Storage Ready Heavy Key
Stream Number	…	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Temperature (°F)	…	100	459	266	266	100	535	535	650	100	100
Pressure (Psia)	…	84.7	22.12	19.1	86.7	84.7	23	23	26	24	84.7
Phase	…	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Vapor	Liquid	Liquid	Liquid
Enthalpy (btu/lbmole)	…	-121,997	-136,215	-159,737	-159,737	-176,563	-159,077	-115,499	-162,869	-261,522	261,436
Mass Flow Rate (lb/hr)	…	6,947	32,860	32,860	32,860	32,860	85,690	96,880	11,190	11,190	11,190
Vol. Flow Rate (bbl/day)	…	638	2,841	2,841	2,841	2,841	8,094	7,179	915	915	915
Density (lb/ft^3)	…	39.0	38.3	38.3	38.3	38.3	38.1	0.6	36.1	36.1	36.1

Table 2: Equipment List

Towers/Vessels
T-101
Height: 95 ft, Diameter: 5.5 ft. Minimum Column Pressure: 20 PSI; Maximum Column Pressure; 23 PSI Minimum Column Temperature: 220°F; Maximum Column Temperature: 535°F Number of Trays: 42, Type of Tray: Sieve Tray Material: Carbon Steel, Height of Trays: 84 ft. Materials of Construction: Carbon Steel
V-104
Height (diameter): 5 ft, Length: 14 ft, Pressure: 17.00 PSI, Temperature: 107°F L/D ratio: ~3, Material of Construction: Carbon Steel
V-102 A/B and V-103 A/B
Height: 35 ft, Diameter: 6.5 ft. Minimum Column Temperature: 100°F Materials of Construction: Carbon Steel Method of Operation: 2 sets of columns (operating & regenerating) in series
Storage Tanks
V-101: 360,000 ft^3 V-105: 53,000 ft^3 V-106: 226,000 ft^3 V-107: 78,000 ft^3
Heat Exchangers
E-101
Type: Fixed Tube Heat Exchanger Duty: 3.99 MBTU/hr, Area: 319 ft^2 MOC: Carbon Steel, Max Temperature: 459°F, Max Pressure: 108 PSIA
E-102
Type: Fixed Tube Heat Exchanger Duty: 7.62 MBTU/hr, Area: 663 ft^2 MOC: Carbon Steel, Max Temperature: 220°F, Max Pressure: 20 PSIA
E-103
Type: Vertical Thermosyphon Reboiler Duty: 15.4 MBTU/hr, 1450 Area: ft^2 MOC: Carbon Steel, Max Temperature: 650°F, Max Pressure: 23 PSIA
E-104
Type: Fixed Tube Heat Exchanger Duty: 0.88 MBTU/hr, Area: 406 ft^2 MOC: Carbon Steel, Max Temperature: 325°F, Max Pressure: 87.7 PSIA
E-105
Type: Fixed Tube Heat Exchanger

Duty: 2.87 MBTU/hr, Area: 387 ft^2 MOC: Carbon Steel, Max Temperature: 266°F, Max Pressure: 87.7 PSIA
E-106
Type: Fixed Tube Heat Exchanger Duty: 3.82 MBTU/hr, Area: 515 ft^2 MOC: Carbon Steel, Max Temperature: 650°F, Max Pressure: 26 PSIA
Pumps
P-101 A/B
Discharge Pressure: 60 PSI, $\Delta P = 43$ PSI, Temperature: 107°F Pump Type: Centrifugal, Driver Type: Electric: 5 hp, Shaft Power: 4.4 hp Pump Flow: 35,940 lb/hr
P-102 A/B
Discharge Pressure: 97 PSI, $\Delta P = 80$ PSI, Temperature: 325°F Pump Type: Centrifugal, Driver Type: Electric; 3 hp, Shaft Power: 2.46 hp Pump Flow: 6,947 lb/hr
P-103 A/B
Discharge Pressure: 96.7 PSI, $\Delta P = 77.6$ PSI, Temperature: 265.9°F Pump Type: Centrifugal, Driver Type: Electric; 10 hp, Shaft Power: 7.49 hp Pump Flow: 32,860 lb/hr
P-104 A/B
Discharge Pressure: 76.7 PSI, $\Delta P = 53.7$ PSI, Temperature: 100°F Pump Type: Centrifugal, Driver Type: Electric; 3 hp, Shaft Power: 2.20 hp Pump Flow: 11,190 lb/hr

Table 3: Utility Consumption

Cooling Water (MBTU/hr)	15.2
Fuel Gas (MBTU/hr)	15.4
Electricity (kW-hr)	31.3

Economics

Capital Cost Estimate

The capital costs incurred for this project may be seen in Table 4 and Figure 2. These costs account for the purchase cost and installation of each unit as of the year 2021. The flare involved in the pressure relief system was assumed to be already acquired and was not considered for capital costs. The costs of safety valves and control systems were not explicitly found under the assumption that the overall capital costs would be sufficient to account for them.

Table 4: Capital Costs

Adsorption Towers	$442,175
Adsorbent	$18,143
Feed Heat Exchanger	$128,618
Reflux Condenser	$138,840
Reboiler	$454,605
Reflux Pump	$39,148
Light Pump	$35,359
Medium Pump	$44,636
Heavy Pump	$44,636
Light Heat Exchanger	$131,988
Medium Heat Exchanger	$131,026
Heavy Heat Exchanger	$137,972
Distillation Column + Trays	$543,145
Reflux Drum	$65,025
Feed Tank	$380,396
Light Tank	$111,350
Medium Tank	$270,444
Heavy Tank	$137,176
Total Cost	$3,254,682

It can be seen from figure 2 that the pumps make up the least of the capital costs and the heat exchangers and storage tanks make up the majority. This is in large part due to the large duty required of the reboiler for the separation as well as the large amount of material that must be stored in each tank.

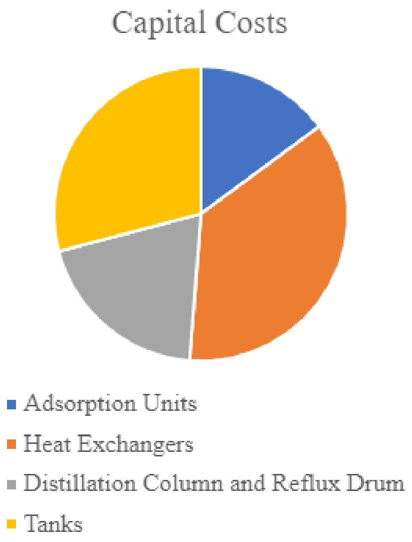


Figure 2: Capital Costs

Variable Cost Estimate

The variable operating costs associated with this process consist of the electricity for the pumps, cooling water for the heat exchangers, and the fuel oil for the distillation columns reboiler. These costs utilize the utility prices provided by the problem statement. In order to account for process downtime, a service factor of 97% was used for these costs.

Table 5: **Variable Costs**

Reflux Condenser	$32,357
Reboiler	$1,958,579
Reflux Pump	$15,366
Light Pump	$9,220
Medium Pump	$30,732
Heavy Pump	$9,220
Light Heat Exchanger	$3,722
Medium Heat Exchanger	$12,184
Heavy Heat Exchanger	$16,225
Total Cost	$2,087,603.73

The reboiler was the largest overall variable cost of the process. This is in large part due to the high costs of transporting natural gas to the plant to be utilized to produce heating oil. Overall, the costs of electricity for the pumps were minimal, as were that of the cooling water. Many of the draws for these utilities were the medium line and the condenser respectively.

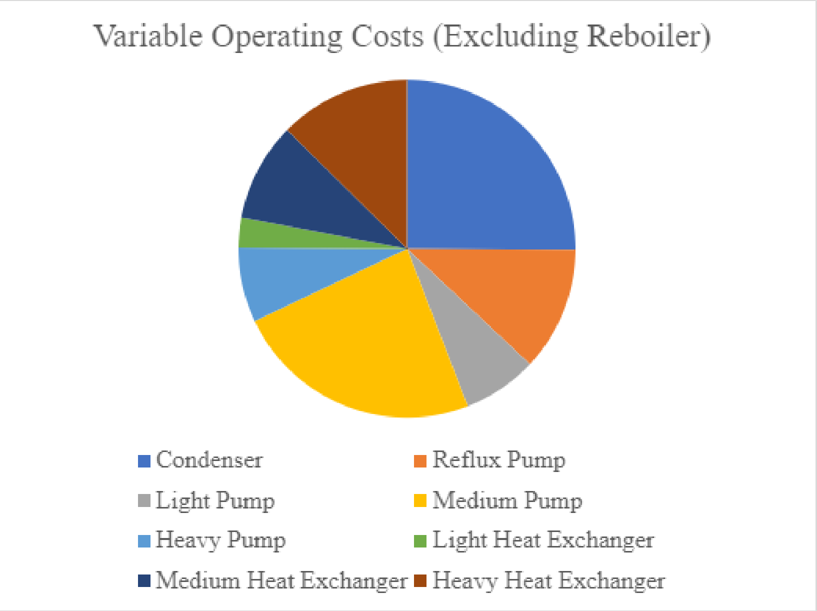


Figure 3: Variable Operating Costs

Fixed Cost Estimate

The fixed costs for this process consist only of the operator salaries, maintenance costs, and the replacement of the absorption catalysts. The maintenance costs are assumed to be around 6% of the total capital cost of the project by a correlation provided by Turton. This cost was about 196k annually. It is highly probable that the actual annual maintenance cost will be higher than the predicted value, mostly as a result of the tendency of the process fluid to foul, especially under the process conditions. Very likely the heat exchangers will require more maintenance.

For the operators, it was found by a correlation per Turton [1]. This indicated that a total of six operators would be required per shift in order to manage the major pieces of equipment. As the plant is intended to operate continuously, it was decided that a total of 18 operators should be hired to operate the plant under a staggered schedule. Given that the average pay of an operator in Indonesia is around 117,000,000 IDR, or about 7585 USD, based on the salary of a chemical plant operator [2]. As such, the cost to hire operators for this process would be roughly 136k USD annually.

The replacement of absorption catalysts is far more difficult to predict. The process is designed with the intent to regenerate the absorption columns with hot nitrogen to restore the catalyst, but it is inevitable that it will eventually be rendered unusable. Given that the absorbent used is activated alumina balls, it is suggested that the absorbent be replaced every two years [3]. This would incur a cost of roughly 18k USD every two years.

Process Safety

Minimizing Environmental Impacts

Since this process involves aliphatic and aromatic saturated hydrocarbons with trace amounts of nontoxic gases, one of the best methods for mitigating the dangers of release is combustion. This plant is specifically designed to operate with an onsite flare in order to burn off any released gases or hydrocarbons into less harmful substances like carbon dioxide and water. Other unit operations are capable of handling these substances, but a flare is the best option for the given process, and other devices would add unnecessary complexity.

Heat integration has been integrated into the design in an attempt to save energy. This will save money but also likely decrease greenhouse gas emissions, as creating energy almost always is correlated with greenhouse gas emission (i.e. burning coal for energy). Reusing energy in any way possible can help combat emissions.

P&ID with controls and alarms

A modified process and instrumentation diagram has been requested, showing a control scheme for the distillation column, as well as its safety relief system. Spared pumps have also been included. The modified P&ID can be seen below, in Figure 4.

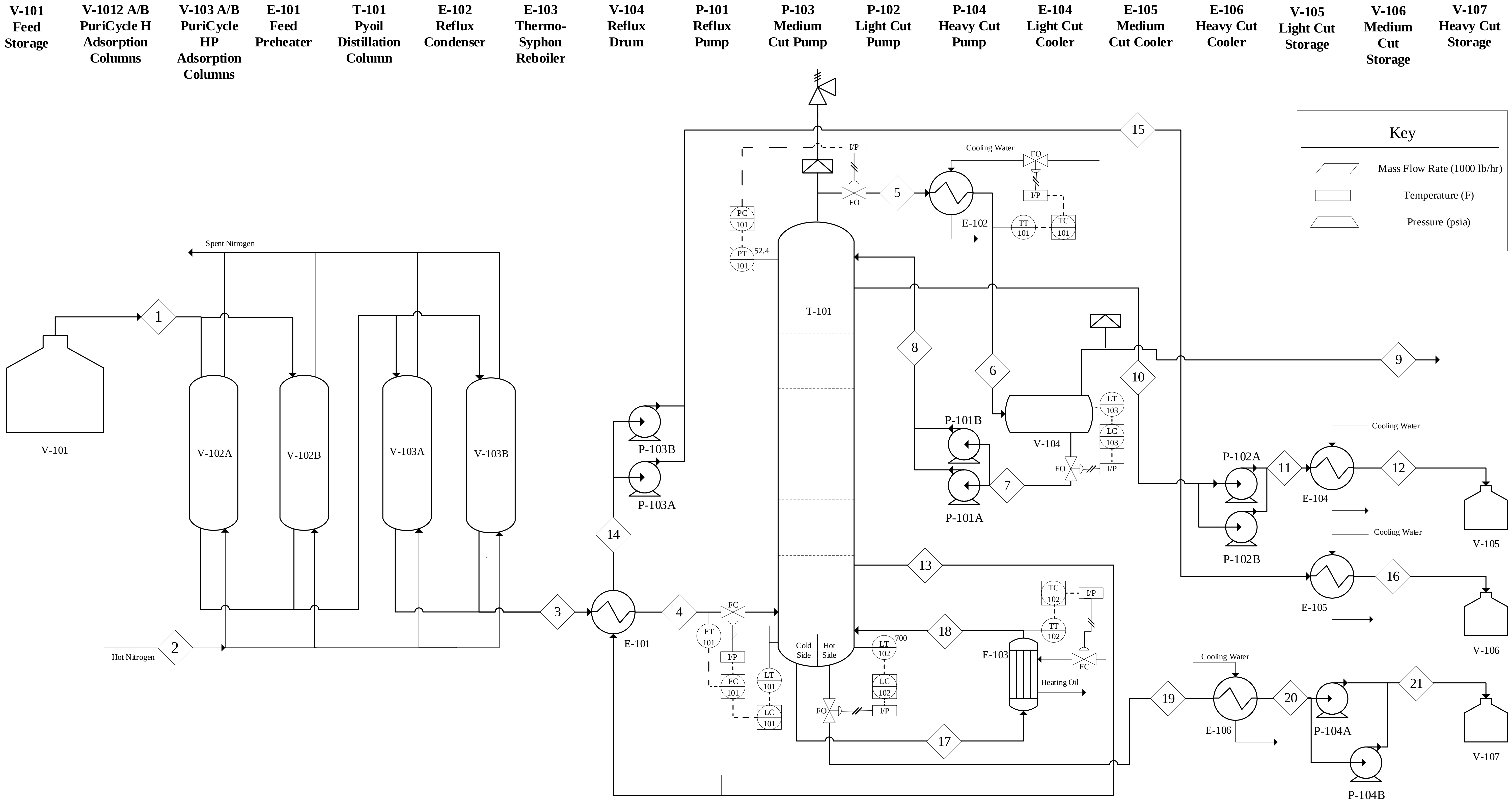


Figure 4: Modified P&ID for Plastic Pyrolysis Purification

When designing the control system, creating the most effective and likely cheapest solution was solved by using temperature and pressure control (primarily). With the exception of feed flow control, all other controls are pressure or temperature control which in turn control the compositions of the products leaving the column. Cascade control has also been implemented to robustly control the feed flow and keep the column in as steady operation as possible.

Loop F-101 controls the feed directly into the column, and is used in a cascade control scheme, with the master control being the feed flow, and the slave control being the cold side liquid level within the column. Essentially, the feed flow will be regulated and controlled based off the liquid level in the column bottom.

Loop L-102 and T-102 control the reboiler and bottoms composition. L-102 maintains the liquid level in the hot side of the reboiler which is the bottoms product (heavy cut). T-102 controls the temperature of the boilup stream re-entering the column by manipulating the heating oil flow rate into the reboiler.

Moving to the top of the column, loop T-101 controls the temperature of the column reflux by manipulating the cooling water flow rate into the condenser. P-101 ensures the correct operating pressure at the top of the column, with an alarm set to alert if the pressure has exceeded the vessels MAWP of 54.2 psig. This ensures the appropriate composition of the refluxed liquid that will re-enter the column.

Once in the reflux drum, L-102 controls the liquid level in the drum to ensure a liquid seal is maintained.

If the plant’s compressed air fails, the failure mechanism of the control system is to cease the feed flow (fail closed) and empty the column (fail open for bottoms outlet). Additionally, steam in the reboiler will fail closed, and cooling water will fail open in the condenser. Essentially, the idea is to stop mass input and decrease heat input as much as possible.

PRV sizing

The design of a pressure relief valve is necessary for the distillation column, due to the number potential overpressure hazards that exist. For the scope of this project, a fire is assumed to be the worst-case scenario, producing the highest vapor flow rate that would need relief. Determining the appropriate valve for this scenario begins with calculating the heat input for a fire. A heuristic of 25 feet was considered as the highest point on the column that a fire could affect. Since the fire will only cause a significant pressure increase (due to vapor evolution) when exposed to a liquid, the wetted area is needed to determine the heat input [4]. Finding the liquid level in the column at failure is complex and has been simplified for the purpose of this project, where the feed valve is assumed to be closed, and all the liquid holdup on all the trays falls to the bottom. In this case, the column accounts for six feet of liquid holdup, and 2 inches of holdup on each tray (total 42 trays). This approximates the liquid level to 13 feet, and for the purpose of unaccounted for liquid, has been rounded up to approximately 15 feet of liquid present in the bottom of the column, given a failure state (this accounts for liquid in reboiler pipes, in reboiler, and any other liquid not accounted for). 15 feet will be used instead of the 25 feet heuristic because it is the smaller of the two. After this, wetted area can be calculated, and the heat input of the fire can be found as a function of surface area. From there, mass flow rate of the relief scenario can be calculated as a function of heat input, heat of vaporization (where the composition of the liquid in the bottom can be approximated as the same composition of the feed), and vapor and liquid densities. These methods were found using the GPSA, 11th Edition [4]. The specifications for the mass flow rate of the fire scenario can be found below, in Table 6.

Table 6: Relief Incident Mass Flow Rate

Liquid level	15 ft
Wetted area	260 ft^2
Heat input	3.3 MMBtu/hr
Mass flow rate	5,111 lb/hr

From this point, the orifice area of the pressure relief valve can be found as a complex function of heat capacity, pressure, molecular weight, temperature, compressibility factor, and mass flow rate [4]. The set pressure was decided to be equal to the MAWP for the vessel, 52.4 psia. Once area is determined, a standard pressure relief valve can be found where area is rounded up to the nearest size. The results from the sizing can be found below, in Table 7.

Table 7: Pressure Relief Valve Specifications

Required minimum orifice area	3.82 in^2
Chosen standard area (round up)	4.34 in^2
Standard pressure relief valve size	4” inlet, 6” outlet

Failure Rate Analysis

Failure rate analysis is a comprehensive review of the mean time to failure (MTTF) and the mean time between failure (MTBF) which determines the rate at which maintenance should be performed on critical systems. With respect to the pyrolysis unit, there are many extremely critical systems that should be reviewed or replaced on a regular basis. These systems include the control valves feeding into the distillation column as well as the other safety valves feeding into the storage tanks. Additionally, all pressure relief systems should be regularly reviewed since there can be large economic and ecological problems if these valves fail. Without input from product designers, it is not possible to give a completely accurate measure of what the MTTF and the MTBF would be for these systems. Much of this information is proprietary. However, the industry standard for many of these systems is that they should be inspected approximately every twelve months [5].

Personnel Exposure Risk

The main components of the pyoil feed are aliphatic and aromatic saturated hydrocarbons. These components are at a high risk for explosion hazards or fires. Specifically, the lighter components such as ethane or propane have been present in many vapor cloud explosions due to their low molecular weight when compared to their heavier counterparts. Aliphatic hydrocarbons should be kept separate from strong oxidizing agents, but they are mostly unreactive with other kinds of aqueous solutions, oxidizing agents, and most reducing agents. When aliphatic hydrocarbons burn, they form carbon dioxide and water in an exothermic reaction. Due to the creation of carbon dioxide hydrocarbons act as asphyxiants and are otherwise nontoxic. Aromatic hydrocarbons share many of the same traits as aliphatic hydrocarbons since they are both combustible and can explode if they undergo extreme oxidation. These compounds are quite dangerous if inhaled and many are carcinogenic. Additionally, it should be noted that there is hot nitrogen gas that is being used to regenerate the adsorption vessels. This gas is nonexplosive and nontoxic, but it is a potent asphyxiant. The following table summarizes The NFPA diamond classification, the lethal dose limit, and the OSHA chemical exposure limits for the streams within the pyrolysis process. This table is limited to the most hazardous chemicals present and the more exhaustive table contained within the SDS datasheet will be present under references. The HAZOP table can be seen in Table 8 [6][7][8][9][10].

Table 8: HAZOP Table

	Fire	Health	Reactivity	Special	Lethal Dose Limit LC 50	OSHA Exposure Limit
Pyoil Feed	3	1	0	-	All the following	All the following
Py Gas	3	1	0	-	1,3- Butadiene Gas 128000ppm Vapor 285 g/m^3	1,3- Butadiene STEL: 5ppm/15 min TWA: 1ppm/8 hrs
Light Cut	3	1	0	-	Benzene Oral 930 mg/kg Inhalation 44 mg/l	Benzene STEL: 5ppm TWA: 1ppm
Medium Cut	2	0	0	-	Phenanthrene Oral 1.8 g/kg	Phenanthrene STEL: N/A TWA: 0.2 mg/m^3
Heavy Cut	2	1	0	-	Heavy Pyrolysis Oil Oral >5000 mg/kg Inhalation 3.7 mg/l	Naphthalene STEL: 15ppm TWA: 10ppm

Atmospheric Detonation of Distillation Inventory

To analyze the severity of detonation of the material contained in the process, the amount of material throughout the components must first be found. This primarily includes the materials in the piping, distillation column, reflux drum, and the storage tanks. For the purposes of analysis, it is assumed that all the material would detonate simultaneously. As such this estimate will be substantially higher than the actual case.

To analyze the explosive properties of the process fluid, it was assumed that all fluid contained in the process resembles gasoline. No distinction was made between any of the process stream compositions except on the basis on density for finding the mass contained within that point of the process.

The mass in the distillation column and absorption columns were found using a holdup time of 5 minutes for both. The volume flow rate was used with this to find the required volume maintained inside each vessel. To account for the additional material contained on the trays of the distillation column, a weir height of 2 inches was assumed as a minimum to constrain the liquid level [11]. The material contained within the piping was assumed to be negligible compared to other points in the process and was neglected.

Table 9: Material in Process

Position in Process	Volume (ft^3)	Density (lb/ft^3)	Mass Contained (lb)
Distillation Column T-101	166	36.1	6,000
Reflux Drum V-103	70.6	41.5	2900
Feed Tank V-107	180,000	48.1	8.660,000
Light Tank V-104	26,000	45.6	1,190,000
Medium Tank V-105	113,000	48.4	5,470,000
Heavy Tank V-106	39,000	51.3	2,000,000
Absorption Column V-101	27.3	48.1	1,300
Absorption Column V-102	27.3	48.1	1,300

Using the entire mass contained in the system and assuming an explosion effectiveness of 2%, the TNT equivalent of the entire facility exploding was found [12]. This yielded a value of roughly 2.5 kilotons of TNT. Most likely the true explosion would be smaller as not all the material contained would participate as some would remain liquid as well as the fact that the entire facility would not explode simultaneously. This value is, however, a cause for concern as it indicates that an explosion in any part of the process could produce catastrophic damage to the surroundings.

The largest concern for detonation of the facility is the storage tanks. They contain the largest amount of material throughout the process and would cause catastrophic failure should one detonate. It is probable that the detonation of a single storage tank would be sufficient to set off a chain detonation in the other tanks given the high detonation potential of each one. Detonation of any other component such as the distillation column would certainly damage the process but are far less likely to cause a chain detonation as the damage would be slightly more superficial.

As such, it is highly recommended that the storage tanks be isolated as much as possible from the rest of the process, with adequate blast protection installed. Any ignition sources should be kept far from the storage tanks, and they should be monitored to ensure no leaks are occurring as any leak could become catastrophic. Given the high potential for the plant to cause extreme damage in the case of an accident, it should be built a fair distance from any residential areas to avoid any potential damage.

HAZOP

When looking at hazards and operability (HAZOP), it is important to identify multiple plausible scenarios that could have large impacts on plant safety, the environment, and the profitable operation of the plant. This analysis will review loss of containment due to overpressure, fires due to loss of containment, pump failures, and loss of electricity to critical systems.

Overpressure is one of the most common causes of loss of containment and must be evaluated at almost all plants in the world. In this pyrolysis plant, the main areas that are concerning for overpressure are T-101 and V-104. Due to regulation, all vessels and storage tanks have been outfitted with pressure relief systems in order to compensate for potential pressure fluctuations. When reviewing the column safety, it was decided that there should be a single pressure relief valve downstream from a rupture disk, due to the long-term necessity of the project, and to avoid any damage to the pressure relief valve over time. Due to V-104 connecting to other pressure relief systems and since it has a relatively low liquid level in most circumstances, it would be outfitted with a single rupture disk in order to alleviate pressure in the most extreme circumstances.

In a plant environment where combustible materials are being used, fire is a significant concern. Unchecked fires can cause harm to personnel and result in substantial damage to plant equipment. This concern is amplified when working with aliphatic and aromatic hydrocarbons during the pyrolysis process since these substances are highly flammable. Therefore, it is crucial to have the necessary controls in place to prevent and mitigate fires. These controls include a firefighting system consisting of sprinklers, as well as the correct orientation of valves. Proper valve orientation is critical in fighting fires within a plant since a significant aspect of controlling fires is cutting off the fuel supply.

Pump failures are another concern since pumps drive a lot of this process and without the ability to remove substances from the system, there is a high probability of overfilling the column which could lead to a loss of containment. In addition to overfilling, pump failure leaves the plant at risk of other events such as fires since there is no way for material to leave the system.

Losing electricity is a logical concern as many of the systems within a plant require electricity to function. When losing electricity there are many problems that occur such as loss of cooling water, loss of steam, and loss of pump functionality. These failures also inhibit the ability of the plant to heat up, cool down, and move product through the process. Electricity loss can be highly dangerous as it can be the start of an overpressure event. Importantly, to mitigate the impact of electricity loss, the control valves must be in the proper orientation to prevent additional damage to the process. Additionally, a properly sized pressure relief system is crucial to avoid any damage to expensive equipment due to overpressure situations.

Recommendations

Part II: Cold Eyes Review

The implementation of the proposed pyrolysis unit is heavily dependent on the abundant presence of flexible plastic waste provided by the community. Currently, the flexible plastic waste is being produced at a sorting facility at a less than ideal rate and quality. This leaves three issues which are the quantity gap, the quality gap, and the affordability gap. The proposed solution to close each of these three gaps is to implement a localized collection center with specified bins for recyclable products, as well as implementing a new drum separator in order to increase the quality the recycled products and the resulting pyrolysis feed. It should be noted that the current production of flexible plastic waste, though, is not sufficient to operate the pyrolysis unit at the specified capacity.

With the quantity gap, the main goal is to increase the throughput of the sorting facility by either increasing the amount of flexible plastic waste produced or by increasing the speed at which the facility processes flexible plastic waste. The first solution of implementing a localized collection center would help to close this gap by allowing a greater number of people to be able to drop off their recycled waste without having to pay the additional money to have a truck stop by their residence in order to pick up the waste. Currently, citizens must pay a small fee (approximately 1% of their income) to pay for a truck to pick up their recyclables. In an already impoverished country, citizens are hesitant to pay this fee. Implementation of a localized center would remove this fee, and citizens could be incentivized to bring their recyclables by receiving a small amount of money based on the amount of plastic they bring. This wouldn’t cost more money than the current solution, as the truck drivers’ salaries are essentially used as the monetary incentive to draw citizens in. This way, citizens can get paid to recycle. This may also create a market in which many people specifically collect recyclables to take to the collection centers in order to make money. While this may not be the intended consequence, the result is that collection centers will receive a large quantity of recyclables which will improve the quality of flexible plastic waste that will be sent into the pyrolysis unit. These centers would be located in the most densely populated areas, ideally within walking distance (or biking distance) for most citizens. This would increase the number of people who would recycle, which would allow for a greater number of recyclables to be collected.

The second major recommendation is for the implementation of a new drum separator which would also work towards the improvement of the sorting plant's throughput by increasing the speed at which the recyclables are sorted. This would also increase the quality of the recyclables being produced in the sorting process. Both of these changes would have a great impact on the operation of the pyrolysis unit as well as the overall throughput of the sorting plant.

In order to promote job opportunities at the recycling center, a social campaign would be required that goes beyond the typical incentives of beautifying the environment or offering small financial rewards for recycling. This social campaign would be a lynchpin of this entire process as without making recycling more popular or easier, there would be a shortage of feedstock for the pyrolysis unit. By increasing the quantity of recyclables collected, a significant number of jobs can be created through the expansion of the sorting plant and by hiring staff at the collection centers. The recycling centers would weigh the recyclables and assist citizens with proper categorization, making the recycling process more efficient and reducing the number of trucks that need to be used in order to transport recyclables.

With the quality gap, the implementation of the drum separator and collection centers is directly created for the purpose of improving the quality of flexible plastic waste. When considering the collection centers, giving citizens the ability to exhaustively sort their recyclables using specific bags and bins will greatly improve the quality of recyclables delivered to the plant and the rate at which the sorting plant produces recyclables.

The drum separator plays an incredibly important role in the process of producing both flexible plastic waste and other recyclables. [13] This separator works by removing stray metals within the recycling stream using a large magnet. This machine is critically important since it would reduce the manpower required to sort recyclables while maintaining a faster rate of sorting. Importantly, with an increased throughput catalyzed by the creation of collection centers, there needs to be a shift towards automation within the sorting plant as the quantity of material fed into the pyrolysis unit is almost ten times more than the total amount of recyclables processed by the entire plant. The goal of the drum separator is to minimize the number of new hires that must be made while still improving the quality of the produced recyclables and the pyrolysis unit feed.

The addition of a social campaign would also lead to an increase in employment of the local citizens working both within the plant and the collection centers. These individuals would also be able to spread knowledge about the proper way to sort recyclables, which not only makes their job easier, but also increase the quality of the recyclables produced by the collection center and the sorting plant.

With the affordability gap, there are expenses and savings that can be made within the recycling process. Firstly, the cost of creating comprehensive collection centers with bags and bins for specific recyclables could come at a heavy cost. The other side of this is that once these centers are built and in service, the amount of recyclables that they produce would surely justify their cost. Additionally, minor monetary incentives would definitely be a reasonable cost to increase the throughput of the recycling system. Also, with decreasing the number of trucks in service and the distance that these trucks are required to travel, the whole process of collecting and transporting waste becomes much more streamlined and less expensive.

Installing a drum separator into service is a sunk cost for the sorting plant. However, this cost is justified by increasing the throughput and quality of the recyclables produced. Looking at the current state of the sorting plant is a discouraging task since the total production within the plant is far lower than the expected inlet flow into the pyrolysis unit. Looking at this, it would be incredibly important to automate the sorting plant to the greatest extent possible in order to increase the throughput. This is because the main generator of profit in the entire venture is the pyrolysis unit since it is the only component of the recycling process capable of creating significant profits that will cover the cost of construction and operation for all of the improvements to the sorting process.

Of the three improvements to the social aspects of the recycling process, the most important is the implementation of collection centers and the creation of financial incentives. This is necessary, as unless the current quantity of recyclables increases, it would be impossible to operate the pyrolysis unit or the sorting plant at any substantial profit. However, it is important to know that each of these suggestions is important because it should also be noted that the profit of the pyrolysis system will be entirely based upon the way the community feels about the plant, recycling, and their ability to increase the amount they recycle. This inherent uncertainty results in a need for multiple layers of plans which all support the process of incentivizing recycling and the production of feedstock for the pyrolysis process.

Conclusions

The design of a plastic pyoil purification unit has been requested for production of py gas, naphtha, gas oil, and a resin cut. Naphtha and gas oil are the “money makers” and will be further used in a steam cracker to produce ethylene, a profitable product. Beginning the process is a pair of adsorption columns in series, responsible for removal of trace contaminants such as water and chlorine. PuriCycle H and HP have been used as the adsorbents for this purpose. Once through the adsorption columns, the feed enters a multi-cut distillation column where it is split into the four different cuts requested. Finally, the products are cooled and compressed to their specified temperature and pressure, with the medium cut (gas oil) being used in a shell and tube heat exchanger to pre-heat the feed.

Capital costs, variable operating costs, and fixed operating costs have been calculated, with the heat exchangers and storage tanks making up a majority of the capital costs, and the reboiler making up a large percentage of the operating costs.

Process safety was a major area of concern with the design of this purification unit, with a control scheme (for distillation), environmental impact analysis, pressure relief valve sizing (distillation), failure rate analysis, personnel exposure risk, atmospheric detonation analysis, and a HAZOP study being conducted. While the process inherently poses hazards, they can be successfully controlled, and the appropriate measures can be put into place to minimize this risk.

In addition to the preliminary design, a “cold eyes” analysis has been requested to solve three major issues with current plastic recycling in Bali, Indonesia. These issues are the quantity, quality, and affordability of the sorting plant that would create the feed for the pyrolysis plant. In brief, the quantity of light plastics being produced by the sorting plant is far below the amount accounted for by this design. Because of this, there needs to be a more streamlined form of recycling in the form of the suggested recycling centers which not only improve the quality of the recycled materials, but it would also allow more residents to recycle without having to pay. Additionally, the number of trucks required to transport recycled materials would be reduced since each recycling center would be able to estimate the number of trucks required to transport its recyclables. The quality of the recyclables would be improved by the implementation of recycling centers as workers there would be able to sort the materials more accurately before they reached the plant. Upon reaching the plant it would take much less effort to place the recyclables in their proper streams. Additionally, the installation of a drum separator to work with the human sorters would be incredibly beneficial. This is because it would improve the quality of the sorted recyclables and would sort them at a higher rate than the human operators. In terms of affordability, there is expenditure required in order to create recycling centers, install the drum separator, and to put out community outreach as well as economic incentives to recycle. However, by putting these measures into place, the added production from the pyrolysis plant would far outweigh the cost of implementing the new recycling system.

Appendices

Adsorption Detail

A total of four adsorption columns have been designed for the removal of trace elements including water, chlorine, silica, calcium, and other trace metals. PuriCycle H and HP have been selected as appropriate adsorbents for this application. The columns are operated in series, with each pair having one column operating actively, and another being regenerated with hot nitrogen. The specifications for the adsorption units can be found below, in Table 10.

Table 10: Adsorption Design Specifications

LHSV	1 hr^{-1}
Nitrogen temperature	500˚F
Chloride levels	50 wppm
Adsorbent capacity	~5% wt

It is assumed that water levels are also in the 50 wppm range, similar to chloride, as the project specifies “low levels” of water potentially present in the feed. Regenerable service is also assumed, where both columns can be regenerated for approximately 2 years until adsorbent needs to be replaced [3]. Another assumption that has been made is that the exothermic adsorption process causes a negligible change in feed temperature, negating the need for a cooling jacket around the columns. This should be investigated further in the detailed design phase, as this assumption could cause adsorption failure if it is an incorrect one. To determine the column dimensions, a superficial liquid velocity must also be assumed, with a typical range for liquids being 0.001 to 0.004 m/s [14]. 0.003 m/s was chosen as a conservative guess. Another big assumption that had to be made was the pricing of the actual adsorbent beads, as BASF is unresponsive to emails, calls, and all other forms of communication. On their website, even the type of adsorbent for PuriCycle H and HP is not given. Therefore, other BASF catalysts that performed similar functions were investigated to obtain a price. BASF F-200 is an activated alumina catalyst that serves a similar purpose to the PuriCycle Adsorbents, and the PuriCycle Decontamination adsorbent is also made of activated alumina [15][16]. Therefore, the selected catalysts have been priced using available activated alumina pricing information. While difficult, with most companies that offer bulk purchase requiring a quote request, a price of approximately \$2 per pound of adsorbent was found [17]. Also, density of adsorbent was assumed to be 750 kg/m^3 , based on other similar BASF catalyst information that was available [17][15]. Table 11 below summarizes the adsorption design assumptions.

Table 11: Adsorption Assumptions

Water concentration	50 wppm
Regenerability	Yes, Replace semianually
Temperature change in feed	No
Superficial liquid velocity	0.003 m/s
Adsorbent density	750 kg/m^3
Adsorbent Price	\$2/lb

The columns were designed based on the 1 hr^{-1} LHSV (liquid hourly space velocity), which specifies, essentially, that the volume flow rate of the liquid entering the columns is equal to the volume of adsorbent required. The columns in this design handle all the feed from the beginning of the process, rather than the medium and heavy cut outputs separately. Having multiple adsorption units, in that case, would inevitably increase complexity and likely capital cost. Diameter was calculated based on the superficial liquid velocity assumption, and consequently height (based on the weight and density of the adsorbent). Using the LHSV to obtain the adsorbent volume allows the cycle time to be determined, approximately 40 days for each of the columns. Details of the columns are shown below, in Table 12.

Table 12: Adsorption Column Specifications

Length (height)	36 ft
Diameter	6.5 ft
Adsorbent Volume (per column)	30 m^3
Adsorbent Weight (per column)	~1000 kg
Cycle Time	40 days

Because each column has a second identical column in parallel, continuous operation can be ensured, with one column active and one regenerating at all times as mentioned before. Essentially, once one of the columns has reached its maximum capacity (of impurities in the adsorbent beads), the feed will switch to the other column that has been regenerated from the previous cycle using hot nitrogen. Nitrogen will then be switched to the “dirty” column to prepare its beads for the next cycle. This is relatively easy to maintain as well, as the cycle time is so long.

While more research needs to be done, it is likely that the nitrogen regeneration cycle will only take a fraction of the time that it takes for the feed to "dirty" the other column (for example, the cycle time is 40 days, but the regeneration may take ~1 day). This would make it possible to periodically open the feed to both columns (both active and what was the regeneration column) to deal with unusually high levels of impurities. This would effectively double the concentration of impurity able to be handled by the system. While outside of the scope of this project, it would be necessary to implement some sort of control system to measure the level of impurities in the feed in order to tell the system when to use both columns. The normal and modified operating schemes of the columns can be seen below, in figures 5 and 6.

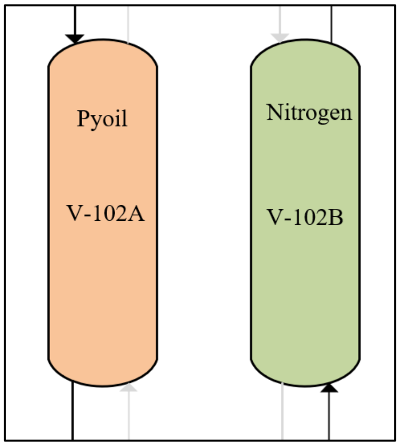


Figure 5: Normal Adsorption Scheme

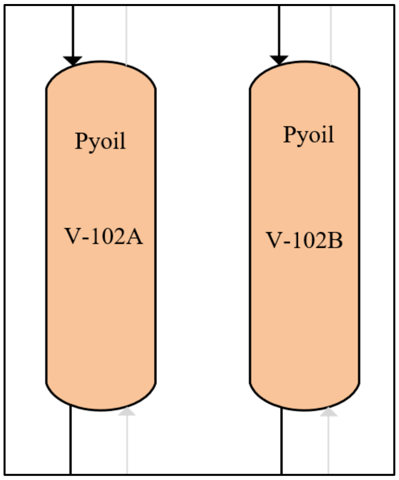


Figure 6: High Impurity Adsorption Scheme

Distillation Detail

As recommended in the design statement, minimizing the number of distillation columns was a key factor in designing the separation unit for the project. In the proposed separation unit, one column was used with multiple cuts for the medium and heavy cut. Using only one distillation column decreases complexity at the potential cost of having a slightly larger energy use. This is because the entire feed/process is subject to the same powerful reboiler, designed to boil the heavy cut (containing large hydrocarbons). It would be more energy efficient to have multiple columns with reboilers of increasing power, but because of the minimization request for towers and the marginal energy savings that this scheme would have, a single column has been selected.

Several assumptions were made about the distillation process throughout the design, beginning with the fluid package chosen. Peng-Robinson was used as it is the industry standard for oil (hydrocarbon) streams and it does a good job modeling low pressure, non-polar molecules. Another assumption that was made was the tray efficiency of 65%, a conservative estimate based on the Drickamer and Bradford correlation [18]. Additionally, a 10% safety factor was added onto the determined number of trays. Per tray, a 0.1 psi pressure drop was assumed. Also, the pressure drop through heat exchangers is estimated to be 3 psig. The distillation assumptions can be seen below, in Table 13.

Table 13: Distillation Assumptions

Fluid package	Peng-Robinson
Tray efficiency	65%
Safety factor (tray)	10%
Pressure drop	0.1 psi per tray
Pressure drop in HEX	3 psi

Aspen HYSYS was used to model the entire process including the distillation column, and was the main point used to design and configure the column. Operating pressure of the condenser was determined to be 3 psig, based on the minimum required 2.4 psig, creating enough driving force for the stream to reach the ethylene plant. Within the column, using assumptions stated above, the top of the column operates at 6 psig, the bottom tray pressure is 8.5 psig, and the reboiler pressure is 11.5 psig. In order to model the pyoil in HYSYS, a theoretical oil assay had to be created, using the specifications provided in the project appendix I. This creates multiple theoretical components that HYSYS uses to model oil. To converge the column and determine the number of trays, 4 specifications had to be made due to the multi-cut nature of the column (whereas a normal column would only require 2). The two most important specifications to be made to ensure product purity are the D86 boiling point specifications for both the light and medium cut. Specifying these is the key to ensuring that the cut ranges are accurate in their composition, as the D86 method is what was referenced in the project statement. Moreover, the condenser temperature was another specification used to converge the column, as the temperature of the py gas (contained in the condenser) was specified. In addition, not specifying the condenser temperature causes HYSYS to attempt and fully condense the top stream, resulting in an extremely low temperature (due to light components like methane present in the stream). Finally, the last specification used was reboiler temperature, as obtaining the lowest temperature will cause a drastic decrease in operating cost. Because of this, finding the lowest temperature while managing reflux ratio became key for this specification. The column specifications can be found below, in Table 14

Table 14: Distillation Column Convergence Specifications

D86 FBP for Light Stream	392 °F
D86 FBP for Medium Stream	620 °F
Condenser Temperature	107 °F
Reboiler Temperature	650 °F

Once the column was converged, optimizing it was the next big step. A basic iterative procedure was followed, comparing the number of theoretical stages to the reflux ratio, attempting to find an optimal point where the combination of number of trays and reflux ratio is at its lowest. This is plotted as the product of number of trays and reflux ratio versus the number of trays. The plot can be found below, in Figure 7.

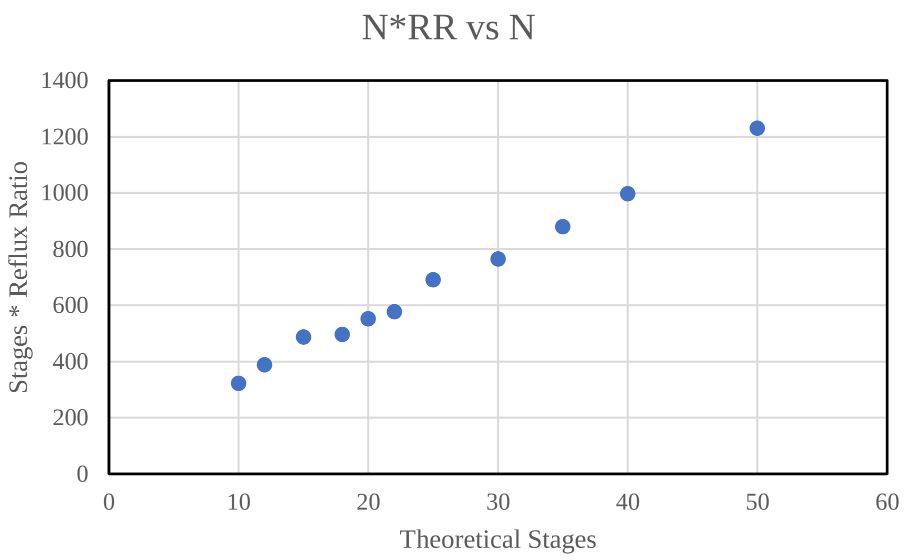


Figure 7: Distillation Optimization

Interestingly, a strictly increasing trend is seen, while usually a sharp increase in reflux ratio occurs when the number of stages becomes very small. This would likely occur when the number of stages is decreased to less than 10, but the HYSYS simulation ceases to converge with less than 10 stages. This is likely due to the complexity of the multiple cuts, making a small column like this unfeasible. Either way, it seemed that this data was too good to be true. Simply build the smallest feasible column and the lowest cost could be obtained. After investigation, it turned out that decreasing the number of stages also decreases the flow rate of our key species:

the light and medium cuts. In addition to Figure 7, another graph was constructed to display the effect of number of stages on the flow rates of the key species and can be seen in Figure 8.

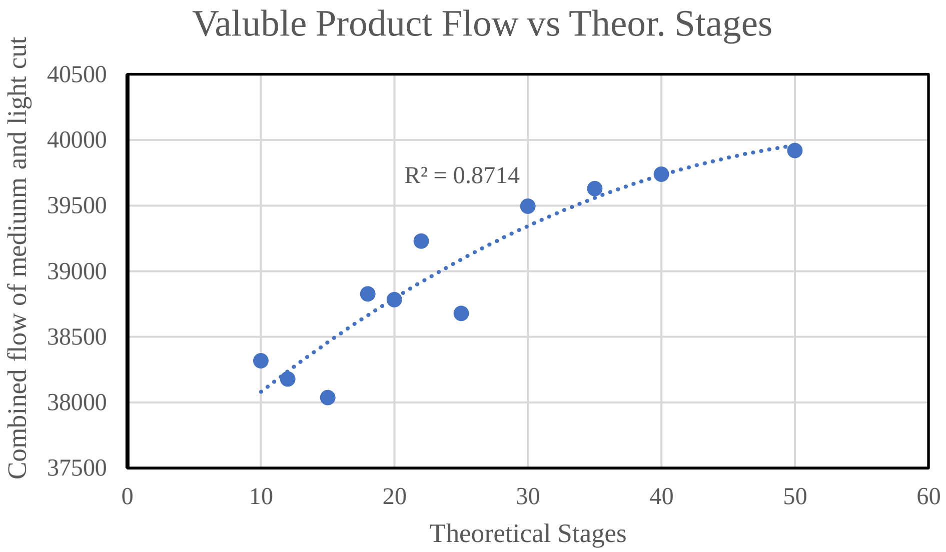


Figure 8: Distillation Flow Optimization

As can be seen, a decrease in the number of stages means less flow of the key products. Optimizing the column, then, must consider the results of both figures. While there are multiple different operating conditions that have their pros and cons, 25 theoretical stages were selected as the ideal number, with a relatively low reflux ratio, and ideal product flow rates. Feed stage is the last specification to be optimized, and it was found that putting the feed in the bottom stage was the most optimal. While having the feed stage higher produced very slightly higher key product flow rates, doing this ultimately resulted in weeping above the medium cut, and a low liquid rate below the medium cut. Having the feed stage higher than the bottoms stage would require a multi-diameter column with a taper into a smaller diameter below the medium cut. This was considered not to be worth the slight increase in product flow rates. Regular sieve trays were selected due to their simplicity and low cost, with other trays causing hydraulic issues. The MAWP of the vessel was chosen to be the greater of 10% of the minimum column pressure, or 50 psig higher than the minimum column temperature [1]. In this case, the 50 psig increase is greater, so the MAWP is 55.3 psig (top pressure is 5.3 psig). A summary of the optimization findings and conclusions can be seen below, in Table 15.

Table 15: Optimized Distillation Operating Conditions

Reflux ratio	25
Theoretical number of trays	25
Theoretical light cut draw stage	3
Theoretical medium cut draw stage	18

Actual number of trays (using tray efficiency and safety factor assumptions)	42
Actual light cut draw stage	5
Actual medium cut draw stage	30
Light cut flow rate	6,947 lb/hr
Medium cut flow rate	32,860 lb/hr
Py gas flow rate	1,432 lb/hr
Heavy cut flow rate	11,190 lb/hr

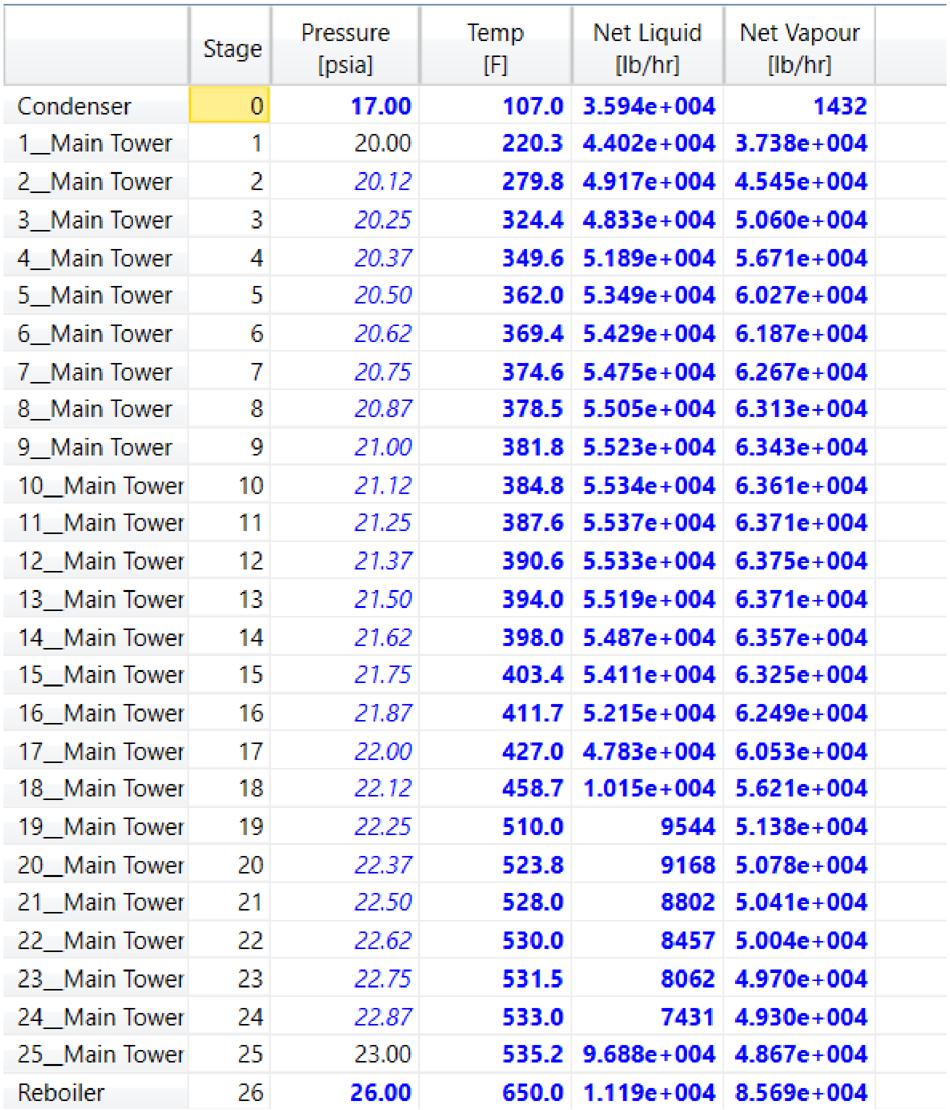
The column reboiler consumes the most energy of any unit operation in the entire process, so optimizing the column is certainly a priority. Given the huge magnitude of the reboiler operating cost (which essentially is equivalent to energy usage), it is the focus of optimization, but the condenser was also considered. As stated above, the reboiler was specified to operate at the lowest possible temperature it could with the column still converging, and the separation still being possible. For example, the energy savings from reducing the reboiler temperature from 700 to 650 is more than 5.5 MMBtu/hr. This is a 36% energy savings, although the reboiler is still (and will be) the highest energy unit operation. Along with this, heat integration has been used to reduce the load on the reboiler, where the medium cut is used to preheat the feed. Essentially, the medium cut will wrap around the column and be used in the shell side of the preheating exchanger, where the feed will be used in the tube side. This reuses energy from the stream (that already needs to be cooled) and increases the feed temperature from 100 to 246 degrees Fahrenheit! It was found that adding more heat integration from other streams would add more complexity to the process without achieving a significant gain. This is primarily due to the lower flow rates of the light and heavy streams.

The heavy stream has no direct value but could be used in several ways. The simplest way would be to simply dispose of it, but this would cost additional money. While low in value, this resid stream can be used as a fuel in a furnace or boiler, or potentially used as a fuel on a sea vessel, called bunker fuel [19]. It is likely, though, that simply disposing of the stream would end up being worth the cost in the lack of complexity of organizing another disposition for the stream.

Due to the placement of the Adsorption columns before the distillation unit, trace water levels should not be worried about in and after the distillation unit. If water was found, it would be a consequence of the adsorption unit or a seal failure of the column.

A control strategy is essential to keeping the product purity from the distillation column as pure as possible, and one has been put in place for this design. Along with product purity, a control scheme is also essential to safety. In the case of this design, a flow control loop has been added to the feed flow, to control flow directly into the column. The rest of the columns production has been controlled by temperature and pressure control loops, as controlling temperature and pressure is directly correlated with the product purity (compositions). More information about the columns control system can be found in the process safety section.

The column profile with temperatures and pressures can be seen below, in Figure 9.



	Stage	Pressure [psia]	Temp [F]	Net Liquid [lb/hr]	Net Vapour [lb/hr]
Condenser	0	17.00	107.0	3.594e+004	1432
1__Main Tower	1	20.00	220.3	4.402e+004	3.738e+004
2__Main Tower	2	20.12	279.8	4.917e+004	4.545e+004
3__Main Tower	3	20.25	324.4	4.833e+004	5.060e+004
4__Main Tower	4	20.37	349.6	5.189e+004	5.671e+004
5__Main Tower	5	20.50	362.0	5.349e+004	6.027e+004
6__Main Tower	6	20.62	369.4	5.429e+004	6.187e+004
7__Main Tower	7	20.75	374.6	5.475e+004	6.267e+004
8__Main Tower	8	20.87	378.5	5.505e+004	6.313e+004
9__Main Tower	9	21.00	381.8	5.523e+004	6.343e+004
10__Main Tower	10	21.12	384.8	5.534e+004	6.361e+004
11__Main Tower	11	21.25	387.6	5.537e+004	6.371e+004
12__Main Tower	12	21.37	390.6	5.533e+004	6.375e+004
13__Main Tower	13	21.50	394.0	5.519e+004	6.371e+004
14__Main Tower	14	21.62	398.0	5.487e+004	6.357e+004
15__Main Tower	15	21.75	403.4	5.411e+004	6.325e+004
16__Main Tower	16	21.87	411.7	5.215e+004	6.249e+004
17__Main Tower	17	22.00	427.0	4.783e+004	6.053e+004
18__Main Tower	18	22.12	458.7	1.015e+004	5.621e+004
19__Main Tower	19	22.25	510.0	9544	5.138e+004
20__Main Tower	20	22.37	523.8	9168	5.078e+004
21__Main Tower	21	22.50	528.0	8802	5.041e+004
22__Main Tower	22	22.62	530.0	8457	5.004e+004
23__Main Tower	23	22.75	531.5	8062	4.970e+004
24__Main Tower	24	22.87	533.0	7431	4.930e+004
25__Main Tower	25	23.00	535.2	9.688e+004	4.867e+004
Reboiler	26	26.00	650.0	1.119e+004	8.569e+004

Figure 9: Distillation Profile

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