Letter of Transmittal

Date: March 10, 2023

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From: Team 14

Subject: Technical & Economic Proposal – Closing Critical Gaps to Enable a Circular Plastics Economy

Per the AIChE 2022 – 2023 Student Design Competition Problem Statement & Rules, along with the information provided in Appendix 1 – Design of Pyoil Purification Unit and Appendix 2 – Jembrana Case Study Narrative, we have attached a technical and economic proposal for closing critical gaps to enable a circular plastics economy. We look forward to hearing your feedback and hope our hard work is reflected in this report.

Best,
Team 14

2022 – 2023 AIChE Student Design Competition

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10 March 2023

Executive Summary

Global Petrochemical Technology is interested in examining the feasibility of a Pyoil purification unit to supply recycled feedstock to a downstream steam cracker in order to follow through on a commitment to produce 10% of their resin-quality plastics from recovered plastic waste. This process will involve the design of a distillation scheme to separate the feed into four product streams: a Py gas stream, a light cut stream, a medium cut stream, and a heavy cut stream. Additionally, units to remove impurities from the products were also designed. Global Petrochemical has also requested an analysis of a manual sorting facility located in Bali, Indonesia to improve the operation of the facility. This analysis will focus on improving the quality, quantity, and cost of the plastic being recovered from the facility.

In the preliminary design phase, the optimal distillation scheme for this separation was determined to be two columns in series. The first column was designed to separate the heavy cut as the bottom product and a mixture of the Py gas, light cut, and medium cut as the distillate product. This distillation column should contain 8 trays. The second column then separates the Py gas and light cut at the condenser with the medium cut as the bottom product and should have 23 trays. Adsorption columns were also designed to ensure that contaminants such as metals and chlorides are removed before being sent to downstream units. The total initial investment needed for this facility is $25 million, with variable and fixed costs per year included in the report.

In addition to the technical design, an analysis of the Bali, Indonesia plastic sorting facility was requested. It was concluded that in order to ensure a consistent, quality feedstock, effort should be concentrated in reducing the cost to enroll in the recycling program as well as increasing staff training. Specifically, incentivizing citizens to participate in plastics recycling by offering a tax credit or cash prize based on the per household amount of plastic provided. Employees would also be educated on the impact of proper sorting on the quality of the product and given extensive training on how to identify different plastics and properly sort them.

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Brief Process Description

Global Petrochemical Technology is focused upon taking a pyrolyzed plastic stream and preparing it for downstream recycling. This proposed design solution includes a Pyoil separation unit to separate the Pyoil into Py gas, Pyoil light cut, Pyoil medium cut, and Pyoil heavy cut. This separation unit is made up of two distillation columns in series and is followed by several adsorption units designed to remove metals and chlorides from the Pyoil light cut and medium cut streams.

Process Detail

Process Flow Diagram

PFD – Pyoil Purification Unit

V-100 DEWATERING UNIT	**P-101 A/B PYOIL TANK PUMPS**	**P-102 A/B PYOIL FEED PUMPS**	**T-100 1ST DISTILLATION COLUMN**	**E-101 COLUMN REBOILER**	**TK-101 HEAVY CUT TANK**	**V-101 CONDENSATE RECEIVER**	**P-105 A/B T-101 FEED PUMPS**	**T-101 2ND DISTILLATION COLUMN**	**P-106 A/B MEDIUM CUT BOTTOMS PUMPS**	**E-107 COLUMN CONDENSER**	**P-107 A/B DISTILLATE/ REFLUX PUMPS**	**E-109 PY GAS HEX**	**V-104 METAL ADSORBER B**	**V-105 CHLORINE ADSORBER A**	**P-109 A/B LIGHT CUT PUMPS**	**V-107 METAL ADSORBER A**	**P-110 A/B MEDIUM CUT PUMPS**	**V-110 CHLORINE ADSORBER B**	**TK-103 MEDIUM CUT TANK**
P-100 A/B WASTE WATER PUMPS	**TK-100 RAW PYOIL TANK**	**E-100 PYOIL FEED HEATER**	**P-103 A/B HEAVY CUT PUMPS**	**E-102 HEAVY CUT HEX**	**E-103 COLUMN CONDENSER**	**P-104 A/B DISTILLATE/ REFLUX PUMPS**	**E-104 T-101 FEED HEATER**	**E-105 COLUMN REBOILER**	**E-106 MEDIUM CUT HEX**	**V-102 CONDENSATE RECEIVER**	**E-108 LIGHT CUT HEX**	**V-103 METAL ADSORBER A**	**P-108 A/B LIGHT CUT PUMPS**	**V-106 CHLORINE ADSORBER B**	**TK-102 LIGHT CUT TANK**	**V-108 METAL ADSORBER B**	**V-109 CHLORINE ADSORBER A**	**P-111 A/B MEDIUM CUT PUMPS**	**TK-104 MEDIUM CUT TANK B**

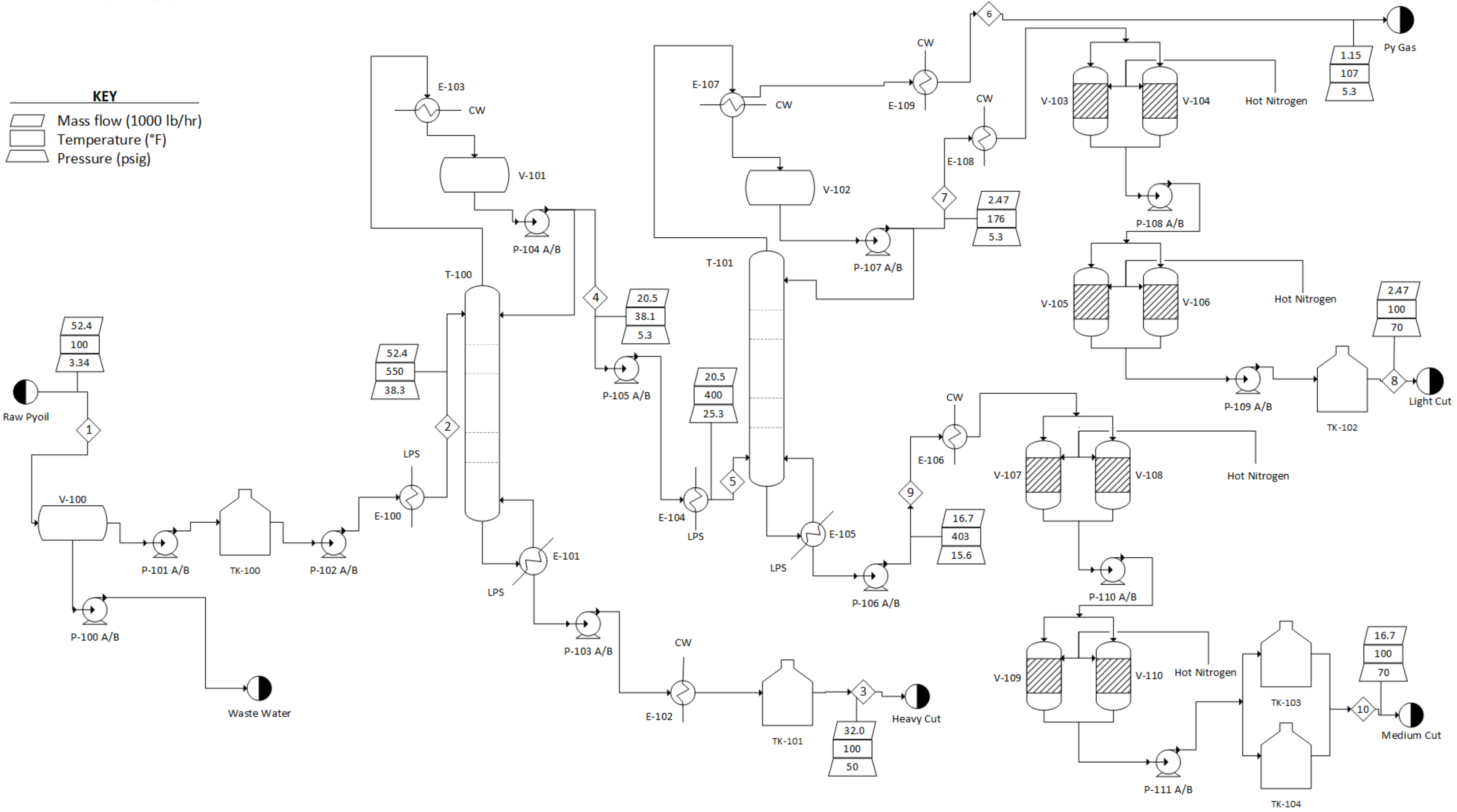


Figure 1: Process Flow Diagram of proposed design for a Pyoil Purification Unit

The process begins with Pyoil feed flowing through the dewatering unit, V-100, to remove any water from the imported stream. The feed is then sent to the holding tank, TK-100, where the feed is stored until needed. The feed is heated and then pumped into the first distillation column, T-100, where Pyoil heavy cut is separated from the three lighter components. The Pyoil heavy cut is sent to storage tank TK-101 until it is disposed or repurposed. Options for repurposing the Pyoil heavy cut include selling the product or using the heavy cut to repair the roads around the sorting facility located in Bali to encourage more residents to participate in the recycling program, which is elaborated on in the analysis of the sorting facility.

The condensate stream of T-100, including Py gas, Pyoil light cut, and Pyoil medium cut, is used as the feed for the second distillation column, T-101. The Py gas and Pyoil light cut are separated in the partial condenser, E-107, in which the Py gas is sent directly to the ethylene plant as an overhead vapor and the Pyoil light cut exits the condenser as a liquid. The Pyoil medium cut leaves T-101 out of the bottom of the column as a liquid. Both the Pyoil light and medium cuts are sent through adsorbers to remove chlorides and calcium/silica metals. There are two adsorbers for each contaminate that is being removed in order to allow regeneration of the material inside of one adsorber while the other is in operation. The Pyoil light and medium cut streams are pumped and cooled in order to provide the products to the ethylene plant at the necessary specifications discussed in Appendix 1 of the problem statement.[1]

Material Balance

Table 1: Stream Summary for Figure 1

Stream Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Stream Label	Pyoil Feed	Tower 1 Feed	Heavy Cut Product	Tower 1 Reflux	Tower 2 Feed	Py Gas Product	Tower 2 Reflux	Light Cut Product	Tower 2 Bottoms	Medium Cut Product
Phase	Liquid	Two Phase	Liquid	Liquid	Two Phase	Two Phase	Liquid	Liquid	Liquid	Liquid
Temperature (°F)	100.00	550.10	100.00	38.11	400.00	107.00	176.00	100.00	402.70	100.00
Pressure (psig)	3.34	38.34	50.00	5.30	25.30	5.30	5.30	55.30	15.55	55.30
Enthalpy (btu/lb)	-906.50	-596.30	-910.40	-929.30	-702.90	-508.00	-874.40	-913.70	-742.80	-916.20
Total Mass Flow Rate (lb/hr)	52,430.00	52,430.00	31,950.00	20,480.00	20,480.00	1,151.00	2,469.00	2,469.00	16,860.00	16,860.00
Actual Volumetric Flow Rate (bbl/day)	4,565.00	4,565.00	2,705.00	1,859.00	1,859.00	137.90	230.90	230.90	1,491.00	1,491.00
Density (lb/ft^3)	48.03	2.02	49.34	48.00	2.02	0.21	42.67	44.90	38.58	47.31

Table 1 includes stream property information for ten of the major streams shown in the process flow diagram of the Pyoil Purification Unit, Figure 1. The streams displayed in the table include feed and product streams as well as intermediate streams for bottoms and reflux flows in the process. The stream summary table illustrates the overall material balance for the designed process and provides information for the phase, temperature, pressure, and flow rates of the specified streams.

Sized Equipment List

Table 2: Sized Pumps

Equipment Label	Equipment Type	Description	Capacity (hp)
P-100 A/B	Pump	Waste Water Pumps	0.1222
P-101 A/B	Pump	Pyoil Tank Pumps	0.3054
P-102 A/B	Pump	Pyoil Feed Pumps	0.9540
P-103 A/B	Pump	Heavy Cut Pumps	2.027
P-104 A/B	Pump	Distillate/Reflux Pumps	1.298
P-105 A/B	Pump	T-101 Feed Pumps	0.3054
P-106 A/B	Pump	Medium Cut Bottoms Pumps	0.0806
P-107 A/B	Pump	Distillate/Reflux Pumps	0.5208
P-108 A/B	Pump	Light Cut Pumps	0.1612
P-109 A/B	Pump	Light Cut Pumps	0.1612
P-110 A/B	Pump	Medium Cut Pumps	0.7677
P-111 A/B	Pump	Medium Cut Pumps	0.7807

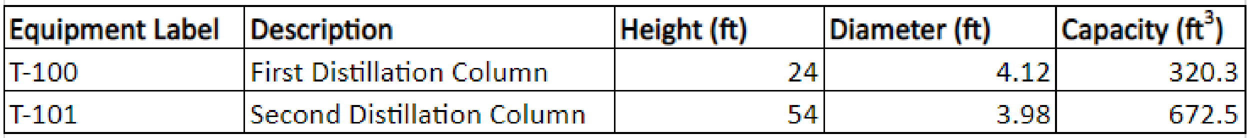
The capacity for each pump in the designed process is listed above in Table 2. Each pump in the process was spared to ensure the purification unit would not shut down in the event of a failure within the system. The pumps were sized in order to accommodate the flow rate and pressure drop necessary to ensure product specifications would be met. The pump efficiency was assumed to be 65%, and the motor efficiency was assumed to be 75%. The capacity displayed in Table 2 is the purchased horsepower for each individual pump.

Table 3: Sized Tanks

Equipment Label	Equipment Type	Description	Capacity (ft^3)
TK-100	Tank	Raw Pyoil Tank	392,900
TK-101	Tank	Heavy Cut Tank	76,720
TK-102	Tank	Light Cut Tank	20,830
TK-103	Tank	Medium Cut Tank	78,830
TK-104	Tank	Medium Cut Tank B	78,830

The information for the volume of the tanks in the proposed process are provided in Table 3 above. This design required that each tank have a week of holdup time and a surge time of 12 hours was chosen to ensure the high liquid level would not be exceeded.[1] The length and diameters of the tanks were determined by varying the ratio of the length to diameter from 3 to 8 and choosing the most reasonable measurements.

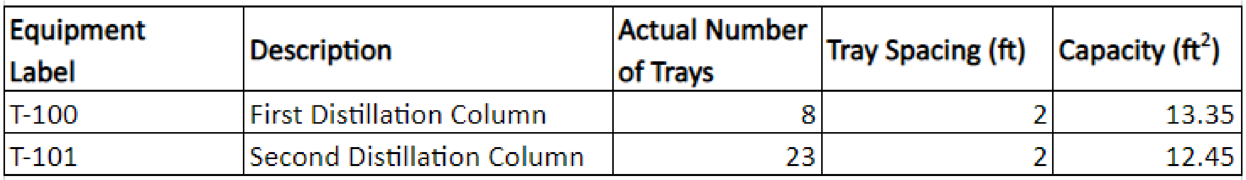
Table 4: Sized Towers



Equipment Label	Description	Height (ft)	Diameter (ft)	Capacity (ft^3)
T-100	First Distillation Column	24	4.12	320.3
T-101	Second Distillation Column	54	3.98	672.5

The distillation towers for the process were modeled in Aspen HYSYS and were sized based upon the height needed for the number of trays in each column, while the diameter was sized to ensure the column could perform the desired separation based upon the inlet flow rate. A more detailed design description including sizing details is included in the distillation section detail in the appendices.

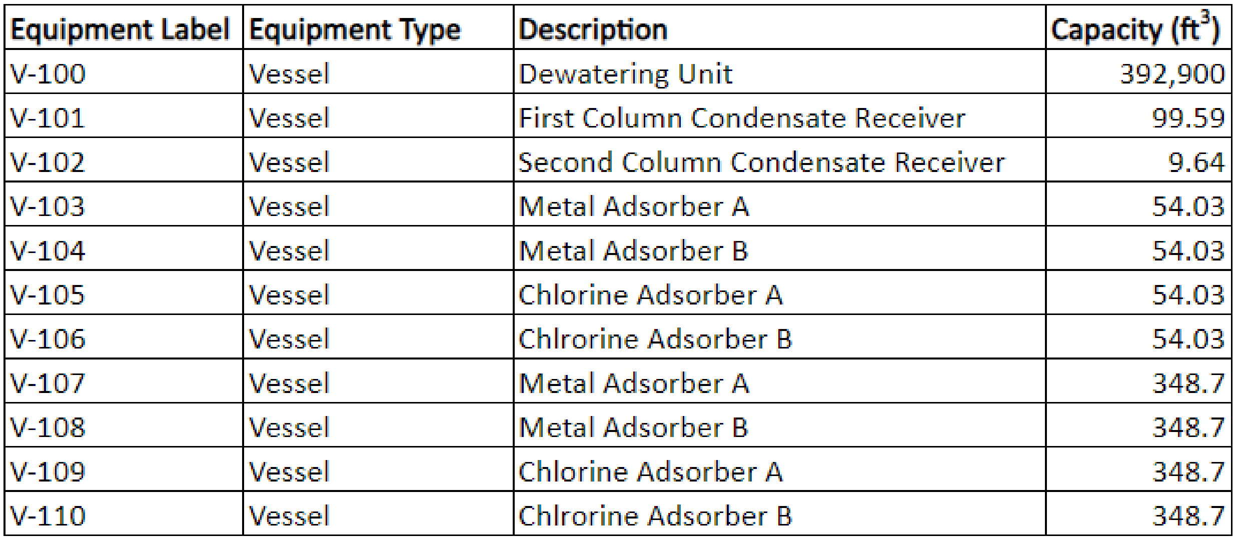
Table 5: Sized Trays



Equipment Label	Description	Actual Number of Trays	Tray Spacing (ft)	Capacity (ft^2)
T-100	First Distillation Column	8	2	13.35
T-101	Second Distillation Column	23	2	12.45

The tray sizing information for both distillation towers is provided in Table 5 above. It was assumed that spacing between the trays was 2 feet and the diameter of each was the same as the diameter calculated for each distillation column.[2] Further details of the design and assumptions made for sizing the trays are provided in the appendices under the distillation section detail.

Table 6: Sized Vessels



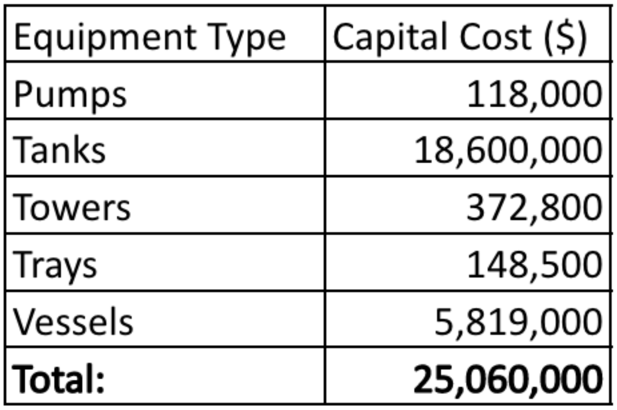
Equipment Label	Equipment Type	Description	Capacity (ft^3)
V-100	Vessel	Dewatering Unit	392,900
V-101	Vessel	First Column Condensate Receiver	99.59
V-102	Vessel	Second Column Condensate Receiver	9.64
V-103	Vessel	Metal Adsorber A	54.03
V-104	Vessel	Metal Adsorber B	54.03
V-105	Vessel	Chlorine Adsorber A	54.03
V-106	Vessel	Chlrorine Adsorber B	54.03
V-107	Vessel	Metal Adsorber A	348.7
V-108	Vessel	Metal Adsorber B	348.7
V-109	Vessel	Chlorine Adsorber A	348.7
V-110	Vessel	Chlrorine Adsorber B	348.7

The equipment listed in Table 6 represents each vessel designed for this process. The dewatering unit and both condensate receivers were designed as horizontal process vessels and sized accordingly.[3] Assumptions for the dewatering unit included a surge time of 12 hours and a holdup time of 1 week to meet process requirements.[1] This was done to prevent overflow of the tank and take precautionary measures in case of process disturbances. Assumptions for each condensate receiver included a surge time of 2 minutes and a holdup time of 3 minutes.[4] For the adsorbers, liquid hourly space velocity (LHSV) was given in the charge memo as 1/hour to provide adequate protection.[1] This information was used to determine the volume of catalyst needed for each adsorber which was assumed to be the volume of the entire vessel. More insight into the design of the adsorbers can be found in the adsorber section detail in the appendices.

Economics

Capital Cost Estimate

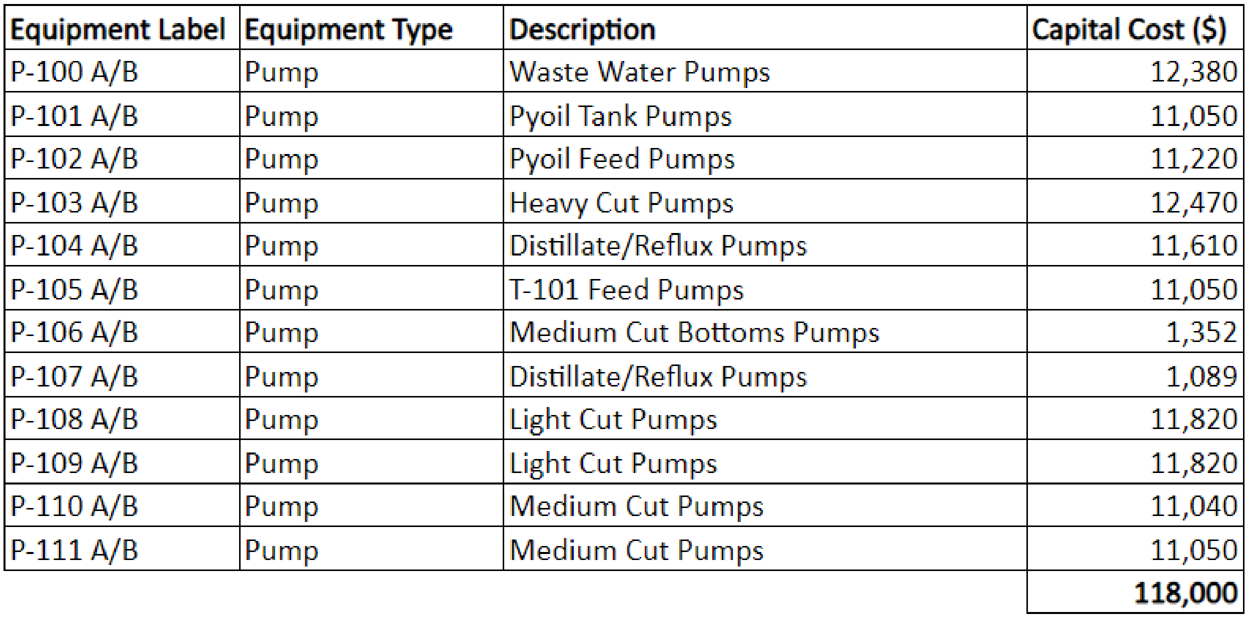
Table 7: Capital Cost Summary



Equipment Type	Capital Cost ($)
Pumps	118,000
Tanks	18,600,000
Towers	372,800
Trays	148,500
Vessels	5,819,000
Total:	**25,060,000**

Depicted above in Table 7 are the individual costs for each equipment category and the total cost for all equipment required to be built for the Pyoil Purification Unit. Each price was calculated based on the size, capacity, material of construction, the CEPCI from October 2022, and the number of units used in the process.[5] The material of construction for each piece of equipment was chosen as stainless steel to prevent any corrosion or fouling associated with this process. These parameters were utilized using heuristics, equations, and procedures from the *Analysis, Synthesis and Design of Chemical Processes* textbook to calculate costs.[6]

Table 8: Capital Cost for Pumps



Equipment Label	**Equipment Type**	**Description**	**Capital Cost ($)**
P-100 A/B	Pump	Waste Water Pumps	12,380
P-101 A/B	Pump	Pyoil Tank Pumps	11,050
P-102 A/B	Pump	Pyoil Feed Pumps	11,220
P-103 A/B	Pump	Heavy Cut Pumps	12,470
P-104 A/B	Pump	Distillate/Reflux Pumps	11,610
P-105 A/B	Pump	T-101 Feed Pumps	11,050
P-106 A/B	Pump	Medium Cut Bottoms Pumps	1,352
P-107 A/B	Pump	Distillate/Reflux Pumps	1,089
P-108 A/B	Pump	Light Cut Pumps	11,820
P-109 A/B	Pump	Light Cut Pumps	11,820
P-110 A/B	Pump	Medium Cut Pumps	11,040
P-111 A/B	Pump	Medium Cut Pumps	11,050
			118,000

Table 8 associates each pump used in the Pyoil Purification Unit with the capital cost required to build and install each unit. Each listed cost was for a single pump, while the total capital cost includes all spared pumps. The capital cost for these pumps was calculated using stainless steel as a material of construction and the power required, calculated in Table 2, to meet certain specifications such as pressure drop throughout the process and the flow rate through each pump.

Table 9: Capital Cost for Tanks

Equipment Label	Equipment Type	Description	Capital Cost ($)
TK-100	Tank	Raw Pyoil Tank	5,185,000
TK-101	Tank	Heavy Cut Tank	1,737,000
TK-102	Tank	Light Cut Tank	2,523,000
TK-103	Tank	Medium Cut Tank	9,151,000
TK-104	Tank	Medium Cut Tank B	9,151,000
			18,600,000

The capital cost for each of the storage tanks used in this process is located in Table 9. These costs were calculated using stainless steel as the material of construction, the volume required to accommodate for flow rates, and the hold up and surge times calculated in Table 3.

Table 10: Capital Cost for Towers

Equipment Label	Equipment Type	Description	Capital Cost ($)
T-100	Tower	First Distillation Column	139,700
T-101	Tower	Second Distillation Column	233,100
			372,800

Table 10 provides the capital costs for both distillation towers used in the purification process. These prices were calculated using stainless steel as the material of construction along with the volume required to achieve the necessary separation of the components entering each tower, calculated in Table 4. These costs include the construction and instillation of the towers but do not include the cost of internal trays which was calculated separately.

Table 11: Capital Cost for Column Trays

Equipment Label	Equipment Type	Description	Capital Cost ($)
T-100	Trays	First Distillation Column	63,930
T-101	Trays	Second Distillation Column	84,600
			148,500

Calculated in Table 11 are the capital costs of the separation trays used in each of the distillation columns described in the purification process. The number of actual trays required for each column was calculated using the number of theoretical trays in the Aspen HYSYS simulation of the process along with a tray efficiency 50%.[7] The capital costs were determined based on the material of construction of stainless steel, the number of actual trays, along with the area of each tray to fit in the distillation columns.

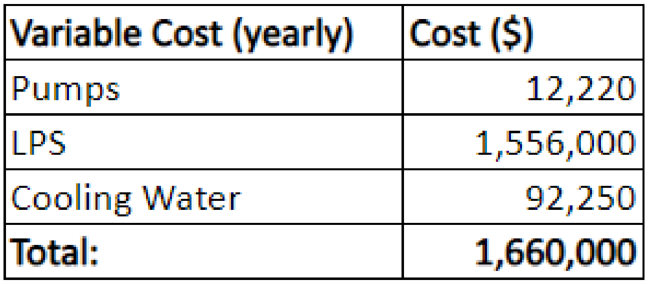
Table 12: Capital Cost for Vessels

Equipment Label	Equipment Type	Description	Capital Cost ($)
V-100	Vessel	Dewatering Unit	5,185,000
V-101	Vessel	First Column Condensate Receiver	70,870
V-102	Vessel	Second Column Condensate Receiver	30,060
V-103	Vessel	Metal Adsorber A	21,840
V-104	Vessel	Metal Adsorber B	21,840
V-105	Vessel	Chlorine Adsorber A	21,840
V-106	Vessel	Chlrorine Adsorber B	21,840
V-107	Vessel	Metal Adsorber A	111,500
V-108	Vessel	Metal Adsorber B	111,500
V-109	Vessel	Chlorine Adsorber A	111,500
V-110	Vessel	Chlrorine Adsorber B	111,500
			5,819,000

Displayed above in Table 12 are the capital costs of all the vessels used in the purification unit. The vessels were priced based on the material of construction of stainless steel along with the calculated volumes necessary to undergo each vessel’s specified process, shown in Table 6. The costs for each of the adsorption units does not include the cost of the catalyst used but is included in the fixed cost estimate.

Variable Cost Estimate

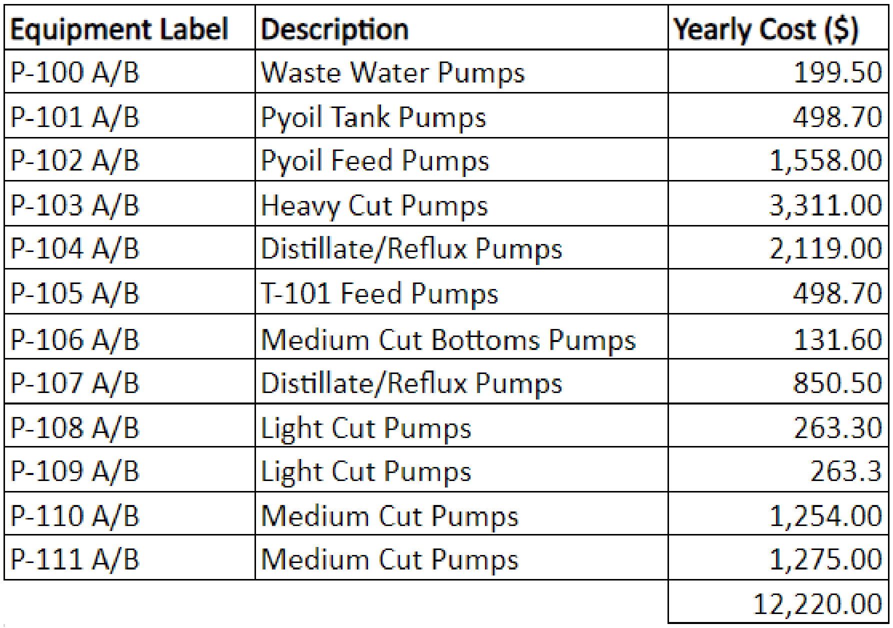
Table 13: Variable Cost Summary



Variable Cost (yearly)	**Cost ($)**
Pumps	12,220
LPS	1,556,000
Cooling Water	92,250
Total:	**1,660,000**

The variable costs provided in Table 13 are the costs of necessary utilities to keep the process running according to required specifications. These utilities include electricity required for the pumps, low-pressure steam, and cooling water for all heat exchangers in the unit. The specific price for each utility is as follows: electricity at $0.25 USD / kW-hr, low-pressure steam at $22.90 / 1000 kg, and cooling water at $0.50 USD / MBTU.[1]

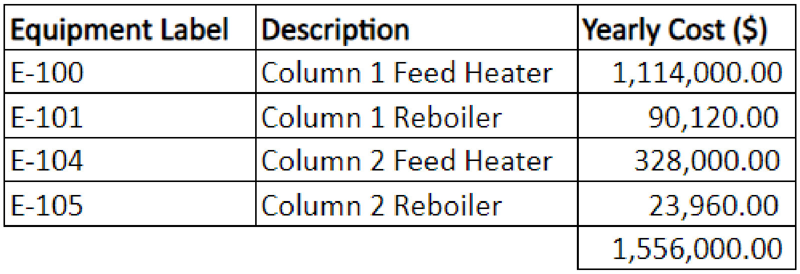
Table 14: Yearly Electricity Cost



Equipment Label	**Description**	**Yearly Cost ($)**
P-100 A/B	Waste Water Pumps	199.50
P-101 A/B	Pyoil Tank Pumps	498.70
P-102 A/B	Pyoil Feed Pumps	1,558.00
P-103 A/B	Heavy Cut Pumps	3,311.00
P-104 A/B	Distillate/Reflux Pumps	2,119.00
P-105 A/B	T-101 Feed Pumps	498.70
P-106 A/B	Medium Cut Bottoms Pumps	131.60
P-107 A/B	Distillate/Reflux Pumps	850.50
P-108 A/B	Light Cut Pumps	263.30
P-109 A/B	Light Cut Pumps	263.3
P-110 A/B	Medium Cut Pumps	1,254.00
P-111 A/B	Medium Cut Pumps	1,275.00
		12,220.00

Table 14 depicts the yearly cost associated with the necessary electricity to run the pumps in the unit. Prices were calculated based on the electrical capacity needed to achieve necessary pressure drops throughout the process.

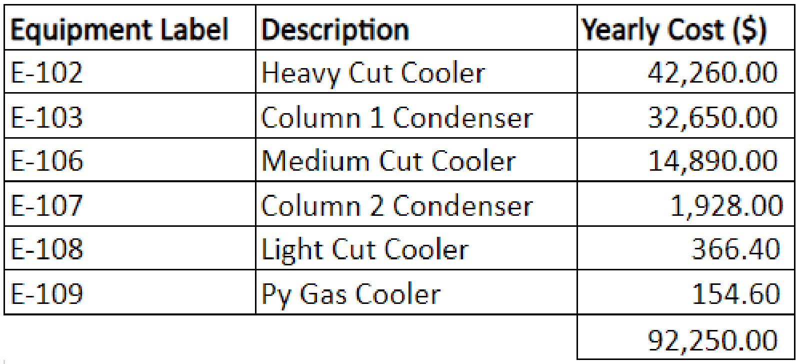
Table 15: Yearly Low-Pressure Steam Cost



Equipment Label	Description	Yearly Cost ($)
E-100	Column 1 Feed Heater	1,114,000.00
E-101	Column 1 Reboiler	90,120.00
E-104	Column 2 Feed Heater	328,000.00
E-105	Column 2 Reboiler	23,960.00
		1,556,000.00

Table 15 displays the yearly cost associated with the use of low-pressure steam in the process. Prices were calculated based on the mass flow rate of low-pressure steam needed to provide necessary heat exchange in the heaters and column reboilers.

Table 16: Yearly Cooling Water Cost

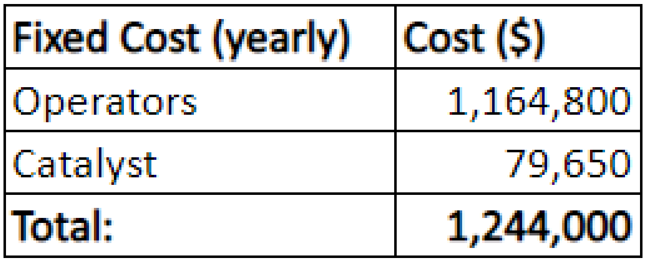


Equipment Label	Description	Yearly Cost ($)
E-102	Heavy Cut Cooler	42,260.00
E-103	Column 1 Condenser	32,650.00
E-106	Medium Cut Cooler	14,890.00
E-107	Column 2 Condenser	1,928.00
E-108	Light Cut Cooler	366.40
E-109	Py Gas Cooler	154.60
		92,250.00

Table 16 displays the yearly cost associated with the use of cooling water in the process. Prices were calculated based on the mass flow rate of cooling water needed to provide necessary heat exchange in the coolers and column condensers.

Fixed Cost Estimate

Table 17: Fixed Cost Summary



Fixed Cost (yearly)	Cost ($)
Operators	1,164,800
Catalyst	79,650
Total:	**1,244,000**

Provided in Table 17 are the yearly costs that are associated with fixed variables such as operator salary and the price of the catalyst used to extract contaminants. The number of operators needed to run the process is 16, determined by the number of major pieces of equipment in the process, working 2,080 hours a year receiving $35/hour.[8] The catalyst will be regenerated with processed nitrogen throughout the year and replaced yearly. Details of the calculations for catalyst price can be found in the adsorption detail section of the appendices.

Process Safety

Minimizing Environmental Impacts

The pyrolysis of plastic waste has the potential to be an environmentally hazardous process. The main priority of the design is to create a process that is inherently safer than other options. This process aims to reduce loss of containment through the design of strategically placed controllers, minimization of complexities in the system, appropriate design pressure and temperature ranges, and selection of utilities.

Temperature, pressure, level, and flow controllers keep the system running safely and efficiently, preventing damages in the system that could cause explosions or lead to hazardous material leaking into the surrounding environment. These sensors ensure that the system stays in the desired design pressure and temperature operating ranges. A detailed description of the controls added to this particular design can be found illustrated in Figure 2 and in the distillation detail section of the appendices.

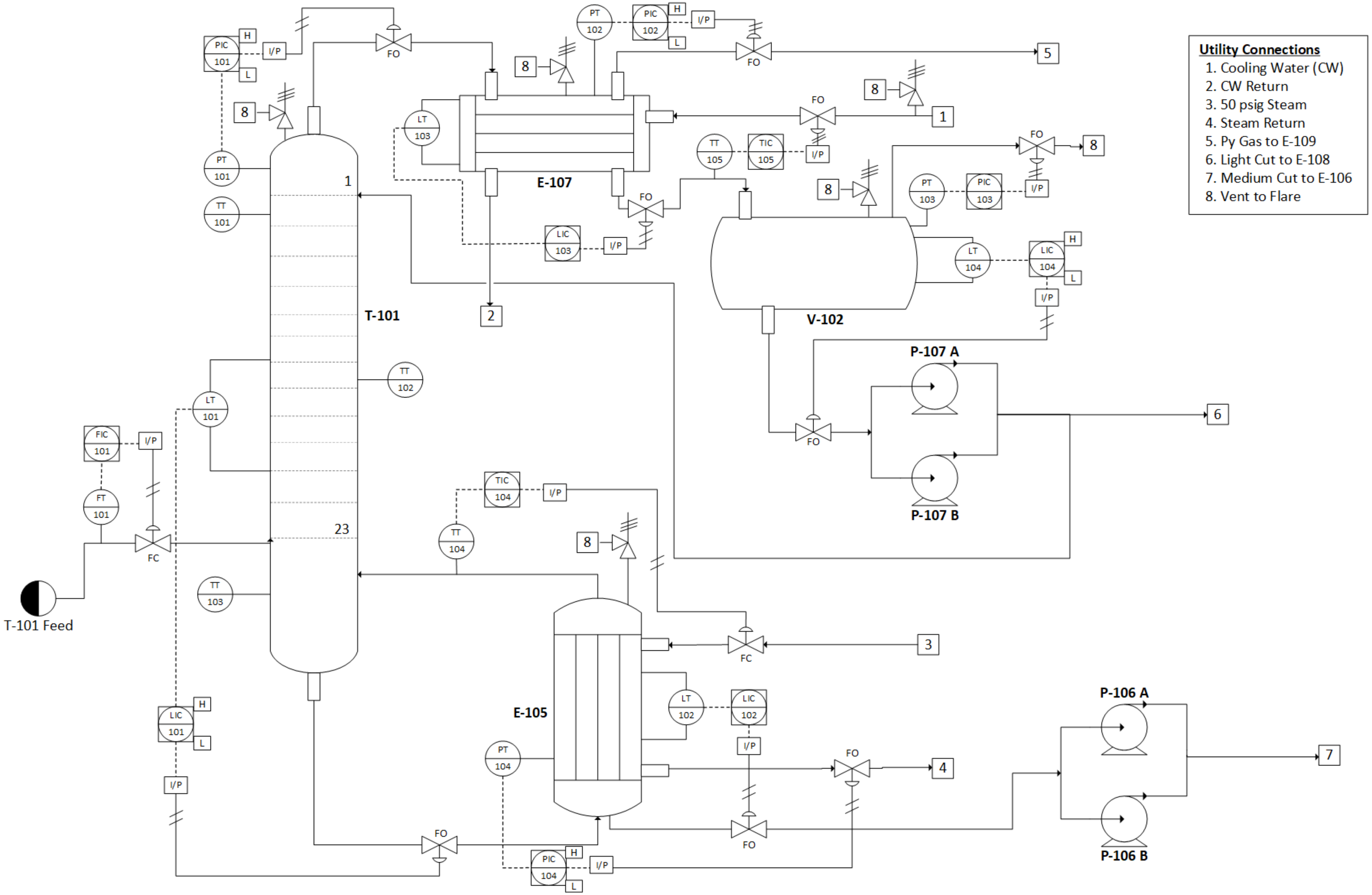
The proposed design is inherently safer because of the use of two distillation columns instead of one. With one column, the feed would need to be heated and pumped to a much higher pressure and temperature than it would with the use of two distillation columns in series. Using two columns allows the design pressure and temperature ranges to be lower, and this lowers the risk of potential damages to the environment in the event of a hazard.

The utilities selected for this process are cooling water and low-pressure steam. The cooling water and low-pressure steam are relatively safer compared to other options such as hot oil and high-pressure steam because of their relatively low pressures and temperatures. Cooling water can be conserved by using a water recycling unit, reducing water pollution. The amount of low-pressure steam needed and the safety of using this utility can be optimized by regular inspections ensuring no leaks are present and using efficient insulation resulting in better heat transfer in the unit and minimized heat loss. The amount of energy consumed to prepare both utilities is much lower than that of alternatives, which reduces the overall energy consumption of the process.

P&ID

Controls systems were added to the design to minimize environmental hazards, mitigate risks, and ensure product specifications were met. A detailed process and instrumentation diagram for the largest tower, T-101 is provided in Figure 2 below. Pressure, temperature, level, and flow sensors were added to the design in order to monitor important properties in various locations of the system. Monitoring these parameters was necessary to avoid loss of containment and protect the environment, community, and equipment in the process. A more detailed description of specific sensors and controllers in Figure 2 is provided in the Appendices.

P&ID – T-101 Distillation Column



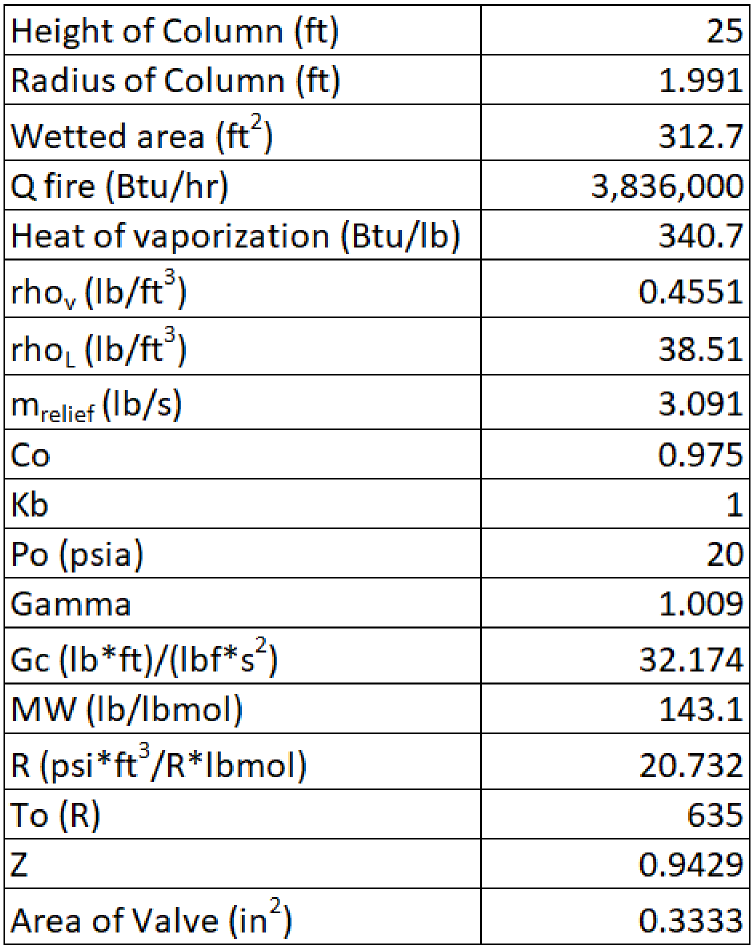
Utility Connections

1. Cooling Water (CW)
2. CW Return
3. 50 psig Steam
4. Steam Return
5. Py Gas to E-109
6. Light Cut to E-108
7. Medium Cut to E-106
8. Vent to Flare

Figure 2: Process and Instrumentation Diagram for largest tower in the design (T-101)

Pressure Relief Valve Sizing

Table 18: Pressure Relief Valve Sizing



Height of Column (ft)	25
Radius of Column (ft)	1.991
Wetted area (ft^2)	312.7
Q fire (Btu/hr)	3,836,000
Heat of vaporization (Btu/lb)	340.7
rho_v (lb/ft^3)	0.4551
rho_L (lb/ft^3)	38.51
m_{relief} (lb/s)	3.091
Co	0.975
Kb	1
Po (psia)	20
Gamma	1.009
Gc ($(lb*ft)/(lbf*s^2)$)	32.174
MW (lb/lbmol)	143.1
R ($psi*ft^3/R*lbmol$)	20.732
To (R)	635
Z	0.9429
Area of Valve (in^2)	0.3333

Table 18 shows values calculated and assumed when sizing pressure relief valves for T-101, along with the calculated area of the pressure relief valve designed for the unit. It was first determined that the pressure relief valve will experience choked flow, which allowed for simplified calculations to determine the area needed for the pressure relief valve. Since a fire would only reach 25 feet up the column, the amount of energy added by the fire was only considered on this part of the column. The wetted area includes this 25-foot measurement and the surface area of that section of the column but excludes the bottom of the column because it will be covered. All other values to determine the size of the pressure relief valve were determined from intermediate equations, heuristics, and values from the Aspen HYSYS simulation.[9]

Failure Rate Analysis

A failure rate analysis was conducted for equipment, sensors, and valves in the largest distillation column, T-101. The data collected is provided in Table 16 below. The data was analyzed from 2 different sources. The first source was an Offshore Reliability Data Handbook that provided failure rates for all equipment, valves, and sensors for different types of failures. The failure rates provided in Table 16 are the average failure rates per 10^6 hours. The type of flow sensors included in this source were electro-mechanical flow sensors. Types of level sensors included in this source were capacitance, conductivity, displacement, magnetic, sonic, and other level sensors. Types of pressure sensors included in this source were capacitance, electro-mechanical, piezo-electric, and semiconductor strain pressure sensors. Types of temperature sensors included in this source were capillary, resistance, and thermocouple temperature sensors.[10]

The second source was a report from Idaho National Engineering Laboratory on Reliability Estimates for Selected Sensors in Fusion Applications. This source provided different failure types, a failure rate, and upper bound failure rate, both rates provided in failure rate per hour. Types of flow sensors included in this source were orifice and venturi flow sensors. The level sensor discussed in this source was a LVDT level sensor. The types of pressure sensors included in this source were strain gauge and LVDT pressure sensors. The types of temperature sensors included in this source were thermocouple and resistance temperature director (RTD) sensors.[11]

From the collected failure rate data, it is clear that the sensor failure rates are fairly low overall for our designed process. The sensors with the lowest failure rates are the pressure and temperature sensors, which are the most important for our design, allowing us to ensure products are on spec and to ensure no overpressure events occur. The flow sensor appears to have the highest failure rate for the sensors. Since flow rates will vary for the feed stream, this higher failure rate should not have a significant impact on the reliability of the design due to the system accounting for variations such as these.

Table 19: Failure Rate Analysis

Equipment Failure	Failure Rate (per 10^6 hours)	Reference
Pump	123.8	[10]
Shell and Tube HEX	69.6	[10]
Distillation Column	285.0	[10]
Flow Sensor	11.8	[10]
	10.0	[11]
Level Sensor	23.8	[10]
	1.0	[11]
Pressure Sensor	5.3	[10]
	1.0	[11]
Temperature Sensor	4.6	[10]
	1.0	[11]
Diapraghm Valve	114.2	[10]
Conventional PRV	24.0	[10]

Personnel Exposure Risk

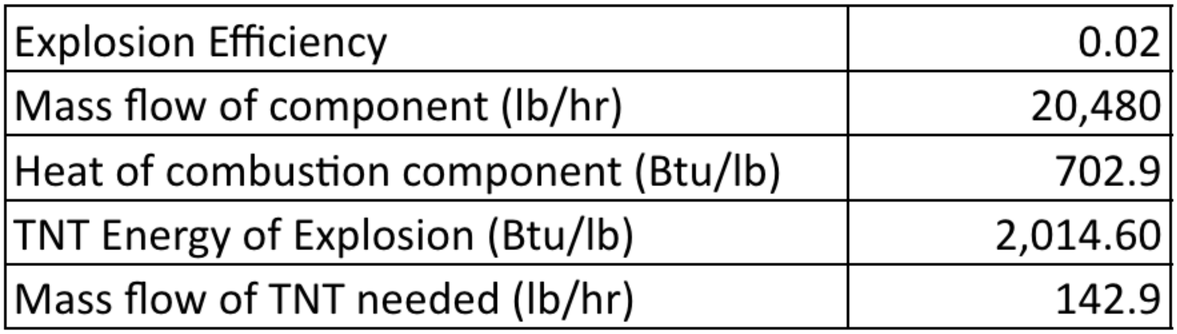
Table 20: Personnel Exposure Risk

			NFPA Diamond Classificaiton			
Chemical	**OSHA PEL (ppm)**	**LD50 (ppm)**	**Health**	**Flammability**	**Reactivity**	**Special**
Nitrogen	-	-	3	0	0	-
Hydrogen	-	-	0	4	0	-
Carbon Monoxide	50	1870	3	4	0	-
Carbon Dioxide	5000	40,000	3	0	0	-
Methane	100	326	2	4	0	-
Ethane	1000	658	1	4	0	-
Ethylene	-	-	2	4	2	-
Propane	1000	-	2	4	0	-
Propylene	-	-	1	4	1	-
Butane	800	658	1	4	0	-
C4 Olefins	800	658	1	4	0	-
1,3-Butadiene	1	100,000	2	4	2	-
Pentane	1000	364	1	4	0	-
Hexane	500	48,000	-	3	0	-
C6+	500	48,000	-	3	0	-

Some of the components throughout the process, listed in Table 20, that are introduced by the Pyoil feed can be hazardous to both the unit and personnel. The most prominent danger when working with the components in the feed given is flammability, especially at high temperatures. Carbon monoxide poisoning is a concern for this design because of the serious effects it can have, especially when inhaled in enclosed spaces. It can cause loss of consciousness, brain damage, and death with constant exposure and lack of oxygen. Ethane and methane are not seriously harmful to humans in small amounts, but they have potential for danger when inhaled in large quantities. These compounds replace oxygen in the respiratory system and can cause asphyxiation, which can lead to brain damage or death. Although not particularly toxic, pentane, hexane, and butane are volatile organic compounds that can be potentially harmful gases to inhale in large quantities. They can cause irritation in the respiratory system, weakness, confusion, or damage to the central nervous system.[12] All employees involved in this design process should be informed of these risks and proper procedures for treating exposure to these chemicals should be put in place.

Atmospheric Detonation of Distillation Inventory

Table 21: Atmospheric Detonation of Distillation Inventory



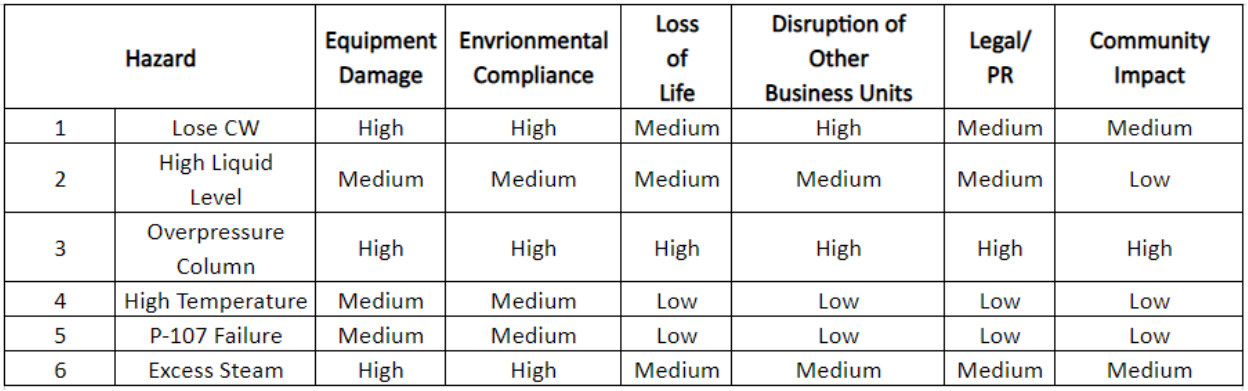
Explosion Efficiency	0.02
Mass flow of component (lb/hr)	20,480
Heat of combustion component (Btu/lb)	702.9
TNT Energy of Explosion (Btu/lb)	2,014.60
Mass flow of TNT needed (lb/hr)	142.9

Table 21 shows the values and intermediate calculations used in determining the mass flow of TNT equivalent to the detonation of the contents of T-101. The mass flow and heat of combustion for the feed was collected from Aspen HYSYS, while the energy of explosion for TNT and equation used were sourced from lecture material.[13]

Hazard and Operability Study

A Hazard and Operability (HAZOP) study was conducted for the largest distillation tower, T-101, to mitigate risks for the process design and is provided in Table 19 below. Different hazards were addressed for the distillation column and included events such as changes in utility flow rate, failure of equipment, and process parameters out of design specifications. Overall, community impact, legal/PR impact, and loss of life risks were relatively lower compared to equipment damage, environmental compliance, and disruption of other business units in the event of a hazard. The hazard that has the highest potential of risk for the process design is overpressure of the column. The hazard that has the lowest potential of risk for the process design is the failure of P-107. This design considers all possible hazards and addresses the risks associated with these hazards.

Table 22: HAZOP Study for T-101



Hazard		Equipment Damage	Envrionmental Compliance	Loss of Life	Disruption of Other Business Units	Legal/ PR	Community Impact
1	Lose CW	High	High	Medium	High	Medium	Medium
2	High Liquid Level	Medium	Medium	Medium	Medium	Medium	Low
3	Overpressure Column	High	High	High	High	High	High
4	High Temperature	Medium	Medium	Low	Low	Low	Low
5	P-107 Failure	Medium	Medium	Low	Low	Low	Low
6	Excess Steam	High	High	Medium	Medium	Medium	Medium

Recommendations for Improvement of the Bali Sorting Facility

Recommendations for closing the Quantity Gap

Implementing a waste sorting facility program in Bali, Indonesia is a crucial step towards reducing waste and promoting sustainability in the area, as well as ensuring that the Pyoil purification process has access to a consistent feed. Only an estimated 5% of waste in Jembrana, Indonesia is recycled, of which 78% is mismanaged and 16% is eventually released into the ocean.[14] To close this gap, there are some important factors to consider. Arguably the most important is increasing education and raising awareness about the waste situation in Indonesia and around the world. Educating the local community about the importance of waste sorting and the impact it can have on the environment can help to achieve this. Currently, participation from households in the area is far less than desired. The volume, efficiency, and productivity of the facility is largely dependent on residential participation. By raising awareness and providing information, more people can be encouraged to participate in the program to keep the environment in which they live clean.

A possible way to increase participation in the recycling program amongst residents is to show them that their efforts are being put to good use in their community. A sizeable amount of the provided feed will be separated as Pyoil heavy cut, which is a tar like substance. This substance could be used to fill in potholes and repair roads in Bali; this would improve the conditions the waste transporters have to work in along with a quality-of-life improvement for residential drivers. If residents are aware that they are making a difference in their community, they will be more inclined to participate in the program.

Providing training, education, and employment opportunities for residents can help to close the quantity gap by creating more economic opportunities. One way to accomplish this would be to hire locals to work at the sorting facility or provide training in waste management and recycling. Encouraging innovation in waste management and recycling can help find new ways to reduce waste and increase recycling rates. By implementing these strategies, the quantity of waste disposed and taken care of can be improved in Bali and can create a more sustainable future for the local community and serve as an example for the reduction of plastic waste worldwide.

Recommendations for closing the Quality Gap

Even with the implementation of the suggestions mentioned above, the operator performance and the quality of waste being received by the facility is rarely consistent. To improve the quality of the separation of waste and desired products, there are multiple factors that should be considered. The most important of which is ensuring that the sorting is done properly. The most applicable way to improve sorting is providing adequate training and education to the workers at the sorting facility. Providing education and training to the local community on waste sorting and recycling can help improve the quality of the waste that is collected, which will help to reduce contamination and increase the value of the recycled materials.

Another remedy for this issue could include intermediate procedures during the sorting process, such as magnets that ensure that all the metal is being removed. These magnets could remove particulates that could be missed by human error. To enhance plastic separation, it would be beneficial to provide adequate training for workers to improve their ability to differentiate between different plastics. Along with this, improving the labeling of containers for specific plastics and waste could also lead to better separation, making it easier to determine where to put certain materials. By investing in modern waste sorting and recycling technology, along with better operator training and resources, the efficiency and quality of the system can be greatly improved.

Recommendations for closing the Affordability Gap

Closing the affordability gap is crucial to ensure the success and sustainability of the program. Affordability is arguably the most important parameter to increase participation amongst households. With this noted, it is imperative to keep the program affordable for the average resident. This could be done by keeping the cost to enroll in the program low as well as making sure that the cost of waste disposal is not too high for low-income families. At the time of the implementation of this project, the cost to enroll in the program is about 1% of the local average income. This is a fair price as compared to most waste management services globally charging on average of about 2% of average local income.[14]

Providing incentives or subsidies to encourage more people to participate in the program could also provide economic motivation to participate in this program. Some incentives could include receiving a tax credit if a household is enrolled in the program or a cash prize for providing a certain amount of usable waste.

Engaging the local community in the program can help to reduce costs for the operation of the sorting facility. Community members can be involved in the physical sorting process, and they can also be responsible for collecting and transporting the waste to the facility. This can help reduce labor costs and ensure the sustainability of the program.

Conclusions

A Pyoil purification unit was designed for Global Petrochemicals in order to stimulate the growth of a circular plastic economy. The proposed design involves separating a pyrolyzed plastic stream into the following products: Py gas, Pyoil light cut, Pyoil medium cut, and Pyoil heavy cut. The design includes two distillation columns in series in which the first column separates the Pyoil heavy cut from the provided feed while the second column separates the last three products. The light and medium cuts are treated for contaminants such as chlorides, calcium, and silica using two adsorbers in series. The process is monitored using a control system to ensure products are provided at the correct specifications outlined in the problem statement.[15] The equipment for the design was priced, and the total capital cost for the design was approximately $25 million. The variable cost was $1.66 million per year and included utility costs for the system; the fixed cost was $1.24 million and included the costs of operators and catalysts.

The most critical aspect of the preliminary design was the mitigation of potential risks. Each piece of equipment was designed to prevent loss of containment and environmental impacts. Control systems were added to each piece of equipment to ensure that any disturbances in the process can be identified and corrected before posing a safety risk. An analysis was also conducted on the failure rates of each type of controller used so that the reliability of the control system could be quantified. Calculations were done to size a pressure relief valve for the larger of the two columns and to determine the TNT equivalent detonation energy associated with the column. Data for the exposure risks for the main chemicals present in the process is included as well as a hazard and operability study.

In addition to the technical design, an analysis was conducted on the sorting facility in Bali, Indonesia to assist in ensuring the plastics provided to the upstream pyrolizer are properly separated and free of any unnecessary contaminants. Recommendations were also made to increase community participation in recycling. It is suggested that increasing the training of the workers at the facility would ensure proper plastics separation and reduce the presence of impurities or contaminants. It was also recommended that citizens enrolled in the recycling program be given a tax break based on the amount of plastic donated from each household or be eligible for a cash prize. These suggestions would greatly increase the quality of the Pyoil feed and help increase the overall participation in the plastics recycling program.

Appendices

Adsorption Section Detail

In order to design the adsorption units associated with this design, it was assumed that the LHSV value provided in the charge memo included the void space of the catalyst. It was also assumed that the density and price of the catalyst was similar to other options currently available on the market. The volume of the beds was calculated using the LHSV value provided in the charge memo assuming that this number included the void space of the catalyst within the vessel.[1] After determining the volume of the catalyst needed, the density was calculated by using an information sheet for a similar catalyst also produced by BASF.[16] In order to determine the cost of the catalyst, it was assumed that the PuriCycle catalyst line being produced by BASF would be priced higher than most catalysts because of its new and experimental nature. After extensive research, it was determined that a cost of $11 per pound of catalyst would be an appropriate estimation.[17] The specific height and diameter values were calculated assuming that the ratio of the length of the column to the diameter was 5 to ensure that the columns were an appropriate size and did not take up unnecessary amounts of area at the process plant.

Since production must continue while the adsorption columns were being regenerated, this design includes two of each adsorption column in parallel to allow the flow to be routed through one column while the other is being regenerated. Piping to accommodate process nitrogen should be included in both units as well as control sensors to notify operators of any upsets in the process. While this does increase the capital costs needed for the plant, it greatly reduces the need for unnecessary shutdown.

The Pyoil feed being supplied can vary greatly depending on the quality of materials being recycled. In order to ensure that high levels of chlorine and metal contamination do not affect the adsorption process, concentration controls were added prior to the adsorption units so that the specific levels of contaminants in the stream can be monitored. If the levels are exceptionally high, operators will be made aware of the situation and can alternate between the two columns in parallel and allow time to regenerate the column not in use.

Distillation Section Detail

For this distillation design, the first column was designed to separate the heavy component from a mixture of the Py gas, light cut, and medium cut; a second column in series was designed to take the mixture of the three lighter components and separate them. T-100, the first tower, had 5 theoretical trays and 8 actual trays, while T-101 had 23 actual trays and 15 theoretical. Both distillation columns used double-pipe condensers and reboilers for the reflux streams and used cooling water and low-pressure steam as their respective utilities.

In order to determine the most optimum distillation scheme for the required separation, several different configurations were simulated and tested in Aspen HYSYS. The feed being provided from the pyrolyzing unit varies and is difficult to accurately model, so the boiling point curve information provided in the charge memo was used to model the feed as an assay with several pseudo components. Additionally, Peng-Robinson was chosen as the fluid package.[18] The pressure drop in the condenser was estimated to be 3 psi with a 5 psi pressure drop in the reboiler; it was also assumed that there would be an additional 10 feet of height in the column due to the reboiler and condenser.[19]

One of the more challenging aspects of this design was choosing which properties within the column to specify to allow the simulation to solve for other variables. Our team chose to use the end boiling points provided in Table 2 of the charge memo in addition to an end boiling point for the heavy cut defined by the end boiling point of the distillation curve provided in Table 1. With this information, we tested different configurations by varying the distillation scheme, number of trays, feed temperature, and reboiler pressure. From these trials, it was determined that separating the heavy components from the feed in the initial column and using the second to separate the three lighter components led to products that matched specifications much better than those from any other configuration.

After determining the most optimum distillation scheme, the columns themselves were optimized to ensure the best possible separation by testing combinations of various feed temperatures and condenser pressure to minimize the reflux ratio. For the first column, it was determined that the lowest reflux ratio occurred when the tower feed was 500°F with a condenser pressure of 20 psia. Similarly, the second column was also optimized and found to have the best separation with a feed temperature of 400°F and a condenser pressure of 20 psia.

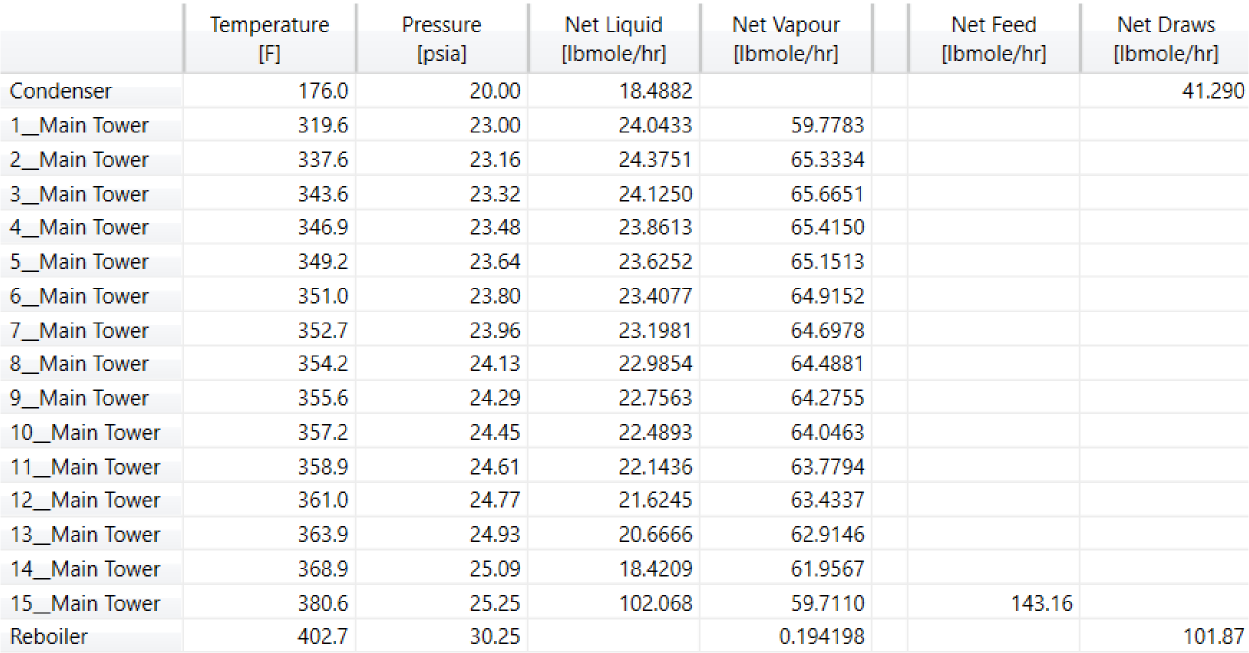
For each column, the material of construction was chosen as stainless steel because of the high potential for fouling in this separation. The height of the column was calculated assuming two feet of spacing in between trays and an additional discharge height of ten feet; the diameter of the column was calculated using the height and the flow in the column to ensure that there was adequate room for proper separation. The price of the column was determined using the heuristics outlined in Appendix A of the textbook, *Analysis, Synthesis, and Design of Chemical Processes*.[6]

In order to ensure that the column configuration minimized energy consumption, the feeds were preheated to limit the amount of steam needed in the reboilers of both columns. The utility for the reboilers and heaters was chosen as low pressure steam to reduce the amount of energy used to pressurize and heat the steam. Additionally, when conducting tests for a single distillation column, it was found that the energy needed for the reboiler and condenser was much higher than that needed for two columns.

The design for the distillation column includes controllers to ensure that all products meet the required specifications. On the tower, there are pressure, level, and temperature sensors to monitor the properties of the column, ensuring in the event a property is not in specification, it can easily be addressed. The condenser also has sensors for pressure, level, and temperature, to ensure that proper heat exchange is occurring in the system, which will have a large effect on the success of separation in the column. The condensate receiver has sensors for level and pressure to ensure no loss of containment occurs, which could possibly shut down the entire process. The reboiler has pressure, level, and temperature sensors, which ensure enough heat is being added to the distillation column safely. This is important to allow for full separation between the Py gas, Pyoil light cut, and Pyoil medium cut. Overall, the sensors added to the design are to ensure a safe process and to avoid any unnecessary risks from hazards. The controls also ensure each product is provided at the correct composition, pressure, and temperature to the downstream ethylene plant.

In order to ensure that no water was sent to any downstream units, a dewatering unit was placed at the beginning of the process. This unit was designed to allow the raw Pyoil feed to settle and any water in the feed to separate into the bottom. A liquid level control was placed on the dewatering tank to detect the presence of any water and a wastewater pump was designed to remove any water detected.

Both columns contained sieve trays in order to minimize the cost of the column and avoid unnecessary complexity. Sieve trays are also easier to clean compared to other tray types which is beneficial, especially in the first column where higher rates of fouling are expected.



	Temperature [F]	Pressure [psia]	Net Liquid [lbmole/hr]	Net Vapour [lbmole/hr]	Net Feed [lbmole/hr]	Net Draws [lbmole/hr]
Condenser	176.0	20.00	18.4882			41.290
1__Main Tower	319.6	23.00	24.0433	59.7783		
2__Main Tower	337.6	23.16	24.3751	65.3334		
3__Main Tower	343.6	23.32	24.1250	65.6651		
4__Main Tower	346.9	23.48	23.8613	65.4150		
5__Main Tower	349.2	23.64	23.6252	65.1513		
6__Main Tower	351.0	23.80	23.4077	64.9152		
7__Main Tower	352.7	23.96	23.1981	64.6978		
8__Main Tower	354.2	24.13	22.9854	64.4881		
9__Main Tower	355.6	24.29	22.7563	64.2755		
10__Main Tower	357.2	24.45	22.4893	64.0463		
11__Main Tower	358.9	24.61	22.1436	63.7794		
12__Main Tower	361.0	24.77	21.6245	63.4337		
13__Main Tower	363.9	24.93	20.6666	62.9146		
14__Main Tower	368.9	25.09	18.4209	61.9567		
15__Main Tower	380.6	25.25	102.068	59.7110	143.16	
Reboiler	402.7	30.25		0.194198		101.87

Figure 3: Temperature and vapor/liquid traffic profile in T-101

Figure 3 above shows the temperature, pressure, vapor, and liquid profiles in the second distillation tower, T-101. The figure was taken from the Aspen HYSYS simulation produced for the proposed design.

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