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Economic Optimization of Pyoil Purification Process Design and Related Management of Waste

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Economic Optimization of Pyoil Purification Process Design and Related Management of Waste

by

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Wesley Hong

Student Name (printed)

Wesley Hong

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4/27/2023

Date

Letter of Transmittal

TO: Alliance to End Plastic Waste

FROM: Global Petrochemicals

RE: Plastic Waste to Pyrolysis Oil Process

DATE: 4/25/2023

In response to your suggestion of plastic waste recycling and conversion into pyrolysis oil in Bali, our attached report provides details on the design, operations, economics, and safety considerations to meet your specifications. Implementing this process will enable the meeting of safety standards while maintaining a solid economic advantage. Based on our design, processing 52,432 pounds of pyrolysis oil every hour will result in an estimated capital cost of $46,458,919 and estimated operational costs per year of $16,471,072.

If there any questions, feel free to contact us at 123-456-7890 or at globalpetrochemicals@gpc.com

Economic Optimization of Pyoil Purification Process Design and Related Management of Waste

Team Lead: Wesley Hong

Members: Hayden Bennett, Kevin Turner, Sullivan Woodlee

Chemical Engineering Senior Design

The University of Alabama in Huntsville

Spring 2023

Executive Summary

TITLE: Economic Optimization of Pyoil Purification Process Design and Related Management of Waste

OVERVIEW: For the construction and operation of the Pyoil processing facility in Bali, Indonesia, the attached report details the design, operation, and safety precautions necessary to meet the required standards. A fractional distillation section will be necessary for the separation of the Pyoil into the required pygas, light, medium, and heavy cuts, and a combination of desalting and catalytic purification can be used to removed salts, metals, water, and chlorides from the process.

DESIGN DETAILS: It was determined that the most efficient way to maintain products that meet specifications while reducing the amount of heavy cut was to use a larger number of trays, utilize side strippers, maintain a high temperature in the reboiler, and to have a moderately high reflux and boil-up ratio. To increase the economy of the system, heat from the light, medium, and heavy cut streams were used to preheat both the desalter feed water and pyoil, as well as the fractionation column feed of pyoil. Desalting of the pyoil feed was done before the column to mitigate the effects of fouling in heat exchangers, while catalytic purification takes place after the column to further treat the feedstock going into the ethylene plant. Reverse Osmosis is also used to treat waste water coming from the desalter to minimize waste and sewage treatment expenses.

FINANCES: The major equipment was sized by ASPEN and the costs were estimated to be $8,526,300. From this, using Lang Factor Analysis and comparing with other estimates the total capital costs were calculated to be **$46,458,919**. Process flow information was used to determine the operational costs which are estimated to be $2,371,356. Using estimates and the capital and variable costs calculated, the total estimated fixed cost was calculated to be $9,006,821. Using these figures and estimates, we finally estimate the annual productions costs to be **$16,498,357**.

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Brief Process Description

Background and technical information is needed for the design of a pyoil purification unit, where the pyoil is purified and fractionated into different cuts for use in an ethylene plant. In order to remove contaminants like chlorides, metals, and water, a desalter unit is used. Desalting works by heating the pyoil to decrease the viscosity, using high voltage to separate water containing the contaminants from the oil. The clean oil flows out the top and contaminated desalter water is removed from the bottom of the desalter for waste treatment. The pyoil is heated using the product streams coming off the column before it is passed to the desalter, just as the desalter water feed is heated. This is important to lower the viscosity of the pyoil as it comes in with an API of 48. The contaminated waste water is treated using reverse osmosis and the resultant waste water is sent to a water treatment facility for further decontamination. The purified oil is then preheated again by the column product stream and fed into a fractionation column with a reboiler on the bottom and a condenser at the top, and two side strippers for the side product streams. Pygas is removed from the top of the column, light and medium cuts are removed from the side, and the bottoms product is the heavy cut. After the light, medium, and heavy cuts are used to preheat the feed streams, they are cooled down using cooling water to meet output specifications. A parallel catalyst purification system is used on the light and medium streams to further remove any impurities from the system, and these catalysts need to be regenerated with hot nitrogen on a scheduled basis.

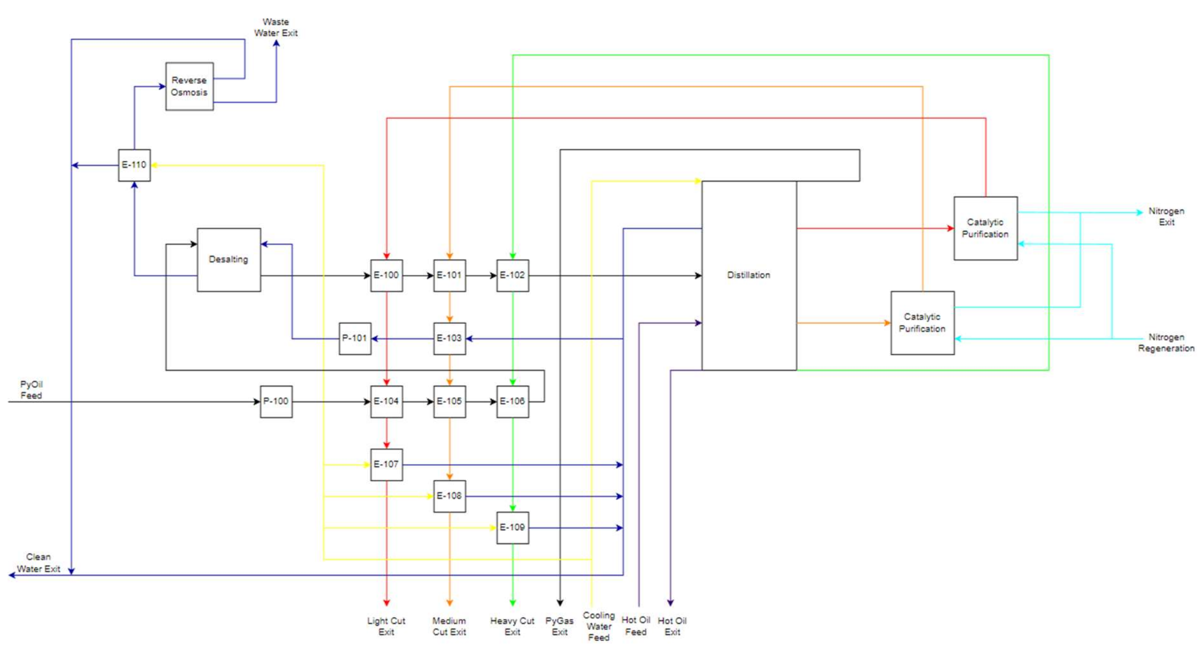

Figure 1: Block Flow Diagram

Process Details

a. Process Flow Diagram for Process and Utilities areas

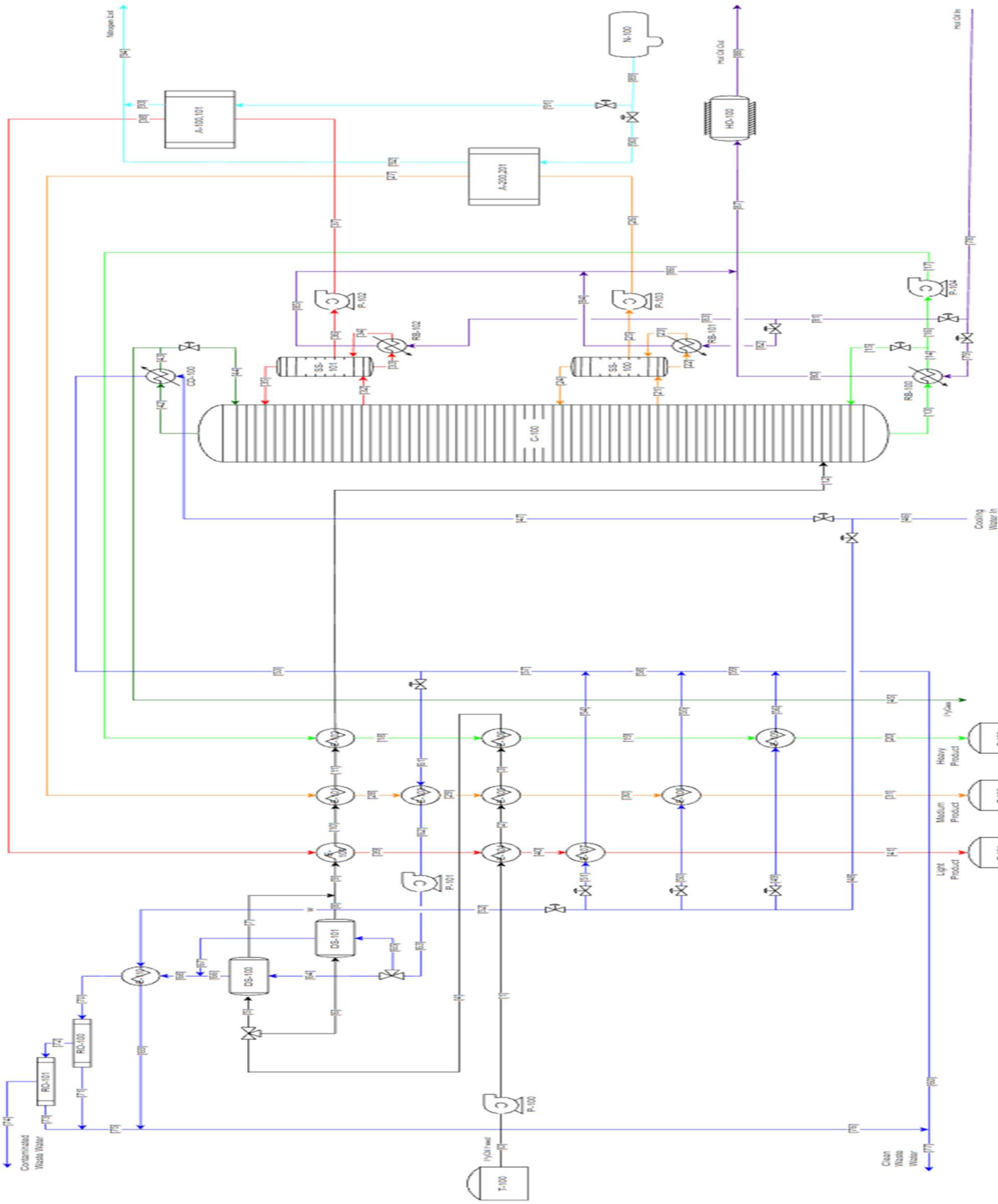

Figure 2: Process Flow Diagram

b. Material balance for major streams including mass rate, composition and key thermal properties

Table 1: PFD Stream Table				
Component: PyOil				
Stream No.	Temperature (F)	Pressure (psia)	Mass Flow Rate (pph)	vapor fraction
0	100	17.88	52432	0
1	100.3	113.5	52432	0
2	100.3	113.5	52432	0
3	130.1	112.7	52432	0
4	208.6	112	52432	0
5	251.6	111.2	52432	0
6	251.6	111.2	52432	0
7	250	112	52432	0
8	250	112	52432	0
9	250	112	52432	0
10	265.2	111.2	52432	0
11	351.5	110.5	52432	0
12	399.1	109.9	52432	0
Component: Heavy Cut				
Stream No.	Temperature (F)	Pressure (psia)	Mass Flow Rate (pph)	vapor fraction
13	694.7	25	1.15E+05	0
14	715	25	1.15E+05	0
15	715	25	1.33E+05	1
16	715	25	9229	0
17	715.4	65.81	9232	0
18	479.9	65.59	9232	0
19	259.8	65.32	9232	0
20	100	60.99	9232	0

Component: Medium Cut				
Stream No.	Temperature (F)	Pressure (psia)	Mass Flow Rate (pph)	vapor fraction
21	460.9	20.96	4.21E+04	0
22	478.2	20.96	4.52E+04	0
23	491.5	20.96	1.40E+04	1
24	465.4	20.96	1.09E+04	1
25	491.5	20.96	3.12E+04	0
26	492	89.3	3.12E+04	0
27	492	89.3	3.12E+04	0
28	360.7	89.1	3.12E+04	0
29	339.1	88.8	3.12E+04	0
30	221	88.43	3.12E+04	0
31	100	60.19	3.12E+04	0
Component: Light Cut				
Stream No.	Temperature (F)	Pressure (psia)	Mass Flow Rate (pph)	vapor fraction
32	328.5	18.23	1.32E+04	0
33	336.1	18.23	1.36E+04	0
34	342.4	18.23	2999	1
35	330.7	18.23	2596	1
36	342.4	18.23	1.06E+04	0
37	342.9	85.22	1.06E+04	0
38	342.9	85.22	1.06E+04	0
39	273.5	84.93	1.06E+04	0
40	144.2	84.67	1.06E+04	0
41	100	84.21	1.06E+04	0
Component: PyGas				
Stream No.	Temperature (F)	Pressure (psia)	Mass Flow Rate (pph)	vapor fraction
42	181.8	17.1	6.12E+04	1
43	107	17.1	6.12E+04	0.02
44	107	17.1	5.98E+04	0
45	107	17.1	1421	1

Component: Water				
Stream No.	Temperature (F)	Pressure (psia)	Mass Flow Rate (pph)	vapor fraction
46	87	84.7	2.00E+05	0
47	87	84.7	5.19E+04	0
48	87	84.7	1.78E+05	0
49	87	84.7	2.80E+04	0
50	87	84.7	1.07E+05	0
51	87	84.7	1.31E+04	0
52	87	84.7	3.00E+04	0
53	294.5	82.7	5.19E+04	0
54	104.5	84.32	1.31E+04	0
55	104.8	81.99	1.07E+05	0
56	294.5	82.7	5.19E+04	0
57	221.75	82.35	4.91E+04	0
58	163.13	83.34	6.22E+04	0
59	133.97	82.67	1.69E+05	0
60	214.34	82.69	2.21E+05	0
61	149	81.99	2769	0
62	14.1	112	2769	0
63	272.2	111.4	2769	0
64	272.2	111.4	2769	0
65	272.2	111.4	2769	0
66	250	112	2769	0
67	250	112	2769	0
68	250	112	2769	0
69	101.9	83.86	3.00E+04	0
70	89.95	111.5	2769	0
71	89.95	101.5	2076.75	0
72	89.95	101.5	692.25	0
73	89.95	91.5	519.19	0
74	89.95	91.5	173.06	0
75	89.95	96.5	2595.94	0
76	95.93	104.25	3.26E+04	0
77	155.14	93.47	2.54E+05	0

Component: Thermal Oil				
Stream No.	Temperature (F)	Pressure (psia)	Mass Flow Rate (pph)	vapor fraction
78	750	244.7	9.19E+05	0
79	750	244.7	7.79E+05	0
80	725	214.7	7.79E+05	0
81	750	244.7	1.40E+05	0
82	750	244.7	1.14E+05	0
83	750	244.7	2.60E+04	0
84	725	214.7	1.14E+05	0
85	725	214.7	2.60E+04	0
86	725	214.7	1.40E+05	0
87	725	214.7	9.19E+05	0
88	725	214.7	1.06E+06	0

Component: Nitrogen				
Stream No.	Temperature (F)	Pressure (psia)	Mass Flow Rate (pph)	vapor fraction
89	500	314.7	5941	1
90	500	314.7	4440	1
91	500	314.7	1501	1
92	500	314.7	4440	1
93	500	314.7	1501	1
94	500	314.7	5941	1

c. Sized equipment list

Table 2: Preheat Train Equipment List				
Major Equipment				
Equipment		Critical Specs	Size	Estimated Cost
Heat Exchanger	E-100	Carbon Steel. Shell and Tube	Eff. Heat Transfer Area: 663.3 ft^2	$38,600
-	E-101	Carbon Steel. Shell and Tube	Eff. Heat Transfer Area: 677.1 ft^2	$,700
-	E-102	Carbon Steel. Shell and Tube	Eff. Heat Transfer Area: 605.9 ft^2	$43,600
-	E-103	Carbon Steel. Shell and Tube	Eff. Heat Transfer Area: 26.49 ft^2	$22,700
-	E-104	Carbon Steel. Shell and Tube	Eff. Heat Transfer Area: 663.3 ft^2	$38,600
-	E-105	Carbon Steel. Shell and Tube	Eff. Heat Transfer Area: 854.5 ft^2	$41,000
-	E-106	Carbon Steel. Shell and Tube	Eff. Heat Transfer Area: 677.1 ft^2	$38,700
-	E-107	Carbon Steel. Shell and Tube	Eff. Heat Transfer Area: 194.6 ft^2	$32,200
-	E-108	Carbon Steel. Shell and Tube	Eff. Heat Transfer Area: 187.0 ft^2	$32,200
-	E-109	Carbon Steel. Shell and Tube	Eff. Heat Transfer Area: 184.7 ft^2	$31,700
-	E-110	Carbon Steel. Shell and Tube	Eff. Heat Transfer Area: 81.2 ft^2	$26,200

Table 3: Pump Equipment List					
Major Equipment					
Equipment		Critical Specs	Size	Estimated Cost	Notes
PyOil Pump	P-100	Cast Iron, Centrifugal	Capacity: 5130 Barrels/day Head: 287.62 ft	$6,800	Feed Pump
Desalter Water Pump	P-101	Cast Iron, Centrifugal	Capacity: 210 Barrels/day Head: 69.7 ft	$4,100	
Reverse Osmosis Pump	P-105	Cast Iron, Centrifugal	Capacity: 208 Barrels/ day Head: 295.5ft	$4,800	
Light Product Pump	P-102	Cast Iron, Centrifugal	Capacity: 1285 Barrels/day Head: 251.2 ft	$5,400	Recycle to preheat train
Medium Product Pump	P-103	Cast Iron, Centrifugal	Capacity: 3900.7 Barrels/day Head: 356.4 ft	$6,200	Recycle to preheat train
Heavy Product Pump	P-104	Cast Iron, Centrifugal	Capacity: 1246.5 Barrels/day Head: 184.6 ft	$5,100	Recycle to preheat train
PyOil Tank	T-100	Carbon Steel, polyurethane coating	Height: 64.04 ft Diameter: 64.04 ft Capacity: 36,768 barrels	$1,544,000	
Light Product Tank	T-101	Carbon Steel, polyurethane coating	Height: 38.38 ft Diameter: 38.38 ft Capacity: 7,915 barrels	$332,000	
Medium Product Tank	T-102	Carbon Steel, polyurethane coating	Height: 54 ft Diameter: 54 ft Capacity: 22,045 barrels	$926,000	
Heavy Product Tank	T-103	Carbon Steel, polyurethane coating	Height: 35.25 ft Diameter: 35.25 ft Capacity: 6140 barrels	$258,000	

Table 4: Associated Treatment Equipment List					
Major Equipment					
Equipment		Critical Specs	Size	Estimated Cost	Notes
Desalter (2-Stage)	DS-100,101	Carbon Steel	Diameter: 6.1 ft Length: 26.5 ft Capacity: 60703 lbm	$1,890,000	
Primary Light Adsorption Column	A-100	Carbon Steel	Diameter: 2.5 ft Height: 203 ft	$415,900	
Primary Medium Adsorption Column	A-200	Carbon Steel	Diameter: 4.1 ft Height: 215 ft	$870,000	
Secondary Light Adsorption Column	A-101	Carbon Steel	Diameter: 2.5 ft Height: 76 ft	$216,400	
Secondary Medium Adsorption Column	A-201	Carbon Steel	Diameter: 4.1 ft Height: 80.5 ft	$449,000	
Nitrogen Generator	N-100	Carbon Steel	1,600 cfpm	$20,000	
Adsorption Catalyst	N/A	PuriCycle® H & HP	Amount: 261,360 lbm	$178,200	
Reverse Osmosis Unit	RO-100,101	Polyamide composite	7.9” x 40” Capacity: 214 Barrels/day	$2000	

Table 5: Distillation Section Equipment List					
Major Equipment					
Equipment		Critical Specs	Size	Estimated Cost	Notes
Main Tower	C-100	Carbon Steel, Trayed	Height: 182 ft Diameter: 7.5 ft	$676,800	
Condenser	CD-100	Carbon Steel, Shell and Tube	Diameter: 3.9 ft Length: 5.9 ft	$33,400	
Reboiler	RB-100	Carbon Steel, Kettle Vaporizer	Diameter: 3.9 ft Length: 5.9 ft	$110,500	
Light SS	SS-100	Carbon Steel	Length: 22 ft Diameter: 6 ft	$71,400	
Medium SS	SS-101	Carbon Steel	Height: 62 ft Diameter: 3 ft	$96,600	
Light SS Reboiler	RB-101	Carbon Steel	Heat Transfer Area: 16.8 ft^2	$8,500	
Medium SS Reboiler	RB-102	Carbon Steel	Heat Transfer Area: 141.6 ft^2	$11,000	

Economics

See Appendix 1, Part 9.0 Economics

a. Capital cost estimate

Table 6: Major Equipment Cost Summary	
Component	Estimated Cost
Pumping & Storage	$3,092,400
Associated Treatment Ops	$4,041,500
Preheat Train	$384,200
Distillation Section	$1,008,200
Total	$8,526,300

Table 7: Capital Cost Breakdown		
Component	Factor (%)	Estimated Cost
Direct Costs		
Major Equipment	21.1	$ 8,526,300
Equipment Installation	16.7	$6,732,500
Instrumentation and Controls	10.0	$4,041,466
Piping, Fittings, & Insulation	11.2	$4,526,442
Electrical Systems	9.0	$3,637,320
Buildings	8.0	$3,233,173
Land & Site Preparation	3.0	$1,212,440
Indirect Costs		
Project Management	2.0	$808,293
Engineering & Supervision	7.0	$2,829,026
Construction Expenses	10.0	$4,041,466
Permits & Fees	2.0	$808,293
Total Estimated Capital Cost		
Contingency	15.0	$6,062,199
Total Cost	115.0	$46,458,919

b. Variable cost estimate

c. Fixed cost estimate

Table 8: Operational Costs		
Component	Estimate	Estimated Cost ($/yr)
Variable Costs		
Miscellaneous Materials	Calculated from PFD	$ 90,998
Utilities	Calculated from PFD	$ 2,109,330
Shipping and Packaging	Calculated from PFD	$ 171,028
Total Estimated Variable Cost		
Total Cost	-	$ 2,371,356
Fixed Costs		
Maintenance	5% Fixed Capital	$ 2,573,377
Operating Labor	5% Fixed Capital	$ 2,573,377
Supervision	20% Operating Labor	$ 514,675
Plant Overheads	50% Operating Labor	$ 514,675
Capital Charges	10% Fixed Capital	$ 1,286,689
Insurance	1% Fixed Capital	$ 514,675
Local Taxes	2% Fixed Capital	$ 1,029,351
Total Estimated Fixed Costs		
Total Cost	-	$ 9,006,821
Total Estimated Direct Production Costs		
Total Cost	Total Variable + Total Fixed	$ 11,378,177
Sales Expense	25% Direct Production Costs	$ 2,844,544
General Overheads	20% Direct Production Costs	$ 2,275,635
Total Estimated Annual Production Costs		
Total Cost	-	$ 16,498,357

Table 6.6. Summary of production costs

Variable costs	*Typical values*
1. Raw materials	from flow-sheets
2. Miscellaneous materials	10 per cent of item (5)
3. Utilities	from flow-sheet
4. Shipping and packaging	usually negligible
Sub-total A	....
Fixed costs	
5. Maintenance	5–10 per cent of fixed capital
6. Operating labour	from manning estimates
7. Laboratory costs	20–23 per cent of 6
8. Supervision	20 per cent of item (6)
9. Plant overheads	50 per cent of item (6)
10. Capital charges	10 per cent of the fixed capital
11. Insurance	1 per cent of the fixed capital
12. Local taxes	2 per cent of the fixed capital
13. Royalties	1 per cent of the fixed capital
Sub-total B	....
Direct production costs A + B	....
13. Sales expense	20–30 per cent of the direct production cost
14. General overheads	
15. Research and development	
Sub-total C	....
Annual production cost = A + B + C =	....

$$\text{Production cost £/kg} = \frac{\text{Annual production cost}}{\text{Annual production rate}}$$

Figure 3: Production Costs Estimate Table

The cost associated with all major equipment totaled approximately $8,526,300. In particular, the equipment associated with removing contaminants make up a large portion of the estimated cost which is to be expected for a facility treating plastic waste. Empirical observations suggest that oil fractionation facilities have a Lang factor of 4.6 to 4.8 meaning the major equipment costs range from around 21.7 to 20.8 percent of the total capital cost. Assuming the major equipment cost is around 21.1 percent of the total estimated capital cost, this project is expected to have a total capital cost of around $40,400,000. Considering a 15 percent contingency brings the total capital cost to roughly $46,500,000. The percentage of the total capital cost associated with piping, fittings, and insulation has a relatively higher weight since the proposed design scheme features a complex preheating train. The estimation also considers that the effect of cheaper land costs in this region will be offset by the lack of available infrastructure. Consequently, the costs associated with installation and construction are also expected to occupy a greater portion of the project's capital demand. The operational costs were calculated using Figure 3, where the variable costs were determined through process information and utility rates to be $2,371,356, the fixed costs were estimated to be $9,006,821, resulting in an estimated direct production cost of $11,378,177. The total estimated annual production costs are then $16,498,357.

Process Safety

a. Minimizing Environmental Impacts

The Pyoil facility will implement program and equipment in order to comply with BACT standards. A procedure to detect and repair leaks in the system should be implemented, including detection devices for volatile organic compounds (VOCs) around potential leak sites, regular maintenance on equipment to reduce possibility of leaks, VOC monitoring every 365 days for open ended pipes and process drains, VOC monitoring every 90 days for valves, compressors and safety relief valves, and visual monitoring of valves and pumps within the system every seven days. Double mechanical seals should be installed on all pumps, pressure relief valves should be directed to the onsite flare in order to minimize VOC emissions, and all VOC containing equipment should be made distinguishable from equipment no containing VOCs. All identified leaks should be repaired within five calendar days of identification, and all detected and repaired leaks should be recorded for BACT compliance.

b. P&ID with controls and alarms

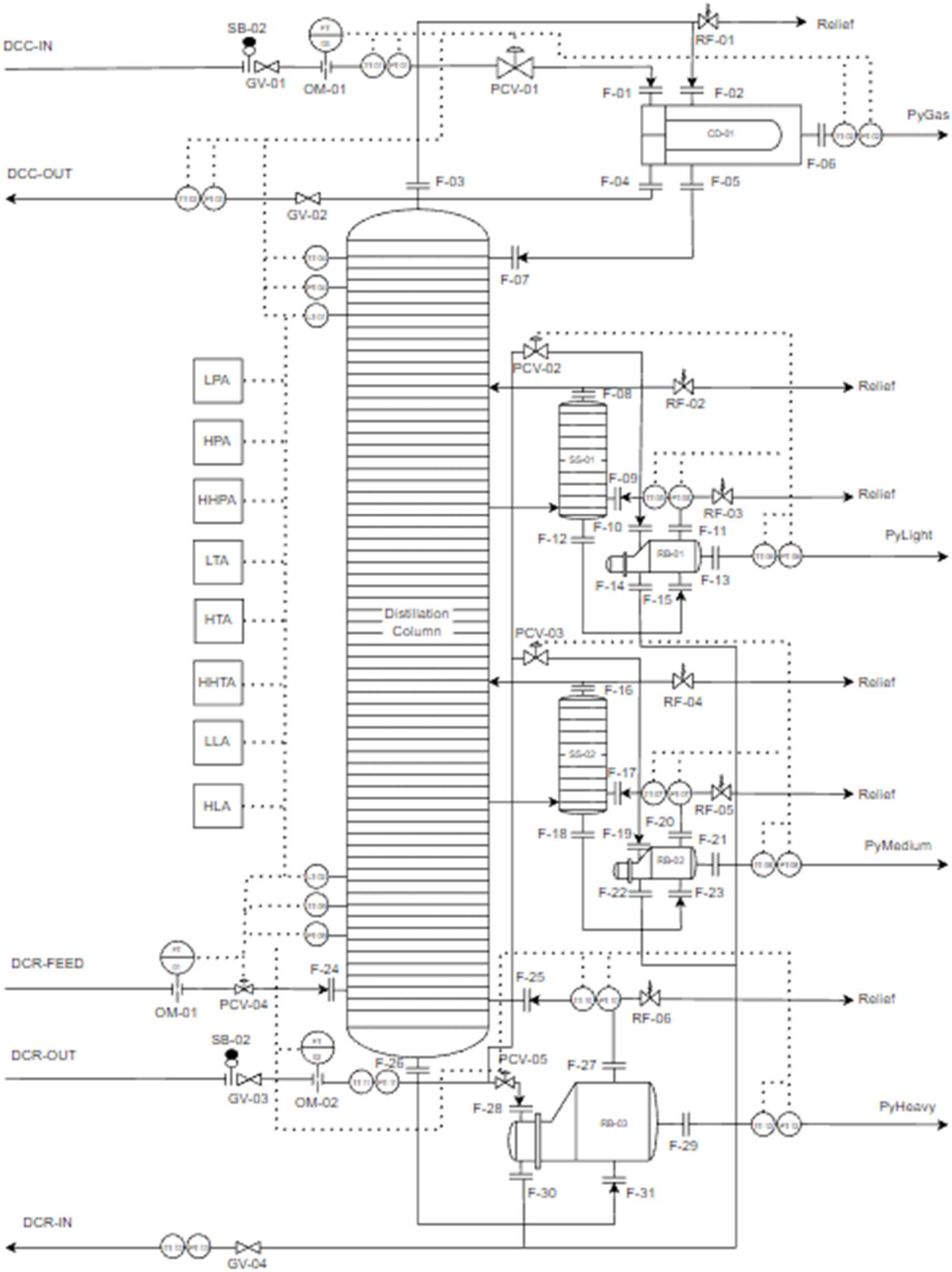

Figure 4: Fractionation Column P&ID

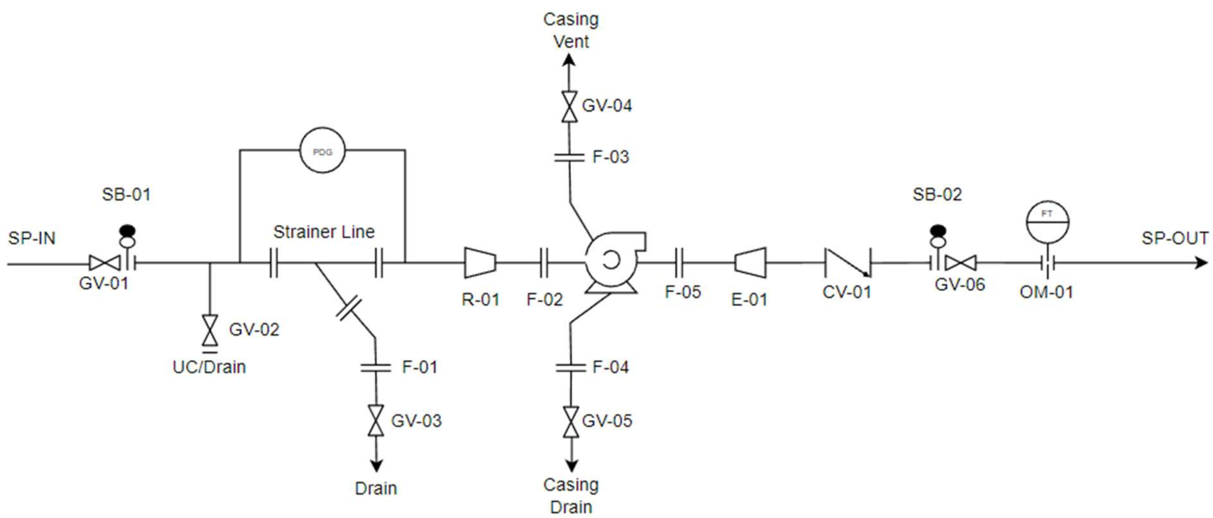

Figure 5: Pump P&ID

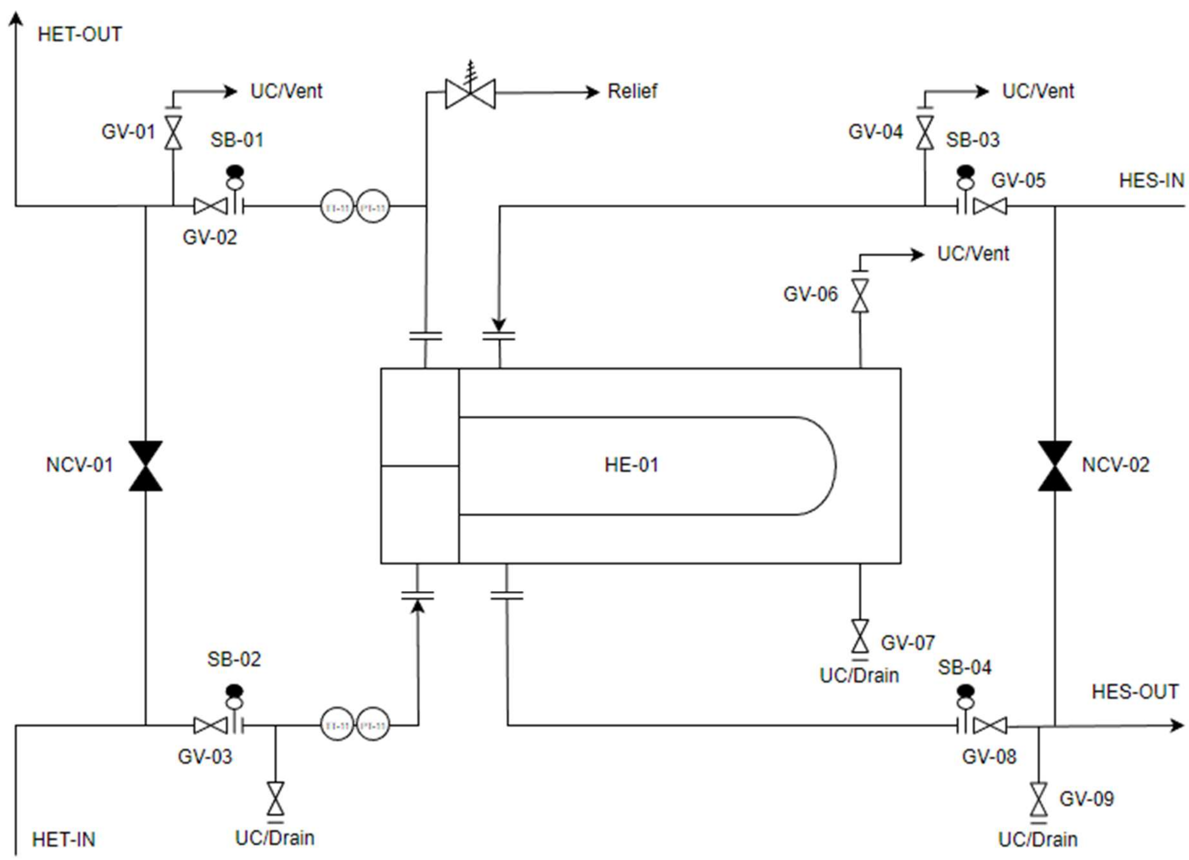

Figure 6: Heat Exchanger P&ID

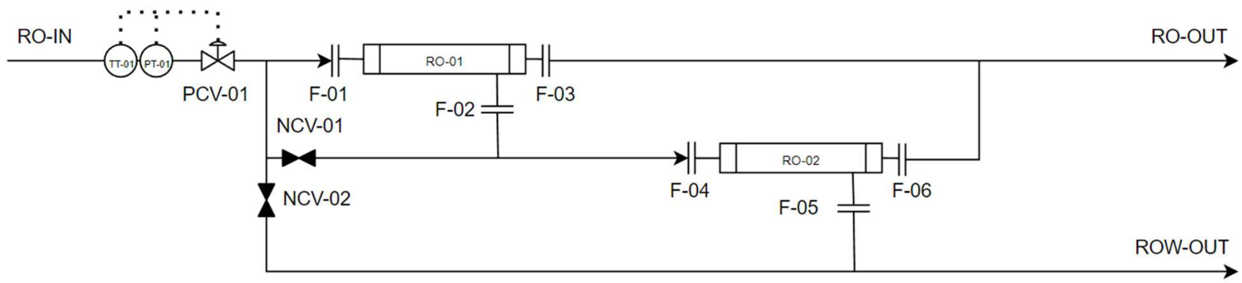

Figure 7: Reverse Osmosis P&ID

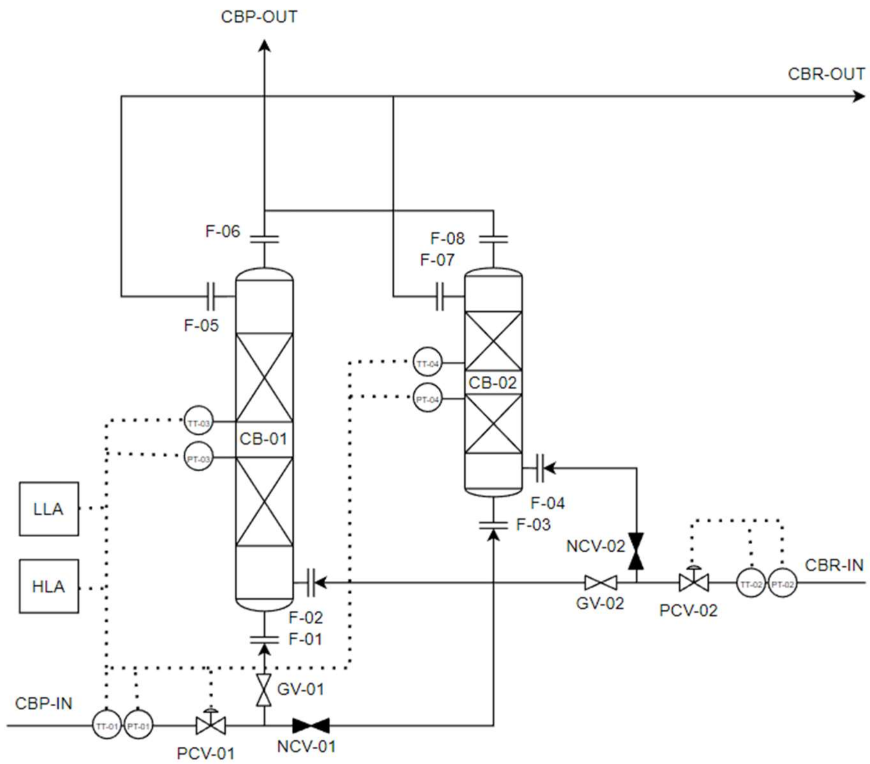

Figure 8: Catalyst Beds P&ID

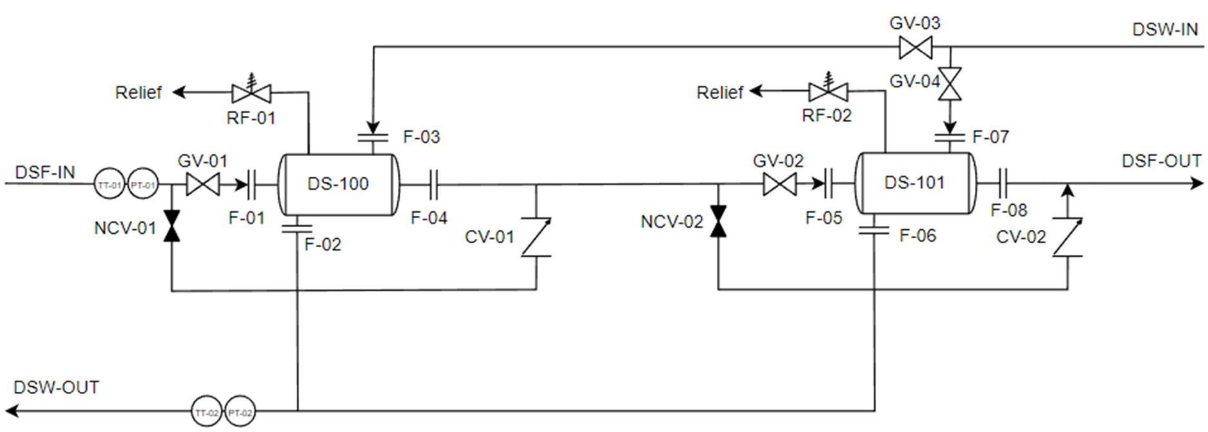

Figure 9: Desalter P&ID

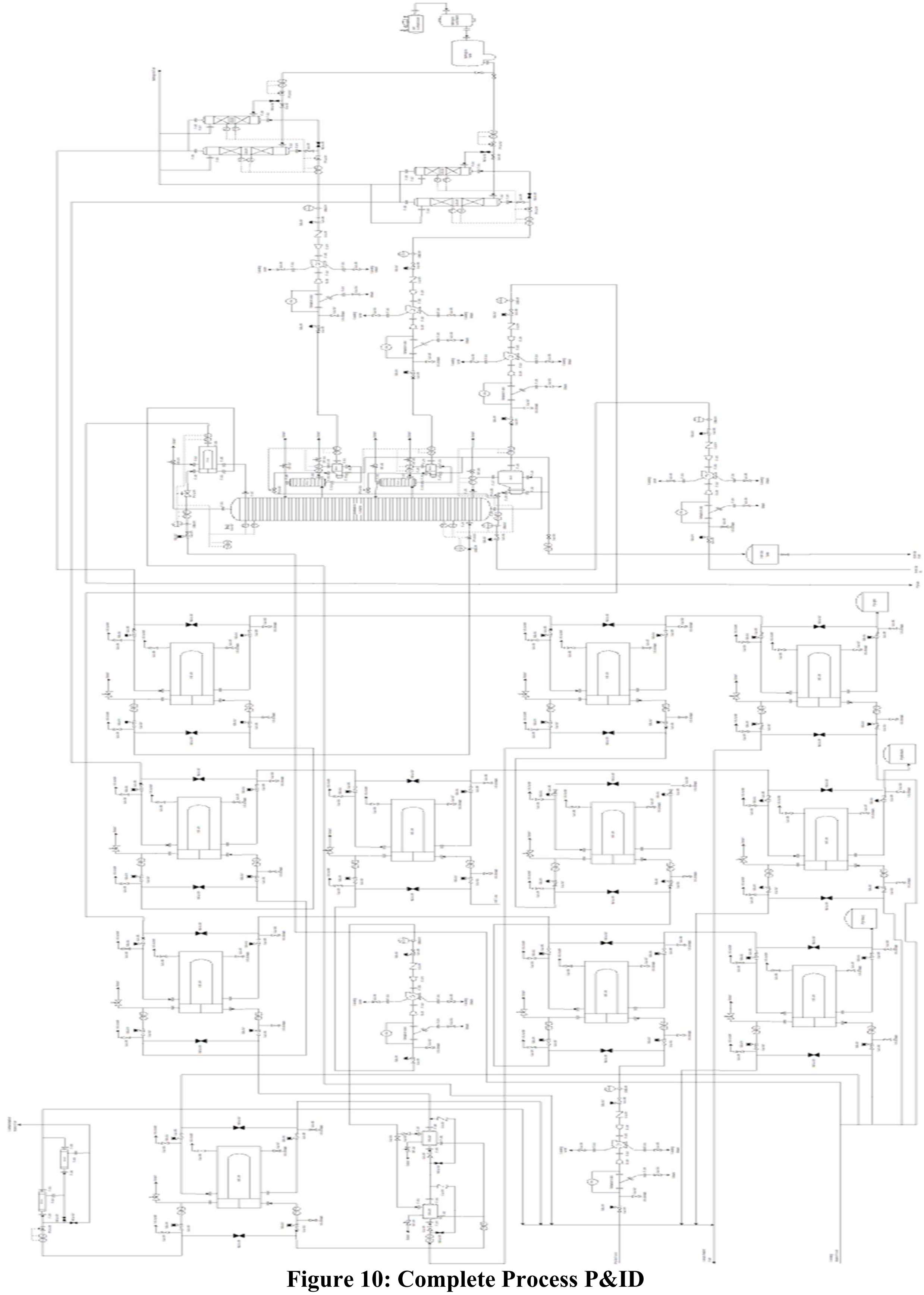

Figure 10: Complete Process P&ID

c. Pressure relief valve sizing

The pressure relief valve for the fractionation column was sized according to the worst case scenario of flow rate required to pass through the valve, with the valve opening at an overpressure of approximately 25 psig within the column.

Table 9: Pressure Relief Valve Sizing

Equipment	Pressure (psia)	Pressure (psig)	Pressure valve Rating (psig)	W (lb/hr)	C	
Fractionation Column	25	10.3	35.3	61231.47265	315	
Kd	P1 (psia)	Kb	Kc	T (R)	Z	MW (lb/mol)
0.62	35.3	1	1	641.8	0.96	81.96
A (in^2)	D (in)					
24.35186648	5.568281548					

d. Failure rate analysis

A LOPA was performed on the fractionation column in order to investigate the potential failure rate of events that could cause an incident to occur.

Table 10: Layers of Protection Analysis (LOPA)					
Fractionation Column					
Scenario	1	2	3	4	5
Event Description	small external fire causing column detonation	large external fire causing column detonation	BPCS failure causing overpressure in column	Tray blockage causing flooding in column	High vapor flowrate causing flooding in column
Initiating Event Frequency	0.1	0.01	0.1	0.1	0.1
Severity Level	Catastrophic	Catastrophic	Very Serious	Serious	Serious
Likelihood	Unlikely	Improbable	Unlikely	Unlikely	Unlikely
Risk Level	A	B	B	C	C
TMEF	1.00E-06	1.00E-06	1.00E-05	1.00E-04	1.00E-04
Enabling Conditions	NA	NA	NA	NA	NA
Conditional modifiers	1	1	1	1	1
Adjusted Event Frequency	0.1	0.01	0.1	0.1	0.1
Existing Layers of protection	Fireproofing - .01; relief valve - .01; BPCS - .1, SIF - .1; Operator Action - .1	Fireproofing - .01; relief valve - .01; BPCS - .1, SIF - .1; Operator Action - .1	relief valve - .01; Operator Action - .1, SIF - .1	BCPS - .1; relief valve - .01; Operator Action - .1, SIF - .1	BCPS - .1; relief valve - .01; Operator Action - .1, SIF - .1
Frequency with existing layers of protections	1.00E-07	1.00E-08	1.00E-05	1.00E-06	1.00E-06

Scenario	6	7	8	9	10
Event Description	Cooling water failure causing excessive temperature in column	Lightning strike on fractionation column	Pump seal failure before column, causing fluid release	piping leak causing fluid release	safety valve opens early, lowering pressure in column
Initiating Event Frequency	0.1	0.001	0.1	0.1	0.01
Severity Level	Serious	Catastrophic	Serious	Serious	Serious
Likelihood	Unlikely	Improbable, but not impossible	Unlikely	Unlikely	Improbable
Risk Level	C	C	C	C	D
TMEF	1.00E-04	1.00E-06	1.00E-04	1.00E-04	1.00E-04
Enabling Conditions	NA	NA	NA	NA	NA
Conditional modifiers	1	1	1	1	1
Adjusted Event Frequency	0.1	0.001	0.1	0.1	0.01
Existing Layers of protection	BCPS - .1; Operator Action - .1, SIF - .1	Fireproofing - .01; Operator action - .1; SIF - .1	BCPS - .1; Operator Action - .1, SIF - .1	BCPS - .1; Operator Action - .1, SIF - .1	BCPS - .1; Operator Action - .1, SIF - .1
Frequency with existing layers of protections	1.00E-04	1.00E-07	1.00E-04	1.00E-04	1.00E-05

e. Personnel exposure risk

Personnel are at risk of exposure to several different compounds within the process. Primarily, several compounds found within the pyoil stream are highly flammable and pose a toxicity risk to workers within the plant. Several compounds within the pyoil, such as butane, pentane, and hexane, can reach auto-ignition temperatures at atmospheric pressure at certain points within the system, leading to small balls of fire potentially occurring at leakage sites. Additionally, the thermal transfer fluid used for heating in the reboilers for the primary column and side strippers is highly toxic and has a risk of damaging the eyes and skin of exposed workers. To mitigate these risks, regular inspections of equipment and piping for leaks should be made, and workers should always wear required PPE (Personal Protective Equipment) within the plant, including but not limited to heat resistant gloves, hard hats, flame retardant clothing, and face masks in areas that may exceed OSHA limits for exposure. Below are lists of OSHA limits, LD50, NFPA diamonds, and autoignition/flash temperatures.

Table 11: OSHA Limits

Compound	TLV-TWA (8 hours)	Compound	TLV-TWA (8 hours)
Nitrogen	NA	1,3 Butadiene	1 ppm
Hydrogen	NA	Pentane	1000 ppm
Carbon Dioxide	10000 ppm	Hexane	500 ppm
Carbon Monoxide	50 ppm	Benzene	10 ppm
Methane	NA	Xylene	100 ppm
Ethane	NA	Toluene	200 ppm
Ethylene	200 ppm	Naphthalene	10 ppm
Propane	1000 ppm	Ethylbenzene	100 ppm
Propylene	500 ppm	Cumene	50 ppm
Butane	800 ppm	Water	NA
C4 Olefins	1 ppm	Dowtherm A	.2 ppm

Table 12: LD50			
Compound	LD50	Compound	LD50
Nitrogen	NA	1,3 Butadiene	5480 ppm
Hydrogen	NA	Pentane	5000 ppm
Carbon Dioxide	NA	Hexane	16000 ppm
Carbon Monoxide	3760 ppm	Benzene	810 ppm
Methane	NA	Xylene	3500 ppm
Ethane	NA	Toluene	2600 ppm
Ethylene	NA	Naphthalene	1110 ppm
Propane	NA	Ethylbenzene	3500 ppm
Propylene	NA	Cumene	1400 ppm
Butane	658 ppm	Water	> 90000 ppm
C4 Olefins	5480 ppm	Dowtherm A	2140 ppm

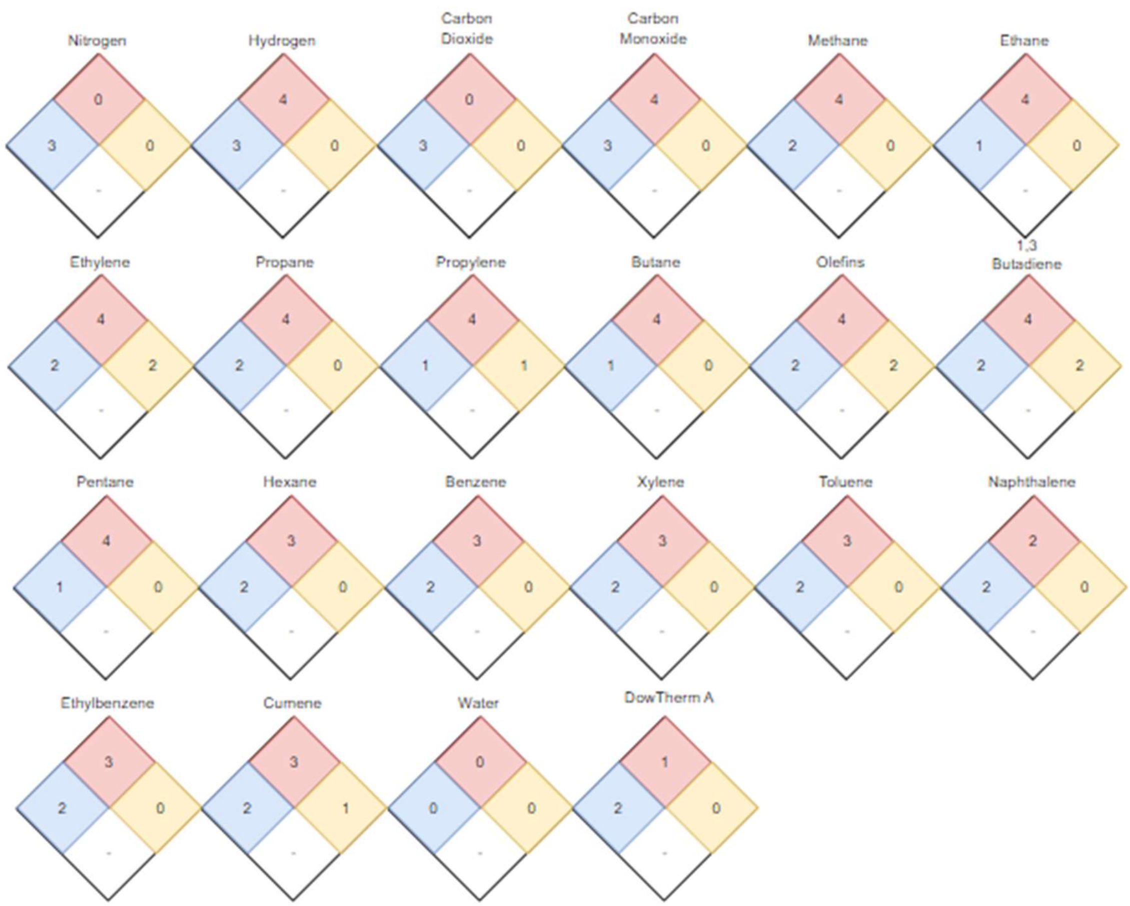

Figure 11: NFPA Diamonds

Table 13: Autoignition/Flash Temperatures					
Compound	Auto-Ignition Temp (F)	Flash Temp (F)	Compound	Auto-Ignition Temp (F)	Flash Temp (F)
Nitrogen	NA	NA	Pentane	500	-57
Hydrogen	1065	NA	Hexane	437	-9.4
Carbon Dioxide	NA	NA	Benzene	1097	12
Carbon Monoxide	1124.6	-311.8	Xylene	867.2	25
Methane	999	-306	Toluene	896	40
Ethane	940	-211	Naphthalene	979	190
Ethylene	842	-213	Ethylbenzene	860	59
Propane	842	-156	Cumene	797	96
Propylene	851	-162	Water	NA	NA
Butane	550	-76	Dowtherm A	1144	235.4
1,3 Butadiene	788	-105			

f. Atmospheric detonation of distillation inventory

Table 14: TNT Equivalency Estimation					
Volume Liquid (ft^3)	Liquid Density(lb/ft^3)	Liquid Mass (lb)			
462.2395441	39.45926474	18239.63254			
Volume Gas (ft^3)	Average column pressure (psig)	Average Column Temp (F)	R	Z	Vapor Mass (lb)
5084.634985	6.4	438.25	10.73	0.96	1311.952959
LHV (BTU/lb)	Total Mass (lb)	BTU	Tons of TNT conversion	Tons of TNT	
13953.59103	19551.5855	272814828	2.52E-07	6.88	

g. Hazard and Operability Study (HAZOP) of the largest distillation column.

HAZOP analysis on the desaltation and fractionation process highlighted several key issues to consider when implementing safety protocols and equipment. For the desaltation process, the primary issues noted were deviation from the operating temperatures and pressures in the column, which can drastically affect the efficiency of the desaltation process. For the fractionation process, the key issues identified were the potential dry out of the column due to low vapor flowrates within the column, potential flooding due to high vapor flow rates within the column, and overpressure potential causing a rupture in the column. Additionally, leakage was highlighted as a key issue within both the desaltation process and fractionation process, with the fractionation column reboilers running at temperatures above the auto-ignition temperatures of compounds within the system, such as butane, pentane, and hexane, potentially causing jets of flame to shoot out at leakage points.

Table 15: Hazard and Operability Study (HAZOP)

Desalting Process									
Node	Parameter	Element	Guide Word	Deviation	Possible Causes	Possible Consequences	Safeguards	Actions Recommended	Action Assigned To
1	Feed Flow	Py Oil/Water	NONE	No flow within process	Ceasing of flow to pump No Py oil/water supply, complete pump failure, no power provided to pump, pump blockage, Valve blockage, valve fails closed, valve closed by worker	Complete halt of element transfers within Process, potential damage to pumps in process, no operation of desalter,	Regular maintenance on process, Flow indicators within process	Consider installing bypass, investigation of scenarios that require emergency plant shutdown	Process Engineer
			LESS	Insufficient flow within process	Restricted flow to pump, existing pump damage, insufficient power provided to pump, pump blockage, excessive pressure within pump, partial valve blockage, valve partially closed by worker, insufficient element supply	Potential damage to pumps in process, insufficient flow to other process equipment	Regular maintenance on process, flow indicators within process	Consider installing bypass, investigation of scenarios that require emergency plant shutdown	Process Engineer
			MORE	Excess flow within process	Excess flow provided by preceding stream, valve fails open, valve opened too much by worker	Potential damage to piping and equipment, insufficient pressure within pumps, Excessive flow to other process equipment	Regular maintenance on process, flow indicators within process	Installation of controller that adjust column flow based upon feed received to reduce impact of excessive flow	Process Engineer
			REVERSE	Reverse flow occurs within process	failure of check valve to inhibit reverse flow, insufficient head provided by pumps	Potential damage to equipment, unintended flow of fluid preceding equipment	Regular maintenance on process. check valves installed within process	Consider installation of flow meters that assist in detecting reverse flow	Process Engineer
			LEAKAGE	Element leaks from process	Existing equipment or piping damage, Insufficient connections between equipment	Py oil/water leaks into surrounding environment, flow rate within process may decrease, potential flammability hazard due to released Py oil, decrease in pressure may occur	Regular maintenance on process, regular inspection for equipment and pipe leakage, regular testing for flammable vapors around process equipment, flame/detonation arrestors	Investigation into connections and equipment that keep leakage to a minimum.	Process Engineer

2	Pressure	Py Oil/Water	LESS	Pressure in process is lower than intended	Existing leaks within the process	desaltation process fails to occur properly.	Regular maintenance on process, Low pressure alarms on desalters, PLC controller that regulates desalter pressure	Regularly check condition of pressure controller	Technician
			MORE	Pressure in process is higher than intended	Insufficient flow causing buildup of elements within equipment, pressure relief valves fail to operate properly	desaltation process fails to occur properly, potential damage to desalting equipment	Regular maintenance on process, High pressure alarms on desalters, PLC controller that regulates desalter pressure, pressure relief valve for overpressure scenarios	Regularly check condition of pressure controller	Technician
3	Temperature	Py Oil/Water	LESS	Temperature in process is lower than operating	Insufficient temperatures of stream entering process, insufficient heating of streams before process	Potential damage to desalting equipment, desaltation process fails to occur properly	Regular maintenance on process, low temperature indicator on desalters, PLC controller that regulates desalter temperature	Regularly check condition of temperature controller	Technician
			MORE	Temperature in process is higher than operating	Overheating of streams entering process	Potential damage to desalting equipment, desaltation process fails to occur properly	Regular maintenance on process, High temperature alarms on desalters, PLC controller that regulates desalter temperature	Regularly check condition of temperature controller	Technician
4	Composition	Py Oil/Water	DIFFERENT FROM	Process fluid is out of specification	desalting process fails to remove the required amount of water	Py oil containing amount of free water exceeding specifications enters the fractionation process	Regular maintenance on process	Regular inspection of Desalter output to determine composition irregularities	Quality Engineer

Fractionation Process									
Node	Item Description	Element	Guide Word	Deviation	Possible Causes	Possible Consequences	Safeguards	Actions Reccomended	Action Assigned To
5	Flow	Py Oil/Py Gas/Light Product/Medium Product/Heavy Product	NONE	No flow within process	Ceasing of flow to pump, No element supply, complete pump failure, No power provided to pump, pump blockage, Valve blockage, valve fails closed, control valve closed	Complete halt of element transfer within Process, potential damage to pumps in process, potential dry out of column, no operation of column, level in distillation column will lower.	Regular maintenance on process, low level alarm on column	Consider installing bypass, investigation of scenarios that require emergency plant shutdown	Process Engineer
			LESS	Insufficient flow within process	Restricted flow to pump, exisiting pump damage, insufficient power provided to pump, pump blockage, excessive pressure within pump, partial valve blockage, control valve partially closed, insufficient element supply	Potential damage to pumps in process, insufficient flow to other process equipment, potential dry out of column, level in distillation column will lower	Regular maintenance on process, low level alarm on column	Consider installing bypass, investigation of scenarios that require emergency plant shutdown	Process Engineer
			MORE	Excess flow within process	Excess flow provided by preceding stream,valve fails open, control valve opened completely	Potential damage to piping and equipment, insufficent pressure within pumps, Excessive flow to other process equipment, flooding in column may occur	Regular maintenance on process, high level alarm on column, Safety interlock that prevents flow of liquid into column from condenser at high liquid levels	Installation of controller that adjust column flow based upon feed recieved to reduce impact of excessive flow	Technician
			REVERSE	Reverse flow occurs within process	failure of check valve to prevent reverse flow, insufficient head provided by pumps	Potential damage to equipment, unintended flow of fluid preceding equipment	Regular maintenance on process. check valves installed within process	Consider installation of flow meters that assist in detecting reverse flow	Process Engineer
			LEAKAGE	Element leaks from process	Exisiting equipment or piping damage, Insufficient connections between equipment	Py oil and fractionation products potentially released into surrounding environment, pressure decrease within process, potential flammability hazard due to released Py oil and fractionation products	Regular maintenance on process, regular inspection for equipment and pipe leakage, regular testing for flammable vapors around process equipment, flame/detonation arrestors	Investigation into connections and equipment that keep leakage to a minimum.	Process Engineer

6	Pressure	Py Oil/Py Gas/Light Product/Medium Product/Heavy Product	LESS	Pressure in process is lower than intended	Existing leaks within the process, faulty check valves, air entering pump	Column separation efficiency may decrease	Regular maintenance on process, low pressure alarm of column	Investigation into quality of associated pumps and check valves	Process Engineer
			MORE	Pressure in process is higher than intended	Insufficient flow causing buildup of elements within equipment, pressure relief valves fail to operate properly	Potential damage to fractionation equipment, increased heat load on reboilers, potential decrease in column separation efficiency	Regular maintenance on process, pressure relief valve on column to release overpressure within column. high pressure alarm on column, safety interlock that assists in reducing pressure when operating pressure exceeds a certain point	Investigation into methods to minimize pressure buildup within the column	Process Engineer
7	Temperature	Py Oil/Py Gas/Light Product/Medium Product/Heavy Product	LESS	Temperature in process is lower than expected operating temperature	Insufficient energy provided by reboiling process, excessive energy removal by condensation process	Potential decrease in column seperation efficiency, increased amount of condensation within column	Regular maintenance on process, PLC controller that increases reboiler duty when column temperature is below the expected operating temperature.	Investigation into efficiency and duty of both reboilers and condenser	Process Engineer
			MORE	Temperature in process is higher than expected operating temperature	Excessive energy provided by reboiling process, insufficient energy removal by condensation process	Potential decrease in column seperation efficiency, increased amount of vaporization within column.	Regular maintenance on process, Safety interlock to reduce temperature when it reaches a certain point above expected operating temperature	Investigation into efficiency and duty of both reboilers and condenser	Process Engineer
8	Composition	Py Oil/Py Gas/Light Product/Medium Product/Heavy Product	DIFFERENT FROM	Process fluid is out of specification	Efficiency of seperation within the column decreases below specifications, flooding occurs within the column	Product streams of distillation column being delivered out of specification to absorbers, overall poorer product quality	Regular maintenance on process	Regular inspection of column output to determine composition irregularities	Quality Engineer
9	Level	Py Oil/Py Gas/Light Product/Medium Product/Heavy Product	MORE	liquid level in column is higher than expected	Vapor flow rate increases above expected rates, fluid output blockage, column internals blockage	Potential damage to fractionation equipment, potential decrease in column seperation efficiency, potential increase in pressure	Regular maintenance on process, high level alarm on column,Safety interlock that prevents flow of liquid into column from condenser at high liquid levels	Investigation into column internals that minimize chance for blockage to occur within column	Process Engineer
			LESS	liquid level in column is lower than expected	Insufficient vapor flow within the column causing weeping, leakage in fractionation equipment	Potential decrease in column separation efficiency, potential decrease in pressure	Regular maintenance on process, low level alarm on column	Investigation into column internals that minimize chance for tray weeping	Process Engineer

Recommendations for Improvement of the Bali Sorting Facility

a. Recommendations for closing the Quantity Gap

Because the plant both depends on plastic waste to run and the fact that Bali is notorious for tons of waste being dumped into the ocean, recycling to the Bali sorting facility is very important. Currently, bicycles go around collecting waste from houses twice a week. Several key things can be implemented to attempt to increase the quantity of recycling. A key factor can be to just increase awareness of the amount of waste being improperly disposed of with commercials, news articles, and billboards. Additionally, perhaps introducing environmental classes into schools and universities that are tailored towards increasing awareness of recycling needs. Another possibility would be to introduce a tax based upon the size of household/income that can be refunded if a certain amount is recycled per month. Additionally, a trash net can be placed around drainage ditches and catch any plastic waste that flows by.

b. Recommendations for closing the Quality Gap

In order to better assist households in recycling, the different colored bags can be replaced with 2 different colored trash/recycling cans in order to assist in separating the waste. In addition, people can be instructed to place particular plastics such as PVCs and PETs into color coded bags. At the sorting facility, employees can wear gloves and ensure that the bags stay separate from the what will be used for the pyrolysis feed.

c. Recommendations for closing the Affordability Gap

As mentioned previously, imparting legislation and a tax upon households to incentivize recycling will increase revenue. A way to also increase the amount of recycling is utilizing several trash barges that flow down the river and collect trash as well. In addition, a tariff can be enforced onto the junk collectors who purchase from the sorting facility.

Conclusions

For the construction and operation of the Pyoil processing facility in Bali, Indonesia, this report details the design, operation, and safety precautions necessary to meet the required standards.

A fractional distillation section was necessary for the separation of the Pyoil into the required pygas, light, medium, and heavy cuts, and a combination of desalting and catalytic purification was used to removed salts, metals, water, and chlorides from the process. The process was economized by reusing the heat from the fractionation product streams, and by careful control of the operating conditions of the column. Reverse Osmosis was also used to mitigate the waste of the process.

The major equipment was estimated to cost $8,526,300. From this, the total capital costs were calculated to be $46,458,919. The operational costs were estimated to cost $2,371,356. The total estimated fixed cost was then estimated to be $9,006,821. The final estimates of the annual production costs were calculated to be $16,498,357.

In the desaltation process, the primary issues noted were deviation from the operating temperatures and pressures in the column, which can drastically affect the efficiency of the desaltation process. In the fractionation process, the key issues identified were the potential dry out of the column due to low vapor flowrates within the column, potential flooding due to high vapor flow rates within the column, and overpressure potential causing a rupture in the column. Leakage is also a key issue within both the desaltation process and fractionation process, with the fractionation column reboilers running at temperatures above the auto-ignition temperatures of compounds within the system, such as butane, pentane, and hexane, potentially causing jets of flame to shoot out at leakage points. Several key events were subjected to a failure rate analysis such as: Pipe leakage, Fractionation column detonation, Pressure relief valve failure, BPCS failure, Flooding within Column, Overpressure within column. Primary protection methods for the system included: Pressure relief valves, BPCS control, Safety interlocks to control pressure/temperature, quick operator response, general fireproofing of system, Low, High, and High-High alarms for pressure, temperature, and level.

To close the quantity gap, our recommendations for the Bali sorting facility are to raise awareness of recycling problem with commercials, news articles, and billboards, mandatory environmental classes in schools and universities, trash taxes, and trash nets. To close the quality gap, we recommend replacing different colored bags with trash/recycling cans, instructing people to place plastics such as PET and PVC in separate bags to ensure employees handle plastics in a sanitary way to avoid contamination. To close the affordability gap, we recommend imparting legislation and a tax, using trash barges to float down the river collecting more, and placing a tariff on junk collectors who purchase from the facility.

Appendix

a. Adsorption Section Detail

The biggest challenge with designing the adsorption section of the plant was the lack of information provided or available regarding the BASF catalysts PuriCycle® H and HP or information regarding their competitors. Therefore, adequate research was conducted on the front end in order to make valid assumptions. From the prompt it was assumed that the 50 ppm chlorides would be reduced to a valid level in each product, typically <1 ppm with the LHSV hr^{-1} being 1 per bed. The other major assumption from the prompt was that the catalyst could be regenerated even though the BASF website explicitly states that it cannot be regenerated [PuriCycle®]. It was found that Silicates and Zn modified Zeolites were effective at removing chlorides from hydrocarbons and were able to be effectively regenerated at elevated temperatures, thus they were used to model the catalysts [Zhang]. Literature was also found suggesting that 24-48 hours was an acceptable amount of time to run the material through the catalysts and properly remove chlorides [Gabelman]. It was also assumed it would take 1/3rd of the time to regenerate the resin. Based upon these assumptions, the bulk density of catalyst was taken to be 49.9 pounds per cubic foot. With all these assumptions, the parameters were calculated and the necessary column sizes were found to be reasonable given the assumptions [Gabelman]. Additionally, N_2 was taken to cost .02 $/kwh to produce and that for every 4 kg of catalyst, 1 kg of Nitrogen would be needed to regenerate [Nitrogen Generators].

Adsorbent will be used for 24 hours before it becomes inadequate at removing chlorides, at which point a control valve will close the feed to the adsorption column and open the feed to the secondary adsorption column which is sized to run for 9 hours and 3 hours of regeneration time. This enables Nitrogen to be fed into the primarily columns in each the light and medium cuts for 8 hours to regenerate the catalyst beds. This enables the plant to continue to run without danger of unwanted chlorides in the products.

If there are large quantities of chlorides in the feed, caustic can be added upstream to assist with the removal of chlorides and the desalter will also assist with a large majority of chlorides. Because of the two-column design, the plant can still be operated. Even though the time between exhaustion cycles will be shorter, the materials should remain within spec until the oil calms down.

b. Distillation Section Detail

When considering potential distillation schemes, much of the focus was placed on minimizing capital costs while maintaining efficient fractionation. To minimize capital costs, we considered schemes that utilize the fewest number of distillation towers. Thus, the proposed design features just one main tower with 85 stages. Modeling this distillation scheme requires a few necessary assumptions. First, the pressure drop through the column is assumed to be linear meaning each stage experiences the same amount of pressure drop. The tray efficiencies were

assumed to equal 1, but in practice, this value is expected to decrease, suggesting that more trays will likely be necessary.

A singular tower can present some design challenges. The degree of fractionation was a primary concern since fewer columns can make it more difficult to precisely separate the fractions, and the project imposes strict specifications on the distillation products. To resolve this issue, side strippers were incorporated into the design. While the main column accomplishes a majority of the separation, the side strippers can be used to fine-tune the exiting compositions.

In practice, cut points can be controlled by the overhead vapor temperature in the column as well as the flow rate of various streams out of the column (Fahim 2010). For a single tower distillation scheme, the overhead vapor temperature is restricted by the temperature necessary to produce the required off-gas. Consequently, this design should, instead, allow for the manipulation of draw-off rates to help ensure the product agrees with the specifications.

More specifically, assuming the draw-off locations are kept constant, changing a lighter component's draw from the main tower affects the heavier component's cut point below it. For instance, when the draw-off rate of a lighter fraction is decreased, the vapor flow rate in the column decreases which can increase the residence time of the heavier components in the column. As a result, both the separation efficiency and cut point of the heavier product leaving the column are increased (Tallmadge 2008). The side strippers accommodate the changes in draw-off rates from the main tower and include additional stages for more precise separation. As the flow rate of a certain fraction into the side stripper is increased or decreased, the boil-up ratio of the reboilers fitted to each side stripper can be raised or lowered accordingly. Thus, a steady product flow out of the distillation unit can be maintained while also ensuring the streams meet the specified cut points. Furthermore, the side strippers have the added benefit of supplying vapor back to the main column, which can help sustain the minimum overhead vapor pressure of 2.4 psig.

The stringent product criteria also call for the continuous removal of free water from the products that feed the downstream steam-cracking furnaces. While the desalter removes a large part of the emulsified water in the pyoil feedstock, the column must be designed to mitigate any water from entering the light and medium product streams. The side strippers are maintained at minimum temperatures of 328 and 460 °F for the light and medium side strippers respectively. Thus, it is highly unlikely that any free water in the column will condense and contaminate the light and medium product streams that leave the strippers.

Another design consideration is the temperature of the main column's reboiler. The hot oil stream available for the reboiling operations is supplied at a maximum temperature of 750°F and must be returned at no less than 725 °F which corresponds to a maximum reboiler temperature of 750 °F. Operating at this temperature assumes ideal heat transfer and is impractical because it risks thermal degradation or fouling of the process fluid, hindering the reboiler's performance. As a more conservative approach, the design considers a reboiler operating temperature of around 725 °F.

Operating at a relatively lower reboiler temperature is expected to help minimize the column's energy consumption. Improving the efficiency of the process will also have a large impact on overall energy consumption. By adding more stages to the column, there is more contact between the liquid and vapor phases which can improve fractionation efficiency and lower the reflux demand. This effect was considered while balancing the increased capital cost and column height associated with adding more stages. In large part, much of the energy that is introduced to fractionate the components exits the column in the form of waste heat carried out with the products. To recover this heat and lower the energy cost associated with preheating the feed to the column, the proposed design incorporates a complex preheating design scheme that recycles a majority of the energy input of the distillation process. The preheat train is used to raise the temperature of the incoming column feed as well as the water required by the desalter. By removing heat in this manner, the project's cooling water demand is also decreased.

Most commonly, sieve trays are employed in oil fractionation towers. They offer high efficiency and can accommodate a relatively wide range of flow rates. Since the feed conditions are expected to vary throughout the operation, sieve trays are an attractive choice for the proposed distillation design. Furthermore, their relative durability ensures that the trays will be able to handle the elevated temperature and corrosive environment associated with this process. Compared to other tray types, sieve trays also offer a simple design capable of facilitating easier removal, maintenance, and cleaning.

Perfect separation of the light and medium products corresponds to a fractionation gap of zero. In other words, the final ASTM D86 boiling point (FBP) of the light product, 392 °F, would equal the initial ASTM D86 boiling point (IBP) of the medium product. Likewise, perfect fractionation of the medium and heavy products would correspond to an IBP of 620 °F for the heavy product. Typically, perfect fractionation is either impossible or impractical. Generally, if the difference between 5% of the ASTM IBP of a heavier product and 95% of the FBP of a lighter product is positive, then the process is considered to have a high degree of fractionation (Fahim 2010). According to the design simulation, the chosen distillation scheme is capable of separating the medium product with an ASTM D86 IBP of 391.1 and the heavy product with an IBP of 613.2, indicating a positive fractionation gap and a very high degree of separation. These results correspond to a production rate of about 1421, 10,550, 31,230, and 9232 lbs/hr for the py gas, light product, medium product, and heavy product respectively.

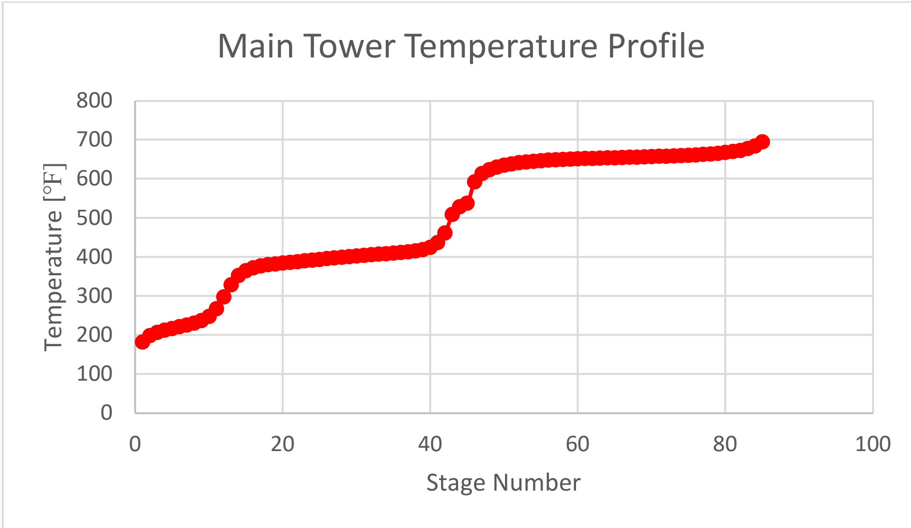

Figure 12: Column Temperature Profile

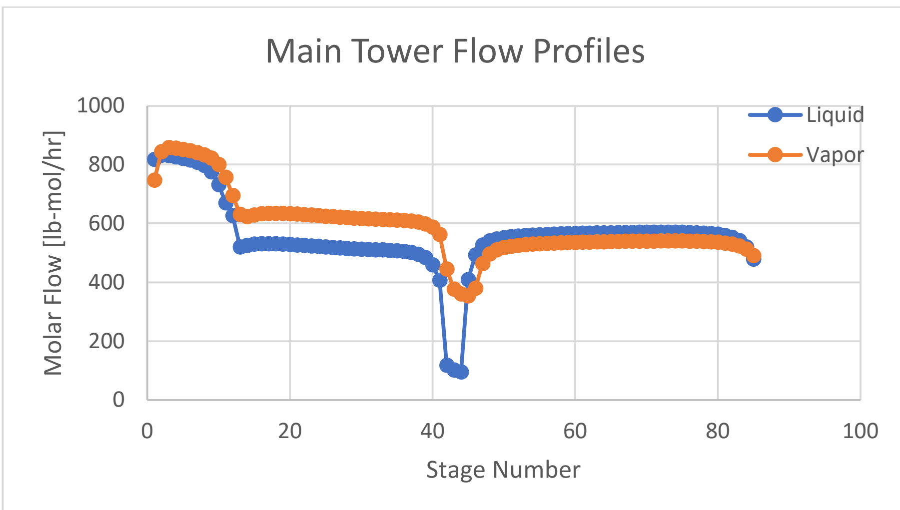

Figure 13: Column Flow Profile

	Specified Value	Current Value
Condenser Temp	107.0 F	107.0
reboiler temp	715.0 F	715.0
SSlight BoilUp Ratio	0.3000	0.3000
SSmedium BoilUp Ratio	0.5000	0.5000
Medium prod D86 FBP	620.0 F	620.0
light prod D86 FBP	392.0 F	392.0
Off Gas prod rate	<empty>	1421
Reflux Ratio	<empty>	28.56
Reflux Rate	<empty>	5.981e+004
SSlight draw	<empty>	1.319e+004
SSmedium draw	<empty>	4.213e+004
Btms Prod Rate	<empty>	9229
Boilup Ratio	<empty>	14.35
SSlight prod flow	<empty>	1.059e+004
SSmedium Prod Flow	<empty>	3.119e+004
medium prod D86 IBP	392.0 F	391.3
Heavy prod D86 IBP	620.0 F	613.1
heavy prod D86 FBP	<empty>	805.4
Light prod D86 IBP	<empty>	229.1

Figure 14: ASPEN Distillation Column Specification

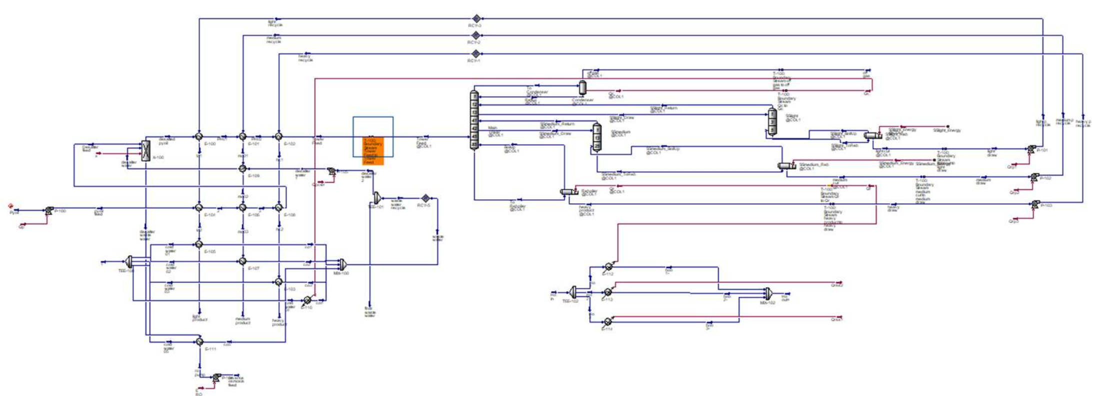

Figure 15: ASPEN System Model

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