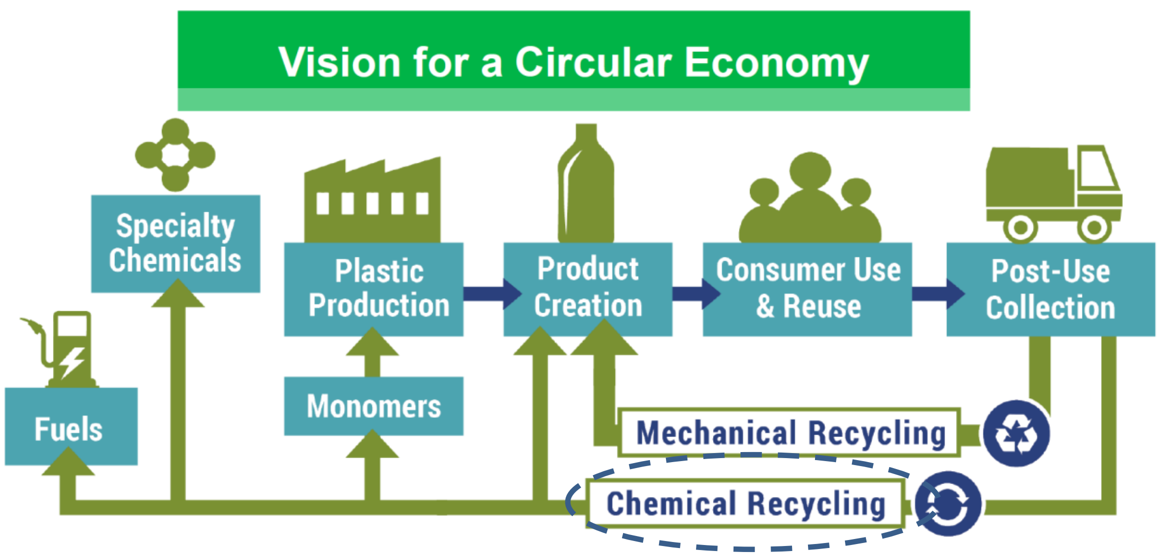
Part 1 Background and Technical Information: Design of a Pyoil Purification Unit for Supply of Recycled Feedstock to a Steam Cracker.

Global Petrochemical is committed to realizing the plastics circular economy. They have contracted to purchase large quantities of raw, untreated pyrolysis oil (Pyoil) from an increasing number of pyrolyzer units that transform sorted plastic waste to hydrocarbon liquids at high temperatures in the absence of oxygen. They will build purification units designed by your team to enable these oils to be processed as feedstock for steam crackers that produce light olefins that are subsequently polymerized to virgin-quality thermoplastics.

In 60 days, the Global Petrochemicals site investment team will review your purification unit process design. The Bali project team will also review your recommendations for closing the three critical circularity gaps that are described in Part 2 of this challenge.

1.0 The Circular Economy:

Purification of Pyoil is a critical step in delivering on the critically needed circular economy for plastics. It is a key enabler to achieve Chemical Recycling, recovering plastic waste and upgrading it to steam cracker feedstock for re-generation and recovery of light olefin monomers and aromatics, suitable for creation of critically needed, high-value products.



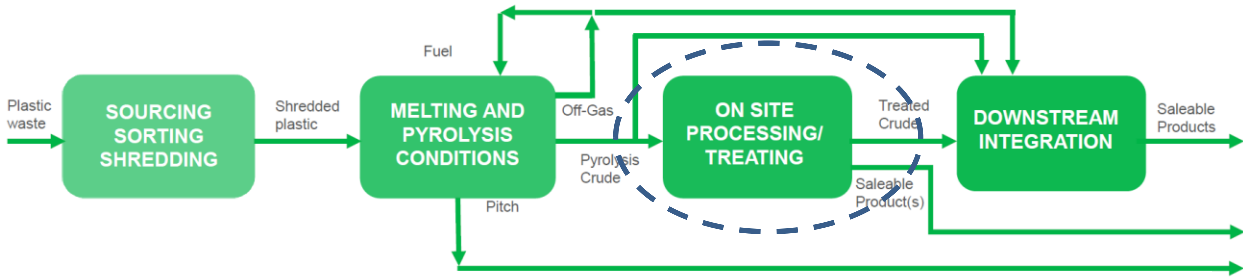
Source: New Hope Energy/Lummus Technology, "How To Produce Oil From Waste Plastics and Where To Use It". 2021 AIChE Spring Meeting

The Chemical Recycling step highlighted above involves two key processes:

1. **Conversion of sorted plastic waste to Pyoil** through grinding, melting, and thermal cracking in a Pyrolyzer, followed by reaction quenching to achieve optimum yields. This conversion step is not subject to direct calculation, requiring experimental testing and complex scale-up from pilot plant to semi-works to

commercial scale. Your company has contracted with several firms that employ this proprietary technology from one of the leading plastic pyrolysis licensing firms.

2. **Purification of Pyoil to enable its use as a feedstock to a downstream process, such as a steam cracker**, replacing conventional hydrocarbon feedstock.



Source: New Hope Energy/Lummus Technology, "How To Produce Oil From Waste Plastics and Where To Use It". 2021 AIChE Spring Meeting

The Part 1 Process Design task requires that you prepare a preliminary Process Design Package for the second of these two processes, the **Pyoil Purification Unit**.

2.0 Objectives for the Pyoil Purification Unit Design:

The purpose of the investment is to capture economic value from plastic waste. Economic success is a critical enabler for achieving the sustainability goal of closing the circular economy. With this in mind, the prioritized project objectives are:

1. Effectively manage all high-consequence process safety risks.
2. Reliably deliver on-specification feedstock to adjacent Global Petrochemicals ethylene plant so that the ethylene plant reliability and economic performance is not degraded.
3. Maximize economic benefit of the investment by minimizing capital cost and variable operating cost.

The design must address all three objectives.

3.0 Upstream Interface / Feedstock to the Pyoil Purification Unit:

Sorted plastic waste from various collection centers is delivered to a Plastics Pyrolyzer, located in Surabaya, East Java. Hot vapor from the Pyrolyzer reactor is rapidly quenched to 107° F to stop the pyrolysis reactions, creating a two-phase mixture. The phases are separated immediately after quenching and the liquid is transported to the Global Petrochemicals plant site by coastal ship, where it is unloaded and stored in a tank which aggregates Pyoil from several other regional Plastics Pyrolyzers.

The liquid product from the Pyrolyzer is a complex, wide boiling mixture of molecules, rich in olefins and aromatics, highly variable in composition, and extremely difficult to speciate with analytical techniques that are generally available at a modern petrochemical manufacturing site. As a result the liquid Pyoil Purification Unit feed is characterized as a boiling curve rather than a speciated list of components. A representative composition of the liquid and vapor feedstocks follows:

Table 1: Raw Pyoil Import Streams from Pyrolyzer to Purification Unit

Mass flow rate, lb/hr	52,432
Temperature, °F	100
Pressure:, psig	Defined by Vapor Pressure
Density, lb/ft³	49.1
Molecular Weight:	182.0
Phase	**Liquid[1]**
Composition wt%	
Nitrogen	
Hydrogen	
Carbon Monoxide	
Carbon Dioxide	
Methane	0.01
Ethane	0.10
Ethylene	0.05
Propane	0.29
Propylene	0.26
Butane	0.36
C4 Olefins	0.62
1,3-Butadiene	0.07
Pentane	0.13
Hexane	0.40
C6+	97.69
TBP (True Boiling Point) at 760 MM HG (wt):	
IBP	-46 °F
5%	289 °F
10%	324 °F
30%	403 °F
50%	483 °F
70%	555 °F

90%	658 °F
95%	717 °F
EBP	844 °F

Note 1: The Liquid stream described in Table 1 is the net feedstock to the Pyoil Purification Unit. *The Pyrolyzer also creates a small Vapor stream, which is difficult to transport and is therefore used locally within the Pyrolyzer facility.*

The Pyoil can contain a range of contaminants that originate from both contamination in the sorted waste and additives that were used in the preparation of the plastic during its original manufacture. The contaminants of greatest concern to the steam cracker are **chlorides**, commonly from the decomposition of polyvinyl chloride (PVC) and **metals, such as calcium and silica.** Chlorides and metals are harmful to the high temperature metallurgy in the steam cracking furnace, and they must be removed to ppm levels.

Although there is no **water** specification in the feed, low levels of water can be present and must be considered in the design, since free water must not be fed to the steam cracker.

4.0 Downstream Interface / Products from the Pyoil Purification Unit:

Economic operation of steam cracking furnaces requires that hydrocarbon feedstocks be separated into defined compositional ranges, commonly known as “boiling ranges”. *These ranges are defined by the end point of the distillation fraction.*

The ethylene plant that is being fed from the Pyoil Purification Unit is designed to accept two specific liquid feed types, commonly known in the steam cracking industry as Naphtha and Gas Oil. **The Py Oil must be fractionated to separate the mixture into the following four streams**, ranging from light vapor to heavy oil.

Table 2: Pyoil Purification Process Products

Purification Unit Product Stream Name	Py Gas	Pyoil Light Cut	Pyoil Medium Cut	Pyoil Heavy Cut
Steam Cracker Feed Name	Olefin-Rich Vapor, fed directly to the Ethylene Plant	Naphtha (Cracking Furnace Feedstock)	Gas Oil (Cracking Furnace Feedstock)	Not suitable for Steam Cracker
End Boiling Point (EBP)[Note 1]	N/A	392° F (200° C)	620° F (327° C)	--
Temperature	107° F	100° F	100° F	100° F
Pressure	Minimum 2.4 psig	70 psig	70 psig	50 psig

Note 1: ASTM D86 at 760 mm Hg, LV%

Comments:

- The Pyoil Heavy Cut is not suitable for feed to an ethylene plant. The team must suggest a disposition for this heavy oil stream.
- The Py Gas stream is the un-condensed, overhead vapor product from the Pyoil distillation tower. This stream can be sent directly to the ethylene plant, *at a minimum pressure of 2.4 psig*, with no further processing required.
    - The 2.4 psig minimum is determined by two considerations:
        1. If a vapor stream is present, the 2.4 psig pressure ensures that it has sufficient pressure to reach the ethylene plant without the need for additional compression.
        2. In the event that there is no overhead vapor distillate present in the tower overhead, the 2.4 psig specification ensures that the tower will operate without the risk of air ingress into the process.

5.0 Design Considerations for the Py Oil Fractionation:

There are several potential distillation strategies for the Py Oil. The designer must consider:

- The hot oil stream available for vaporizing feed and reboiling the tower has a maximum temperature of 750° F.
- The minimum distillation tower pressure is 2.4 psig, as described in Section 4.0. *The design must consider how this minimum pressure will be assured as composition of the Liquid Feed can vary.*
- The Pyoil Light Cut and the Pyoil Medium Cut must not contain free water. *The design must consider how trace levels of water in the Pyoil feed will be removed from the tower.*
- The Pyoil Heavy Cut is not suitable for feed to a steam cracking furnace because of its heavy tail. This material must be sent to tankage and transported offsite. *The designer must suggest possible dispositions for this stream.*
- Capital cost is a significant challenge in this project. *The designer is strongly encouraged to consider distillation schemes that minimize the number of distillation towers.*

6.0 Treatment of Contaminants

Contaminant levels are highly variable and difficult to predict. BASF, among others, (https://catalysts.basf.com/industries/chemical/adsorbents/puricycle#Dehalogenation) offer a sophisticated range of adsorbents and catalysts specifically developed to address the contaminant issues associated with purification of Pyoil. Adsorbents are also available from several other qualified suppliers.

- Experience has shown that two beds in series (BASF PuriCycle® H and PuriCycle® HP), each with an LHSV = 1 hr^{-1} provides adequate protection.
- It can be assumed that both beds are regenerable with hot nitrogen at 500° F. The designer must ensure that Pyoil Light Cut and Pyoil Medium Cut stay on spec while a bed is out of service for regeneration.
- It can be assumed that "typical" chloride levels in the Pyoil products is 50 wppm. Adsorbents of this type have a maximum adsorbate capacity of ~5% wt.
- Separate treatment is required on the Pyoil Light Cut and Pyoil Medium Cut products.

7.0 Utilities Available at Battery Limit:

	Pressure (psig)	Temperature (°F)
Cooling Water Supply:	70	87
Cooling Water Return:	40	107

	Pressure (psig)	Temperature (°F)
Thermal Fluid (Hot Oil) Supply:	230	750
Thermal Fluid Return:	200	725

Other utilities and raw materials (e.g. electricity, nitrogen, process water, compressed air, etc.) are available as needed at battery limits.

8.0 Tankage

Tankage is required for all liquid feeds and products.

- Tank holdup for all liquid streams (imported Pyoil feed, Pyoil Light Cut, Pyoil Medium Cut and Pyoil Heavy Cut) shall be 1 week at design rates.
- The designer shall specify each tank, ensuring that the selected tank provides safe storage that minimizes emissions.

9.0 Economics

Global Petrochemicals is committed to conversion of plastic waste as a critical business priority, but the economics are challenging, meaning the designer must deliver a design that accomplishes the key project priorities for Safety, Reliability and Cost Effectiveness described in Section 2.0.

Your design team's work is a critical input for Global Petrochemicals' value-sharing price negotiation with Pyoil feed suppliers. In preparation for this negotiation, your team must provide:

- A Capital Cost estimate for the facility. *Basis: US dollars, year 2021, Singapore location*.
    - The cost estimate must include all process facilities as well as the following utility systems:
        - Tankage, including emission control
        - Flare
    - Other utility systems will take advantage of existing facilities at the adjacent ethylene plant without incurring capital cost.
- Variable Operating Cost estimate (excluding Pyoil feed cost), based on the following price set. Note that energy costs at this location are high since the main source of fuel is imported LNG:

Electricity	$0.25 USD / kW-hr
Fuel gas	$15.00 USD / MBTU HHV
Cooling Water	$0.50 USD / MBTU
HP Steam, 600 psig, 750° F	$51.90 / 1000 kg
MP Steam, 150 psig	$35.00 / 1000 kg
LP Steam, 50 psig	$22.90 / 1000 kg

  - MP & LP Steam generated by extracting HP steam through a turbine with ~75% isentropic efficiency
  - Hot oil is heated by firing fuel gas in existing furnace
- Fixed Operating Cost (labor, maintenance, cats & chems allowance)

10.0 Environment, Health and Safety:

Environmental, Health and Safety (EHS) aspects are critical to the economic viability, sustainability and social responsibility of Global Petrochemicals' business and operations. These aspects must be carefully considered during design to ensure that processes minimizes raw material consumption, safely contains process materials, and effectively treat potentially harmful discharges prior to release to the environment.

These aspects are especially important when processes employ or produce toxic and flammable materials. Your design will be judged in part on your recognition of the potential environment, health and safety hazards inherent in the process, as well as on the mitigation steps you incorporate to ameliorate these potential hazards.

1. **Minimizing Environmental Impacts**[1]
    a. You should assume that regulatory authorities require the application of *Best Available Control Technology (BACT)* to minimize and treat gaseous and liquid waste generated by the process.
    b. Prepare a detailed process and instrumentation diagram (P&ID) for the distillation column.[2] Your P&ID should include automatic controllers for pressure, level, and composition (temperature) management as well as alarms informing operators of abnormal conditions.
    c. Size a pressure relief for this column assuming an onsite flare is available for the safe and complete combustion of vented material.
    d. Finally, tabulate the annual failure rate of column automatic controllers and alarmed indicators based on literature data. This analysis builds confidence that your design is reliable, minimizing off-spec production and flaring.

2. **Assessing and Mitigating Potential Health Impacts**
Your design must recognize the hazards associated with potential human exposure to process materials, including raw materials, intermediate and finished products, by-products and wastes. To recognize hazards compile a table of OSHA chemical exposure limits, NFPA diamond classifications, and lethal dose (LD50) limits for process chemical constituents. This information is often found on Safety Data Sheets (SDS), formerly known as Material Safety Data Sheets MSDS. Screening for potential health risks is an important element of process safety that informs personnel protective equipment and standard operating protocols.

3. Safety – Learning from Experience[6]
The design must consider relevant lessons learned from the industry, especially with respect to hydrocarbon explosions.

    a. Highlight the risks in hydrocarbon processing by performing a TNT equivalency calculation for the atmospheric detonation of all chemicals from the largest, by inventory, process distillation column. For worst-case consideration assume all fractionator contents instantly and gaseously vent to atmosphere.
    b. To mitigate risks, tabulate a Hazard and Operability (HAZOP) study for the distillation tower.

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[1] Crowl DA & Louvar JH <u>Chemical Process Safety</u>. Prentice Hall.
[2] Turton R et al. <u>Analysis, Synthesis & Design of Chemical Processes</u>. Prentice Hall.
Sloley AW (2000) "Effectively control column pressure." *Chemical Engineering Progress*. vol. 97, iss. 1, pg. 39-48.