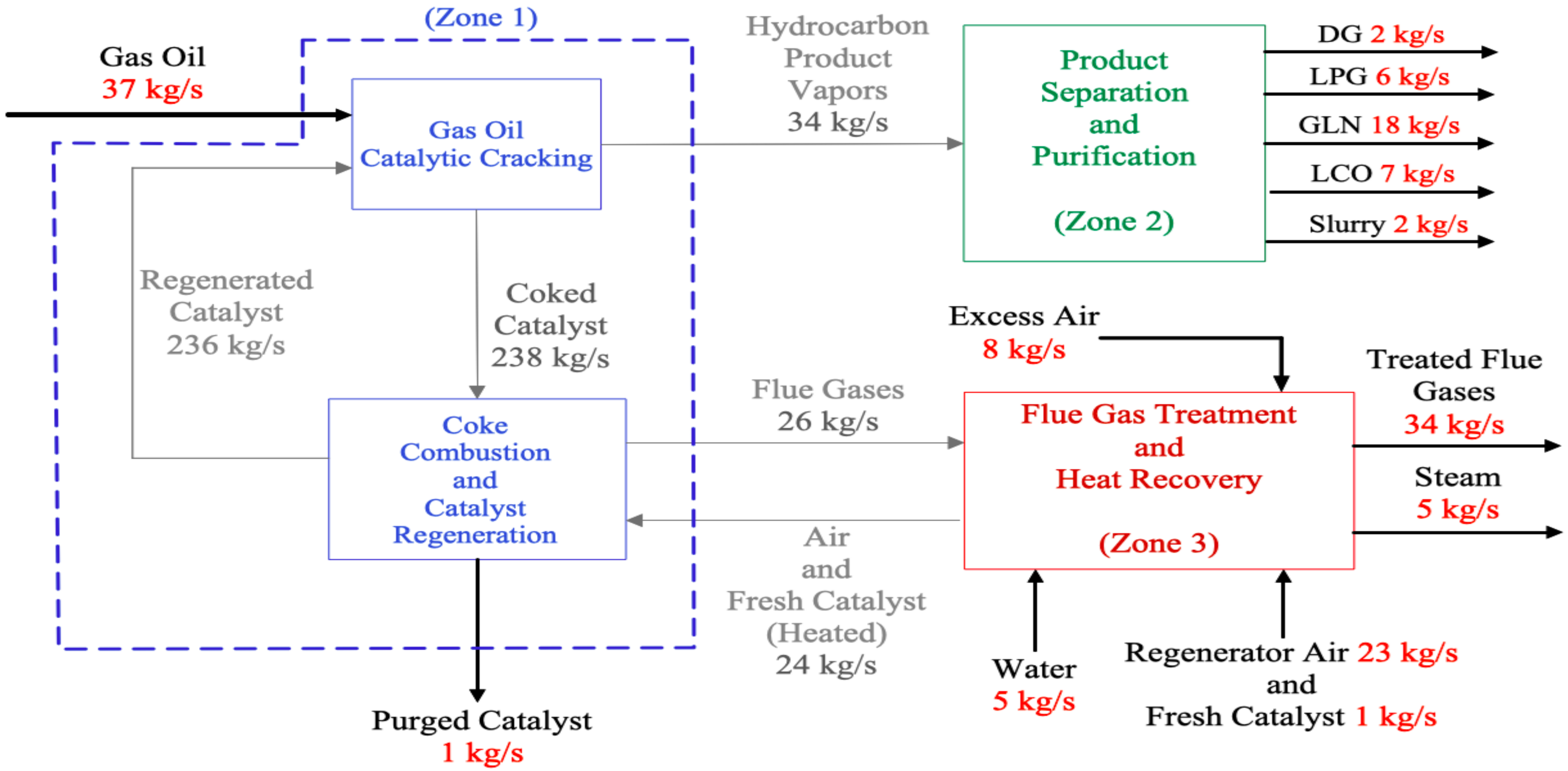
Fluid Catalytic Cracking: Process Design and Economics

Basir Miah
Christian Pena
Slah Yehya
Jameel Hammad

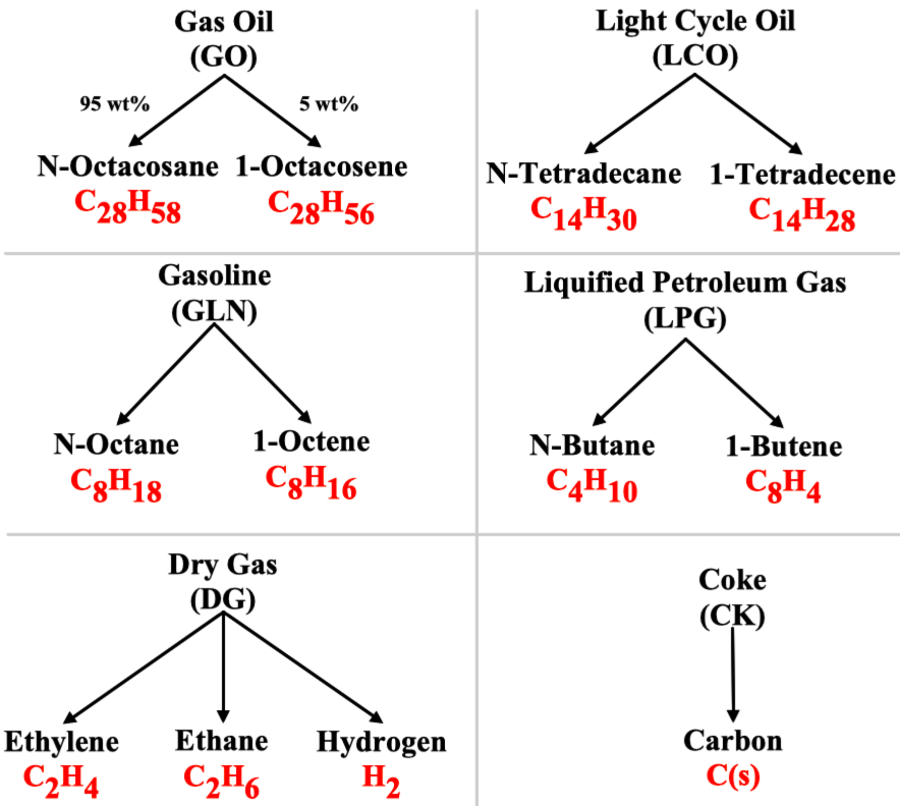
Introduction

- According to the U.S. EIA, there are 700 petroleum refineries worldwide, roughly 500 of these facilities utilize FCC (processing 56,000 to 227,000 bbl/cd per unit).
- In petroleum refineries, cracking is a process where high-molecular weight hydrocarbons are broken into lighter hydrocarbons.
- Fluid Catalytic Cracking (FCC) is a chemical process that converts gas oil into saleable petroleum products, in the presence of zeolite catalyst.

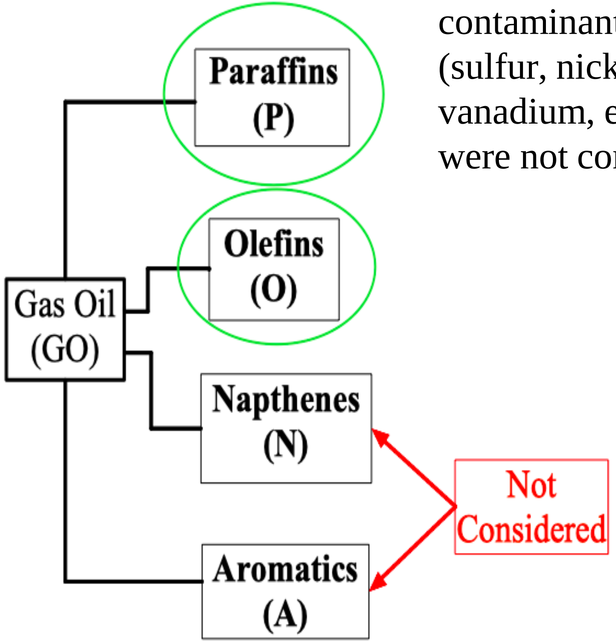
Overall Process: Zone-by-Zone Breakdown



Reactants and Products of Gas Oil Catalytic Cracking



Impurities and contaminants (sulfur, nickel, vanadium, etc.) were not considered

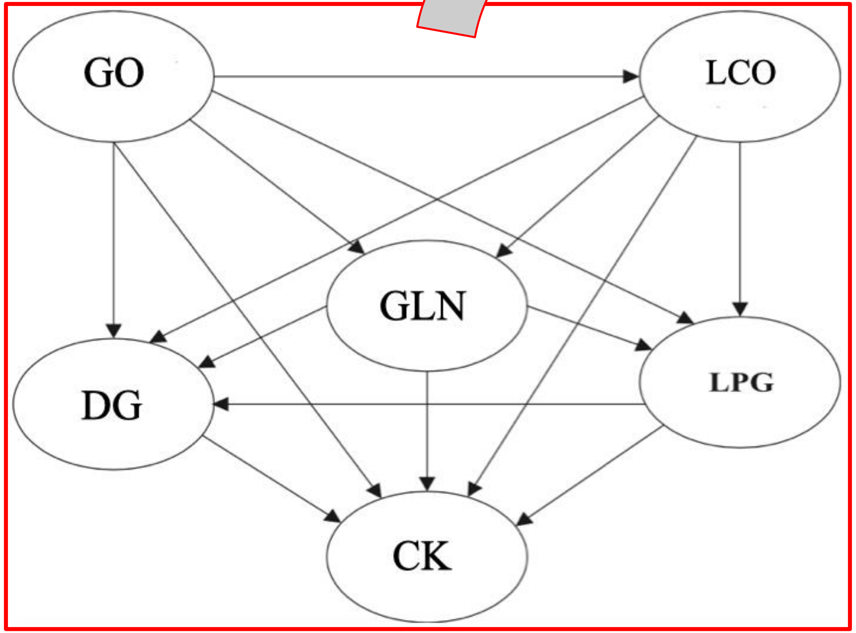


Zeolite (Catalyst) $\longrightarrow$ **Kaolinite** $Al_2Si_2O_7{*}H_2O$ (s)

Reaction Kinetics

$$R_{go} = -(k_1 + k_2 + k_3)y_{go}^{2}\varnothing_c$$

Model w/ Aspen's activity factor option



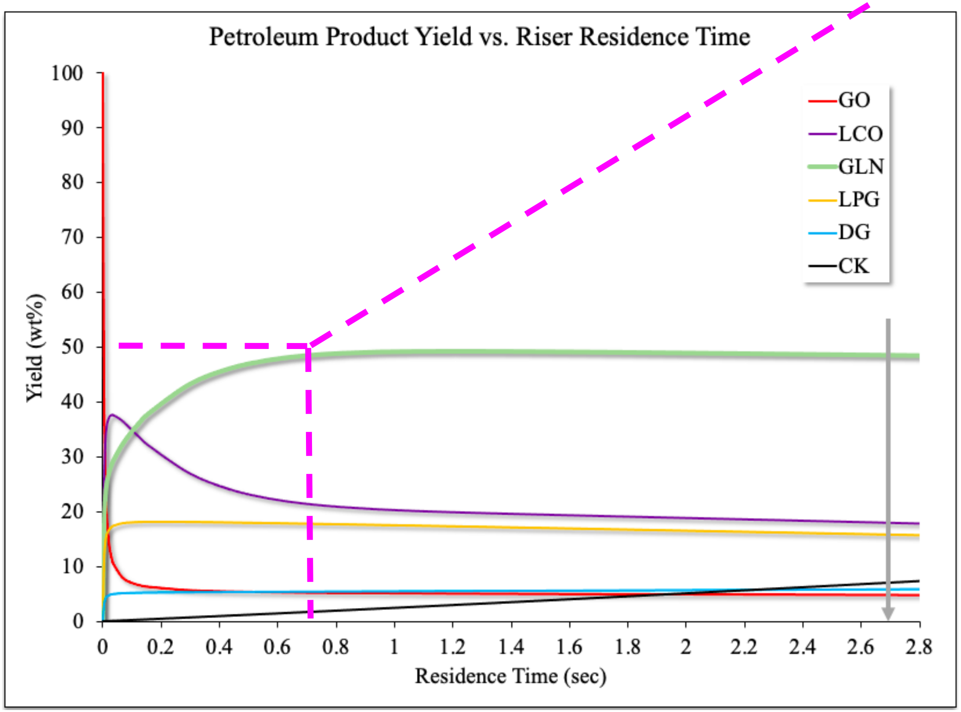
Reaction* (Lump Form)	Reaction (Explicit Form)
GO → LCO	$C_{28}H_{58} \rightarrow C_{14}H_{30} + C_{14}H_{28}$
GO → GLN	$C_{28}H_{58} \rightarrow C_8H_{18} + 2.5C_8H_{16}$
GO → LPG	$C_{28}H_{58} \rightarrow C_4H_{10} + 6C_4H_8$
GO → DG	$C_{28}H_{58} \rightarrow C_2H_6 + 13C_2H_4$
GO → CK	$C_{28}H_{56} \rightarrow 28C + 28H_2$
LCO → GLN	$C_{14}H_{30} \rightarrow C_8H_{18} + 0.75C_8H_{16}$
LCO → LPG	$C_{14}H_{30} \rightarrow C_4H_{10} + 2.5C_4H_8$
LCO → DG	$C_{14}H_{30} \rightarrow C_2H_6 + 6C_2H_4$
GLN → LPG	$C_8H_{18} \rightarrow C_4H_{10} + C_4H_8$
GLN → DG	$C_8H_{18} \rightarrow C_2H_6 + 3C_2H_4$
LPG → DG	$C_4H_{10} \rightarrow C_2H_6 + C_2H_4$
LCO → CK	$C_{14}H_{28} \rightarrow 14C + 14H_2$
GLN → CK	$C_8H_{16} \rightarrow 8C + 8H_2$
LPG → CK	$C_4H_8 \rightarrow 4C + 4H_2$
DG → CK	$C_2H_4 \rightarrow 2C + 2H_2$

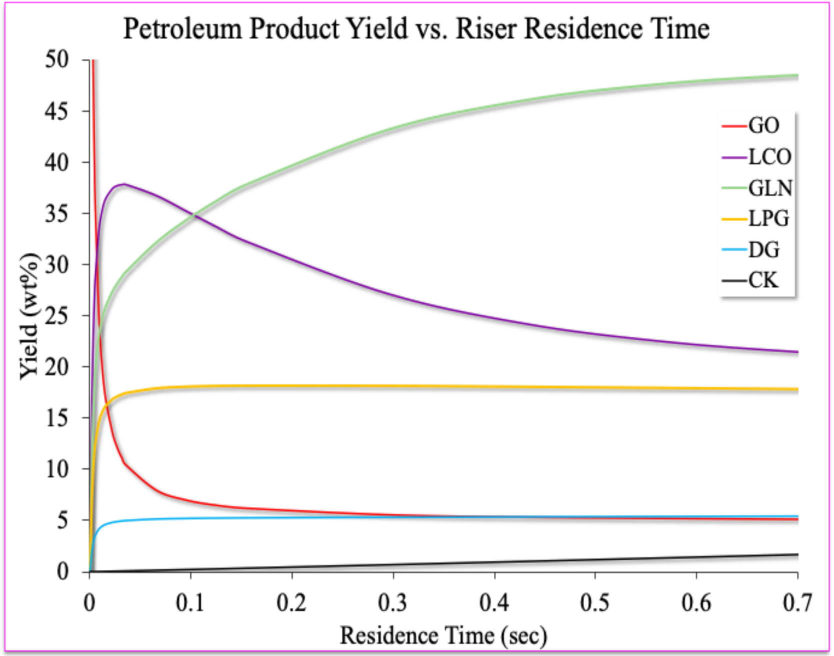
Two Observations in Cracking Chemistry:

- Long-Chain Paraffin → Short-Chain Paraffin + Olefin
- Olefin → Coke

Riser Yield Profiles

- Residence Time (RPlug): 2.7 seconds
- Gas Oil Conversion: 95 wt%
- C/O Ratio: 6.4 kg catalyst/kg gas oil





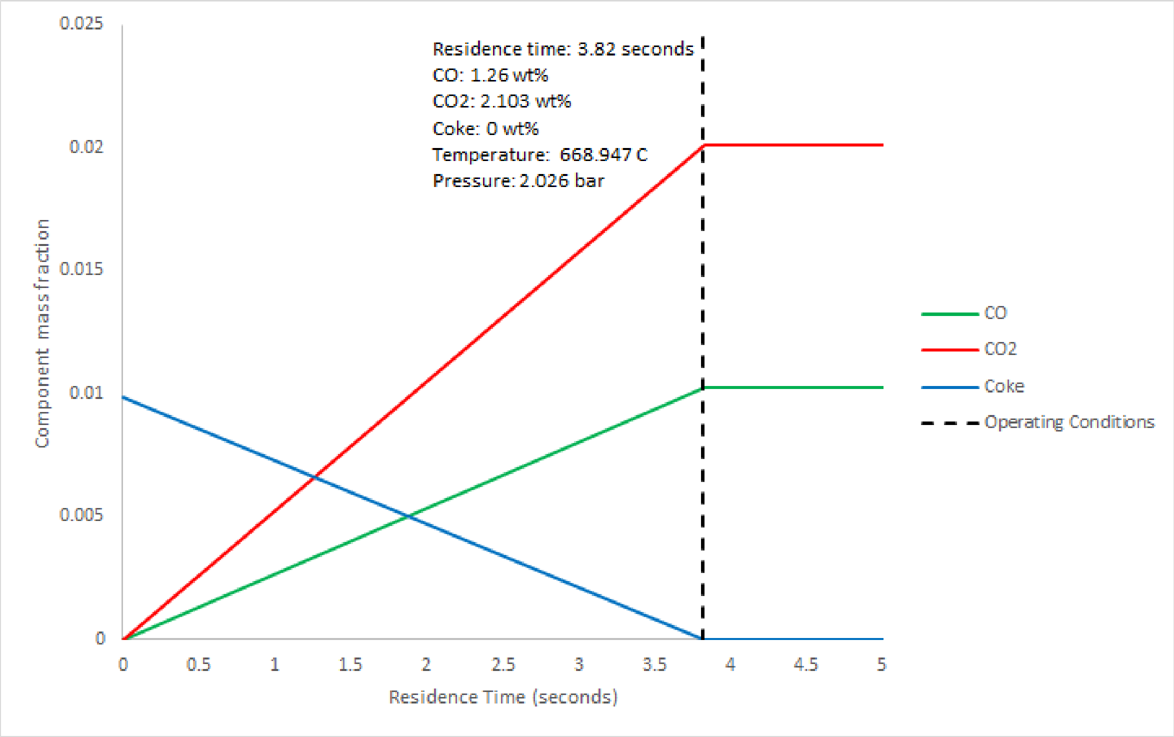
	Simulation Yield	Commercial Yield
GLN	49 wt%	46 - 51 wt%
LPG	16 wt%	12 - 15 wt%
LCO	18 wt%	15 - 23 wt%
DG	6 wt%	~ 5 wt%
CK	7 wt%	4 - 6 wt%

Regenerator

- Used to burn off the solid coke generated in the riser reactor from the catalyst.

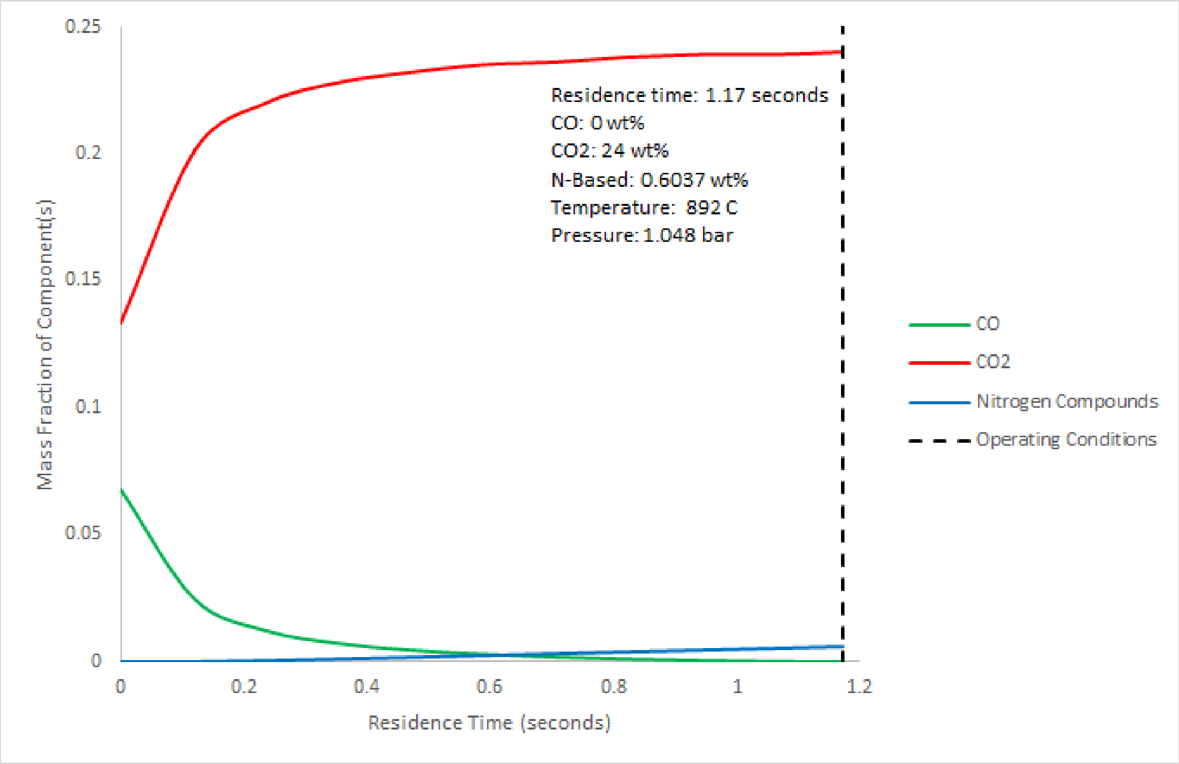
- Coke burns and forms CO and CO_2.

- The outlet enters a solid cyclone in which the regenerated catalyst is separated from the gases generated from the burning of the coke.

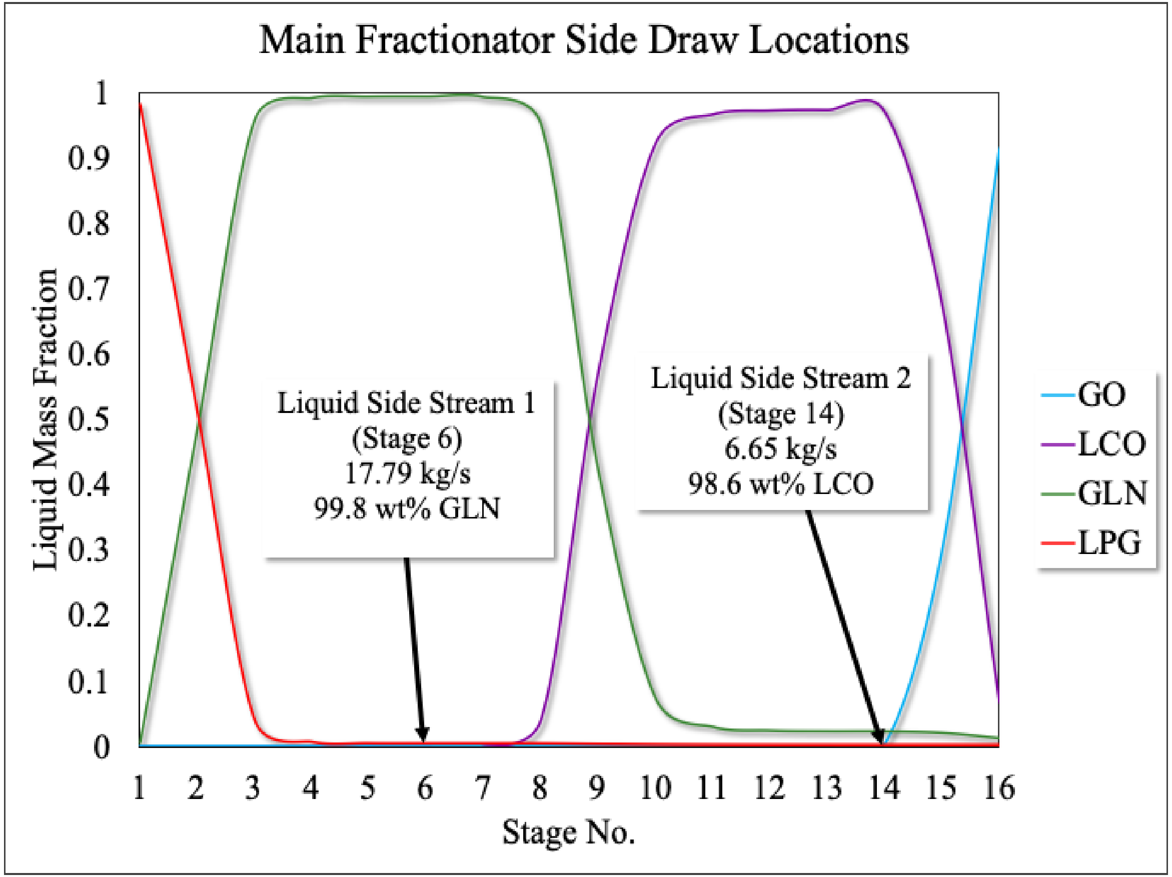


CO Boiler

- Comprised of a furnace and heat exchanger.
- Treats the gases coming from the regenerator outlet to ensure that excess CO is not emitted into the environment.
- Reactions have also been included to model the formation of nitrogen based pollutants during combustion.
- The hot flue gases that are emitted enter a heat exchanger where they are used to heat water to generate steam.



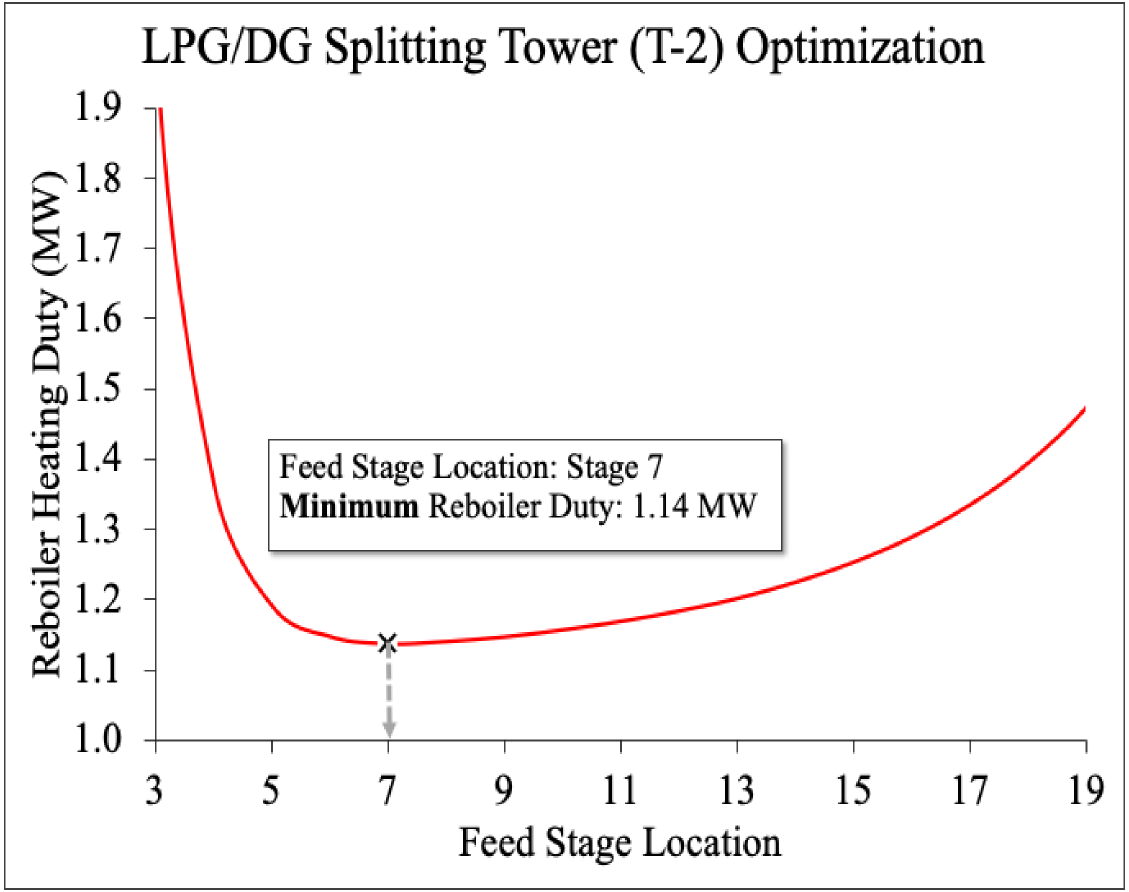
Petroleum Product Fractionation (Zone 2)



Compound	GLN	LCO
Purity (wt%)	99.8	98.6
Recovery (wt%)	99.5	99.0
Stage No.	6	14
Flow Rate (kg/s)	17.79	6.65

- Lighter gases (LPG and DG) comprise the overhead distillate and are further separated
- Bottoms product (Slurry) contains unreacted gas oil and ~ 4 wt% LCO

Petroleum Product Fractionation (Zone 2)

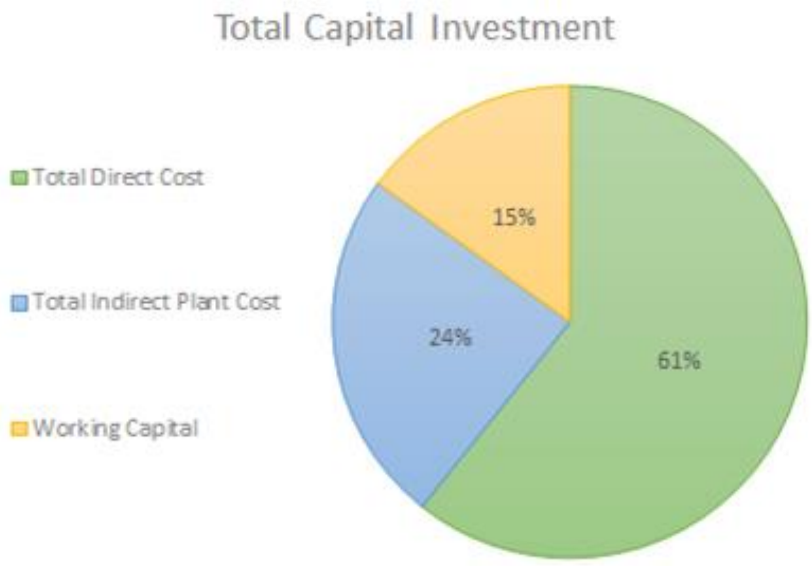


Variables held constant:

- Purity Targets (via Design-Spec)
- Number of Stages (30)
- Operating Pressure (~ 29 bar)
- Feed Composition, Temperature, Pressure, and Flow Rate

Compound	DG	LPG
Purity (wt%)	99.9	99.9
Recovery (wt%)	99.8	99.2
Stage No.	1	30
Flow Rate (kg/s)	2.16	5.76

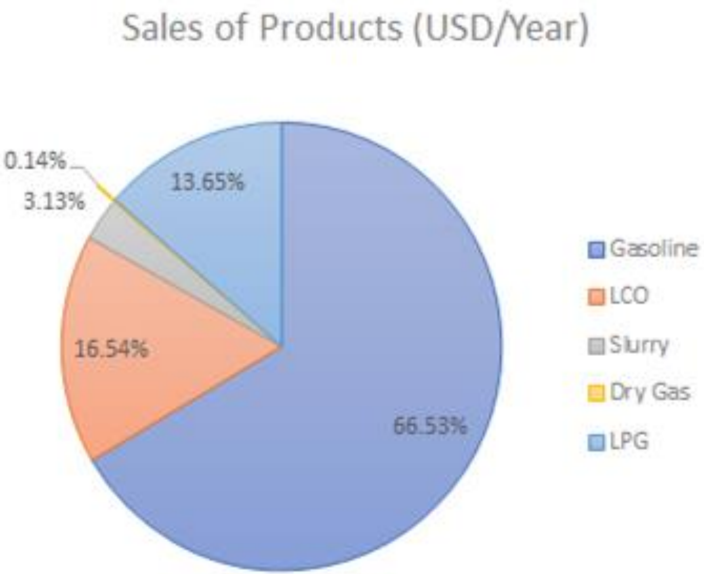
Breakdown of Capital Investment



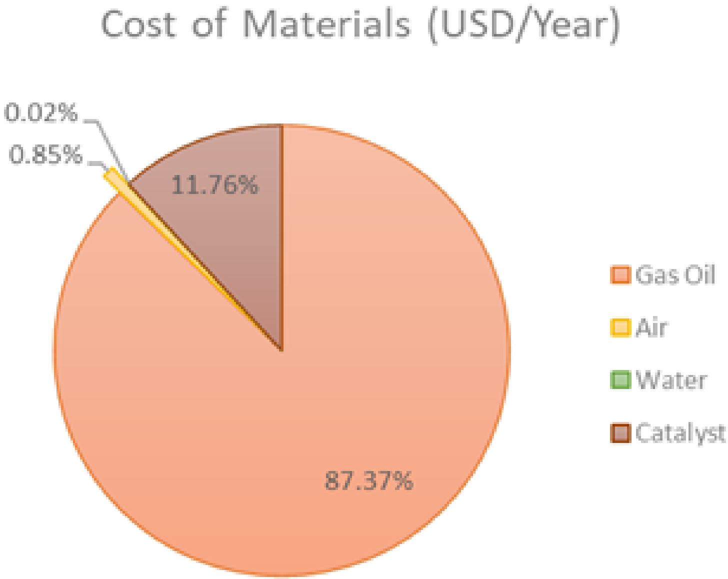
Total Direct Cost (USD)	59,508,758.34
Total Indirect Plant Cost (USD)	23,803,503.34
Working Capital (USD)	14,711,887.48
Total Capital Investment (USD)	98,024,149.15

- Total Direct Cost includes purchased equipment, installation, instrumentation and controls, electrical systems, land, etc.
- Total Indirect Cost includes engineering an supervision, construction, legal expenses, and contingency.
- The working capital was estimated to be 89% of the purchased equipment cost and is required to get us up and running.

Economic Analysis (Annual Sales and Cost of Materials)

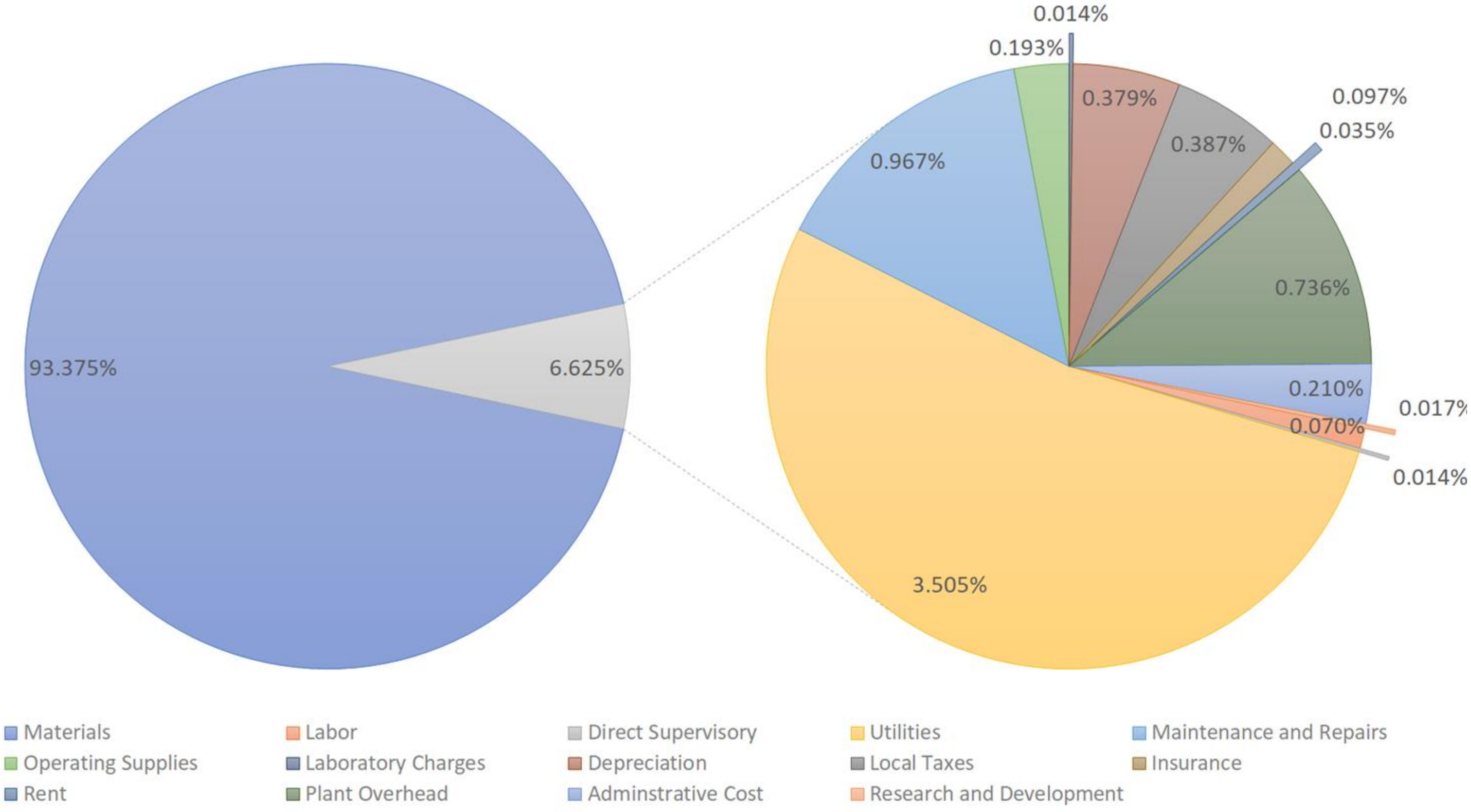


Product	Sales (USD/Year)
Gasoline	600,953,043.46
LCO	149,425,814.66
LPG	123,318,374.40
Slurry	28,281,484.80
Dry Gas	1,282,359.41
Revenue per year	**903,261,076.73**



Material	Sales (USD/year)
Gas Oil	702,748,224.00
Catalyst	94,608,000.00
Air	6,816,964.30
Water	154,021.82
Cost per Year	**804,327,210.13**

Breakdown of Total Operation and Maintenance Costs



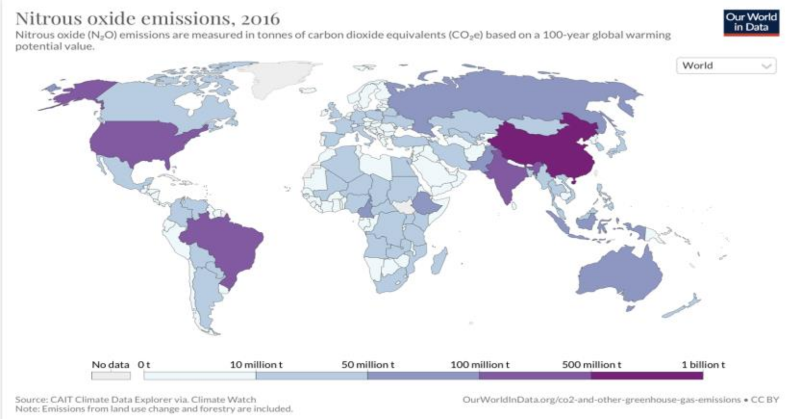
Revenue, Costs, Profit, ROI, and Payback Period

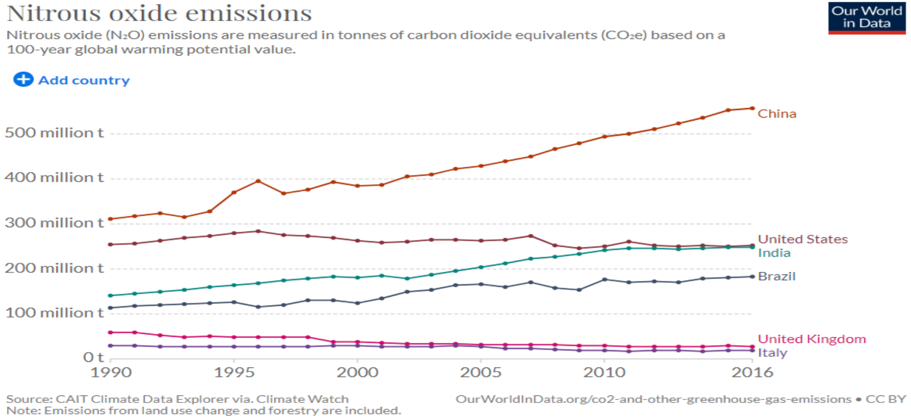
Revenue (USD/Year)	903,261,076.7
Costs of Materials (USD/Year)	804,327,210.1
Annualized Capital Cost (USD/Year)	9,802,414.915
O&M Costs (USD/Year)	57,053,144.11
Profit Before Taxes (USD/Year)	32,078,307.57
Profit After Taxes (USD/Year)	21,492,466.07
ROI	3.68 %
Payback Period	4.60 Years

- Revenue is approximately 903 million dollars. Total operating and maintenance cost is about 861 million dollars. Annualized capital cost is almost 10 million dollars. After taxes, we have a profit of almost 21 million dollars.
- Revenue, costs, profit, ROI, and payback period were all determined accounting for depreciation, a yearly inflation of 3%, a discount factor of 10%, and a flat tax rate of 33%.

Environment, Health, and Safety

- Most of the environmental concerns are due to flue gas emission to the atmosphere primarily by producing NOx (nitric oxide) compounds
- Refineries in the U.S. are operating under consent an agreement with the EPA to lower air emissions from their FCC units.
- EPA limits allowable NOx emission to the atmosphere to 20 ppm.





Environment, Health, and Safety

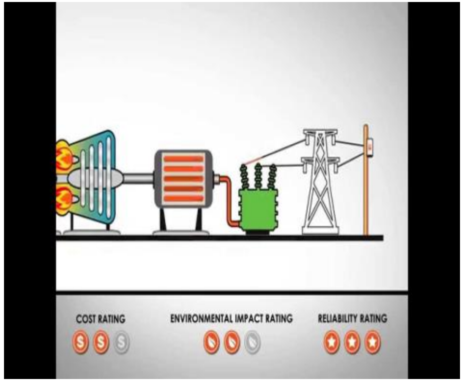
General and Environmental Hazards of FCC Products and Reactants	
Gas Oil	● Oil spills contaminate land and water; deadly to animals. ● Air and water pollution hurts local communities.
LCO Gasoline	● Toxic to aquatic life, with a long term effect on its environment. ● May be fatal if swallowed or enters airways. ● Can cause skin and eye irritation.
LPG	● Skin and eye irritant. ● May cause explosive mixture with air. ● At high concentration, may displace oxygen and cause suffocation.
Dry Gas	● Extremely flammable gas.
Catalyst (Zeolite Y)	● May cause respiratory irritation if inhaled.

Thank You!

Questions?

Applications

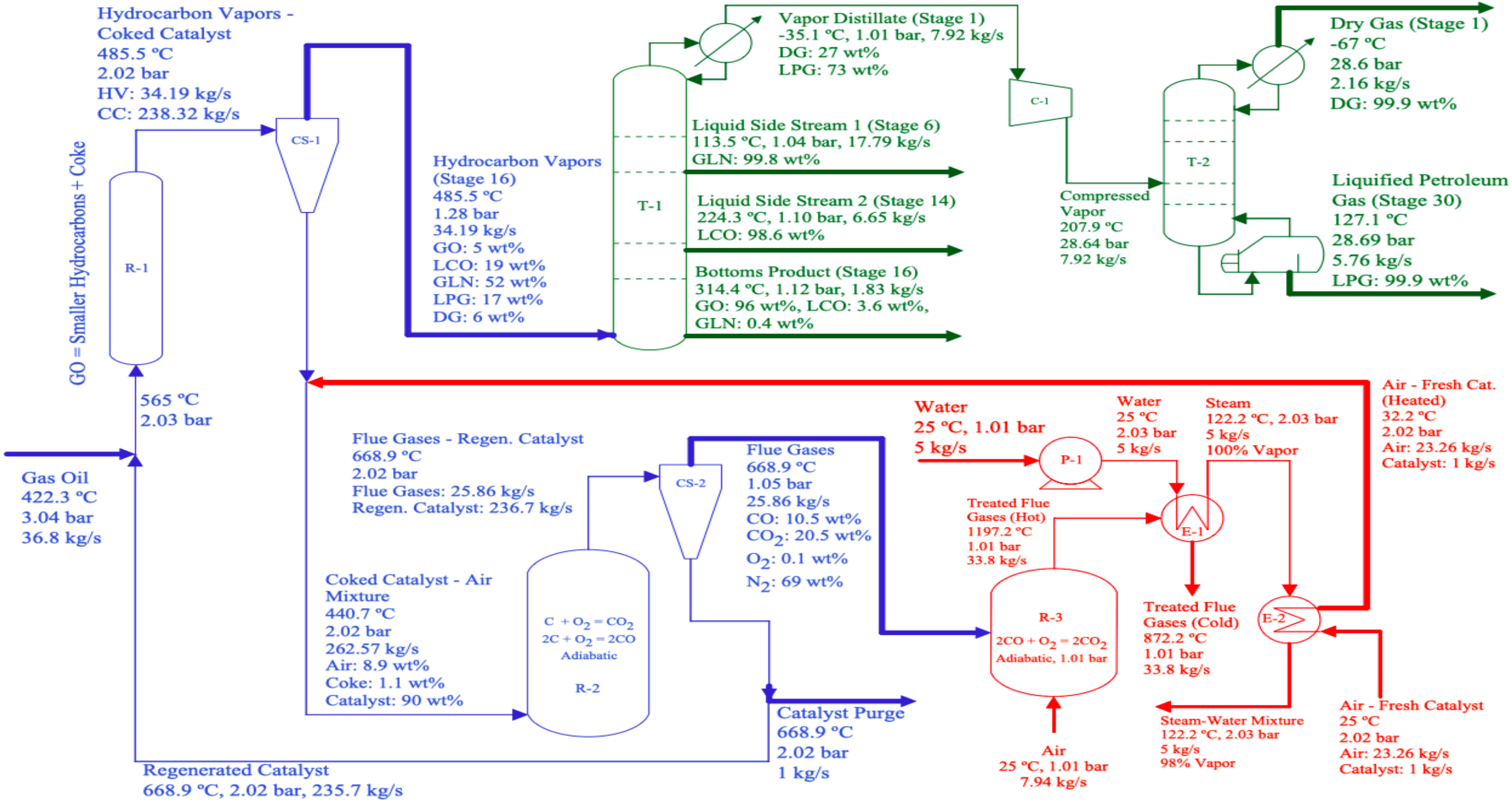
- **Dry Gas**
  - Generate electricity
  - Fuel for process heating
  - Heat buildings and water
  - Fuel to operate compressors
- **Liquified Petroleum Gas**
  - Vehicle fuel
  - Cooking
- **Gasoline**
  - Fuel for vehicles, boats, and small aircraft… etc.
- **Light Cycle Oil**
  - Fuel usually for larger, commercial automobiles
- **Slurry**
  - Asphalt base for roads
  - Heating oil for engines



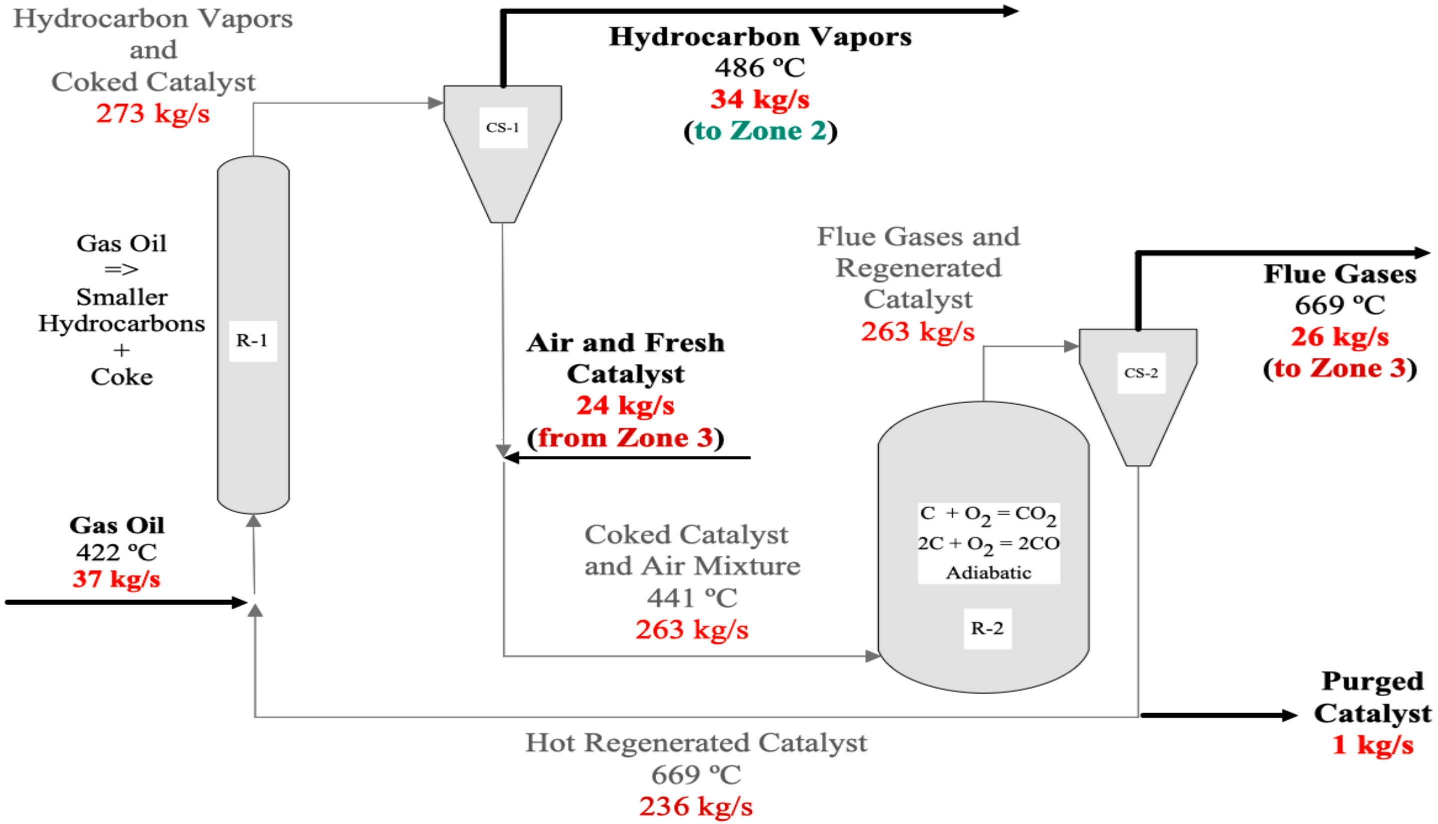
Thermal cracking vs. Catalytic cracking

Thermal cracking	Catalytic cracking
Involves cracking by applying temperature that ranges from 500 to 700 degrees Celsius.	Involves cracking by applying temperature that ranges from 475 to 530 degrees Celsius.
Requires high pressure (around 70 atm)	Can go under relatively low pressure (>20 atm)
Used to obtain high yield of C2 and C3 olefins and low yield of gasoline and other distillates	Used to obtain high yield of C4 olefins and high yield of gasoline and other distillates
Produces thermal gasoline (low octane number)	Produces gasoline with higher octane number
Doesn’t use catalyst	Uses catalyst

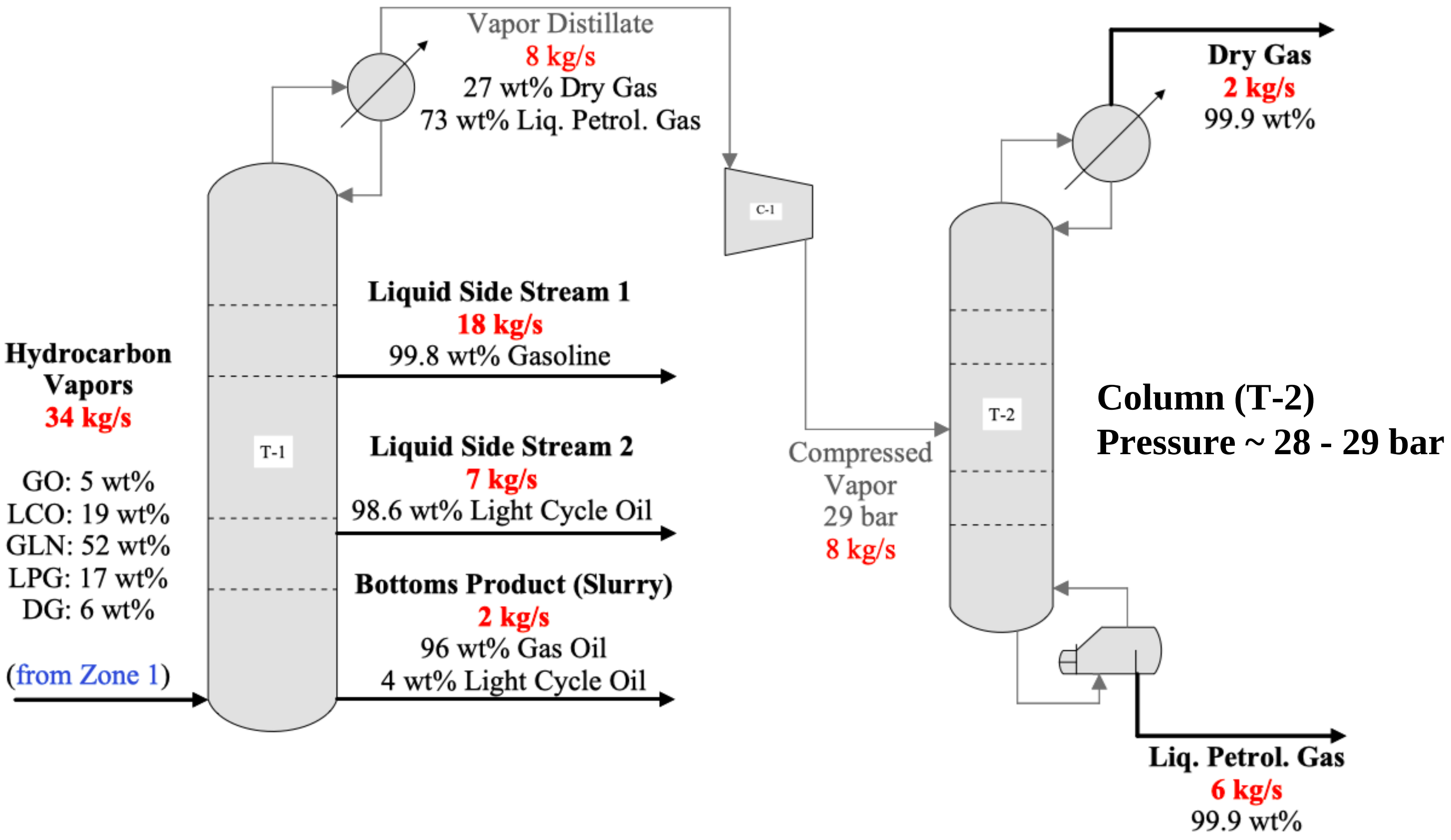
Process Flow Diagram



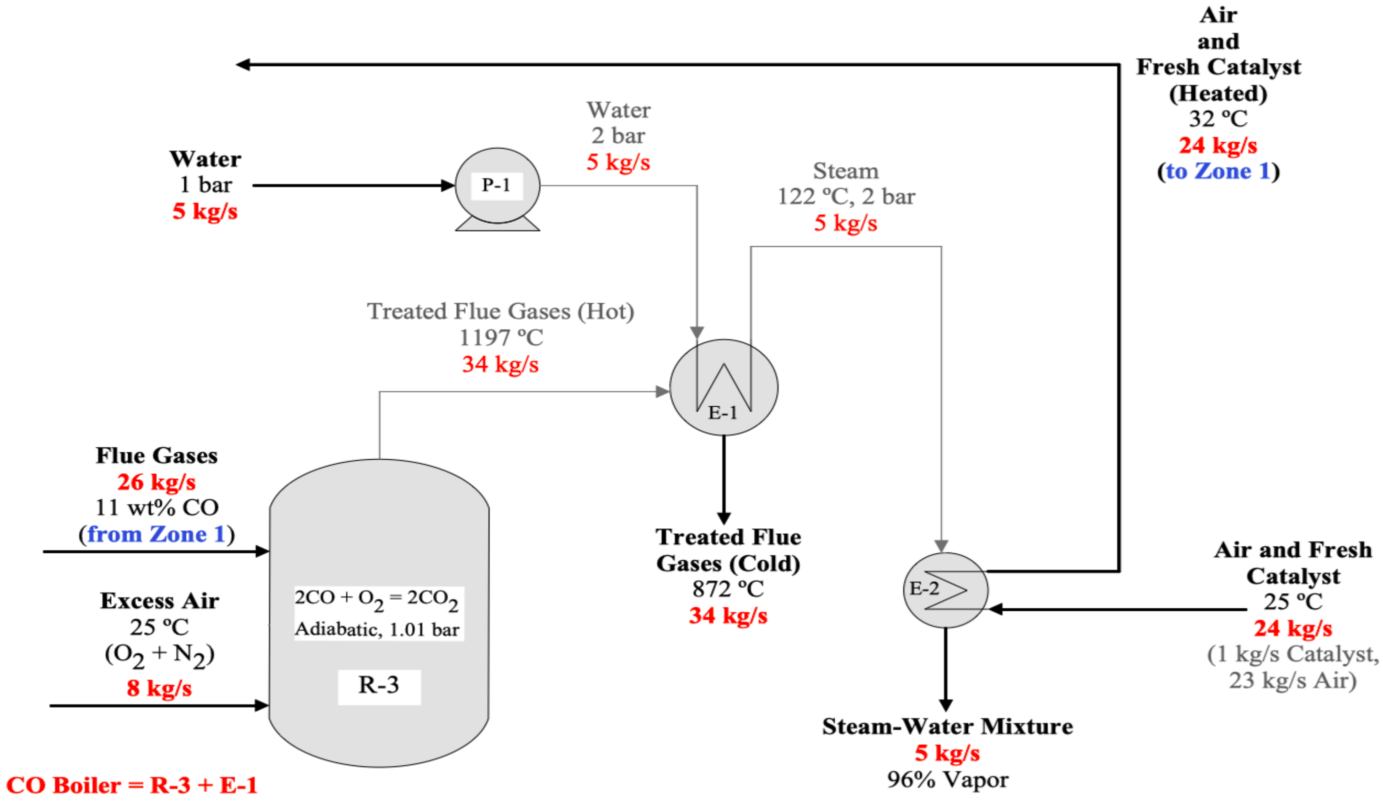
Zone 1: Gas Oil Cracking and Catalyst Regeneration



Zone 2: Product Separation and Purification



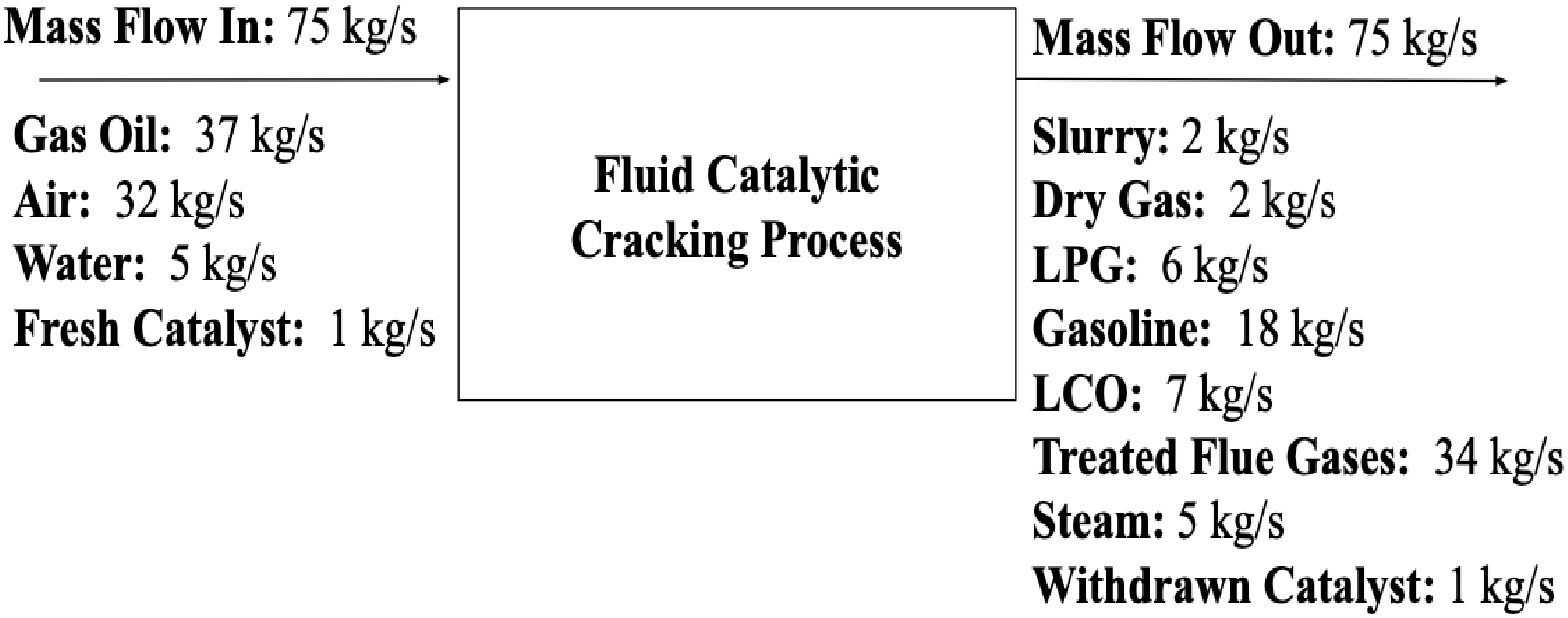
Zone 3: Flue Gas Treatment and Heat Recovery



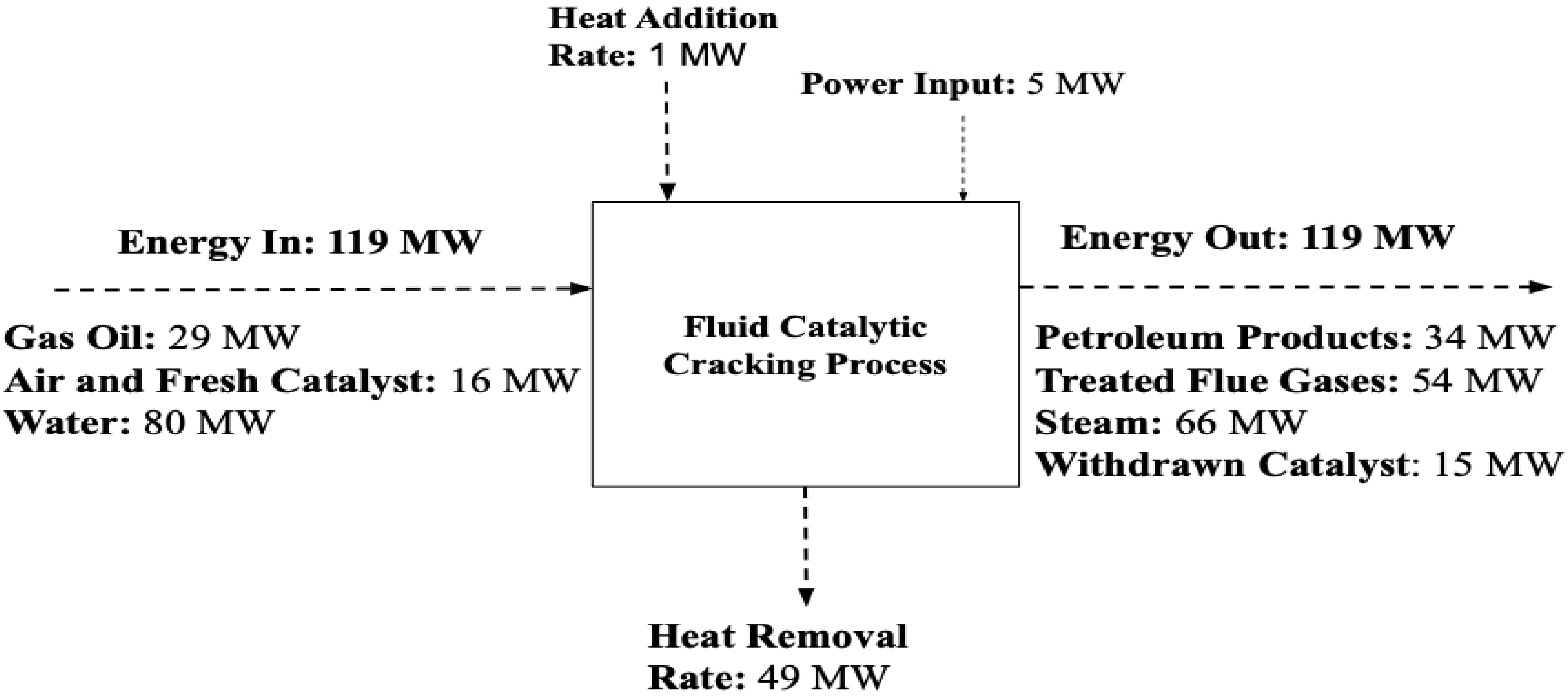
Full Set of Regenerator and CO Boiler Reactions

Reaction	Pre-Exponential Factor ($\frac{m^3}{kmol*s}$)	Activation Energy ($\frac{J}{mol}$)	Reactor the Reaction Takes Place In
$C + O_2 \rightarrow CO_2$	$4.12 * 10^7$	97,000	Regenerator (R-2)
$2C + O_2 \rightarrow 2CO$	$1.65 * 10^7$	97,000	Regenerator (R-2)
$CO + O_2 \rightarrow CO_2 + O$	$2.5 * 10^9$	199,576.8	CO Boiler (COB*)
$CO + O \rightarrow CO_2$	$1.8 * 10^7$	995,792	CO Boiler (COB*)
$N + O_2 \rightarrow NO + O$	$5.9 * 10^6$	26,275.52	CO Boiler (COB*)
$NO + O_2 \rightarrow NO_2 + O$	$1.7 * 10^9$	194,538.42	CO Boiler (COB*)
$CO + NO_2 \rightarrow CO_2 + NO$	$1.9 * 10^9$	122,426.19	CO Boiler (COB*)
$N_2 + O \rightarrow N + NO$	$7.6 * 10^{10}$	315,917.10	CO Boiler (COB*)
$N_2 + O_2 \rightarrow N_2O + O$	$6.3 * 10^{10}$	458,911.16	CO Boiler (COB*)

Overall Mass Balance



Overall Energy Balance



Deriving Lumped Reactions (Part 1)

Take for example the reaction: **GO → LCO** (1 of 15 reactions in the 6-lump network)
Important Data:

Lump	Gas Oil (GO)	Light Cycle Oil (LCO)
Boiling Point (Range)	330 - 550 ºC	221+ ºC
Molecular Weight	~ 400 g/mol	~ 200 g/mol
Model Component (N-Alkane)	N-Octacosane ($C_{28}H_{58}$)	N-Tetradecane ($C_{14}H_{30}$)

Now, let's put it together:

$$GO \rightarrow LCO$$
$$C_{28}H_{58} \rightarrow C_{14}H_{30} + ?$$

Stoichiometry is NOT balanced; need additional compound(s)

What should we do now? How do we go about choosing this second compound?

Part 2

Deriving Lumped Reactions (Part 2)

This is it!

We are strictly considering two observations in FCC chemistry:

(1) Long, straight-chain paraffin → shorter, straight-chain paraffin + **olefin**

(2) Olefin → coke

Olefins end with **"-ene"** in their name. We need an **alkene** that has **14 carbon atoms**. This secondary LCO needs to have a boiling point close to that of N-Tetradecane. Let's go with…. **1-Tetradecene ($C_{14}H_{28}$)**.

Let's try this again:

$$GO \rightarrow LCO$$

$$C_{28}H_{58} \rightarrow C_{14}H_{30} + C_{14}H_{28}$$

Balanced; lump reaction created.

Now, do the remaining **14**

Part 3

Deriving Lumped Reactions (Part 3)

Now, the coke (CK) formation reactions are a little different. In the literature, we discovered that coke has a little bit of hydrogen in it. So, we thought about using solid hydrogen (H_2). Not a good idea. So, the H_2 that forms is **coupled** with the dry gas (DG).

Here's an example:

GO → CK

Olefin → Coke

$C_{28}H_{56} \rightarrow 28\ C\ (s) + 28\ H_2\ (g)$

Treat the H_2 (g) as a dry gas (DG) attribute

In total, there are **5 reactions** (in our 6-lump network) that form coke.

Economic Analysis (Capital Investment Summary)

Equipment	Purchased Cost (USD)
Reactor Cyclone (CS-1)	306,433.58
Regenerator Cyclone (CS-2)	1,254,721.29
Main Fractionator (T-1)	3,750,000
Distillation Column (T-2)	70,000
CO Boiler (R-3 and E-1)	1,065,408.73
Heat Exchanger (E-2)	5,360
Water Pump	40,000
Compressor	26,000
Total Purchased Equipment Cost	**16,530,210.65**

Direct Cost	Percent of Delivered Equipment Cost	Plant Cost
Purchased Equipment Delivered	1	16,530,210.65
Purchased Equipment Installation	0.47	7,769,199.006
Instrumentation and Controls	0.36	5,950,875.834
Piping (Installed)	0.68	11,240,543.24
Electrical Systems (Installed)	0.11	1,818,323.172
Buildings	0.18	2,975,437.917
Yard Improvement	0.1	1,653,021.065
Service Facilities (Installed)	0.7	11,571,147.46
Total Direct Cost	**3.6**	**59,508,758.34**
Indirect Costs		
Engineering and Supervision	0.33	5,454,969.515
Construction Expenses	0.41	6,777,386.367
Legal Expenses	0.04	661,208.426
Contractor's Fee	0.22	3,636,646.343
Contingency	0.44	7,273,292.686
Total Indirect Plant Cost	**1.44**	**23,803,503.34**
Fixed Capital Investment	**5.04**	**83,312,261.68**
Working Capital	0.89	14,711,887.48
Total Capital Investment	**5.93**	**98,024,149.15**

Materials and Products

Material	gal/sec	USD/gal	Cost (USD/day)
Gas Oil	18.57	1.20	1,925,337.60
Air	6,732.00	0.00003211	18,676.61
Water	1.32	0.0037	421.98

Material	ton/sec	USD/ton	Cost (USD/day)
Catalyst	0.001	3,000.00	259,200.00

Product	gal/Sec	USD/gal	Sales (USD/Day)
Gasoline	7.50	2.54	1,646,446.69
LCO	2.93	1.62	409,385.79
Slurry	0.76	1.18	77,483.52
Dry Gas	43.03	0.00	3,513.31
LPG	3.76	1.04	337,858.56

FCC (POWERLAW)

Stoichiometry | Kinetic | Equilibrium | Activity | Information

Rxn No.	Reaction type	Stoichiometry
1	Kinetic	C28H58 --> C14H30 + C14H28
2	Kinetic	2 C28H58 --> 2 C8H18 + 5 C8H16
3	Kinetic	C28H58 --> C4H10 + 6 C4H8
4	Kinetic	C28H58 --> C2H6 + 13 C2H4
5	Kinetic	C28H56 --> 28 C + 28 H2
6	Kinetic	4 C14H30 --> 4 C8H18 + 3 C8H16
7	Kinetic	2 C14H30 --> 2 C4H10 + 5 C4H8
8	Kinetic	C14H30 --> C2H6 + 6 C2H4
9	Kinetic	C8H18 --> C4H10 + C4H8
10	Kinetic	C8H18 --> C2H6 + 3 C2H4
11	Kinetic	C4H10 --> C2H6 + C2H4
12	Kinetic	C14H28 --> 14 C + 14 H2
13	Kinetic	C8H16 --> 8 C + 8 H2
14	Kinetic	C4H8 --> 4 C + 4 H2
15	Kinetic	C2H4 --> 2 C + 2 H2

Incorporate activity factors to model catalyst deactivation. Find a handbook with typical product yields corresponding to a set/range of operating conditions/parameters. Then, employ trial-and-error.

Define activity

Name	AGOGLND	AGOLCOU	ALCOD	ALPGCKU	ADGCKU	ALPGDG	ALCODG
Value	0.3	1	0.15	25	12	0.6	0.25

Select activity

Rxn No.	Rxn type	Activity	Activity
1	Kinetic	AGOLCOU	
2	Kinetic	AGOGLND	
3	Kinetic		
4	Kinetic		
5	Kinetic		
6	Kinetic	ALCOD	
7	Kinetic	ALCOD	
8	Kinetic	ALCODG	
9	Kinetic		
10	Kinetic		
11	Kinetic	ALPGDG	
12	Kinetic	ALCOD	
13	Kinetic		

Yields were compared to yields reported in literature (ensure *realistic* product output). Bumping down GLN caused the other component yields to change (i.e., they were "fixed").