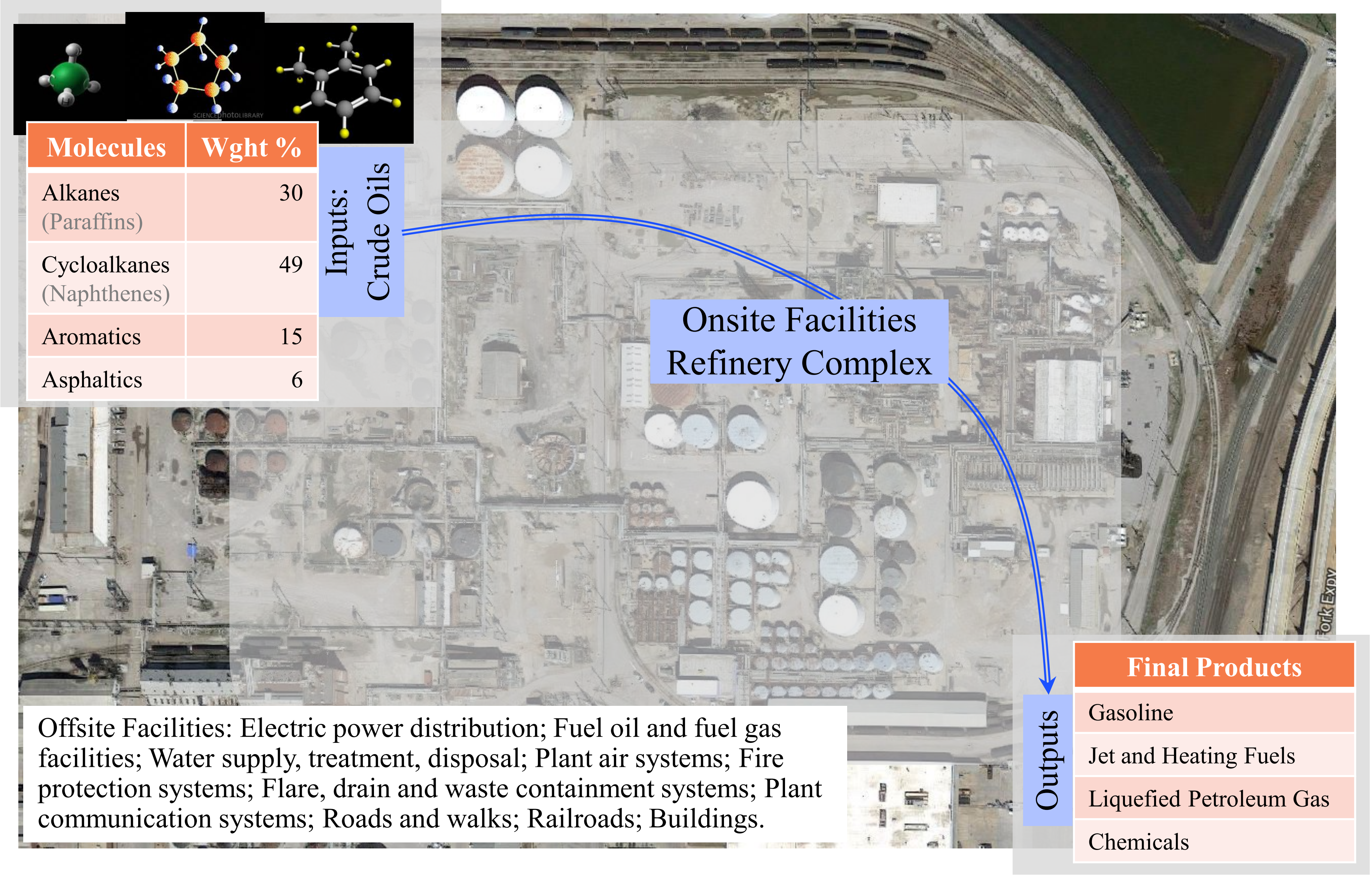
# Refining

**Outline**

- Refinery processes
- Refining Markets: Capacity, Cost, Investment
- Optimization of Refinery Operations

Updated in Spring 2020

# Crude Oil → Gasoline, Fuels, LPG, Chemicals



| Molecules | Wght % |
|---|---|
| Alkanes (Paraffins) | 30 |
| Cycloalkanes (Naphthenes) | 49 |
| Aromatics | 15 |
| Asphaltics | 6 |

Inputs: Crude Oils

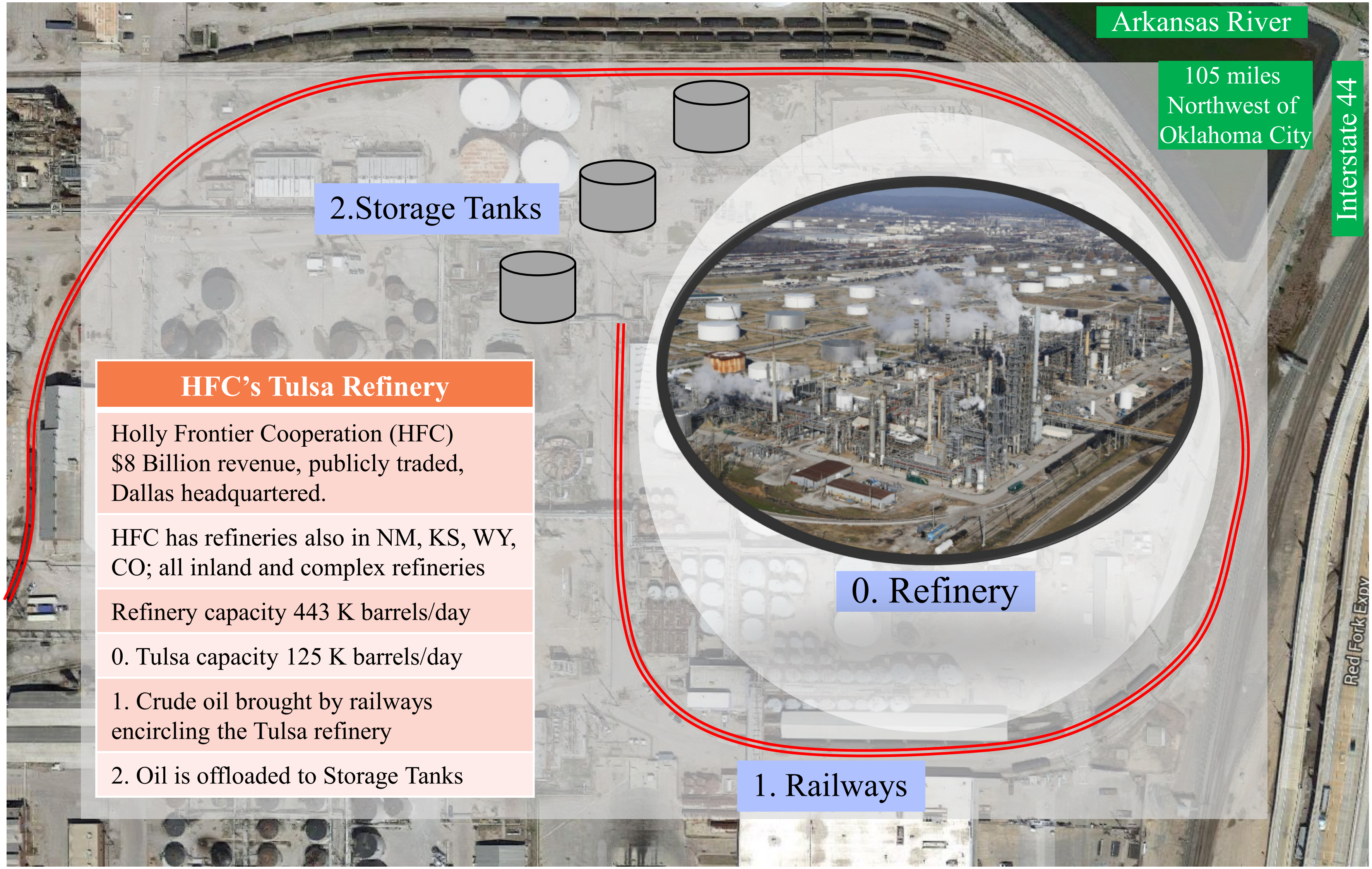
Onsite Facilities
Refinery Complex

Outputs

| Final Products |
|---|
| Gasoline |
| Jet and Heating Fuels |
| Liquefied Petroleum Gas |
| Chemicals |

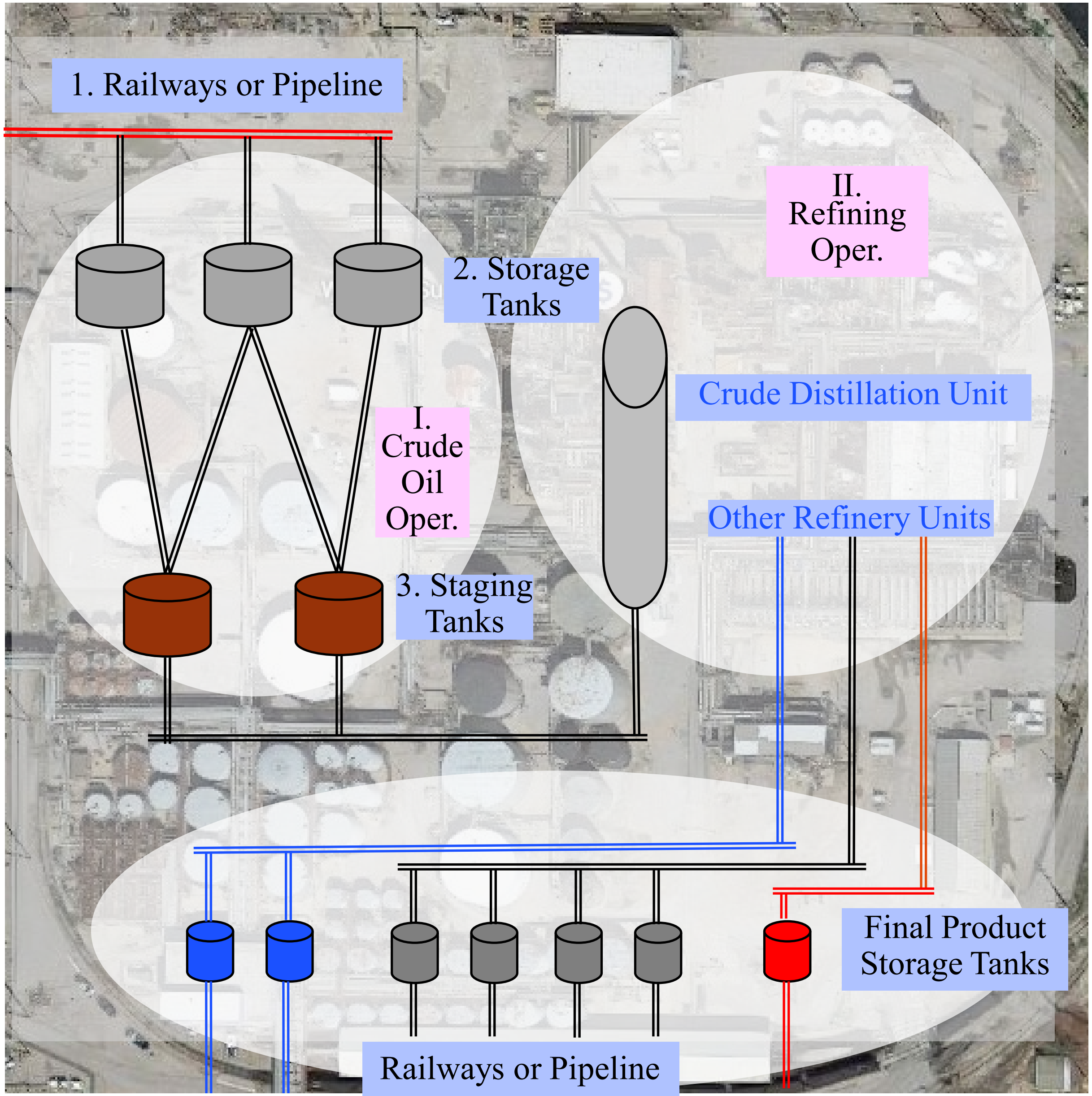
Offsite Facilities: Electric power distribution; Fuel oil and fuel gas facilities; Water supply, treatment, disposal; Plant air systems; Fire protection systems; Flare, drain and waste containment systems; Plant communication systems; Roads and walks; Railroads; Buildings.

# Inland Refinery: Holly Frontier's Tulsa



| HFC's Tulsa Refinery |
|---|
| Holly Frontier Cooperation (HFC)<br>$8 Billion revenue, publicly traded, Dallas headquartered. |
| HFC has refineries also in NM, KS, WY, CO; all inland and complex refineries |
| Refinery capacity 443 K barrels/day |
| 0. Tulsa capacity 125 K barrels/day |
| 1. Crude oil brought by railways encircling the Tulsa refinery |
| 2. Oil is offloaded to Storage Tanks |

# Crude Oil Operations, Refining Operations, Final Product Storage



1. Railways or Pipeline

2. Storage Tanks

3. Staging Tanks

I. Crude Oil Oper.

II. Refining Oper.

Crude Distillation Unit

Other Refinery Units

Final Product Storage Tanks

Railways or Pipeline

## Crude Oil Operations

Receive Crude Shipments
- Continuous or in Parcels

Store Crude in Storage Tanks
- Hedge against crude unavailability risk
- 15-day thruput storage often adequate

Use Staging Tanks
- Mix different crudes
- Remove Brine (Salts)
- Hedge against input unavailability
  - 3-4 day thruput storage often adequate

Pump Crude to the Distillation Unit

Crude oil operations are discrete processes if done in parcels

## Refining Operations

4 processes, to be detailed later

Refining is the process of converting crude to usable products.

Refining operations are continuous processes

## Final Product Storage

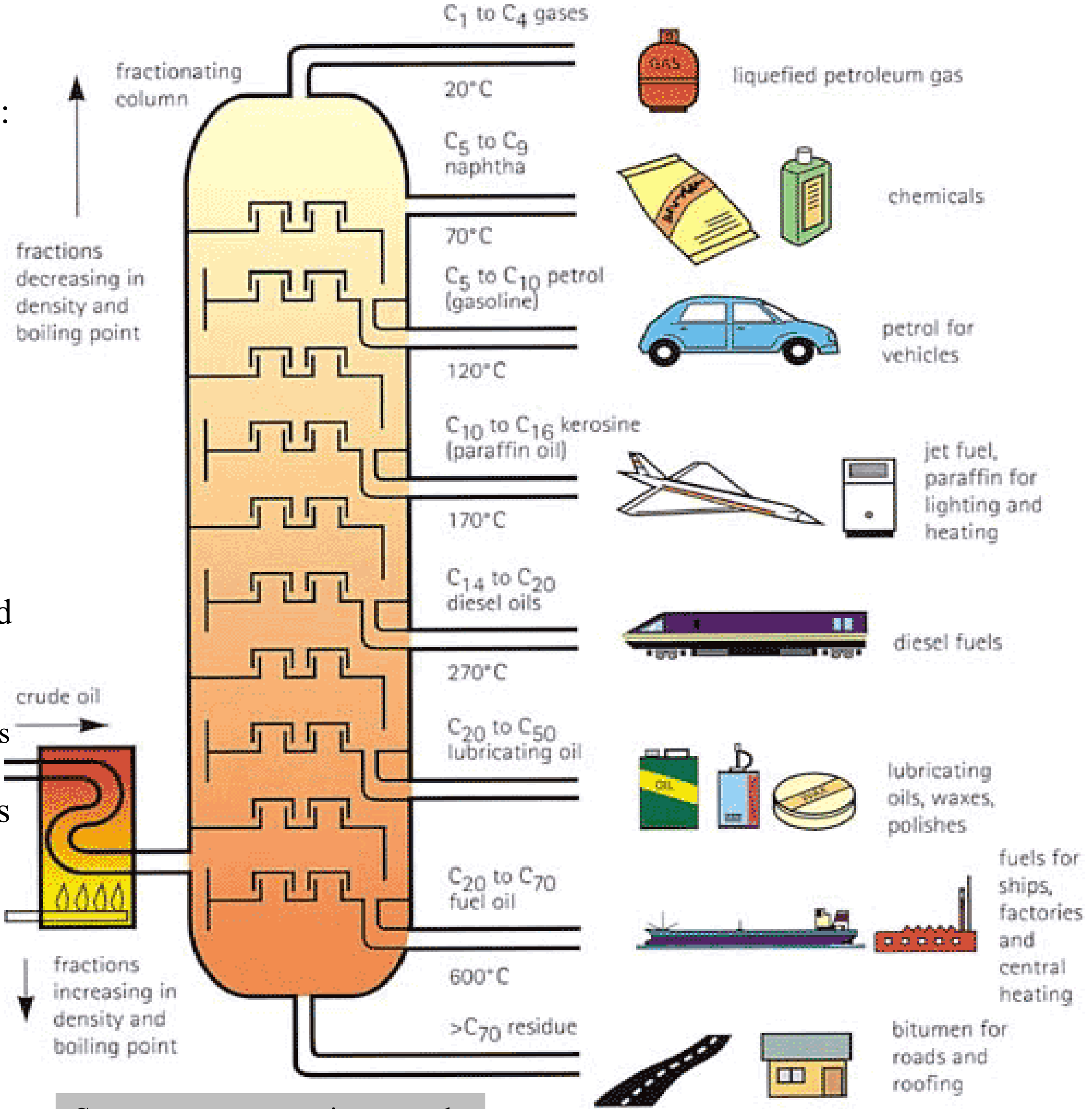
Until train, tanker truck, tanker ship pick up or pipeline shipments
- Capacity with 10 days of thruput

# Crude Distillation Unit (CDU)

- Hydrocarbons in crude have different boiling temperatures.
  - At 20 °C boiling are few-carbon alkanes: methane (1C), ethane (2C), propane (3C), butane (4C)
  - Around 70 °C boiling are cycloalkanes: pentane (5C), hexane (6C),
  - Around 120 °C boiling is heptane (7C). Liquids are octane (8C), nonane (9C)

- Heated crude turns into vapor and rises in the distillation tower (≈10-30 metres).

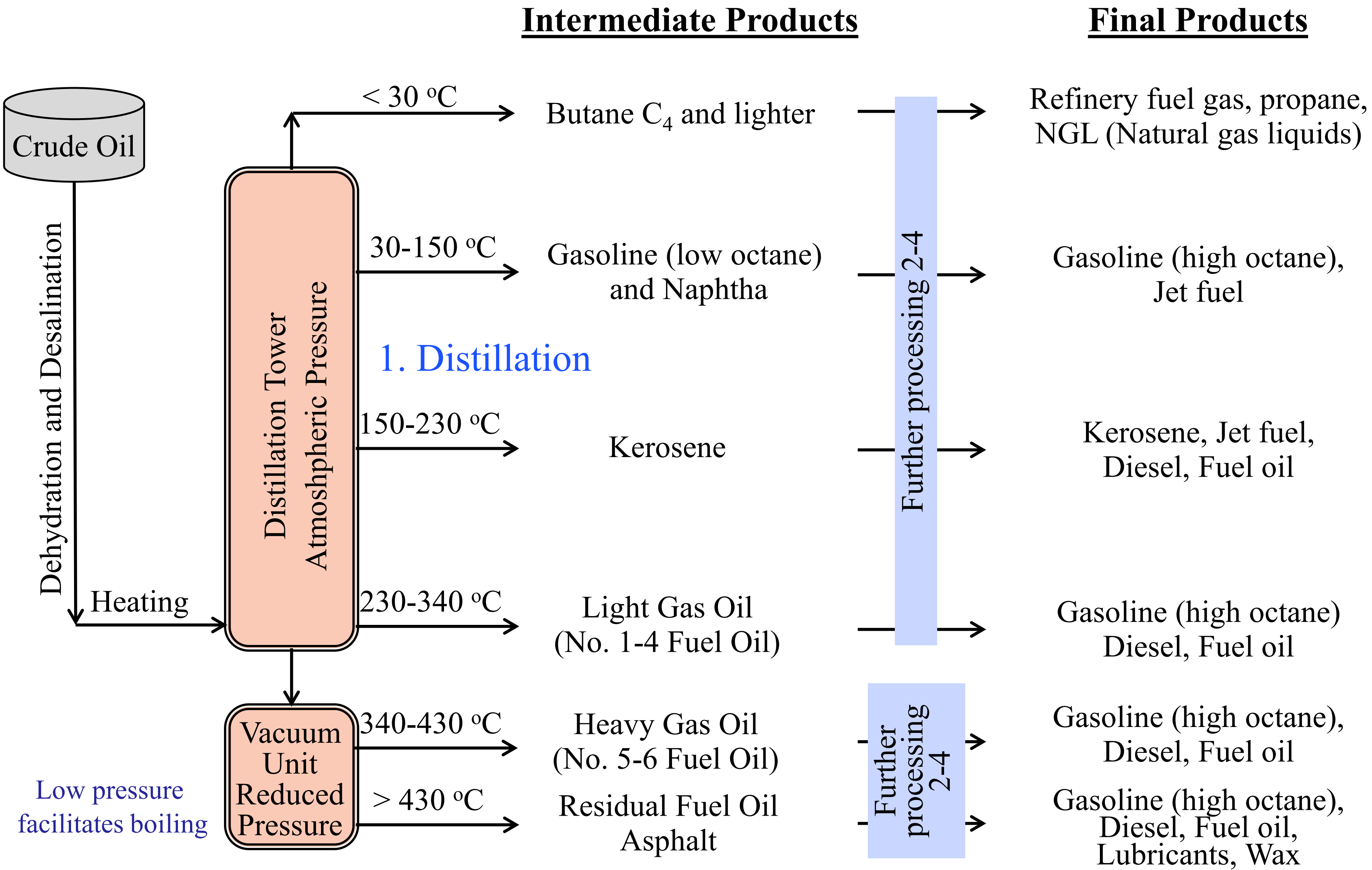
- As rising, it cools & condenses on trays.
  - At 20 °C, 1C-4C are in the gas phase and exit from the top of the distillation (fractioning) column.
  - At 120 °C. Some of 5C-9C exit as gas, some as gasoline.
  - At 170 °C , Kerosene condenses & flows out from its tray.
  - At 600 °C , Fuel oil condenses & flows out from its tray.
  - Residue (bottom) is asphalt & liquid when heated, but solidifies in room temperature.



Source: www.energyinst.org.uk

# 1. Distillation Process: Physical separation

## 1.A. Atmospheric towers & 1.B.Vacuum towers



**Intermediate Products**

**Final Products**

Crude Oil

Dehydration and Desalination

Heating

Distillation Tower
Atmoshpheric Pressure

1. Distillation

< 30 $^{o}$C → Butane $C_4$ and lighter → Refinery fuel gas, propane, NGL (Natural gas liquids)

30-150 $^{o}$C → Gasoline (low octane) and Naphtha → Gasoline (high octane), Jet fuel

150-230 $^{o}$C → Kerosene → Kerosene, Jet fuel, Diesel, Fuel oil

230-340 $^{o}$C → Light Gas Oil (No. 1-4 Fuel Oil) → Gasoline (high octane) Diesel, Fuel oil

Further processing 2-4

Vacuum Unit
Reduced Pressure

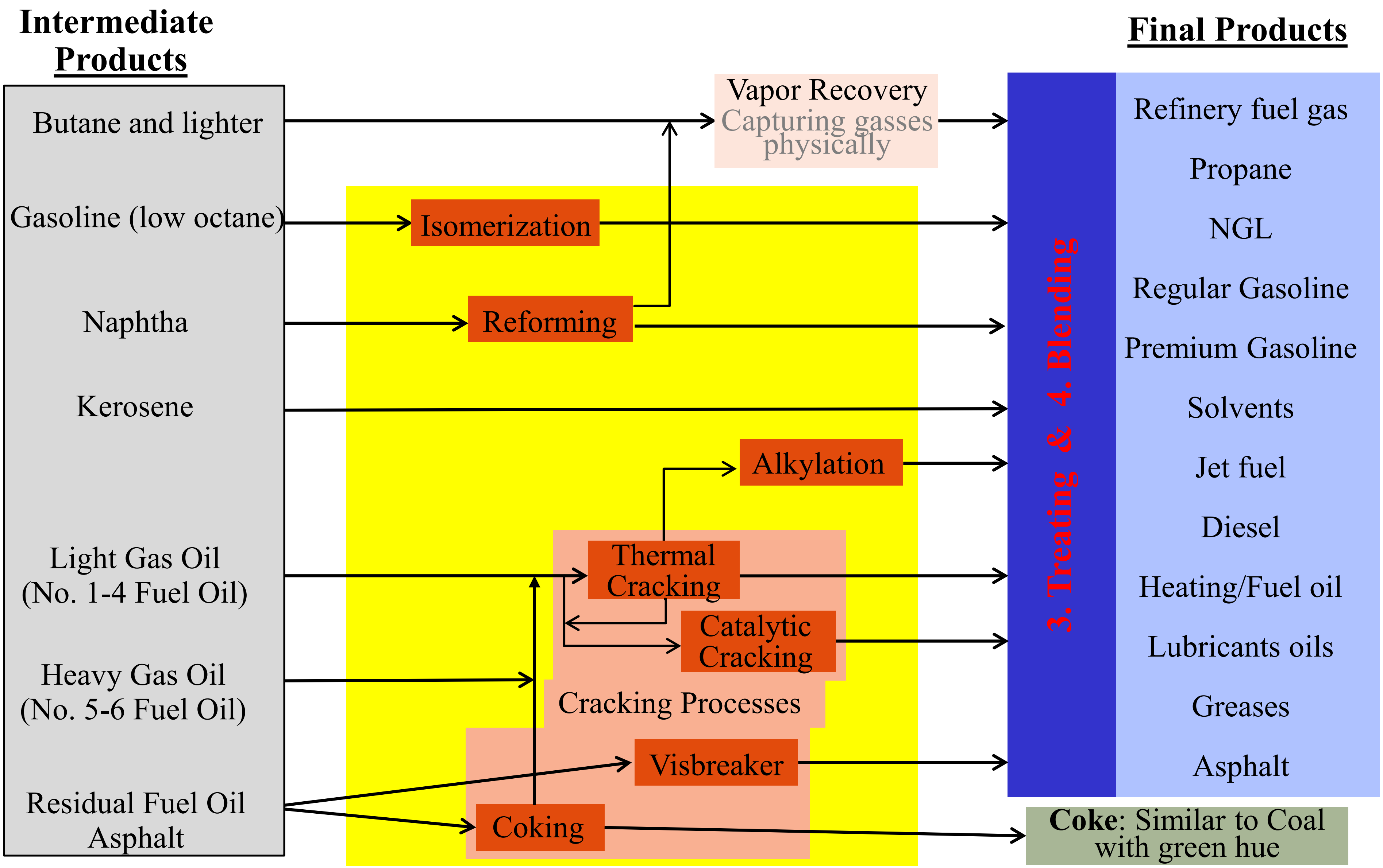
Low pressure facilitates boiling

340-430 $^{o}$C → Heavy Gas Oil (No. 5-6 Fuel Oil) → Gasoline (high octane), Diesel, Fuel oil

> 430 $^{o}$C → Residual Fuel Oil Asphalt → Gasoline (high octane), Diesel, Fuel oil, Lubricants, Wax

Further processing 2-4

# 2. Conversion Processes: Decompose (Crack), Unify, Reform



**Intermediate Products**

- Butane and lighter
- Gasoline (low octane)
- Naphtha
- Kerosene
- Light Gas Oil (No. 1-4 Fuel Oil)
- Heavy Gas Oil (No. 5-6 Fuel Oil)
- Residual Fuel Oil Asphalt

Vapor Recovery
Capturing gasses physically

Isomerization

Reforming

Alkylation

Thermal Cracking

Catalytic Cracking

Cracking Processes

Visbreaker

Coking

**3. Treating & 4. Blending**

**Final Products**

- Refinery fuel gas
- Propane
- NGL
- Regular Gasoline
- Premium Gasoline
- Solvents
- Jet fuel
- Diesel
- Heating/Fuel oil
- Lubricants oils
- Greases
- Asphalt

**Coke**: Similar to Coal with green hue

# 2. Conversion Process Descriptions
## 2.A. Cracking

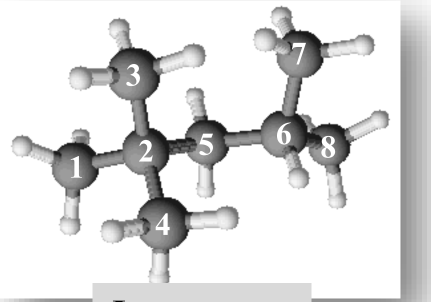
- Cracking: Breaking down heavier and larger HCs into lighter and smaller HCs.
  - Thermal Cracking: Using heat to crack.
    - Steam-cracking: Using steam to crack; sound-like steam flooding in EOG.
    - Visbreaking: Using moderate heat to crack with the purpose of reducing viscosity
    - Coking: Using extreme heat to crack residue to obtain heavy oil and coke.
      - Coke is sent to coal power plants to be mixed with coal and burnt
  - Catalytic cracking: Using a catalyst (facilitator) under high temperature.
    - Fluid catalytic cracking (FCC): Using zeolites (aluminium + silicates) powder as catalyst
    - Hydro cracking: Using water (hydrogen) as catalyst

| **Use zeolites ↑ gasoline yield & hydrogen ↑ kerosene yield.** | **Fluid catalytic cracking** | **Hydro cracking** |
|---|---:|---:|
| LPG | 14% | 6% |
| Gasoline | **45%** | 4% |
| Kerosene | 1% | **40%** |
| Diesel (Gasoil) | 23% | 38% |
| Other: gas, naphta, residue, coke | 17% | 12% |

Based on Figure 240 on p.171 of GOGI.

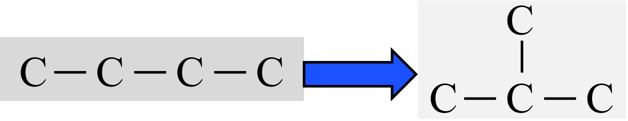
# 2. Conversion Process Descriptions
# 2. B. Reform and 2.C. Combine (Unify)

- Higher Octane Level ⇒ Better combustion under pressure.
  - Level indicates the amount of pressure a HC can withstand before self-ignition.
  - Octane levels are defined relative to iso-octane.
  - As there can be more pressure resistant HCs, octane levels >100 ok for them.
  - E.g.: Methane has octane number 120.

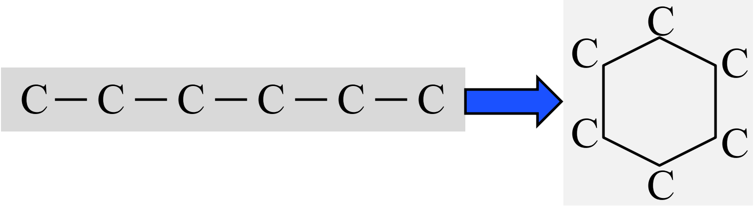


Iso-octane

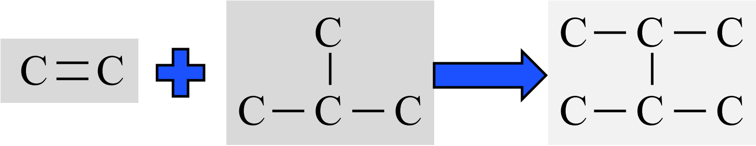
- **Isomerization** is changing the geometry of the molecule.
  - This increase the octane level.



- **Reforming** is obtaining cyclic HCs from chains.

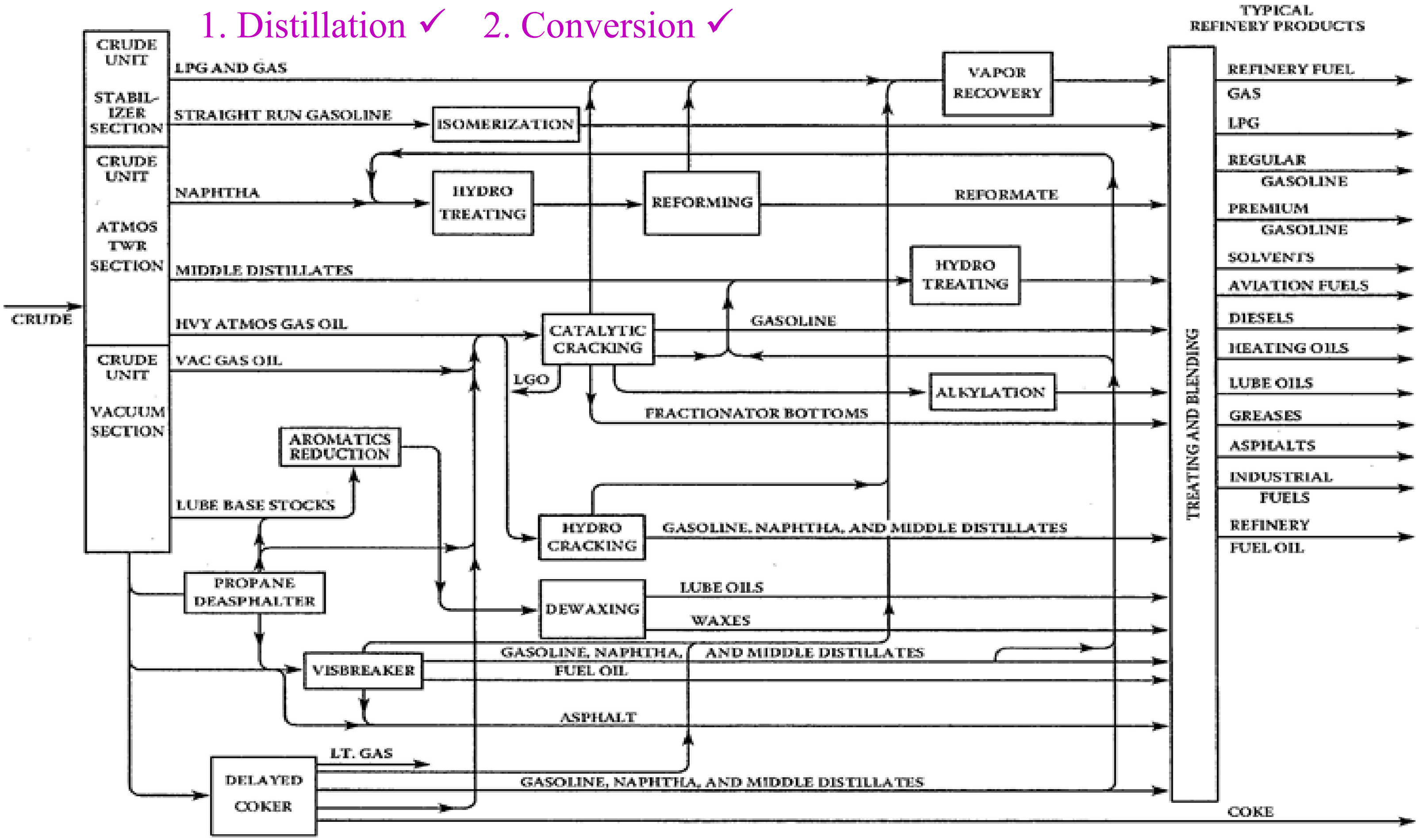


- **Alkylation** is obtaining alkanes (saturated) HCs from non-saturated ones.
  - This yields larger molecules with higher octane levels.



# 3. Treating

1. Distillation ✓ 2. Conversion ✓



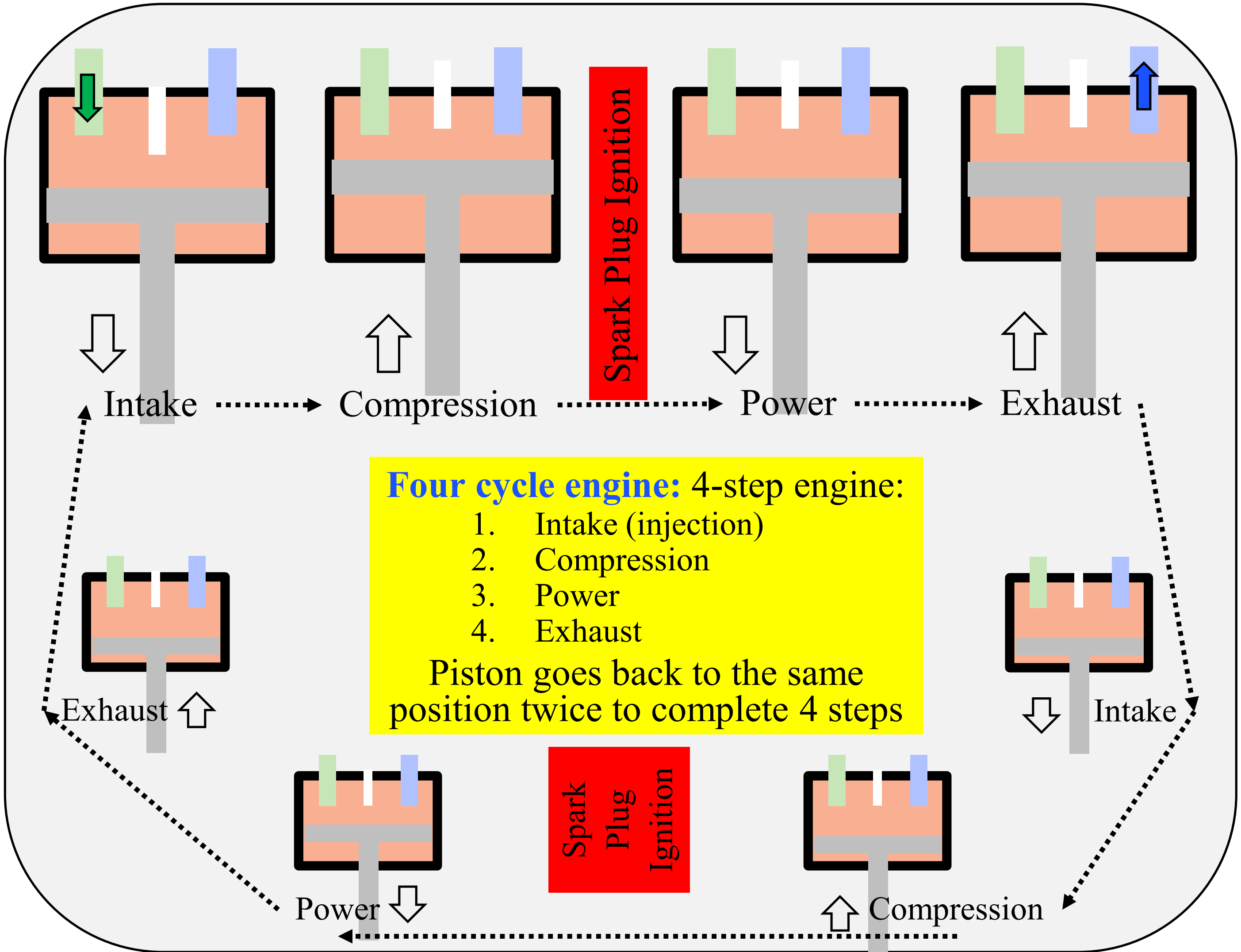
**3. Treatment**: Preparation of HCs and finished products by using chemical / physical separation.

- Removing unwanted substances: Salt, Suplhur, nitrogen, oxygen, metals (lead, mercury)
  - Desalting
  - Hydrodesulfurization: Sulfur removal yields elemental sulfur that is used in agriculture (as fertilizer) and in pharmaceuticals. Some sulfur can remain in fuel oil and coke.
- Dewaxing to avoid solidification under low temperature and to improve gasoline flow in winters.

# 4. Blending

1. Distillation ✓ 2. Conversion ✓ 3. Treating ✓

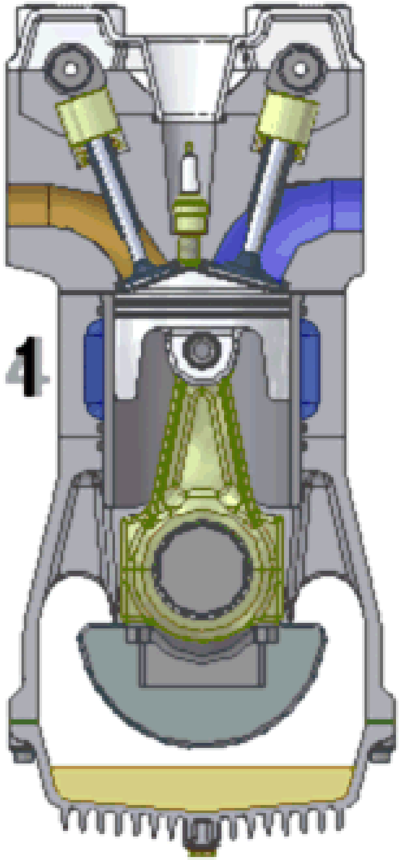
4. Blending: Mixing of HCs in certain fractions to obtain finished products with specific properties.



**Four cycle engine:** 4-step engine:

1. Intake (injection)
2. Compression
3. Power
4. Exhaust

Piston goes back to the same position twice to complete 4 steps



# 4. Blending for Specific Properties

Ignition Properties:

- Octane level: Gasoline mostly has octane $C_8H_{18}$ and some heptane $C_7H_{16}$ & others.
  - Gasoline with octane number 90 has the same combustion properties as 90% iso-octane and 10% heptane.
  - Similarly octane number 80 indicates the same combustion properties as 80% octane and 20% heptane.
  - High octane rating ⇒ smooth & sustained combustion with less combustible gas to avoid knocking
    - » Knocking: Self-Ignition of gasoline on its own before spark plug ignition.
      - Self-ignition is more likely if the pressure on the gasoline is high
      - The pressure on the gasoline is high in engines with high compression ratio
      - Compression ratio $= \frac{\text{Highest volume of an engine block}}{\text{Lowest volume of the engine block}}$
      - Sport cars: high compression ratio engines to obtain more power ⇒ high risk of self-ignition
        - Sport cars need less combustible gasoline, which is high octane gasoline
- RVP (Reid Vapor Pressure) measures the surface pressure to keep a liquid (gasoline) from vaporizing. Liquid gasoline is hard to burn. Spraying charcoal igniter liquid on barbeque ok, if the liquid is cold.
  - High RVP ⇒ Liquid vaporizes easily. Low RVP ⇒ Liquid does not vaporize easily
  - A fuel injector sprays gasoline & oxygen at the right mix and pressure into the engine block for combustion.
    - » Injector needs 6-12 psi RVP;
  - Temperature ↓ ⇒ RVP ↑
    - » RVP of 12 psi for Fargo, North Dakota in winters; less RVP, gasoline remains as liquid and does not burn.
    - » RVP of 6 psi for Dallas in summers; more RVP, gasoline vaporizes while pumping
  - EPA wants less RVP to reduce evaporative emissions. The limits are stricter during the summer ozone season.

Corrosion Properties:

- Sulphur level: Crude with > 0.5% Sulphur is corrosive (sour).
- TAN (Total Acid Number) is the concentration of potassium hydroxide (KOH, a base) needed to neutralize the acid in the crude. Crude with TAN > 1 mg KOH/g is corrosive.

# 4. Blending Computations

4. Blending:

- Octane level:
  - Gasoline with different octane levels can be blended
  - 50-50 Blending of 90 octane gasoline with 80 octane gasoline yields 85 octane gasoline.
  - 20-80 Blending of 90 octane gasoline with 80 octane gasoline yields 82 octane gasoline.
    - $82 = (0.2)90 + (0.8)80$
  - Suppose we are selling mid-grade gasoline with 88 octane. In what proportions should we blend 90 octane gasoline and 80 octane gasoline to obtain 88 octane gasoline?
    - $88 = 90x + 80(1-x)$ gives $x = 0.8$.

- These linear blending computations are assumed to be valid for sulfur content, TAN & RVP, i.e., for a characteristic $C_{blend}$, we obtain it from the characteristic $C_i$ of the ingredient $i$ by using volume (or weight) $V_i$.
  - Take a weighted average of characteristics where weights can be relative volumes (weights)

$$C_{blend} = \sum_{i \in \text{Ingredient}} \left( \frac{V_i}{\sum_{j \in \text{Ingredient}} V_j} \right) C_i$$

  - There also is a nonlinear but more exact formula for RVP: $RVP_{blend} = \left( \sum_i \frac{V_i}{\sum_j V_j} RVP_i^{1.25} \right)^{\frac{1}{1.25}}$
  - The nonlinear blending equation above is suggested by William Jackson, Merit 18.

# Blending then and now: Preference for Alcohol over Lead in the Engines

*More hands are pumping*

**ETHYL GASOLINE**

*than any other motor fuel*

EVERY fifth hand you see pumping gasoline is at an Ethyl pump. On the market only eight years, Ethyl Gasoline is now the biggest selling motor fuel in the country.

For instance: On Route 42 between Cincinnati and Cleveland a recent survey showed 589 Ethyl pumps, more than one-fifth of the total 2359. The next largest selling gasoline on this road had 211 pumps.

Nothing could have brought this about in so short a time except the simple fact that Ethyl is *more* than gasoline. It is *good* gasoline *plus* Ethyl fluid, the ingredient that *controls combustion*.

Instead of exploding in sharp, irregular bursts (that cause power-waste, harmful knock and overheating) Ethyl Gasoline delivers power to the pistons with a smoothly increasing pressure.

Millions of car owners, driving cars of every size, age and make, have found from experience that controlled combustion makes their cars run better.

Try Ethyl in your car and see the improvement it makes. Ethyl Gasoline Corporation, New York City.

WITH ETHYL BRAND OF ANTI-KNOCK COMPOUND ETHYL GASOLINE CORPORATION NEW YORK, U.S.A.

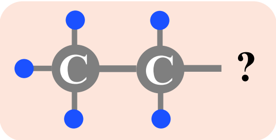
Controls Combustion

The Ethyl emblem on any pump stands for tested gasoline of Ethyl quality. Constant inspection of gasoline from Ethyl pumps throughout the country guards this standard. Ethyl Gasoline is always colored red. © E. G. C. 1931.

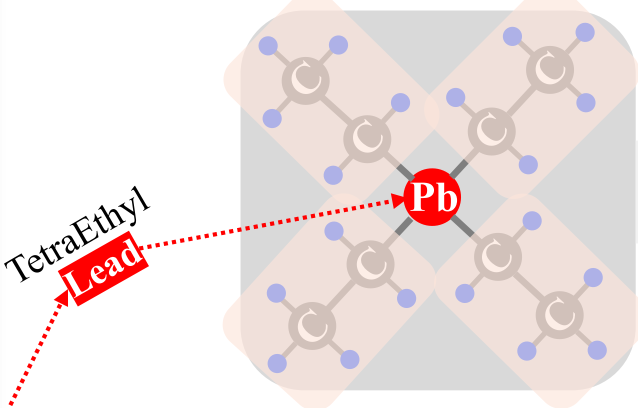
**ETHYL GASOLINE**

*The active ingredient used in Ethyl fluid is lead.*

- Ethyl Cooperation (www.ethyl.com) founded in 1923 ran ads like the one on left. This ad is from National Geographic 1931 – 8 years after Ethyl's founding.
- The "Ethyl Fluid" mentioned in the ad is to
  - "deliver power … with a smoothly increasing pressure"
  - rather than "sharp, irregular bursts (that cause power-waste, harmful knock and overheating)"
- Ethyl component $CH_3CH_2 - [?]$ has an open bond to connect with [?]



- Lead Pb (Plumbum in latin) in "Ethyl Fluid" of then.



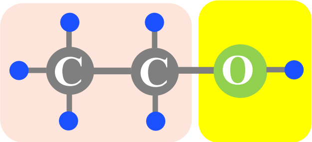
− Lead is toxic

+ But radiation shield

- Gasoline is lead-free now in most countries.
- Now Ethyl alcohol (octane number 108) is blended with gasoline up to 25% in Brazil & 10 % in the USA.

Ethanol = Ethyl Alcohol

$= CH_3CH_2OH$



# Refinery Operations and Yields

I. Crude oil receipt and operations
   1. Mix
   2. Desalt

II. Refining operations
   1. Distillation
      a) Atmospheric
      b) Vacuum
   2. Conversion
      a) Cracking
         i. Thermal Cracking: Steam-cracking, Coking, Visbreaking
         ii. Catalytic cracking: Fluid catalytic cracking, Hydro cracking
      b) Reforming
         i. Isomerization
         ii. Reforming
      c) Combining (Alkylation)
   3. Treating
      a) Desalt
      b) Hydrodesulfurization
      c) Dewax
   4. Blending

III. Final product storage and shipment

- Refinery yields in US in 2003:
  - 46.9% Gasoline
  - 23.7% Distillate fuel oil (inc. Diesel)
  - 4.2% Residual fuel oil (heating & ship fuel)
  - 9.5% Jet Fuel
  - 5.1% Coke
  - 3.2% Asphalt
  - 4.2% Liquefied gas

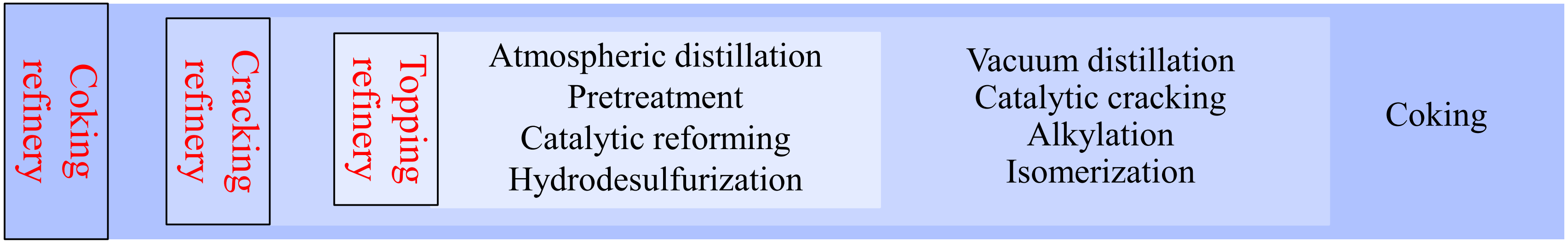
- Refinery yields in Europe p.168 of GOGI:
  - 21% Gasoline + 6% Naphta
  - 36% Distillate fuel oil
  - 19% Residual fuel oil
  - 6% Kerosene used in Jet Fuel
  - 9% Residuals like Asphalt
  - 3% Petroluem gas like Liquefied gas

More gasoline in US. More Diesel & Fuel oil in Europe.

# Refinery Markets:

## Capacity, Cost, Investment

# Refinery Characteristics: Types and Products



Coking refinery

Cracking refinery

Topping refinery

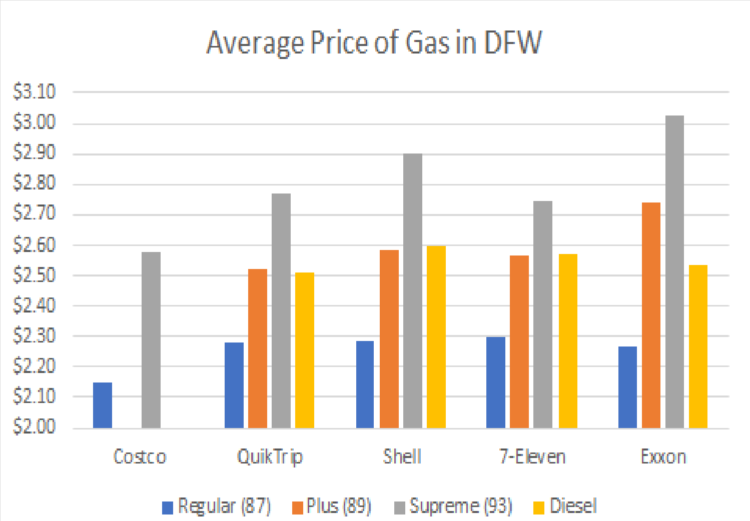
Atmospheric distillation
Pretreatment
Catalytic reforming
Hydrodesulfurization

Vacuum distillation
Catalytic cracking
Alkylation
Isomerization

Coking

- Simple refineries have low margins and are owned by small & niche companies.
- Complex refineries have higher margins.
  - Their margins ↑ when the spread (light sweet crude price − heavy sour crude price) ↑
- Refinery outputs are commodities: Middle distillates (Gasoline); Middle distillates (diesel fuel, jet fuel, heating oil); Other products (lubricants, wax, solvents, machine oils)
  - Output markets are more segmented by location, regulation, season, quality.
  - Product prices are related to crude prices whose prices are volatile.
  - Product prices are volatile as demand is inelastic in the short-term.

| Study | Product | Short-term elasticity | Long-term elasticity |
|---|---|---|---|
| Dahl & Sterner 1991 | Gasoline | 0.26 | 0.86 |
| Espey 1998 | Gasoline | 0.26 | 0.58 |
| Graham & Glaister 2004 | Gasoline | 0.25 | 0.77 |
| Brons et al. 2008 | Gasoline | 0.34 | 0.84 |
| Dahl 1993 | Oil | 0.07 | 0.30 |
| Cooper 2003 | Oil | 0.05 | 0.21 |



Averages are over 8 weeks in Fall 2017.
Source: S. Chen, S. Chordiya, Q. Le, S. Ouseph, A. Zacheis. 2017. Factors Affecting Gas Prices. DemReMan Project Report.

# Refining Characteristics: Margins

- Refineries, capital-intensive, long lifetime, very specific physical assets
  - Cost of a refinery: Equipment and buildings, next page
  - High initial investment and exposure to financial risk: interest rate, investment cycle, crude cost.
  - Gross margin = Revenues from product sales – Cost of crude was $8.68 per barrel in 2004.
  - Net Margin = Gross margin – Cost of (marketing + internal energy + operating) was $3 per barrel in 2004.
  - Booms and Busts: Profitability of refinery peaked in 1988 and 2001: 15%. It plunged to -1.7% in 2002.

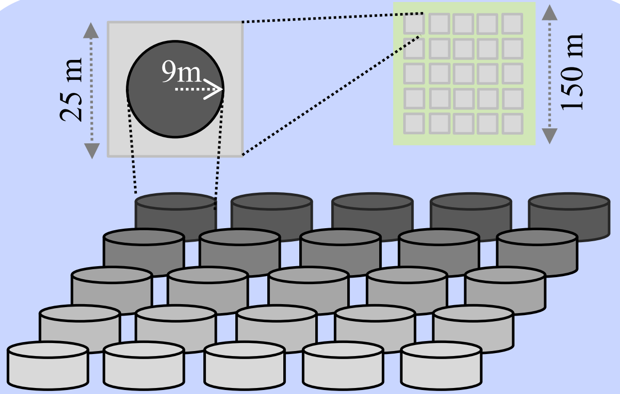
| Complexity | US Capacity | Gross Margin $/barrel | Net Margin $/barrel |
|---|---|---|---|
| Topping | 5.6% | 0.5 to 1.5 | -0.5 to 1.5 |
| Cracking | 28.7% | 3 to 4.5 | 0 to 2.5 |
| Coking | 65.7% | 5 to 7 | 0.5 to 4 |

- Refining is energy intensive.
  - US refining consumed 6.4 quads ($10^{15}$) BTU in 2004. This is 28% of energy consumption in US manufacturing.
    - US Department of Energy, Office of Industrial Technologies, Manufacturing Energy Consumption Survey, August 2004.
  - 30-40% of refining energy is spent on distillation.
  - 20% spent on hydrotreating (removal of sulfur, nitrogen, oxygen and metals).
  - Close to 60% of operating expenses are for the energy.
- Crudes are becoming heavy and sour (high-sulfur).
  - Recent capacity expansion of US refineries is to provide bottom-of-the-barrel processing to handle heavy crude.
  - This is profitable and required by environmental regulations.
    - Cracking refineries are becoming coking refineries over time with the capacity and process expansions.

# Investment Cost for a Refinery in 1994 by Major Equipment Estimates

- BPSD (barrels per stream day): max # of barrels of input a distillation unit can process
- Onsite facilities of a refinery cost: $ 82,976 K

| Unit | Capacity | Cost in K$ |
|---|---|---|
| Desalter | 30,000 BPSD | 1,800 |
| Atmospheric distillation | 30,000 BPSD | 27,000 |
| Vacuum distillation | 18,000 BPSD | 14,500 |
| Naphtane desulfurization | 4,000 BPSD | 6,600 |
| Reforming | 3,000 BPSD | 11,000 |
| Catalytic reformation | - | 600 |
| Cold water | 8,240 gallons/min | 824 |
| Steam | 30,900 pound/hr | 2,472 |
| Storage | 12 day thruput | 18,000 |



2290 m$^3$=Volume of tank height 9 m, radius 9 m

57,143 m$^3$ = 25 tanks each with 2,290 m$^3$

57,143 m$^3$ $\leq$ 3 tanks with 20,000 m$^3$

1 m$^3$ = 6.3 barrels, 360,000 barrels = 57,143 m$^3$

360,00 gallons in 150 x 150 m$^2$

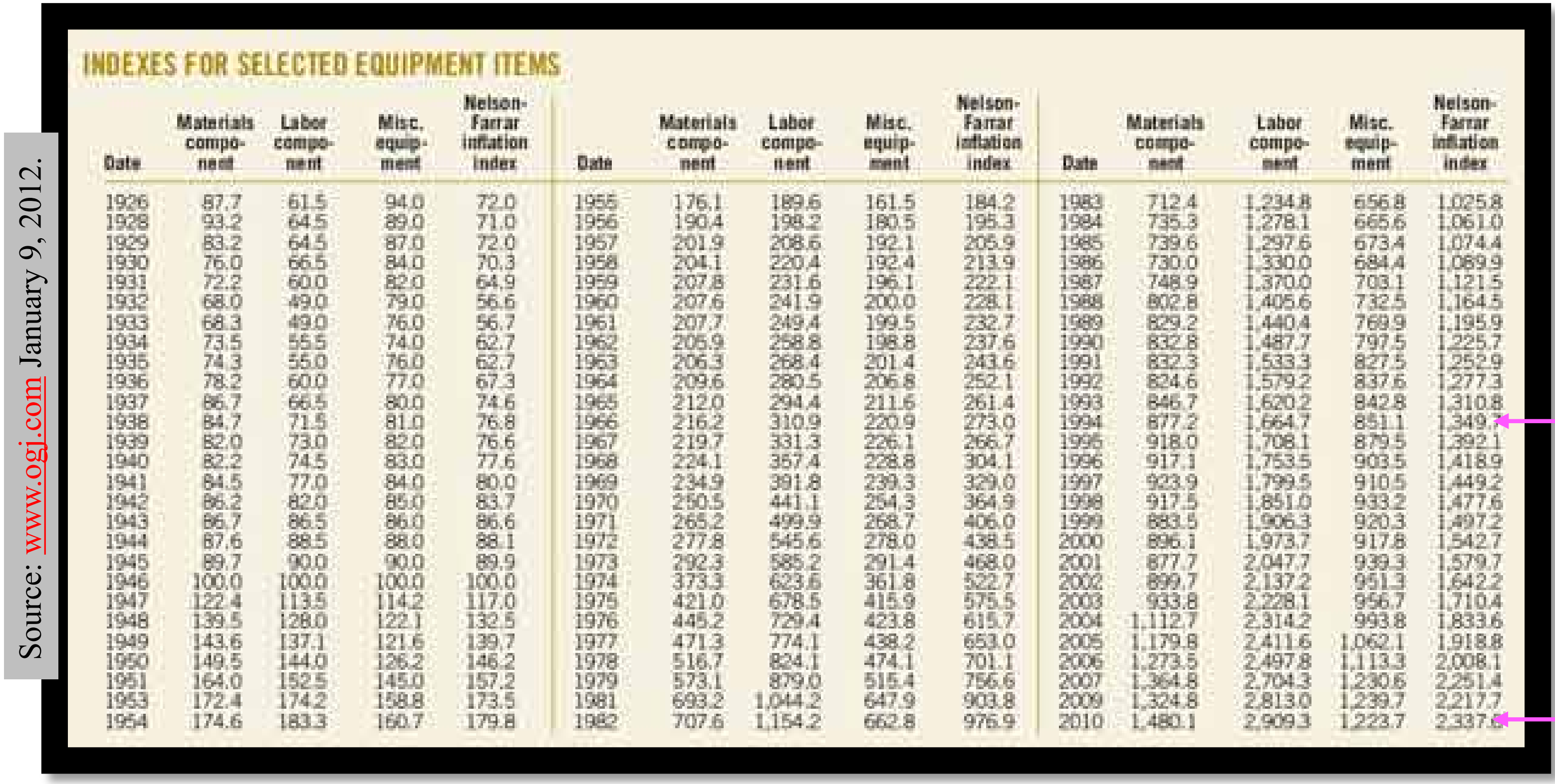
Storing 360,000 = 12 ∗ 30,000 barrels at the cost of \$50/bbl

- Offsite facilities: Electric power distribution; Fuel oil and fuel gas facilities; Water supply, treatment, disposal; Plant air systems; Fire protection systems; Flare, drain and waste containment systems; Plant communication systems; Roads and walks; Railroads; Buildings.
  - For a midsize refinery offsite costs are 30% of onsite facility cost.
  - Offsite facilities cost: \$ 24,893 = 82976 ∗ 0.3 K.
- Location factor: Location determines climate (affects design & construction costs), local rules & taxes.
  - US Gulf coast refineries are relatively cheaper and have location factor of 1.0.
  - St. Louis has a factor of 1.4. Alaska North Slope has a factor of 3.0.
- Contingencies: 15% allowance for major loopholes and inaccuracies.

Source: Cost Estimation. Chapter 17. Petroleum Refining: Technology and Economics, 3rd ed. by J.H. Gary, and G.E. Handwerk 1994.

# Take Inflation Factor into Account

- Cost of a midsize refinery in St. Louis in 1994 was about $174 million.
  - (82,976) (1.3) (1.4) (1.15) = 173,582
- We have found the cost of a simple refinery to be $174 million in 1994. To bring it to 2010 use:



Source: www.ogj.com January 9, 2012.

INDEXES FOR SELECTED EQUIPMENT ITEMS

| Date | Materials component | Labor component | Misc. equipment | Nelson-Farrar inflation index | Date | Materials component | Labor component | Misc. equipment | Nelson-Farrar inflation index | Date | Materials component | Labor component | Misc. equipment | Nelson-Farrar inflation index |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1926 | 87.7 | 61.5 | 94.0 | 72.0 | 1955 | 176.1 | 189.6 | 161.5 | 184.2 | 1983 | 712.4 | 1,234.8 | 656.8 | 1,025.8 |
| 1928 | 93.2 | 64.5 | 89.0 | 71.0 | 1956 | 190.4 | 198.2 | 180.5 | 195.3 | 1984 | 735.3 | 1,278.1 | 665.6 | 1,061.0 |
| 1929 | 83.2 | 64.5 | 87.0 | 72.0 | 1957 | 201.9 | 208.6 | 192.1 | 205.9 | 1985 | 739.6 | 1,297.6 | 673.4 | 1,074.4 |
| 1930 | 76.0 | 66.5 | 84.0 | 70.3 | 1958 | 204.1 | 220.4 | 192.4 | 213.9 | 1986 | 730.0 | 1,330.0 | 684.4 | 1,089.9 |
| 1931 | 72.2 | 60.0 | 82.0 | 64.9 | 1959 | 207.8 | 231.6 | 196.1 | 222.1 | 1987 | 748.9 | 1,370.0 | 703.1 | 1,121.5 |
| 1932 | 68.0 | 49.0 | 79.0 | 56.6 | 1960 | 207.6 | 241.9 | 200.0 | 228.1 | 1988 | 802.8 | 1,405.6 | 732.5 | 1,164.5 |
| 1933 | 68.3 | 49.0 | 76.0 | 56.7 | 1961 | 207.7 | 249.4 | 199.5 | 232.7 | 1989 | 829.2 | 1,440.4 | 769.9 | 1,195.9 |
| 1934 | 73.5 | 55.5 | 74.0 | 62.7 | 1962 | 205.9 | 258.8 | 198.8 | 237.6 | 1990 | 832.8 | 1,487.7 | 797.5 | 1,225.7 |
| 1935 | 74.3 | 55.0 | 76.0 | 62.7 | 1963 | 206.3 | 268.4 | 201.4 | 243.6 | 1991 | 832.3 | 1,533.3 | 827.5 | 1,252.9 |
| 1936 | 78.2 | 60.0 | 77.0 | 67.3 | 1964 | 209.6 | 280.5 | 206.8 | 252.1 | 1992 | 824.6 | 1,579.2 | 837.6 | 1,277.3 |
| 1937 | 86.7 | 66.5 | 80.0 | 74.6 | 1965 | 212.0 | 294.4 | 211.6 | 261.4 | 1993 | 846.7 | 1,620.2 | 842.8 | 1,310.8 |
| 1938 | 84.7 | 71.5 | 81.0 | 76.8 | 1966 | 216.2 | 310.9 | 220.9 | 273.0 | 1994 | 877.2 | 1,664.7 | 851.1 | 1,349.7 |
| 1939 | 82.0 | 73.0 | 82.0 | 76.6 | 1967 | 219.7 | 331.3 | 226.1 | 266.7 | 1995 | 918.0 | 1,708.1 | 879.5 | 1,392.1 |
| 1940 | 82.2 | 74.5 | 83.0 | 77.6 | 1968 | 224.1 | 357.4 | 228.8 | 304.1 | 1996 | 917.1 | 1,753.5 | 903.5 | 1,418.9 |
| 1941 | 84.5 | 77.0 | 84.0 | 80.0 | 1969 | 234.9 | 391.8 | 239.3 | 329.0 | 1997 | 923.9 | 1,799.5 | 910.5 | 1,449.2 |
| 1942 | 86.2 | 82.0 | 85.0 | 83.7 | 1970 | 250.5 | 441.1 | 254.3 | 364.9 | 1998 | 917.5 | 1,851.0 | 933.2 | 1,477.6 |
| 1943 | 86.7 | 86.5 | 86.0 | 86.6 | 1971 | 265.2 | 499.9 | 268.7 | 406.0 | 1999 | 883.5 | 1,906.3 | 920.3 | 1,497.2 |
| 1944 | 87.6 | 88.5 | 88.0 | 88.1 | 1972 | 277.8 | 545.6 | 278.0 | 438.5 | 2000 | 896.1 | 1,973.7 | 917.8 | 1,542.7 |
| 1945 | 89.7 | 90.0 | 90.0 | 89.9 | 1973 | 292.3 | 585.2 | 291.4 | 468.0 | 2001 | 877.7 | 2,047.7 | 939.3 | 1,579.7 |
| 1946 | 100.0 | 100.0 | 100.0 | 100.0 | 1974 | 373.3 | 623.6 | 361.8 | 522.7 | 2002 | 899.7 | 2,137.2 | 951.3 | 1,642.2 |
| 1947 | 122.4 | 113.5 | 114.2 | 117.0 | 1975 | 421.0 | 678.5 | 415.9 | 575.5 | 2003 | 933.8 | 2,228.1 | 956.7 | 1,710.4 |
| 1948 | 139.5 | 128.0 | 122.1 | 132.5 | 1976 | 445.2 | 729.4 | 423.8 | 615.7 | 2004 | 1,112.7 | 2,314.2 | 993.8 | 1,833.6 |
| 1949 | 143.6 | 137.1 | 121.6 | 139.7 | 1977 | 471.3 | 774.1 | 438.2 | 653.0 | 2005 | 1,179.8 | 2,411.6 | 1,062.1 | 1,918.8 |
| 1950 | 149.5 | 144.0 | 126.2 | 146.2 | 1978 | 516.7 | 824.1 | 474.1 | 701.1 | 2006 | 1,273.5 | 2,497.8 | 1,113.3 | 2,008.1 |
| 1951 | 164.0 | 152.5 | 145.0 | 157.2 | 1979 | 573.1 | 879.0 | 515.4 | 756.6 | 2007 | 1,364.8 | 2,704.3 | 1,230.6 | 2,251.4 |
| 1953 | 172.4 | 174.2 | 158.8 | 173.5 | 1981 | 693.2 | 1,044.2 | 647.9 | 903.8 | 2009 | 1,324.8 | 2,813.0 | 1,239.7 | 2,217.7 |
| 1954 | 174.6 | 183.3 | 160.7 | 179.8 | 1982 | 707.6 | 1,154.2 | 662.8 | 976.9 | 2010 | 1,480.1 | 2,909.3 | 1,223.7 | 2,337.6 |

- Cost in year (t) = [Cost in year (s)] * [Index in year (t) / Index in year (s)]
- Cost in year 2010 = [Cost in year 1994] * [2,337.6 / 1,349.7] = 174 * 1.732 = $ 301.36 Million.
- If this refinery were to be built in Alaska North Slope, the cost would be

$$= 301.36 * \left[\frac{\text{Location factor in North Slope}}{\text{Location factor in St.Louise}}\right] = 301.36 * \left[\frac{3}{1.4}\right] = \$\,646 \text{ Million.}$$

# Cost of Capacity ⇒ Complexity

- Cost of a $q$ =30,000 BPSD refinery in Alaska in 2010 has been found to be $ 646 Million.
- The cost increases but does not double if we double the capacity. In particular,

$$\text{Cost of capacity } Q = \text{Cost of capacity } q * \left(\frac{Q}{q}\right)^{0.6}.$$

- Doubling the capacity in Alaska, the cost of refinery increases to 646 $(2)^{0.6}$ = $ 979 Million.
- A rough estimate of refinery cost is $15,000 for each BPSD.
  - Using this, the cost of a 60,000 BPSD refinery turns out to be $900 Million, similar to the detailed estimate obtained for the same size refinery in Alaska.
  - However, this rough estimate becomes $450 Million for a 30,000 BPSD refinery whose detailed cost estimate is $ 646 Million. The rough cost estimate can be inaccurate by about 50%.
- Complexity of a refinery can be defined in terms of complexity of its units.
  - Complexity of atmospheric distillation unit ← 1. This unit gives the most output (BPCD) per $ invested.

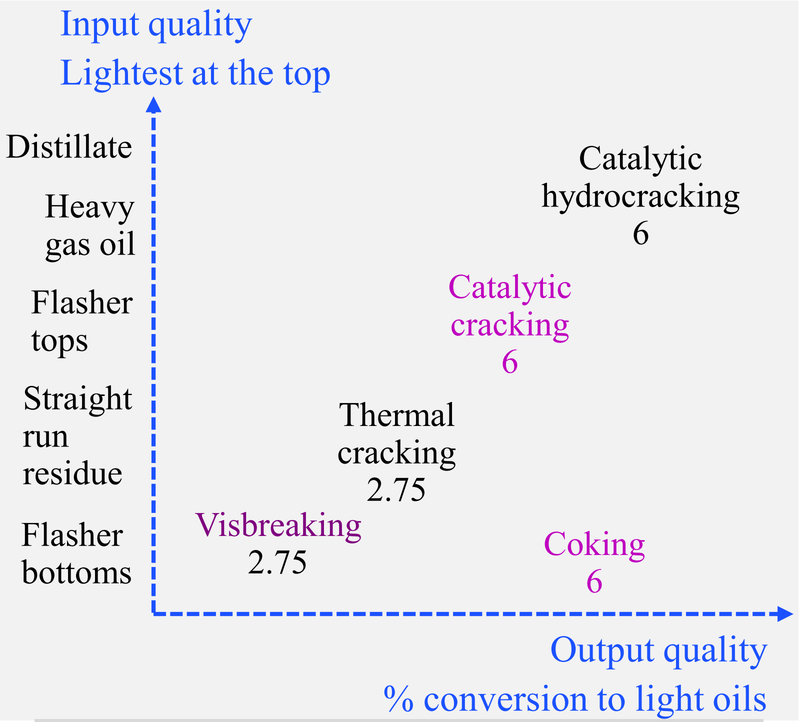
$$\text{Complexity of a unit} = \frac{\text{Cost of that unit per BPCD}}{\text{Cost of atmospheric distillation per BPCD}}$$

    - » If a 100,000 BPCD distillation unit costs $10 Million, the cost per BPCD is $100.
    - » If a 20,000 BPCD catalytic reforming unit costs $10 Million, the cost per BPCD is $500.
    - » Catalytic reforming is 500/100=5 times more complex than atmospheric distillation.
  - Some example complexities: Catalytic Hydrocracking 6; Alkylation 10; Isomerisation 15; Lubricants 60.
  - This complexity definition dates back to 1960s and was developed by W. Nelson.
  - Update is on the next page

# Empirical Complexity

| Refining unit | Complexity in 1998 |
|---|---|
| Atmospheric distillation | 1 |
| Vacuum distillation | 2 |
| Thermal cracking, visbreaking | 2.75 |
| Coking (delayed) | 6 |
| Catalytic cracking | 6 |
| Catalytic reforming | 5 |
| Catalytic hydrocracking | 6 |
| Catalytic hydrorefining | 3 |
| Catalytic hydrotrating | 2 |
| Alkylation | 10 |
| Polymerization | 10 |
| Aromatics | 15 |
| Isomerization | 15 |

Based on Table 3 of M.J. Kaiser. 2017. A review of refinery complexity applications. Petroleum Science (14): 167-194.



Input quality
Lightest at the top

Distillate
Heavy gas oil
Flasher tops
Straight run residue
Flasher bottoms

Catalytic hydrocracking
6

Catalytic cracking
6

Thermal cracking
2.75

Visbreaking
2.75

Coking
6

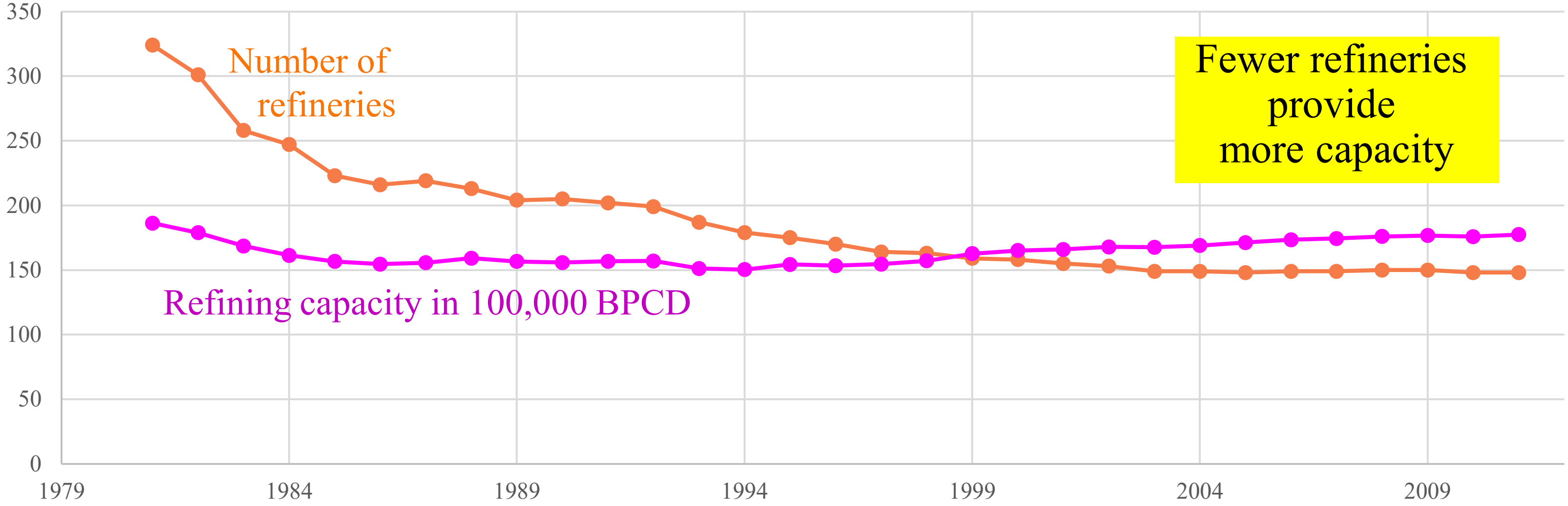
Output quality
% conversion to light oils

Cracking units by their input, output and complexity.
Based on Fig 13-5 of Leffler. 2018. Petroleum Refining.

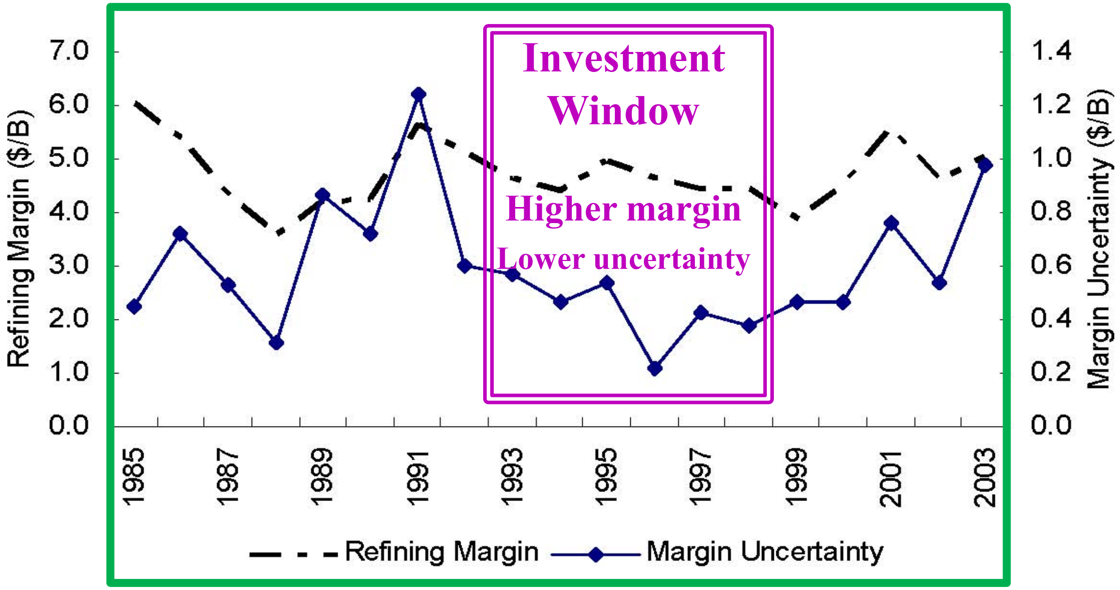
Inserted in response to Kanguk Cha, Merit 20

- US Refinery complexity by company in 2003:
  - Valero 13.4; Exxon 12.8; ChevronTexaco 12.3; BP 11.6; Citgo 11.4; Shell 11; Marathon 10.6; ConocoPhillips 10.3; Premcor 9.4; Sunoce 8.7; Tesore 8.5.
  - "Higher complexity allows Valero to process cheaper higher sulfur crudes while maintaining a highly desirable product slate. Higher complexity usually means more energy input per barrel of crude."
    - Source: Valero Energy Strategy. G. Faagau, Director, Energy Optimization, Valero Energy Corporation.

# When to Invest?



Fewer refineries provide more capacity



**Investment Window**

**Higher margin**

**Lower uncertainty**

**An increase in uncertainty decreases the probability a refinery adjusts its capacity.**

Source: T. Dunne and X. Mu. 2008. Investment Spikes and Uncertainty in the Petroleum Refining Industry. Working paper, Fed. Reserve Bank of Cleveland.

# US Refining Capacity and Structure

- US refining capacity (of Atmospheric Oil Distillation column)
  - was 19.4 million BPCD (Barrels per calendar day) in 1981.
  - is 17.7 million BPCD in 2011.
- Vacuum distillation capacity is 8.6 million BPCD. Thermal cracking capacity is 2.7 million BPCD. Catalytic hydro-cracking capacity is 1.9 million BPCD.
- Although the number of refineries significantly dropped from 324 in 1981 to 148 in 2011, the capacity did not.
  - Existing refineries expanded their capacities.
  - Expansion is more economic than a brand-new facility.
    - Economies of scale
    - Regulatory requirements are easier to overcome.

  - Top 3 US refineries process 36% of the crude oil; top 10 process 77%.
  - Concentrated ownership: There are fewer companies owning refineries now than before.
  - Diverse ownership: Vertically integrated major companies used to own most of refining capacity. Now midsize and independents are also involved in refining. Various ownership structures exist:
    - Holly Frontier (2828 N Harwood St, Dallas, TX 75201) is on its own and public.
    - Motiva enterprises (of Houston) 50-50 joint venture between Royal Dutch Shell & Saudi Refining.
    - Koch industries is privately owned.
    - ConocoPhillips is separating its production (upstream) from refining (downstream). Separation is expected to be completed in the second quarter of 2012. Downstream company will be called Phillips 66.
  - Regardless of ownership structure, refineries tend to be run as separate profit centers.

# Optimization of Refinery Operations

- Optimization of Refining Operations
  - Continuous processes → Continuous variables
- Optimization of Crude Oil Operations
  - Continuous crude inflow from a pipeline → Continuous variables
  - Discrete crude shipments as parcels → Discrete variables

# Optimization of a Refinery

- A simple refinery receives 20,000 barrels of crude A and 30,000 barrels of crude B.
- Crudes have 4 processes: Distillation (light & middle), reforming, cracking (regular & coking), blending.
- **Distillation** separates crudes into

| | Cycloalkanes | | | | | |
|---|---|---|---|---|---|---|
| **Output/ Input** | **Light Naphta** | **Medium Naphta** | **Heavy Naphta** | **Light Oil** | **Heavy Oil** | **Residuum** |
| Crude A | 0.10 | 0.20 | 0.20 | 0.12 | 0.20 | 0.13 |
| Crude B | 0.15 | 0.25 | 0.18 | 0.08 | 0.19 | 0.12 |

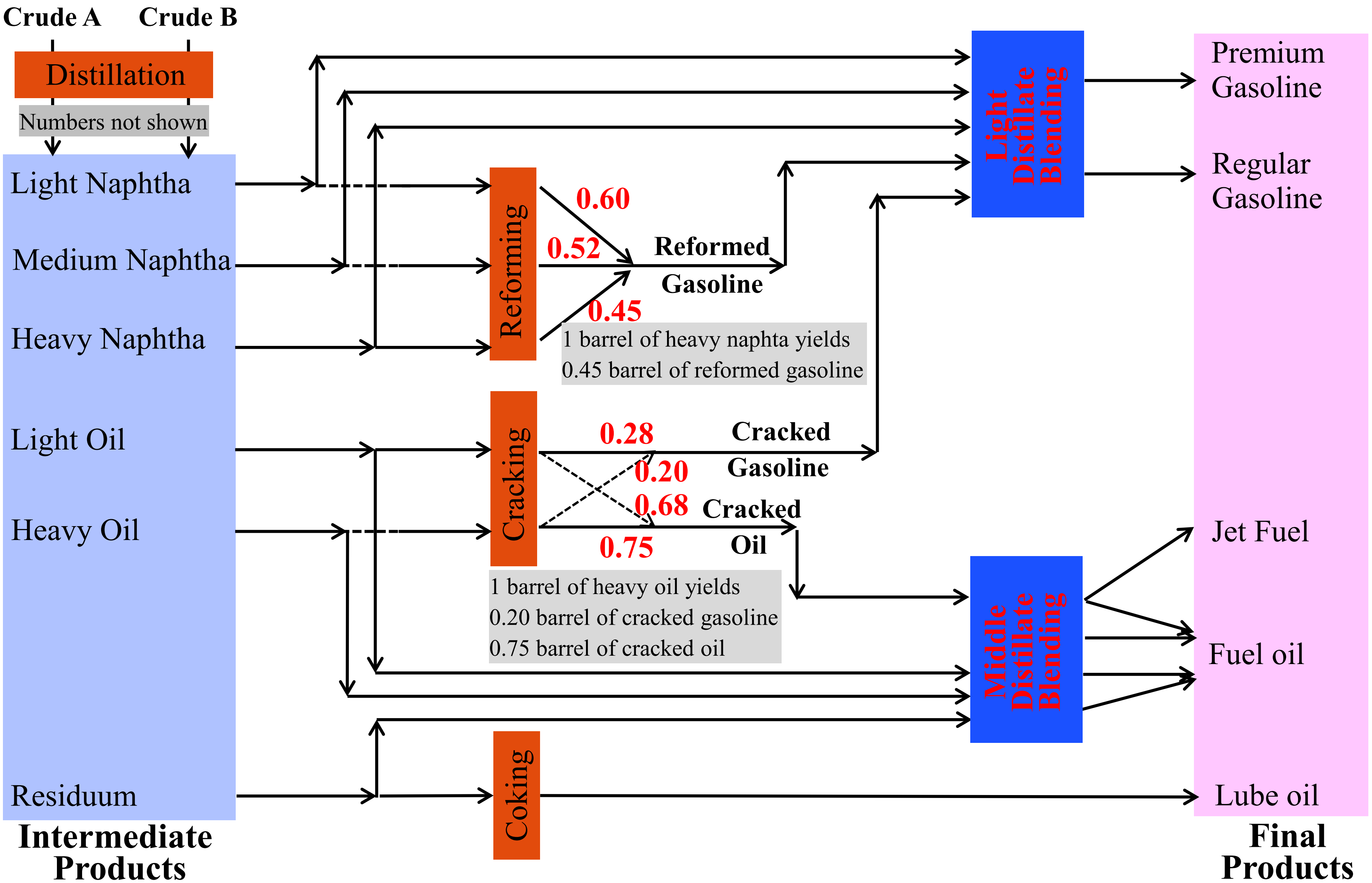
- Light, medium and heavy naphtas have octane numbers 70, 80, 90. Light ignites faster.
- **Naphtas** can be blended to produce refined products or can go to reforming.
  - Reforming's output is reformed gasoline with octane number 115. Yield of each barrel of naphta:

| | Light Naphta | Medium Naphta | Heavy Naphta |
|---|---|---|---|
| Reformed gasoline | 0.60 barrels | 0.52 barrels | 0.45 barrels |

- **Oils** can be blended to produce jet fuel/fuel oil or can go to cracker.
  - Cracker's output is cracked oil and cracked gasoline with octane number 105. Yield of each barrel of oil: E.g., 1 barrel of light oil yields 0.68 barrel of cracked oil and 0.28 barrel of cracked gasoline.

| | Light oil | Heavy Oil | Used for blending |
|---|---|---|---|
| Cracked oil | 0.68 | 0.75 | Fuel oil and jet fuel |
| Cracked gasoline | 0.28 | 0.20 | Gasoline |

# Processes Map and Yields Partial



Crude A
Crude B

Distillation

Numbers not shown

Light Naphtha
Medium Naphtha
Heavy Naphtha
Light Oil
Heavy Oil
Residuum

**Intermediate Products**

Reforming

0.60
0.52
0.45

**Reformed Gasoline**

1 barrel of heavy naphta yields
0.45 barrel of reformed gasoline

Cracking

0.28
0.20
0.68
0.75

**Cracked Gasoline**

**Cracked Oil**

1 barrel of heavy oil yields
0.20 barrel of cracked gasoline
0.75 barrel of cracked oil

Coking

**Light Distillate Blending**

**Middle Distillate Blending**

Premium Gasoline
Regular Gasoline
Jet Fuel
Fuel oil
Lube oil

**Final Products**

# Optimization of a Refinery

- **Residuum** can be used for producing lube oil or middle distillate blending in to jet fuel and fuel oil. Yield of each barrel of residuum is below.

| | Residuum |
|---|---|
| Lube oil | 0.50 |

- **Regular and premium** are two types of gasolines obtained by light distillate blending naphtas, reformed gasoline and cracked gasoline. Their octane numbers must be at least

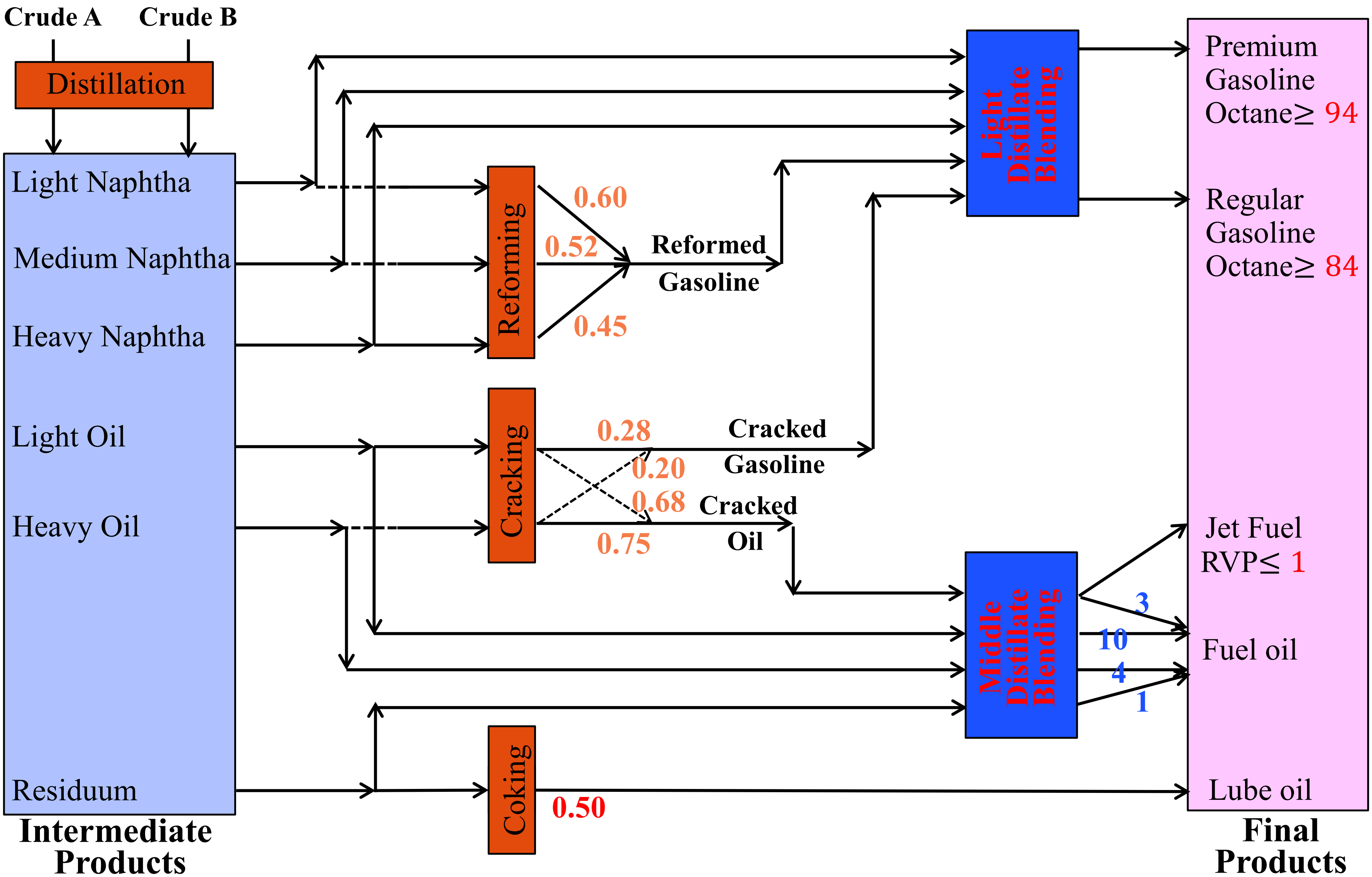
| | Regular gasoline | Premium gasoline |
|---|---|---|
| Octane number ≥ | 84 | 94 |

- **Jet fuel** is obtained by blending light, heavy, cracked oils and residuum. Its RVP (Reid Vapor Pressure) must be less than 1 kg/cm$^2$. The pressures of the inputs are as follows.

| | Light oil | Heavy oil | Cracked oil | Residuum |
|---|---|---|---|---|
| RVP | 1.0 | 0.6 | 1.5 | 0.05 |

- **Fuel oil** is obtained by blending cracked, light, heavy oil and residuum in the ratios of 3:10:4:1.
  - E.g., blending 3 barrels of cracked oil, 10 barrels of light oil, 4 barrels of heavy oil and 1 barrel of residuum results in 18 barrels of fuel oil.

# Processes Map and Yields Completed



**Crude A** **Crude B**

Distillation

Light Naphtha
Medium Naphtha
Heavy Naphtha
Light Oil
Heavy Oil
Residuum

**Intermediate Products**

Reforming
0.60
0.52
0.45
**Reformed Gasoline**

Cracking
0.28
0.20
0.68
0.75
**Cracked Gasoline**
**Cracked Oil**

Coking
0.50

Light Distillate Blending

Middle Distillate Blending
3
10
4
1

Premium Gasoline Octane≥ 94
Regular Gasoline Octane≥ 84
Jet Fuel RVP≤ 1
Fuel oil
Lube oil

**Final Products**

# Process Capacities, Limits and Prices

**Capacities:**

- **Distillation Capacity 45,000 barrels per day.**
- **Reforming capacity is 10,000 BPD.**
- **Cracking capacity is 8,000 BPD.**

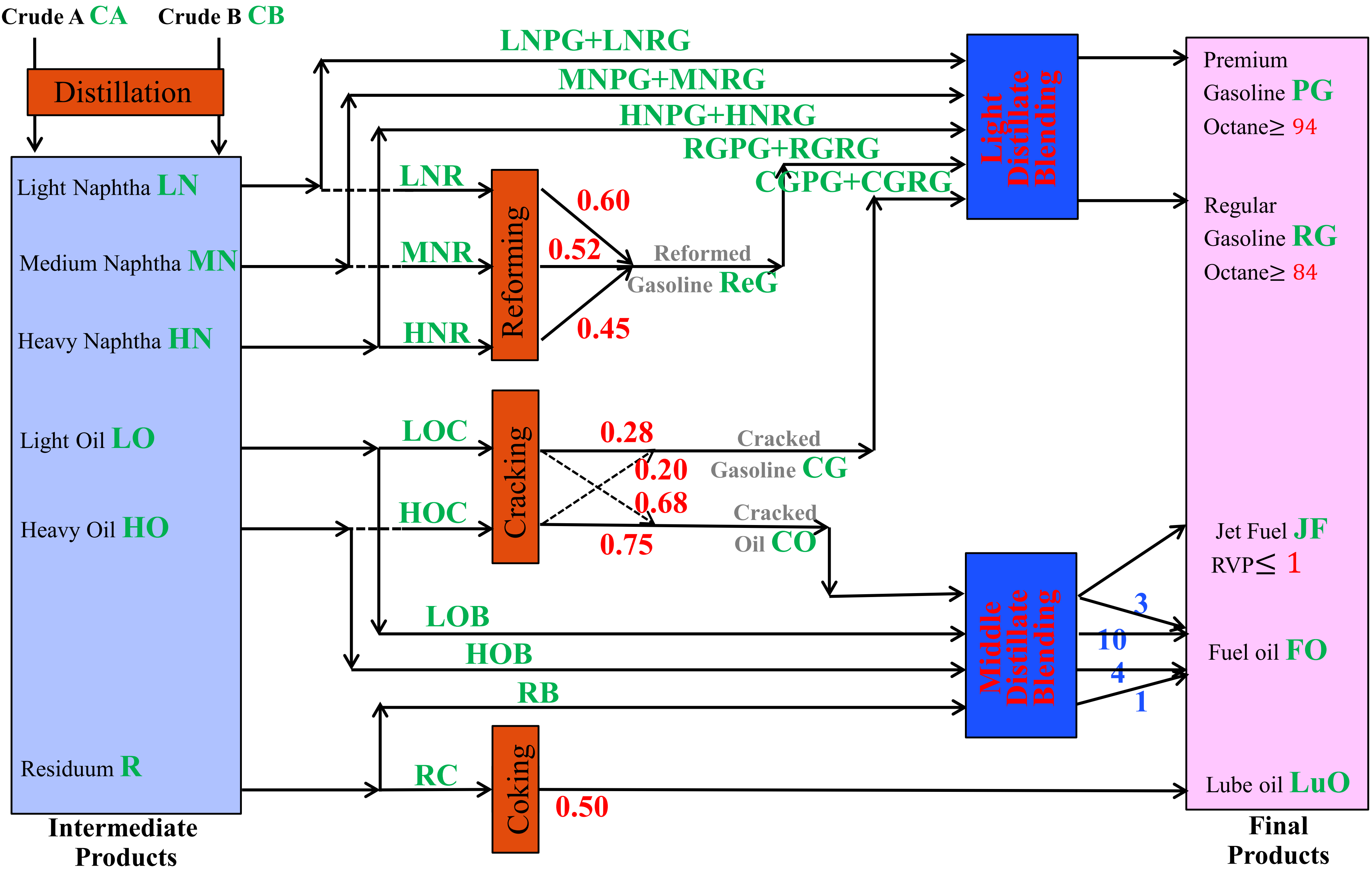
**Limits on the final products:**

- **Daily lube oil production must be between 500 and 1000 BPD.**
- **Premium gasoline production must be at least 40% of regular gasoline production.**

- **Refined product prices in $/barrel**

| Premium gasoline | Regular gasoline | Jet fuel | Fuel oil | Lube oil |
|---|---|---|---|---|
| 140 | 120 | 80 | 70 | 30 |

# Processes with Decision Variables



# Constraints

- **Contractual availability of crudes**

$$CA \leq 20{,}000$$
$$CB \leq 30{,}000$$

- **Process capacities**

$$CA + CB \leq 45{,}000 \text{ at distillation}$$

$$LNR + MNR + HNR \leq 10{,}000 \text{ at reforming}$$

$$LOC + HOC \leq 8{,}000 \text{ at cracking}$$

- **Daily lube oil production must be between 500 and 1000 BPD.**

$$LuO \leq 1{,}000$$
$$LuO \geq 5{,}000$$

- **Premium gasoline production must be at least 40% of regular gasoline production.**

$$PG \geq 0.4\ RG$$

# Constraints: Distillation

- **Distillation** separates crudes into light, medium, heavy naphta, light, heavy oil and residuum.

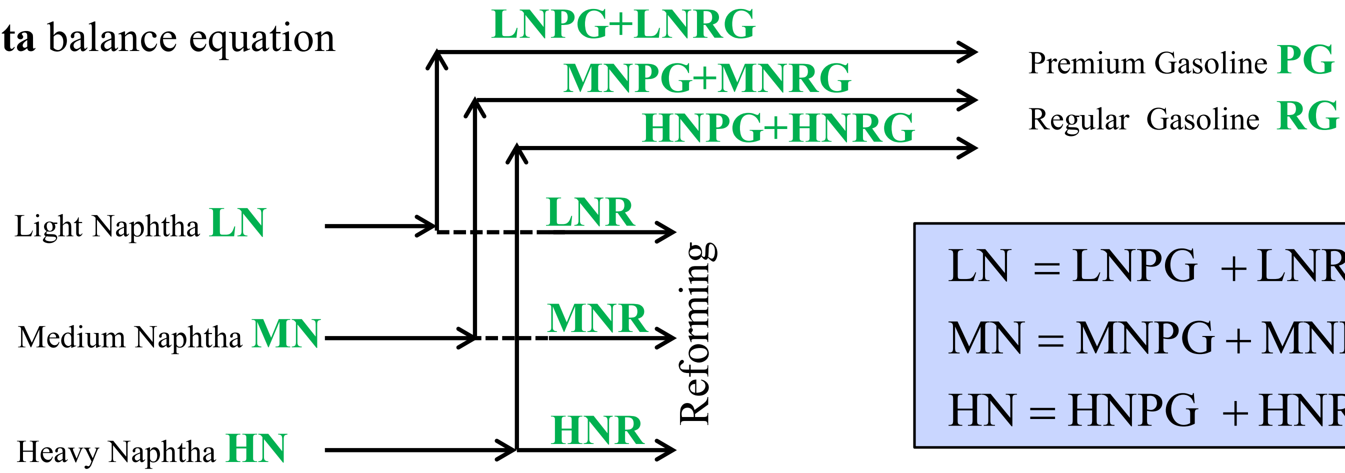
| | Light Naphta LN | Medium Naphta MN | Heavy Naphta HN | Light Oil LO | Heavy Oil HO | Residuum R |
|---|---|---|---|---|---|---|
| Crude A CA | 0.10 | 0.20 | 0.20 | 0.12 | 0.20 | 0.13 |
| Crude B CB | 0.15 | 0.25 | 0.18 | 0.08 | 0.19 | 0.12 |

| | CA | CB |
|---|---|---|
| LN | 0.10 | 0.15 |
| MN | 0.20 | 0.25 |
| HN | 0.20 | 0.18 |
| LO | 0.12 | 0.08 |
| HO | 0.20 | 0.19 |
| R | 0.13 | 0.12 |

$$\begin{aligned}
LN &= 0.10\,CA + 0.15\,CB;\\
MN &= 0.20\,CA + 0.25\,CB,\\
HN &= 0.20\,CA + 0.18\,CB,\\
LO &= 0.12\,CA + 0.08\,CB,\\
HO &= 0.20\,CA + 0.19\,CB,\\
R &= 0.13\,CA + 0.12\,CB.
\end{aligned}$$

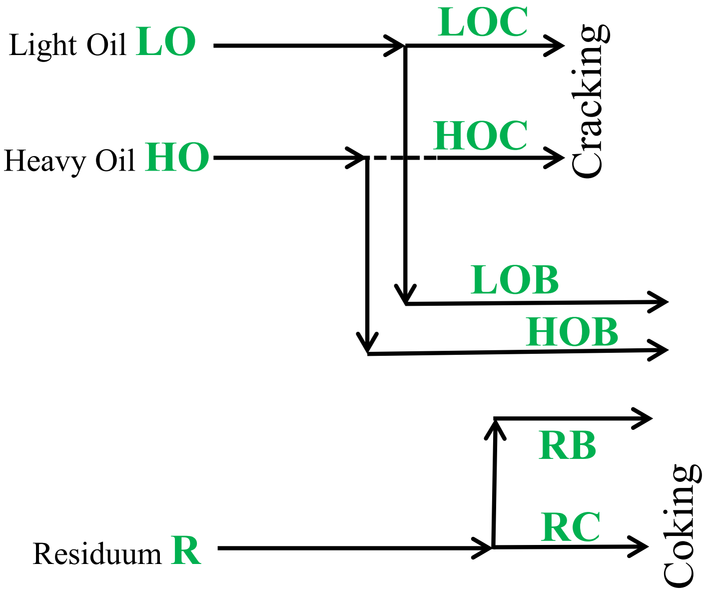
# Constraints: Naphta, Light, Heavy Oil, Residuum

- **Naphta** balance equation



$$
\begin{aligned}
LN &= LNPG + LNRG + LNR,\\
MN &= MNPG + MNRG + MNR,\\
HN &= HNPG + HNRG + HNR.
\end{aligned}
$$

- **Light, Heavy Oil and Residuum** balance equations

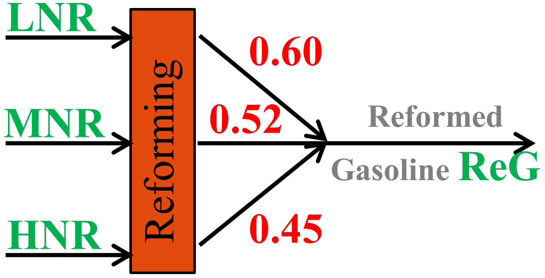


$$
\begin{aligned}
LO &= LOC + LOB,\\
HO &= HOC + HOB.
\end{aligned}
$$

$$R = RC + RB.$$

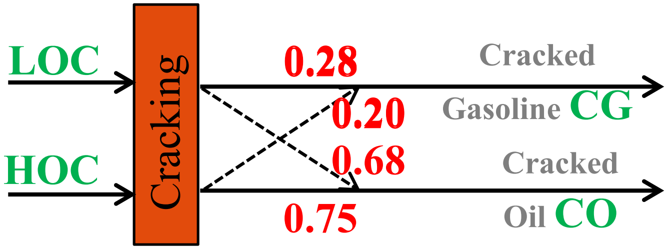
# Constraints:
# Process Balance Equations

- **Reforming** balance equations



$$ReG = 0.60\ LNR + 0.52\ MNR + 0.45\ HNR.$$

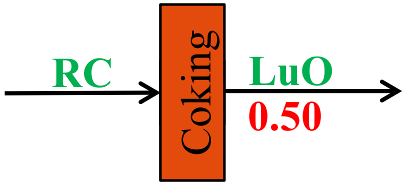
- **Cracking** balance equations



$$CG = 0.28\ LOC + 0.20\ HOC,$$

$$CO = 0.68\ LOC + 0.75\ HOC.$$

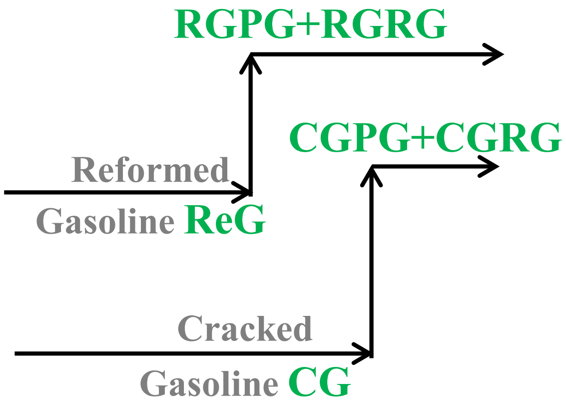
- **Coking** balance equations



$$LuO = 0.50\ RC.$$

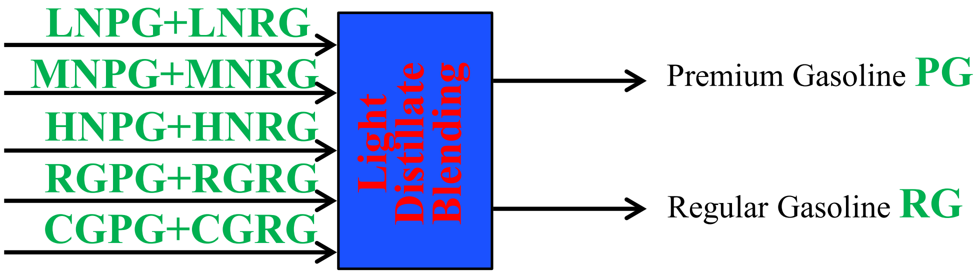
# Constraints: Light Distillate Blending

- **Reformed and Cracked Gasoline** balance equations



$$\begin{aligned} \text{ReG} &= \text{RGPG} + \text{RGRG}, \\ \text{CG} &= \text{CGPG} + \text{CGRG}. \end{aligned}$$

- **Light Distillate Blending**

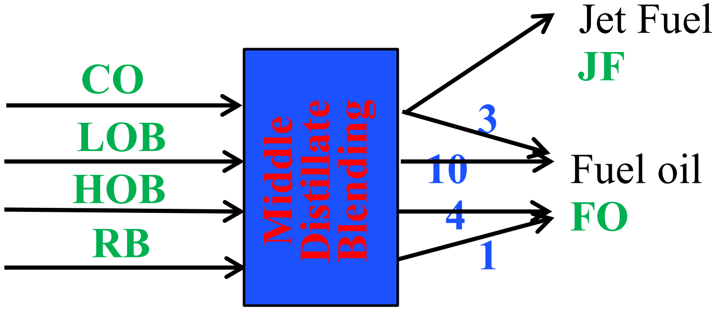


$$\begin{aligned} \text{PG} &= \text{LNPG} + \text{MNPG} + \text{HNPG} + \text{RGPG} + \text{CGPG}, \\ \text{RG} &= \text{LNRG} + \text{MNRG} + \text{HNRG} + \text{RGRG} + \text{CGRG}. \end{aligned}$$

# Constraints: Middle Distillate Blending Recipe for Fuel Oil

- **Middle Distillate Blending**

  - To produce 180 barrels of FO, we blend
    30 barrels of **C**racked **O**il,
    100 barrels of **L**ight **O**il to **B**lending,
    40 barrels of **H**eavy **O**il to **B**lending,
    10 barrels of **R**esiduum to **B**lending.



  - If we have,
    70 barrels of CO, 40 barrels extra goes into JF,
    110 barrels of LOB, 10 barrels extra goes into JF,
    40 barrels of HOB, 0 barrels extra goes into JF,
    60 barrels of RB, 50 barrels extra goes into JF.

  - Eventually, we produce 180 barrels of FO and 100 barrels of JF.

$$CO \geq \frac{3}{18}FO; \qquad LOB \geq \frac{10}{18}FO; \qquad HOB \geq \frac{4}{18}FO; \qquad RB \geq \frac{1}{18}FO;$$

$$JF = \left(CO - \frac{3}{18}FO\right) + \left(LOB - \frac{10}{18}FO\right) + \left(HOB - \frac{4}{18}FO\right) + \left(RB - \frac{1}{18}FO\right)$$

# Constraints:
# Octane and Vapor Pressure

- **Octane numbers**

  Light, medium and heavy naphtas have octane numbers 70, 80, 90.

  Reformed gasoline has octane number 115.

  Cracked gasoline has octane number 105.

| | Regular gasoline | Premium gasoline |
|---|---|---|
| Octane number ≥ | 84 | 94 |

$$\frac{LNRG}{RG}70+\frac{MNRG}{RG}80+\frac{HNRG}{RG}90+\frac{RGRG}{RG}115+\frac{CGRG}{RG}105\geq 84,$$

$$\frac{LNPG}{PG}70+\frac{MNPG}{PG}80+\frac{HNPG}{PG}90+\frac{RGPG}{PG}115+\frac{CGPG}{PG}105\geq 94.$$

- **Vapor pressure**

  Jet fuel RVP must be less than 1 kg/cm$^2$.

| | Light oil | Heavy oil | Cracked oil | Residuum |
|---|---|---|---|---|
| RVP | 1.0 | 0.6 | 1.5 | 0.05 |

$$\frac{LOB-(10/18)FO}{JF}1+\frac{HOB-(4/18)FO}{JF}0.6+\frac{CO-(3/18)FO}{JF}1.5+\frac{RB-(1/18)FO}{JF}0.05\leq 1.$$

# Objective

- **Maximize the revenue from final products** whose prices are $/barrel

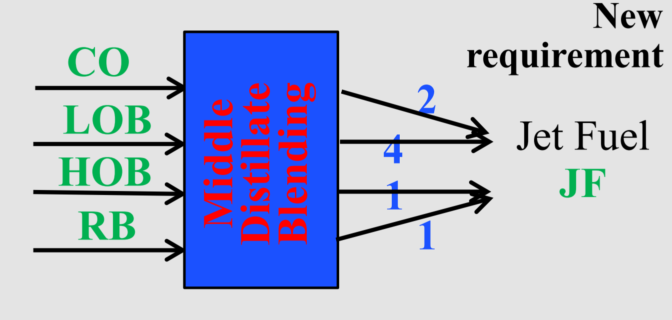
| **Premium gasoline** | **Regular gasoline** | **Jet fuel** | **Fuel oil** | **Lube oil** |
|---:|---:|---:|---:|---:|
| 140 | 120 | 80 | 70 | 30 |

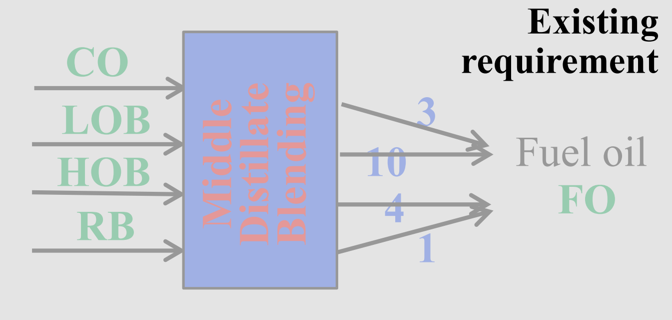
$$\text{Maximize } 140\ PG + 120\ RG + 80\ JF + 70\ FO + 30\ LuO.$$

- **Inputs come through an existing contract. They are fixed and their costs are sunk.**

# Alteration Exercise: Modifying Middle Distillate Recipe for Jet Fuel in addition to Fuel Oil

- **Middle Distillate Blending**
  - Suppose that JF needs to be produced now by blending cracked, light, heavy oil and residuum in the ratios of 2:4:1:1. This modification is inspired by a question from Juan Vanegas Merit'14.
  - To produce 80 barrels of JF, we blend
    - 20 barrels of CO,
    - 40 barrels of LOB,
    - 10 barrels of HOB,
    - 10 barrels of RB.
  - If we want 80 barrels of JF and 180 barrels of FO, we need at least
    - 20 and 30 barrels of CO respectively for JF and FO,
    - 40 and 100 barrels of LOB respectively for JF and FO,
    - 10 and 40 barrels of HOB respectively for JF and FO,
    - 10 and 10 barrels of RB respectively for JF and JO.





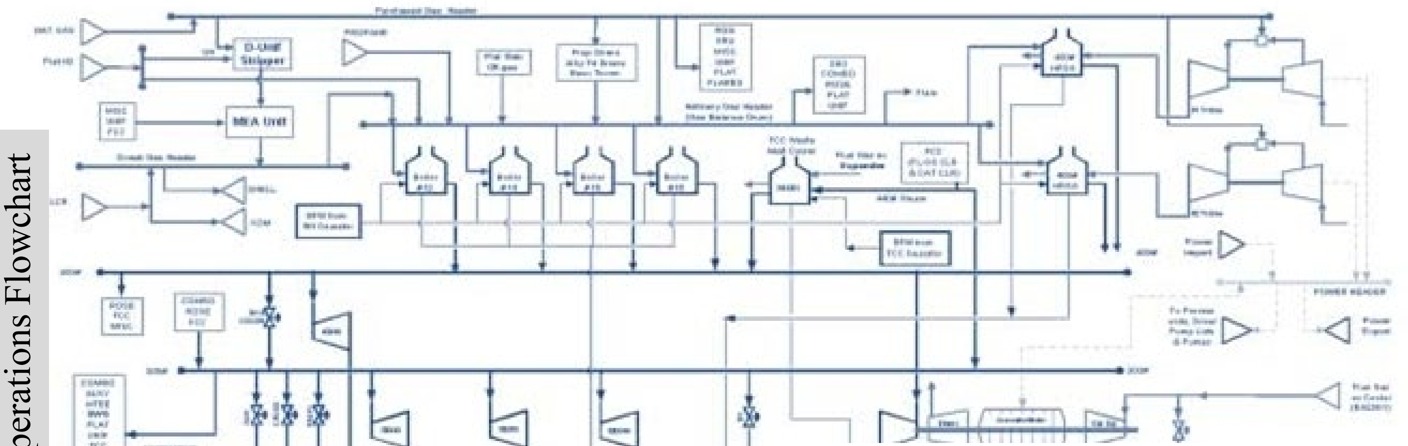
$$CO \geq (2/8)\,JF + (3/18)\,FO; \qquad LOB \geq (4/8)\,JF + (10/18)\,FO;$$
$$HOB \geq (1/8)\,JF + (4/18)\,FO; \qquad RB \geq (1/8)\,JF + (1/18)\,FO.$$

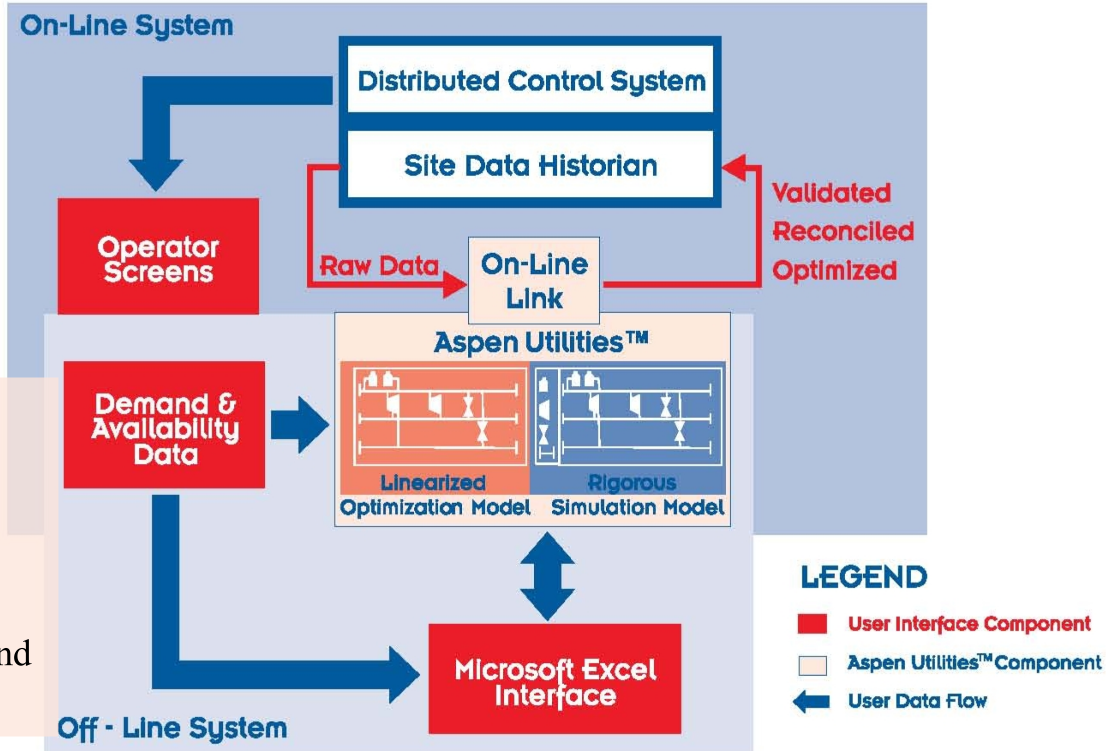
- Jet fuel RVP must be less than 1 kg/cm$^2$. When CO, LOB, HOB and RB are mixed at ratios of 2:4:1:1, the JF has RVP of $(2/8)1.5 + (4/8)1 + (1/8)0.6 + (1/8)0.05 = 7.65/8 < 1$. No RVP constraint is necessary!

| | Light oil | Heavy oil | Cracked oil | Residuum |
|---|---|---|---|---|
| RVP | 1.0 | 0.6 | 1.5 | 0.05 |

# Refinery Optimization in Practice

Refinery Operations Flowchart





- Drop-down menu for a symbol
- Data entry by
  - typing numbers into tables
  - reading from Excel files
  - importing from database
- Inequalities often are in the background
- Check inequalities before solving

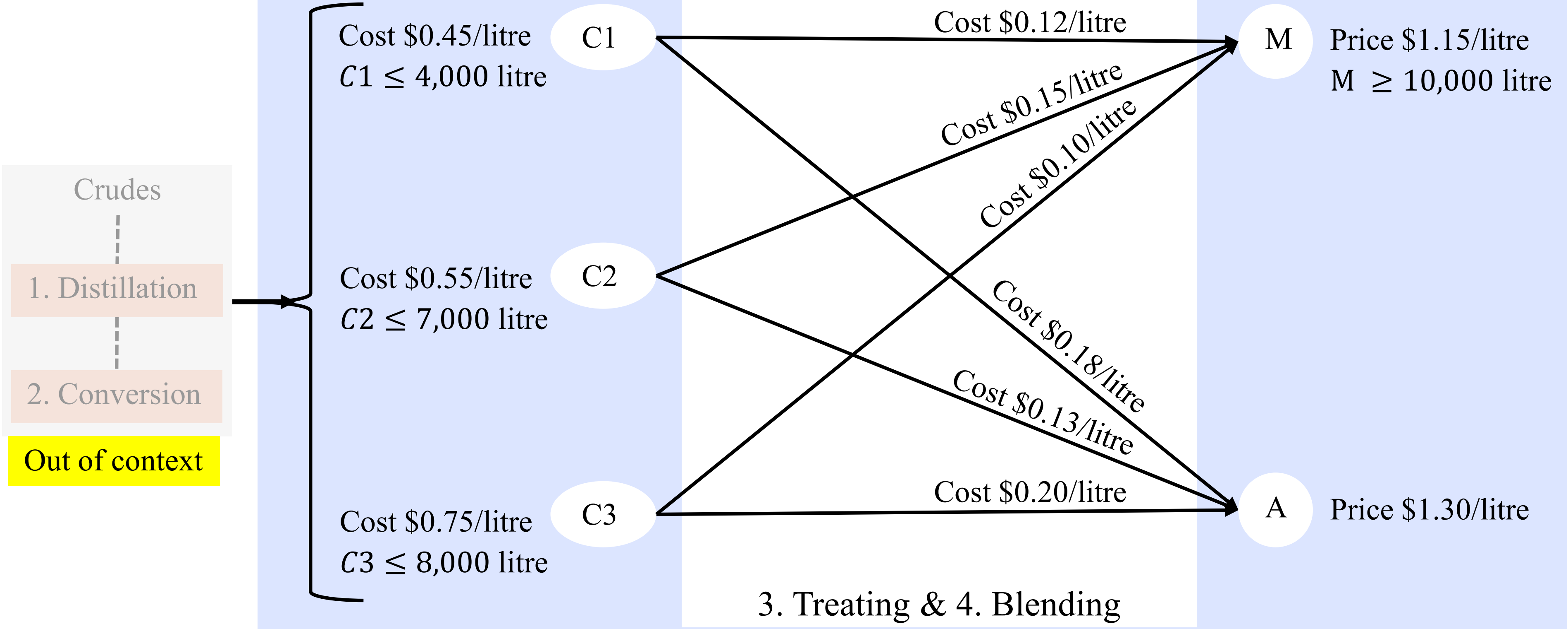
# Refinery Optimization in Class
## Texas Refinery Context

Texas refinery obtains 3 intermediate products (components) C1, C2, C3 after distillation/conversion and plans to use these to produce 2 coatings: MightyPlate and Aluminum.

- The sales price of coatings are $1.15 / litre for MightyPlate and $ 1.30 / litre for Aluminum.
- Texas refinery has a contract to produce at least 10,000 liters of MightyPlate.
- The cost of producing 3 components (through purchasing crude, distillation, conversion) are $0.45 / litre for C1, $0.55 / litre for C2 and $0.75 / litre for C3.
- With current processes & input, the refinery can produce 4000 liters of C1, 7000 liters of C2 and 8000 liters of C3.
- There are technological constraints while blending components to make the coatings
    - MightyPlate can contain at most 55% C1 and at most 25% C3 and must contain at least 35% C2
    - Aluminum can contain at most 45% C2 and must contain at least 15% C1 and 25% C3.
- The processing (including treating and blending) costs are given as ¢ / litre by the table below

| | C1 | C2 | C3 |
|---|---:|---:|---:|
| MightyPlate | 12 | 15 | 10 |
| Aluminum | 18 | 13 | 20 |

# Texas Refinery Context Visualization



Crudes

1. Distillation

2. Conversion

Out of context

Cost \$0.45/litre
$C1 \le 4{,}000$ litre

Cost \$0.55/litre
$C2 \le 7{,}000$ litre

Cost \$0.75/litre
$C3 \le 8{,}000$ litre

C1

C2

C3

Cost \$0.12/litre

Cost \$0.15/litre

Cost \$0.10/litre

Cost \$0.18/litre

Cost \$0.13/litre

Cost \$0.20/litre

3. Treating & 4. Blending

M

A

Price \$1.15/litre
M $\ge$ 10,000 litre

Price \$1.30/litre

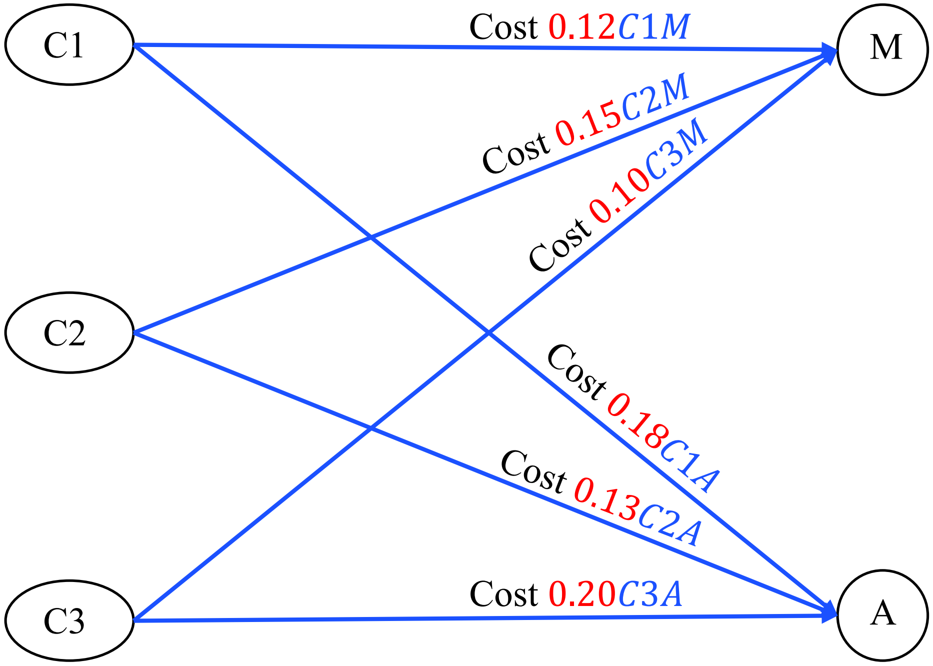
Technological constraints

- M can contain $\le$ 55% C1 and $\le$ 25% C3 and must contain $\ge$ 35% C2.
- A can contain $\le$ 45% C2 and must contain $\ge$ 15% C1 and $\ge$ 25% C3.

Context

# Texas Refinery
# Ingredients of a Formulation

To formulate: Define decision variables for each arrow:
$C1M, C2M, C3M, C1A, C2A, C3A$



Cost $0.45(C1M + C1A)$
$C1M + C1A \leq 4{,}000$

Cost $0.55(C2M + C2A)$
$C2M + C2A \leq 7{,}000$

Cost $0.75(C3M + C3A)$
$C3M + C3A \leq 8{,}000$

Revenue $1.15(C1M + C2M + C3M)$
$C1M + C2M + C3M \geq 10{,}000$

Revenue $1.3(C1A + C2A + C3A)$

| | |
|---|---|
| M can contain ≤ 55% C1 | $C1M \leq 0.55(C1M + C2M + C3M)$ |
| M can contain ≤ 25% C3 | $C3M \leq 0.25(C1M + C2M + C3M)$ |
| M must contain ≥ 35% C2 | $C2M \geq 0.35(C1M + C2M + C3M)$ |

| | |
|---|---|
| A must contain ≥ 15% C1 | $C1A \geq 0.15(C1A + C2A + C3A)$ |
| A must contain ≥ 25% C3 | $C3A \geq 0.25(C1A + C2A + C3A)$ |
| A can contain ≤ 45% C2 | $C2A \leq 0.45(C1A + C2A + C3A)$ |

# Texas Refinery

# Formulation: Objective Function and Constraints

$$\begin{aligned}\text{Maximize } & 1.15(C1M + C2M + C3M) + 1.3(C1A + C2A + C3A) \\ & -0.45(C1M + C1A) - 0.55(C2M + C2A) - 0.75(C3M + C3A) \\ & -0.12C1M - 0.15C2M - 0.10C3M - 0.18C1A - 0.13C2A - 0.20C3A\end{aligned}$$

$$C1M + C2M + C3M \geq 10{,}000$$

MightyPlate Contract

$$\begin{aligned} C1M + C1A &\leq 4{,}000 \\ C2M + C2A &\leq 7{,}000 \\ C3M + C3A &\leq 8{,}000 \end{aligned}$$

Component Availability

$$\begin{aligned} C1M &\leq 0.55(C1M + C2M + C3M) \\ C3M &\leq 0.25(C1M + C2M + C3M) \\ C2M &\geq 0.35(C1M + C2M + C3M) \end{aligned}$$

MightyPlate Technology

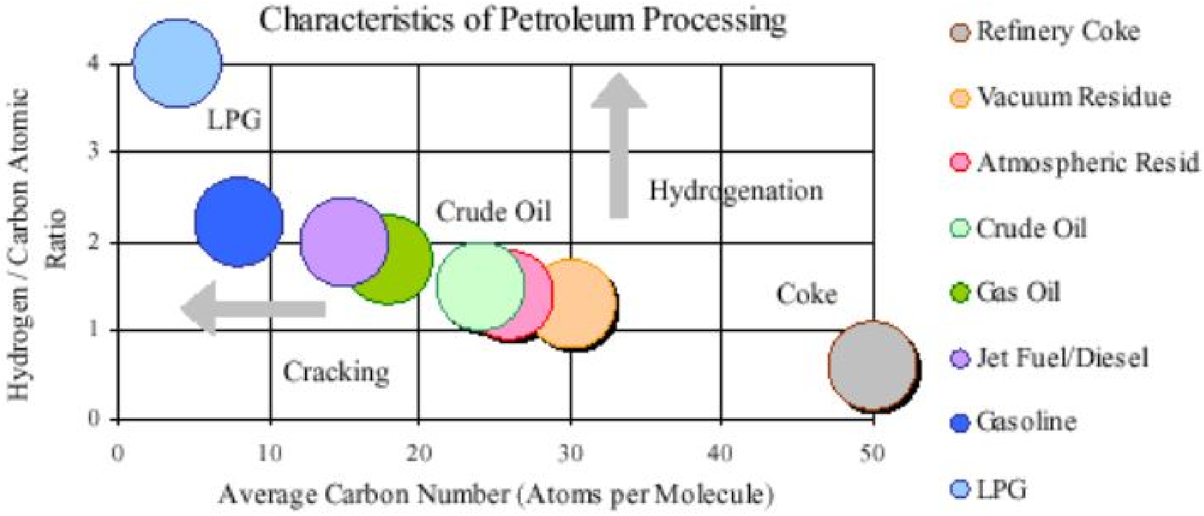
$$\begin{aligned} C1A &\geq 0.15(C1A + C2A + C3A) \\ C3A &\geq 0.25(C1A + C2A + C3A) \\ C2A &\leq 0.45(C1A + C2A + C3A) \end{aligned}$$

Aluminum Technology

All variables are nonnegative

For numerical solution see texasRefinery.xlsx

# Summary



- **Processes**
- **Markets**
- **Optimization**

Based on

- Introduction. Chapter 1 of Petroleum Refining: Technology and Economics, 5th edition by J.H. Gary, G.E. Handwerk and M.J. Kaiser 2007.
- Refining Process Handbook. Surinder Parkash. Published by Elsevier. 2003.
- A Guide to Oil and Gas Industry (GOGI). By Deutsche Bank Market Research, 163-187.
- Petroleum Refining. 4th edition by W.L. Leffler, 2008.

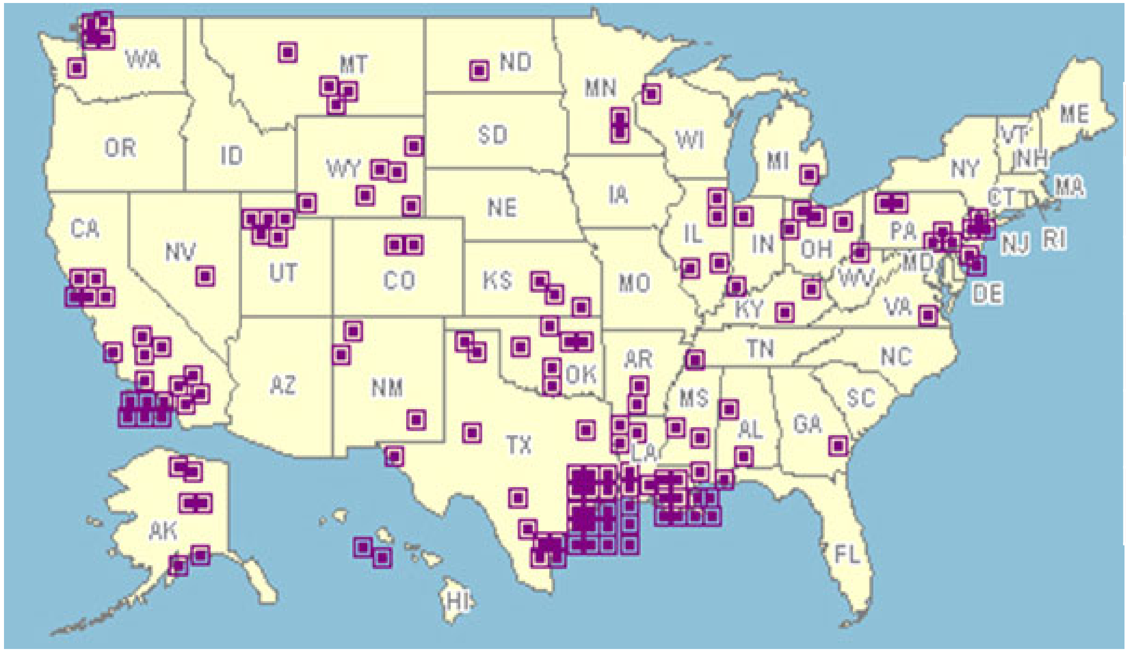
# Refining Characteristics: Pollution

- Refineries create pollution
  - Pollution gases emitted during refining operations: Particle matter (dust, dirt, smoke, soot), Sulfur dioxide, Carbon monoxide, Nitric oxides, Volatile organic compounds (paints, adhesives). All of these are created by catalytic cracking and coking units.
  - Pollution created by refinery products such as gasoline. Reducing the pollution from burning gasoline?
  - Refineries are subject to several regulations.
    - Air Acts: Clean Air 1963, amendments 1967, 1970, 1975, 1977, 1990. Motor Vehicle Air Pollution 1965. Air Quality 1967.
    - Water Act: River and Harbor, Refuse, Federal Water Pollution Control, Clean Water, Water Quality, Safe Drinking Water.

- Each refinery is unique and evolve with expansions over time.
  - **ConocoPhillips' Borger Refinery** is located in Borger, TX, in the TX Panhandle about 50 miles north of Amarillo and includes an NGL fractionation facility. The refinery's gross crude oil processing capacity is 146 MBD, and the NGL fractionation capacity is 45 MBD.
    - Facilities: coking, fluid catalytic cracking, hydrodesulfurization and naphtha reforming that enable it to produce a high percentage of transportation fuels.
    - Input: Primarily medium sour crude oil and natural gas liquids received through pipelines from West TX, the TX Panhandle, WY and CA. It can receive foreign crude via company-owned and common-carrier pipelines.
    - Output: A high percentage of transportation fuels (gasoline, diesel fuel and jet fuel), coke, NGL and solvents.

  - **ConocoPhillips' Sweeney Refinery** located in Old Ocean, TX, 65 miles southwest of Houston, has a crude oil processing capacity of 247 MBD. It processes mainly heavy, high-sulfur crude oil, but also processes light, low-sulfur crude oil.
    - Facilities: fluid catalytic cracking, delayed coking, alkylation, a continuous regeneration reformer and hydrodesulfurization units.
    - Input: Domestic and foreign crude oil, received primarily through wholly and jointly owned terminals on the Gulf Coast, including a deepwater terminal at Freeport, TX.
    - Output: A high percentage of transportation fuels (such as gasoline, diesel fuel and jet fuel). Other products include petrochemical feedstocks, home heating oil and coke.
    - The refinery operates nearby terminals and storage facilities in Freeport, Jones Creek and on the San Bernard River, along with pipelines that connect these facilities to the refinery.

# US Refineries and PAD Districts



| From\To | I | II | III | IV | V |
|---|---|---|---|---|---|
| I | | 123 | 2 | | |
| II | 27 | | 81 | 20 | |
| **III** | **1185** | **410** | | **17** | **14** |
| IV | | 23 | 52 | | 12 |
| V | | | | | |

Shipments in Million Barrels in 2004 of petroleum products among PADDs

- PADDs (Petroleum Administration for Defense Districts) were established during WW II.
  - PADD I: East: CT, ME, MA, NH, RI, VT, DE, DC, MD, NJ, NY, PA, FL, GA, NC, SC, VA, WV
  - PADD II: Midwest: IL, IN, IA, KS, KY, MI, MN, MO, NE, ND, SD, OH, OK, TN, WI
  - PADD III: South: AL, AR, LA, MS, NM, TX
  - PADD IV: Rockies: CO, ID, MT, UT, WY
  - PADD V: West: AK, AZ, CA, HI, NV, OR, WA
- US Capacities. PADD I 1.7; II 3.6; **III 8.1**; IV 0.6; V 3.2 million BPCD in 2005.
- Global Capacities. Africa 3.2; Asia 22.2; Eastern Europe 10.2; Middle East 7.0; North America 20.6; South America 6.6; Western Europe 14.9 million BPCD in 2005.

# Optimization of Crude Oil Operations

- **See http://newton.cheme.cmu.edu/interfaces/crudeoil/main.html**
- X. Chen, I. Grossmann, L. Zheng. 2012. A comparative study of continuous-time models for scheduling of crude oil operations in inland refineries. Computers and Civil Engineering, Vol.44:141-67. Articles by Modules/Refining/ChenComparingModelsSchedulingRefineries