Basics of Refining and Optimization

January 12, 2017
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Gary Simmons
Senior Vice President – International Operations and Systems Optimization
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Crude Oil Characteristics

- Crude oils are blends of hydrocarbon molecules
  - Classified and priced by density, sulfur content, and acidity
- Density is commonly measured in API gravity (relative density of crude oil to water)
  - API > 10: lighter, floats on water
  - API < 10: heavier, sinks in water
- Sulfur content is measured in weight percent
  - Less than 0.7% sulfur content = sweet
  - Greater than 0.7% sulfur content = sour
- Acidity is measured by Total Acid Number (TAN)
  - High acid crudes are those with TAN greater than 0.7
  - Acidic crudes are corrosive to refinery equipment, require greater investment to process significant volumes or higher TAN levels

Light, sweet, low TAN crudes are easier to process and tend to trade at premiums to heavier, higher sulfur, more acidic crudes which require additional conversion capacity to upgrade
Crude Oil Basics

Estimated 1.66 Trillion Barrels of Oil Reserves (2015)

- Middle East: 49%
- Western Hemisphere (excl North America): 20%
- Canada: 10%
- Mexico: 1%
- Africa: 7%
- FSU / Eastern Europe: 7%
- Western Europe: 1%

Source: EIA

Crude Oil Quality

- Majority of global crude oil reserves are sour
- Most quoted benchmarks are light sweet crude oils (WTI, Brent, Tapis)

Source: Industry reports
What’s in a Barrel of Crude Oil?

**Crude Oil Types**

**Light Sweet**
(e.g. WTI, LLS, Brent)

**Medium Sour**
(e.g. Mars, WTS, Arab Medium, Basrah)

**Heavy Sour**
(e.g. Maya, Cold Lake, Western Canadian Select)

**Characteristics**

- **Light Sweet**
  - > 34 API Gravity
  - < 0.7 % Sulfur
  - 35% Demand
  - Most Expensive

- **Medium Sour**
  - 24 to 34 API Gravity
  - > 0.7 % Sulfur
  - 50% Demand
  - Less Expensive

- **Heavy Sour**
  - < 24 API Gravity
  - > 0.7 % Sulfur
  - 15% Demand
  - Least Expensive

**Inherent Yields**

- **Light Sweet**
  - 3%
  - 32%
  - 30%
  - 35%

- **Medium Sour**
  - 2%
  - 24%
  - 26%
  - 48%

- **Heavy Sour**
  - 1%
  - 15%
  - 21%
  - 63%

**2016 U.S. Refinery Production**

- **4%** Refinery Gases
- **47%** Gasoline
  - RBOB
  - CBOB
  - Conventional
  - CARB
  - Premium
- **38%** Distillate
  - Jet Fuel
  - Diesel
  - Heating Oil
- **11%** Heavy Fuel Oil & Other

Source: EIA refinery yield through Oct 2016

Refineries upgrade crude oil into higher value gasoline and distillates.
Basic Refining Concepts

Crude Oil → Furnace → Crude Distillation Unit → Vacuum Distillation Unit → Intermediates → Final Products

- **Intermediates**
  - Light Ends Recovery & Treatment
  - Isomerization
  - Reformer
  - Hydrotreater
  - FCC
  - Hydrocracker

- **Final Products**
  - Refinery fuel gas
  - Propane
  - NGLs
  - Gasoline
  - Jet fuel
  - Petrochemicals
  - Kerosene
  - Diesel
  - Fuel oil
  - Gasoline
  - Diesel
  - Fuel oil
  - Gasoline
  - Diesel
  - Fuel oil
  - Lube stocks

- **Crude Oil Temperature Ranges**
  - C1 to C4: < 90°F
  - C5 to C8: 90–220°F
  - C8 to C12: 220–315°F
  - C12 to C30: 315–450°F
  - C30 to C50+: 450–650°F
  - C30 to C50+: 650–800°F
  - C50 to C100+: 800°F
Hydroskimming (Topping) Refinery

Low complexity refineries run sweet crude
Crude and Vacuum Distillation Towers
Moderate complexity refineries tend to run more sour crudes, yield more high value products, and achieve higher volume gain.
High Conversion: Coking/Resid Destruction

High complexity refineries can run heavier, more sour crudes while achieving the highest light product yields and volume gain.
Cokers

**Delayed Coker**
Superstructure holds the drill and drill stem while the coke is forming in the drum

**Fluid Coker**
Hydrocracker

- Enables capture of arbitrage between natural gas and crude oil
- Upgrades high sulfur gasoil into low sulfur gasoline, jet, and diesel
- Increases volumetric yield of products through hydrogen saturation
A Few Comments on Octane

Drivers of octane tightness – 2015
- Increased gasoline demand
- Light crude, condensate, NGLs growth from shale production created low octane naphtha length

Drivers of octane tightness – 2016
- Continued strong gasoline demand
- Cheap NGL competes with naphtha to Asian petchems markets
- Increased fuel economy standards

Octane definition
- Octane numbers – measures of whether a gasoline will knock in an engine. The higher the octane number, the more resistance to pre or self-ignition.

Octane enhancing refining processes
- Alkylation – upgrades light olefins to large molecules with higher value, higher octane for blending into gasoline.
- Catalytic reforming – heavy straight run (HSR) naphthas are chemically changed to increase their octane.
- Polymerization – combines smaller molecules to produce high octane blendstock.
- Isomerization – light straight run (LSR) naphthas are chemically changed to produce high octane blending components.

Note: Each process has advantages and disadvantages.
Maximizing Refinery Profit

Feedstocks (100+):
- Prices
- Qualities
- Availabilities (purchase volumes)

Products (30+):
- Prices
- Specifications
- Market demand (sales volumes)

Refinery:
- 10 to 25+ individual process units
- Unit hardware constraints
- Operating parameters
- Operating costs

Relationship between variables modeled in series of linear equations
Linear program used to find combination of feed and product slates, operating rates and parameters that delivers highest profit
LP Example: What’s for Breakfast?

Nutritional Information

<table>
<thead>
<tr>
<th>Serving Size</th>
<th>$/Serving</th>
<th>Protein (g)</th>
<th>Total Fat (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bagel 1 large bagel</td>
<td>$2.00</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Oatmeal 1 cup</td>
<td>$2.50</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Eggs 2 large eggs</td>
<td>$3.50</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Bacon 3 slices</td>
<td>$4.00</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Orange juice 1 cup</td>
<td>$2.50</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Your goal is to consume at least 18 grams of protein, but not more than 10 grams of total fat for the lowest COST.
Optimizing Breakfast from an Engineer’s Point of View

Consume at least 18 grams of protein

\[
\text{Bagel Servings} \times 3 \text{ g} + \text{Oatmeal Servings} \times 4 \text{ g} + \text{Eggs Servings} \times 6 \text{ g} + \text{Bacon Servings} \times 8 \text{ g} + \text{Juice Servings} \times 2 \text{ g} \geq 18 \text{ grams protein}
\]

Consume no more than 10 grams of total fat

\[
\text{Bagel Servings} \times 1 \text{ g} + \text{Oatmeal Servings} \times 1 \text{ g} + \text{Eggs Servings} \times 5 \text{ g} + \text{Bacon Servings} \times 8 \text{ g} + \text{Juice Servings} \times 0 \text{ g} \leq 10 \text{ grams total fat}
\]

Minimize the cost of breakfast

\[
\text{Bagel Servings} \times $2.00 + \text{Oatmeal Servings} \times $2.50 + \text{Eggs Servings} \times $3.50 + \text{Bacon Servings} \times $4.00 + \text{Juice Servings} \times $2.50 = \text{Minimum}
\]

Even with only five food choices, there are so many possible combinations that using trial and error to find the one with the lowest cost isn't efficient
## What’s Best?

<table>
<thead>
<tr>
<th>Servings</th>
<th>Unit Cost</th>
<th>Protein (g)</th>
<th>Total Fat (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bagel</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oatmeal</td>
<td>2.7</td>
<td>X $2.50 = $6.75</td>
<td>X 4 = 10.8</td>
</tr>
<tr>
<td>Eggs</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bacon</td>
<td>0.9</td>
<td>X $4.00 = $3.60</td>
<td>X 8 = 7.2</td>
</tr>
<tr>
<td>Orange juice</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total meal</strong></td>
<td></td>
<td><strong>$10.35</strong></td>
<td><strong>18</strong></td>
</tr>
</tbody>
</table>

**GOAL = Lowest cost**

Min 18 g protein

Max 10 g fat

- Linear programming is a branch of applied mathematics concerned with problems of constrained optimization
- Started in 1947 and used by the US Air Force to optimize logistics
- Price and “quality” of each variable drive the optimum solution
Crude Oil Valuation

• Linear programs are used to calculate relative refining values (quality differentials) for crude oils versus a benchmark, such as Brent or WTI

• Relative value for a crude is largely determined by its yields

• Wider discounts ($/bbl) are needed for medium and heavy sour crudes to break even with light sweets in a higher flat price environment than at lower flat prices

• Percentage discount required for medium and heavy sours to break even with light sweets stays about the same at low and high flat prices
## Crude Break Even Values

**Reference Crude**

<table>
<thead>
<tr>
<th>Yields</th>
<th>“Reference Crude”</th>
<th>“Alternate Crude”</th>
<th>Prices $99/bbl crude</th>
<th>Prices $51/bbl crude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Sweet</td>
<td>3%</td>
<td>2%</td>
<td>$49</td>
<td>$31</td>
</tr>
<tr>
<td>Medium Sour</td>
<td>1%</td>
<td>1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy Sour</td>
<td>1%</td>
<td>1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refinery gases</td>
<td>3%</td>
<td>2%</td>
<td>$49</td>
<td>$31</td>
</tr>
<tr>
<td>Gasoline</td>
<td>32%</td>
<td>24%</td>
<td>$109</td>
<td>$60</td>
</tr>
<tr>
<td>Distillate</td>
<td>30%</td>
<td>26%</td>
<td>$118</td>
<td>$69</td>
</tr>
<tr>
<td>Heavy fuel oil</td>
<td>35%</td>
<td>48%</td>
<td>$80</td>
<td>$41</td>
</tr>
</tbody>
</table>

Note: Prices do not crossfoot due to rounding.

(1) Reference crude
(2) Gasoline crack: $9/bbl
(3) Distillate crack: $18/bbl
(4) Heavy fuel oil: 80% of reference crude value

### Break Even Value (BEV) = Alternate Crude Total Product Value - Reference Crude Total Product Value

<table>
<thead>
<tr>
<th>Break Even Versus</th>
<th>$99/bbl Crude</th>
<th>$51/bbl Crude</th>
<th>BEV as % of Crude Value @ $99/bbl</th>
<th>BEV as % of Crude Value @ $51/bbl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Sweet Crude</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium sour</td>
<td>-$3.55</td>
<td>-$2.58</td>
<td>96%</td>
<td>95%</td>
</tr>
<tr>
<td>Heavy sour</td>
<td>-$7.76</td>
<td>-$5.65</td>
<td>92%</td>
<td>89%</td>
</tr>
</tbody>
</table>

**BEV for alternate crude as a percentage of reference crude value is relatively insensitive to flat price environment**
Crude Oil Differentials Versus ICE Brent

Source: Argus; 2017 prices through January 5. All prices are spot values. ASCI represents Argus Sour Crude Index.
Questions and Answers
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Major Refining Processes – Crude Processing

• Definition
  – Separating crude oil into different hydrocarbon groups
  – The most common means is through distillation

• Process
  – Desalting – Prior to distillation, crude oil is often desalted to remove corrosive salts as well as metals and other suspended solids.
  – Atmospheric distillation – Used to separate the desalted crude into specific hydrocarbon groups (straight run gasoline, naphtha, light gas oil, etc.) or fractions.
  – Vacuum distillation – Heavy crude residue (“bottoms”) from the atmospheric column is further separated using a lower-pressure distillation process. Means to lower the boiling points of the fractions and permit separation at lower temperatures, without decomposition and excessive coke formation.
Major Refining Processes – Cracking

• Definition
  – “Cracking” or breaking down large, heavy hydrocarbon molecules into smaller hydrocarbon molecules through application of heat (thermal) or the use of catalysts

• Process
  – Coking – Thermal non-catalytic cracking process that converts low value oils to higher value gasoline, gas oils and marketable coke. Residual fuel oil from vacuum distillation column is typical feedstock.
  – Visbreaking – Thermal non-catalytic process used to convert large hydrocarbon molecules in heavy feedstocks to lighter products such as fuel gas, gasoline, naphtha and gas oil. Produces sufficient middle distillates to reduce the viscosity of the heavy feed.
  – Catalytic cracking – A central process in refining where heavy gas oil range feeds are subjected to heat in the presence of catalyst and large molecules crack into smaller molecules in the gasoline and lighter boiling ranges.
  – Catalytic hydrocracking – Like cracking, used to produce blending stocks for gasoline and other fuels from heavy feedstocks. Introduction of hydrogen in addition to a catalyst allows the cracking reaction to proceed at lower temperatures than in catalytic cracking, although pressures are much higher.
Major Refining Processes – Combination

• Definition
  – Linking two or more hydrocarbon molecules together to form a large molecule (e.g. converting gases to liquids) or rearranging to improve the quality of the molecule

• Process
  – Alkylation – Important process to upgrade light olefins to high-value gasoline components. Used to combine small molecules into large molecules to produce a higher octane product for blending into gasoline.
  – Catalytic reforming – The process whereby naphthas are changed chemically to increase their octane numbers. Octane numbers are measures of whether a gasoline will knock in an engine. The higher the octane number, the more resistance to pre or self-ignition.
  – Polymerization – Process that combines smaller molecules to produce high octane blendstock.
  – Isomerization – Process used to produce compounds with high octane for blending into the gasoline pool. Also used to produce isobutene, an important feedstock for alkylation.
Major Refining Processes – Treating

• Definition
  – Processing of petroleum products to remove some of the sulfur, nitrogen, heavy metals, and other impurities

• Process
  – Catalytic hydrotreating, hydroprocessing, sulfur/metals removal – Used to remove impurities (e.g. sulfur, nitrogen, oxygen and halides) from petroleum fractions. Hydrotreating further “upgrades” heavy feeds by converting olefins and diolefins to paraffins, which reduces gum formation in fuels. Hydroprocessing also cracks heavier products to lighter, more saleable products.
## Refining Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>AGO</td>
<td>Atmospheric Gas Oil</td>
</tr>
<tr>
<td>ATB</td>
<td>Atmospheric Tower Bottoms</td>
</tr>
<tr>
<td>B–B</td>
<td>Butane-Butylene Fraction</td>
</tr>
<tr>
<td>BBLs</td>
<td>Barrels</td>
</tr>
<tr>
<td>BPD</td>
<td>Barrels Per Day</td>
</tr>
<tr>
<td>BTX</td>
<td>Benzene, Toluene, Xylene</td>
</tr>
<tr>
<td>CARB</td>
<td>California Air Resource Board</td>
</tr>
<tr>
<td>CCR</td>
<td>Continuous Catalytic Regenerator</td>
</tr>
<tr>
<td>DAO</td>
<td>De-Asphalted Oil</td>
</tr>
<tr>
<td>DCS</td>
<td>Distributed Control Systems</td>
</tr>
<tr>
<td>DHT</td>
<td>Diesel Hydrotreater</td>
</tr>
<tr>
<td>DSU</td>
<td>Desulfurization Unit</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>ESP</td>
<td>Electrostatic Precipitator</td>
</tr>
<tr>
<td>FCC</td>
<td>Fluid Catalytic Cracker</td>
</tr>
<tr>
<td>GDU</td>
<td>Gasoline Desulfurization Unit</td>
</tr>
<tr>
<td>GHT</td>
<td>Gasoline Hydrotreater</td>
</tr>
<tr>
<td>GOHT</td>
<td>Gas Oil Hydrotreater</td>
</tr>
<tr>
<td>GPM</td>
<td>Gallon Per Minute</td>
</tr>
<tr>
<td>HAGO</td>
<td>Heavy Atmospheric Gas Oil</td>
</tr>
<tr>
<td>HCU</td>
<td>Hydrocracker Unit</td>
</tr>
<tr>
<td>HDS</td>
<td>Hydrodesulfurization</td>
</tr>
<tr>
<td>HDT</td>
<td>Hydrotreating</td>
</tr>
<tr>
<td>HGO</td>
<td>Heavy Gas Oil</td>
</tr>
<tr>
<td>HOC</td>
<td>Heavy Oil Cracker (FCC)</td>
</tr>
<tr>
<td>H2</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>H2S</td>
<td>Hydrogen Sulfide</td>
</tr>
<tr>
<td>HF</td>
<td>Hydroflouric (acid)</td>
</tr>
<tr>
<td>HVGO</td>
<td>Heavy Vacuum Gas Oil</td>
</tr>
<tr>
<td>kV</td>
<td>Kilovolt</td>
</tr>
<tr>
<td>kVA</td>
<td>Kilovolt Amp</td>
</tr>
<tr>
<td>LCO</td>
<td>Light Cycle Oil</td>
</tr>
<tr>
<td>LGO</td>
<td>Light Gas Oil</td>
</tr>
<tr>
<td>LPG</td>
<td>Liquefied Petroleum Gas</td>
</tr>
<tr>
<td>LSD</td>
<td>Low Sulfur Diesel</td>
</tr>
<tr>
<td>LSR</td>
<td>Light Straight Run (Gasoline)</td>
</tr>
<tr>
<td>MON</td>
<td>Motor Octane Number</td>
</tr>
<tr>
<td>MTBE</td>
<td>Methyl Tertiary–Butyl Ether</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatt</td>
</tr>
<tr>
<td>NGL</td>
<td>Natural Gas Liquids</td>
</tr>
<tr>
<td>NOX</td>
<td>Nitrogen Oxides</td>
</tr>
<tr>
<td>P–P</td>
<td>Propane–Propylene</td>
</tr>
<tr>
<td>PSI</td>
<td>Pounds per Square Inch</td>
</tr>
<tr>
<td>RBOB</td>
<td>Reformulated Blendstock for Oxygenate Blending</td>
</tr>
<tr>
<td>RDS</td>
<td>Resid Desulfurization</td>
</tr>
<tr>
<td>RFG</td>
<td>Reformulated Gasoline</td>
</tr>
<tr>
<td>RON</td>
<td>Research Octane Number</td>
</tr>
<tr>
<td>RVP</td>
<td>Reid Vapor Pressure</td>
</tr>
<tr>
<td>SMR</td>
<td>Steam Methane Reformer (Hydrogen Plant)</td>
</tr>
<tr>
<td>SOX</td>
<td>Sulfur Oxides</td>
</tr>
<tr>
<td>SRU</td>
<td>Sulfur Recovery Unit</td>
</tr>
<tr>
<td>TAME</td>
<td>Tertiary Amyl Methyl Ether</td>
</tr>
<tr>
<td>TAN</td>
<td>Total Acid Number</td>
</tr>
<tr>
<td>ULSD</td>
<td>Ultra–low Sulfur Diesel</td>
</tr>
<tr>
<td>VGO</td>
<td>Vacuum Gas Oil</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile Organic Compound</td>
</tr>
<tr>
<td>VPP</td>
<td>Voluntary Protection Program</td>
</tr>
<tr>
<td>VTB</td>
<td>Vacuum Tower Bottoms</td>
</tr>
<tr>
<td>WTI</td>
<td>West Texas Intermediate</td>
</tr>
<tr>
<td>WWTP</td>
<td>Waste Water Treatment Plant</td>
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