Capturing Maximum Value with Tight Oil Feeds in the FCC

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What is Tight Oil?

- The term Tight Oil (sometimes referred to as shale oil) is used to describe oil produced from low permeability (e.g. tight) shale, sandstone and carbonate rock formations.

- The USA is legally prohibited from exporting crude to other nations → hence all domestic tight oil production will be consumed in the USA.

  - US refiners achieve a cost advantage compared to other global refineries.
  - The abundant natural gas from tight oil production also gives manufacturing an advantage.
  - Pricing for fields like Bakken low due to transportation infrastructure bottlenecks.

Source: EIA (US Energy Information Administration)
Shale Plays

<table>
<thead>
<tr>
<th>Country</th>
<th>Technically Recoverable Shale Oil Resources (Billion Barrels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Russia</td>
<td>75</td>
</tr>
<tr>
<td>US</td>
<td>48</td>
</tr>
<tr>
<td>China</td>
<td>32</td>
</tr>
<tr>
<td>Argentina</td>
<td>27</td>
</tr>
<tr>
<td>Libya</td>
<td>26</td>
</tr>
<tr>
<td>Australia</td>
<td>18</td>
</tr>
<tr>
<td>Venezuela</td>
<td>13</td>
</tr>
<tr>
<td>Mexico</td>
<td>13</td>
</tr>
<tr>
<td>Pakistan</td>
<td>9</td>
</tr>
<tr>
<td>Canada</td>
<td>9</td>
</tr>
<tr>
<td>Others</td>
<td>65</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>335</strong></td>
</tr>
</tbody>
</table>

Source: U.S. Energy Information Administration based on data from various published studies. Canada and Mexico plays from API. Updated: May 9, 2011.
Tight Oil is Here to Stay

In 2010, ~50% of the Crude Oil in the US came from North America.

In 2020, that number increases to ~80%.
Tight Oil Quality

- High naphtha and middle distillate cuts
- Almost no vacuum resid
- Lower: boiling point, S, N, CCR, Ni, V,
- Can have higher Na, Ca, K and Fe
- Quality varies even from the same field!

### Properties

<table>
<thead>
<tr>
<th>Properties</th>
<th>TX Shale</th>
<th>Bakken Core</th>
<th>WTI</th>
<th>Maya Blend</th>
<th>Peace River</th>
<th>Cold Lake</th>
<th>Wabasca</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude API</td>
<td>47.9</td>
<td>41.9</td>
<td>41</td>
<td>31.2</td>
<td>32.3</td>
<td>20.3</td>
<td>19.2</td>
</tr>
<tr>
<td>Crude Sulfur</td>
<td>0.09</td>
<td>0.14</td>
<td>0.32</td>
<td>1.84</td>
<td>2</td>
<td>3.9</td>
<td>3.99</td>
</tr>
<tr>
<td>Offgas</td>
<td>3.0%</td>
<td>2.7%</td>
<td>1.8%</td>
<td>1.5%</td>
<td>2.3%</td>
<td>1.6%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Naphtha</td>
<td>27.4%</td>
<td>27.8%</td>
<td>24.6%</td>
<td>18.0%</td>
<td>15.7%</td>
<td>16.3%</td>
<td>12.9%</td>
</tr>
<tr>
<td>Mid Distillate</td>
<td>40.2%</td>
<td>36.9%</td>
<td>38.6%</td>
<td>33.7%</td>
<td>33.6%</td>
<td>18.1%</td>
<td>26.2%</td>
</tr>
<tr>
<td>VGO</td>
<td>26.0%</td>
<td>27.2%</td>
<td>26.7%</td>
<td>28.2%</td>
<td>28.6%</td>
<td>28.4%</td>
<td>32.6%</td>
</tr>
<tr>
<td>Vac Resid</td>
<td>3.4%</td>
<td>5.5%</td>
<td>8.3%</td>
<td>18.6%</td>
<td>19.9%</td>
<td>35.6%</td>
<td>27.8%</td>
</tr>
</tbody>
</table>

Source: KBC
Tight Oil Quality Impacts on the Refinery

- Crude processing capacity severely affected by the increased volume of the lighter oil cuts
- The naphtha cut of tight oil is more paraffinic → lower octane
  - Consider using ZSM-5 to increase FCC gasoline octane within gas plant constraints
  - Reformulate FCC catalyst to a lower REO
  - Alkylation will be an important part of the refinery configuration
  - Refiners are maxing out the reformer capacity
- With low vacuum resid consider shutting down the resid units and feeding the resid directly to the FCC (helps with FCC heat balance)
- Crude compatibility needs to be considered when blending light/sweet crudes with heavy/sour crude due to asphaltene precipitation
FCC Tight Oil Feed Cut Quality

- VGO Cut
  - Very low Sulfur
  - Same or lower Nitrogen
  - Low metals
  - Low carbon producing feed
- Resid properties show similar behavior

<table>
<thead>
<tr>
<th>VGO Properties</th>
<th>TX Shale</th>
<th>Bakken Core</th>
<th>WTI</th>
<th>Maya Blend</th>
<th>Peace River5</th>
<th>Cold Lake</th>
<th>Wabasca</th>
</tr>
</thead>
<tbody>
<tr>
<td>API Gravity</td>
<td>31.9</td>
<td>24.5</td>
<td>26.3</td>
<td>21</td>
<td>24.4</td>
<td>14.9</td>
<td>13.4</td>
</tr>
<tr>
<td>Sulfur wt%</td>
<td>0.18</td>
<td>0.27</td>
<td>0.46</td>
<td>2.05</td>
<td>2.29</td>
<td>3.56</td>
<td>4.31</td>
</tr>
<tr>
<td>Acidity mg KOH/g</td>
<td>0.049</td>
<td>0.053</td>
<td>0.095</td>
<td>0.085</td>
<td>0.522</td>
<td>1.279</td>
<td>1.658</td>
</tr>
<tr>
<td>Nitrogen wt%</td>
<td>0.01</td>
<td>0.11</td>
<td>0.13</td>
<td>0.18</td>
<td>0.13</td>
<td>0.12</td>
<td>0.16</td>
</tr>
<tr>
<td>Refractive Index 67°C</td>
<td>1.4588</td>
<td>1.4824</td>
<td>1.4759</td>
<td>1.498</td>
<td>1.4832</td>
<td>1.5257</td>
<td>1.5351</td>
</tr>
<tr>
<td>Nickel ppm</td>
<td>0.09</td>
<td>0.47</td>
<td>0</td>
<td>0.64</td>
<td>0.07</td>
<td>1.8</td>
<td>3.79</td>
</tr>
<tr>
<td>Vanadium ppm</td>
<td>0.08</td>
<td>0.14</td>
<td>0</td>
<td>4.48</td>
<td>0.28</td>
<td>5.18</td>
<td>5.1</td>
</tr>
<tr>
<td>Con Carbon wt%</td>
<td>0.03</td>
<td>0.68</td>
<td>0.01</td>
<td>0.47</td>
<td>0.07</td>
<td>1.69</td>
<td>1.41</td>
</tr>
</tbody>
</table>

Source: KBC
FCC Operation with Tight Oil

- If Feed Sulfur is reduced:
  - Help meet the Tier 3, 10 ppm Gasoline spec. Consider using Gasoline Sulfur Reduction additives such as BASF’s LSA to meet spec without capital investment.
  - Lower SOx emissions from the stack. Consider cutting back if using a SOx additive.

- Lower NOx emissions from less Nitrogen in feed
- Higher LPG yields which may limit the gas plant
- Less hydrogen and coke from lower metals
- Tight Oil has lower coke making tendencies which may constrain the unit on heat balance

- Some chemical we are seeing include: Barium, Phosphorus, and Lead. However, the chemical levels are low and have no discernible effects on the FCC yields or catalyst selectivities.
Iron in Tight Oil

- Some Tight Oils have been shown to contain high iron.

- Fe acts as a dehydrogenation catalyst and increases coke and hydrogen yields (1/10\textsuperscript{th} that of Ni).

- Very high levels of iron can produce “iron nodules” which are spike-like protrusions from the surface of the catalyst.
  - Iron nodules formation is indicated by an increase in Fe and reduction of the ECat ABD.
  - Very high iron levels can cause pore mouth plugging.
    - BASF’s DMS & Prox-SMZ catalysts have good porosity giving them excellent iron tolerance.

- Iron will act as a CO promoter, which can cause problems in a partial burn unit.

ECat from a unit processing Tight Oil, Fe = 1.5 wt%
High Iron on ECat

- High porosity catalyst such as BASF’s DMS and Prox-SMZ have very high tolerance to iron pore mouth plugging

- One unit successfully ran above 2 wt% iron on ECat with BASF catalyst
Heat Balance Problems
Operating with Lower Regenerator Temp

- Minimum regen bed temperature is set by maintaining stable operation and efficient coke burning, typically 1250-1260°F dense phase.

- Rapid operating moves to increase bed temp if needed, all increase delta coke:
  - Increase CO promoter or FCC catalyst additions
  - Reduce partial burn or go into Full burn and reduce excess O2 levels
  - Raise feed preheat
  - Increase O2 injection
  - Increase HCO or slurry recycles
  - Last Resorts
    - Turn on air preheater, check distributor design
    - Add torch oil
    - Reduce dispersion or stripping steam

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### BASF Benchmarking

<table>
<thead>
<tr>
<th>Regen Bed Temp, °F</th>
<th>Feed ConCarbon, wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1150</td>
<td>0</td>
</tr>
<tr>
<td>1200</td>
<td>2</td>
</tr>
<tr>
<td>1250</td>
<td>4</td>
</tr>
<tr>
<td>1300</td>
<td>6</td>
</tr>
</tbody>
</table>

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11
Longer Term Methods to Increase Delta Coke

Raise the regenerator bed temperature with higher delta coke by:

- Feed more resid to the FCC
- Turn down the cat feed hydrotreater
- Increase the catalyst delta coke by
  - Increase catalyst activity through higher cat adds or higher fresh catalyst activity
  - Increase REO
  - Change to a higher delta coke catalyst
- Consider an advanced catalyst management program such as the use of BASF Co-Catalyst Converter® to add in activity in response to the feed quality variability
Increase feed preheat
- If using a FG fired heater, this may provide improved economics over burning coke due to the low price of natural gas
- Increases liquid yield due to less coke production
- Maximum preheat set by metallurgical limit and prevention of feed thermal precracking and/or feed vaporization
- Usually the first, best operational move

Slide Valve dP Limited
- Can manipulate vessel bed heights as allowable
- Consider modifying slide valve port size during next TAR
About 5% of all units are running feed preheat temperatures above 650°F

Highest Preheat is 805°F
Low Slurry Make

- With low slurry make watch:
  - Slurry ash
  - Slurry velocity for exchanger fouling and line settling
  - Very high residence time in bottom of column due to low yields
  - Keep main column bottom liquid active and well distributed
58% of BASF customers have successfully switched to processing tight oil

- Three switched from competitors’ catalysts to BASF
Case #1: VGO FCC Processing Tight Oil

- Gulf Coast unit is running 100% Eagle Ford
- Catalyst: NaphthaMax®
- API gravity increased from 22 to 28
- The lower feed N reduced NOx emissions
While metals such as Ni and V decreased, Na and Fe increased.

Ultimately, cat adds were increased 20% to maintain the same ECat activity.
Case #1: VGO FCC Processing Tight Oil

- To maintain regenerator bed temp, slurry recycle was increased to 15%
- No issue with catalyst circulation limit
Conversion increased from 75 vol% to 86 vol% going to 100% tight oil
VGO FCC Processing Tight Oil

- Gasoline increases, then enters into the overcracking regime
- The gasoline RON decreases as the feed is more paraffinic
VGO FCC Processing Tight Oil

- Total LPG increased from 24 vol% to 30 vol%
- This large increase in LPG may constrain the gas plant

![Graphs showing LPG and C3= concentrations](image-url)
Case #2: HT VGO FCC Processing Tight Oil

- This refinery processes VGO, ~70% of which is hydrotreated
- Went to 80% Eagle Ford
- Using BASF’s NaphthaMax® II catalyst
- Since it is hydrotreated, properties are similar
  - No major unit operating changes
- Limited by minimum regen temperature

<table>
<thead>
<tr>
<th>Operation</th>
<th>Base</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed Gravity API</td>
<td>26.6</td>
<td>+0.7</td>
</tr>
<tr>
<td>Feed Sulfur wt%</td>
<td>0.5</td>
<td>+0.1</td>
</tr>
<tr>
<td>Feed Nitrogen ppmw</td>
<td>960</td>
<td>-90</td>
</tr>
<tr>
<td>Feed Concarbon wt%</td>
<td>0.16</td>
<td>-</td>
</tr>
<tr>
<td>Preheat Temperature °F</td>
<td>Base</td>
<td>+43</td>
</tr>
<tr>
<td>Reactor Temperature °F</td>
<td>Base</td>
<td>+3</td>
</tr>
<tr>
<td>Cat-to-Oil Ratio wt/wt</td>
<td>5.8</td>
<td>-0.2</td>
</tr>
<tr>
<td>Dense Temperature °F</td>
<td>Base</td>
<td>+3</td>
</tr>
<tr>
<td>Catalyst Addition tons/day</td>
<td>Base</td>
<td>-</td>
</tr>
<tr>
<td>ZSM-5 Additions</td>
<td>Yes (5%)</td>
<td>No</td>
</tr>
</tbody>
</table>

**Equilibrium Catalyst**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>wt%</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECat FACT</td>
<td>77</td>
<td>-</td>
</tr>
<tr>
<td>Ni + V</td>
<td>1500</td>
<td>+50</td>
</tr>
<tr>
<td>Fe wt%</td>
<td>0.62</td>
<td>-</td>
</tr>
<tr>
<td>Na wt%</td>
<td>0.19</td>
<td>-0.01</td>
</tr>
</tbody>
</table>
Case #2: HT VGO FCC Processing Tight Oil

- Conversion increased
- Lower dry gas and coke
- Despite ZSM-5 being removed, the C3= make and total LPG is higher
- Higher total liquid yield
- Unit is operating very well with NaphthaMax® II catalyst with no need to make a catalyst change

<table>
<thead>
<tr>
<th>Normalized Yields</th>
<th>Base</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion</td>
<td>vol%</td>
<td>80</td>
</tr>
<tr>
<td>Dry Gas</td>
<td>wt%</td>
<td>1.8</td>
</tr>
<tr>
<td>C3=</td>
<td>vol%</td>
<td>8.4</td>
</tr>
<tr>
<td>LPG</td>
<td>vol%</td>
<td>27.7</td>
</tr>
<tr>
<td>Gasoline</td>
<td>vol%</td>
<td>63.6</td>
</tr>
<tr>
<td>LCO</td>
<td>vol%</td>
<td>15.3</td>
</tr>
<tr>
<td>Slurry</td>
<td>vol%</td>
<td>4.8</td>
</tr>
<tr>
<td>Coke</td>
<td>wt%</td>
<td>4.10</td>
</tr>
<tr>
<td>Total Liquid Yield</td>
<td>vol%</td>
<td>111.3</td>
</tr>
</tbody>
</table>
Case #3: 
Mild Resid FCC Processing Tight Oil

- Prior to the introduction of Bakken, the FCC ran VGO
- The lack of VGO in Bakken resulted in extra FCC capacity, to fill this extra capacity the refinery sent resid to the FCC which improved economics for the refinery
- CCR increased from 0 to 1 wt%, and the 1050F+ fraction doubled
- Changed catalyst from BASFs NaphthaMax® to Fortress™ for excellent metals tolerance

![Feed API](image1)

![Feed CCR](image2)

![Feed >1050F](image3)
Case #3: Mild Resid FCC Processing Tight Oil

- Due to the high contaminant levels the catalyst activity fell 7 numbers with 25% higher cat adds
- Conversion decreased from 82 vol% to 77 vol%
- The high contaminant levels of Na and Ca may lead to high corrosion rates in the unit
Assuming Tight Oil feed and typical Gulf Coast Economics

- Maximize Conversion over LCO, Also many tight oils have more straight run diesel which also reduces the need to maximize LCO from the FCC

- Maximize LPG= selectivity: C3= and C4= continue to be valuable, while LPG saturates are not. Balance catalyst activity, REO level and ROT to increase the LPG olefinicity. Consider using ZSM-5 if the gas plant has room.

- Increase Gasoline Octane: Very high octane values of over $2/bbl are being seen in the Gulf Coast (likely due to the low octane of the SR gasoline from the tight oil). Lower REO and ZSM-5 typically will both improve the economics despite the gasoline loss, but the increase in LPG may not be feasible

- Maximize Preheat: it is more economical to burn NG then make coke to keep the FCC in heat balance

- Catalyst Management: More proactive catalyst management due to the variability of the feed

- Contaminants: High alkali metals and iron requires proper catalyst management
Wide Variety of Catalysts Used in Tight Oil Application

Gas Oil Max Conversion
- NaphthaMax®
- NaphthaMax® II
- NaphthaMax® III
- PetroMax™

Gasoil Max Distillate Units
- HDXtra™

Resid Max Conversion Units
- Endurance®
- Flex-Tec®
- Fortress™

Resid Max Distillate Units
- Stamina™
Summary

- Advantaged tight oil production will continue to rise in North America, providing economic feedstocks to US refiners
- FCCs processing tight oil generally experience:
  - Higher conversion
  - Circulation constraints
  - Minimum regenerator temperatures
  - Higher alkali and iron contaminant
- FCC catalyst technology and service must be flexible to meet the changing feed quality and operating conditions associated with the crude
  - There is no universal catalyst solution for tight oil
- BASF is the market leader for tight oil FCC applications providing catalyst solutions to meet the unique challenges of processing tight oil