Residue Hydrocracking Solutions For Refinery Sustainability

RefComm Galveston
April 29 - May 3, 2019

Dan Gillis - Director, Technology
Chevron Lummus Global
License a wide array of Hydroprocessing and Heavy Oil Upgrading Technologies

Addressing IMO 2020 and crude to chemicals objectives with innovative solutions
Operational Excellence Through Chevron

One of the world’s leading refiners

- High level of hydroprocessing
- Operates >100 high-pressure hydroprocessing reactors
- In USA operates 6 ISOCRACKING units
- Operate 4 Delayed Cokers

CLG Benefits as:

- Part of Chevron Hydroprocessing Best Practice Network
- Draws on Chevron’s operating expertise
Entire Project Support from McDermott
Market Pressures Driving Residue Upgrading Solutions to High Conversion

Demand higher for PetChem than for transportation fuels

Transportation fuels & LSFO strong demand

Weak demand for HSFO and Coke

Residue Hydrocracking is best fitted to meet all requirements
Crude Oil to Chemicals: Optimal Refinery – Steam Cracker Complex

Only McDermott can provide all technologies and offer overall complex guarantees – Chemical yields, on-stream factor

100+ VGO steam cracker heaters

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Crude Oil to Chemicals: Optimal Refinery - Petrochemicals Complex

Only McDermott can provide all technologies and offer overall complex guarantees – Chemical yields, on-stream factor

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THE SOLUTION TO MAXIMIZING CONVERSION TO HIGH-VALUE PRODUCTS

THE LC-FINING™ PLATFORM
Robust LC-FINING™ Ebullated Bed Residue Hydrocracking Technology Platform

**Reactor Features**

- Upflow Reactor
- Low pressure drop
- Recycle pump backmixes and expands single catalyst bed
- Nearly isothermal
- Catalyst can be added and withdrawn on line

![Diagram of Reactor](image)

- Feed and Hydrogen
- Gas Bubbling Up in Expanded Catalyst Bed
- Recycle Pump
- Recycle Cup
- Products
LC-FINING™ Residue Hydrocracking Meets Future Product Demands

Extensive Commercial Experiences

- **Gas Cooling Purification & Compression**
- **Hydrogen Make-up**
- **HDT Naphtha**
- **ULSD Diesel**
- **VGO**
- **UCO (VR)**

- **Vacuum Residue**

- **Reactor Temperature**: 410–440°C (770–824°F)
- **Reactor Pressure**: 110–180 bar (1600-2600 psig)
- **Resid Conversion**: 55–85%
- **Desulfurization**: 60–85%
- **CCR Reduction**: 40–70%
- **Demetallization**: 65–88%

High Pressures and Temperatures

High Conversion and contaminant removal
LC-FINING™
Product Separation and Fractionation System

- From last EBED Reactor
- From Interstage Separator
- Hot High Pressure Separator
- Warm High Pressure Separator
- Cold High Pressure Separator
- MP Amine Absorber
- HP Amine Absorber
- Membrane Unit
- Make-Up Compression
- Warm Medium Pressure Separator
- Cold Medium Pressure Separator
- Low Pressure Flash
- Warm Medium Pressure Separator
- Hot Medium Pressure Separator
- Recycle Gas
- Make Up Hydrogen
- Light Ends to Gas Plant
- Naphtha
- Diesel
- Make Up Compression
- Atmospheric Fractionator
- To Fuel Gas
- Vacuum Fractionator
- LVGO
- HVGO
- UCO
- Diesel
- Atmospheric Fractionator
- To Fuel Gas
- Vacuum Fractionator
- LVGO
- HVGO
- UCO

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LC-FINING™ Reliability Enhanced by Design Features and Best Practices

Customer Performances:
- A 96%+ on-stream factor
- B ran for 42 months straight from first day of oil in
- C has 3 units with typically 4 years between turnarounds

Reliability and High Operating Factors are Absolutely Essential!

Whole Refinery Operation will Ride on Residue Upgrading Unit!
LC-FINING™ Commercialization of Innovations

Innovations
- PSA and Membranes for recycle gas purification
- Interstage reactor separator
- Close coupled integrated hydrotreating
- Combined LC-FINING and hydrocracking

New applications
- LC-MAX for 90+% conversion
- LC-LSFO to make IMO 2020 ULSFO
- LC-SLURRY for full conversion

Lowers Costs and Increases Benefits
LC-FINING™ with Integrated Hydrotreating Produces Clean High Quality Products

Integrating Hydrotreating simplifies fractionation and produces clean products

Hydrotreating equipment 50% of stand alone unit, 60-70% of standalone cost
LC-FINING™ with Integrated Two-Stage Hydrocracking Maximizes Distillates

Key is a “clean” second-stage for Selective Cracking to Euro V Diesel
WHY IS CONVERSION LIMITED IN RESIDUE HYDROCRACKING?
Asphaltenes and CCR in Vacuum Residue

<table>
<thead>
<tr>
<th>Temperature</th>
<th>CCR (%)</th>
<th>Hydrogen Content (%)</th>
<th>Asphaltenes (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>565°C+</td>
<td>~24%</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>700°C+</td>
<td>~38%</td>
<td>9.2</td>
<td>56</td>
</tr>
</tbody>
</table>

*Arab Heavy VR

As we push conversion we have to convert more and more difficult type of asphaltenes!
What Do We Know About Asphaltenes?

- Asphaltenes can be of many different types – good, bad and really ugly!

- CLG has developed proprietary methods to identify types

- Allows us to know at what conversion level the converted, heaviest asphaltenic cores will drop out of solution (sediment formation)

- Defines the maximum conversion without serious reactor & downstream equipment fouling

*CLG large database of commercial data used to set conversion limits for each unit*
Managing Sediment Formation is the Key to High Conversion in Residue Hydrocracking

Sediment vs Conversion

Feed properties impact conversion

- Aromatic diluents
- Additives / co-catalysts?
- Catalyst advances
- Flow scheme solutions

Full reactor potential not realized by sediment in UCO

Feed A
- high sediment forming

Feed B
- low sediment forming

Typical Acceptable level

Sediment increases at higher conversions
Aromatic Diluents Improve Solvency and Reduce Sediment

FCC Slurry Oil is an ideal diluent

Temperature Profiles need to be considered

Injection downstream can reduce separation sections fouling

Injection location important

Can reduce sediment by 0.1 wt% and increase conversion by 2-3 wt%
Soluble Molybdenum Co-Catalyst Benefits?

Type of pilot plant important in determining benefits

Several units have seen severe fouling under reactor distribution grid when using co-catalyst

Suggests large sediment reduction

Sediments

Large pilot plant with Co-Catalyst injection

Base operation (No Catalyst)

Large pilot plant indicates no sediment reduction

Small backmixed pilot plant with Co-Catalyst injection

VR Conversion
A Comparison of Two LC-Fining Units and their EB Reactor Reliability

- Unit A and Unit B are both LC-Fining Units.
- Unit A and Unit B were commissioned within 3 years of one another, and so have incorporated very similar equipment technology.
- Both Units have been designed with 3 Reactors in series.
- Both Units have been designed to process a similar feed, with similar conversion targets.
- Both Units have been designed with very similar Space Rates.
A Comparison of Two LC-Fining Units and their EB Reactor Reliability

- Unit A has been working very closely with CLG and their catalyst supplier:
  - Several CLG recommended LC-Fining Reactor internal modifications have been performed.
  - They now operate with a dual solid catalyst system.
  - Conversion now exceeds design values.
- Unit A has achieved a 4 year run length on their 1st Reactor with one exception since the initial plant start up
  - This exception involved opening all of the LC-Fining Reactors while necessary repairs were carried out elsewhere in the plant during their 3rd run cycle.
EB Reactor Run Lengths
A Comparison

Unit A 1st Reactor Run Lengths

- R101 Run Length in Months - Actual
- R101 Run Length in Months - Planned
A Comparison of Two LC-Fining Units and their EB Reactor Reliability

- Unit B operates with a single solid catalyst system.
  - Plant modifications are now underway to allow operation of a dual solid catalyst system
- During the first 3 out of 4 unit runs Unit B achieved their target run length of 3+ years.
  - Their first run was cut in half due to an 8+ hr site wide power failure which required all 3 LC-FiningReactors be cleaned.
  - During run 6, 7, 8 & 9 under grid fouling in the 1st LC-Fining Reactor necessitated a SD for cleaning after approx. 1 year of operation.
  - During run 6, 7, 8 & 9 Unit B injected organo-moly into their feed stream.
A Comparison of Two LC-Fining Units and their EB Reactor Reliability

Unit B 1st Reactor Run Lengths

- R101 Run Length in Months - Actual
- R101 Run Length in Months - Planned
A Comparison of Two LC-Fining Units and their EB Reactor Reliability

- CLG has been working closely with two of our licensees who have chose to inject organo-moly into their feed.
- Both of these units have experienced severe under grid fouling in the 1st LC-Fining Reactor.
- Extensive analysis of the under grid fouling deposits shows them to contain a high percentage of moly, but little to no alumina.
- A third LC-Fining unit which has processed feed containing naturally occurring organic Moly has also experienced severe under grid fouling in the 1st LC-Fining Reactor.
Catalyst Advances Allow Higher Conversion

Conversion-Sediment Tradeoff Pattern

Higher Conversion obtained with:
- Advanced catalyst formulations
- Dual catalyst system
- Optimized operating conditions
LC-FINING™ Flow Scheme Solutions increase Residue Hydrocracking Performances

Option:
- Processing LC-FINING UCO in a Delayed Coker
- Modifying Feedstock such as with an upfront SDA
- Selective conversion of feedstock components
- Converting low value UCO into high value LSFO or FCC feed
- Utilizing advanced micron sized catalysts

Solution Examples:
- Marathon LC-FINING UCO is processed in a coking unit with overall conversion >88%
- Neste Oil SDA unit on part of LC-FINING feed boosts conversion
- LC-MAX flow scheme to obtain >93% conversion - selected for several new units
- Integration of CLG LC-FINING + RDS technologies
- LC-SLURRY advanced slurry hydrocracking to maximize high value products
CLG LC-FINING™ plus Coking

More Feed Flexibility

Increased liquid yields

Combined Liquids

Feed

Hydrogen

Unconverted Bottoms

Coke

Better hydrogen utilization

Less and higher-quality coke

Combination results in high conversion (88-90%)
LC-FINING™ + Coking Increases Liquid Yields and Produces High-Value Coke

Anode Grade Coke
High Value = about 1/3 of liquid prices
CLG LC-MAX®
for High-Conversion and High-Quality products

Unique flow scheme using proven processing steps

Separate DAO higher severity reactor

VGO suitable for Hydrocracking

Small residue stream <10%

High conversion with high liquid selectivity in one process
LC-MAX® – Process Features

- 93%+ conversion for difficult crudes
- Fully integrated two-stage process
- Whole VR is hydrocracked in a first reaction stage
- Stage 1 UCO is deasphalted to remove heavy asphaltenes
- DAO is hydrocracked in Stage 2 (much higher rate constant and cleaner operation)
- Hydrogen not wasted in hydroconversion of difficult heavy asphaltenes
- Avoids production of 4-ring HPNA that are very difficult to upgrade

<table>
<thead>
<tr>
<th>Processing Urals VR</th>
<th>LC-FINING</th>
<th>LC-MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion, %</td>
<td>63</td>
<td>88-92</td>
</tr>
<tr>
<td>Feed Flexibility</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Reactor Volume</td>
<td>Base</td>
<td>0.9 x Base</td>
</tr>
<tr>
<td>Chemical Hydrogen</td>
<td>Base</td>
<td>Base x 1.15 for 20% Higher Conversion</td>
</tr>
<tr>
<td>Catalyst Addition Rate</td>
<td>Base</td>
<td>Base x 0.88</td>
</tr>
<tr>
<td>Bottoms Product</td>
<td>LSFO</td>
<td>Coker Feed, Gasifier Feed</td>
</tr>
<tr>
<td>Fractionation Section Fouling</td>
<td>Base</td>
<td>&lt;&lt; Base</td>
</tr>
</tbody>
</table>
CLG LC-MAX®-G
for High-Conversion and FCC based refineries

LC-MAX based flow scheme

- Vacuum Residue
- LC-FINING Reactors (1-2)
- Heavy Oil Fractionation
- VGO
- DAO
- SDA Extractor
- Pitch
- Vacuum Residue
- Distillates
- FCC Feed
- RDS Reactor

RDS reactor has moderate LHSV & 2+ year life

High quality distillates and FCC feed

Small residue stream <10%

High conversion to high-quality FCC feed
LC-MAX® Achieves High Liquid Yields and has Yield Selectivity Options

C5-VGO: 73.3
+ 19.0 MS UCO

IDHC = Integrated Distillate Hydrocracking
CLG LC-LSFO™ (LC-FINING plus RDS) for Conversion and LSFO production

Great solution for customers wanting conversion plus LSFO

Heavy Oil Hydrotreated to make LSFO or RFCC Feed

Produce only high-value products

No low-quality residue

Filtration to enable hydrotreating
CLG LC-SLURRY™
for Full Conversion to High-Quality Products

Unique high activity ISOSLURRY™ Catalyst

Integrated Hydrotreating assures high-quality products

Full conversion with highest liquid yields and product values

LC-FINING based platform

Vacuum Residue

Heavy Oil is catalyst free and suitable for further processing

Catalyst Recycle

Heavy Oil Fractionation

Heavy Oil

Spent Catalyst to Metals Recovery

Vacuum Residue

Fresh Catalyst

Catalyst Recovery

Heavy Oil (Catalyst Free)

VGO

Distillates

Heavy Oil

Catalyst Recovery

Spent Catalyst to Metals Recovery

Heavy Oil

Integrated Hydrotreating assures high-quality products

Full conversion with highest liquid yields and product values

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LC-FINING™ Liquid Yields Increase Significantly with Flow Scheme and Catalyst Advances

LC-FINING

<table>
<thead>
<tr>
<th>C5-VGO:</th>
<th>73.3</th>
<th>82.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 19.0 MS UCO</td>
<td>84.7</td>
<td></td>
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LC-MAX

<table>
<thead>
<tr>
<th>C5-VGO:</th>
<th>79.4</th>
</tr>
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<tbody>
<tr>
<td>+ 12.7 LS UCO</td>
<td>86.7</td>
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</table>

LC-LSFO

<table>
<thead>
<tr>
<th>C5-VGO:</th>
<th>61.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 4.0 LS UCO</td>
<td>60.0</td>
</tr>
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</table>

Legend:
- C1-C4
- Naphtha
- Diesel
- VGO+
- Residue
Residue Hydrocracking Options Case Study

Existing refinery basis:
- 300,000 BPD,
- Arab light crude
- VGO HC, FCC, and visbreaking conversion units
- Produces transportation fuels and HSFO

Evaluated impact and benefit of:
- Residue hydrocracking alternates
- Aromatics complex – make Para-Xylene
- Steam cracker – make Ethylene and derivatives
Feed and Product Pricing Basis

Assumptions:
- 2020+ scenario with HSFO sold as if at distressed prices
- Availability of Natural Gas by pipeline
- Gasoline desired over distillates
- Coke/Pitch assumed low in value

<table>
<thead>
<tr>
<th>Product</th>
<th>$/MT</th>
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<tbody>
<tr>
<td>LPG</td>
<td>665</td>
</tr>
<tr>
<td>Finished Butadiene</td>
<td>1079</td>
</tr>
<tr>
<td>Finished Ethylene</td>
<td>1296</td>
</tr>
<tr>
<td>Propylene PG</td>
<td>1021</td>
</tr>
<tr>
<td>Benzene</td>
<td>798</td>
</tr>
<tr>
<td>Para Xylene</td>
<td>923</td>
</tr>
<tr>
<td>Euro V 95 RON Gasoline</td>
<td>847</td>
</tr>
<tr>
<td>Jet A1</td>
<td>757</td>
</tr>
<tr>
<td>Euro V Diesel</td>
<td>794</td>
</tr>
<tr>
<td>HSFO</td>
<td>200</td>
</tr>
<tr>
<td>LSFO</td>
<td>692</td>
</tr>
<tr>
<td>Coke/Pitch</td>
<td>50</td>
</tr>
<tr>
<td>Sulfur</td>
<td>70</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Feed stocks</th>
<th>$/MT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arab Light Crude, $/bbl</td>
<td>70.8</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>158</td>
</tr>
<tr>
<td>($/MSCF)</td>
<td>(3.50)</td>
</tr>
<tr>
<td>Methanol</td>
<td>365</td>
</tr>
<tr>
<td>Natural Gas ($/MSCF)</td>
<td>(3.50)</td>
</tr>
</tbody>
</table>
Residue Conversion Addition
Impact on Refinery Yields

Process:
- LC-FINING
- LC-MAX
- LC-LSFO
- LC-SLURRY

High Value Products Increase:
- LC-FINING: 16.3% + 6.7% MSFO = 23.0%
- LC-MAX: 21.1%
- LC-LSFO: 18.2% + 4.5% LSFO = 22.7%
- LC-SLURRY: 21.1% + 1.5% LSFO = 22.6%

Residue S, wt%:
- LC-FINING: <2.0
- LC-MAX: 4.3
- LC-LSFO: <0.5
- LC-SLURRY: <0.5

Diagram shows the weight percentage of Crude Oil products for each process.
Residue Conversion Addition Economic Benefits

Process:  
- LC-FINING
- LC-MAX
- LC-LSFO
- LC-SLURRY

Profitability Index

- LC-FINING: 2.6
- LC-MAX: 2.9
- LC-LSFO: 3.2
- LC-SLURRY: 3.2

NPV, 10%, 15years

CAPEX

Incremental Revenue, MM$/yr
LC-LSFO™ and Petrochemical Options
Impact on Refinery Yields

<table>
<thead>
<tr>
<th>Process</th>
<th>High Value Products Increase</th>
<th>Residue S, wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC-FINING</td>
<td>16.3% + 6.7% MSFO</td>
<td>&lt;2.0</td>
</tr>
<tr>
<td>LC-LSFO</td>
<td>18.2% + 4.5% LSFO</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>LC-LSFO + Cracker</td>
<td>20.2% + 4.1% LSFO</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>LC-LSFO + Cracker + PX</td>
<td>18.2% + 4.3% LSFO</td>
<td>&lt;0.5</td>
</tr>
</tbody>
</table>

- LPG
- Petrochemicals
- Gasoline
- Jet/Diesel
- Fuel Oil
LC-LSFO™ and Petrochemical Options
Economic Benefits

Profitability Index

<table>
<thead>
<tr>
<th>Process</th>
<th>NPV, 10%, 15years</th>
<th>CAPEX</th>
<th>Incremental Revenue, MM$/yr</th>
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<tbody>
<tr>
<td>LC-FINING</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>LC-LSFO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LC-LSFO + Cracker</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LC-LSFO + Cracker + PX</td>
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Residue Hydrocracking is Now the Preferred Residue Upgrading Process

Highest conversion and liquid yields

Very reliable process

Catalyst advances

Flow scheme integrated solutions

Meets future product requirements