

LC-MAX and LC-SLURRY
High Conversion Residue Hydrocracking Technologies

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Over the past several years there have been several significant market changes that have challenged the profitability of refining. Two of the changes have a dramatic effect on the economics of residue conversion. The recent crude price decreases, have put pressure on refinery and upgrading margins. Also, the International Maritime Organization's (IMO) requirements starting in January 2020, that ships burning bunker fuel oil will have to reduce their SO_x emissions which is the equivalent of reducing the bunker fuel oil sulfur from 3.5 wt% to 0.5 wt%.

Refineries will want solutions to these challenges with more efficient and profitable approaches to residue upgrading than the traditional technologies such as coking and conventional residue hydrocracking. Directionally, this implies high conversion residue hydrocracking that is both highly selective in making desired products, cost effectively utilizes hydrogen, and meets refiners' needs for solutions grounded on proven technologies.

In the June 2017, Hydrocarbon Engineering magazine CLG explained the options for residue upgrading and the role residue hydrocracking could play, especially to maximize gasoline and Petrochemical feedstocks. Also in this article, it was highlighted that CLG has responded to these requirements with new residue hydrocracking technologies built on the LC-FINING technology and reactor platform.

The high conversion residue hydrocracking offerings include:

1. High conversion LC-FINING that obtains conversion levels of 85+ wt% within the LC-FINING flow scheme, depending on the nature of the feedstock.
2. LC-FINING + Coking for high liquid yields and production of high-value anode grade coke.
3. LC-MAX that obtains conversion of 90-93 wt% for most feedstocks. This is a flow scheme advancement on LC-FINING where a SDA section is incorporated into the LC-FINING unit to reject sediment precursors into the SDA Pitch stream and converts the SDA DAO into lighter components in a separate LC-FINING reactor.
4. LC-SLURRY with conversion levels of 97+wt% and produces no residue product even on the heaviest and most difficult residues to convert. This is achieved by the use of a highly active and unique slurry catalyst that results in very high conversion in conventional LC-FINING reactors and process conditions, plus full separation of the catalyst from the heavier products.

This now provides refiners with high conversion residue hydrocracking choices that meet all of the possible requirements depending on the specific refiner's configuration, crude choices, and product objectives. The relative yields compared to coking are shown in Figure 1.

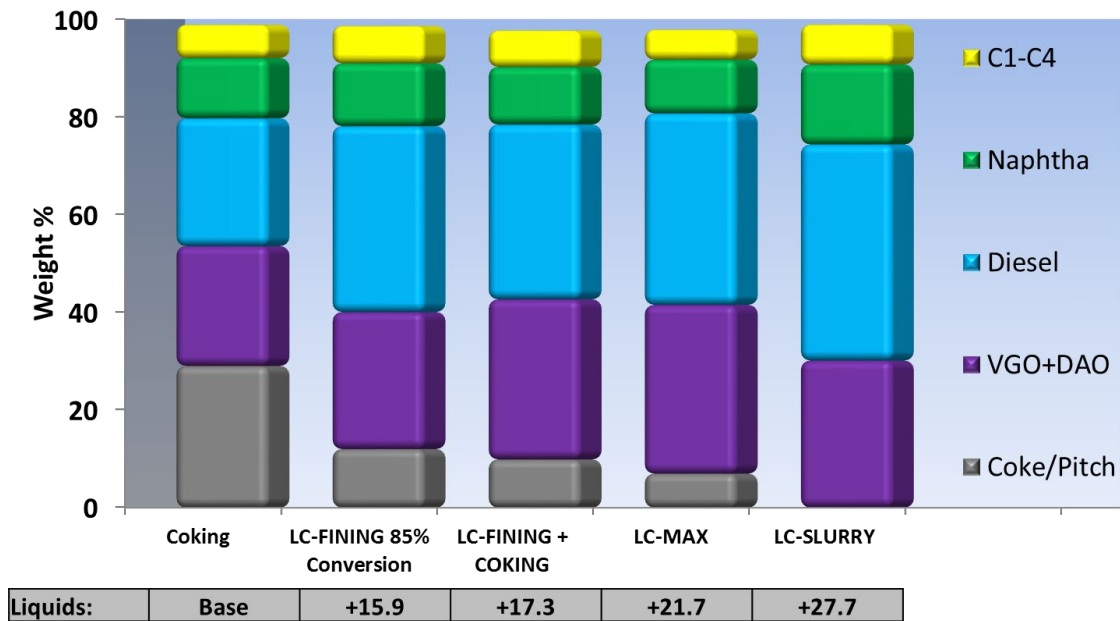


Figure 1: Yield Comparisons between Coking and Residue Hydrocracking Options

As can be seen from this yield comparison bar chart, the residue hydrocracking yields based on the LC-FINING platform have significant yield advantages compared to coking. Constant improvements and advancements of CLG’s LC-FINING residue hydrocracking has led to its present high conversion offering. Additionally, LC-FINING reactor train capacity has been significantly increased while maintaining very high reliability and onstream factor. Depending on the nature of the feed source, LC-FINING can achieve high conversions of 85%, or even higher. This has been due to the constant improvements and innovative solutions CLG has developed and have had commercialized over the years. Some of these include:

- Use of hydrogen recovery membranes for recycle gas purification and elimination of the recycle gas compressor which have increased hydrogen partial pressure and reduced recycle gas and power requirements.
- Reactor interstage separators, allowing increased conversion and capacity by more efficiently using the last ebullated bed reactor.
- Use various aromatic rich liquids for stabilizing the reactor liquid composition.
- Optimizing the operating conditions of the equipment in the Separation and Fractionation sections to ensure long-term equipment reliability and operation.

All of the above have also resulted in the LC-FINING process becoming a highly reliable process that typically will have a run length of 3 years or more before it is shut down for inspection and routine maintenance.

Referring back to the chart in Figure 1, even though LC-FINING conversion can approach that of LC-FINING + Coking, the greatest yield gains are with LC-MAX and LC-SLURRY, which are uniquely positioned to maximize liquid yields compare to other residue hydrocracking approaches.

Detailed discussions of the benefits and features of LC-MAX and LC-SLURRY technologies are provided below:

LC-MAX

Even though LC-FINING can now obtain high conversion, there are some residues that have high tendencies to form sediment, which can lead to fouling in the downstream separation and fractionation sections. These types of residue, even with the latest improvements in LC-FINING, can still be limited to conversion levels of under 70 wt%. This has led to the development of the LC-MAX process.

LC-MAX process combines very well proven LC-FINING technology with solvent de-asphalting SDA. The reactor section of LC-MAX is shown in Figure 2.

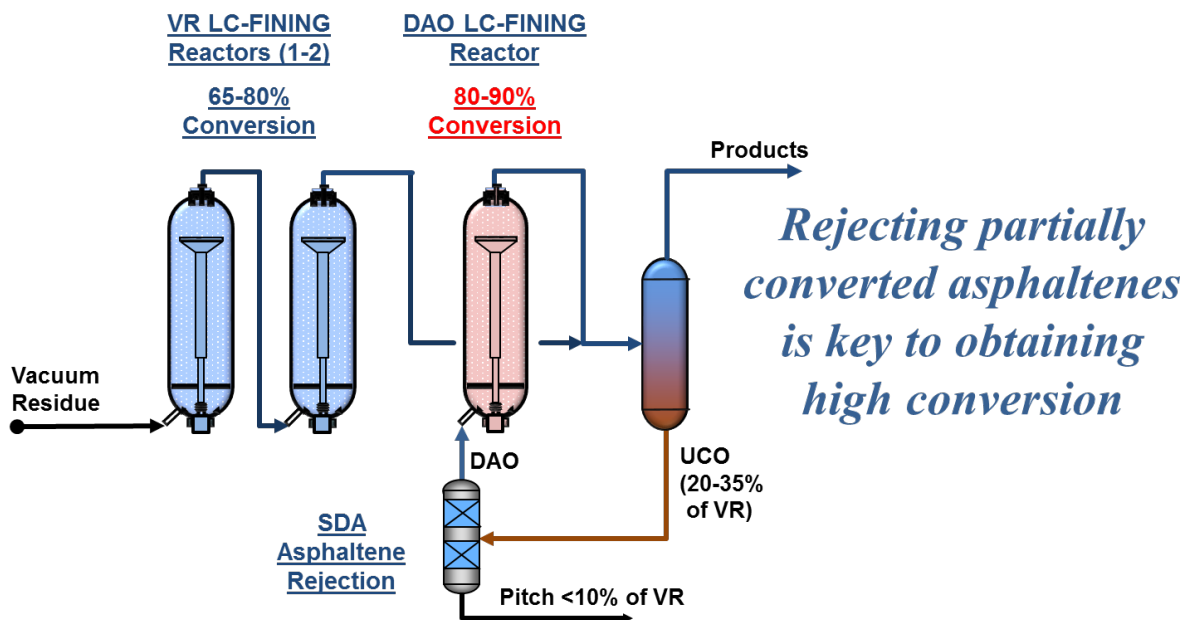


Figure 2: LC-MAX Reactor Section

The LC-MAX reaction section consists of 2 stages:

- LC-MAX 1st reaction stage processes vacuum or atmospheric residue at moderate to high conversion. Conversion in 1st stage is carefully selected and set by adjusting reactor severity to suppress sediment formation and fouling of downstream equipment. CLG's proprietary kinetics model predicting residue conversion and deep understanding of residue molecules allows varying reactor conditions and processing low cost opportunity crudes.
- LC-MAX 2nd stage takes full advantage of asphaltenes and sediment precursor molecules rejection in SDA section. This also occurs with a relatively high lift of 75-85 vol% from the LC-MAX 1st reactor stage unconverted oil. The 2nd stage is able to obtain high conversion of the deasphalted oil (DAO) from the SDA section as the DAO is relatively highly reactive, and it contains relatively very little sediment precursors, thus allowing operation of the DAO LC-FINING reactor at a high severity.

The Pitch from the SDA section is concentrated with the remaining asphaltenes and higher boiling point molecules, as well as the bulk of the contaminants in the unconverted oil. As such it is relatively high in density, CCR, viscosity, and metals. It is suitable for use as a liquid combustion fuel, and is ideally solidified for combustion applications such as in CFB boilers or Cement kilns. It can also be burnt as a liquid fuel fed to gasifiers, like other SDA Pitches.

CLG has worked with the leading vendor of solidification equipment to develop a practical and cost-effective method to solidify the Pitch. Both CFB vendors and Cement kiln manufactures have verified that the solidified form of the LC-MAX Pitch is a suitable fuel source for their equipment.

High value products from LC-MAX such as naphtha, diesel and VGO can be further hydrotreated or hydrocracked depending on refinery configurations and economics. CLG has been the first licensor to incorporate and commercialized hydrocracking and hydrotreating in the same reaction loop. Integrated hydro-processing scheme allows 30-40% investment saving compared to standalone unit.

Because of the efficiency of the LC-MAX flow scheme it is able to obtain up to 25 wt% conversion higher than with LC-FINING. When processing difficult feedstocks, LC-MAX typical performance indicators relative to LC-FINING at say 70% conversion are:

- Reactor volume is the same
- Conversion is increased by over 20 wt%
- Liquid yield is increased by 15-17 wt%
- Catalyst addition rate is reduced by ~12%
- Hydrogen consumption is increased by ~15%
- Capital cost is increased by ~15-20%

In summary, LC-MAX is an excellent solution for high residue conversion while employing the proven LC-FINING flow scheme with well proven SDA technology. Several new units are currently in various stages of design or construction.

LC-SLURRY:

LC-SLURRY technology is the next generation of slurry hydrocracking as it is based on CLG's commercially demonstrated LC-FINING technology and uses a very unique catalyst. LC-SLURRY converts near 100% of vacuum residue or solvent de-asphalting (SDA) pitch to high-value liquid products.

Unlike LC-FINING or LC-MAX that use conventional extruded residue hydrocracking catalysts, LC-SLURRY employs a unique, breakthrough ultra-fine, proprietary bimetallic high-activity ISOSLURRY™ catalyst that can be recovered and recycled in the process. The catalyst has high pore volumes to capture feed metals and coke precursors eliminating fouling concerns associated with other catalyst or additive systems. A comparison of ISOSLURRY™ catalyst to conventional Ebullated bed catalyst is shown in Figure 3.

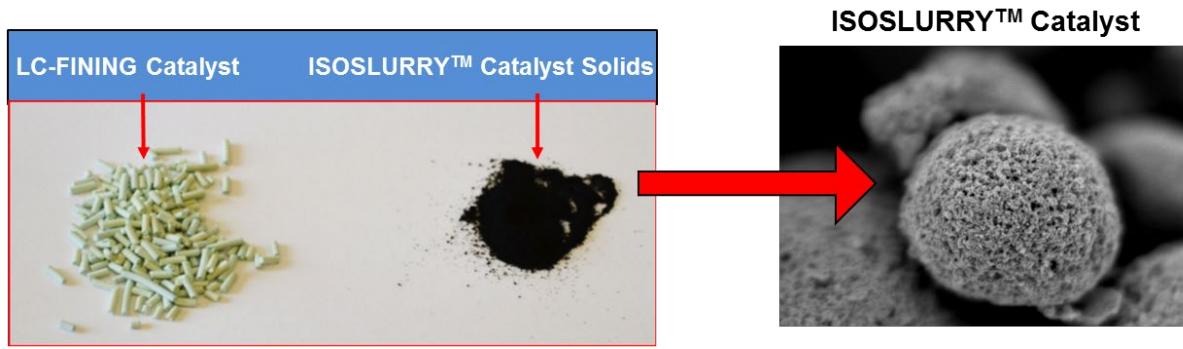


Figure 3 – ISOSLURRY™ Catalyst

LC-SLURRY uses the proven and optimal LC-FINING Platform with similar reactor temperature and pressure, leading to superior hydrogenation, coke suppression and stable and reliable operation. Figure 4 shows the wide range of difficult feedstocks processed in the LC-SLURRY Demonstration unit. These very high conversion levels result in liquid yields of over 90 wt% as shown in Figure 1.

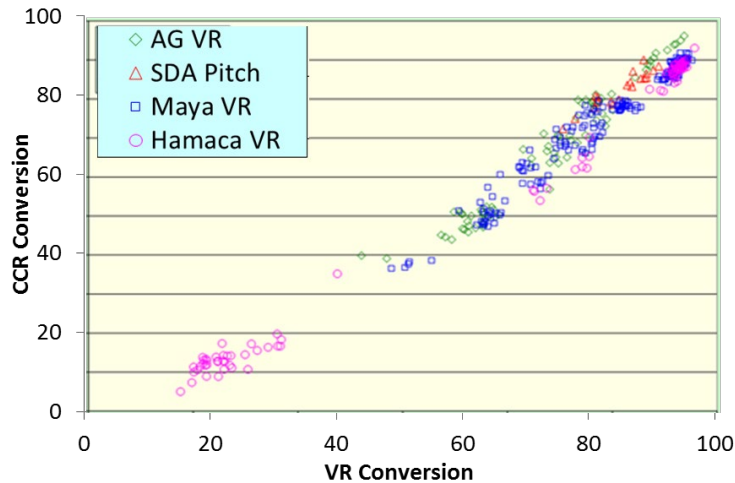


Figure 4 – LC-SLURRY Conversion on Difficult Feedstocks

Extensive development and pilot plant studies have verified these advantages. The demonstration unit has verified that LC-SLURRY can achieve conversion levels of 97 wt% or even higher on difficult to process residues. Even when processing the most difficult residues, such as SDA Pitch both the conversion and CCR reduction are very high.

The LC-SLURRY flow scheme is very similar to LC-FINING's. Major differences are that with LC-SLURRY there is continuous slurry catalyst injection into the feed and separation of the spent catalyst from the heaviest liquid product. The flow scheme can also be adapted to produce maximum Euro-V diesel or maximum naphtha by converting all LC-SLURRY VGO when integrating ISOCRACKING™ technology into the LC-SLURRY flow scheme.

With the addition of integrated VGO Hydrocracking, the yields of Euro-V Diesel can be over 80 vol%. Unconverted residue (Heavy Oil stream) can also be upgraded to ULSFO (<0.5 wt% sulfur) or high-quality RFCC feed. This is due to full separation of the spent catalyst from the heavy oil stream. Due to zero residue production potential with LC-SLURRY, with no undesirable, low-value streams, it redefines residue hydrocracking.

A typical LC-SLURRY flow scheme with integrated product and heavy oil hydrotreating is shown in Figure 5. It can be seen that it is very similar to LC-FINING with major differences due to continuous addition of the ISOSLURRY™ catalyst into the feed and recovery of the spent catalyst in a proprietary catalyst recovery section.

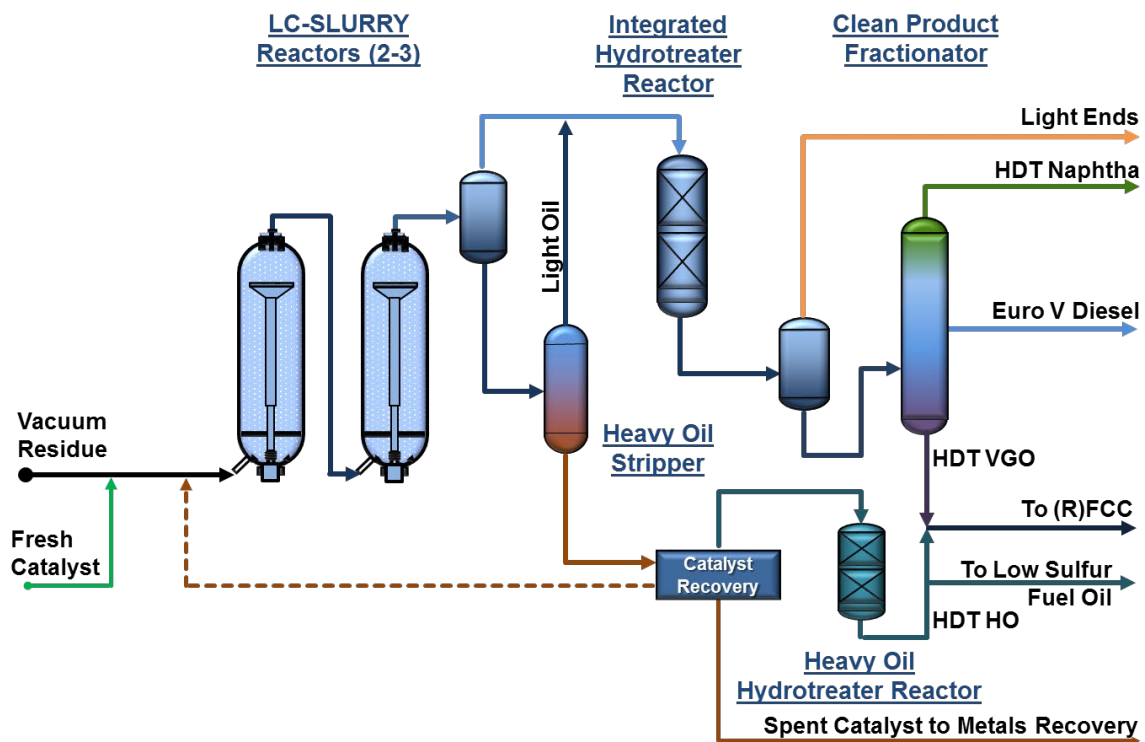


Figure 5 – LC-SLURRY with Integrated Hydrotreating and Heavy Oil Hydroprocessing Option Flow Scheme

Technology Selection Case Studies:

Which technology to select is complicated by the many demands and constraints for each project. There are many reasons for particular technology selections. The main reasons are usually due to the technologies fit with the application, resulting in the best economic return, and the performance expectations of the project, which are greatly impacted by the licensor's experience and capabilities to fully support the technology. Relatively recently CLG has been fortunate that both LC-MAX and LC-SLURRY have been selected. As such, two recent licensed applications, one for LC-MAX and one for LC-SLURRY are provided here to provide examples where one or the other technology are best fits.

Case 1: Asian refinery selects LC-MAX over conventional Slurry Hydrocracking to achieve high conversion and produce sufficient residue to meet power and steam demands.

Case 2: European refinery selects LC-SLURRY to process Russian Export Vacuum Residue, maximize high-quality Diesel, and does not have a need for power production.

In assessing these two cases it is interesting to compare both LC-MAX and LC-SLURRY from a general perspective as shown in Table 1.

Relative to LC-FINING at 70% conversion	<u>LC-MAX</u>	<u>LC-SLURRY</u>
Conversion	+ 20-25%	+30%
Liquid Yield	+14 wt%	+ 20 wt%
Off gas (C ₁ -C ₄)	+1 wt%	+3 wt%
H ₂ Consumption	1.15 x	1.30 x
Investment cost	1.20 x	1.15 x
Catalyst cost	0.88 x	2.0 x
Utilities	1.2 x	1.05 x
Strategic fit	<ul style="list-style-type: none"> ✓ When easy pitch disposal is available ✓ Superior economics ✓ Mature technology ✓ Maximize liquids ✓ Ability to maximize FCC feed 	<ul style="list-style-type: none"> ✓ No low value product ✓ Superior economics ✓ Green project: zero residue, maximize high-quality products, catalyst recycle and offsite metals recovery
Licensing Status	<ul style="list-style-type: none"> ✓ Several units are at various stages of design, engineering and construction in Asia and Europe 	<ul style="list-style-type: none"> ✓ Selected by a European refinery
Licensor Support	<ul style="list-style-type: none"> ✓ Proven technical expertise and high quality personnel to support refiner 	<ul style="list-style-type: none"> ✓ Proven technical expertise and high quality personnel to support refiner

Case 1 Asian Refinery

In this case the refiner wanted a technology that could provide the following benefits:

- Obtain high conversion and liquid yields.
- Ability to integrated within the flow scheme hydrocracking of both the processes and straight run VGOs to high-quality diesel.
- Solution to utilize the unconverted residue to meet the expansion project's power and steam demands.
- Core components of technology commercialized on similar feeds.
- Feedstock flexibility

LC-MAX not only met all of the above requirements, it had the lowest investment cost due to its ability to integrate with VGO Hydrocracking, efficiently use hydrogen, and had an acceptable solution for processing the unconverted residue, (Pitch solidification).

Case 2 European Refinery

In this case the refiner's constraints were different they needed a technology with the following benefits:

- Ability to process Russian Export Vacuum Residue
- Maximize Euro-V Diesel
- Meet refiner's desire for project to be labelled as a green project. This implies no heavy residue solid streams or minimize if possible.
- Minimize investment cost of entire project

In this scenario, LC-SLURRY was an ideal fit as:

- Integration of ISOTREATING and ISOCRACKING within the LC-SLURRY flow scheme resulted in minimizing the investment cost while maximizing production of high quality diesel.
- It is a unique slurry hydrocracking process that for this application the heavy oil stream is able to meet ULSFO specifications.
- No residue production meant no residue combustion power plant which would have reduced the economics of the project as the refinery gets low cost power from utility suppliers.

Summary

High conversion residue hydrocracking is now available and is commercially grounded. This will allow refiners to maximize refinery margins and make the products they desire. CLG's LC-MAX and LC-SLURRY technologies are two approaches, each with its own benefits that allow refiners to realize the margins only available with this type of approach to residue conversion.