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New Hydrocracking Developments Demonstrate Lower Capex and Lower Opex Hydrocracker Designs and Revamps

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New Hydrocracking Developments Demonstrate Lower Capex and Lower Opex Hydrocracker Designs and Revamps

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Abstract

Refineries are continuously challenged to produce more and cleaner products from a broad range of feeds, with limited or no capital investments. Even when capital is available, highest capital efficiency — most capacity/economic value — is a highly sought-after objective. Modern highly stable zeolitic hydrocracking catalysts and innovative configuration changes enable refiners to run their hydrocrackers to the limit and also enable new designs with lower capital cost and reduced operating expense without compromising distillate yield. We share examples of new catalysts and innovative designs and their deployment in revamps and in new designs that are achieving capacity and/or product value improvements currently with 30-50% lower capex and opex.

Hydrocracking Fundamentals

Hydrocracking has been around for over 50 years, since Chevron U.S.A. Inc. (Chevron) built the first commercial unit at Standard Oil of Ohio in the 1960's. There are now over 300 hydrocrackers around the world — almost as popular as the FCC, and getting more popular as world demand turns more toward distillate and other heavier product and feed slate processing. Many new innovations in catalyst and process configuration have enabled this success. Chevron Lummus Global LLC (CLG), a joint venture of Chevron U.S.A. Inc. and CB&I Technology Ventures, Inc., utilizing the industry-leading operating and design experience of both companies, has been especially active and successful with its “ISOCRACKING” technology.

A simple hydrocracker looks, for those that do not have one in their refinery, just like a hydrotreater. Figure 1 shows major equipment of a single-stage once-through (SSOT) hydrocracker consisting of a high pressure section in orange and a low pressure section in blue. Depending on the processing objectives, the reactors can be multiple reactors in series or in parallel and with or without a hot high pressure separator and with or without a high pressure amine scrubber. The fractionation section can vary slightly, mainly with or without a vacuum tower.

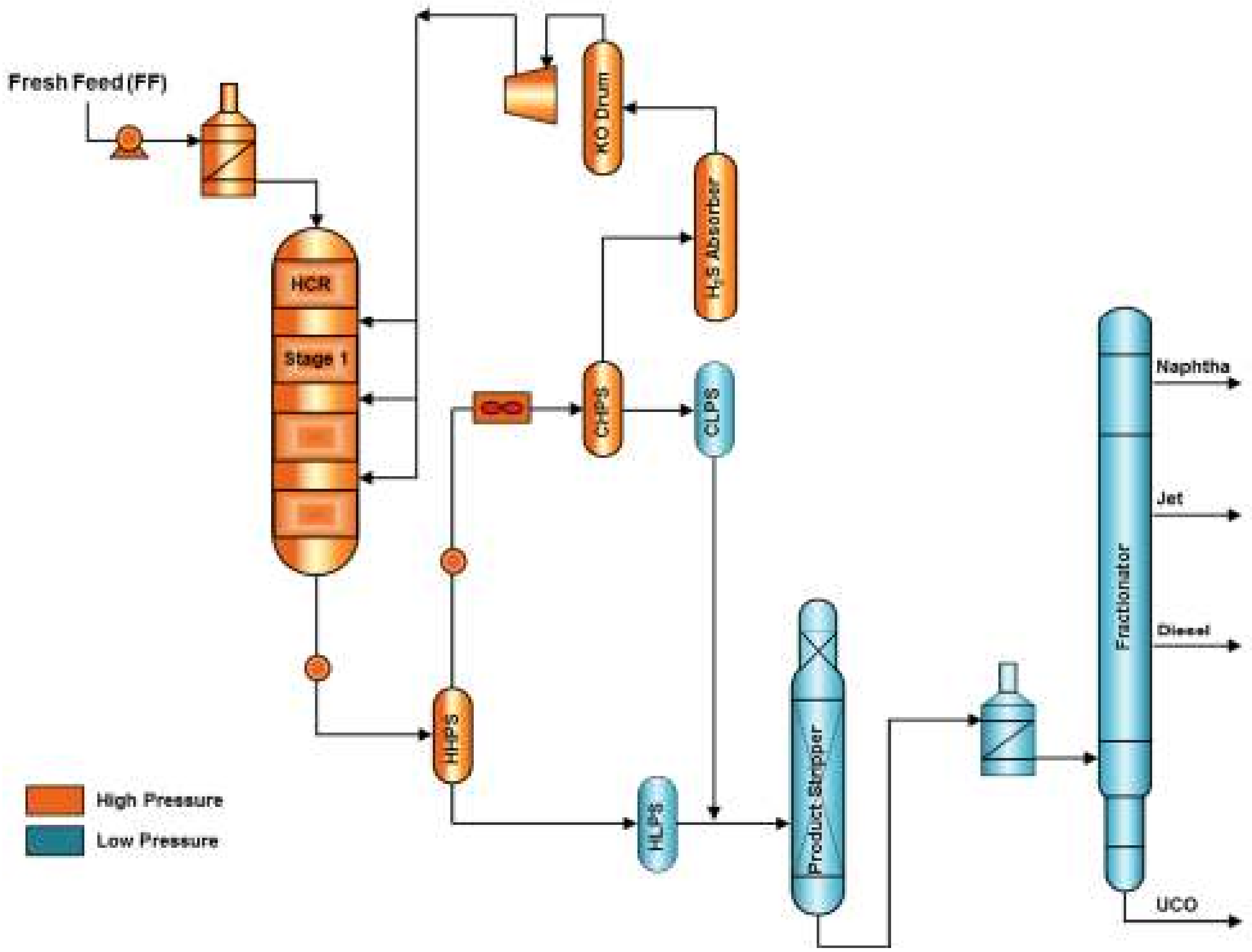

Figure 1 – Single-Stage Once-Through Hydrocracker

Many once-through units were built with nominal conversion ranging from 40-60%. Unconverted oil (UCO) has many uses in the refinery. Many refiners with good gasoline markets used UCO as

FCC feed to improve gasoline yield and control gasoline sulfur as well as SOx emissions. Many refineries have also used UCO as base oil feedstock for further processing into finished lubricants.

There was also another reason for the popularity of SSOT design which limited conversion. Traditional hydrocracking catalysts suffered from selectivity decline with increased conversion. The primary objective of the hydrocracker is to convert VGO and other nominally 700ºF plus boiling hydrocarbons (heavy coker gas oil, visbroken gas oil, DAO, synthetic VGO, etc.) into naphtha, jet and diesel. Especially with the product demand pattern over the last ten years, hydrocracker diesel with low sulfur and high cetane has been a highly preferred product. But as Figure 2 shows, the conventional catalysts do not necessarily yield higher diesel as more UCO is converted. The bottom data points are examples of conventional catalysts from a pilot plant study showing limited improvement to declining diesel yield beyond an optimum once-through conversion level. With conventional catalysts, the net effect past optimum conversion level is that every extra UCO barrel produces naphtha with low octane and low value. Unless the refinery had a petrochemical outlet, this would not be desirable.

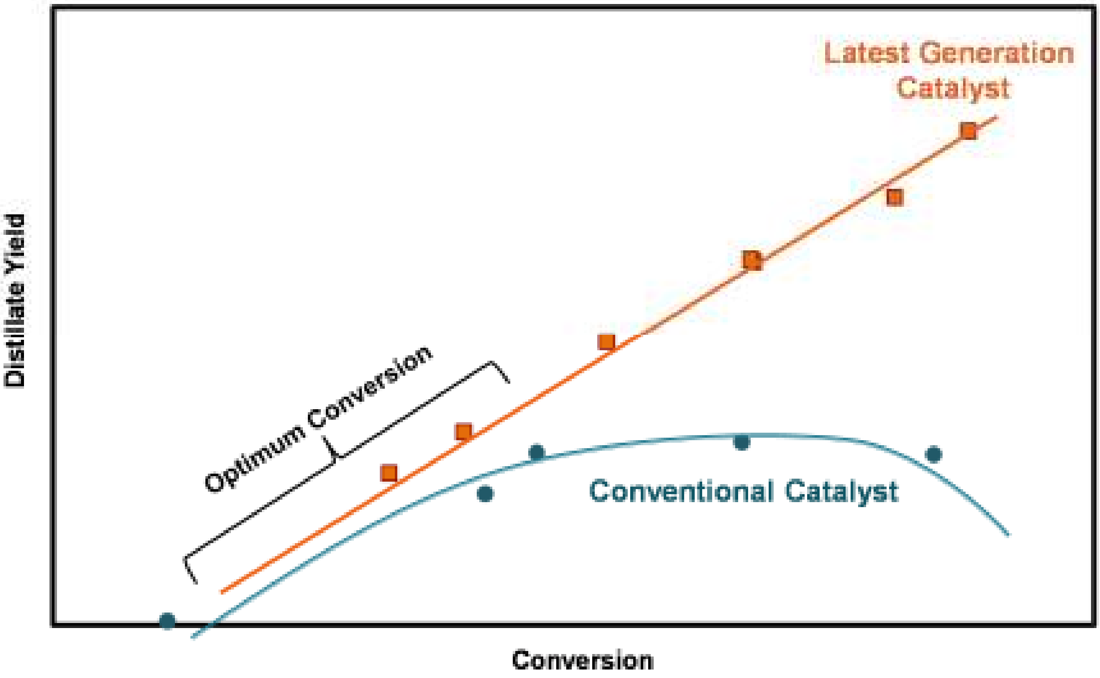

Figure 2 – Effect of Conversion on Distillate Yield

This is not because UCO beyond certain conversion severity cracked directly to naphtha. Extra UCO conversion still produces a similar slate of products including diesel. However, the cracking reaction becomes less selective and the catalysts begin to crack the diesel that was produced in the earlier part of the hydrocracking reactor. The end result is that there is no net increase in diesel production, even as more UCO is cracked.

Extra cracking of diesel also requires additional hydrocracking catalysts. In theory, a 100% conversion once-through hydrocracker would require an infinite amount of catalyst volume and very large investment cost. The reason for this is that, to achieve full conversion, ever larger amounts of diesel would need to be cracked in order to crack ever smaller amounts of UCO, moving through the reactor. Therefore, traditional SSOT hydrocrackers tend to be run at moderate conversions of 40-60%.

One way to overcome this conversion limitation was through a recycle operation. In a recycle operation, after a nominal once-through conversion of 40-60%, the whole liquid product stream would be separated. This can be done in a low pressure fractionation as well as in a high pressure separation. Each has advantages and disadvantages. Both types of separation schemes have been designed and operated by Chevron and CLG-licensed hydrocrackers. The UCO can be sent back to the fresh feed reactor, as shown in dotted line in Figure 3, or sent to a separate high pressure reaction loop, shown on the right side in Figure 3. Traditionally, the flow configuration where UCO is sent back to the fresh feed reactor was called a single-stage recycle hydrocracker (SSREC). When the UCO, after separation, is sent to a separate reaction loop, it was called a two-stage recycle hydrocracker (TSREC). (This definition of stages — reactant separation whether high pressure or low pressure then to a separate reaction loop — has been upended with some innovative process configuration schemes, as will be explained in the latter section of this paper.)

Without a competing diesel reaction in the intermediate stream, diesel selectivity can be maintained as UCO conversion is pushed higher and higher in the recycle hydrocracker reactor.

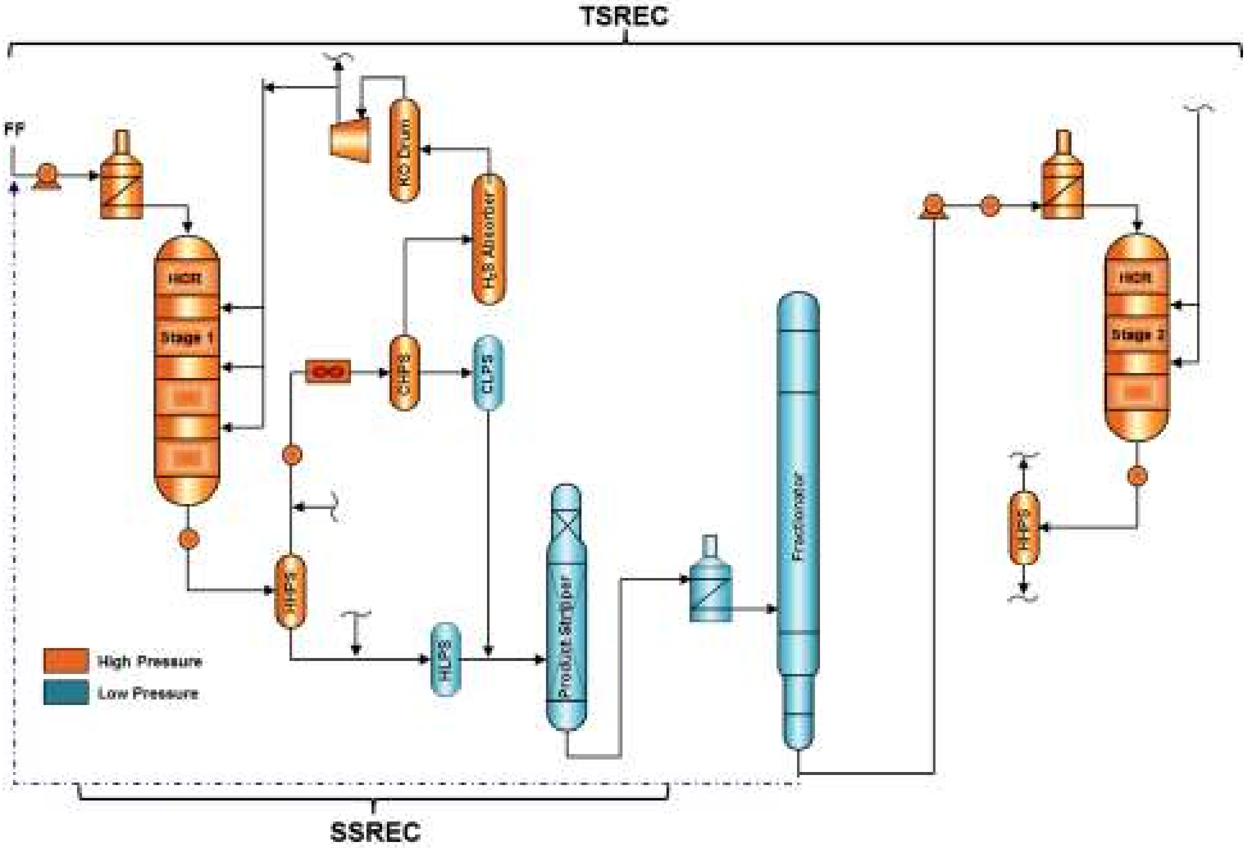

Figure 3 – Recycle Hydrocrackers

New Catalyst Development

A recycle hydrocracker, whether SSREC or TSREC, can deliver higher distillate yield at higher conversion. A recycle operation unit is, of course, more expensive to build and operate than an

SSOT unit. Each refiner's situation will dictate whether the conversion economics favor a recycle hydrocracker.

In addition to recycle operation, a catalyst solution can also increase distillate yield/selectivity at high conversion. Since the 1990's, Chevron and CLG have commercialized selective paraffin wax isomerization and cracking technology into a major force in lube base oil production through hydroprocessing. ISODEWAXING technology enabled 90% plus retention of difficult to crack paraffin molecules with shape selective zeolite. Before this technology, paraffin was cracked to naphtha and LPG. Applying the know-how from this technology, Chevron developed and deployed selective wax cracking catalysts for fuels hydrocracking application.

The hydrocracking reactant stream as it travels through the reactor becomes very paraffinic. The conventional catalysts with ~1 nm wide USY zeolite pores, ~10 nm wide amorphous aluminosilicate pores and base metal sulfides were insufficiently selective. Advanced computational methods have established that wax adsorption and conversion requires zeolite pores about half as wide as those of USY [1]. Replacement of the ~1 nm wide USY zeolite pores with the optimum amount of these narrower pores enabled selective cracking of paraffinic waxy UCO, preferentially to diesel.

The second set of data from the pilot plant study (shown in Figure 2 with a straight line conversion versus diesel yield) demonstrates the success of this technology. Even at higher conversion levels, the distillate selectivity is maintained.

<u>A European Refinery Takes Advantage of New Shape Selective Catalyst</u>

One of the first deployments of the new shape selective hydrocracking catalyst was at a CLG-designed European refinery hydrocracker. This unit is a TSREC design similar to that shown in Figure 3. The unit initially had utilized USY zeolite catalyst and changed to a shape selective ICR 18# series of catalyst for the second cycle.

Figure 4 shows normalized hydrocracking reaction levels for the first and second cycles of the first stage reactor. The new catalyst is operating at an almost 25% higher reaction rate during the second cycle. Higher conversion with conventional catalysts can lead to lowered distillate selectivity. However, as shown in Figure 5, there is no impact on the distillate selectivity. There are many other details not shown here for brevity. The net conversion increased from around 80% to 90%. With conventional catalysts, such change would have resulted in lowered distillate selectivity. Figure 5 shows that selectivity stayed the same, implying additional 700°F plus material hydrocracked produced the same ratio of distillate as the first barrel of 700°F plus material.

An added benefit of the new shape selective hydrocracking catalyst is also in conversion activity. Higher conversion activity allowed CLG to modify the catalyst system to increase the hydrotreating component in the system.

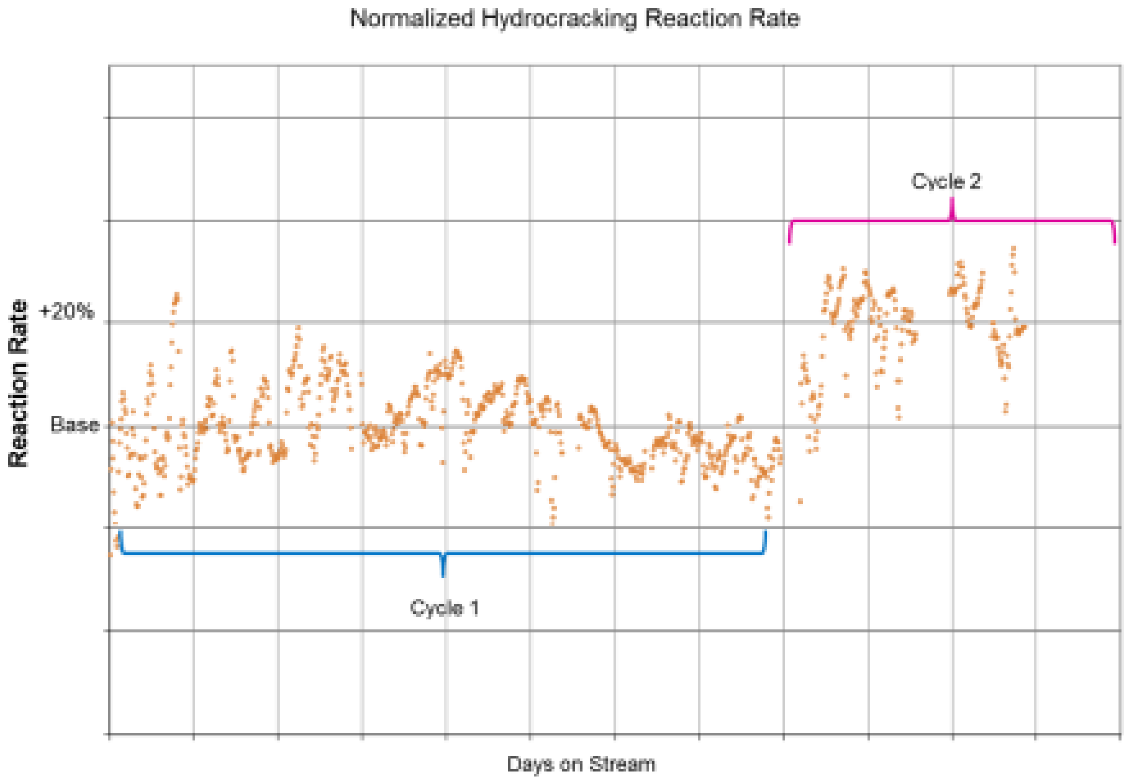

Figure 4 – HCR Reaction Rate

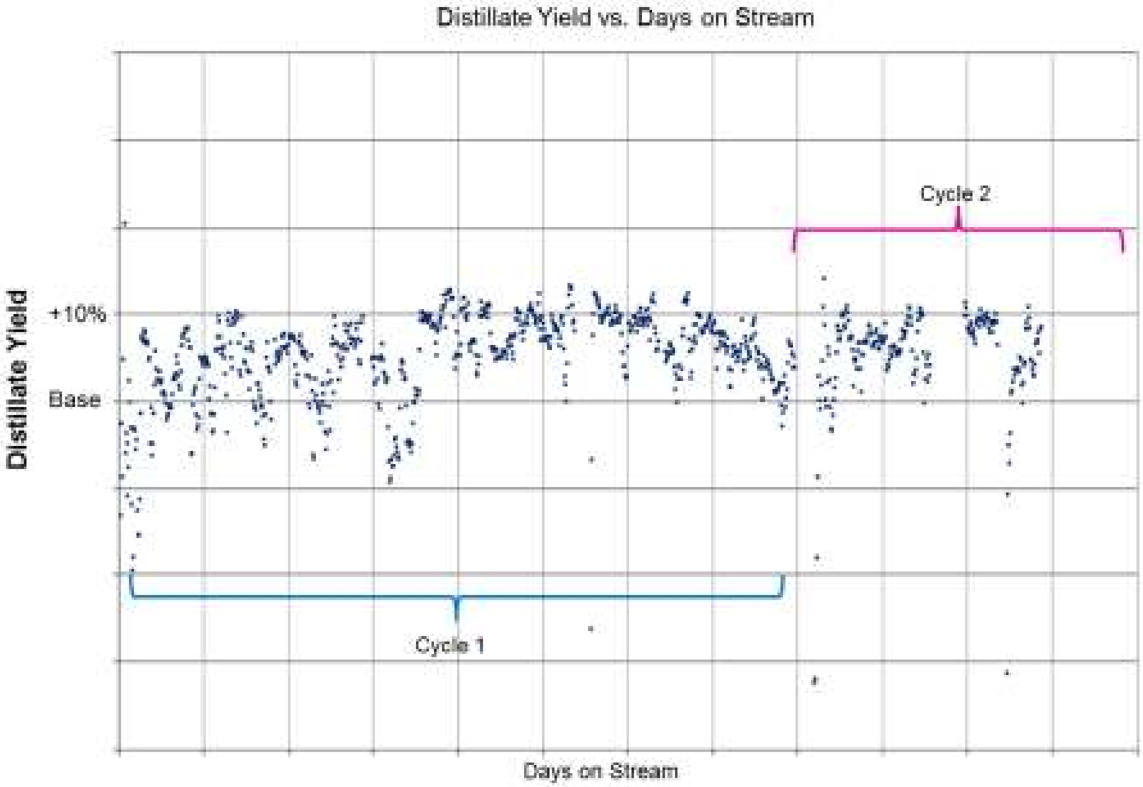

Figure 5 – Multi-Cycle Distillate Yield

Total hydrocracking catalyst component loading in the first stage was lowered by almost 60% while maintaining hydrocracking activity. This enabled higher hydrotreating capability, increasing the potential to process more difficult feed. This refiner is planning to use enhanced first stage capability to lengthen the second stage catalyst life to an unprecedented ten years! (The longest hydrocracking catalyst life without unloading is about nine years at a Chevron hydrocracker.) Figure 6 shows a portion of normalized steady hydrocracking reaction rate in the second stage reactor. The current load is from March 2009.

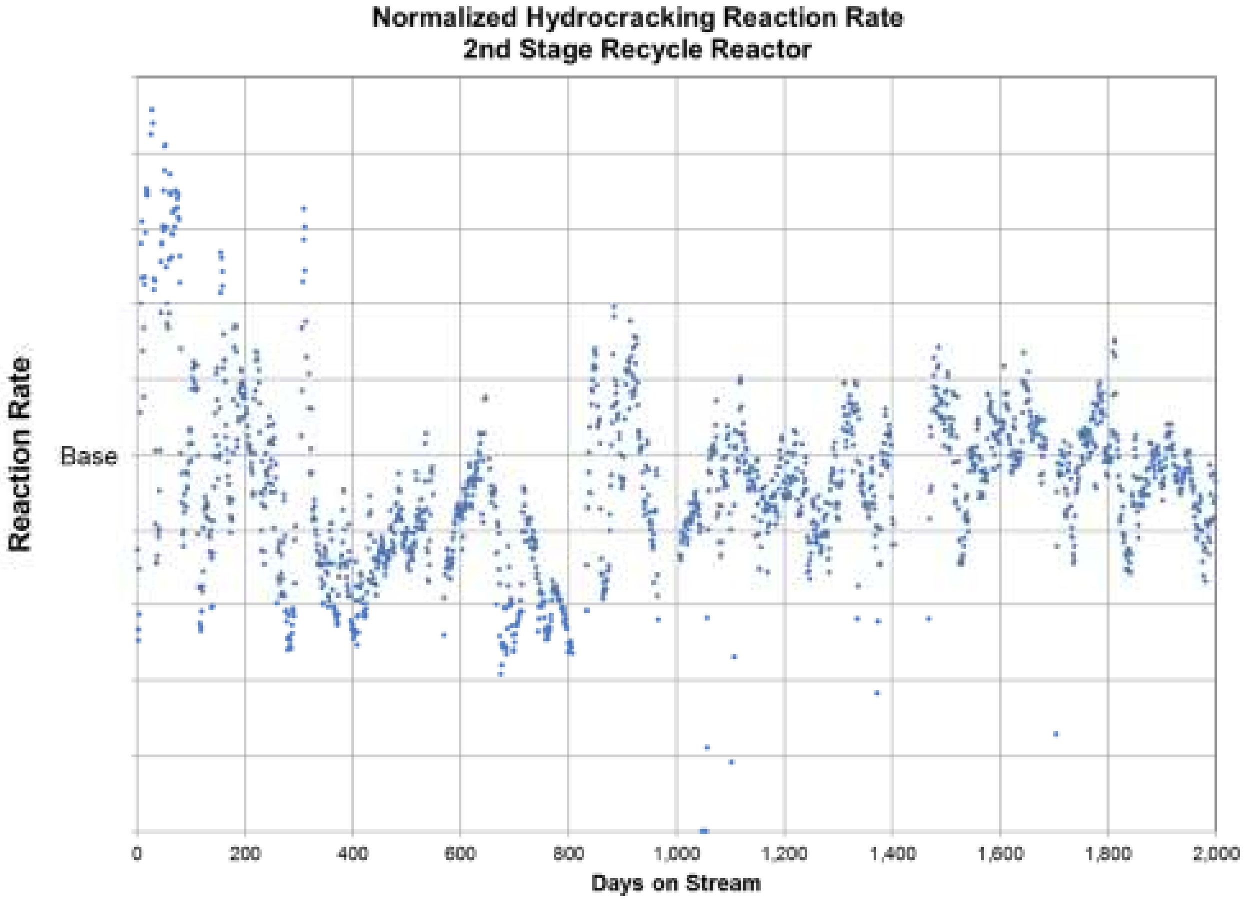

Figure 6 – Unprecedented Long First Cycle Catalyst Life

Increased Conversion Revamp Projects

CLG has licensed a number of simple once-through revamp projects which take advantage of these new developments. Some are in design phase, some in construction and some in operation.

One of the simplest revamp projects was a simple reactor addition either upstream or downstream of the existing reactor(s) to take advantage of new catalysts, as shown in Figure 7. Conversion can and has been increased; product quality or cycle length has also been increased, depending on the project objectives. CLG has implemented such projects in Europe, Asia and North America successfully.

A more recent design for a Chevron affiliate is shown in Figure 8, where a parallel reactor was added along with the latest catalysts to increase conversion, improve yield selectivity, product quality and capacity with no other major equipment revamp.

Of course, a refinery could also take some of the advantages of new technology with just a catalyst change-out only. These projects are handled by CLG's sister organization Advanced Refining Technology, Ltd. (ART), which handles all hydroprocessing catalyst opportunities on behalf of CLG, Chevron and Grace. Every refiner's situation and unit limitations are different, but CLG has found that profit improvement opportunities abound in these times of rapidly changing feedstock and product demand.

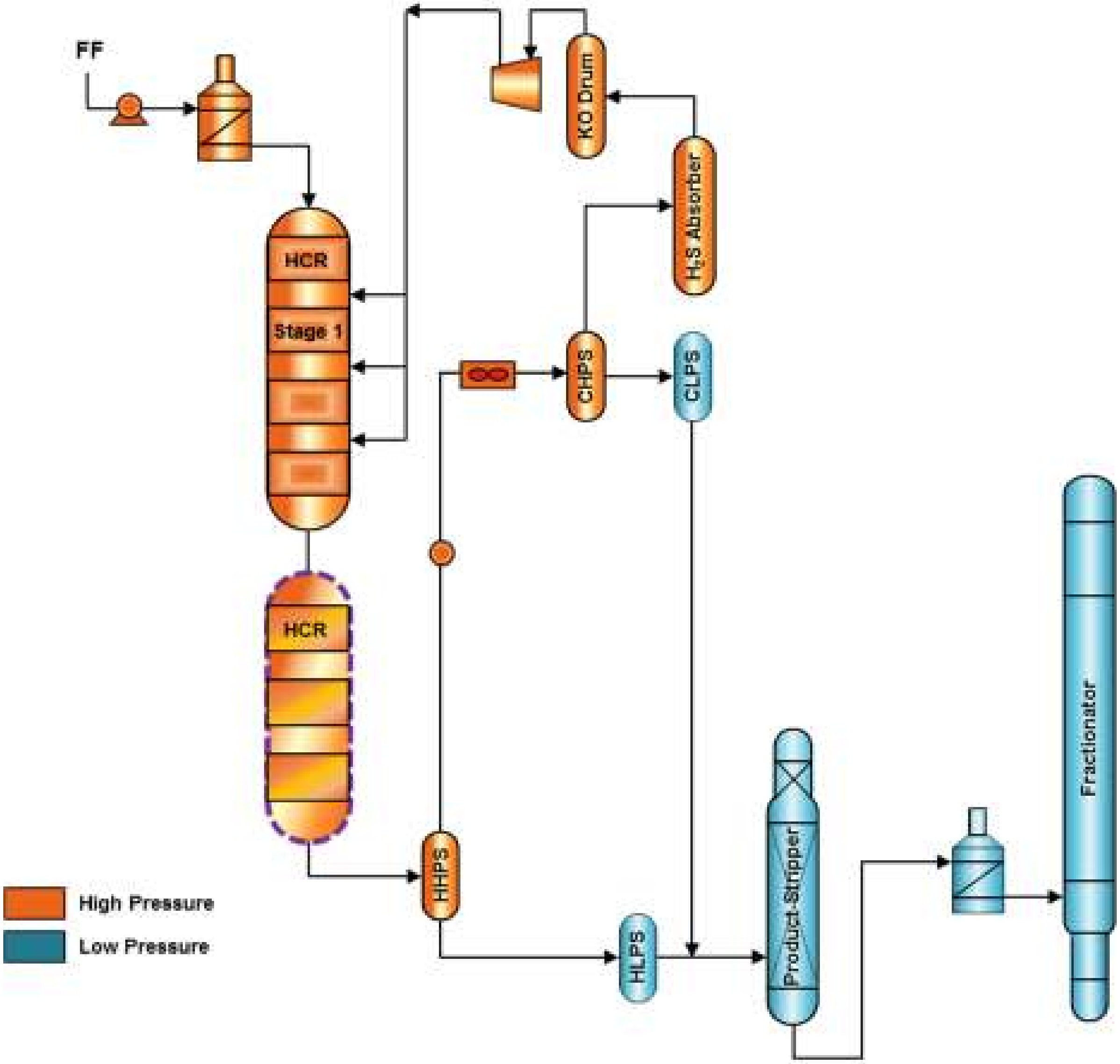

Figure 7 – Series Reactor

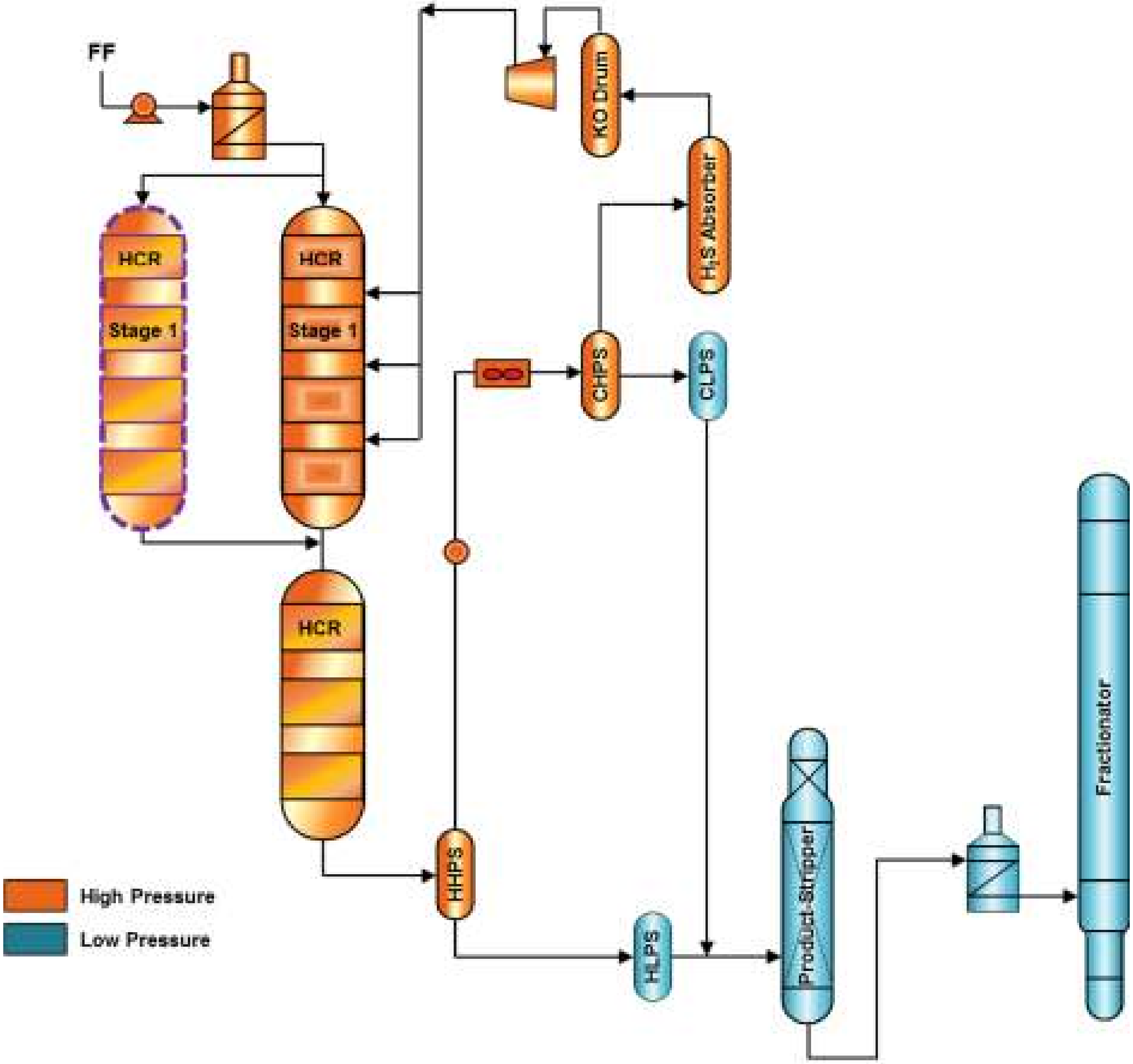

Figure 8 – Parallel Reactor

Application to New Unit Designs

Refiners interested in a new unit design will benefit from the same technology of high conversion distillate selective catalysts. When diesel selectivity is maintained through high conversion, the design of a unit will reflect that and substantial capex and opex savings can be achieved.

Cost data from a recent (2013, Northern Europe) CLG-designed hydrocracker were used to demonstrate potential benefits achievable. Figure 9 shows a conventional catalyst system SSREC design operating at near full conversion of 90% processing 36,000 BPSD of Middle Eastern VGO. Previously, to maximize distillate yield, an optimum per pass conversion would have been around 60%. As explained before, increasing per pas conversion further would result in more gas and naphtha make and would not necessarily yield more distillate. UCO or recycle oil of around 18,000 BPSD would be recycled back to the reaction section for reprocessing. Total reactor charge rate and liquid flow through the unit will be around 54,000 BPSD. The cost of the unit will be proportional to this liquid rate.

However, with the new generation high conversion distillate selective catalyst, once-through per pass conversion can be increased to upwards of 85%. Distillate production will remain the same. Nevertheless, the cost of the unit will be based on a much lower liquid rate of around 38,000 BPD, with UCO or recycle oil being only around 2,000 BPD.

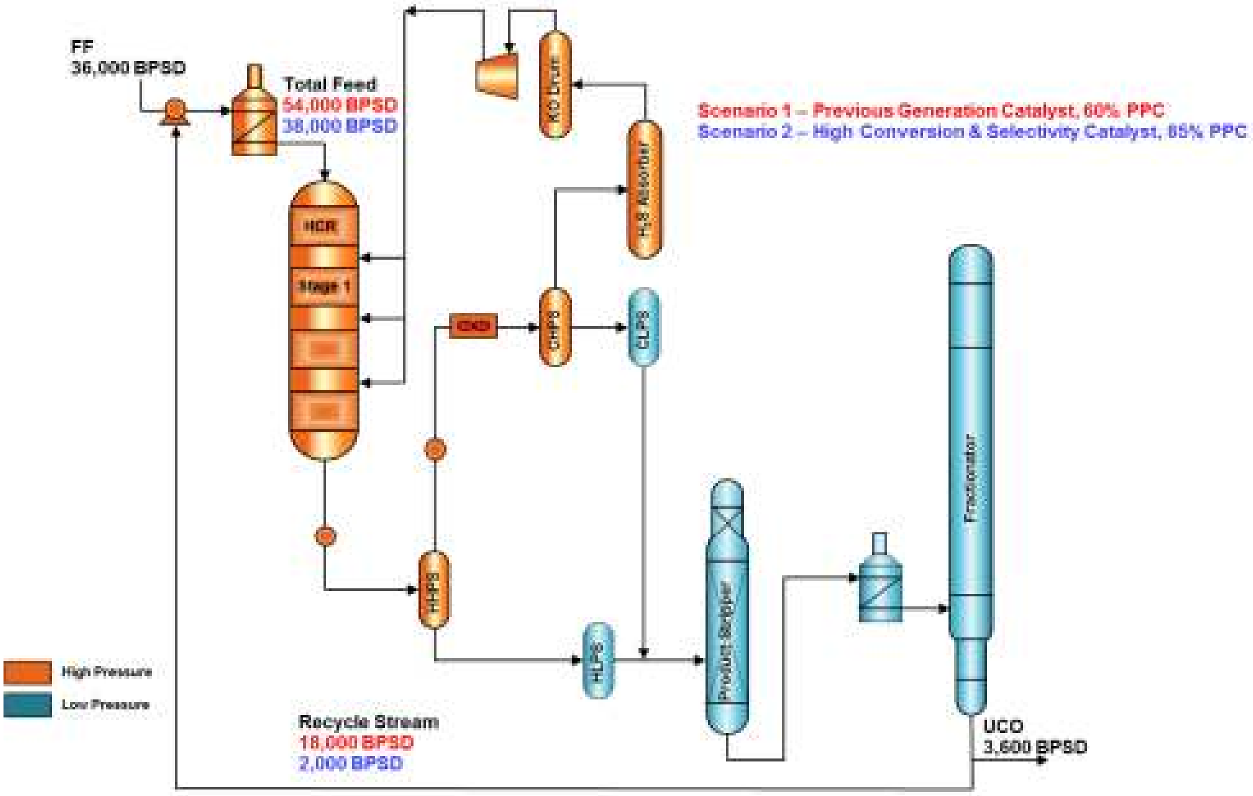

Figure 9 – SSREC, Different PPC

Due to reduced liquid flow rates in the unit as well as reduced gas requirement, significant savings in equipment cost and utilities consumption are achieved. Based on a recent (2013) design the following savings were estimated:

Scenario	PPC	Equipment Cost, €	Power Consumption	Fuel Fired Duty Required	HP & MP Steam Consumption
Previous Generation Catalyst	60%	Base	Base	Base	Base
High Conversion & Selectivity Catalyst	85%	Base – 21 Million	90%	70%	70%

Innovative Process Configurations

CLG has also developed and deployed some unique hydrocracker configurations to maximize benefits from catalyst developments. Figure 10 shows three different units (or four including base case single-stage once-through design): 1) a separate downstream reactor mixes different fresh feed with the effluent of the upstream reactor, utilizing the recycle gas and heat sink, to optimize the design and operation to achieve maximum profitability. Multiple units of this type (SFC = split feed configuration) have been designed and are in operation around the world; 2) in another variation, some of the SFC units also utilize recycle to the first reactor; 3) in the last variation, the upstream reactor is fed only the recycle oil and no fresh feed. Multiple units of this type (SSRS = single stage reverse staging) are in operation. Each one of these innovations have improved product yields, increased cycle length, reduced catalyst volume, and reduced opex and/or capex compared to standard SSOT, SSREC or TSREC configurations.

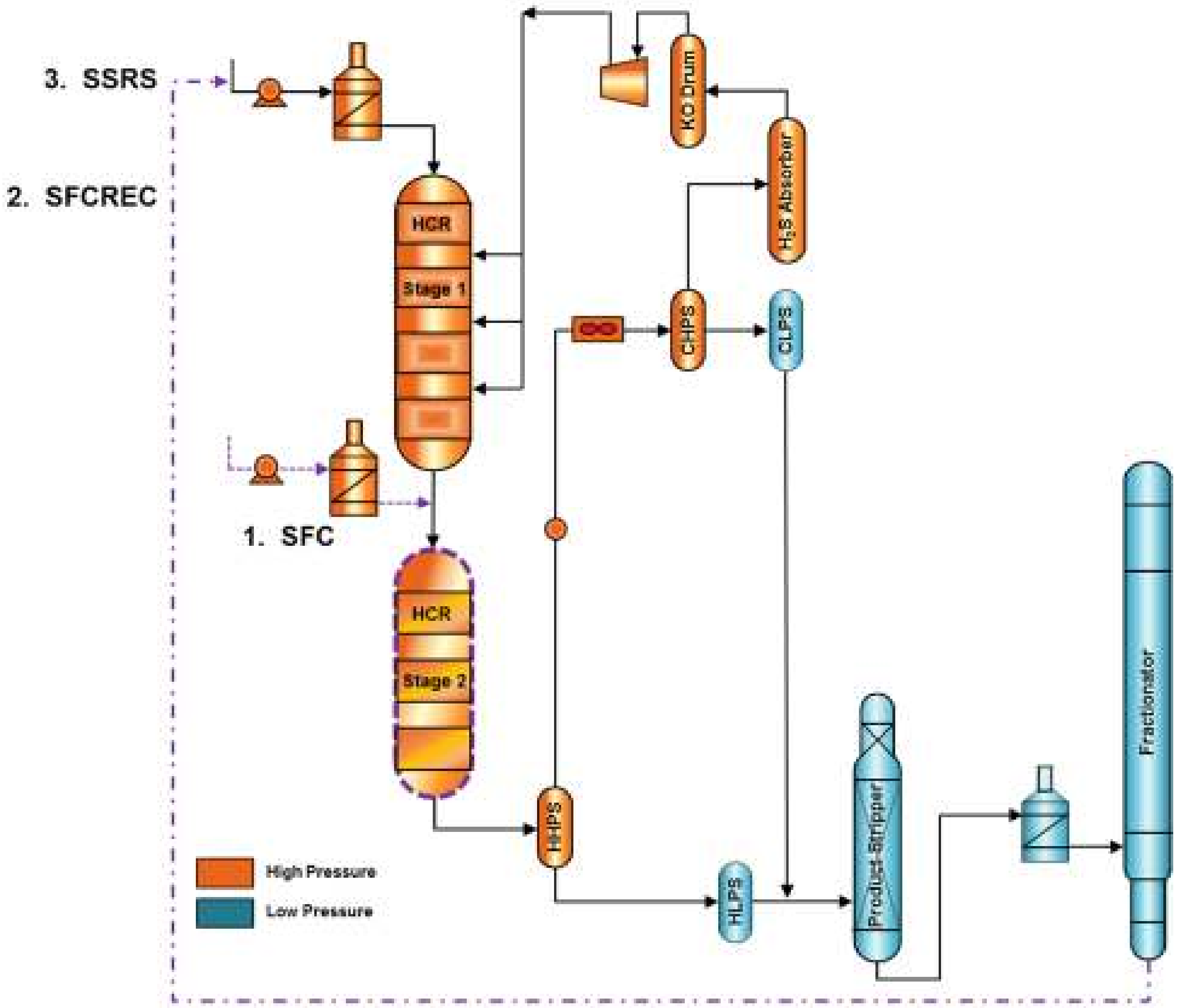

Figure 10 – SFC, SFCREC, SSRS

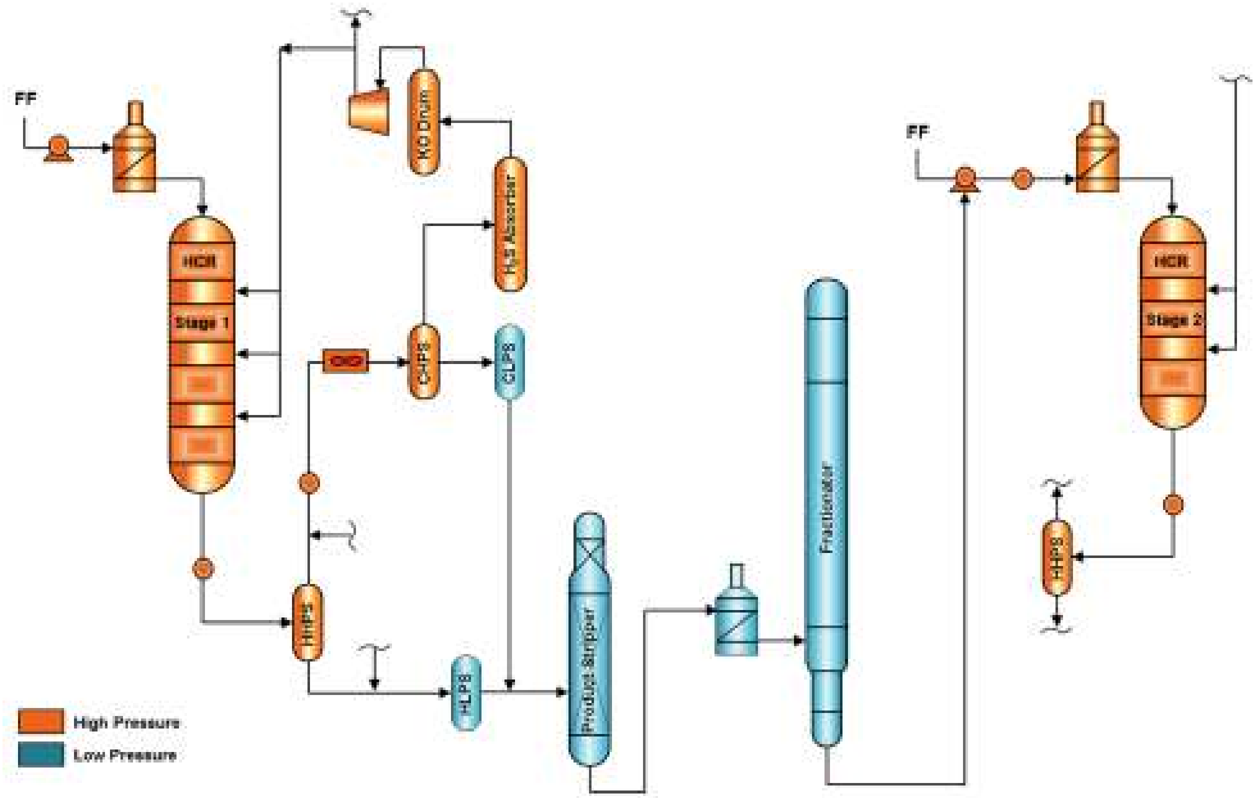

Figure 11 – TSRECFF

Even the standard TSREC did not escape CLG innovation! Figure 11 shows a purposely designed TSREC that processes fresh feed in the second stage reactor. Typical TSREC processes only the recycle oil in the second stage reactor. Addition of fresh feed and mingling of recycle oils, some that have been recycled many times and some that have been not been recycled, enable the operation to target specific product demand. Multiple units of this type are in operation around the world.

There are many advantages and disadvantages to each configuration and applicability to different refineries, feedstock and product objectives. Detail would be too much for this paper/forum. Each of these designs has been commercially operational for at least two years.

World's Most Complex Hydrocracker, Three Stages?

Known for our technology innovations, a South Asian refinery came to CLG to commission a revamp project to increase capacity 80% while maintaining conversion and selectivity and increasing cycle length at minimum cost. The existing unit was originally designed by Chevron with a nominal capacity of 30 MBD ME VGO as a full conversion TSREC, very much like that shown in Figure 3. Catalysts were changed out every two to three years depending on the processing and feedstock severity. The refinery challenged CLG to revamp the unit to achieve nominally 50 MBD, but using heavier VGO with minimum cost, including a condition of no revamp to the high pressure recycle gas system, four years cycle length, full conversion and the same distillate selectivity!

CLG employed all the tools from its toolbox ranging from the latest catalysts to innovative process configuration ideas. As shown in Figure 12, the end product is the most complex hydrocracker which some call the world's only three stage hydrocracker! (This figure is simplified to show a few main changes only. R1 and R2 reactors were original. R3 and R4 reactors were added in the revamp.)

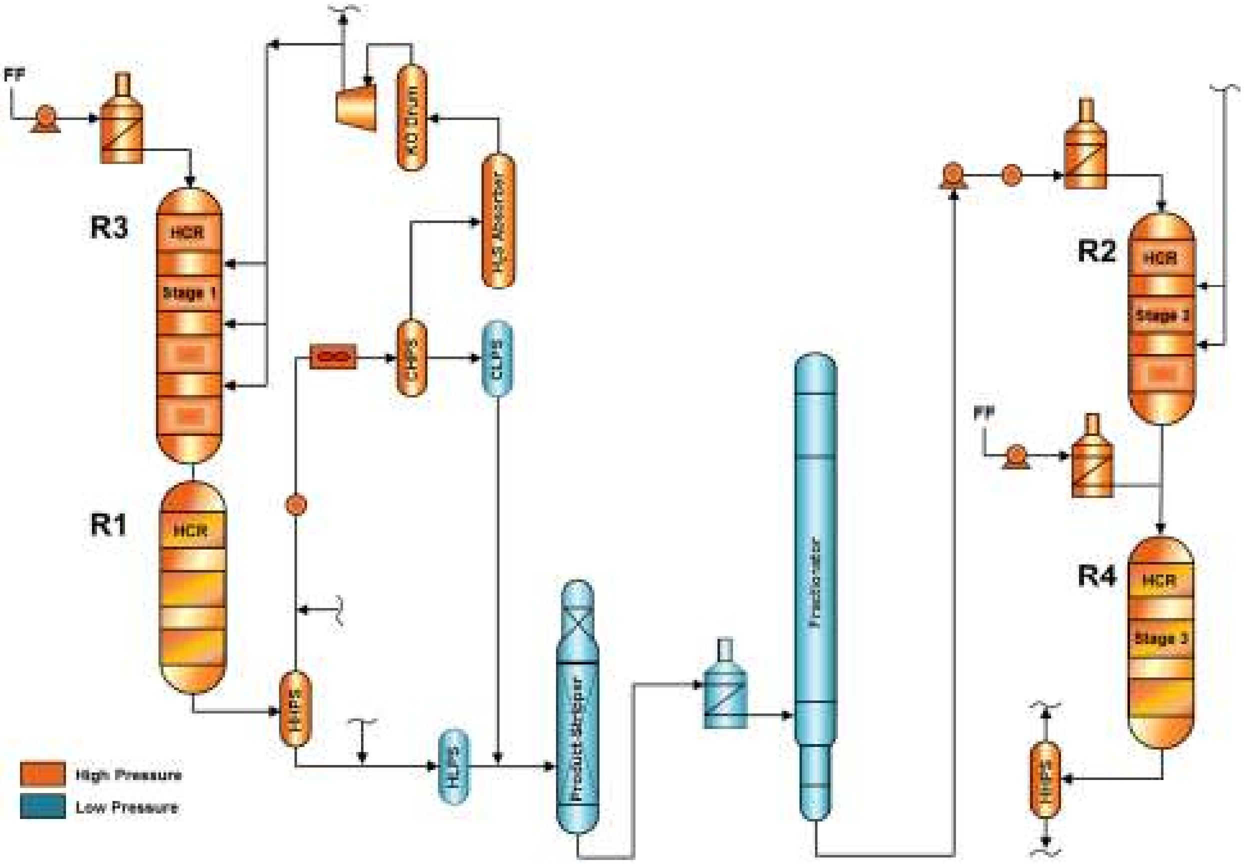

Figure 12 – Three-Stage Hydrocracker

Essentially, with the addition of reactor R4 and a small feed heater for reactor R4, the unit achieved 50 MBD revamped throughput at full conversion with same distillate selectivity. There were many other success factors on the project:

1. Operational staff and EPC company support were crucial. The unit was down only around thirty days (over regular turnaround duration) to make all the connection changes!
2. The innovative concept to process fresh feed in reactor R4 utilizing R2 effluent to provide the heat sink and hydrogen source enabled the revamp without change to the recycle gas loop.
3. New catalysts in R2 and R4, especially in R4 where the effective once-through conversion of R2 feed approached nearly 90%, enabled diesel selectivity to be maintained. Conventional catalysts would have resulted in diesel loss at such high conversion rate as shown/discussed in Figure 2.
4. New reactor R3 and large pore catalysts capable of processing deep cut VGO — from CLG's sister organization ART who specializes in hydroprocessing catalysts development and manufacture — enabled more economic, heavier and diverse VGO processing at the same time doubling the run length.

Figure 13 shows the project in phases from a few months before first tie-in when R3 reactor was added and loaded with demetallation catalysts to when the newest generation catalysts were loaded into R1, R2 and R4. The unit faced feed shortages (refiners are always aggressive in wanting the most capacity for the lowest cost!), meter and data normalization difficulties. However, Figure 13 demonstrates continued improvement in distillate yield and improved cycle length at high capacity throughput.

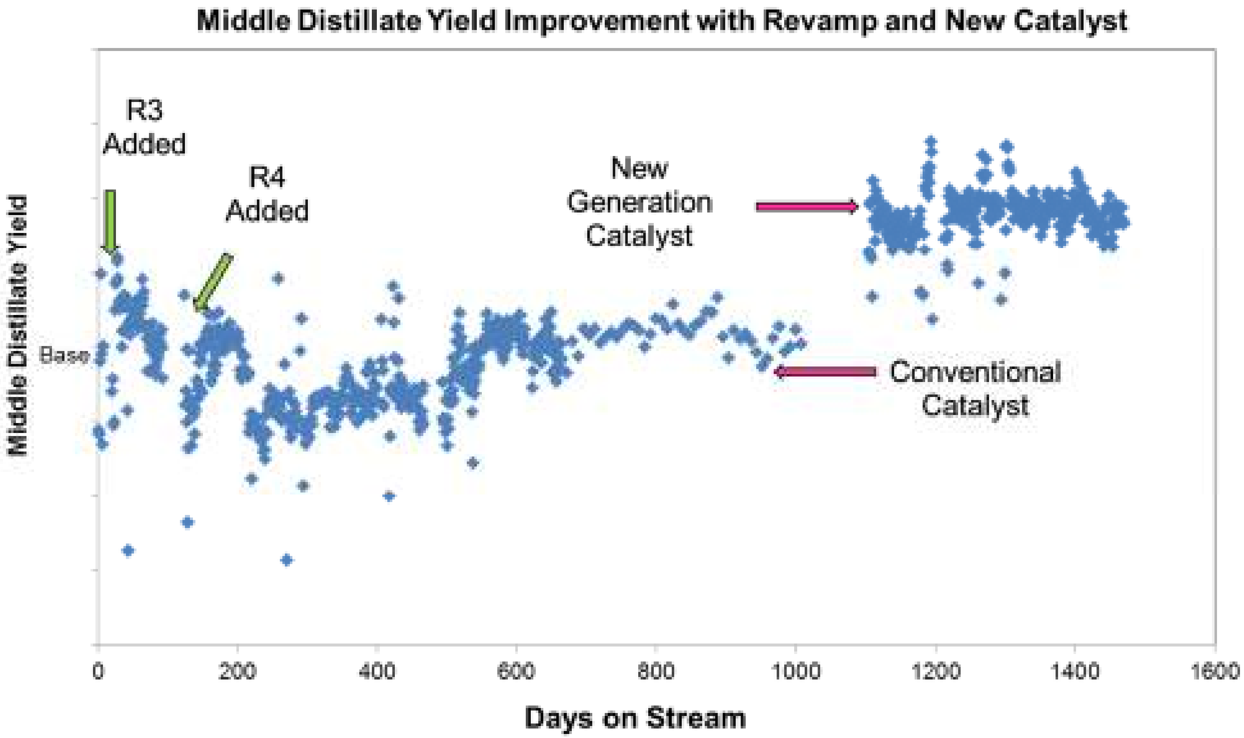

Figure 13 – Distillate Yield Improvement

Summary and Conclusions

Every refinery's situation is unique. A high level overview only of each project is presented here to demonstrate the potential savings that could be achieved employing new catalyst development and/or innovative configurations for revamps or new hydrocracking units. Each example involved many man-days of optimization by CLG working closely with each refinery. All have been implemented and are operating successfully.

Hydrocracking has served our industry for well for over half a century and has been rapidly on the rise. As illustrated in the above examples, hydroprocessing has enabled greater refinery utilization by way of revamps or often simply by a catalyst change. Continued advancement in catalyst technology and innovative configurations will ensure a prominent role for hydrocracking well into the 21st century.

Reference

1. Groeneveld, L. R.; Maesen, T.; Torchia, D., Hydrocarbon Engineering (2010), 15(11), 39-40, 42, 44, 46-47.