PROVEN BEST PRACTICES FOR ULSD PRODUCTION

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Introduction

As refiners begin to contemplate options to meet Ultra Low Sulfur Diesel (ULSD) fuel production (<15 wppm sulfur) by 2006, many are concerned that their existing equipment cannot be modified to deliver the required performance. Although utilizing existing assets would be the best financial option for ULSD production, many refiners are hearing that high-pressure solutions requiring sizable grassroots investment are the only option. Criterion Catalyst & Technologies' (CC&T) and Shell Global Solutions' experience has proven that ULSD can be produced at moderate pressures via unit revamps or grassroots investment for a more cost effective solution. By truly understanding the ULSD chemistry, the latest generation catalysts can be applied (in the right combinations) with the most current process/hardware know-how and proper hydrocarbon management to achieve <15 wppm sulfur at today's typical diesel hydrotreater pressures. This knowledge plus proper planning in the near term can confirm current refinery capabilities to meet the future requirements. Not only does this approach maximize investment returns for ULSD, it allows the refiner to take advantage of improved unit capabilities now to realize immediate financial benefits. This paper will review some commercial cases to demonstrate what proven best practices can be applied to existing hydroprocessing assets to produce ULSD.

Break the Problem Down Into It's Basic Elements

"With the right tools, you can make the job easier."

Determining whether a given refinery can utilize existing units or equipment to make the jump from current sulfur levels down to <15 wppm sulfur can seem quite an overwhelming endeavor at first. A good place to start is to become educated with the chemistry required to achieve ULSD.

"*Understand the problem thoroughly so you can decide what tools to use.*"

Many have written of the importance of partial hydrogenation of multi-substituted dibenzothiophenes as an HDS prerequisite when product sulfur is pushed below 50 wppm.[1] It is equally important to understand the reactivity of these refractory sulfur species and nature of a given feed.[2] Feedstock properties like crude source, sulfur distribution, prior processing history (catalytically cracked, thermally cracked, hydrotreated) and cut point all play a role in determining the feedstock reactivity and subsequent processing conditions necessary to produce ULSD.

"Once you know what you're dealing with, it then becomes an exercise in applying the different tools available which can improve unit performance to determine whether a revamp option is feasible."

Applying new generation catalysts and different catalyst combinations can make significant progress toward lowering product sulfur, but in most cases this is not a total solution. Utilizing best available reactor internals can provide as big a boost to performance as the next generation catalyst, especially considering that reactor hardware has improved substantially even over the last 5 years. Lastly, hydrocarbon management is critical. Unit designs can be greatly impacted by crude selection, feed balancing between units, cut point adjustment to exclude refractory sulfur, and product blending of jet, diesel and heating oil pools.

Given the complexity of the solution outlined above, one can see how important it is to organize the evaluation effort and be systematic in weighing options. A single technology or standard approach will not solve all problems. It is essential that vendors work closely with customers to understand refinery capabilities, identify bottlenecks and limitations, and work together to provide a solution that meets ULSD requirements, unit flexibility and investment criteria within the desired time frame. This paper describes a methodology for approaching ULSD designs, showing that "It's not as hard as you thought" if you break it down into the basic elements. We will demonstrate that while high-pressure designs are more than adequate to do the job, the economics of such solutions are less attractive than proven lower-pressure solutions.

Determine what it takes to reduce sulfur from current level to <15 wppm

The answer to this question is usually framed in terms of increased reactor temperature required (T_{req}) or improved catalyst activity. Note that catalyst activity and reactor volume are somewhat interchangeable variables to put the adjustment in perspective. The answer can vary significantly depending on the nature of the feedstock and other operating conditions as demonstrated in Figure 1.[3] Due to the refractory nature of the last-removed sulfur species, the additional T_{req} can even be larger for the last 20 wppm as it was for the first as 270 wppm as in the case of SRGO 2.

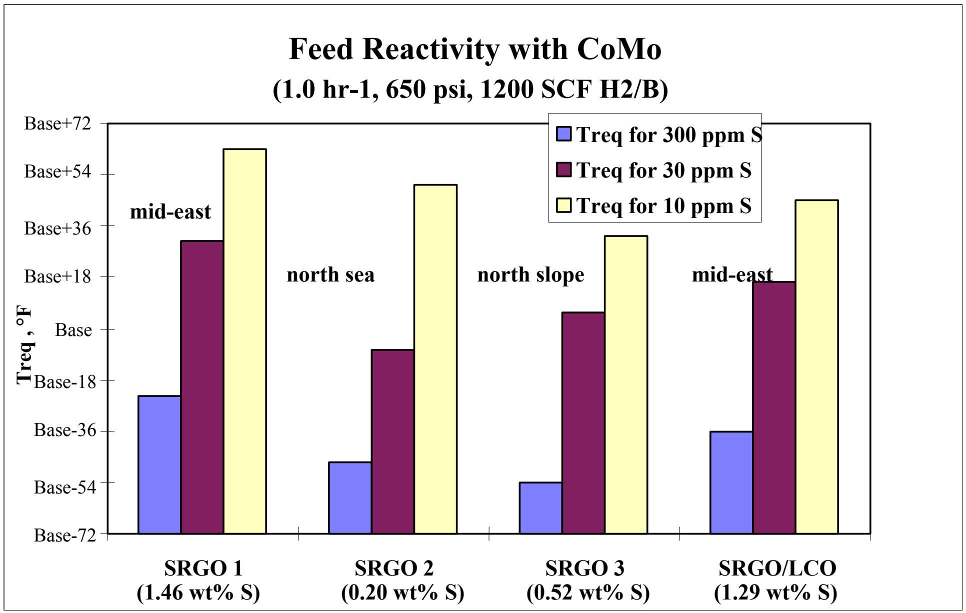

Figure 1: Feed reactivity at different product sulfur levels

Assess the Situation

"Look at the tools available in the toolbox and choose the right ones for the job."

In order to assess an existing DHT operation and begin to develop ULSD solutions, it is helpful to examine a specific case and evaluate incremental improvements to see if they are sufficient to traverse the path from current to ultra-low sulfur levels. Assuming that a conventional CoMo catalyst is being used to make 350-500 wppm product sulfur today, Figure 2 depicts a pathway for achieving lower sulfur levels.[3] Two solutions could be to either drop in a catalyst with 3½-4½ times the current activity level OR raise the start-of-run (SOR) reactor temperature by ~100°F to achieve <15 wppm product sulfur with no other unit or feedstock modifications. While either option can be part of the ultimate solution, other modifications are necessary to supplement better catalysts or reactor temperature changes in order to make ULSD with a reasonable unit cycle length.

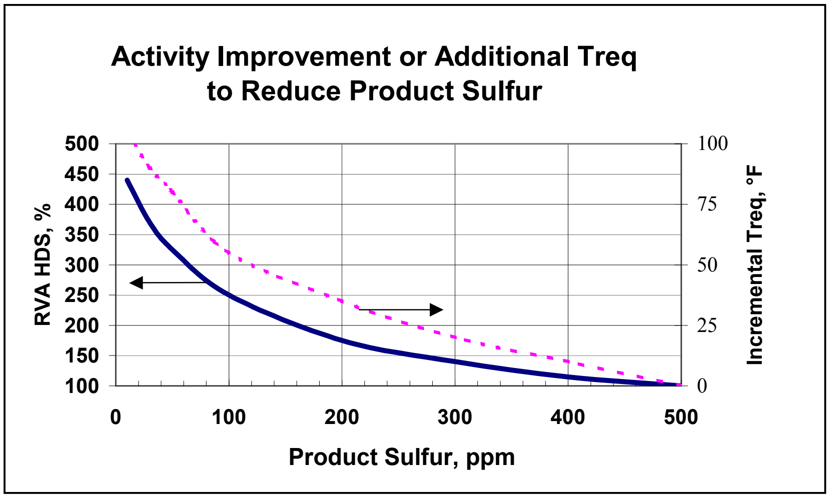

Figure 2: Activity Improvement and Reactor Temperature Increase Required to Reduce Product Sulfur

"Let's look at the list of tools available in a typical toolbox to modify diesel unit operations and lower the product sulfur."

Option #1: Manage Feed Quality and Disposition

Good hydrocarbon management is critical to ensure that refinery economics are not compromised when trying to achieve ULSD. This element is especially important in refineries that currently operate or will manage multiple units to produce ULSD in the future. Matching the right feeds with the existing unit capabilities will maximize utilization of existing capital investment and may minimize grassroots investment. In general, the more difficult feeds containing LCO, coker distillates and even heavy SRGO's should be matched with existing higher pressure units within a given site, although this is not always the case depending on the technology solutions employed.

Feed undercutting has been commonly employed to remove the heavier-boiling refractory sulfur species and enable a much easier feed to be treated in the existing units. One can make significant progress toward lowering the product sulfur with the existing reactor capabilities by excluding most of the refractory sulfur species that boil above 640 °F. A unit today processing a feedstock with a T90 of 680 °F and making 500 wppm product sulfur can cut levels to 50-100 wppm by reducing the T90 to 645 °F as shown in Figure 3, because almost all of the sterically hindered multi-substituted dibenzothiophenes are excluded.[3] This undercutting can effectively increase HDS activity by 60-70% or reduce SOR T_{req} by 25-30 °F because the remaining sulfur species are much easier to process. While in principle this modification is easy to implement, one must consider the implication of downgrading a non-trivial amount (10-20%) of middle distillate to a lower value product disposition and weigh whether reduction of capital investment is justified against overall refinery economics.

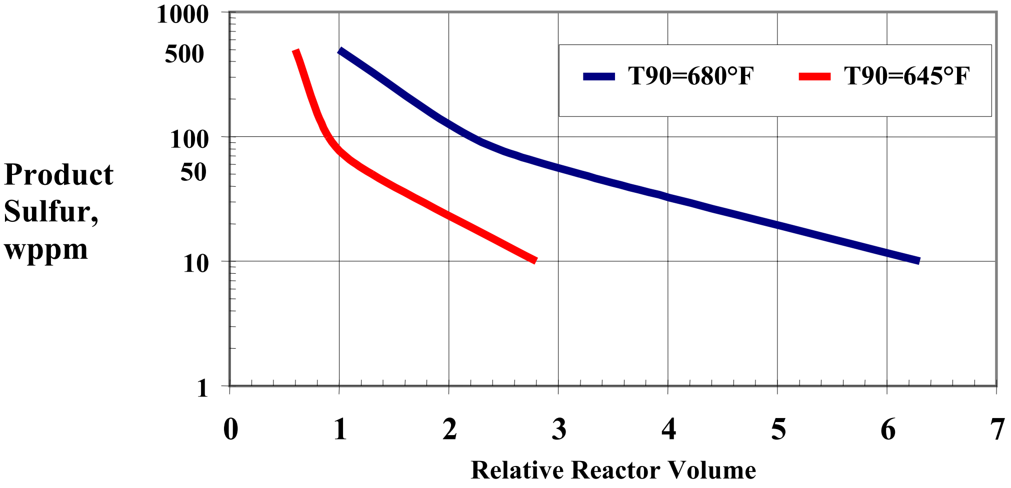

Figure 3: Relative reactor volume as a function of feed endpoint

A consideration that is sometimes overlooked is the quality of fractionation responsible for generating middle distillate feeds. In some atmospheric distillation units, and more frequently in FCC and coker fractionators, the heavy end of the diesel fraction can have a long tail. This long tail can carry a significant quantity of refractory sulfur species, even when the nominal cut point is low. There may be some opportunity to improve the fractionation between middle distillate and VGO fractions to capture as many easy-to-treat middle distillate barrels without entraining too many heavier refractory sulfur species, making it more difficult to achieve ULSD levels.

Option #2: Upgrade to a New Generation Catalyst

Installing a new high activity catalyst is one of the drop-in changes that can have a large effect on sulfur reduction. New catalysts like CENTINEL that have emerged in the last few years offer a substantial increase in performance to produce ULSD over the catalysts being used today to produce 350-500 wppm product diesel fuels. Depending on the feedstock and operating conditions, the performance advantage can range from 30-70% higher activity, especially at ultra-low product sulfur levels. The additional activity can easily knock the sulfur down in a typical unit's product from 500 to 200 wppm. While this sounds like a lot of progress, it's just a first step.

One benefit of CENTINEL catalysts (CoMo DC-2118 or NiMo DN-3110) is that their performance advantage relative to conventional catalysts increases as the sulfur-slip decreases. The increased activity comes from a higher level of dispersion of active sites and improved hydrogenation functionality.[4] The improved hydrogenation allows the catalyst to work more effectively on the most refractory sulfurs.

The question of when to apply DC-2118 or DN-3110 is dependent on a number of different variables: feedstock, product sulfur level, operating pressure and other product quality targets. In general, DC-2118 is used at low to medium pressures (<700 psia H_2pp) while DN-3110 is applied at higher pressures as shown in Figure 4.[5] Since it has demonstrated a much higher hydrogenation activity than typical CoMo catalysts, DC-2118 can be used in the moderate pressure range where others have chosen to use NiMo catalysts. The benefit of using the DC-2118 at these pressures is the improved stability of a CoMo catalyst in a region where NiMo's typically deactivate more rapidly.

Stacking of CENTINEL catalysts provides fewer HDS advantages compared with stacking of conventional catalysts (Figure 4). The enhanced hydrogenation power of DC-2118 diminishes the need to stack CENTINEL CoMo and NiMo to enhance ultra-deep HDS performance. However there is additional incentive to apply a stacked CENTINEL system when additional product quality improvements (cetane, density) are desired, particularly when trying to squeeze as many lower value LCO or CGO barrels into the ULSD pool. CENTINEL catalyst systems can also be tailored to match the hydrogen demand or restrictions for a given set of circumstances. It is important to satisfy HDS requirements with high activity systems; however it also essential not to waste hydrogen by over-treating the feed if the upgrading benefits cannot be realized.

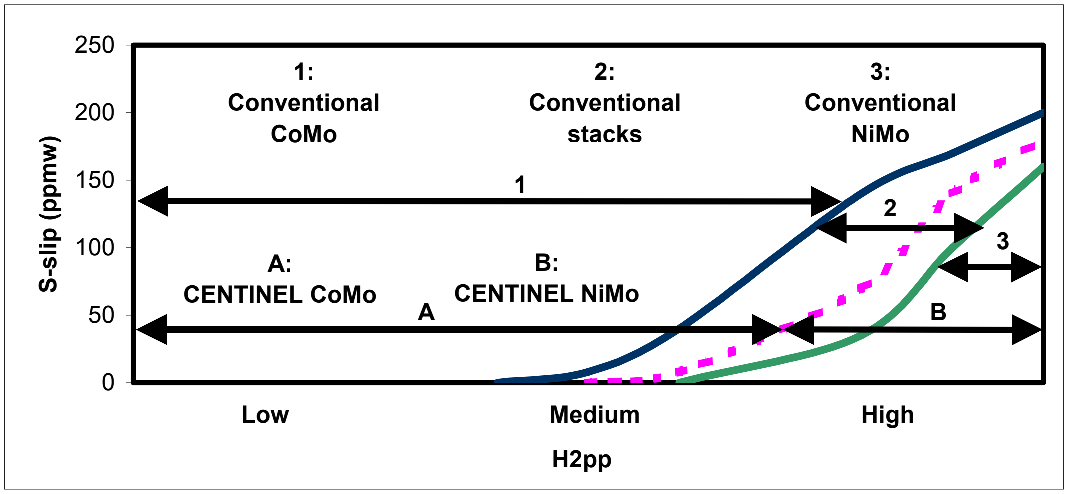

Figure 4: Application area of conventional CoMo and NiMo catalysts versus CENTINEL in distillate HDS.

Option #3: Increase Hydrogen Partial Pressure (H_2pp)

The partial pressure of hydrogen is one of the key variables that drive the desired HDS reactions. Reactor H_2pp is primarily controlled by total operating pressure and treat gas purity, but is also affected by feed vaporization, treat gas rate, hydrogen consumption and light ends production. Of the various elements affecting H_2pp, **treat gas rate** (TGR) and **treat gas purity** (TGP) are the two that are most easily changed during a unit revamp. Each one can have a significant impact on improving overall system H_2pp, and combining the two can have the effect of raising unit overall pressure by several hundred psig as shown in Figure 5.

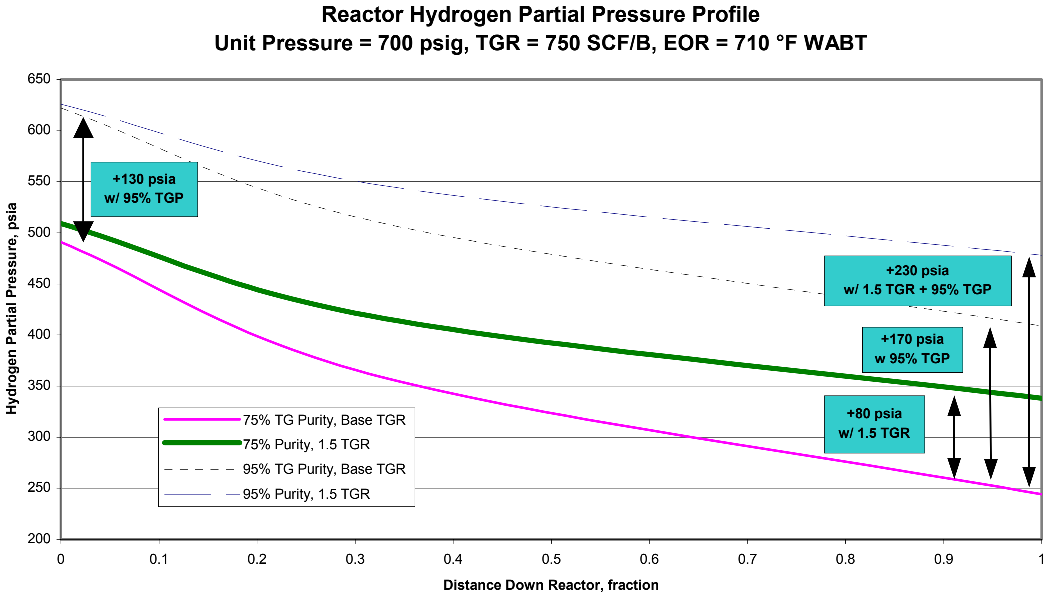

Figure 5: Effect of Improving Treat Gas Rate and Purity on H_2pp

In addition to the benefit of raising the overall H_2pp, increasing TGR also lowers the effect of reaction inhibitors like H_2S and NH_3, which impede HDS reactions. However, increasing TGR has the negative effect of increasing feed vaporization, especially for feeds with light components. Lastly, raising reactor H_2pp, especially toward the outlet where temperatures are highest, can reduce the deactivation rate by suppressing coking reactions. The pluses and minuses of each remedy must be balanced against the final design constraints (unit hardware or economics) to develop a workable solution.

The importance of maintaining adequate H_2pp increases as sulfur levels approach the zero level, because the primary HDS reaction shifts from a predominantly non-reversible, single-step reaction to a reversible, equilibrium-limited, two-step reaction. At lower sulfur levels, the remaining species behave like poly-aromatics and therefore the chemistry of their removal obeys similar rules to the saturation of poly-aromatics.[6] Figure 6 shows the effect of process conditions on PNA saturation.

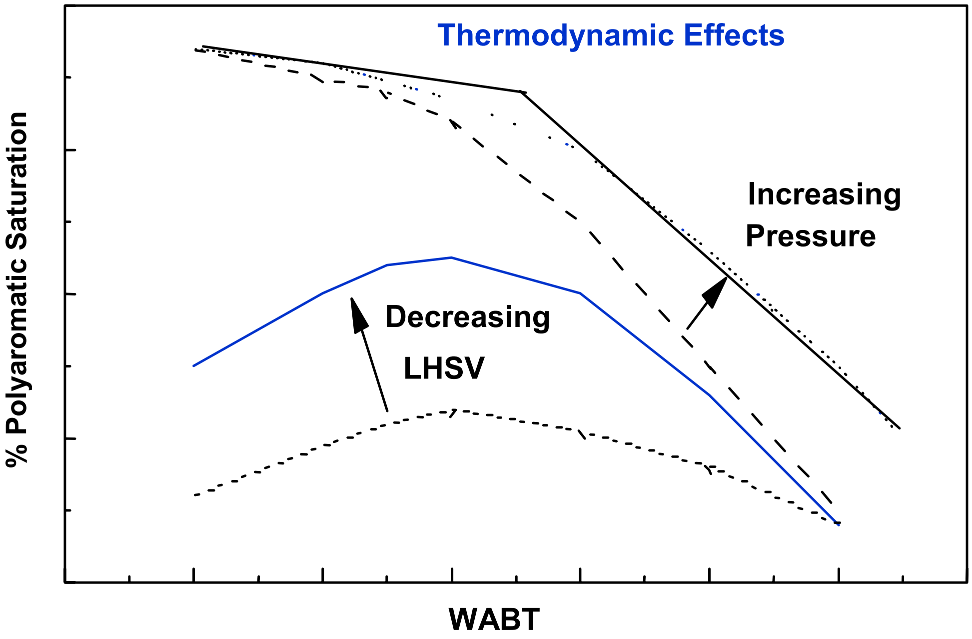

Figure 6: The Impact of process conditions on poly-aromatic saturation

As units approach higher operating temperatures at end-of-run (EOR) conditions, many lower pressure units may struggle to meet sub-15 wppm product sulfur levels because of the effects of the thermodynamic equilibrium. Figure 6 also demonstrates that decreasing LHSV increases the absolute level of poly-aromatics saturation, but only slightly opens the operating window to ensure that these tough sulfur targets can be met for reasonable cycle lengths at lower pressure. Increasing the total pressure might be the only option if it's not possible to increase the H_2pp by improving treat gas purity.

Option #4: Use Alternative Catalysts / Combinations to Beat the Aromatics Equilibrium

Alternatively, one can employ different chemistry and catalysis using process conditions and catalysts like CC&T's SynCat series to deal with the poly-aromatic sulfurs. As temperatures increase, the performance of the SynShift technology's SynCat catalyst causes ring opening that decreases equilibrium constraints. This increases the operating window especially at very low product sulfur levels. Figure 7 shows more poly-aromatics are converted than with conventional catalysts at higher temperatures.

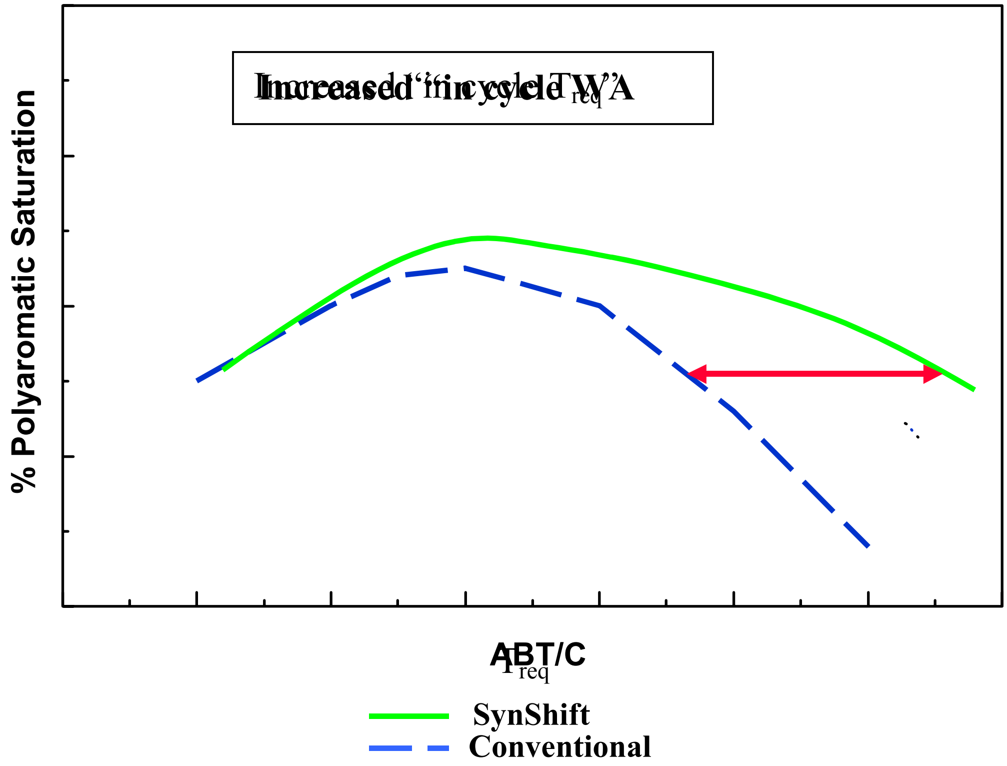

Figure 7: "Beating" the thermodynamic equilibrium

The bi-functionality of the SynCat catalyst allows consistent production of ULSD throughout the cycle. There is also significant density improvement. In a recent commercial application, the density reduction was consistently 50% higher than the levels achieved in previous cycles with conventional catalysts. SynShift brings additional benefits, particularly as this Refiner can co-process LCO to make ULSD and gives a higher volumetric yield through improved density reduction. In real terms this means every barrel of LCO processed yields more ULSD than straight-run material.

Option #5: Modify Reactor Internals

Since the 1970s there have been tremendous advances in reactor design, internal distribution systems, catalyst loading and grading techniques.[7] These advances are designed to increase the capacity of the catalytic reactor within the limits of the existing shell. However, a detailed evaluation of the performance and design of the existing reactor system coupled with a thorough review of the reactor upgrading options available is required to cost effectively realize the full potential of the reactor system. Whether it's the design of a new reactor or revamp of an existing reactor, there are two fundamental principles that should be followed: 1) Maximize catalyst volume within the reactor shell and 2) Ensure such catalyst is fully utilized.

Maximize Catalyst Volume Inside Reactor

Each hydroprocessing reactor vessel must give up a certain percentage of the available reactor volume to reactor internals at the expense of the primary catalyst. Proper selection and design of reactor internals will maximize the mixing of the reactants (gases and liquids) and enable efficient use of the primary catalyst. Poor selection and design of reactor internals can lead not only to a significant and unnecessary loss of reactor volume, but also significant under-utilization of the installed catalyst volume.

There are many types of reactor internals that can be applied in trickle flow reactors:

- Inlet device
- Fouling collection tray
- Primary liquid and gas distribution tray
- Catalyst support beams and screens
- Interbed quench/mixing tray(s) + re-distribution tray(s)
- Outlet device

Since reactor internals occupy reactor volume that could otherwise be filled with catalyst, there is a continuing effort to reduce their size, or where possible, to remove them entirely. A review of several hydrocracking and mild-hydrocracking units designed as "state-of-the-art" prior to 1990 has shown that even in such high performance units, the typical reactor volume utilization was approximately 70% for first stage (pretreat) and as low as 60% for second stage reactors. Even very recent 1998-99 designs using typical configurations (e.g. expired patents, open literature) deliver little improvement. However, if we review the latest reactor designs available from Shell Global Solutions, reactor volume utilization upwards of 86% is achievable. The improvement in volume usage from 65 to 86% has a net effect of increasing catalyst activity by >30% or reducing SOR T_{req} by >12 °F.

The general view seems to be that additional reactor volume will be required for many units to achieve ULSD. In addition to the expense, there are long lead-times for new reactor vessels resulting in delays before the benefits are attained. CC&T and Shell Global Solutions have successfully demonstrated on numerous occasions that the net reactor performance can be increased 15-50% at a fraction of the investment cost of a new vessel and with implementation within a matter of months (typically during next planned shutdown). The example in Figure 8 demonstrates that improved space utilization can either result in 1) construction of a 20% smaller reactor if considering a grassroots design or 2) a 28% increase in catalyst volume within an existing vessel.

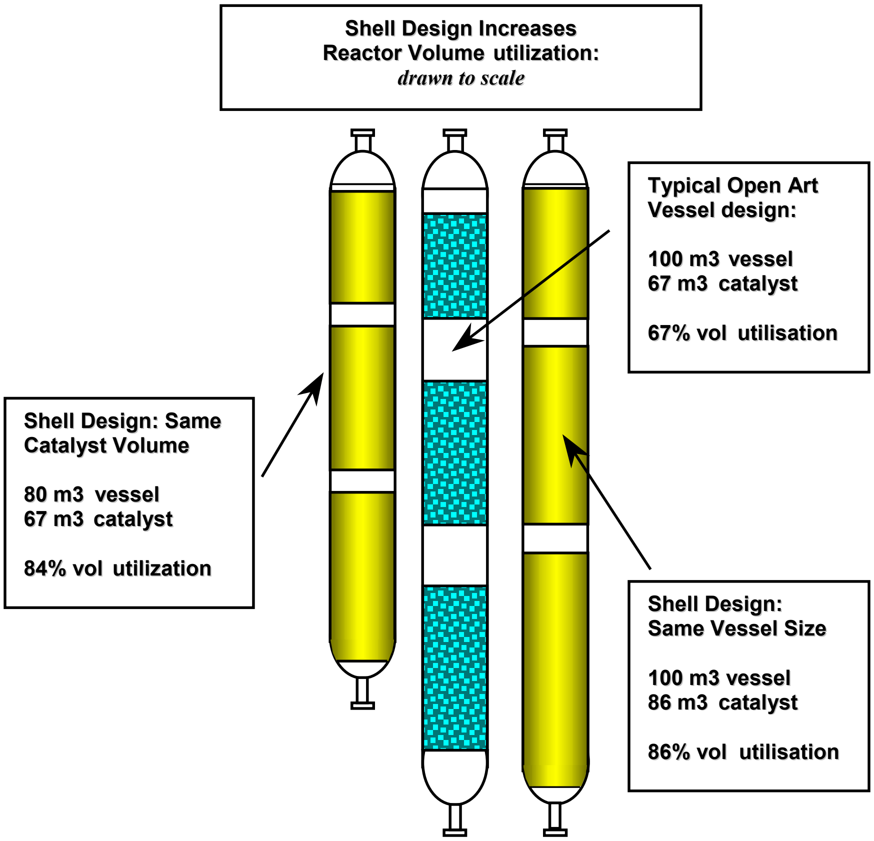

Figure 8: Improved reactor space utilization can decrease size of a reactor design or increase available catalyst volume in an existing vessel.

Maximize Catalyst Utilization

Maximum catalyst utilization can only be achieved if the gas and liquid reactants are uniformly distributed both volumetrically and thermally before they are introduced into the very top of each catalyst bed. As mentioned previously, some competitive designs as recent as the late 1990's don't use distribution trays that have high dispersion. In contrast, Shell Global Solutions' High Dispersion (HD) and Ultra Flat Quench (UFQ) trays have been developed to incorporate the use of the unique HD nozzles that attain near 100% catalyst utilization for trickle phase reactors. The HD tray is the latest proprietary Shell design, creating an almost perfectly uniform liquid distribution as depicted in Figure 9. The UFQ tray also provides nearly perfect mixing of process liquid and gas, and quench medium between the beds, while using minimum reactor volume. The Shell internals can boost the catalyst utilization from 80 to nearly 100%, generating an equivalent improvement in HDS activity of 25% or reduction in SOR T_{req} of 10 °F.

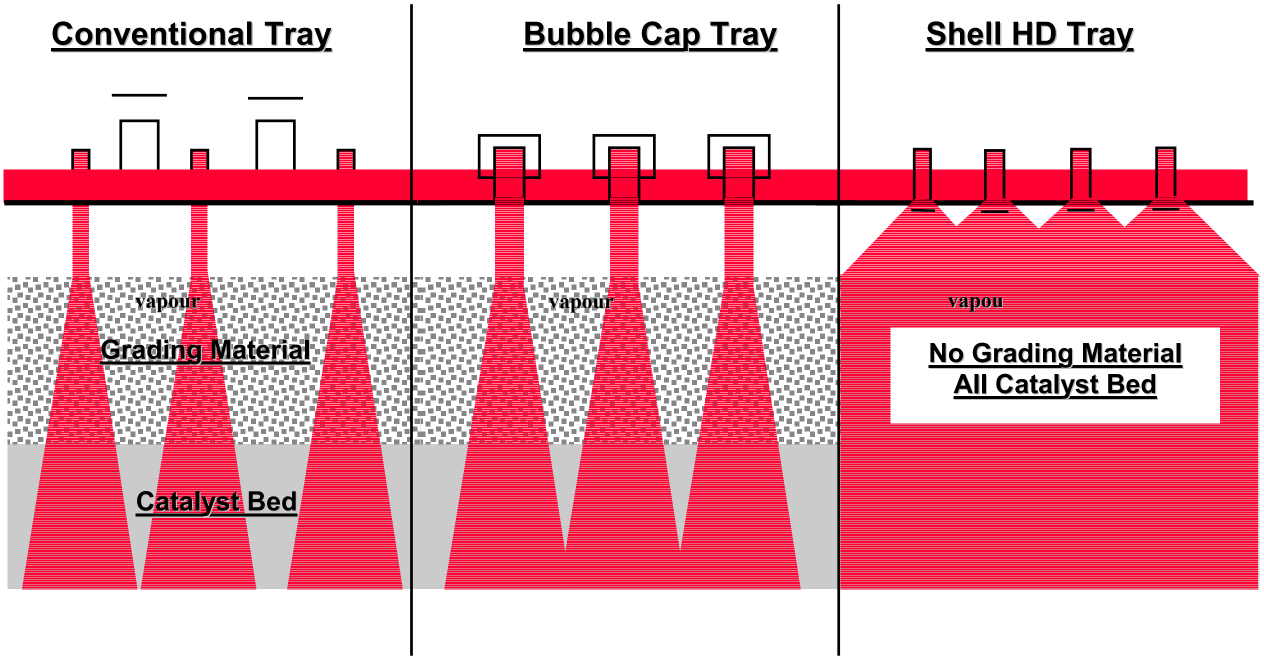

Figure 9: Depiction of distributor tray flow patterns

Option #6: Raise SOR Temperature – Shorten Cycle Run Length

There is not much flexibility to dramatically alter SOR reactor temperatures on the road to reducing product sulfur at the expense of cycle length. Most distillate units running to 350-500 wppm product sulfur levels today achieve run lengths of 2-3 years. Little flexibility exists to shift turnaround schedules by other than 1-year increments; perhaps on occasion a shift by 6-months is achievable. With typical distillate unit deactivation rates of 1-2 °F per month, a move to shorten the cycle by 12 months by raising SOR T_{req} by 12-24 °F initially seems like it could be a reasonable option worth considering. However, as was described in the earlier section on H_2pp, EOR reactor temperatures may be reduced by 10-20 °F in ULSD mode compared with current operations due to equilibrium limitations. Thus, the available temperature window for operation could potentially be reduced from both ends (SOR and EOR) resulting in unacceptably short cycle lengths.

Option #7: Remove H_2S from Recycle Gas

H_2S is a byproduct of HDS reactions ($R\text{-}S + H_2 \rightarrow R + H_2S$). The lower the concentration of H_2S entering the reactor, the better the reaction can proceed to completion. This is especially important in the ULSD environment, where conversion levels are pushed from current day levels of 95% to ULSD levels of >99.8%. The benefits of adding amine scrubbing to remove H_2S can be considered in sour systems where H_2S levels are greater than 2 vol%, resulting in a reduction of SOR T_{req} of >10 °F.

Option #8: Add Reactor Volume

The addition of reactor volume can seem like a big change relative to some of the other options already described, but it can provide an attractive investment option, especially compared with a grassroots investment. In addition to lowering the LHSV comes the added benefit of improved hydrogenation when aromatic equilibrium limitations apply. As shown in Figure 6, adding catalyst volume lowers overall LHSV, which increases the levels of poly-aromatic saturation and subsequent ultra-deep HDS. This ultimately expands the operating window a little compared with a design based on a higher LHSV. A typical revamp design doubles with catalyst volume yields an improvement in HDS activity of 100% or reduction in SOR T_{req} by 35 °F.

Evaluate which options can be exercised for your refinery

"Choose the right tools and apply to your operations."

We have described many of the options you can choose from to assess whether your distillate unit(s) in your refinery can be modified to achieve ULSD. In general, options to utilize improved catalyst or catalyst systems and upgrade reactor internals provide the biggest, most cost-effective benefits. However, the two alone are frequently not enough to bridge the gap to achieve <15 wppm product sulfur levels. Fractionation improvements or undercutting feeds can deliver big benefits, however the costs need to be evaluated for additional product downgrade. Furthermore, increasing reactor volume is a more capital-intensive, yet effective way of quickly closing the gap after some of the easier modifications are made. Finally, improving overall H_2pp, increasing treat gas rate and removing H_2S from treat gas require more effort and capital, but can provide measurable improvements toward achieving ULSD when used in combination with the other changes.

The example in Figure 10 illustrates what steps could be taken to treat a fairly difficult feed in a moderate pressure unit which had an existing single reactor. The easy fixes of new catalyst and better internals made significant progress toward lower product sulfur levels, however additional modifications to the hydrogen system and a new reactor were required to complete the journey to <15 wppm product sulfur levels. Different combinations of options are possible and should be evaluated for technical feasibility, operating flexibility, expansion capability and overall cost.

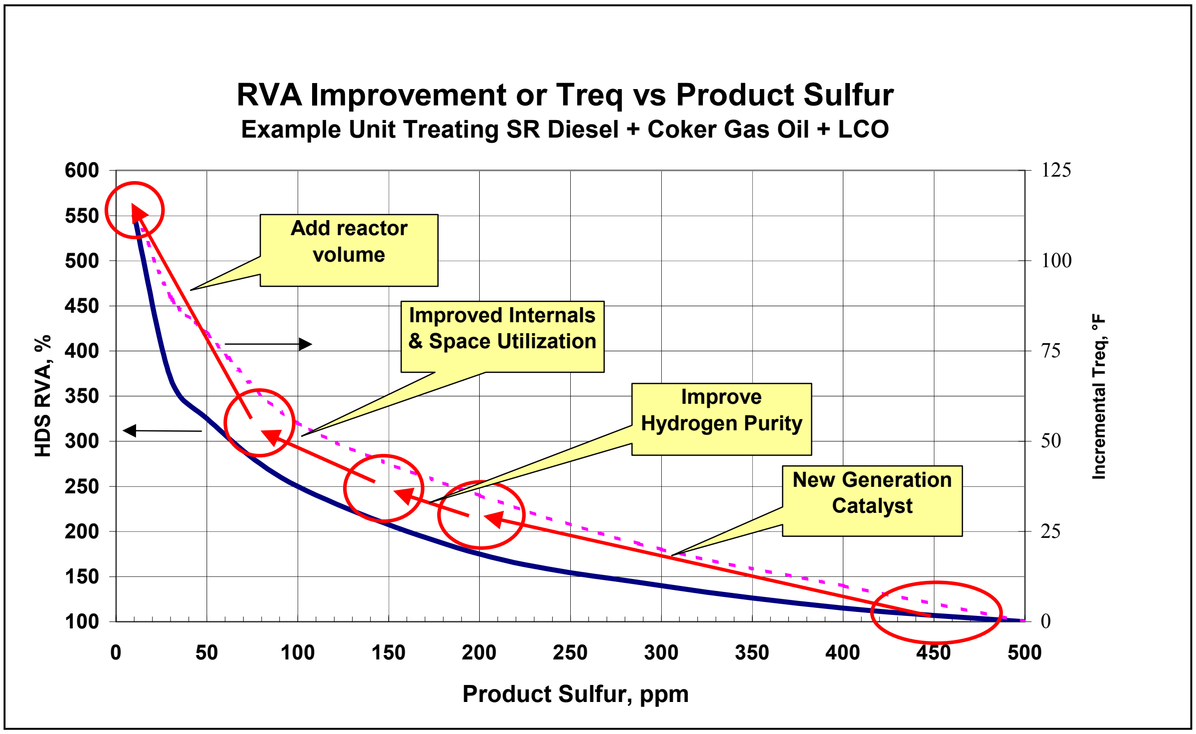

Figure 10: Example Revamp Scenario from 500 wppm Sulfur to ULSD

Commercial Experience

CC&T and its marketing alliance team members have designed a number of units over the last decade which have achieved ULSD using some combination of the “tools” described earlier.

ULSD – European Refiner

One client has used a drop-in catalyst solution while simultaneously increasing throughput to maximize the returns available for producing zero-sulfur middle distillates for the German market.[6] The refiner took advantage of low sulfur SRGO, a relatively light boiling range feed without a significant tail, and excluded cracked feeds in order to produce this ULSD product. The unit started up in 3Q01 and an overview of the operating conditions is shown in Table 1.

Table 1

Feed Quality – European Refiner

Property	**Units**	**Value**
% Straight Run	%	100
% Cracked Stock	%	0
Sulfur	wt%	0.23
Density	°API	35.0
Total PNA’s	wt%	10.3
Total Aromatics	wt%	28.2
D86 IBP	°F	410
5%	°F	482
50%	°F	545
90%	°F	608
95%	°F	644
FBP	°F	657

Typical Product Quality Values

Property	**Units**	**Value**
Sulfur	wppm	10-30

Main Operating Conditions

	Units	***Value***
H_2 partial pressure	psia	475
SOR T_{req}	°F	653
Expected Cycle Length	Months	48

ULSD / Upgrade at Lyondell-Citgo, Texas

In 1996, Lyondell-Citgo in Pasadena, Texas revamped a DHT as part of a billion dollar refinery expansion to allow processing of Venezuelan BCF-17 heavy crude oil. The existing, low pressure, two-reactor distillate hydrotreater was revamped using Syn technologies to give a good yield of ULSD along with a minimum 7°API gain and 7-10 number improvement in Cetane Index (feed to product), while processing a difficult blend of ⅓ light cycle oil, ⅓ coker gas oil and ⅓ straight run gas oil.[8]

Naphtha and light gas make were minimized due to the low operating pressure of the existing unit, and, by use of special SynCat catalyst combinations. Since the technology for distillate unit revamp was one of the last decisions made by Lyondell as part of the upgrading scheme, schedule was an important project element. In order to save time and avoid having to extensively modify an existing reactor, the processing scheme adopted was all co-current flow. The as-revamped unit operates in two stages: the new, world-scale first stage reactor utilizes advanced reactor internals as well as an optimized mixture of SynCat catalysts, and the second stage, a retrofit of the larger of the existing two reactors of the original unit, contained a special SynCat noble metal catalyst. The smaller of the existing two reactors of the original unit was converted to second stage flash drum service.

The design and operation of this unit demonstrated that practically any poor quality middle distillate feedstock can be upgraded at moderate pressures, and this client was able to recoup the investment cost in relatively short order. The first stage reactor operations from that unit are displayed here in Table 2 because it produced an ULSD as part of the design criteria for the revamp.

Furthermore, during the second cycle Lyondell changed the first stage operation to adopt SynShift technology to give additional density reduction, boiling point shift and cetane improvement with the addition of a special bi-functional SynCat catalyst.[9] This type of project sequencing is a good example of how to pre-invest monies for a capability or flexibility that you can use at a later (perhaps yet undetermined) point in time.

Table 2

Lyondell-Citgo Operation

	Units	First Stage Operation Commercial Results
Feed Properties		
Density	°API	23.8
Sulfur	wt%	1.24
Nitrogen	wppm	820
Distillation, D-2887		
T50	°F	556
T90	°F	675
FBP	°F	781
Product Properties		
Density	°API	31.5
Sulfur	wppm	10-20
Nitrogen	wppm	7-15
Operating Conditions		
H_2 Partial Pressure	psia	520

Other Options

There are other options to consider beyond those already described. It is possible to convert an existing single stage unit producing 350-500 wppm diesel fuel products to a two stage operation using interstage separation with gas scrubbing. This provides clean treat gas to the second reactor, whose volume can now be reduced compared with a once-through operation. It is even possible to consider operating the second stage at a higher pressure as in the case of SynFlex technology, where even very low-pressure units can be revamped to achieve ULSD. SynFlex utilizes low treat gas rates to save on compression and scrubbing costs, provides an estimated 40% investment savings compared with a grassroots investment, and still offers staged investment options for future aromatic saturation. These two stage retrofits are more expensive compared with the single stage revamps described earlier, but offer alternatives if a single stage design is not able to meet all processing objectives as well as giving future feedstock processing flexibility.

Depending on refiners' existing capabilities and product objectives, it's possible that a grassroots investment might be preferred. This option could become more prevalent if additional capacity is necessary to meet new regulations directed toward reduction in sulfur of off-road diesel, which for the US represents a significant volume of the total distillates market.

Investment Costs

In most cases, revamping an existing unit as described in this paper is more economical than either adding a second stage with interstage stripping or a grassroots investment. While higher pressure options can certainly meet ULSD requirements, low to moderate pressure options can provide significant investment savings as shown in Table 3.

Table 3

Investment Ranges for Various ULSD Options

Investment Option	**Investment Cost, $/B ISBL**[*]
Reactor Addition Only	300-400
Revamp of Low or Moderate Pressure Unit	500-1000
Grassroots Unit, 800 psig < P < 1100 psig	1000-1300
Grassroots Unit, P≥ 1500 psig	1500-2000

[*] ISBL = InSide Battery Limits

Summary

"We didn't say producing ULSD would be easy, but hopefully it's not as hard as you thought."

Criterion Catalysts & Technologies, Shell Global Solutions and their alliance team members have already developed and commercialized catalyst and technology to economically upgrade middle distillate feedstocks to achieve ULSD. This has been accomplished through a unique combination of 1) Knowledge regarding how to achieve ULSD at lower pressure conditions, 2) Ultra-high activity CENTINEL catalysts, 3) Syn technology and SynCat catalyst combinations, 4) Reactor internals which offer significant performance benefits compared with what is currently installed or available and 5) Commercial experience in many refineries including over 7 years producing ULSD at Scanraff, Sweden. Individually, these elements each contribute toward improved project design and economics for ULSD, but taken together these proven best practices can provide a more sizable investment savings, making single stage revamp strategies increasingly attractive compared with more elaborate two stage designs and particularly grassroots investments.

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