1. Introduction

Refiners today are challenged to produce transportation fuels containing near-zero levels of contaminants mandated by legislation in the US, Asia and Europe. At the same time, the price escalation of crude oil has magnified the light-heavy oil cost differential motivating refineries to process less expensive but increasingly heavy, contaminant laden oil. Together, these factors motivate a refiner to produce cleaner products from dirtier feeds.

Increasingly stringent specifications for low sulfur fuel oil are contributing to reduced fuel-oil demand, and forcing refiners to find alternative outlets for their vacuum tower bottoms. A central issue for the most economical conversion of heavy oil is the disposition of the heaviest fraction, the vacuum residuum (VR). VR contains most of the contaminants such as Microcarbon Residue (MCR), nickel and vanadium present in heavy oil. This paper presents the results of hydrotreating heavier Atmospheric Residuums (AR) in RDS pilot plants with Ni-Mo supported catalysts. RDS pilot plant life tests are conducted and validated for analysis and further RFCC testing. Process condition variation and new catalyst development has been applied to improve RDS capability to handle heavier, more contaminated residuum. The RDS products are tested for RFCC reactivity using Advanced Cracking Evaluation (ACE) tests. The development of improved RFCC catalyst is applied to boost cracking catalyst tolerance of residuum metal contaminants. Judicious selection of newly developed RDS and RFCC catalysts enable production of higher yields of gasoline from heavier AR’s. The coordinated application of new RDS and RFCC catalysts enables the conversion of dirtier residuum feedstock to produce greater yields of distillates.

Keywords
Residuum desulfurization, Hydrotreatment, Residuum fluid catalytic cracking, Nickel molybdenum catalyst

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and is a starting point for a more detailed description of recent advances in RDS/VRDS processes and catalysts. Comparisons of pilot plant products exploring the effects of feed quality and catalyst improvements with RDS/RFCC yields will be discussed. Improvements to the combination of RDS/VRDS upstream of an RFCC deliver high yields of gasoline and chemical naphtha with minimal fuel oil co-product. The benefits of coupling new RDS developments with RFCC improvements to deliver enhanced yields of cleaner products from heavier oils are presented.

2. Delayed Coking

Delayed Coking is a widely applied residuum upgrading technology (Fig. 1). It often represents a baseline process consideration for residuum conversion that is well understood by the refiner. When total investment is a primary concern and existing hydroprocessing units in a refinery have the capacity to process the hydrogen deficient liquids from a Coker, coking VR can be the preferred option. It is able to handle the heaviest, most contaminated crudes, and it produces modest yields of mid-distillates (relative to naphtha or FCC feedstock). Recent process improvements have enabled shorter cycle times boosting throughputs, made decoking procedures safer for operations, and reduced furnace fouling. These developments have permitted refiners already using Delayed Coking to economically increase their residuum handling capacity by incremental capacity increases.

3. LC-FINING

The near maximum utilization of existing refinery desulfurization facilities has motivated the more complete conversion of residuum into finished products. New residuum conversion projects are motivated to deliver not only primary conversion but also transform residuum into fully hydproprocessed product blend streams. Such conversion/transformation avoids additional investment for multiple product hydproprocessing units. Recent developments of LC-FINING technology and its associated product hydproprocessing meet these needs (Fig. 2). For heavy feedstocks containing high levels of metal impurities, the LC-FINING process produces substantially higher liquid yields than Delayed Coking. Similar to Delayed Coking, the product slate is weighted towards mid-distillates. Steady improvements have been made to the reliability and economic effectiveness of LC-FINING technology. This includes improvements that allow high feed rates per train, high residuum conversion, and in-line hydrotreating to produce high quality distillates. A further refinement of residuum conversion to high quality products couples LC-FINING with Delayed Coking to further reduce the quantity of low value fuel oil.

4. RDS/RFCC

A third process option for residuum conversion couples RDS/VRDS hydrotreating with RFCC (Fig. 3). In this scheme, the residuum hydrotreater serves two purposes: hydrogen addition to reduce sulfur, Conradson carbon residue, and nitrogen and nickel/vanadium removal. Together, these processes can
effectively pretreat RFCC feedstock to control FCC catalyst deactivation, excessive carbon burnoff in the FCC catalyst regenerator, and boost liquid yields. Most of the naphtha range product of RFCC processing schemes is directly blendable to gasoline. RFCC’s also produce significant volumes of olefins that are useful for petrochemicals. Altogether, this scheme offers a balance of hydrogen addition/carbon rejection to produce a nearly bottomless product slate. Because both the RDS/VRDS and the RFCC are negatively impacted by metals, this scheme can tolerate comparatively fewer metals than the Coking and LC-FINING options.

An overview of the yield structures from the hydroprocessing section of each option is shown in Fig. 4. Some comparisons that affect the choice of the most suitable process are:

1. Relative yields of each liquid fraction
   Generally, Delayed Coking and LC-FINING produce more mid-distillates than VRDS/RFCC which produces relatively more gasoline and chemical naphtha.

2. Availability and expense of hydrogen
   In general, greater upgrade requires more hydrogen. Note that the Coking route requires significant hydrogen to upgrade the hydrogen deficient Coker liquid prod-
(3) Choice of feedstock

There is a practical limit to the amount of metals that hydrotreatment routes can tolerate. RDS/VRDS can tolerate feed Metal’s levels up to the 100+ ppm range before requiring uneconomic catalyst change-outs. Addition of an On-stream Catalyst Replacement (OCR®) or Up-Flow Reactor (UFR®) guard bed in front of an RDS can increase this tolerance by nearly two times. LC-FINING can tolerate feed metals into the several hundreds. Coking can economically process almost any level of feed metals.

Details of the Delayed Coking and LC-FINING process options have been discussed in detail previously. For the purpose of aiding the refiner make a choice between all three options, a closer look at the RDS/VRDS-RFCC option will be discussed in more detail here. In addition, we report the RFCC yields from selected RDS pilot plant products collected during middle of run (MOR). These results provide an overall comparison for the RDS/RFCC case that delivers more closely finished transporation fuels for comparison to the LC-FINING and Coking products.

4.1 OCR/UFR and VRDS/RDS Developments

The application of RDS/VRDS hydrotreatment has evolved significantly from its original focus on fuel oil hydrotreating. In combination with RFCC, the heaviest crude oil fractions can be converted to high yields of transportation fuels. In anticipation of higher light-heavy oil cost differentials, the On-stream Catalyst Replacement (OCR) and Up-flow Reactor (UFR) processes were commercialized to enable the processing of heavier, more contaminant laden residua. Chevron Lummus Global (CLG) was the first licensor to commercially design and practice liquid filled up-flow reactor technology with OCR (Fig. 5). This process has catalyst moving in counter current flow direction to the reaction mix of residuum and hydrogen, thus ensuring maximum utilization of the catalyst. The least deactivated catalyst sees the most reactive feed at the reactor (bottom) inlet, and spent catalyst is withdrawn from the bottom. The least reactive feed sees the freshest, most active catalyst at the reactor exit (top), the point at which fresh catalyst is introduced during the online catalyst replacement cycle.

CLG learned from the development of the design of liquid filled up-flow reactor technology that substantial benefits are obtained from the UFR regardless of employing the catalyst handling system for online catalyst replacement. Without the reactor internals necessary for on-stream catalyst replacement, an Up-flow Reactor, UFR, still imparts further protection against metals and particulate fouling that extends RDS runs or enables

![Fig. 4 Resid Conversion Process Yields (including HDT of products)](image_url)

![Fig. 5 OCR/RDS Reactor System](image_url)
processing of heavier, dirtier residuums. A particular advantage of the OCR/UFR reactor is its suitability to retrofit existing RDS units, due to its inherently small pressure drop (Fig. 6).

Anticipation of higher crude oil prices has also motivated development of new, more metals-tolerant OCR, UFR and RDS/VRDS catalysts. In 2007, a new OCR/UFR catalyst with increased metal capacity was developed. It delivers 10% greater metal conversion with the capacity to absorb 7% more metal (Fig. 7). The benefits of this improvement can be directed towards processing a heavier feed, reducing the metal’s slip to the fixed bed residuum reactors enabling the use more active deep HDS conversion catalysts, or even reducing the consumption of OCR catalyst.

These developments in residuum pretreatment, the OCR/UFR process and associated new catalysts, increase the capability of the RDS/VRDS to hydrotreat heavier, dirtier residuums. They also increase the RDS flexibility to produce cleaner products to meet more stringent sulfur limits for transportation fuels and fuel oils. In practice, it has often been most economical to target some aspects of both, to produce cleaner products from a dirtier feed.

4.2. RDS Processing Options: feed quality vs. product quality considerations

A significant choice each refiner must make which impacts RDS operation is the balance between processing heavier, cheaper crudes and the requirement to meet more stringent transportation fuel specifications. Each refiner’s ability to meet finished product specifications will depend on existing desulfurization units in their refinery as well as the RDS. Therefore, each refiner will have different capability to handle heavier crudes. Within this construct, the RDS catalyst system via the catalyst system design increases flexibility to balance the process between cleaner products and heavier crudes.

To understand the tradeoffs that such feed and product choices involve, a series of pilot plant tests were conducted. The experimental design and the RDS product properties are shown in Table 1. This design enables measurement of the effect of feed quality (Arabian Light versus Arabian Heavy), the effect of RDS severity, and the effect of catalyst modification on RDS product quality and cycle time.

4.3. Impact of Feed Quality

RDS catalyst systems are designed for cycle times of nominally one year. Our need for quicker evaluation of full cycle results prompted the use of accelerated aging methods in pilot plant testing. Accelerated aging is accomplished by a combination of processing extra heavy feeds at increased liquid rates relative to normal process conditions. For a substantial portion of each run, accelerated aging conditions using Arabian Heavy Atmospheric Residuum (AHAR) were applied. The consequence is that what would normally be a year-long run is compressed into three to four months. Pilot plant processing is reset to commercial operating...
conditions (non-accelerated) to collect the middle of the run (MOR) yield and product quality data.

A comparison of run plots for hydrodesulfurization (HDS) activity as measured by the reactor temperature increase required to convert 90% sulfur versus time is shown in Fig. 8. Both tests ran AHAR over identical catalyst, the difference between runs being the duration of non-accelerated testing and a period of Arabian Light Atmospheric Residuum (ALAR) testing. The first test (Case 1) lasted one month longer than the second (Case 2) because more extensive testing was conducted under commercial, non-accelerated conditions, including several weeks processing ALAR (around 1300-1700 h in Case 1). The equivalence of these two tests is verified by comparing each catalyst activity plot as a function of metal loaded onto the catalyst system (Fig. 9).

As shown in Figs. 8 and 9, catalyst activities were tested at several liquid hourly space velocities (LHSVs) during the middle of the run (MOR). Their purpose is not to show the change in the operating temperature of the LHSV, but to obtain the kinetic parameters of the reaction to determine reaction rate constants. Figure 9 shows that LHSV changes did not significantly affect the catalyst life; instead the cumulative metals loading mainly affected the catalyst life. Despite the difference in processing time, each test absorbed metals to a similar loading with equal effect on catalyst activity.

A comparison of the product qualities from the non-accelerated portions of each test are shown in Table 1. Higher quality product is obtained from the ALAR feed than from the AHAR feed: lower product sulfur, Microcarbon Residue (MCR), and metals. A more detailed comparison will be discussed below.

4.4. Impact of RDS Severity

RDS severity is usually limited by the fuel oil stability and the need to meet a full year cycle time. More severe operation boosts conversion in RDS, but reduces the metal capacity of the catalyst system and can produce unstable fuel oil. Higher severity can reduce cycle time too much even when product stability of RDS product is not a problem. Nevertheless, there can be room for more severe operation with increased reactor temperatures with the benefit of lower product sulfur and MCR and greater VR conversion.

To assess the tradeoff in RDS product qualities with catalyst life, the above catalyst system was retested with higher overall temperature (Case 3). Temperature was increased enough to reduce product sulfur by 25% (from 0.54 to 0.40 wt%). The sulfur level in this high severity product is less than the sulfur level obtained by processing ALAR at standard severity. Increased severity also boosted MCR conversion, VR conversion and nitrogen removal, while maintaining product stability. The product qualities from the non-accelerated period during MOR are listed in Table 1. Higher severity operation reduced catalyst life by 35% in metal capacity shown in the run plot comparison for HDS in Fig. 10.

4.5. Moderating Catalyst Deactivation with More Metals Tolerant RDS Catalyst

For most RDS operations, a 35% sacrifice to metal capacity (compare the metal loading at EOR for Case 2

Table 1 Experimental Design and RDS Product Properties

<table>
<thead>
<tr>
<th>Case</th>
<th>Catalyst</th>
<th>Feed</th>
<th>Severity</th>
<th>RDS product properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sulfur [wt%]</td>
</tr>
<tr>
<td>1</td>
<td>Demet/Conversion</td>
<td>ICR</td>
<td>ALAR</td>
<td>Standard</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>ICR</td>
<td>AHAR</td>
<td>Standard</td>
</tr>
<tr>
<td>3</td>
<td>Demet/Conversion</td>
<td>ICR</td>
<td>AHAR</td>
<td>High</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>ICR</td>
<td>AHAR</td>
<td>Standard</td>
</tr>
<tr>
<td>5</td>
<td>New catalyst</td>
<td>ICR</td>
<td>AHAR</td>
<td>High</td>
</tr>
</tbody>
</table>

a) Boiling point distributions measured by Simulated Distillations of ASTM D 7169.
versus Case 3 shown in Fig. 10) for a few tenths of a percent lower sulfur and MCR is not practical. Refinery turnaround schedules cannot tolerate such a large loss of RDS catalyst metal capacity, even considering the improved value from cleaner RDS products. To enable RDS operation under more severe conditions, a new RDS conversion catalyst was commercialized. Its main feature is its stability toward metal fouling. This enhanced stability enables high catalyst loading percentages and more severe RDS operation.

A comparison of run plots for HDS activity of the new catalyst system (Case 4) to the standard catalyst (Case 2) at standard RDS severity (Case 4) is shown in Fig. 11. Reduced susceptibility to fouling and increased HDS activity of the new catalyst system have increased the system’s metal capacity by 8%. Since a yield period was not collected under non-accelerated aging conditions in the test of the new catalyst system, non-accelerated product qualities were estimated from MOR catalyst activities (Table 1). At standard RDS severity, the new catalyst (Case 4) delivers modest improvements to RDS product quality; product MCR is reduced by 5% relative to the standard catalyst system (Case 2).

The new catalyst system was tested using high severity life test process conditions (Case 5) to more fully utilize its added stability. The high severity HDS run plot is compared to the standard catalyst system in Fig. 12. The run plot of the standard catalyst system operated at normal severity is also shown for comparison. At high severity, the metal capacity of the new conversion catalyst (Case 5) is 20% more than the standard catalyst (Case 3). Relative to the standard catalyst run at normal severity (Case 2), the net sacrifice to overall metal capacity delivered by the new catalyst at high severity (Case 5) is 15%. This is significantly better than the 35% sacrifice to metal capacity by high severity operation achieved with the standard catalyst (Case 3).

Product qualities produced during MOR with the new catalyst system are listed in Table 1. The new RDS catalyst produced Sulfur, MCR and Nitrogen levels comparable to those produced by the standard catalyst at high severity (Case 5 versus Case 3), and superior to the standard catalyst operated at normal severity (Case 5 versus Case 2). With the exception of metals, product quality from the new catalyst is superior to the product from ALAR over the standard catalyst (Case 5 versus Case 1).

The new RDS catalyst moderates the sacrifice of metal capacity at high severity operation. The tradeoff in RDS product qualities for catalyst life is shown in Fig. 13 for HDS, and Fig. 14 for MCR. A larger product quality improvement is obtained with a smaller tradeoff of metal capacity. A 30% relative reduction in product sulfur (0.54% versus 0.40%) and a 20% relative reduction in product MCR is achieved with only a 15% sacrifice to metal capacity from a comparison of
Case 5 to Case 2.

4.6. RFCC Yields from RDS Products

To better understand the overall yield structure to transportation fuels with the RDS/RFCC option, the 650°F+ fractions from each MOR RDS test were tested in FCC ACE (Advanced Cracking Evaluation) Tests\(^9\). In addition, we wanted to understand what effects RFCC catalyst selection had on mitigating the impact of some of the differences in RDS product qualities, such as MCR and Metals. We observe that by balancing RDS and RFCC catalyst and process variables, enhanced yields of products can be produced from heavier feedstocks with qualities comparable to those derived from the lighter feedstock.

To understand the effects of RDS product qualities on RFCC yields, products from the RDS life tests were tested at Grace Davison’s research facilities in Columbia, Maryland. Testing of the 650°F+ fractions from Cases 1-3 and 5 of Table 1 was conducted in an ACE fluidized bed pilot plant reactor after deactivation by the cyclic propylene steaming (CPS) protocol\(^1\). Feed metals levels and theoretical catalyst addition rates were used to project equilibrium catalyst metals levels and simulate commercial operation. These calculated metals levels were then targeted during the metals impregnation phase of the deactivation procedure.

Variables of the ACE tests include conversion levels between 70-75%, Catalyst-to-Oil ratios between 4 to 9, reaction temperature 1000°F, catalyst addition rates, and RFCC catalyst properties, differentiated by Type I (conventional RFCC catalyst) and Type II (state of the art RFCC catalyst with high metals trap and bottoms cracking ability) RFCC catalyst names. A summary of these process variables and their associated results are shown in Table 2.

Type I is the conventional RFCC catalyst based on the Grace Davison’s proprietary alumina sol technology. The catalyst shows good selectivities, as well as activity retention, and excellent unit retention properties in FCC units. Type II catalyst is the state of the art RFCC catalyst which combines Grace Davison’s proprietary alumina sol catalyst platform with rare earth stabilization technology. The catalyst combines next generation integral high metals trapping ability, advanced zeolite stabilization, and superior matrix metals passivation properties for high bottoms cracking and to achieve the ultimate in coke selectivity\(^1\).

For the purposes of comparison here, two extremes will be considered. RDS processing of ALAR followed by RFCC processing with Type I RFCC catalyst represents conventional processing of a comparatively light residuum for a gasoline focused product slate (column 1 in Table 2). RDS processing of AHAR with the new RDS catalyst system, at high severity followed by RFCC processing with Type II RFCC catalyst represents processing of a heavier residuum for a gasoline focused product slate (column 6 in Table 2). The second extreme is chosen as a potentially optimum tradeoff of RDS product quality for RDS cycle time for the heavier residuum. For a specific refinery application, the optimal balance of light/heavy feed with overall product qualities could lie somewhere between these extremes.

At 75% conversion in the RFCC, processing the

![Fig. 14 MCR Product Quality—Tradeoff with Metal Capacity](image)

<table>
<thead>
<tr>
<th>RDS case</th>
<th>Type I</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFCC cat. addition</td>
<td>1×</td>
<td>1×</td>
</tr>
<tr>
<td>Cat-to-Oil ratio</td>
<td>5.4</td>
<td>10.8</td>
</tr>
<tr>
<td>Hydrogen [wt%]</td>
<td>0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Total C(_1)'s + C(_2)'s [wt%]</td>
<td>1.9</td>
<td>2.2</td>
</tr>
<tr>
<td>Propylene [wt%]</td>
<td>4.7</td>
<td>4.5</td>
</tr>
<tr>
<td>Total C(_3)'s [wt%]</td>
<td>5.5</td>
<td>5.1</td>
</tr>
<tr>
<td>Total C(_4)= [wt%]</td>
<td>6.5</td>
<td>6.7</td>
</tr>
<tr>
<td>Total C(_5)'s [wt%]</td>
<td>10.7</td>
<td>9.6</td>
</tr>
<tr>
<td>(RON+MON)/2</td>
<td>85.8</td>
<td>86.8</td>
</tr>
<tr>
<td>LCO [wt%]</td>
<td>17.4</td>
<td>18.6</td>
</tr>
<tr>
<td>Bottoms [wt%]</td>
<td>7.6</td>
<td>7.8</td>
</tr>
<tr>
<td>Coke [wt%]</td>
<td>6.8</td>
<td>10.0</td>
</tr>
</tbody>
</table>

\(^a\) Conversion is the volume % of fresh feed converted to gasoline, lighter products, and coke in FCC products.

343°C + fraction from ALAR requires a 5.4% Catalyst-to-Oil ratio to produce a 49.9% yield of C5 + gasoline (Case 1—column 1 in Table 2). This base case condition produced 6.8% coke on catalyst. Processing AHAR RDS product from the same RDS catalyst system at standard (Case 2—column 2 in Table 2) or high severity (Case 3—column 3 in Table 2) nearly doubles the Catalyst-To-Oil ratio and the coke on RFCC catalyst; gasoline yields also drop due to the increased contaminants from the heavier feed. These results demonstrate the penalty in the RFCC associated with simply running heavier feed. These penalties can be mediated for the high severity RDS product by the selection of a more suitable RFCC catalyst at 50% increased addition rate (Type II RFCC catalyst of column 4 in Table 2). A small increase in gasoline yield is obtained albeit with a slightly elevated coke level on catalyst. However, this case still suffers from the 35% sacrifice to RDS catalyst system life.

A superior tradeoff results with the combination of high severity RDS operation using new RDS catalyst with Type II RFCC catalyst. At comparable Catalyst-to-Oil ratios, a 3% absolute increase in gasoline yield and reduced coke on RFCC catalyst (column 6 in Table 2) are obtained. Other key product yields and qualities from RFCC processing of AHAR RDS product are comparable to products from the base case with ALAR. The improved RDS product quality (Case 5 versus Case 1 of Table 1) has marginally improved the gasoline yield. Instead, the main improvement derives from the RFCC catalyst improvement. These results demonstrate that altering the RDS and RFCC catalysts along with the RDS process severity can deliver product yields and qualities from a heavier residuum superior to those produced from a lighter residuum.

For residuum-feed units whose performance is impacted by contaminant metals and high feed carbon, catalyst activity retention and coke selectivity are the most important catalyst performance characteristics. The integral metals trapping technology used in Type II RFCC catalyst substantially decreases contaminant metals related coke and dry gas, compared to conventional RFCC catalysts. In addition, the excellent activity retention of the Type II catalyst results in high activity, which along with the good coke selectivity results in improved gasoline yield. These results demonstrate that altering the RDS and RFCC catalysts along with the RDS process severity can deliver product yields and qualities from a heavier residuum superior to those produced from a lighter residuum.

4.7 Process Comparisons between Coking, LC-FINING and RDS/RFCC

The combination of RDS with RFCC yields is shown relative to Coking and LC-FINING process yields in Fig. 15. This comparison identifies several distinctions between these processes. LC-FINING and RDS/RFCC produce enhanced yields of liquid products. The liquid products from LC-FINING and Coking are similar, weighted towards mid-distillate production. LC-FINING yields greater liquid yields at the expense of greater hydrogen consumption. RDS/RFCC produces liquid yield intermediate between Coking and LC-FINING, with intermediate hydrogen consumption (1175 SCFB relative to 800 or 1970 SCFB). RDS/RFCC products are more concentrated in the lighter fractions, gasoline and LPG. One consequence of the lighter product distribution from RDS/RFCC is a smaller yield of fuel oil.

5. Conclusions

To meet the demand for heavy oil upgrading, CLG licenses a number of processes targeting bottoms reduction. In combination with recent catalyst advances for residuum hydrotreating, practical process schemes are offered that deliver a spectrum of transportation fuel focused product slates. Advances in RFCC catalyst development also contribute towards increased flexibility to process heavier crude oils.

References

Meeting, Salt Lake City, Utah, March 19-21, 2006.


要 旨

RDS/VRDS-RFCC プロセスと触媒の技術進歩による残油アップグレーディング性能の向上

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原油中の高沸点残留をより高価値の残油にアップグレードするためのプロセスの選択肢について概観した。残油水素化脱硫（RDS）と残油流動接触分解（RFCC）の組合せにより、副製品の生成を最小限に抑えつつ輸送用燃料と化学原料の製造収率を最大化することが可能である。このプロセススキームでは、重質油中に含まれる残留炭素やニッケル・バナジウム等の不純物により、RDS 触媒／RFCC 触媒ともに厳しい環境にさらされることから、技術的な困難を伴う。本論文ではまず、Ni-Mo を担持した RDS 触媒をバイロット試験装置で適用し、重質の常圧残油（AR）を水素化処理した結果を示した。RDS バイロット試験装置で触媒の寿命試験を行い、製晶サンプルを採取して蒸留し、分析を行った。RDS ユニットに開発した触媒を用いて新しいプロセスの組合せ、すなわち、RDS-AR-FRCC を適用するとともに、不純物を除去できるよう RDS の能力向上を図った。この RDS 製品を原料として、Advanced Cracking Evaluation（ACE）試験装置を用いて RFCC 触媒の反応性を確認した。改良された RFCC 触媒は残油中の耐メタル性を向上させ、原料油の分解に促進する。RDS 触媒と RFCC 触媒の組合せを最適に選択することにより、重質な残油から高価値の残油を高収率で製造できることを示した。