Prospectus for 2006 Multi-Client Strategic Report:

Opportunity Crudes: Technical Challenges and Economic Benefits

Strategies of processing high acid crudes and the bottom-of-the-barrel using advanced technologies

Hydrocarbon Publishing Company

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INTRODUCTION

The definition of opportunity crudes changes over time. Back in the 1970s, it referred to sour crudes or high-sulfur crudes. As refiners installed more hydrotreaters, the price differential tightened. Nowadays, the opportunity crudes are high-acid crudes (HACs)—which have high naphthenic acid content or high Total Acid Number (TAN) exceeding 0.5-1.0 mg KOH/g—or heavy sour with high sulfur content (>0.7-1.0% S), considerable amount of nitrogen and aromatics, low API gravity (< 26-28°), and high proportion of heavy residues from the distillation towers or so-called bottom-of-the-barrel (BOB). These crudes are difficult to process and the difficulties cannot always be predicted.

The primary objective of this Report is, therefore, to identify and analyze the latest technologies to process HACs and BOB, reveal the factors behind the unpredictability, highlight operational experiences of refiners and technology developers, and define the optimum scenarios wherein refiners can take advantage of the inexpensive crudes based on dynamic crude economics, technology advances, and operational flexibility.

REPORT SCOPE AND FOCUS

Key discussions begin in **Section III** with a survey of the recent and proposed specifications for motor gasoline, middle distillates, and residual fuel oil. **Section IV** identifies the current worldwide supply and demand of motor gasoline, middle distillates, and residual fuel oils to assess the consumption trends as well as market potential and dynamics. **Section V** highlights the latest industry events and directions in major refining centers, particularly mergers and acquisitions, refinery expansions and revamps, unit additions, and plant closures. **Section VI** analyzes installation capacity and recent construction activities of resid upgrading units. In addition, this section presents the patenting activities of refiners and technology companies. **Section VII** identifies and analyzes the latest technologies for (1) high-TAN crudes (discussing HAC properties and composition, product yield and quality, naphthenic acid corrosion and management techniques, desalter operation, and fouling, (2) heavy, sour crudes (discussing crude blending and incompatibility, desalters, crude distillation, coking, visbreaking, solvent deasphalting, and resid FCC, hydrotreating and hydrocracking, (3) unconventional treating and upgrading techniques of processing opportunity crudes, and (4) upgrading bitumen and extra-heavy oil to syncrude. **Section VIII** reveals the economic implications and assesses costs and benefits. To conclude this report, we strategically analyze the technical challenges and economic benefits of processing HACs and BOB in **Section IX**. Most importantly, we offer insightful observations and analyses that lead to constructive and valuable recommendations for refiners and technology developers. <u>The goal is to enhance the abilities of our subscribing clients to tackle the</u>

challenges and to capitalize on the opportunities when the crude slates of the world are at the beginning of a historical shift.

Primary sources of information include: interviews with technology holders and catalyst and additive suppliers; an extensive literature search and evaluations; discussions in recent refinery operations and trouble-shooting Q&A conferences, in-depth patent analyses and reviews; and insightful technology and business strategy assessments by experienced practitioners.

HIGH ACID CRUDES (HACS)

Crude Sources and Supply Outlook

There are basically four types of crudes available to refiners around the world. They are light sweet (30-40°API, <0.5 wt% sulfur), light sour (30-40°API, 0.5-1.5 wt% S), heavy sour (15-30°API, 1.5-3.1 wt% S), and extra heavy (<15 °API and ≥3 wt% S).

High acid crudes (HACs) are defined by having values for overall acidity that exceed some specified limit. Overall acidity is expressed as a neutralization number or Total Acid Number (TAN), which is defined as the number of milligrams of potassium hydroxide (KOH) needed to neutralize the acidity in one gram of oil, and for this reason HACs are also called high-TAN crudes. Crudes with a TAN of 0.5 mg KOH/g oil or higher are called high acid crudes, and they are known to create problems in a refinery. Although not all acidic components in crude are potentially corrosive, refineries would like to handle crude with TAN <0.5 and subsequent process streams containing TAN <1.5.

There are different worldwide HACs production estimates offered by various companies (e.g. Chevron, Nalco, Purvin & Gertz, Shell, and Total SA), and their figures differ depending on TAN numbers and when the forecasts were presented to the public. In 2005, a joint effort by Chevron and Nalco revealed that total global production of HACs (TAN>1.0 mg KOH/g) was 2.29MM b/d in 1998, 2.96MM b/d in 2000 and 3.96MM b/d in 2004. In 2004, the Americas led the production rate with 1.94MM b/d, followed by the Far East at 805K b/d, Northern Europe at 740K b/d, and West Africa at 475K b/d. Chevron forecasted that West African (excluding ExxonMobil's Block 15 projects) and Far Eastern production will rise to 700K b/d and 1.2MM b/d by 2008 respectively. On the other hand, the North Sea's high acid crude output will rise to 900K b/d in 2006 and then decline to 600K b/d by 2010.

Growing Refiner Acceptance of HACs

US refiners are equipped to handle heavy, sour, as well as high acid crudes. According to a May 2005 announcement, ConocoPhillips planned to boost high acid crude processing capacity from 11% to 24%. Reported in

May 2005, Sunoco processes mainly light, sweet crudes, ignoring the excellent spread between sweet and sour grades. However, it also uses some high acid crudes, which are showing favorable spreads. In 4Q 2004, almost 5% of the company's feedstock slate was heavy, sweet, and high acid crudes; Sunoco planned to increase that portion to 10% in 1Q 2005. During the 1Q 2005, Valero processed approximately 1.2MM b/d of sour and acidic crudes, which is approximately 70% of the US's total crude throughputs.

Californian refineries, which have a high degree of complexity and extensive resid upgrading capabilities, have been processing predominantly sour, medium and heavy crudes, mostly from indigenous local production and the Alaska North Slope. Both of these sources are dwindling at an average rate of 4%/y. The increasing shortfall of ANS and Californian crudes will be covered by imports from Latin America, West Africa, Canada, the Middle East, and the Pacific Rim. Additional imports from Canada will mostly be high-TAN, high-sulfur, heavy oilsands-based crude (Syn-Bit). Also, the incremental West African and Pacific Rim imports will be high-TAN, low-sulfur, heavy crudes.

In Europe, UK North Sea heavy oil reserves are 10-11B barrels and potential deliveries are about 250K b/d by 2008. These oils are known to have 9-15°API, 2-9 TAN and 0.5-1.3% sulfur and are traded at high discounts to Brent—up to $20/bbl. Though many refineries are not equipped to handle crudes with TAN exceeding 0.5 since anti-corrosion measures are expensive, lower prices for high-TAN grades have generated interest from some refiners. Nautical Petroleum predicts that the UK may eventually become the center for heavy acidic oil processing. In 2004, Chevron's Pembroke, Wales refinery completed a $12.8MM project to adapt its equipment to process 21°API, acidic, high-calcium Doba crude from Chad.

In Asia, China National Offshore Oil Corp. (CNOOC) announced plans in June 2003 to build a new 12MM-mt/y refinery in Huizhou, Guangdong, China. The company's Penglai crude—which is highly acidic, registers 20ºAPI gravity, and has a high aromatics content—will be used as 85% of the feedstock for the facility. The crude quality makes the intended naphtha production more costly. Acid- and aromatics-extraction units will be necessary. As early as April 2002, South Korean and Taiwanese refiners were looking to use Chinese Qinhuangdao crude as a cheaper alternative sour feedstock. Its competitive price attracted firms despite its increased acidity and sulfur content. QHD crude is produced offshore in northern China at Bohai Bay, but output averages only 20K b/d. Owner/operator CNOOC plans to raise production to 40K b/d by July of that same year. In Jan. 2003, Indian Oil Corp. unveiled plans for a 36-month expansion project at its Koyali refinery. The work would allow the facility to process cheaper, acidic crudes in addition to meeting upcoming tighter fuel specifications. Capacity was to have been expanded from 270K b/d to 360K b/d.

Africa is the last frontier for many international majors and oil-thirsty Asian companies because the continent has significant proven reserves and is the only place still friendly to foreign investment in oil exploration and production. West Africa has new production coming onstream and some fields are full of HACs. Sudan's

Ministry of Energy and Mining signed a $1B agreement with Malaysian refiner Petronas in Aug. 2005 for construction and joint operation of a 100K-b/d export refinery that will be located in Port Sudan. The refinery will process domestic Dar Blend crude and is expected to be operating by early 2009. In South Africa, Caltex's Cape Town refinery announced in mid 2002 that it would upgrade to process high acid crudes from West Africa.

Technical Challenges

HACs have the potential of significant economic benefits for refiners, but realizing these benefits requires overcoming negative impacts of HACs on product yields and quality (e.g. diesel with a low cetane number) and on the reliability and operations of the refinery in various areas. Other adverse effects include corrosion, desalter problems, fouling, catalyst poisoning, product degradation, and environmental discharges. According to our statistical analysis on assay data, there are on average significant differences between HACs and low-TAN crudes in terms of key bulk properties. Extension of the analysis to the distilled products finds on average lower yields of naphtha and distillates and higher yields of VGO and resids for HACs.

Although TAN value is used to define which crudes are HACs, it is not a reliable indicator of the potential of the crude oil for causing problems with reliability and operations in the refinery. Corrosion at various sites in the plant is one of these problems. **The Report discusses the classification of the acids in crude oils and the efforts that are being undertaken to characterize their content and chemical structures.** All of the characterization work is motivated by the hope of facilitating the identification of crude oils with high potential for causing corrosion and other problems and aiding the development of new options for processing them.

High-TAN crudes tend to cause high temperature corrosion in the range of 400-600°F (204-315°C), though it could happen at less than 250°F (121°C) in crude unit overhead equipment. Safety and reliability are major concerns. The overall acid number of a crude is less important than that of the individual side cuts. The Report has extensive discussions on naphthenic acid corrosion (NAC) and the influencing factors such as crude oil history, process temperature and flow conditions, and metallurgy. Also the presence of sulfur compounds has considerable impact on the corrosion of iron and its alloys by naphthenic acids, resulting in three types of corrosion that will occur in different locations. All of this indicates that the observed rate for NAC will depend on the relative concentrations of naphthenic acids and sulfur compounds.

There are various ways of managing naphthenic acid corrosion. These include: (1) predicting the corrosion behavior of crudes and their relative risk levels; (2) inspection and monitoring to identify specific areas that are at risk for NAC and to verify that control methods are being used effectively; and (3) applying corrosion control methods. Methods for predicting corrosion behavior are used to establish potential corrosivity of crude oils and the relative levels of risk involved in using them. If the metallurgy is not of proper quality to run HACs, a chemical injection system with a neutralizer will be needed to protect the crude unit and the cost should be considered in the overall economics. **Our discussion of these includes checklists, experiential databases, screening tests, and laboratory tests and models for corrosion rates.** Though refiners have preferred metallurgical properties of alloys like 316 SS and 317 SS to fight corrosion, the Report describes other alloys that appear to be even more corrosion-resistant.

Naphthenic acids are implicated in problems with downstream units like hydrotreaters, FCCUs and lube plants, and we provide specific examples that have been cited by refiners at the conferences of National Association of Corrosion Engineers (NACE) and National Petrochemical and Refiners Association and elsewhere. Also, difficulties arise with desalting, and there are risks of increased fouling due to low API gravities of HACs and their contents of asphaltenes, naphthenic acids and calcium naphthenates. **The Report includes a master table of the effects of HACs on the downstream refining processes and products as well as solutions to mitigate or avoid problems.** For instance, Baker Petrolite's EXCALIBUR Metals Removal Technology, which incorporates emulsion breakers, corrosion inhibitors and scale inhibitors, is said to remove calcium and other metals that prevents fouling of the desalter and downstream equipment.

In the future, modifying or removing naphthenic acids would come from four areas: neutralization, decarboxylation, hydrotreating, and extraction according to recent R&D works. We compare and analyze advantages and disadvantages of these corrosion control methods.

Economic Benefits

As more heavy, high-TAN crudes become available, refiners need to reassess their crude acquisition strategies and new processing investment. The blending low TAN with high-TAN crude can be used to deal with corrosion problems in refineries but it raises logistical costs.

There is a saying among refiners that crude costs plus chemical costs are a constant. There is a trade-off between inexpensive crudes and expenses required to process them. Also, there are concerns over product yield structures and long-term reliability. Therefore, it is paramount for refiners to adopt cost-effective techniques to take advantage of the price differentials and to overcome the concerns.

A section of the Report includes a discussion of the economics of refining HACs. We combine the supply forecast with regional averages for crude properties from our own database of crude assays and project a trend in HAC characteristics over the next five years. Because of their properties relative to benchmark crudes like Brent, HACs are offered at a discount to the benchmark costs. Regression models based on bulk properties have been used to predict price differentials for crudes. We look at one approach that has been developed to rationalize the discount for an HAC and illustrate its use in estimating a global average discount.

BOTTOM-OF-THE-BARREL (BOB)

Heavy Sour Crude Sources and Supply Outlook

Over half of the world's oil supply nowadays is heavy and sour. Between 1994 and 2003, heavy and medium sour crude experienced the largest growth in production. In 2003, only 30% of all crude produced was light, 56% was medium, and 14% was heavy. In terms of crude quality, 60% of light crudes produced were sweet, about 20% of mediums were sweet, and 15% of heavies were sweet as shown in the table below. On the other hand, almost all of the heavy oils produced in recent years have been either medium sour or fully sour.

Crude type	2003 global crude production, K b/d	% of total global crude production	Production growth from 1994 to 2003, %
Medium and sour	26,788	38.2	7.0
Light and sweet	12,055	17.2	2.4
Medium and sweet	7,797	11.1	43.5
Unassigned	5,862	8.4	-5.5
Heavy and sour	5,604	8.0	39.2
Light and sour	2,481	3.5	30.2
Heavy and medium sour	1,908	2.7	128.5
Ultra light	1,665	2.4	46.7
Medium and medium sour	1,623	2.3	-1.0
Heavy and sweet	1,365	1.9	16.3
Total	70,046	99.9	13.8

Gravity: light (>35°API), medium (26-35°API), heavy (10-26°API), extra heavy (<10°API).
Sulfur levels: sweet (<0.5 wt% S), medium sour (0.5-1.0 wt% S), sour (>1.0 wt% S).
Source: Lifschultz, D.K. "Oil refiners' gathering storm: help is on the way." *Hydrocarbon Processing* Sept. 2005: p 59.
Note: in some definitions, light (>39°API) and heavy (<28°API); and sour (>0.7 wt% S)

The trend of crude becoming heavier and more sour will continue in the future despite new light crude discoveries (e.g. West Africa). For instance, the latest new oil production schedule in the Western Hemisphere indicates that over 1MM b/d of heavy crude from Brazil will come onstream in 2006-2009. Colombia's newest field also offers heavy sour crudes. About 60% of crudes imported to the US are medium and heavy sour with an average API of 30.5° and 1.4% sulfur because most of them come from Canada, Mexico, the Middle East, and Venezuela. Due to their lack of heavy oil processing capability and the need to produce light products, high- quality crudes are in constant demand by developing countries (such as China and India). Furthermore, new heavy crude production will keep light/heavy spreads wide and allow refiners to take advantage of the opportunity crudes.

Price Incentives for Heavy Crudes

In the US Gulf Coast, lower-quality crudes (either heavy or sour or both)—such as Maya, Mars, Dubai, Oman, Russian Urals—are priced significantly lower than WTI (Cushing). According to the US Energy Information Administration, the spread between relatively light, sweet Brent and a heavier, sour Mexican Maya widened from \$5/bbl in May 2002 to \$15/bbl in May 2005 as global production of light, sweet crude declined between 2000 and 2004 and fuel sulfur specifications around the world became increasingly stringent. The easiest way to meet the low sulfur standards is to process a lighter, sweeter crude. Likewise, the five-year (2000 to mid-2005) average spread between spot WTI (Cushing) and Maya was above \$9/bbl. An industry observer said that the peak oil production of light sweet crude has already passed. The average API gravity of non-OPEC oil has decreased, and the sulfur content has been creeping up.

In Europe, Russian Urals and heavy sour crudes from Iran had surprisingly surged in popularity in the summer of 2005 as increasing sweet crude production was a problem in OPEC and elsewhere but fuel demand was not slowing. Fuel oil's discount to crude had shrunk to about \$20/bbl after a year-high in May.

The Report performs statistical analyses on data from 1982 through 2004 for the margins obtained by coking and cracking refineries and for three sets of price differences between light and heavy crude oils (e.g. WTI-Maya.) The intent is to characterize the statistical significance of relationships between margins and reveal a window of opportunity for refiners to capture the benefits of widening differentials.

Flurry of Heavy Oil Projects around the World

In view of rising prices of light, sweet crudes and surging demand for light transportation fuels, some refiners may either build a grassroots refinery or revamp their existing facilities to handle heavy crudes. It has been a particularly urgent issue for refiners in developing countries such as those in Asia. There are numerous heavy oil projects undertaken in many parts of the globe. Some of them are listed in the following table.

Region	Country	Projects
North America	The US	ConocoPhillips announced in Nov. 2005 that it plans to allocate additional funds to expand its US refining capacity by 11% and, at the same time, invest \$3B to boost its capability of handling lower-quality crudes
		In late Nov. 2005, Motiva decided to expand the heavy sour crude processing capacity of its Port Arthur, TX refinery by 325K b/d.
		In 4Q 2004, more than half of the oil used by Valero was sour or both heavy and sour, including Mars from the Gulf of Mexico and Mexican Maya. In the past two years, the largest US independent refiner has added 545K b/d of heavy sour crude processing capacity by either buying refining assets or expanding its own plants. [Note: US Republican senator has considered introducing a measure to give tax relief to refiners that invest in refining sour crude as part of tax breaks to encourage the construction of new refineries or the upgrading of existing ones after the Katrina and Rita damages in late summer 2005.]
		Canada's Suncor Energy is spending \$300MM to upgrade its Denver refinery in the US so that it can handle heavy oil from its own oilsands operations.
Europe	France and the UK	In April 2005, France's Total SA, the largest refiner in Europe, announced its intention to increase its heavy oil processing capacity. Also, in Sept., it indicated that it will invest €200MM at its 223K b/d Lindsey refinery in Immingham, UK to process additional sour crudes and a similar plan is under study for its 231K-b/d Donges refinery in France. The company sees a shift to crudes from Russia and the Caspian Sea as production in the North Sea is dwindling.
	Italy	ERG considers reconfiguring its ISAB refineries to process more sour crudes at the expense of sweet crudes according to a news announcement in late Nov. 2005.

Region	Country	Projects
	Spain	In Nov. 2005, Repsol YPF announced that it will spend €2.7B ($3.2B) to increase its refining capacity in Spain and enable its facilities to process heavy crudes. Upgrades will take time to change crude price fundamentals, as new processing units will take several years to build and start up.
Middle East	Saudi Arabia	Saudi Aramco plans to build five grassroots refineries with a combined capacity of 300-400K b/d to take advantage of a global surplus of heavy, sour crudes. These units will be built at home and abroad between 2006 and 2015.
Asia	China	Although China has only one refinery capable of handling heavy oils, China National Petroleum Corp. signed a one-year agreement with PDVSA in mid-Nov. 2005 to import 160K b/d of heavy oil and fuel oil. Venezuela plans to quadruple oil exports to China in 2006 in order to lessen its export dependence on the US.
	Japan	Japan Energy Corp. might upgrade its 200K-b/d facility at Mizushima, western Japan to handle more heavy crude by raising the capacity of an existing coker. The decision reflected a shift in the fuel demand pattern in the country—rising gasoline consumption at a modest 0.5% per year to 2008 while heavy fuel oil used by thermal power plants is projected to decline 15.1% per year.
	S. Korea	In late Nov. 2005, Saudi Aramco indicated that it may build a $3.0B-$3.5B fuel oil or Bunker-C cracking plant to produce clean fuels in the country, where it has a 35% stake in the third largest refiner, S-Oil Corp. Earlier in the month, SK Corp. announced that it will spend $6B over the next three years to upgrade its facilities to produce clean fuels and raise its heavy, sour oil processing capacity by 56% to 335K b/d by 2008. In July, GS Caltex indicated that it will invest 1 trillion KRW ($962MM) to install a 50-60K b/d unit to convert heavy fuel oil into lighter oil.
	India	In Aug. 2005, Indian Oil Corp. announced its plan to build new facilities to increase the percentage of heavy, sour crudes processed from 40% to 73%. Also, it will add a new delayed coker at its Koyali refinery.

Growing Production of Oilsands, Tarsands, and Oil Shale

At the same time, alternative sources—such as oilsands, tarsands, and oil shale—are being sought by refiners around the world. Paris-based International Energy Agency in its recent report called "Resources to Reserves" puts the global reserves of heavy oil bitumen and oil shales at 6 trillion bbl, of which 2 trillion bbl may be ultimately recoverable. Oilsands or tarsands are a mixture of bitumen and sand that can be mined and processed into oil, while oil shale is a rock containing organic material that can be crushed and heated to produce oil. Potential reserves of Canada's unconventional supply from Alberta bitumen-like tarsands (about 175B bbl of proven reserves estimated by US Department of Energy) and Venezuela's Orinoco oilsands (about 235B bbl) are more than half of present known reserves of conventional crude.

Recent technological advancements will enable most of the heavy oil resources of Canada, Venezuela, and elsewhere to be economically feasible at oil prices of $20-40/bbl. That includes the cost of mitigating CO_2 emissions from production. On the other hand, oil shale such as that in Australia might require crude price levels of $25-70/bbl to be economical for the best performing projects.

Many bitumen/extra heavy crudes (e.g. Athabasca bitumen and Orinoco Cerro Negro) have high TAN content. Based on four existing projects, less than 1MM b/d of Alberta's bitumen is currently upgraded into heavy oil, called syncrude, and sent by pipeline to refineries; that amount may increase to about 3MM b/d in the next decade. Virtually the entire output is sent to refineries in US Midwest refining hubs such as Chicago and Minneapolis. Canadian Enbridge plans to spend $300MM in a new pipeline to deliver the oil to St. Louis and a 1,160-km pipeline from the provincial capital of Edmonton to Canada's Pacific Coast to ship the heavy oils to Asia. At the same time, US pipeline company Kinder Morgan proposed to build a new pipeline running down from Canada to the Rocky Mountains and West Coast refining centers as well as sending crudes to the Pacific. ExxonMobil is considering reversing the Texas-Illinois pipeline so that it can send the Canadian crudes down to the Gulf Coast. Within a decade, the announced oilsands projects, which total C$100B, could triple bitumen and syncrude supply.

In Venezuela, the synthetic crude produced by four extra heavy crude upgrader projects—joint ventures between state-owned PDVSA, BP, Chevron, ConocoPhillips, ExxonMobil, Statoil, and Total—may climb from about 600K b/d from 2005 to 1.5MM b/d by 2015. Currently, most upgraded crudes (with 16-32°API and 0.1-3.3% S) are destined for specific refineries in the US Gulf Coast with small quantities shipped to Europe.

Down under in Australia, production of oil shale products is also on the rise, and Southern Pacific Petroleum is developing reserves beyond 20B bbl. Production could go up to 150K b/d by 2012 with Australian and Asian refineries being the primary beneficiaries.

The diesel cuts derived from bitumen and syncrude have low cetane numbers (<30 for Canadian Athabasca) and very high sulfur and nitrogen contents. Therefore, it is difficult to meet both road cetane and ultra-low sulfur specifications on bitumen-derived crudes. High nitrogen content also inhibits desulfurization, particularly with respect to dibenzothiophene. In handling these low-quality crudes, modifications of the distillate, kerosene, and naphtha hydrotreater must be addressed. The naphtha reformer must also be adjusted since bitumen-derived naphthas have high naphthene and aromatics content. Auxiliary units such as hydrogen plants and sulfur complexes should be re-evaluated for their added responsibilities.

This Report has a section on the latest upgrading technologies to convert bitumen and extra-heavy crude oil to syncrude and/or light products.

Declining Demand for Residual Fuel Oil

There are two types of resids, depending on the source: atmospheric resid (or bottoms) from atmospheric distillation towers and vacuum resid (or bottoms) from vacuum towers operated at a reduced pressure of 25-100 mm Hg. Heavy crudes carry disproportionate amounts of vacuum bottoms, e.g. 38% for Maya, 55% for Orinoco Cerro Negro, 52% for Athabasca versus 10% for Brent and 18% for Arab Light. On the other hand, synthetic crudes derived from extra heavy crudes and bitumen from Canada and Venezuela contain no residual cuts, but are acidic. DilBit and Synbit, which are blends of Athabasca bitumen and condensate or syncrude have 36% and 27% vacuum bottoms. Meanwhile, global residual supply is surpassing demand, with the surplus deepening from

4.5MM b/d in 2000 to a projected 7.5MM b/d in 2005, 9.2MM b/d in 2010, and 11.2MM b/d in 2015. Consumption of residual fuel oil is declining because of its sulfur content, and it is being replaced by natural gas in power generation. HFO consumption has been declining from 29% of global product demand in the early 1970s to 13% in 2005. More vacuum bottoms will be need to be processed and substantial investments must be made in refineries and field upgraders. In most of 2005, No. 6 fuel oil's discount to Arab Light in the US ranged from $4/bbl to more than $11/bbl.

Technical Challenges

A major concern with processing heavy crudes is blending and mixtures, since it is common for compatible crudes (e.g. Louisiana Light Sweet, West Texas Intermediate and Alaskan North Slope) from multiple fields to be mixed in pipeline systems since a lot of refineries are short on crude tankage. These crudes have different compositions and there are economic penalties for that variance. Since there are incompatibilities between the high-asphaltene crudes and the high-paraffinic crudes, Asian refiners that often process waxy crudes may have problems accepting heavy crudes from Canada and Venezuela. Aromatics/heavy crudes are often separated from light, paraffinic crudes to avoid asphaltene precipitation. Crude oil incompatibility and the precipitation of asphaltenes on the blending of crudes can lead to catastrophic fouling and coking in the preheat train, resulting in net economic loss. Common problems are stable water emulsions in the desalter, fouled preheat exchangers, and/or coking in the pipestill furnace tubes. Therefore, it is important to use the oil compatibility model and tests to predict the proportions and order of blending of oils that would prevent incompatibility prior to the purchase and scheduling of crudes. Test methods for compatibility, many of which are proprietary, have been developed, principally by the larger companies in the industry. Smaller refiners would benefit by licensing one or more of these methods. **There is a section in the Report discussing analytical tests and measurements, blending issues, desalter problems, and the techniques (e.g. additives, condensates, and diluents) to avoid unit upsets.** Chemical treatments of crudes can alleviate desalters upsets such as hydrocarbon contamination of the effluent water, rag layer build-up, and poor crude dehydration in tankage.

High-TAN crudes may compete with heavy, sour crudes requiring more residual processing capacity. On the other hand, some of the oilsands bitumen blends have high acid content that requires investment in improved metallurgy and chemical additives.

No matter which resid conversion technology is selected, coke and sediment formation are often the major concerns. Furthermore, byproducts of a heavier, carbonaceous nature will be produced and refiners have to find outlets for these materials as part of the overall economic considerations. Most resid upgrading processes can be made up of combinations of separations (distillation or deasphalting), thermal processing (coking or visbreaking), fluid catalytic cracking, and hydroprocessing.

Revamps of crude distillation towers

When crude blends get heavier, atmospheric and vacuum tower distillate cut points tend to suffer due to increasing difficulty of vaporization. Therefore, changes can be made such as increasing the temperature and residue stripping efficiency, lowering the pressure and flash zone oil partial pressure, and modifying the pumparounds. For the atmospheric unit, other key areas include the oil preheat train and charge furnace, column internals, and metallurgy of the unit exposed to higher sulfur and high TAN; for the vacuum towers, evaluations should be made regarding furnace sizing and outlet temperature, decoking capability, wash-zone capacity, and steam requirement (if it is a wet column). Deep-cut vacuum distillation via a revamp of the unit to cut deeper into the resid to make additional FCC or hydrocracker feed is one of the first and most attractive options a refiner should consider. **The Report describes actual unit revamps and explains what parameters must be adjusted to increase diesel, AGO, and HVGO production at the expense of atmospheric and vacuum tower bottoms.**

Coking

Delayed coking, a carbon rejection technology, is the most popular way to upgrade residual oils with current global capacity of 4.4MM b/d. About 52% of the capacity resides in the US, which has seen its coking capacity surge 50% while total refining capacity has dropped 10% over the last 25 years. Since 1994, 625K b/d of new capacity has been added in the US. Coking refineries in the US Gulf Coast are said to give the higher historical gross refining and typical net refining margins—$5-7/bbl and $0.5-4.00+/bbl versus $3-4.50/bbl and $0-2.50/bbl—by cracking refineries according to Baker & O'Brien in 2005.

The pitfall of delayed coking is that only 70-80% of the total heavy oil barrels are converted into valuable transportation fuels while the remaining portion is downgraded to less valuable coke. There are three limitations to achieving higher liquid yields: (1) secondary cracking of valuable volatile liquid products, (2) a combination of smaller-ring aromatics to form polynuclear aromatics and (3) the formation of polynuclear aromatics via aromaticization of hydroaromatics. To minimize the secondary cracking of volatile liquid products, a coker reactor with a very short vapor residence time but a lengthy resid residence time to achieve complete conversion to coke of 100% CCR is preferred. The latter two limitations can be minimized by separating the higher-quality fraction of the resid prior to coking. The latest developments in the conventional delayed coking technology emphasize design and operation of major equipment (e.g. coke drums, heaters and fractionators), coke quality and yield flexibility, and operability and safety. Research work and patent activity focus on the effect of feedstock quality on coker product yields. **The Report has detailed discussions and comparison of the technologies of ABB Lummus Global, ConocoPhillips, Envision Technologies, ExxonMobil, Foster Wheeler, KBR, Lurgi-ExxonMobil, Petrobras, US CokerTech, and other novel technologies being developed to improve liquid yields, safety, and reliability.**

Visbreaking

This process was originally used to reduce the resid viscosity for meeting heavy oil specs. Nowadays, it cracks SR fuel oil into valuable gasoline and gas oil and produces residual fuel oil sold as marine fuel. The conversion is low because of its low tolerance for coke formation. The problem could be resolved by raising the solubility of converted asphaltenes in the reacting oil by stripping off the volatile liquid product, which is a nonsolvent for converted asphaltenes. Operating a typical 200-t/h visbreaking unit in maximum conversion mode to boost gas oil production by 1% can provide an annual increase in profits of about $1MM. However, as the operating severity is increased to maximize conversion, coking and fouling also increase and the stability of the visbroken resid and consequently the stability of the heavy fuel oil decrease. Research works establish that coke formation is a function of the production of condensed polyaromatic hydrocarbons. Two of the patented approaches for dealing with this problem include the use of a catalyst to activate existing hydrogen in resid feeds and the addition of hydrogen-donor streams to the feed. **The Report identifies many innovations in visbreaking from ABB Lummus Global/Shell Global Solutions, Axens, Foster Wheeler-UOP, KBR, and Lurgi Oil and Gas Chemie.**

Solvent Deasphalting

This process can be used to separate the high-quality, lighter paraffinic fraction from vacuum resid to be used as a feed for traditional FCC and hydrocracking units. Solvent deasphalters (SDA) can process HACs directly from atmospheric tower bottoms. The latest SDA design features include application-specific extraction devices, optimal design of heat-exchange systems, lowest solvent-to-oil ratio, supercritical solvent recovery, and multiple product recovery. Large volume throughput to save both capital and operating costs is critical to achieve maximum efficiency. Therefore, the towers tend to have low length/diameter ratios and trays instead of packings. The deasphalted oil yield is increased if butane or pentane is used instead of propane, though more metals and Conradson carbon are found in the product. Since there is a molecular limitation to heavy oils separation undertaken by deasphalting, it is advantageous to integrate deasphalting with visbreaking, coking or hydrocoversion. The result is a very heavy pitch, which is basically asphaltenes and contains most of the metals, nitrogen, and coke precursors. Potentially new outlets for the asphaltenes are feedstock for gasification units and pelletization for shipment as a solid fuel. **The Report discusses, in detail, many technologies including major processes by Axens (Solvahl), KBR (ROSE), Petrobras (PASD^{sc}) and Foster Wheeler-UOP (SDA).**

Resid Fluid Catalytic Cracking

Resid fluid catalytic cracking (RFCC) offers better selectivity to high gasoline and lower gas yields than coking or hydroprocessing, though it needs higher-quality feeds (e.g. mixtures of VGO and atmospheric resids and CCR limited to 3-8 wt%) than the other two processes. Nowadays, about 75% of FCCUs worldwide process a portion of resid in their feedstock. From the standpoint of refinery profitability, the benefit of resid upgrading is that it offers a way to reduce fuel oil production and produce greater volumes of valuable products without processing larger amounts of crude.

As discussed in the Report, we have seen rigorous developments in RFCC catalysts and process hardware. Important operating parameters for resid operations are feed temperature, reactor temperature, dispersion steam, stripping steam, recycle rates, rate of heat removal, CO production, and catalyst selection. Catalyst matrices are being designed to provide coke-selective bottoms cracking and reduction of the dehydrogenation activity of contaminant nickel and vanadium. Another feature is a pore structure that does not limit access of large hydrocarbon molecules to active cracking sites and permits rapid egress of product molecules so as to prevent secondary cracking to less valuable materials. Catalyst suppliers have developed more sophisticated and controlled ways of putting their products together, even to the extent of being able to tailor catalysts for more specific applications. Albemarle, Engelhard, Grace Davison, Intercat, and Nalco have developed and commercialized many novel catalysts and additives for the resid FCC application. The latest catalyst research shows interest in fluoride salt, crystalline aluminosilicate zeolite in inorganic oxide matrix, outboard vessel containing a vanadium trap, and so on.

In order to control unit heat balance and to recover some of the heat for steam production, RFCC design includes two-stage regeneration, mix temperature control, and/or catalyst coolers. Areas on the hardware side that are getting some attention include feed injection and catalyst stripping, along with the riser (to minimize slip) and termination device (to reduce the secondary reactions occurred in the dilute phase.) Improved injection and stripping are needed to meet the challenge of getting a high conversion of heavier feeds to valuable products. High dispersion of feed maximizes cracking on the catalyst's active sites. More effective stripping reduces the hydrocarbon load on the spent catalyst, keeps the regeneration temperature down, and increases conversion. Vendors such as ABB Lummus Global, ExxonMobil, KBR, Petrobras, Shell Global Solutions, Sinopec/RIPP, Stone & Webster, and UOP are offering novel process hardware. Neste Oy is working on a compact novel design that puts the reactor/regenerator in a single pressure vessel.

A separate section is dedicated to the latest advances in spent catalyst separation and rejuvenation as well as metal-passivation additives.

Resid Hydroprocessing

Hydroprocessing (or hydroconversion) offers better liquid yields (as high as 85%) than commercial coking's 50-60%, has about 20% of global resid upgrading capacity, and can take several forms depending on the purpose. Resid hydrotreating (RHT) improves quality for product blending or additional processing, whereas resid hydrocracking (RHC) is the most rigorous form of hydroconversion. Hydrotreating of atmospheric resid ahead of a

RFCCU has gained in popularity as a way to reduce fuel oil production. However, the RHT and coking combination may be a preferred route based on metals and concarbon contents of the resid. Between 1998 and 2004, global RHT capacity fluctuated around 1.4MM b/d whereas RHC increased from 400K b/d to 610K b/d over that period. **The Report reveals recent developments in catalyst designs and process technology and analyzes the economic viability of resid hydrotreating and hydrocracking in the future.**

High-conversion facilities with upgraded hydrotreating capabilities using higher-activity catalysts are the most effective plant configurations. However, RHT has several drawbacks: high pressure (200 bar), hydrogen requirement, metal contamination, short catalyst life due to fast poisoning rate, diffusion of asphaltenes through small catalyst pores, and deposition of coke and sediment downstream of the reactor in hot and cold separators. That is why there are innovations from Chevron Lummus Global—On-stream Catalyst Replacement (OCR) and upflow reactor (UFR) and Axens (Permutable Guard Reactor system). To produce low-sulfur fuel oil, the combination of UFR and RDS technology could offer better economic benefits as claimed by Chevron.

Several companies—including Advanced Refining Technologies, Albemarle, Criterion Catalysts & Technologies, and Haldor Topsøe—have introduced new resid HDM, transition, and HDS catalysts in the past few years. Because of the importance of protecting downstream cracking catalysts, particular focus has been on the development of HDM catalysts with optimized alumina pore systems that provide high metals capacity and activity. Meanwhile, China's Research Institute of Petroleum Processing said its "Butterfly" extrudate RHT catalyst offers good HDM and HDS activities as well as long life in treating RFCC feedstocks.

Resid hydrocracking catalysts used in ebullated-bed processes need to be multifunctional, i.e. performing the simultaneous removal of metals, sulfur and carbon residue as well as the hydrocracking of vacuum bottoms. Recent work in RHC catalysis has focused on pore size distribution to maximize conversion and minimize sediment formation. Also, dispersed catalyst compositions have been patented for use in suspension-bed reactors to prevent coke from forming. The key to higher conversion is to design a reactor to maximize the solubility of the converted asphaltenes, and the economics depend on how to use the unconverted carbonaceous, high PNA byproducts. A tendency for sediment to form when vacuum resid conversion exceeds 50-60% has been tackled by Axens in its H-Oil process and by Chevron Lummus Global in its LC-Fining process. A third generation LC-Finer design is now on the market. A recent development in processing technology combines slurry hydrotreatment conducted at mild conditions in the presence of a molybdenum-based dispersed catalyst with solvent deasphalting. Designed by EniTecnologie and Snamprogetti, the EST (Eni Slurry Technology) process is said to yield higher-quality products than delayed coking or visbreaking, offer greater feedstock flexibility than fixed-bed hydroconversion, and achieve higher conversion than ebullated-bed hydroconversion. To produce ULSD, both Axens and CLG concur that integration of hydrotreating and resid hydrocracking offers significant investment benefits.

Unconventional Treating and Upgrading Technologies

New process concepts for converting resids and other heavy feeds are at various stages of development ranging from just patent coverage to commercial application. **The Report analyses various emerging technologies such as thermal cracking, hydroconversion, catalytic cracking, adsorption, and emulsification.**

Thermal cracking processes are most heavily represented and include operations where cracking is carried out in the presence of hydrogen donors to increase the conversion of resid feeds and the hydrogen content of the products without the use of elemental hydrogen. Other concepts use a heated medium to increase the rate of heat transfer to the feed, thereby reducing the contact time at high temperatures and providing lesser amounts of gas and coke and greater volumes of liquid products. Mechanically-activated cracking of a heated feed is yet a third idea. This is claimed to remove virtually all metals and to selectively crack more than 90 vol% of the feed to a mixture of naphtha, distillates, and gas oil. Innovation in hydroconversion includes improvements in mild slurry hydroprocessing that eliminate the need for catalyst filtration and recycle, and thereby reduce capital and operating costs. Of more significance is a process configuration developed by Genoil. Catalytic cracking processes seem to be less represented here, but they include one that has already been commercialized.

These innovations are in response to the criteria of economics, flexibility, and selectivity, where need for improvement over older processes are seen. They also suggest what to expect from future commercial processes in terms of benefits.

Economic benefits

Processing heavy, sour crudes is rather complicated for refiners because the upgrading refining margins are determined by many parameters. They are crude oil quality and availability, light/heavy spread, residual fuel oil supply/demand, refinery upgrading additions, the product demand mix, and environmental regulations on ultra-clean gasoline and distillates. In order to take advantage of the economic benefits, one needs to consider all aspects of refinery operations. **The Report strategically examines all pertinent factors. The following is just an example of the issues we discuss in detail.**

First, the wave of coker-building that occurred in the late 1990s and early 2000s may reappear again in the US if heavy crudes are offered at a big discount. On the other hand, the big coker push may not happen because refiners may consider other options (e.g. RFCC and resid hydroprocessing) to satisfy the rising demand for motor gasoline and middle distillates. **This Report evaluates the economic options of coking, visbreaking, deasphalting, resid FCC, resid hydrotreating, and resid hydrocracking in detail, and selects "winners" for individual refinery situations based on case studies.** For example, European refiners facing dwindling demand for high-sulfur fuel oil and excess gasoline capacity could pursue resid hydroprocessing to produce much needed diesel. The region is expected to see a 20% shortage in diesel supplies by 2015 according to Wood Mackenzie.

Russian and Middle Eastern imports will not be able provide enough barrels to offset the shortfall. Situations in the US, Asia, the Middle East, and Latin America are rather different. A paramount challenge for operators is to be able to characterize the crudes well enough at the time of purchase and understand the impact on the refinery operation both in the short term (desulfurization requirements and yield) and in the long term (e.g. corrosion).

Second, despite talk of the increasing availability of heavy sour crudes, not all the new barrels have higher gravity and/or more sulfur, as supported by the arrival of oils from North Africa, West Africa, and the Caspian Sea. It poses the biggest challenge to refiners in prediction of the light-heavy price spread. Therefore, operational and process flexibility coupled with economic and business agility will allow refiners to decide to commit to maximize the benefits of running opportunity crudes—regardless of quality—at any given time. Some market observers see no clear trends of the price differential over the past several years, and expect that there may not be in the future either.

Third, refiners need to monitor closely supply and demand and to forecast price movements. As the shipments of these crudes to refineries increase, value against other crudes may decline due to refinery constraints, such as process limitations, lower-value product slates, product blending, and environmental emissions. Some refineries use linear programs such as PIMS to determine the optimum crude for them. Nowadays, the US and Canadian markets are saturated with heavy oil. One potential caveat of running BOB in the medium term is refiners building more cokers and/or upgrading units resulting in rising demand for heavy crudes and price compression. Also, depending on export preferences of Saudi Arabia, the price differential between light, sweet and heavy sour crudes could be squeezed. This scenario took place when oil prices were depressed several years ago and forced the Kingdom to export more lights to boost revenues. Additionally, the current sharp price disparity is likely to narrow further over time as more refineries are equipped with desulfurization capabilities and as producers develop new light crude fields. The profit margins could dwindle and history could repeat itself, as a market watcher warned.

Fourth, for newcomers to resid upgrading, there are many questions to be answered, namely what are my environmental exposures and permit requirements, do I have at least five years lead time to install new units, can I afford to build a big processing plant (>100K b/d, $12-15K/ bpd) to take advantage of the economies of scale, can I secure a long-term crude supply, and can I compete against lower-cost foreign refiners? There is not enough refining capacity to process heavy sour crudes because the conversion is a multi-year, multi-billion-dollar project.

Finally, since crude can represent up to 50% of the clean fuel production expense, crude selection is the most important decision refiners have to make on a daily basis. The criteria to determine which crudes to acquire include oil source reliability and term deals, delivery advantage, discounts versus other crudes (viz opportunity cost), plant operational flexibility, potential processing problems and risks, mitigation options and costs, environmental concerns, and product demand mix. **In this Report, a separate section is devoted to economic justification and risk management strategy of processing opportunity crudes.**

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