Originally appeared in:
March 2014, pgs 91-95.
Used with permission.
HYDROCARBON PROCESSING®

HP | Refining Developments

S. KRESNYAK, S. PRICE, and **J. WAGNER,**
Expander Energy, Calgary, Alberta, Canada

Convert heavy oil residue into synthetic fuel

Over the past several decades, oil extractors and refiners have been maximizing the production of easy-to-drill, high-quality light sweet oil, mostly concentrated on the Arabian Peninsula. With "easy oil" resources becoming scarcer, and demand for oil products on the rise in the developing world, oil producers are forced to utilize heavy crude deposits with the following characteristics:

- Sour (oil contains greater than 0.5% sulfur)
- Heavier
- More acidic
- Harder to produce or recover
- More costly to produce
- Contain a higher percentage of waste components.

Global heavy crude production is expected to exceed 8 million bpd (MMbpd) by 2020, driven primarily by extraction in Canada, Venezuela and the Middle East. Increasing production of highly viscous crudes significantly increases costs of production, processing and transportation for oil companies. Additional challenges include:

- Processing heavy, high-sulfur feedstocks
- Upgrading residue to improve margins and yields
- Improving fuel quality to meet new specifications
- Reducing emissions to meet environmental regulations
- Remaining flexible to meet changing market demands.

Upgrader concepts. Bitumen is the heaviest, most viscous form of petroleum; it is highly hydrogen deficient, and it does not flow at normal pipeline temperatures. In most instances, it has to be mixed with lighter hydrocarbons (diluents) before it can be transported by pipeline for upgrading into synthetic crude oil and refined products. Bitumen upgraders can generally be defined in two categories:

1. Carbon rejection
2. Hydrogen (H_2) addition.

In both instances, the hydrogen deficiency is corrected through the upgrading process. Upgrading is also used to correct sulfur and nitrogen levels, engage in hydroprocessing, reduction of the total acid number (TAN) and have heavy metals removed. The process allows for the creation of synthetic crude oil (SCO)—typically consisting of naphtha, diesel and gasoil—or finished refinery products that can then be offered to the market.

Meanwhile, carbon rejection is inherently inefficient and wasteful in most cases (significant volumes of petcoke are produced). Hydrocracking processes, which require the addition of significant volumes of hydrogen, offer a much higher liquid yield (95 vol% to 100 vol% yield) and better distillate qualities and quantities, but this comes at a higher capital expense. Other hydrocracking drawbacks include higher hydrogen demand and higher greenhouse gas (GHG) emissions.

The recent bitumen upgraders in Alberta, Canada, use the hydrogen addition process. With this approach, regardless of the ultimate hydroprocessing configuration, there is always unconverted residue. There are two basic options to utilize the unconverted residue:

1. Gasification and syngas conversion using partial or full water-gas-shift (WGS) reaction to produce hydrogen to satisfy upgrader requirements, resulting in a low-Btu syngas or pure carbon dioxide (CO_2) byproduct
2. Gasification and syngas conversion without the use of WGS, and, therefore, the carbon monoxide (CO) and H_2 are fully converted to synthetic fuels.

The choice between these two options is primarily dependent on the natural gas/crude oil price relationship.

Markets for residuum products. There are several main fuels derived from refined crude and many specialized products within each fuel group. As seen in **FIG. 1,** petcoke and residual fuel oil are only expected to generate a combined 6.4% of all refined product revenue in 2013. As residuum is priced to sell, this figure sheds light on the room for efficiency improvement concerning crude oil yield.

After processing the residuum to extract more valuable fuel products, the remaining vacuum bottoms are even more

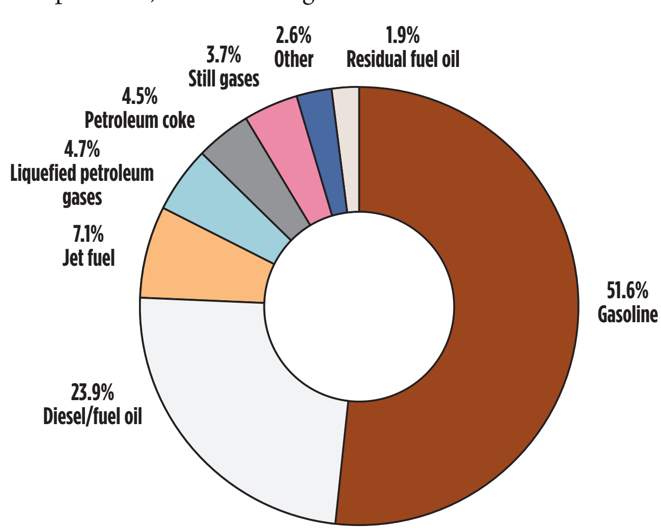

FIG. 1. Industry revenue by product or service.

viscous than the original residuum feedstock. These bottoms are then transported to either an asphalt plant or the facility coking unit where the medium is heated to a high temperature to produce coke.

Heavy oil and bitumen, in particular, have come under intensive public scrutiny for their energy-intensive extraction and refining processes.

Global petroleum coke consumption is increasing in line with growing refinery coking capacity and declining quality of feedstock (heavy crude and bitumen). Asian countries drive the majority of the demand, primarily using the coke as a cheap fuel source. Market price for petcoke is highly volatile, as demand is negatively correlated with the price and availability of coal and other low-value fuel sources.

This petroleum byproduct is priced to sell and refiners prefer to move residuum at any price the market demands rather than taking the alternative option of disposal. Unfortunately for producers, petcoke is a byproduct of both upgrading and refining, meaning much of this solid medium must be transported to market by rail, adding a logistical component. If the shipping economics are not favorable, companies sometimes opt for piling the petcoke in fields or reburying it in decommissioned mines. For these reasons, the petcoke market is not regarded as a profit driver for refiners but a means to transfer responsibility of the product with a small margin. **TABLE 1** further explains this point.

Environment. The increase in refining efficiency has been, in part, spurred on by an increase in environmental regulations that mandate refiners to improve the quality of refined products by substantially reducing GHG emissions and product pollutants. Heavy oil and bitumen, in particular, have come under intensive public scrutiny for their energy-intensive extraction and refining processes. In the US, federal legislation has continually pressured energy firms to reduce emissions and increase operating efficiency. In California, the low-carbon fuel standard (LCFS) would penalize any carbon insensitive production method, such as found with heavy oil processing. Regulations are expected to increase which will force refiners to invest an estimated \$8 billion (B) to meet these standards.

In Alberta, there are five upgraders with the combined capacity of handling 1.3 MMbpd of bitumen. Estimated carbon dioxide output of these upgraders would be in the range of 67,000 tpd to 75,000 tpd. If the residue conversion to a synthetic fuels process was implemented in all five Alberta upgraders, emissions would decrease by 54% (**TABLE 2**).

Based on this analysis, Alberta could meet its 2020 GHG emission targets for the oil sands if the residue conversion process was successfully applied. In other states and countries where carbon restrictions are placed, this process could theoretically eliminate penalties imposed on bitumen processing.

TABLE 1. The pet-coke market is not a revenue driver

Product	Price, \$/bbl	Price, \$/MMBtu
Crude oil (WTI)	\$94.05	
Gasoline	\$118.23	
Low-sulfur No. 2 diesel	\$128.31	
Jet fuel	\$128.52	
Propane	\$42.21	
Petcoke (barrel of oil equivalent)	\$11.36	\$2.01
Coal (for comparison)	\$13.06	\$2.36

TABLE 2. Residue conversion could reduce GHGs by 54% at five upgraders in Alberta

Current emissions	Emissions with residue conversion	% difference	Tax savings, \$40/ton
28.1 million tons	12.9 million tons	–54%	\$608 million

Source: www.energy.alberta.ca/OilSands/792.asp

Social. Although the advent of steam-assisted gravity drainage (SAGD) extraction has drastically improved the environmental footprint of bitumen mining, foreign buyers of Western Canadian Select (WCS) sourced petroleum products still consider it to be "dirty oil." Significant infrastructure projects are already in danger due to the perceived environmental and social impacts of Alberta's oil sands activities. With current pipeline capacity at or near capacity, any opposition to pipeline expansion would negatively impact Alberta's economy. One of the main concerns posed by opponents is the nature of oil sands production and its impact on climate change. They do not want to support the growth of this industry.

In addition to pipelines, petcoke has been recently highlighted as a major concern for the public. Petcoke is extremely dirty, generating 53.6% more carbon emissions than coal by weight, thereby creating a greater impact on air quality when burned as fuel.

Again, residue conversion processes could have a significant impact on these GHG emissions. Both government and refiners/upgraders could demonstrate an effective response to GHG mitigation and address some of the public's concerns by embracing residue conversion. It would also eliminate petcoke production in favor of more commercially valuable products, offering the opportunity to improve economic output and solve environmental concerns in one fell swoop. This would also mesh with the Government of Alberta's intent on improving its social license.

Residue conversion. The concept is based on incremental synthetic fuels production utilizing gasification of upgrader residue, combined with the reforming of natural gas, to produce optimum syngas formulation for the Fischer–Tropsch (F-T) synthesis. A number of significant and valuable synergies result from the integration of a gas-to-liquids (GTL) "island" into a refinery/upgrader facility—mainly, the effective utilization of the bottom of the barrel. Unconverted residue from either an upgrader or refinery can be gasified to syngas, and additional synthetic fuels can be produced through F-T synthesis. The F-T process produces primarily paraffinic naphtha and highly valuable sulfur- and aromatics-free diesel fuel, with typical cetane numbers in excess of 70. Hydrogen required for the upgrader is produced through a standard steam-methane reforming (SMR) process using cheap natural gas, liquefied petroleum gas (LPG), refinery fuel gas or naphtha as feedstock.

Syngas originating from gasification of a high carbon-content feedstock (like bitumen residue) is by definition hydrogen deficient, and is not directly suited for F-T synthesis, as it does not have the required stoichiometric H_2/CO ratio. Therefore, in addition to the standard gasification/syngas/F-T synthesis configuration, this concept also includes hydrogen enrichment of syngas. Hydrogen-rich syngas is produced through a standard SMR or auto thermal reformer (ATR) process, or a combination of both processes using natural gas, LPG, RFG or naphtha as a feedstock. The referenced SMR process, in addition to enriching the syngas, provides the required amount of hydrogen for the bitumen upgrader as well as for the F-T products upgrade. A common SMR process is typically used and provides high-reliability syngas and pure hydrogen for the upgrader needs.

In addition to the economic advantages, there are other inherent benefits to this concept:

- Upgrader operation is critically dependent on a reliable source of hydrogen. In this concept, hydrogen is produced from a highly dependable source (SMR) as opposed to a relatively low-reliability gasification operation.
- There are major reductions in CO_2 emissions. In this concept, no WGS stage is required, which eliminates the major source of CO_2 emissions and retains the carbon as CO for conversion to synthetic fuels.
- Sufficient energy is produced to satisfy the full refinery steam and electric power needs.
- Surplus high-quality process water is produced to fully satisfy the water makeup requirements of the refinery/upgrader. There will also be excess high-quality water available to meet the requirements of makeup water needed for the upstream SAGD facility.
- The syngas generator can be configured to consume not only natural gas, but also excess LPG, naphtha and CO_2 from other refinery sources (such as furnaces and boilers). This offers an opportunity to significantly reduce overall upgrader/refinery GHG emissions and increase yield of high-value diesel/jet fuel.

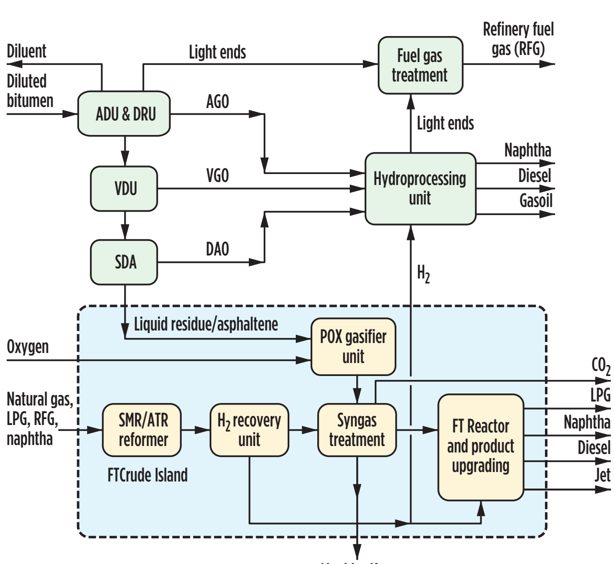

FIG. 2. Illustrated residue conversion concept.

The residue conversion concept is patented or patent-pending worldwide, and applies proven and commercially available technologies for all the processing steps. As a result, there is very limited technical risk. A simplified block diagram illustrating the concept is found in **FIG. 2.**

Case study. A process design has been developed for an integrated bitumen upgrader/residue conversion system with an upgrader capacity of 50,000 bpd of neat bitumen feed. In one preferred configuration, the upgrader process is based on hydrocracking of deasphalted oil (DAO) and vacuum gasoil (VGO), and hydrotreating of straight-run and hydrocracked naphtha, diesel and GO. The residue conversion section receives asphaltenes from the solvent deasphalting (SDA) or vacuum distillation unit (VDU) as feed. This heavy residue liquid (+10°API to –12°API) is gasified in a partial oxidization (POX) reactor unit with pure oxygen (O_2) (> 98 wt% O_2) to generate a sour-hydrogen-lean syngas. After gasification, the heavy metals and other detrimental compounds are removed from the raw syngas to form the clean, hydrogen-lean syngas (H_2:CO = 0.8 to 1.0). Separately, an SMR syngas generator provides additional hydrogen-rich syngas to combine with the hydrogen-lean syngas for the F-T synthesis. The SMR process is a combined service to provide sufficient hydrogen for both the bitumen upgrader and F-T product upgrad-

TABLE 3. Summarized material balance for the case study

Feed streams		**kg/hr**
Bitumen (excl. diluent)	50,000 bpd	334,560
Natural gas	98 MMscfd	78,090
Steam (SMR)		179,722
Oxygen (POX)		45,526
Steam (POX)		25,292
Total feed streams		**663,190**
Product streams and effluents		
Upgrader		
Naphtha	2,625 bpd	13,234
Diesel	22,014 bpd	125,421
GO	22,653 bpd	136,301
F-T crude		
Offgas	41.1 MMscfd	52,033
LPG	542 bpd	2,392
Naphtha	1,715 bpd	7,798
Diesel	11,412 bpd	57,899
Process water	13,023 bpd	87,519
SMR water	17,310 bpd	116,352
CO_2	11.1 MMscfd	24,306
Other effluents by difference		39,935
Total products streams and effluents		**663,190**

ing. Based on 50,000 bpd of neat bitumen feed to the upgrader, 47,300 bpd of 30° API SCO, 1,715 bpd of F-T naphtha and 11,412 bpd of F-T diesel is produced. To achieve this production, 98 MMscfd of natural gas is used for the combined SMR.

About 60,500 bpd of 35° API SCO is produced when the F-T products are included. This represents approximately 121% volumetric yield on bitumen. **TABLE 3** summarizes the overall material balance for the study case.

Pre-FEED capital costs (+/– 30%) for this integrated case installed in Northern Alberta was estimated to be in the range of $4 B–$5 B (Canadian dollars) or about $65,000/bpd to $85,000/bpd of total SCO blend, subject to the level of contingency, escalation, actual location and extraneous infrastructure requirements.

It should be noted that the capital costs include the upgrader and residue conversion process areas, as well as utilities and offsites as a full greenfield total installed cost (TIC). Oxygen supply for the gasifier is considered to be over the fence, and the oxygen plant's capital costs are not included.

Concept economics. An economic comparative assessment tool was used to assess the financial robustness of the concept. **FIG. 3** indicates project unlevered internal rate of returns (IRRs) for the base case of three natural gas prices. These are $3, $6 and $12 per gigajoule (GJ) as a function of WTI crude oil prices. It can be seen that negative net present values (NPVs) are only observed at very low crude oil prices. Consequently, assuming longer term crude oil prices being in the range of $90/bbl to $110/bbl, the concept can be considered economically robust and able to tolerate significant increases in natural gas prices beyond the $3/GJ to $12/GJ range.

TABLE 4. Case 1 vs. Case 2

	CASE 1	CASE 2
DAO yield %, lift	73	58
DAO flow to HCU, bpd	20,126	16,296
Asphaltenes to POX, bpd	6,286	10,116
Natural gas, MMscfd	98	143
Total SCO, bpd	60,500	68,525
Product yield, vol%	121%	137%
CAPEX, $ million CDN	$4,000	$4,600

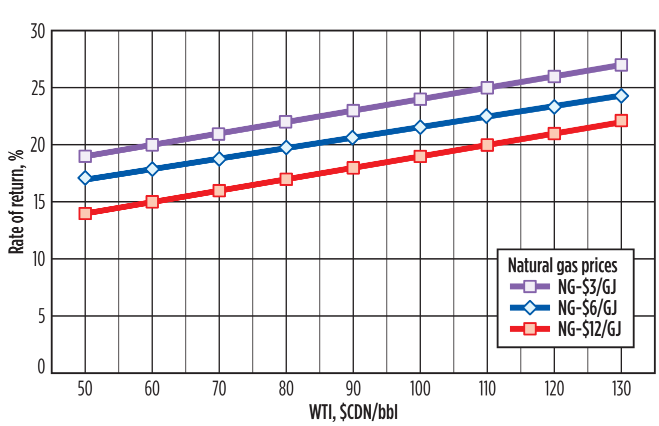

FIG. 3. Residue conversion economic feasibility base case.

Using the same tool, an analysis was made to identify a balancing "sweet spot" between the upgrader hydroprocessing and the residue conversion section capacities. As the economics are sensitive to diesel prices, a range of diesel price assumptions are analyzed along with a range of natural gas and SCO prices.

The interface between the bitumen upgrader and the residue conversion unit is downstream of the SDA unit. The SDA produces DAO and asphaltenes. The asphaltenes are sent (via intermediate storage) to a POX unit (gasifier). The operation of the SDA controls the volume, API gravity and other properties (viscosity, CCR, sulfur and metals content) of the feed to the gasifier and subsequently controls the balance point between the bitumen upgrader and the residue conversion unit. Two main cases were compared:

Case 1. The conversion unit (min.) case: The SDA unit produces the lowest volume and lowest API density (> –10° API) asphaltenes being fed to the gasifier, thereby maximizing the volume of DAO feed to the hydrocracker/hydrotreaters. For Case 1, the amount of heavy metals and CCR in the DAO may have impact on the conventional hydrocracker catalyst.

Case 2. The conversion unit (max.) case: The SDA unit produces the highest volume and highest API density (0° to 10° API) asphaltenes being fed to the gasifier, minimizing the volume DAO feed to the hydrocracker, thereby representing the minimum throughput and highest DAO quality feed for the hydrocracker. For Case 2, the amount of heavy metals and CCR in the DAO are below the maximum allowed for a typical hydrocracker catalyst, allowing for the use of less expensive conventional single fixed bed reactors.

TABLE 4 shows the basic parameters for the two cases, based on vacuum residue feed to the SDA unit. Both cases are compared for the same project return as a function of natural gas and crude prices. The results are presented in **FIG. 4.** At a crude oil price range of $80/bbl to $100/bbl and with natural gas prices below $14/GJ, the Case 2 economics are strongly favored.

Concept opportunities. The residue conversion through gasification and the subsequent F-T liquids production concept can be applied in a wide variety of facilities. These include existing upgraders that produce asphalt and asphaltenes, as well as unconverted hydrocracked residue or petcoke. Similarly, this concept can also be applied in any heavy or deep conversion refinery

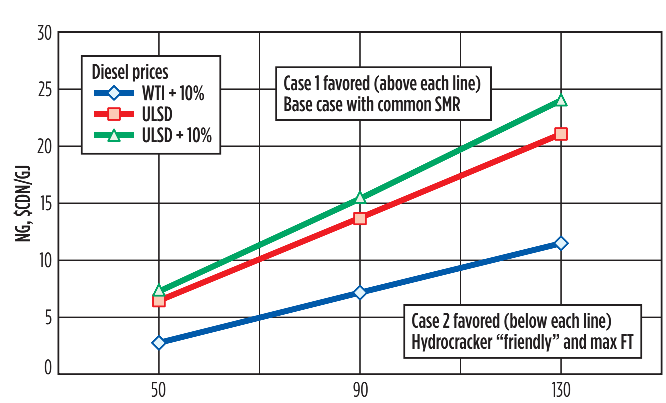

FIG. 4. Case 1 vs. Case 2 when considering the relative ratio of product and natural gas prices at equal project return.

producing asphalt or heavy fuel oil as unconverted residue. In the North American context of low natural gas and high crude oil prices, the opportunities are numerous. Because of the demonstrated tolerance of this concept to relatively high natural gas prices, it can also be applied in many facilities in Europe and Asia.

Further, due to the high carbon retention inherent to the concept, there is minimum 50% reduction and as great as 80% reduction in CO_2 emissions compared to other upgrading and refining technologies. This reduction in GHG emissions will be a significant driver for retrofitting existing facilities.

Last, but not necessarily least, residue conversion will increase the reliability of operation for hydrogen addition upgraders, since hydrogen production is shifted from a less reliable operation (gasification) in the plant to highly reliable and industry proven SMR technology.

Attractive concept. Under current and medium-term forecasts for natural gas and crude oil pricing, residue conversion to incremental synthetic fuels rather than to hydrogen production is economically, technically, socially and environmentally very attractive. The concept is economically robust for a wide range of natural gas and crude oil prices and can be used for partial and full bitumen upgrading, as well as for complex bitumen refineries producing high-quality transportation fuels (gasoline, jet fuel and diesel). Further, residue conversion utilizes proven and commercially available technologies for all processing steps. As a result, there is very limited technical risk. Finally, the concept provides significant improvements in SCO yields, operational reliability and carbon conversion efficiency (> 90% conversion), resulting in sizeable reduction of CO_2 emissions. HP

STEVE KRESNYAK is the chief technology officer for Expander Energy. He is a consulting engineer with over 36 years of experience assisting clients worldwide engaged in the upstream, downstream and offshore hydrocarbon energy industry. He primarily works in process, conceptual and front-end design of oil and gas production, heavy oil and bitumen processing, upgrading and refining. Mr. Kresnyak holds several process patents and has successfully developed and implemented many new technologies in his work with Expander Energy, WorleyParsons and Colt Engineering.

STEVE PRICE is president of Expander Energy. He is a professional engineer with experience in the fields of engineering and management (including corporate operations), evaluations and facilities design and operation. Mr. Price is also vice president of Caiterra International Energy Corp. and a past vice-president of HCO Energy. He has a degree in electrical engineering and is a member of the Association of Professional Engineers and Geoscientists of Alberta.

JAN WAGNER is a process engineer with over 40 years of experience. His diverse career includes conceptual and detail design of crude oil processing units, heavy-oil upgrading and gas production and processing. He also has worked with cogeneration, NGLs, syngas derivatives and F-T processes. Mr. Wagner has published and presented numerous technical papers. He received his MS degree in process engineering in the former Czechoslovakia and is a registered professional engineer in Alberta and British Columbia. He is a technical specialist consultant for Expander Energy and works as a principal process engineer for WorleyParsons.