



Current situation of emerging technologies for upgrading of heavy oils



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ABSTRACT

With the increased production of heavy and extra-heavy crude oils, and the need to add them into the regular diet to refineries, there has been much interest for developing new technologies for upgrading those heavy materials. Traditional commercially available carbon rejection and hydrogen addition routes are still applicable for this purpose, however they have shown some limitations when the oil is heavier, which directly impact in the economy of the technology. Various emerging technologies have been reported in the literature, mainly in patents, which have been developed and tested at different scale and with a wide variety of heavy petroleum. The most important emerging technologies for upgrading of heavy crude oils are reviewed and discussed. Particular emphasis is put in a comparison with the available information. It is recognized that all the technologies have great opportunity to be applied commercially depending on the support that they receive by the petroleum companies.

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1. Introduction

A number of technologies have been developed over the years for heavy crude and residue oil upgrading, which include processes that are based on carbon rejection, hydrogen addition and combination of both routes [1,2], most of them with proven commercial experience. Fig. 1 summarizes the distribution of these technologies and their processing capacity. Carbon rejection processes represent 56.6% of the total worldwide processing capacity mainly due to its relative low investment.

There are also other technologies at different level of development or close to commercialization or even already used, that have been abandoned as uncompetitive during the years of cheap crude oil.

The changing prices of crude oils as well as the increasing production of heavy and extra-heavy crude oils have motivated more research and development aiming at upgrading of such heavy materials. The new approaches are named emerging technologies. This group of technologies is reviewed in this work and their advantages, disadvantages and current situation are highlighted.

2. Typical technologies for upgrading of heavy oils

Standard technologies developed for heavy crude and residue oil upgrading include processes that are based on carbon rejection, hydrogen addition and combination of these two routes.

2.1. Carbon rejection

Carbon rejection is one of the first types of conversion processes applied in the oil industry, and has been used since 1913 for different fuels and heavy hydrocarbons heated under pressure. This group of technologies includes processes such as visbreaking, thermal cracking, and coking. Foster Wheeler and Universal Oil Products made an agreement to combine their technical experiences, developing over 50 visco-reduction plants. Shell and ABB-Lummus have developed and commercialized a drum type application namely Reaction Chamber (Soaker), with over 80 projects based on this process [3,4]. Fluid coking and Flexicoking are developments of Exxon Mobil Research & Engineering (EMRE). The combined capacity of Fluid coking and Flexicoking amounts 241,000 and 426,000 bbl/day, respectively. Delayed Coking a mature technology is offered by Foster Wheeler SYDEC (Selective Yield Delayed Coking) with over 25 revamps designed in the last 10 years, and over 20 new units designed in the last 5 years [5].

2.2. Hydrogen addition

Traditional upgraders reduce carbon-to-hydrogen ratio by adding hydrogen obtained from natural gas. Hydrogen addition technologies are classified depending on the type of reactor used, e.g. fixed-bed, moving-bed, ebullated-bed and slurry-bed processes.

Axens technology utilizing its Hyvahl process (Permutable Reactor System), has reached an important commercialization level. Chevron Lummus Global (CLG) licenses On-stream Catalyst Replacement technology (OCR) for processing high-metal feeds and the revamp alternative, an Upflow reactor (UFR). Shell developed

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Nomenclature

AB	Athabasca bitumen
ADC	Accelerated decontamination
AERI	Alberta Energy Research Institute
AMEC	AMEC Group Ltd.
BA	BA Energy Inc.
CAT	CAT process
CCR	Conradson carbon
CCU	Catalytic Crude Upgrading
CDP	Commercial Demo Plant
CE3	Canadian Environmental Equipment and Engineering
CIMAV	Centro de Investigación en Materiales Avanzados
CLB	Cold Lake Bottoms
CLG	Chevron Lummus Global
CP	Cracking Process
CPBB	Chinese Paraffinic Bottoms Blend
CPJ	Conversion Pierre Jorgensen
DAO	Deasphalted oil
DBT	Dibenzothiophene
DBTO	Dibenzothiophene sulfone
DC	Delayed Coking
DRV	Distillate Recovery Unit
EMRE	Exxon Mobil Research & Engineering
EST	Eni Slurry Technology
FCC	Fluid Catalytic Cracking
FGDSU	Flue Gas Desulphurization Unit
GCC	Gulf Cooperation Council
GHG	Green House Gases
GHU	Genoil Hydroconversion Upgrader
HCAT	Hydrocracking technology
HCU	Heavy Crude Upgrader
HDC	Hydrocracking
HDCCR	Conradson Carbon Residue Reduction
HDM	Hydrodemetallization
HDN	Hydrodenitrogenation
HDS	Hydrodesulfurization
HDT	Hydrotreating
HGO	Prototype heavy oil upgrader
HOG	Heavy oil upgrader
HOUP	Heavy Oil Upgrade Project
HP	High pressure
HRH	Heavy Residue Hydroconversion
HTGI	Headwaters Technology Innovations Group
HTL	Heavy to light
HVGO	Heavy vacuum gas oil
HYCON	Hydroconversion process
HYT	Haiyitong Inc.
IBA	Ion Beam Applications
IFP	Institut Français du Pétrole
IGCC	Integrated Gasification Combined Cycle
IMP	Instituto Mexicano del Petróleo
LP	Low pressure
LVGO	Light Vacuum Gas Oil
MIB	Maya–Isthmus blend
NCUT	National Center for Upgrading Technology
NRC	National Research Council
NRL	National Refinery Limited
OCR	On-Stream Catalyst Replacement
P	Pressure
PDVSA	Petroleos de Venezuela Sociedad Anonima
PEMEX	Petroleos Mexicanos
PONA	Paraffin, Olefin, Naphthenic, Aromatic

PSA	Pressure Swing Adsorption
RFCC	Residue Fluid Catalytic Cracking
RIPI	Research Institute of Petroleum Industry
RTP	Rapid Thermal Processing
RVP	Reid Vapor Pressure
RVTI	Company Rival Technologies Inc.
SAGD	steam assisted gravity drainage
SCO	Synthetic crude oil
SDA	Solvent deasphalting
SYDEC	Selective Yield Delayed Coking
T	Temperature
TaBoRR	Tank Bottoms Recovery and Remediation
TDG-1	Terre de Grace
TRU	TRU process
UAOD	Ultrasound assisted oxidative desulfurization
UFR	Upflow reactor
UOP	Universal Oil Products
USP	Ultra selective pyrolysis
USPTO	United States Patent and Trademark Office
VCG	Value Creation Technology
VCI	Value Creation INC
VGO	Vacuum gas oil
VR	Vacuum residue
VTB	Vacuum tower bottoms
WHB	Waste heat boiler
WRI	Western Research Institute
WRITE	Western Research Institute Thermal Enhancement
ΔP	Pressure drop

the HYCON process (Bunker Reactor System) which uses conventional fixed-bed reactors and a system for continuous catalyst replacement [6,7].

In the ebullating-bed processes, the H-Oil process of Axens/IFP and the LC-Fining process of Chevron Lummus Global, similar in concept but different in some mechanical details, offer a final product containing around 25% of non-converted residual [8,9].

The slurry phase reactor processes employ disposable catalysts whose development aimed at decreasing the cost of the catalyst inventory, i.e., cost of the fresh hydroprocessing catalysts and that of the spent catalysts. A number of processes employing a disposable catalyst are in a developmental stage and others are in a near commercial stage [10].

2.3. Combined technologies

The main advantages of the integrated process schemes are in terms of product yields, quality of products, elimination of low-value by-products, and reduction of impurities. Various integrations of upgrading processes are reported in the literature, which include deasphalting, gasification, delayed coking, RFCC, ebullating-bed reactor, slurry phase reactor and fixed-bed hydrotreating [11].

3. Emerging technologies

Since the light crude reservoirs are getting scarce and because the current processes in refineries are not totally adequate to process heavy and extra-heavy crude oils a new group of technologies has emerged as a promising solution of the problem. These technologies are focused on the upgrading of the properties of those crudes, i.e. increase of API gravity and reduction of viscosity and impurities content such as sulfur, nitrogen and metals, either to transportation purposes or to feed to refineries.

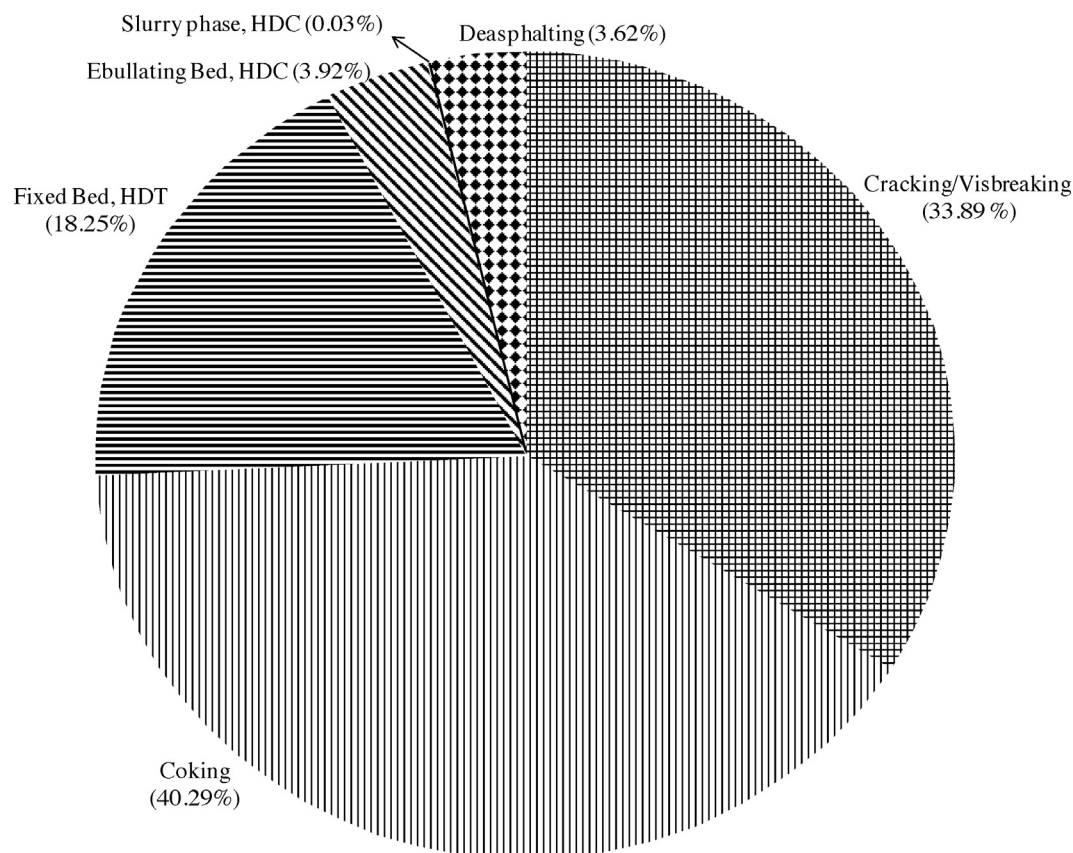


Fig. 1. Worldwide distribution of commercial residue processing capacity [1,2].

A compilation of such emerging technologies is summarized in Table 1. A brief description, history, patent and current situation of each technology is described in the following sections [12–16].

3.1. HCAT process

Headwaters Technology Innovations Group (HTIG) developed a catalytic heavy oil upgrading technology known as HCAT. Fig. 2

Table 1
Emerging technologies for heavy, extra-heavy crude oil processing.

Emerging technology	Remarks
HCAT Process (Headwaters Heavy Oil)	Reported as a breakthrough process to convert low quality feedstock (high asphalt and metals). Conversion up to 95% and higher reactor throughput. Uses a molecule sized catalyst (slurry phase reactor) and offers several significant advantages over supported catalysts based processes
HTL (Heavy-to-Light) Process (Ivanhoe Energy)	Short contact time thermal conversion process (rapid thermal processing) that operates at moderate temperature and atmospheric pressure. Unique thermal cracking technology that solves some of the disadvantages of delayed coking, fluid coking, and visbreaking processes
GHU Process (Genoil Inc. Technology Inc.)	Multiple fixed-bed reactor system. Feedstocks ranging from 6.5 to 17.5° API. Only tested with feeds that have relatively low metals content
Viscositor process-Ellycrack-Wescorp	Process for upgrading of heavy oil at the oil field; based on the atomization of oil with steam and further collision with heated sand in a high-velocity chamber to "crack" the oil where any catalyst is not required. Low severity makes this process technically feasible
IMP Process (Mexican Institute of Petroleum)	Low or moderate pressure technology for upgrading of heavy oils and residua. Catalysts with improved stability and proper selection of reactors and feedstock preparation to work under moderate conversion regime that allow for working with low sediment formation
NexGen-Ultrasound process	System for upgrading heavy oil employing ultrasonic waves to break long hydrocarbon chains and simultaneously adds H ₂ generated from purified water to the molecules. It uses ultrasonic waves to create cavitation bubbles within the working fluid, in this case, oil
HRH (heavy residue hydroconversion)	Catalytic hydrocracking process, which targets conversion of heavy and extra-heavy crude to valuable crude. This technology can be used for two main purposes: Hydroconversion in refining and Hydroconversion in wellhead
CCU (catalytic crude upgrading)	Based on traditional FCC principles processing only enough of the crude to create sufficient accumulation to produce a synthetic crude meeting pipeline specifications. High coke yield, opportunity to produce large quantities of steam and electrical power
Sonocracking, SulphCo, Inc.,	Ultrasound technology to desulfurize and hydrogenate heavy crude oil. The transfer of hydrogen from water to the numerous petroleum streams leads to the conversion of crude oil
Eni Process	Process enables an almost complete conversion of the feedstock (>95%) and guarantees an excellent level of upgrading of the products. Flexible in treating different types of heavy feedstocks, such as VR, heavy and extra-heavy crudes and bitumen from oil sands

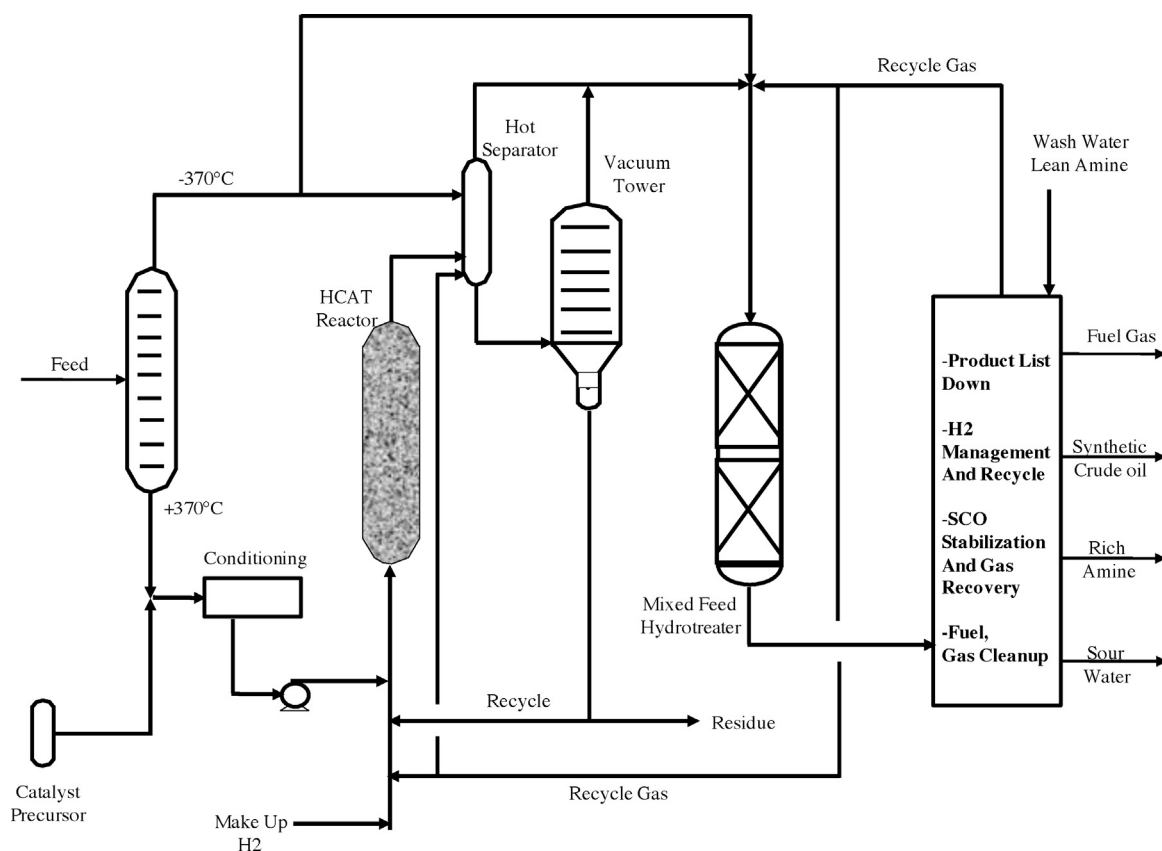


Fig. 2. HCAT process with integrated hydrotreating scheme [17].

shows the HCAT process which converts low quality feedstock such as heavy oil, residue and oil sands bitumen into synthetic crude oil. The process uses a molecule sized catalyst, chemically generated within the reactor system through a conditioning process, to achieve high conversion of oil. HCAT significantly improves the conversion of heavy oil as well as reduces sediment formation [17,18].

HCAT technology offers several advantages over processes using supported catalysts such as non-deactivating molecular catalyst, constant product quality, feedstock flexibility, flexible conversion (up to 95%), higher reactor throughput, simple, two-phase gas–liquid reactor.

3.1.1. History

The (HCAT/HC)3 process was initially developed by Alberta Research Council and designed to upgrade indigenous heavy crude oils or bitumens. Now the process is called HCAT and licensed by Headwaters. In this process the catalyst is homogeneously dispersed as a colloid with particles similar in size to that of asphaltene molecules, whereby high conversion of the asphaltenes can be achieved. Catalysts used in the process are oil-soluble, such as iron pentacarbonyl or molybdenum 2-ethyl hexanoate with excellent anti-coking performance. Conversion ranged from 60% to 98% when the Cold Lake bitumen was treated in a pilot unit [10].

These solid catalysts, typically a combination of two or more transition metals on an alumina support base, are limited by their physical structure as to the amount of heavy oil they can process and the quality of the product slate that can be produced [19].

3.1.2. Patents

Patent No. US 7,578,928 B2 (August 2009), hydroprocessing method and system for upgrading heavy oil using a colloidal or molecular catalyst. Patent Application Publication US

2010/0294701 A1, methods for hydrocracking a heavy feedstock using an in situ colloidal or molecular catalyst and recycling the colloidal or molecular catalyst. Since 2008, the United States Patent and Trademark Office (USPTO) has given the HCAT trademark serial number of 77,042,411 to Headwaters Incorporated, South Jordan, UT 84095.

3.1.3. Current situation

Recently HTIG has announced that Neste Oil Corporation's Porvoo Refinery at South Jordan, Utah, is the first refinery to commercially implement Headwater's HCAT heavy oil upgrading technology. During 2011 Neste Oil and HTI completed a 40-day commercial test at the Porvoo refinery. Since more than 500,000 barrels of heavy oil are processed in their upgraders every day, at least 200,000 BPD of additional capacity would be added by 2014 [20].

3.1.4. Results

Different feedstocks have been tested with this technology. Table 2 shows the typical results for a reactor temperature between 430 and 450°C, reactor pressure of 2000 psig, and the hydrogen treat rate was 5000 standard cubic feet per barrel of heavy oil.

3.2. HTL-heavy oil upgrading

Ivanhoe Energy has developed and patented the Heavy-to-Light (HTL) upgrading process. HTL is a heavy oil upgrading process that converts heavy, viscous crude oil to lighter, transportable and more valuable synthetic oil. HTL operates at a significantly smaller scale and at a fraction of the per-barrel costs as compared with conventional technologies [21].

Table 2
Results of the test (conversion).

	Feedstock			
	AB	CLB	MIB	CPBB
Properties				
Temperature cut		565 °C+	538 °C+	
API gravity	8.5	0.4	1.5	
Sulfur, wt%	5.02	6.22	4.7	
Nitrogen, wt%	0.66			
Nickel, ppm	79	176		
Vanadium, ppm	209	416		
C ₇ Asphaltenes, wt%	12.6			
CCR, wt%	12.8	26.9		
975 °F+ resid conversion, %	94	94	63	95
Asphaltene (C ₅ Ins.) conversion, %	95	93	67	96
Sulfur conversion, %	78	78	56	92
Impact of colloidal or molecular catalyst on sediment formation and fouling				
Residuum conversion, wt%	50	60	71	60
Time On-Stream, hours	0–132	133–220	204–272	272–400
RUN "A": sediment, wt% (EB catalyst only)	0.12–0.22	0.59–0.86	N/A	N/A
RUN "B": sediment, wt% (EB catalyst + C or M catalyst)	0.06–0.15	0.32–0.36	0.72–1.06	0.23–0.35

AB: Athabasca bitumen, CLB: Cold Lake Bottoms, MIB: Maya/Isthmus Blend, CPBB: Chinese Paraffinic Bottoms Blend.

Run A: 220 h, stopped when ΔP in the second reactor increased significantly. A post-run inspection showed significantly fouling on the screen of the reactor liquid recycle cup.

Run B: 400 h, little change in reactor ΔP . The screen at the reactor liquid recycle cup with minimal fouling.

The HTL processing plant can be located upstream, at or near the well-head, fully integrated with field operations. Alternatively, it can be located midstream, upgrading heavy crude oil from onshore and offshore resources and exporting upgraded product to refineries that have limited coking capacity.

The HTL process uses a circulating transport bed of hot sand to heat the heavy feedstock, such as vacuum tower bottoms (VTB) and convert them to lighter products. The high yield and high quality configuration can be applicable to heavy oil or bitumen upgrading, where upgraded products are quenched at the exit of the reactor cyclone and routed to the atmospheric distillation unit where distillate and lighter material are sent to product tank and blended with straight-run gas oils. Atmospheric bottoms are recycled to the front end of the vacuum unit to separate VGO and lighter material. VTB can be recycled to extinction depending on the site specific energy requirements. The general flow process scheme is shown in Fig. 3.

The major drawbacks of HTL technology are the large size equipment for heat recovery, low volumetric yield of upgraded crude, low capacity for extra-heavy oil processing because the high dimensions of the regenerator and high formation of coke, low sulfur reduction, high formation of olefins and diolefins susceptible to polymerization and high production of sand rich in spent heavy metals, fine particulate and ash.

3.2.1. History

In 1998 Ensyn Group, Inc. initiated the development of a petroleum application of Rapid Thermal Processing (RTP) for heavy oil upgrading. An RTP petroleum pilot facility was built in 1998 in Ottawa, funded by Gulf Canada Resources, followed by a 1000 barrels per day heavy oil RTP facility in Bakersfield, California in 2004. In 2005 the petroleum applications of RTP were sold to Ivanhoe Energy Inc.

3.2.2. Patents

Patent No. US 8,105,482 B1 (January 2012). Rapid thermal processing of heavy hydrocarbon feedstock. Since 08/22/2006, the USPTO has given the HTL trademark serial number of 76,647,666 to Ivanhoe Energy, Inc., Bakersfield, CA 933899279.

3.2.3. Current situation

Ivanhoe Energy has completed HTL technology development, scale-up and testing operations, and is now working with AMEC, its main engineering contractor, in the design and engineering of full-scale HTL facilities for identified heavy oil projects. Ivanhoe Energy is currently focused on projects in Canada, Latin America and the Middle East. The HTL process is economic at feed capacities as low as 10,000–30,000 barrels per day, and the typical Class 4 cost estimate for the HTL plant ranges from USD \$12,000 to \$20,000 per installed barrel of capacity [22,23].

3.2.4. Results

The properties of the HTL product compared with the original heavy oil feedstock are shown in Table 3.

3.3. Genoil process

Genoil Hydroconversion Upgrader (GHU) is a catalytic hydroconversion technology that upgrades and increases the yields from heavy crude, bitumen and refinery residues. The GHU facility has conversion of 70–90% based on the various types of feedstocks (Heavy crude oil, vacuum or atmospheric residue or bitumen),

Table 3
Properties of the feedstock and product of the HTL process.

Property	Athabasca bitumen	Upgraded crude oil
API gravity	8.5	18.8
Kinematic viscosity		
@40 °C, cSt	>23,000	23
@100 °C, cSt	161	11
Sulfur, wt%	5.02	2.91
Nitrogen, wt%	0.66	0.40
Nickel, ppm	79	15
Vanadium, ppm	209	27
Residue, 1000 °F+, wt%	52	6
Composition, volume%		
Naphtha, 1BP–375 °F	0	2.5
Kerosene, 375–455 °F	1	4.5
Distillate, 455–650 °F	12	24
VGO, 650–1000 °F	35	63
Residue, 1000 °F+	52	6

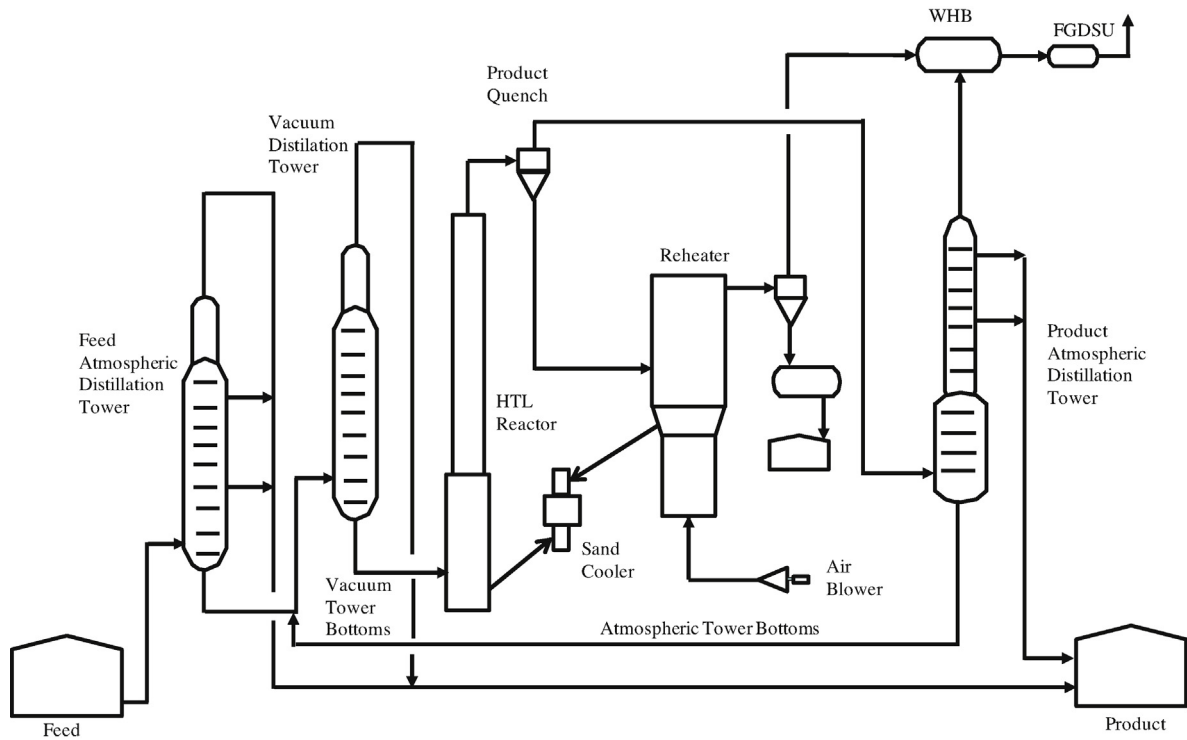


Fig. 3. HTL process in high quality mode [21,23].

controlling the unconverted residue by variations in temperature and pressure in the process. From the integration of a distillation unit after the GHU and sending the residue to a synthesis gas unit, it is able to increase the API gravity from 24 to 34°. Fig. 4 shows a schematic of the GHU technology [24].

The GHU can be utilized to upgrade heavy crude, bitumen and refinery residue streams. The processing scheme is based on a fixed-bed reactor system with a reactor sequence. The first vessels are HDM guard reactors, followed by a second main reactor using HDS, or a combination of HDS and HDN beds. Genoil has

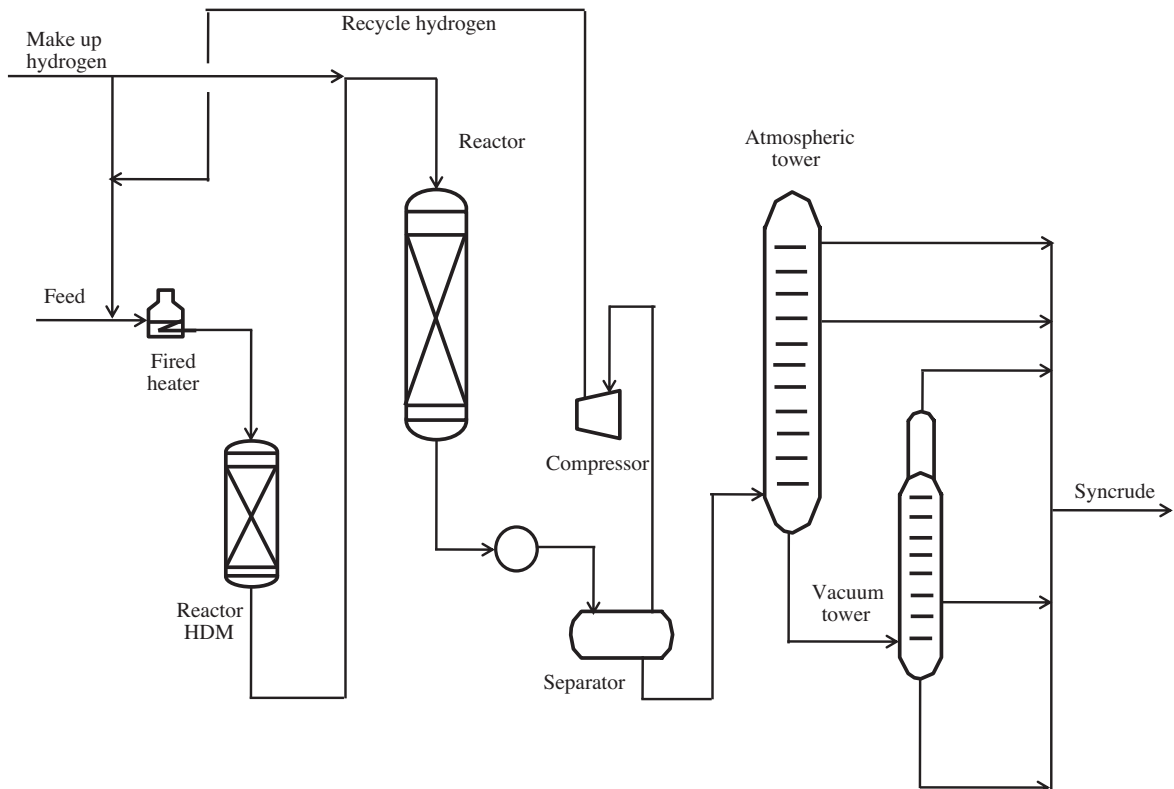


Fig. 4. Simplified scheme of Genoil heavy oil upgrader [24].

conducted multiple pilot plant test on various sour heavy crude, bitumen and residue oil feed stocks ranging from 6.5 to 17.5 °API gravity with the following results: desulfurization: 75–97%, denitrogenation: 37–53%, demetallization: 76–98%, Conradson carbon reduction: 47–87%, residue conversion: 37–88% [25].

3.3.1. History

Starting in May 1998, Genoil (formerly CE3 Technologies Inc.: Canadian Environmental Equipment and Engineering Technologies Inc.) researched innovative processes for the upgrading of heavy crude oils. The Genoil concept is to upgrade on-site heavy crude oil to much lighter oil meeting pipeline specifications even for a small-scale field unit of 10,000 bpd.

From May 1998 to January 1999, Genoil evaluated the TaBoRR process (Tank Bottoms Recovery and Remediation) from the Western Research Institute in Laramie, WY, and the CAT process, which is typically used to make diesel fuel. The evaluation of these processes concluded that a major shift would be required to offer an economical process for heavy oil upgrading [26].

Based on the TaBoRR process, which is a carbon rejection method, using a heavy oil feedstock (12 °API), a liquid yield of 77.8 wt% was achieved with an average API gravity of 32.3°. However, it would be commercially viable only if the liquid yields could be increased.

In 1998, Genoil started to develop its own heavy oil upgrading process acquiring the visbreaking technology from the Eadie Group and the “Bullet” technology from the Acquasol Corporation. Although the Bullet technology maximizes the mass transfer between two fluids, it was replaced by Genoil with a more effective mixing technology.

Key features of the Genoil upgrading are the addition of the hydrogen to the feedstock, and the mixing of the hydrogen with the liquid feed. To confirm this concept, Genoil constructed a laboratory scale prototype vessel together with the appropriate mixing gas/liquid devices. Then, Genoil conducted bench-scale tests, at various operating conditions on a Cold Lake Bitumen with an API gravity between 11 and 13°. The original Genoil targets were to upgrade the Cold Lake Bitumen from an 11 to 13 °API gravity to an API gravity of 19–20° without a hydrotreating catalyst, to an API gravity of 22–24° with small amounts of catalyst, and to an API gravity of 28–30° with a hydrotreating reactor (hydroconversion). After testing the mixing vessel and devices, several simulation studies were conducted to optimize the initial design concept.

3.3.2. Patents

Patent No. US 7,001,502 B1 (February 2006). Process for treating crude oil using hydrogen in a special unit. Since 2004, the USPTO has given the GHU trademark serial number of 78,492,903 to Genoil Inc., Sherwood Park, Alberta T8H2H3.

3.3.3. Current situation

In 2006, Genoil and Haiyitong Inc. (HYT) agreed to jointly build a 19,500 bpd upgrader at Nampaihe Town, Huanghua City, Hebei refinery in North Eastern China. The GHU unit for HYT was designed to process heavy oil and refinery residues [27].

Based on fixed-bed technology, GHU converts heavy feed into naphtha, diesel, and gasoil. Unconverted heavy end is used as IGCC feed. IGCC supplies H₂ and all utilities requirements. All products integrate into existing refinery.

In 2007, Genoil tested in its pilot facility heavy oil samples from HYT. Results showed a significant improvement in the quality of the upgraded oil. After independent laboratory analysis, the first level of engineering and design of the upgrading unit was completed. A Chinese engineering firm conducted an economical feasibility and estimated the total cost of the project at US\$170 million.

Table 4

Properties of the feedstock and product of the Genoil process.

	Bitumen feed	Syncrude
API gravity	8.5	24.8
Sulfur, wt%	5.14	0.24
Nitrogen, wt	0.27	0.14
C ₅ Asphaltenes, wt%	17.3	1.6
C ₇ Asphaltenes, wt%	12.6	1.2
CCR, wt%	12.8	2.6
Composition		
IBP–340 °F	0.0	8.7
340–450 °F	2.0	11.5
450–649 °F	12.4	33.0
649–975 °F	32.3	36.7
975 °F	53.3	10.1
Process results		
°API increase	16.3	
%HDS	95	
%HDN	48	
CCR conversion, %	80	
nC ₇ asphaltenes conversion, %	90	
975 °F+ conversion, %	81	

3.3.4. Results

The properties of a bitumen feedstock extracted from Western Canada and synthetic crude obtained in the GHU process are shown in Table 4.

3.4. Viscositor process

Ellycrack AS, a Norwegian company has patented the Viscositor technology, which is a process for upgrading of heavy oil at the oil field; it is based on the atomization of oil with steam and further collision with heated sand in a high-velocity chamber to “crack” the oil where any catalyst is not required. Low temperature and low pressure make this process technically feasible. Ellycrack will develop, refine and commercialize this technology in the field of production of heavy oil [28].

The basic Viscositor process shown in Fig. 5 can be described as follows: from a reactor, hot fine divided particles (sand), heated by coke combustion are pneumatically conveyed into a “collision” riser by hot combustion gases. Pre-heated steam atomized heavy oil is injected into the riser and collide with the particles causing an instant evaporation and cracking. In the cyclone the solids and generated coke are separated from the stream and routed to a regenerator and the oil gas and non-condensable gases are routed to a dual condensation system. The generated coke is used to fuel the process where the regenerated solids used as a heat carrier are routed into the reactor and riser again in a loop.

The main advantages of this process are: low temperature due to low partial oil pressure, self sustained with energy by coke combustion, no advanced catalyst, fine grained minerals as heat carriers, metal reduction by 90%, sulfur reduction by 50–60%, 5% hydrogenation, but not yet fully understood.

3.4.1. History

Invention developed by the University of Science and Technology, Norway and the University of Oslo. Ellycrack A/S (Norway) and Wescorp Energy Inc. (Canada) are the owners of this technology. SINTEF Energy Research, Trondheim, Norway, is responsible for continued research and technological development. Ellycrack after initial studies invented and patented the process from 1996 to 2000. In 2000 a test rig was designed and built, and an agreement with Petroleos de Venezuela Sociedad Anónima (PDVSA) was signed. The following year the incorporation of Ellycrack and funding of NOK were applied on research and development activities to accomplish the Viscositor process at Sintef Energy Research AS, Trondheim,

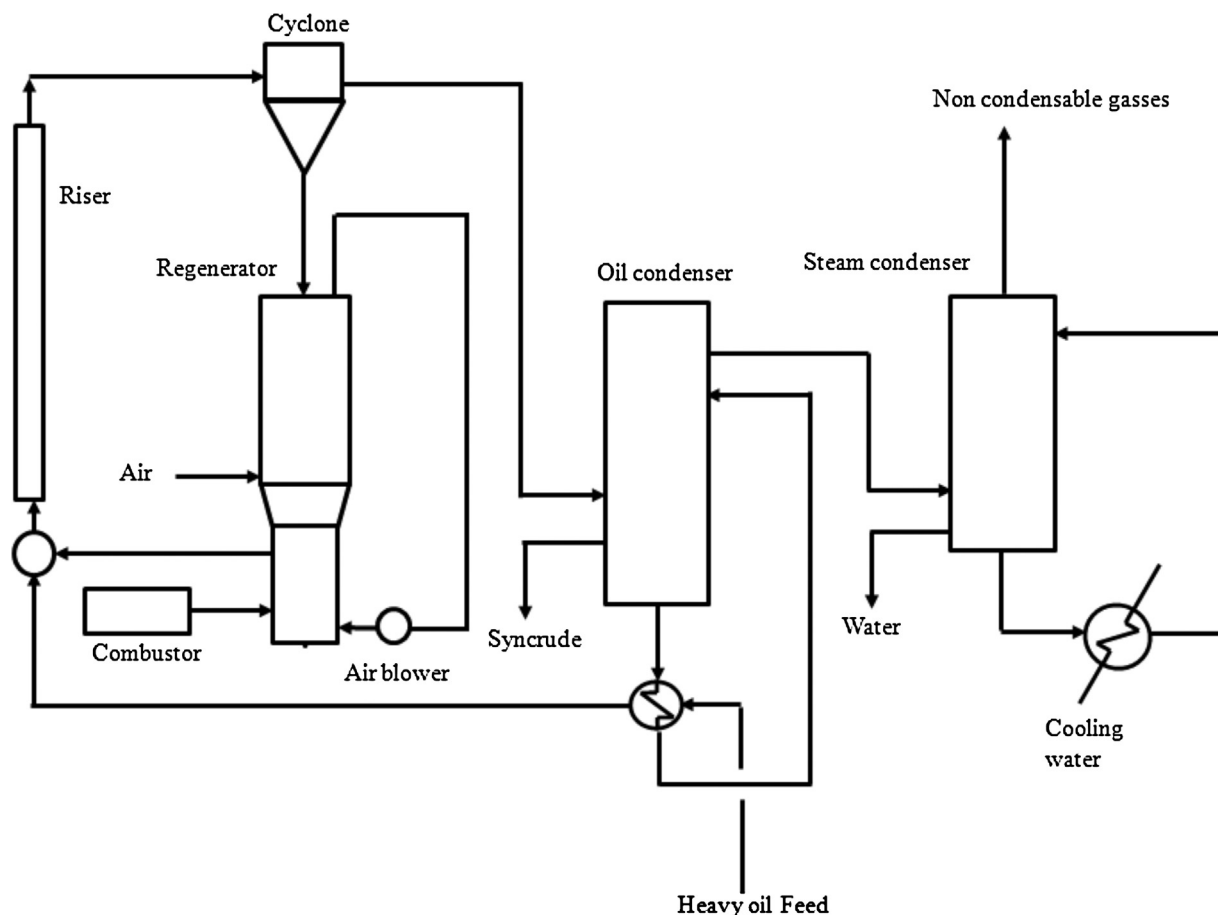


Fig. 5. Scheme of Viscositor process [28].

Norway. The verification of upgrading on this technology was done on 2003, and the next year a demonstration testing was performed for PDVSA, Statoil and Wescorp Energy on a 200 bbl/day unit. In 2005 the Viscositor technology was verified, the patents granted and a joint venture with Wescorp Energy was signed. The National Research Council of Canada (NRC) approved a grant to Wescorp Energy in 2006. These funds were used to support an enhanced and detailed test program of the Viscositor [29].

3.4.2. Patents

Patent No. US 6,660,158 (December 2003). Catalytic cracking process. Patent No. US 7,892,416 B2. Low temperature thermodynamic cracking and conversion for upgrading of heavy oils.

3.4.3. Current situation

The short-term strategy of Ellycrack is to prepare the pilot plant for new extensive testing, invite heavy oil producers to test their oil on the pilot plant and assure sufficient funding to develop the company according to chosen business plan.

3.4.4. Results

The testing program developed in 2007 yielded the results shown in Table 5.

3.5. IMP-HDT Process

The IMP process is based upon the catalytic hydrotreatment/hydrocracking of the heavy oil at moderate operating conditions, and achieves a high removal of metals, sulfur,

nitrogen and asphaltenes and a significant conversion of the heavier portions of the feedstock to more valuable distillates, while keeping the formation of sediments and sludge at very low levels. The most important characteristics of this process are relatively low investment and operating costs and an attractive return on investment.

The improvements in the quality of heavy crude oils obtained by applying IMP's technology include higher yields of distillates, lower contents of sulfur, metals, asphaltenes and coke formation precursors, lower acidity, corrosivity, viscosity and deposits formation tendency. These characteristics facilitate handling, transportation and refining of heavy and extra-heavy crude oils and increase their value for the refiner.

The main applications of IMP's process are:

- Conversion of heavy and extra-heavy crude oils to intermediate crude oils of higher value
- As a first processing unit for heavy and extra-heavy crude oils in a refinery.

Table 5

Tests performed on different heavy oils with Viscositor process.

Feed	Initial API	Upgraded API
Pit oil from Venezuela, PDVSA	6.2	22.5
Crude from Venezuela, PDVSA	9.3	20
Blended oil from Venezuela, PDVSA	14.9	21.5
Blended oil diluted from Venezuela, PDVSA	14.9	29.3
Crude from NORSE HYDRO	18	29.5
Canadian crude SUNCOR	13.18	25.2

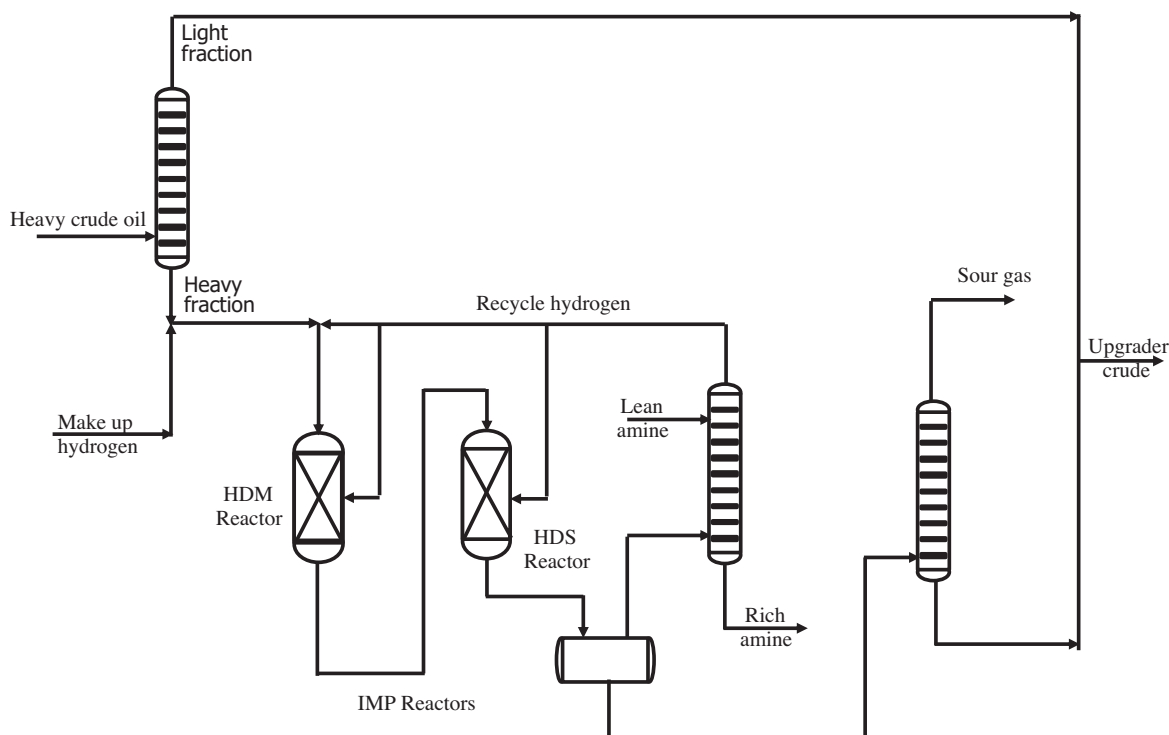


Fig. 6. Simplified scheme of HDT-IMP process [30].

In the application to heavy crude oils upgrading, the light fraction and the products from the reactor system are integrated into an upgraded crude oil stream. In the refinery application, the reaction section is integrated within a conventional combined distillation unit. Fig. 6 shows a simplified scheme of IMP-HDT process.

The use of a series of beds of catalysts with different formulations allows for better selectivities in the hydrodesulfuration and hydrodemetallation reactions and a higher efficiency in the use of the catalysts, thus providing for a product with lower sulfur and metals contents and for a lower catalyst consumption than the conventional catalytic high-severity hydrocracking processes. The conversion of heavy molecules to lighter fractions and the relatively low selectivity to gaseous products lead to liquid products yields of 104–105% by volume.

Due to the moderate operating conditions, investment costs are significantly lower than those of conventional catalytic hydrocracking processes. The lower catalysts and hydrogen consumptions translate into lower operating costs [30,31].

3.5.1. History

IMP started developing exploratory studies in heavy crude oil upgrading since 1990, and was granted its first Mexican patent in 1995 (No. 9,200,929: an approach for hydroprocessing of heavy crude oils to produce synthetic crude oil). From 1995 to 2003, the process was extensively studied and optimized for its application for a wide range of heavy and extra-heavy crude oils. The technological development of the IMP process was performed from 2003 to 2006, which included long-term pilot plant experiments (about 6 months). Two semi-commercial demonstration tests were carried out in 2006 and in 2008 in a 10 barrels per day unit with high metal and asphaltenes content crude oils having API gravity ranging from 10 to 16°. The results of these tests indicated that the IMP process produces an upgraded crude oil having a consistently high quality.

Optimization and engineering have been carried out during 2008–2011, and the IMP process is ready for commercial application.

3.5.2. Patents

Patent No. US 7,651,604 B2 (January 26, 2010). Process for the catalytic hydrotreatment of heavy hydrocarbons of petroleum. The invention is also protected in Mexico (No. 271,028), Russia (No. 2,339,680) and Singapore (No.118,896). In addition, an application of this patent has been submitted to European Union, Australia, Canada, Brazil, Japan and Venezuela. Patents of the catalysts have also been granted.

3.5.3. Current situation

The IMP Process has been satisfactorily tested at semi-industrial level with heavy and extra-heavy crude oils. The main features of the process have been extensively tested in the optimization of the catalysts system and operating conditions as well as in the definition of the useful life of the catalysts.

Technical and economic studies carried out to evaluate the application of IMP technology in a heavy crude oil upgrader and in a typical refinery scheme show important advantages of IMP's process in comparison with the main technologies commercially available for bottoms-of-the-barrel processing.

All of the components of IMP's heavy crude oil upgrading technology have been demonstrated at the industrial level in hydrotreatment/hydrocracking units. The key elements of the technology (the activity and selectivity of the catalysts system, the operation at moderate conditions with very low sediments formation and the ability to process very difficult feedstocks) have been extensively tested at the pilot plant level and confirmed in a semi-industrial unit.

The possibilities of application of this technology in a first industrial unit are being analyzed with Petroleos Mexicanos (PEMEX).

3.5.4. Results

Table 6 shows the results of IMP process for upgrading of heavy crude oils in the range of 10–16 API gravity at moderate reaction conditions.

Table 6
Results of upgrading of different heavy crude oils with IMP process.

Property	Crude oil	Upgraded oil	Crude oil	Upgraded oil	Crude oil	Upgraded oil
API gravity	15.93	25.1	13.14	23.38	9.89	22.6
CCR, wt%	15.87	7.1	16.78	8.1	20.42	8.3
Sulfur, wt%	4.602	1.102	5.10	1.15	5.723	1.145
Nitrogen, wt	3570	2291	4771	2925	5650	2971
C ₇ Asphaltenes, wt%	15.66	4.7	16.95	5.33	25.06	5.3
Metals, ppm						
Ni	69.2	26	91.2	22	94.2	28
V	361.0	71	452.7	76	494.0	71
Ni+V	430.2	97	543.9	98	588.2	99

3.6. NexGen-ultrasound process

The NexGen technology is a new system invented for upgrading heavy oil employing ultrasonic waves to break the long hydrocarbon chains and simultaneously adds hydrogen generated from purified water to the molecules.

The fundamentals for the NexGen technology derived of a project undertaken by the developer group to overcome fuel stability problems in MIG fighter jets. Further, this group developed this technology for using within the oil upgrading sector [32].

Fig. 7 shows the physical basis of NexGen Technology, which is a cavitation process. It uses ultrasonic energy waves to create cavitation bubbles within the working fluid, in this case, oil. By further application of this energy the bubbles are taken to collapse at high temperature and pressure. This collapse causes the breaking of the long chain hydrocarbon molecules.

The prototype heavy oil upgrader (HOG) shown in Fig. 8 is fed with heavy crude oil. The crude contains salt water and small amounts of solids. To remove the salt water and solids, the crude is heated to about 200 °C which causes the water and solids to drop out of the oil. The material is removed by the fresh water circuit shown at the front of the process.

Once the water and solids are removed the crude oil is passed through a membrane separation process where the asphaltenes are separated from the lighter crude oil. The pure asphaltenes form small crystals which in volume behave much like a low viscosity liquid. The two separate streams are first sent to what Energy Quest calls the Cracking Process (CP) which is a chemical–magnetic induced process. The CP process will be operated differently for the two streams.

Once the asphaltenes and heavy oil have been partially cracked by the CP process, they are sent to the next cracking process which has great control on the type of hydrocarbon formed. Energy Quest calls the second ultrasound upgrader the HOG. The 10 step HOG followed by the 4 step HOG produces a finished product that only has to be separated by distillation.

The 10 step HOG allows the operator to control the paraffin–olefin–naphthenic–aromatic (PONA) ratio of the formed products. The 4 step HOG allows the operator to control the purity of the products by eliminating sulfur, nitrogen and oxygen.

3.6.1. History

NexGen's team has developed and proven the technology over the last 5 years. Scientists of NexGen have proven the ability to upgrade heavy oil from 8 to 42 °API gravity at an energy input of 20 kWh/bbl.

3.6.2. Patents

So far, the corresponding patent claiming this technology was unavailable to be retrieved.

3.6.3. Current situation

NexGen is now designing a 10,000 barrels per day commercial upgrading plant that plans to install in Edmonton, Alberta, near the Athabasca tar sands. The estimated cost of this commercial plant is about \$45 million, and will be sufficiently large enough to demonstrate the capabilities of the system. Upon successful completion of this upgrader unit NexGen will promote the systems, including NexGen-owned and operated systems, joint

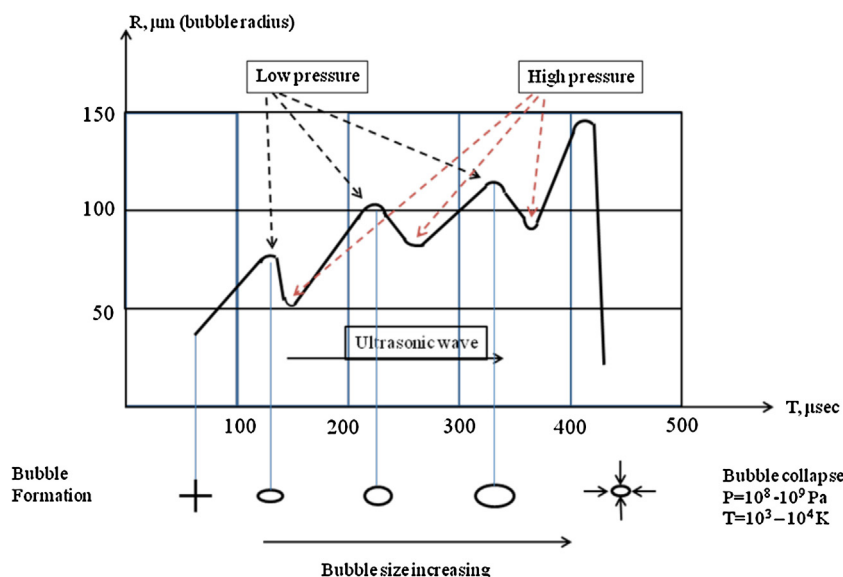


Fig. 7. Physical basis of NexGen technology (cavitation process) [32].

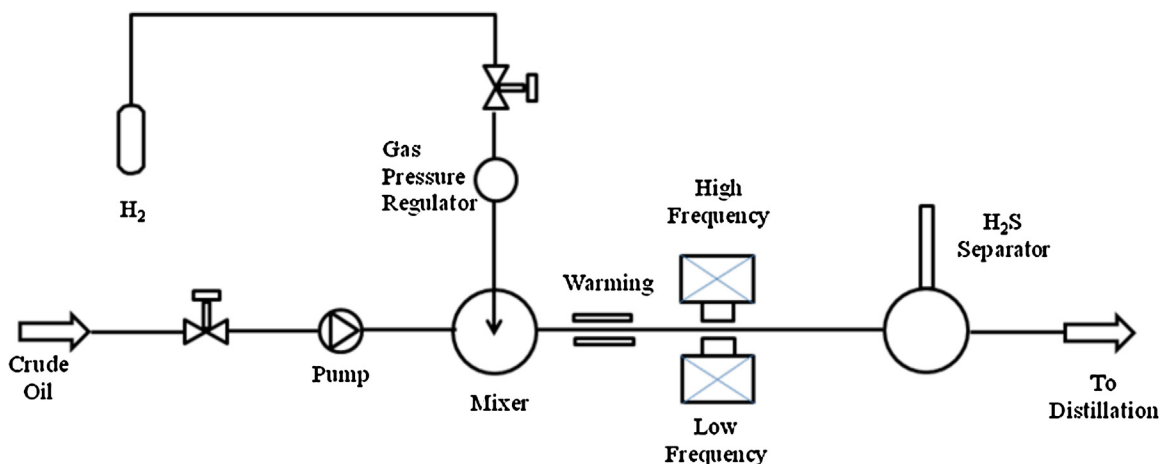


Fig. 8. Prototype installation of NexGen technology [32].

venture partnerships with other petroleum companies, and licensing and royalty arrangements.

3.6.4. Results

The system operates at lower temperatures and pressures, avoiding the need of the complex and expensive hardware in traditional refineries, hence, investment costs will represent a fraction of conventional upgraders.

All processes are carried out at $T=0-70^{\circ}\text{C}$ and $P=1-5$ bar, consequently energy consumption is reduced and operating and maintenance costs are reduced by 50%.

Volumetric yields are 20–50% higher than the traditional process, therefore profits are increased and the use of petroleum supplies is maximized. Profit margins are greatly increased, initial construction time is reduced, and harmful environmental emissions virtually eliminated.

The technology takes place in oil pipelines during pumping and no catalyst is engaged. The systems are modular with processing capacities of 500–100,000 bbl/day or more, so they can be sized to meet the local demand.

The technology can process feedstocks such as bottoms, heavy oil, extra-heavy oil (bitumen), and light oil, and eliminate the need for condensate. It considerably improves oil quality before the oil refining takes place; significantly improves yields and coking is not present.

Due to viscosity reduction, this technology substantially reduces or eliminates blending during oil transportation along pipelines. No down time to replace catalyst.

3.7. Sulph-ultrasound process

SulphCo has developed an economic process employing ultrasound technology for desulfurization and hydrogenation of crude oil and other oil related products. The technology upgrades sour heavy crude oils into sweeter, lighter crudes, producing more gallons of oil per barrel. Fig. 9 shows a flow diagram of the process.

3.7.1. History

SulphCo was founded in 1999 leading most of the testing at its facility in the United Arab Emirates and some also in Nevada.

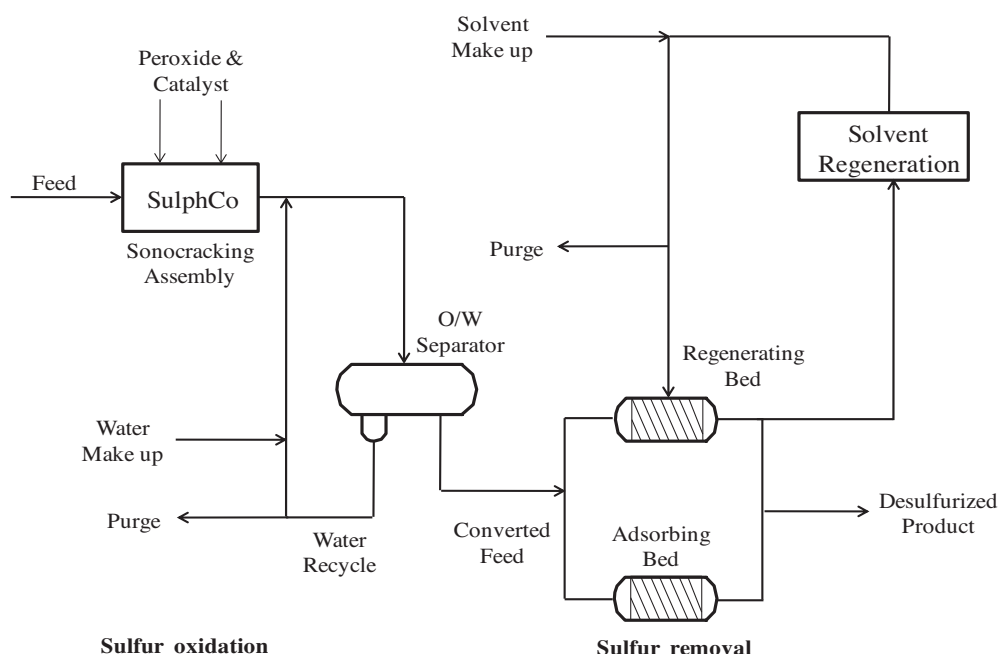


Fig. 9. Process block flow diagram and applications of Sulph-Ultrasound process [34].

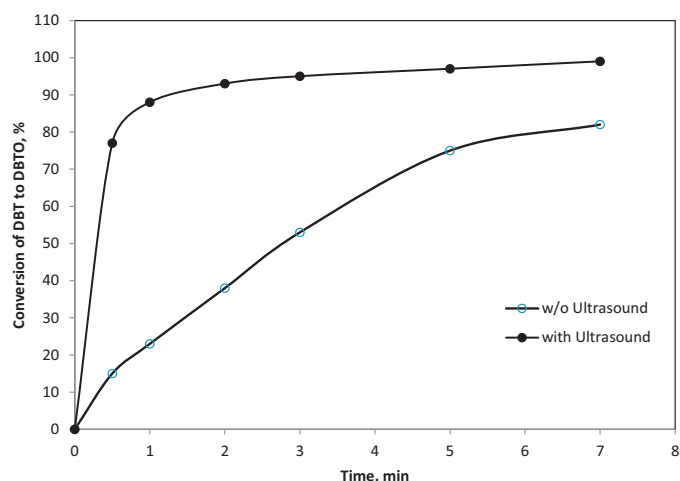


Fig. 10. Conversion of DBT to DBTO with and without the use of ultrasound.

SulphCo has conducted four separate series of sonocracking trials recognizing that Sonocracking is almost ready since 2002. In February 2008 SulphCo signed a deal with Pt. Isis Megah, an oil distributor in India, Malaysia, Singapore, and Indonesia to implement sonocracking technology in their plants. The technology has not yet been installed.

3.7.2. Patents

SulphCo has five U.S. patents issued to cover the development and production of its high-powered ultrasound technology and equipment: 6,402,939 (2002), 6,500,219 (2002), 6,652,992 (2003), 6,827,844 (2004), and 6,897,628 (2005). SulphCo's Sonocracking ultrasound process increases the distillate yield while at the same time reducing sulfur and nitrogen content. The patent granted in 2005, "High-Power Ultrasound Generator and Use in Chemical Reactions", covers the electromagnets and other machinery in SulphCo ultrasound generator and how the mechanism works to produce a chemical reaction when ultrasonic waves are introduced. The company has six other patents pending plus corresponding applications pending around the world.

3.7.3. Current situation

SulphCo has already contracted its sonocracking technology to Pt. Isis Megah which operates in India, Malaysia, Singapore and Indonesia, however, the technology has not yet been installed. The company also is expecting opportunities in Austria, South Korea, South America, and Canada [33].

3.7.4. Results

Table 7 shows the efficiencies and recoveries of the sonocracking technology in ultrasound assisted oxidative desulfurization (UAOD) on diesels and Fig. 10 shows the conversion of DBT to dibenzothiophene sulfone (DBTO) with and without the use of ultrasound [34].

3.8. HRH process

Heavy residue hydroconversion (HRH) developed by Research Institute of Petroleum Industry (RIPI) of Iran, is a catalytic hydrocracking process, which targets conversion of heavy and extra-heavy crude to valuable crude. In this process, shown in Fig. 11, the hydrogen, feed and the catalytic complex are heated separately. Then feed and the catalytic complex are mixed and heated again. Finally, the mixture of feed, catalytic complex and hydrogen are heated and entered into the reactor where heavy residue feed is cracked and

hydrogenated. Outlet gas products from top of the reactor are condensed and separated. In the first stage of separation, unreacted hydrogen and light hydrocarbon are separated, treated in amine contactor and recycled to the system by a compressor. In the second stage, off gas is separated, treated in amine contactor and conducted to the flare system. After separation, liquid products are fractionated by distillation. However, catalytic complex remains in the distillation residue that is separated by filtration then it is recovered by burning and adding a solvent to the ash [35,36].

This technology can be used for two main purposes: Hydroconversion in refining application and Hydroconversion in wellhead application. By using this process, heavy and extra-heavy crude can be converted to valuable crude and high added value obtained.

3.8.1. History

The HRH process has been run with a variety of feeds in different capacities. In 1991 a 200 BPD semi-industrial pilot plant was located in Russia to evaluate this technology. Further, 1 L lab batch unit and 2 BPD pilot unit were used in Teheran, and a 5 L/day continuous pilot plant was located in Russia. The basic design was completed on a 10,000 BPD heavy oil upgrader in Persian Gulf area and the final completion of this development was obtained in a 200 BPD refinery residue demo plant located at Bandar-Abbas refinery. Currently, an 180,000 BPD unit is under basic design at heavy oil upgrading and refining complex in Iran.

3.8.2. Patents

Patent US 7,585,406 B2 (September 2009), Publication No. EP 1,754,770 A1 (February 2007) and Application No. EP 05,107,538.0 (August 2005), process for hydroconverting of a heavy hydrocarbonaceous feedstock. Further during 2006 year the invention was protected in other countries such as USA, Canada, Venezuela, Cuba, Mexico, China, Iraq, Japan and South Korea as well in the Gulf Cooperation Council countries (GCC).

3.8.3. Current situation

Industrial projects on conversion of heavy crude oil to light crude and also heavy vacuum residue to synthetic crude has been studied and designed for several commercial scales from 10,000 to 180,000 BPD. The technology can be licensed through Mobis in Canada. Research Institute of Petroleum Industry (RIPI) offers opportunities for cooperation in its HRH process in technology transfer, process development package, carrying out detailed design, and other related engineering activities.

3.8.4. Results

The HRH process has been investigated in pilot plant and demo scales. Experimental data for hydroconversion of Bandar-Abbas vacuum residue is shown in Table 8.

3.9. CCU process

The UOP catalytic crude upgrading process (CCU) offers a solution to trapped nontraditional crude production. The process is based on traditional FCC principles processing only enough of the crude to create sufficient accumulation to produce a synthetic crude meeting pipeline specifications.

The process has a high coke yield, which results in the opportunity to produce large quantities of both steam and electrical power. The produced steam and power supply the utility needs of the complex as well as the surrounding oil field, the upgrading complex and the infrastructure necessary to support the project [37].

The process can be adapted to meet the needs of a number of stranded oil projects where natural gas and electricity supplies are unavailable. The CCU process is applicable to heavy oil projects

Table 7
Efficiencies and recoveries of the sonocracking technology in ultrasound.

	Sonication time (min)	Sulfur content (wt%)			Sulfur removal (%)	Recovery of oil (%)
		Original	After oxidation	After extraction		
Diesel A	18	0.7744	0.7545	0.0142	98.2	82.8
Diesel B	10	0.3011	0.2696	0.0039	98.7	87.2
Diesel C	10	0.1867	0.1670	0.0012	99.4	85.5

Table 8
Feed and product specifications of Bandar–Abbas VR upgraded by HRH.

Specification	Feed	Product
Specific gravity	1.0429	0.865
API	4.56	32
Total sulfur, wt%	4.74	2
Total nitrogen, wt%	0.73	0.35
Kinematic viscosity @ 135 °C, cSt	667	
Pour point, °C	>+50	–2
Vanadium, ppm	323	Null
Nickel, ppm	73	Null
ASTM 1160, °C*		
IBP	322	8
5%	566	95
10%	623	154
20%	373	188
30%	698	224
50%	747	280
70%	803	335
90%	877	422
FBP	992	593

* ASTM D-86 original data were converted to ASTM D-1160 through Hysys simulator.

such as those where high quality waxy crude cannot be pipelined because of pour point restrictions.

3.9.1. History

UOP developed the CCU process in 2005 as a cost effective option to upgrade heavy crude oils and bitumen-derived crude. The process reduces the viscosity of the crude allowing it to travel easily

through pipeline transport without the use of external diluting agents.

3.9.2. Patents

US 2007/0034550 A1, (February, 2007). “Process and apparatus for improving flow properties of crude petroleum”.

3.9.3. Current situation

Albemarle Corporation signed in 2008, a technology cooperation agreement with UOP LLC, a Honeywell company, and Petroleo Brasileiro (Petrobras) to accelerate the commercialization of UOP’s Catalytic Crude Upgrading (CCU) process technology. Under the terms of the agreement, the three companies will collaborate to demonstrate the performance and quality of this innovative technology as a cost effective option to upgrade heavy crude oils and bitumen-derived crude. Under the agreement, Albemarle and Petrobras, will provide an improved FCC catalyst solution to be used in this proprietary process. UOP will provide the technology, equipment and system design.

Petrobras has demonstrated the CCU technology in pilot plants in CENPES development center and developed the catalytic system solution through a long-term partnership with Albemarle in FCC catalyst [38].

3.9.4. Results

The CCU process is catalytic, not thermal, and therefore carries with it significant conversion and yield selectivity benefits. This results in a higher API liquid product. Table 9 shows the Rubiales and CCU crude properties where the primary objective

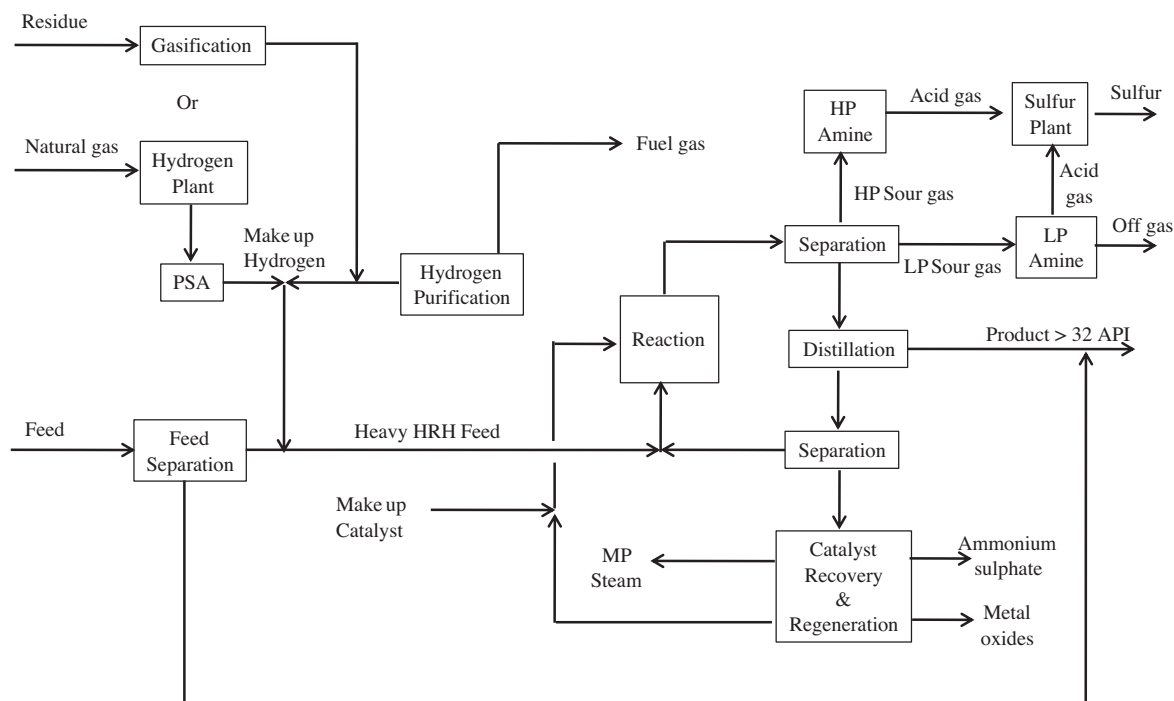


Fig. 11. Scheme of HRH process for heavy crude oil upgrading [35].

Table 9

Properties of the crudes obtained in the CCU process.

Properties	Rubiales crude	CCU product crude
BPSD	30,000	28,413
Lb/h	429,198	341,739
API	12.4	39.7
RVP @ 100 °F, psia	0.85	28.9
Viscosity @ 100 °F, cSt	933.3 (122 °F)	1.1
Viscosity @ 210 °F, cSt	127.0 (176 °F)	0.4

of the properties is producing synthetic crude that meets pipeline specifications [37].

3.10. Eni process

The Eni Slurry Technology (EST) process was developed by Snamprogetti and EniTecnologie, both companies of the Eni Group. Fig. 12 shows a scheme of this process. The EST process enables an almost complete conversion of the feedstock (>95%) and guarantees an excellent level of upgrading of the products. The process proved extremely flexible in treating different types of heavy feedstocks, such as vacuum residues, heavy crudes, extra-heavy crudes and bitumens from oil sands [39,40].

The heart of the process consists of a hydrotreating reactor in which the heavy crude feedstock undergoes a hydrogenation treatment in relatively mild conditions (410–420 °C and 160 bar). The hydrotreating is carried out in the presence of several thousand ppm of a molybdenum based catalyst finely dispersed in the liquid mass so as to promote the upgrading reactions (metal removal, desulfurization, denitrogenation and reduction of the carbon residue).

Typical overall performances achieved in the reaction system, by recycling unconverted bottoms show:

- Metal removal (HDM) > 99%;
- Conradson carbon residue reduction (HDCCR) > 97%;
- Sulfur reduction (HDS) > 85%;
- Nitrogen reduction (HDN) > 40%.

3.10.1. History

Eni Slurry Technology (EST) is a process developed in the early 1990s, after catalyst screening studies in laboratory microreactor and bench-scale autoclave tests [41,42]. Further a pilot plant with a capacity of 0.3 bbl/day was started up in 1999. Eni/Snamprogetti has proposed conceptual designs for the processing of Athabasca bitumen and Venezuela Zuata heavy crude oil. In 2005 it was completed and started up a 1200 BPSD of a Commercial Demo Plant (CDP) at Eni Taranto Refinery [43,44].

3.10.2. Patents

U.S. Patent 8,017,000 B2, (Sep, 2011). Process for the conversion of heavy feedstocks such as heavy crude oils and distillation residues. U.S. Patent 7,691,256 B2, (Apr, 2010). Process for the conversion of heavy charges such as heavy crude oils and distillation residues. U.S. Patent 8,147,675 B2, (Apr, 2012). Process for the total conversion of heavy feedstocks to distillates. U.S. Patent 8,057,660 B2, (Nov, 2011) process for the total conversion of heavy feedstocks to distillates [45,46].

3.10.3. Current situation

The implementation of the first EST industrial plant (23,000 BPSD capacity) is in progress at Eni Sannazzaro de' Burgondi Refinery (Pavia, Italy) expecting to be in operation by the end of 2012.

Table 10

EST process performances.

Feedstock	Zuata crude	Maya crude	Athabasca bitumen
Temperature cut	530 °C+	500 °C+	300 °C+
API gravity	2.5	1.5	7.8
Sulfur, wt%	4.2	5.2	4.6
CCR, wt%	22.1	29.3	13.6
Nickel, ppm	154	132	70
Vanadium, ppm	697	866	186
Nitrogen, wt%	0.97	0.81	0.48
C ₇ asphaltenes, wt%	19.7	30.3	12.4
Product yields, wt%			
C ₁ –C ₄	15.1	9.9	12.9
Naphtha	14.0	3.9	4.1
Atmospheric gasoil	39.1	26.9	39.1
Vacuum gasoil	23.3	34.9	32.1
DAO	8.5	24.9	11.8
Products upgrading			
%HDS	86	84	83
%HDN	59	52	47
%HDN	>99	>99	>99
% removal of CCR	98	96	95

3.10.4. Results

Table 10 shows the performance of the EST process on different feedstocks [47].

3.11. Houp process

The Heavy Oil Upgrade Project (HOUP) developed by Pre-mium Engineering-Research and Development focuses on two main areas: first, the upgrading of high viscosity and low API gravity heavy oils at the production site by converting them into lighter synthetic crude oil, and second, the refining of heavy oil residues at refineries.

The HOUP process is based on a major modification of the thermal cracking process and does not require the use of catalysts nor of hydrogen, and has a minimal infrastructure requirement which means that it can be used at production sites.

The most important feature of the process is the manner in which feedstock molecules receive energy required for cracking. This approach is based on conventional pre-heating and the use of superheated steam as an energy source which results in uniform and almost simultaneous heating. The level of the supplied energy is adjusted to crack only the weakest bonds of large molecules. In other words the level of energy supplied minimizes excessive cracking and increases the yield of distillate fractions. The HOUP process can be used to convert different heavy residues at refineries [48].

3.11.1. Patents

Additional information of this emerging technology is not accessible in the open literature, however, it is expected that this process would be patented in the short time to be competitive with other similar technologies under the name "Method and apparatus for heavy oil processing".

3.12. Uniflex process

The UOP Uniflex process, a high-conversion slurry hydrocracking technology resulted from a combination of elements from the Canmet process reactor section and UOP Unicracking and Unionfining process technologies [49,50]. The typical Uniflex process flow scheme is shown in Fig. 13, which is similar to that of a conventional UOP Unicracking process unit. In this scheme liquid feed and recycle gas are heated to temperature in separate heaters, with a small portion of the recycle gas stream and the required amount

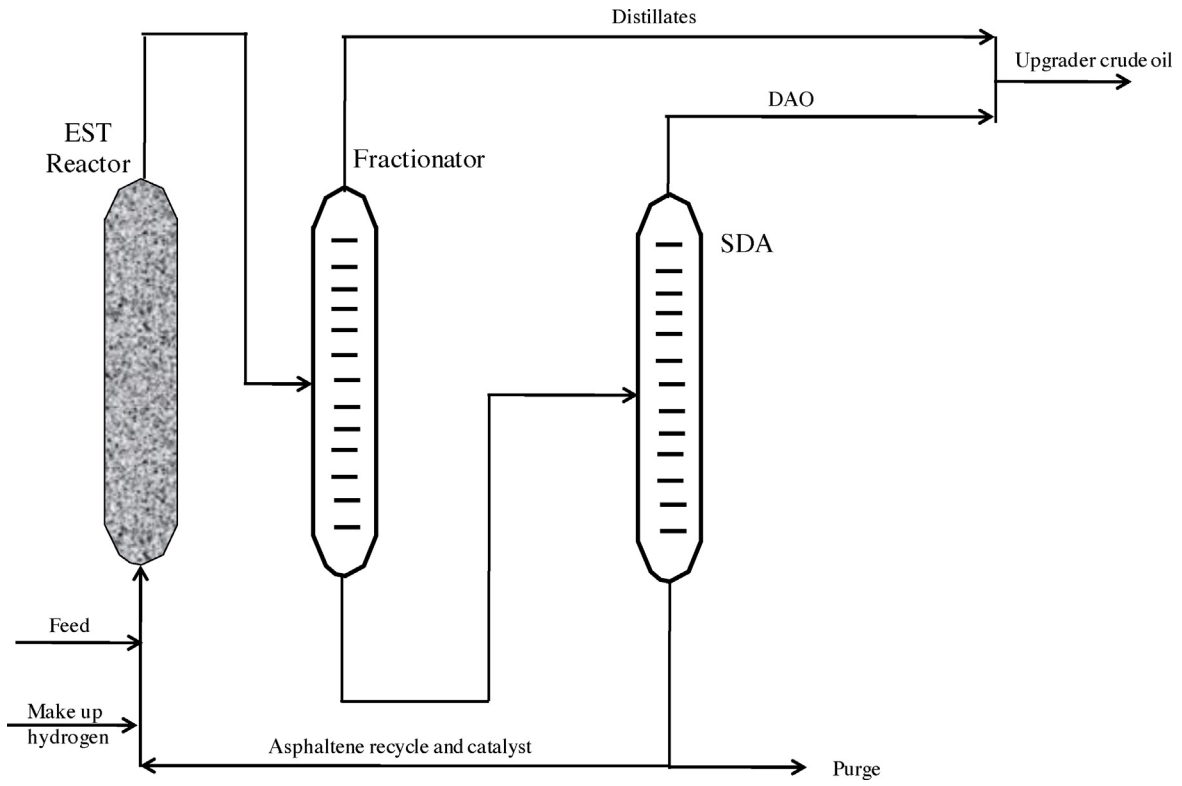


Fig. 12. Simplified scheme of the EST process (ENI) [40].

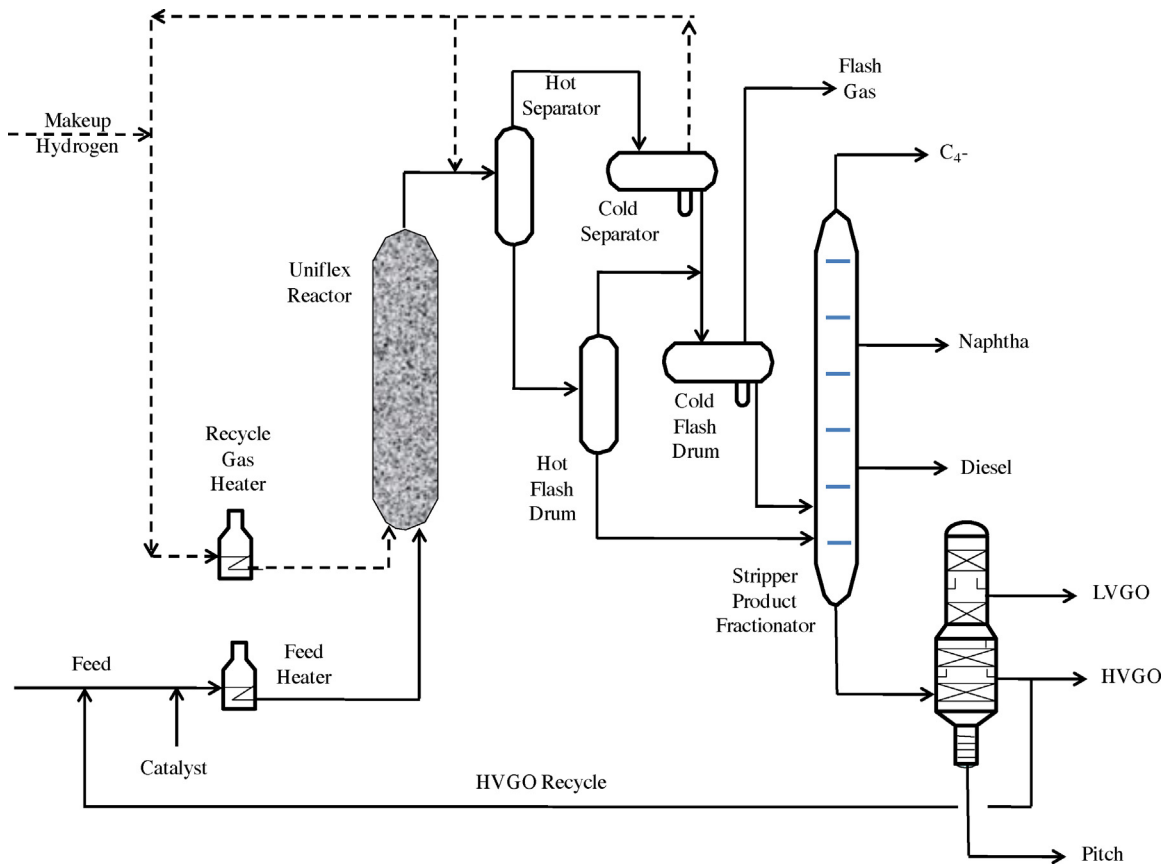


Fig. 13. Uniflex process flow scheme [49].

of catalyst being routed through the oil heater. The outlet streams from both heaters are fed to the bottom of the slurry reactor.

The reactor effluent is quenched at the reactor outlet to terminate reactions and then flows to a series of separators with gas being recycled to the reactor. Liquids flow to the fractionation section for recovery of light ends, naphtha, diesel, vacuum gas oils and unconverted feed (pitch). Heavy vacuum gas oil (HVGO) is partially recycled to the reactor for further conversion.

The heart of the Uniflex Process is its upflow reactor that operates at moderate conditions (435–471 °C and 138 bar). The reactor's feed distributor, in combination with optimized process variables, promotes intense backmixing in the reactor without the need for reactor internals or liquid recycle ebullating pumps.

3.12.1. History

In 2000 UOP evaluated several options focused on a slurry hydrocracking technology concluding that the most efficient approach involved Canmet hydrocracking process. In 2006 UOP worked with NRCAN to evaluate and improve the process technology package before UOP acquired the exclusive worldwide rights to license the Canmet process.

Further, UOP has invested significant effort in improving catalyst performance, engineering design and feedstock processing flexibility with financial support and strategic input from the Alberta Energy Research Institute (AERI) as part of its Hydrocarbon Upgrading Demonstration Program. This program is aimed at developing and demonstrating commercially viable advanced technologies that convert bitumen and bitumen-derived products into higher-valued products.

The Uniflex process catalyst costs are lower relative to other slurry hydrocracking technologies because expensive catalytic materials, such as molybdenum, are not required.

3.12.2. Patents

Patent US 8,110,090 B2 (February 2012), Deasphalting of gasoil from slurry hydrocracking and the original Patent US 4,299,685 (1981). Since 2009, the USPTO has given the Uniflex trademark serial number of 77,722,028 to UOP LLC, Des Plaines, IL 600,175,017.

3.12.3. Current situation

UOP's engineering efforts have included the development of an updated and improved engineering design. UOP pilot plants are able to confirm the design basis for new applications because UOP and NRCAN have over 100,000 h of cumulative pilot plant experience with the Uniflex process technology. Performance of these pilot plants has been validated against the Petro-Canada demonstration unit.

UOP announced in January 2012 that its Uniflex process has been selected by National Refinery Limited (NRL) to maximize diesel and lubricant production in Pakistan. The NRL facility, scheduled for start-up in 2016, will produce 40,000 barrels daily of diesel fuel and 4500 barrels daily of lube base oils [51].

3.12.4. Results

The Uniflex process employs a proprietary, nano-sized solid catalyst which is blended with the feed to maximize conversion of heavy components and inhibit coke formation. The catalyst is dual functional, with its primary function being to impart mild hydrogenation activity for the stabilization of cracked products while also limiting the saturation of aromatic rings. As can be seen in Fig. 14, this permits the reactor to operate at both very high asphaltene and non-distillable conversion levels.

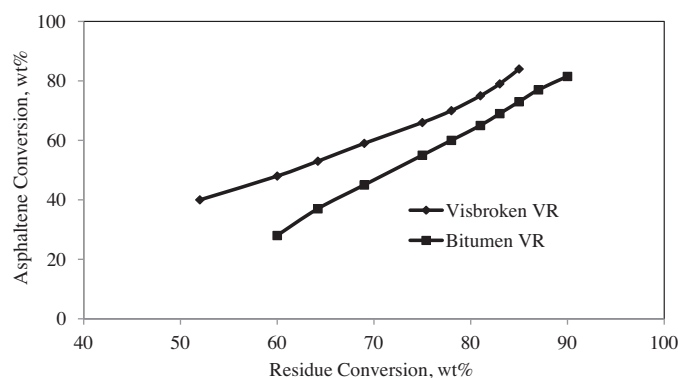


Fig. 14. Uniflex process asphaltene conversion.

3.13. WRITE process

WRITE is an upgrading process that produces residuum-free oil from heavy oil and bitumen with undiluted density and viscosity that exceed general pipeline specifications. WRITE uses two processing stages to accomplish low and high temperature conversion of heavy oil or bitumen. The first stage Distillate Recovery Unit (DRU) operates at mild thermal cracking conditions, yielding a light overhead product and bottoms material. These bottoms flow to the second stage, a coker that operates at severe pyrolysis conditions, yielding light products (pyrolyzate) and coke. The combined pyrolyzate and mildly cracked overhead streams yield synthetic crude oil (SCO).

An application of the WRITE process for partial upgrading would eliminate the need for diluents step, and could possibly eliminate the need for a coker at the upgrader, since a coker is already integral to the WRITE process itself. Fig. 15 shows a block diagram of the WRITE process for upgrading a bitumen stream [52,53].

3.13.1. History

Western Research Institute (WRI) and MEG Energy Corporation (MEG) have been jointly developing the WRI Thermal Enhancement (WRITE) process upgrader since 2004. WRITE process was developed in three phases. Phase 1 involves the completion and analysis of bench-scale tests (1 BPD), the design of a pilot facility for field testing, and development of preliminary economics for a commercial facility. Phases 2 and 3 involve the construction and operation of a pilot plant (5 BPD) sited at a production facility using actual run bitumen.

Testing comprised three series: the first series, run with undiluted bitumen, explored the effects of sweep gas composition and space velocity. The second series run with diluted and undiluted bitumen, varied temperature and space velocity. The third series, run with dilbit (diluted bitumen), explored a range of reduced space velocities [54].

3.13.2. Patents

Patent US 2011/0284425 A1, (November, 2011), hydrocarbonaceous material upgrading method.

3.13.3. Current situation

A preliminary economic analysis conducted by MEG and their engineering consultant concluded that the WRITE process is a technically feasible method for upgrading bitumen producing SCO that meets pipeline specifications. Subsequent development stage will be to scale-up the 5 BPD pilot plant to a suitable sized demonstration pilot in 2013. The size of the field demonstration unit may range from 300 BPD to 1500 BPD [55].

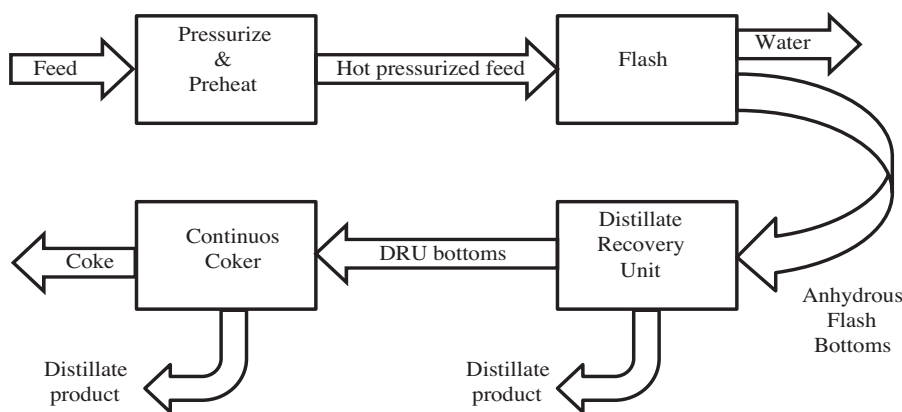


Fig. 15. Block diagram of the WRITE process [52].

3.13.4. Results

The results reported in the WRITE process indicate an increase in API gravity of 13 units for feeding bitumen 10.4° API.

3.14. Wildcatter HCU process

The Wildcatter technology is based on new processes and catalysts designed to perform in field upgraders located directly at the wellhead of extra-heavy crude oil production sites. The wildcatter process converts heavy and extra-heavy crude oil into high grade, high value petroleum products and steam. The process is conducted in three major processes in series. In the first process crude oil is converted into lighter sweeter crude, coke and light gases in a catalytically enhanced pyrolysis reaction. The second process employs typical techniques to convert coke and select chemicals into H₂ and CO. Finally, the chemicals produced in process one and two are used to strip hydrogen from water in process three. The reaction is exothermic and most of the head produced is recovered as steam. Fig. 16 shows a block diagram of the overall process [56].

These processes can be installed at a wellhead and require only water and energy input to produce between 871 and 1042 barrels per day (BPD) of higher quality than >30° API liquids from each 1000 BPD of heavy crude input. Modular construction allows easy shipment to a site for setup and production.

3.14.1. History

The performance tests were developed in 15 BPD pilot plant in El Paso, Texas. The HCU reactor operates at atmospheric pressure and without addition of high pressure hydrogen.

3.14.2. Patent

U.S. patent 7,223,713 B2 (Sep, 2007). Molybdenum sulfide/carbide catalysts.

3.14.3. Current situation

The patent will be licensed to Refinery Science Corp. by the University of Texas and Centro de Investigacion en Materiales Avanzados (CIMAV) Mexico. The Company intends to use the catalyst in its Wildcatter Heavy Crude Upgrader.

3.15. Value creation technology (VCG)

The technology has been developed as two proprietary steps: the Accelerated Decontamination (ADC) process and the Ultra-Selective Pyrolysis (USP) process, which can be used individually and in combination. The ADC unit removes asphaltenic contaminants very selectively and as completely as desired, using colloidal physics, mild temperature and low pressure conditions. The USP unit cracks the heavy residue component in to light oil products in an energy efficient manner. The prototype ADC and USP plants have been constructed and demonstrated at Techno-economics technology center located in High River, Alberta and at an industrial site in Calgary, Alberta, respectively.

The process will yield a range of light to medium, semi-sour crude oil and very low in heavy residues and contaminants [57].

3.15.1. History

Value Creation Inc. (VCI) is a private Alberta company established in 1999. The vision they focuses is: "Sustainable Development of Oil sands (and extra-heavy-oils) to produce crudes

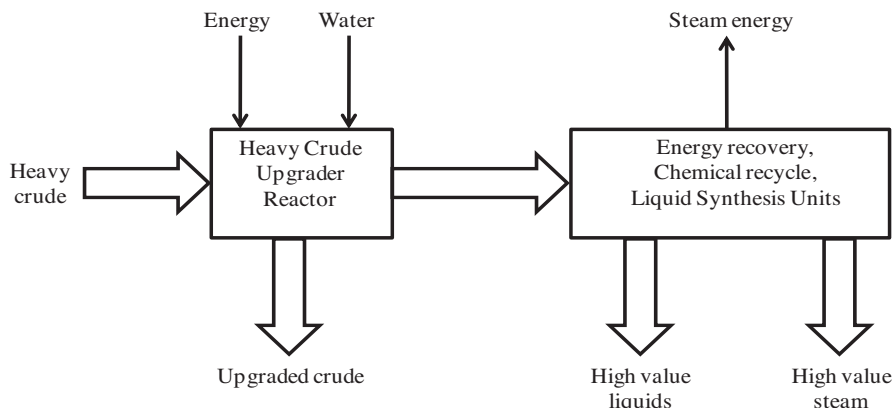


Fig. 16. Block diagram of the Wildcatter process [56].

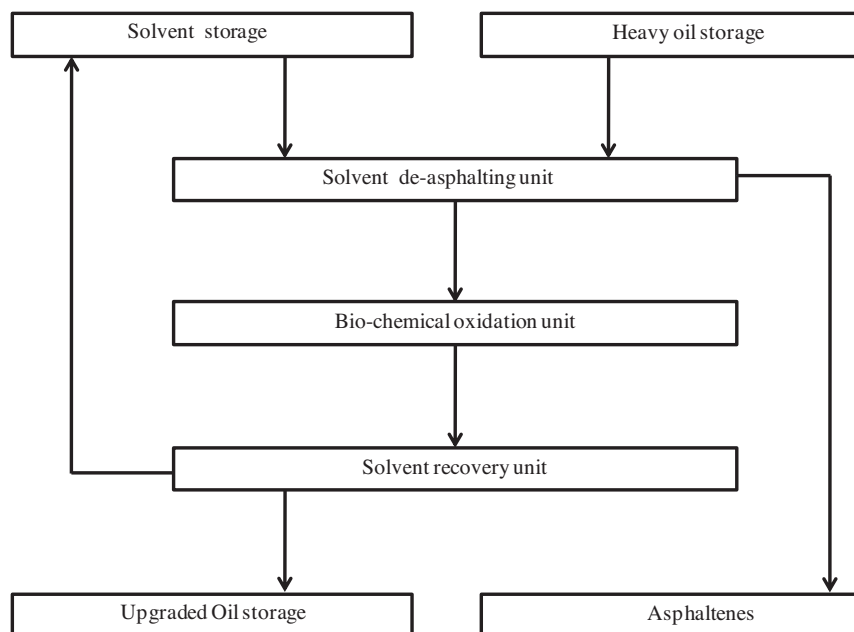


Fig. 17. Block diagram of the Petrosonic upgrading process [60].

customized for broad spectrum of refineries, at the lowest all-in-costs”.

On March 7, 2007, VCI announced the company is proceeding with its first Athabasca oil sands production project, Terre de Grace (TDG-1), which will combine in situ recovery and field upgrading.

In December 2007, the company filed a joint regulatory application with the Energy Resources Conservation Board and Alberta Environment for the development of an integrated in situ bitumen pilot production and upgrading project on its Terre de Grace Lease.

VCI announces that BA Energy Inc. has become a wholly owned subsidiary of Value Creation effective February 26, 2008. BA Energy is constructing the Heartland Upgrader, a commercial bitumen upgrader using proprietary upgrading technologies developed by Value Creation in Strathcona County, northeast of Edmonton, Alberta.

Value Creation has submitted its Project Disclosure document and proposed Terms of Reference for review to the Alberta Energy and Utilities Board and Alberta Environment. After regulatory approvals, the upstream-upgrading project is expected to begin production in 2011.

The Terre de Grace block is one of several held by Value Creation, which entirely owns one of the largest oil sands resources held by an independent Canadian company.

3.15.2. Patents

Patent US 7,625,466 B2 (Dec, 2009) “Systems for the decontamination of asphaltic heavy” assignee to Value Creation Inc. Calgary, Alberta, Canada, and US 2012/0048713 A1 (March, 2012) “Pyrolysis of residual hydrocarbons”.

3.15.3. Current situation

Based on an independent consultant’s calculation and Value Creation’s own estimate, TDG-1 has “exploitable bitumen in place” of 2.45 to 2.77 billion barrels. Economic recoverable bitumen will depend on reservoir characteristics and technical cost.

TDG-1 is expected to be an 80,000 bbl/day upstream-upgrading project, developed in two 40,000 bbl/day, steam assisted gravity drainage (SAGD) phases and producing light, refinery-ready crudes. The capital cost of the Project is projected to be in the range of \$3.5–4.0 billion (2007 dollars).

3.16. TRU process

The TRU Oiltech technology is a mild thermal reagent-based upgrading process added to heavy crude oil and oil sand bitumen in order to improve viscosity for transfer in pipeline systems.

A bitumen feedstock and our cracking resistant additive are introduced into a non-coking visbreaker where the bitumen is cracked, then sent for distillation. The additive is recovered and the gas oil is sent for blending. H₂S rich off-gases from the non-coking visbreaker and distillation tower functions are re-directed for potential process fuel supply. Next, the gas oil distillation residue is sent to a solvent deasphalter where the residual extractable (deasphalter pitch) are separated from the asphaltenes. The solvent is recovered and the deasphalter extract is sent for blending with the gas oil. The resulting metal free, low sulfur, ultra high yield blend is a premium synthetic crude oil [58,59].

3.16.1. History

In the third quarter of 2008, the Company Rival Technologies Inc. (RVTI) commenced preliminary engineering and design for the pilot plant and construction. The TRU process has been proven in the laboratory by the Alberta Research Council, and the intellectual property is protected by a provisional patent. The next step is a fully functional pilot plant [59].

3.16.2. Patent

U.S. patent WO/2008/124912 issued on 10-23-2008 titled “Method of upgrading heavy oil crude”.

3.16.3. Current situation

RVTI has recently (2012) started its first license agreement relating to commercial development and use of TRU Technology. This agreement provides the Licensee with worldwide rights to TRU Technology when used in combination with a separate hydrotreating technology; and allows Rival to continue to develop and license TRU as a standalone technology to other oil producers and refiners. This first license will help advance TRU Technology to commercial use, and provide revenue to Rival through payment of license fees and royalties. RVTI is now focused on licensing TRU Technology to oil producers and other potential users. Rival is also pursuing

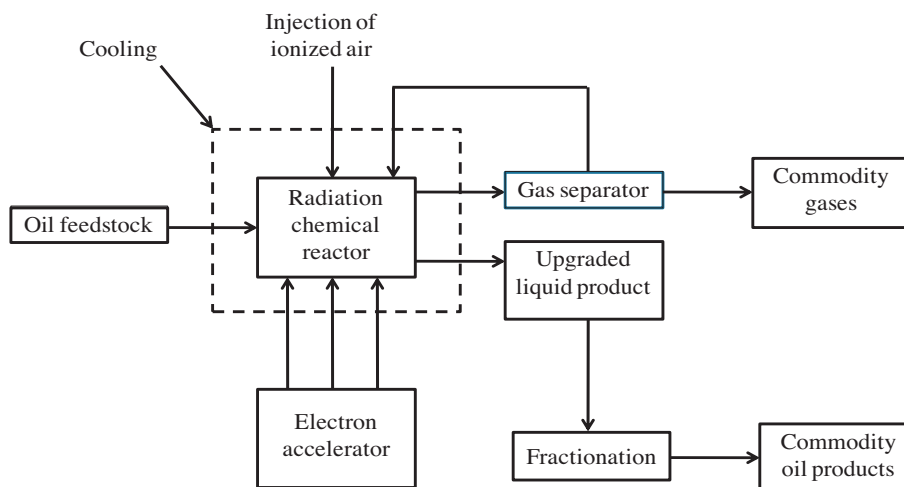


Fig. 18. Block diagram of the PetroBeam process [62].

a financing that will allow it to complete additional testing, finalize its worldwide patent and develop its own continuous feed pilot plant.

3.16.4. Results

Preliminary results show decreased sulfur content 67% and reduced the total acid number 88% for heavy crude oil.

3.17. Petrosonic process

The Petrosonic process developed by Sonoro Energy Ltd., consists of a first phase of rapid de-asphalting of oil that is expected to increase the API approximately 6–10 degrees, reduce sulfur and metal by 40% and lower viscosity by 99%. The second phase of the process utilizes a chemical oxidation process which can upgrade oil by an additional 6–10°API. The final phase is the solvent recovery; the recovered solvent is reused at the solvent de-asphalting stage to complete the closed loop on the Petrosonic upgrading process. A block diagram of the overall process is shown in Fig. 17.

The main advantage of this technology originated in the use of its sonic reactor technology and the unique cavitation and enhanced mass transfer effects that it provides. The sonic reactor, using its patented low-frequency/high-energy/high-amplitude reactor design, allows for significant improvement in the mass transfer efficiency of the solvent de-asphalting step [60,61].

3.17.1. Patents

WO/2009/111871 A1, (Sep 2009) “Method for treating heavy crude oil”, assignee to Sonic Technologies Solutions Inc, Vancouver, CA.

3.17.2. Current situation

Sonoro Energy is commercializing its patented sonic generator and related technologies through wholly owned subsidiaries and joint ventures.

The Company has commenced commercialization of the Petrosonic process through a 1000 barrels per day (bpd) joint venture (60% Sonoro) in Albania. Other commercial applications of this process include converting waste fly ash from coal-fired power stations into a cement substitute and the separation and extraction of oil sands from oil.

3.18. PetroBeam process

PetroBeam process is a cold cracking technology, which uses high-energy electrons instead of energy-intensive catalysts to reduce the viscosity of heavy oil. The process uses electricity rather than heat generated from natural gas to effect changes in the crude oil and do not require expensive catalysts. The process is also more environmentally benign than thermal and chemical-based methods now in use. A block diagram of this process is shown in Fig. 18.

3.18.1. History

E-beam processing has a 50 years history of industrial success in a wide range of applications. E-beam processing is safe and economical and has been used in a wide range of commercial applications for many decades.

PetroBeam plans the migration of this industrial process, applying it to the midstream and downstream sectors of the petroleum industry. The technology has been studied and researched by its scientists for over 15 years. Laboratory scale tests have shown that heavy components, such as asphaltene, in crude oil and bitumen are disrupted and partially decomposed by e-beam processing.

The company had expected to complete its next stage of development using its 75 bbl/day rate pilot facility by mid-2009 and further demonstrate the process in its 1000 bbl/day pilot plant, which was expected to be completed by the end of 2009. However, although they made most of progress from 2007 to 2009 the slumping economy has forced them to greatly slow their work and focus on patent instead of scale-up [62,63].

3.18.2. Patents

US 8,192,591 B2, (Jun 2012) “Self-Sustaining cracking of hydrocarbons”, assignee to Petrobeam, Inc., Raleigh, NC (US). International publication number: WO 2007/070698 A2 (Jun 2007) “Self-sustaining cracking of hydrocarbons”. The Mexican patent (MX/a/2008/007791) is proceeding and expecting it to be issued.

3.18.3. Current situation

The process has been tested successfully on heavy oil from the Athabasca oil sands and on heaviest from other areas of the world.

PetroBeam expects to build, operate and license its process to producers and refiners. Since foundation, it has raised more than \$9.5 million in capital, including \$6 million equity investment from Ion Beam Applications. The Company has been working in partnership with IBA to develop the commercialization plans for a

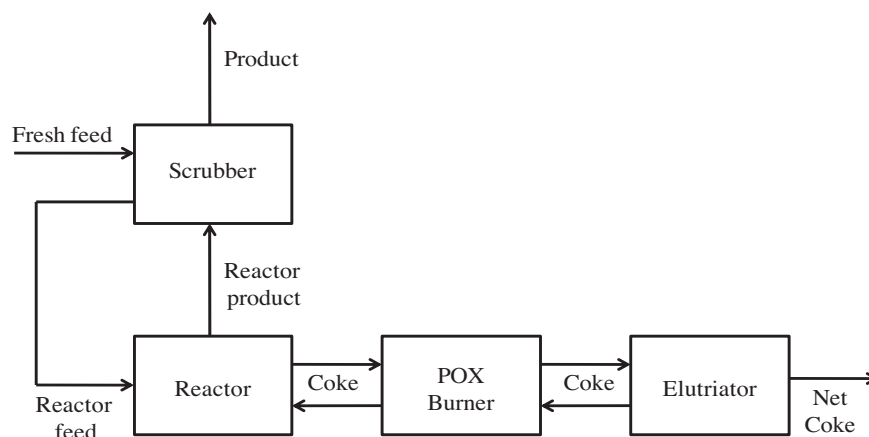


Fig. 19. Block diagram of IYQ process [64].

\$30 million 10,000 bbl/day facility. The primary component of the facility is the electron beam accelerator, the TT1000 Rhodotron[®] produced by IBA.

3.19. I^YQ process

ETX's fluid bed coking reactor is a revolutionary technology developed to convert heavy crude feedstock, such as Athabasca bitumen, into a bottomless synthetic crude oil. ETX systems have combined cross flow fluidized bed technology with thermal cracking experience, leading the design as I^YQ process. Fig. 19 shows a scheme of this process where hot solids are introduced at one end of the reactor, flowing by gravity through the vessel as a fluidized bed. Pitch is introduced into the bed, reacting to produce liquids products, coke and non-condensable gas. The coke remains on the fluidized solids, while the fluidization gas and other reaction products are collected overhead. The solids leave the reactor at a lower temperature than they were fed, since heat in the solids provides the energy required to carry out the chemical reactions [64,65].

A major advantage of the designs is that the mixing characteristics of the reactor severely reduce short-circuiting of unreacted feed compared to competing fluidized bed technologies.

3.19.1. History

The technology has followed a rigorous gated development process over the past 10 years. Having successfully completed a 1 bbl/day pilot with its claims intact, the technology is ready for a commercial demonstration at a 1000 bbl/day scale.

3.19.2. Patent

US 2012/0211402 (August, 2012) "A method for converting a liquid feed material into a vapor phase product", assignee to ETX Systems Inc.

3.19.3. Current situation

The planned completion date for the full-scale demonstration is 2015.

3.19.4. Results

ETX technology is capable to provide the following key benefits to the primary upgrading market: maximize saleable liquid products, minimize low-value by-products, substantial capital and operating cost advantage, reduced environmental footprint including GHG emissions, suitable for field upgrading and integration with thermal production, and produce pipeline stable SCO with no diluents required to transport.

3.20. EADIEMAC process

Eadie Oil Inc. licenses the EADIEMAC Process as a practical solution to the need for field upgrading units, onshore or offshore. This thermal process is designed to change heavy crude oil by visbreaking into much lower viscosity higher value oil [66].

3.20.1. History

Eadie Oil Inc. has successfully run a 1.5 bbl/day pilot unit.

3.20.2. Patent

US 5,110,447 (May 1992) "Process and apparatus for partial upgrading of heavy oil feedstock", assignee to Kasten, Eadie technology Ltd., Edmonton Canada.

3.20.3. Current situation

Eadie Oil Inc is currently working to commercialize the EADIEMAC Process and related proprietary processes in field units from 2500 bbl/day up to larger central plants of 20,000 bbl/day capacity or more.

3.20.4. Results

The results of a continuous run using a 13.6°API "Fort Kent" feedstock in a 1.5 bbl/day pilot plant located at the Alberta Research Council, report 17.0°API and reduction of viscosity from 14,500 to 133 cps.

3.21. CPJ process

Upgrading is a process of changing heavy crudes and bitumen from oil sands to light, less viscous, higher value synthetic crude oil. The comparison with delayed coking (DC) points out that selectivity and yield of the CPJ process are far superior to DC [67].

3.21.1. History

The CPJ process has been proven over several years since 1991 at a pilot scale of 1–2 BPD and at a semi-commercial scale of 50 BPD. Wesco engineers integrated the CPJ process in its facility in Conroe Texas in 2001. A larger demonstration plant was built in 2003 which confirmed the ability to upscale the technology while maintaining a superior product. Since 2004, Wesco has successfully upgraded over 250 runs of 20 different bitumen crudes from Fort McMurry, Alberta Canada.

The Advantages of the CPJ Process and Technology comprise: upgrading of heavy oil and bitumen in the field or into the pipeline producing a higher value crude oil, provides gravity and pipeline capacity boosts, upgrading without coke production with higher

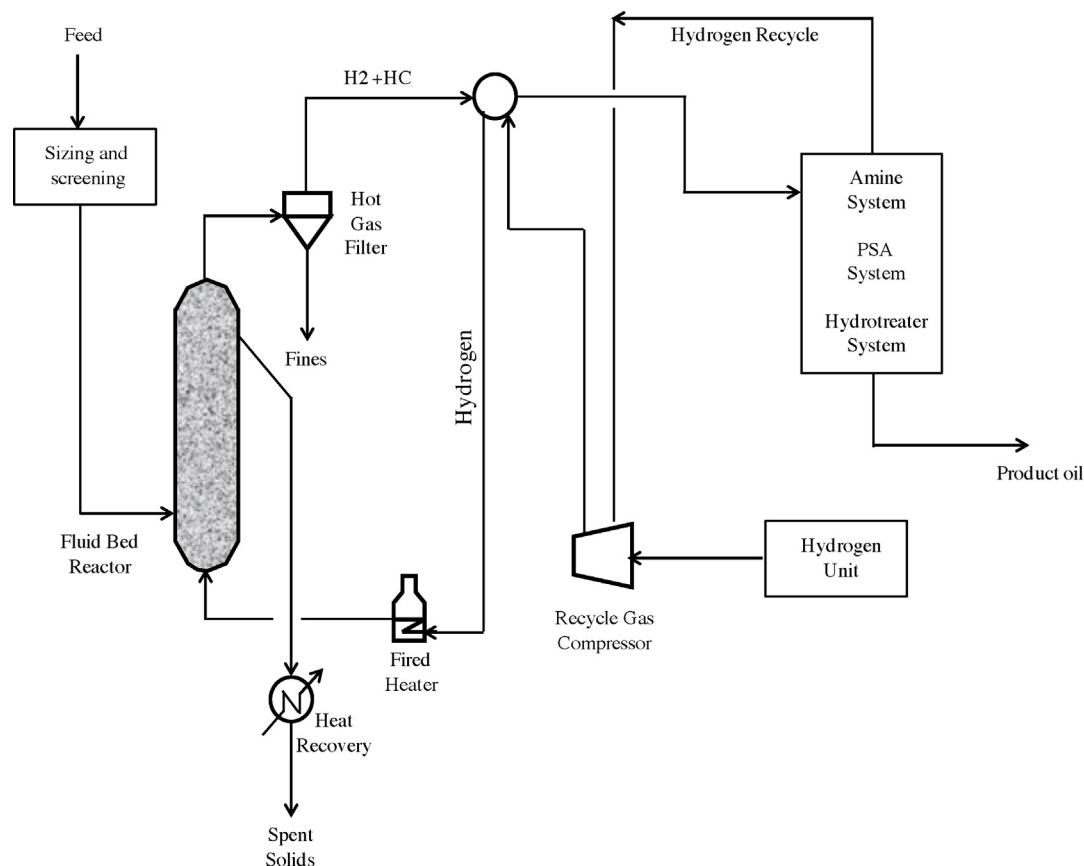


Fig. 20. Scheme of Chattanooga process [68].

liquid yields, reduces or potentially eliminates need for diluents, upgrades heavy crudes to stable lighter oils that can be optimally processed by bottoms constrained refineries.

3.21.2. Patent

US 6,989,091 B2 (Jan 2006) "Deep conversion combining the demetalization and the conversion of crudes, residues or heavy oils into light liquids with pure or impure oxygenates compounds", assignee to World Energy Systems Corporation, Scottsdale, AZ.

3.21.3. Results

CPJ process was found to upgrade as much 86% of the crude to lighter liquids. Test using 8.77 °API vacuum residue yielded 51% gasoil, 23% diesel and 10% kerosene or naphtha for an average gravity of pipeline grade 20.3 °API, leaving only 16% as sulfur laden pitch to make asphalt or burn for process heat.

3.22. Chattanooga process

The Chattanooga process is a continuous process for producing synthetic crude oil from oil bearing materials such as oil shale, oil sand or bitumen. These materials are treated in a fluidized reactor operating at elevated pressure and temperature in the presence of hydrogen gas only. This process combines all extraction, separation and upgrading steps into one continuous process.

Fig. 20 shows the Chattanooga process. The main equipment of this technology is the pressure fluid bed reactor and associated fired hydrogen heater. The reactor can continuously convert oil via thermal cracking and hydrogenation into hydrocarbon vapors while removing spent solids [68].

3.22.1. History

The Chattanooga process has been developed in two experimental plants, Pilot Plant I commissioned in 2000 and Pilot Plant II commissioned in 2004. This process has the ability to remove 99.8% of all sulfur.

3.22.2. Patent

US 6319.395 B1 (Nov 2001) "Process and apparatus for converting oil shale or tar sand to oil" assignee to Chattanooga Corporation, Bradenton, FL (US).

3.22.3. Current situation

Chattanooga Corp. is preparing to design, construct and operate a demonstration facility as the next step in the commercialization process. In parallel, Chattanooga will expand its relationship with selected energy producers, government agencies, financial institution and investors to promote and establish commercial-scale facilities and create licensing and royalty agreements.

3.22.4. Results

The Chattanooga Process for bitumen proven in Pilot Plant I testing conducted at the National Centre for Upgrading Technology (NCUT) in Devon, Alberta, Canada produced 32–36 °API synthetic crude oil from bitumen.

Pilot Plant II testing conducted at NCUT achieved yields 51 gallons/ton for Colorado oil shale; comparable results for Kentucky oil shale were achieved. These results were used to verify that the Chattanooga Process is commercially viable both for Eastern and Western oil shale.

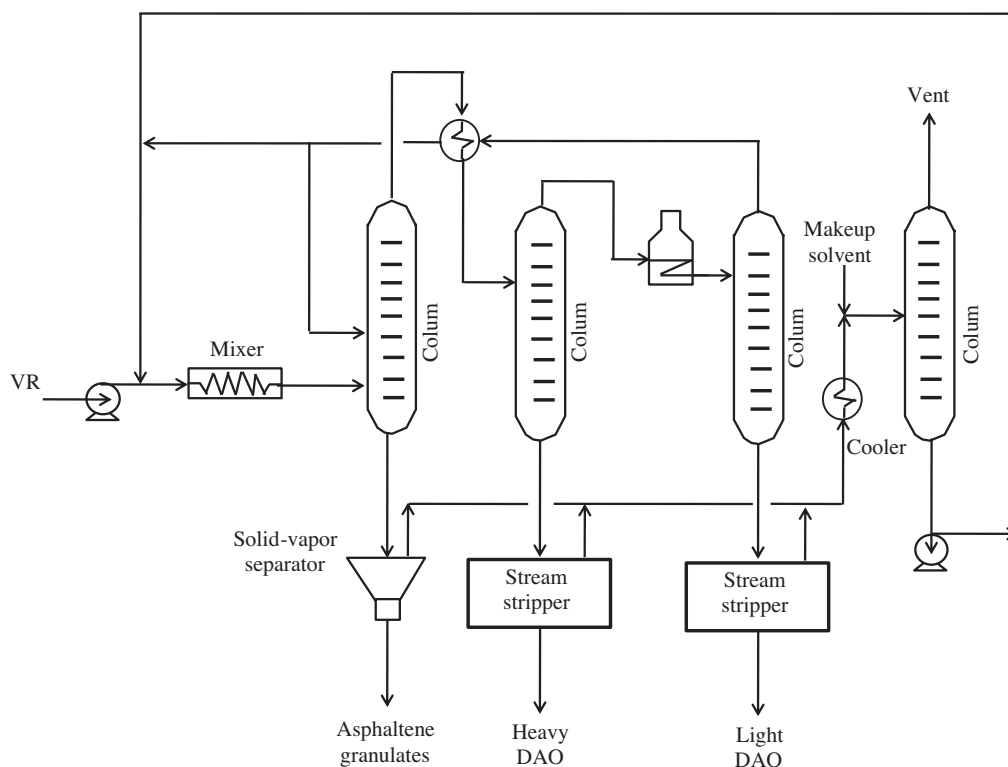


Fig. 21. Scheme of SELEX-Asp process [69].

3.23. SELEX-Asp process

Selective asphaltene extraction (SELEX-Asp) is a novel separation process that is capable of removing the contaminants from oil sands bitumen. The use of SELEX-Asp will allow the oil sand operators to produce a clean and pipeline transportable feedstock which is suitable for conventional refinery processes.

SELEX-Asp is a supercritical solvent extraction process (Fig. 21). The principle of supercritical solvent extraction for a petroleum system is based on the combination of an anti-solvent with multicomponent phase equilibria. SELEX-Asp has been enhanced to selectively remove the solid asphaltenes from residuum and to recover the desirable oil components from residuum. This includes smaller and simpler extractor design, higher energy efficiency, fewer solvent requirements as well as deeper and cleaner separation. The selection of process provides the highest theoretical liquid yield of desirable oil components in the form of asphaltenes-free resid [69,70].

3.23.1. History

The technical basis of SELEX-Asp has been investigated and validated in various scales of experimental setups. A comprehensive feedstock process ability database has been developed for the world's major heavy crudes such as Canadian bitumens, Venezuelan extra-heavy oils, Arabian Heavy, and Chinese heavy oils [71,72].

Extensive bench-scale laboratory tests were conducted to determine the optimum SELEX-Asp operating conditions for the Panjin refinery's vacuum residue. The process was carried out in a 1-bbl/day continuous-flow pilot unit for 2 days.

The success of SELEX-Asp in recovering a substantial amount (78.45 wt%) of high quality DAO from vacuum residue prompted PetroChina to construct a 500-b/d field demonstration unit at the Panjin refinery. The process operating conditions were similar to those of the pilot plant.

3.23.2. Patents

US 7,597,794 B2 (Oct 2009) "Deep separation method and processing system for the separation of heavy oil through granulation of coupled post extraction asphalt residue" assignee to China University Petroleum, Beijing, China.

3.23.3. Results

The vacuum residue contained 19 wt% Conradson carbon residual and 242 wppm metals, SELEX-Asp removed 21.55 wt% of vacuum residue as asphaltenes which contained 47% CCR and 1000 wppm metals, which accounted for 56% and 90% of total CCR and metals, respectively, in the vacuum residue.

4. Comparison of technologies

Emerging technologies have discussed different process alternatives for upgrading heavy crude oil. In order to satisfy the properties for transportation, some of these processes are used for partial upgrading of oil and others can be adapted for total upgrading with high conversions and significant removal of impurities such as sulfur, metals, asphaltenes, etc.

Processing routes of evaluated emerging technologies include: the addition of hydrogen, carbon rejection, ultrasound, solvent extraction, electron accelerator and combinations between them.

Some emerging technologies have reported sufficient information to make a comparative evaluation, while others indicate only the basic concept with a few results at bench scale or pilot plant.

The results in each emerging technology are dependent on the type of oil feed and the test level. Since most technologies have processed different kind of feed and test level, it is difficult to perform a quantitative comparison through mass balances.

For this reason in this work, two types of qualitative comparison have been performed, the first is based on the process route and the second with the property characteristics of each emerging technology and those with enough information.

Process Route	bench scale	Pilot plant	Demonstration plant
Others	Petrosonic Petrobeam I ^Y Q		
Extraction	Selex-Asp		
Ultrasound		Nexgen Sonocracking	
Carbon rejection	HUOP Writte Value creation TRU CPJ EDIAMAC		HTL Viscositor
Hydrogen addition	Wildcatter Chattanooga	Genoil CCU	HCAT IMP HRH ENI Uniflex
	bench scale	Pilot plant	Demonstration plant
	Test level		

Fig. 22. Test level as function of process route of emerging technologies.

Table 11
Comparison of emerging technologies for heavy oil upgrading based on the process route.

	Hydrogen addition	Carbon rejection	Ultrasound	Extraction
Quality of upgrading crude oil	High	Low	Low	Medium
Yield of upgrading crude oil	High	Medium	Medium	Medium
Complexity	High	Medium	Low	Medium
Flexibility	High	Medium	Low	Low
Development level	Medium	Medium	Low	Medium
Investment cost	High	Medium	Medium	Medium
Operating cost	High	Low	Medium	Low

Table 11 shows a comparison of the most important properties of emerging technologies for upgrading crude oil such as: quality, yields, complexity, flexibility, development level, investment costs and operating costs as function of the processing route.

From the table, the following comments can be made:

- The hydrogen addition processes have better quality and yield of upgraded crude oil, but high investment and operating costs.
- The carbon rejection processes, ultrasound and solvent extraction have investment and operating costs more attractive than hydrogen addition but lower oil quality and yields of upgraded crude oil.
- Catalytic or hydrogen addition high-severity processes can be mainly used for full upgrading crude oil, while carbon rejection, ultrasound and solvent extraction can be applied for partial upgrading crude oil to transport. Hydrogen addition working at moderate severity can also be used for partial upgrading.

The upgraded crude oil obtained with hydrogen addition technologies can be mixed with virgin heavy oil in the required volume ratio to achieve the specifications for transportation, thus the volume of crude to be transported will be greater than that produced from one partial upgrading technology. The selection of the best technology for transportation of crude oil will require a technical and economic evaluation considering the level of development of each one.

Fig. 22 shows the highest test level of different technologies depending on the processing route. This illustration points out that:

- Most emerging technologies have produced experimental results at a laboratory scale.

- Technologies for the route of hydrogen addition have experienced higher test level (demonstration plant) followed by carbon rejection.

Important features such as the API gravity increase and the volumetric yields of the upgraded crude oil are required to evaluate an emerging technology. Fig. 23 shows API gravity differential versus volume yields of upgrading crude oil of emerging processes. The following observations can be made:

- In general, carbon rejection processes have a range of volumetric yields of 65–95% and the API increase is in the range of 7–19°.
- The hydrogen addition processes supply an increase of API gravity in the range of 10–25 and volumetric yields between 100% and 108%.

Another important aspect to evaluate emerging technologies is economics, particularly the investment and operating costs; Fig. 24 shows the investment and operating costs associated to emerging technologies. It is observed that:

- The emerging technologies based on ultrasound involve lower investment and operating costs.
- The carbon rejection processes exhibit similar investment cost with different values in operating costs derived from the process characteristics.
- The hydrogen addition technologies have higher investment and operating costs.
- The IMP upgrading technology account for investment and operation costs very similar to those of carbon rejection technology

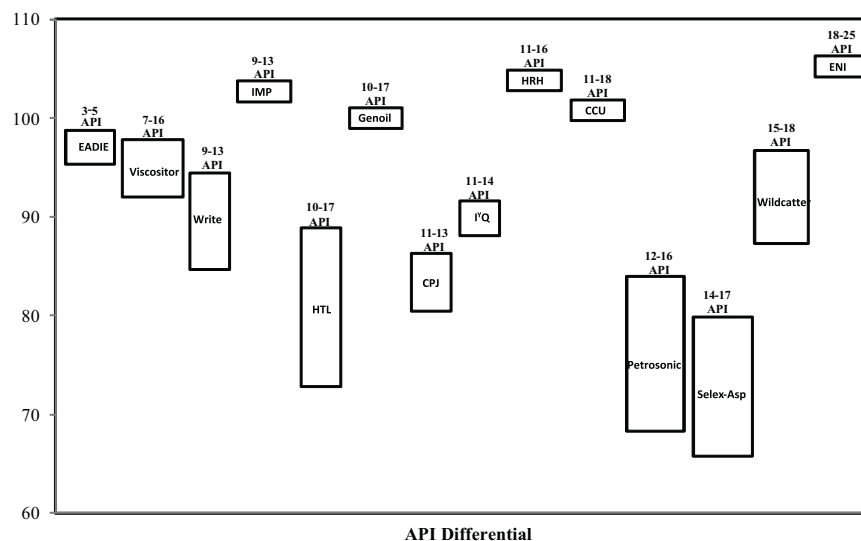


Fig. 23. API differential as function of volumetric yield of upgraded crude oil.

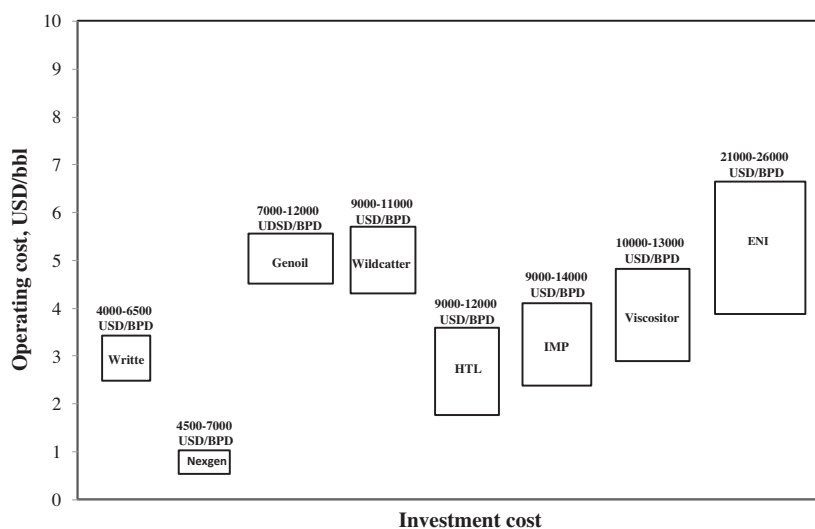


Fig. 24. Investment and operating cost of emerging technologies.

because it operates at moderate reaction conditions and conversion.

5. Final remarks

The increased interest in the upgrading of heavy and extra-heavy oils is due to the depletion of light crude oil (conventional oil) in the petroleum production countries, which has forced researchers and refiners to develop new technologies to convert heavy petroleum into more valuable products. The main objective in such developments has been to increase the API gravity and reduce the impurities content, along with high selectivity toward gasoline and middle distillates. Detailed information of such technologies is quite difficult to find because most of the work is at the laboratory scale or in the scale-up level, and the companies keep it as secret.

The emerging technologies are either in the development stage or tested at different experimental scales (laboratory, bench, pilot plant, and semi-commercial). Because the details of such processes are limited, it is complicated to infer any conclusion about their commercial applicability and advantages/disadvantages among

them. Thus only basic information can be obtained from the Internet and in the open literature.

Emerging technologies have definitively attracted the attention of the refiners. Feasibility studies are being carried out by many petroleum companies to make proper decision about what technology to use. Most of them may be good for one feedstock but not for others because of the great variety of properties of the different crude oils.

The development of emerging technologies for heavy oil upgrading has been traditionally aimed toward the routes of carbon rejection and hydrogen addition. Emerging processes based on hydrogen addition have shown higher development performing tests at demonstration scale with great potential for installation of commercial plants in the middle and long term. Emerging processes based on carbon rejection exhibit low yields of upgraded crude oil (75–95 vol%) and volatile fractions requiring additional processing. While hydrogen addition based technologies achieve more than 100 vol% yields and stability of the fractions of upgraded crude oil.

The investment and operating costs of the hydrogen addition processes are greater than those of carbon rejection processes due to its complexity that depends on the operating conditions, type

of reactor and flexibility in operation. Processes that operate at moderate reaction conditions with low conversion, such as the IMP process, produce low sediments and significantly favor the investment costs compared with other emerging technologies of hydrogen addition.

High-severity hydrocracking processes yield high content of sediments, leading to be impractical and expensive when upgrading heavy oils. Emerging processes of carbon rejection yield by-product of low commercial value such as petroleum coke, with the need for additional process equipment and large areas required for handling and disposal within the same plant.

There is unfortunately not a general rule that can give a solution to all refineries. There are many factors such as oil and product prices, market trends, local needs, physical and chemical properties of the available heavy oil and residua, refinery configuration, among others that are all involved and must be taken into consideration to define a specific upgrading process scheme. Therefore, each refinery will define its own scheme for heavy oil upgrading. In other words, there is no one single upgrading solution that is suitable for all refineries.

The successful selection of an emerging technology for heavy crude upgrading should consider at least the degree of development of the process, the type and properties of the feedstock to be processed, quality of upgraded crude oil, complexity and flexibility of the process, operating conditions in the reaction system, availability or processing of by-products and the profitability of the process.

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