

HS-FCC for Propylene: Concept to Commercial Operation



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The Fluid Catalytic Cracking (FCC) process has undergone a long evolution of hardware and catalyst changes from bed cracking with amorphous catalyst to short contact time riser cracking with sophisticated zeolite catalyst systems. Improvements to the process have provided a wide degree of flexibility to selectively target production of distillates or gasoline or propylene from VGO and residue feeds thereby making the FCC the most widely used conversion process.

More generally, the objective of the process is to produce high valued products and increasingly this includes fuels and petrochemicals, including light olefins and aromatics. At present, over 30% of the worldwide propylene supply comes from FCC related processes (FCC, RFCC, DCC). Fluctuating product demand and price have caused most new project developers to demand product flexibility for long term profitability and process integration with

petrochemical facilities for added synergy and cost savings.

In order to respond to these market demands, a new High Severity down flow FCC (HS-FCC™) process



Figure 1. HS-FCC Semi-Commercial Unit



has been developed by an alliance of Saudi Aramco, JX Nippon Oil & Energy (JX), King Fahd University of Petroleum and Minerals (KFUPM) culminating in a 3,000 BPD semi-commercial unit in operation since 2011 in Japan. The process provides high light olefin yield from a wide variety of feedstocks utilizing high severity reaction conditions, a novel down flow reaction system, and proprietary catalyst. HS-FCC™ is now available for license from a Global Alliance by Axens and Technip Stone & Webster Process Technology.

Features of HS-FCC

FCC utilizes acidic zeolite catalysts to crack heavy hydrocarbons into lighter fuels such as gasoline and distillate, and under more severe conditions into lighter olefins such as propylene and butylene (and to a lesser extent ethylene). Complex secondary reactions that can degrade the primary products to less valuable components should be limited to retain product selectivity and refinery profitability. For HS-FCC, the objective is to not only improve the selectivity for normal fuels production, but also to maximize the potential of light olefin and petrochemical production at high severity. HS-FCC provides a total system to maximize product selectivity and, in particular, propylene yield. Three key elements are required to attain this objective:

- Highly selective catalyst and additive system;
- Optimized reaction conditions; and
- Down flow, short contact time reaction system with rapid catalyst separation.

The balance of these elements and realization at commercial scale is the key to success.

Catalyst System

The catalytic cracking reaction pathways are complex, with primary formation of olefinic products and parallel bi-molecular hydrogen transfer reactions leading to paraffin formation and aromization of naphthenes. Managing the acid site density of the

catalyst can suppress hydrogen transfer and isomerization reactions to maximize olefins production. When coupled with ZSM-5 pentasil cracking catalyst additives, the increased olefins in the gasoline cut can be selectively cracked to further increase the propylene yield.

The HS-FCC catalyst uses a high USY zeolite content system with very low acid site density formulated to minimize hydrogen transfer reactions for high olefin selectivity and low coke and gas selectivity. This catalyst has been shown to be more effective for propylene production when coupled with ZSM-5 additives as shown in Figure 2. Commercial catalysts and HS-FCC catalyst exhibited a similar trend in gasoline and propylene yield as a function of conversion (severity), but the customized HS-FCC catalyst was much more effective in 'feeding' the ZSM-5 additive with more olefins, and more accessible linear olefins, to produce more propylene.¹

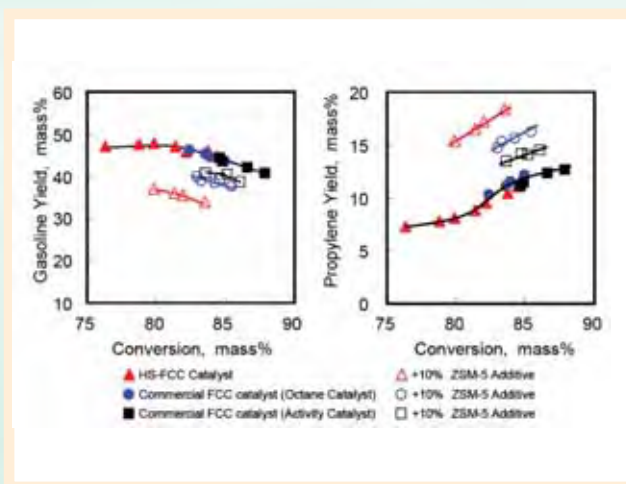


Figure 2: Proprietary catalyst boosts ZSM-5 effectiveness for more propylene

Optimized Reaction Conditions

When targeting maximum petrochemicals production, HS-FCC operates under more severe conditions than conventional FCC. The main reaction conditions applied and the advantages and

⁽¹⁾ Maghrabi, A., "HS-FCC Process for Maximized Propylene Production", 10th Annual Saudi-Japanese Symposium on Catalysis in Petroleum Refining and Petrochemicals, Dhahran, 2000.

challenges presented are summarized below:

	Advantages	Challenges
High Temperature	High conversion & olefins selectivity	Increased thermal cracking, product degradation
Short Contact Time	Reduced secondary reactions & thermal cracking	Reduced conversion, rapid mixing and separation required
High Catalyst / Oil	Increased catalytic cracking	Very high catalyst circulation, uniform flow, mixing, & separation

High reaction temperature coupled with short contact time increases the primary reactions towards olefins while limiting the unwanted secondary reactions of hydrogen transfer and thermal degradation. A consequence of the increased severity and short time is the need for higher catalyst

circulation (Catalyst to Oil mass ratio or C/O) to provide the required heat to the reactor and sufficient catalyst activity to achieve high conversion at short contact time. The range of operating conditions for a conventional FCC and HS-FCC are summarized in Table 1.

	FCC	HS-FCC
Reaction T, C	500-550	550 - 650
Contact Time, s	2 - 5	0.5 - 1.0
Catalyst / Oil, wt/wt	5 - 8	20 - 40
Reactor Flow	Up Flow	Down Flow

Table 1 - Typical operating conditions for FCC and HS-FCC

Down Flow Reaction (DFR) System

The specific reaction conditions with very high C/O result in certain challenges in a conventional up flow FCC riser reactor system where the catalyst required for the reaction is lifted up the reactor pipe or riser by the vaporized and cracked hydrocarbon feed. In up flow fluid-solid systems, the solids or catalyst are conveyed upwards against the force of gravity by drag forces from the rising gases (hydrocarbons). As a result, all riser reactor systems have varying degrees of catalyst back-mixing and reflux along the walls, particularly in the feed injection or catalyst pickup zone at the bottom of the riser reactor. At very high C/O significant back-mixing is unavoidable. This problem is overcome in a down flow reactor (DFR) where both the catalyst and feed flow downwards together (Figure 3).

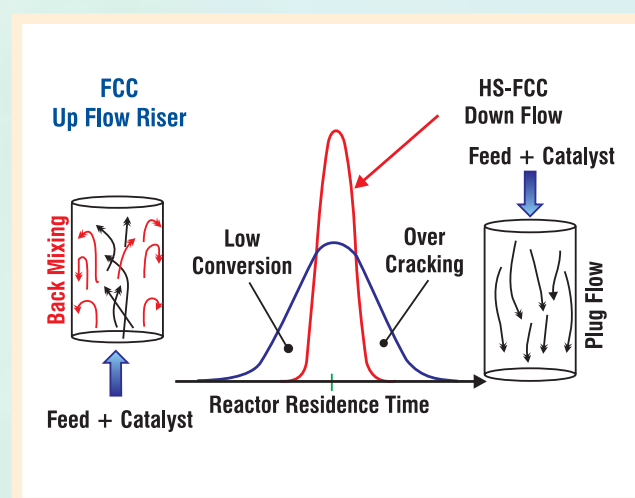


Figure 3: Up Flow vs Down Flow residence time profiles



Down flow fluid-solid reaction systems have been of increasing interest in recent years to achieve plug flow reaction conditions as summarized Cheng². When plug flow conditions are achieved, more selective primary cracking results in greater selectivity. FCC pilot work demonstrating the effects of short contact time and down flow have been reported by Del Poso³ and Abul-Hamayel⁴ as shown in Figures 4 a-b. The general trend reported is that of greater gasoline selectivity at short contact time down flow with a maximum yield achieved at a higher conversion level. This effect is seen in Figure 4a where the maximum gasoline yield is about 5 wt% higher in the down flow system. When olefins are of interest, the more selective down flow reaction environment can produce substantially more light olefins (C2-C4) at the same gasoline yield compared to a conventional up flow system (Figure 4b).

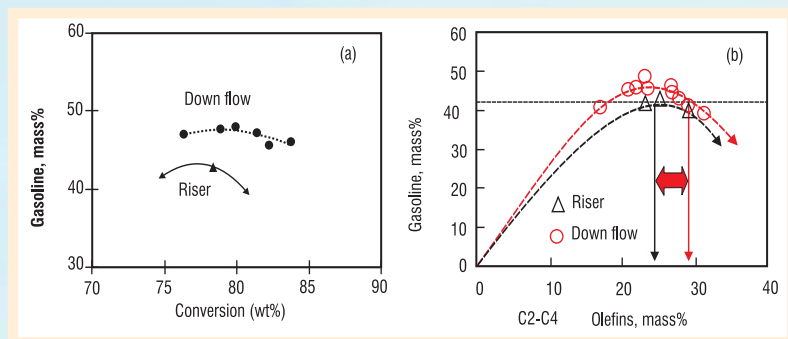


Figure 4: Selectivity benefits of a down flow reaction system (4)

Although the idea of controlled high severity, short contact time down flow reaction, has been considered for some time, achieving this successfully at commercial scale has been elusive. Extensive pilot work at the 0.1 BPD scale demonstrated the principle, catalyst system and operating conditions, but did not address how rapid mixing, reaction and efficient catalyst/gas separation can be achieved at large scale with a target residence time on the order of 0.5 sec. At commercial scale, equipment design for very short

contact time with the mechanical integrity to withstand high velocity catalyst circulation in a coking environment requires extensive research, development, and demonstration.

R&D History

The challenges of developing this new technology required a systematic research program undertaken by JX, KFUPM & Saudi Aramco with support of Japan Cooperation Center, Petroleum (JCCP). Early pilot work by both JX and KFUPM in 1996-2000 demonstrated the benefits of high severity operation at controlled short contact time in down flow mode. Aramco became an active participant in the scale up effort to design a 30 BPD demonstration unit. JX conducted large scale, 30 BPD equivalent, cold flow testing of the catalyst circulation loop and reactor-separator equipment to validate the design of the demonstration unit.

The demonstration unit shown in Figure 5 was operated from 2003-2004 at the Aramco Ras Tanura refinery. Results from the demonstration unit validated the HS-FCC concept with good agreement between 0.1 BPD pilot results and 30 BPD demonstration as shown in

Figure 6.^{5, 6}



Figure 5: HS-FCC Demonstration unit

- (2) Cheng, Y., "Downer reactor: From fundamental study to industrial application", *Powder Technology*, 183, 2008.
- (3) Del Poso, M., "Development of Ultra Selective Cracking Technology", *2nd IFP and S&W FCC Forum*, The Woodlands, Texas, 1996.
- (4) Abul-Hamayel, M.A., "Comparison of Downer and Riser Based Fluid Catalytic Cracking Process at High Severity Conditions: a Pilot Plant Study", *Petroleum Science Technology*, 22, 2004.
- (5) Redhwi, H., "Meeting Olefins Demand in a Novel FCC Technology", *18th World Petroleum Congress*, South Africa, 2005
- (6) Okazaki, H., "High-severity Fluidized Catalytic Cracking (HS-FCC) - Go for Propylene!", *20th World Petroleum Congress*, Doha, 2011.

A low sulfur VGO was cracked at high severity in both the pilot and demo units using only the new HS-FCC catalyst without ZSM-5 additive. A very high propylene yield over 10% was obtained along with a very high octane gasoline.

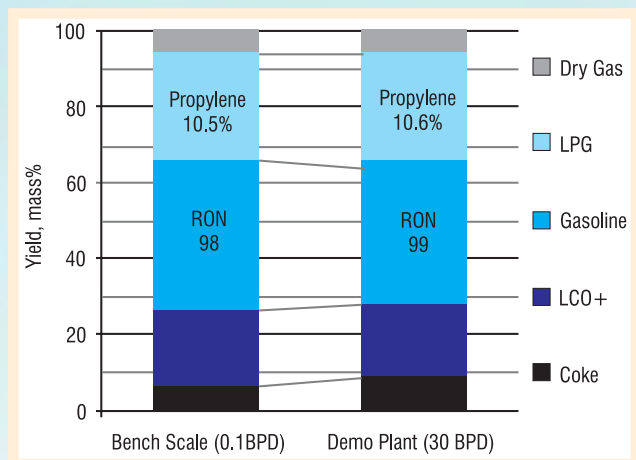
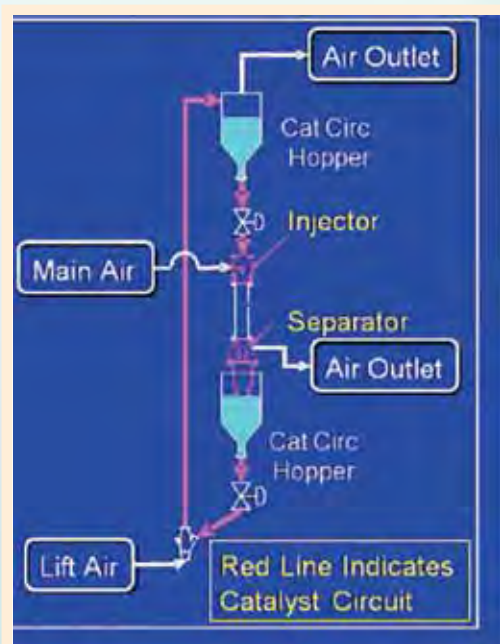


Figure 6: Bench scale vs demonstration scale results on low sulfur VGO at high severity without ZSM-5

Work immediately began on scale-up to a commercial unit. Important lessons were learned concerning equipment design and larger scale cold flow work was undertaken by JX in Japan at the 500 BPD equivalent scale to optimize feed injection zone and separator design - Figure 7. This work was coupled with CFD simulations to assist in larger scale equipment design⁶.



Figure 7: 500 BPD equivalent cold flow testing to scale-up and optimize reaction system



Semi-Commercial Unit

With the successful demonstration of the HS-FCC technology at the 30 BPD scale completed, it was time to look forward to scale-up to a full size commercial unit and plan for future licensing of the technology. Several FCC licensors were interviewed and evaluated before Axens and Technip Stone & Webster Process Technology were selected to assist in the design of a 3,000 BPD semi-commercial unit, plan for a larger commercial unit, and serve as exclusive licensor for the HS-FCC technology, relying on their extensive knowledge in FCC and RFCC design.



A complete 3,000 BPD HS-FCC unit with main fractionator, gas plant, and flue gas treatment was designed for the JX Mizushima refinery. Chiyoda Engineering performed the detailed engineering and construction of the plant (Figure 1) which was put on-stream in early 2011.

Performance trials are on-going to evaluate yields and product properties for widely different feeds and to demonstrate equipment reliability. Preliminary results showing yields for several blends of VGO, Hydro Cracker (HC) bottoms, DAO and Atmospheric

Residue are shown in Table 2. Combined light olefins (C2-C4) yields of 30 to 40 wt% have been demonstrated with 15 to 19 wt% propylene and 4 wt% ethylene. The yield of butenes is similar to propylene and offers opportunities for greater petrochemical integration, including oligomerization and the FlexEne™ configuration for even higher propylene production⁷. These results are without the use of post separator quench injection which will improve olefin selectivity further. The catalyst system continues to be optimized for the various feeds.

	VGO + HC Btm	HDT VGO	VGO + DAO	VGO+ AR
Feed SG	0.845	0.860	0.891	0.921
Reactor T, °C	575	600	580	600
Conv, w%	93.2	88.1	83.0	90.6
Light Olefins, w%	39	40	31	33
C2=	4	4	3	5
C3=	19	20	15	17
C4=	16	16	13	11
C5-220 Gasoline, w%	35	34	34	31
RON	98.5	96.4	98.1	97.6

Table 2: Semi-Commercial Unit Performance

When viewed from a petrochemicals perspective, the ethylene produced becomes a significant boost to the economics. The gasoline also has value beyond fuels with an octane of 98-99, olefin content of 25 to 40 wt%, and 35 to 50 wt% aromatics.

With a controlled short contact time, high C/O and plug flow reaction system, HS-FCC is well adapted to be highly selective for both light and residue feed conversion to petrochemicals.

Throughout the program equipment evaluation, inspection and reliability data have been gathered to guide further development and scale-up to a fully commercial scale of at least 30,000 BPD and up to 120,000 BPD so far. In parallel to this work, CFD simulation of the Down Flow Reactor (DFR) and separator hydrodynamics are being combined with a kinetic model to analyze the results, validate the kinetic models, and enable accurate predictions at commercial scale for future feeds and reactor configurations.

⁽⁷⁾ Ross, J., "(R)FCC Product Flexibility with FlexEne™", WRA Downstream Asia, Singapore, 2011 and www.axens.net website.



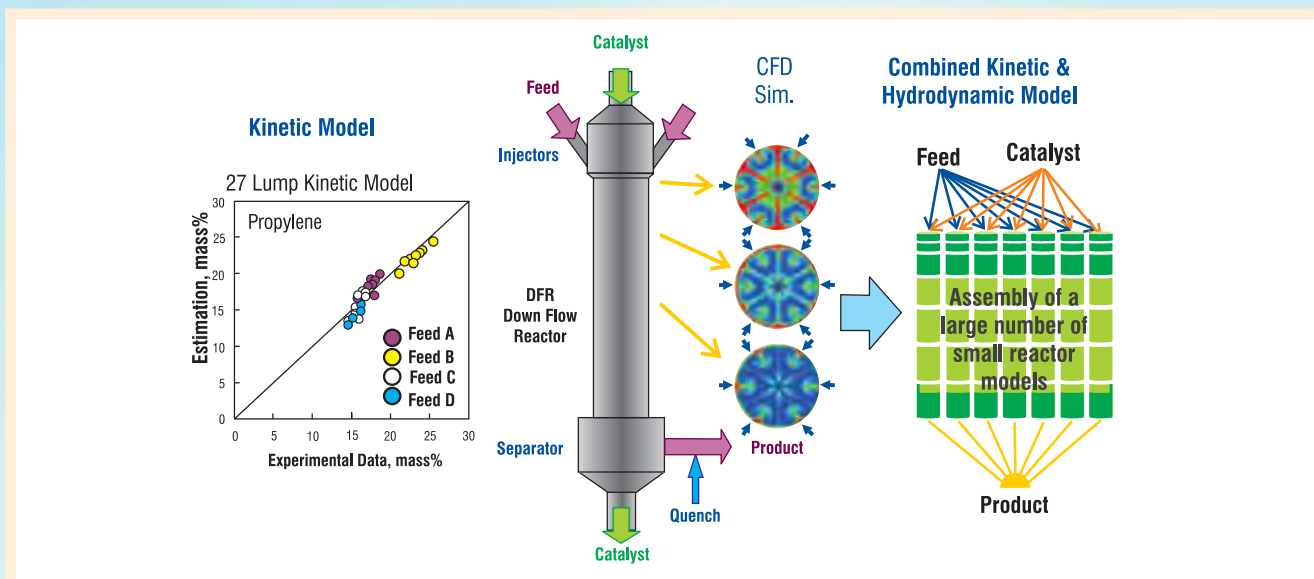


Figure 8: Combined kinetic and hydrodynamic modeling assists design and scale up

Upon completion of the testing program which concluded with a long-term run on residue feedstock, the semi-commercial unit operation was discontinued in 2014. Building on the successful demonstration of the HS-FCC technology benefits, two licenses have been awarded to Axens⁸.

HS-FCC in the Family of Catalytic Cracking Processes

The HS-FCC process expands the operating window of catalytic cracking to encompass heavier feeds and greater propylene potential. Commercial processes for high propylene production from light distillate feeds and residue feeds include DCC⁹, High

Propylene FCC (HP FCCTM), and Resid to Propylene (R2PTM). More severe conditions for residue feeds to attain higher propylene yield has proven challenging in the past due to undesired secondary reactions. High severity combined with an optimized catalyst system and a controlled short contact time DFR reaction system, allows the new HS-FCC technology to provide selective conversion with lower fuel gas production and greater olefin and petrochemicals yield even with heavy residue feeds. Indeed, the selectivity of the system presents opportunities to crack a wide range of conventional and unconventional feedstocks.

The technology mapping by severity and feedstock is shown in Figure 9.

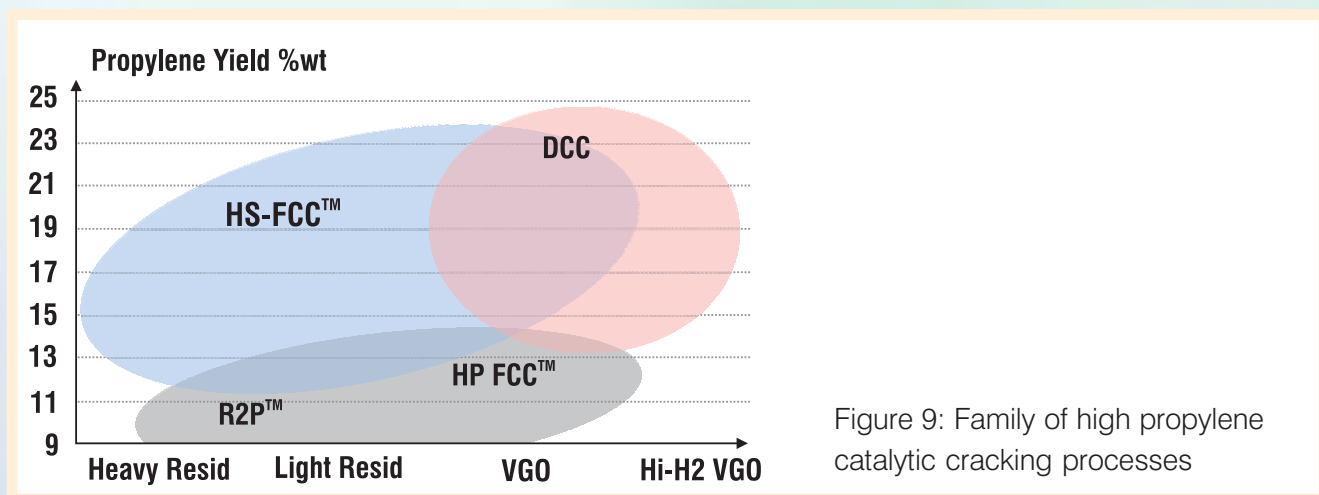


Figure 9: Family of high propylene catalytic cracking processes

⁽⁸⁾ Press release available at <http://www.axens.net/news-and-events/news/359/axens-to-supply-technologies-for-s-oils-residue-upgrading-capacity-expansion-project.html#.VqeqO53LQd>

⁽⁹⁾ Dharia, D., "Increase Light Olefins Production", Hydrocarbon Processing, April 2004.



With the option to operate at conventional severity or high severity, the refiner will have the ability to select an operating mode and feedstock best suited to the prevailing economic conditions. A high severity product slate rich in olefins and aromatics also

makes integration with petrochemicals plants more attractive so that the natural synergy of shared intermediate products and recovery schemes can be realized¹⁰. An example of HS-FCC integration with petrochemical complex is shown in Figure 10.

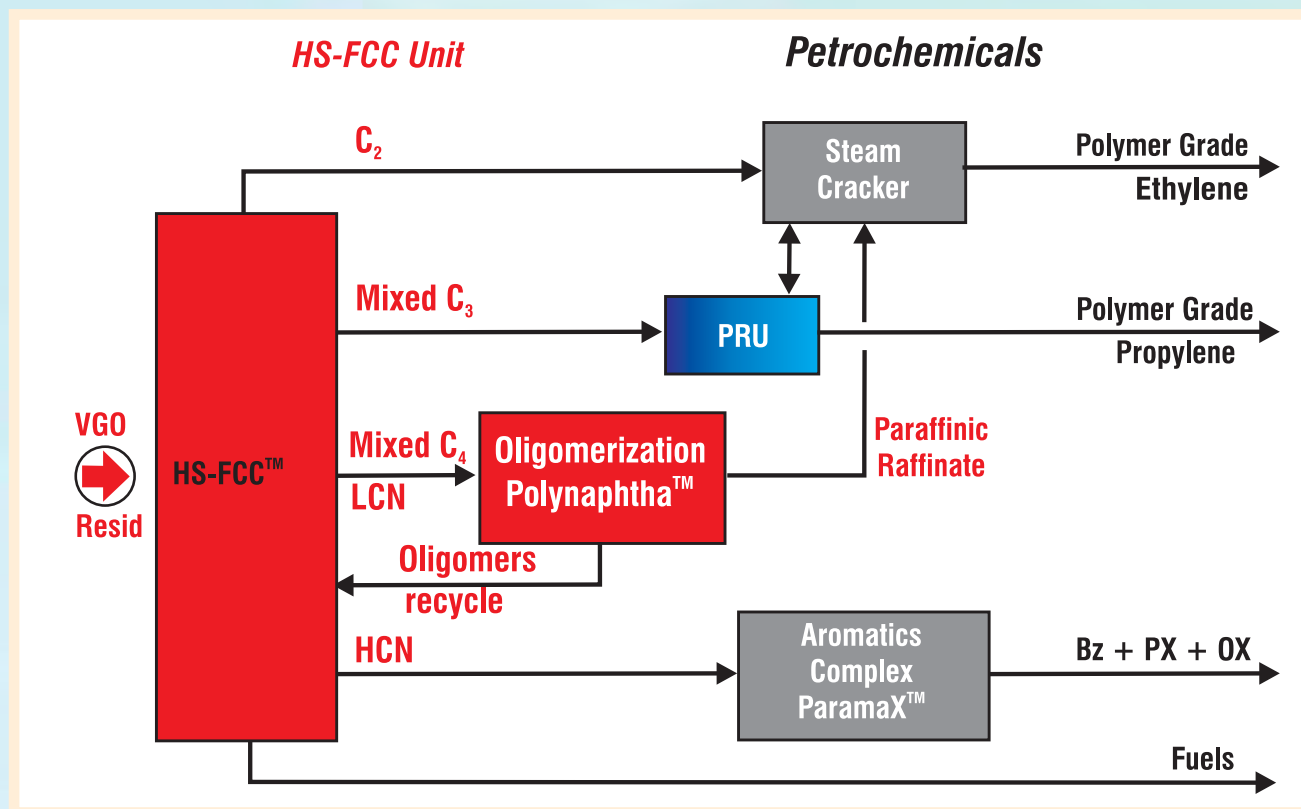


Figure 10: Integrated refinery-petrochemical complex

Global Alliance for Commercialization

The HS-FCC technology is the product of systematic process research, catalyst development, pilot work, 30 BPD demonstration unit testing, and on-going semi-commercial operation and testing at the 3,000 BPD scale associated with the commitment of

several actors. These successful results and the modeling tools developed for further scale up ensured a fast and sound readiness for commercialization of this innovative technology. Axens and Technip Stone & Webster Process Technology are now offering HS-FCC technology on behalf of the HS-FCC Global Alliance team.

⁽¹⁰⁾ Roux, R., "Upgrading of Heavy Cuts into Max Olefins through HS-FCC", JPI Petroleum Refining Conference, Tokyo, 2012 and www.axens.net website.

“Strength does not come from physical capacity. It comes from an indomitable will.”

~ Mahatma Gandhi