Oil-to-Chemicals: Technological Approaches and Advanced Process Configurations

Multi-Client Study Presentation

(Study Completed December 2017)

December 2017

TCGR THE CATALYST GROUP RESOURCES™

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Oil-to-Chemicals: Technological Approaches and Advanced Process Configurations

STUDY COMPLETED!

I. INTRODUCTION

This TCGR multi-client study was completed in December 2017. The study's scope, and specific contents (as depicted in the TofC on pages 11-19) reflect the inputs from a group of "charter" subscribers who indicated their priorities for coverage, areas to be expanded/ deepened and focal points for emphasis in opportunity identification. These are leading industrial integrated refiners and petrochemical producers and users.

There is a need for an objective assessment and detailed technological analysis of the activities directed towards **oil-to-chemicals** pursuits. It is clear that among the leading positions/approaches developed to date, notably by ExxonMobil and Saudi Aramco/SABIC, the full breadth of the potential need may not be addressed because each user will require a unique solution. **Therefore it would be useful to evaluate the olefins and/or aromatic needs of chemical plants in reverse order, back towards the intake of crude oil using different existing and new technologies that may prove more economical at smaller scale than the massive CAPEX schemes currently being proposed by licensors, as solutions.** Beyond these leading activities, numerous independent technology developers like UOP/Honeywell, Axens, CB&I and other majors are working towards combinations of technologies which can achieve a similar objective.

TCGR's assessment, entitled ***"Oil-to-Chemicals: Technological Approaches and Advanced Process Configurations,"*** takes an end-market based approach, using numerous subscriber-defined process configurations, with the objective of documenting the available technologies, plus those in development (including the needed combinations) to maximize the return on conversion based on product slate (chemicals/petrochemicals and specialty/intermediates). Such optimization is required if such practices are expected to be competitive with low-cost thermal cracker routes as well as increasingly large aromatics complexes based on scale.

The results provide practitioners, developers and prospective partners/evaluators, especially the major global chemical (olefins, aromatics) producers, with the tools needed to evaluate technology options in specific case study applications, via mixing and matching unique solutions, in order to determine viability in practice or worthiness of further investment.

II. BACKGROUND

The movement towards the production of chemicals and petrochemicals such as olefins and aromatics directly from crude oil, as opposed to via thermal cracking of naphtha/ethane (for olefins) and via traditional refining reforming (for aromatics), is being driven by numerous

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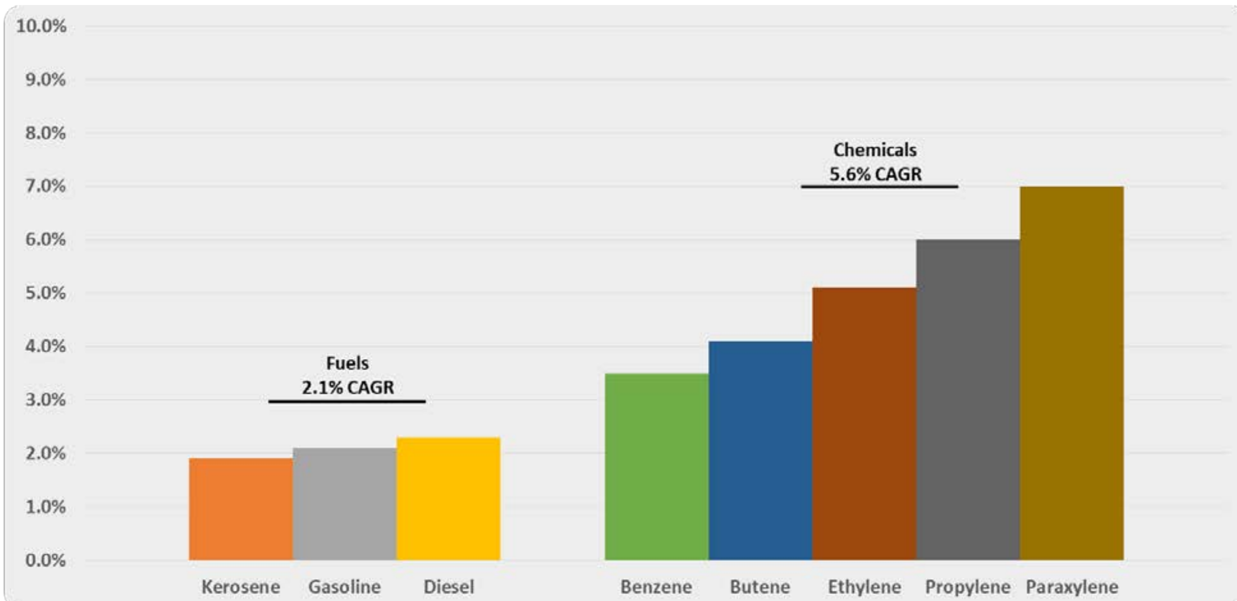
factors, the most important of which is the imbalance between demand for oil-derived liquid fuels (diesel, gasoline) and the more rapid growth in markets for petrochemicals like olefins (ethylene, propylene), aromatics (BTX) and specialty intermediate streams like C_4s and higher olefins. The imbalance has made the idea of using crude as a direct feedstock more appealing for integrated producers of fuels and chemicals as well as direct chemical companies.

Figure 1. The Imbalance between Growth for Oil-derived Fuels (Diesel, Gasoline) vs. Petrochemicals/Chemicals (Olefins, BTX, etc.) is Driving Crude-to-Chemicals Considerations



Sources: OPEC 2016, IEA 2016, IHS 2016, Platts 2016, and TCGR 2016

The technologies for these novel, and important, chemical/petrochemical production processes are being pursued by industry leaders like ExxonMobil and Saudi Aramco/SABIC, but also affect the competitiveness of peer participants, i.e. all chemical producers, as well as EPCs, process licensors and technology developers like CB&I, Axens, UOP/Honeywell. Added to this are traditional routes being potentially made uncompetitive, such as naphtha cracking, and there is strong, widespread and urgent interest in approaches to, and justification for, these opportunities/threats.

Depending on the crude oil feedstock, the avoidance of refinery fuels production and using specialty hydrocracking (HC) processes to naphtha or via fluid catalytic cracking (FCC) to olefins or BTX could provide lower costs than participating in the current/historical refinery value chain. As an example, CP Chem's Aromax™ can provide BTX from olefins and the resid FCC unit could be more inexpensively tailored towards $C_2^=$ and $C_3^=$ olefins production, rather than the more costly and less selective steam cracking of naphtha.

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In its completed multi-client study, entitled ***"Oil-to-Chemicals: Technological Approaches and Advanced Process Configurations,"*** TCGR takes a market-driven approach towards technology development, availability and implementation, to capture viable routes (including technology combinations) to allow the oil-to-chemicals practitioner to practice and profit from various feedstock conversion routes. The study's breadth includes a range of crude oils (heavy to light) plus bio-crudes, as well as a range of product slates from propylene-focused to a mix of chemicals, including specialty/C_4s. Included are three major market segments for chemicals/petrochemicals from the processes: (1) olefins; (2) aromatics; and (3) specialty/intermediates (e.g., C_4 and higher olefins). The emphasis is on economically viable or developing technological solutions for cost-effective chemical/petrochemical supply via direct oil-to-chemicals routes.

Of particular interest to chemical producers is how from the end-product (e.g., BTX) can you back integrate into the best configuration for costs based on the crude oil type and are there attractive margins to consider these new configurations/combinations?

III. THE NEED FOR THE STUDY

The documentation to date has been centered on ExxonMobil and Saudi Aramco/SABIC comparisons, each of which has its own internally-derived rationale for pursuing oil-to-chemicals, whether it is taking advantage of the imbalance in growth rates between chemicals/petrochemicals and fuels or the need to further add value to crude oil resources providing higher rates of returns on investments. In many cases, others in the chemicals/petrochemicals industries may have different needs for the output or preferred routes/relationships with technology licensors or developers to get there. **In TCGR's independent, detailed technological assessment, analytical and critical perspectives are taken, across alternative approaches, to ensure that both the benefits and costs are considered. It will also highlight the state of availability/development of the technologies, alone or in combination, so that a mix and match approach can be assessed.**

Today, most have only seen the reports from various sources, including IHS Chemicals' Process Economics Program (PEP) which explains and benchmarks ExxonMobil's Singapore plant compared against Saudi Aramco's patents. Others may be familiar with recent references such as SABIC's presentation at the ME-TECH (Feb. 2017; Dubai) and/or CB&I's presentation from the MERTC conference (Jan. 2017; Bahrain). Notably, there is the Corma paper "Crude to Chemicals: Light Olefins from Crude Oil" (Catal. Sci. Technol., 2017, 7,12-46) which provides a review of resid FCC upgrading but does not adequately appreciate resid hydrocracking (HC) or catalytic steam cracker (CSR) advances, although there is a brief review of Sinopec's catalytic pyrolysis process (CPP).

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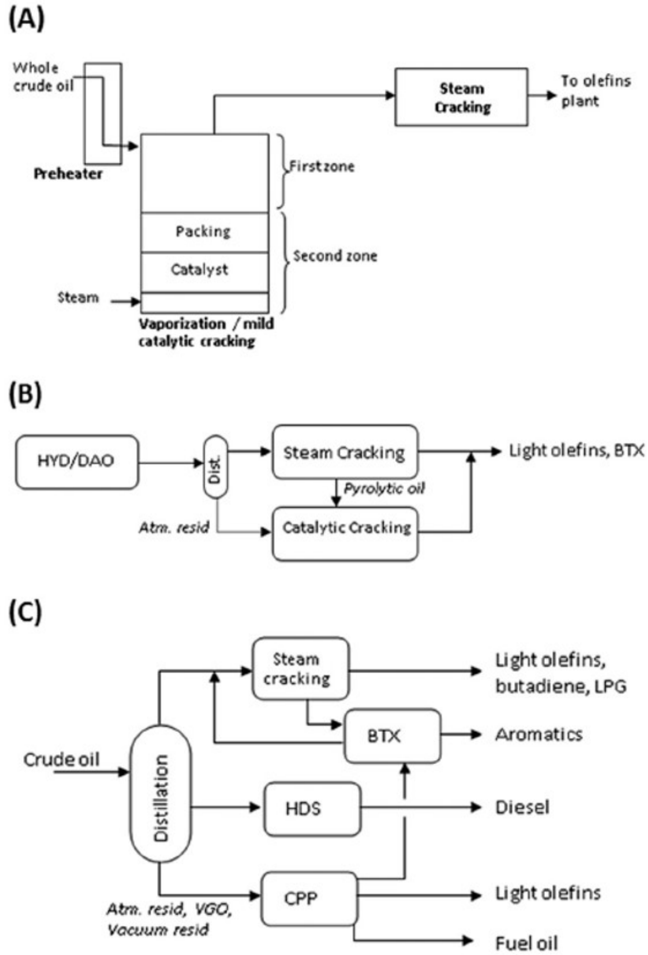
Figure 2. Refining Strategies to Maximize Light Olefins from Crude Oil



Source: Corma, 2017

Table 1
Main Processes Dedicated to Crude Oil Cracking with Circulating Solids, Operating Conditions, and Ethylene Yields (adapted from Matsunami et al., Hydrocarbon Process., 1970, 49(11), 121-26)

Licensor	BASF	BASF	Chiyoda chemical	UBE	Lurgi	Gulf/S&W
Process/bed type	FB, 1 reactor	FB, reactor – regenerator	Fluid bed	Jet flow	Fluid bed	Fluid bed
Crude oil	Minas	Minas	Khafji	Minas	Irak	n/a
Heat supply	Crude partial combustion	Coke burning	Coke burning	Crude partial combustion	Coke burning	Coke burning
Particles in bed	Coke	Inorganic oxide	Coke	Inorganic oxide	Sand	Coke
Temperature/°C	725	760	850	840	760	750
Yields (wt%)						
C_2–C_4 olefins	41.5	41.5	37.6	47.8	41.6	n/a
Ethylene	23	25	26.8	28.1	23.1	22.5
Propylene	12.5	11.2	5.8	11.3	12.8	13.9

Source: Corma, 2017

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Key questions addressed in the study include how chemical companies can target this technology opportunity - from an olefins and aromatics/BTX chemical plant feedstock point of view - but enhance the olefins and/or BTX yields even higher through retrofit catalysts and known process technology incremental revamps?

What is needed is to document recent catalyst and process advances relevant to olefins and BTX chemical products that avoid the upfront investment in catalytic distillation units (CDUs) and vacuum distillation units (VDUs) and other parts of the refinery while maximizing BTX and olefin yields (primarily C_{3+} and C_{4+}) beyond typical refinery economics and normal/known process configurations that have historically been optimized for fuels production.

Table 2
Analysis of Crude to Chemicals Complexes: Case Studies

	Minimum Investment; No Resid Upgrader; No Fuels; Sell HSFO	LC-FINING; No Fuels; Sell LSFO	LC-FINING With Fuels; Sell LSFO	LC-FINING With Fuels; Sell LSFO - Two Train Cracker	LC-FINING + Delayed Coking; No Fuels; Produce Anode Coke	LC-Slurry With Fuels; Produce ULSFO
Crude (Arab Light), BPD	195,000	162,000	227,000	400,000	137,689	246,515
Ethylene, KTA	2,000	2,000	2,000	4,000	2,000	2,000
Propylene, KTA	1,480	1,493	1,469	2,805	1,481	1,489
Butadiene, KTA	357	358	347	774	373	326
Euro VI Diesel, BPD	0	0	74,500	94,265	0	106,000
Fuel Oil, BPD	54,000	25,000	20,000	36,935	0	8,500
Anode Coke, KTA	0	0	0	0	194	0
H2 Required, MMSCFD	167	251	379	665	282	417
% Required H2 from Cracker	39	26	18	22	24	16
Natural Gas Required, KTA	596	777	1,011	1,872	794	992
Chemical Yield on Crude, %	58	70	49	57	83	45
Total Project Cost, MM$	6,954	7,995	8,910	14,173	8,492	9,285
%IRR	14.6	22.4	24.4	33.0	21.4	25.0
Notes						
1.	3%S HSFO	1%S LSFO	1%S LSFO	1%S LSFO	Anode Coke	0.1%S ULSFO
2.	All cases includes Hydrocracker + Olefins Conversion Technology					
3.	All cases produces MTBE, Butene-1, Benzene, Xylenes					
4.	3% HSFO priced at $21/Bbl less than crude					
5.	%IRR based on 70 / 30 debt / equity ratio					

Source: CB&I, 2017

IV. SCOPE AND METHODOLOGY

Oil-to-chemicals routes for three (3) product groups, via numerous case study approaches, are addressed as follows: 1) olefins; 2) aromatics; and 3) specialty/intermediates (e.g., C_4s and higher olefins)

The study includes coverage addressing:

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- Upstream to the feedstock/oil source, in order to differentiate between pre-treatment steps (if required)
  - Heavy/sour crudes: S. America, Russia/Urals; Canadian tar sands; opportunity crudes
- Product slate via technology approach, i.e., %olefin by carbon (C_2, C_3, C_4, etc.).
  - Ethylene, propylene, C_4 and higher olefins
- Implications on technology implementers, to assess economic/financial metrics (CAPEX, product costs, ROI, etc.)
  - Steam cracker modifications, combinations/integrations, etc.
- Advancements in technology (catalysts, processes, combinations) yielding novel options for consideration/evaluation in retrofit
- Impacts on technology developers and users, to gauge readiness levels and timing of commercial impacts
  - Practitioners, licensors, developers, etc.
- Potential end-market and competitor/supplier implications, indicating likely winners and losers
  - Optimal crude/product combinations, integrated vs. independent suppliers, etc.

The scope includes numerous process configurations, some of which are proposed by the study's "charter" subscribers (i.e., those who committed to supporting it prior to formal launch), with consideration of the following:

- Modified steam crackers; catalytic steam cracking
- Gasoil/steam cracking, gasoil/HSFCC
- Resid FCC: Multiple riser systems, R2R, Milos (Shell), HSFCC (Axens)
- Hydrocracker/FCC; Flexicoking/FCC; FCC/Reforming
- H-Oil and slurry HC (IFP); LC Fining (Lummus/CB&I)
- Hydroconversion upgrader (GHU, Genoil)
- Ebullated bed – EST (Eni)
- Pyrolysis catalytic cracking (PCC)
- Deep catalytic cracking (DCC)
- Aromax (CP Chem), Cyclar (UOP/Honeywell), etc.
- Others

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Table 3

Representative Advances in Oil-to-Chemicals Technologies: Upping Olefins and BTXs

Heavy Oil/Bitumen Canada Upgrading Technologies	• Pyrolysis Upgrading. – Ivanhoe HTL, piloted in CA – WESCO's CJP Process – USP Process by Value Creation – CPP, Sinopec	• Slurry Hydrocracking. – ENI, EST Process. – HCAT, Heatwaters/HTI – HRH, Mobis – GHU, Genoil, perhaps slurry modified – UOP, Uniflex, Fe based ex PetroCanada – Chevron, Slurry HC.
FCC and Cracking Advances	• R2R Advances, TOTAL/S&W • Indmax, IOC • HSFCC, Aramco/Axens, including downstream dimerization • DCC Advances, Sinopec/S&W • Regular FCC, two riser e.g. Milos.	
Cold (Sonic) Cracking	• Sonoprocess, Petrosonic • CCU, Pristec • CCC, Bayshore Petroleum	
Novel Pipeline Processes (all to pilot or commercial)	• Gasolfin, InovaCat, naphtha to olefins/BTX swing fixed bed. • Gasolin Equivalent, Chiyoda Corp, Japan • Maxene, UOP, naphtha/paraffins pretreat to up olefins. • Olefin/Paraffin Membranes separations – Permylene, Imtex – Optiperm, CMS, Compact Membrane Systems – ECN, Amsterdam • ACO Process, KBR/SK, naphtha to olefins	• Corrillo feedstock separation process • DSU Process, Molten Na separation of metals and S • Shock Wave Reactor, Hydrodynamics Inc. (vs. thermal cracker • Cyclar Upgrades, UOP • Aromax Upgrades, CP Chem.

Source: TCGR, 2017

Via a market-driven approach documenting detailed technological assessments (including combinations) as determined by the industry's leading participants as "charter" subscribers, TCGR's study presents a state-of-the art assessment in oil-to-chemicals approaches to addressing the imbalance between olefin supply/demand in this uncertain but opportunistic period.

TCGR uses in-house and external resources, as well as expertise from within industry as well as our highly-regarded DIALOG GROUP ® in order to complete:

- Technology evaluations
- Patent reviews and analyses
- Representative economics
- Market needs/drivers
- Competitive implications (developers vs. users)

A refined/expanded Table of Contents is provided on pages 11-19 in order to depict the breadth and depth of the study as envisioned.

References

Corma 2017; Crude to Chemicals: Light Olefins from Crude Oil (Catal. Sci. Technol., 2017, 7,12-46)
CB&I, 2017; Crude to Chemicals: Opportunities and Challenges of an Industry Game-Changer; MERTC, Bahrain
IEA, 2016
IHS, 2016
OPEC, 2016
Platts, 2016

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V. QUALIFICATIONS

The Catalyst Group Resources, a member of The Catalyst Group, works with clients to develop sustainable competitive advantage in technology-driven industries such as chemicals, refining, petrochemicals, polymers, specialty/fine chemicals, biotechnology, pharmaceuticals, and environmental protection. We provide concrete proven solutions based on our understanding of how technology impacts business.

Using our in-depth knowledge of molecular structures, process systems, and commercial applications, we offer a unique combination of business solutions and technology skills through a range of client-focused services. Often working as a member of our clients' planning teams, we combine our knowledge of cutting-edge technology with commercial expertise to:

- Define the business and commercial impacts of leading-edge technologies
- Develop technology strategies that support business objectives.
- Assess technology options through strategy development, including:
  - Independent appraisals and valuations of technology/potential
  - Acquisition consulting, planning and due diligence
- Provide leading-edge financial methodology for shareholder value creation
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- Provide leading information and knowledge through:
  - World-class seminars, conferences and courses
  - Timely technical publications

The client-confidential assignments conducted by The Catalyst Group include projects in:

- Reinventing R&D pipelines
- Technology alliances
- Technology acquisition
- Market strategy

We have built our consulting practice on long-term client relationships, dedication, and integrity. Our philosophy is clear and focused:

We Provide the "Catalysts" for Business Growth by Linking Technology and Leading-Edge Business Practices to Market Opportunities

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VI. DELIVERABLES AND PRICING

This report is timely and strategically important to those industry participants and observers both monitoring and investing in the development and implementation of technologies for the conversion of oil-to-chemicals. TCGR's report, based on technology evaluations, commercial/ market assessments and interviews with key players goes beyond public domain information. As a result, subscribers are requested to complete and sign the "Order Form and Secrecy Agreement" on the following page.

The study, **"Oil-to-Chemicals: Technological Approaches and Advanced Process Configurations"** was completed in December, 2017.

Post-production subscribers	after December, 2017	$23,500

Oil–to–Chemicals: Technological Approaches and Advanced Process Configurations

Report in PDF format, in addition to subscription price	$1,000

** Charter subscribers (those who signed up for the study before its launch) had the opportunity to work with TCGR to further refine the scope of the report by nominating specific process/configuration content as well as delineating areas of particular interest for inclusion in the assessment.*

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Please enter our order for **"Oil-to-Chemicals: Technological Approaches and Advanced Process Configurations,"** completed in December, 2017, as follows:

____ **"Oil-to-Chemicals: Technological Approaches and Advanced Process Configurations,"** for $23,500 (post production)

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In signing this order form, our company agrees to hold this report confidential and not make it available to subsidiaries unless a controlling interest (>50%) exists.

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CONTENTS

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FIGURES

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TABLES

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