THE CATALYST REVIEW

February 2024
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Technical & Commercial Progress in the Global Catalytic Process Industries

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THE CATALYST REVIEW

An industry-focused, leading edge catalysis technology reference from The Catalyst Group Resources

FROM YOUR EDITOR: Photo Finish



We hope you have noticed some refinements over the past year-plus at ***The Catalyst Review***. Among them, as is presently self-evident, we have started dedicating this introductory space to what you can expect to see in the present edition, and we've ended each month with an announcement of 'coming attractions.' You will find this month's version on Page 20. So, according to newly established tradition, I am eager for you to catch our Special Feature, "Maximum Propylene with Ultralow GHG Emissions," from Inovacat's Ray Fletcher; the first installment of a series spotlighting presentations at this year's International Congress on Catalysis (ICC) from Victoria Laura Barrio of the University of Bilbao and Valérie Meille from IRCELYON; as well as our reigning Mover-Shaker, David Brown of Drochaid Research Services in Scotland.

Further, just as this edition was headed to press, we were made aware of a significant development from Dr. Gregory Arzoumanidis regarding his team's breakthrough in artificial photosynthesis. Gregory is one of the leading inventors in the industry, with whom my TCGR colleagues have had a longstanding rapport.

We hope to learn and share a lot more about this topic in due course, but for the moment, this information will be presented to you as it was to us, in the form of a 'Letter to the Editor' from Dr. Arzoumanidis, sharing what details can be revealed at this early stage, and promising a significant amount of information down the line.

Therefore, in a somewhat paradoxical break with tradition, we are hereby beginning, rather than ending, the February 2024 edition with a preview of something significant that is yet to come.

Kevin O'Brien, Managing Editor
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Announcing a Breakthrough in Artificial Photosynthesis

A team led by Dr. Gregory Arzoumanidis developed a "living" chemical system energized by harnessing visible light, capturing CO_2 and H_2O (humidity) directly from the atmosphere under ambient conditions. The system is self-organizing, performing continuously and autonomously complex chemical operations, producing long-chain (C_5 to C_20) oxygenated organic materials. It is based on easily accessible, earth-abundant metal coordination compounds in the solid state, forming hydrolysis and carbonated metal derivatives, subsequently reduced by an internal, photochemically generated hydrogen. The initially produced C_1 materials oligomerize by a novel self-catalyzed process, operating within the system. These operations have been monitored by accurate Maldi-Tof (matrix assisted laser desorption ionization-time of flight) mass spectroscopy (MS), assisted by infrared (IR) and nuclear magnetic resonance (NMR) data. The system is in the early stages of development, and several growth operating parameters and conditions must be carefully defined; new methods for product removal must be worked out. Although the system has been operating for several months, the stability for continuous uninterrupted operation must be developed. This diverse, visible-light photocatalytic system is novel, and has no resemblance to any other known or reported system so far in the chemical literature. The simplicity of setting-up and operating the system is expected to make scale-up a reality within reach. Additional information is available from Gregory Arzoumanidis PhD, MBA at arzoumandis@gmail.com.

**Want to share your thoughts with our readership as well?
Contact Kevin O'Brien today!**

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Industry Perspective

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Are 'LOHCs' the Key…?

Liquid Organic Hydrogen Carriers: A Promising Renewable Resource for Hydrogen Transport and Storage with Significant Impacts on Catalysis

By Victoria Laura Barrio and Valérie Meille

Status on Hydrogen Storage

Hydrogen appears to be the energy source of choice in the fight against greenhouse gas emissions. Major efforts are being made to obtain green hydrogen. Hydrogen technologies will play an important role in conjunction with renewable sources to mitigate the fluctuations in production and to transport the energy produced as well. Once produced, hydrogen has to be stored and/or transported, to be used later and/or in another place.

To date, many technologies have been proposed for hydrogen storage, all of them focused on the aim of increasing hydrogen volumetric energy density. However, security problems arising from the high pressures needed and/or low temperatures are current drawbacks for the development of the hydrogen economy. To overcome these limitations, liquid organic hydrogen carriers (LOHCs) have recently gained interest. This technology consists of reversible hydrogenation/dehydrogenation reactions using cyclic hydrocarbons and offers the possibility of transporting the hydrogen through the existing infrastructures for liquid fuels and long-term hydrogen storage without losses.

What Are the LOHCs?

LOHCs (https://unlohcked.cnrs.fr/) include an important list of molecules which are able to store and release an average of 6wt-% of hydrogen. The storage consists of a catalytic hydrogenation of a hydrogen-lean compound (LOHC-) yielding a hydrogen-rich compound (LOHC+). A well-known system is Toluene/Methylcyclohexane, with a H_2 storage of 6.1wt-% and 47.4kg/m^3. To release hydrogen from the LOHC+, a catalytic dehydrogenation has to be performed. Due to the high dehydrogenation enthalpy, the reaction has to be performed at high temperatures (200 – 350°C).

Catalyst Requirements for the Hydrogenation/Dehydrogenation Steps

Depending on the use of the LOHCs, the catalysts for hydrogenation and for dehydrogenation can be the same or different. In both cases, more important than the catalytic activity is the selectivity of the reaction. Indeed, as the organic molecule is just a hydrogen carrier, many cycles hydrogenation/dehydrogenation must be achievable without having to renew the liquid carrier. In the case of the most standard LOHC systems (Aromatics/Cycloalkanes), supported noble metals are the most used catalysts, both for their activity and selectivity. However, to reach sustainable processes, the replacement of at least a part of platinoid metals is a priority challenge.

The UnLOHCked Project

The European project entitled *Unlocking the potential of LOHCs through the development of key sustainable and efficient systems for dehydrogenation* (UnLOHCked), coordinated by V.L. Barrio from the Bilbao School of Engineering, aims at developing new catalysts for the dehydrogenation of H_{12}-benzyltoluene. Among different LOHC molecules, benzyltoluene has a hydrogen storage capacity of 6.2 wt%, is not flammable and has a high thermal stability under a wide range of temperatures. Regarding the catalysts used, platinum is known to be one of the best options due to its high selectivity that enhances the rate of reaction; however, the elevated cost, availability of the platinum group metal (PGM) and metal/LOHC ratio are concerns that need to be addressed.

The main objective of the UnLOHCked project is the development of a breakthrough innovative CO_2 free technology to convert LOHC to hydrogen to generate clean electricity using critical raw material (CRM)-free catalysts. Thus, new CRM-free catalytic formulations active and stable will be developed. This will enable the development of an innovative, cost-efficient and sustainable LOHC technology with improved thermal energy efficiency in the dehydrogenation step (< 17 kWh input/kg H_2 recovered), high catalyst productivity (>0.02 g H_2/g catalyst/min in dehydrogenation) and high level of catalytic stability (loss of performances < 0.1%/cycle) to be used in a demo unit of a LOHC dehydrogenation plant thermally coupled with a solid oxide fuel cell (SOFC) to generate renewable electricity and hydrogen.

UnLOHCked consortium's final goal is to unravel the full potential of LOHC technologies for hydrogen logistics by the development of a fully CO_2-free dehydrogenation unit for power generation through directly coupled technology to convert liquid hydrogen carriers at energy efficient conditions and with highly optimized catalysts into electric power and hydrogen.

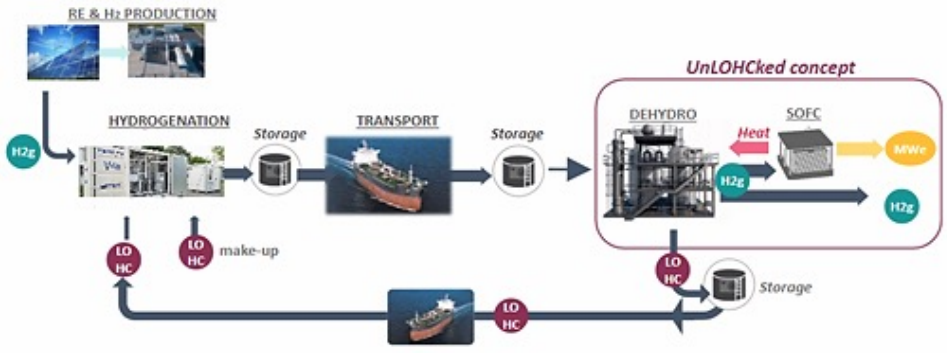


Image source: Authors

Continued on page 15.

Commercial News

BASF, Heraeus Launch Precious Metals Recovery Facility in China



BASF Environmental Catalyst and Metal Solutions (ECMS) and Heraeus Precious Metals have commenced operations of a new joint venture facility, BASF HERAEUS Metal Resource Co., Ltd, (BHMR) located in Pinghu, China. The facility recovers precious metals from spent automotive catalysts, enabling a circular economy, while supporting China's security of supply and sustainability goals. The facility is a 50:50 joint venture between the two industrial leaders and involved a mid-double digit million Euro investment. BHMR has a recycling capacity of approximately 10,000 tons of autocatalysts annually. The commencing of operations comes at a crucial juncture with the earliest platinum group metals (PGMs) carrying automobiles enter the recycling phase. China relies heavily on imported precious metals due to limited domestic supplies. This highlights the importance of recycling to meet the country's needs, particularly for essential metals like platinum, palladium and rhodium, which are utilized in various industries such as petrochemicals, pharmaceuticals and automobiles. According to market research, the Chinese autocatalyst recycling market is expected to experience remarkable growth, with an estimated annual growth rate of 18%. Recycling precious metals offers a substantial reduction in carbon footprint, potentially saving up to 98% of carbon emissions compared to mining operations. Source: Heraeus, 1/17/2024.

OMV, ADNOC to Iron Out Terms of Deal for Chemicals Tie-up

Abu Dhabi National Oil Co (ADNOC) and Austria's OMV are poised to resume talks to agree final terms of a tie-up that would create a chemicals group with more than $20 BIL in combined annual sales, sources close to the deal said. OMV said in July last year it entered into talks to merge petrochemicals group Borealis, owned by OMV and ADNOC in a 75:25 split, and Borouge, listed in Abu Dhabi and owned 54:36 by ADNOC and Borealis. The two sides had reportedly been close to agreement, but a number of sticking points remain, including a provision for job guarantees in Austria, a requirement for a Vienna listing and an Austrian chairman of the new company, sources said. A dual listing in Vienna and the UAE could be an option. An OMV spokesperson said the two sides were in "ongoing negotiations." In October, the Austrian company's CEO said the company would be listed on the stock exchange. A deal is still expected to happen as the obstacles are surmountable, sources indicate. The terms of the deal would also include a capital infusion to ensure both parties have the same equity share in the new company, according to published reports. Previously OMV said both Borealis and Borouge would become "equal partners under a jointly controlled, listed platform for potential growth acquisitions to create a global polyolefin company." OMV is partly state-owned and has Abu Dhabi's Mubadala as its second largest shareholder. Mubadala's shares in OMV will be taken over by ADNOC, as previously announced. Separately, state-owned ADNOC said it would allocate $23 BIL for decarbonization and lower-carbon projects, up from a previous $15 BIL target. Source: Hydrocarbon Processing, 1/22/2024.

SABIC to Proceed with China-based Petrochem Complex

SABIC, a global leader in diversified chemicals, announced the final investment decision (FID) for the SABIC Fujian Petrochemical Complex (Sino-Saudi Gulei Ethylene Complex Project) in China's Fujian province. SABIC FUJIAN Petrochemicals Co. Ltd, a 51:49 joint venture between SABIC Industrial Investment Company (wholly owned by SABIC) and Fujian Fuhua Gulei Petrochemical Co., Ltd. (holding by Fujian Energy and Petrochemical Group) agreed to build the Complex in Fujian's Gulei Industrial Park. With an estimated total investment of RMB 44.8 billion ($6.4 BIL), it is a centerpiece of SABIC's investment footprint in China and by far the largest foreign investment in Fujian. The complex will consist of a mixed feed steam cracker, with an expected annual ethylene capacity up to 1.8 million tons, with a series of world-class downstream facilities, including ethylene glycol (EG), polyethylene (PE), polypropylene (PP), polycarbonate (PC) and several other units. The construction of the project targets to complete in 2026. Source: SABIC, 1/21/2024.

Ecovyst Updates Plans for Expansion of Orange, Texas, Catalyst Activation Facility

Ecovyst plans to invest in a new air emission control system at its Orange, Texas site as part of a project that is expected to increase the efficiency of the facility's emission control process and, through additional permitting, enable the future expansion of production capacity. The site is part of Ecoservices' Chem32 business, a leading ex-situ sulfiding and pre-activation provider for hydro-processing catalysts used in the production of traditional and renewable fuels. Once installed, the new control system is expected to meet or exceed regulatory-required performance standards for applicable pollutants while allowing for expansion at the site to meet the increasing demand for catalysts used in the production of cleaner burning fuels. Source: Ecovyst, 1/22/2024.

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Process News

Scientists Design New Catalyst to Generate Green Fuel from Water

Scientists at South Korea's Dongguk University have synthesized an efficient catalyst for the oxygen evolution reaction, facilitating a water-splitting process that produces hydrogen and oxygen. The new catalyst, synthesized using molybdenum and ruthenium, exhibits high activity, reaction rates and durability. The study involved implanting ruthenium oxide into a two-dimensional molybdenum carbide to create a catalyst (Mo_2TiC_2TxMXene) with high mass activity, turnover frequency and durability. Calculations also indicated that the ruthenium sites had a strong affinity towards oxygen species, which enhanced the reaction. These findings are significant, as the global aim is to achieve 80% renewable electricity by 2050. Notably, more than 90% of hydrogen is in petroleum recovery and refining (47%) and ammonia production (45%) alone. This study thus serves as a guide for researchers to create new catalysts for acidic water oxidation. It also sheds light on achieving cost-effective, large-scale catalyst production using diverse materials, such as dual-transition metal catalysts. Source: AZO Cleantech, 1/31/2024.

Scientists Find Close-loop Recycling Process for LDPE

Researchers at Germany's University of Bayreuth have achieved the targeted replication of the chemical structure of low-density polyethylene (LDPE). The team has incorporated so-called "recycling points" into the new plastic, at which the polymer can be chemically broken down into smaller fragments that are soluble in organic solvents at moderate temperatures and can therefore be recycled. The components can then be recombined, allowing them to be reused in a closed cycle. LDPE is produced in a high-pressure process under extreme reaction conditions (at 250°C with 2,500 to 4,000 bar) via the free radical polymerization of ethylene. The new material, known as LDPE-mimic, is close to commercial LDPE in its chemical structure. The new catalysts produce defined building blocks of a certain size under correspondingly mild reaction conditions, around 70°C, which could then be combined to form the final plastic material. Source: Phys.org, 1/31/2024.

NETL Research Provides Insight into Catalysts for Carbon Conversion

Researchers at the National Energy Technology Laboratory (NETL) demonstrated that a catalyst support can have a dramatic impact on its performance. The team managed to grow, analyze and quantify interactions between small silver particles and carbon catalyst supports, focusing on electronic metal support interactions (EMSIs) between carbon-based supports and metal/oxide nanostructures to enhance interactions. By creating defects in the carbon supports, which exposes more surface area, the team determined that metal-carbon interactions between the supports and small-diameter silver particles improved catalytic activity. When they made their discovery, the multi-disciplinary NETL team was investigating how to overcome problems associated with a decrease in selectivity as the particle size of catalysts based on gold, copper and silver (coinage metals) decreases. In this research, the NETL team found that by creating defects in the carbon supports, which exposes more surface area, the metal-carbon interactions between the supports and small-diameter (less than two nanometers) silver particles improved catalytic activity. The team further demonstrated the importance of EMSIs by growing small silver nanoparticles at the defect sites of a commonly used carbon black (CB) support. The CB-supported silver nanoparticles also exhibited EMSIs and demonstrated high selectivity during six hours of electrolysis. Source: NETL, 1/24/2024.

Researchers Produce Phosphines that Act Like Metal Catalysts

Researchers from the University of Toulouse and the University of York have demonstrated that commercially available tributylphosphine can act as a catalyst to break carbon-fluorine bonds on organic molecules and swap in hydrogen or an amine, with no metal needed. Phosphorus can happily sit in either the +3 or +5 oxidation state, and it is not difficult to get it to switch between them. The challenge is to get it to do that in a catalytic cycle. The researchers' reaction scheme produces hydrodefluorination of an aromatic molecule using a tributylphosphine catalyst. Unlike catalysts used in previous research, theirs was not a bespoke pincer-shaped compound; this new work shows that the fancy structure is not needed for a phosphine to act as a catalyst. The steps that the phosphorus goes through in the reaction are the same as what a typical metal catalyst does. First is oxidative addition to break the C–F bond. Then the phosphine passes the fluoride to a silane in exchange for a hydride or amide. Finally, reductive elimination regenerates the catalyst and creates the final product. Source: Chemical & Engineering News, 1/29/2024.

Oxygen's Role in Nickel Catalysts Used in Dry Reforming of Methane

Researchers from the Fritz Haber Institute of the Max Planck Society in Berlin provided fundamental insights into the processes occurring at the catalyst surface and on how this modulates the catalytic performance during dry reforming of methane (DRM). In particular, they studied the role of different oxygen species on a Nickel catalyst during DRM by using a combination of experimental and computational science techniques, including operando scanning electron microscopy, near ambient pressure X-ray photoelectron spectroscopy and computer vision. They highlighted the critical role of dissociative CO_2 adsorption in regulating the oxygen content of the catalyst and CH_4 activation. Furthermore, they discovered the presence of three metastable oxygen species at the catalyst: atomic surface oxygen, subsurface oxygen and bulk NiOx. Significantly, these exhibited different catalytic properties and their interplay and transformation gave rise to oscillations in the surface states and in the catalytic function. They observed that some of the surface oxygen leaked into the catalyst bulk, reducing the availability of the catalyst for CH_4 activation and favoring CO_2 and O diffusion instead. The extent of the leakage was further proved by X-ray spectroscopy and transmission electron microscopy, revealing the presence of oxygen several nanometers below the surface of the catalysts. Consequently, new metallic sites were exposed, thus leading to an increased rate of the oxygen uptake and a decrease of the H_2/CO product ratio. Lastly, they understood that co-feeding of CO_2 is essential for CH_4 conversion, likely assisting its activation together with the presence of oxygenated species. Source: Chemeurope, 1/22/2024.

Naphtha-to-Olefins Conversion

Maximum Propylene with Ultralow GHG Emissions

By Ray Fletcher

Inovacat™ has developed a catalytic-driven naphtha-to-olefins technology – Gasolfin™ – which converts conventional and bio-derived naphthas into light olefins (ethylene, propylene, and butylene). Propylene selectivities are up to 46 wt% depending upon feedstock composition. The Gasolfin process also reduces CO_2 emissions by 50% or more when compared with polymer-grade propylene produced from the fluid catalytic cracking (FCC) and propane dehydrogenation (PDH) processes.

The definition of highly valued chemical (HVC) for Gasolfin is the sum of ethylene, propylene and butylene. HVC for PDH and FCC is propylene and ethylene for steam cracking.

The Gasolfin catalyst converts naphtha boiling range hydrocarbons – excluding aromatics – from butane through undecane (C_4 – C_{11}). The catalyst also converts pentane, recognized as the lowest valued and most refractive of gasoline components.

InovaCat's technology is based upon a novel catalyst system protected by multiple patents. This technology has been in development since 2017 and has successfully passed both bench and pilot plant scale testing.

Inovacat is currently in collaboration with an Asian refiner to build and operate an 800 liter/day demonstration plant. This plant is expected to go into construction in mid-2024 and to be in production in late-2025. Inovacat anticipates having the technology ready for deployment in 2027.

A Novel Process

What makes the Gasolfin™ process special?

- *Light-ends Conversion Process.* Gasolfin is the first-ever catalytic light ends conversion process capable of converting low molecular weight paraffins, such as pentane, into high-value ethylene, propylene, and butylene.
- *Conversion of Conventional and Bio-derived Naphthas.* Gasolfin converts fossil-derived and bio-derived naphthas into, respectively, light olefins and light bio-olefins. Gasolfin is a competitive transition technology for today's refineries and for future anticipated renewable fuels and chemicals refineries.
- *Gasolfin Produces Light Olefin with 50-66% Lower CO_2 Emissions.* Gasolfin produces polymer-grade propylene and ethylene at a very low 0.45 tons CO_2/ton Olefin ratio. An FCC unit produces propylene at 0.783-0.869 tCO_2/tOlefin, while a steam cracker produces ethylene at 1.231 tCO_2/tOlefin.
- *Gasolfin Improves the Flexibility of the Fuels-based Refinery and the Steam Cracker-based Chemical Plant.* Gasolfin converts any naphtha regardless of the source (crude unit, hydrotreater, coker, etc.) and petrochemical plant intermediate and by-product streams.
- *Gasolfin Enables Reduced Severity in Other Catalytic Operations.* Depending upon crude slate, a refiner employing a Gasolfin unit to convert light straight run (LSR) naphtha will observe up to a 1.5 research octane number (RON) octane increase by elimination of this stream into the gasoline pool.

Ultralow CO_2 Emissions

The Gasolfin process sets a new benchmark for the industry with respect to producing light olefin with significantly lower CO_2 emissions than the three leading propylene producing technologies: FCC, steam cracking, and PDH. See **Chart 1.**

Gasolfin produces 0.45 tons of CO_2 for every ton of total olefin produced, annotated as "tCO_2/tHVC," where tHVC abbreviates "ton highly valued chemical." This excellent metric enables a side-by-side comparison of an FCC and a steam cracker.

A benchmark paper for establishing greenhouse gas (GHG) emissions for existing technologies, "Energy and GHG Reductions in the Chemical Industry via Catalytic Processes" (https://shorturl.at/JMT45), was produced in 2013. The article places the GHG emissions of an FCC between 0.783 and 0.869 tCO_2/tHVC. A steam cracker processing naphtha at 0.700 and processing ethane at 0.964 for an average GHG emissions level of 0.832 tCO_2/tHVC. A PDH unit produces 1.231 tCO_2/tHVC.

Gasolfin's GHG emissions are significantly lower than each of the above existing technologies and are attributable to the following primary factors:

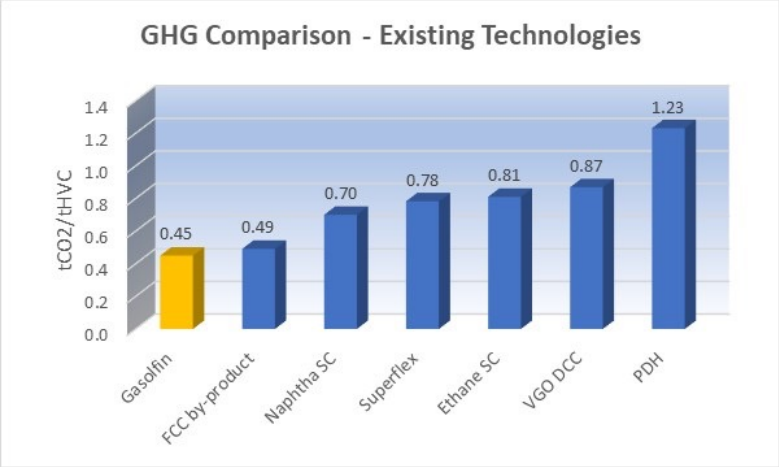


Chart 1. Comparison with existing technologies.
Source: Author

- *Lower Heat of Reaction.* Gasolfin's feedstock boils in the naphtha range, which has a much lower heat of reaction than for ethane cracking or propane dehydrogenation.
- *Narrow Feed Slate.* The Gasolfin unit cracks naphtha boiling molecules to extinction. Feed boiling over the naphtha range is excluded from the feed.
- *Low Coke Selective Catalyst.* Gasolfin's patented catalyst features an extremely low coke selectivity. FCC and PDH have coke yields of 4-5 wt%, while the Gasolfin coke yield is well below 0.5 wt%. The chemical CO_2 contribution is an order of magnitude less than FCC or PDH.
- *Hybrid Product Recovery Section.* The inclusion of cryogenic distillation for ethylene recovery and conventional distillation for propylene and butylene recovery offers significant heat integration capabilities not typically found in a polymer-grade propylene or polymer-grade ethylene operation.

Gasolfin Catalyst Development

Inovacat began catalyst studies in 2017 utilizing the CPERI laboratories in Thessaloniki, Greece. The catalyst development work was initially carried out in a microactivity test (MAT) reactor with many catalyst formulations, including multiple zeolite types and sources, as well as alumina types and sources, each with various metal types and levels. The catalysts were tested fresh and with incremental deactivation severities. The bulk of the testing was carried out at end-of-life conditions with the goal to achieve near-constant olefin selectivities as the catalyst ages. Inovacat carried out approximately three hundred individual tests before selecting the final few catalyst formulations. These catalysts were then advanced to the pilot plant phase. Inovacat tested the final catalysts for approximately one hundred days of continuous operations. The feedstocks selected for these tests were pentane, hexane, octane, LSR, full range naphtha (FRN), and FCC naphtha. Additionally, Inovacat has tested in excess of twenty-five commercially derived feeds from various refineries and petrochemical plants.

The Gasolfin Catalyst System

Gasolfin has created a catalyst system that efficiently converts all naphtha boiling range hydrocarbons excluding aromatics into light olefins. The catalyst produces ethylene, propylene, and butylene with a total olefin yield of 60-88 wt%. There are no higher molecular weight by-products produced, such as diesel or heavier. The ethylene-to-propylene-to-butylene product ratio (EPB ratio) is feedstock dependent. Paraffinic feeds such as LSR and FRN present an EPB ratio of 21:50:29, while olefinic feeds such as FCC naphtha present an EPB ratio of 18:49:33.

Gasolfin has cracked more than twenty-five commercially derived feedstocks in CPERI's Thessaloniki Greece laboratory. These feeds include pentanes, LSR, medium straight run (MSR), FRN, light FCC naphtha (LCN), full range FCC naphtha (HCN), pyrolysis naphtha (PN), Fischer-Tropsch naphtha (FTN), bio-naphtha (BN), and various petrochemical intermediate streams. The petrochemical intermediate streams included various paraffinic naphthas, olefinic naphthas, oxygenated naphthas, and naphtha streams bearing a mix of both olefinic and oxygenated components. The EPB ratios of these streams were all consistent with the typical ranges stated above.The ease of cracking is directly related to the composition and molecular weight of the feeds. In general, the order of cracking is unsaturated naphthenes and olefins > oxygen bearing molecules > saturated naphthenes and normal paraffins > isoparaffins. **Table 1** presents the average conversion levels for cracking FCC naphtha over the Gasolfin catalyst.

Naphtha cracking proceeds efficiently up to undecane (C_{11}), at which point steric hindrances begin to affect reaction rates. Higher molecular weight molecules crack faster than low molecular weight molecules. Pentane cracking follows the following order: Pentenes > isopentane > normal pentane. Butane is the lightest molecule cracked by the Gasolfin catalyst, while undecane (C_{11}) is the heaviest molecule.

Feed PIONA Conversions	wt%
Unstaurated Naphthene	75
Normal Olefin	74
Iso-olefin	73
Normal Paraffin	60
Saturated Naphthene	59
Isoparaffin	48

Table 1. Feed PIONA conversion.
Source: Author

Not all refiners have sufficient alkylation capacity to process the additional butylene produced by a Gasolfin unit. Additionally, many refiners operating in Europe and Asia do not possess alkylation units. The Gasolfin catalyst efficiently converts butylene, enabling further conversion to light olefin. Inovacat recommends recycling the mixed butane stream (C_3C_4 column bottoms) back to the feed for alkylation capacity limited refineries. The butylene cracks over the Gasolfin Catalyst to 42.8 wt% ethylene and 57.2 wt% propylene, as will be illustrated in a later section of this article.

The butane selectivity for the Gasolfin catalyst converting LSR feed is about 21.8 wt%. The typical composition of the butane stream is 5% isobutane, 13% normal butane, and 82% butylene. A butylene cracking operation yields approximately 42.8 wt% ethylene and 57.2 wt% propylene. Such an operation enables a Gasolfin operation to be profitable in a refinery without (additional) alkylation capacity.

Catalyst Poisons

The catalyst is not poisoned by sulfur; however, it is recommended that sulfur be removed prior to the Gasolfin unit for polymer-grade propylene production. Removal of mercaptan and disulfide sulfur is recommended when processing cracked naphthas. Thiophene and benzothiphene are removed with the aromatics in the aromatic extraction step. The Gasolfin catalyst is not affected by moisture.

The Gasolfin catalyst is temporarily impacted by the presence of nitrogen. The higher nitrogen contents of cracked naphthas such as FCC naphtha or coker naphtha, are addressed by increasing the reactor catalyst loading. Nitrogen is released during regeneration; sodium is a permanent poison.

Conversions and Yield Selectivities

Two important considerations are conversion and yield selectivity. Conversion is defined as "100 – recycle." The targeted conversion is 35 wt% for maximum propylene yield. An additional term related to conversion is single pass conversion, defined as the conversion the reactor feed experiences after one pass through the reactor. The terms, conversion and single pass conversion, are used interchangeably within the Gasolfin technology.

Yield selectivity is defined as "100 * (*Product yield)/(conversion*)." Gasolfin converts all non-aromatic naphtha boiling range feeds to extinction. The yield selectivity is the final yield for any product after feed extinction. The propylene yield selectivity of 35 wt% implies that the catalyst will convert the feedstock with a final yield of 35 wt% propylene at the exit of the unit.

Propylene. The propylene selectivity ranges from 30-46 wt% depending upon feed composition. The propylene yield increases 3-5 wt% for the first 24 hours of a given cycle. The product yield asymptotically approaches the average value for the cycle. The propylene yield remains constant as the reactor temperature is increased to maintain conversion as the cycle length progresses; see **Chart 2**. The FCC yields are representative for the cracking of the olefins and unsaturated naphthenes present in the feedstock, as is the case in **Chart 3** and **Chart 4.**

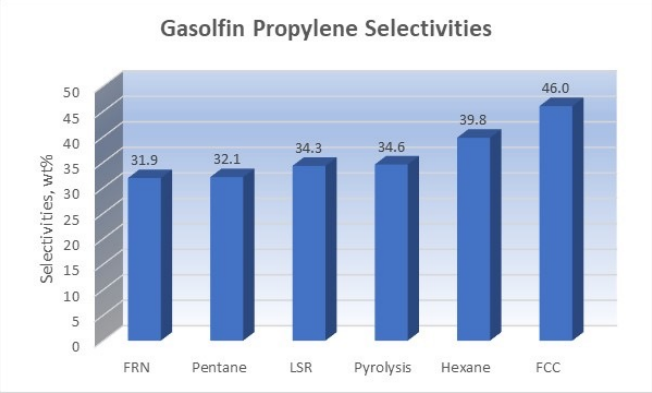


Chart 2. Typical propylene selectivities for various feedstocks.
Source: Author

Ethylene. The ethylene selectivity averaged 16.3 wt% with a low of 7.1 wt% for hexane cracking and a high of 27.2 wt% while cracking butane. The ethylene yield increases gradually across the cycle length by 2-3 wt%. Ethylene yield increases by 1.0 wt% for each 10 °C reactor temperature as the temperature is increased to maintain conversion as the cycle length progresses.

Butylene. The butylene selectivity ranges from 16-30 wt%. The butylene yield increases as the average molecular weight of the feed increases. The butylene yield increases about three wt% for the first 24 hours of a given cycle. The product yield asymptotically approaches the average value for the cycle. Butylene yield decreases by 0.5 wt% for each 10 °C reactor temperature as the temperature is increased to maintain conversion as the cycle length progresses.

Methane and Ethane. The methane and ethane selectivity decreases gradually in direct proportion as the olefin yields increase over the course of the first 24 hours of the cycle. The methane yield increases by about 1.0 wt% and the ethane selectivity by about 0.75 wt% for each 10 °C reactor temperature as the temperature is increased to maintain conversion as the cycle length progresses.

Propane, Normal Butane and Isobutane. The C_3 and C_4 paraffin selectivities all decline as the catalyst ages during the catalyst cycle. The paraffin selectivities decrease at the expense of the light olefin selectivities. The propylene and butylene yields increase to an asymptotic value over the first 20-30 hours of the cycle while the ethylene selectivity increases by about 0.5 wt% for each 10 °C reactor temperature increase. Notably, the normal butane yield is most sensitive to reactor temperature increases with an approximate 0.5 wt% selectivity decline for each 10 °C increase.

Coke. Low coke yield is a requirement for a fixed-bed operation. The initial cracking studies performed by Gasolfin produced a coke yield too high for a fixed bed operation as observed by cycle lengths of a few hours up to about 12 hours. After substantial work, Gasolfin has developed a catalyst system with coke yields averaging less than 0.25 wt% permitting cycle lengths of 100-120 hours (4-5 days) yet delivering the activity required to convert low molecular weight paraffins such as normal and isopentane. This catalytic breakthrough is protected by several patents and trade secrets. **Table 2** presents the feed qualities and yield selectivities for the feeds employed while designing the Gasolfin catalyst system.

	Pentane	Hexane	LSR	FRN	Pyrolysis	FCC
PIONA (wt%)						
Total Iso Paraffins	42.3	2.5	36.9	36.2	14.9	30.9
Total Normal Paraffins	48.9	97.1	46.2	38.5	16.9	4.1
Total N-Olefins	1.7	--	--	0.1	16.8	11.6
Total I-Olefins	1.3	--	--	--	17.3	19.4
Total Di Olefins	0.3	--	--	--	2.2	0.3
Total Saturated Naphthenes	2.0	0.4	14.7	14.9	15.7	7.4
Total Unsaturated Naphthenes	0.1	--	--	--	10.4	4.2
Total Aromatics	3.4	--	2.3	10.3	5.8	22.4
Total	100.0	100.0	100.0	100.0	100.0	100.0
Carbon Number (wt%)						
Butanes (C4)	1.0	--	0.5	3.9	8.6	1.2
Pentanes (C5)	88.8	0.1	38.5	19.1	78.6	25.2
Hexanes (C6)	7.2	99.8	59.9	24.9	8.4	22.8
Helptanes (C7)	1.7	0.1	1.1	23.5	4.5	19.5
Octanes (C8)	0.8	--	--	20.0	--	17.4
Nonanes (C9)	0.3	--	--	5.6	--	10.0
Decanes (C10)	--	--	--	0.0	--	3.6
Undecanes (C11)	--	--	--	3.0	--	0.4
Total	100.0	100.0	100.0	100.0	100.0	100.0
Yield Selectivities (wt%)						
Conversion	35.2	34.2	30.9	35.2	35.3	36.1
Hydrogen	0.8	0.7	0.6	0.8	0.5	0.4
Methane	7.8	1.5	7.8	5.6	3.7	1.5
Ethane	10.1	9.5	10.4	7.3	6.0	2.2
Ethylene	19.2	7.1	16.5	12.6	17.3	11.7
Propane	5.4	12.3	8.6	8.4	10.0	4.7
Propylene	32.1	39.8	34.3	31.9	34.6	46.0
Isobutane	0.8	0.9	1.0	2.8	2.2	0.9
Normal butane	7.6	4.5	2.8	11.2	5.7	2.8
Butylene	16.1	23.7	18.0	19.4	20.1	29.7
Total olefin	67.4	70.7	68.8	63.9	72.0	87.5

Table 2. Gasolfin yield selectivities.
Source: Author

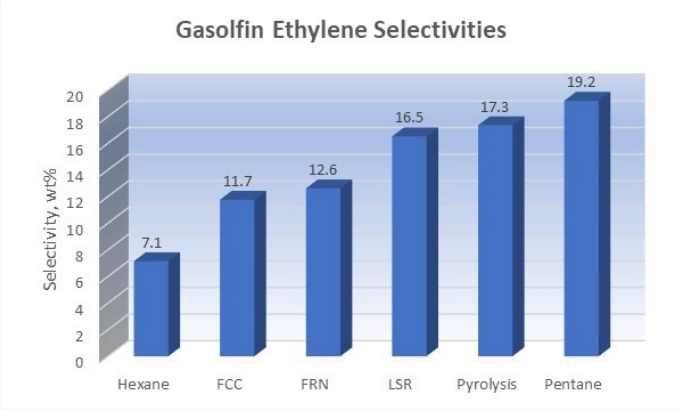


Chart 3. Typical ethylene selectivities for various feedstocks.
Source: Author

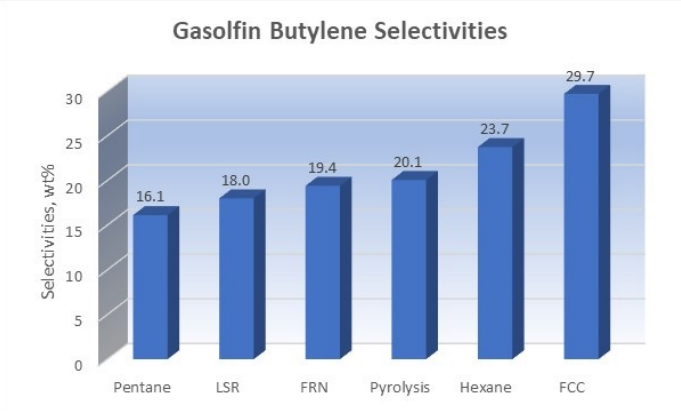


Chart 4. Typical butylene selectivities for various feedstocks.
Source: Author

Inovacat recently converted three feedstocks, LSR, FRN and HCN, from an Asian refiner seeking maximum propylene. These feeds were converted across a single batch of Gasolfin catalyst deactivated to simulate a mid-catalyst life age. The LSR and FRN feeds were cracked at an initial reactor inlet temperature of 600 °C and a 550 °C reactor inlet temperature for the FCC naphtha. The reactor temperature was increased once the conversion had reduced by 25%. The reactor temperature was gradually increased as the catalyst deactivated. Each cycle was terminated when the reactor temperature reached 620 °C. The cycle length for each feed was three to four days.

Table 3 provides the feed composition while **Chart 5** provides the conversion for the LSR feed and **Chart 6** provides the propylene yield for the FRN feed.

Chart 5 indicates the effect of reactor temperature on conversion for LSR naphtha. The cycle was initiated at 600 °C. The reactor temperature was increased by 10 °C after 48 hours followed by a second 10 °C increase after 63 hours. The conversion increased by 3.7 wt% for each 10 °C temperature increase. The rate of conversion loss was -0.15 wt%/hr after 48 hours at

600 °C followed by a -0.10 wt%/hr at 610 °C and -0.12 wt%/hr at 620 °C. The average conversion rate of decline was -0.136 wt%/hr over the 76-hour cycle. The cycle was terminated after 76 hours with a final conversion of 24.0 wt%, representing a 10% overall conversion loss after three days of operations. The cycle length for LSR feeds is expected to be approximately 110 hours (4.5 days) prior to reaching end of run temperatures.

Chart 6 demonstrates that the propylene yield for the FRN feed began at 30 wt% and gradually increased by 2.0 wt% over the first 24 hours of operation. The propylene selectivity averaged 32.0 wt% for the remainder of the cycle. The reactor temperature was increased by 20 °C after 62 hours to compensate for conversion loss. It is significant to note that propylene selectivity is insensitive to reactor temperature increases. The butylene selectivity dropped by 0.9 wt% after the temperature increase whereas the ethylene selectivity increased by 2.6 wt%. The total olefin selectivity showed a net increase of 1.5 wt% after the temperature adjustment. Similar responses were observed for the LSR and HCN feeds.

Feed Analysis	LSR	FRN	FCC
PIONA (wt%)			
Total Iso Paraffins	36.9	36.2	32.7
Total Normal Paraffins	46.2	38.5	7.0
Total N-Olefins	--	--	8.2
Total I-Olefins	--	0.2	15.1
Total Di Olefins	--	--	0.0
Total Saturated Naphthenes	14.6	14.9	8.4
Total Unsaturated Naphthenes	--	--	3.2
Total Aromatics	2.3	10.3	25.5
Total	100.0	100.0	100.0
Carbon Number (wt%)			
Butanes (C4)	0.5	3.9	1.0
Pentanes (C5)	38.5	19.1	23.3
Hexanes (C6)	59.9	24.9	20.6
Helptanes (C7)	1.1	23.5	16.2
Octanes (C8)	--	20.0	15.2
Nonanes (C9)	--	5.6	11.8
Decanes (C10)	--	0.0	7.1
Undecanes (C11)	--	1.0	3.8
Dodecanes (C12)	--	2.1	1.1
Total	100.0	100.0	100.0

Table 3. Refiner feed properties.
Source: Author

The Gasolfin process rapidly converts olefins and unsaturated naphthenes present in cracked naphthas (HCN, PN). The Gasolfin process is modified for converting cracked naphthas. The aromatics are first extracted followed by the reaction of the olefins and unsaturated naphthenes at relatively mild reaction conditions. The more refractive paraffinic and saturated naphthenes are then cracked under more severe operations.

Reactor Configuration and Operations

The Gasolfin catalyst has been designed to operate in a fixed-bed reactor. The conversion for maximum propylene yield is feed dependent but typically is about 35 wt%. Paraffinic feeds are delivered to the Gasolfin unit feed drum. This feed will exchange heat with the reactor effluent and then receive additional heating in a fired heater. Typical reactor inlet temperatures are 500-600 °C. The reaction is endothermic resulting in a temperature drop in the adiabatic reactor. The reactor effluent is cooled and then delivered to a single stage equilibrium flash drum. The light ends are sent to product recovery while the non-reacted feed is returned to the feed drum. The Gasolfin catalyst reacts all non-aromatic feeds to extinction. The recycle ratio is 2.0-2.5 depending on the feed composition.

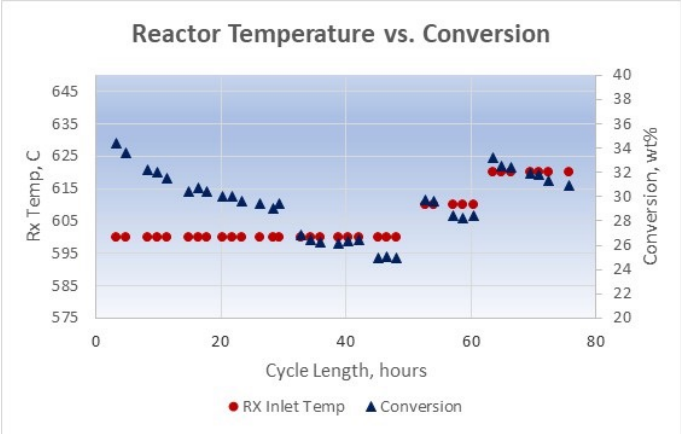


Chart 5. Reactor temperature vs. conversion – LSR feed.
Source: Author

The reactor section is operated as a simulated moving bed operation in which multiple reactors are operating in parallel having differing degrees of time on-stream. The cycle length of each reactor is up to five days. At the end of each reactor cycle the reactor will be taken offline, stripped of residual hydrocarbon, then submitted to an in situ regeneration. The de-coking operation lasts about six hours. After completion, the reactor will be purged of oxygen and placed in standby mode under an inert atmosphere until the reactor is placed into service for the next cycle. The catalyst life is expected to be at least three years.

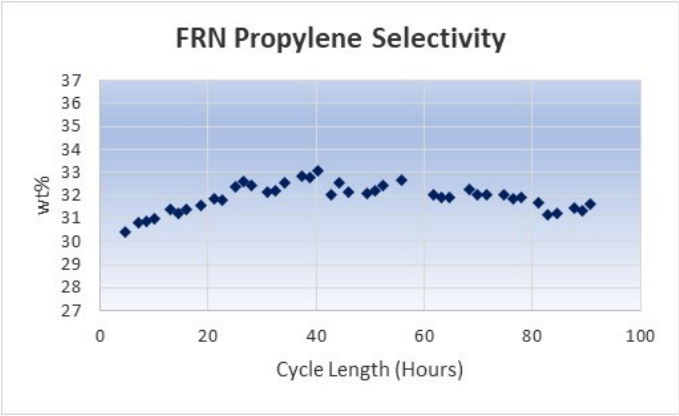


Chart 6. Propylene selectivity – FRN feed.
Source: Author

Gasolfin Enhances Flexibility

The Gasolfin catalyst is the first genuine catalytic-driven light ends conversion process in the refining and petrochemical industries. The Gasolfin process enables a standard fuels refinery to expand its olefin producing capacity well beyond the

levels possible in the FCC unit. This process converts naphtha produced in the crude distillation unit, the hydrocracker, hydrotreaters, and all conversion processes such as fluid cracking and coking. The process is equally efficient at converting intermediate and by-product naphtha streams.

The Gasolfin process enables refiners the following upgrading capabilities:

- *Pentane cracking.* Normal pentanes have an octane level of 61.7 RON. Normal and isopentanes have high vapor pressures of 15.7 and 72.6 psia at 38 °C, respectively. These two characteristics have a strong negative impact on the refinery gasoline pool. The operating severity of the high-octane units such as catalytic reforming, isomerization, and alkylation must be increased to offset the octane penalty while the amount of butane blending is reduced due to the high vapor pressures. The Gasolfin process allows a refiner to divert all pentane streams away from the gasoline blending plant into the Gasolfin unit. A 64 wt% total olefin yield is observed with pentane cracking. The propylene selectivity is 32 wt% with an EPB ratio of 28:47:25.

- *Polymer-grade propylene.* A Gasolfin unit will enable all operators to either begin polymer-grade propylene production or increase existing capacity.

- *Hydrocracker-based refineries.* Hydrocracker-based refineries have the excess isobutane required for alkylation but lack the butylene typically produced in the fluid cracker. A hydrocracker centered refinery may divert its virgin naphthas and/or its hydrocracker naphtha to a Gasolfin plant to produce propylene and butylene. Such an operation will permit the construction of an alkylation unit to enhance the production of premium gasoline.

- *Steam cracker operations.* Steam crackers processing a mix of light gas (ethane, LPG, etc.) and light naphtha are required to recycle pentanes back to the feed furnace to thoroughly convert these refractive molecules. By including a Gasolfin unit into the steam cracker complex may more efficiently convert the pentanes into ethylene, propylene, and butylene, thereby eliminating this recycle stream and increasing fresh feed rate.

- *Transition technology.* The Gasolfin catalyst will convert both fossil-derived and bio-derived naphthas without loss in efficiency. A Gasolfin unit will convert traditional naphthas today and all bio-derived naphthas in the future. The Gasolfin process is an ideal transition technology.

The Gasolfin Process – Paraffinic Feedstock Conversion

The Gasolfin naphtha-to-olefins process will convert naphtha boiling range hydrocarbons from any process within the refinery, petrochemical plant, or gas field. The highest efficiency and lowest GHG emissions are achieved by eliminating LPG, diesel fractions, and aromatics from the feed. The Gasolfin process receives all paraffinic feedstocks into a feed surge drum. The fresh feed is combined with recycle (non-reacted feedstock) and enters the reactor feed effluent heat exchange network. The feed is heated to the reactor inlet temperature in a fired heater and charged to the Gasolfin reactor.

The required reactor inlet temperature for conversion is a function of the feed composition. Low molecular weight feeds require more severe reaction conditions than higher molecular weight feeds. For example, pentane requires more energy to crack than nonane. The reactor inlet temperature will be increased as the percentage of pentane in the feed increases.

The endothermic Gasolfin reactor is a once through fixed-bed reactor system in which multiple reactors are operating in parallel. The number of reactors employed is a function of the desired unit feed rate. The typical cycle length for each reactor is up to five days. In a four-reactor operation, three reactors will be in service with the fourth reactor in regeneration or in standby mode. Each reactor will have a target conversion rate of 30-40 wt%. A typical start-of-cycle reactor inlet temperature will be 550-600 °C with an end-of-cycle temperature of 625-650 °C. The temperature is increased to maintain conversion. A reactor recently brought into service will have the lowest inlet temperature while the reactor longest in service will have the highest temperature.

The propylene selectivity increases asymptotically to the maximum level over the first 24 hours of operations (per **Chart 6**). The propylene and butylene selectivity are not affected by reactor inlet temperature while the ethylene selectivity increases with reactor temperature.

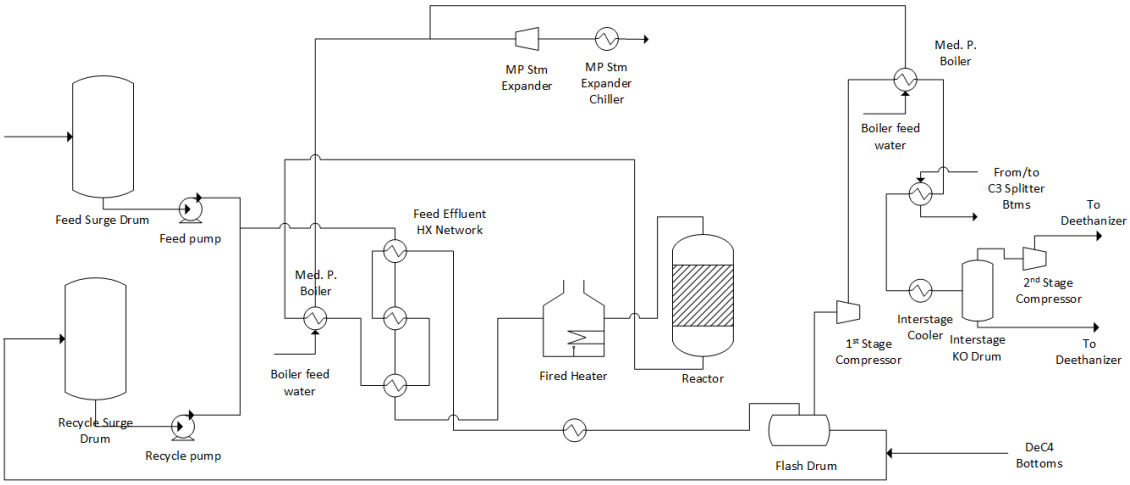
Catalytic cracking generally produces too much coke to enable operation in a fixed bed process. Gasolfin has developed a patented catalytic system which modulates the catalyst active sites to enable a swift reaction rate while suppressing coke formation. The PDH and FCC processes operate with moving or fluidized catalyst beds due to the significant coke yields of 4-5 wt% in each process. The Gasolfin coke yield produces more than one order of magnitude less coke during reaction than FCC and PDH, which permits the process to be operated in the much simpler fixed bed configuration. The Gasolfin process is not only the first light end catalytic conversion process in the industry, but unique in its ability to operate in a fixed bed.

The effluent product from each reactor is combined and routed to the feed effluent heat exchange system. The heat exchange network efficiently exchanges heat with the feed thereby limiting the duty of the fired heater.

Additional heat in the reactor effluent is extracted to generate medium pressure steam and then is further cooled to setpoint via cooling water prior to being charged to an equilibrium flash drum. The light olefin is separated from the reactor effluent and charged to the reactor effluent two-stage compressor. The remaining non-reacted feed is recycled back to the reactor feed.

The compressed light gasses are charged to a cryogenic deethanizer column for the extraction of the ethane and lighter fraction. The Gasolfin process deviates from the standard light ends recovery section of the FCC unit by the replacement of the stripper–absorber–sponge column configuration with a cryogenic deethanizer. The Gasolfin cryogenic deethanizer column reduces overall energy consumption, eliminates the need of a depropanizer column, and results in smaller equipment in the cryogenic ethylene recovery system. The deethanizer overhead stream is sent to a methane stripper (demethanizer) followed by the ethane ethylene splitter (C_2 splitter) tower. The ethylene is recovered as 99.5% or greater purity polymer grade ethylene.

The bottoms stream from the deethanizer column is delivered to a debutanizer column. The bottoms stream from the debutanizer column consists of non-reacted feed. The non-reacted feed being returned to the reactor inlet enables conversion of the feedstock to extinction.



PFD #1. Paraffin conversion reaction section PFD. Source: Author

The debutanizer overhead stream is delivered to the C_3C_4 splitter column. The overhead propane propylene stream is sent to the propane propylene splitter (C_3 splitter). A 99.5% purity or greater propylene product is recovered which may be sold as polymer grade propylene. The propane stream is sent to storage.

The C_3C_4 column bottoms product consists of butylene plus small amounts of normal and isobutane. This stream may be sent to an alkylation unit to produce a high-quality blending component, alkylate, or sent to product storage. Alternatively, this butylene enriched stream may be directed to an optional butylene conversion reactor for conversion into additional ethylene and propylene.

A unique quality of the Gasolfin naphtha-to-olefins process is the high degree of heat integration. A portion of the ethane produced in the process is used as refrigerant for the demethanizer feed cold box and to chill the deethanizer overhead condenser. The waste heat generated by compression of the ethane refrigerant is used to reboil multiple distillation columns including the debutanizer, deethanizer, and other columns.

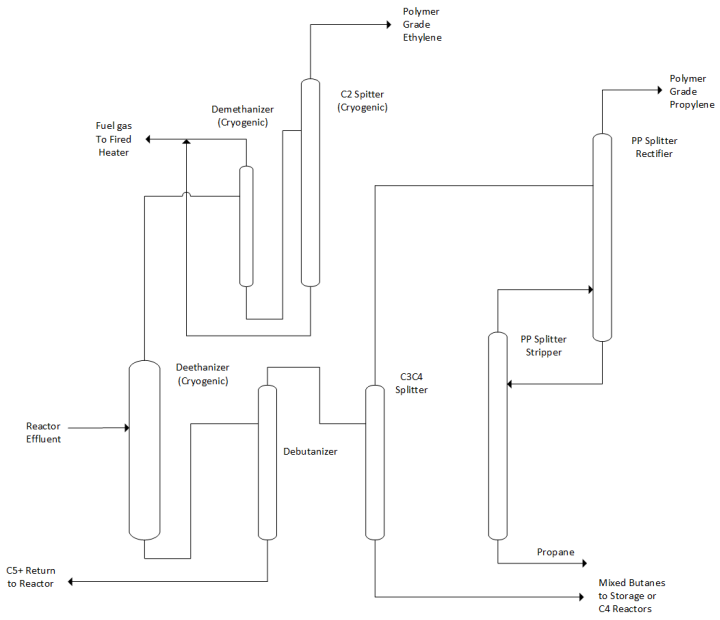
The C_2 splitter condenser operates at a higher temperature than do many of the other cryogenic distillation columns. A propane refrigerant system has been selected as a more energy efficient, lower compression required, alternative coolant for this and other cryogenic columns. The waste heat generated via the compression of the propane refrigerant is also used to reboil several distillation columns.

Finally, waste heat from the first stage reactor effluent compressor is used to reboil the C_3 splitter column and to produce additional medium pressure steam from remaining heat present in the compressor discharge. The medium pressure steam generated from first stage reactor effluent compressor and from in the remaining heat in the reactor effluent after the reactor feed effluent exchange network is then converted to electricity. This electricity is used to drive all the pumps on the process plus the second stage reactor effluent compressor.

The Gasolfin Process – Olefinic Feedstock Conversion

The Gasolfin naphtha-to-olefins process will also convert olefinic feedstocks from the FCC, delayed coker, pyrolysis naphthas, and other sources. Olefinic feeds typically consist of up to 50% olefins and up to 25 wt% aromatics with the remainder consisting of paraffins and naphthenes. The olefins in these feeds are significantly more reactive than paraffins and require lower reaction severity for complete conversion.

The aromatics present in olefinic feedstocks are inert in the Gasolfin process. These aromatics will first be extracted using state of the art aromatic extraction solvents which are not deactivated by the presence of olefins. One such commercially proven aromatics extraction process is the Sulzer GT-BTX-PluS technology.

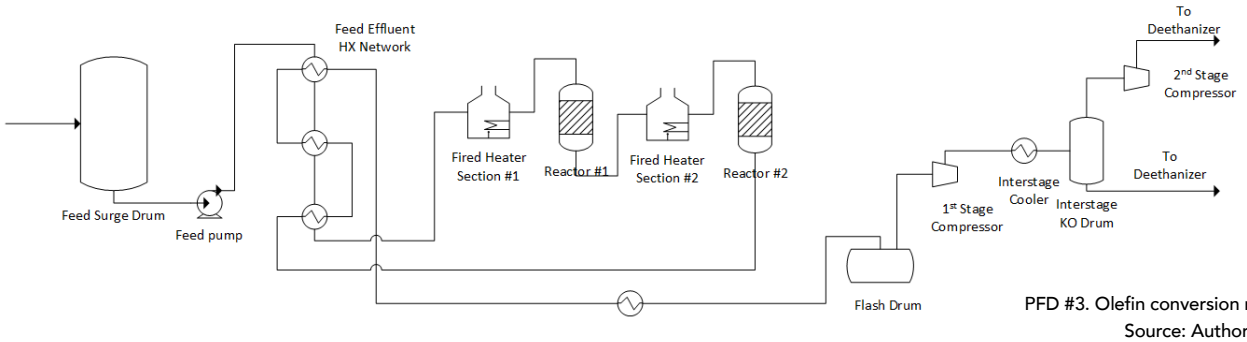


PFD #2. Gasolfin product recovery section PFD.
Source: Author

The olefinic feed is then preheated in a reactor feed effluent heat exchanger network and then further heated to rection temperature in a sectioned fired heater. The first section of the radiant zone heats reactor #1 feed while section #2 of the radiant zone heats reactor #2. Reaction temperatures are lower than for paraffin conversion. The reactor effluent from reactor #1 is routed directly to the second radiant section of the fired heater and returned to reaction temperature. The olefins and unsaturated naphthenes will be fully converted after reactor #2.

The olefins and unsaturated naphthenes are fully converted in the olefin reactors, while the paraffins and saturated naphthenes remain unconverted. Avoiding paraffin conversion prevents hydrogen production in the reactors, thereby eliminating hydrogen transfer reactions. In this manner, the maximum value from these olefins is achieved by maintaining the maximum light olefin yield. Additionally, the series operation of these reactors limits the fired heater duty requirement in the olefin conversion section.

The remaining paraffins and saturated naphthenes will be converted in paraffin reaction section under increased severity. The standard Gasolfin operation is to first convert the olefins and unsaturated naphthenes at low severity followed by paraffin and saturated naphthene conversion at higher severity. The paraffins and saturated naphthenes exiting the Olefin conversion section may be combined with additional low valued paraffins present in the refinery or petrochemical plant such as pentane or LSR naphtha.



PFD #3. Olefin conversion reactor PFD.
Source: Author

The Gasolfin Process – Butylene Conversion

Many refineries in Europe and Asia are not equipped with Alkylation plants and therefore place low value on the butylene produced in the Gasolfin process. Additionally, some refiners may not possess the capacity to process additional butylene into alkylate. Gasolfin offers an optional reaction system for the conversion of butylene into additional ethylene and propylene Gasolfin butylene conversion.

This process initiates with the C_3C_4 splitter bottoms stream. In this process, the mixed butane stream is heated via a feed effluent heat exchange network. The feed is then passed through a sectioned fired heater and then fed to reactor #1. The reactor effluent from reactor #1 is reheated and then fed to reactor #2. The reactor effluent from Reactor #2 then exchanges heat with the feed. Like the Olefin conversion section, the reaction conditions of the butylene reactors will drive the full conversion of the butylene without conversion of the C_4 paraffins.

Avoiding normal and isobutane conversion eliminates hydrogen production in the reactors, thereby preventing hydrogen transfer reactions. In this manner, the maximum value from the butylene is achieved by maintaining the maximum propylene and ethylene yield. Additionally, the series operation of these reactors limits the fired heater duty requirement in the butylene conversion section.

The reactor effluent stream is compressed in the butylene conversion compressor and sent to a depropenizer column. The bottoms product is composed of saturated butanes which are sent to product storage. The overhead stream is composed of ethylene and propylene. This stream is further compressed and delivered to a deethenizer column. Polymer grade ethylene at 99.5 wt% plus is recovered as the overhead product and polymer grade propylene at 99.5 wt% plus as the bottoms product.

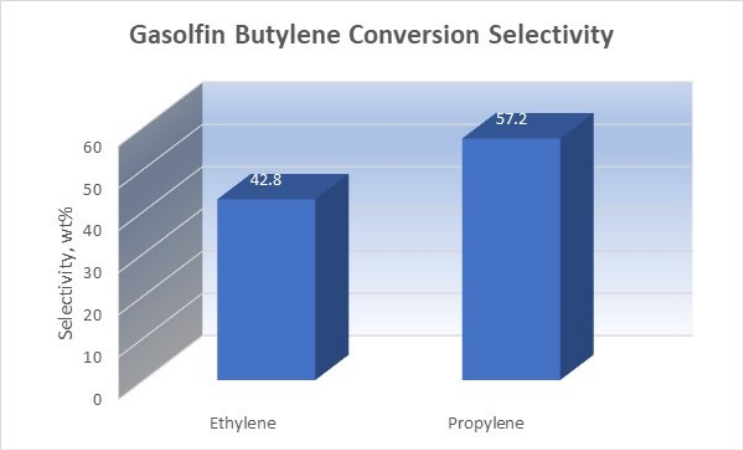
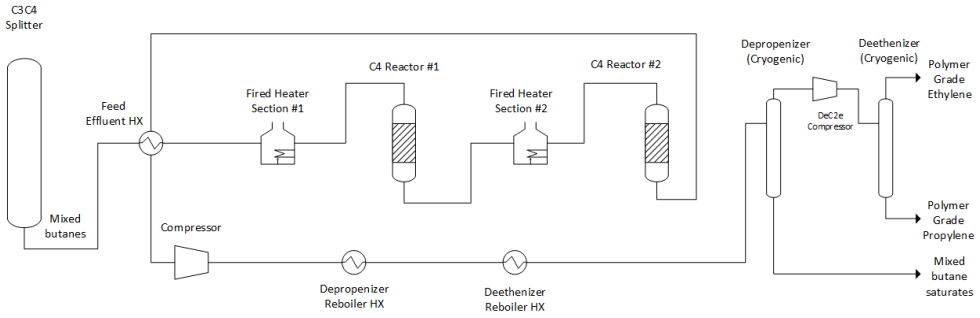


Chart 7. Butylene conversion selectivity.
Source: Author

This portion of the unit also benefits from significant heat exchange. The deethenizer and depropenizer columns are both reboiled using waste heat from the butylene conversion compressor. The deethenizer and depropenizer condensers are chilled using the propane refrigerant system produced in the olefins recovery section of the standard Gasolfin process.



PFD #4. Butylene conversion section PFD.
Source: Author

Meeting GHG Emissions Targets

The Gasolfin process enables refiners and petrochemical operators to convert low-valued paraffinic naphthas to the highly valued ethylene, propylene, and butylene olefins with ultralow GHG emissions. The catalytic-driven Gasolfin process operates at lower temperatures than a steam cracker. Both FCC and PDH processes are catalytic driven, yet with a coke yield of 4-5 wt%. The Gasolfin process is more than an order of magnitude lower in coke yield. This results in a significant reduction in the chemical CO_2 contribution of the Gasolfin process when compared with the FCC and PDH processes. The higher molecular weight of naphtha when compared with propane for PDH and ethane for most steam cracking operations also contributes to a lower heat of reaction.

The Gasolfin process will enable all light olefin operations to reduce GHG emissions. This process converts sustainable and bio-naphthas as readily as fossil-derived naphthas. This includes naphtha produced in Fischer Tropsch, pyrolysis, vegetable oil and animal fat operations, etc. The Gasolfin process is an ideal transition technology capable of producing highly valued olefins at very high yields.

Gasolfin Status

Inovacat has completed the bench scale and pilot plant testing of this technology. Inovacat is currently finalizing the FEED study for a demonstration unit to be operated in an Asian refinery. The demonstration plant will begin operations in 2025 and will be ready for commercialization in 2027. **Illustration 1** provides a simplified 3D image of the Gasolfin demonstration plant. This diagram provides an indication of the major pieces of equipment without all the interconnecting piping and secondary equipment. Inovacat is now in fundraising mode to finance this program to full commercialization.

Conclusion

The Gasolfin technology will accelerate the industry's reduction in GHG emissions, both in the conventional refinery and in a renewable refinery. The Gasolfin naphtha-to-olefins process converts paraffins, naphthenes, and olefins into maximum propylene with 50% or greater ultralow GHG emissions reductions. The applications for this new technology are many:

- An FCC centered refinery may transition their FCC catalyst to a high rare earth-based catalyst formulation for maximum naphtha yield followed by a Gasolfin operation for maximum propylene.
- All refiners will be enabled to separate their pentane and/or LSR streams currently being blended into gasoline and convert this low-octane, high-RVP component into light olefin.

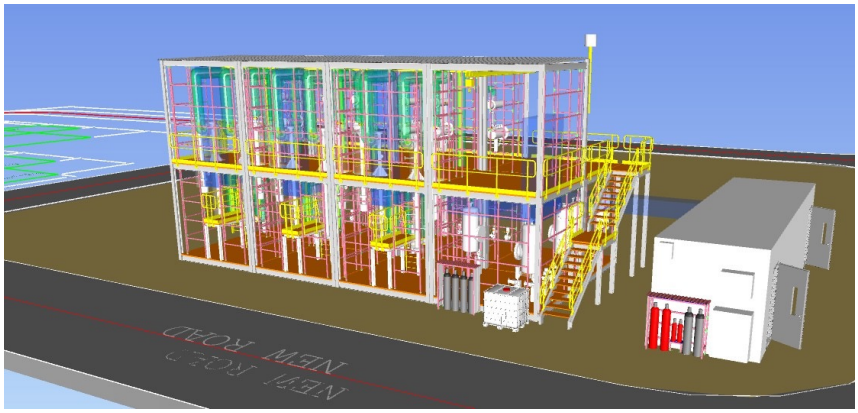


Illustration 1. Simplified Gasolfin demonstration plant.
Source: Author

- The Gasolfin unit is an investment today for processing fossil naphthas and for renewable naphthas in the future with low GHG emissions.

Your Author



Ray Fletcher, a chemical engineer with over 36 years of operating and process design experience, is Chief Technology Officer for Inovacat. Ray began his career working in the oil refining industry with Shell Oil and Texaco. He then worked for several catalyst companies including Albemarle and Johnson Matthey where he led various international FCC technical service and development divisions. Ray is currently working as Chief Technology Officer in two technology start-ups. These include Inovacat, which has developed the Gasolfin naphtha-to-olefins technology, and Alleo Energy, which has developed a modified pyrolysis process for the direct conversion of cellulose-to-fuel.

Industry Perspective continued from page 3.

The interdisciplinary consortium includes seven partners (three industrial and four research centers and universities) from five countries: the Bilbao School of Engineering; two French research centers: CEA (Commissariat à L'énergie Atomique et Aux Énergies Alternatives) and the CNRS (Centre National de la Recherche Scientifique); NWU (North-West University, South Africa); and leading companies in the sector like: Heraeus and Framatome (Germany), and Hygear (Netherlands). This consortium has experience, resources, infrastructure and recognized prestige in the field of LOHC technology and has come together to develop a LOHC dehydrogenation technology free of CO_2 emissions.

The International Congress on Catalysis (ICC) 2024

Hydrogen storage implying catalytic reactions is one of the topics of the 18th International Congress on Catalysis (ICC) that will be held in Lyon from July 14-19, 2024.The ICC 2024 (https://www.icc-lyon2024.fr/) will be attended by more than 2,000 expected delegates from sixteen countries. The scientific program comprises six plenary lectures delivered live by: 1) Prof. Umit Ozkan, Ohio State University; 2) Prof. Benjamin List, Director of the Max-Planck-Institut für Kohlenforschung; 3) Prof. Keiichi Tomishige, University of Tokyo; 4) Prof. Jeroen A. van Bokhoven, Paul Scherrer Institute; 5) Prof. Ulrike Diebold, Vienna University of Technology and 6) Prof. Thomas Maschmeyer, University of Sydney. The program also includes twenty-six keynote lectures, 320 oral presentations and 1,500 posters by recognized specialists in catalysis dedicated to thirty-three topics and a variety of satellite events. In the case of twenty-second topic, *Catalytic Reaction for Hydrogen Storage and Release*, it is mainly dedicated to hydrogen storage and transport including all technological advances for the H_2 value chain. Apart from LOHCs, other catalytic reactions linked to hydrogen storage, such as ammonia cracking and solid hydrides, will be presented.

Your Authors

Prof. Victoria Laura Barrio



Prof. V. Laura Barrio: industrial engineer and doctorate at the University of the Basque Country UPV/EHU. She was a postdoctoral researcher at the Engler-Bunte-Institut (Karlsruhe Institute of Technology). Professor at Bilbao Faculty of Engineering, current research fields are reactors and catalytic processes focused on advanced reaction systems for syngas/hydrogen production from renewable sources, hydrogen storage, CO_2 valorisation and LCA analysis. Barrio is co-author of more than 90 articles and patents on these subjects. Collaboration with Spanish accreditation agency (ENAC) in EPD process certifications.

Dr. Valérie Meille



Dr. Valérie Meille, a chemical engineer from CPE Lyon, received her PhD in kinetics and catalysis in 1997 from Université Claude Bernard Lyon 1. After a postdoctoral placement at Shell research, she obtained a permanent researcher position at the CNRS. She worked for 22 years in a catalysis and chemical engineering lab (LGPC), working on structured catalytic reactors. She has been pursuing her research at IRCELYON (Institute for Research in Catalysis and Environment) since 2020. Her main research fields currently concern air catalytic treatment and the chemical storage of hydrogen.

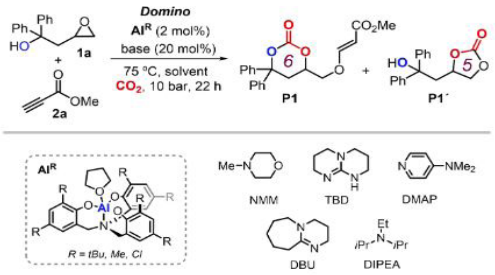
Experimental Abstracts

Catalytic Domino Three-component Synthesis of Functionalized Heterocycles from Carbon Dioxide

Among the catalytic transformations of carbon dioxide (CO_2) into functionalized molecules, its conversion into cyclic carbonates is of significant importance. Although five-membered cyclic carbonates are readily available via catalytic (3+2) annulation reactions of epoxides and CO_2, coupling of larger cyclic ethers (oxetanes) has proven more challenging. Herein, the authors describe the development of a catalytic domino, three-component reaction that utilizes β–epoxy alcohols, CO_2, and a variety of electrophiles capable of transforming carbon dioxide into functionalized six-membered cyclic carbonates. The catalytic process combines an initial carboxylative cyclization of 13-epoxy alcohols followed by an oxa-Michael reaction, affording a broad array of heterocyclic structures.

Based on the premise that upon reaction with CO_2, a β-epoxy alcohol would yield a six-membered cyclic carbonate with a pendant primary free alcohol, these workers developed a screening technique which ultimately identified a tert-butyl substituted Al^{III}-complex (Al^{tBu}) and 4-methyl morpholine (NMM) as an effective binary catalyst. The choice of reaction solvent was found to have a pronounced effect. Thus, using toluene instead of methyl ethyl ketone (MEK) resulted in a 90% yield of the target compound P1 (see **Table 1).** Subsequent studies included evaluations of alternative aluminum catalysts, the scope of propiolic esters and β-epoxy alcohols generated using this catalyst system, and the use of other types of electrophiles under the optimized reaction conditions. Finally, control experiments were conducted to investigate the requirement of both catalyst components to induce a domino process.

Table 1. Selected data for screening of the optimal conditions. [a]

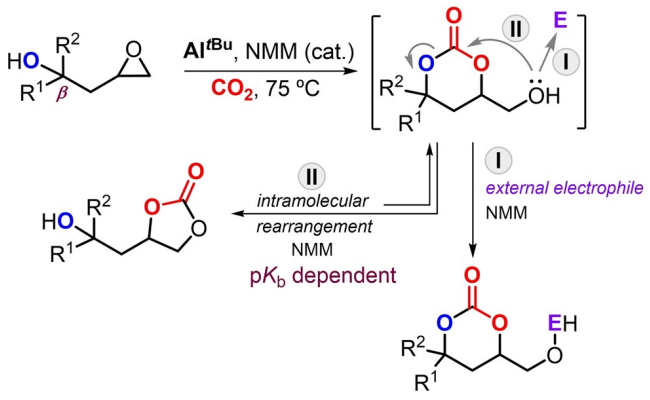


Entry	Al^R (R)	Base	Solvent	Conv. [%][b]	2a [equiv]	P1 [%][b]	P1' [%][b]
1[c]	tBu	NMM	MEK	>99	1.5	42	37
2	tBu	NMM	MEK	>99	1.5	71	18
3	Me	NMM	MEK	>99	1.5	33	27
4	Cl	NMM	MEK	15	1.5	<10	<10
5	tBu	TBD	MEK	>99	1.5	trace	79
6	tBu	DMAP	MEK	>99	1.5	trace	22
7	tBu	DBU	MEK	>99	1.5	trace	22
8	tBu	DIPEA	MEK	<10	1.5	–	–
9[d]	tBu	NMM	MEK	>99	1.5	72	18
10[e]	tBu	NMM	MEK	>99	1.5	74	18
11[e]	tBu	NMM	MEK	>99	2.0	87	11
12[e]	tBu	NMM	MEK	>99	2.5	84	10
13[e]	tBu	NMM	MEK	>99	3.0	80	10
14[e]	**tBu**	**NMM**	**Tol**	**>99**	**2.0**	**90(88)[f]**	**<10**
15[e]	tBu	NMM	ACN	>99	2.0	71	18
16[e]	tBu	NMM	1,4-DO	>99	2.0	80	<10

[a] Unless stated otherwise, all the reactions were carried out with **1a** (0.30 mmol), **2a** (0.45-0.90 mmol), 0.006 mmol of Al^R (2 mol%), 0.06 mmol of the base (20 mol%; premixed with 0.40 mL of solvent) at 10 bar CO_2 and 75 °C for 22 h. [b] Determined by ^1H NMR ($CDCl_3$) using mesitylene as internal standard, the ratio of *E/Z* for all cases was >20:1. [c] Base and solvent were not premixed. [d] 0.30 mL of solvent was used. [e] 0.20 mL of solvent was used. [f] Yield of isolated product. Abbreviations: MEK = methyl ethyl ketone, Tol = toluene, 1,2-DO = 1,4-dioxane, NMM = *N*-methyl morpholine.

The authors propose the following mechanism based on the control experiments and other observations (**Scheme 1**). The first step begins with the conversion of the 3-epoxy alcohol into a free-alcohol six-membered carbonate based on the presence of both the Al-complex and NMM acting as a binary catalyst. Whereas the Al-complex has the potential to activate the epoxide, the base NMM is likely involved in the activation of the alcohol group to facilitate its attack on CO_2. The resulting carbonate species can then ring-open the activated epoxide, forming the six-membered heterocyclic intermediate. From this point onwards, the reaction can proceed through two distinct and competitive pathways (**I and II**). Activation of the alcohol in the six-membered intermediate by NMM offers a way to engage it in an oxa-Michael reaction, affording the desired functionalized carbonate (**pathway I**) with E representing an electrophilic reaction partner. Alternatively, the activated alcohol in the six-membered heterocyclic intermediate can advance towards the free-alcohol, five-membered cyclic carbonate (**pathway II**) through an isomerization process, which is thermodynamically driven and lowers the yield of the larger-ring congener in the domino process. The authors suggest that the pKb of the base used in this process controls the equilibrium between the five- and six-membered free-alcohol carbonates and, thus, the chemo-selectivity of the domino process. Shi, Wangyu, Chang Qiao, Jordi Benet-Buchholz, and Arjan W Kleij. 2023. ChemSusChem. https://doi.org/10.1002/cssc.202301626.

Scheme 1. Proposed mechanism.



Controlling the Coke Formation in Dehydrogenation of Propane by Adding Nickel to Supported Gallium Oxide

Additional preparative methods not based on the use of petroleum-based feedstocks are currently under development to meet the growing demand for propylene. Production of propylene from abundant shale gas reserves is of particular interest. The non-oxidative propane dehydrogenation (PDH) is of high value since it generates hydrogen as a valuable byproduct. Although this technique has proven effective, the high temperatures associated with these processes result in catalytic deactivation due to coking. The use of Pt or Pt alloys such as Pt-Ga can partially offset this phenomenon. Pt-Ga alloys have been reported to yield propylene with selectivity (around 95%), high propane conversion (up to 40%), and inhibited coke formation. In an effort to replace Pt with a less costly alternative, the authors herein report the synthesis of a gallium oxide catalyst, modified with NiGa alloys, capable of producing comparable results.

The preparative procedure employed by these workers involved using atomic layer deposition (ALD) and incipient wetness impregnation on silica (**Figure 1**). The resulting product was then used as a starting material to investigate different nickel loadings in PDH under industrially relevant Oleflex-like conditions. X-ray diffraction (XRD) measurements indicated the formation of Ni_3Ga_1, Ni_1Ga_1, and Ni_2Ga_3 alloys, while lower nickel loadings yielded gallium-richer species. Although the NiGa alloys did not directly affect propane conversion, the selectivity to propylene was significantly enhanced. Conducting in situ thermogravimetric analysis under PDH conditions revealed that the addition of Ni to GaO_x reduced the coking rate by over 50%. Because NiGa alloys are known for their capability to activate hydrogen, the coke reduction can be explained by a hydrogen spillover from NiGa to GaO_x. Energy dispersive X-ray diffraction (EDX) scans were conducted to determine the location of nickel and gallium along the sample (**Figure 2**). The mappings disclosed that the nanoparticles consist of nickel and gallium, while the nickel counts are always situated in close proximity to gallium. An EDX line scan along two particles of the Ni (1.6 wt %)-GaO_x specimen shows that the average counts of nickel were approximately two-thirds that of gallium along both particles. Consequently, nickel and gallium are always situated next to each other in a constant composition.

Use of the Ni(1.6%)-GaO_x/SiO_2 catalyst resulted in the highest propylene yield among the Ni—GaO_x samples, prompting further investigation of this system in multiple consecutive PDH cycles. Catalyst regeneration during a periodic PDH process was achieved by an oxidative treatment in which the coke was successfully burned off between the PDH cycles. XRD and STEM indicated that although the structural integrity of the nano-alloys and gallium oxide was disturbed, propylene selectivity was maintained in all three PDH periods. Baumgarten, Robert, Piyush Ingale, Fabian Ebert, et al. 2023. ChemCatChem. https://doi.org/10.1002/cctc.202301261.

Figure 1. Schematic synthesis procedure of the NiGa-modified gallium oxide catalysts, supported on silica. The denotation ALD indicates atomic layer deposition and IWI stands for incipient wetness impregnation.

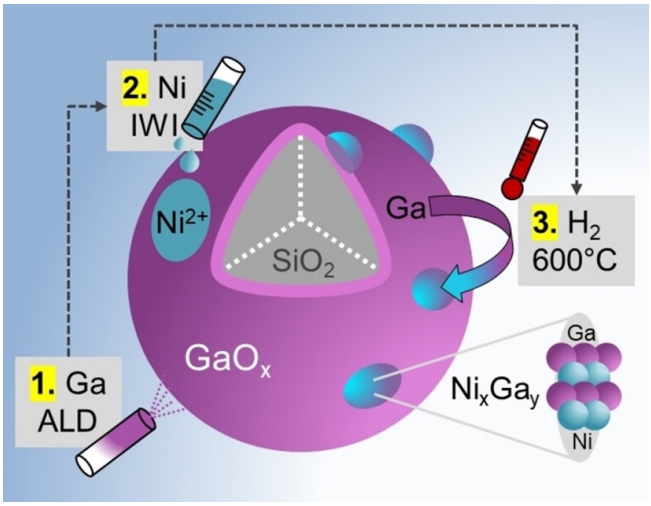
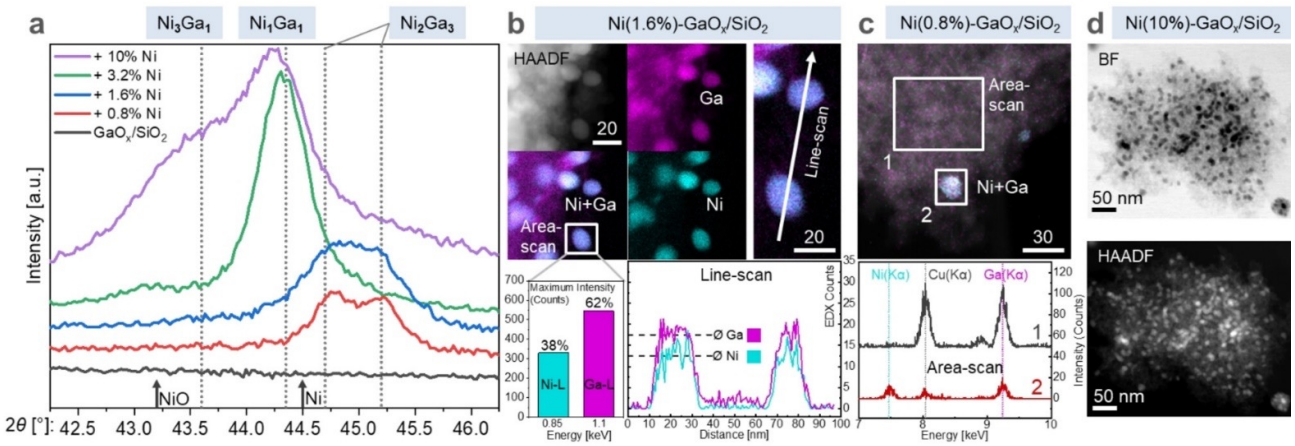


Figure 2. (a) X-ray diffractograms of the Ni-modified gallium oxide catalyst after 12 h TOS. The main reflections of crystalline NiGa alloys, Ni metal, and NiO are indicated according to literature. (b) Scanning electron microscopy (STEM) images (HAADF), EDX mappings and EDX line scan of GaO_x/SiO_2 modified with 1.6 wt% Ni. Atomic counts of Ni and Ga were collected and determined by the EDX detector. Ga is indicated in purple and Ni in turquoise color. (c) EDX mappings of 0.8 wt% Ni on gallium oxide. (d) STEM images of 10 wt% Ni on gallium oxide. All measurements were conducted on spent catalysts, after 12 h PDH.



Shearing Liquid-crystalline MXene into Lamellar Membranes with Super-aligned Nanochannels for Ion Sieving

The use of ion-selective membranes has emerged as a critical technique for separating monovalent/ multivalent ions. However, efficient monovalent/monovalent ion sieving has proved challenging due to their same valence and similar radii. Herein, the authors discuss the preparation and use of a two-dimensional MXene membrane with super-aligned slit-shaped nanochannels with ultrahigh monovalent ion selectivity. This membrane exhibited ultrahigh selectivities toward Li^+/Na^+, Li^+/K^+, and Li^+/Rb^+ separation and a permeation rate outperforming state-of-the-art membranes.

MXenes are formed from layered MAX-phase materials (such as Ti_3AlC_2) possessing the generic formula $M_{n+1}X_nT_x$ where M represents an early transition metal, X denotes carbon and/or nitrogen, T refers to the terminating surface functional groups (— OH, =O, and —F), and n varies from 1 to 4. These researchers discovered that applying shear pressures to a liquid-crystalline (LC) MXene nanosheet dispersion (**Figure 1a**) resulted in the formation of defect-free membranes with super-aligned nanochannels, good in-plane stacking order, and accurate interlayer spacing of 6 Å. These LC MXene membranes exhibited rapid and selective transport of Li^+ over other monovalent ions M^+, resulting in superior Li^+/M^+ separation performance.

A series of MXene membranes were prepared from MXene nanosheet dispersion of different concentrations. In addition, MXene membranes were generated from the non-liquid-crystal MXene dispersion with a lower MXene concentration (NLCMM). Evaluation of the liquid-crystalline Mxene membrane (LCMM) indicated that the number of permeated ions increases linearly with time (**Figure 2a**), with the permeation rate of Li^+ being as high as ~ 0.35 mol m^{-2} h^{-1}, compared to much lower values for Na^+, K^+, and Rb^+, (0.0079, 0.0070, and 0.0057 mol m^{-2} h^{-1}) However, for the NLCMM, the permeation rate of Li^+ is as low as ~ 0.025 mol m^{-2} h^{-1} (**Figure 2 b**) a result likely associated with the MXene nanosheet stacking order of the membranes. The super-aligned structure endows the LCMM with a precise channel size of ~ 6 Å, while disordered nanosheet stacking might lead to a broader distribution of channel sizes for NLCMM.

To better understand the ion sieving mechanism, these investigators performed density functional theory (DFT) and classical molecular dynamics (MD) simulations of the ion hydration states and ion transport through simulated LCMM and NLCMM channels. The results indicate that in MXene nanochannels, the hydrated Li^+ with a tetrahedral shape has the smallest diameter among the monovalent ions, contributing to the highest mobility. In addition, the weakest interaction was found between hydrated Li^+ and MXene channels, which also contributes to the ultrafast permeation of Li^+ through the super-aligned MXene channels. Lingzhi H, Haoyu W, Li D, et al. 2024. Angew. Chem. Int. Ed. doi.org/10.1002/anie.202314638

Figure 1. Preparation of the LCMM. (a) Schematic illustration of the fabrication of LCMM by shearing LC MXene nanosheets and the corresponding separation process. (b) Scanning electron microscopy (SEM) images of MXene nanosheets and (c) size distribution based on 200 nanosheets. (d) Polarized optical microscopy (POM) images of MXene dispersions for the concentrations of 5, 10, 15, and 20 mg ml^{-1} with the illustrations of MXene nanosheets changing from isotropic to nematic state. (e) Viscosity versus shear rate for MXene nanosheet dispersions at different concentrations. Digital photos for (f) the viscous LC MXene dispersions at 15 mg ml^{-1} and (g) the as-prepared LCMM.

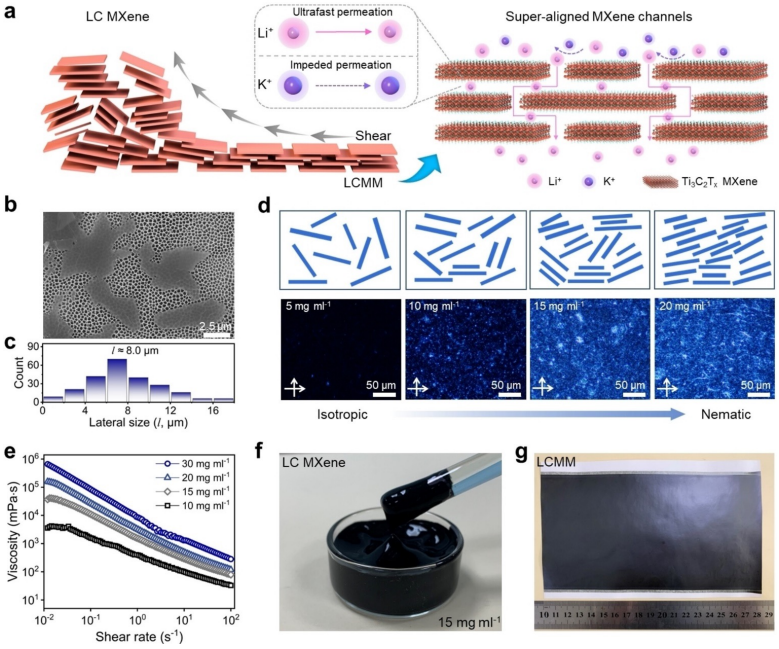
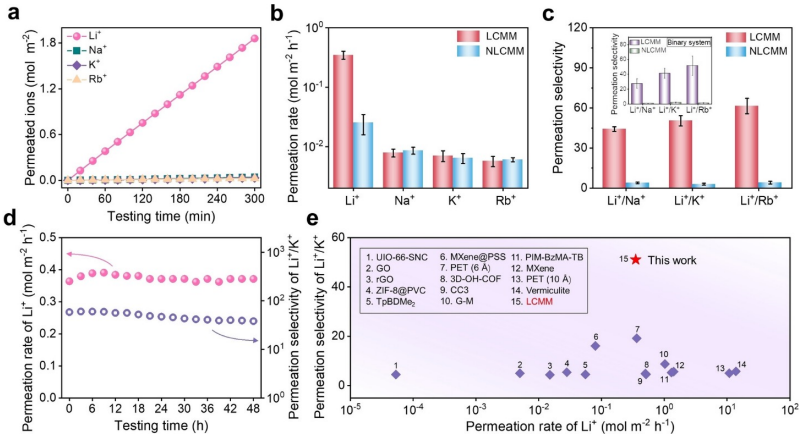


Figure 2. Ion separation performance. (a) Permeated ions (Li^+, Na^+,/K^+, and Rb+) through the LCMM as a function of testing time. (b) Comparisons of the permeation rates through LCMM and NLCMM. (c) Permeation selectivity of Li^+/Na^+, Li^+/K^+, and Li^+/Rb^+ through LCMM and NLCMM. Inset is the binary ion selectivity of LCMM and NLCMM. (d) Long-term stability of the LCMM. (e) Comparisons of Li^+/K^+ selectivity of various membranes





Membranes: Commercial and Technical Advances in Industrial Applications – Update 2023

A ground-breaking assessment of membranes and their role in sustainability, decarbonization and industrial applications.

The Catalyst Group Resources (TCGR) is pleased to announce the completion of our forward-thinking evaluation of membranes in industrial applications. This updated edition is refined for close inspection and interpretation of key industry elements yet expands the scope in other areas of membranes and separations technologies, which includes vital conclusions on the extensive impacts these advances have on the markets, illustrated below.

- The market for membranes for fuel cells and electrolyzers will see rapid growth over the next decade.
- Carbon capture offers a huge opportunity for membrane developers, but still needs to overcome technical challenges.
- Applications as diverse as biogas purification, ethanol dehydration, and hydrogen recovery and purification will all see better than average growth rates.
- Newly synthesized polymers hold promise for reduction of the cost of fuel cells, batteries and electrolyzers.
- Utilization of new polymers, inorganic materials and composite membranes can overcome the 2008 Robeson upper bound for separation of gases.

Visit the study's webpage for additional information, including the study presentation, table of contents and order form. Contact Steve Deutsch today at +1.215.628.4447 or sdeutsch@catalystgrp.com to discuss this study and other exclusive TCGR reports and materials.

A Must-Have for Anyone in the Refining, Petrochemicals/Syngas, Natural Gas and Industrial Gases Markets!

Membranes: Commercial and Technical Advances in Industrial Applications – Update 2023 goes beyond statistics to provide competitive insights and analyses vital to stakeholders in the refining, petrochemicals/syngas, natural gas and industrial gases markets, while also providing strategic guidance for innovation, growth and investment opportunities across the entire value chain.

TCGR The Catalyst Group Resources™
Vision > Intelligence > Impact

Commercial News continued from page 4.

Braskem, Shell Join Forces to Produce Circular Polypropylene from Mixed Plastic Waste

Braskem Netherlands B.V. and Shell Chemicals Europe B.V. announced an agreement to produce circular polypropylene from mixed plastic waste. With this agreement, Shell will upgrade a variety of pyrolysis oils into virgin-quality circular feedstocks at the Shell Chemicals Park Moerdijk, Netherlands. Braskem will then convert this feedstock into circular polypropylene in its plant in Wesseling, Germany. Source: Braskem, 1/17/2024.

Michelin, IFPEN, Axens Advance Bioethanol-to-Butadiene Project in France

Michelin, IFPEN and Axens inaugurated the first industrial-scale demonstrator of a plant producing bio-based butadiene in France, at Michelin's site in Bassens near Bordeaux. The demonstrator was built within the framework of the BioButterfly project, involving the three partners, and supported by ADEME (French Agency for Environment and Energy Management) with the aim of developing and commercializing butadiene from ethanol derived from biomass, to replace butadiene from petrochemicals. Source: IFPEN, 1/19/2024.

INEOS Polymer Used to Create World's First Sustainable Gas Pipeline in France

INEOS-produced bio-based high-density polyethylene (HDPE) has been used to create the world's first fully sustainable gas pipeline in Clermont-Ferrand, France. The pipeline is made from bio-based, certified HDPE made from wood processing residues from the paper industry, which are transformed into tall oil, a bio-naphtha. The tall oil is turned into bio-ethylene in INEOS Cologne and transported to INEOS' polymer plant in Lillo, Belgium, where it is used to manufacture bio-based HDPE. Source: Hydrocarbon Processing, 1/18/2024.

Movers & Shakers

David Brown, PhD

Technical Director, Drochaid Research Services, St. Andrews, Scotland



Dr. Brown graduated with an honours degree in Chemistry from the University of Edinburgh in 1993 and received his PhD from the University of Cambridge in ruthenium carbonyl cluster chemistry in 1997. Post-doctoral positions and a Teaching Company Associate position with Pozzani Pure Water followed. In 2002, David joined Sasol Technology UK as Principal Research Scientist when they were setting up their research facility in St Andrews. In 2018, he joined the newly formed contract research company Drochaid Research Services, where he is now Technical Director. Throughout his career in industry, David has worked in several areas spanning the petrochemical industry and, more recently, the transition to renewable feedstocks. He has extensive expertise in preparing and characterizing heterogeneous catalysts, particularly how preparation procedures can affect catalyst structure and performance. He can be reached at david.brown@drochaidresearch.com.

The Catalyst Review asked Dr. Brown to share his thoughts on the growing use of catalysts for converting renewable feedstocks into commercial products.

New commercial applications for catalytic chemistry arise when there is a significant driver for change. This is currently evidenced by the commitment of most chemical producers to shift from fossil fuel-derived carbon feedstocks to renewable or recycled carbon. It is an ongoing process requiring new and improved catalysts and process technologies to achieve this raw material shift.

An example of this switch to renewable feedstocks is the production of sustainable aviation fuels (SAFs), with several options being developed over recent years. One route is the biotransformation of hydrogen and carbon dioxide into the building blocks for jet fuels such as fatty acids, alcohols, and aldehydes, followed by chemical catalysis to transform these molecules into jet fuel. The combination of biocatalysis and chemical catalysis offers both opportunities and challenges to tailor an effective and efficient process that can transform renewable feedstocks to SAF.

Another route to SAFs is to use Fischer–Tropsch (FT) technology, where the syngas for the FT process can be generated either from CO_2 and green hydrogen or a number of non-fossil carbon sources, including municipal waste and biomass. This challenges the successful commercialization of catalysts, as the feedstock sources are variable and widely distributed by their very nature. Catalysts for this process must be flexible and robust to allow for the seasonal variations in feedstock and resultant catalyst poisons and manage the shorter-term variability linked to renewable energy supplies. Fulcrum Bioenergy's commercial-scale waste-to-fuels facility began production in Nevada in 2022 and is an early example of the successful application of Fischer-Tropsch technology to the conversion of syngas derived from landfill waste.

Another research area that has stimulated much interest is the use of lignin as a source of renewable carbon for valorization to fuels and chemicals. A significant issue for the commercialization of such processes is the structural variability of lignin depending on the source of the lignocellulosic biomass. The transformation of lignocellulosic biomass via lignin to key chemical building blocks involves both homogeneous and heterogeneous catalysis steps. The tailoring of these processes through innovative catalysis offers excellent scope to realize commercially viable technologies for value-added products.

These two areas highlight some opportunities whereby catalysis can enable the transition from fossil fuel sources to renewables by addressing many of the challenges inherent in this shift. Many of these processes will likely be deployed at a smaller scale and be more widely distributed than the traditional integrated mega-plants. This implies developing a range of fit-for-purpose processes that can be chosen to suit location/substrate/volume. Drochaid has developed extensive capabilities in these new catalytic applications in response to changing customer needs, which can accelerate the transition to renewable carbon products. Success in this area will rely on robust, multi-disciplinary collaboration and novel process and product development approaches.

Coming Soon – Topics Include:

- **Bio-lubricants**
- **Polyolefin Supports**
- **Sulfide Catalysis at the Crossroads**
- **Electricity-based Heating in Catalysis**