K-PRO™ – Propane Dehydrogenation

KBR’s Innovative Technology Option for Reliable, Low Cost On-Purpose Propylene Production
K-PRO™ – KBR Propane Dehydrogenation

- Attractive Economics
- Rising Propylene Demand
- Innovative Process
- Expertise
- K-PRO™
- Superior Equipment
- Lowest Total Cost of Ownership
- Advantaged Feedstock
- Reliability Guaranteed
- Propane Dehydrogenation
K-PRO™ – Innovation based on Commercially Proven Technology

- K-PRO™ Technology is based on the commercially proven K-COT™ technology and KBR’s extended experience in FCC reactor design

KBR K-PRO™ is based on over 70 years of innovation and improvements
Propylene – A Key Commodity Chemical with Strong Growth

Market Outlook

- Propylene demand continues to grow above GDP with rising living standards
- Main application remains polypropylene but strong demand also for other key chemicals like oxo-alcohols, acrylic acid, propylene oxide
- CAGR of 3-4%

World PG/CG Propylene Demand by End Use

Source: IHS Markit
On-Purpose

• On-purpose production share reached 23% in 2017, it is expected that on-purpose propylene supply will reach 31% and 34% by 2022 & 2027 respectively
• Main drivers for on-purpose increase are lighter feedstocks reducing propylene yield from steam cracking and slowdown in refinery expansions

25 MMTA in 10 years | >80% will be PDH | 4-6 world scale PDH plants per year
On-Purpose Propylene Demand Increase

Regions

• Main capacity growth in
  – China, India, SE Asia (demand & import independence) plus availability of LPG imports
  – US, Middle East (feedstock advantage)
  – Everywhere where there is a need or benefit to having on-site on-purpose propylene production for further growth or integration

Global Propylene Capacity Additions 2017-2027

Source: IHS Markit
Propane Dehydrogenation Basics

- **Desirable reaction:** Propane Dehydrogenation (PDH):

  \[ \text{C}_3\text{H}_8 + \text{H}_2 \rightarrow \text{C}_3\text{H}_6 \]

  \[ \Delta H^\circ = 124 \text{ kJ/mol} \]

- **Key Definitions:**
  - **Conversion** – % conversion of propane to propylene (via desirable PDH reaction) and additional byproducts (via undesirable reactions)
  - **Selectivity** – % selectivity of propane to propylene versus propane to additional byproducts
Propane Dehydrogenation Basics

- **Undesirable reactions:**
  - Undesirable reactions lead to lower selectivity
    - More propane feed required for set propylene product rate
  - Higher temperature promotes undesirable reactions
    - Opposing higher temperature favoring increased propane conversion
    - Avoid reactor temperature >650°C
    - Minimize residence time in reactor at high temperature
    - Maintain feed pre-heat temperature <550°C to minimize thermal cracking

**Cracking to ethylene and methane:**

\[
\text{C}_3\text{H}_8 \rightarrow \text{C}_2\text{H}_4 + \text{CH}_4
\]

**Ethylene hydrogenation:**

\[
\text{C}_2\text{H}_4 + \text{H}_2 \leftrightarrow \text{C}_2\text{H}_6
\]

**C4+ and coke formation:**

\[
\text{C}_x\text{H}_{2x+2} \leftrightarrow \text{C}_x\text{H}_{2x} \leftrightarrow \text{C}_x\text{H}_{2x-2} \leftrightarrow \text{Polymers} \rightarrow \text{Coke}
\]
Propane Dehydrogenation Basics

• **Fundamentals:**
  - Reaction is endothermic, continuous heat addition required to keep reaction going
  - Thermodynamically limited:
    - Higher temperature results in increased conversion to propylene, but higher temperature also increases undesirable reactions
    - Lower pressure (more specifically hydrocarbon partial pressure, $P_{HC}$) results in increased conversion to propylene
  - All PDH processes require a propane recycle in order to fully convert propane
    - Higher per pass conversion leads to lower propane recycle
K-PRO™ PDH Technology

- KBR Orthoflow Reactor
- Commercially Proven
- No Pt
- No Cr

PROVEN REACTOR + PROPRIETARY CATALYST + PROPYLENE RECOVERY

Reactor Effluent
- Extensive design experience in olefins recovery
- Consideration of client requirements and site specific utility costs

Recovery
- Tail Gas
- Propylene
- C4+

Propane Recycle
K-PRO™ PDH Technology

**K-PRO™ Reaction Section**

- To Flue Gas System
- Catalyst Fines
- KBR Orthoflow Converter
- Fresh Propane plus Recycle Propane
- F/E Exchanger
- Optional Steam Generation
  - Fuel Oil
  - Steam
  - BFW
- Fuel Oil
- Oil Wash Tower
- Catalytic Storage and Handling
  - Regen Air
  - F/E Exchanger
  - F/E Exchanger
- Effluent to Process Gas Compressor

1. Oil Wash Tower may be substituted with Water Quench Tower if primary fuel source used is Fuel Gas
2. Fuel Gas source can be either or a combination of product C$_2^+$, product C$_4^+$, or other available Fuel Gas source
K-PRO™ Typical Product Recovery Section

**Diagram Description:**
- **Reaction Section:** Fresh Propane plus Recycle Propane to Reaction Section
  - Fresh Propane Feed
  - Recycle Propane
- **Feed Section:**
  - F/E Exchanger
  - Depropanizer
- **Flash Drum**
- **Caustic Wash**
- **Drier**
- **Deethanizer**
- **Optional PSA**
- **Low Temperature Section/Cold Box**
- **C_3 Splitter**
- **Polymer Grade Propylene Product**
- **High Purity H_2**
- **Low Purity H_2**
- **C_1 Rich**
- **C_2 Rich**

**Flowchart:**
- Fresh Propane plus Recycle Propane flows through the Reaction Section, then to the Feed Section.
- From the Feed Section, it goes through the F/E Exchanger and Depropanizer.
- The process gas then flows through the Flash Drum and Caustic Wash.
- The gas is further processed through Driers and Deethanizer.
- Optional PSA can be added for purification.
- The final product includes High Purity H_2, Low Purity H_2, C_1 Rich, C_2 Rich, and Polymer Grade Propylene Product.
## Technologies Comparison Overview

<table>
<thead>
<tr>
<th>Other Commercial Technologies</th>
<th>KBR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reactor Type</strong></td>
<td><strong>K-PROTM</strong></td>
</tr>
<tr>
<td><strong>Regeneration</strong></td>
<td>Orthoflow FCC Continuous</td>
</tr>
</tbody>
</table>

| Comments | 4 stacked radial flow reactors with inter-reactor heaters along with Continuous Catalyst Regeneration (CCR) | 3-10 fixed bed reactors cycling between on-line, steam purge, hot air/reheat, evacuation/vacuum, reduction, back to on-line | Tubular fixed bed reactor/furnace design similar to Steam Methane Reforming (SMR) technology, 2 reactors in parallel alternating between on-line and regeneration |
| catalyst | Pt-Sn on Alumina | Chromium Oxide (Chromia) on Alumina | Pt-Sn on Zn-Ca Aluminate |
| conversion, % | 30 - 40 | 45 | 30 - 40 |
| Selectivity, wt. % | 85.5 - 88 | 87 | 80 - 90 |
| Reactor Pressure (bara) | 1.4 | 0.5 | 5.0-6.0 |
## Impact of Conversion and Reactor Pressure

- **Higher conversion**
  - Lower propane recycle rate – smaller compressor, lower power consumption, smaller recovery section, lower CAPEX and OPEX
- **Higher reactor operating pressure**
  - Higher compressor suction pressure – smaller compressor, lower power consumption, lower CAPEX and OPEX

<table>
<thead>
<tr>
<th>Other Commercial Technologies</th>
<th>PDH Technology 1</th>
<th>PDH Technology 2</th>
<th>PDH Technology 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Type Regeneration</td>
<td>Moving Bed Continuous CCR</td>
<td>Fixed Bed Cyclic (in-situ)</td>
<td>Fixed Bed Cyclic (in-situ)</td>
</tr>
<tr>
<td>Conversion, %</td>
<td>35</td>
<td>45</td>
<td>35</td>
</tr>
<tr>
<td>Total Propane (Feed + Recycle)/Feed</td>
<td>2.7</td>
<td>2.1</td>
<td>2.7</td>
</tr>
<tr>
<td>Reactor Pressure (bara)</td>
<td>1.4</td>
<td>0.5</td>
<td>5.0</td>
</tr>
<tr>
<td>Compressor Suction / Discharge Pressure (bara)</td>
<td>1.0 / 14.0</td>
<td>0.3 / 14.0</td>
<td>4.0 / 14.0</td>
</tr>
<tr>
<td>Compressor No. of Stages</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Compressor Power (HP/MTA Propylene)</td>
<td>50.0</td>
<td>48.3</td>
<td>22.7</td>
</tr>
<tr>
<td>C₃ Splitter Feed Rate (MTA/MTA Propylene)</td>
<td>3.23</td>
<td>2.45</td>
<td>3.25</td>
</tr>
<tr>
<td>Recovery Section Size (% of Base)</td>
<td>BASE (100%)</td>
<td>76%</td>
<td>101%</td>
</tr>
</tbody>
</table>
Selectivity Comparison

- Higher selectivity achieved by:
  - High catalyst activity, stability, continuous regeneration yields low residence time requirement, less time for undesirable reactions
  - Lower feed preheat temperature minimizes thermal cracking
- Leads to lower propane feed rate for same propylene product, lower OPEX

<table>
<thead>
<tr>
<th>Other Commercial Technologies</th>
<th>KBR K-PRO™</th>
<th>Orthoflow FCC Continuous</th>
<th>F/E and/or Steam Heating</th>
<th>FCC, continuous combustion for regeneration gives heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Type Regeneration</td>
<td>PDH Technology 1</td>
<td>Fixed Bed Cyclic (in-situ)</td>
<td>Fixed Bed Cyclic (in-situ)</td>
<td>Fixed Bed Cyclic (in-situ)</td>
</tr>
<tr>
<td>Feed Preheat Method</td>
<td>F/E and Fired Heater</td>
<td>F/E and Fired Heater</td>
<td>F/E and Furnace</td>
<td>F/E and Fired Heater</td>
</tr>
<tr>
<td>Feed Preheat Temperature</td>
<td>~625°C</td>
<td>&lt;550°C</td>
<td>&lt;550°C</td>
<td>&lt;550°C</td>
</tr>
<tr>
<td>Reactor Heat Method</td>
<td>Feed Preheat and Inter-Reactor Heaters</td>
<td>Regeneration cycle includes air reheat before being brought back online</td>
<td>Reactor/Furnace similar to Steam Methane Reformer (SMR)</td>
<td>Reactor/Furnace similar to Steam Methane Reformer (SMR)</td>
</tr>
<tr>
<td>Residence Time (min)</td>
<td>30-60</td>
<td>7-15</td>
<td>20</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Selectivity, wt.%</td>
<td>85.5 - 88</td>
<td>87</td>
<td>80 - 90</td>
<td>87-90</td>
</tr>
<tr>
<td>Propane Feed / Propylene Product (kg/kg, 100% basis)</td>
<td>1.14-1.17</td>
<td>1.15</td>
<td>1.11-1.25</td>
<td>1.11-1.15</td>
</tr>
</tbody>
</table>
K-PRO™ Delivers
20%-30% LOWER CAPEX

- Single reactor design with inherent continuous catalyst regeneration and heat input
- High conversion / selectivity
  - Lower propane recycle
  - Smaller Compressor and Recovery Section
- Smaller Plot Space
K-PRO™ Delivers
10%-20% LOWER OPEX

- Direct fuel combustion for catalyst regeneration provides efficient heat input
- Efficient energy utilization
- Lower compressor power consumption
- High activity & stable catalyst
- Minimum catalyst losses and catalyst make-up
K-PRO™ – High On-Stream Factor

K-PRO™ Delivers
High On-Stream Factor

- Turnaround Time 4-6 years
- Smooth start-ups
- Energy efficient and stable process
- Catalyst replacement without unit shutdown
- Typical FCCU operation; no moving bed or switching reactors
- Simple reactor design leads to simple operation
K-PRO™ Delivers Safe & Environmentally Friendly Performance

- Safe, commercially proven, environmentally compliant design
- KBR proprietary catalyst (Non Cr/Pt)
- Low emissions: reduced NO$_x$ and CO$_2$ emissions
- Low opacity: low flue-gas particulate emissions
K-PRO™ – The Right Choice

- K-PRO™ represents a paradigm shift in on-purpose propylene production
- K-PRO™ meets or exceeds performance of any commercially available competitive alternative
- K-PRO™ offers attractive economics
- K-PRO™ is safe and environmentally sound
- K-PRO™ is innovation based on proven technology

K-PRO™ – The right choice to meet your demand for propylene