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KBR Ammonia Cracking, H2ACT^{SM} - A roadmap from clean energy source to sustainable hydrogen supply

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The advances in clean hydrogen and ammonia production, either via hydrocarbons and Carbon Capture & Storage (CCS) or via renewable energy and electrolysis, are fueling worldwide interest in a new market for hydrogen and ammonia for supporting a reliable, low-carbon energy future. Clean hydrogen is earmarked as a sustainable fuel of the future while clean ammonia offers a high energy density solution for storage and distribution, utilizing existing and reliable infrastructure, which can be expanded to the growing market demand.

The advent of ammonia cracking technology, dissociating clean ammonia back into hydrogen, completes the missing link in the roadmap to sustainability, enabling the production of clean ammonia where the needed resources are abundant with the ability to supply clean hydrogen to locations with high demand but low availability of natural resources to produce it.

KBR has a long history as a market leader in ammonia technology. Built on a legacy of technology innovation and industry records, KBR's Ammonia Cracking technology, H2ACT^{SM}, delivers a pathway to large scale, sustainable hydrogen production, with efficiency and high technology readiness at the heart of the process.

H2ACT^{SM} is built using proven, reliable technology elements and process operations from the ammonia production industry, capable of providing a record single-train capacity of 1,200 MTPD of clean hydrogen.

This paper presents the KBR technology roadmap from energy source to sustainable hydrogen supply where it is needed most, highlighting the process steps and performance achieved while completing the ammonia to hydrogen value chain without emitting CO_2.

1. INTRODUCTION

The world is facing an incredible challenge in the race to decarbonization, imposing a change of landscape in the technologies and fuels used to support sustainable modern-day life in the future.

The journey towards Net Zero by 2050 requires double digit trillion dollars investment in technologies and infrastructure for low carbon fuels and electrification.

Both hydrogen and ammonia are predicted to play a major role in this journey, to support the decarbonization of industries and regions which are either hard or uneconomical to electrify. Clean hydrogen is taking a leading position as a sustainable fuel of the future, while ammonia can serve as a clean fuel on its own or as a carrier of hydrogen.

The majority of these key molecules are expected to be produced via renewable power and electrolysis, often designated Green, but a significant share will be produced via reforming of fossil fuels and carbon capture, often designated Blue, as a cost-effective first step to a sustainable future.

As a technology powerhouse with decades of know-how in efficient ammonia processes and reliable equipment design, coupled with market proven capability for scale-up and commercialization, KBR offers technologies across the full sustainable hydrogen and ammonia value chain, completed by the advent of KBR's ammonia dissociation technology, H2ACT℠.

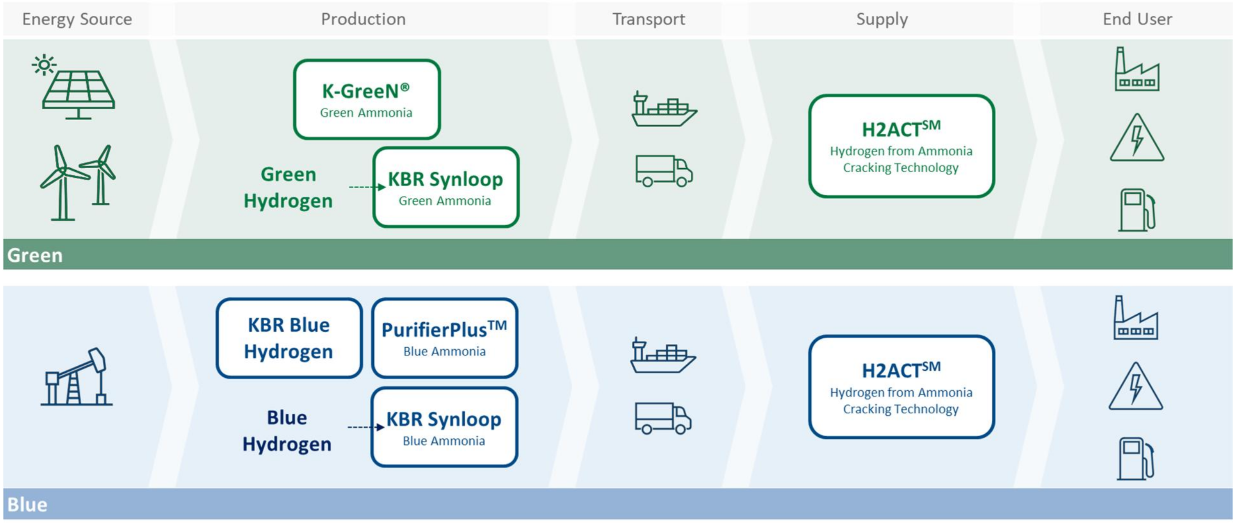

Fig. 1: KBR Clean Ammonia & Hydrogen Technologies

Built on a legacy of technology innovation and industry records, KBR's Ammonia Cracking technology, H2ACT℠, completes the pathway to large scale, sustainable hydrogen production, with efficiency and high technology readiness at the heart of the process.

2. Ammonia As Energy Vector

Ammonia is the most promising clean hydrogen carrier for long distances in the short to medium term.

Advantages

Ammonia has a high hydrogen storage density and can be liquefied at -33°C at atmospheric pressure, providing a low energy-intensity means of hydrogen storage and transportation. Ammonia production technologies are mature and efficient, already operating at large scale. Ammonia can rely on well-established and rapidly advancing infrastructure for storage, loading, unloading and transportation. Both ammonia production and transportation are already expanding to the growing demand for ammonia as an energy vector. An additional advantage of ammonia is that it can be used directly as fuel, such as in co-firing with coal, helping to abate existing coal-based power plants.

Safety

Ammonia toxicity is similar to other hydrogen carriers such as methanol, MCH and toluene. Ammonia may be a toxic chemical, but one that is already produced, stored and transported safely around the world today. It is harmful to health at concentrations in excess of 400 ppm but its odor is an advantage in leak detection, with the pungent smell of ammonia in the air detectable at concentrations as low as 5 ppm. It is lighter than air so it rapidly diffuses and oxidizes on leakage making inhalation or contact less likely. Ammonia flammability is lower than other hydrogen carriers, with a high auto-ignition temperature of 650°C, rendering it safer to transport.

Comparison to other hydrogen carriers[1]

The ammonia carrier value chain has the lowest levelized cost and carbon intensity, with energy output similar to liquefied hydrogen. Today, liquid hydrogen is limited by the liquefaction step, with train capacities ~30tpd limiting the ability for vessels to scale past 10,000m3. Methanol is contrained due to its need for carbon capture, utilization and storage while MCH has significantly higher cost and carbon intensity, with lower energy output and technology readiness.

[1] Source: WoodMackenzie Hydrogen Horizon Outlook Q42022

3. The Ammonia Dissociation Reaction

Ammonia decomposition is an endothermic reaction (1), needing 46 kJ for one mole of ammonia to dissociate into nitrogen and hydrogen.

(1) $2NH_3 \leftrightarrows N_2 + 3H_2$ ($\Delta H° = 92$ kJ mol^{-1})

Thermodynamically, equilibrium is favored by high temperature and low pressure. Theoretically, the reaction is near completion:

- At > 550°C @ 1 bara
- At > 800°C @ 5 bara
- At > 1000°C @ 30 bara

Catalysts can be used to improve the rate of reaction and lower reaction temperature, improving the efficiency of the ammonia cracking process. Both base and precious metals can be used to promote the reaction, with nickel-based catalysts in successful commercial operation today.

4. H2ACT^{SM} New Market, Established Technology

Today, ammonia dissociation technology is available in the market serving a different purpose. The installed units are fully electricity driven, very small capacity and operate at equilibrium-favored conditions (low pressure, high temperature) to supply hydrogen or nitrogen as utilities in remote locations and without emphasis on energy efficiency or carbon intensity. While these units serve the installed purpose, they are not suitable for what industry is demanding for energy transition, with new technology called to produce at larger scale, sustainably and efficiently.

While the market for ammonia dissociation for decarbonization is new, the technology elements to dissociate ammonia at scale are established and proven in operation, bearing great resemblance to steam methane reforming of natural gas for syngas generation.

KBR's Ammonia Cracking technology, H2ACT^{SM}, is built on a legacy of technology innovation and industry records in ammonia production. It completes the pathway to large scale, sustainable hydrogen production, with efficiency and high technology readiness at the heart of the process.

4.1. Process Flow-scheme Overview

The following is a high-level block flow diagram for a typical ammonia cracking unit.

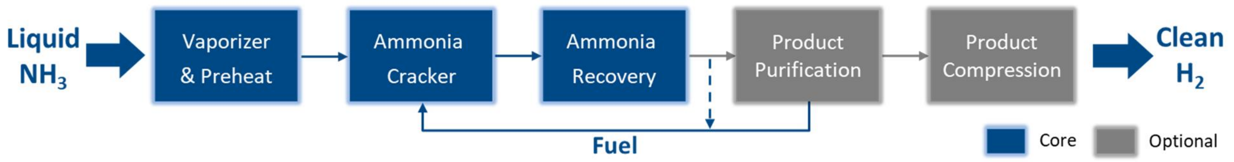

Fig. 2: Ammonia cracking process block flow diagram

Liquid ammonia from storage is pumped to the required pressure, vaporized and preheated in preparation for decomposition to hydrogen and nitrogen.

Ammonia cracking is largely driven by a fuel-fired cracker, leveraging on decades of KBR experience in furnace design in industrial steam methane reforming. The furnace design is based on the well-proven KBR down-fired primary reformer design with hundreds of references from small to large scale capacity and decades of experience and know-how in robust, safe and efficient design of this equipment.

The cracking reaction is performed under the presence of catalyst with heat supplied by combustion of clean fuel via the down-fired burners. The heat source for the cracker is fuel from the process, consisting of tail-gas from the hydrogen purification section, supplemented by cracked gas (H2/N2) if necessary.

The ammonia cracking furnace is designed to attain maximum thermal efficiency by utilizing process waste gases as part of the fuel, as well as by recovering heat in the convection section from the flue gases, to drive dissociation, feedstock vaporization and preheat.

The furnace convection section is furnished with a selective catalytic reduction (SCR) system as standard, able to meet the most stringent environmental emission requirements.

Cracked product purification, where necessary, is based on well-proven and commonly used industrial processes:

- Ammonia Recovery: Remove ammonia by simple water-based ammonia absorption / distillation unit – designed and in operation in a multitude of KBR ammonia plants worldwide
- Product Purification: Remove nitrogen by Hydrogen PSA technology - proven, reliable cost-effective and used in a variety of industries

Typical hydrogen delivery pressure of around 30-40 barg is achievable without additional hydrogen compression. If higher delivery pressure is required, compression can be added, and the flow-scheme will be optimized for the higher delivery pressure.

4.2. Technical Maturity Level

The following table presents an evaluation of the technical maturity for each system (block) within the H2ACT^{SM} ammonia cracking plant.

Table 1
H2ACT^{SM} Technology Readiness Level

System	Technical Maturity	TRL	Remarks
Ammonia Storage Tank and Refrigeration	Well-proven	9	System available in many operating ammonia plants around the world.
Pump and Vaporizer	Well-proven	9	System available in many operating ammonia plants, where ammonia is used as (vaporised) refrigerant within the ammonia plant.
Ammonia Cracking Reactor	Proven in Similar Service	5-7	Equipment design and large-scale operation proven in similar service in steam methane reforming in KBR ammonia plants. Down-fired furnace design with 200+ references. Catalyst proven at small scale in commercial units. Optimized and improved catalyst for large scale application proven in testing by leading catalyst manufacturers.
Ammonia Purification	Well-proven	9	System available in many operating ammonia plants, with similar operating conditions.
Nitrogen Purification	Well-proven	9	PSA-based, commonly used in a variety of industries and scales
Hydrogen Compression	Well-proven	9	Hydrogen compressors commonly used in hydrogen plants, refinery units, etc.

4.3. Key Performance Data

H2ACT^{SM} can deliver hydrogen at any purity required depending on the industrial application the ammonia cracking plant is serving.

Key performance indicators such as efficiency, hydrogen yield and levelized cost of production will vary depending on the industry the cracking unit is serving, carbon intensity requirements and opportunity for integration with existing facilities.

Nonetheless, for a given application, the performance of the H2ACT^{SM} ammonia cracking plant is consistently maintained across the entire capacity range, from small to mega-scale production.

Indicatively, the following table presents typical performance for an H2ACT[SM] ammonia cracking unit, based on zero direct carbon intensity production, using only proven technology elements (i.e. using most proven commercially available Nickel-based catalysts, no ammonia co-firing, conventional PSA unit, etc).

Table 2
H2ACT[SM] Key Performance Indicators

KPI	Unit of Measure	Value
Capacity	MTPD H2	**10 to 1200**
Product Specification – H_2 Purity	mol%	**75 to 99.97+**
Product Specification – NH_3 Content	ppmv	**As low as <0.1**
Product Specification – H_2O Content	ppmv	**As low as <1**
Product Specification – Delivery Pressure	barg	**As Required** **(40 barg without compression)**
Carbon Intensity (Direct)	kg CO_2 / kg H_2	**0**
Typical Hydrogen Yield[1]	wt%	**78**
Typical Energy Efficiency (HHV)[1,2]	%	**88**
Electricity Demand[1]	kWhr / ton H_2	**100**
Availability[3]	%	**>95**
Turndown	%	**<50**
Flexibility (load change)	% per hour	**20+**

Notes:
1. *For stand-alone unit, self-sufficient in terms of steam demand, H_2/N_2 fuel, hydrogen delivery pressure of 40 barg.*
2. *Energy Efficiency = (Energy out as H_2) / (Energy in as NH_3 + Power). Power efficiency is 50% or 1720 kcal/kWhr.*
3. *Including planned turnaround of 30 days every 4 years*

Flexibility and Turndown

The typical turndown capacity for the H2ACT[SM] cracking unit is 50-60%, however the plant can be designed to be operated at lower turndown if necessary.

The typical ramp-up / ramp-down rate is 20% per hour, suitable for most industrial applications. The plant load can vary frequently and daily between nominal capacity and turndown without adverse impact on plant integrity. This can be improved significantly if additional operational flexibility is required (e.g. for power generation industry) to match offtaker variability, minimizing or eliminating hydrogen storage requirements.

On-stream time, Reliability and Availability

KBR ammonia plants are the most reliable in the industry, with records in on-stream time. As compared to an ammonia production facility, nearly all critical equipment in the ammonia cracking plant operate at milder conditions. The ammonia feedstock quality is consistent, without catalyst poisons such as sulfur or chlorides and no side-reactions. Hence, maintenance and replacement costs are expected to be comparatively lower and plant reliability equal or higher to ammonia production.

Generally, time required between turnaround is dependent on maintenance demands for rotating equipment (such as hydrogen compressor if applicable) and the catalyst life. The typical recent benchmark for turnaround period for similar industrial plants including reformers is 4 years with 30-40 days for maintenance works, therefore on-stream time for the ammonia cracking unit of 8,400 hours per calendar year is realistic and easily achievable for KBR design and technology.

5. SCALE-UP & COMMERCIALIZATION

KBR offers optimized designs to the market for capacities ranging from 5 to 1200 MTPD hydrogen production. H2ACT^{SM} is versatile, with design features tailored to individual project requirements such as carbon intensity, product quality and pressure, delivering the lowest levelized cost of cracked hydrogen product for each client and industry application.

KBR can support clients taking different routes for technology scale-up and commercialization of ammonia cracking technology. The following diagram presents three routes to reach commercial scale hydrogen production via a KBR H2ACT^{SM} plant.

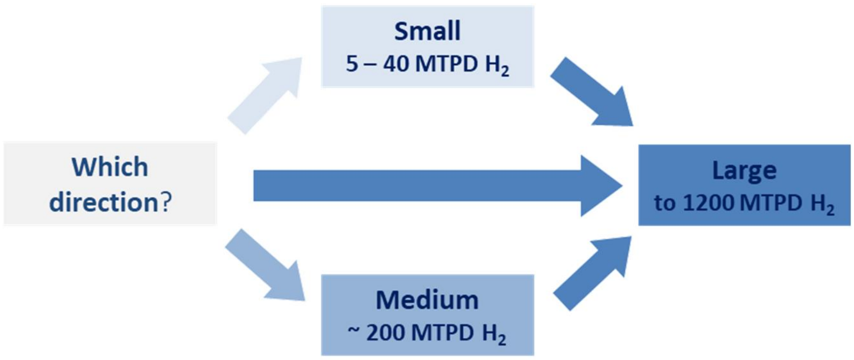

Fig. 2: Routes to Commercial Scale Cracked Hydrogen Production

A small-scale ammonia cracking plant refers to a demonstration or a pilot ammonia cracking plant. Depending on budget allocated and specific demonstration objectives required, the design of this small-scale plant can range from full to simplified process scheme.

- A simplified pilot plant could demonstrate ammonia dissociation in a fired tube (or radiant tube) furnace under chosen catalyst at projected operating pressure & temperature, proving catalyst performance.
- A full design pilot plant could additionally prove equipment design, energy efficiency and product purity.

A medium-scale ammonia cracking plant is a commercial unit engineered and constructed based on a complete process scheme. It can serve decentralized ammonia cracking applications e.g. for decarbonizing existing industrial sites. The medium-scale plant is an ideal candidate for phased approach to centralized world-scale cracking applications, staggering the production in line with feedstock supply availability or offtaker demand. Lessons-learned from commercial operation of the medium-scale plant can be applied to improve the next generation units, both in terms of technology and operation.

KBR is ready to license and guarantee H2ACT^{SM} at large scale today, as technology features are well-proven and ammonia cracker equipment design is already available. As with any new technology, cracking ammonia is expected to advance rapidly in the short-to-medium term. KBR anticipates a flexible and pro-active approach to engineering and design of the first commercial units, ensuring that technology advances (such as catalysts or burner technology) can be incorporated in the design or easily retrofitted in existing units. As a result, KBR's low risk, maximum opportunity flow-scheme can support first-mover advantage in this new market, leveraging on experience of successful technology commercialization over 80 years.

6. CONCLUSIONS

H2ACT^{SM} can provide up to a record single-train capacity of 1,200 MTPD of clean hydrogen, via a versatile flow-scheme which can be tailored to maximize yield and minimize levelized cost for each client and industry.

KBR is ready to license and guarantee H2ACT^{SM} technology today because it is based on proven, reliable technology elements and process operations, available in the market today, built on KBR legacy of success and records in the ammonia industry.

KBR can support partners through a variety of routes to scale-up and commercialization, leveraging on a legacy of 80 years of innovation and experience in successful technology commercialization.

KBR anticipates a flexible and pro-active approach to engineering and design of the first commercial units, ensuring that technology advances can be incorporated in the design or easily retrofitted in existing units. As a result, KBR's low risk, maximum opportunity flow-scheme can support first-mover advantage in this new market, empowering energy transition through ammonia cracking.