Ammonia
Key to Expanding Deployment & Utilization of Green Hydrogen

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Accounts for ~35% of CO₂ emissions

High power and/or temperature precludes batteries, electrification
Ammonia: The Ideal Vector for H₂@Scale

Solves the storage & distribution problem

- T = 25 °C >> -253 °C
- P = 10 bar << 700 bar
- Liquid NH₃: 40% more H by volume than liquid H₂
- Liquid NH₃: 60% more energy by volume than liquid H₂
- Existing production/distribution/storage infrastructure

Ammonia pipelines in the US

CapEx Competitive

Ammonia: Clean Combustion

Single, dense liquid fuel source
- Difficult to burn ammonia directly
- Partial decomposition into H₂/NH₃ mixtures
- Flame speed scales monotonically with H₂ fraction
- Drop-in replacement for hydrocarbons
- Ignotes, burns nominally identically (except it’s orange)

Target Market
Hydrocarbons
- Fuel oil
- Natural gas
- Gasoline
- Jet Fuel

Directly from CSM Reformer

\[
2\text{NH}_3 \rightarrow 3\text{H}_2 + \text{N}_2 \\
2\text{NH}_3 + 1.5\text{O}_2 \rightarrow 3\text{H}_2\text{O} + \text{N}_2 \\
\text{H}_2 + 0.5\text{O}_2 \rightarrow \text{H}_2\text{O}
\]
Generation of NH₃/H₂ Mixtures

Conventional Technology
- Packed bed reactor (PBR)
- Atmospheric pressure, high T (>600°C)
- Inflexible, large pressure drop

Catalytic Membrane Reactor (CMR)
- Fully decompose fraction / recover H₂
- Remove H₂ inhibition, much higher throughput
- Mix with NH₃ sweep: tune composition
- Sweep enables isobaric operation
- Robust: >1000 hrs online and performance improves
- No Nitrogen! Benefits for performance

\[ r = \frac{k(K_{PA})^2}{(K_{PA}P_H^{1.5})^2} \]
Example: Internal Combustion Engines

Modified standard SI engine (Frigo lab)
- Compared NH$_3$/H$_2$ (CMR) vs. NH$_3$/H$_2$/N$_2$ (PBR)
- Benefits of N$_2$ removal:
  - Achieved ~35% more power, greater range of stable operation
  - Produced >65% less NO$_x$ (even less than gasoline)

Requires Dynamic Composition Control
- ~50% H$_2$ at ignition
- ~10% H$_2$ under full load
- Easily achieved in CMR


Example: Gas Turbines

Recent Mitsubishi Patent

- Need to increase volumetric energy density
- Achieved by increasing pressure (up to 50 bar)
- High temperature decomposition
- 4 compressors with inter-stage cooling (CapEx & OpEx)


CMR: Sweep Enables Isobaric Operation

- CMR maintains hydrogen high recovery
- Pump liquid ammonia at high pressure
- Vaporize with low grade heat (T < 100 °C)
- Pressure for free
Ongoing Work: Scale-up & Validation

CMR Demonstration Module

• Capacity: 40 slm ammonia
• Ultrasonic membrane fabrication / improved catalyst
• Switch from gas to liquid delivery: Enable high pressure operation (to > 50 bar)
• Targeting 10X further improvement in performance

Validation of Combustion Performance

• Quantify benefits of NH$_3$/H$_2$ over NH$_3$/H$_2$/N$_2$
• Flame speed / temperature / emissions
• Potential Concerns: NO$_x$ & NH$_3$ slip
• Characterize as a function of NH$_3$/H$_2$ and equivalence ratios, pressure

Summary: NH₃ a Key to Industrial De-carbonization

Attributes of Ammonia

- Single liquid fuel with high H₂ and energy density
- Leverage existing production / distribution / storage infrastructure
- Partially decomposed NH₃/H₂ is a tunable drop-in replacements for hydrocarbons

Efficient Reforming: Catalytic Membrane Reactors

- Compact / energy efficient / low temperature (down to 350 °C)
- Dynamic control over H₂/NH₃ composition
- No N₂ = More Power / less NOₓ
- Enables high pressure / isobaric operation = Pressure for free
- Looking for OEM collaborators for integration / optimization