Generation and Utilization of NH_3/H_2 Fuel Blends

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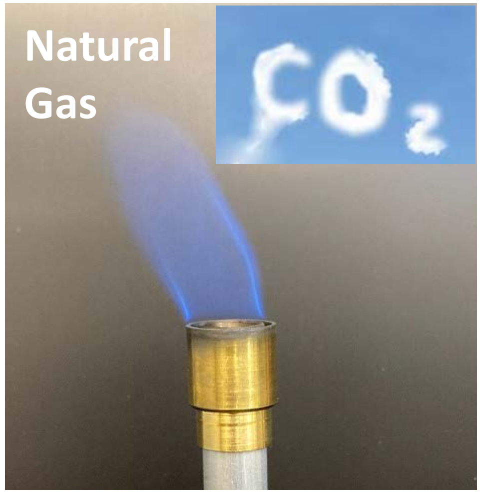
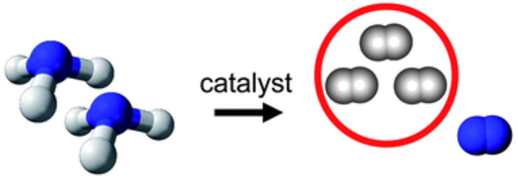
Ammonia Combustion Technology Webinar: 7/8/2025

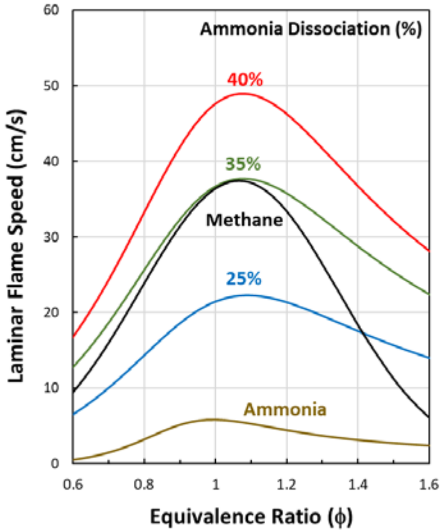
Ammonia-Hydrogen: The Goldilocks Blend

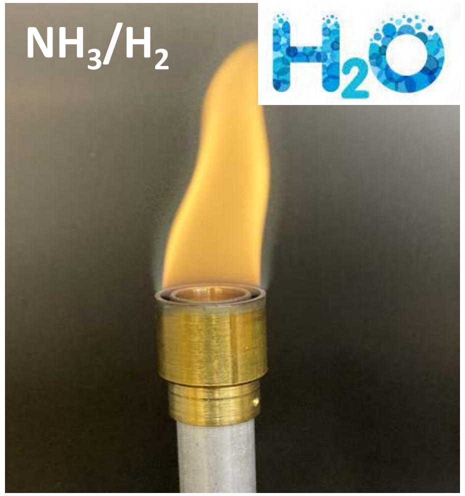
Fuel	ΔH_c (kJ/mol)	LFS (cm/s)	MIE (mJ)	Flammability
NH_3	382.6	7	680	15 – 28%
H_2	285.8	>200	0.017	4 – 75%
CH_4	890.4	35	0.28	5 – 15%
NH_3/H_2	~300	Tunable: Whatever you want		



$$2NH_3 \rightarrow 3H_2 + N_2$$



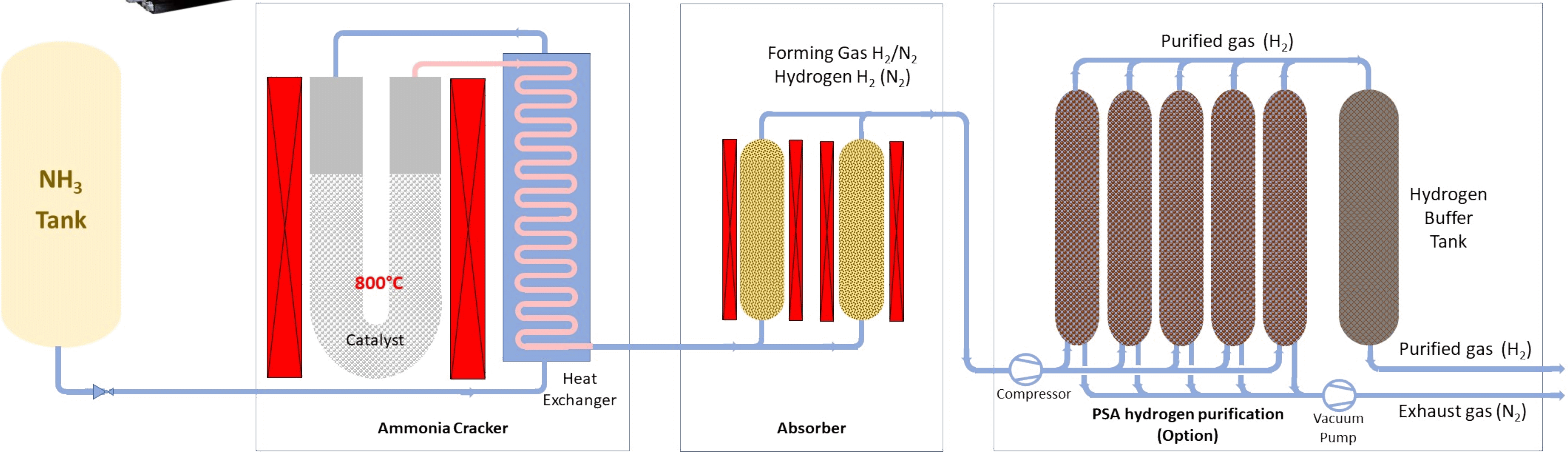




Current Technology for NH_3 cracking

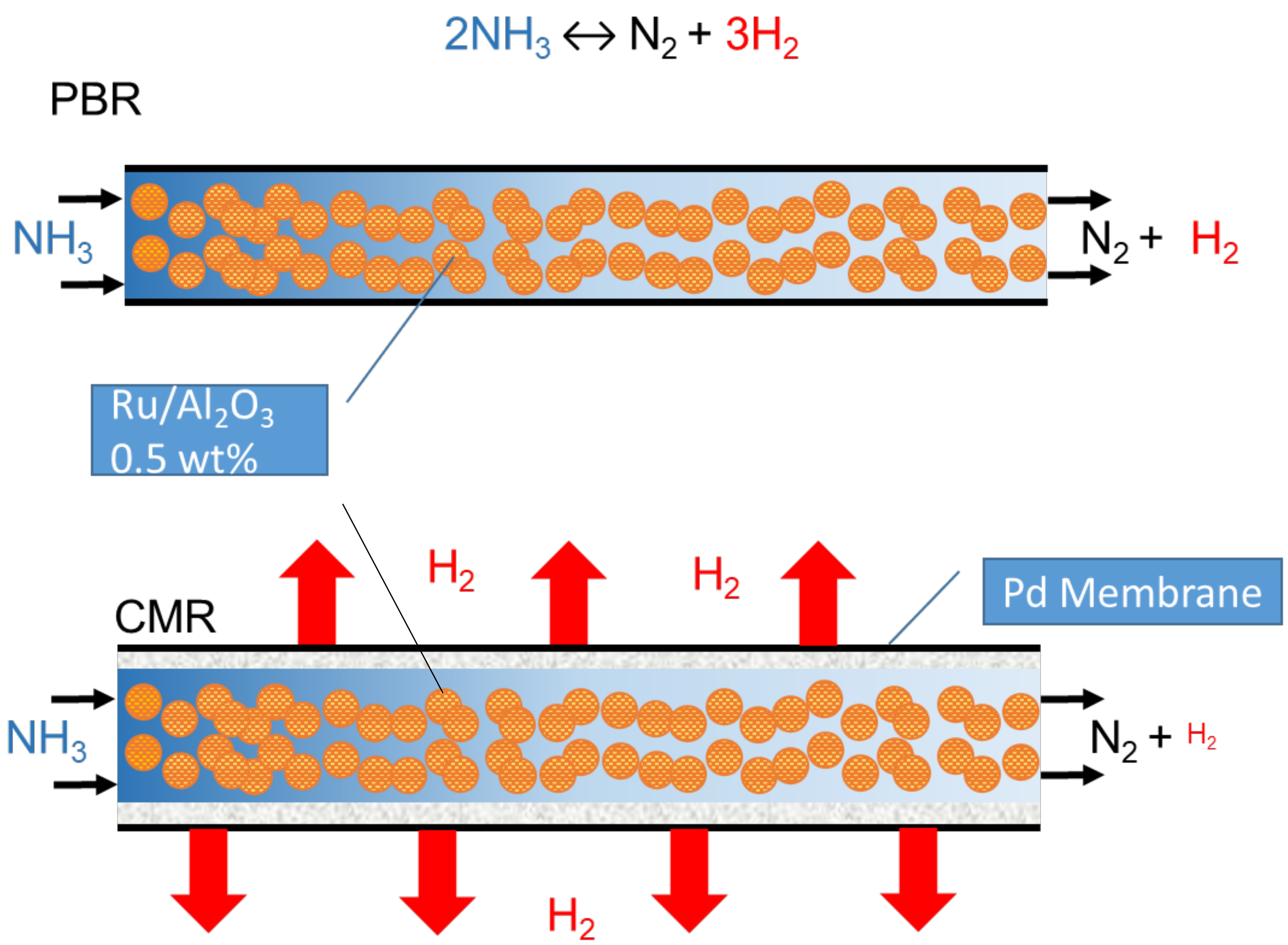
CapEx & OpEx Intensive

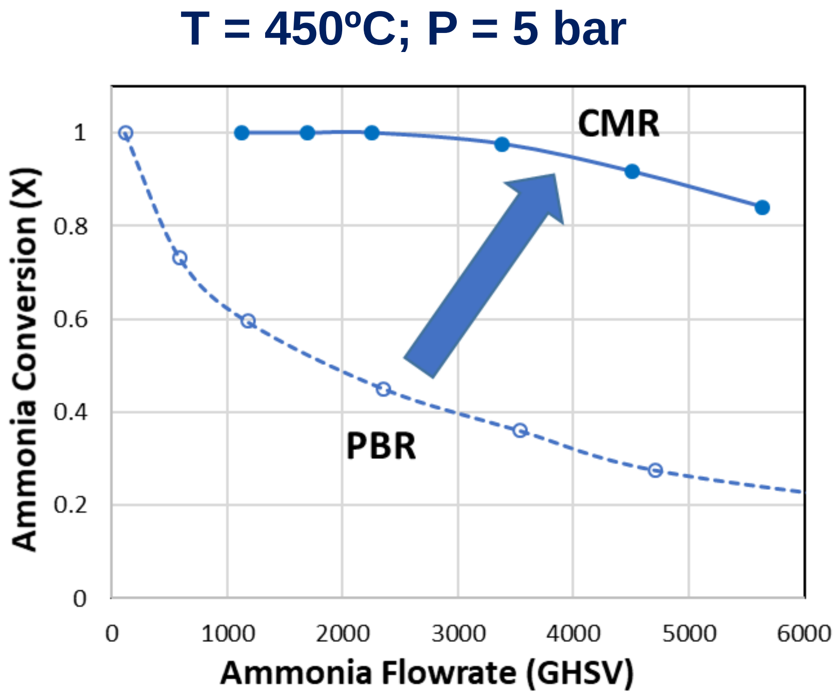
- Very high temperature for complete dissociation
- Compressors, PSA for purification



https://www.crystec.com/

Catalytic Membrane Reformer (CMR)



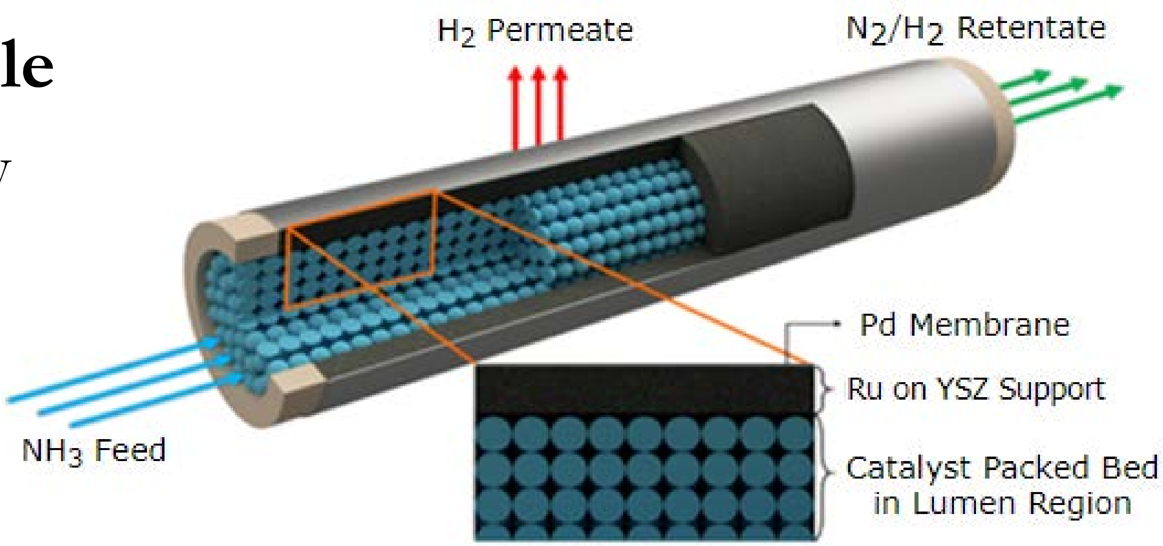


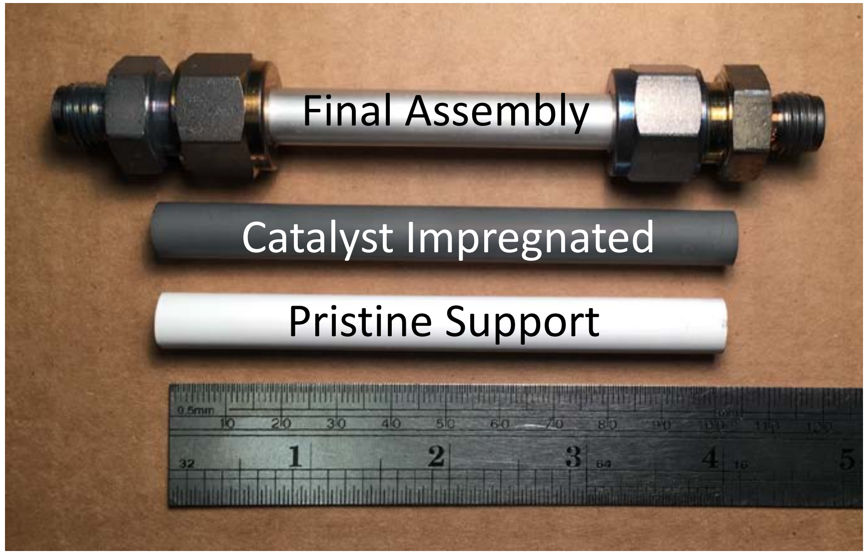
$$r = k_f \left[\left(\frac{P_{NH_3}^2}{P_{H_2}^3} \right)^{\beta} - \frac{P_{N_2}}{K_{eq}} \left(\frac{P_{H_2}^3}{P_{NH_3}^2} \right)^{1-\beta} \right]$$

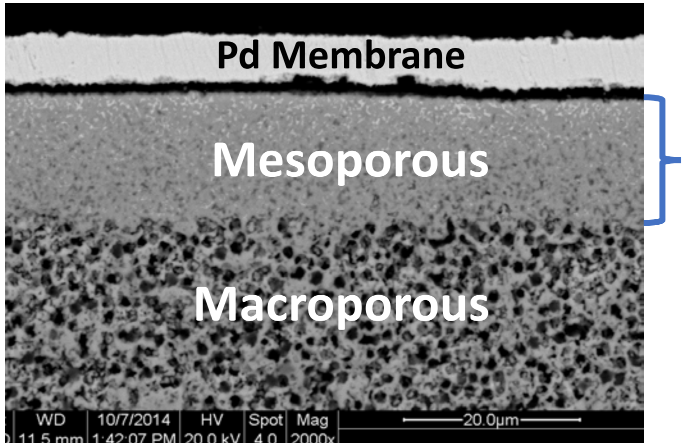
Initial Target: UHP Hydrogen

Attributes fully demonstrated at lab scale

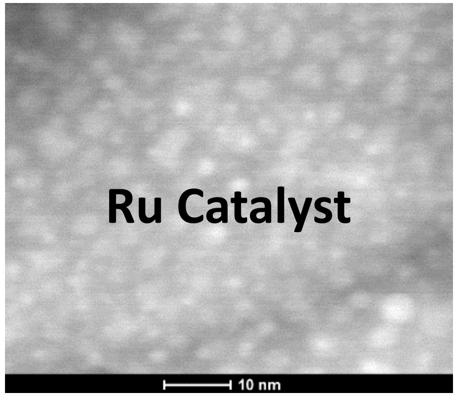
- Patented catalytic membrane reformer geometry
- Innovation fabrication
- Achieved record productivity
- Reduce T < 450°C







FIB - TEM

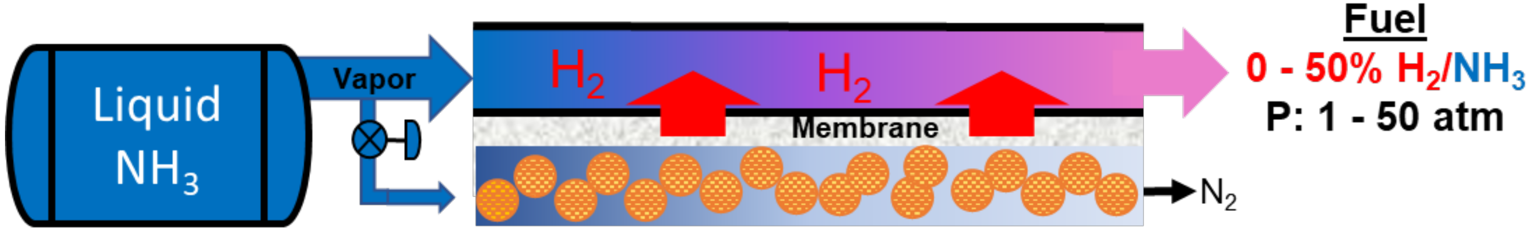


R. Sitar, J. Shah, Z. Zhang, H. Wikoff, J. D. Way and C. A. Wolden, "Compact ammonia reforming at low temperature using catalytic membrane reactors", *Journal of Membrane Science* **644,** 120147 (2022).

Pivot: Use sweep to generate NH_3/H_2 Blends

CMR Operation

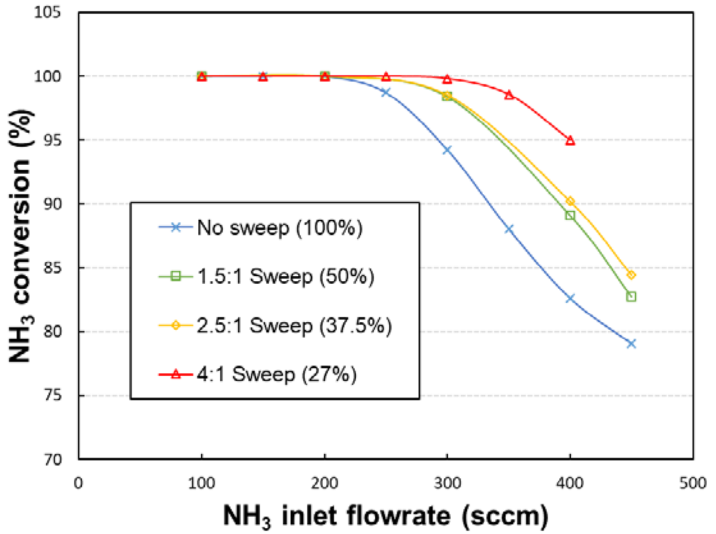
- Send a fraction to reformer, completely decompose
- Extract all the hydrogen into sweep gas, reject N_2
- Enables 100% H_2 recovery



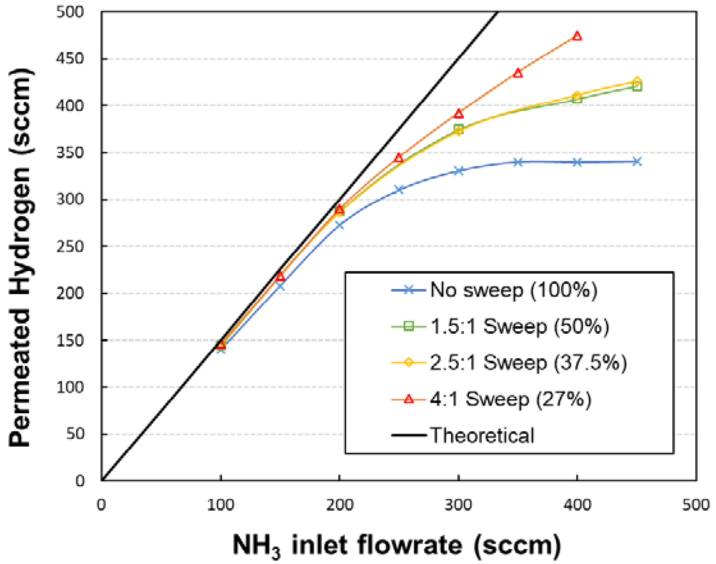
Sweep Gas Options

- Ammonia: Tunable H_2/NH_3 Blends
- Methane: Hydrogen enriched natural gas (HENG)
- Steam: Humidified Hydrogen

Higher Conversion



Improved Recovery



R. Sitar, J. Shah, J. D. Way and C. A. Wolden, "Efficient generation of H_2/NH_3 fuel mixtures for clean combustion", *Energy & Fuels* **36,** 9357-9364 (2022).

CMR Advantage: N_2 Rejection

$$S_L = S_{LO} T_n^{\alpha} P_n^{\beta} \gamma$$

$$S_{LO} = f(\phi, x_{H_2})$$

$$\alpha = f(\phi, x_{H_2})$$

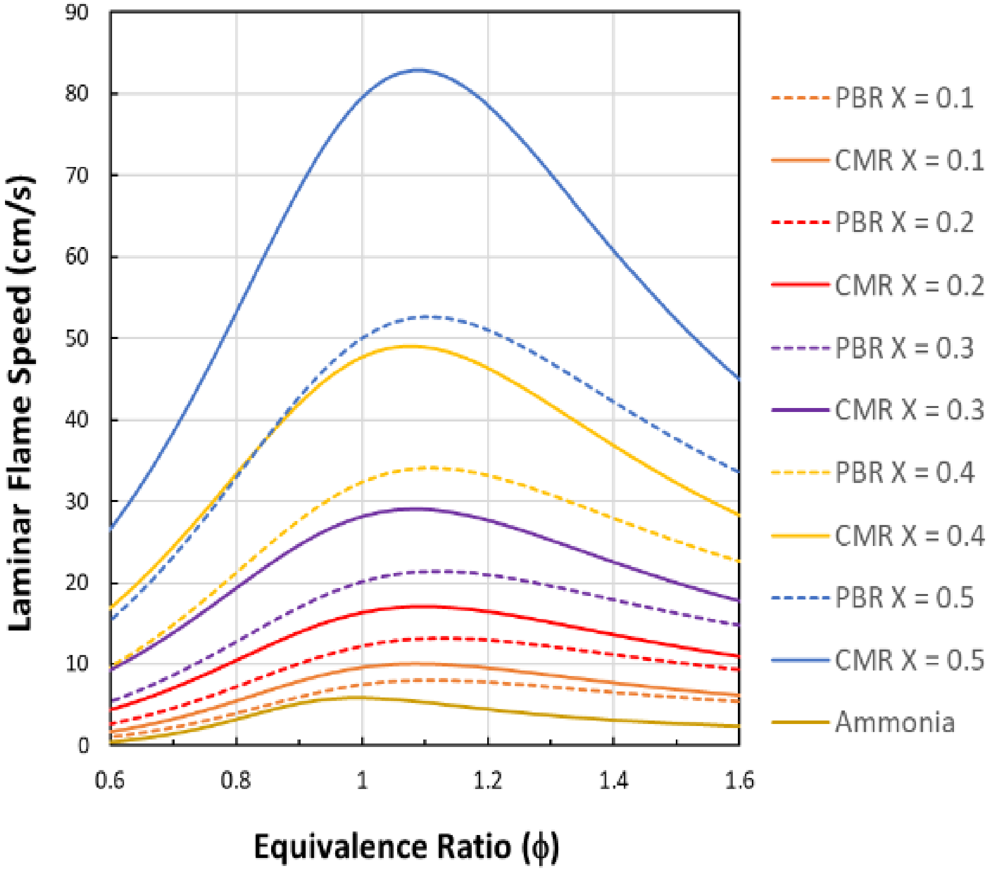
$$\beta = f(\phi, x_{H_2})$$

$$\gamma = f(\phi, x_{N_2}, x_{H_2}, T_n, P_n)$$

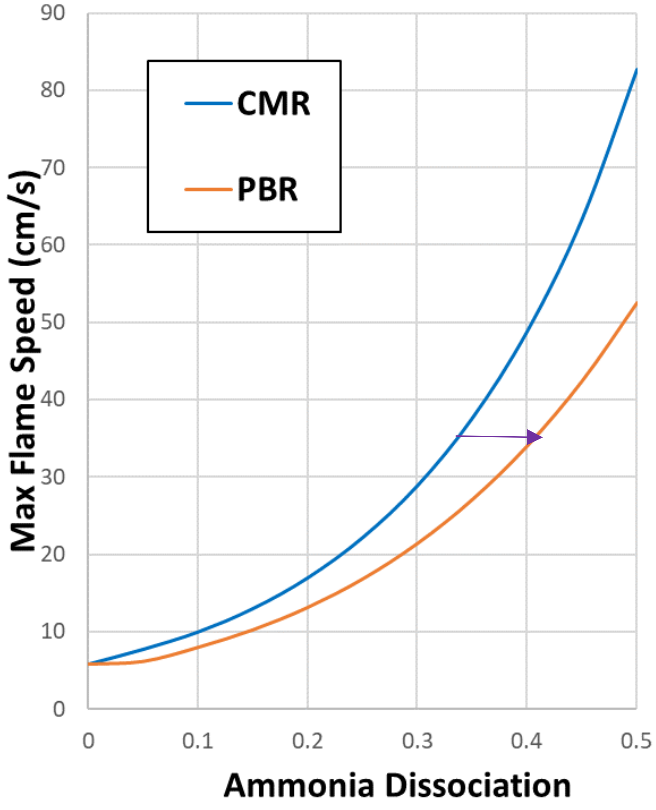
Benefits

- CMR: 25 – 60% higher LFS
- Match Methane
  - CMR requires 35% conversion
  - PBR requires 42% conversion
  - 20% more energy
  - Higher adiabatic flame temperature

CMR: Solid Lines (NH_3/H_2)
PBR: Dashed Lines ($NH_3/H_2/N_2$)



CMR: NH_3/H_2
PBR: $NH_3/H_2/N_2$



X = Ammonia Conversion

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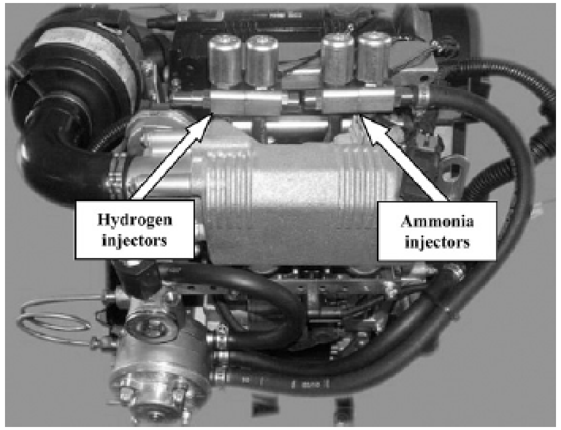
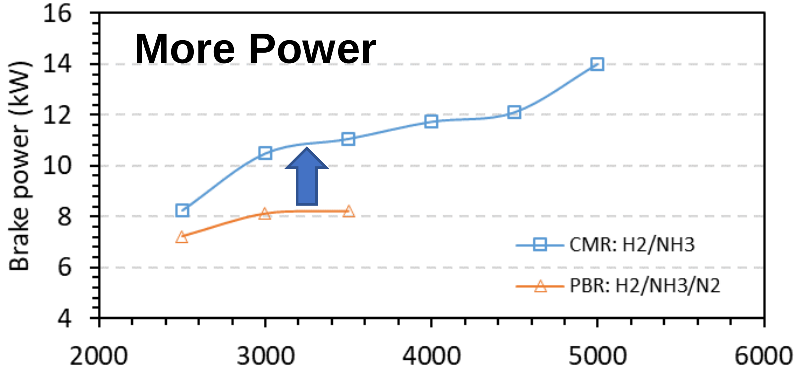
Potential Benefits of Nitrogen Removal

Modified standard SI engine (Frigo lab in Italy)

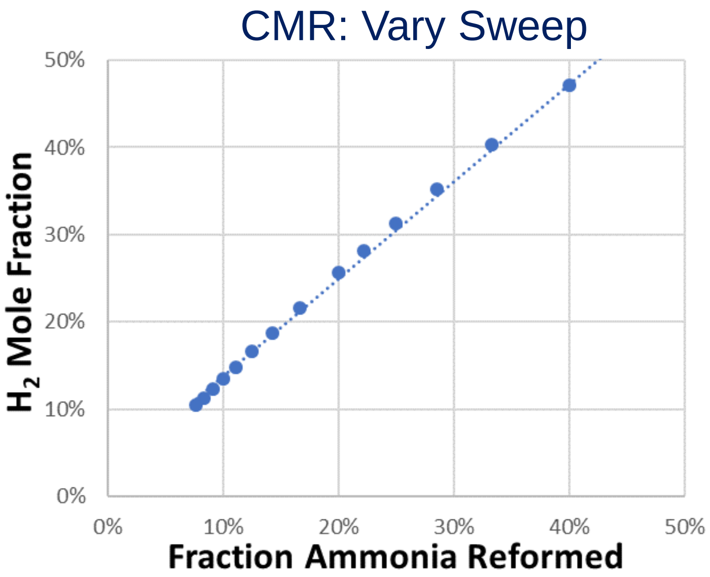
- Compared NH_3/H_2 (CMR) vs. $NH_3/H_2/N_2$ (PBR)
- Benefits of N_2 removal:
  - Achieved ~35% more power, greater range of stable operation
  - Produced >65% less NO_x (less than gasoline operation)

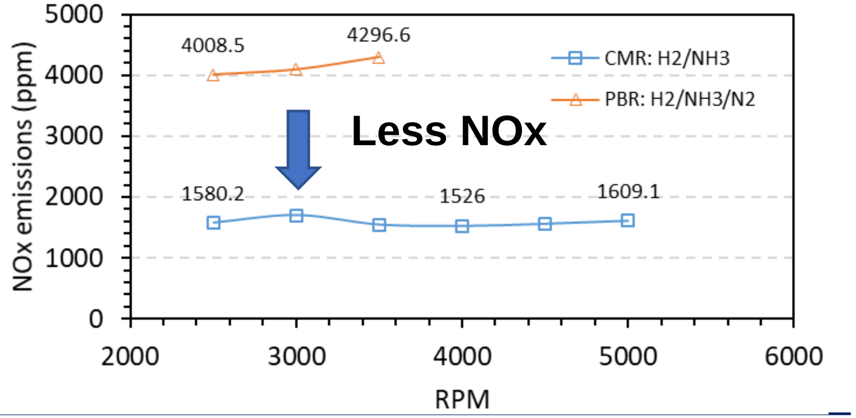




Requires Dynamic Composition Control

- ~50% H_2 at cold start
- ~10% H_2 under full load
- Easily achieved in CMR





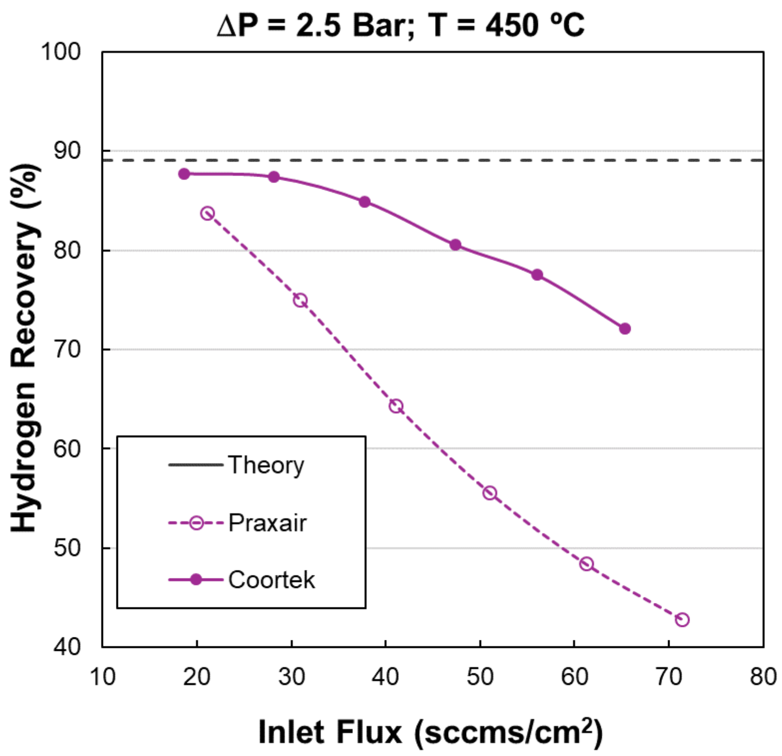
M. Comotti and S. Frigo, "Hydrogen generation system for ammonia–hydrogen fuelled internal combustion engines," *International Journal of Hydrogen Energy* **40,** 10673 (2015).

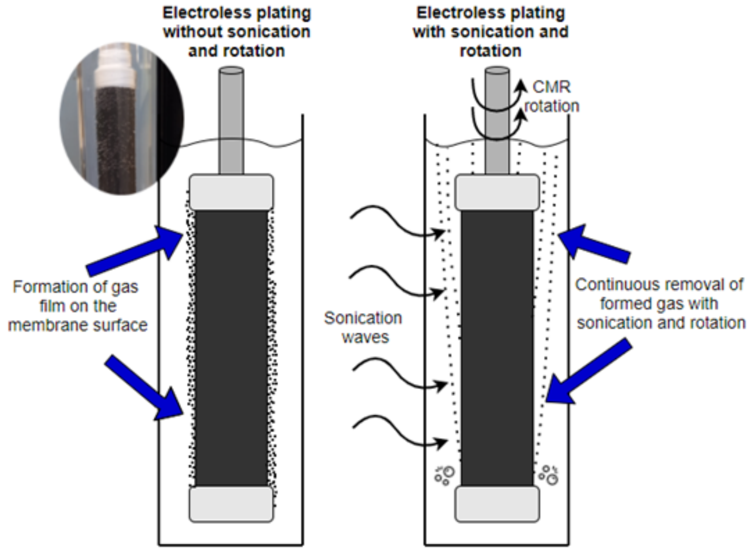
S. Frigo and R. Gentili, "Analysis of the behaviour of a 4-stroke SI engine fuelled with ammonia and hydrogen," *International Journal of Hydrogen Energy* **38,** 1607 (2013).

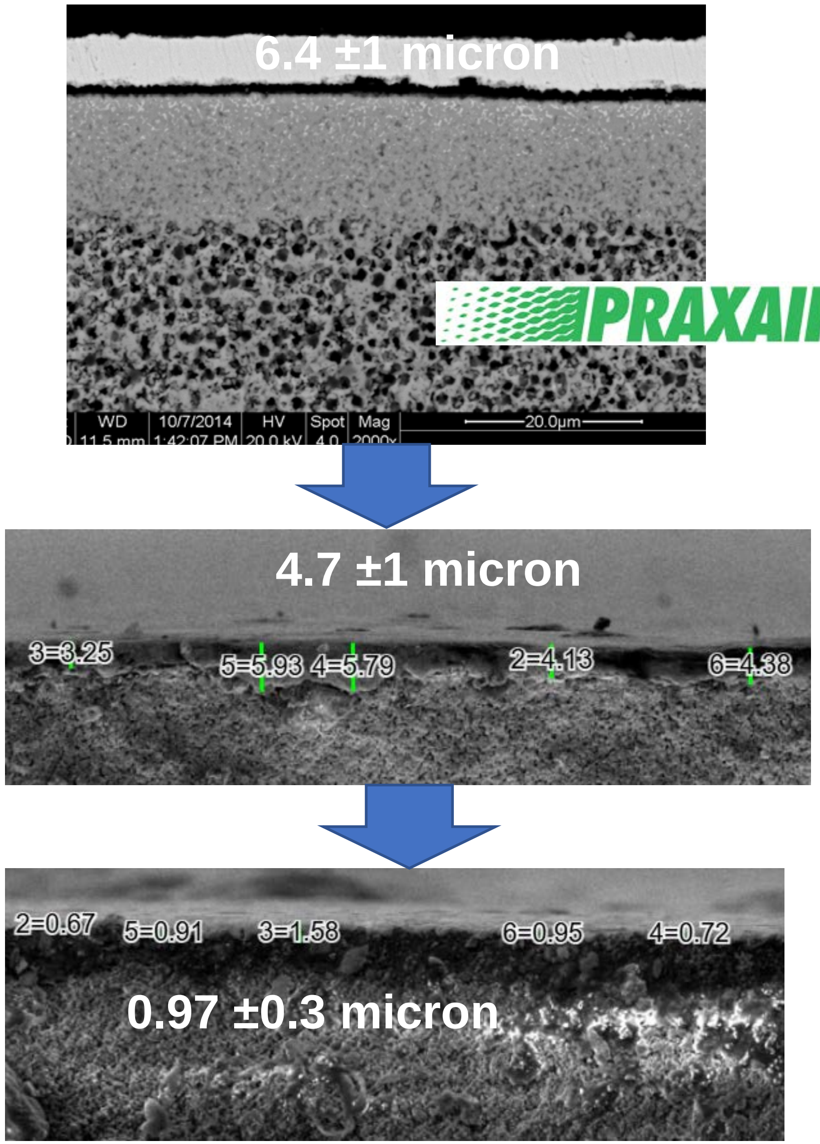
Goals of Current Project: Better Performance & Cheaper

Better Membranes

- Performance Limited by Flux
- Reduce Pd from 6.4 to < 1 μm
- Reduce resistance of membrane support
- Recovery from 75% H_2/25% N_2







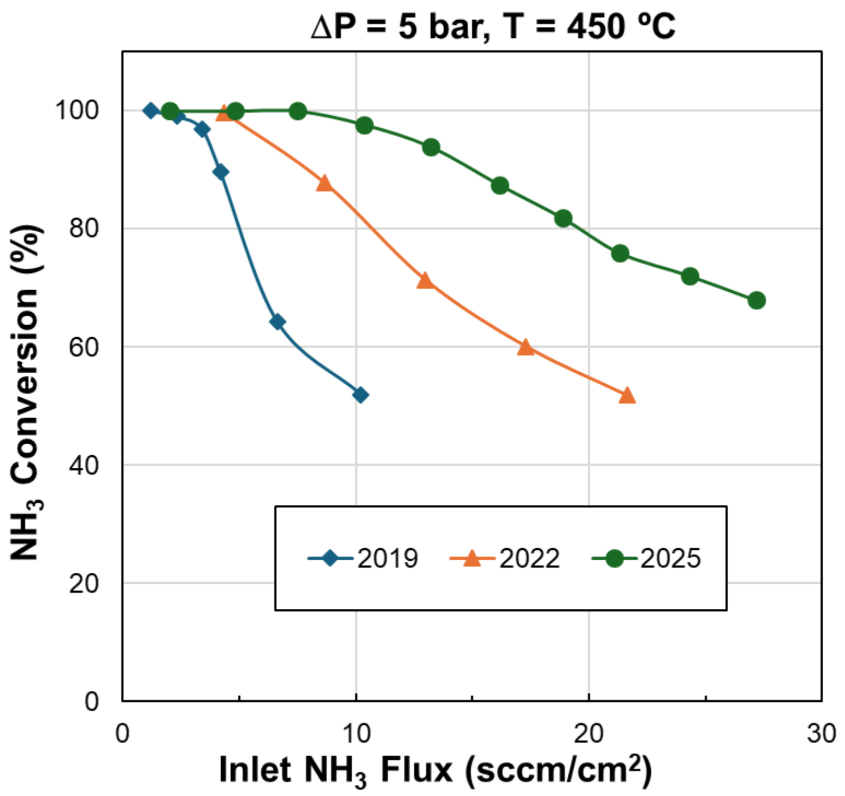
PRAXAIR

COORSTEK

Goals of Current Project: Better Performance & Cheaper

Performance Evolution

- No catalyst in lumen
- 4X enhancement in throughput



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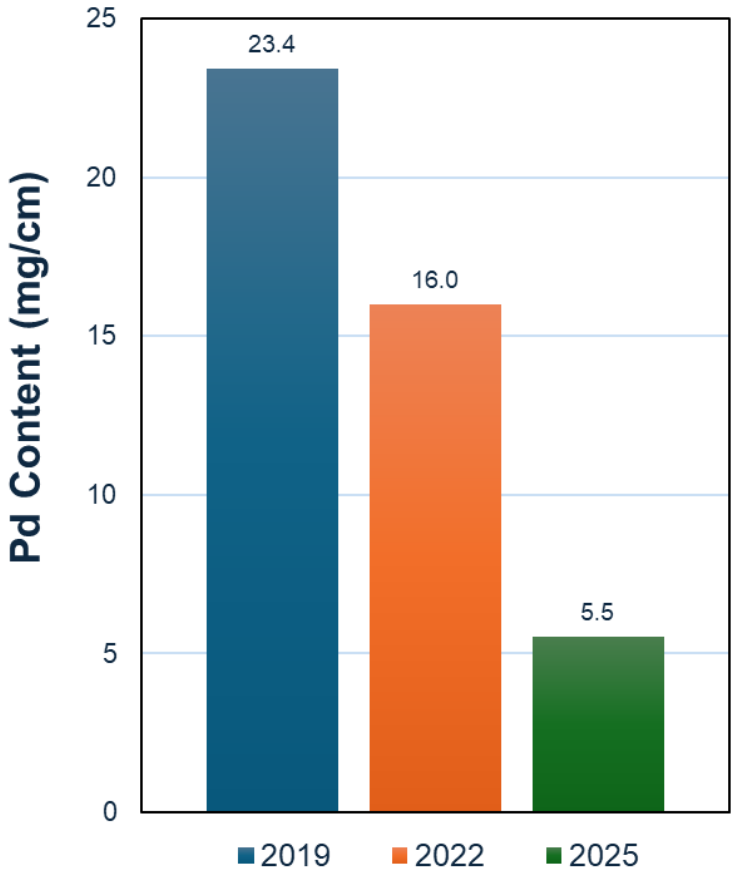
Pd Inventory

- >4X reduction



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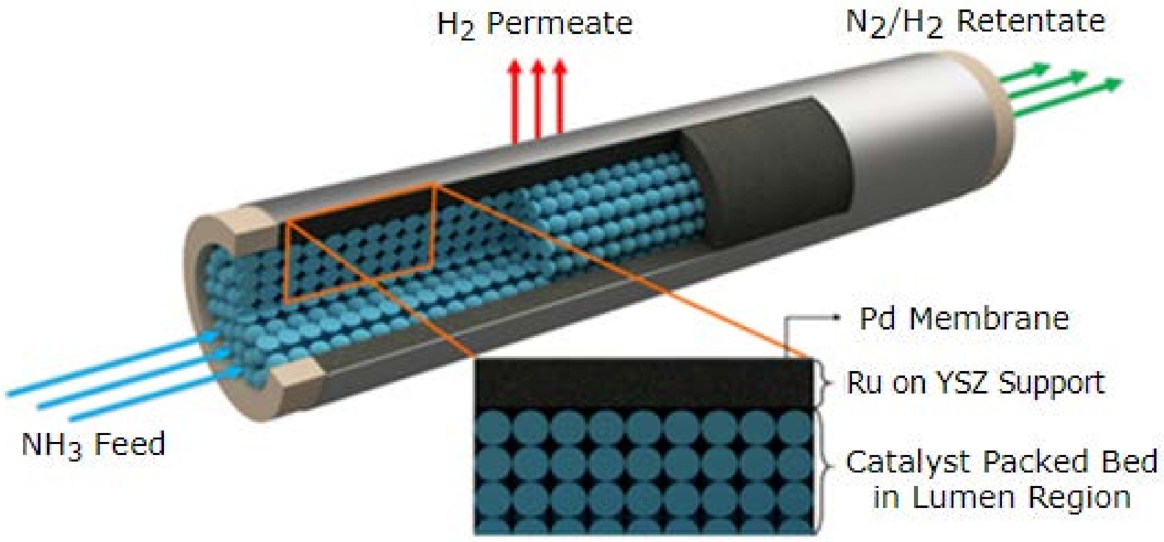
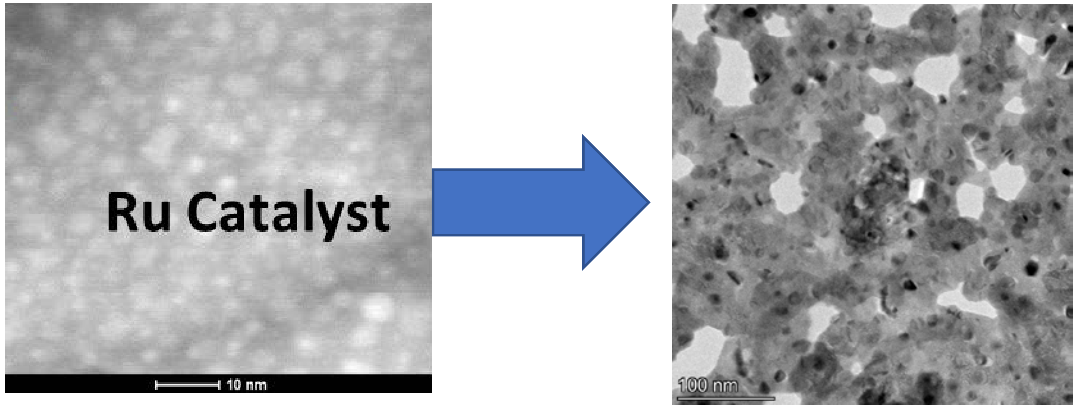
Goals of Current Project: Better Performance & Cheaper

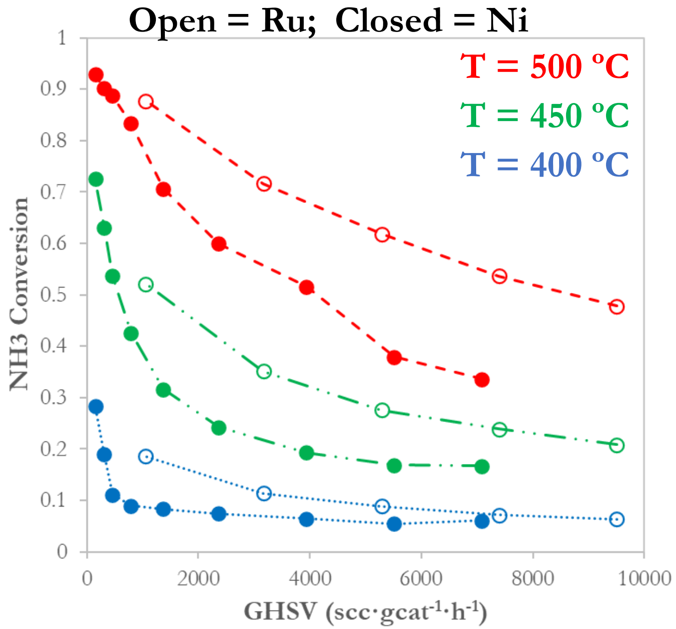
Cheaper Catalysts

- Ru costs > Pd Costs
- Significant Ru in Lumen
- Developing Nanoscale Ni Catalyst
- Approaching performance of Ru Control (BASF)





Ni/La_2O_3

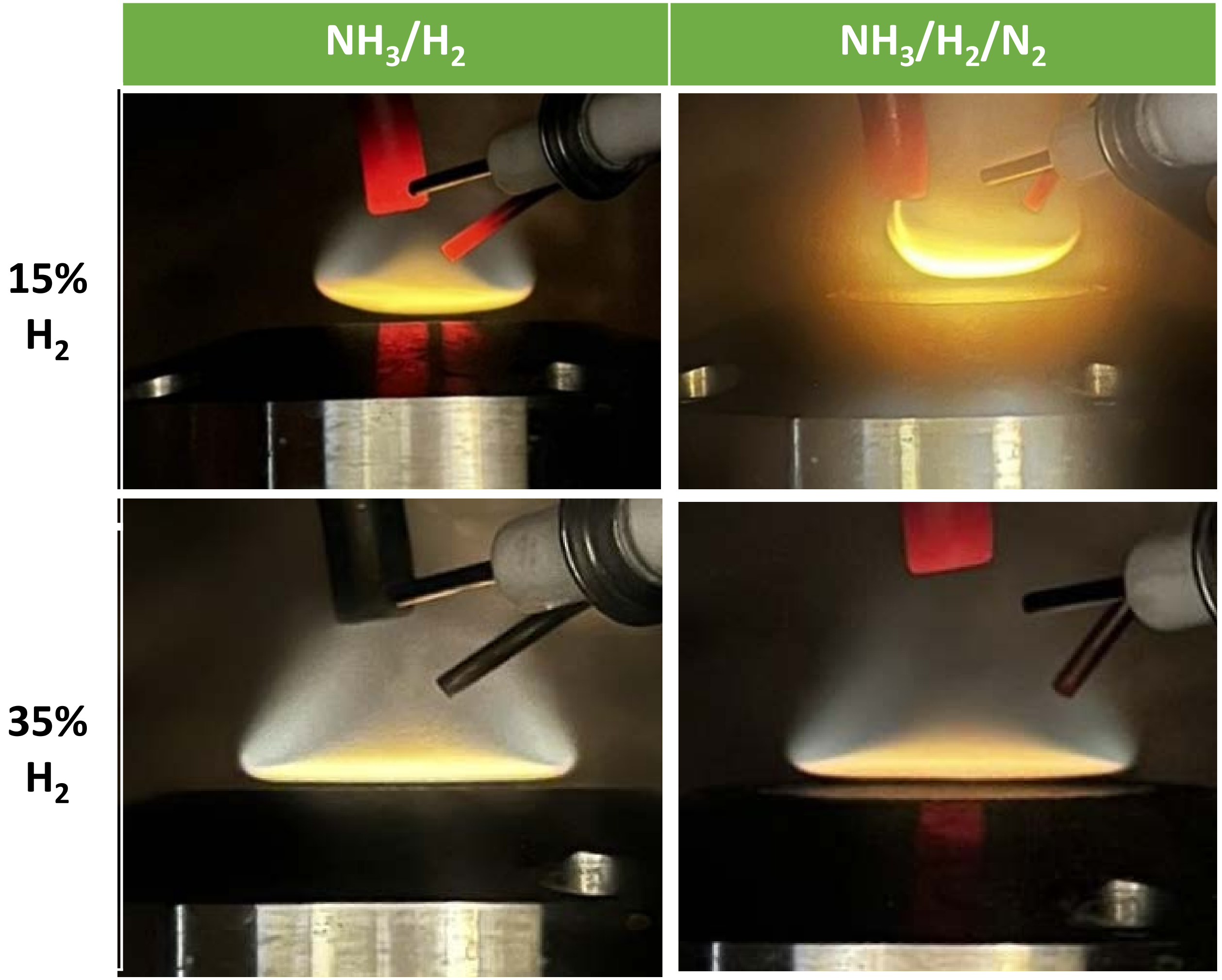


R. Sitar, A. D'Aquila, J. L. Jechura and C. A. Wolden, "Techno-economic analysis of zero-carbon ammonia-hydrogen fuel blend production through a catalytic membrane reformer and packed bed reactor," *Renewable and Sustainable Energy Reviews* **199,** 114469 (2024).

Utilization of NH_3/H_2: Laminar Flame Burner

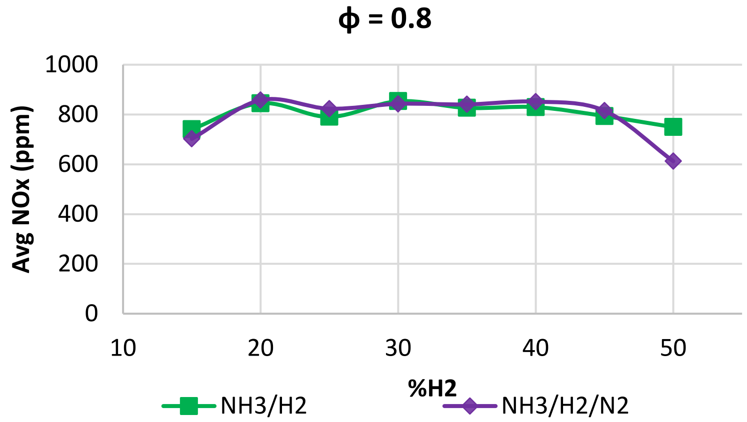
Any Benefit to N_2 Removal?

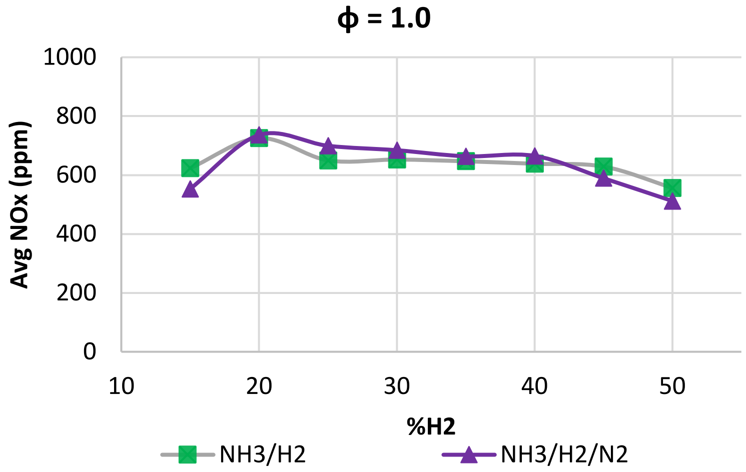
Explored %H_2 and ϕ



Improved Flame Stability

Negligible Impact on NO_x





Utilization of NH_3/H_2: Generator

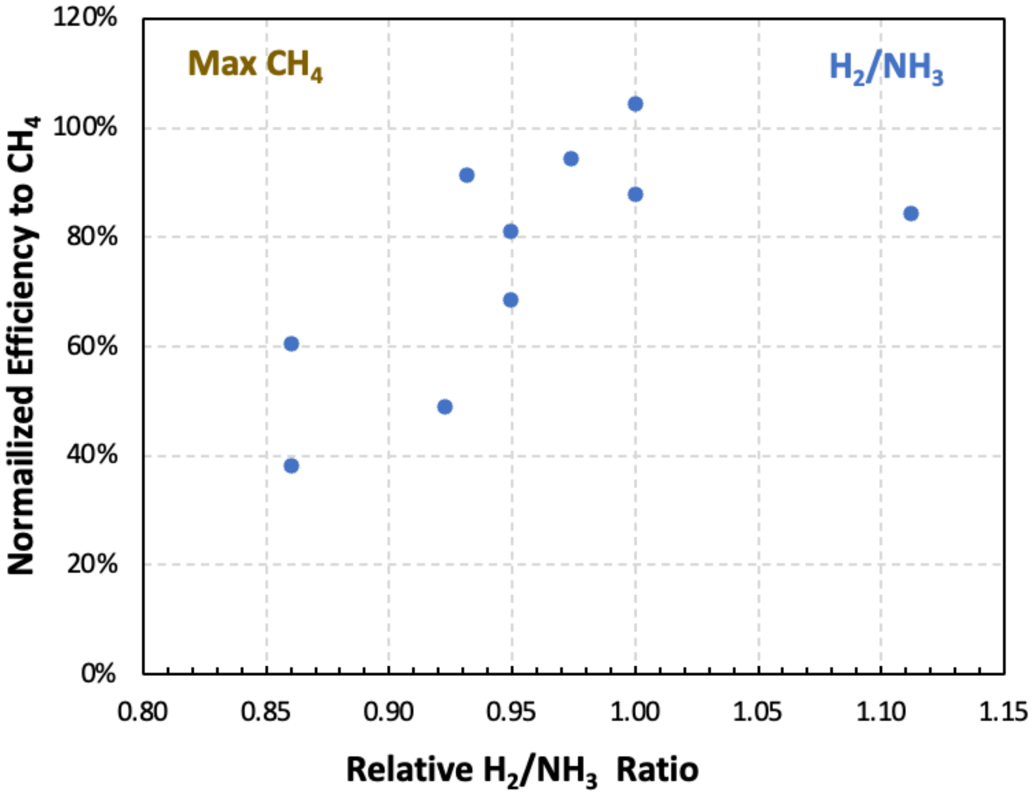
Is it a true drop-in Fuel?

Firman Tri-Fuel Generator (Gasoline/LPG/CH_4)

Compared CH_4 with NH_3:H_2 blends

Zero Modification

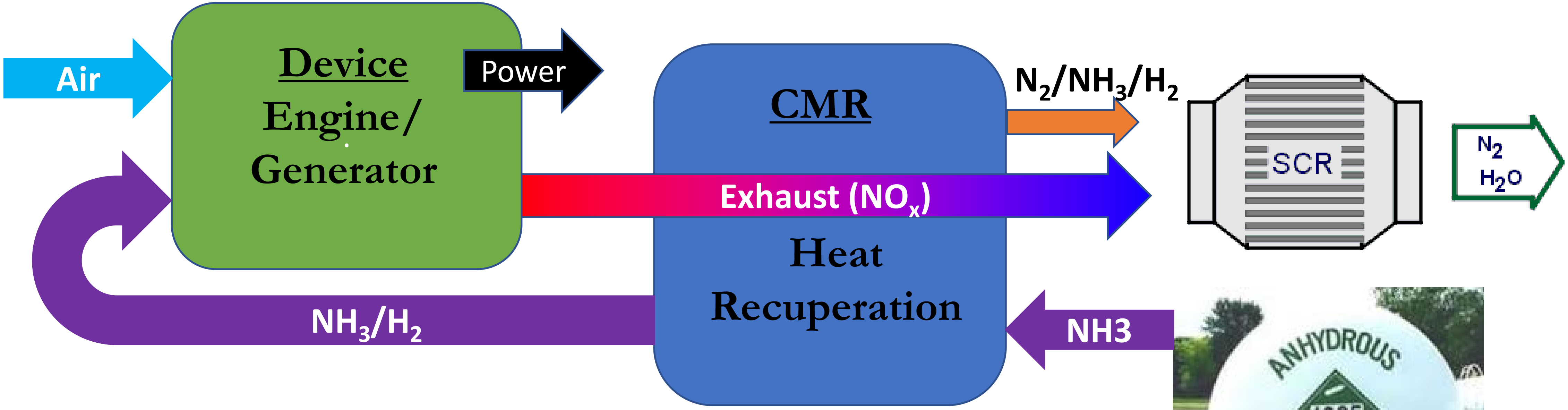
$$\eta = \frac{Electrical\ Power}{\dot{n}_{fuel} \times LHV}$$



NH_3/H_2 Generator

- Stable operation with varied load
- Fuel to power efficiency comparable to CH_4
- Exhaust temperature suitable for heat integration

Concept: Integrated Carbon-Free Power



Ideal Operation

- Carbon –free Power
- No NO_x
- Adiabatic Operation

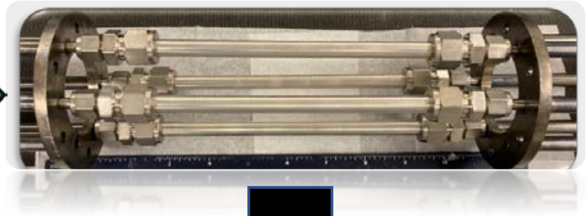
BLAZE ENERGY

- CEO: Dr. Rok Sitar
- Email: rok@blazeenergytech.com
- Website: https://blazeenergytech.com/

Summary: Catalytic Membrane Reformer

NH_3

Catalytic Membrane Reformer (CMR)



N_2

NH_3:H_2

tunable, drop-in replacement for hydrocarbons

Single, dense liquid fuel source

<$0.4/kg H_2

Better Storage

- Existing infrastructure
- 25X lower storage costs
- Zero carbon

Better System

- Higher throughput (>10X)
- Energy Efficient (T < 400°C)
- Low OpEx/CapEx

Better Fuel

- Dynamic control (H_2/NH_3)
- High pressure delivery
- No N_2: More power

Acknowledgements

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