Scalable, Low-cost Hydrogen Delivery Systems

Nolan Kelley, Sean Mathews, Kagan Killough, Rok Sitar, Ben Ivie, J. Douglas Way, and Colin A. Wolden
Department of Chemical and Biological Engineering, Advanced Energy Systems. Colorado School of Mines, Golden CO 80401

COLORADOSCHOOLOFMINES
EARTH • ENERGY • ENVIRONMENT

Project ID: IN045

AMR Criteria

Project Goal
- Reduce platinum group metal (PGM) content >90% while maintaining catalytic membrane reactor productivity for delivering H_2 from NH_3

Project Overview
- Reduce Pd inventory and increase flux across membrane
- Develop Ni-based alternatives to Ru based catalyst
- Timeline: 3 years 1/1/24 - 12/31/26
- Budget: $987,954
- Partners: HyMARC Team

Potential Impact
- Reduce cost for delivery of UHP hydrogen and clean combustion mixtures

Approach
- Nanoscale engineering of supports to increase H_2 flux
- Ni nanocrystals on rare earth supports with alkali promoters
- Experiments reviewed & approved by environmental health and safety

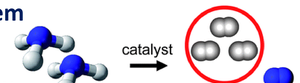
Accomplishments and Progress
- Project officially under contract effective 3/1/24
- Ordered required catalyst characterization equipment

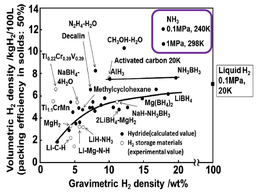
Collaboration and Coordination
- Met with HyMARC collaborators and NREL technical monitors
- Remaining Challenges and Barriers: The proposed work

Technology Transfer Activities
- In discussion to license IP to startup Blaze Energy Technologies

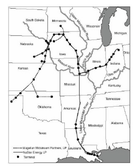
NH_3: The Ideal Vector for H_2@Scale

Solves the Storage & Distribution Problem
- T = 25 °C >> -253 °C
- P = 10 bar << 700 bar
- Liquid NH_3: 40% more H by volume than liquid H_2
- Liquid NH_3: 60% more energy by volume than liquid H_2
- Leverage existing production/distribution/storage infrastructure

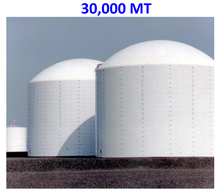




Ammonia pipelines in the US



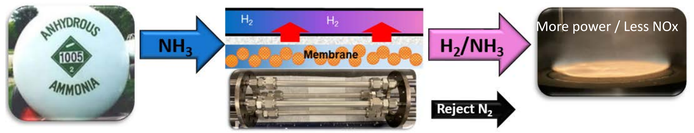
30,000 MT



A. Valera-Medina et al., "Ammonia for power," *Progress in Energy and Combustion Science* **69**, 63-102 (2018)

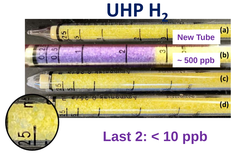
Production of UHP H_2 & NH_3/H_2

Catalytic Membrane Reactor (CMR) Reformer



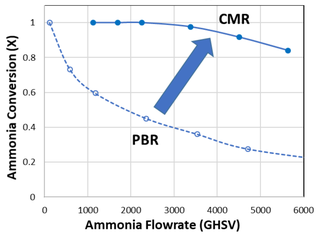
Competitive Advantages
- Process a fraction of NH_3 / fully decompose / extract hydrogen
- Hydrogen removal accelerates kinetics
- Operating temperature as low as 350 °C
- Earth abundant zeolite for UHP H_2
- Tune NH_3/H_2 ratio by adjusting sweep rate
- No N_2: Important for performance
- Sweep allows elevated pressure operation

UHP H_2

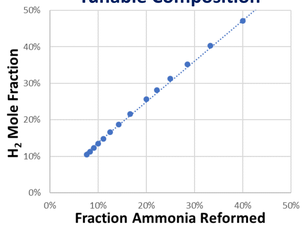


Last 2: < 10 ppb

10X Higher Throughput



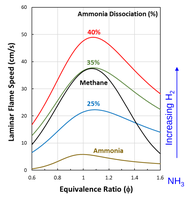
Tunable Composition

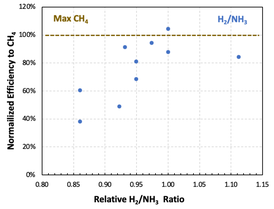


Clean Combustion Applications

Ammonia = Fuel Flexible, Drop-in Hydrocarbon Replacement
- NH_3: Difficult to ignite, low flame speed
- H_2: Dangerous, high flame speed, requires specialized equipment
- NH_3/H_2 mixtures: Tunable flame properties
- Demonstration: Commercial generator w/no modification
- Compared performance between methane and NH_3/H_2 mixtures
- Nominally identical or superior performance
- No ammonia slip; NOx ~150 ppm << diesel generators

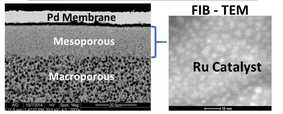
$$\eta = \frac{Electrical\ Power}{\dot{n}_{fuel} \times LHV}$$





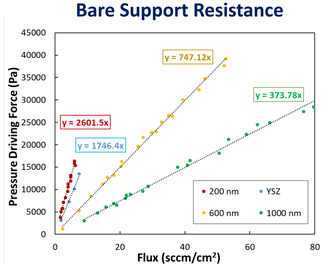
Current Configuration

Current CMR Components
- Commercial asymmetric YSZ support ($)
- Ru-based catalysts ($$)
- Several microns of Pd membrane ($$)
- Pure H_2 flux limited by support

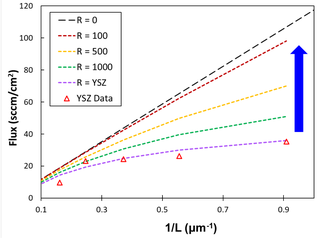


$$\Delta P = R * Flux \qquad Flux = \frac{\pi}{L}\left(P_1^{1/2} - P_2^{1/2}\right)$$

Bare Support Resistance



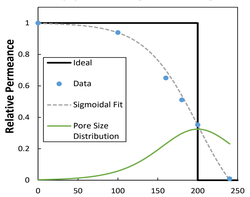
Pure H_2 Flux at ΔP = 12.5 psi



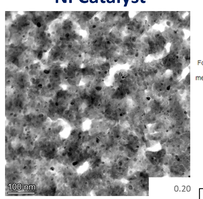
Increase Performance/Reduce Cost

Increase Hydrogen Flux
- Employ low cost, low resistance symmetric supports (ceramic, steel)
- Nanoscale introduction of asymmetry using ALD
- Reduce external pore size / maintain high permeance
- Couple with ultrasonic assisted electroless plating
- Reduce Pd thickness <1 micron w/ high selectivity

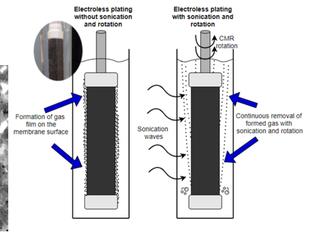
Support Engineering



Ni Catalyst



Ultrasonic Plating



Replace Ru with non PGM Catalyst
- Focus: Oxide supported Ni catalysts
- Control dispersion / faceting
- Rare earth oxides / alkaline promoters
- Validate vs. commercial Ru/Al_2O_3
- Preliminary results encouraging