Protonic Ceramics for Energy Storage and Electricity Generation with Ammonia

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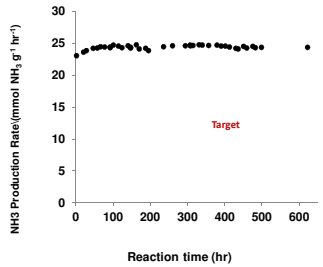
Project goals:

Develop reversible proton-conducting ceramic cells that **synthesize ammonia** for energy storage, and also, **convert ammonia into electricity** for power generation.

Technology development path:

1. Integrate ruthenium based catalyst within proton-conducting cells for ammonia production (energy storage mode) and decomposition (power production mode).
2. Develop reversible proton-conducting ceramic cells that convert ammonia into electricity for power generation, or synthesize ammonia for energy storage.
3. Develop fabrication processes for cost-effective manufacturing of scaled-up protonic ceramic cells.
4. Demonstrate operation of a proton-conducting stack prototype manufactured using commercially relevant processes.
5. Complete detailed techno-economic analyses that maximize the value proposition of the reversible ammonia system.
6. Pathways for proton-conducting ceramic technology applications for ammonia synthesis.

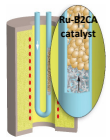
1. Ru- catalyst shows excellent stability over 600 hours of continuous operation



1wt%Ru supported catalyst developed by CSM

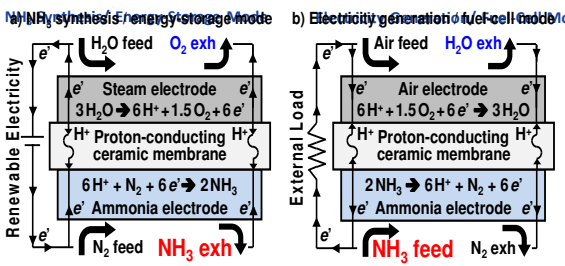
Catalytic tests: 30 psi, $3H_2$:$1N_2$

0.2 g catalyst diluted with 0.4 g Al_2O_3

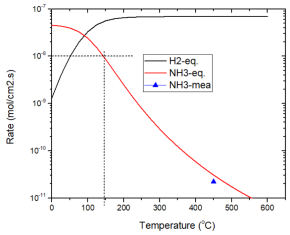


Packed-bed reactor

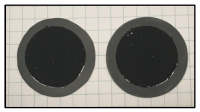
2. Cell Configurations: reversible operation



2.1 Ammonia-production cell with integrated catalyst in NH_3 electrode



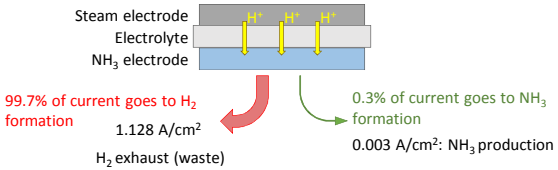
Proton-Conducting Cell



2.2 Original design: efficiency and production are limited by low equilibrium conversion

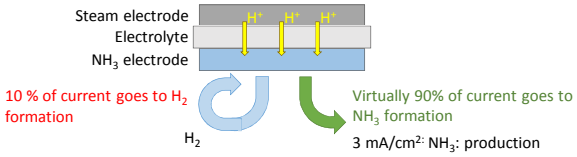
Our target of 1 x 10^{-8} mol NH_3 / cm^2·s

- Most H^+ flux goes to H_2 due to low equilibrium-conversion rate.
- H_2 is swept out with exhaust gas.



2.3 Efficiency is greatly improved by H_2 recirculation

- Run high current at startup to generate excess H_2, then recirculate.
- At steady state, provide only enough current to replenish consumed H_2.



2.4 Comparisons of results with references reflect CSM's record-high NH_3-production rates

Table. Summary of ammonia production rate from literature studies and the recent CSM work

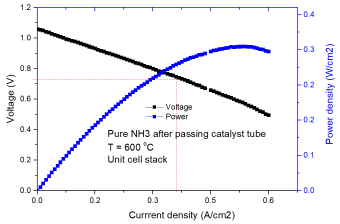
Materials Set: Steam Electrode | Electrolyte | NH_3 Electrode	NH_3 production rate ($mol \cdot S^{-1} \cdot cm^{-2}$)	Conversion efficiency (%)	Temp. (°C)
Pd | $SrCe_{0.95}Yb_{0.05}O_{3-\delta}$ | Ru [1]	9.10 x 10^{-14}	~0.00015	650
LaCsFeNi | (Li,Na,K)CO_3-GDC | LaCsFeNi [2]	1.20 x 10^{-10}	0.06	400
Pt | BZY | Pt [3]	< 1 x 10^{-12}	< ~0.006	550
LSCF | BZY | LSCF [3]	8.50 x 10^{-11}	0.33	550
CSM Electrolyte supported | electrolysis	3.29 x 10^{-11}	0.06	600
CSM Anode supported | electrolysis	8.74 x 10^{-9}	TBC*	600
CSM Anode supported | electrolysis | cylinder gas	4.06 x 10^{-8}	TBC	600
CSM Reactor: cylinder gas only	9.65 x 10^{-7}	TBC	500

[1] A. Skodra, M. Stoukides, *Solid State Ionics* 180 (2009) (23) 1332.
[2] R. Lan, K.A. Alkhazmi, I.A. Amar, S. Tao, *Electrochimica Acta* 123 (2014) 582.
[3] D.S. Yun, J.H. Joo, J.H. Yu, H.C. Yoon, J.-N. Kim, C.-Y. Yoo, *Journal of Power Sources* 284 (2015) 245.

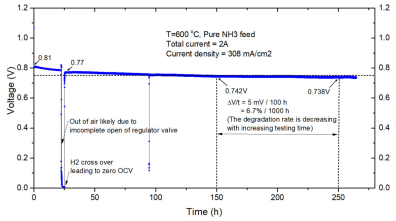
* TBC: to be calculated

2.5 Excellent performance from an NH_3-fueled unit-cell stack

NH_3 passes through Ru catalyst
400 mA / cm^2 at 0.75 V, 600°C



Only stack-level NH_3-fueled PCFC result ever reported.
Electrolysis Performance: > 250h steady state

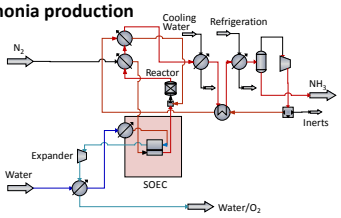


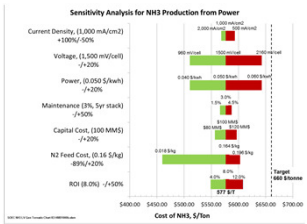
3. & 4. Established success in scale-up, manufacturing & commercialization of fuel-cell and allied electrochemical systems

- Pilot manufacturing of solid oxide fuel cell (SOFC) and stacks.
- Tape casting/screen printing/co-firing fabrication process has been scaled up to 1000 cm^2.
- Production volumes of 500 kW annually.

5. Techno-economic analyses: FCE evaluates value proposition of reversible NH_3 cells

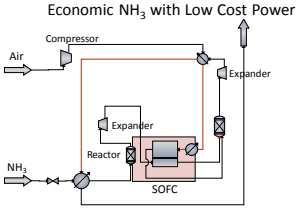
Ammonia production

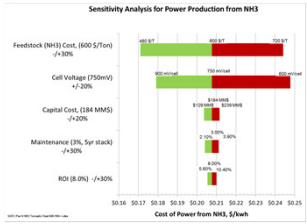




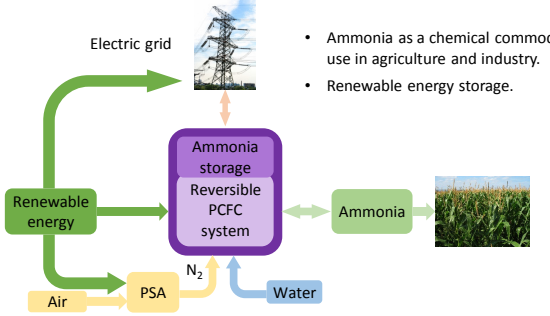
Power Production

Economic NH_3 with Low Cost Power





6. Pathways for PCFC technology applications for ammonia synthesis



- Ammonia as a chemical commodity for use in agriculture and industry.
- Renewable energy storage.