Solid State Ammonia Synthesis

NHThree LLC

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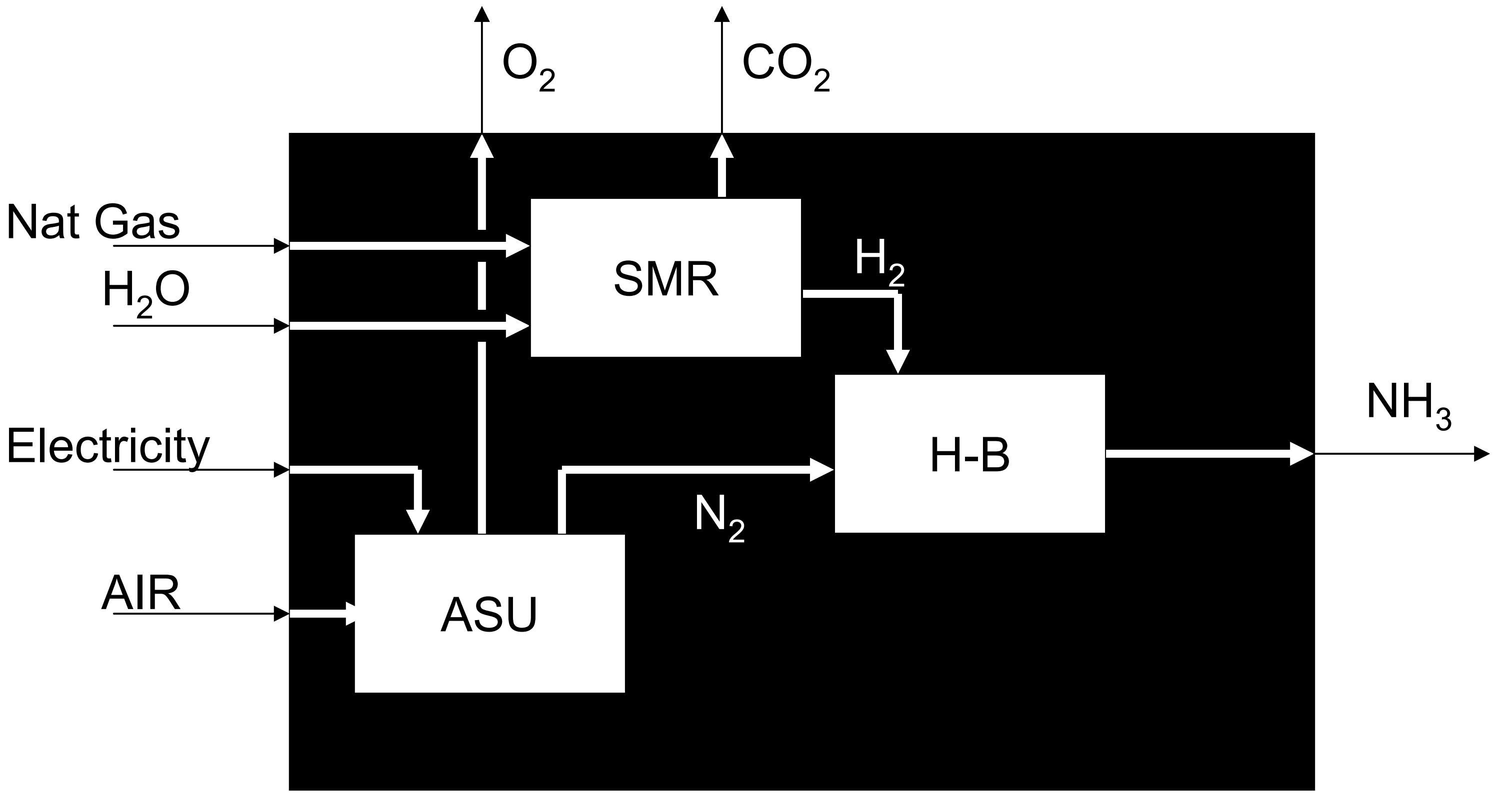
Ammonia - A Sustainable, Emission-Free Fuel
October 15, 2007

Inside the Black Box: Steam Reforming + Haber-Bosch

$$3\ CH_4 + 6\ H_2O + 4\ N_2 \rightarrow 3\ CO_2 + 8\ NH_3$$



Energy consumption ~33 MBtu (9500 kWh) per ton NH_3

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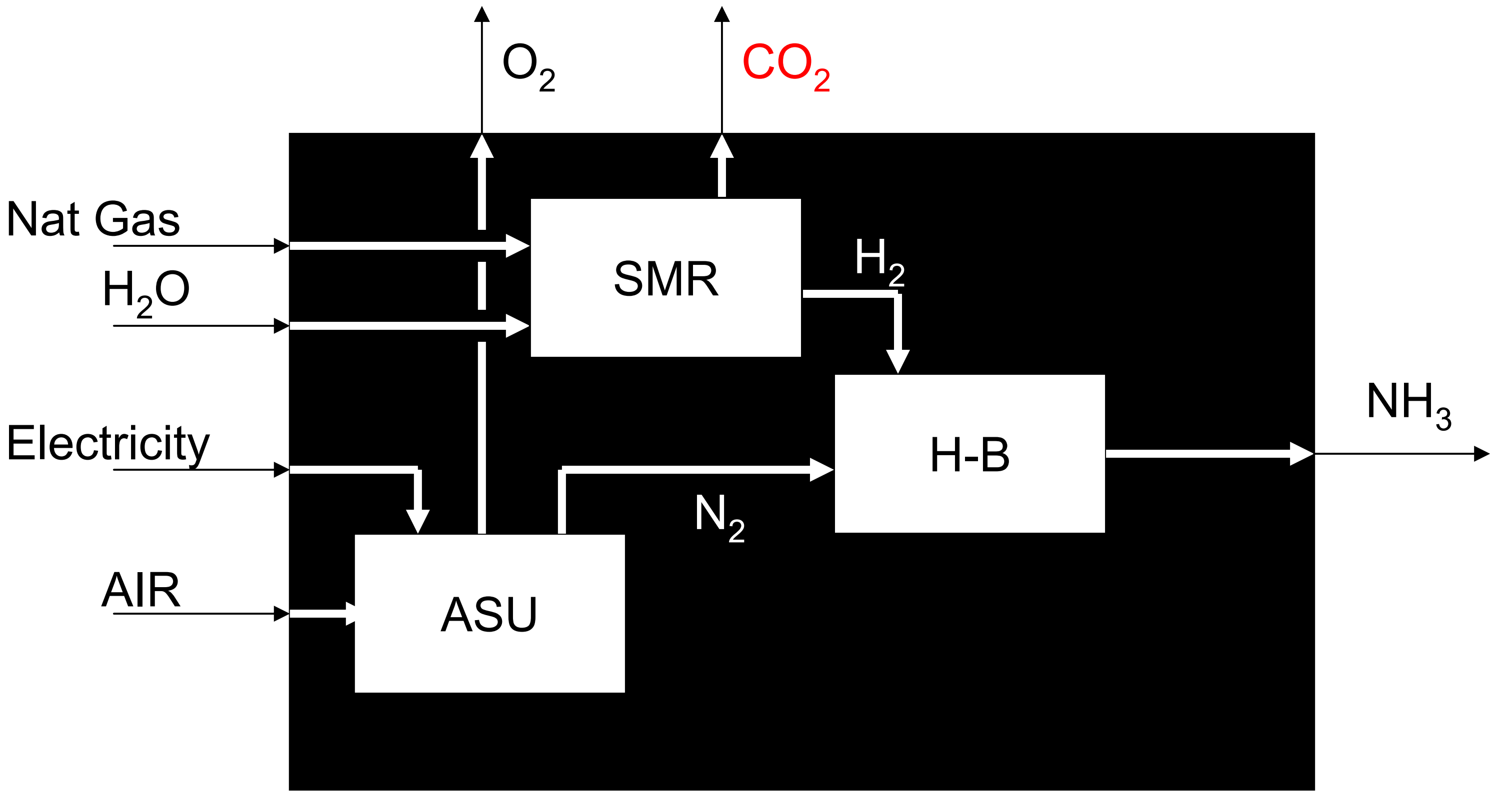

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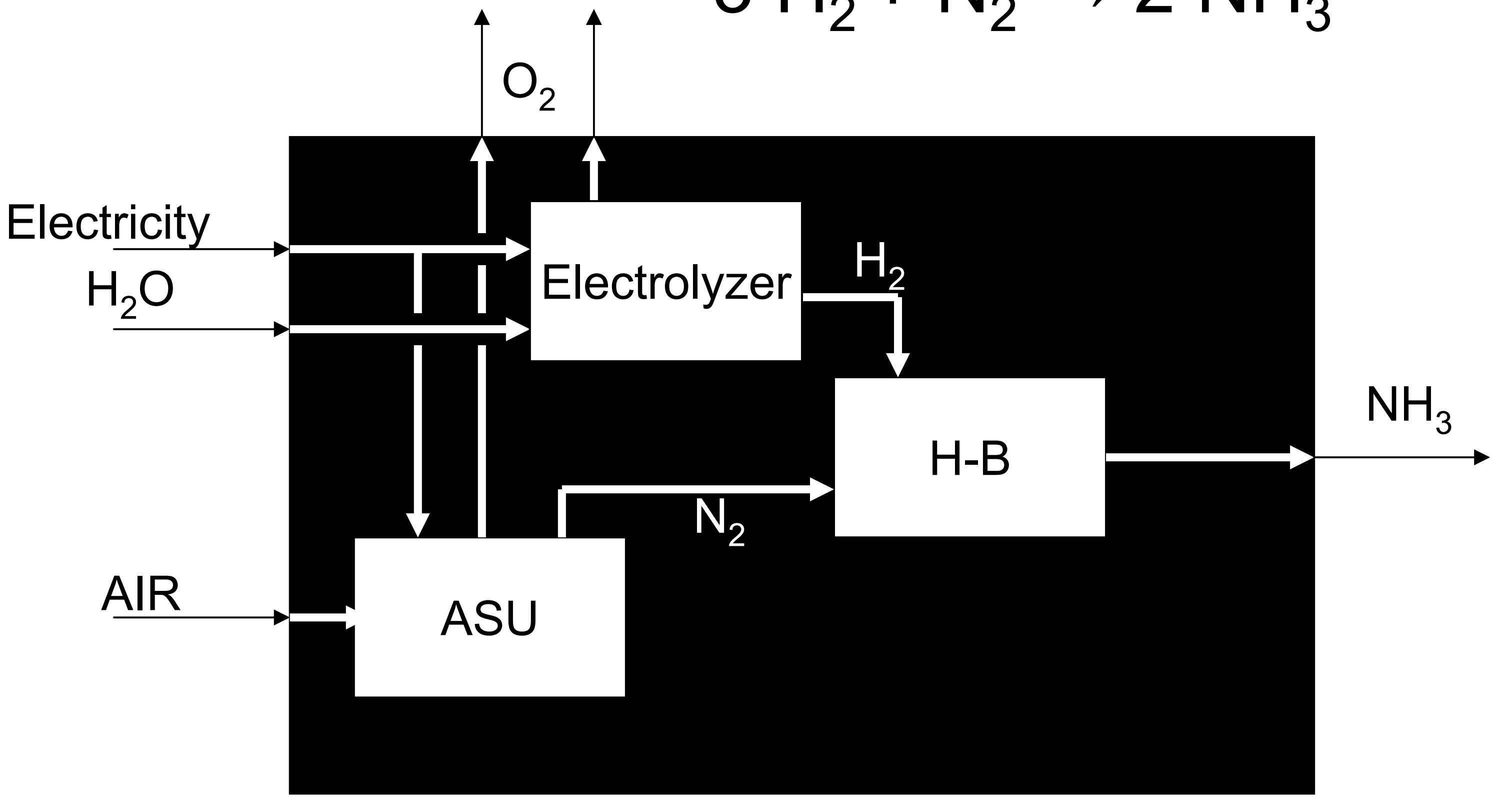
Inside the Black Box: HB Plus Electrolysis

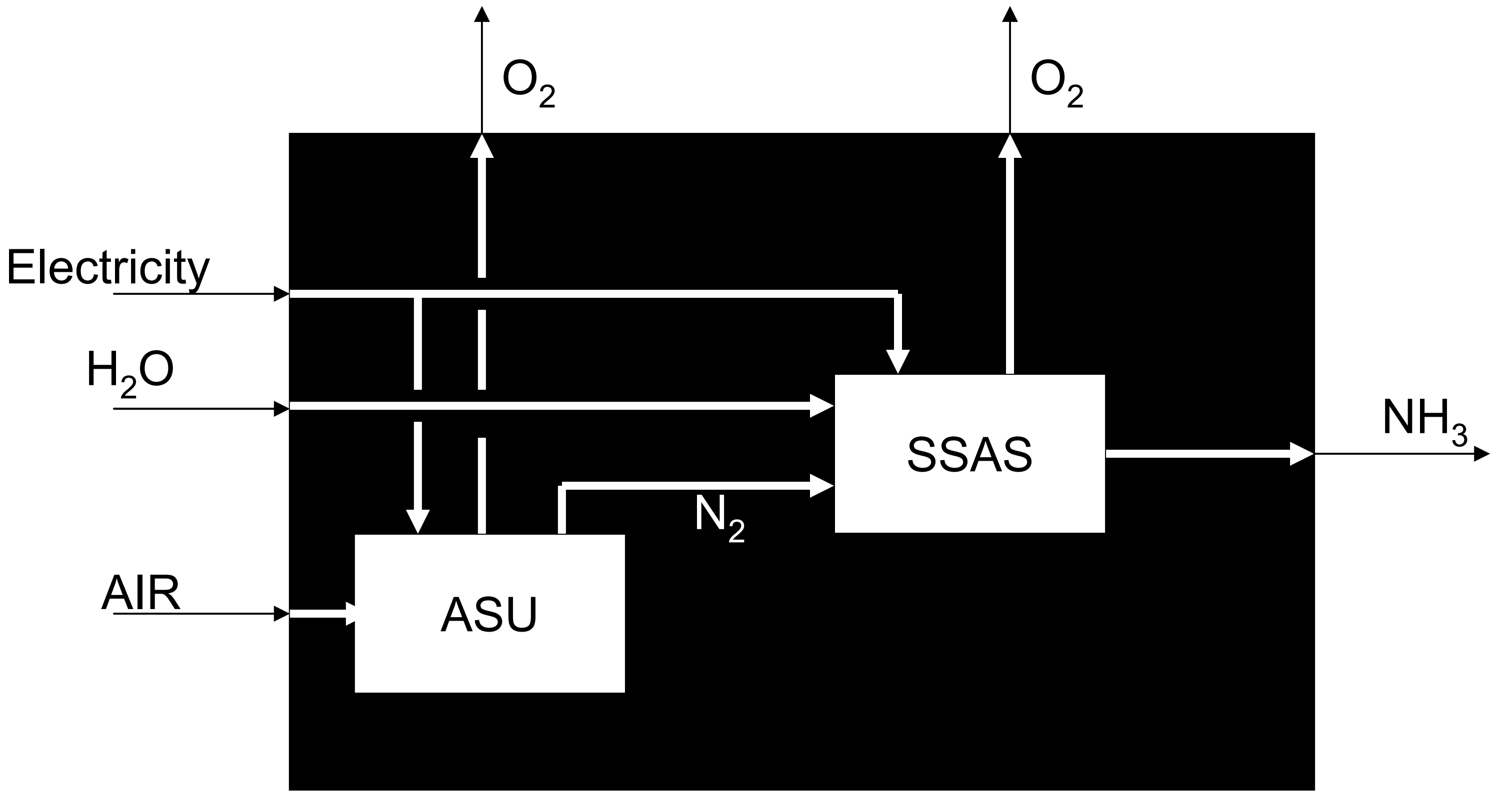
$$3\ H_2O \rightarrow 3\ H_2 + 3/2\ O_2$$
$$3\ H_2 + N_2 \rightarrow 2\ NH_3$$



Energy consumption ~12,000 kWh per ton NH_3

Inside the Black Box: Solid State Ammonia Synthesis

$$6\ H_2O + 2\ N_2 \rightarrow 3\ O_2 + 4\ NH_3$$



Energy consumption 7000 - 8000 kWh per ton NH_3

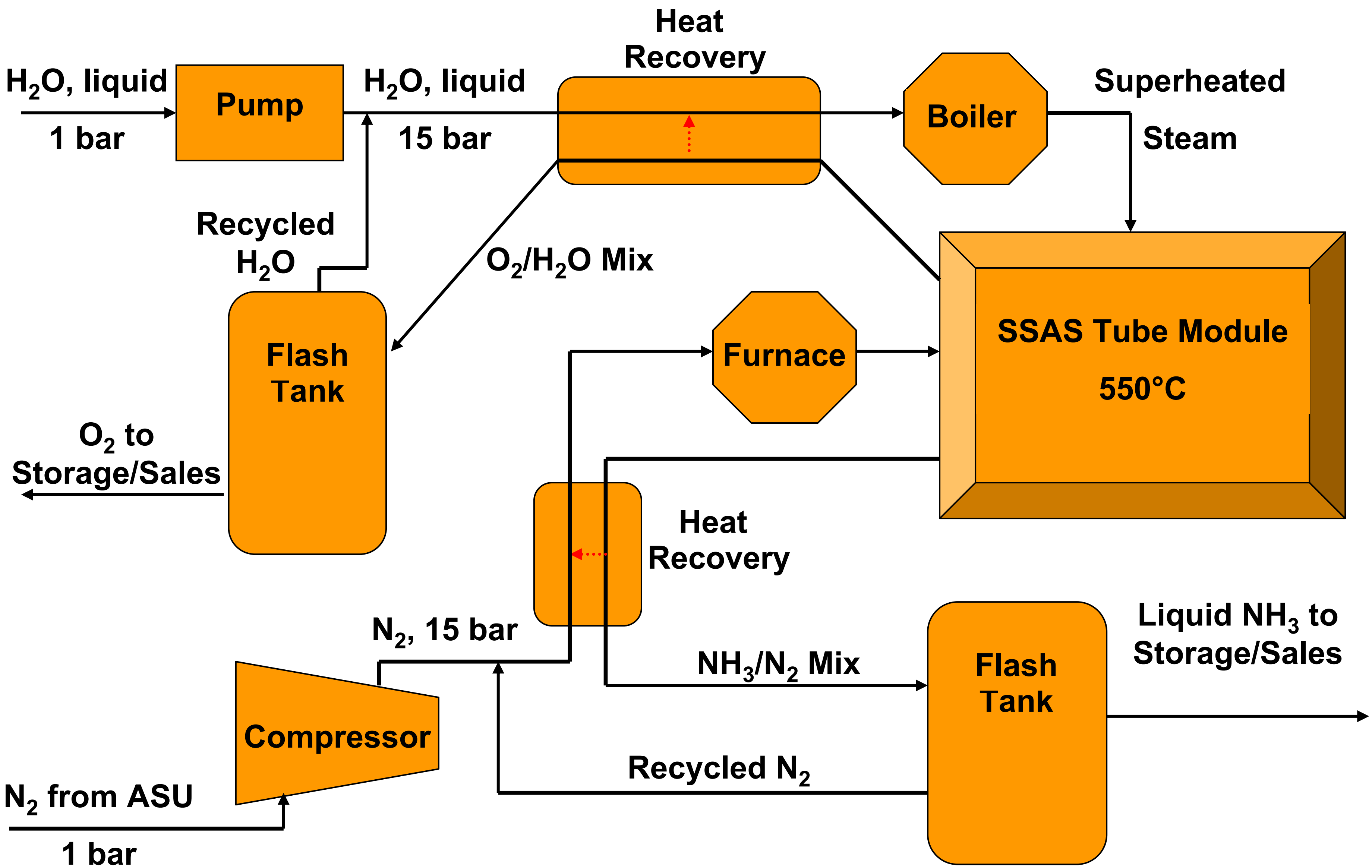
SSAS in a Nutshell

- Solid-state electrochemical process
- Water (steam) decomposed at anode
- Hydrogen atoms adsorb, stripped of electrons
- Hydrogen conducts (as proton) through proton-conducting ceramic electrolyte
- Protons emerge at cathode, regain electrons, and react with adsorbed, dissociated nitrogen atoms to form NH_3
- Patent application – February 2007

SSAS Features and Advantages

- Does not require expensive, energy-intensive electrolyzers
- High pressures (e.g. for Haber-Bosch synthesis) are not required
- Co-production of oxygen gas
- Synthesis reactors in the form of multiple tube bundles in geometric arrangement
- Straightforward NH_3 capacity expansion by adding synthesis tube bundle modules

SSAS Primary Components



Current Work: Protonic Ceramic

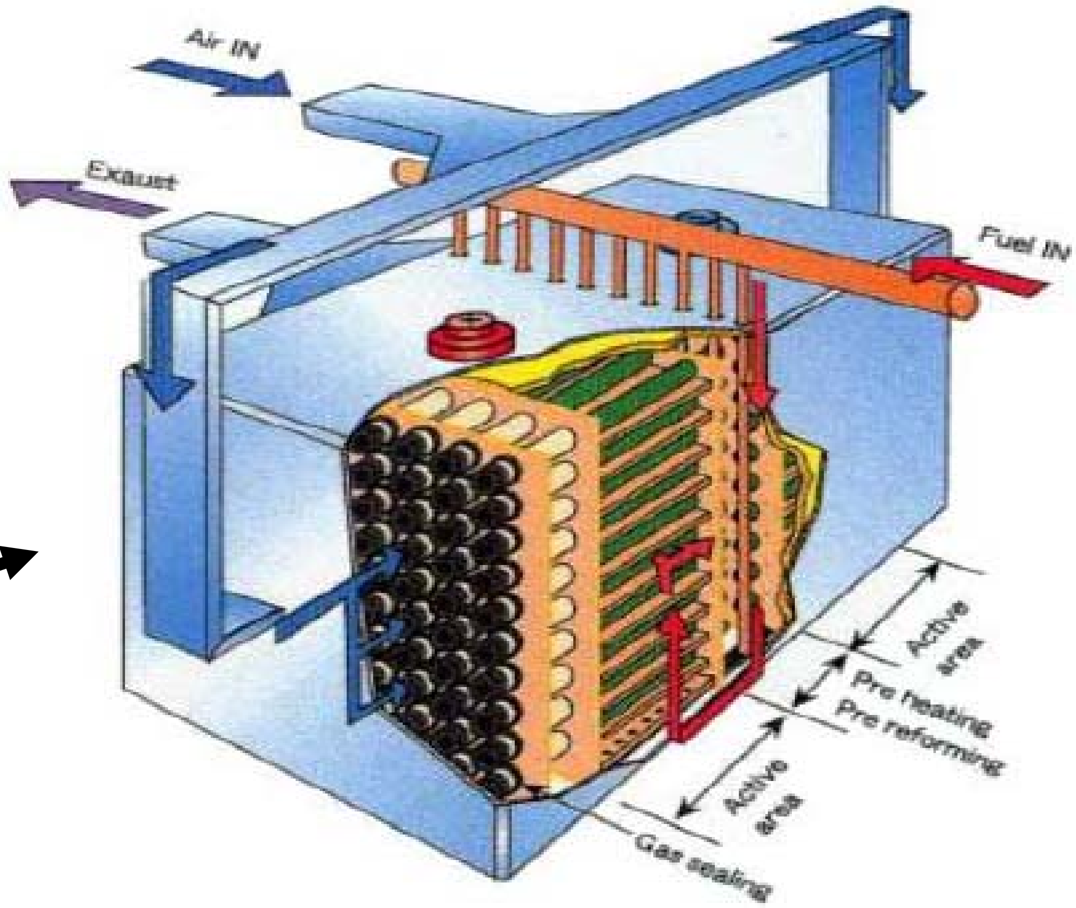
- **Preferred compositions identified**
  - Good thermal stability, capable of thermal cycling
  - High ionic conductivity
  - Stability in humid or dry atmospheres
  - Stable in reducing, neutral, or oxidizing conditions
- **Refinement of processing techniques**
  - Ceramic synthesis routes
    - Solid state chemical reaction vs. autoingintion
    - Sintering and densification, catalyst support
  - Ceramic forming
    - Bulk powder pressing
    - Tape casting, spin coating

Current Work: Catalysis

- **Maximize: ionic and electronic conductivity, surface area, catalytic action**
- **Oxidizing atmosphere present**
  - Co-generation of oxygen gas
  - Intermediate temperatures: less severe conditions
- **Reducing atmosphere present**
  - Ammonia product is a strong reducing agent
    - -Protects stability of many catalyst types
    - -Converts metal oxides to high surface area metallic catalysts
  - Intermediate temperatures: helps prevent sintering of catalyst particles

Mass Production: Tubular Geometry

Tubular SOFC



SSAS reactor module will have similar tube and manifold arrangement

PCC Tubes in R&D Labs

PCC tube fabricated for LANL by TYK Corporation (Japan) by extrusion, used for tritium recovery.

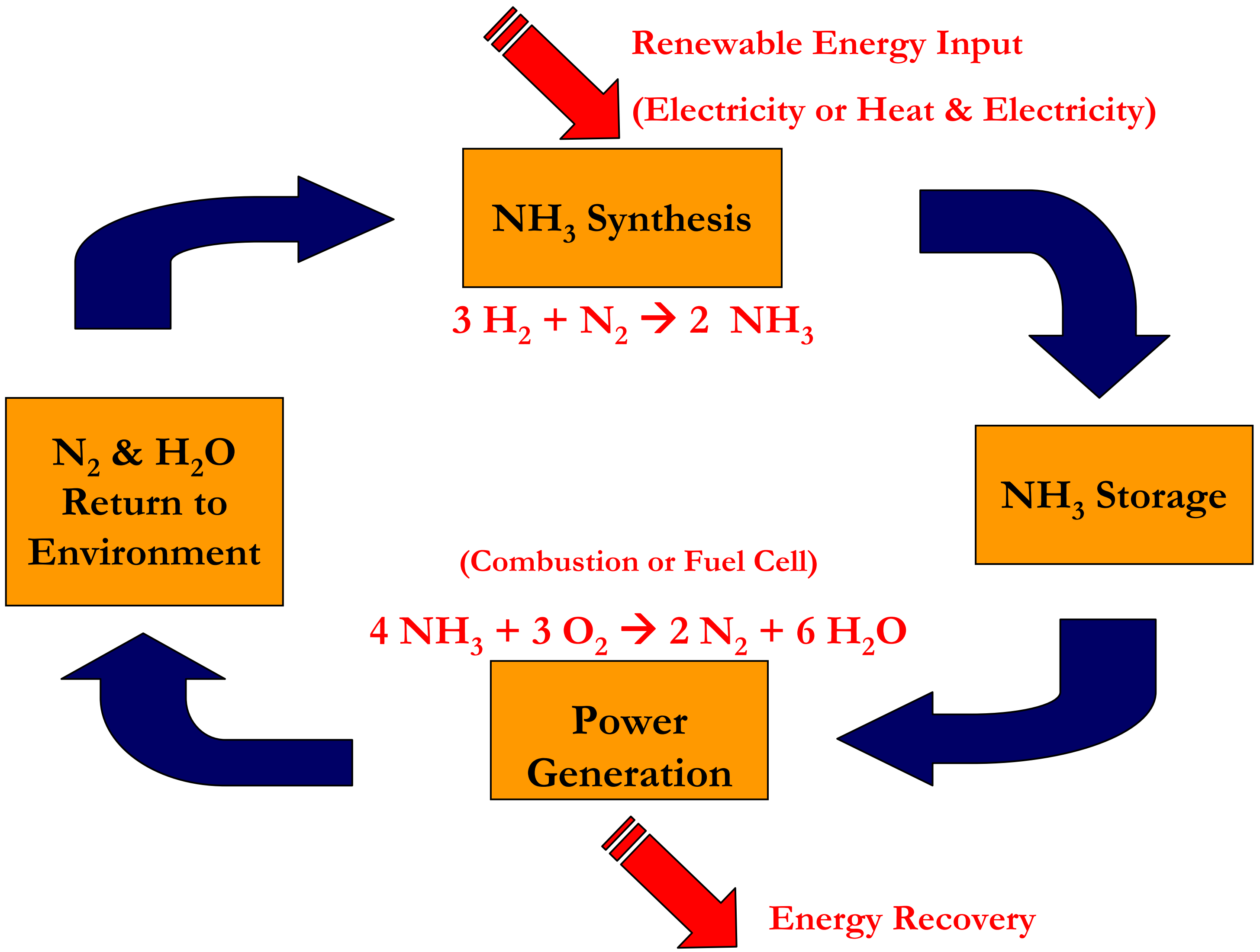
Economic Comparison

Measure	Production Method		
	Natural Gas	Electrolyzer + H-B	SSAS
Energy required per ton of NH_3	33 MBtu = 9700 kWh	~12,000 kWh (H2 production only)	7000-8000 kWh
Capital cost per ton/day NH_3 capacity	~$500,000	~$750,000 (Cost dominated by electrolyzer)	<$200,000
"Fuel" cost to produce 1 ton of NH_3 at large scale [1]	Depends on location and NG cost	$420 (3.5 ¢/kWh) $240 (2 ¢/kWh)	$245 (3.5 ¢/kWh) $140 (2 ¢/kWh)
Cost of 1 ton NH_3 at moderate to large scale [2]	Depends on location and NG cost	>$600 (3.5 ¢/kWh) >$400 (2 ¢/kWh)	~$315 (3.5 ¢/kWh) ~$210 (2 ¢/kWh)
Tons of CO_2 emitted per ton of NH_3 produced	1.8	-0-	-0-

[1] For NHThree's planned demonstration project, Douglas Co. WA will supply standard 2 ¢/kWh power from hydroelectric

[2] Using a capital recovery factor of 12% and purchased nitrogen at $30 per ton of N_2

Green Ammonia –
a Renewable Cycle



The “Sweet Spot” for SSAS

- **Inexpensive electric power**
  - Stranded wind or geothermal
  - Hydroelectric
  - Nuclear
  - Off-peak fossil energy in Midwest
  - OTEC
  - Reliable water supply, need not be pure
  - 420 gallons H_2O/ton NH_3
- **Inexpensive heat source to improve efficiency**
  - Concentrated solar thermal
  - Nuclear