

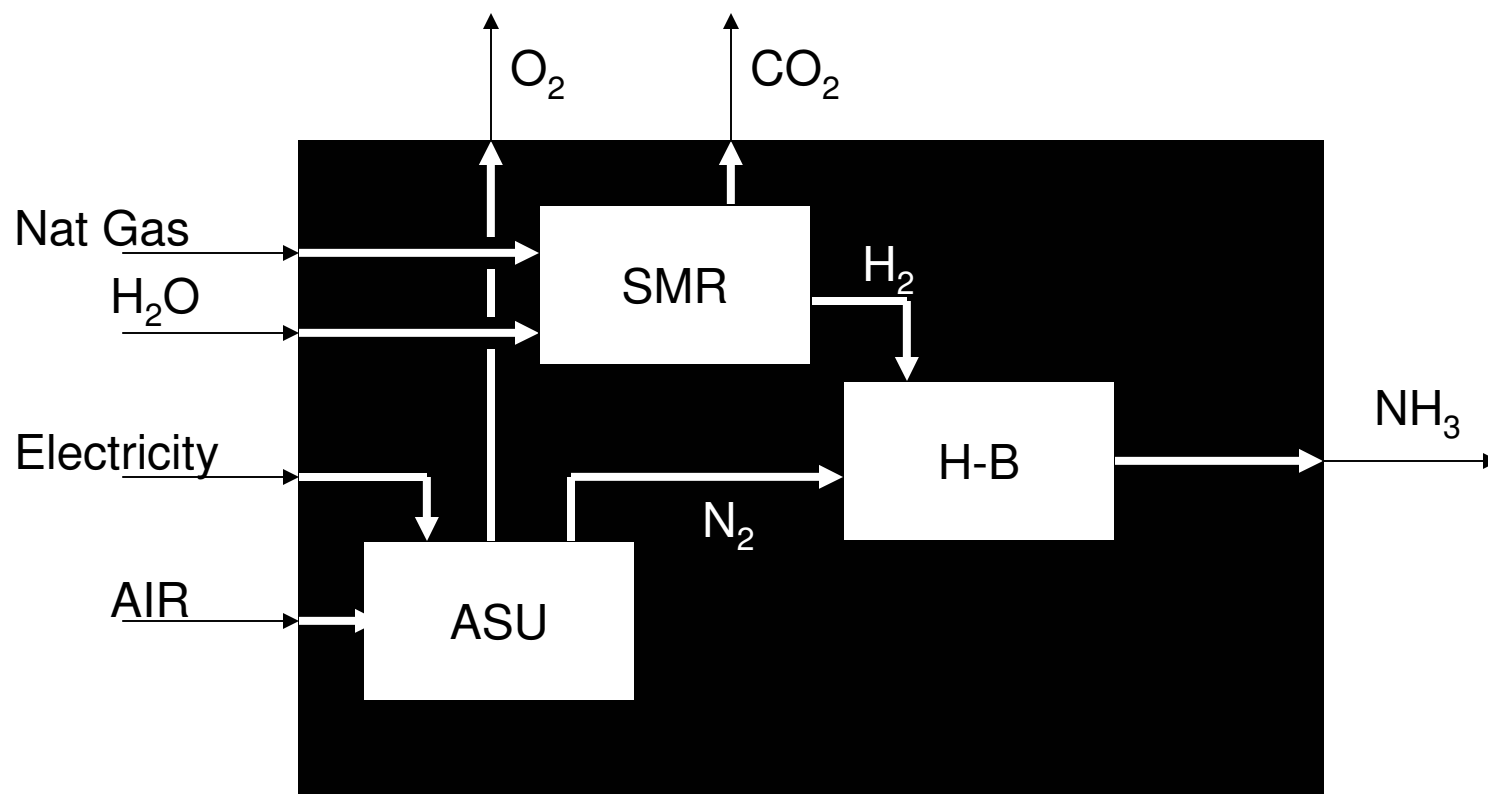
Solid State Ammonia Synthesis

NHThree LLC

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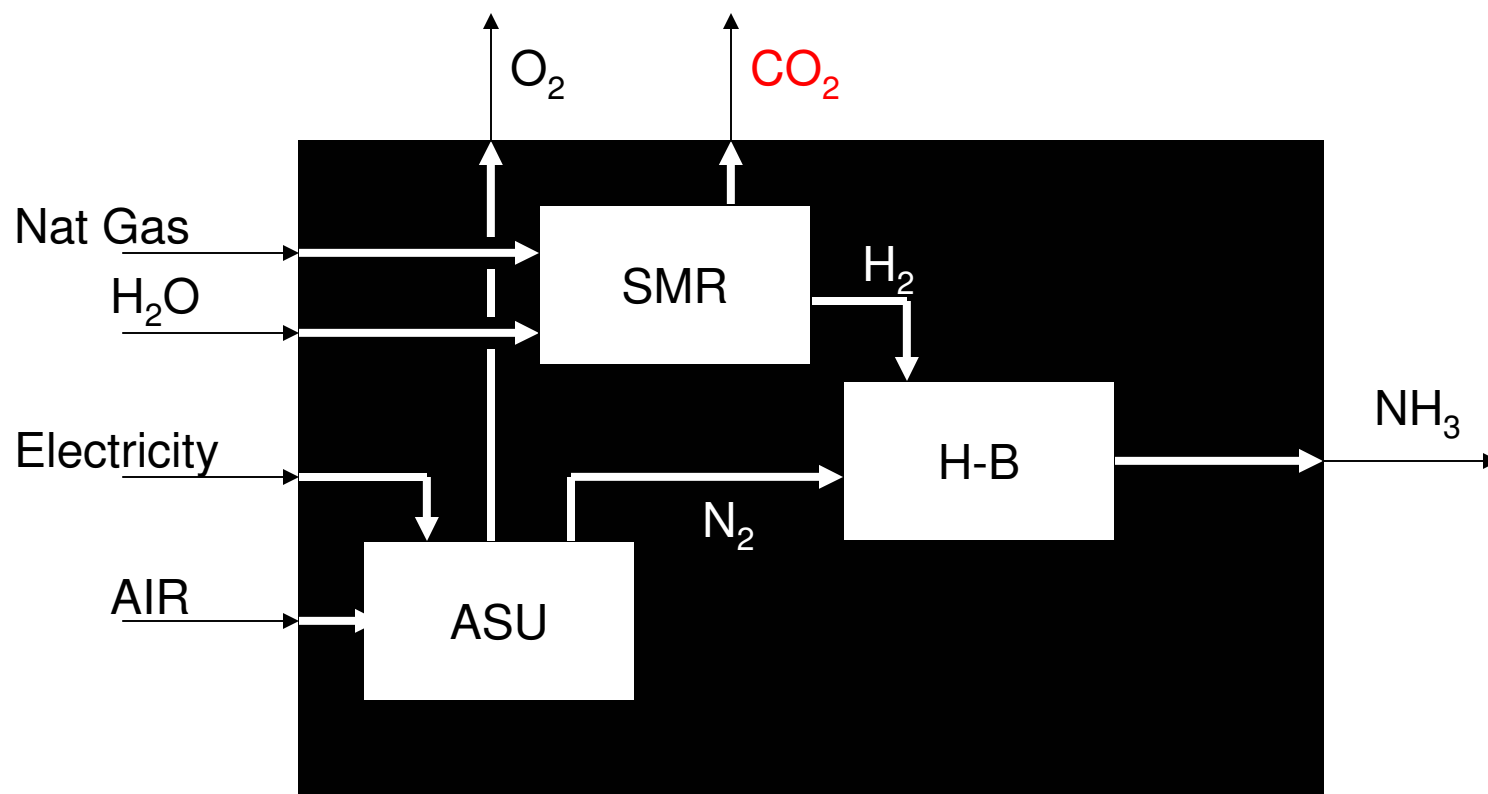
Ammonia - A Sustainable, Emission-Free Fuel
October 15, 2007

Inside the Black Box: Steam Reforming + Haber-Bosch



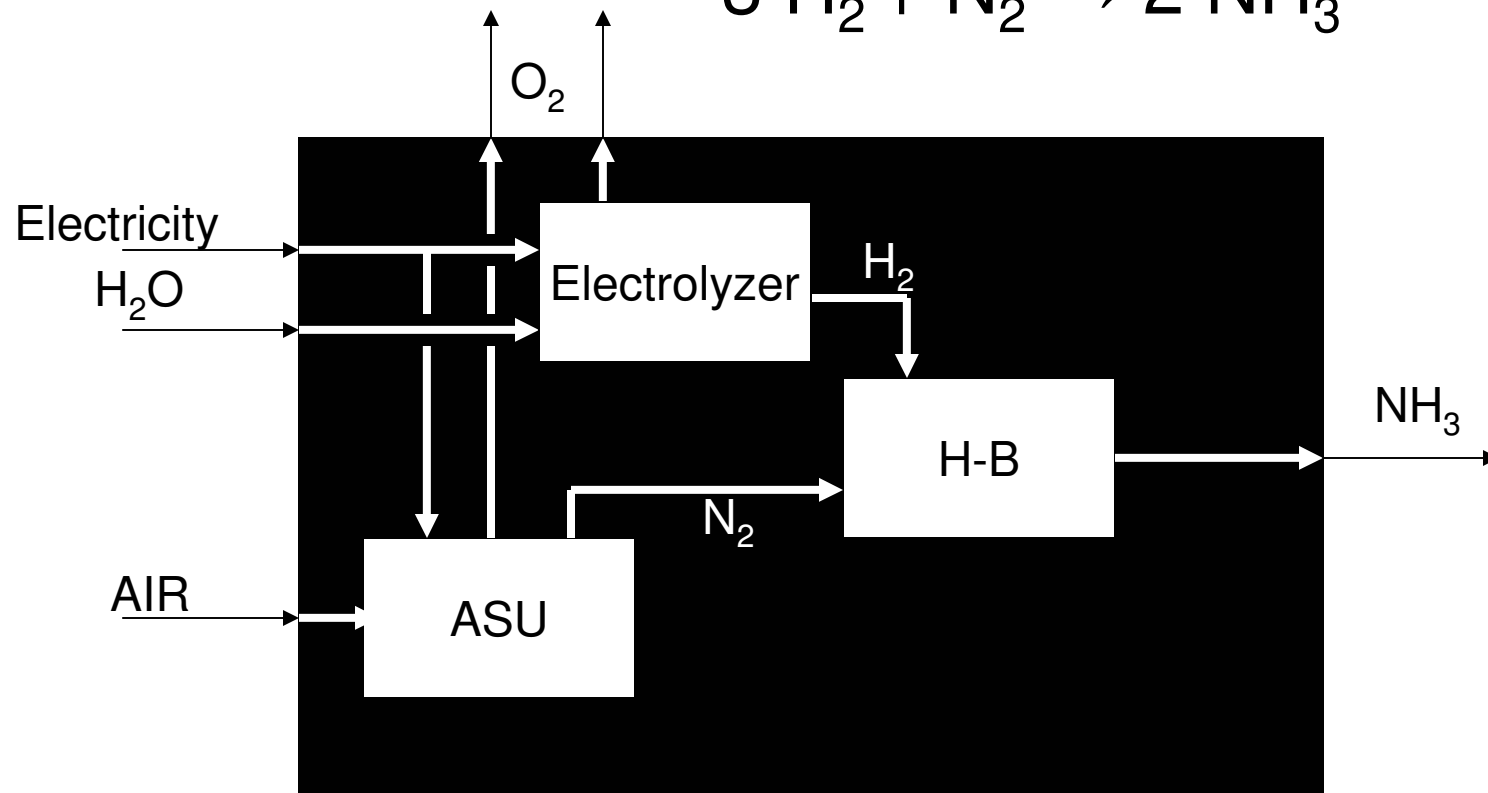
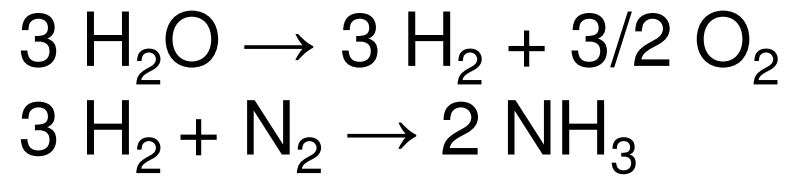
Energy consumption ~33 MBtu (9500 kWh) per ton NH₃

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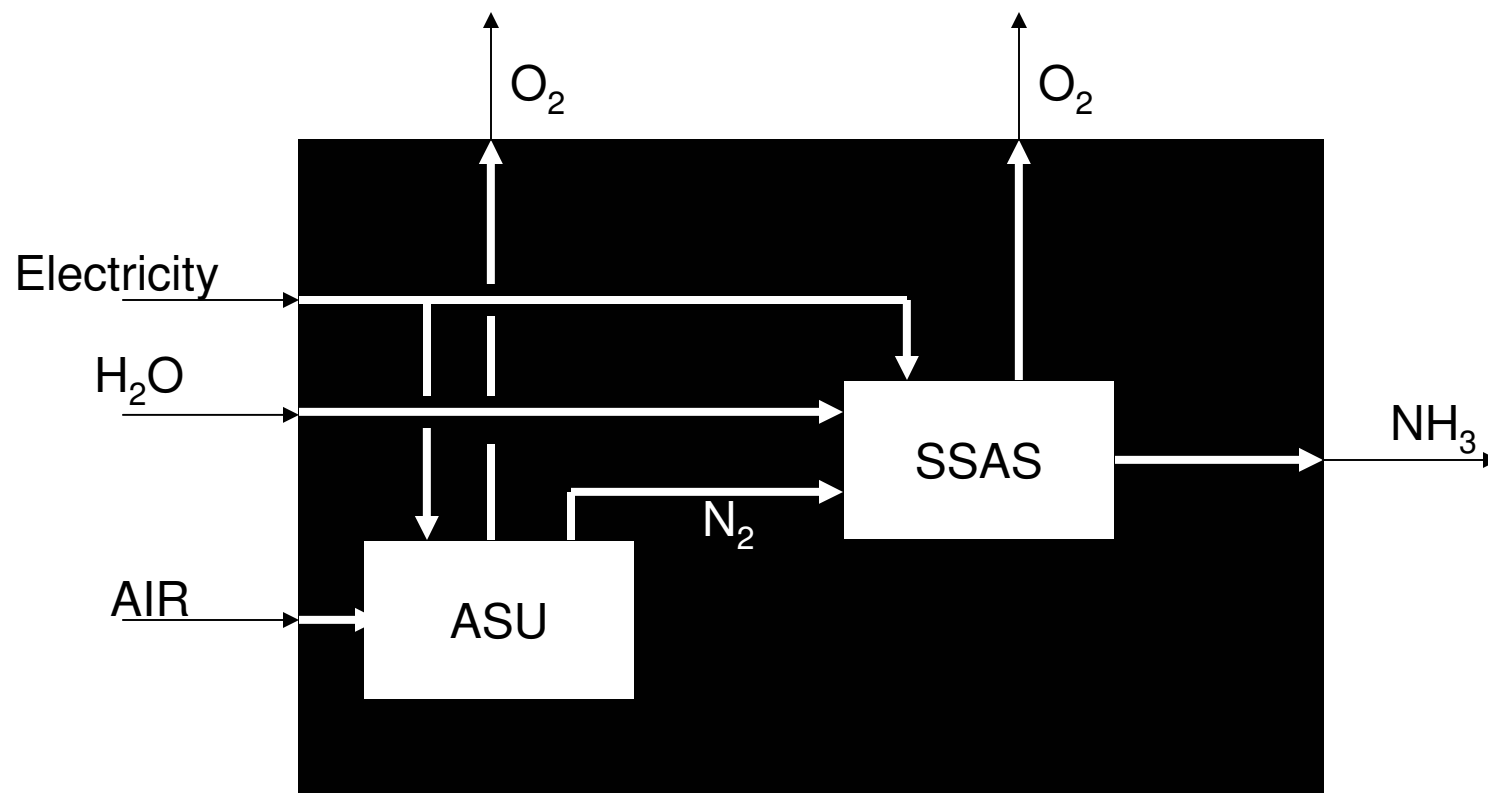
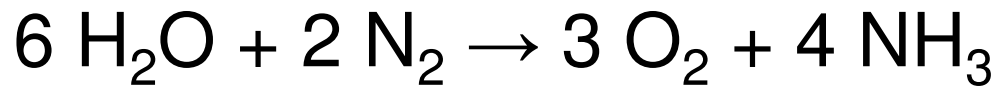
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Inside the Black Box: HB Plus Electrolysis



Energy consumption ~12,000 kWh per ton NH₃

Inside the Black Box: Solid State Ammonia Synthesis



Energy consumption 7000 - 8000 kWh per ton NH₃

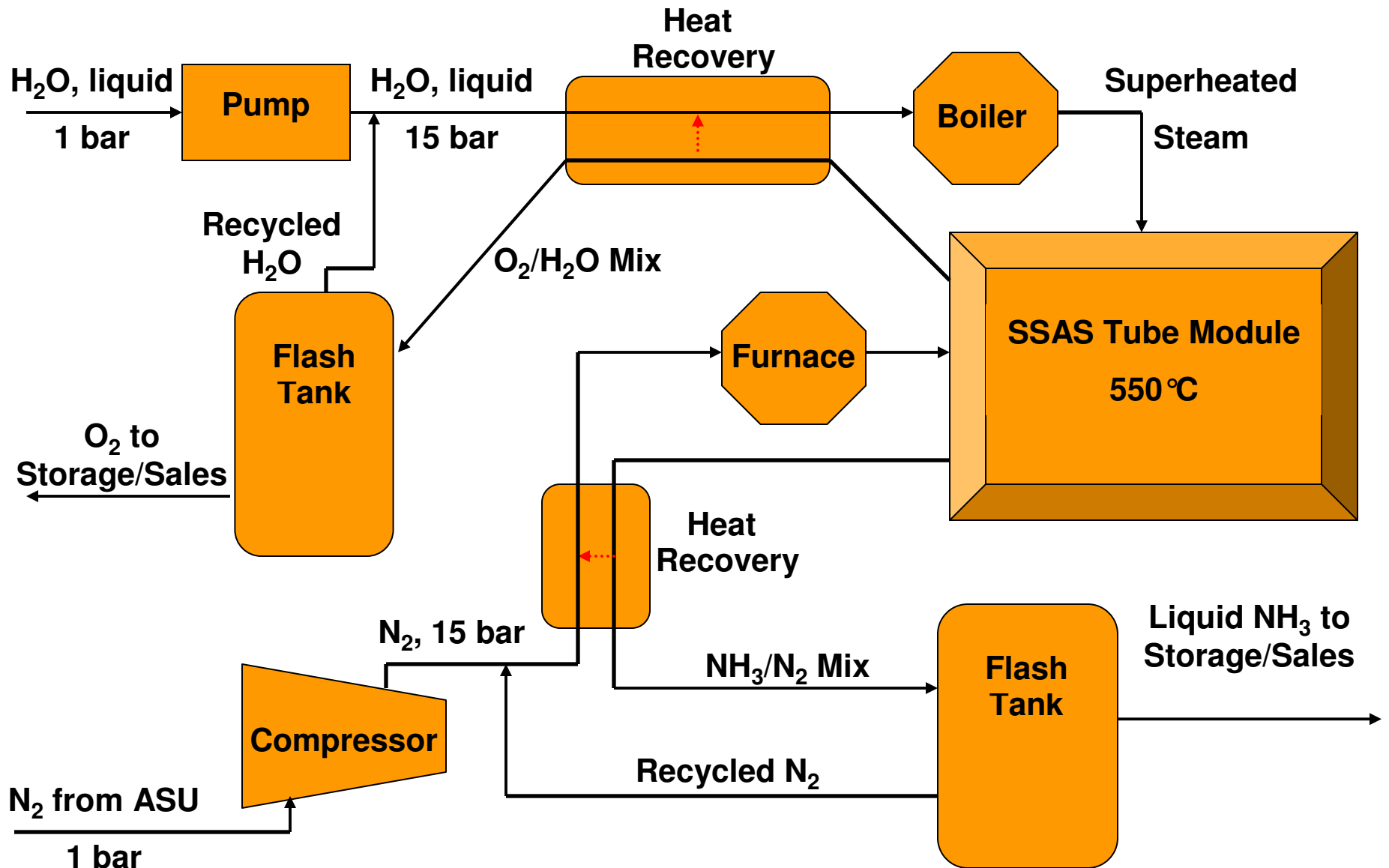
SSAS in a Nutshell

- **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

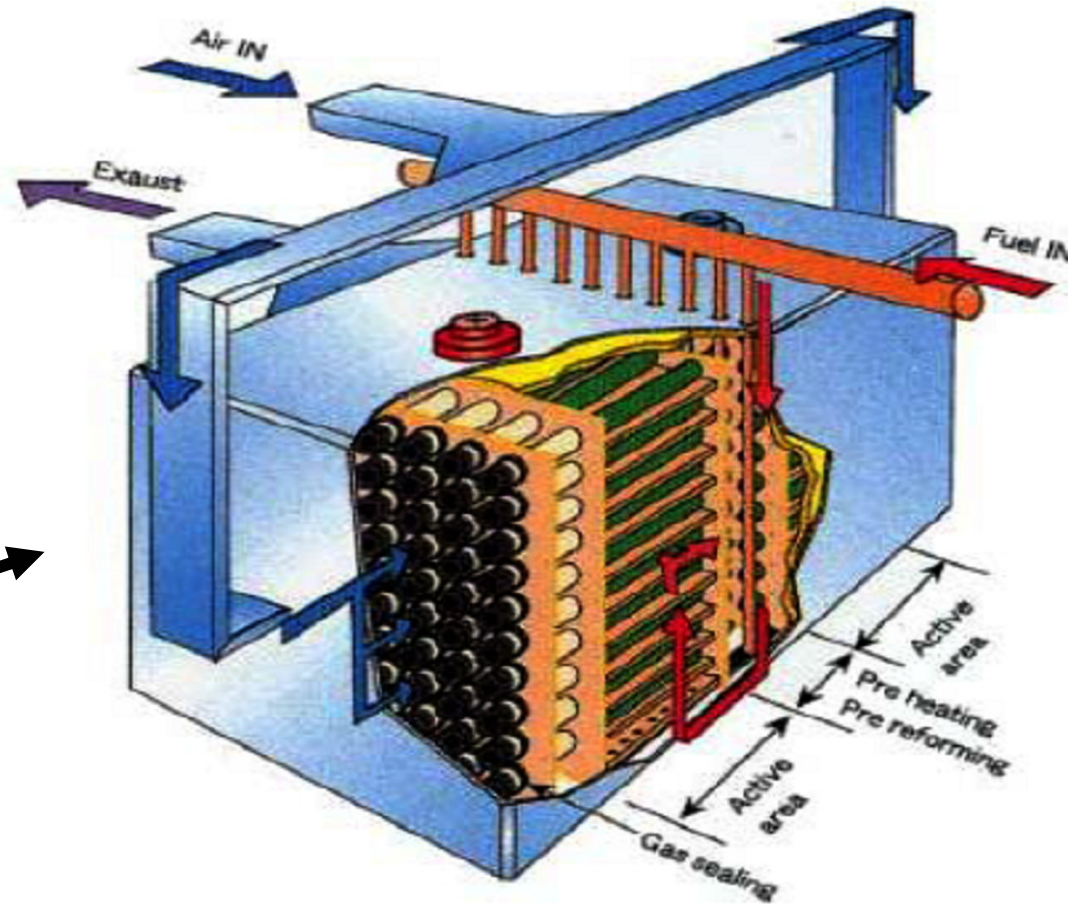
- Ceramic synthesis routes
 - Solid state chemical reaction vs. autoignition
 - Sintering and densification, catalyst support
- Ceramic forming
 - Bulk powder pressing
 - Tape casting, spin coating

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.

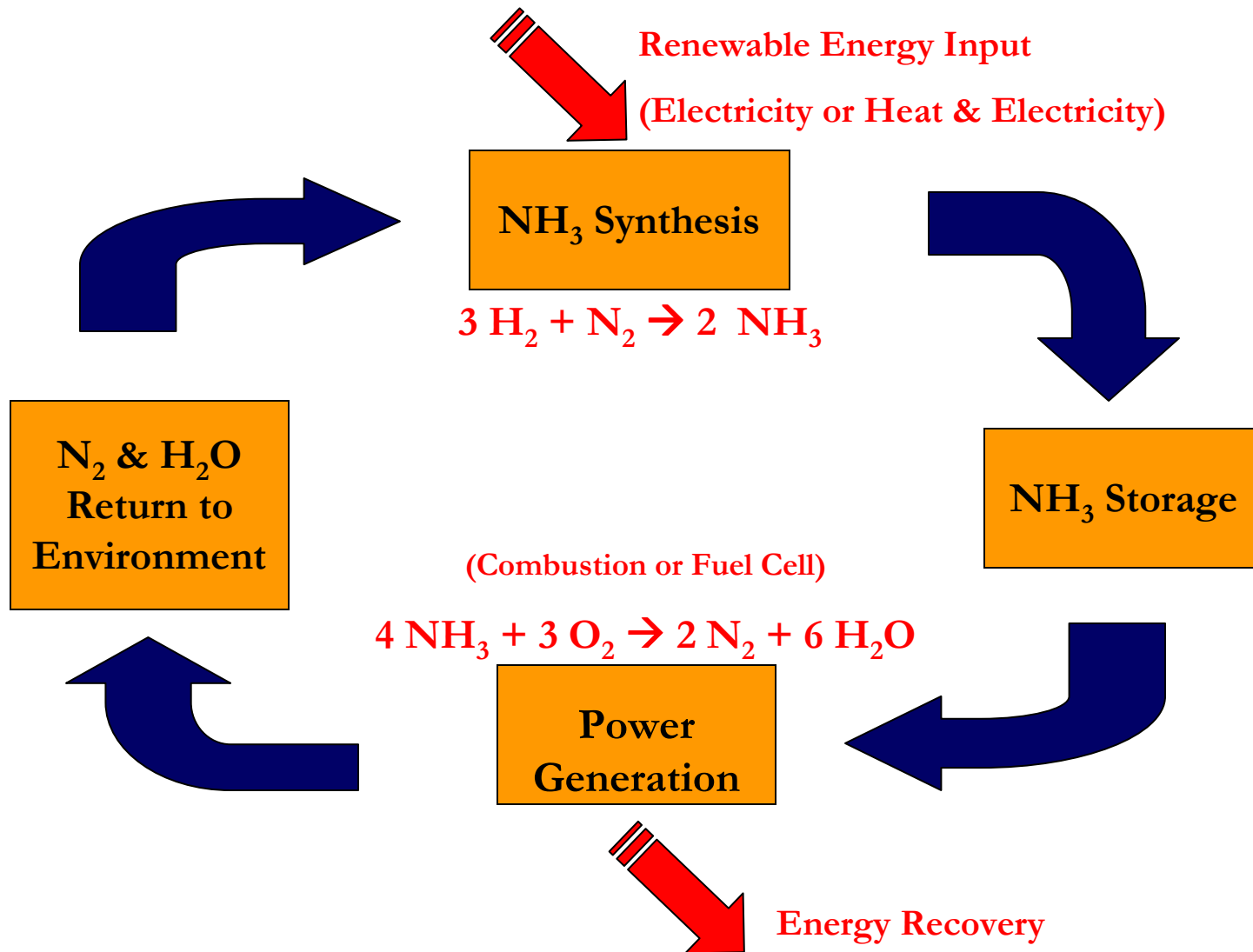
Economic Comparison

Measure	Production Method		
	Natural Gas	Electrolyzer + H-B	SSAS
Energy required per ton of NH ₃	33 MBtu = 9700 kWh	~12,000 kWh (H ₂ 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 N₂

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 H₂O/ton NH₃
- **Inexpensive heat source to improve efficiency**
 - Concentrated solar thermal
 - Nuclear