Co-production of Electricity and Hydrogen Using NH3-Fueled SOFC Systems

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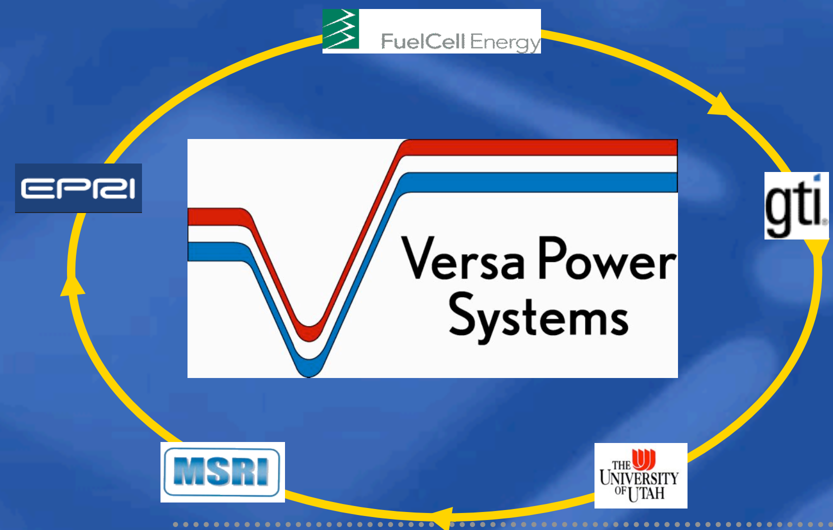
Overview

- VPS Team Intro
- VPS SOFC Technology Status
- Ammonia fuel cell systems
- SOFCs & the Hydrogen Infrastructure
- Path forward

Company Overview: Versa Power Systems

- A U.S. for-profit company with operations in Colorado and Calgary
  - Founded in 2001: a joint venture between the members of the Solid Oxide Fuel Cell Consortium
- Strategic Alliances
  - Cummins: mobile and small scale applications
  - FuelCell Energy: commercial and industrial DG/combined heat and power (CHP)
- Our product: planar solid oxide fuel cell system
  - Demonstrated ability to achieve high electrical power densities and long life using low cost materials
  - Validated manufacturing processes; scalable to high volume production rates

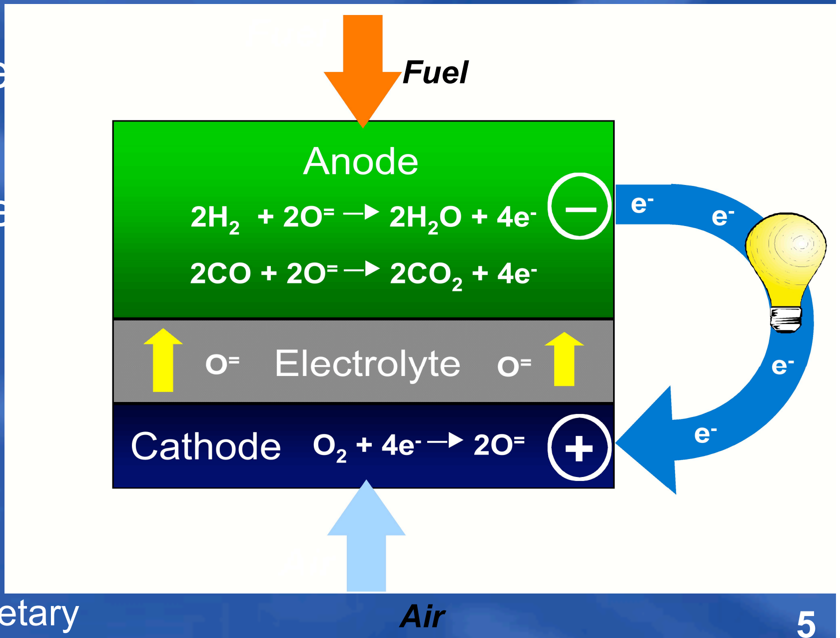


U.S. DOE SECA: ~$1.5 billion Program

- Program goal: accelerate commercialization of low-cost SOFCs through attainment of technical and cost metrics
- VPS is part of two out of six industrial teams
  - VPS/FuelCell Energy
  - VPS/Cummins
  - General Electric
  - Siemens Westinghouse
  - Delphi/Battelle
  - Acumentrics
- $600MM of basic technology research is available to the industrial teams. Research conducted by—
  - MIT, University of Utah, UC Berkeley, Northwestern University, University of Wisconsin,
  - Los Alamos National Laboratories, National Energy Technology Laboratory, Pacific Northwest National Laboratory, Argonne National Laboratory, and Chevron Technology Ventures

Introduction to Fuel Cell Technology

- A fuel cell is an electrochemical energy conversion device that generates electricity directly from electrochemical reactions between a fuel and an oxidant
- A solid oxide fuel cell is a high temperature electrochemical device with a solid oxide electrolyte that produces electric power from a variety of fuels (such as hydrogen, natural gas, propane or diesel)
- Higher efficiency than competing technologie
- The core SOFC cell is ceramic and has three layers
  - Anode, electrolyte and cathode
  - Inexpensive materials



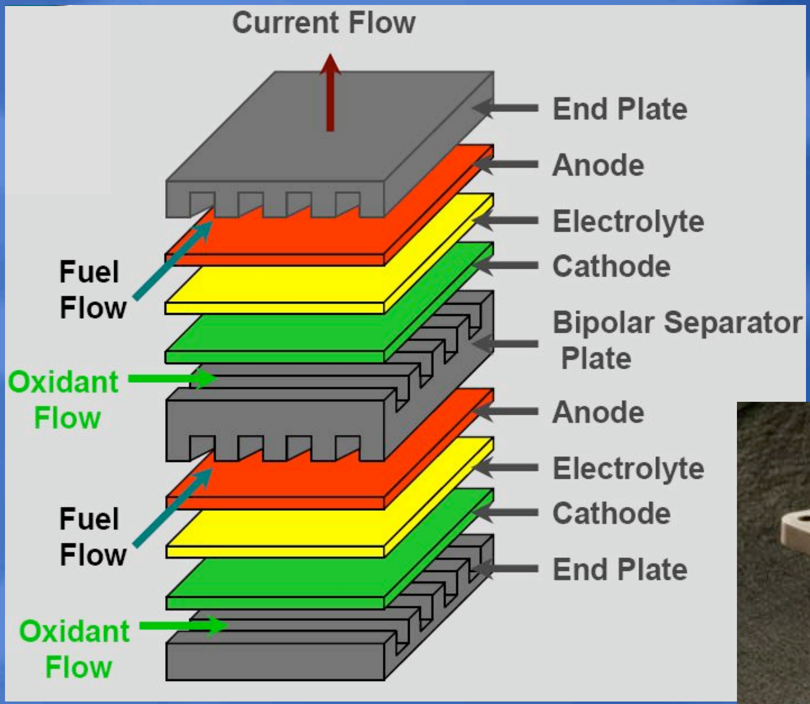
SOFC Principle of Operation

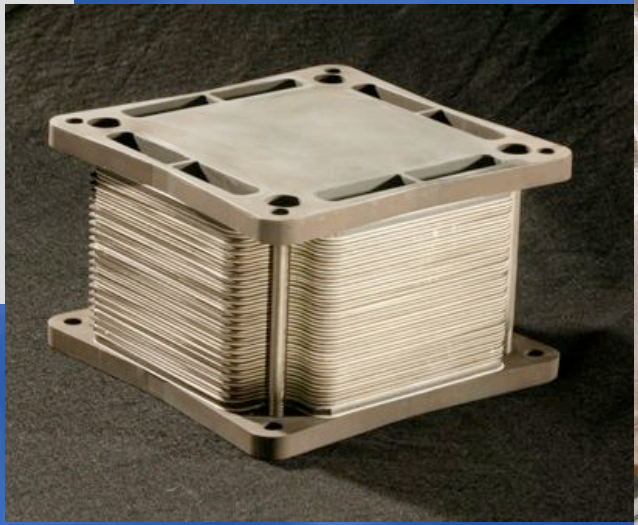
- *Anode* – nickel-zirconia cermet, ~ 1 mm thick
- *Electrolyte* – yttria-stabilized zirconia (YSZ), ~ 5 μm thick
- *Cathode* – conducting ceramic, ~ 50 μm thick

Benefits of Solid Oxide Fuel Cell Technology

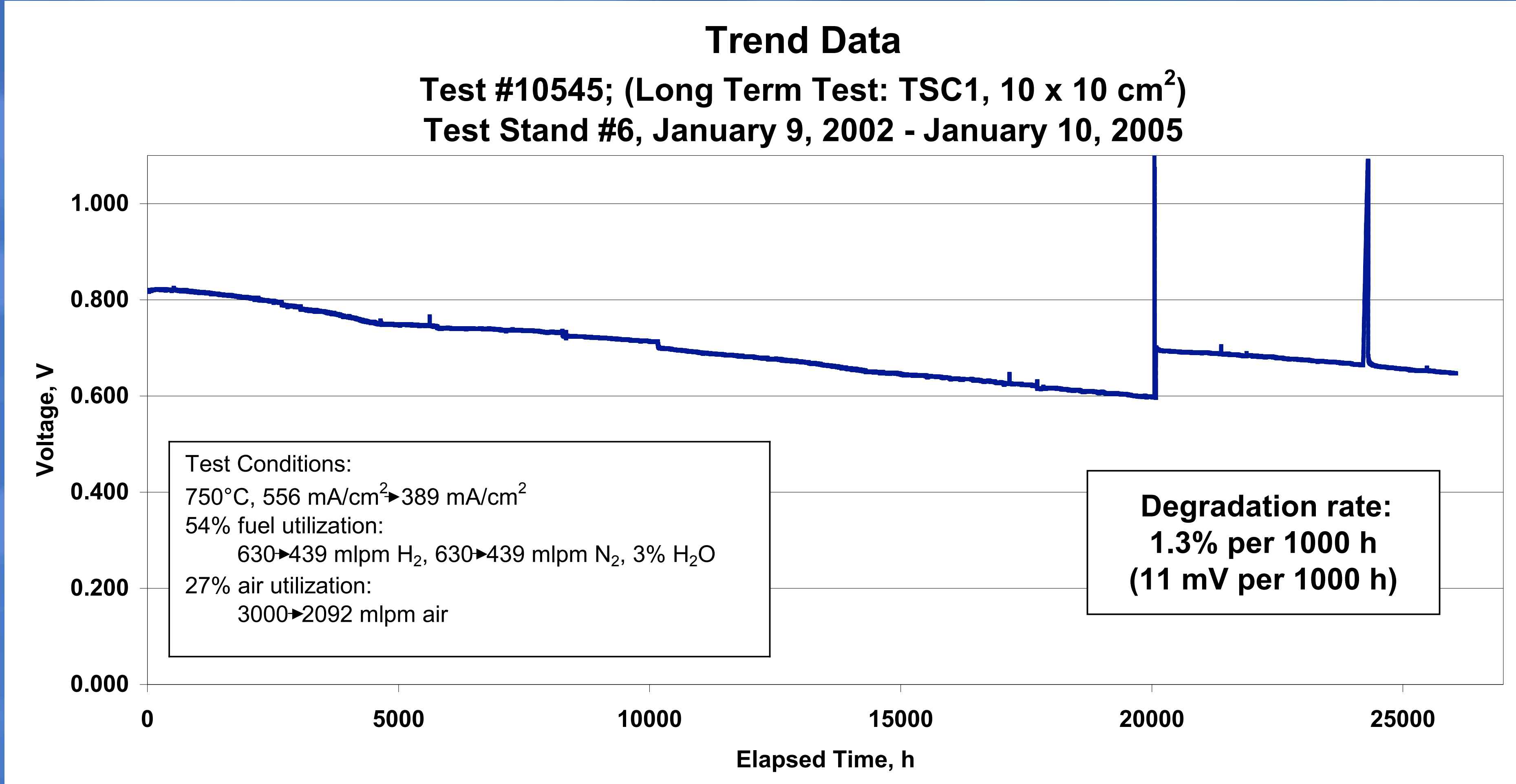
- Customer & environmentally friendly
  - Quiet operation
  - Compact package for more flexible installations
  - Negligible emissions of air pollutants
  - ***Ideal for residential and commercial CHP***
- Higher efficiency than competing technologies
  - SOFCs are expected to be around 50% efficient at converting fuel to electricity
  - In applications that capture the system's waste heat (CHP), overall fuel use efficiencies could top 80%
  - ***Higher efficiencies lead to lower emissions levels than competing technologies***
- Adaptability to many practical fuels
  - Solid oxide fuel cells operate at high temperatures (around 650-1,000°C)
  - Removes the need for precious-metal catalyst, thereby reducing cost
  - Allows SOFCs to reform fuels internally, enabling the use of a variety of fuels and reduces the cost associated with adding a reformer to the system

VPS Planar SOFC Design



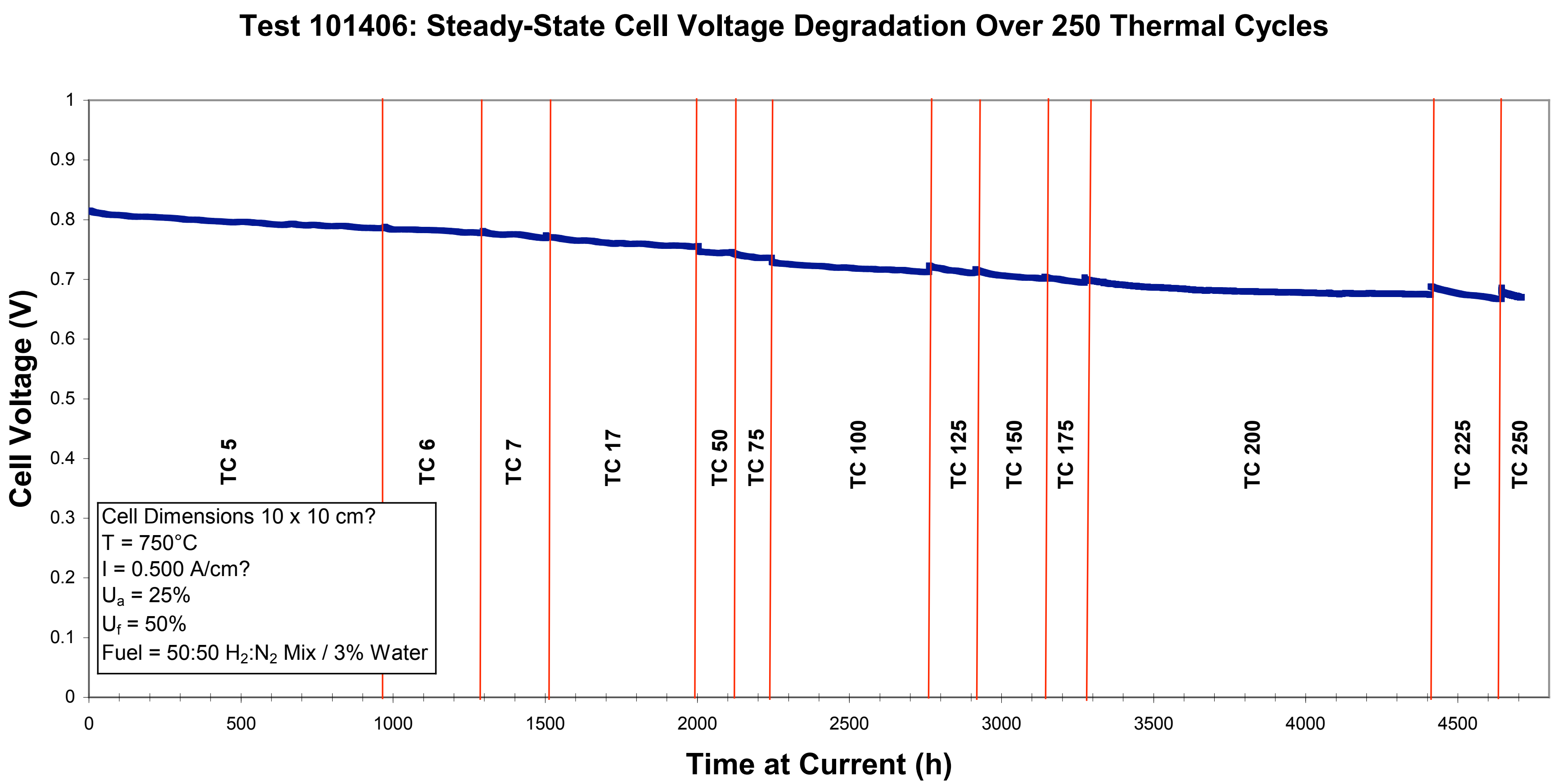


Single Cell Test



Long term benchmark testing achieves 26,000 hrs

VPS Cell Reliability



VPS single cell demonstrated durability-- steady-state voltages after 250 thermal cycles and 4700 hours operation

Stack Development Path

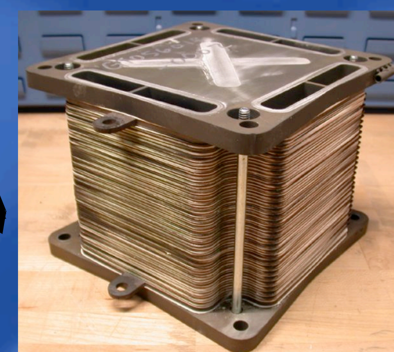
Component Development

Technology Development

- Cell
- Seal
- Interconnect
- Contacts
- Current Collection
- Flow Management
- Thermal Management
- Manufacturability
- Repeatability
- Tolerance

Stack Engineering Integration

Stack Manufacturing Process Development



Stack Performance
- Characterization & Qualification -

Development of Low Cost SOFC Manufacturing at Versa Power Systems

Tape Casting
"T"

Screen Printing
"S"

Co-Sintering
"C"

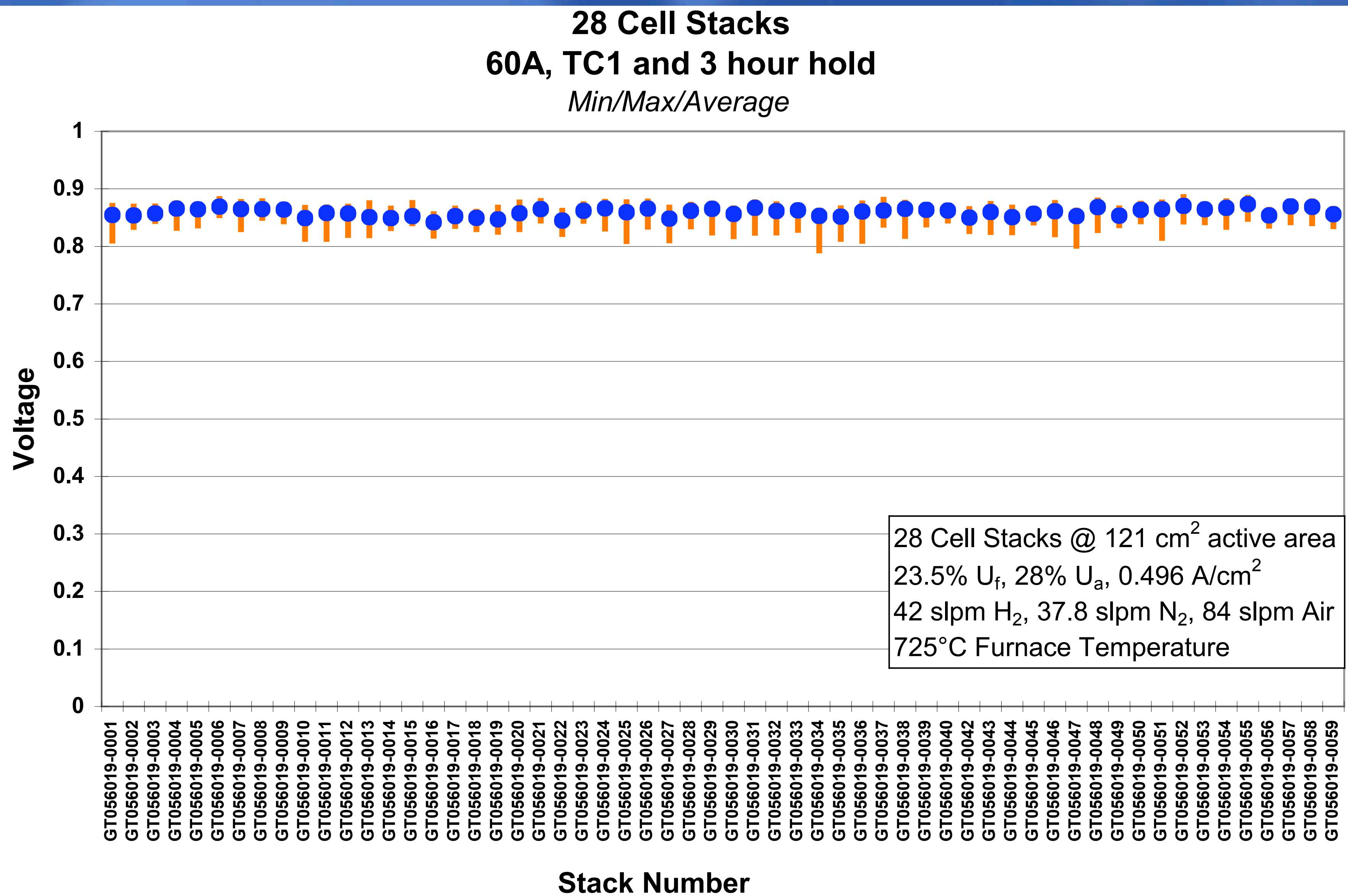
The VPS ***"TSC"*** process for SOFC manufacture is proven:

- One firing step
- Cost effective
- High yields: a result of process control

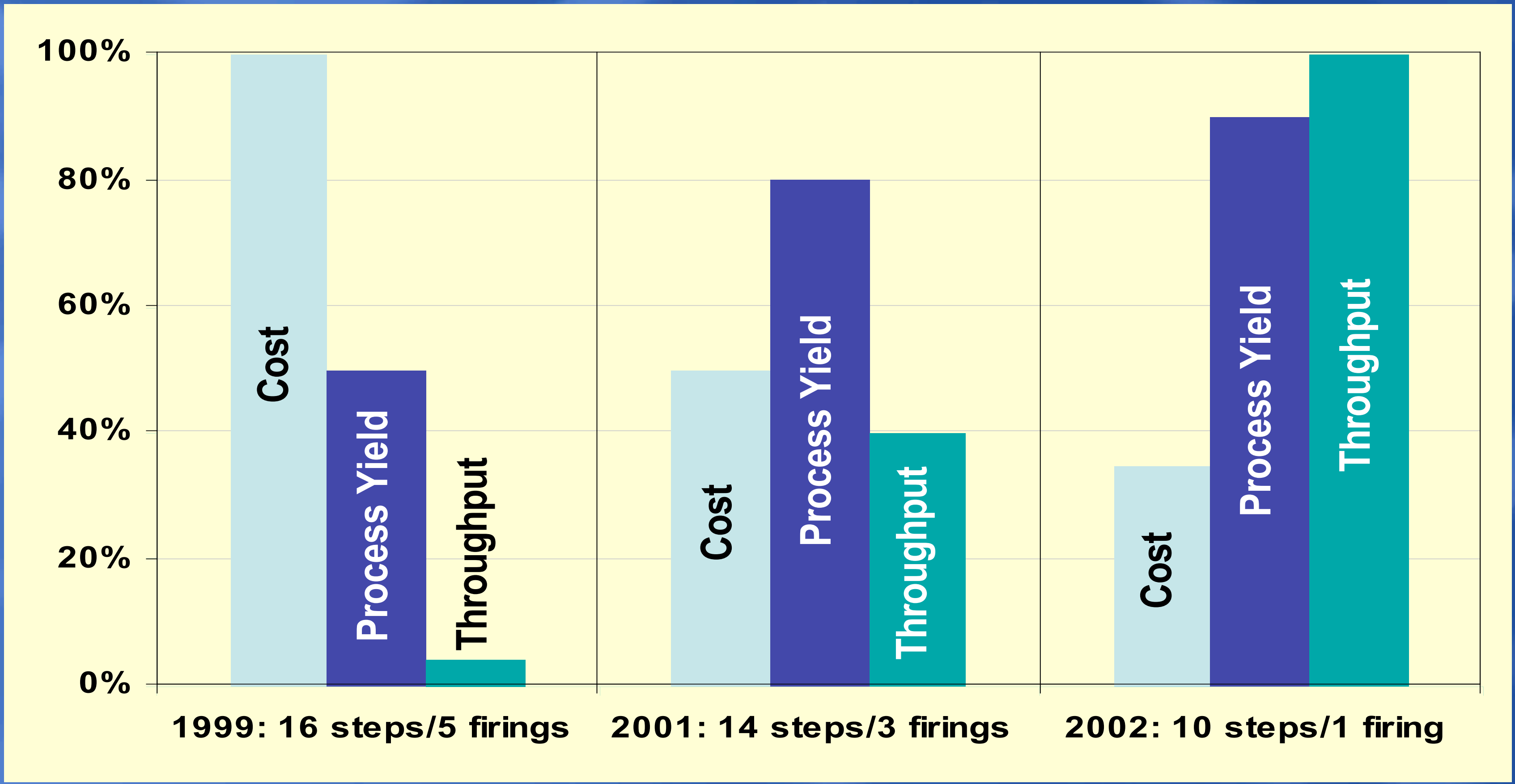
Versa Power Systems

Versa Power Systems

Stack Repeatability

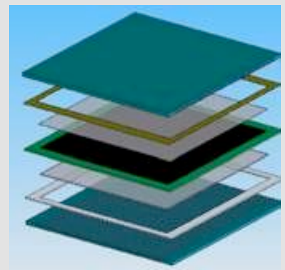


Manufacturing Process Development

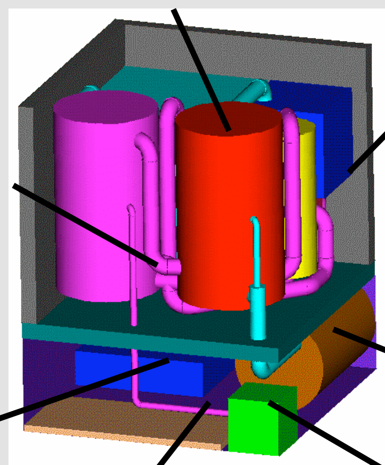


SOFC Power System Build-Up

Ceramic cell interconnects & seals form unit cell



Multi unit cells are combined into stack



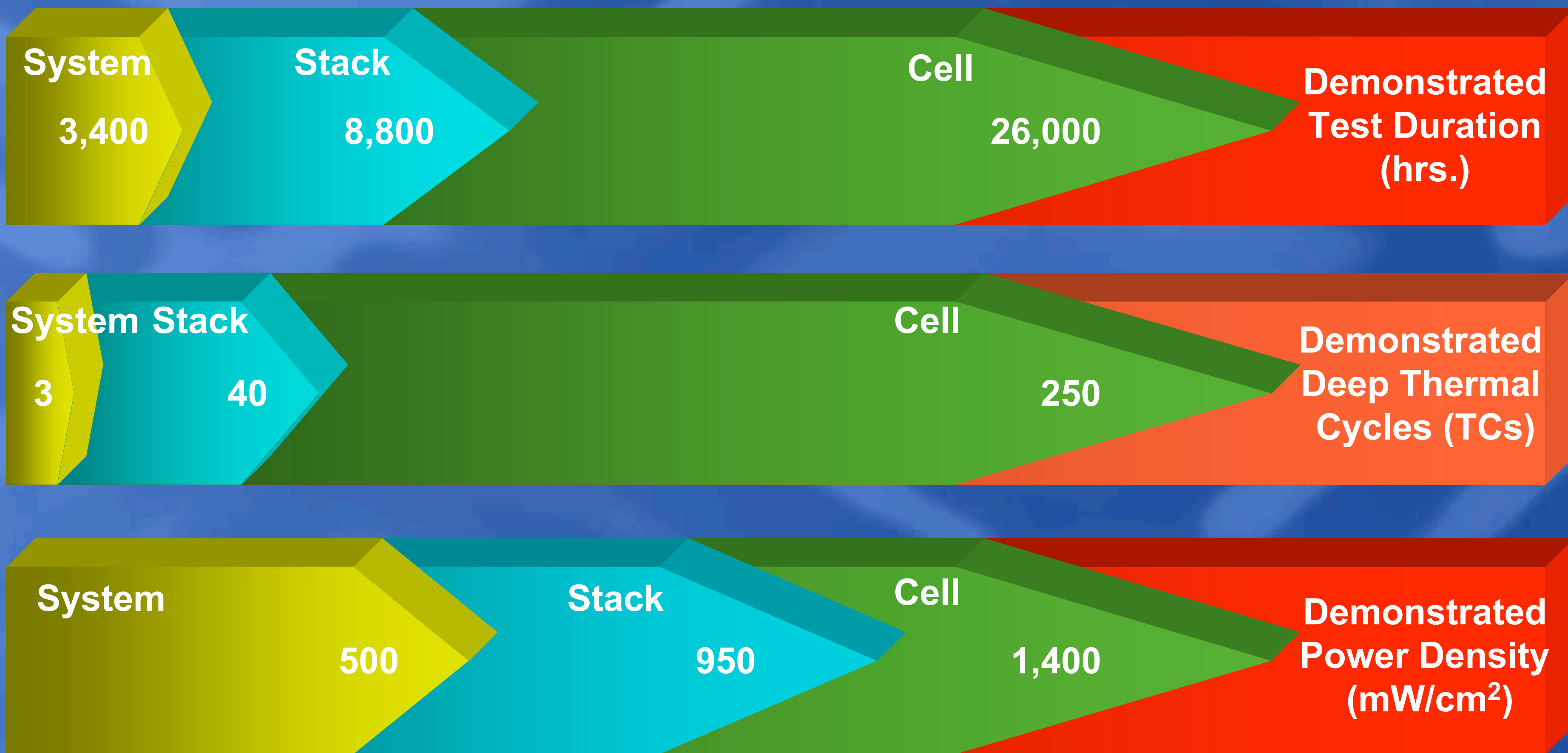
The stack is integrated with the balance of plant components into a power system

System Testing

3 kW Prototype System (3-1)

- **Thermally integrated power system**
- **Pipeline natural gas fuel**
- **Autonomous control**
- **Grid connected (parallel)**
- **Designed towards applicable codes and standards compliance**
- **Builds on the experience gained from >40,000 h of accumulated operation of previous prototypes**

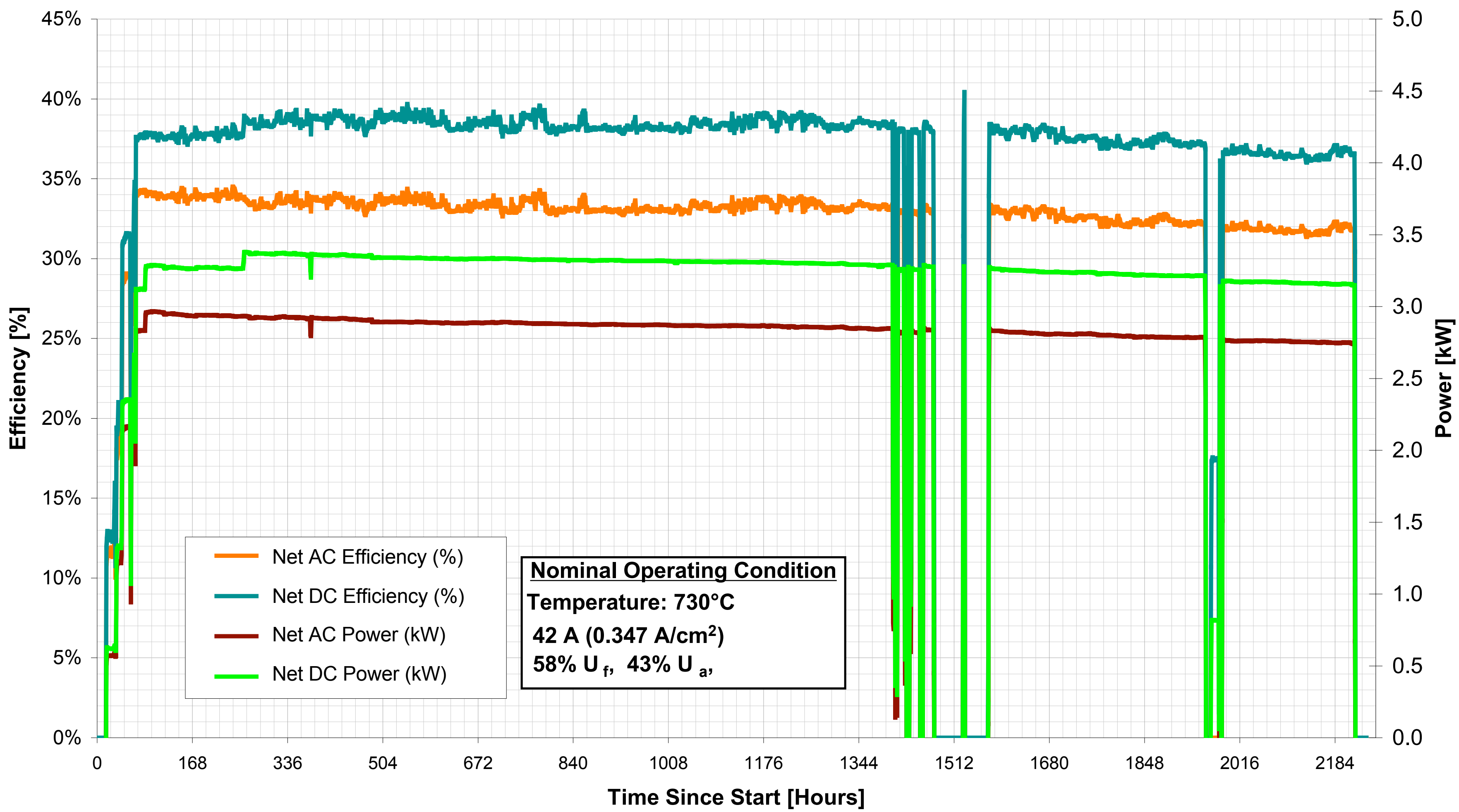
The VPS SOFC Technology



SECA Targets

Minimum Requirements	SECA Phase 1	SECA Phase 2	SECA Phase 3
Power	3 – 10 kW	3 – 10 kW	3 – 10 kW
Cost	$US 800 / kW @50,000 / yr.	$US 600 / kW @50,000 / yr.	$US 400 / kW @50,000 / yr.
Efficiency	Mobile - 25% Stationary - 35%	Mobile - 30% Stationary - 40%	Mobile - 30% Stationary - 40%
Steady State Operation - Availability - Delta Power	80% <2% / 500 hrs.	85% <1% / 500 hrs.	95% <0.1% / 500 hrs.
Transient Operation	<1% / 10 cycles	<0.5% / 10 cycles	<0.1% / 10 cycles
Fuel Type	NG	NG, Propane, Diesel	NG, Propane, Diesel
Maintenance Interval	>1,000 hrs.	>1,000 hrs.	>1,000 hrs.
Design Lifetime	40,000 hrs.	40,000 hrs.	40,000 hrs.

Efficiency and Power Output
3-1 System

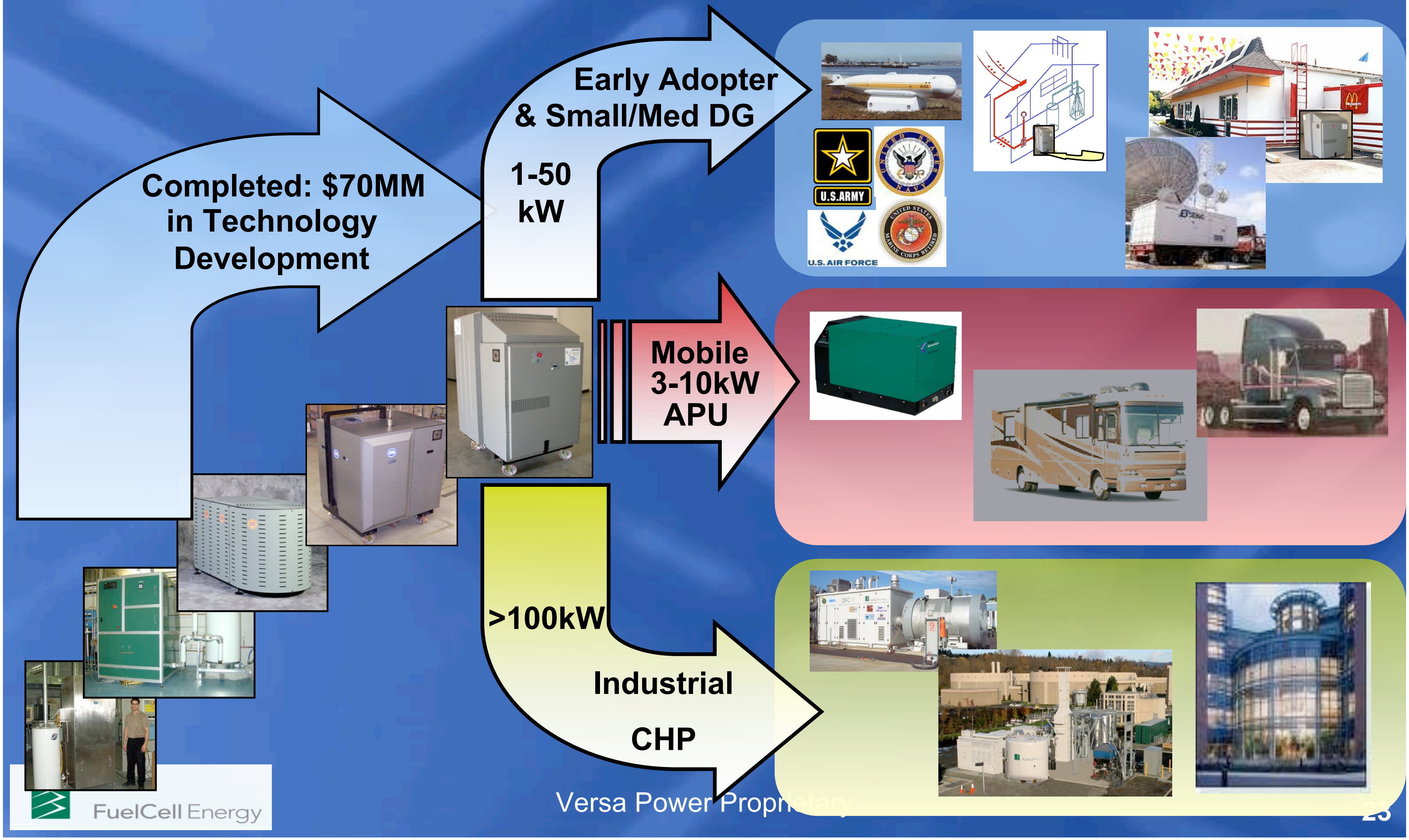


Prototype 3-1 kW System Test Summary

	DOE Target	Result
Fuel Type	Natural Gas	Pipeline NG
Steady state degradation	≤ 2% / 500 h	1.28% / 500 h
Transient degradation over 10 cycles	≤ 1%	0.87%
Peak Net DC Electrical Power	3-10 kW	5.26 kW
Peak Net DC Electrical Efficiency	≥ 35%	39.6%
EOT Net DC Electrical Efficiency	≥ 35%	36.4%
Availability	≥ 80%	98.6%
Cost	≤ 800/kW	$773/kW

Notes: Hourly averaged data
Efficiencies based on LHV Calgary pipeline natural gas

VPS SOFC System Status & Markets



The Co-production Concept Using Ammonia

Ammonia → Fuel Cell → Electricity, Hydrogen

$$2NH_3 \xrightarrow{\text{heat}} N_2 + 3\,H_2$$

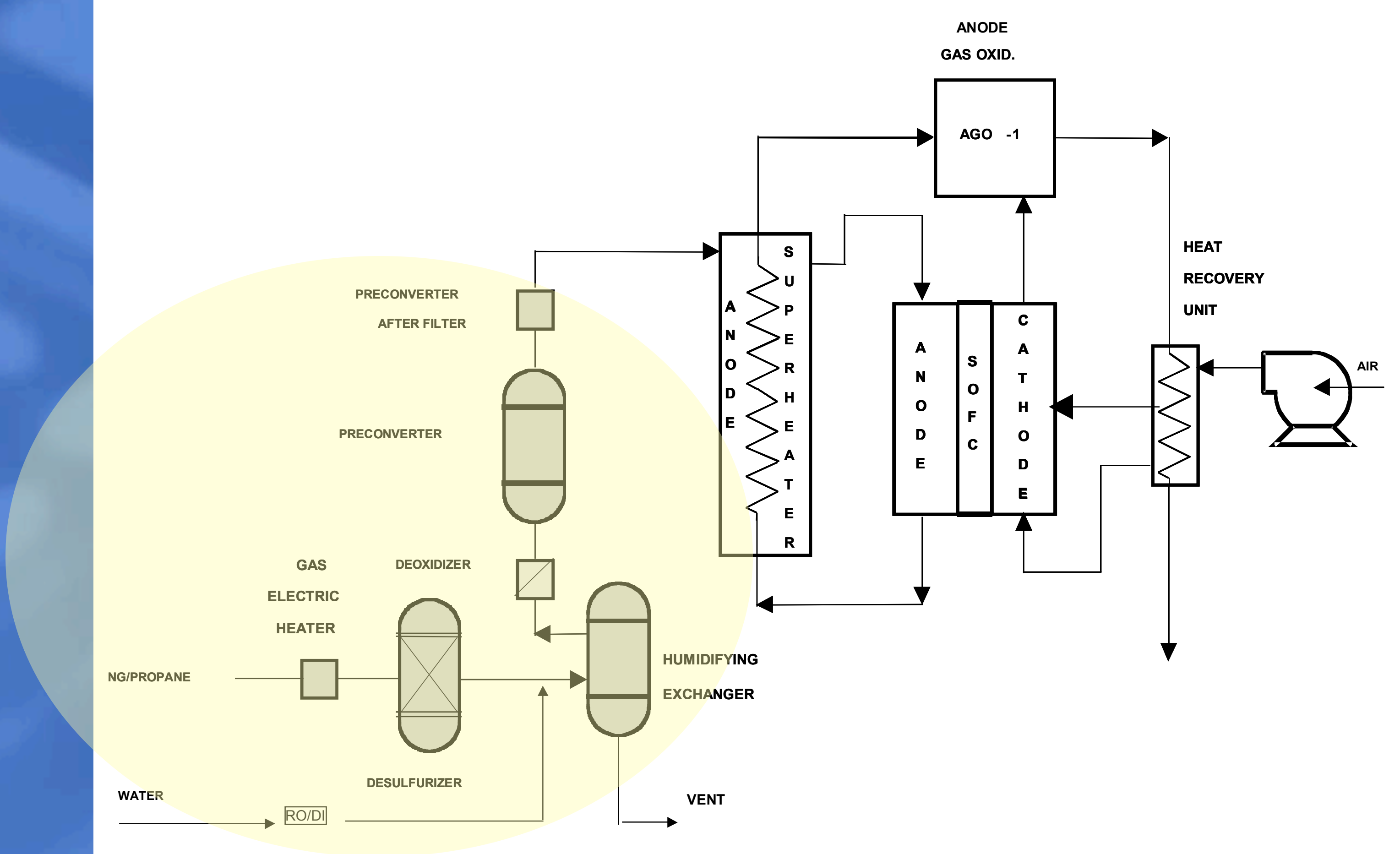
(34 lbs) → (28 lbs) + (6 lbs)

Ammonia and Different Types of Fuel Cells

Type of Fuel Cell	Operating Temp., °C	Potential Benefits	Considerations
Polymer Electrolyte Membrane (PEM) Phosphoric Acid (PAFC)	60-120 180-200	▪ Reduced fuel processing steps ▪ Moderate efficiency	▪ Filter for trace ammonia ▪ Ammonia cracker
Carbonate (MCFC)	600-700	High efficiency; moderate simple system	Source of CO_2
Solid Oxide (SOFC)	700-900	Simplest; highest system efficiency	Thermal integration

SOFC is the Most Suitable Technology

Ammonia Vs. Conventional Fuel Systems



Conventional Hydrocarbon-Based SOFC System:

Highlighted fuel pre-treatment equipment increases system complexity and cost.

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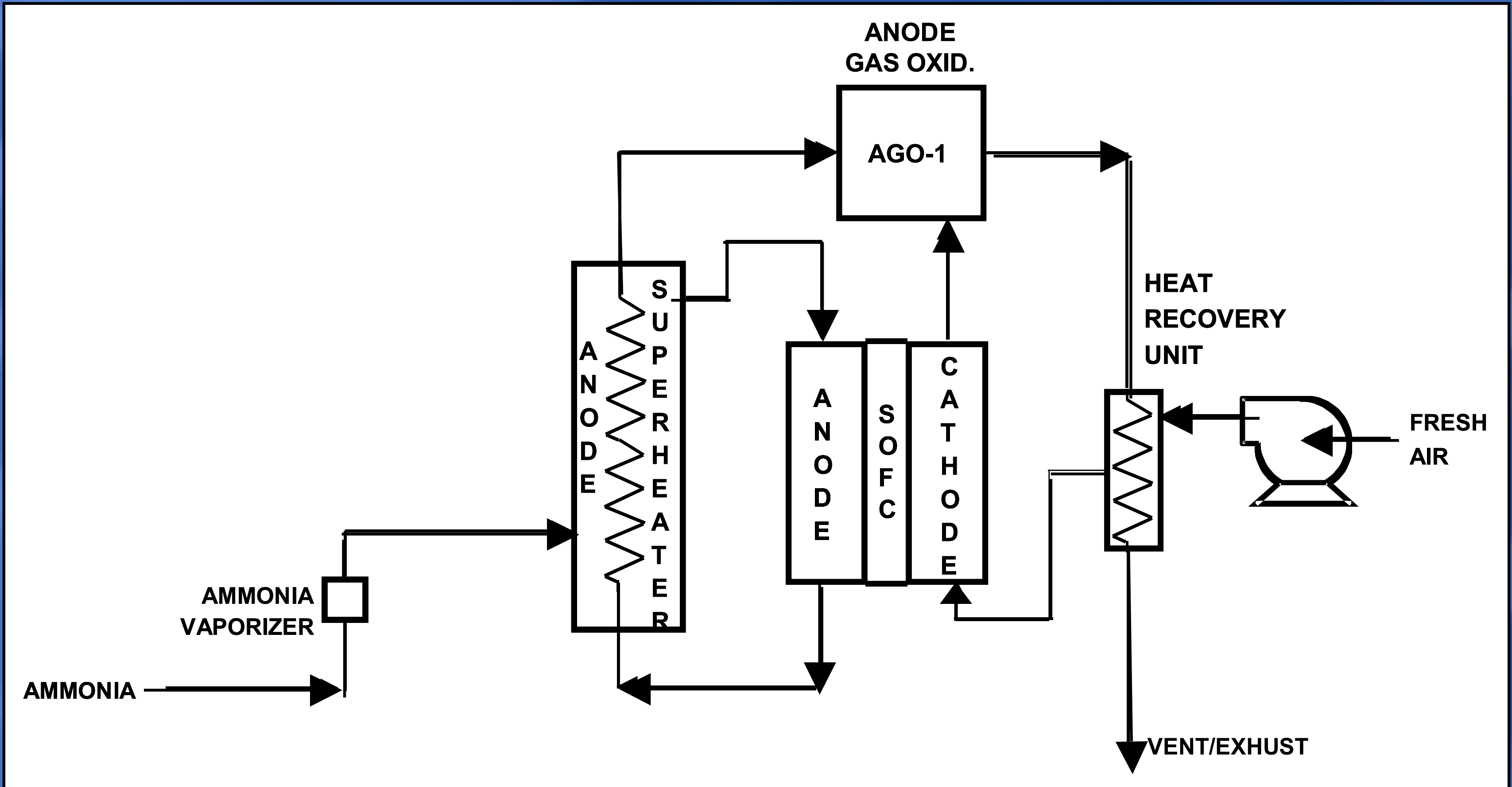


Candidate Ammonia SOFC System:

Simple system with practically no fuel pre-treatment equipment.

Ammonia and Propane System Costs and Cost of Electricity

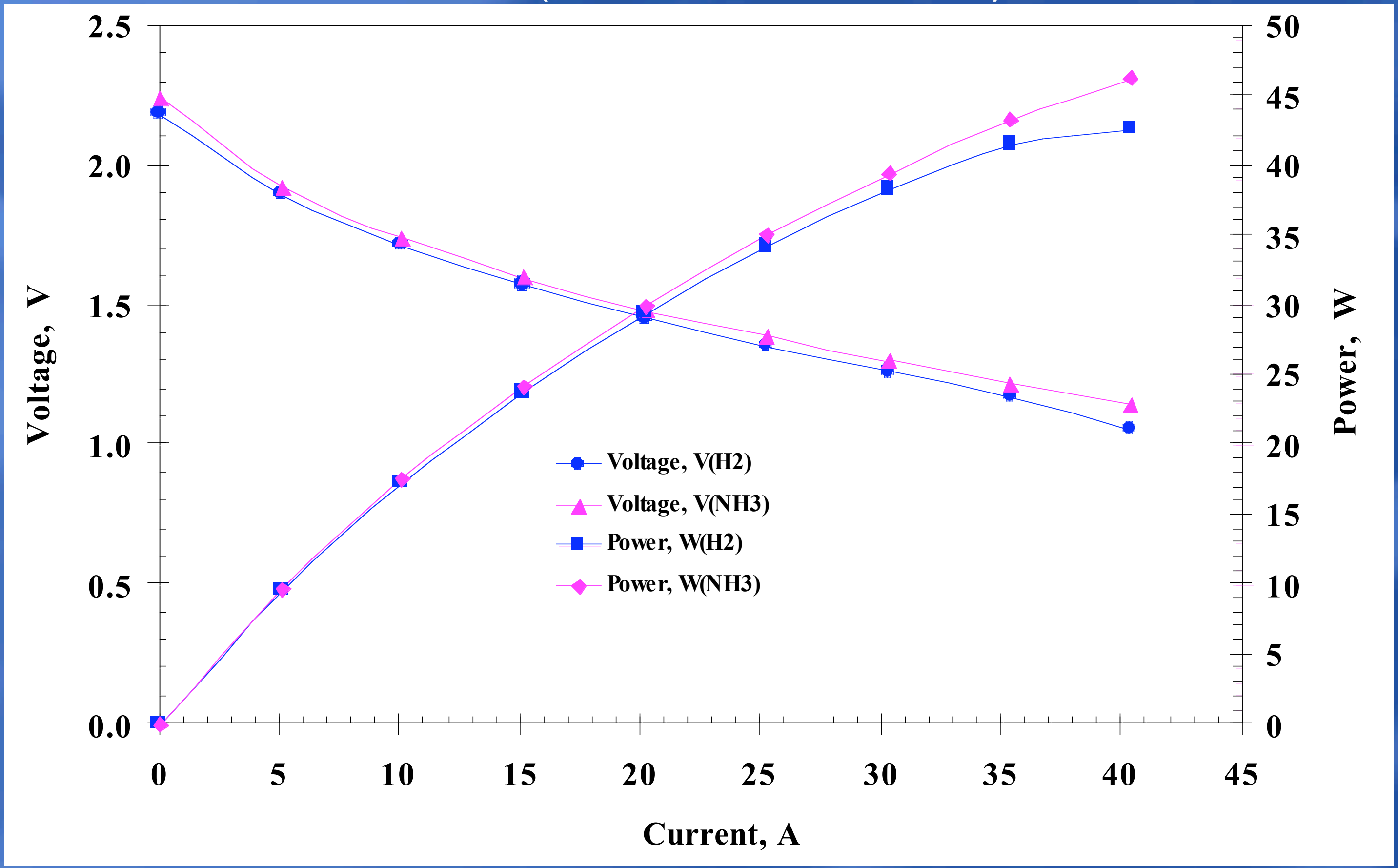
$/kW	PSOFC	ASOFC
Fuel Processing	788	67
Fuel Cell Stack	1,079	636
Inverter	841	745
Auxiliary Equipment	231	127
Total Cost	**2,739**	**1,575**

	Estimated Levelized Cost of Electricity, cents/kWh		
	$5/MMBTU	$10/MMBTU	$15/MMBTU
PSOFC	17.8	22.2	26.6
ASOFC	11.6	16.0	20.5

Ammonia can cost more than $6/MMBTU higher than propane and deliver the same COE.

Old Generation Performance on Ammonia and Hydrogen

(100 cm^2, 2-cell Stack)



Preliminary Data Indicates Performance Comparable to Operation on Hydrogen

Ammonia Required for Co-production

Size of Fuel Cell	Ammonia Required tons/day	Co-production		Fuel Cell Cars Served
		Electricity kW	Hydrogen lbs/day	
Sub-MW	**2.5**	**250**	**300**	**250**
Megawatt	**10.0**	**1000**	**1200**	**1000**

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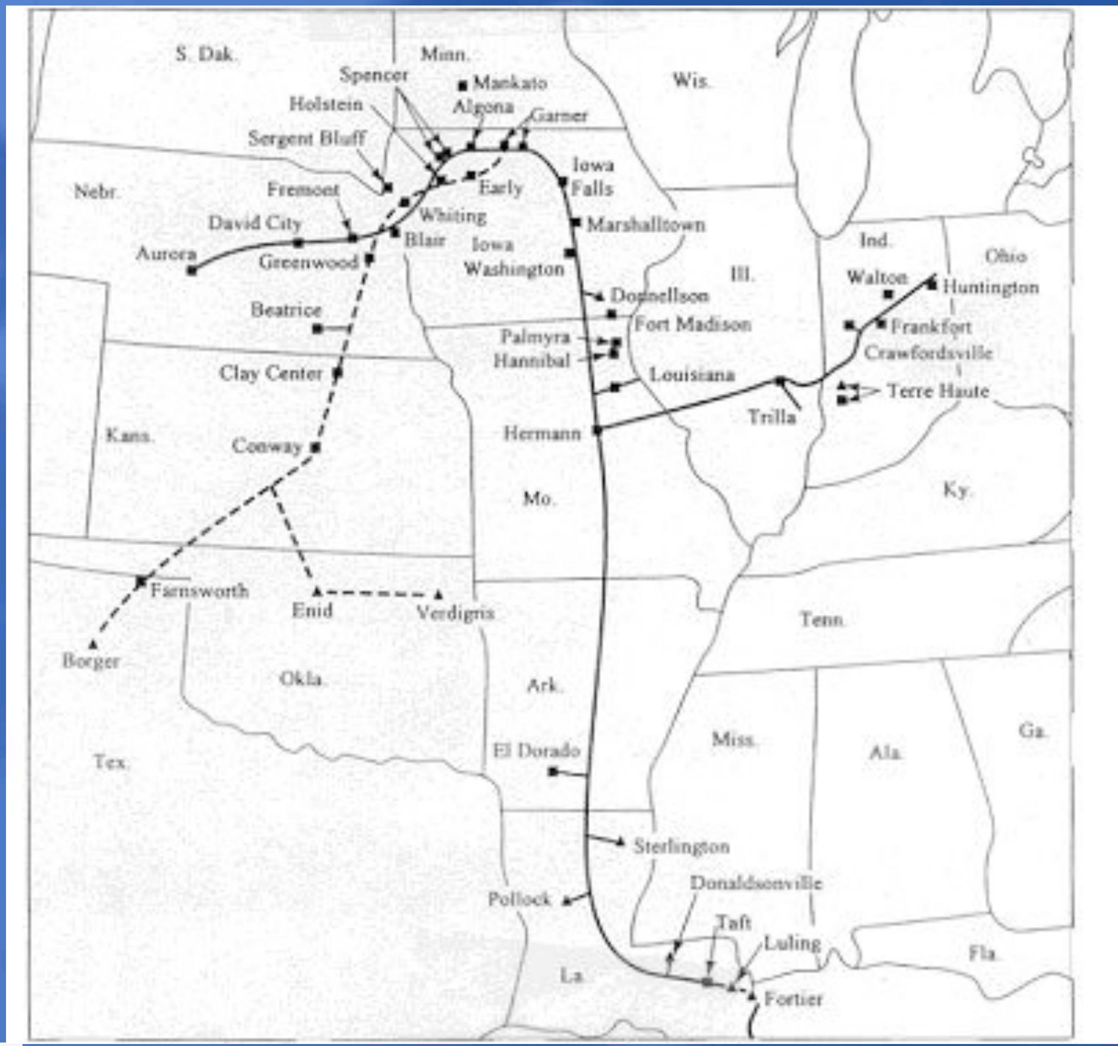
Ammonia & the Hydrogen Infrastructure

- Ammonia as a carrier of hydrogen has ~18 wt% capacity (DOE target: >6 wt%)
- Safety and handling systems are established
- Distribution system is reasonably developed in the US (pipeline, train, large, trucks)
- On-site extraction of hydrogen via catalytic cracking is commercially available & relatively simple
- Can be made from coal, the abundant feed stock
- Can contribute to the much needed “bridge” to Hydrogen Economy

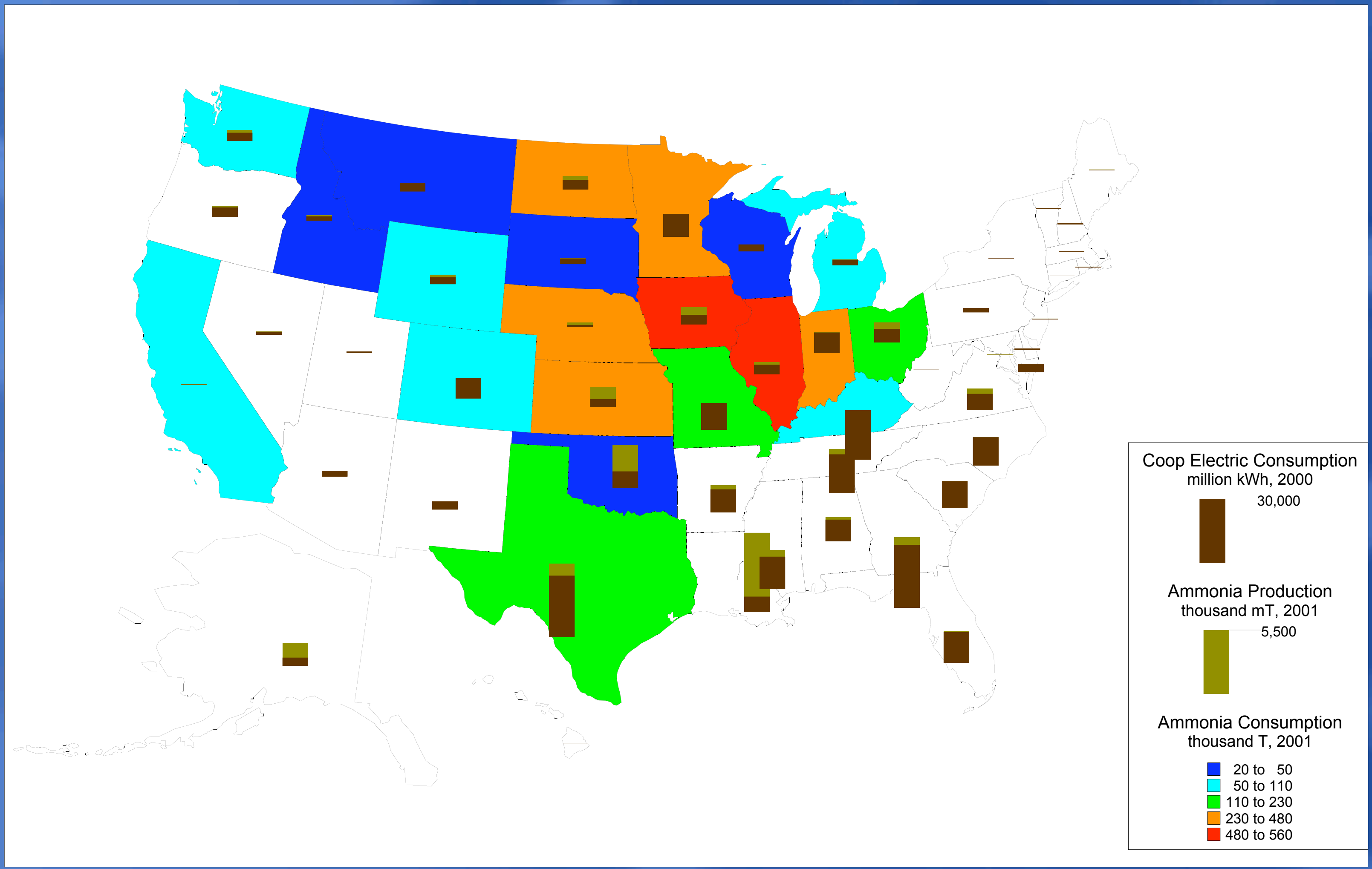
Ammonia Pipeline Infrastructure



MAPCO and GULF Pipelines

Rural Electric Coop Operating Territories

Co-op Electric Demand; Ammonia Production and Consumption



Ammonia SOFC in Co-Op Applications-Perspective

- Rough Ammonia SOFC Consumption:
  - ~ 9 slpm/kW
  - ~0.9 lb/kWh
- Basis: Per 1% of Co-Op Annual Electric Consumption Converted to ASOFC: ~2BBkW-h
- At ~11,500 kW-h per household per year:
  - ~175,000 households
  - ~ 0.8 MM mtons ammonia consumed
- REF: Total US Ammonia Consumption 2005, ~14.7MM mtons

Per 1% of Co-Op Electric Consumption Converted to ASOFC– This represents ~175,000 households, and ~ 6% of the annual ammonia consumption.

Ammonia-SOFC Opportunities & National Economic Benefits

Features of ASOFC	Potential Benefits
Utilization of indigenous, domestic feedstock	Improved energy security, reduced imports New use: creates additional demand and jobs

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Significant reduction in system cost	**Can Accelerate SOFC commercialization and export markets in general**