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DOE Hydrogen Program

Development of a Novel Efficient Solid-Oxide Hybrid for Co-generation of Hydrogen and Electricity Using Nearby Resources for Local Application

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2009 DOE Hydrogen Program Annual Review

May 22, 2009

Project ID#: FC_47_Tao

Overview

Timeline

- Project started: 02/10/2006
- Project ends: 07/31/2009
- Percent completed: 80%

Budget

- Total budget funding
  - DOE $2,480k
  - Contractor $ 620k
- Funding received in FY08
  - $ 823k
- Funding for FY09
  - $ 0k

Barriers

Hydrogen generation by water electrolysis

- G – Capital cost
  - Low-cost, durable high-temperature materials development
  - Lower operating temperature
- H – System efficiency

Partners

- University of Alaska Fairbanks – (UAF) anode fracture mechanisms and modeling of residual stresses (**S. Bandopadhyay**)
- Missouri University of Science and Technology – (MST) cathode & seal materials development (**H. Anderson; R. Brow**)
- University of Utah – (UU) interconnect development (**A. Virkar**)

Objective/Relevance

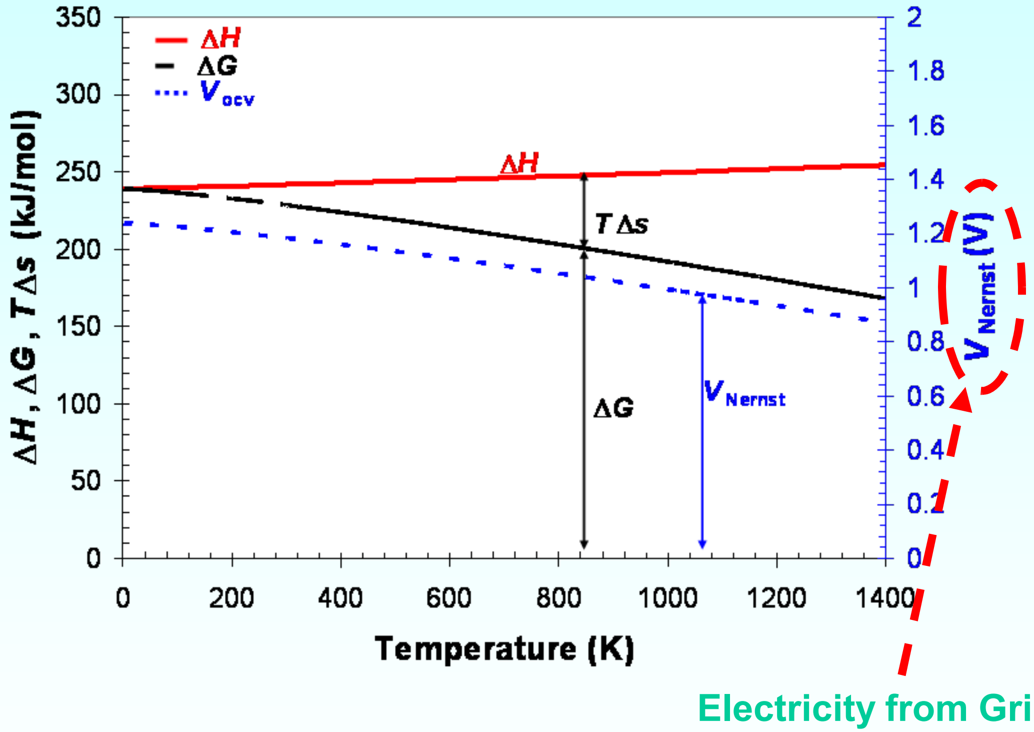
Overall Objective	• To develop a low-cost and highly efficient 5 kW SOFEC-SOFC hybrid system co-generating both electricity and hydrogen to achieve the cost target of < \$3.00/gge when modeled with a 1500 gge/day hydrogen production rate • The project focuses on materials R&D, stack design & fabrication, proof-of-concept of cogeneration, and system design, manufacture & experimental verification
2008	• 5 kW SOFEC-SOFC hybrid system development – Stack design – Hybrid system design – BOP components development (design and fabrication) – Cell & non-cell repeat units fabrication
2009	• 5 kW SOFEC-SOFC hybrid system evaluation – SOFC and hybrid SOFEC-SOFC module assembly and evaluation – Control system assembly & programming – System final assembly and evaluation – Implementation of H2A model for cost analysis

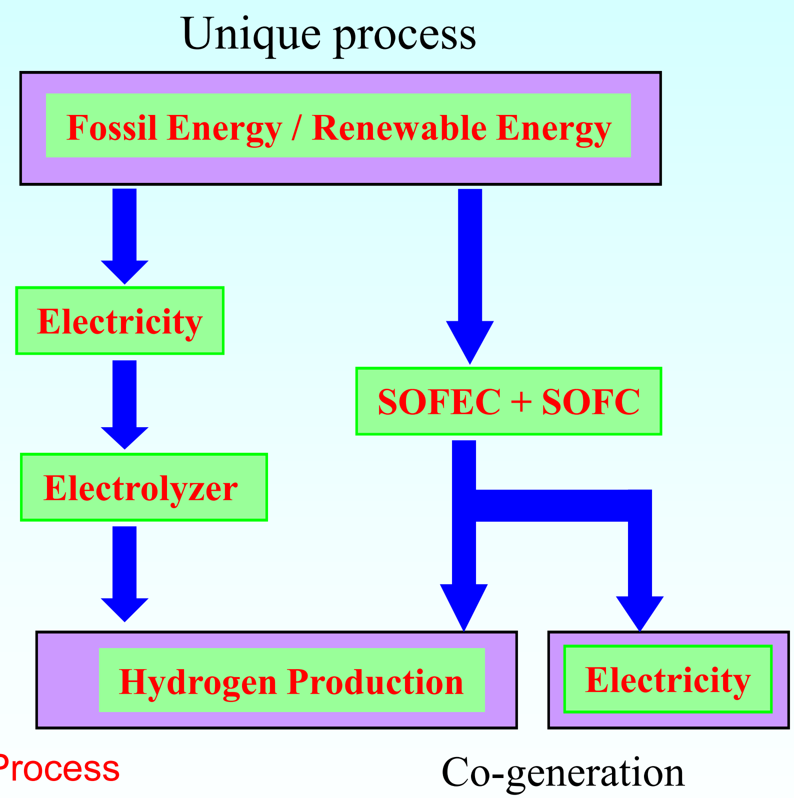
Milestones

Quarters, FY	Milestone
2nd Quarter, FY08	Completed the design of the 5 kW system and major BOP components
4th Quarter, FY08	Completed fabrication and pre-test of most BOP components. Purchased off-the-shelf hardware for the hybrid system
1st Quarter, FY09	Completed fabrication of cell/stack components. Assembled and evaluated the 1st kW SOFC stack with new designs. Hosted a site visit of the DOE Hydrogen Safety Panel
2nd Quarter FY09	Assemble and run burn-in cycle of 1st kW SOFEC-SOFC hybrid module
3rd Quarter FY09	Finish assembly and burn-in of remaining modules. Initiate system assembly

Background

A Solid Oxide Fuel-Assisted Electrolysis Cell (SOFEC) directly applies the energy of a chemical fuel to replace the external electrical energy required to produce hydrogen from water/steam; decreasing the cost of energy relative to a traditional electrolysis process.





CH_4-assisted SOFEC Reaction

$4H_2O + 8e' \rightarrow 4H_2 + 4O^{2-}$ — Electrochemical Process at cathode

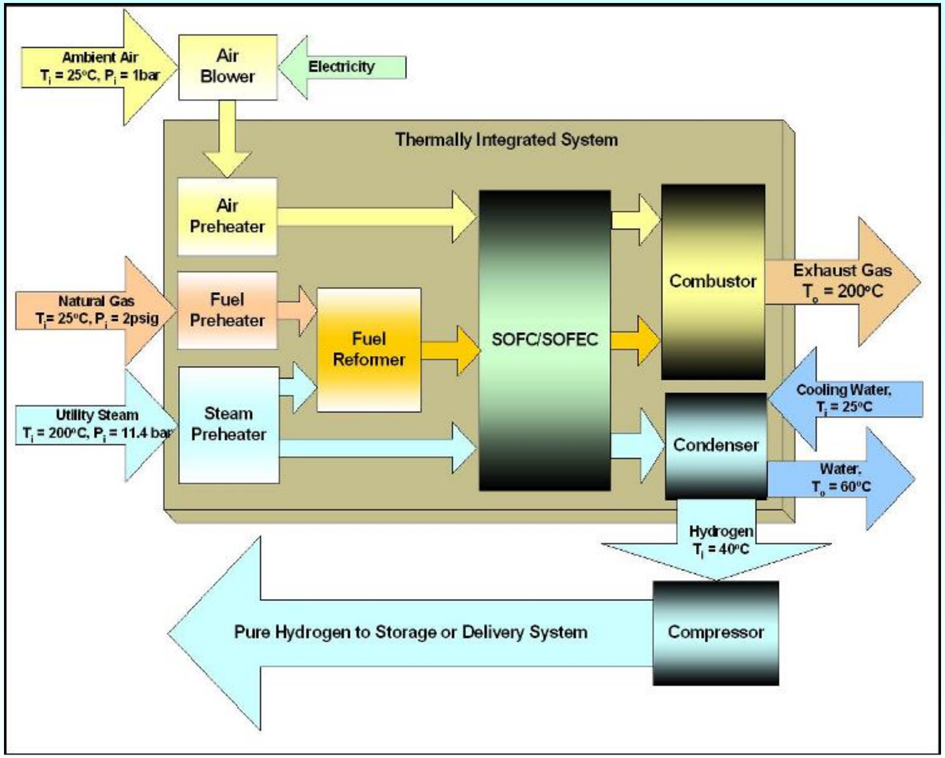
$4O^{2-} + CH_4 \rightarrow CO_2 + 2H_2O + 8e'$ — at anode

$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$

Pure H_2 formed. No need for H_2 separation membranes. Lower electricity requirement.

Concept of Hybrid SOFEC-SOFC Integral System

Technical Challenges and Solutions



Cost of Hydrogen

SOFC-SOFEC performance

- cathode materials: composition, microstructure, catalytic characterisitcs;
- anode material: porosity, tortuosity, composition;
- low operating temperature: inexpensive materials, non-precious metal catalysts;
- manufacturability.

System efficiency

- SOFC-SOFEC hybrid architecture;
- thermal integration;
- co-generation concept.

Long-term durability

- "invert" seal material thermalmechanical compatibility and thermalchemical stability;
- anode mechanical strength.

- Pure H_2 & electricity co-production from feedstock: hydrocarbon fuel, steam, and air
- Hybrid comprised of SOFECs and SOFCs
- SOFECs produce pure H_2 and SOFCs generate electricity for a high H_2 production rate
- Thermal integration improves system efficiency

Approach

Materials Development

A. Cathode materials Dev.

B. Anode optimization

C. Electrolyte optimization

D. Catalyst studies

E. Seals development

F. Fabrication Q.A.

100% complete

Cell / Stack /System Design

A. Stack design

B. 5kW system design

C. BOP design/dev.

D. Stresses analyses

E. Seals application

F. Economic analysis

90% complete

Experimental Verification

A. Short stacks in dif. modes

B. 1 kW hybrid stack

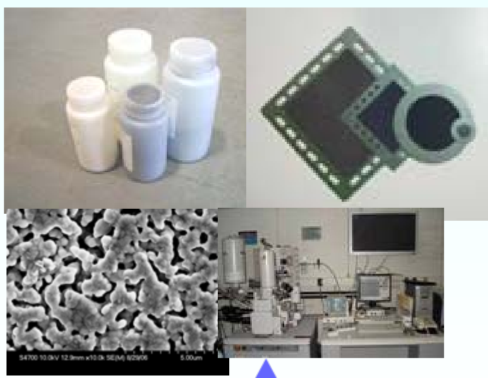
C. Durability evaluation

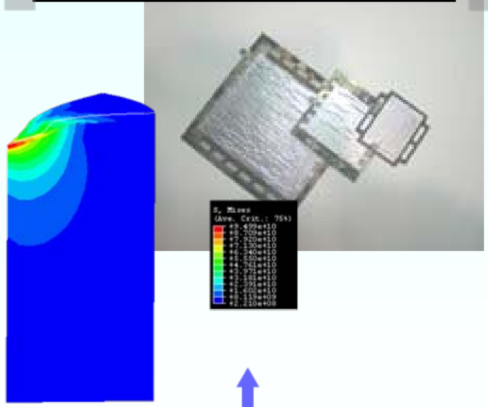
D. BOP design & evaluation

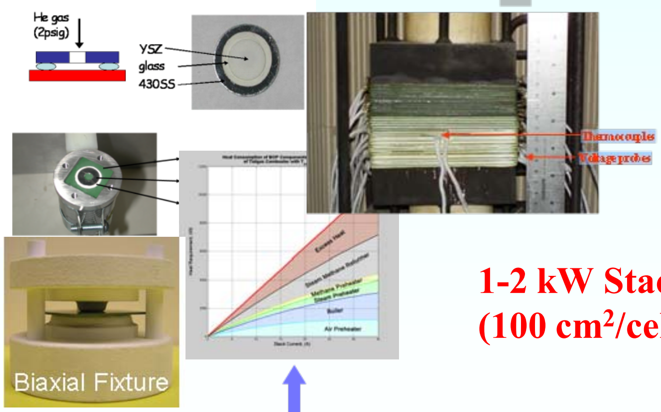
E. 5 kW hybrid system development & evaluation

70% complete

Success







1-2 kW Stack ($100\ cm^2$/cell)

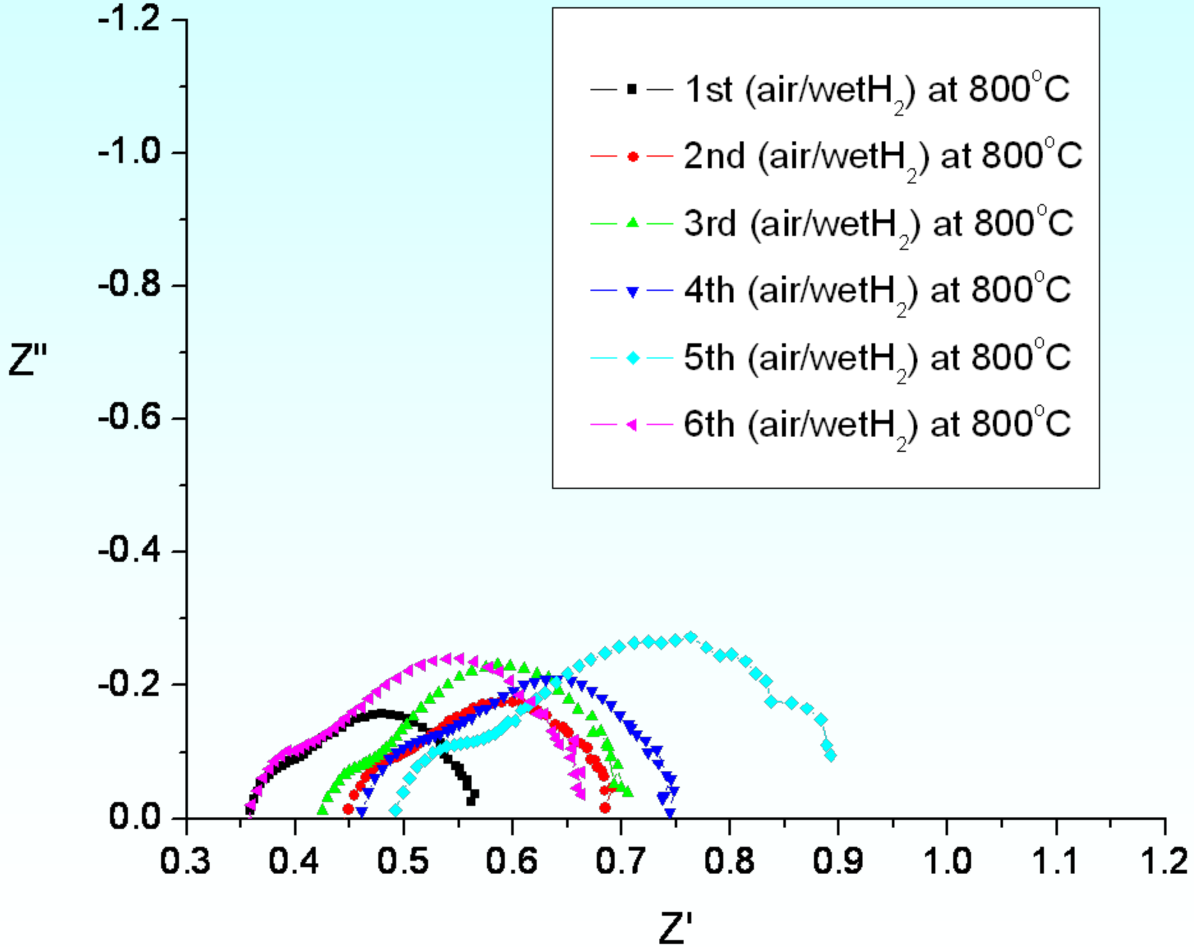
MSRI, MST

MSRI, UAF, MST, UU

MSRI, UU, MST

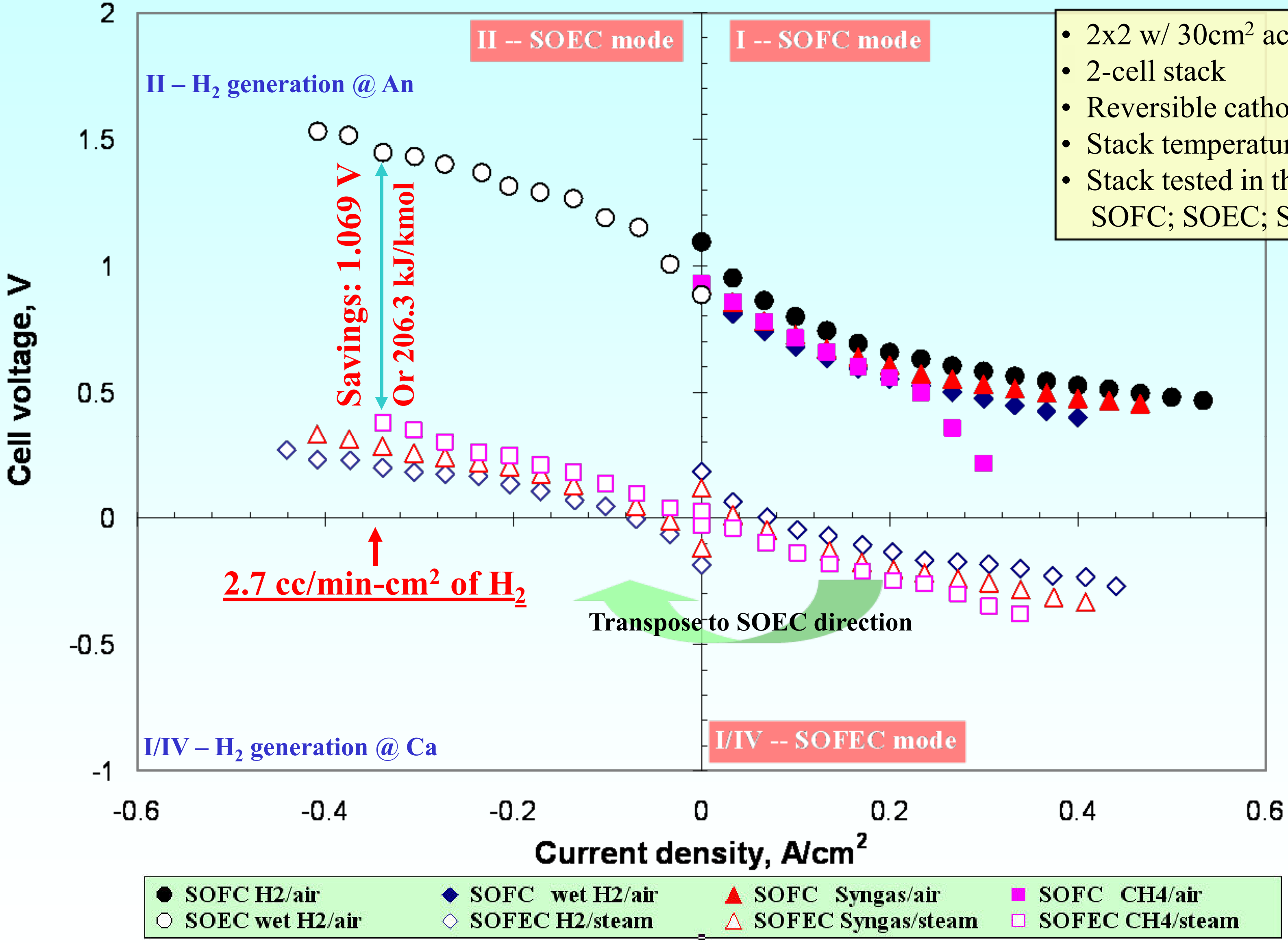
SOFEC Cathode Materials Development

LSCM Redox Stability Study



- Previous studies show that $(La,Sr)(Cr,Mn)O_3$-based cathode material is electrocatalytically and chemically stable in both reducing and oxidizing atmospheres
- Previous long-term tests show degradation rate < 1% per 1000hrs over a 4500 hrs continuous test in the SOFC mode.
- Redox stability is desired for reversible applications

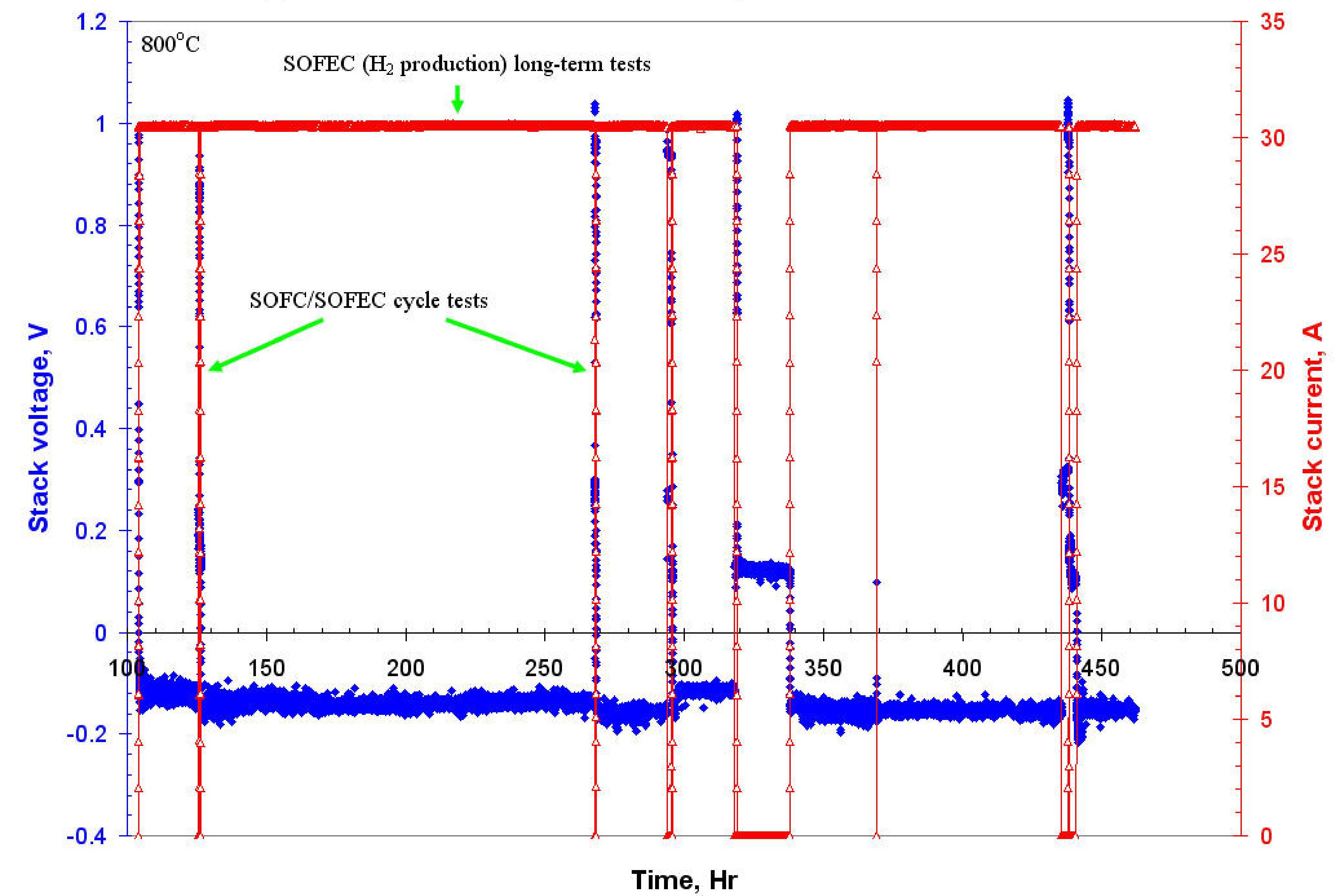
Stack Performance Characteristics in SOFC/SOEC/SOFEC Modes



- 2x2 w/ 30cm^2 active area
- 2-cell stack
- Reversible cathode, LSCM
- Stack temperature at 800^{o}C
- Stack tested in three modes: SOFC; SOEC; SOFEC

SOFEC Stability Test

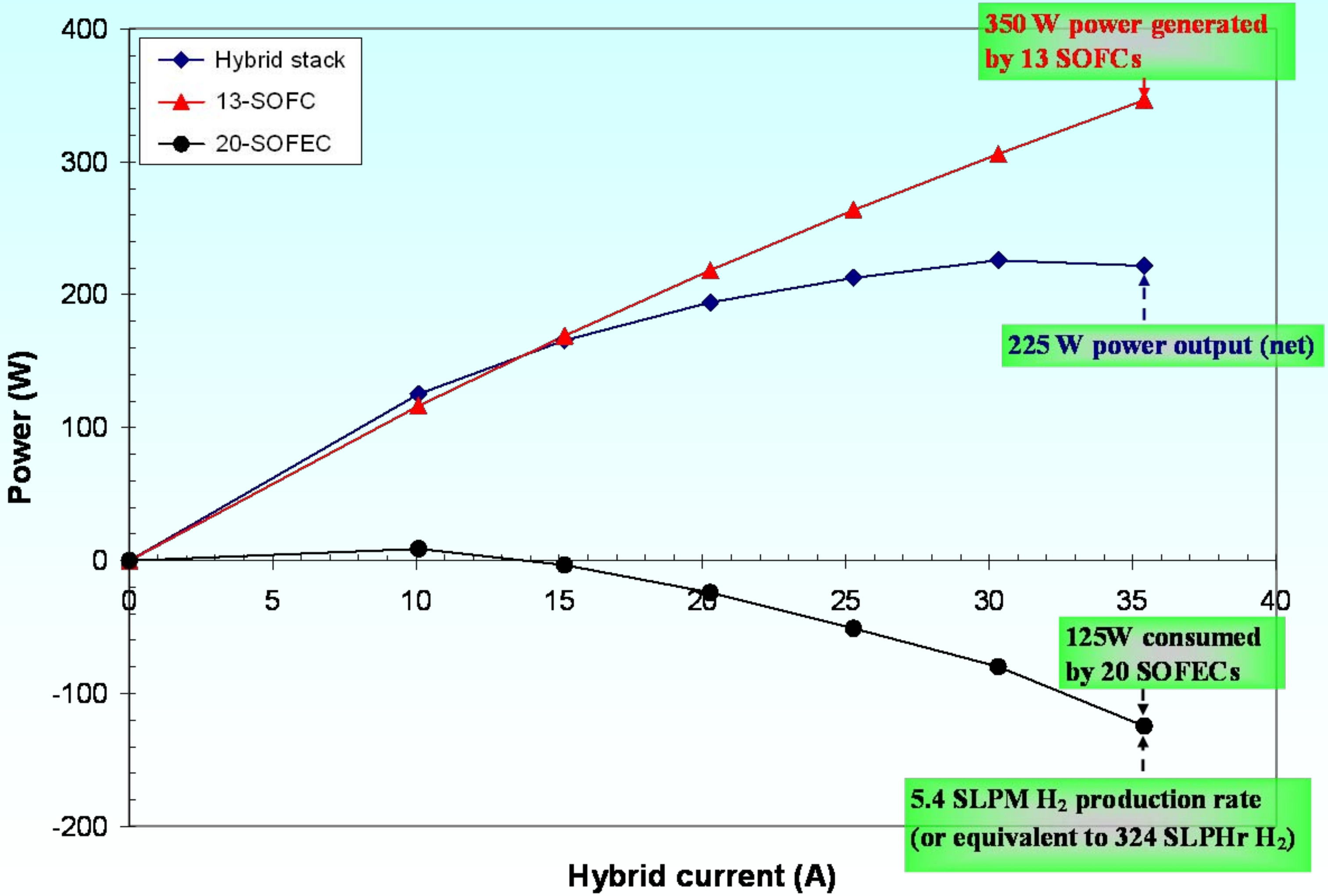
Single-cell stack with 100 cm² per-cell active area



H_2 production rate: 13.92 standard liters of H_2 per hour, or 27.54 grams per day

Proof-of-concept: Hybrid Stack Co-generation of H_2 & Electricity

Power – Current curve: Hybrid vs. 13-SOFC vs. 20-SOFEC

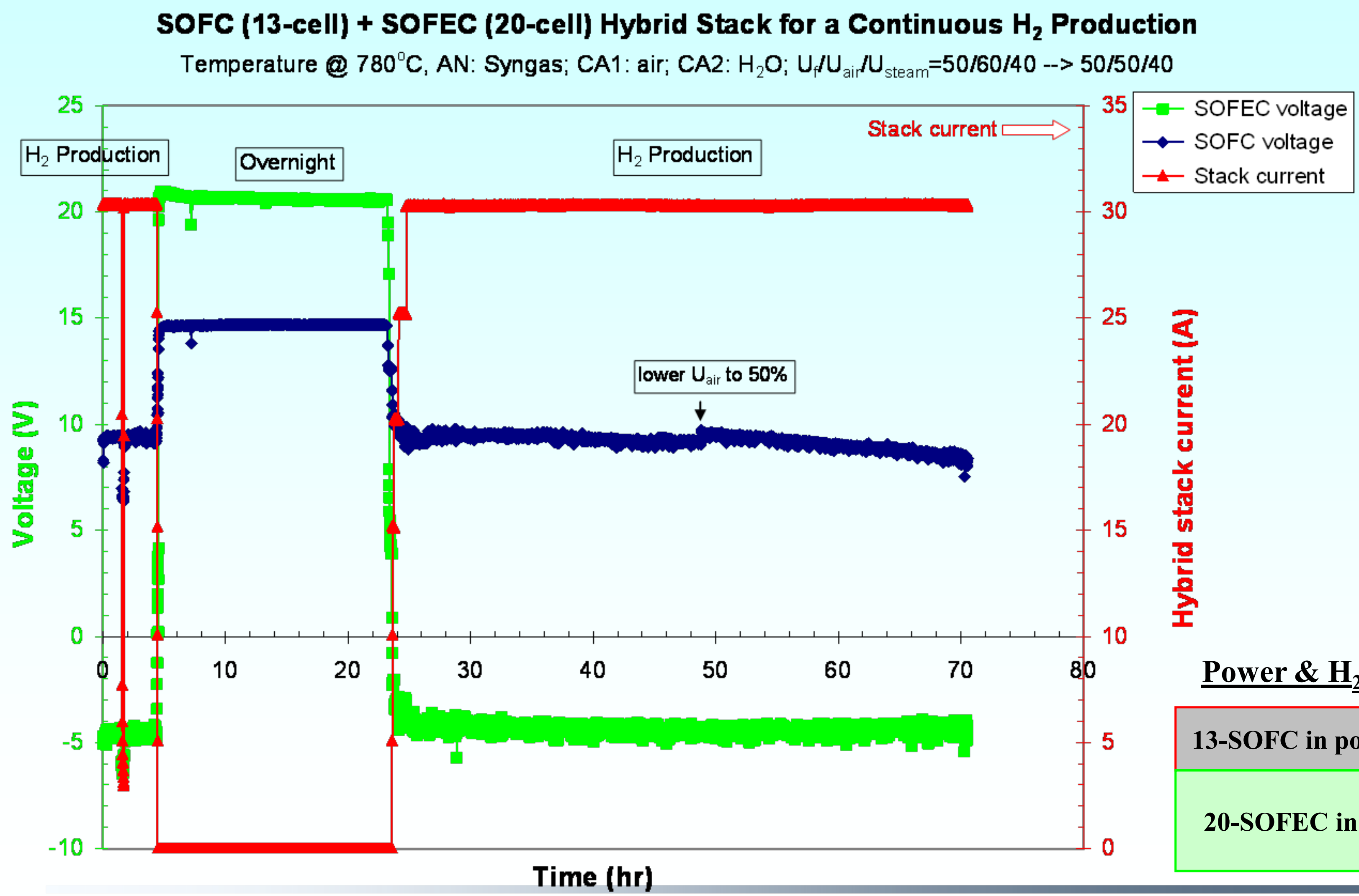


Hybrid stack

- 13 SOFCs
- 20 SOFECs
- T = 770°C
- Anode: Syngas
- Cathode 1: air
- Cathode 2: steam
- $U_f = 40\%$
- $U_{air} = 40\%$
- $U_{steam} = 40\%$

SOFEC-SOFC Hybrid Continuous Cogeneration

Co-Production rate: Net power output @ 130 Watts and 270 standard liters of H_2 per hour (or 0.534 kg/day)



Power & H_2 cogeneration

13-SOFC in power generation
20-SOFEC in H_2 production

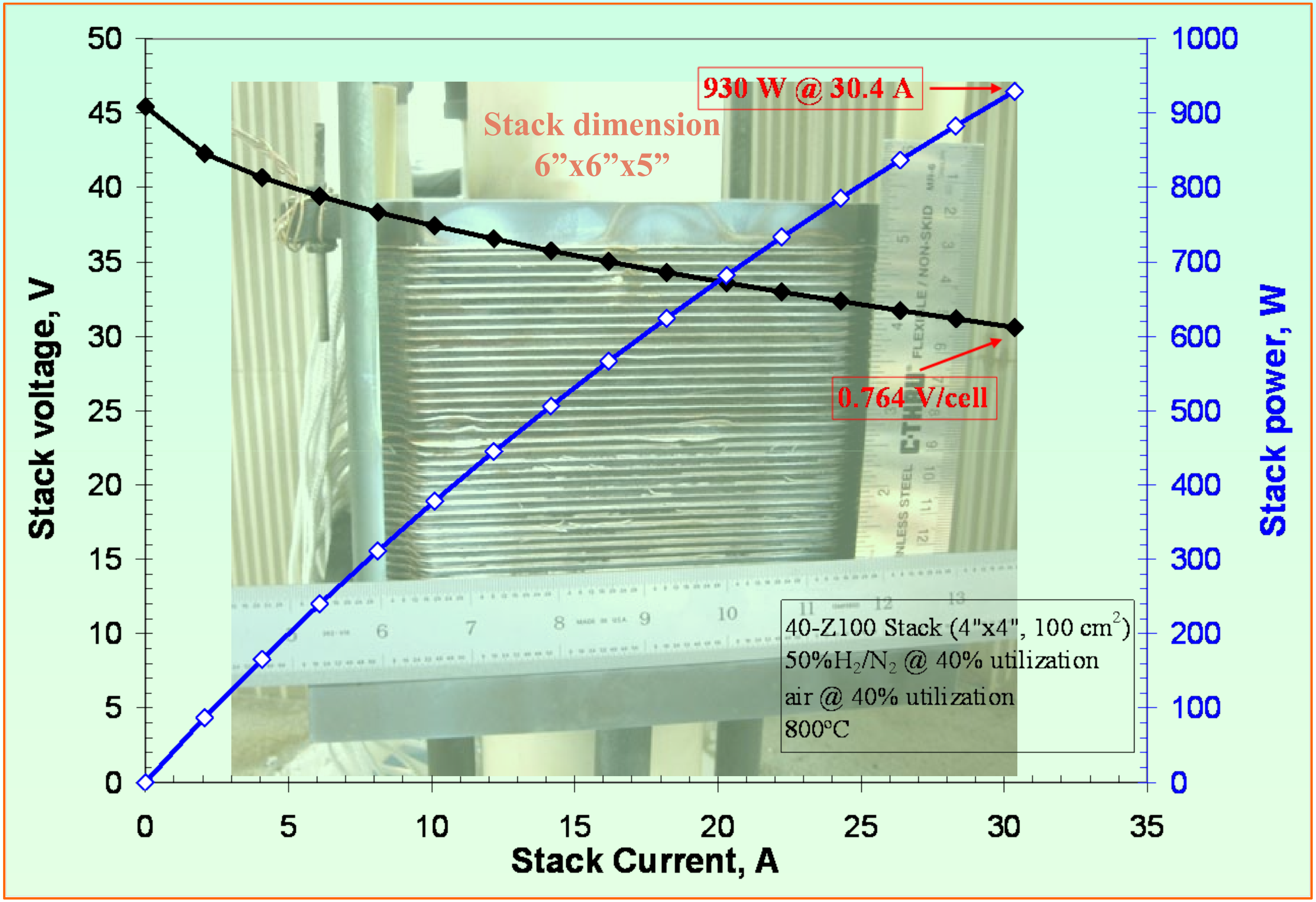
5 kW System Development – Cell Fabrication

- Completed cell fabrication for 3 SOFEC-SOFC hybrid stack for cogeneration hydrogen and electricity
- Completed cell fabrication for 3 dedicated SOFC stacks for power generation
- Six modules will be tested individually before assembly into system

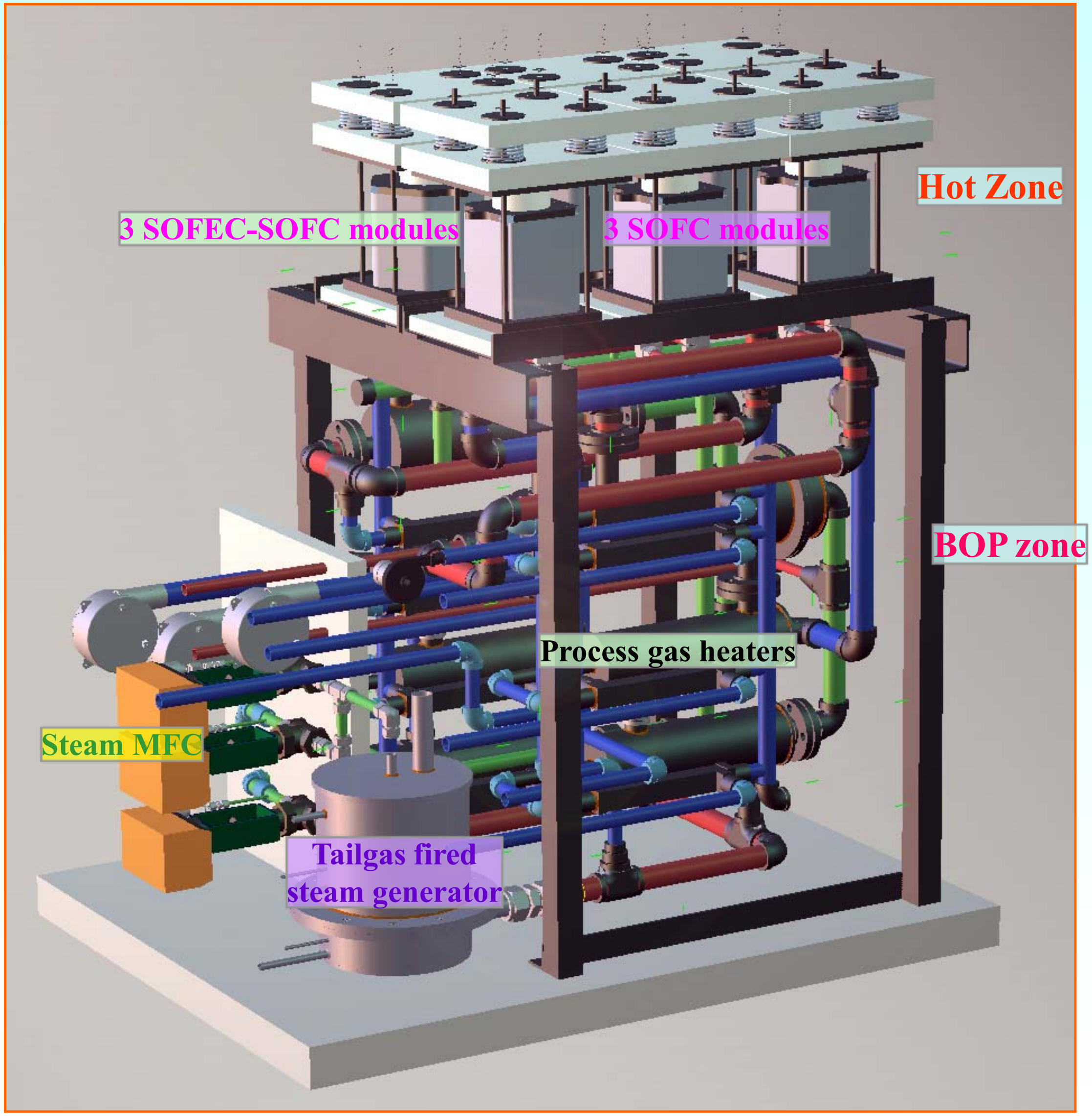
Interconnect Brazing System Development

- Developed and refined interconnect brazing process in-house:
  - Intermediate furnace-brazing temperature in a controlled atmosphere
  - High yield consistency
  - Gas leak-tight bonds between each metal grill/foil
  - High quality interconnect assembly without creep-flattening
  - Significant cost-reduction in materials and machining

1 kW SOFC Stack Evaluation



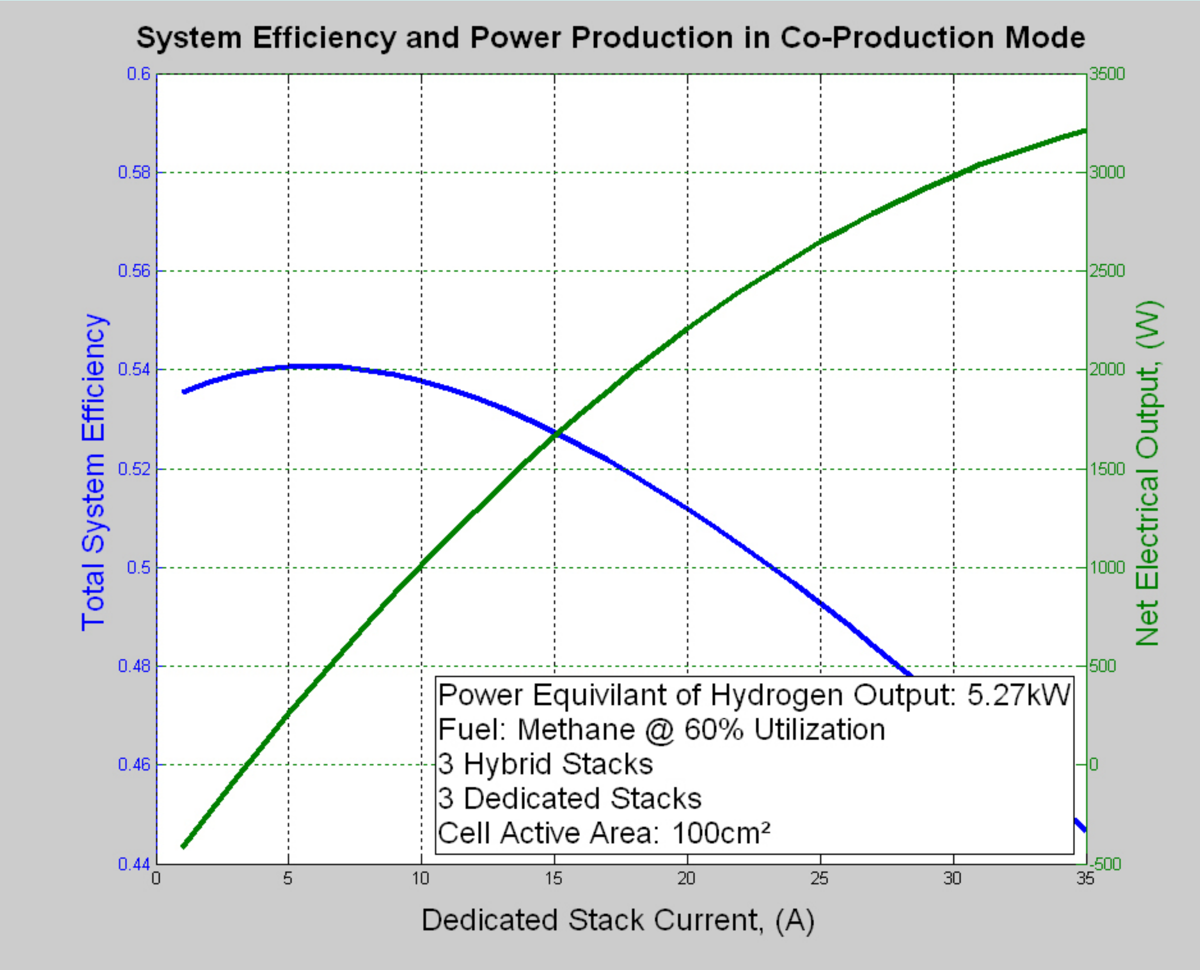
5 kW Hybrid System Design



- 3 hybrid SOFEC-SOFC modules
- 3 dedicated SOFC modules
- Modular compression hardware
- Separate tailgas fired process gas heaters for hybrid and dedicated modules
- Central steam generator feeding reformers and SOFEC cathode chamber
- Tailgas combustors designed for partial combustion of lean tailgas mixture
- Variable speed air control to tailgas combustors
- Combustion air heated by cathode exhaust for high efficiency
- 100% of heat to BOP components recovered from stack exhaust stream

5 kW Hybrid System Efficiency Estimation

- Value calculated based on sum of H_2 produced (LHV) and net electrical output divided by fuel consumed. (LHV of CH_4)
- Efficiency varies with output level, operating mode, and fuel utilization.
- Peak cogeneration efficiency: 54%

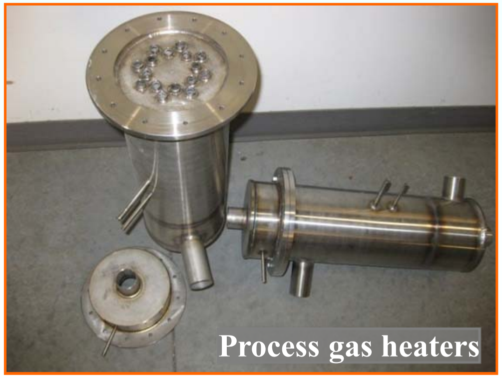


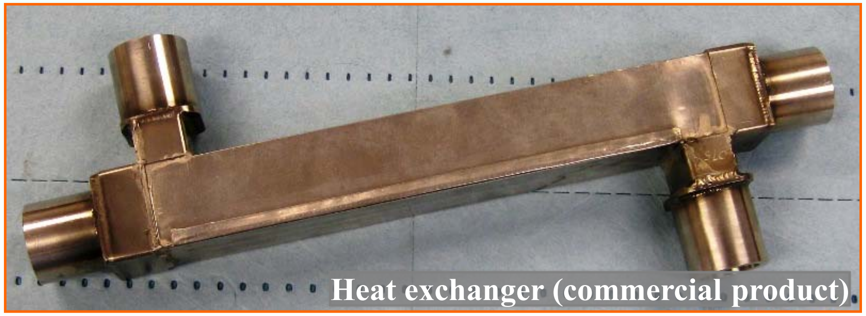
Design, Fabrication, and Test of BOP Components

- Process gas heaters, reformers and steam generators were designed, fabricated and tested prior to system integration
- Catalytic combustors ensure minimal noxious byproducts

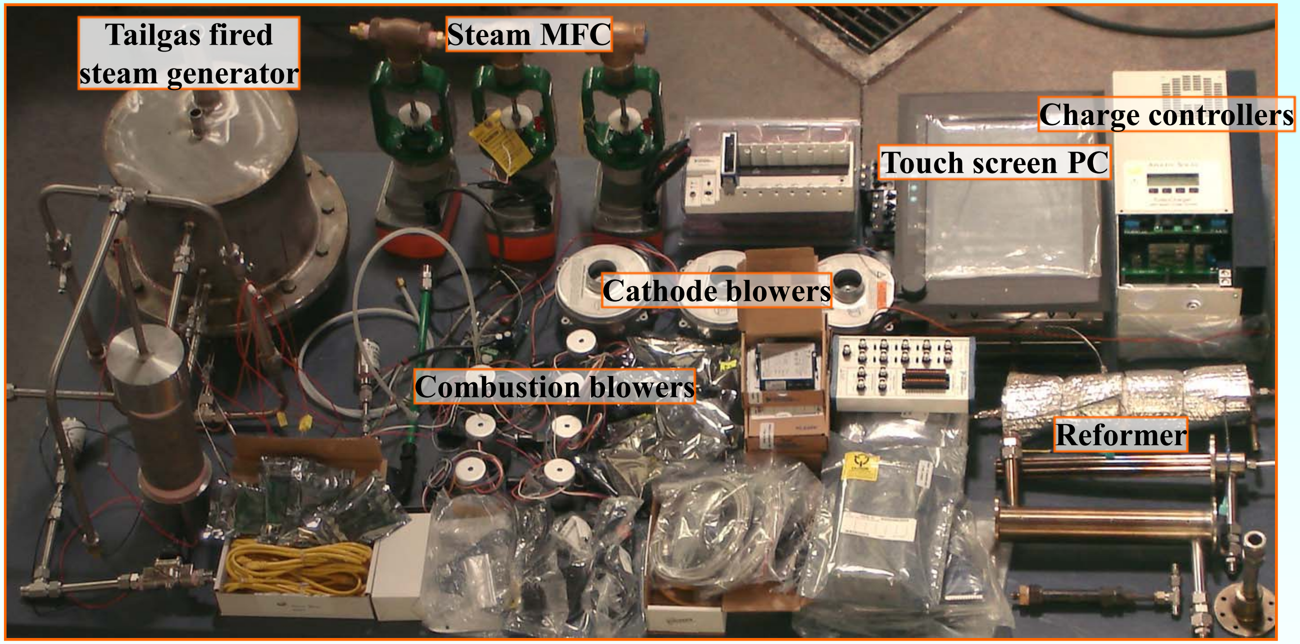

Tailgas fired steam generator


Reformers


Process gas heaters


Heat exchanger (commercial product)

Off-the-Shelf Hardware Acquisition



- Control Hardware (Real Time DAQ)
- Power Electronics
  - Commercial PV charge controllers
  - High current SSR for load switching
- Blowers
  - 7 Combustion blowers
  - 3 Cathode blowers
- NG line booster & cleanup
- Flow Control
  - 2 NG MFC
  - 3 Steam MFC
- Instrumentation
  - Thermocouples
  - Pressure sensors
  - Current/Voltage readings
- User Interface
  - Manual shutoff valves
  - Touch screen PC
  - Automated controls

Future Work (FY 09)

FY 09

- 5 kW Hybrid System Assembly and Evaluation
  - SOFC module assembly and burn-in
  - SOFEC-SOFC hybrid module assembly, integration and burn-in
  - 5 kW hybrid system assembly
  - System testing and evaluation
  - Implementation and optimization of system controls
  - Hydrogen production cost analysis using H2A model

Project Summary

Relevance: Investigate an alternative means to provide low-cost and highly efficient distributed electricity and hydrogen

Approach: Develop a 5 kW SOFEC-SOFC hybrid system based on innovative materials development and system design research to co-generate hydrogen and electricity

Project Accomplishments and Progresses:

Materials development: – Evaluated redox stability and long-term stability of the promising cathode material for SOFEC applications.

5 kW hybrid system development: – Conducted long-term stability tests of hydrogen production to reduce cost. – Finalized the design of hybrid modules with improved thermal and flow management. – Designed, fabricated, and tested main balance-of-plant components. – Fabricated cell/stack components for the 5 kW system. – Assembled and evaluated 1kW SOFC stack with new design.

Proposed Future Research: Complete assembly and burn-in test of hybrid SOFEC-SOFC modules and dedicated SOFC modules; complete control system assembly & programming; implement 5 kW system experimental evaluation and perform cost analyses using DOE H2A model.