High Temperature Solid Oxide Electrolyzer System

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2005 DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program Review

Project ID: PD24

Overview

Budget

(total for INL plus partners below)

FY-04: $1050 k
FY-05: $1440 k

Partners

Ceramatec, Inc.
- Development of planar cell technology

Argonne National Laboratory
- Computation Fluid Dynamics of Cells
- Overall Plant Flowsheet
- Advanced Electrode and Electrolyte Materials

Oak Ridge National Laboratory
- High Temperature Inorganic Membranes for Steam/Hydrogen separations

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Technical Barriers

Adapted from 3.1.4.2.2 Hydrogen Generation by {Water} Electrolysis

G. Capital Cost - *R&D is needed to develop lower cost materials with improved manufacturing capability to lower capital costs while improving the efficiency and durability of the system. Development of larger systems is also needed to improve economies of scale.*

H. System Efficiency *– Development is needed for low-cost cell stack optimization considering efficiency, electrochemical compression and durability.*

I. Grid Electricity Emissions – *Low-cost, carbon-free electricity sources are needed.*

K. Electricity Costs – *High Temperature solid oxide electrolysis can use lower cost energy in the form of steam for water splitting to decrease electricity consumption. Technically viable systems for low-cost manufacturing need to be developed for this technology.*

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Research Objectives

- Develop energy-efficient, high-temperature, solid-oxide electrolysis cells (SOECs) for hydrogen production from steam
- Develop and test integrated SOEC stacks operating in the electrolysis mode
- Develop optimized plant configuration for coupling to Generation IV Reactor
- Combine components in an Integrated Laboratory-scale Experiment
- Scale-up to a 200 kW Pilot Plant and a 1 MW Engineering Demonstration Facility

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Approach (vs Objectives)

- Develop energy-efficient, high-temperature, solid-oxide electrolysis cells (SOECs) for hydrogen production from steam.
  - Optimize energy efficiency, cost and durability
    - optimize electrolyte materials (e.g., YSZ, ScSZ, sealants)
    - investigate alternate cell configurations (e.g., electrode-supported or tubular)
- Develop and test integrated SOEC stacks operating in the electrolysis mode with an aim toward scale-up to a 200 kW Pilot Plant and a 1 MW Engineering Demonstration Facility
  - Increase SOEC stack durability and sealing with regard to thermal cycles
  - Improve material durability in a hydrogen/oxygen/steam environment
  - Perform a progression of electrolysis stack testing activities at increasing scales and complexities
  - Develop computational fluid dynamics (CFD) capability for SOEC
  - Utilize advanced systems modeling codes (e.g. HYSYS, ASPEN)
  - Perform Cost and Safety Analyses

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HTE FY-05 Task Area Overview

WP#	Org/ PIs	FY 05 k$ (inc. FY04 Carryover)	Description/Goal
HTE Systems Definition			
[ID15EL11]	INL / O'Brien, Herring	400	Engineering analyses in support of experiments and development of larger scale HTE facilities.
[CH15EL11]	ANL / Petri	237	ANL work also includes SOEC materials research
HTE Experiments			
[ID15EL21]	INL / Stoots, Herring	832	HTE Experimental activities, including scale-up.
HTE Membrane Technologies			
[OR15EL21]	ORNL / Bischoff	60	Evaluate the applicability of inorganic high-temperature membranes for use in large scale HTE operations

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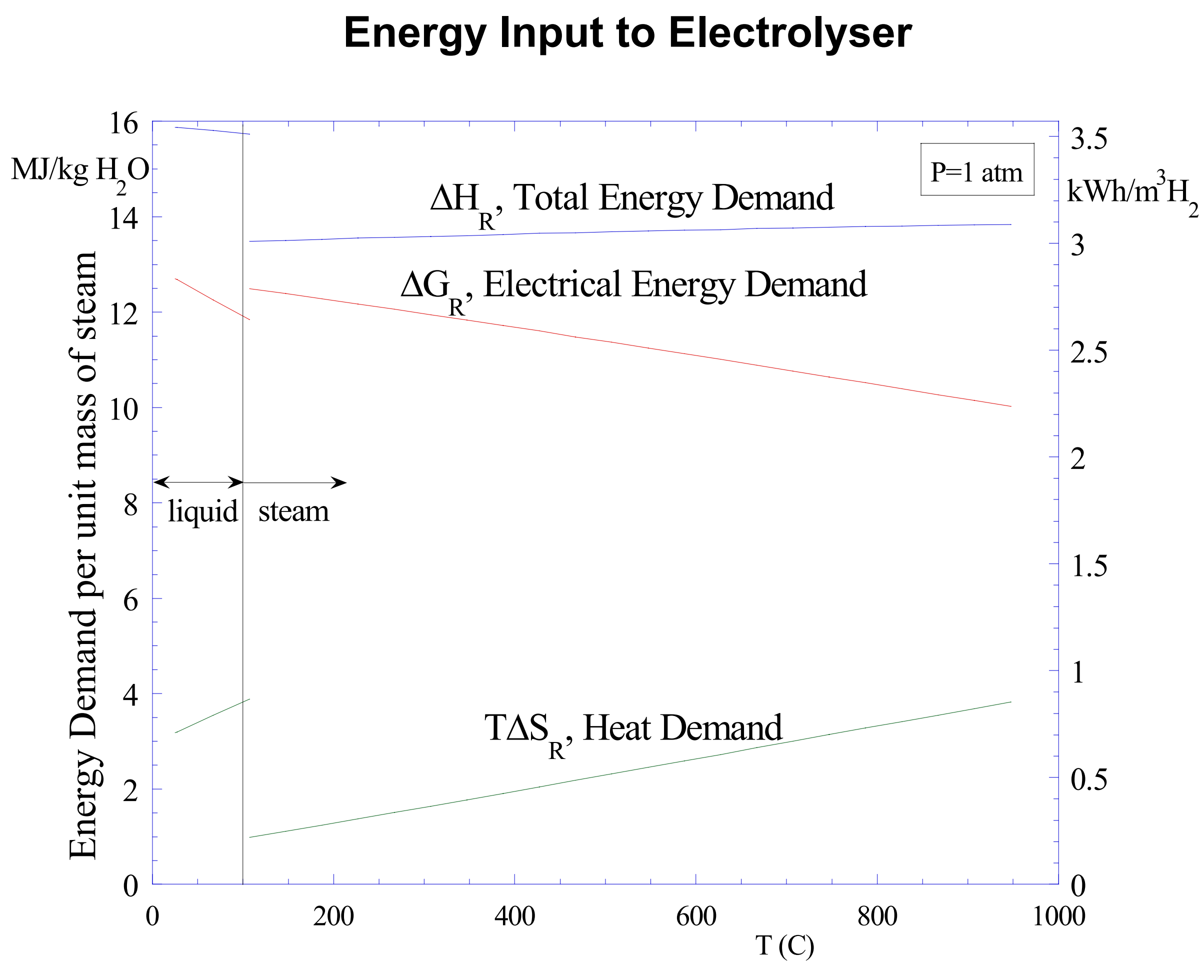
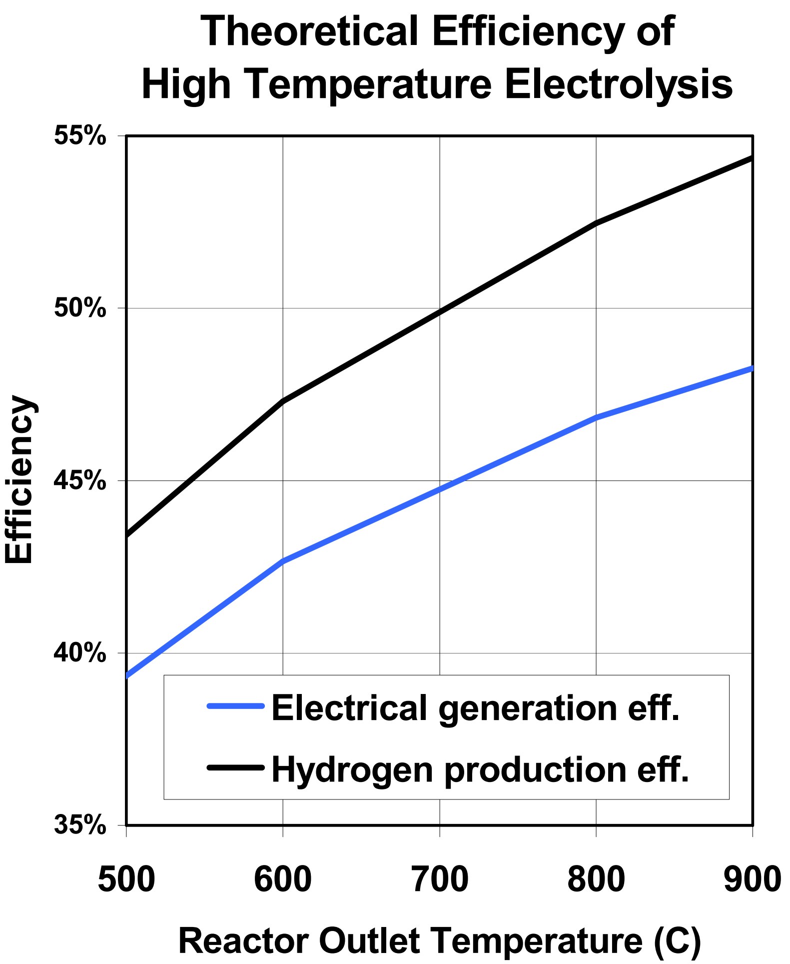
Technical Accomplishments

HTE Accomplishments since May 2004

FY2004	• An assessment of the engineering materials issues and requirements for construction of an HTE system was completed to provide input to the high temperature materials testing program. • The high-temperature electrolysis system configuration study was completed, identifying the options and technical issues for HTE systems, including electrolyzer cell and module configurations and high-temperature steam distribution. • An experiment plan for the development of high-temperature electrolysis components and systems was completed to provide input to the longer term scaling of HTE systems. • An assessment of the high temperature reactor and HTE process interface requirements was completed • Completed engineering analyses for high-temperature electrolysis scaling demonstration experiments, including steam distribution systems and electrolyzer cell and module configurations. • Completed a series of button cell experiments to examine cell operational characteristics under a range of conditions. • Completed initial testing of a 10 cell stack in preparation for hydrogen production testing. • Complete final design for laboratory-scale HTE experiments
FY2005 (to date)	• Developed engineering process model for HTE system performance evaluation, including the development of CFD and electrochemical modeling for planar geometry electrolyzer cells, including mass and thermal transport. • Demonstrated high-temperature electrolysis stack testing at a production rate of 50 normal liters per hour of hydrogen. • Produced 15 button cells using plasma deposition on nickel aluminide substrate (now being tested)





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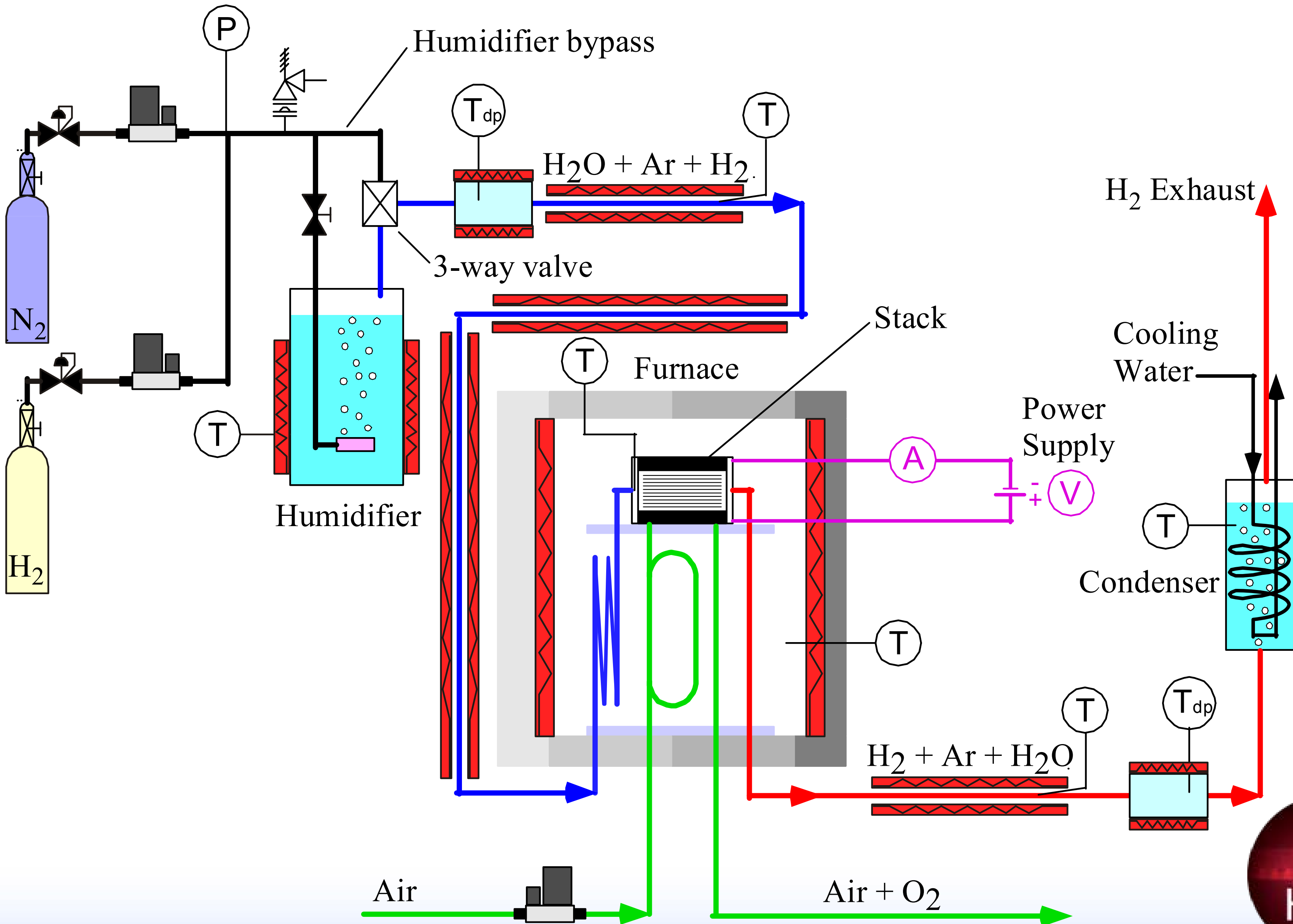
Schematic of Stack Testing Apparatus



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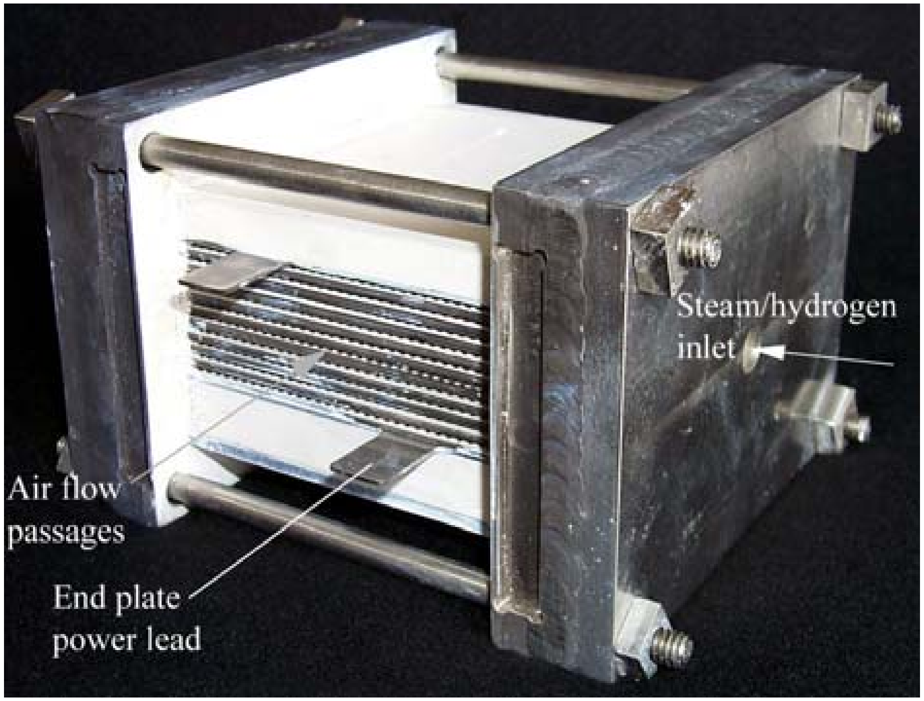
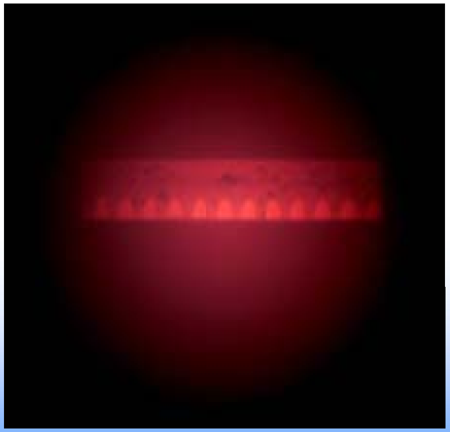
Electrolysis Stack Performance Testing Hardware

10-cell electrolysis stack; has produced up to 100 SLPH H_2



Stack mounted on test fixture

View of air flow passages, inside furnace at 800°C



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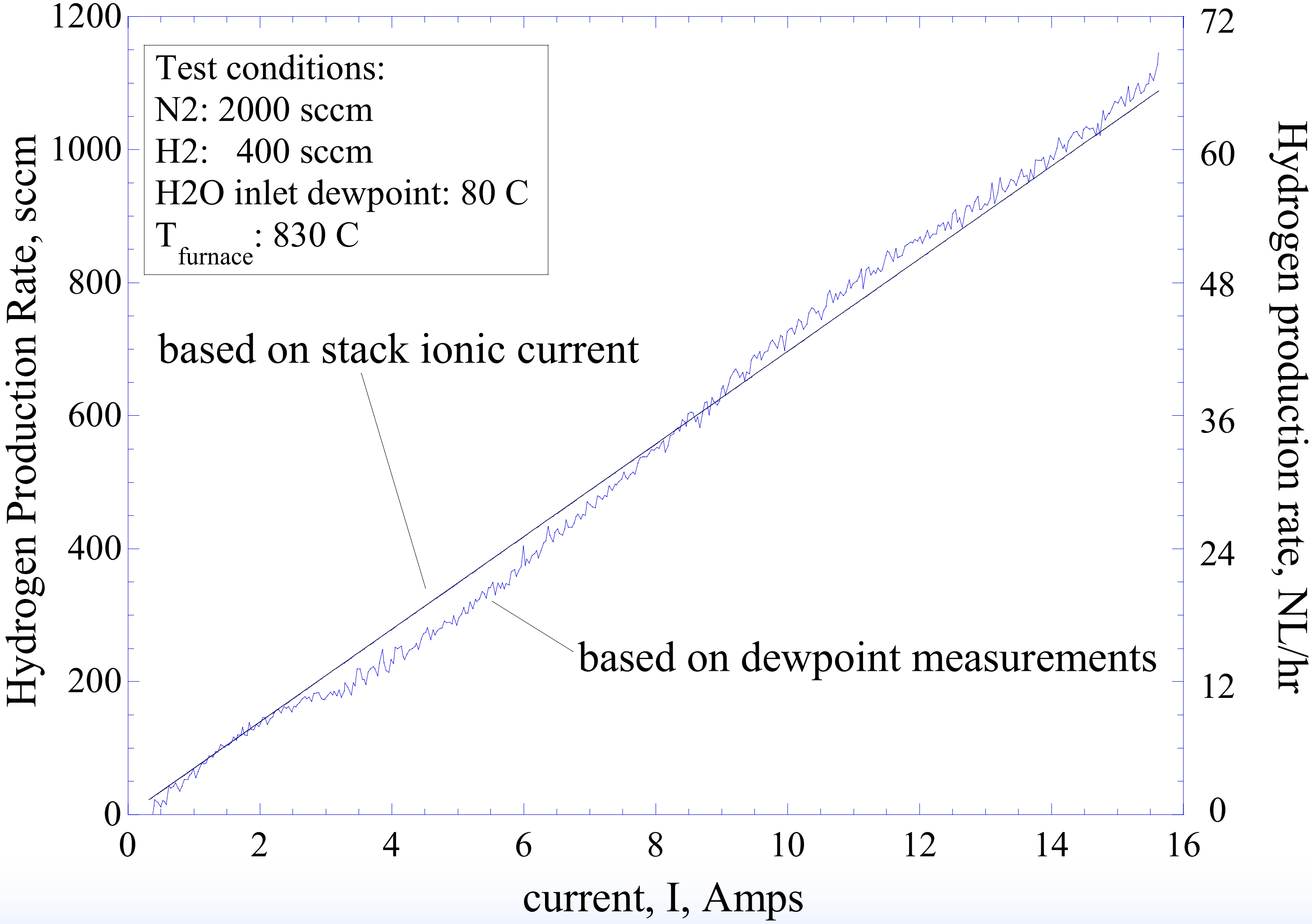
Hydrogen Production at 830° C



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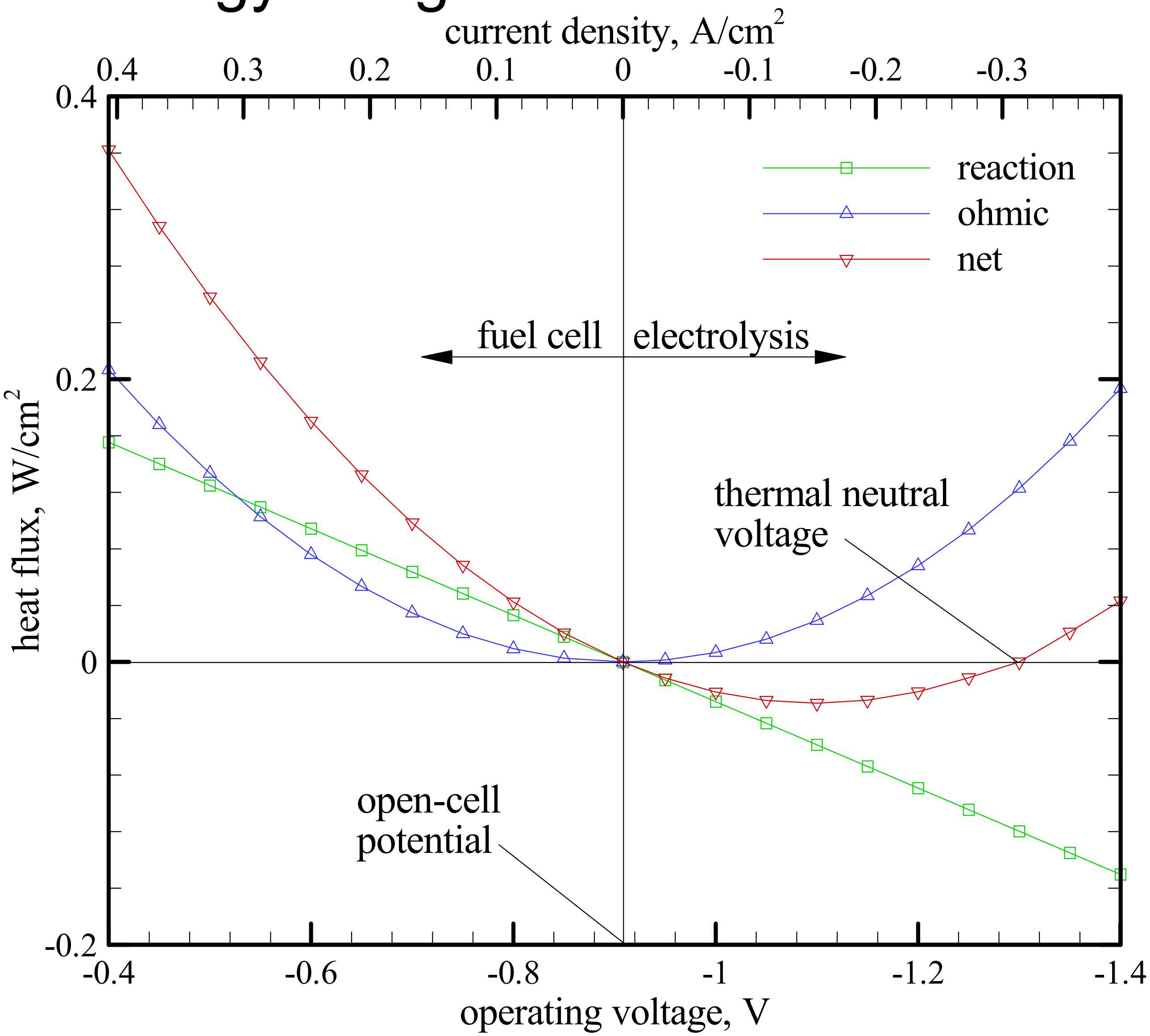
Energy Budgets in fuel-cell and electrolysis modes

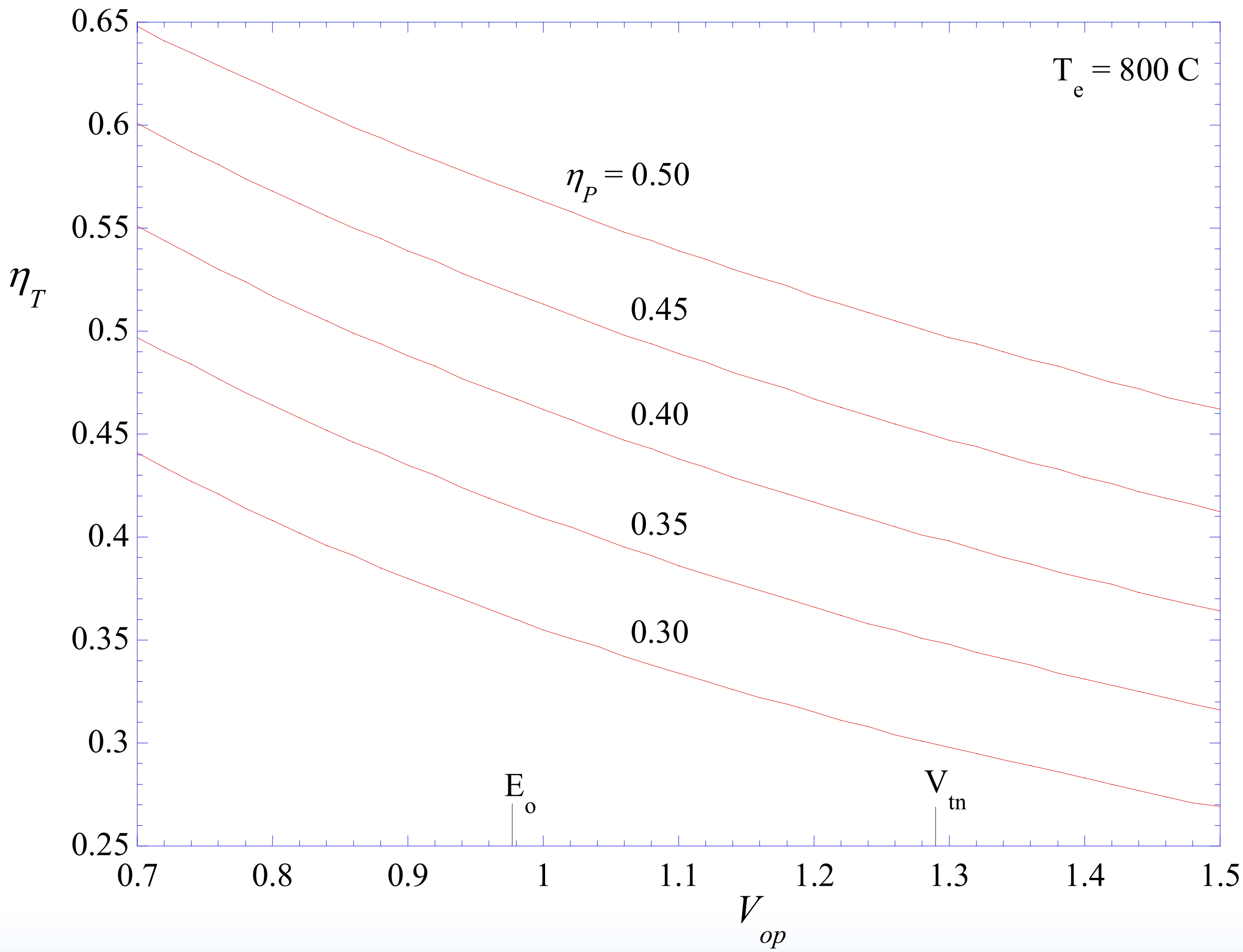


Stack ASR = 1.25,
T = 927 C,
$y_{H2,i}$ = 0.1,
$y_{H2,o}$ = 0.95

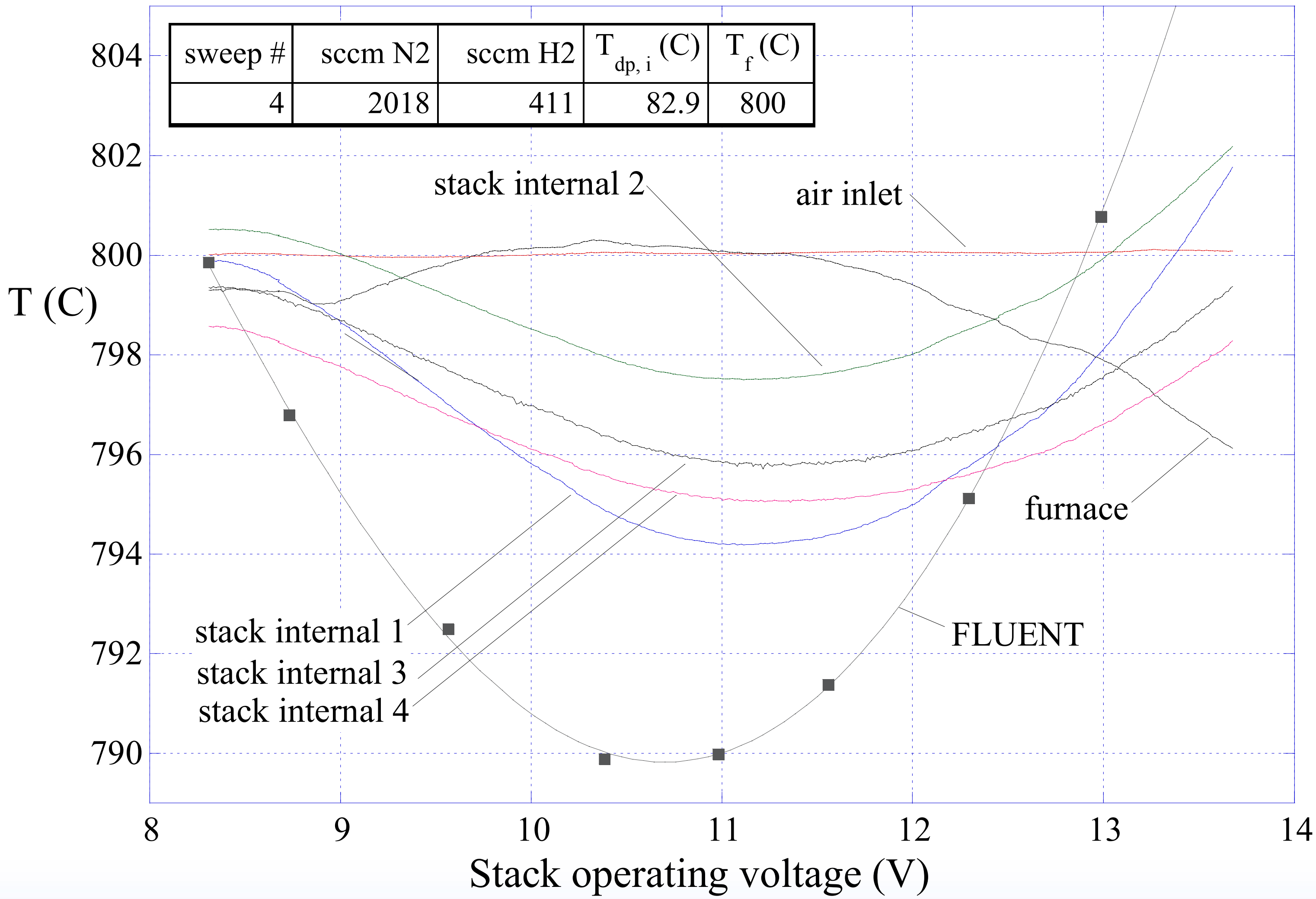
$$V_{tn} = \frac{-\Delta h_R}{2F}$$

(1.291 V at 1200 K)

Overall hydrogen production efficiencies as a function of power-production thermal efficiency and electrolyzer per-cell operating voltage

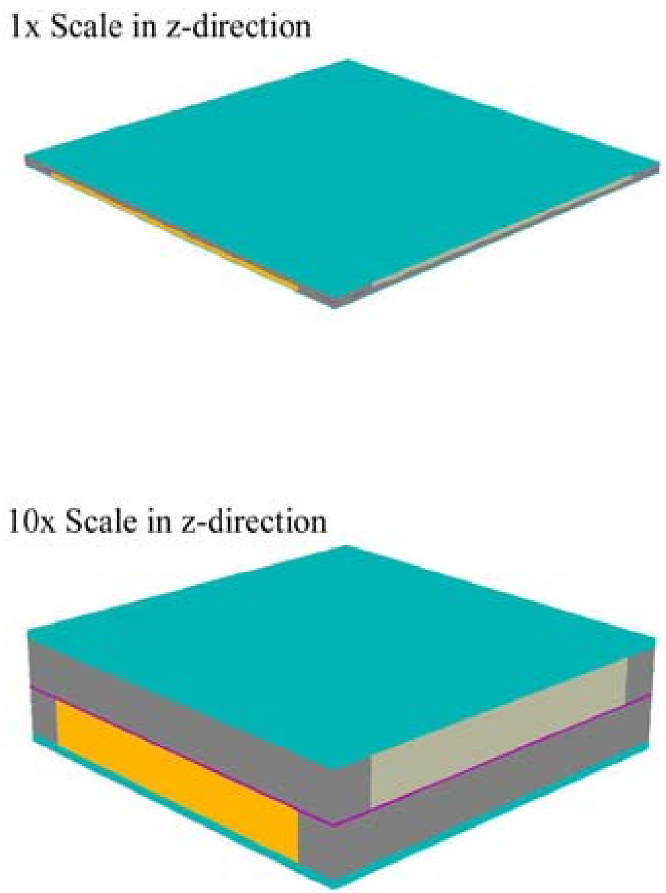


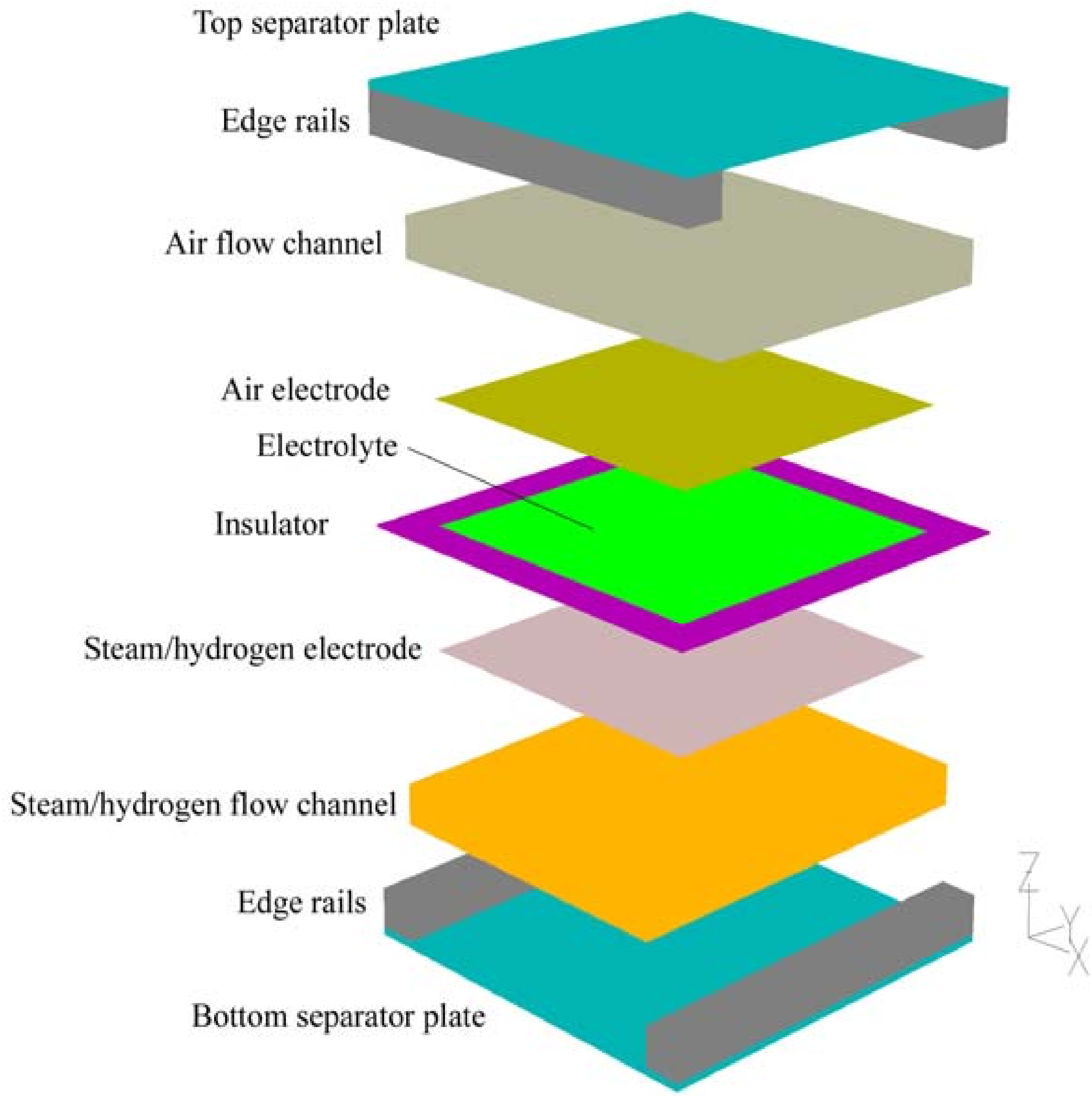
Stack temperatures during a DC potential sweep; comparison to FLUENT results



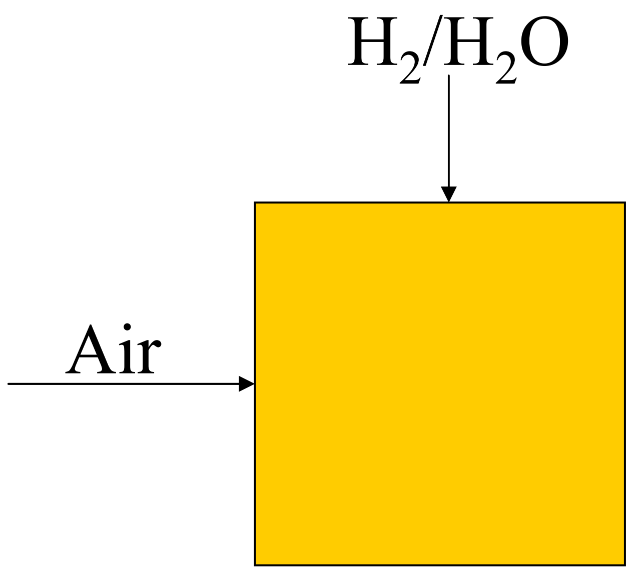
sweep #	sccm N2	sccm H2	$T_{dp,i}$ (C)	T_f (C)
4	2018	411	82.9	800

FLUENT Single-Cell SOEC Model



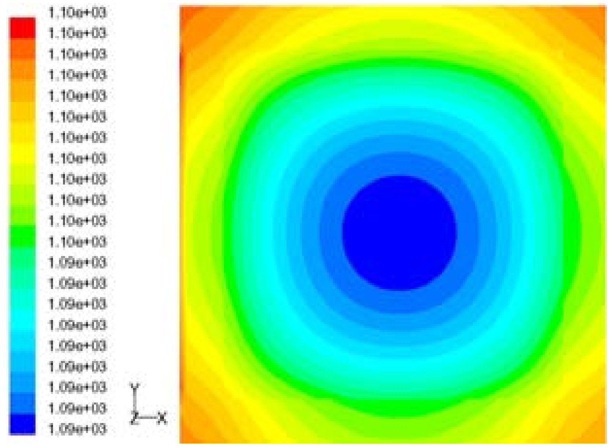


CFD Contour Plots



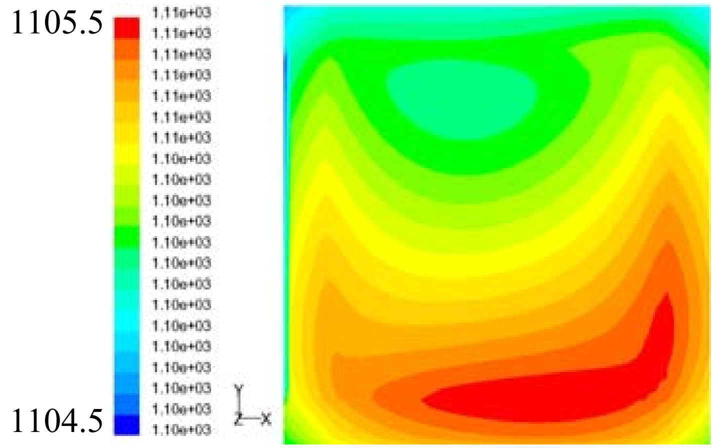
Electrolyte/insulator temperature contours

0.156 A/cm^2; 1.164 V



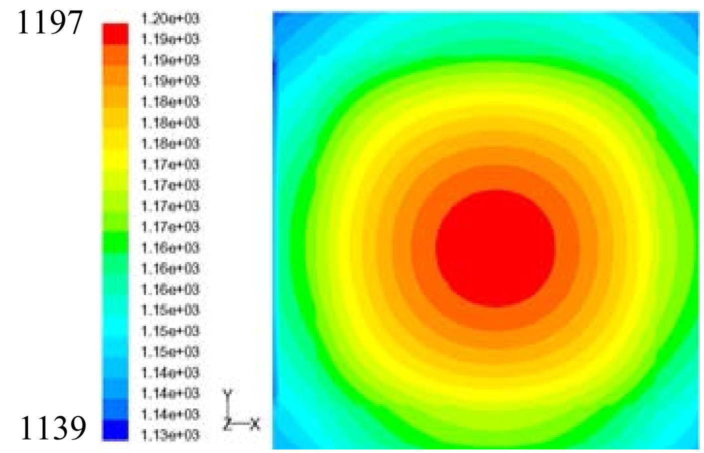
near thermal minimum

0.2344 A/cm^2; 1.306 V



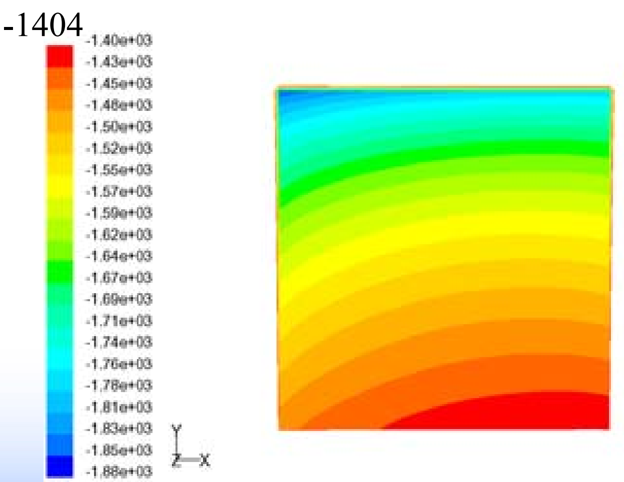
near thermal neutral

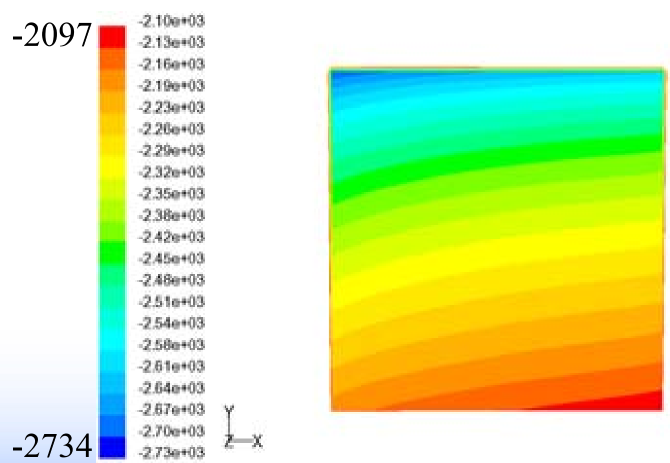
0.4688 A/cm^2; 1.640 V

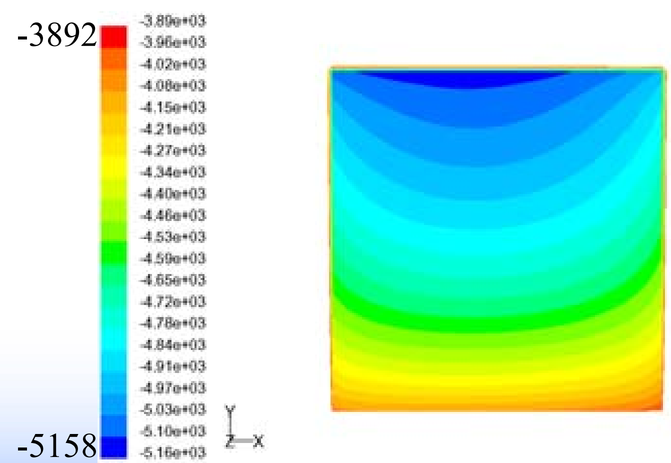


above thermal neutral

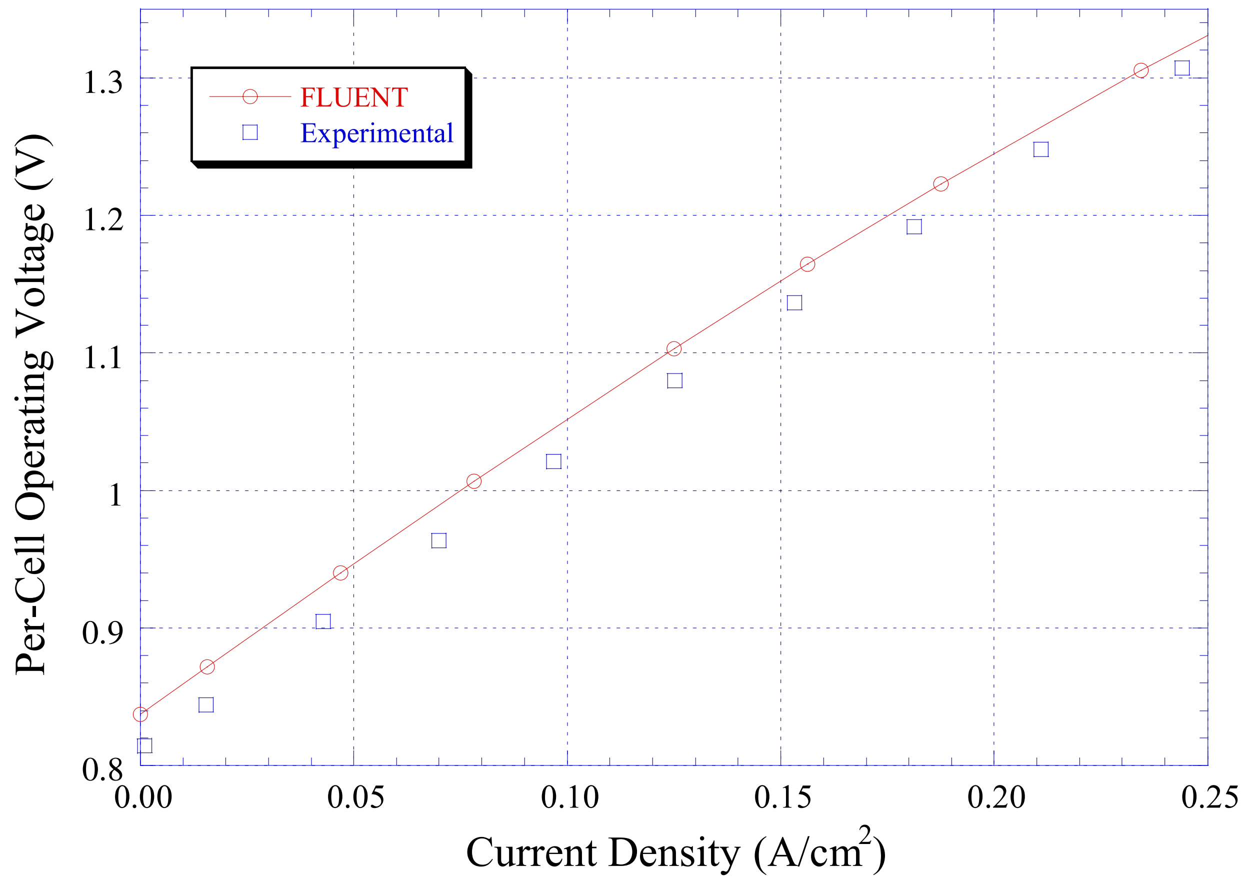
Electrolyte current density contours







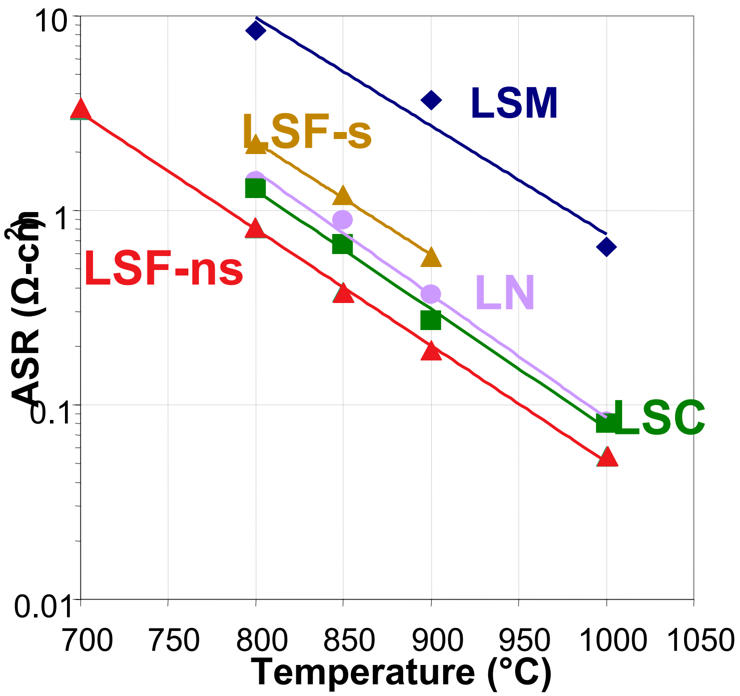
Voltage-current characteristics of actual electrolysis stack and FLUENT model



Electrode exchange current densities and several gap electrical contact resistances were determined empirically by comparing FLUENT predictions with stack performance data

HTE System Definition
ANL, PIs: Petri, Myers, Carter, Yildiz

ANL's oxygen and hydrogen electrode development



Area-specific resistance (ASR), Ω-cm²

Oxygen Electrode Composition	Temperature (°C)			
	800	850	900	1000
$La_{0.8}Sr_{0.2}MnO_3$ (LSM)	8.4	nd	3.7	0.65
$La_{0.8}Sr_{0.2}FeO_3$ (LSF-s)	2.2	1.2	0.58	nd
$LaNiO_3$ (LN)	1.4	0.89	0.37	0.082
$La_{0.8}Sr_{0.2}CoO_3$ (LSC)	1.3	0.67	0.27	0.080
$La_{0.7}Sr_{0.2}FeO_3$ (LSF-ns)	0.81	0.38	0.19	0.054

-s : stoichiometric
-ns: non-stoichiometric
nd : no data

- **ANL's non-stoichiometric LSF (LSF-ns) shows improved oxygen electrode performance over LSM.**
  - **Further improvement in LSF-ns performance is expected by optimizing the electrode microstructure and electrode/electrolyte interface.**
- **Single-phase, mixed-conducting hydrogen electrodes are being studied as alternatives to Ni-YSZ (Nickel – Yttria Stabilized Zirconia).**
  - **Addresses oxidation-related degradation in high steam environment.**

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Timeline

Project start: Jan '03 (DOE-EE)
(became part of the Nuclear Hydrogen Initiative Jan '04)

	HTE Systems Analysis and Experiments
FY2005	•Develop engineering process model for HTE system performance evaluation, including the development of CFD and electrochemical modeling for planar geometry electrolyzer cells, including mass and thermal transport. Done •Demonstrate high-temperature electrolysis stack testing at a production rate of 50 normal liters per hour of hydrogen. . Done •Demonstrate high-temperature electrolysis stack testing at a production rate of 100 normal liters per hour of hydrogen. •Complete conceptual design documentation for HTE pilot-scale experiments
FY2006	•Complete design of HTE integrated laboratory-scale experiments •Construct stack /module arrays for integrated laboratory-scale experiments
FY2007	•Begin HTE integrated lab-scale experimental operations •Complete HTE cell testing •Conduct HTE stack / module tests •Perform initial testing on candidate pilot scale module tests •Complete preliminary pilot scale experiment design
FY2008	•Pilot-scale experiment final design •Complete HTE integrated lab-scale experimental operations •Implement cell/module technology improvements

Supplemental Slides

The following three slides are for the purposes of the reviewers only – they are not to be presented as part of your oral or poster presentation. They will be included in the hardcopies of your presentation that might be made for review purposes.

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INL HTE Publications since May 2004:

Hawkes, G. L., O'Brien, J. E., Stoots, C. M., Herring, J. S., Shahnam, M., "Thermal and Electrochemical Three Dimensional CFD Model of a Planar Solid Oxide Electrolysis Cell," to be presented at the 2005 ASME Heat Transfer Conference, July 17-22, 2005, San Francisco.

O'Brien, J. E., Stoots, C. M., Herring, J. S., Lessing, P. A., Hartvigsen, J. J., and Elangovan, S., "Performance Measurements of Solid-Oxide Electrolysis Cells for Hydrogen Production from Nuclear Energy," *Journal of Fuel Cell Science and Technology*, Vol. XX, August 2005, pp. XXX-XXX.

Herring, J. S., O'Brien, J. E., Stoots, C. M., and Hawkes, G. L., "Progress in High-Temperature Electrolysis for Hydrogen Production using Planar SOFC Technology," submitted for presentation at the 2005 AIChE Spring Annual Meeting, April 10 – 14, 2005, Atlanta, GA.

O'Brien, J. E., Stoots, C. M., Herring, J. S., and Hartvigsen, J. J.,"Hydrogen Production Performance of a 10-Cell Planar Solid-Oxide Electrolysis Stack," submitted for presentation at the ASME 3rd International Conference on Fuel Cell Science, Engineering, and Technology, May 23 – 25, 2005, Ypsilanti, MI.

Hawkes, G. L., O'Brien, J. E., Stoots, C. M., Herring, J. S., Shahnam, M., "CFD Model of a Planar Solid Oxide Electrolysis Cell for Hydrogen Production from Nuclear Energy," to be presented at the 11th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics NURETH-11, Popes Palace Conference Center, Avignon, France, October 2-6, 2005.

O'Brien, J. E., Herring, J. S., Stoots, C. M., Lessing, P. A., "High-Temperature Electrolysis for Hydrogen Production From Nuclear Energy," to be presented at the 11th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics NURETH-11, Popes Palace Conference Center, Avignon, France, October 2-6, 2005.

Herring, J. S., O'Brien, J. E., Stoots, C. M., Lessing, P. A., Hartvigsen, J. J., and Elangovan, S., "Hydrogen Production through High-Temperature Electrolysis," chapter in book edited by Dr. Masao Hori, "Nuclear Production of Hydrogen - Technologies and Perspectives for Global Deployment, International Nuclear Societies Council, *Current Issues in Nuclear Energy*, 2004.

Herring, J. S., Anderson, R., Lessing, P. A., James E. O'Brien, J. E., Stoots, C. M., Hartvigsen, J. J., and Elangovan, S., **"**Hydrogen Production through High-Temperature Electrolysis in a Solid Oxide Cell," presented at the National Hydrogen Association 15th Annual Conference, Los Angeles, April 26-29, 2004.

O'Brien, J. E., Stoots, C. M., Herring, J. S., and Lessing, P. A., "Characterization of Solid-Oxide Electrolysis Cells for Hydrogen Production via High-Temperature Steam Electrolysis," Proceedings, 2nd International Conference on Fuel Cell Science, Engineering, and Technology, June 14-16, 2004, Rochester, NY, paper# 2474, pp., 219 – 228.

S. Elangovan, J. Hartvigsen, J. E. O'Brien, C. M. Stoots, J. S. Herring, P. A. Lessing, "Operation and Analysis of SOFCs in Steam Electrolysis Mode," Proceedings, 6th EUROPEAN SOLID OXIDE FUEL CELL FORUM, 28 June – 2 July 2004, Kultur- und Kongresszentrum Luzern, Lucerne, Switzerland.

Herring, J. S., O'Brien, J. E., Stoots, C. M., Lessing, P. A., Anderson, R. P., Hartvigsen, J. J., and Elangovan, S., "Hydrogen Production from Nuclear Energy via High-Temperature Electrolysis," Proceedings, 2004 International Conference on Advances in Nuclear Power Plants (ICAPP '04), June 13-17, 2004, Pittsburgh, PA, paper no. 4322.

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Hydrogen Safety

The most significant hydrogen hazard associated with this project is:

Compressed gas handling

Hot surfaces

Hydrogen combustion or explosion hazard

Hydrogen Safety

Our approach to deal with this hazard is:

Independent Hazards Review
Independent, laboratory-wide review of operating procedures and safety measures
Experiment design
Over-pressure prevention – see experiment schematic,
Instrumentation
Hydrogen Detectors
On-line (firewall-protected) access to experiment parameters
Training of Project Personnel:
Compressed gas training (TRN1041)
R&D Laboratory awareness (TRN670)
Flammable & combustible materials (SMJS992B)
Chemical Hygiene (TRN13)