Thermally Integrated High Power Density SOFC Generator

By

FuelCell Energy, Inc.

Versa Power Systems, Inc.

At

SECA Annual Meeting

Pacific Grove, California

April 18-21, 2005

Acknowledgements

- **Contributors**

  FCE: Pinakin Patel, Peng Huang
  VPS: Randy Petri, Brian Borglum
  GTI: Robert Remick, Kevin Krist
  MSRI/UU: Tad Armstrong, Anil Virkar
  PNNL: Prabhakar Singh

- **Funding Support**
  - **DOE-NETL: SECA Program**
  - **California Energy Commission**
  - **GTI, VPS, FCE**

Overview

- **Program Objectives**
- **Technology Progress**
  - Cell
  - Stack
  - System
- **Summary**

SECA Program Objectives

- Develop a kW-class SOFC power plant per SECA goals
- Natural gas as baseline fuel
- Thermal integration for higher efficiency
- Manufacturing cost reduction
- 9-year, 3-phase program

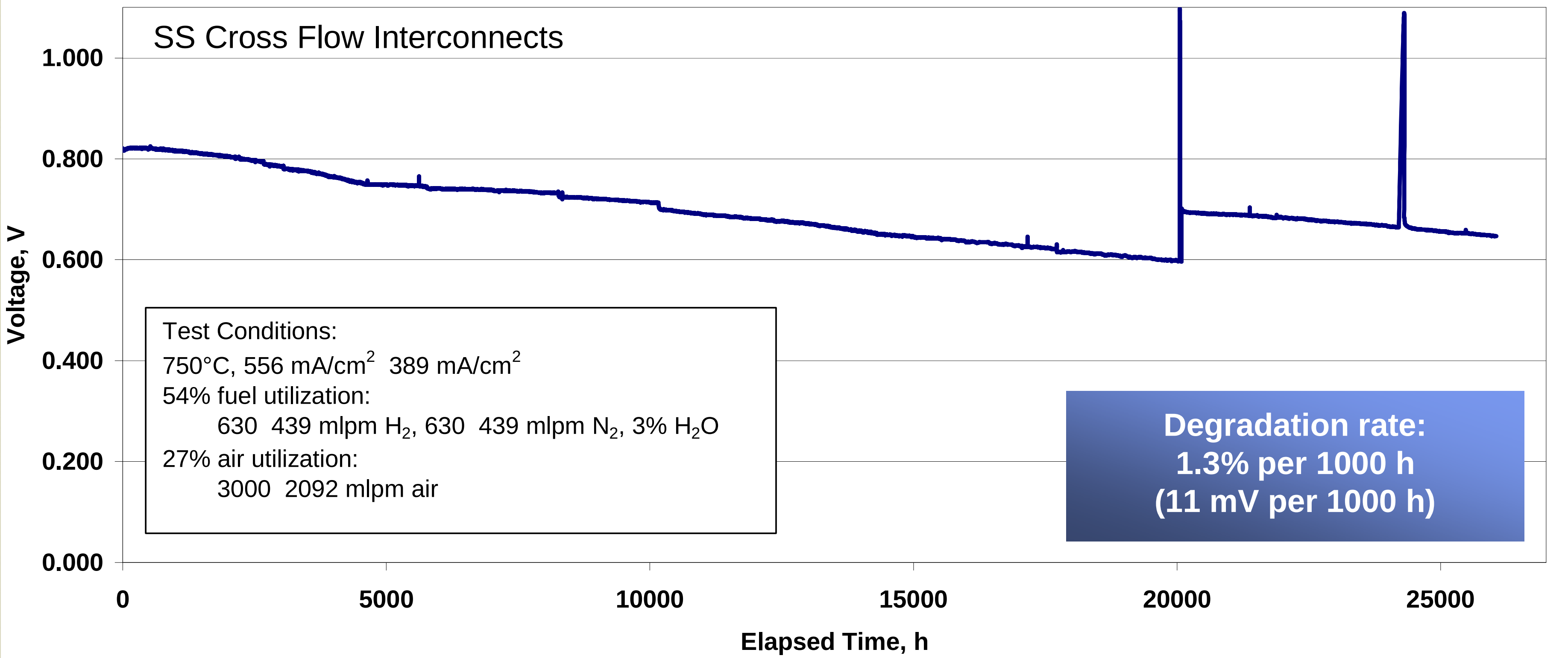
Cell Technology

- Long Term Testing (VPS)
- Modeling (PNNL)
- Cathode Development (MSRI-UU)
- Sulfur Tolerance (MSRI, GTI)
- Redox Tolerance (MSRI, VPS)

Long Term Cell Testing

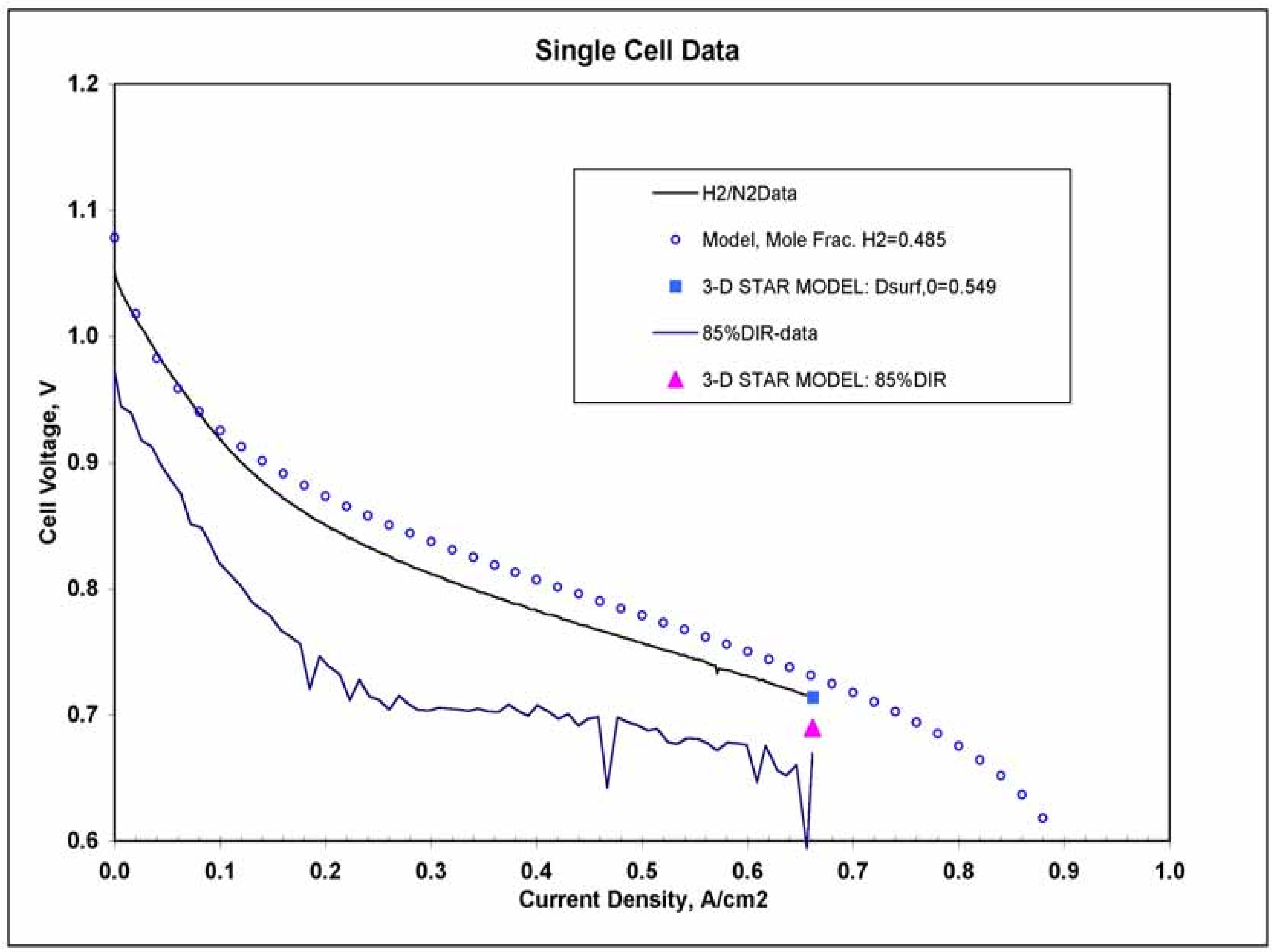
Trend Data

Test #10545; (Long Term Test: TSC1, 10 x 10 cm^2)
Test Stand #6, January 9, 2002 - January 10, 2005



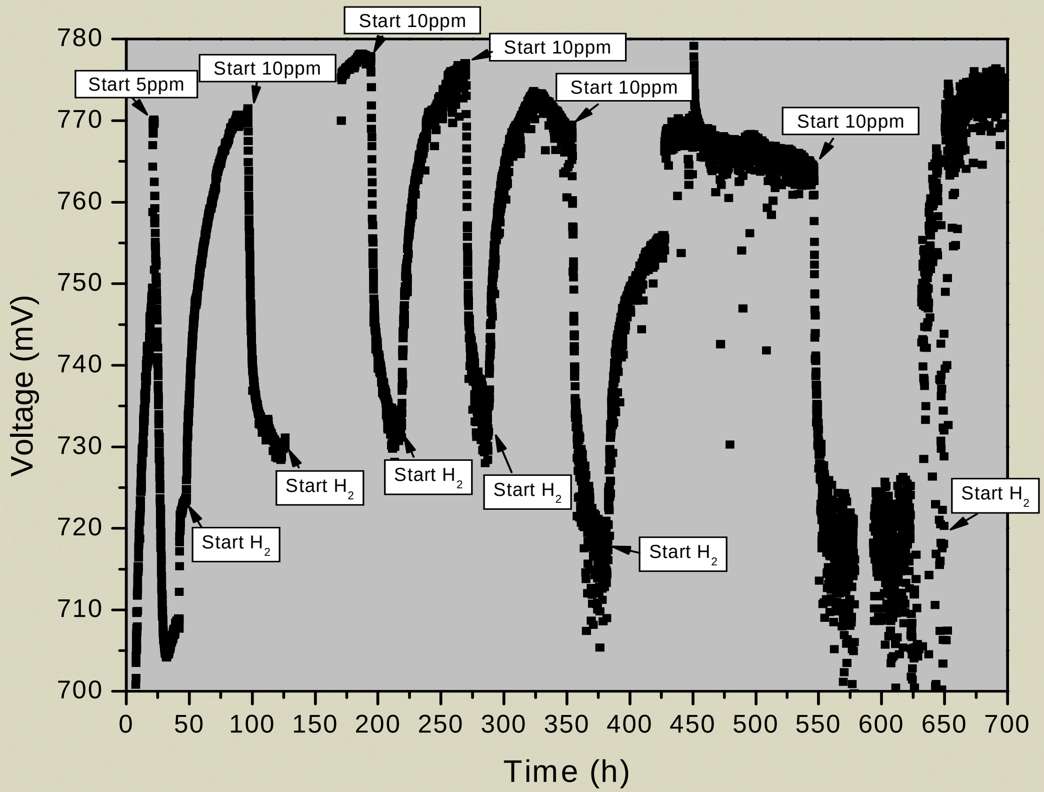
26,000 hours of Operation

PNNL Modeling



Sulfur Tolerance of Anodes

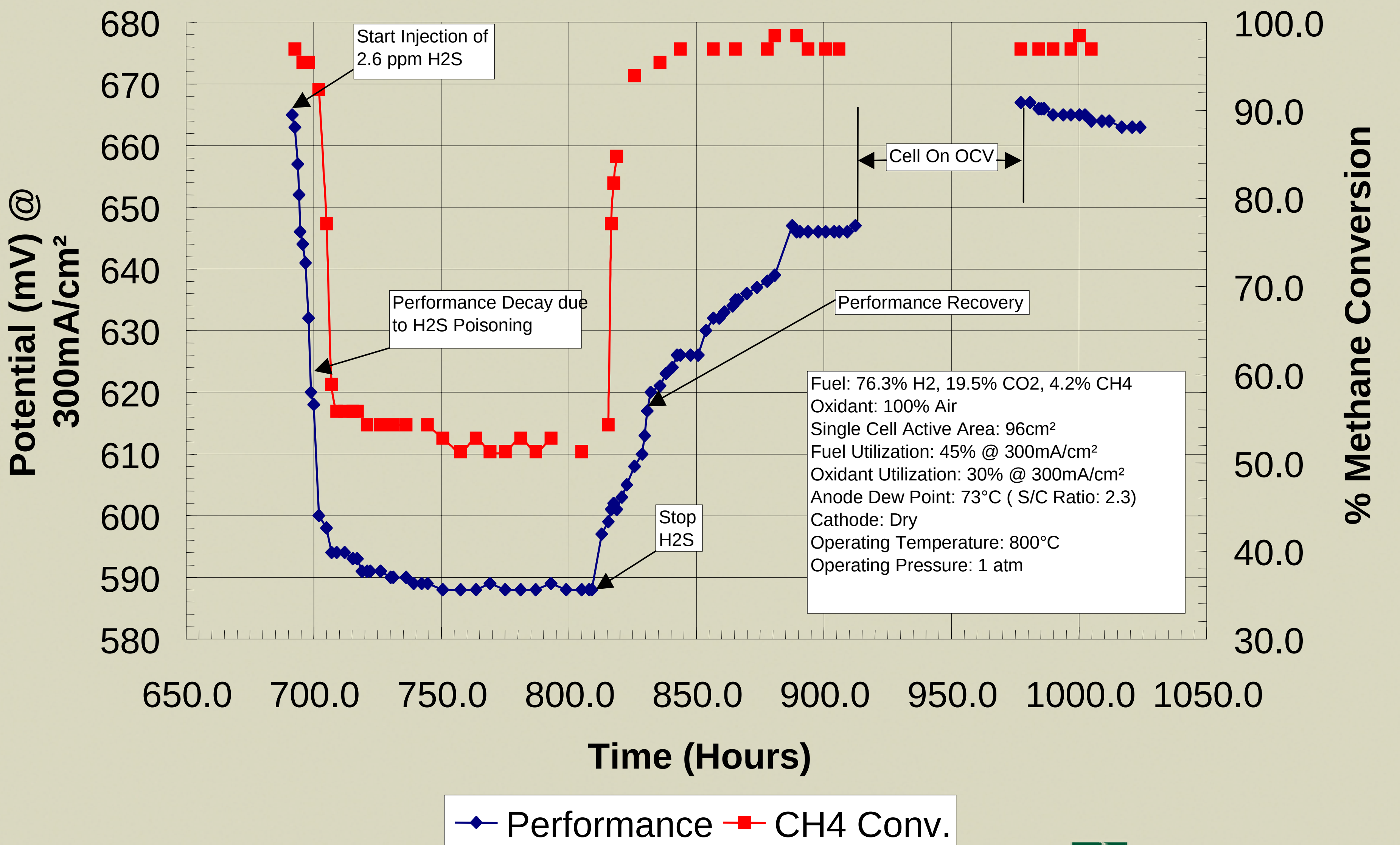
- Anode tested with 1, 5, 10, and 100 ppm H_2S in fuel
- Performance degradation of ~6% with 10 ppm H_2S
- Degradation rate decreases with time until equilibrium is established
- Complete recovery with sulfur free fuel
- No permanent degradation or failure of anode observed



•Tested at 800 °C

•Cycled between H_2 and H_2 with 10ppm H_2S

Effect of H_2S Poisoning on Cell Performance



Stack Technology

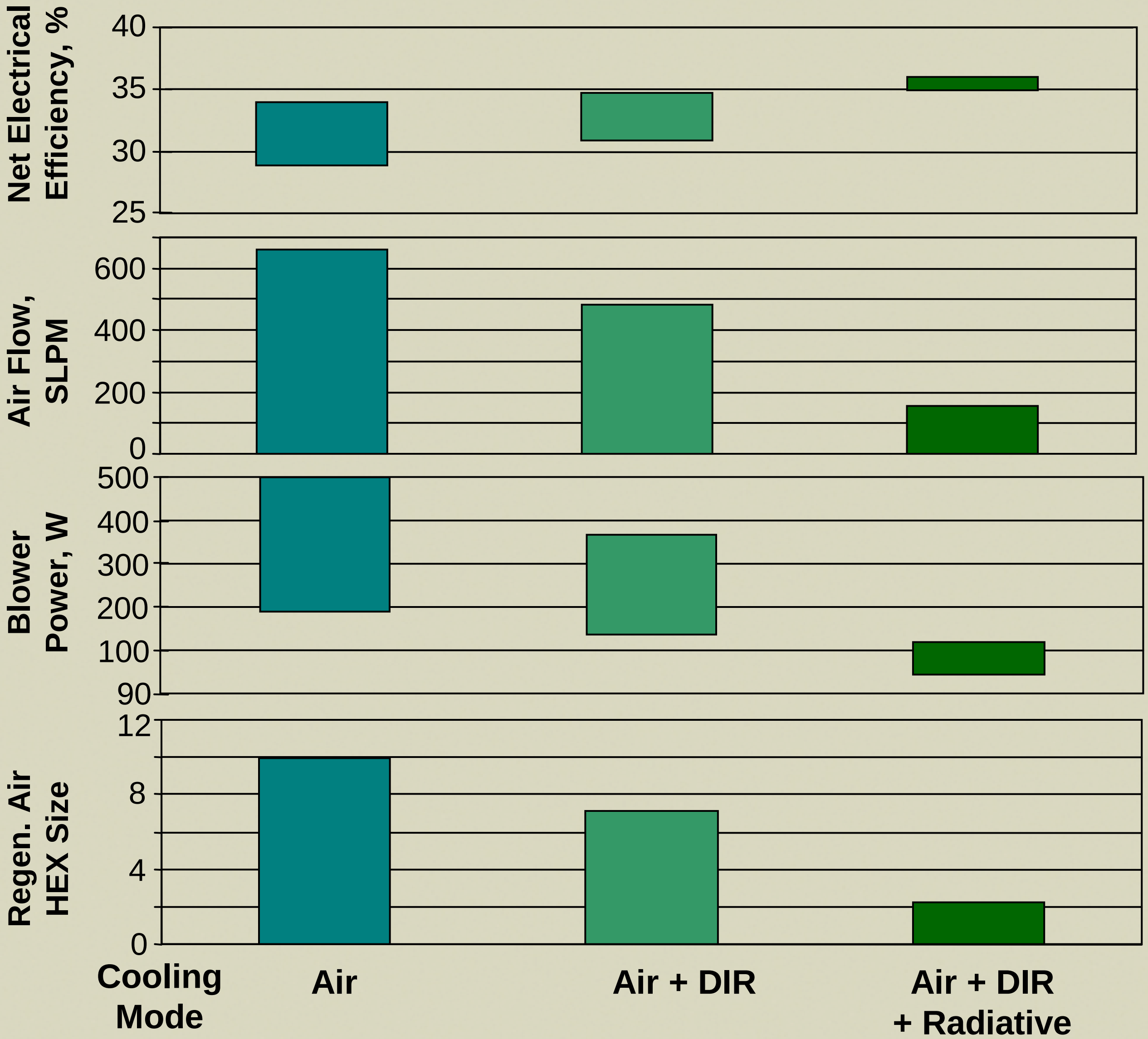
- Stack Design for Greater Output (VPS)
- Triple Mode Cooling (VPS-FCE)
- Radiative Cooling (CEC Program)
- Thermal Cycling (MSRI, VPS)
- Gasket Development (MSRI, FCE, VPS)

Stack Design For Greater Power Output

Aurora Stack	3-1 Stack
84-cell single tower with 4 stack modules	112-cell single tower with 4 stack modules
21-cell stack module	28-cell stack module
0.33 A/cm^2	0.36 A/cm^2
2600 W DC $_{gross}$ BOL	3800 W DC $_{gross}$ BOL

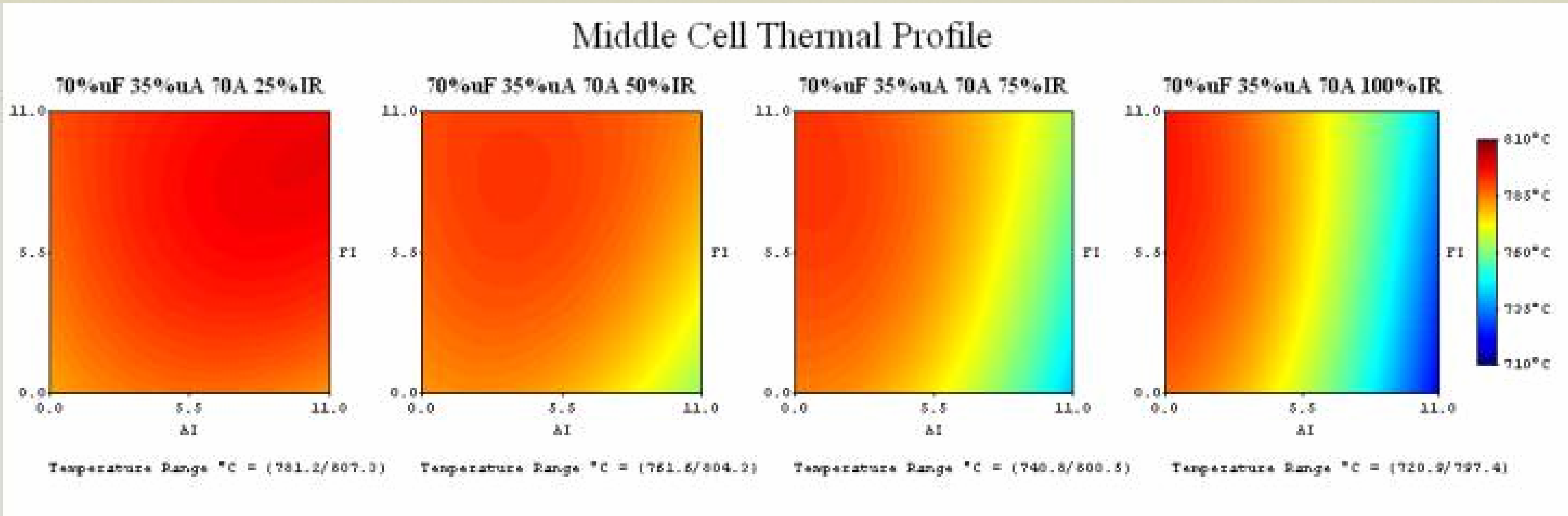
50% Increase In Stack Power

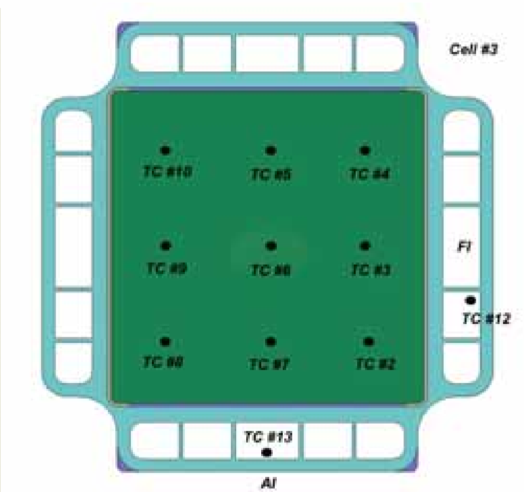
Benefits of Triple Mode Cooling: 2 kW Aurora System



Higher Efficiency and Reduced BOP Cost

Impact Of DIR On Cell Temperatures



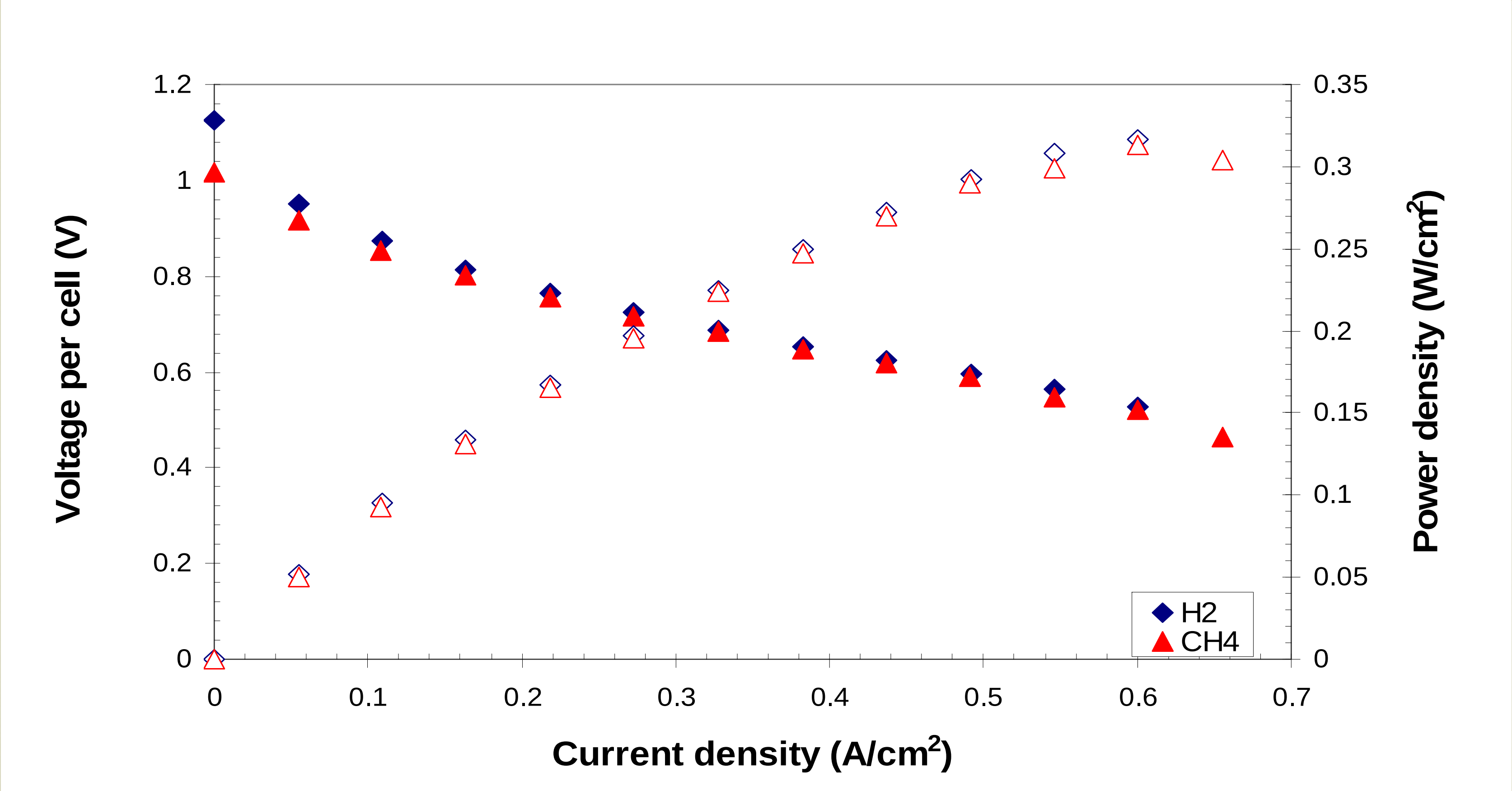


Temperature mapping performed on middle cell of a 5-cell, 121 cm^2 active area stack with city natural gas

- 0-25% DIR has high DT: hot spot at AO/FI corner
- 75%-100% DIR has high DT: cold spot at AI/FI
- 50% DIR has lowest DT: optimal voltage vs. degradation balance

FuelCell Energy

Stack Operation With 100% Methane DIR



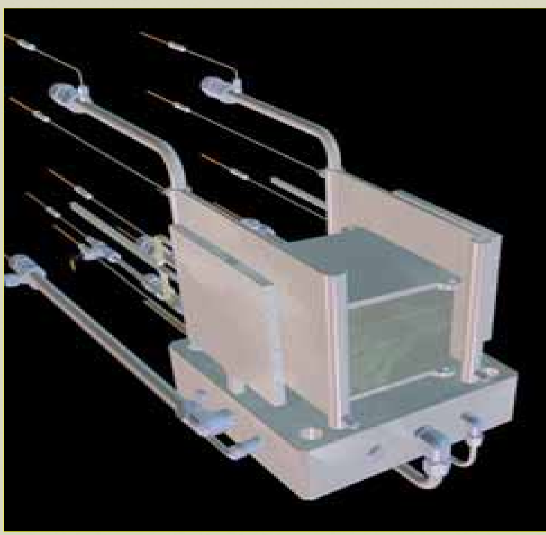
- 10-cell stack, 92 cm² active area per cell
- Tested at 800°C
- Steam to carbon ratio of 2:1
- 60%Uf / 50% Uo

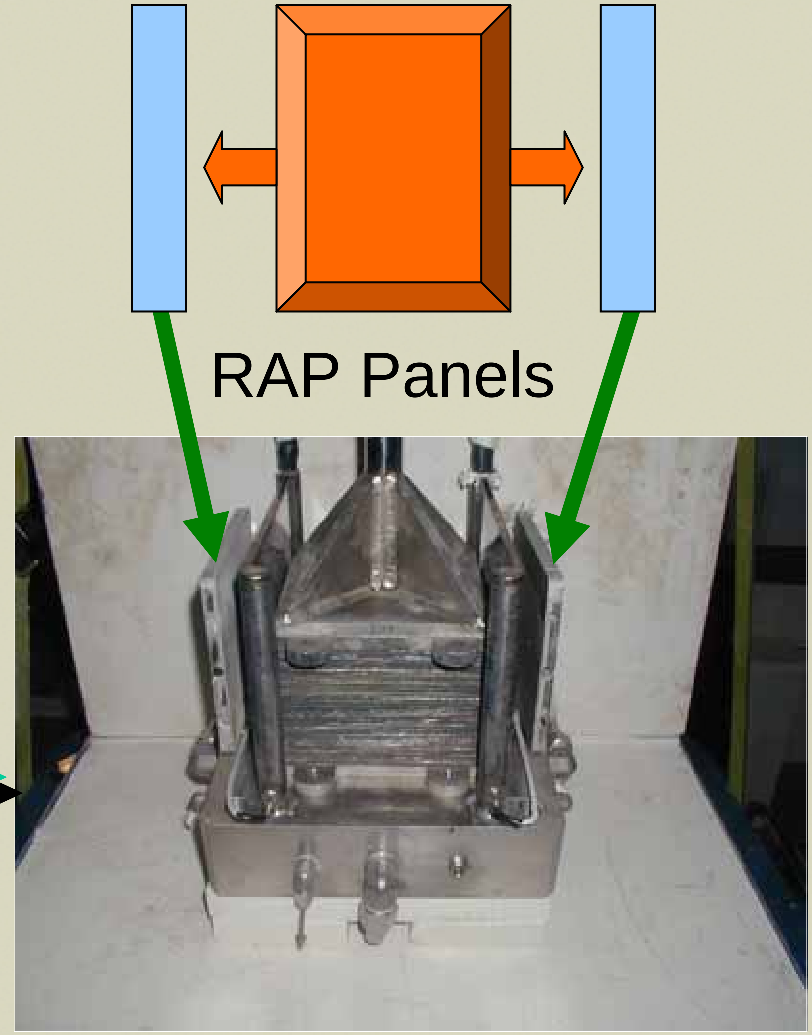
CEC Project: Radiative Cooling

- Goals: Prove concept of radiant air pre-heaters at multi-kilowatt sizes (Higher power density, Lower operating temperature, Lower costs)
- Design 10 kW power module
- RAP/Stack module Tests at GTI and MSRI
- Kevin Krist of GTI will Present CEC Progress on Wednesday at 4:30 pm

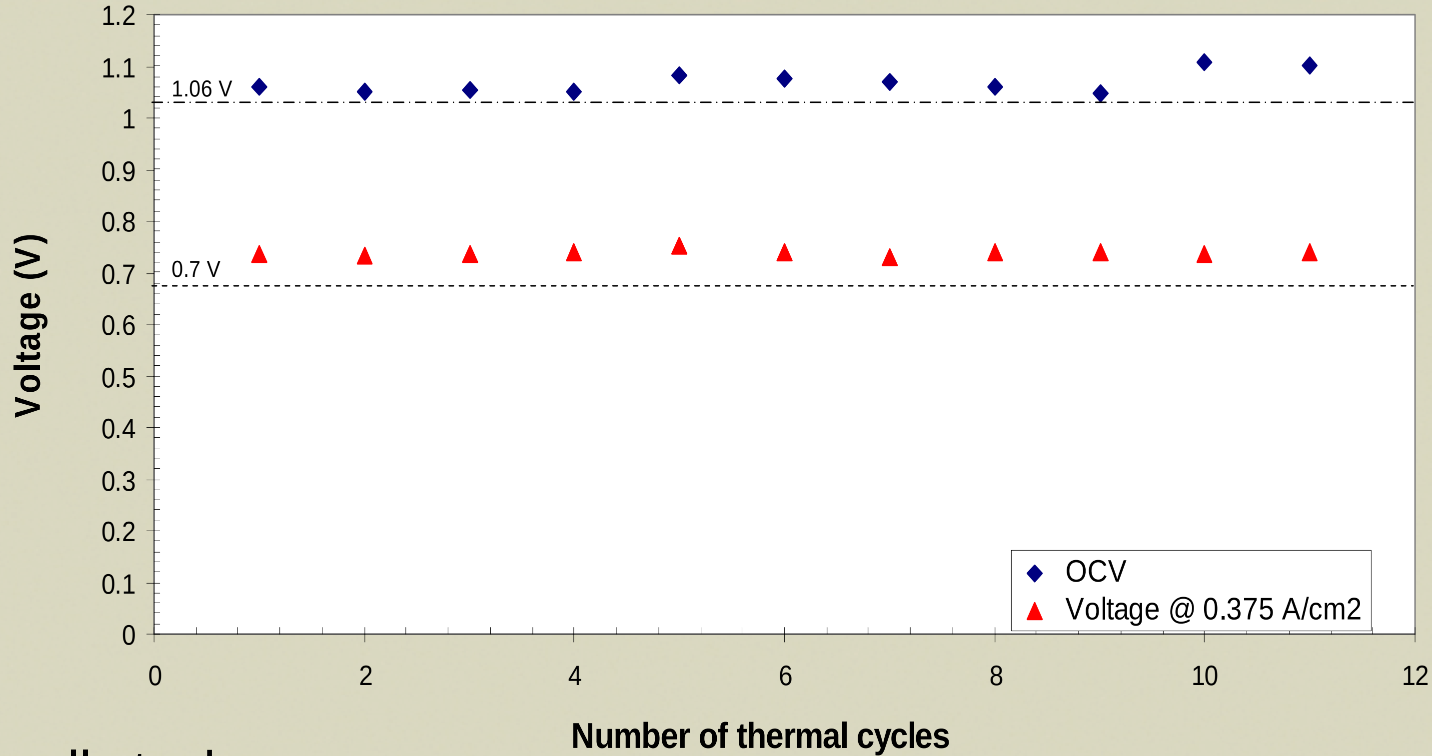
Radiative Cooling For Stack

- Preheat Air With Radiation From Stack (RAP)
- Decreased Thermal Stresses
- Reduced Cooling Air Flow



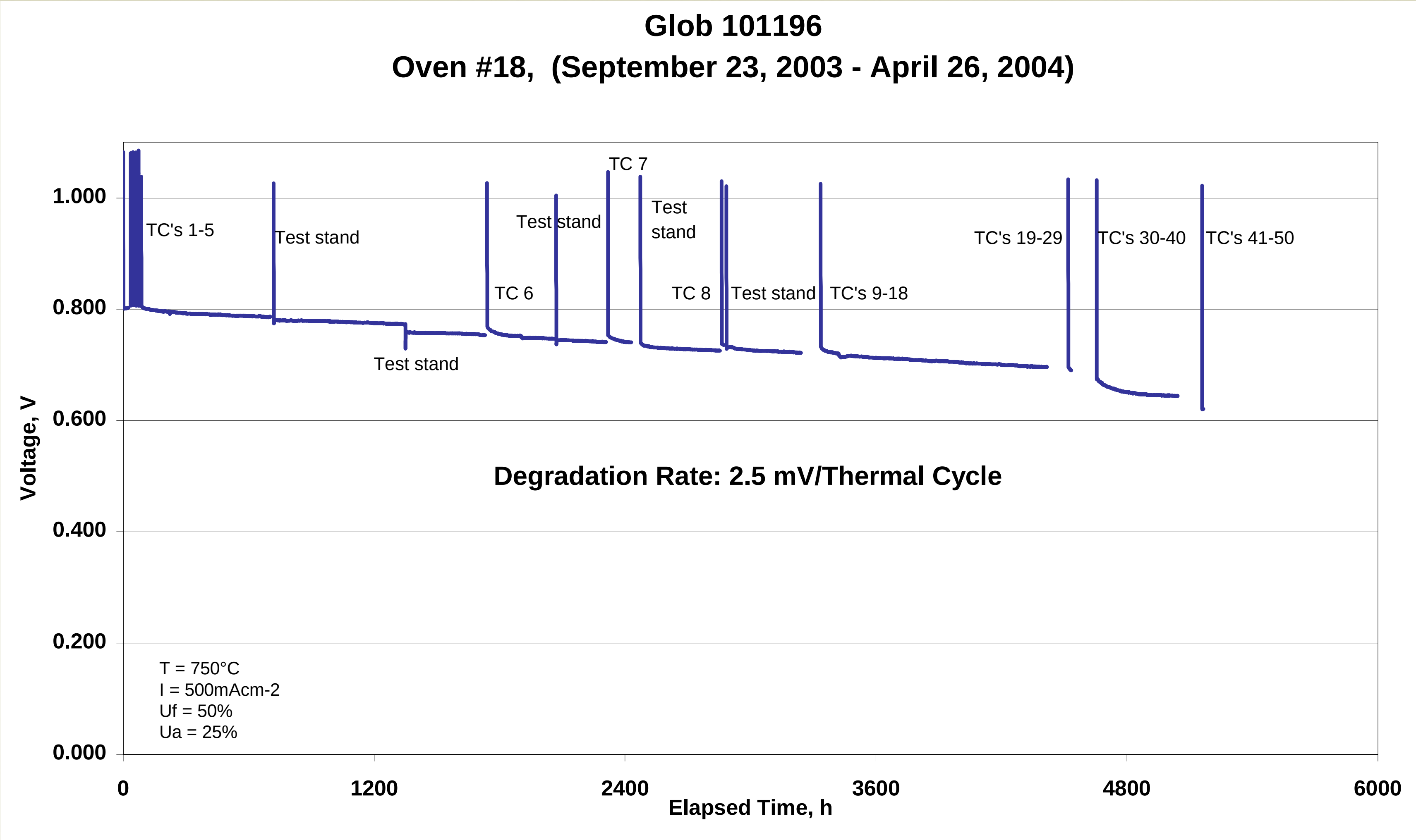


Thermal Cycling of Stacks



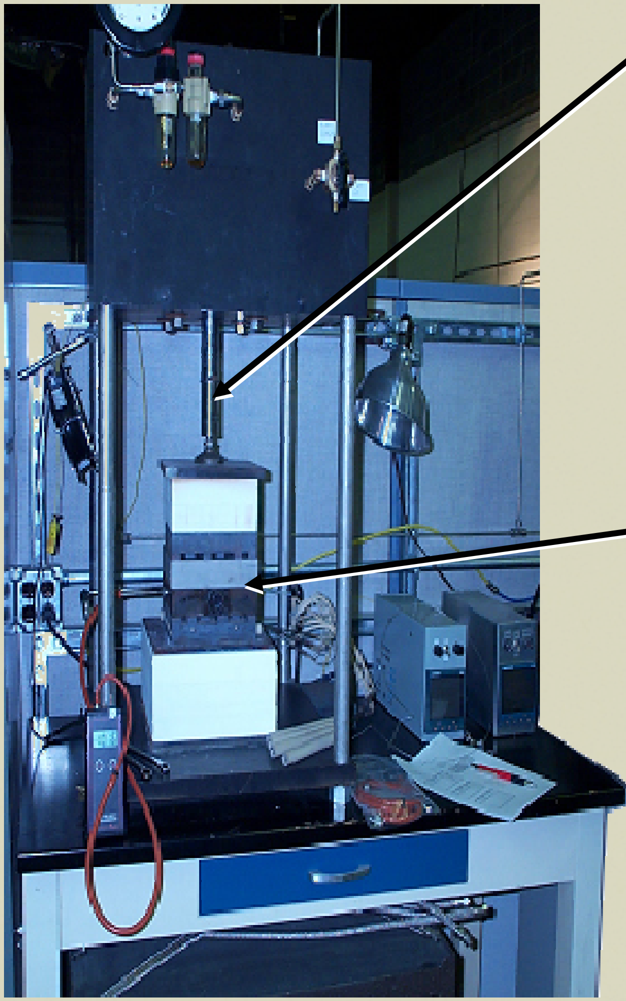
- 5-cell stack
- Tested at 800 °C
- Newly developed metal seal
- 98% sealing efficiency of hydrogen gas

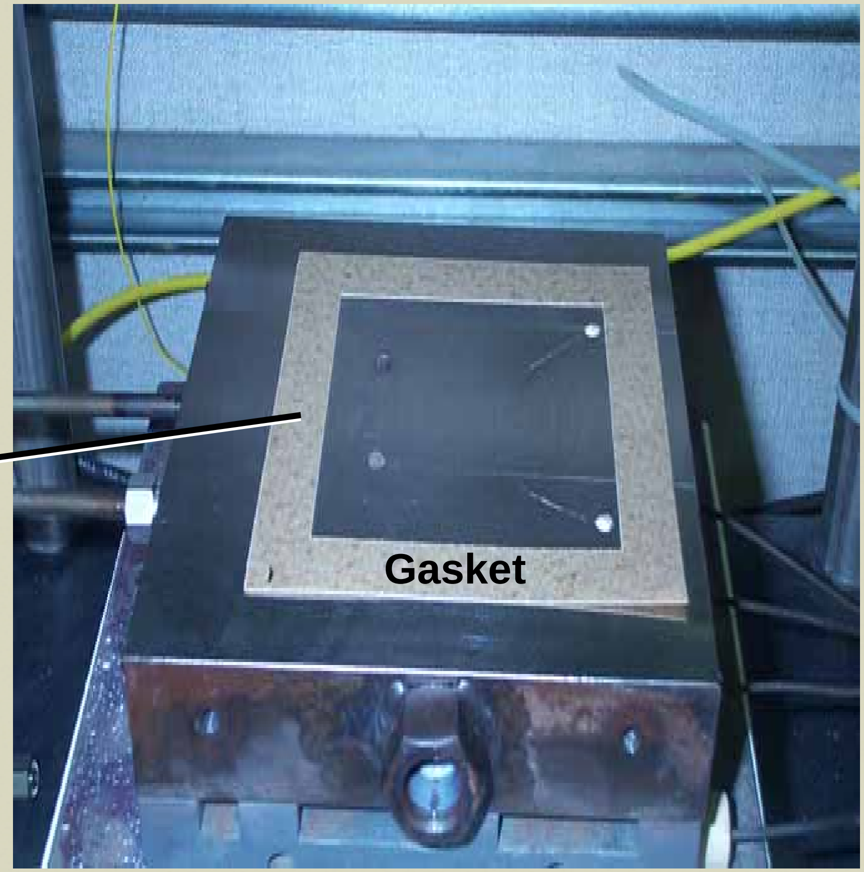
Stack Repeat Unit Testing – 50 Thermal Cycles over 5000 hours



Gasket Test Facility

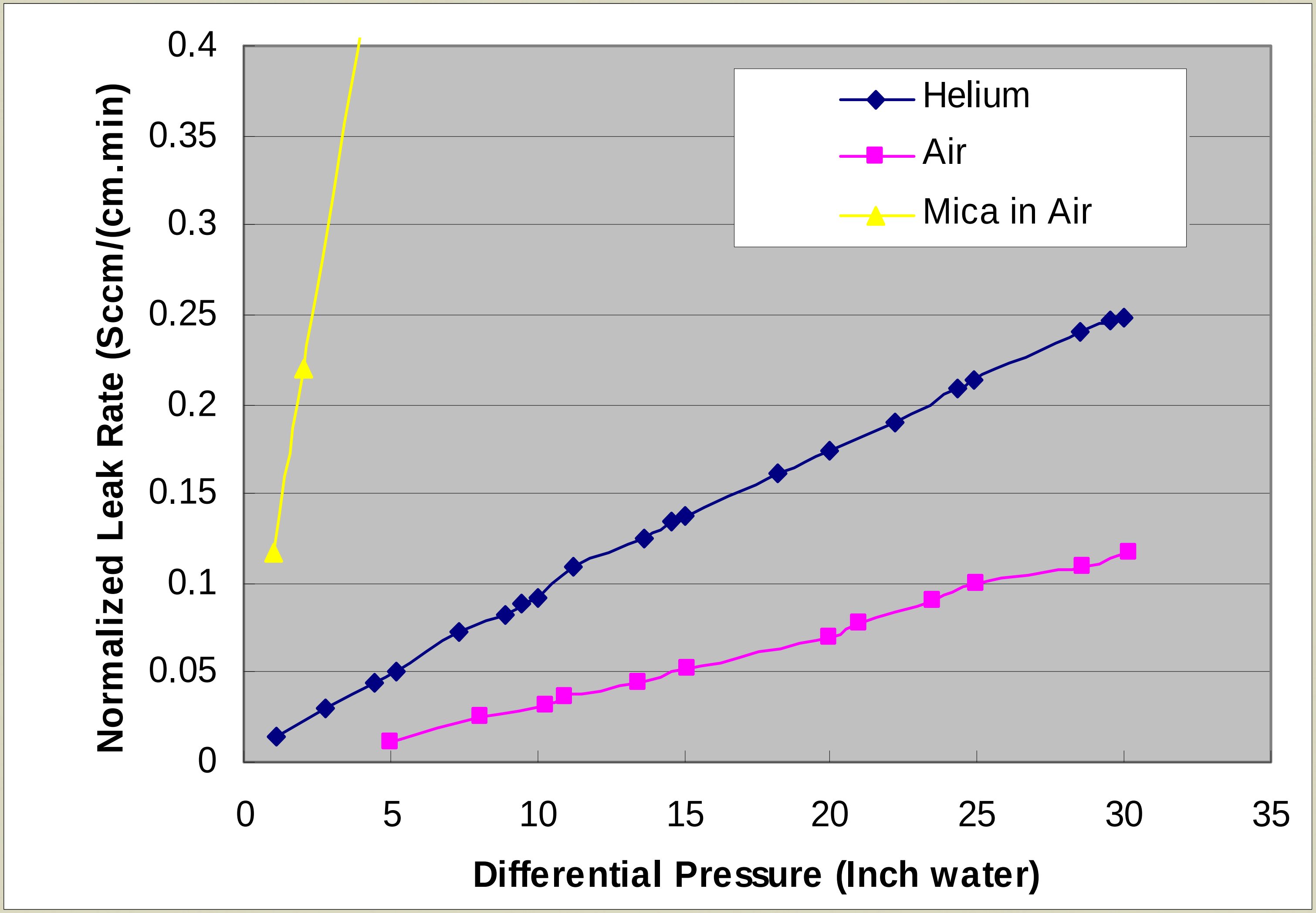
Compression System
(Active, Pneumatic)





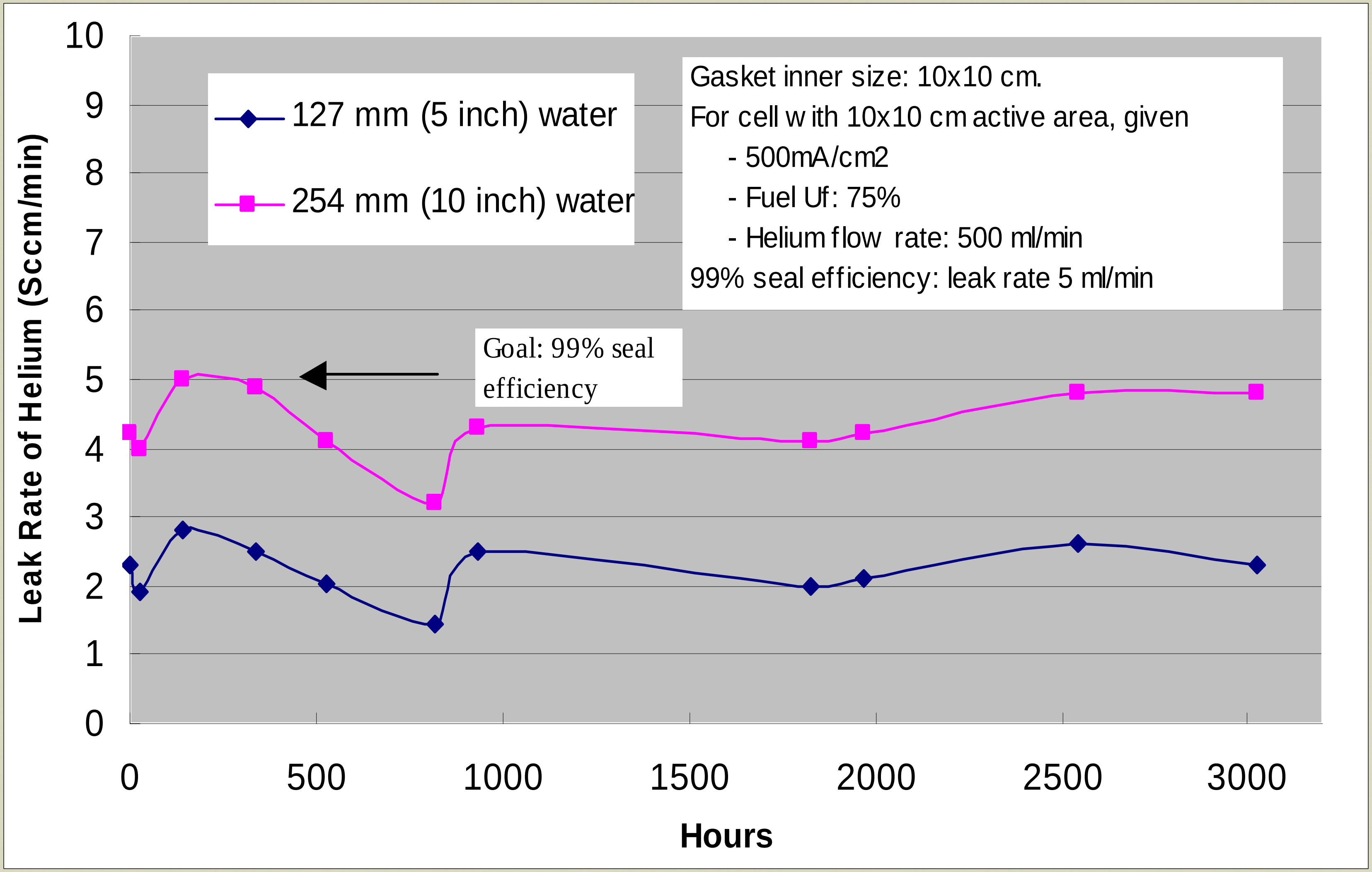
Set Up for Controlled Test Conditions

Normalized Gas Leak Rates of PH-2 Gasket



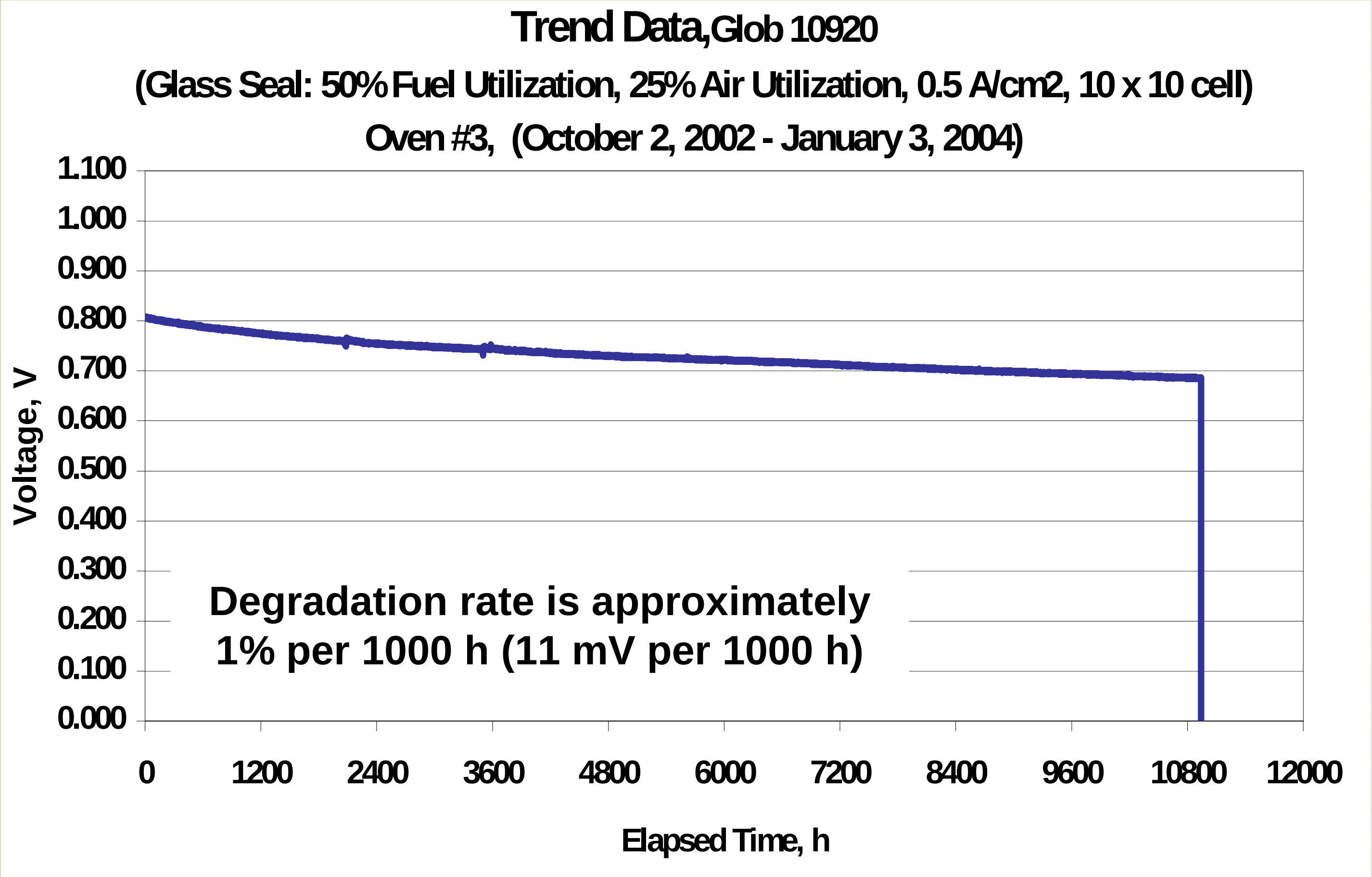
An Order of Magnitude Better Than Mica Gasket

Composite Gasket: Performance on Helium



Stable Seals for the 3000-hour Test

Single Cell Longevity Testing of Glass-Ceramic Seal - 750ºC



Advantage of Glass Seals = Hermetic fuel cavity

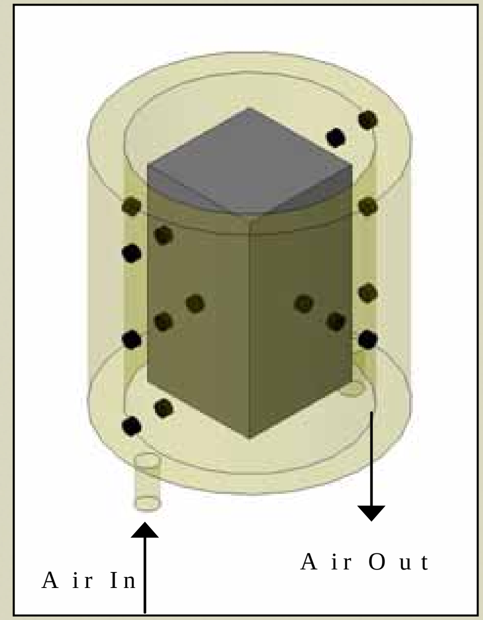
System Development

- Basis: Natural Gas Fuel, Grid Parallel Operation
- Aurora System with Radiative HEX (2 kW- net AC)
- Baseline System (3 kW-net AC)
- Advance System (10kW-net AC)

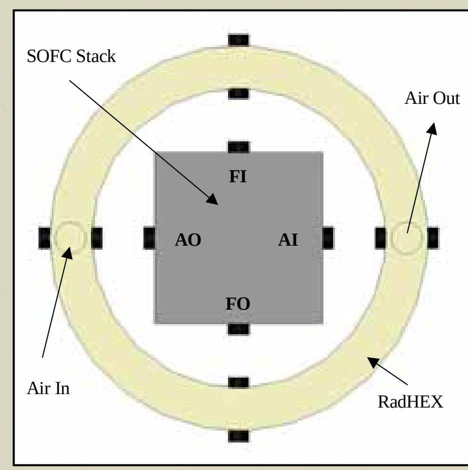
Aurora & 3-1 Hot Power Module & T/C Layout

Aurora hot power module without RadHEX

Aurora hot power module with RadHEX

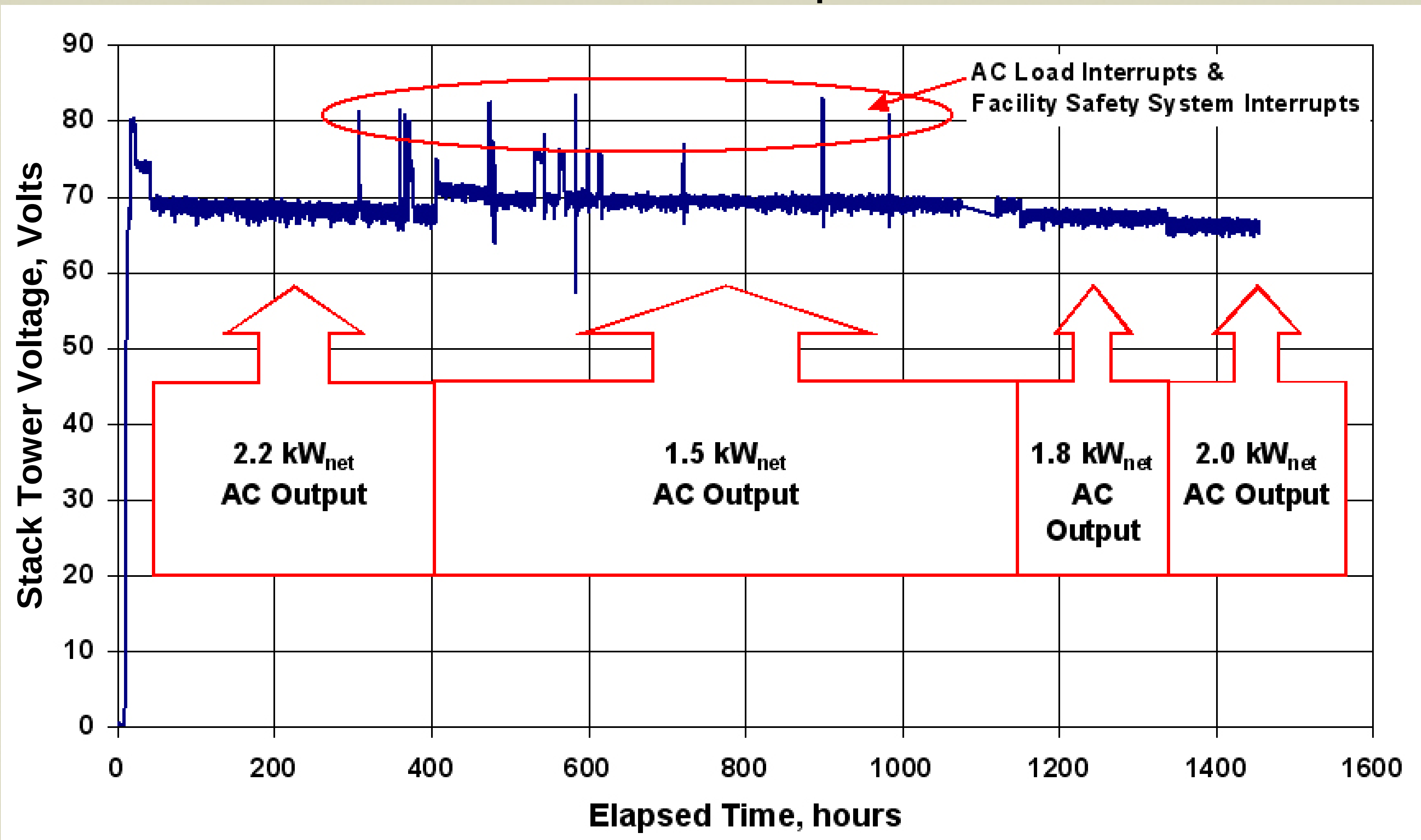


Black ‘dots’ denote thermocouple locations



Aurora System Operation On Natural Gas

Grid Parallel Operation for 1600 + hours
02-Feb-05 to 05-Apr-05



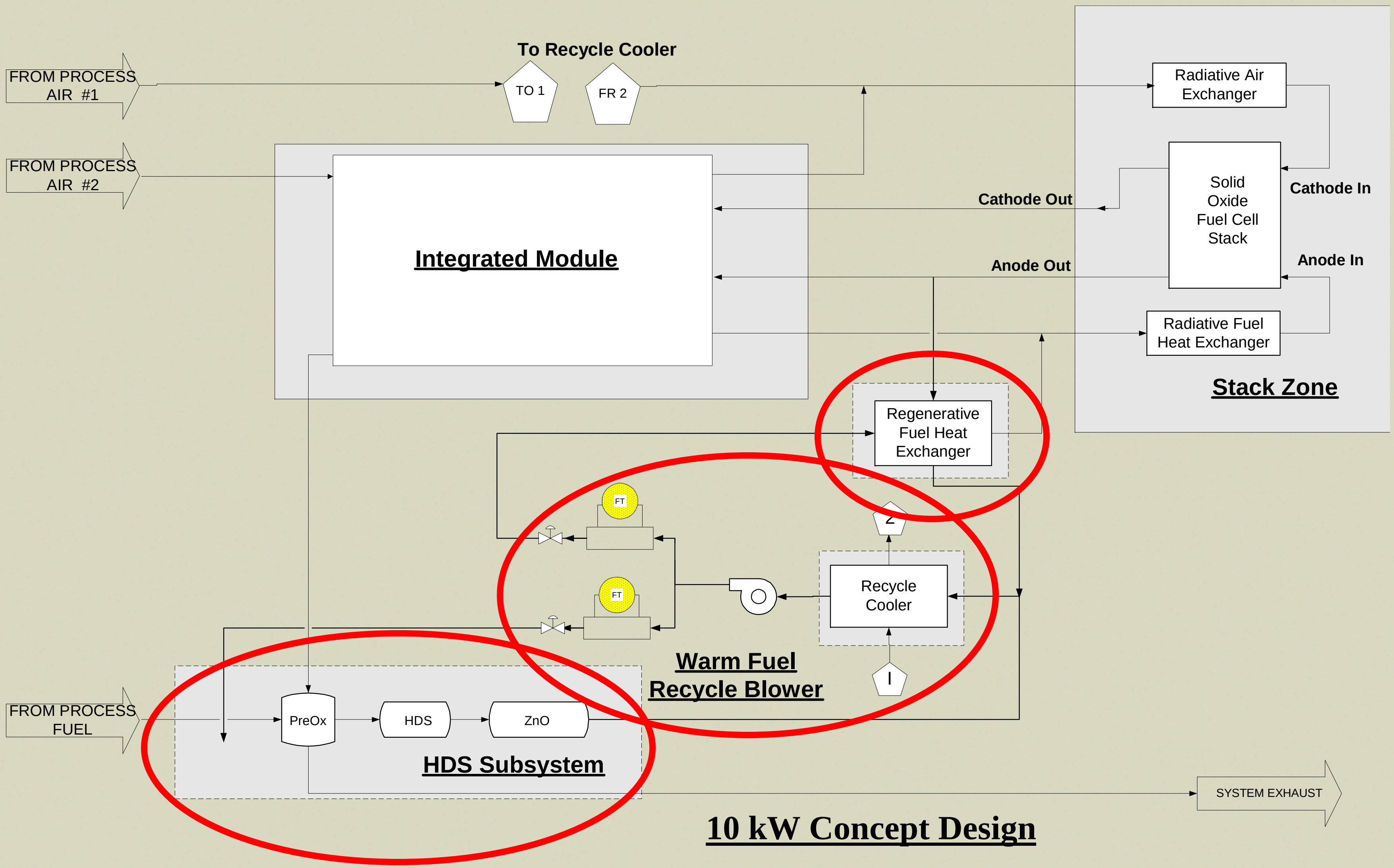
Scale-up to 3 kW

2 kW$_{net}$ System "Aurora"

3 kW$_{net}$ System "3-1"

3 kW$_{net}$ system commissioning underway

10 kW Advance System



10 kW Concept Design

Parker Blower to be Used as a Baseline

Developed for use with PEM Fuel Cells

Maximum Temperature Rating of 120°C

Regenerative Fuel HX

- **Current Specifications call for a working range of 750°C inlet to 200°C outlet.**
- **Four vendors have been identified**
  - Small size is a problem – not a typical product
  - Temperature range limits manufacturing methods to welding – not brazing
  - Small initial sales volume is a problem for cost reduction

Hydrocarbon Variability

Composition	Full Range	80% Range
Methane	73 to 99%	89 to 97%
Ethane	0.5 to 13%	1 to 5%
Propane	0 to 8%	0.2 to 2%
C_4 and above	0 to 13%	0.1 to 2%
Unsaturated	0 to 7%	Trace
Hydrogen	0 to 4%	<0.01%
Nitrogen	0 to 10%	0 to 3%
CO_2	0 to 2%	0 to 2%
HHV Btu/SCF	970 to 1200	1000 to 1050

Odorant Analysis: Natural Gas at NETL

Component Name	PPMV
Ethyl Mercaptan	0.10
T-Butyl Mercaptan	0.37
Dimethyl Sulfide (DMS)	0.23
Methyl Ethyl Sulfide	0.84
Diethyl Sulfide	0.97
Dimethyl Disulfide	0.13
Thiophene	0.29
Thiophane	1.14
Others	0.57
Total	**4.64**

Impurities

Composition	Full Range	80% Range
Odorants	2 to 12 ppmv	2 to 10 ppmv
Total Sulfur	2 to 17 ppmv	2 to 12 ppmv
H_2O, lb/MMSCF	0.5 to 10	0 to 8

Odorant Removal

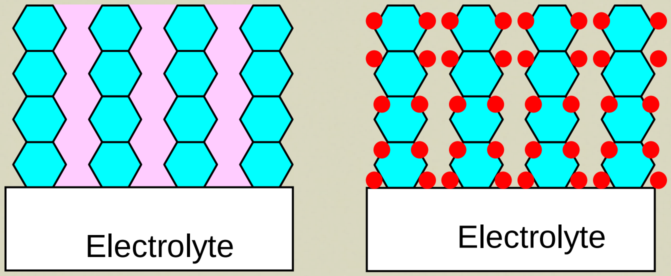
- Copper impregnated adsorbents work well but have a low capacity for DMS.
- Mole sieve adsorbents for DMS are expensive.
- Hydrodesulfurization (HDS) could be a universal odorant removal system but it requires hydrogen, doesn't handle unsaturated hydrocarbons well, and will overheat if propane-air is injected.

Summary

- Single Cell Operation using SS Interconnects Demonstrated for 26,000 hours (Degradation Rate: 1.3% per 1000 hr)
- Performed 50 Thermal Cycles in a Stack Repeat Unit During 5000 hours of Operation
- Work Initiated in Improving Redox and Sulfur Tolerance of the Anode Verified
- The 112 cell Stack Tower Showed a 50% Increase in Power Output(3.8 kW/Stack Tower)
- Aurora System Operated for 1600 + hours on Natural Gas Fuel and in Grid Parallel Mode

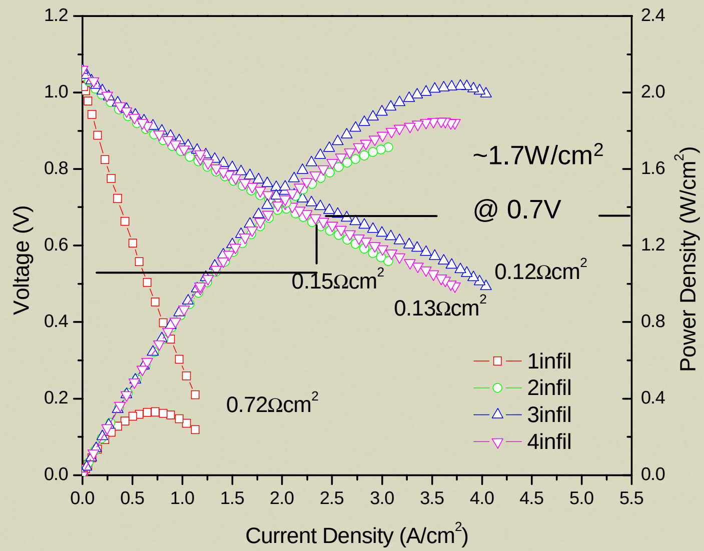
Approach to Advanced Cathodes

- Novel materials.
- Transport and adsorption properties; focus on materials with strong tendency for oxygen adsorption.
- Particle size and morphology; inter-particle contact.
- Microstructure stability at elevated temperatures.
- Introduction of electro-active species by infiltration.
- Identification of electro-active materials using patterned electrodes.



Introduction of aqueous salt solutions into porous cathode

Firing to form nanosize particles of electro-active materials

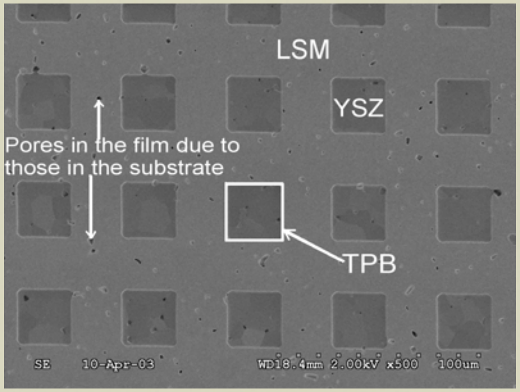


Performance of a button cell (2 cm^2 cathode) at 800ºC

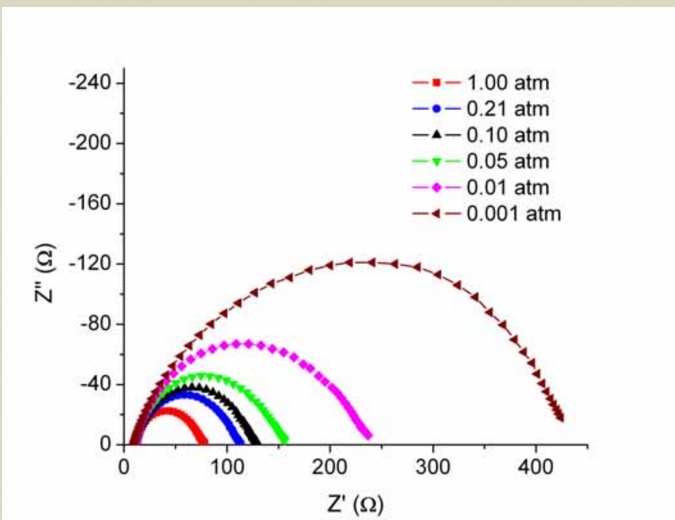
THE UNIVERSITY OF UTAH *Distributed Energy Generation*

FuelCell Energy

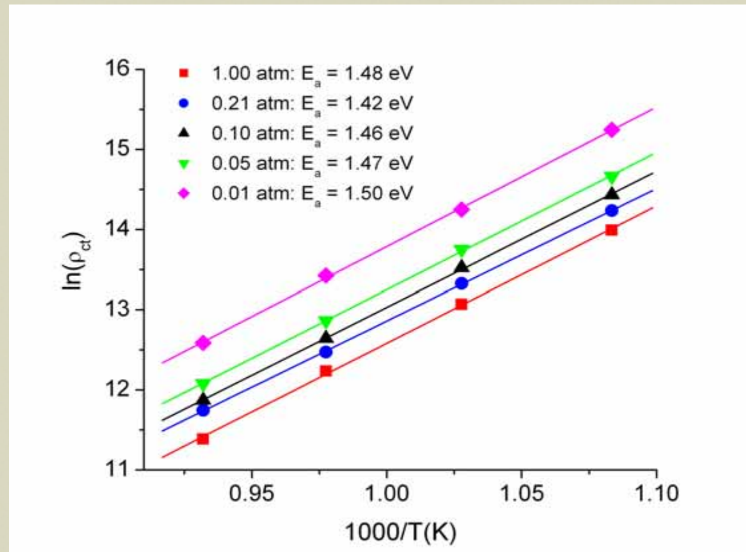
Patterned Electrodes – Impedance Spectroscopy – Charge Transfer Resistivity



Patterned Electrodes



Impedance spectra at various pO2

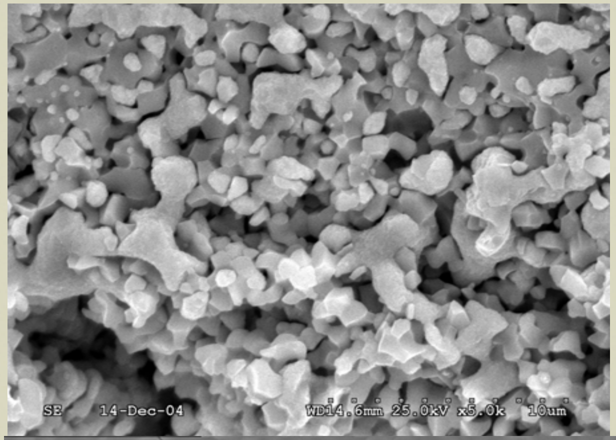


Charge transfer resistivity as a function of temperature and pO2

Collaborative work: University of Utah and PNNL

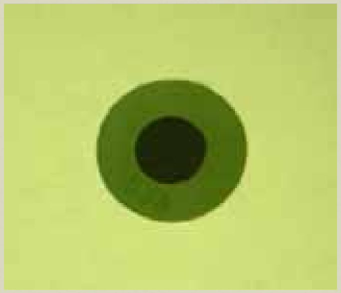
Development of Redox Tolerant Anodes

- Standard Ni-YSZ anodes tested for redox tolerance
- Tested at 600-800 °C
- Cells mechanically fail
  – Electrolyte microcracks
  – Anode support weakened
  – Some delamination
- Mechanism: expansion of Ni during oxidation microcracks YSZ in anode



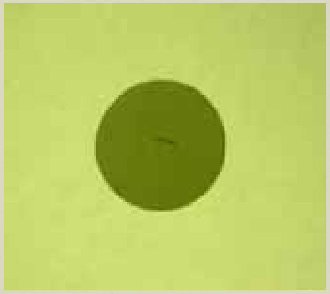
Development of Redox Tolerant Anodes

- New anode compositions have been developed
- Exhibit better redox tolerance
  - Anode support mechanically intact after redox cycling
  - No microcracking of electrolyte
  - Delamination has been suppressed
- Future work
  - Improve anode strength after deep redox cycles
  - Optimize compositions and microstructure



As-sintered

Reduced



Reoxidized

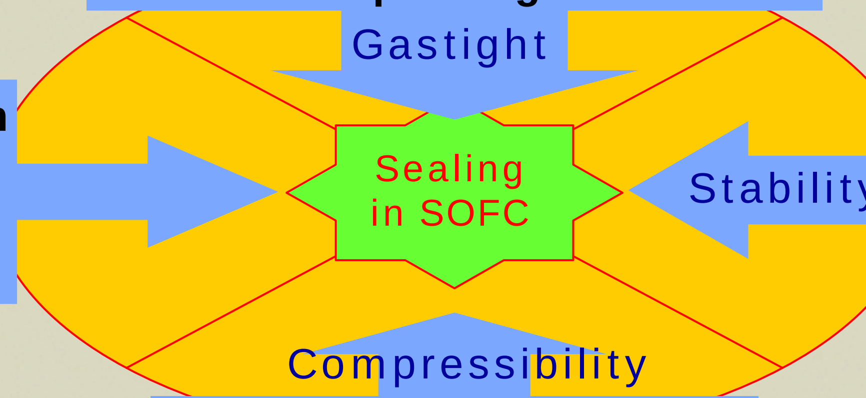
Glass-Ceramic Seal Thermal Cycling Testing – 750°C

	Cell Voltage (mV) at			
Thermal Cycle Number	Open Circuit	0.74A/cm2, low Uf	0.5A/cm2, 50% Uf, 25% Ua	0.5A/cm2, 70% Uf, 35% Ua
0	1.078	788	795	748
1	1.078	799	803	759
5	1.072	794	801	759
15	1.073	783	793	753
25	1.080	780	792	759

Sealing Requirements in SOFC

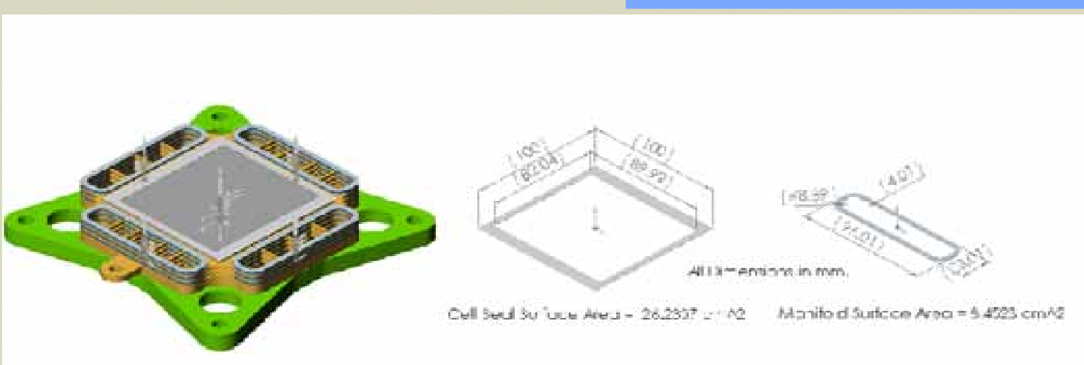
- **Within designed leakage tolerance over the life of the stack at both steady state and transient operating conditions**

- **More than 10^5 ohm·cm to avoid possible current leakage and cell shortening**



- **Thermal, chemical and mechanical stability to stack components and conditions**

- **More than 30% to allow deformation for stack assembly requirements**

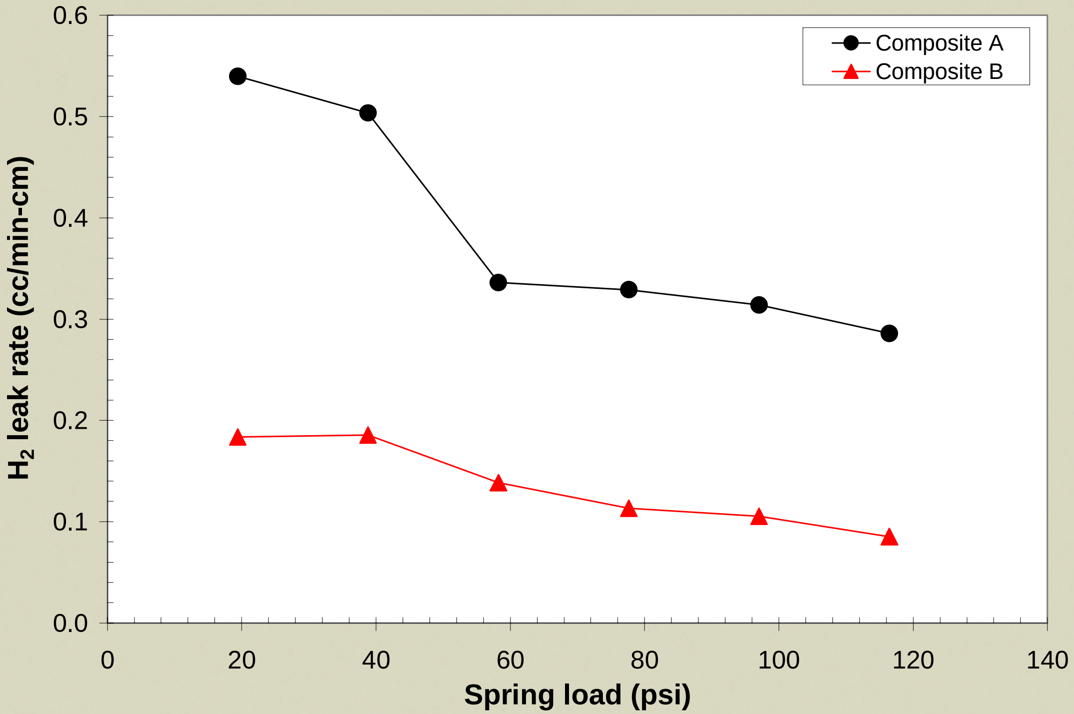


Development of a high temperature seal requires integrated solutions to these requirements

Composite Seal Test

Green tape of MSRI composite seal

800ºC, H_2 gas maintained at 4 kPa



- Thermally and mechanically robust
- Flexible configuration
- Tape cast, easy manufacturing, and low cost