Thermally Integrated High Power Density SOFC Generator

By:

FuelCell Energy, Inc.

Versa Power Systems

Presented At

The Annual SECA Conference

Boston, Massachussetts

May 11-13, 2004

POWERING A CLEANER FUTURE **TODAY**

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Presentation Overview

- FCE Profile
- Program Objectives
- FCE Team and Synergistic Strength
- Approach for Phase I
- Progress Made: Pre-award Period
- Near Term Plans and Summary

FuelCell Energy Profile

- Delivering commercial products now with advanced Direct FuelCell® technology
- #1 high temperature stationary fuel cell manufacturer and developer including carbonate and solid oxide applications
- Over 33 million kWh of electricity generated to date from the 30 units delivered to global commercial and industrial customer sites
- A leading fuel cell technology developer for over 30 years – over $400 million invested
- Headquarters in Danbury, CT
  Manufacturing Facilities in Torrington, CT
- Strong balance sheet with $193 million in cash (1/31/04)
- NasdaqNM:FCEL

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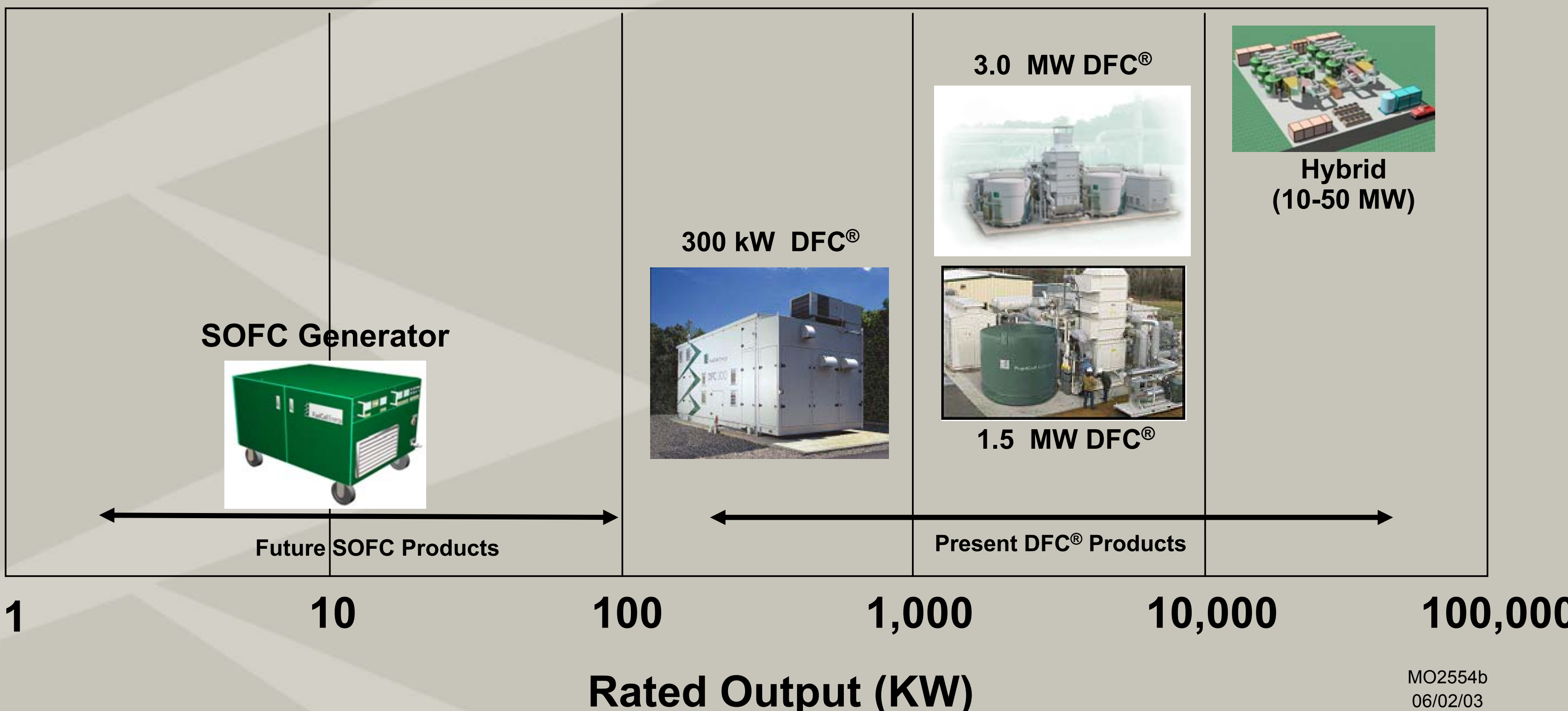
Current Customers

- Institutional
  - Hospitals
  - Universities
- Commercial
  - Hotels
  - Data Centers
  - Office/Shopping
- Industrial
  - Waste Water
  - Telecom
  - Food & Beverage
  - Chemical
  - Manufacturing
- Utility
  - Grid-support

SOFC – Complementary Products

SOFC GENERATOR COMPLEMENTS EXISTING PRODUCT LINE



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Program Objectives

- Develop 3-10 kW-class SOFC power plant per SECA goals
- Fuel options: Natural gas (Phase I)

  Propane and diesel in Phase II
- Thermal integration for higher efficiency
- Manufacturing cost reduction
  - High power density (300-500 mW/cm^2 at system conditions)
  - Implement DFC technology experience
  - Focused input from complementary programs

FCE-VPS Team Members

VPS is the joint venture between FCE, GTI, EPRI, MSRI and UU

FuelCell Energy
Internal Reforming
Metal Interconnects
Stack Manufacturing
Power Plant Experience

DANA
Gaskets, HEX,
Low Cost Manufacturing

PNNL
Modeling

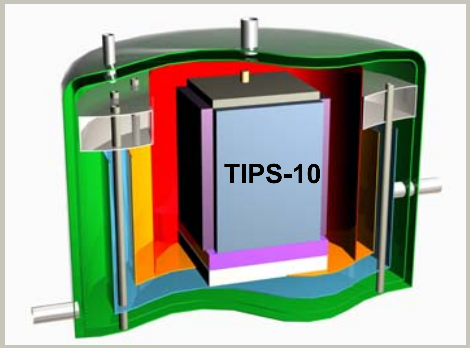
VersaPower Systems
- **TECHNOLOGY DEVELOPMENT**
- **COMMERCIALIZATION**

THE UNIVERSITY OF UTAH
Cell Technology

MSRI
High Power Density Stacks
Advanced Materials

gti
System Design
Fuel Processing
Gas Utility Customers

EPRI
Power Electronics
Utility/Distributed Gen.



SOFC SYSTEM

MARKET PARTNERS		
Teledyne	Verizon	
Alpha	Sempra	Marubeni

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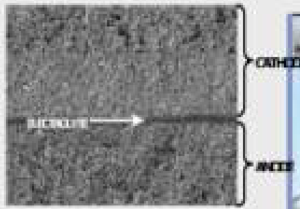
Versa Power Systems

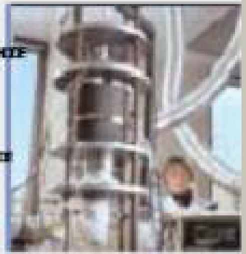
The Technology

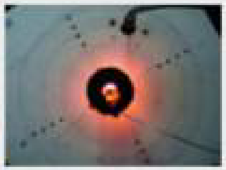
- Patented planar, reduced temperature SOFCs
- Proprietary thermally integrated power system (TIPS) design
  - pathway to low-cost, compact power gen systems with the highest efficiency and power density

Status

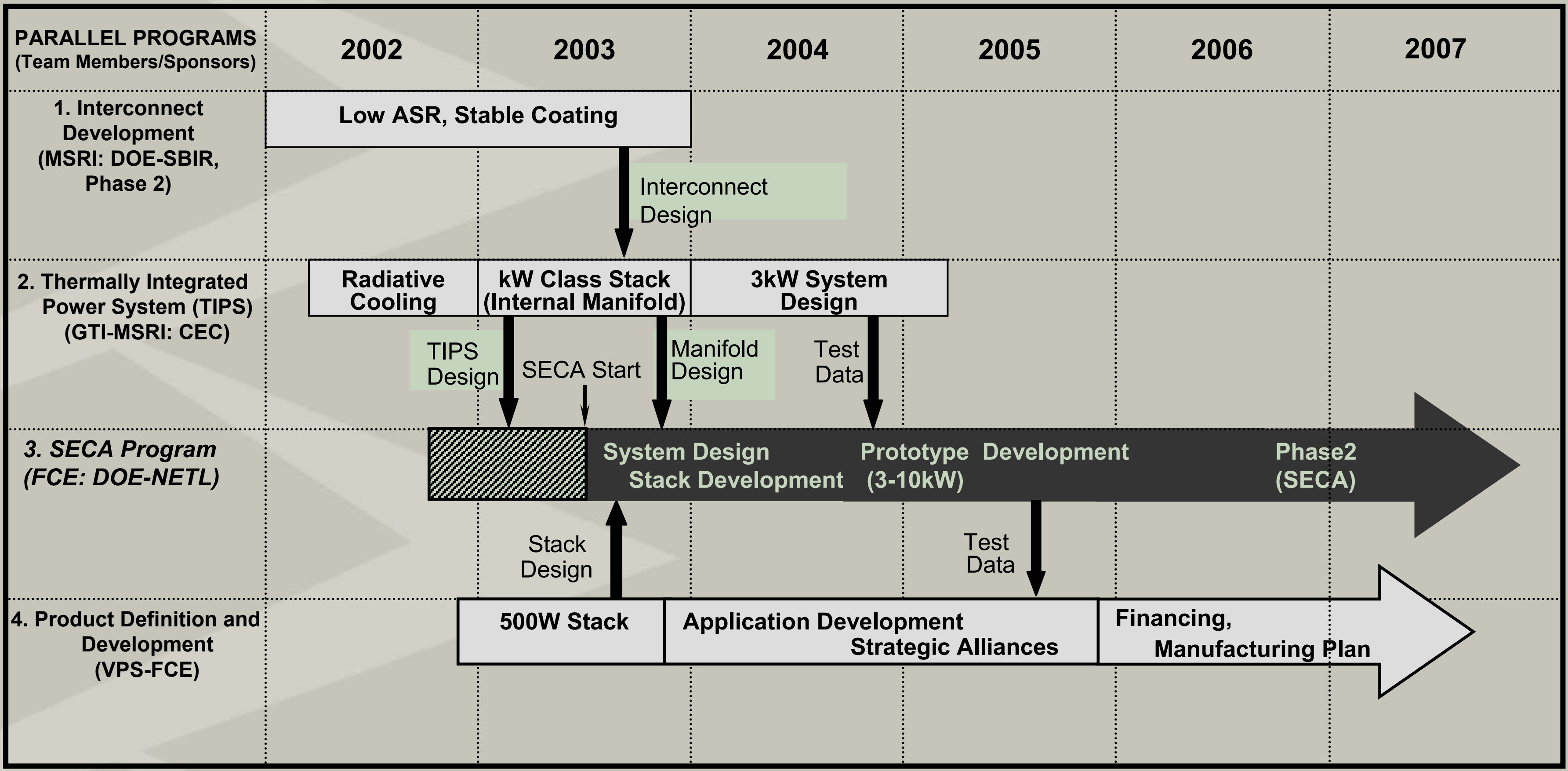
- SOFC technology demonstrated in both 40-cell, 2"square and 25-cell, 4"-square stacks (370 to 420 W/l)
- Over 10,000 h lab scale durability
- Prototyping & scale-up underway







Parallel Activities



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The Ongoing Activities Provide Valuable Design Input

Global Thermoelectric Resources Available

- **Global Thermoelectric's SOFC technology strengthens the FCE's team**
- **High temperature technologies are synergistic – technical solutions to MCFC can apply to SOFC and vice versa**
- **Provides access to the emerging fuel cell opportunities in Canada**
- **Complementary products make companies an ideal fit for the present and the future**
- **Discussion in progress for optimal integration of all resources**

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Approach: Phase I

- Cell technology based on thin-film anode-supported SOFC operating at 700-750°C
- Utilize FCE's Direct Fuel Cell (DFC) technology experience
  - Internal reforming to maximize efficiency and simplicity
  - Thin sheetmetal interconnects
  - External vs. internal manifolds
  - Thermo-mechanically compliant composite seals
- System based on triple mode cooling for high power density
- Simplify manufacturing process

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Progress Made in Cell Technology Development

- Trilayer performance increased to 2400 mW/cm^2 at UU (button cells, H_2, high flows)
- Cell performance with interconnects increased to 1400 mW/cm^2
- Long term cell tests on hydrogen and methane show encouraging results
- Large area cell testing initiated (100-400 cm^2)
- Lowered operating temperature from 800 to 750°C (BOP cost reduction)
- Trilayer manufacturing process simplified from multiple fire to a single fire

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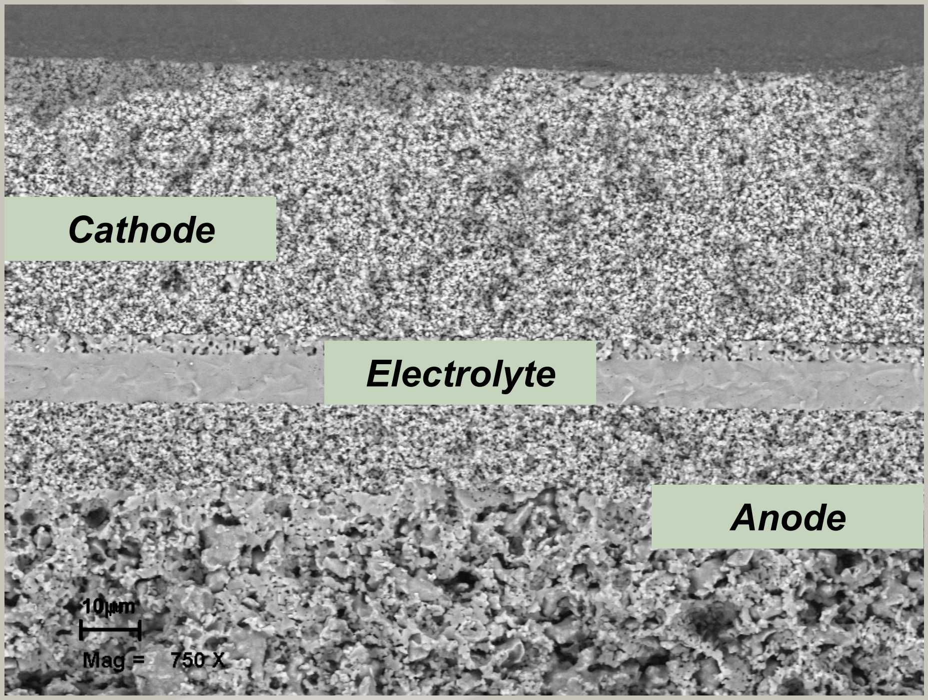
Cell Architecture



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

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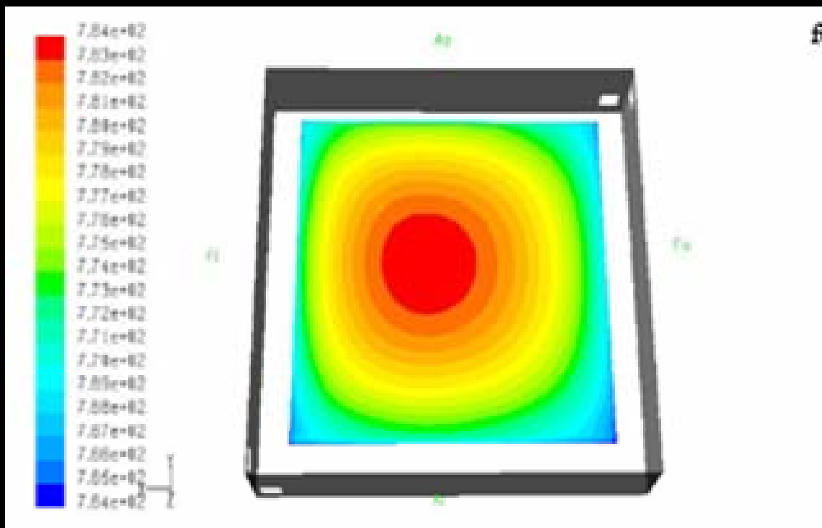
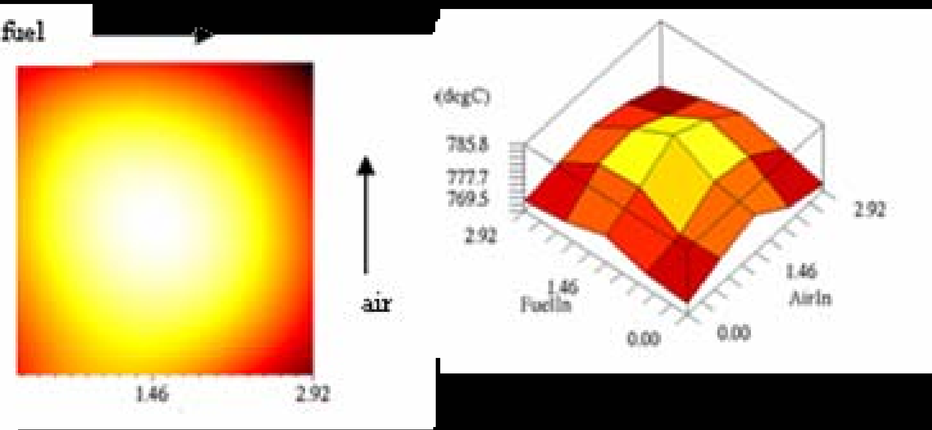
Single Cell Modeling





Predicted Thermal Profile

Actual Thermal Profile

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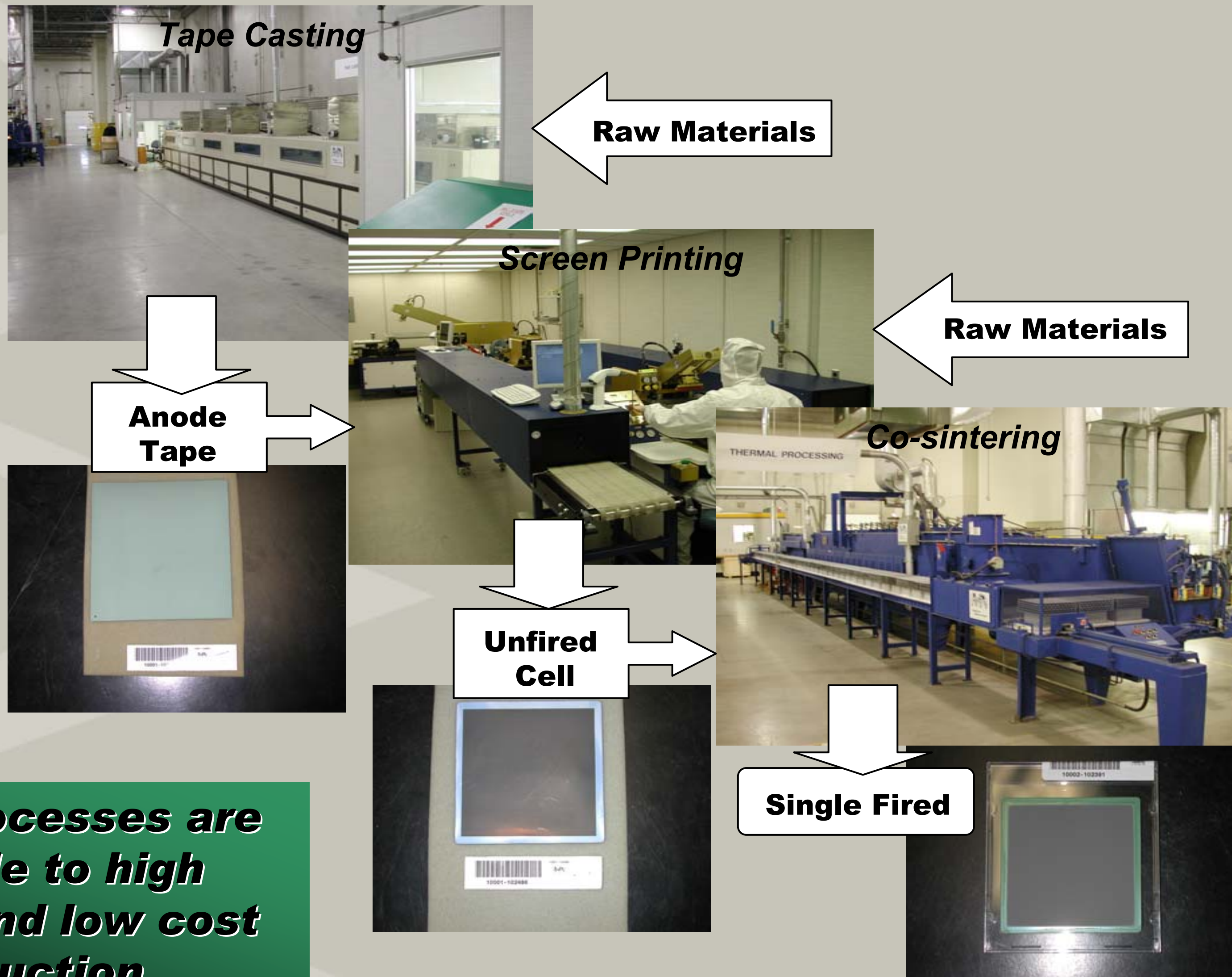
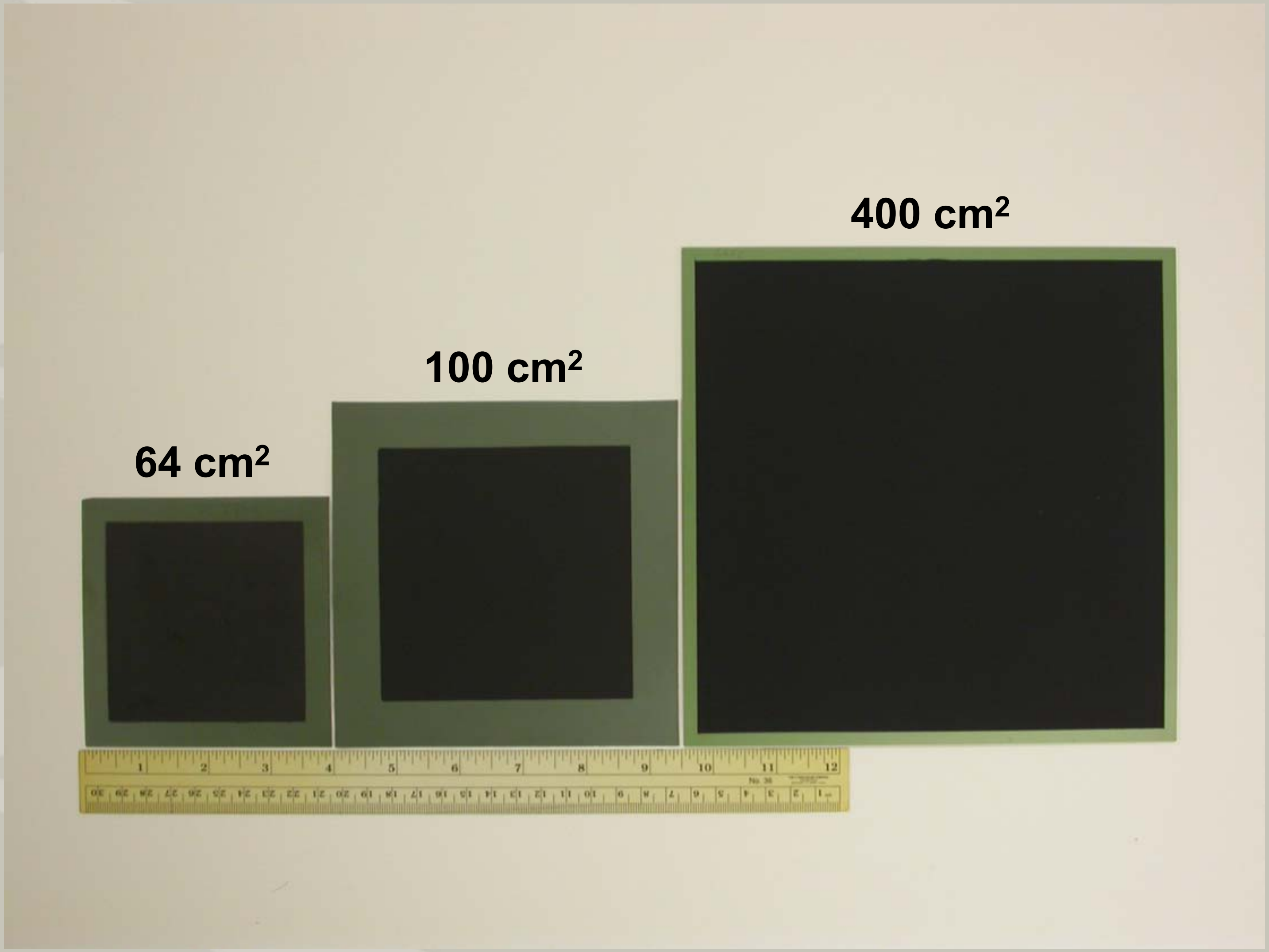
Cell Manufacturing Process Flow

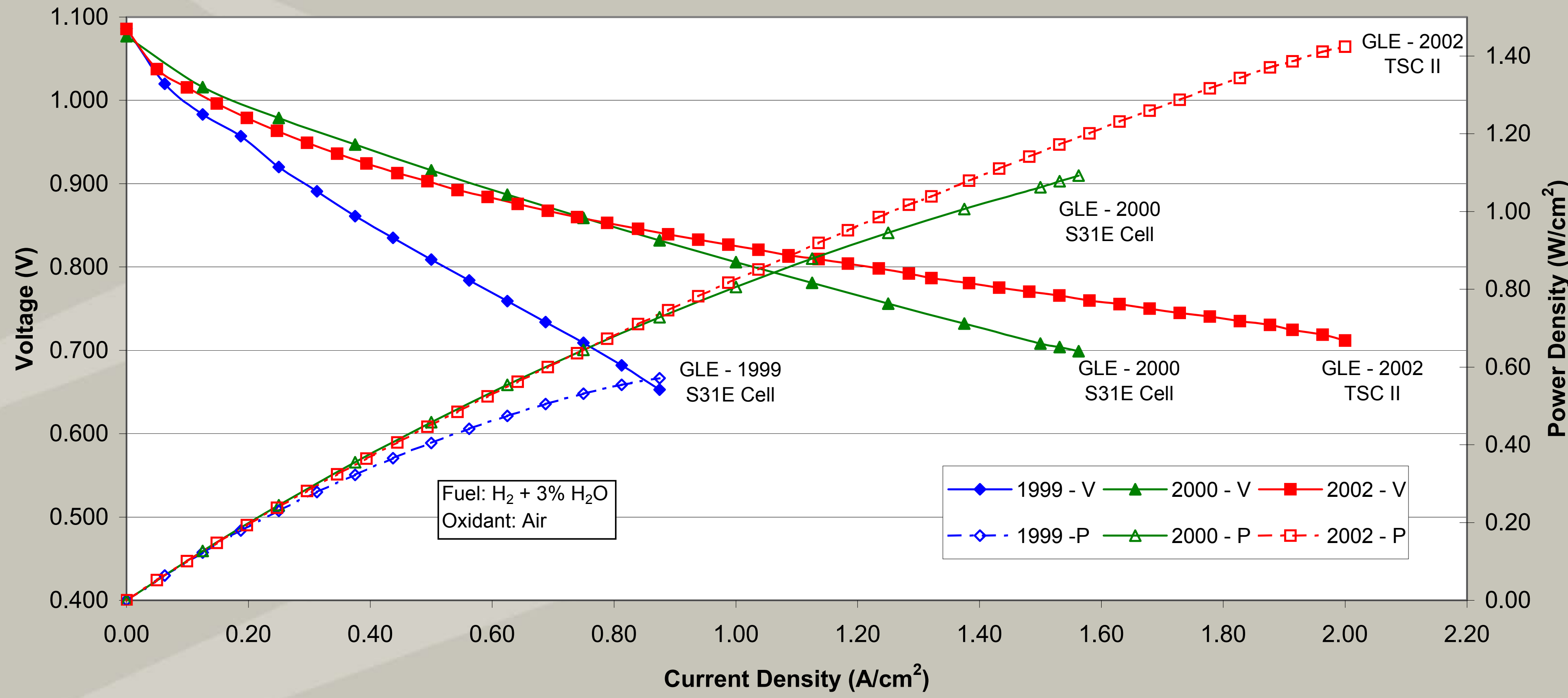


These processes are scalable to high volume and low cost production

Cell Size Scale-up In Progress



Single Cell Performance at 750°C



Cell performance for a 10 x 10 cm² cell using stainless steel current collectors, cross-flow gas delivery

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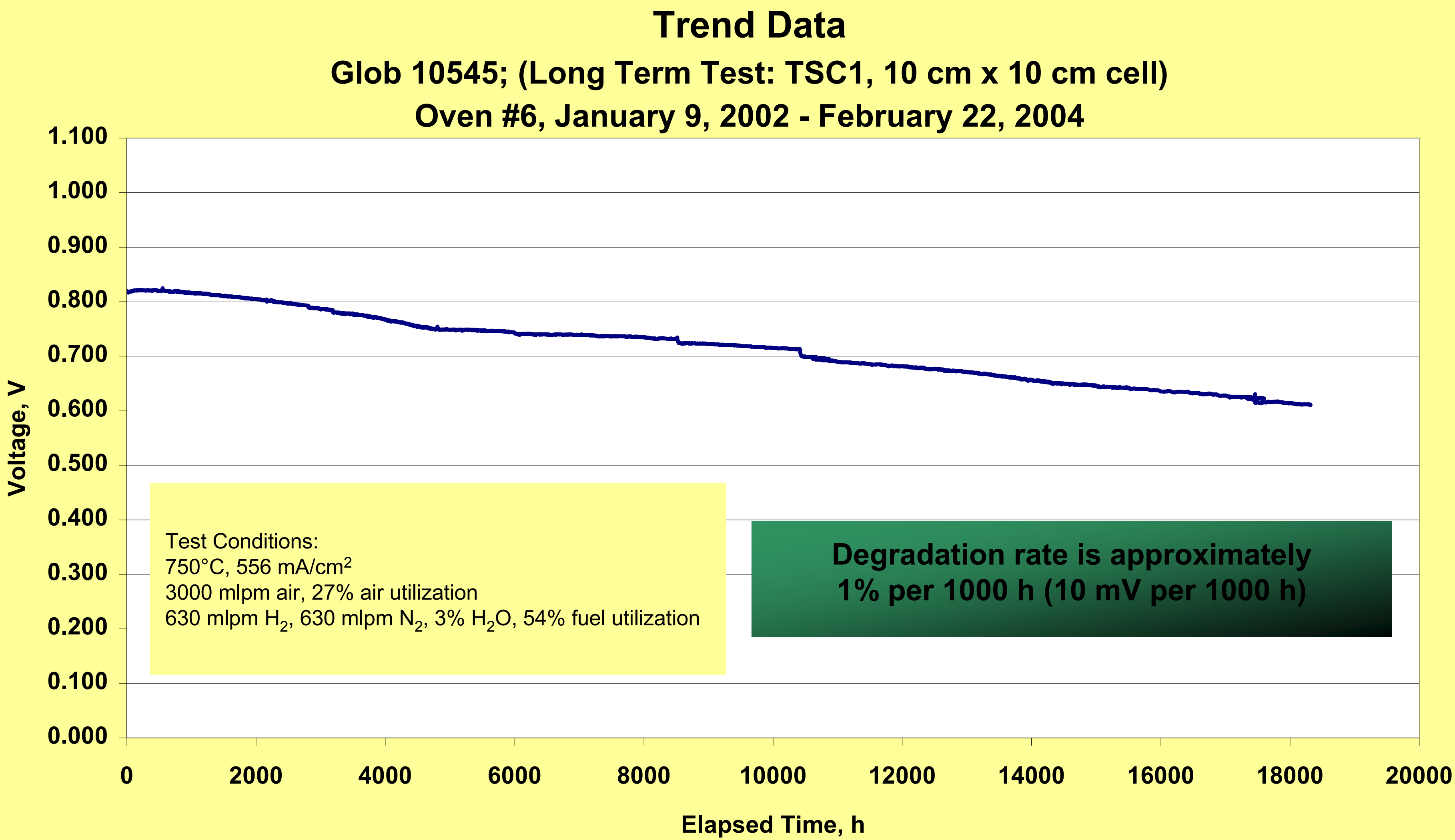
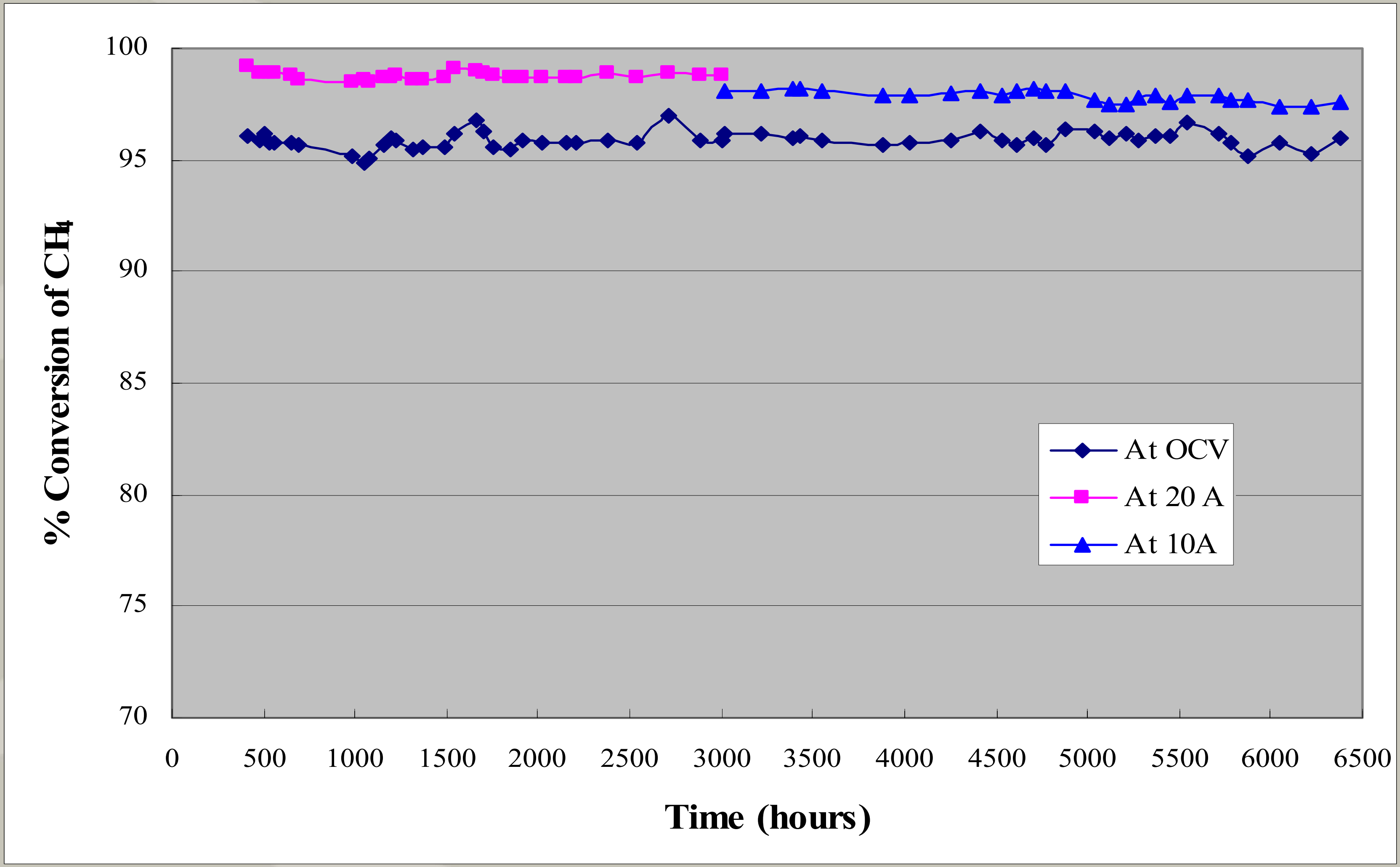
Single Cell Endurance at 750°C



Internal Reforming of Methane – Excellent Stability



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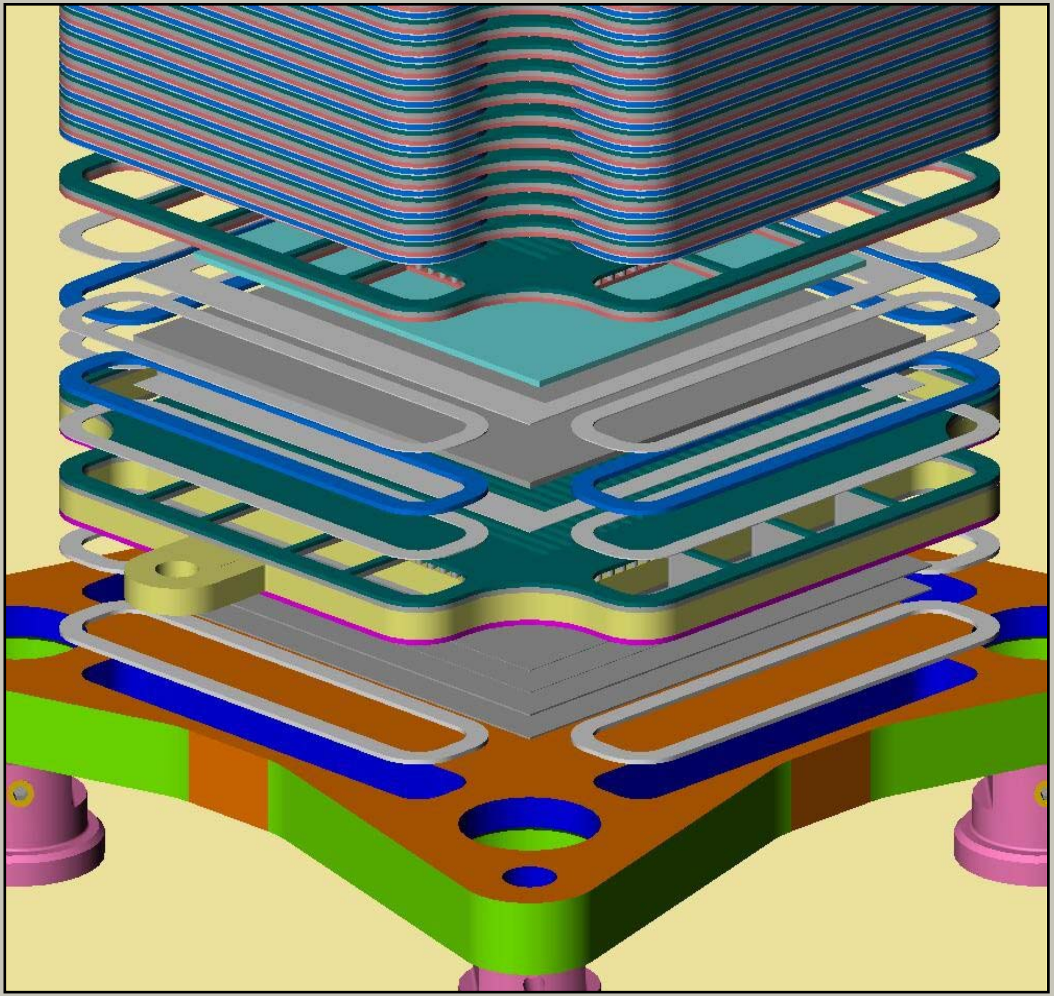
Gen 4.x Stack Assembly

Characteristics:

- **Internally manifolded**
- **700-750ºC operation**
- **Stainless steel interconnects, current collectors, end plates**
- **Compressive seals**
- **Internal compression system**
- **Cross flow**



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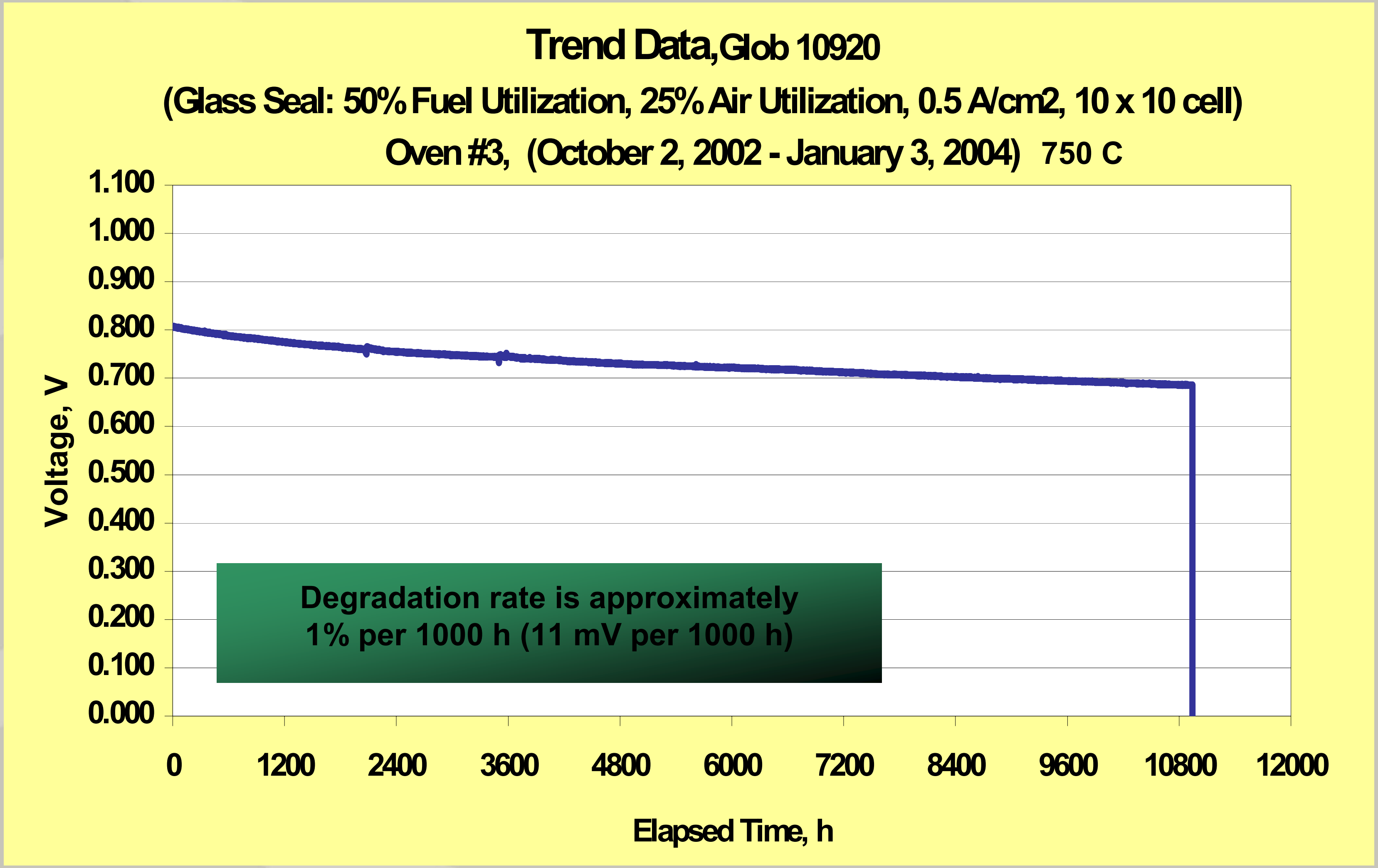
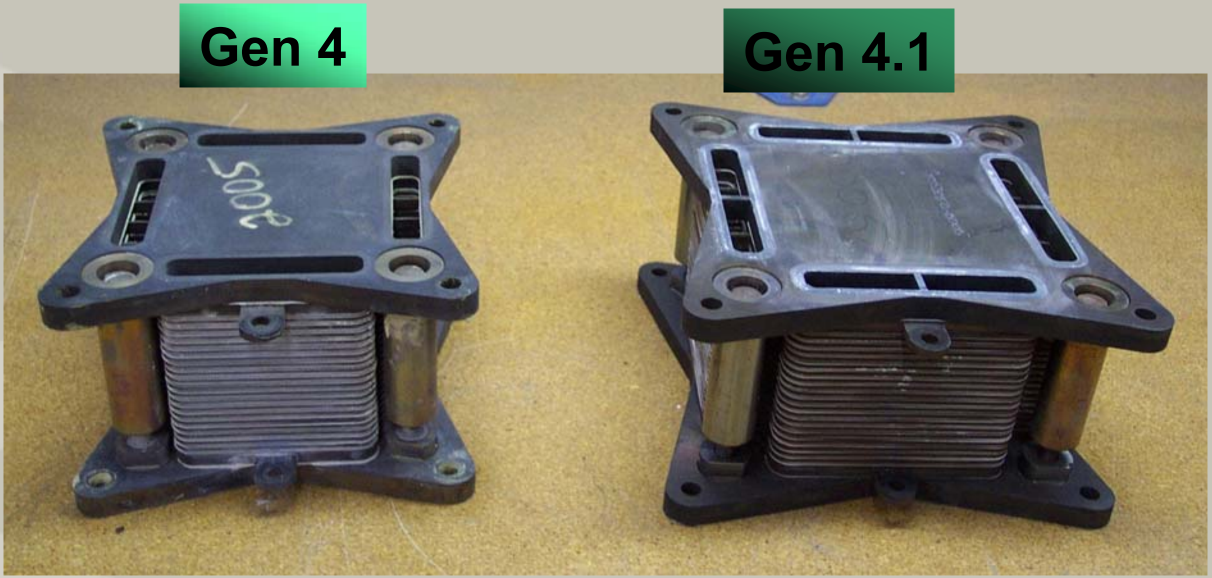
Glass Seal Development

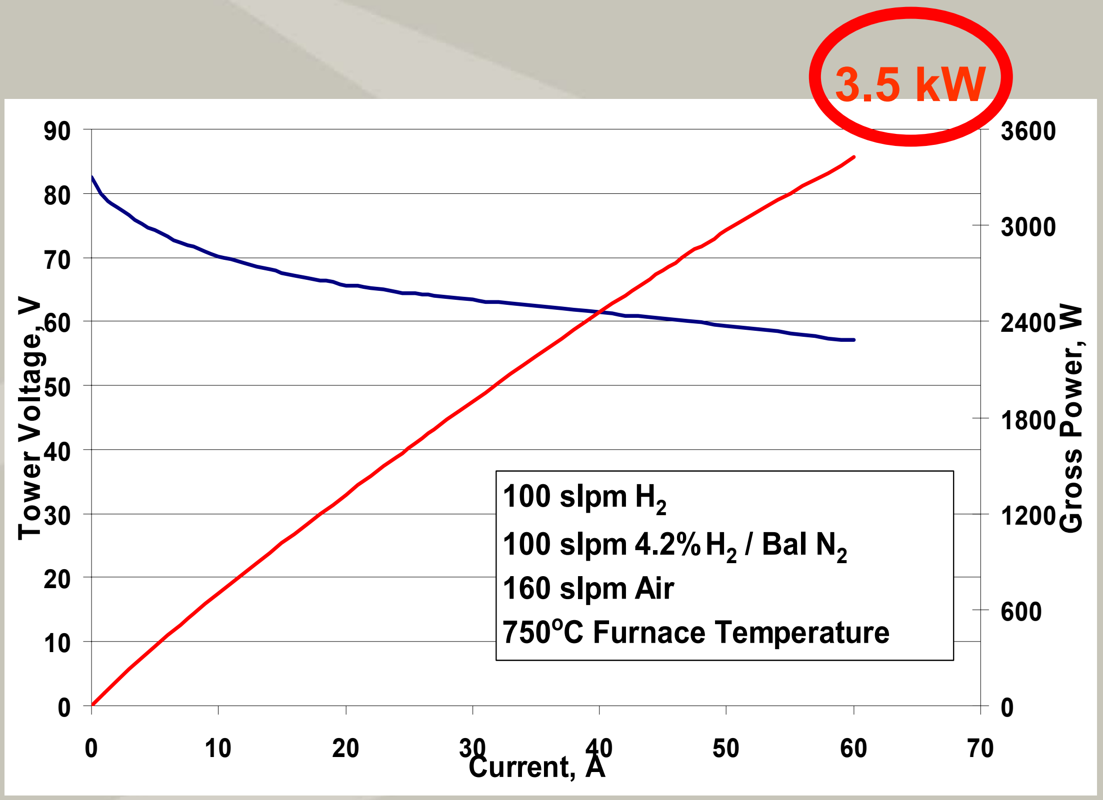


Gen 4 → Gen 4.1

- **Cell active area: 81 cm^2 → 121 cm^2**
- **Number of cells: 16→20**
  - **Increase in stack active area = 87%**



Gen 4.1 80-Cell Tower – Q2 2003



This tower is used in the Aurora System

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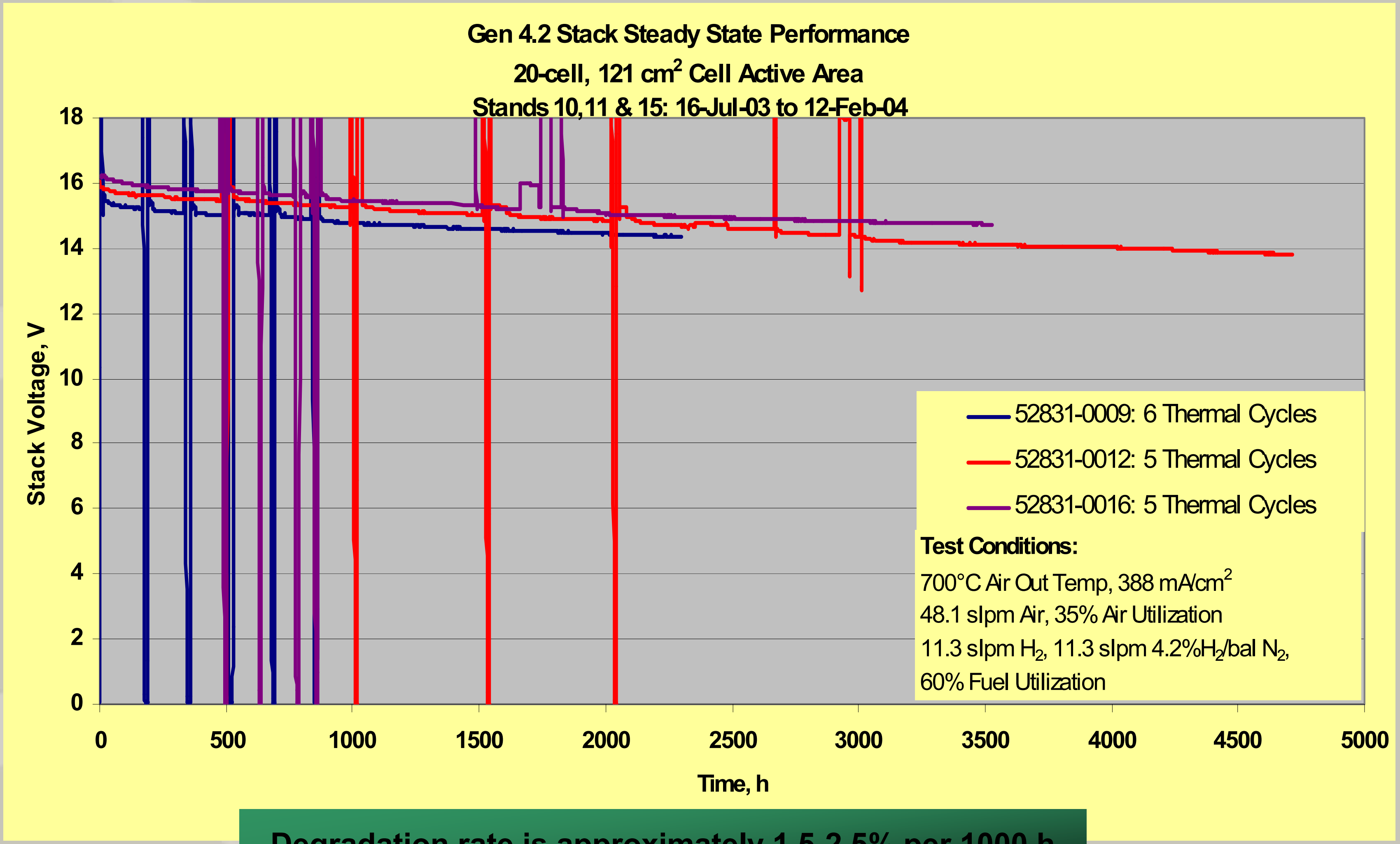
Gen 4.2 Stack Performance



Degradation rate is approximately 1.5-2.5% per 1000 h (16-20 mV per 1000 h)

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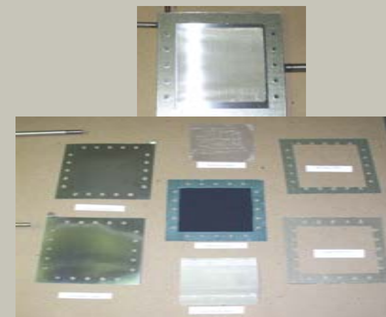
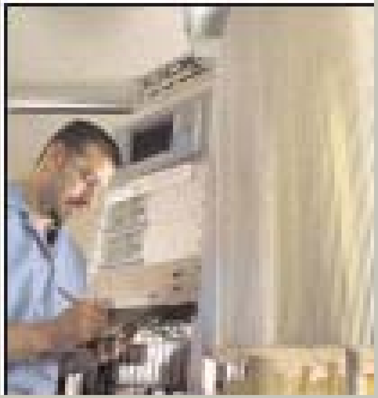
Sub-scale Stack Development

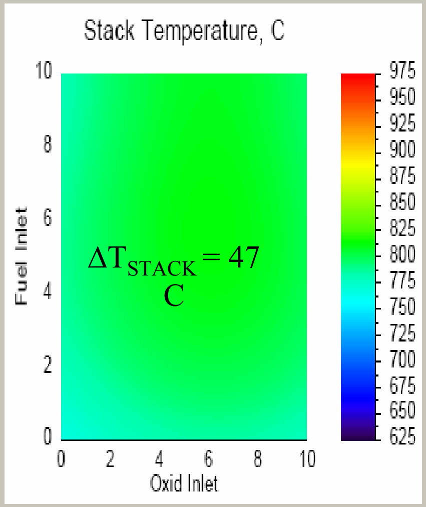
- **MSRI**
  - **Fabricated, QC'd and delivered 50 single cells and hardware for baseline Team testing.**
- **GTI- short stack gear-up**
  - **Refurbished existing DOE single-cell, FC test stand**
  - **Ready for endurance tests of short stacks-- 100-200 W**
  - **NG, all simulated gases**

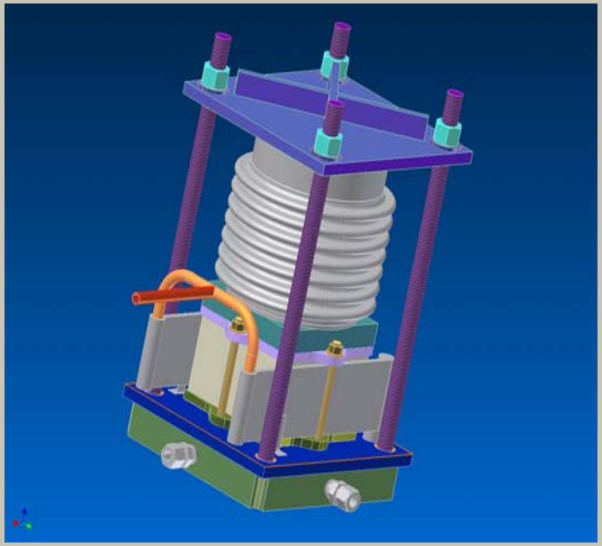




System Development: Radiative Cooling

- CEC program is developing modules that radiate stack-generated heat to air pre-heating panels
  - Reduces airflow in large systems
  - Provides “active” insulation in small systems
  - Smoothes out in-plane temperature distribution by selectively removing stack heat
  - Facilitates compactness, modularization, and scale up





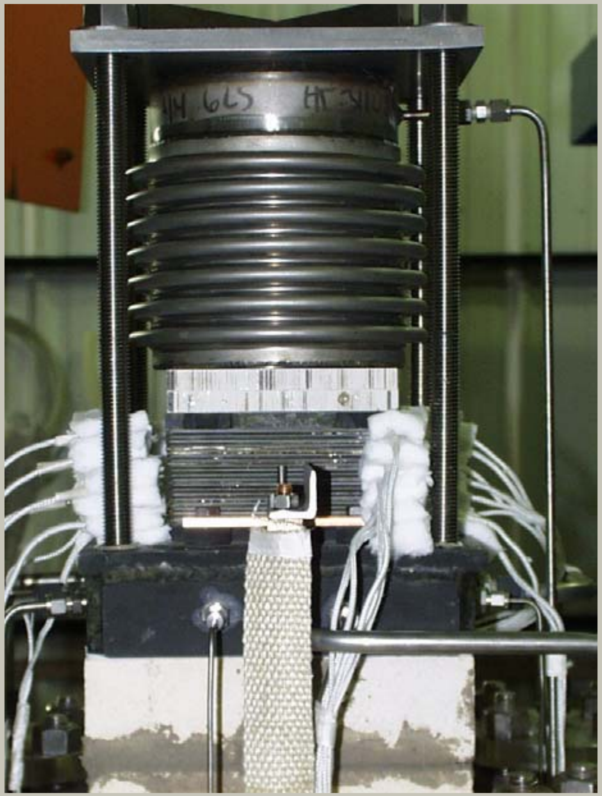
System Development: Model Verification

- MSRI has tested multiple 5, 10, 20, 25, and 40-cell stacks Results suggest that ~0.5 W/cm^2 will be obtainable on a kW level with realistic conditions and fuels at 700-800°C

- Out-of-stack tests have verified the desired temperature rise in the air preheater panels

- Completed preliminary facility “shakedown” test on a 20-cell stack without panels

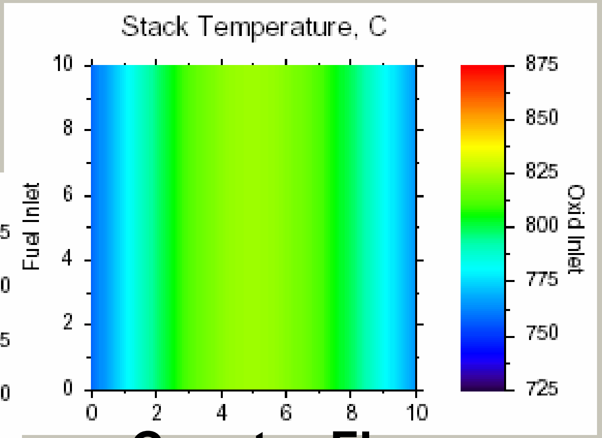
- Scheduled first stack/air preheater panel test
  - May 24
  - 40-cell, 100-cm^2 stack
  - Blended gases will simulate various fuels



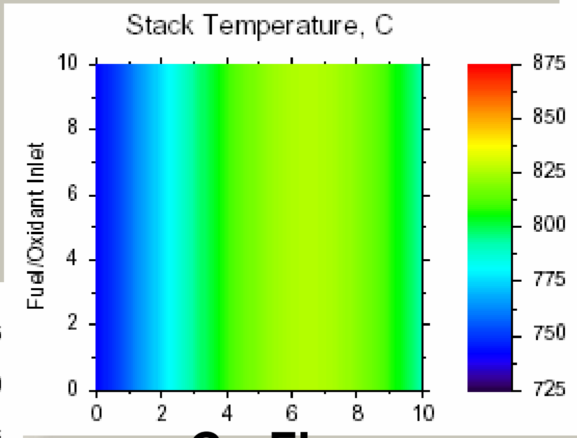
Stack/RAP Model Runs – Flow Configuration

Counter Flow Yields Lowest ΔT

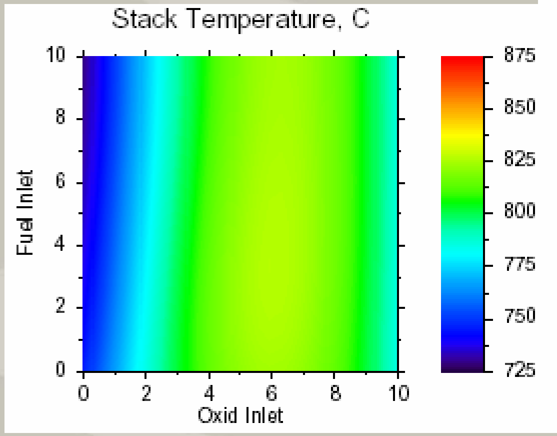
- ~0°C Gas ΔT;
- 50° to 100°C Stack Hardware ΔT Possible



Counter-Flow: 67°C Hardware ΔT



Co-Flow: 86°C Hardware ΔT



Cross-Flow: 99°C Hardware ΔT

- **Ideal Case- No Limit RAP**
- **100 cm^2, 0.6V @400mA/cm^2, 80%UtF/54%UtO**
- **Stack Cooling: 65% Radiation/35% IR/0%Air Cooling**

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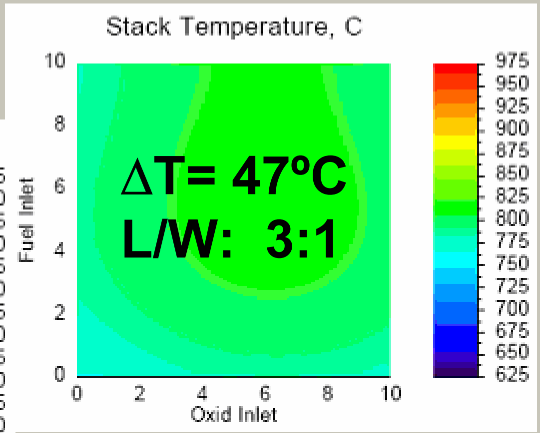
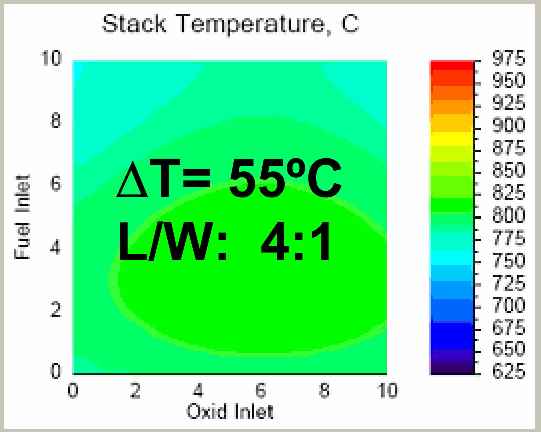
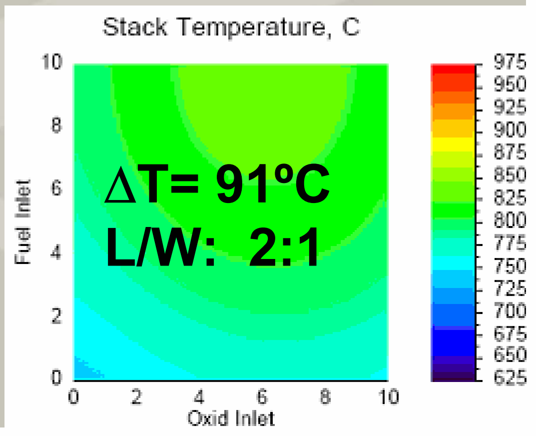
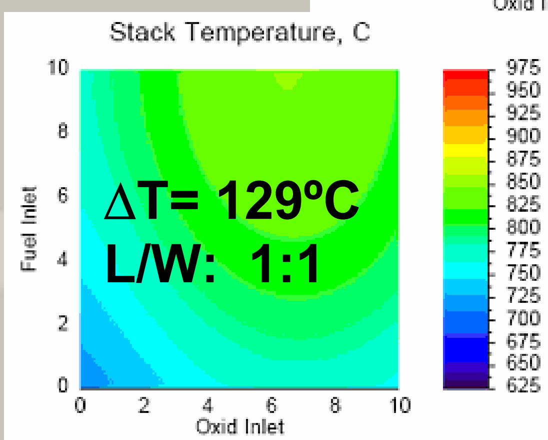
Stack/RAP Parametric Model Runs

Cell *L/W, RAP/IR* Variable





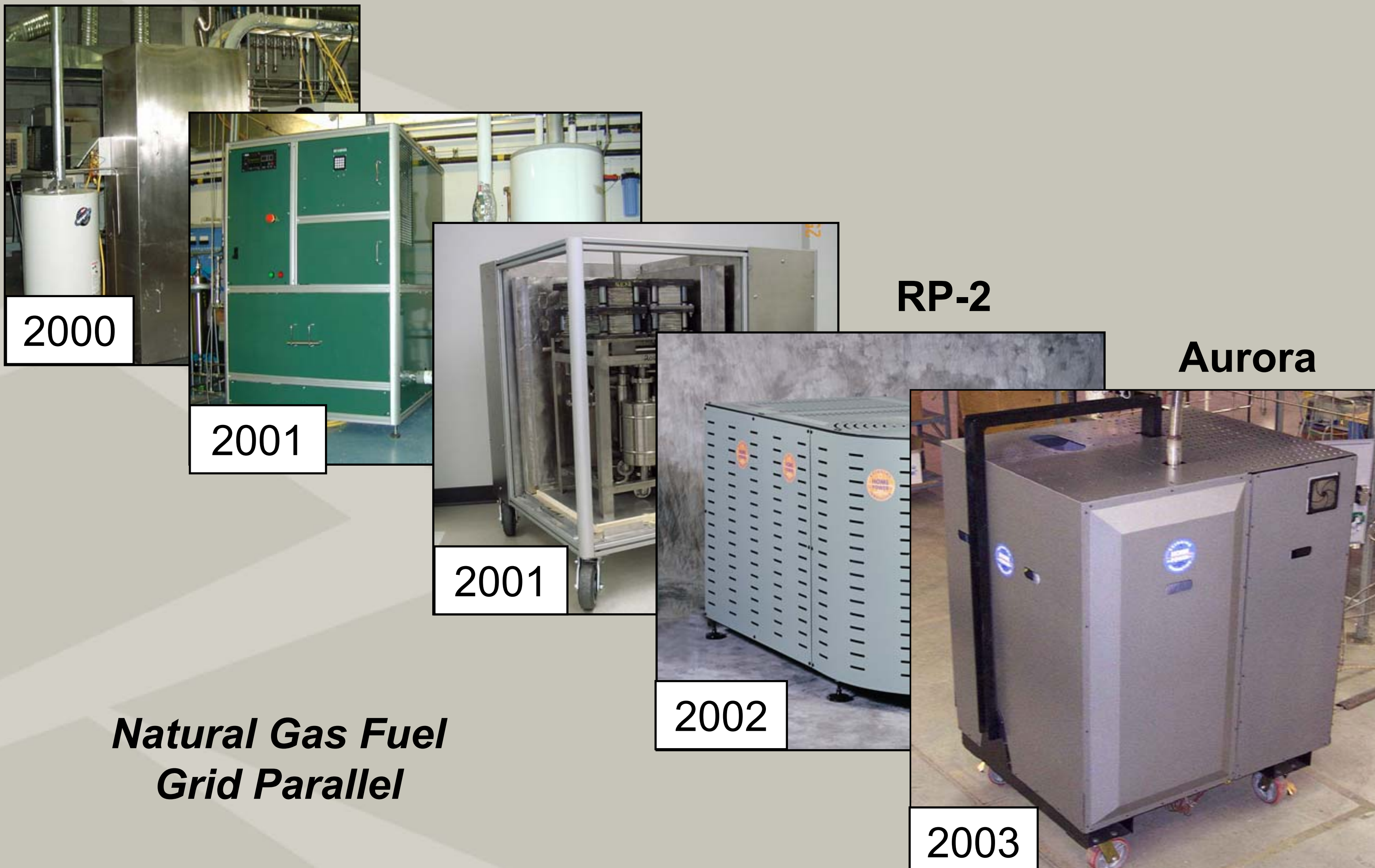




Stack Hardware ΔT can be <50ºC

- Cross-flow; 81% U_{FU}, 54% U_{OX}
- Stack Avg T: 800ºC
- Cooling: 34% RAP; 40% IR; 26% Air
- Cell Perf: 610 mV @ 400 mA/cm^2
- Including Bench RAP Data

Prototype Systems: kW-class



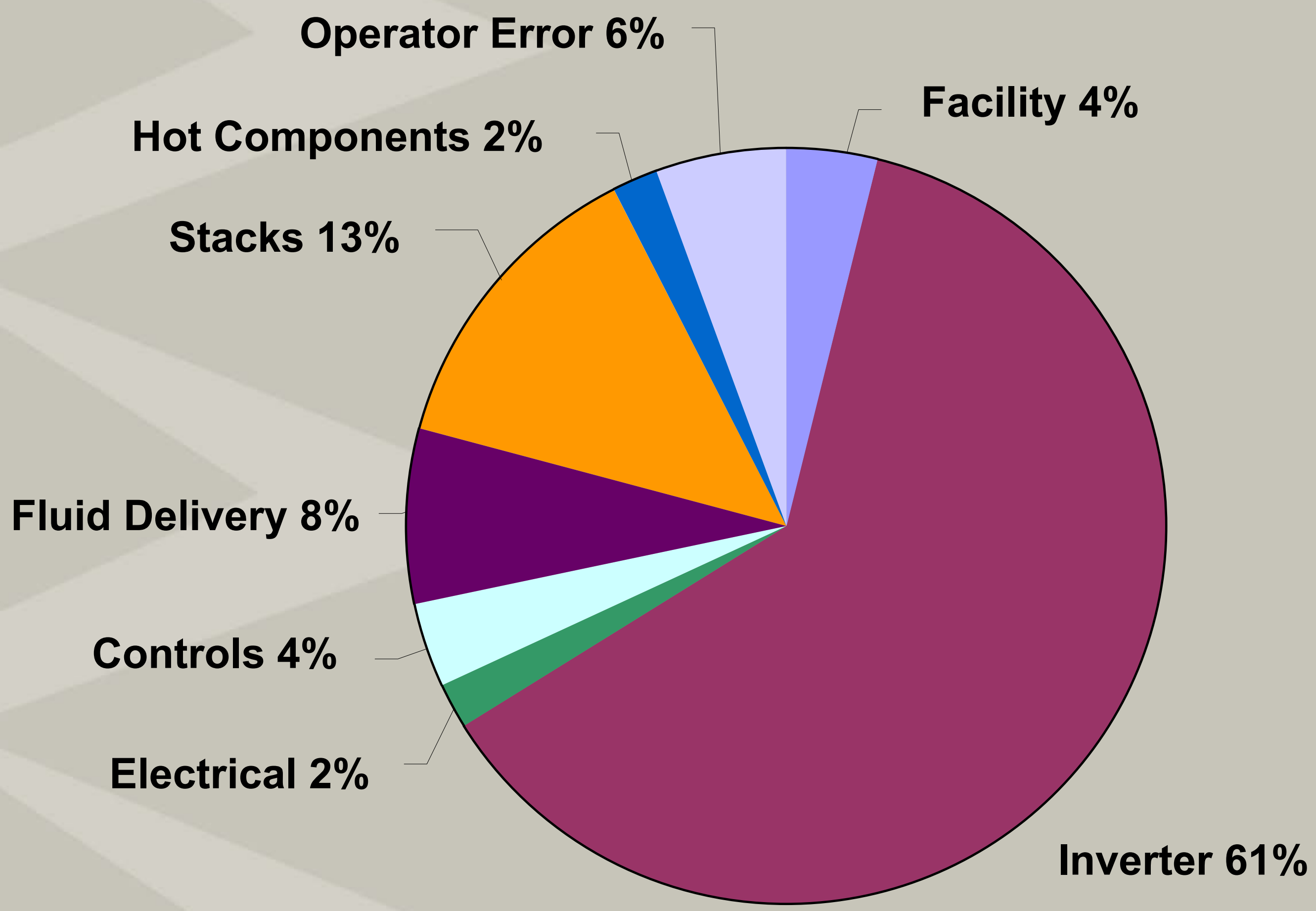
Natural Gas Fuel
Grid Parallel

RP-2 Prototype Highlights

Number of Systems Operated	5
Original Commission Date	May 2002
Final Decommission Date	December 2003
Total Hours Operated	24,387 hours
Total kWh Produced	7,856 kWh
Peak Net Power Output (AC)	2.1 kW
Peak Net Electrical Efficiency	31%
Total Thermal Cycles	39
Fleet Availability	50.7%

RP-2 Experience: Forced Outages

Opportunity: Improve BOP Reliability Also



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Aurora System

- Smaller volume ~ 1.3 m^3
- New approach to thermal integration to maximize performance, efficiency and controllability at 2 kW net AC
- Single 80 cell stack tower with external compression in compact Hot Zone
- Designed towards applicable codes and standards compliance

Aurora System Performance Summary

Heat-up Time (h)	**13**
Peak Net AC Power Output (kW)	**2.275**
Peak Net Electrical Efficiency (%)	**35.4%**
Average Net Electrical Efficiency (%)	**24.7%**

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System Development Plan

- Baseline System
  - Incorporate lessons learned from the CEC program and other on-going FCE activities
  - Upgrade the current kW-class system to expand operability on methanol and improve performance.
  - Target Capability: Handle 80% of US natural gas quality variations
  - Well-packaged 3 kW system suitable for delivery to the DOE NETL in 2006.
- Advanced System
  - Develop and incorporate advance options to improve efficiency and reduce cost (10 kW).

Summary

- **Cell and Stack technology development**
  - **Key mechanisms identified for performance and decay**
  - **20,000 h cell operation at 450 mA/cm^2 at 750°C**
  - **7,000 h cell with stable internal reforming**
  - **High volume manufacturing developed**
  - **Three 20-cell stacks accumulated over 12,000 h, 16 thermal cycles at 400 mA/cm^2 and 700°C**

Summary (continued)

- System Experience
  - Models developed for thermal management at high power density, verification in progress
  - kW-class systems accumulated greater than 24,000 h, peak net AC efficiency >30%
  - Opportunities for further improvement in mBOP and eBOP identified

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