Cell and Stack Development at Versa Power Systems

10th Annual SECA Workshop
Pittsburgh, PA
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Brian Borglum

FuelCell Energy

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Outline

- **Cell**
  - > **Process Background**
  - > **Scale-up**
  - > **Development Activities**
- **Stack**
  - > **Design Background**
  - > **Testing Methodology**
  - > **Scale-up**
  - > **Development Activities**
- **Conclusions**

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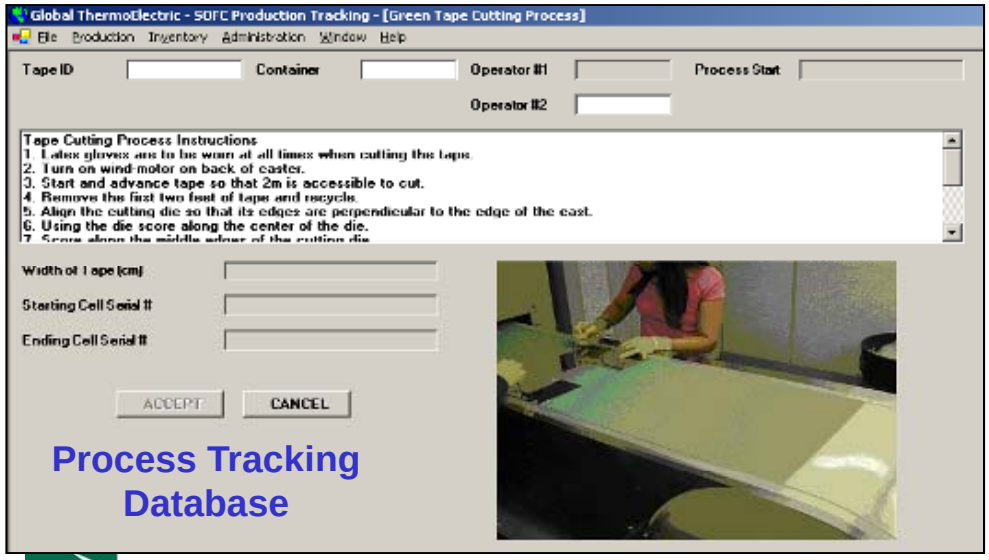
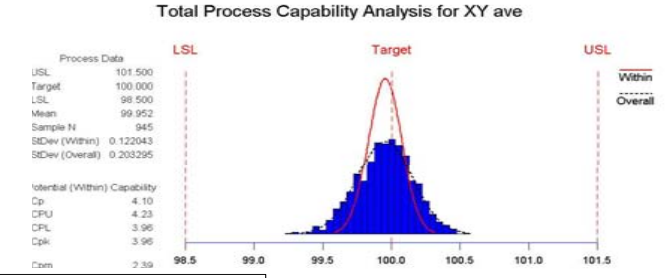
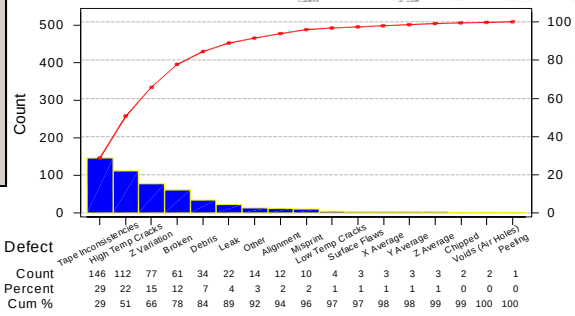
Cell Manufacturing Process

These processes are flexible & scalable to high volume and low cost production



Process Tracking Database





Statistical Process Control

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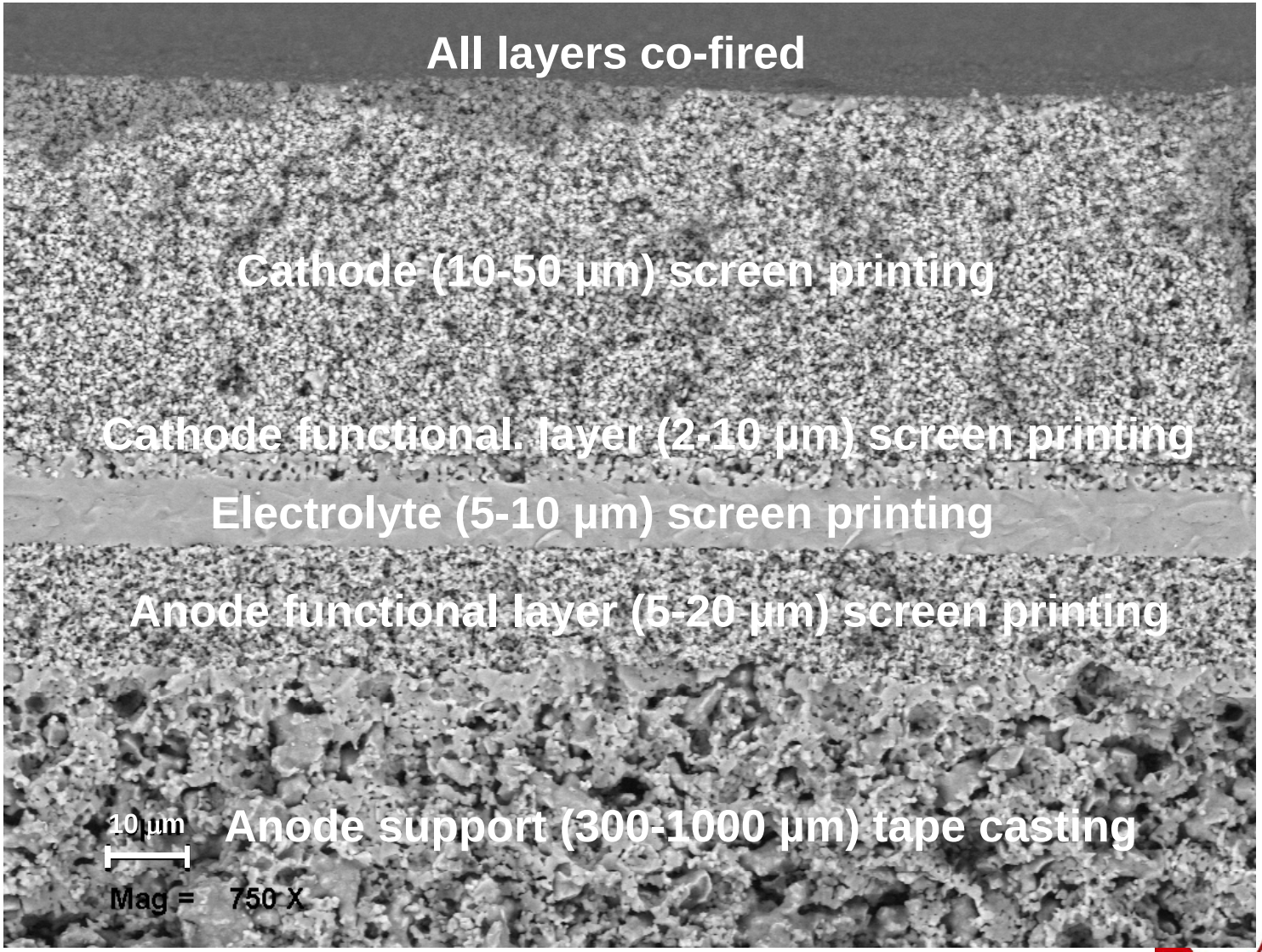
Cell Microstructure – SEM Image



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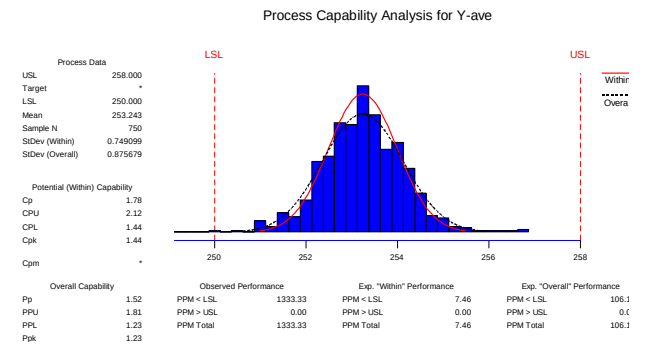
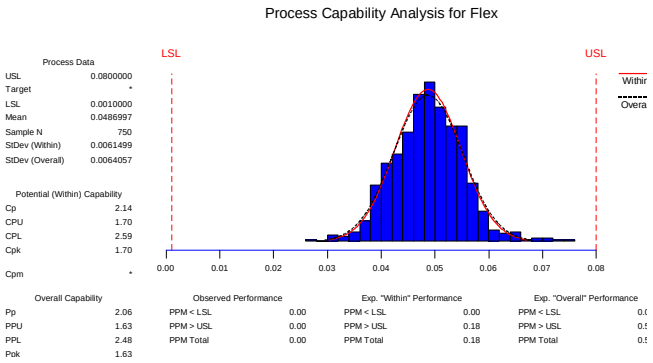
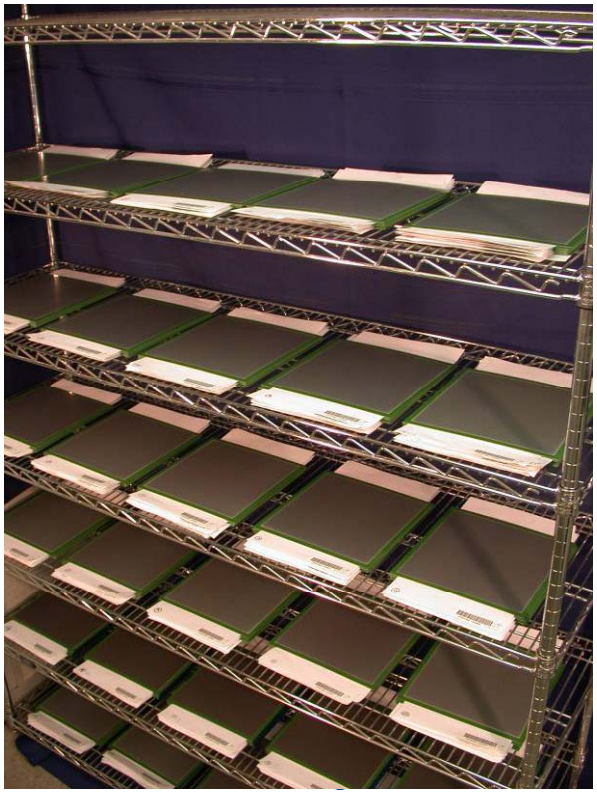
Cell Scale-Up Development

- Capital equipment for all major process units was added in order to accommodate increased cell size and volume (1 MW annual capacity)
- Cell process development was conducted to evaluate process capability for cells up to 33 x 33 cm^2
- 25 x 25 cm^2 cells with 550 cm^2 active area were selected for stack development
- More than 2000 cells (25 x 25 cm^2) have been fabricated - production yields greater than 95% and volumes of 500 kW (annual) have been demonstrated

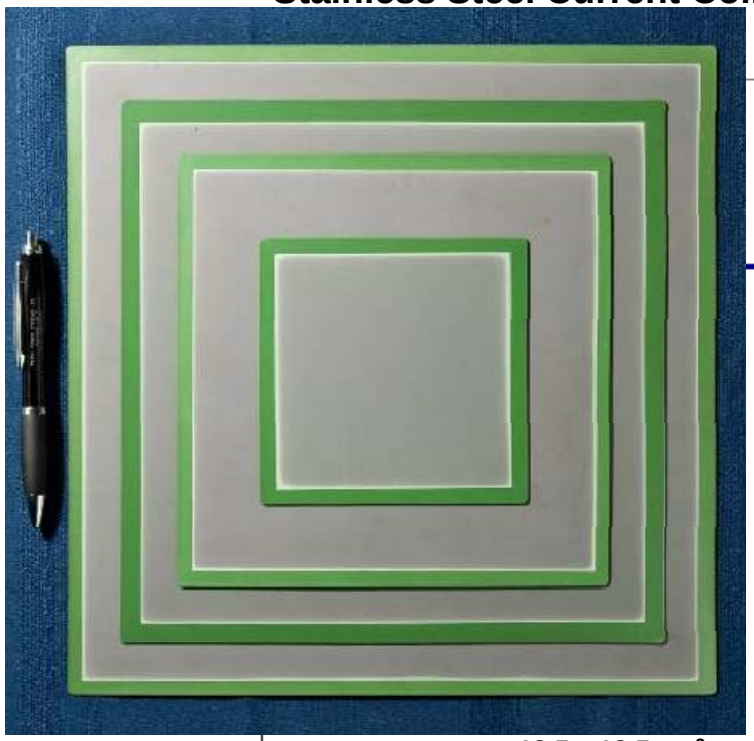






Cell Scale-Up Testing Summary

Stainless Steel Current Collectors, Cross-Flow Gas Delivery



Power	49	72	214	346	612
Power Density	0.608	0.598	0.612	0.606	0.612

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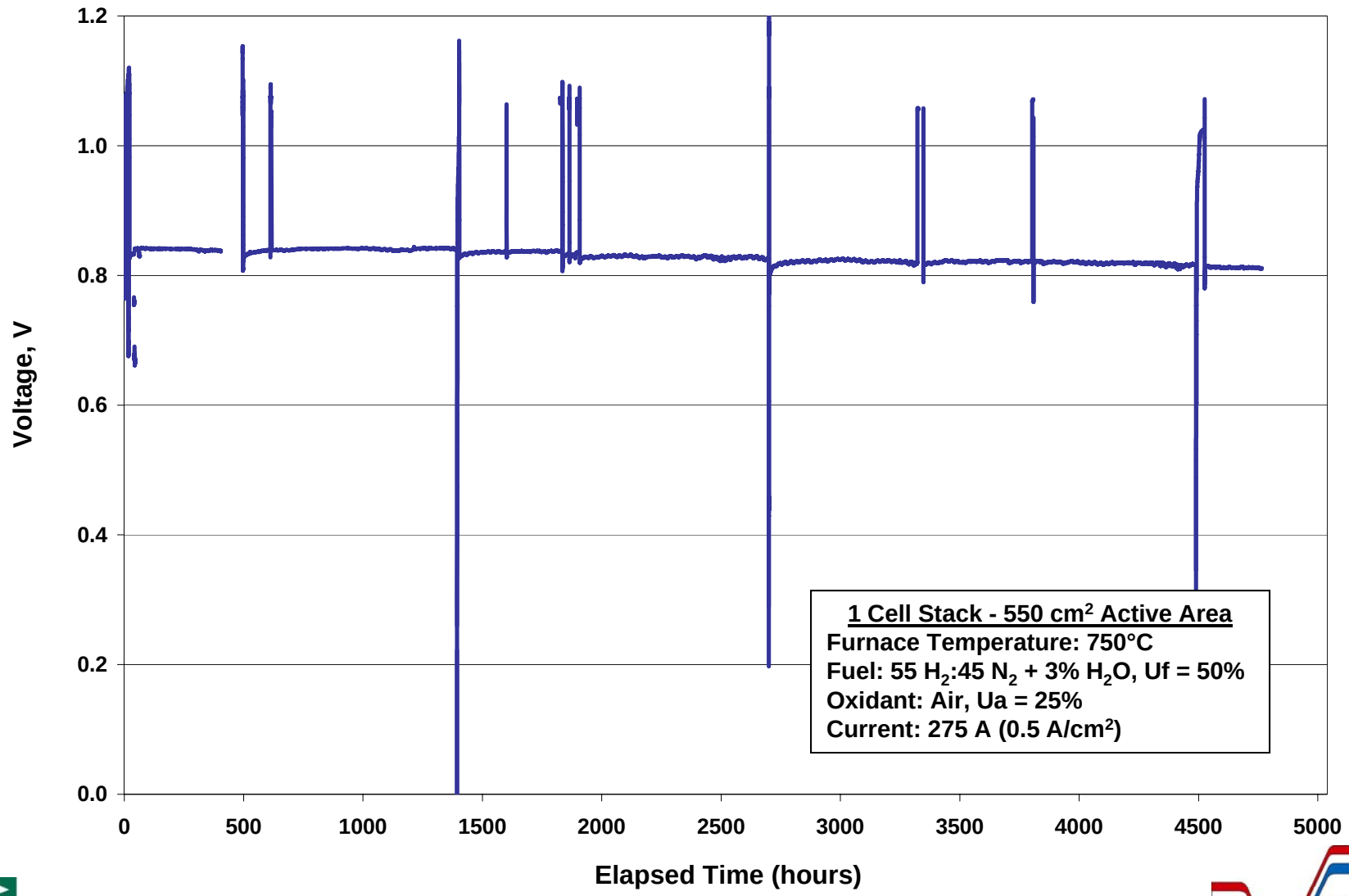
25 x 25 cm^2 – Long Term Testing



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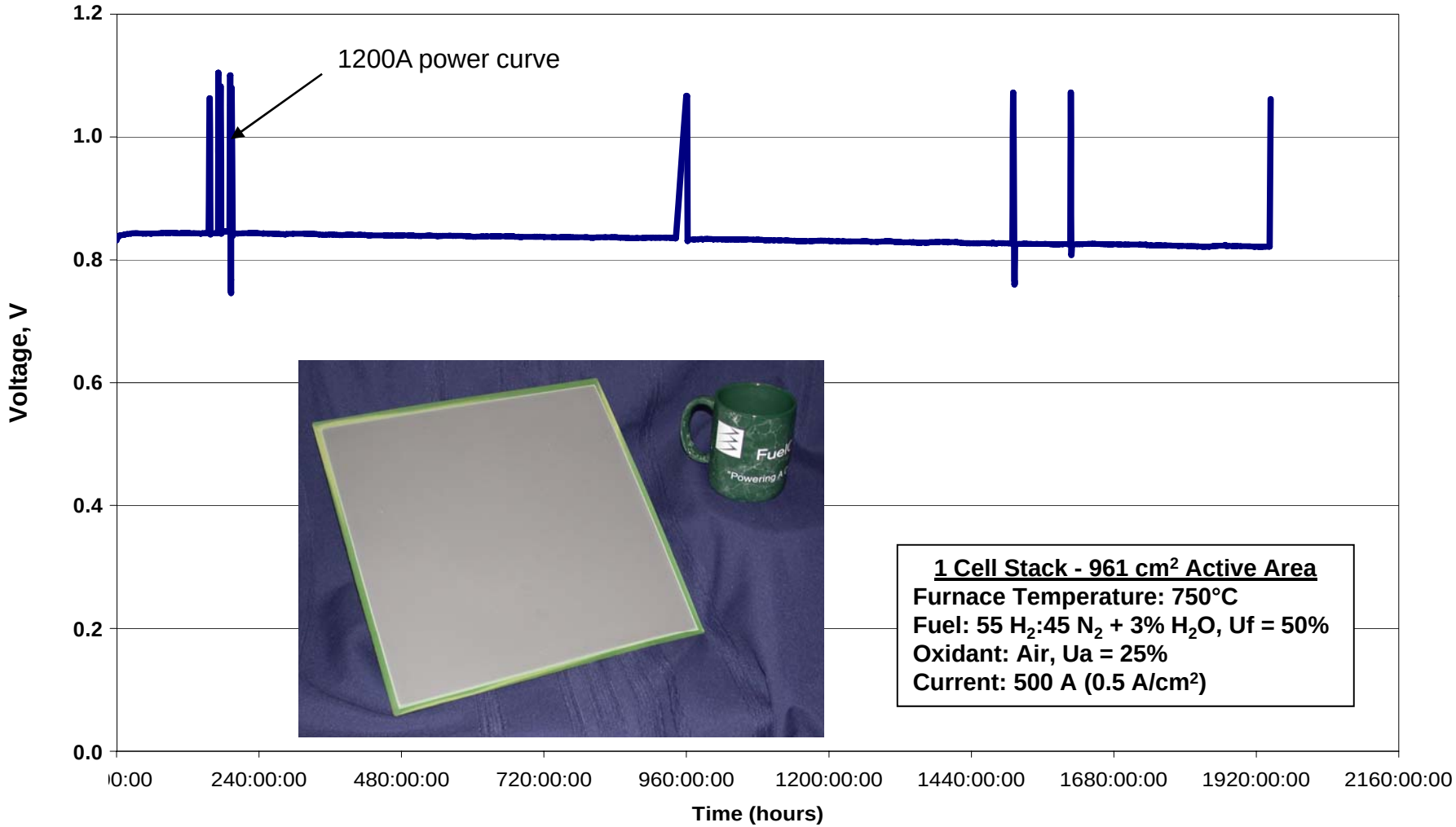
33 x 33 cm^2 – Long Term Testing



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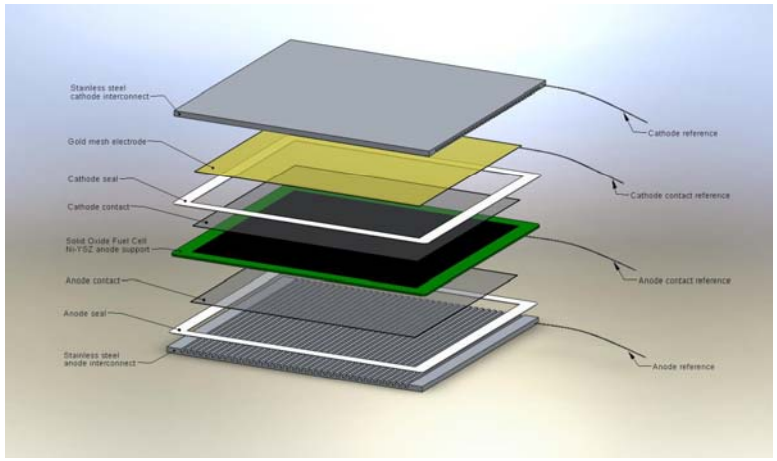
Materials Research Activities

- Investigate degradation mechanisms at various operating conditions
- Reduce cell degradation
- Enhance cell performance
- Develop thinner scaled-up cells
- Evaluate metallic alloys and coating technologies



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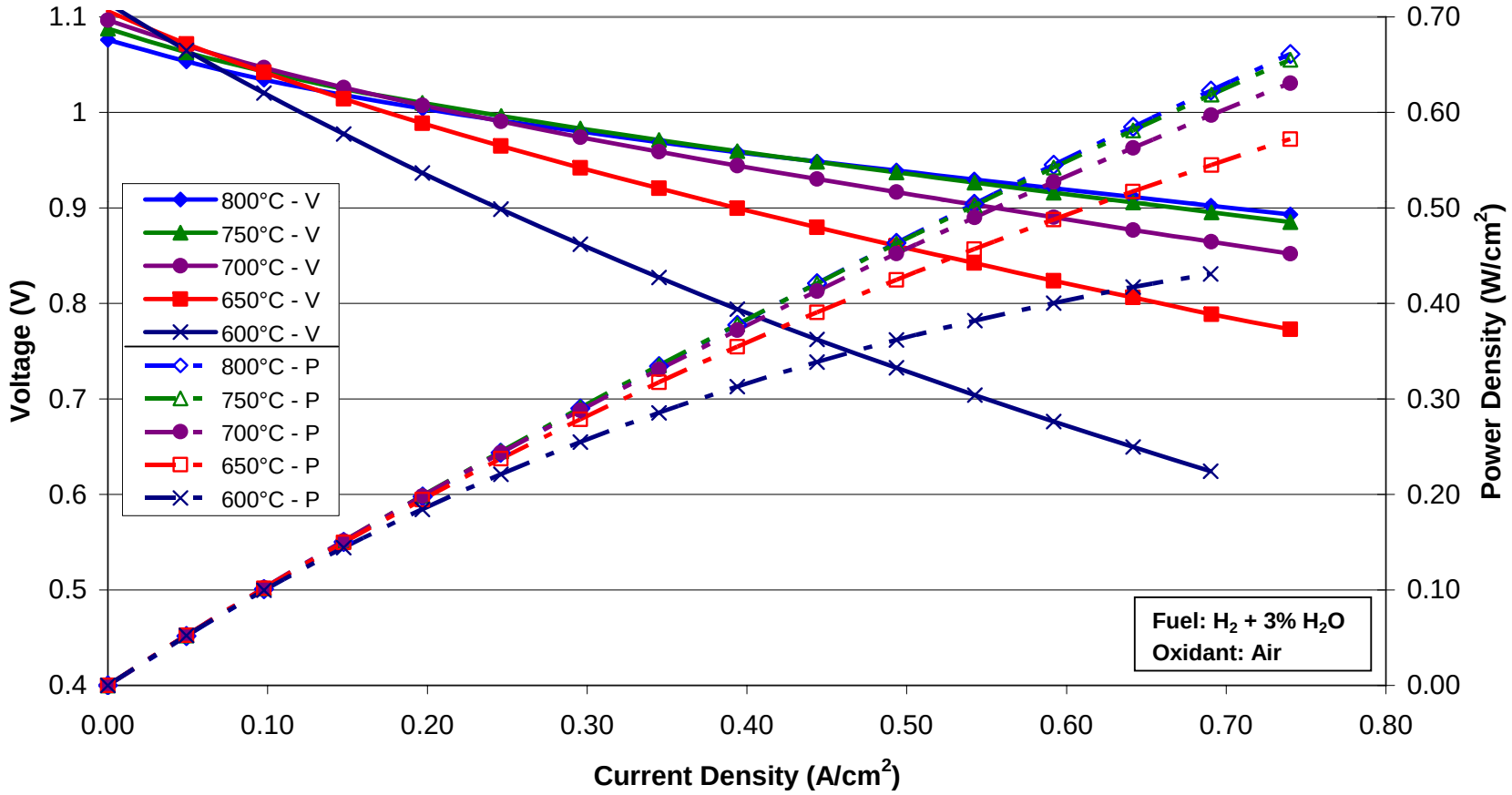
Cell Performance Enhancement

10 x 10 cm^2 Cell. Stainless Steel Current Collectors. Cross-Flow Gas Delivery



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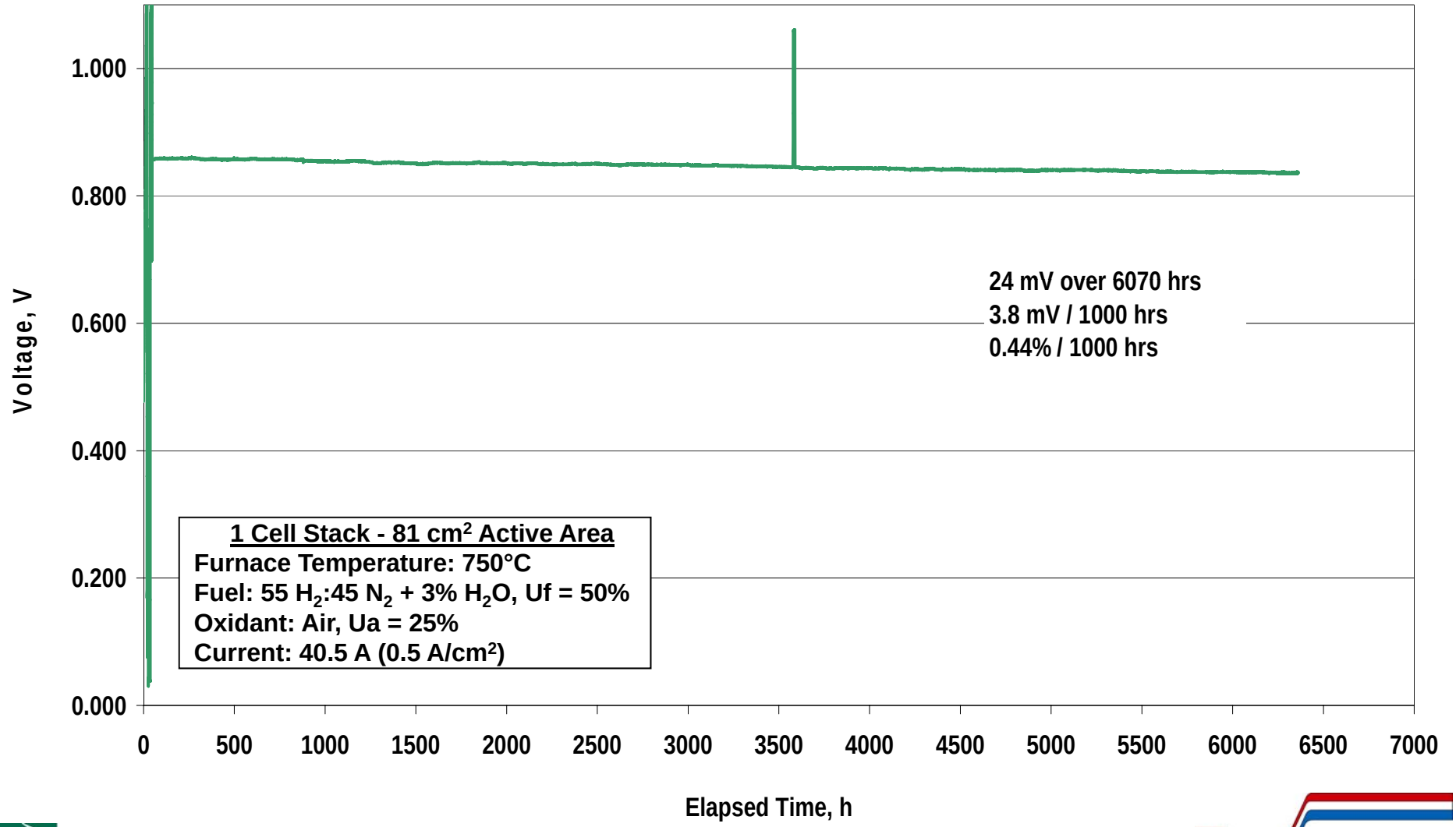
Cell Endurance Enhancement



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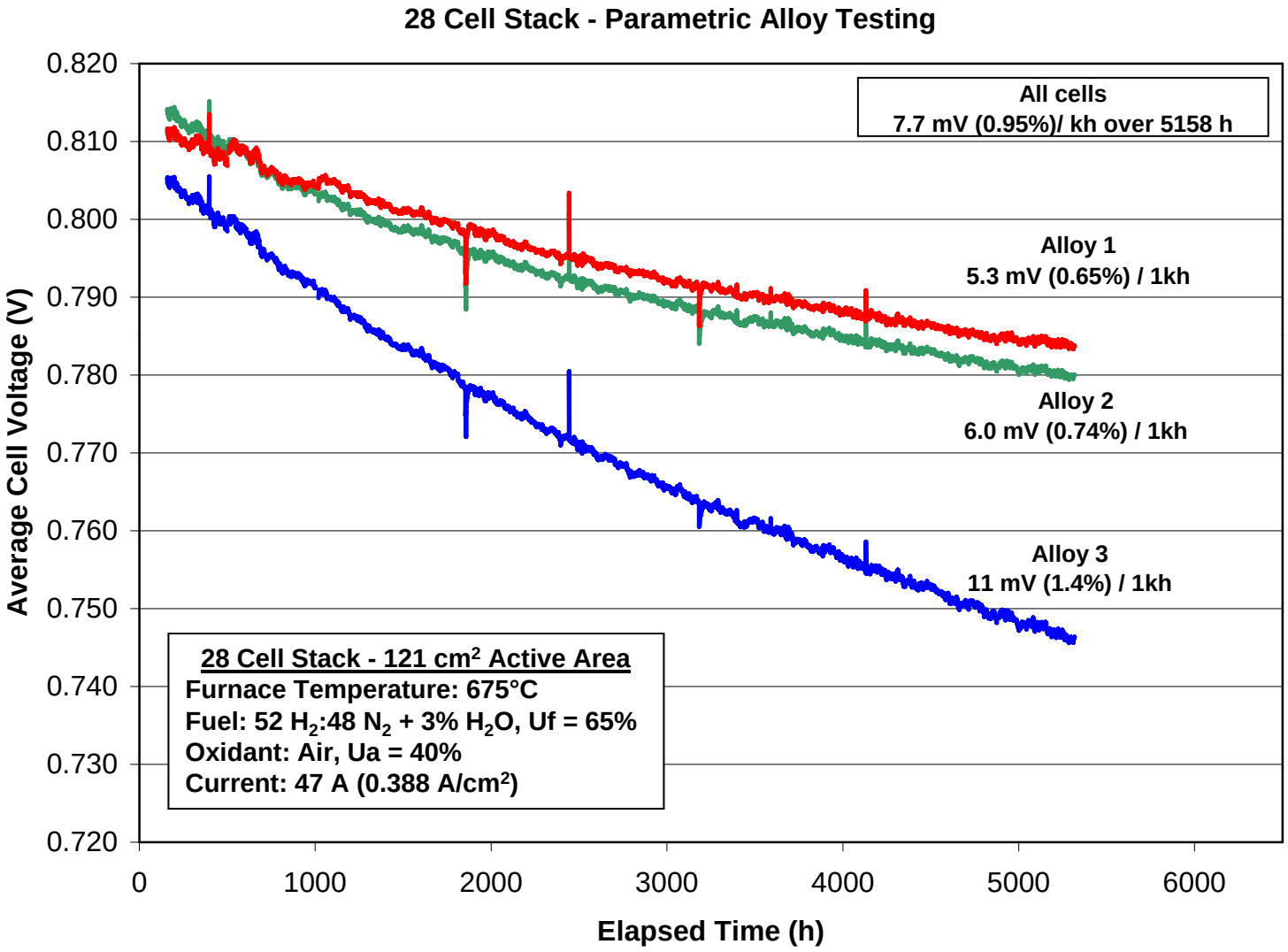
Alloy Investigation Using 28 Cell Stack



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Stack Development

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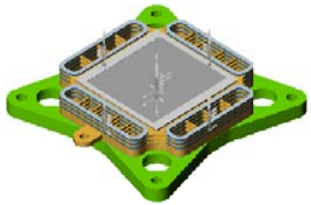
Stack Development Methodology



Component Development

Cell

Seal

Interconnect

Contacts

Current Collection

Flow Management

Thermal Management

Manufacturability

Repeatability

Tolerance

Technology Development

Stack Engineering & Integration

Process Development and Piloting

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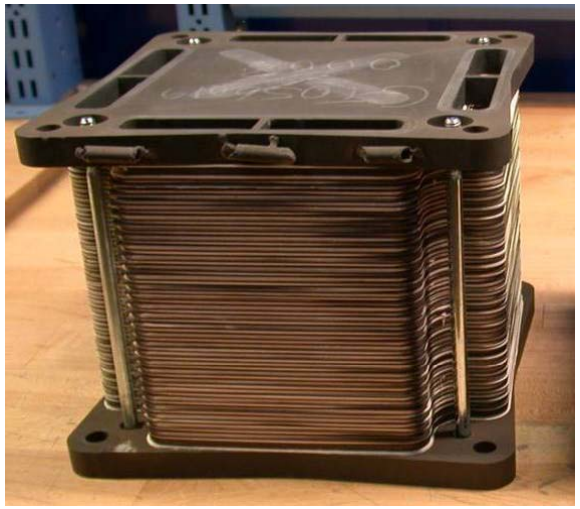
1 kW Stack Module



- Ferritic stainless steel sheet metal interconnect
- Cross-flow gas delivery with manifolds integrated into the interconnect
- Compressible ceramic gasket seals
- Cell Active Area = 121 cm^2
- Number of Cells = 28
- Successfully implemented in a 4 x 1 kW configuration, with multiple long term tests

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Stack Testing:
Characterization & Qualification

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Stack Testing:
Characterization & Qualification

- **Defined stack testing and qualification criteria are used to at VPS in order to assess the initial quality of a stack before it is used for other purposes:**
  - > **Long-term testing which studies voltage degradation over time**
  - > **Thermal cycle testing**
  - > **Delivery to external customers**

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Stack Qualification Minimum Requirements

Description	*Condition*	*Requirement*
Open Circuit Voltage	1.65 slpm/cell H_2, 1.35 slpm/cell N_2, 3% H_2O	All cells > 1.01 V
Full Flows	28% Uf, 34% Ua, 0.500 A/cm^2	All cells > 0.8 V
Air Utilization	50% Uf, 60% Ua, 0.388 A/cm^2	All cells > 0.7 V
Fuel Utilization	75% Uf, 50% Ua, 0.388 A/cm^2	All cells > 0.7 V
Thermal cycle degradation	Each condition is compared before and after thermal cycle at 0.500 and 0.388 A/cm^2	Cell degradation < 0.006 V
Hold	Stack held at 65% Uf, 35% Ua, 0.388 A/cm^2 for 50 h	Cell degradation < 0.010 V

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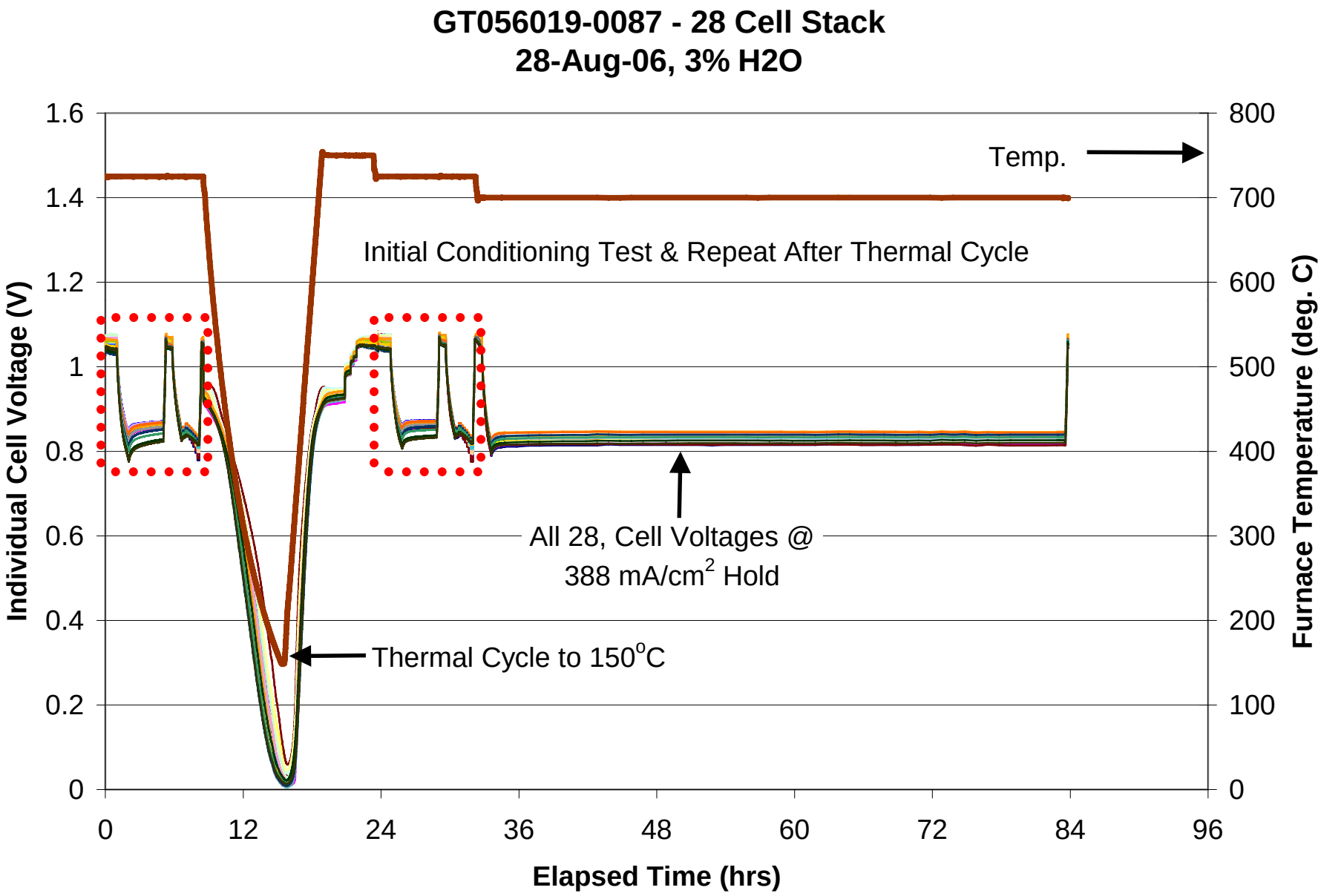
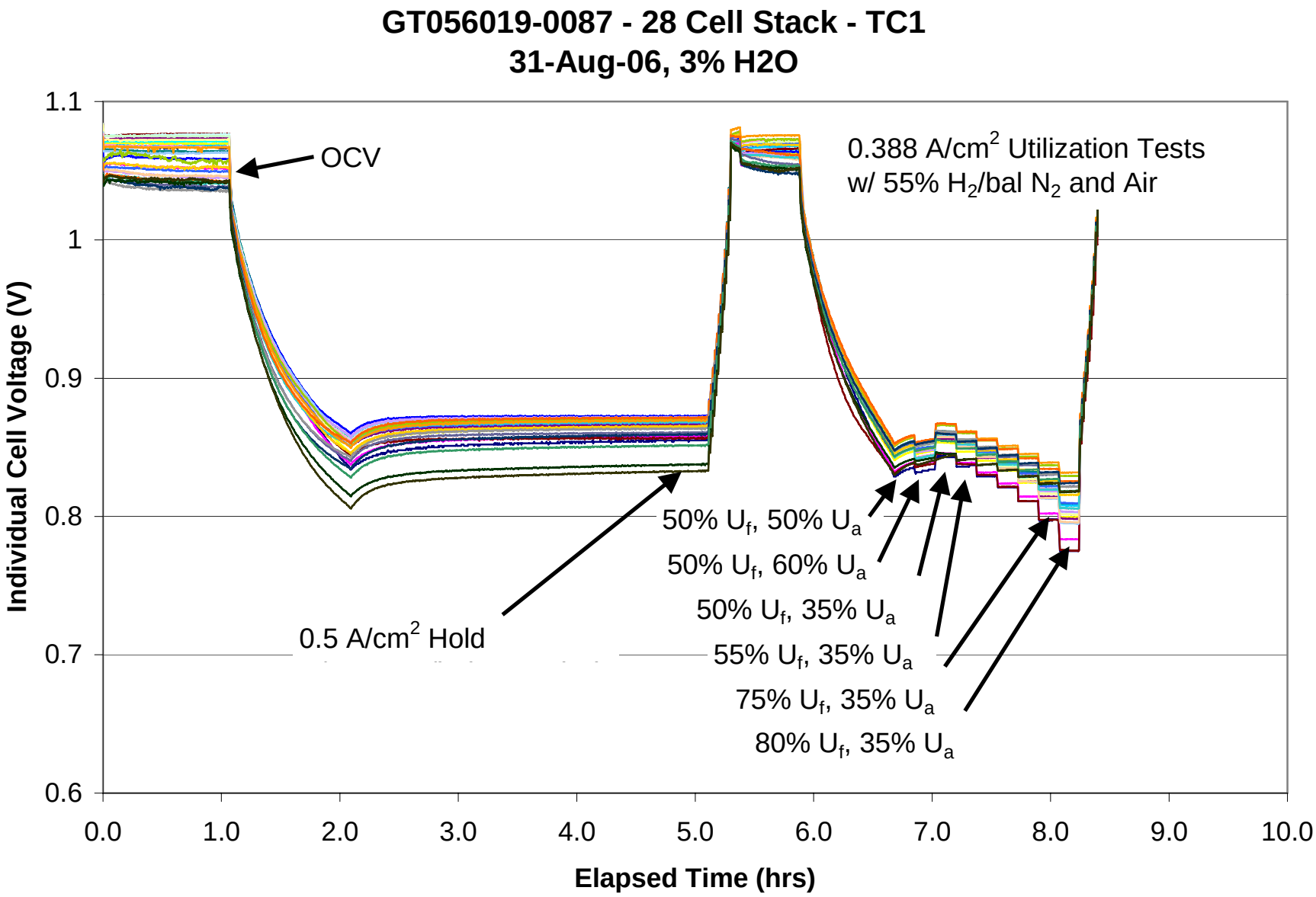
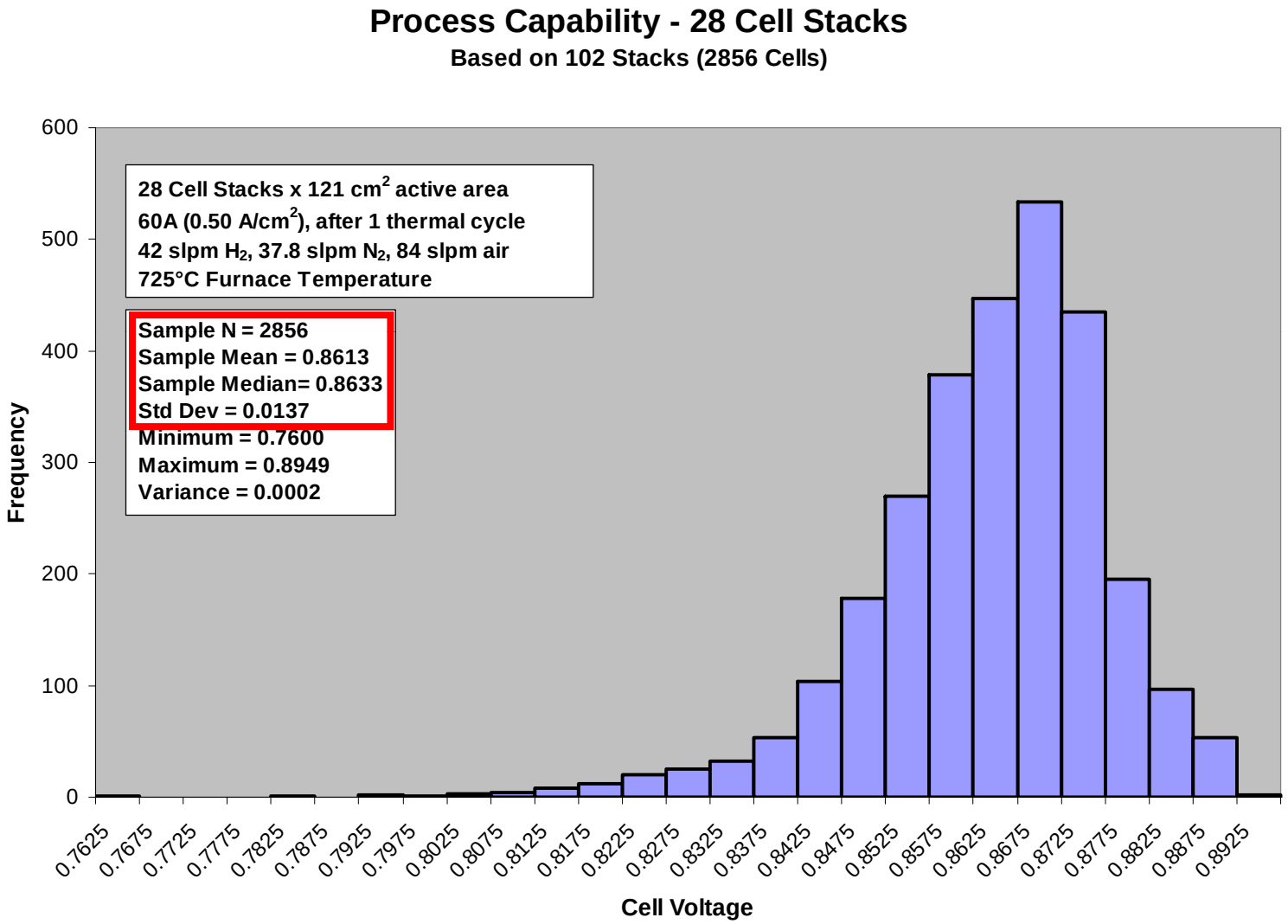
Standard Qualification Testing



Standard Qualification Testing – TC1



Process Capability:
28 x 121 cm^2 active area cells



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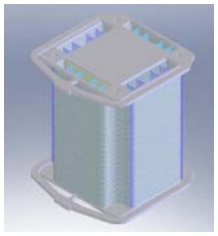
The SECA Challenge

Develop a SOFC stack that accomplishes all performance & cost requirements, can scale to a suitable stack block, progress to stack tower and SOFC power module

SOFC Power Module

Stack Tower

10 kW Stack



1 kW Stack

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Phase I Metric Test

PHASE I Metric Test SECA Coal-Based Systems	
DELIVERABLE POWER RATING	≥10kW
STEADY STATE TEST (Normal Operating Conditions)	5000 hours
	Δ Power < 4.0% degradation/1000 hours
TEST SEQUENCE	1) Start-up 2) Peak Power Test 3) Steady State Test 4) Shut-down
FUEL TYPE	Simulated (subject to DOE concurrence, up to 25% CH_4, dry basis)
MAINTENANCE INTERVALS	Design aspects should not require maintenance at intervals more frequent than annually.

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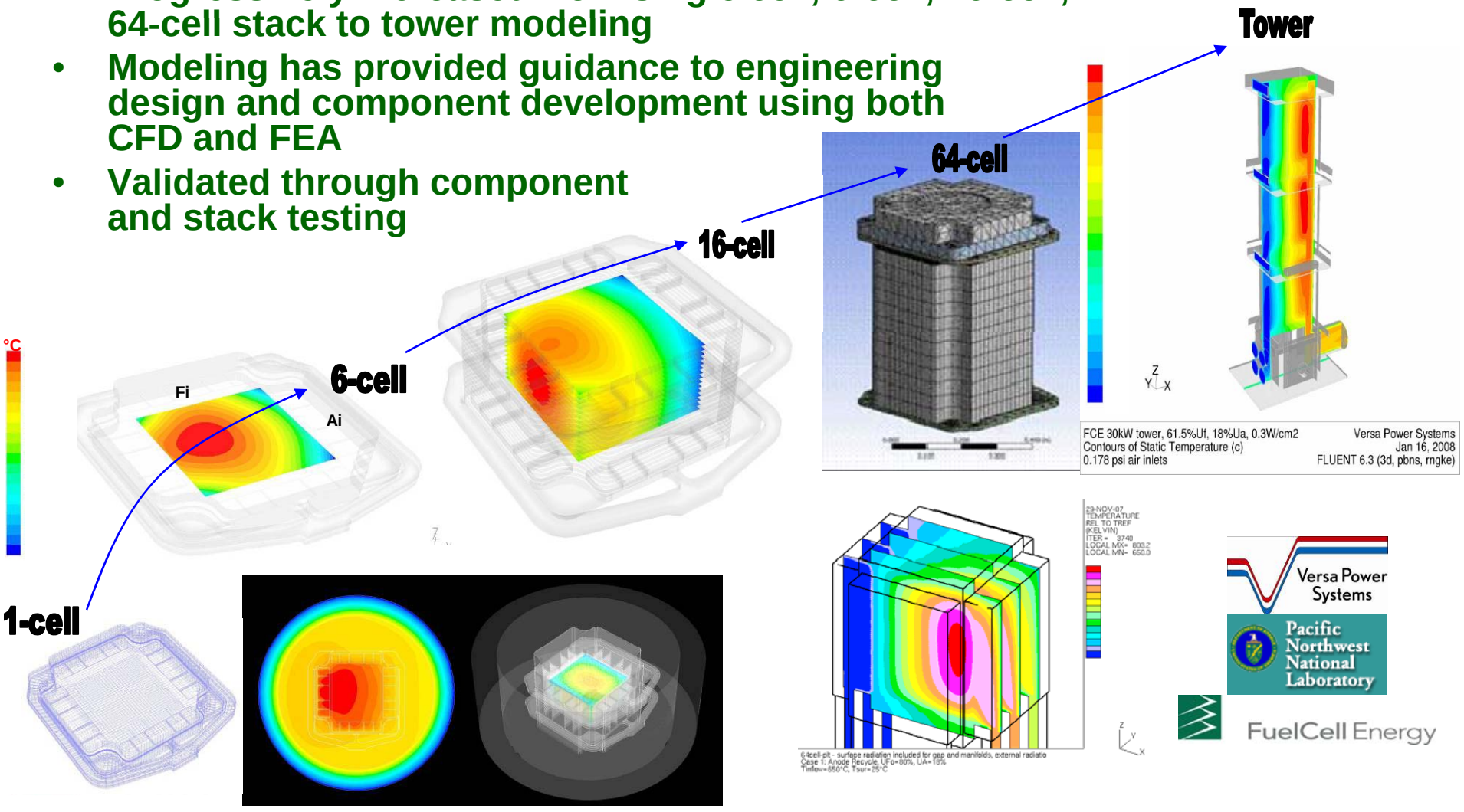
Stack Scale-up & Design

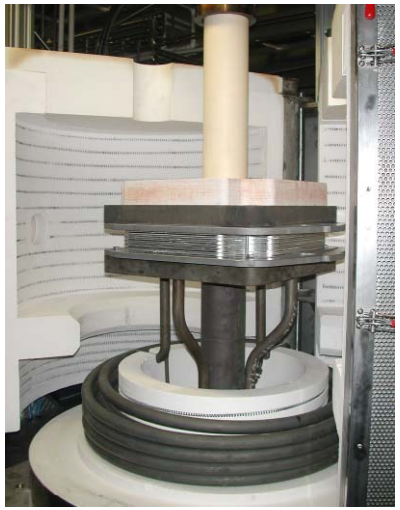
- VPS has used a modeling-driven design approach for specific challenges in conjunction with PNNL & FCE
- Progressively increased from single cell, 6-cell, 16-cell, 64-cell stack to tower modeling
- Modeling has provided guidance to engineering design and component development using both CFD and FEA
- Validated through component and stack testing



Stack Scale-up Progression

0.16 kW
1-cell

1 kW
6-cell



2.5 kW
16-cell

10 kW
64-cell

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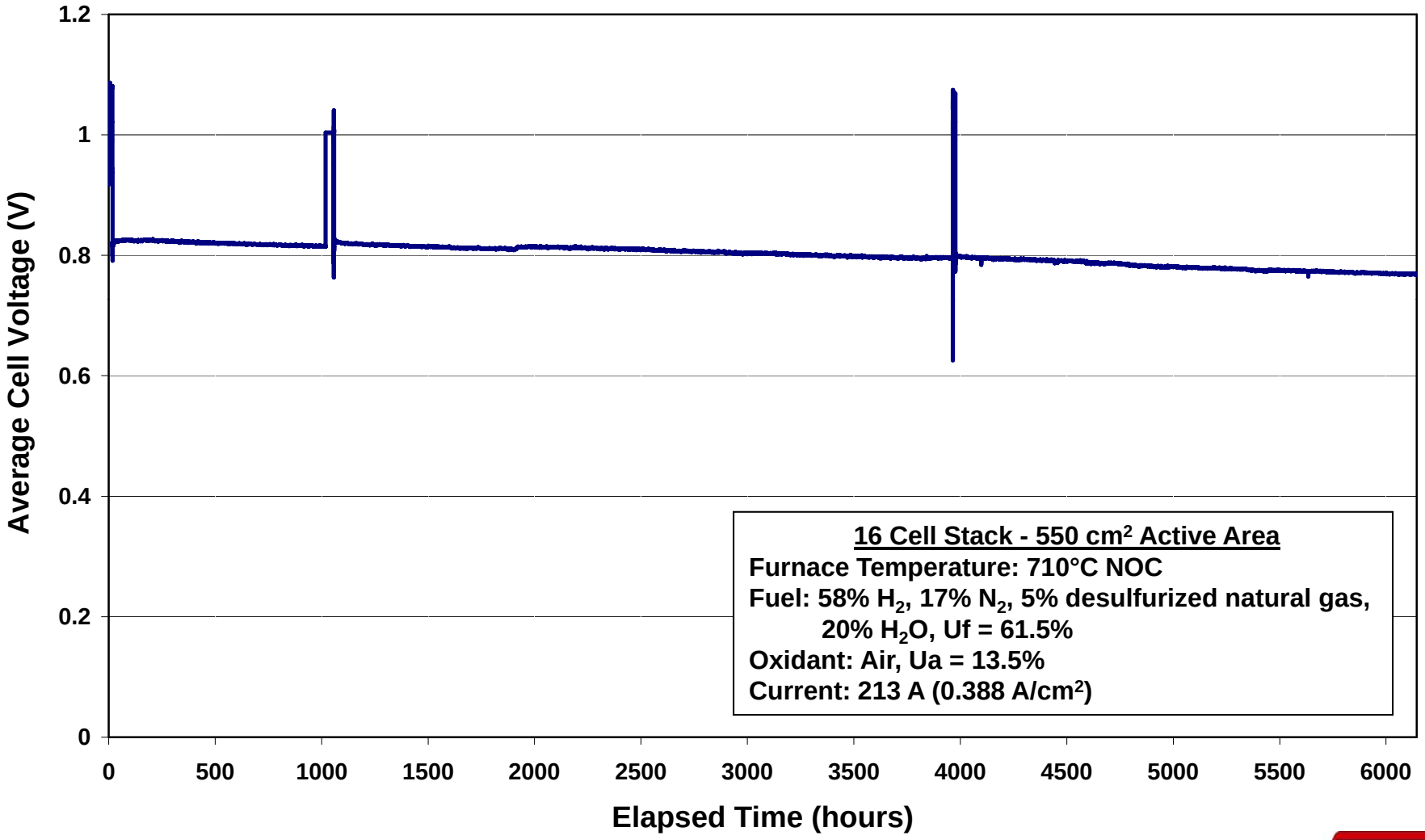
16-cell Stack – Long Term Testing



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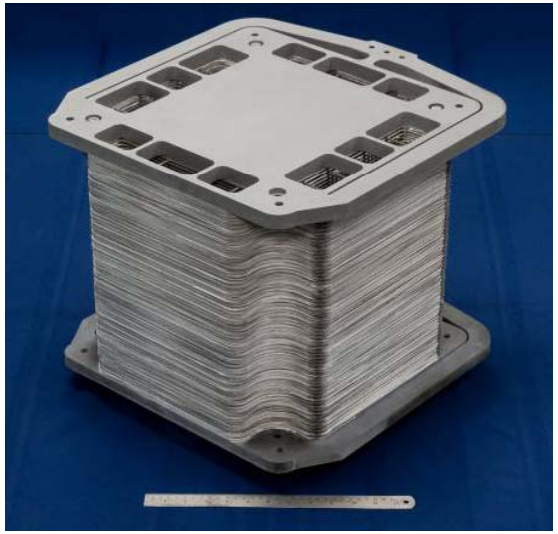
64-cell Stack - Normal Operating Conditions



Normal Operating Conditions – BOL	
Fuel Utilization	61.5%
Air Utilization	10 to 18%
Stack Current	200 A (364 mA/cm^2)
Gross DC Electrical Power	~10,000 W

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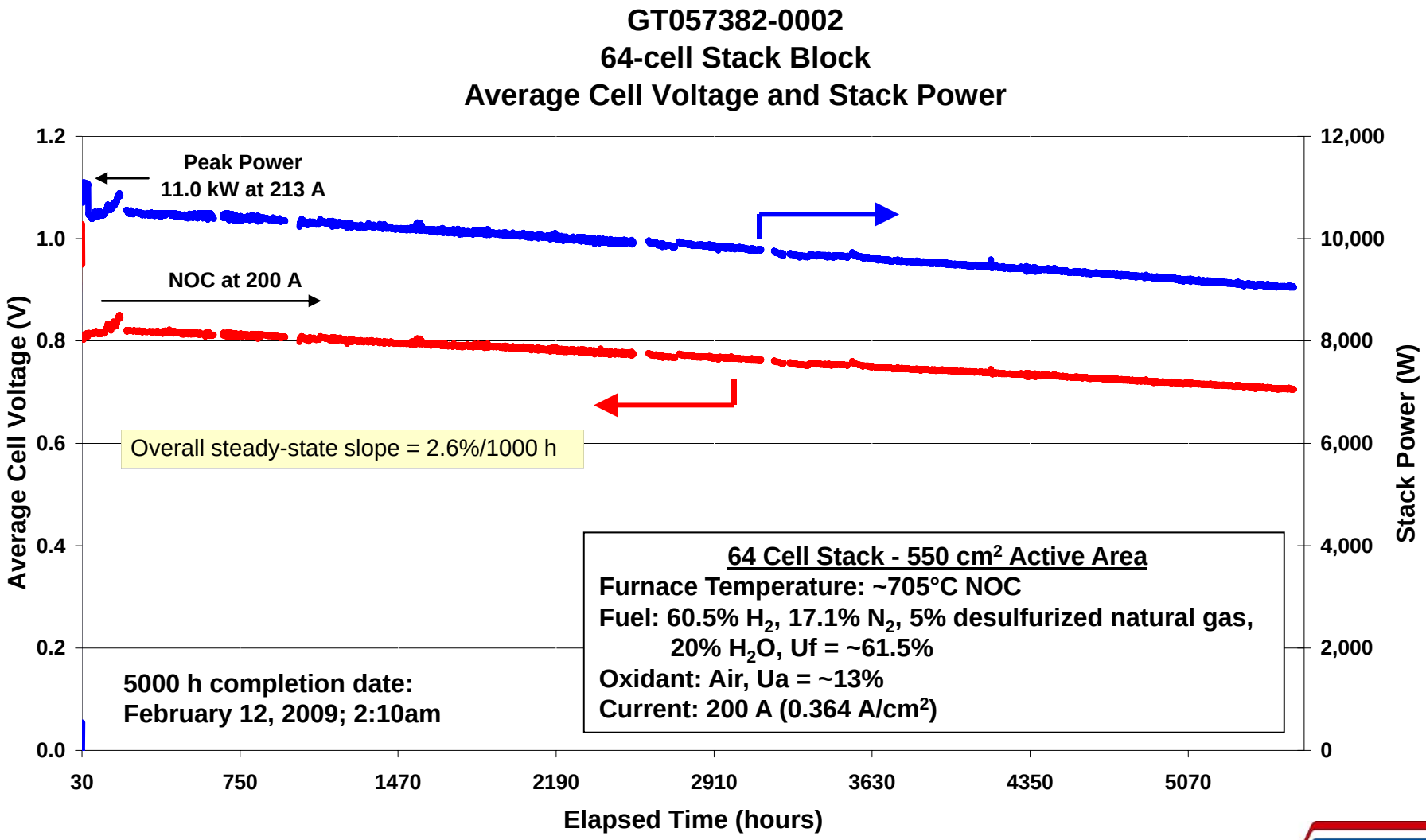
64-cell Stack – Long Term Testing



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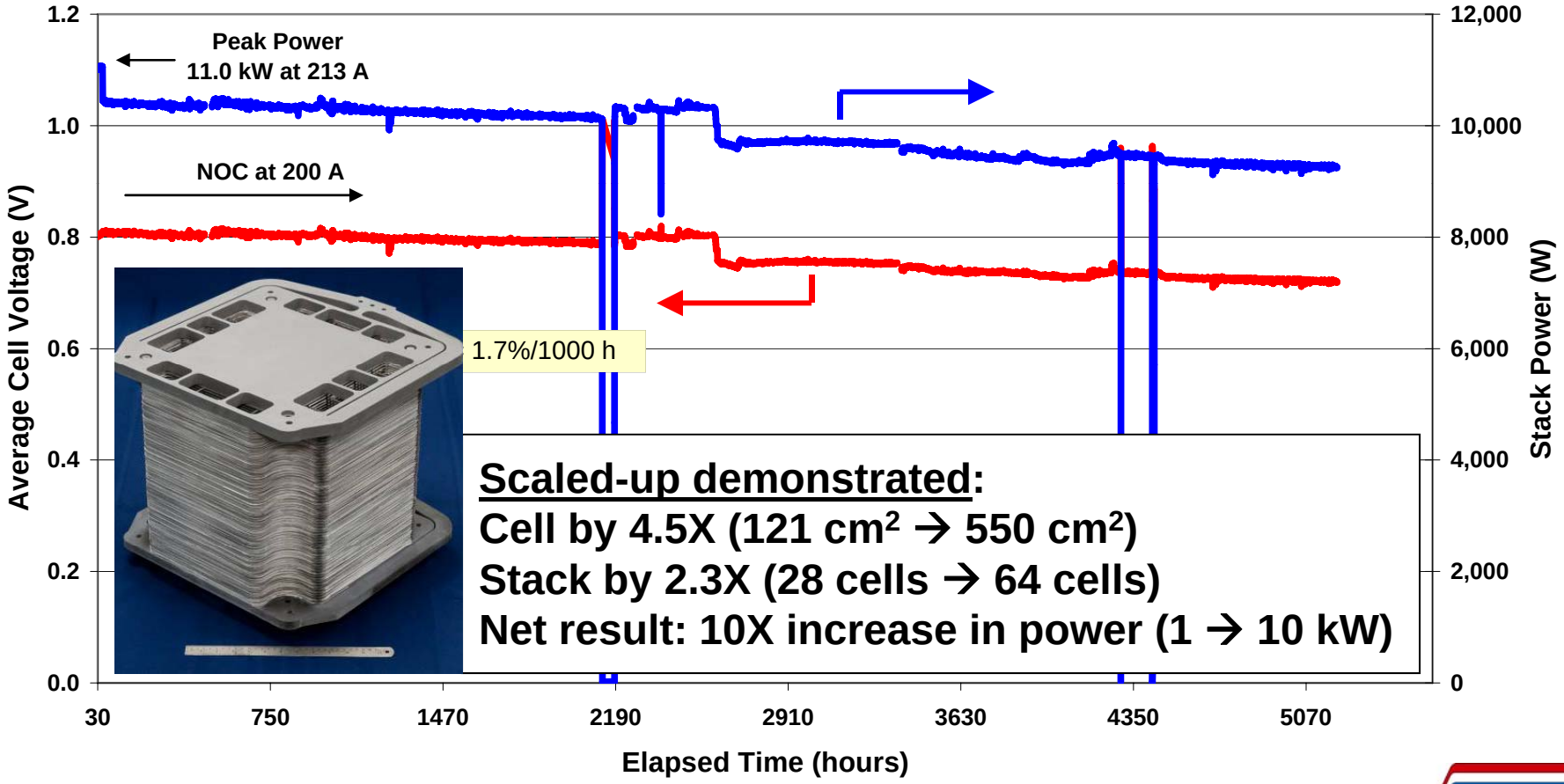
64-cell Stack – Long Term Testing

GT057382-0003
64-cell Stack Block
Average Cell Voltage and Stack Power



Scaled-up demonstrated:
Cell by 4.5X (121 cm² → 550 cm²)
Stack by 2.3X (28 cells → 64 cells)
Net result: 10X increase in power (1 → 10 kW)

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Publications
News Release

Release Date: March 24, 2009

Fuel Cell Stacks Still Going Strong After 5,000 Hours

SECA Fuel Cell Stacks Meet, Surpass DOE Goals

Washington, DC —Two fuel cell stacks developed by FuelCell Energy (FCE) in partnership with Versa Power Systems achieved 5,000 hours of service in February, meeting a goal of the U.S. Department of Energy's Solid State Energy Conversion Alliance (SECA). The milestone marks a step toward the ultimate SECA objective of providing low-cost solid oxide fuel cell (SOFC) technology for coal-based power plants and other power generation applications.

The FCE/Versa Power fuel cell stacks not only surpassed SECA's requirement of 5,000 hours of service, they also exhibited an overall degradation of only 1.7 percent and 2.6 percent per 1,000 hours—much less than SECA's 2008 (interim) target of 4.0 percent per 1,000 hours. One of the fuel cell stacks continues to run; the data will be used to further assess and refine the current design.

"The team's successful scale-up puts us firmly on the road to incorporating this highly efficient SOFC technology in a wide range of settings, including distributed generation and combined heat and power applications—from tens to hundreds of kilowatts and eventually, megawatts," said Robert Stokes, CEO of Versa Power Systems.

The fuel cells' strong performance has won a project continuation from DOE in which the FCE team is challenged to build a minimum 25-kilowatt SOFC stack that will meet SECA requirements for both performance and manufacturing costs. The new stack is to form the basis for a minimum 250-kilowatt fuel cell power module and a 5-megawatt proof-of-concept system that will operate on coal-derived synthesis gas, a fuel created by reacting coal at high temperatures. Fuel cell scale-up is part of SECA's manufacturing strategy to produce the overall lowest SOFC system cost.

Current Stack Development Initiatives

- Improve stack thermal management (dT reduction) through stack design and operating conditions
- Incorporate advanced cells & components in stacks
- Cost reduction initiatives
- Stack block power increase
  - 64 → 92 cell count

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Current Stack Development Initiatives

- 2009 focus is on 92-cell stack
  - >18-20 kW stack block
  - >Stack Tower Test Platform
- Potential future adjustments in cell count (~100 cells) in late 2009 / early 2010
- Modular tower development focusing on 3 or 4 x 96 cell tower (up to 384 cells)

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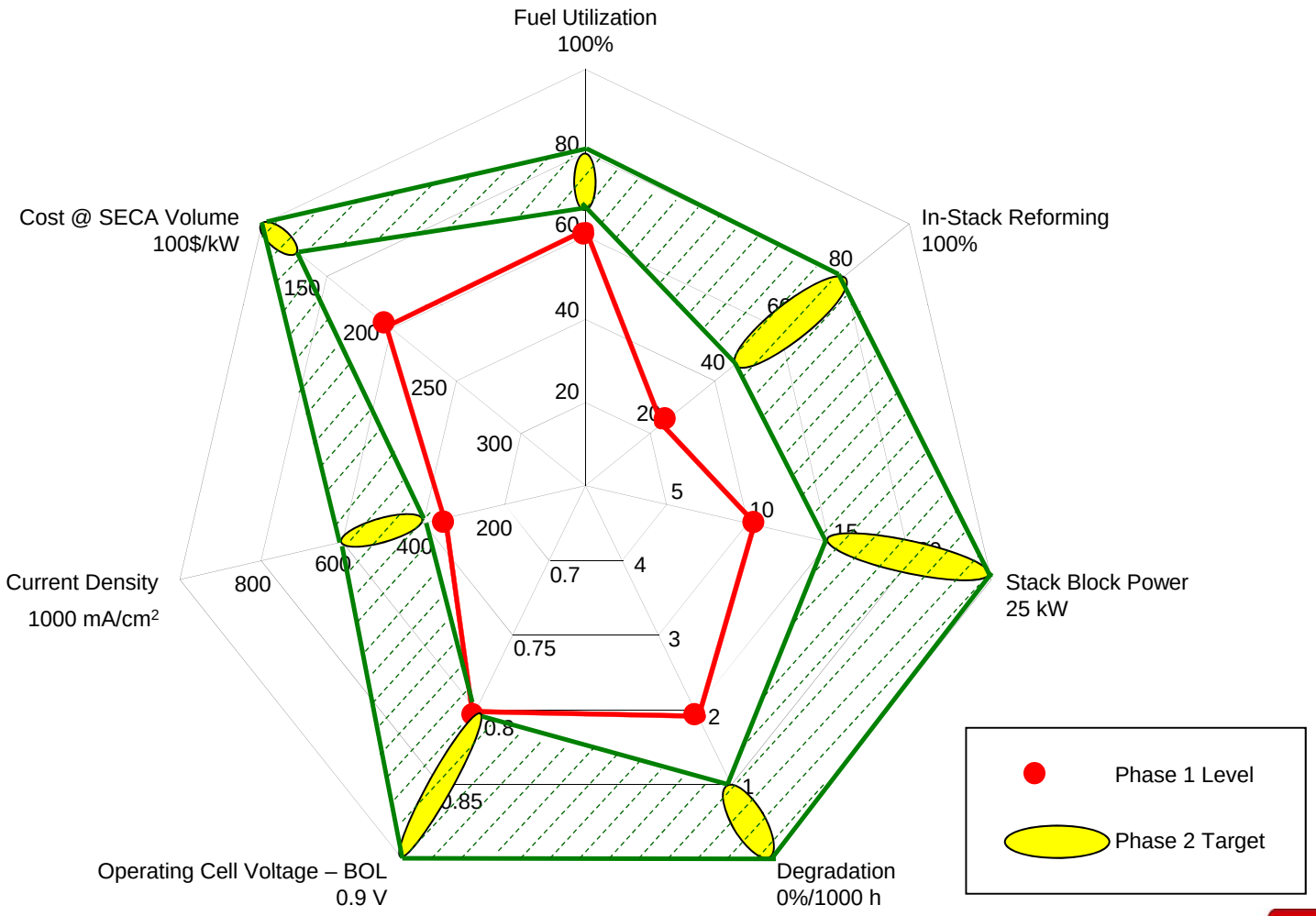
Stack Development Focus Areas



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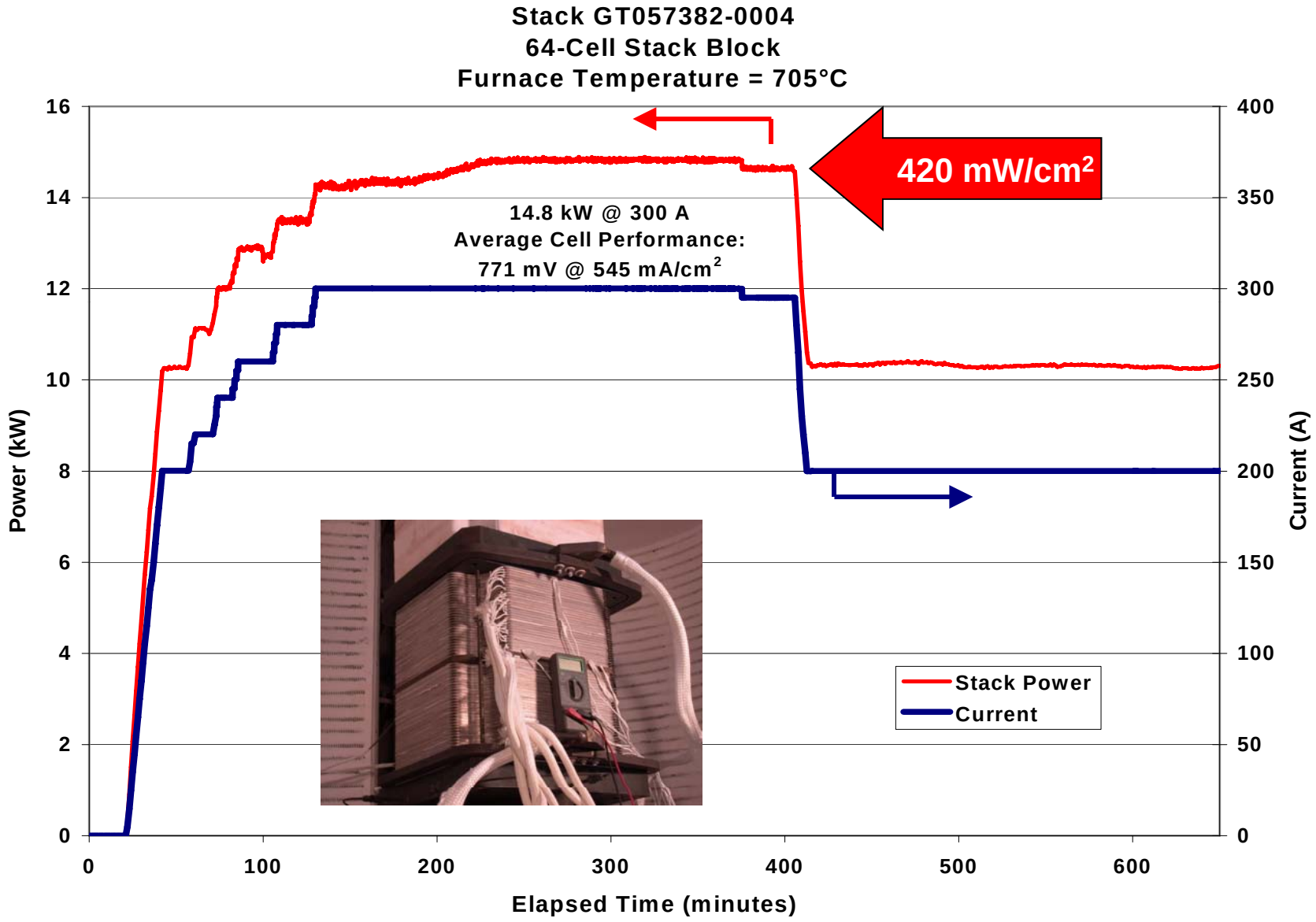
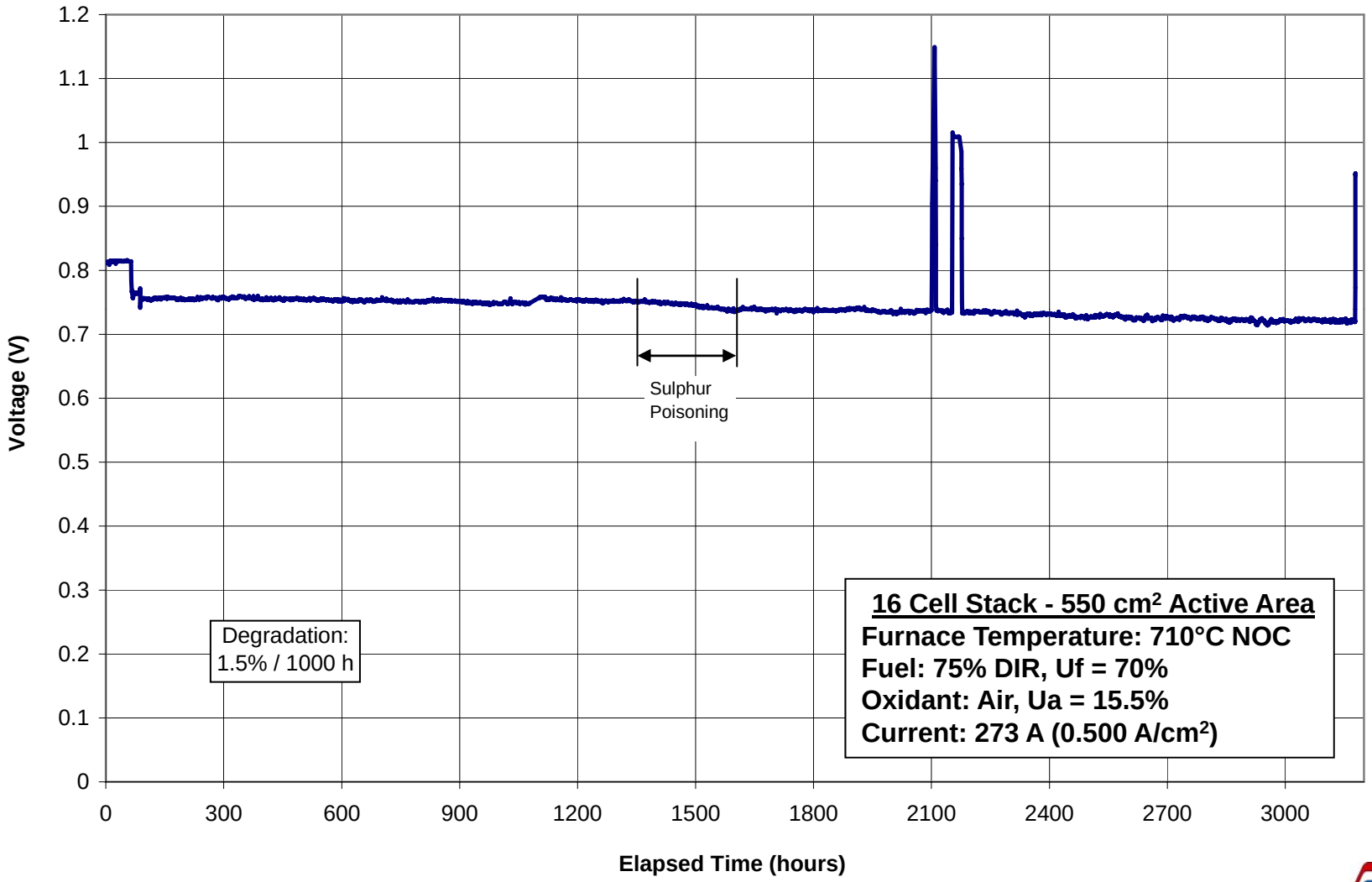
64-cell Stack – High Power Testing



16-cell Stack Operating Condition Test



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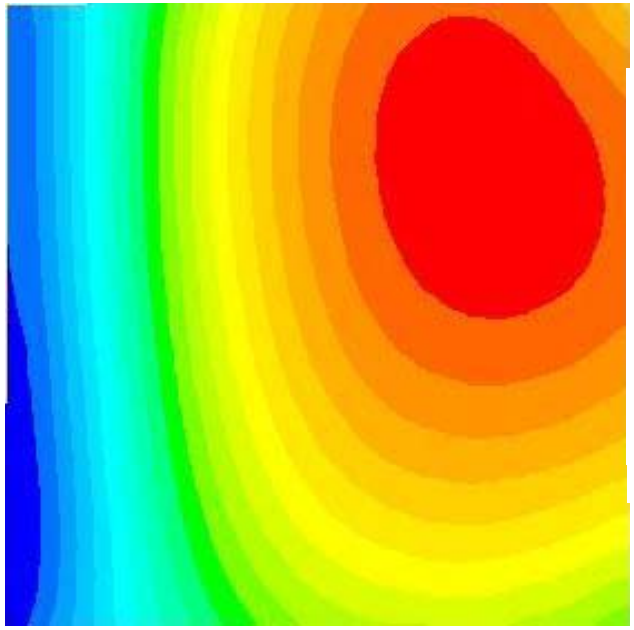
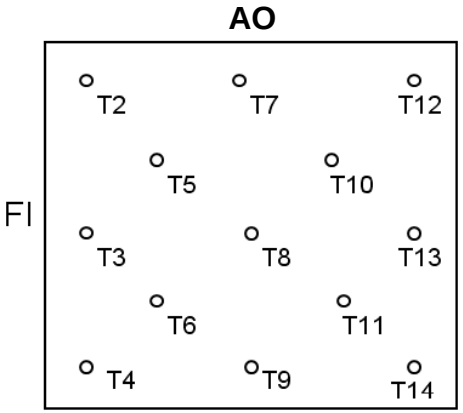
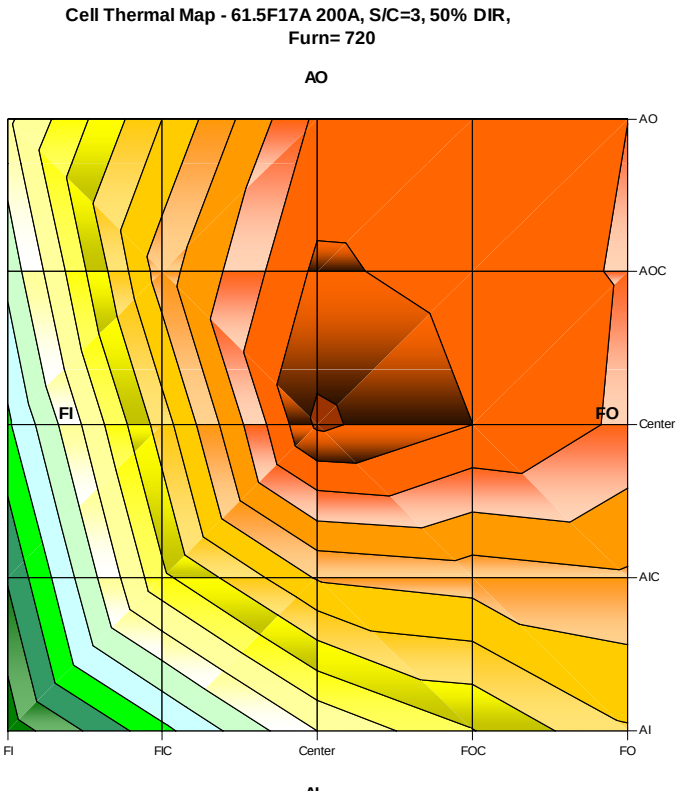
Comparison of Stack Thermal Profile: Model vs. Test

- VPS now routinely incorporate thermocouples into stack
- Provides temperature profiles at different stack cross-sections over test duration
- Validated CFD models allow virtual stack designs to be evaluated at BOL and EOL conditions







Modeled ***Measured***

***dT* = 82°C vs. 84°C**

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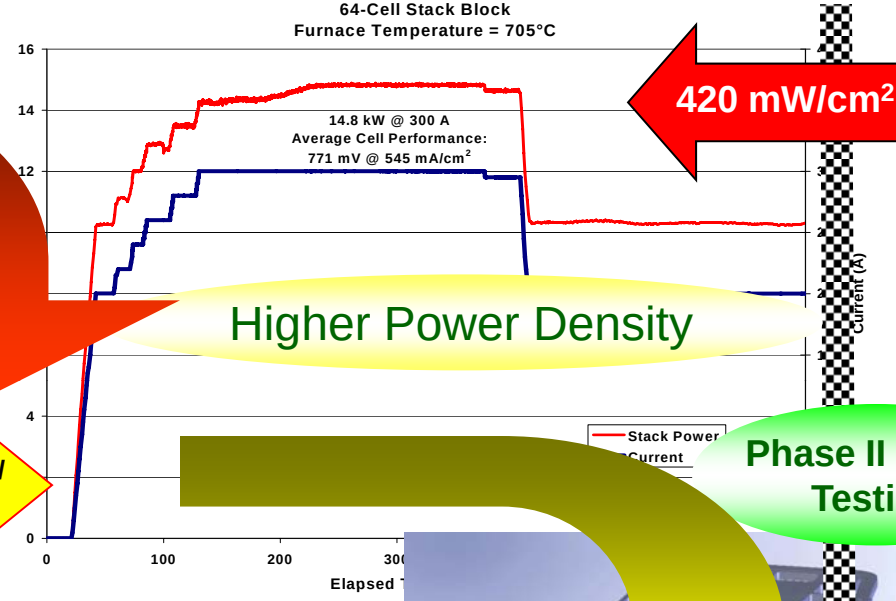
Phase II Stack Cost Reduction Path

$197/ kW

Stack GT057382-0004
64-Cell Stack Block
Furnace Temperature = 705°C

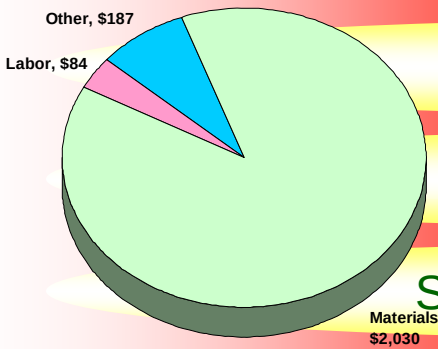


420 mW/cm²

Higher Power Density

$165/ kW

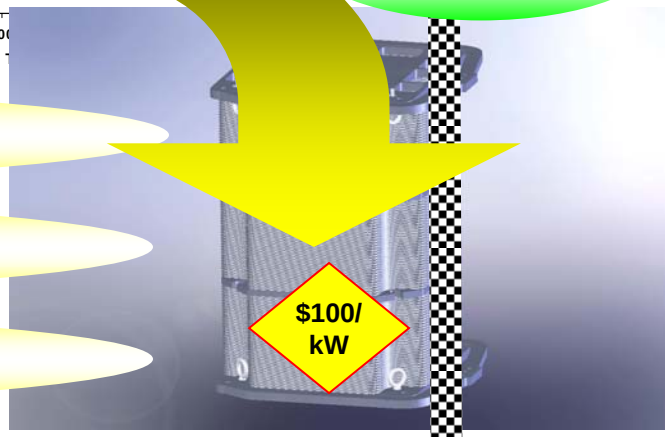
Phase II Metric Testing



Stack Block Scale Up

Thin Component Development

Stack Materials Reduction



$100/ kW

Q4 2008 | Q1 2009 | Q2 2009 | Q3 2009 | Q4 2009 | Q1 2010 | Q2 2010 | Q3 2010 | Q4 2010

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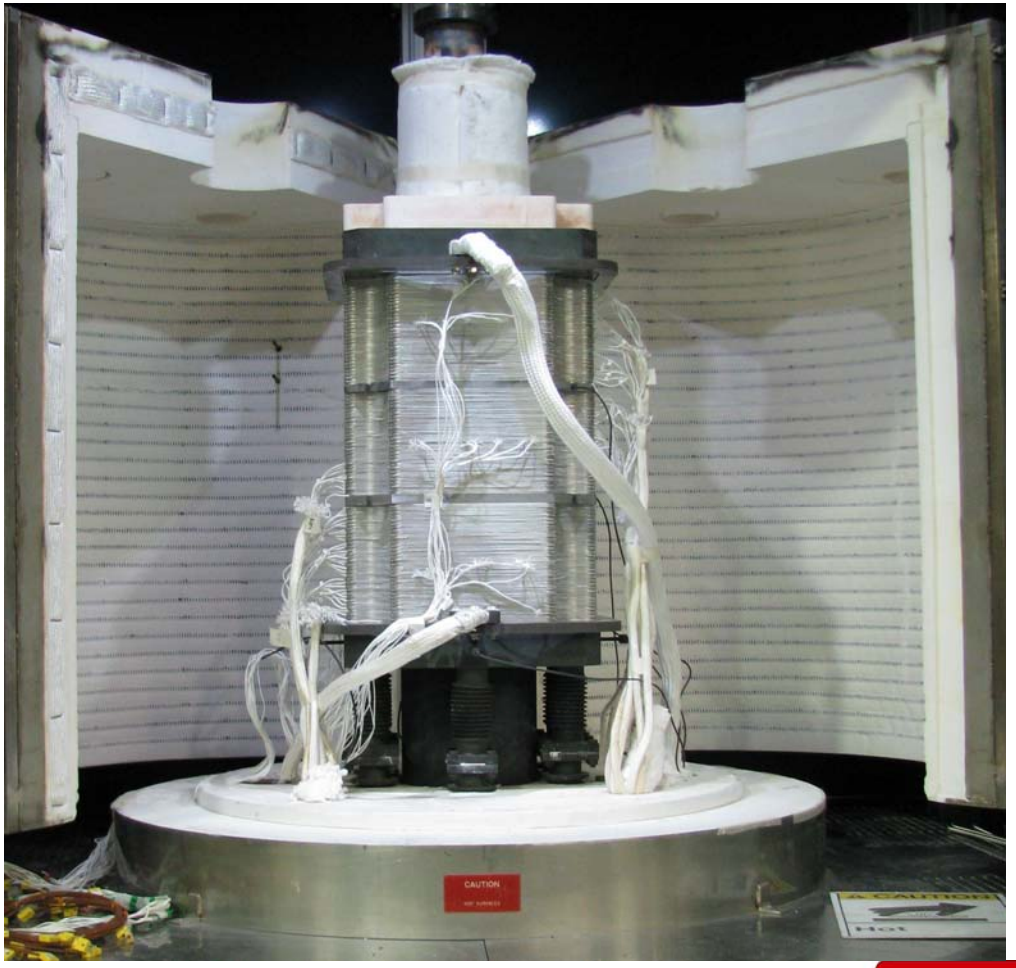
Upcoming Tests

3 x 64-Cell Stack Tower
30 kW

92-Cell Stack Block
18-20 kW



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Conclusions

Several significant technical milestones in cell and stack development have been achieved:

- **An integrated cell fabrication process has been developed for a new baseline 25 x 25 cm^2 cell and a production volume of 500 kW annually was demonstrated**
- **Cells as large as 33 x 33 cm^2 have been tested**
- **Cell materials development has been conducted and the results are encouraging**
- **Stack design & development achieved repeatability allowed the 10 kW stacks to meet the Phase I targets in cost, endurance and performance**
- **Activities are underway to advance the stack further with respect to these metrics and demonstrate stack tower operation**

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Acknowledgements

- SECA Program support provided by the US Department of Energy through the co-operative agreement DE-FC26-04NT41837 (FCE Prime)
- Thanks to Travis Shultz and Wayne Surdoval for their project and technical guidance
- FuelCell Energy team
- Versa Power Systems team

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