Solid Oxide Fuel Cell Program
at
FuelCell Energy Inc.

9th Annual SECA Workshop
Pittsburgh, PA
August 5-7, 2008

Hossein Ghezel-Ayagh

FuelCell Energy

Versa Power Systems

Presentation Outline

- **Introduction:**
  - FCE SECA program team members
  - SOFC cell and stack technology overview
- **SECA Coal-Based SOFC Program Outline**
- **Technical Approach and Status:**
  - Cell development (performance, endurance, area scale-up)
  - Stack development (performance, endurance, stack height scale-up)
  - MW module development
- **System and Cost Analyses:**
  - Integrated Gasification Fuel Cell (IGFC) System Configuration
  - Stack Cost Estimate
  - Baseline (400MW) Power Plant Cost Estimate
- **10 kW Stack Metric Test**
- **Conclusions**

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FuelCell Energy (FCE)

R & D

Danbury, CT

MANUFACTURING

Torrington, CT

FCE is a high temperature fuel cell company that has been involved in development of fuel cells for stationary power applications for over 30 years. Much of this development work has been supported by DOE programs.

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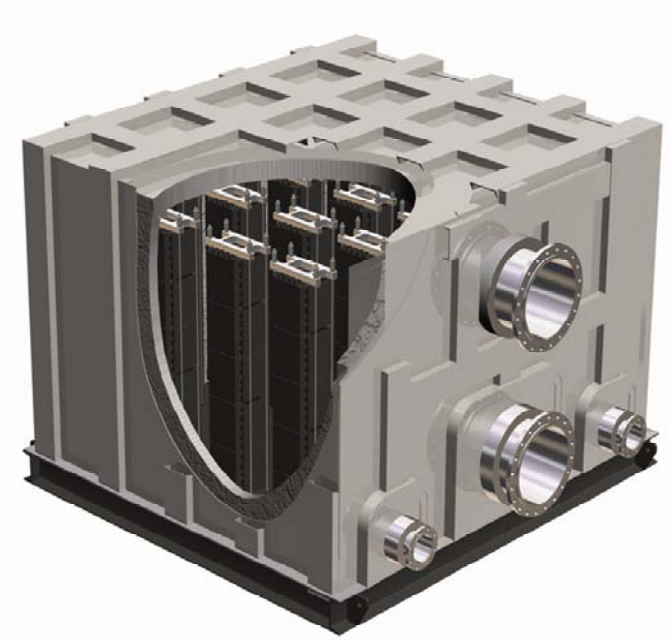
FCE SECA SOFC Programs

SECA COST REDUCTION PROGRAM

- FuelCell Energy, Inc (FCE) has been engaged in a DOE managed, SECA program to develop a 3-10kW SOFC power plant system since April, 2003. Phase I of this program ended in Sept 2006, surpassing all DOE specified metrics for performance. endurance and cost.



SOFC MW Module

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SECA COAL BASED PROGRAM

- In September 2006, the FCE team initiated work on a multi-phase SECA program to develop an affordable, multi-MW size SOFC power plant system to operate on coal syngas fuel, with near zero emissions.

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FCE SECA Coal-Based SOFC Team

The FCE team is comprised of diverse organizations with expertise in key functional areas:

FuelCell Energy Inc. (FCE), Danbury, CT

- Manufacturing and commercialization of fuel cell power plant systems in sizes ranging from 300kW to Multi-MW.

Versa Power Systems Inc. (VPS), Littleton, CO

- Solid Oxide Fuel Cell (SOFC) development and manufacturing technologies.

Gas Technology Institute (GTI), Des Plaines, IL

- Gasification and fuel Processing Technologies. SOFC contaminant studies.

Pacific Northwest National Laboratory (PNNL), Richland, WA

- SOFC cell and stack computational modeling.

WorleyParsons Inc. (WP), Reading, PA

- Power generation experience, including turbine and gas clean-up technologies.

Nexant Inc. San Francisco, CA

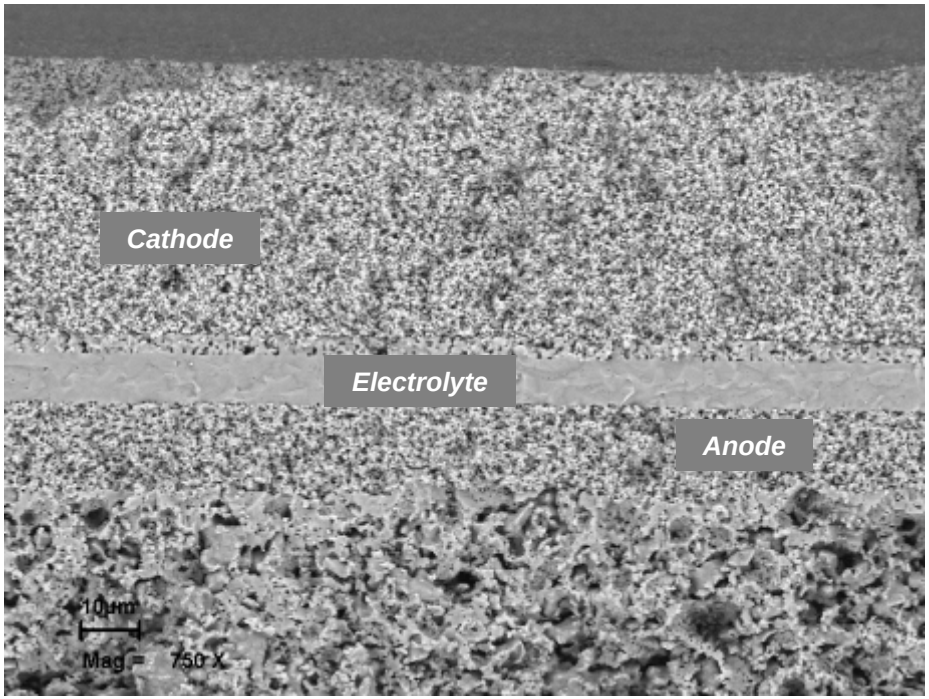
- Energy consulting and technology services.

SatCon Power Systems Inc. Burlington, ON, Canada.

- Power control and conditioning systems.

VPS Cell Technology

- **FCE utilizes the cell and stack design of its technology team partner, Versa Power Systems Inc. (VPS) for all its SOFC programs.**



ANODE SUPPORTED PLANAR CELL DESIGN:

Anode – nickel-zirconia cermet *(~1mm thick)*
Electrolyte – yttria-stabilized zirconia (YSZ) *(~10µm thick)*
Cathode – conducting ceramic *(~ 50µm thick)*

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VPS SOFC Manufacturing

VPS has been developing cost effective SOFC manufacturing procedures since 1998 and has well established processes, quality procedures and equipment for the manufacture of fuel cells and stacks.

Tape Casting
"T"

Screen Printing
"S"

Co-Sintering
"C"

The "*TSC*" process for SOFC component fabrication has proven to be cost effective with high yields and excellent quality.

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Cell and Stack Technology

The FCE team employs a building block approach to its power plant development. This enables simplified, low cost manufacturing processes with high production yields.

Anode Supported, Planar Cell Design

Internally Manifolded Stack Building Block Design

Stack Building Blocks Assembled Into Stack Tower

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Coal-Based SOFC Power Plant Development Program

Program Objectives:

Development of large scale (>100 MWe) coal-based SOFC systems with:

- At least 50% overall efficiency from coal (higher heating value)
- Performance to meet DOE specified metrics for power output, degradation, availability, reliability, etc.
- Factory cost <$400/kW
- >90% of carbon capture from coal syngas for sequestration

⇨ ***The FCE team will utilize the SOFC cell and stack technology successfully demonstrated in the SECA Cost Reduction Program as the basis for scale-up and further development in the Multi-MW Coal-Based SECA Program***

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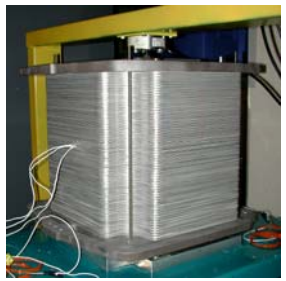
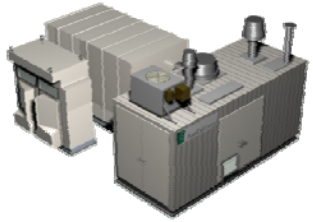
SECA Coal Based Multi-Phase Program Plan

10 kW Stack

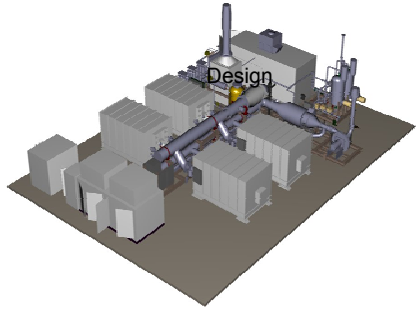


Multi-Stack Tower

≥ 250 kW Module Demonstration Unit



5 MW Proof of Concept



2008 2010 2012 2015

Phase I **Phase II** **Phase III**

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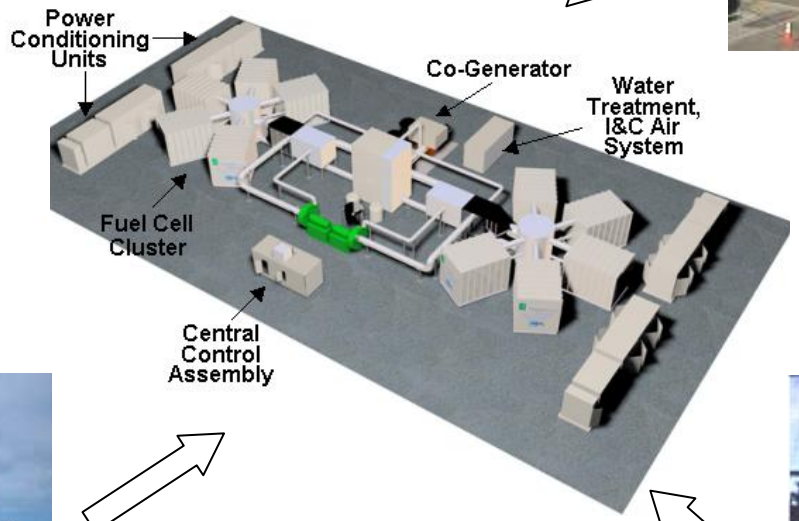
SECA Coal-Based Multi-MW SOFC Power Plant Development

3-10kW SOFC Development (Versa Power Systems)
DOE SECA (2003 - 2006)

MULTI-MW SOFC POWER BLOCK CONCEPTUAL DESIGN



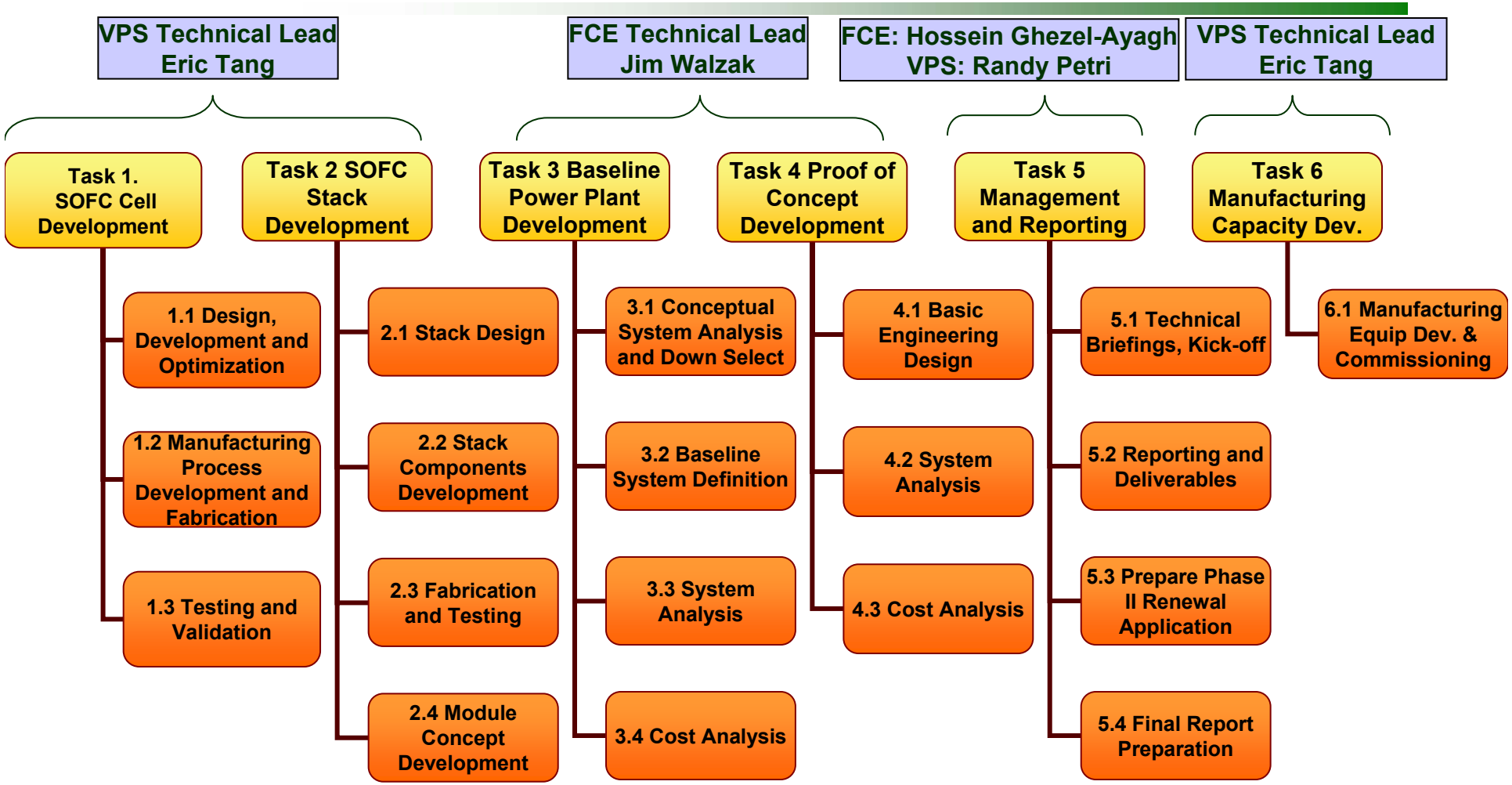
FCE MW Class Fuel Cell Product Development
DOE PDI (1994 - 2005)

FCE High Efficiency Hybrid Fuel Cell–Turbine Product Development
DOE Vision 21 (2000 - 2008)

- **Coal-Based SOFC power plant development benefits from other successfully demonstrated DOE supported programs.**

20kW DFC Operating on Destec Coal Syngas (4,000 hours)
DOE-EPRI (1990 - 1992)

SECA Coal-Based Program Work Breakdown Structure



- **The work breakdown structure is designed to ensure success in achieving the program objectives with minimal risk.**

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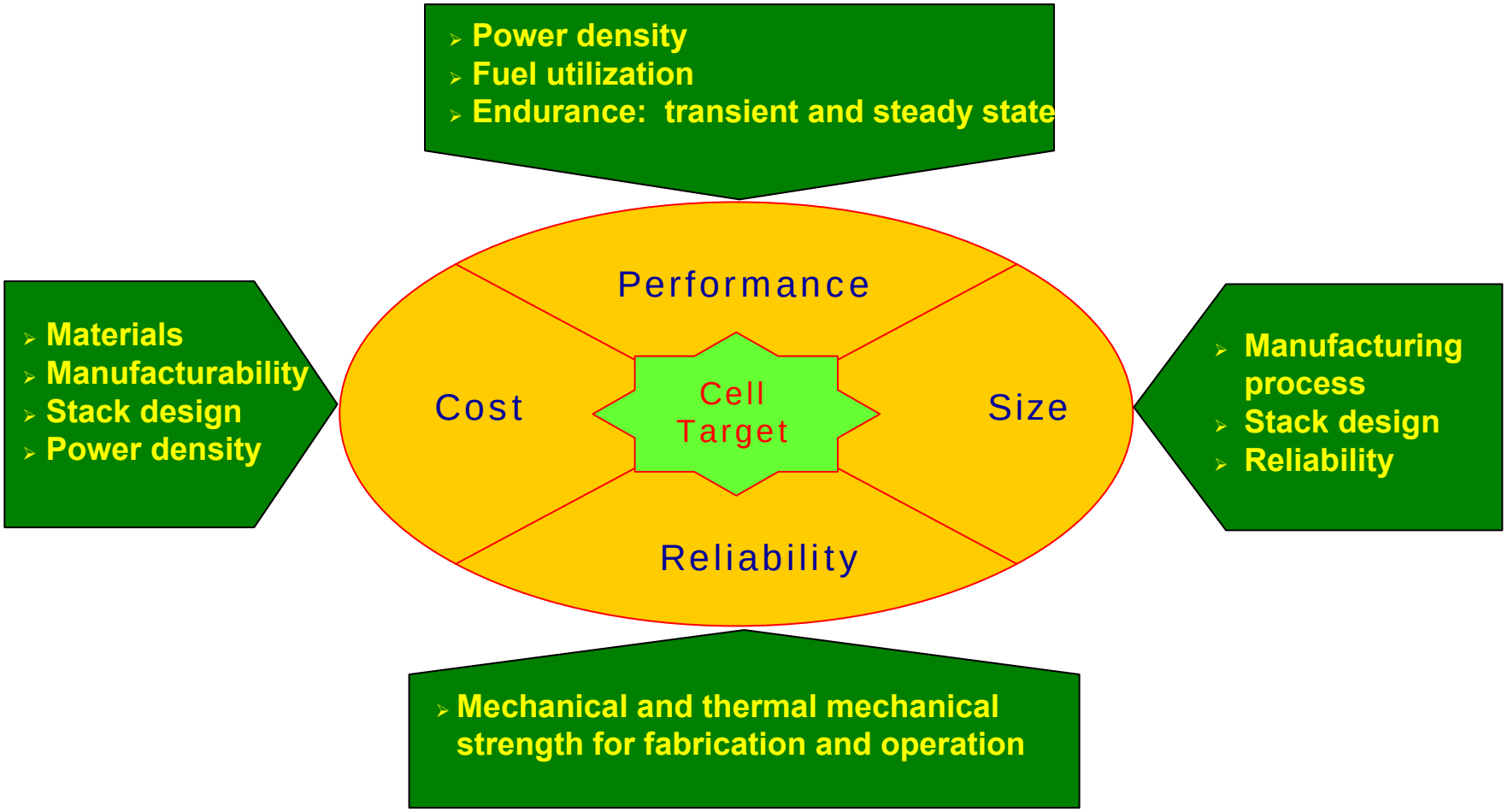
SOFC Key Technical Improvements



There has been significant accomplishments in key areas including: performance, cost, size, and reliability.

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Performance and Endurance Enhancement

Cell Type	Performance at 700°C, 0.74 A/cm^2		Performance at 750°C, 0.74 A/cm^2		Degradation Per 1000 hrs		Testing Duration
	Peak V	Gain	Peak V	Gain	mV	%	
Baseline	730 mV	Baseline	812 mV	Baseline	14	1.7%	6500 hrs
New Cell #1	788 mV	8%	854 mV	5%	13	1.5%	8600 hrs
New Cell #2	783 mV	7%	864 mV	6%	14	1.6%	7100 hrs
New Cell #3	852 mV	17%	885 mV	9%	13	1.5%	4300 hrs
New Cell #4	794 mV	9%	847 mV	4%	6	0.7%	5000 hrs

Single cell testing of high performance components shows a potential performance gain of 4-17% and a significant increase in endurance (decreased degradation of 50%).

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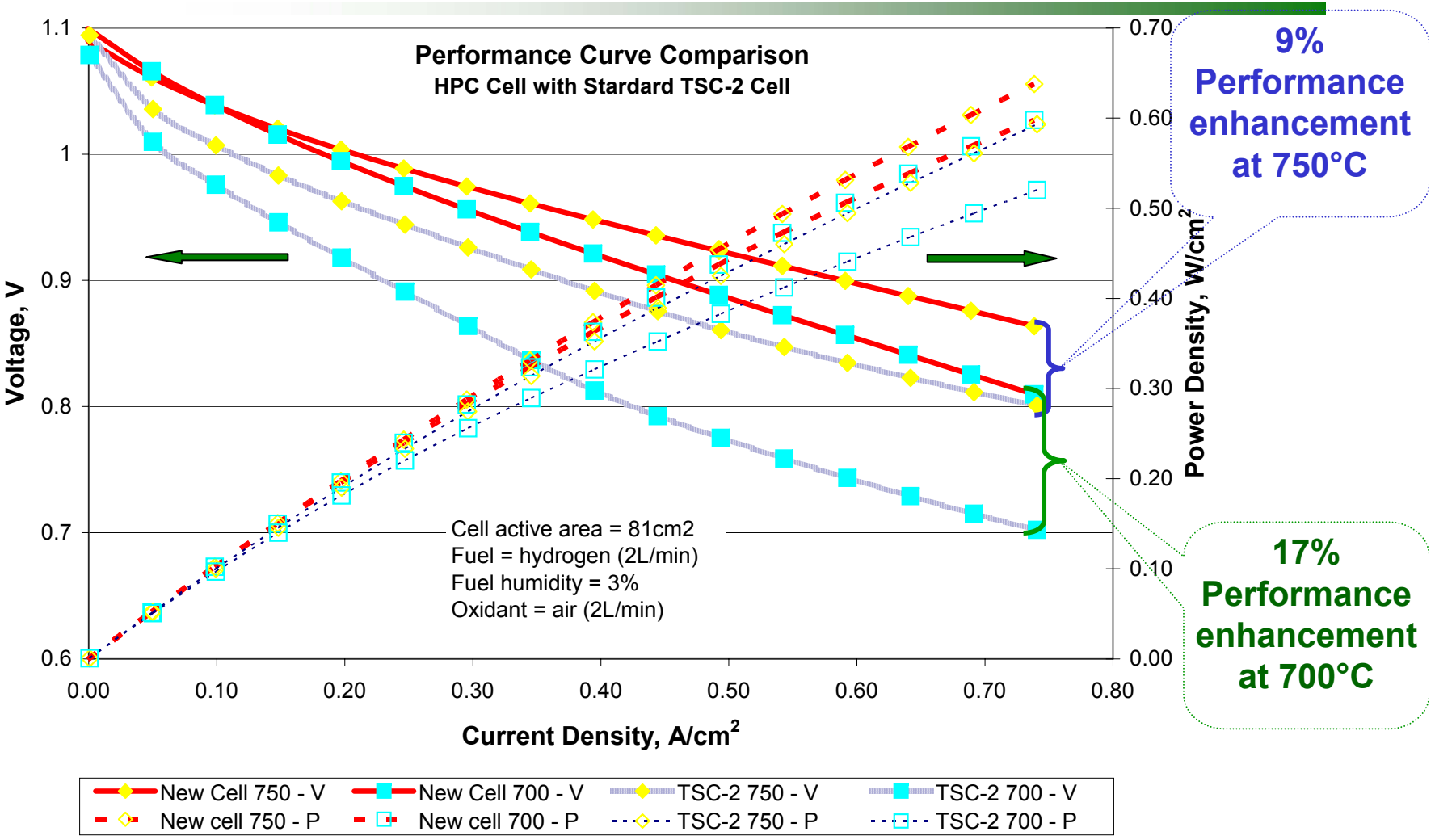
Cell Performance Enhancement



New high performance components show significant performance (voltage) improvement as compared to baseline component cells.

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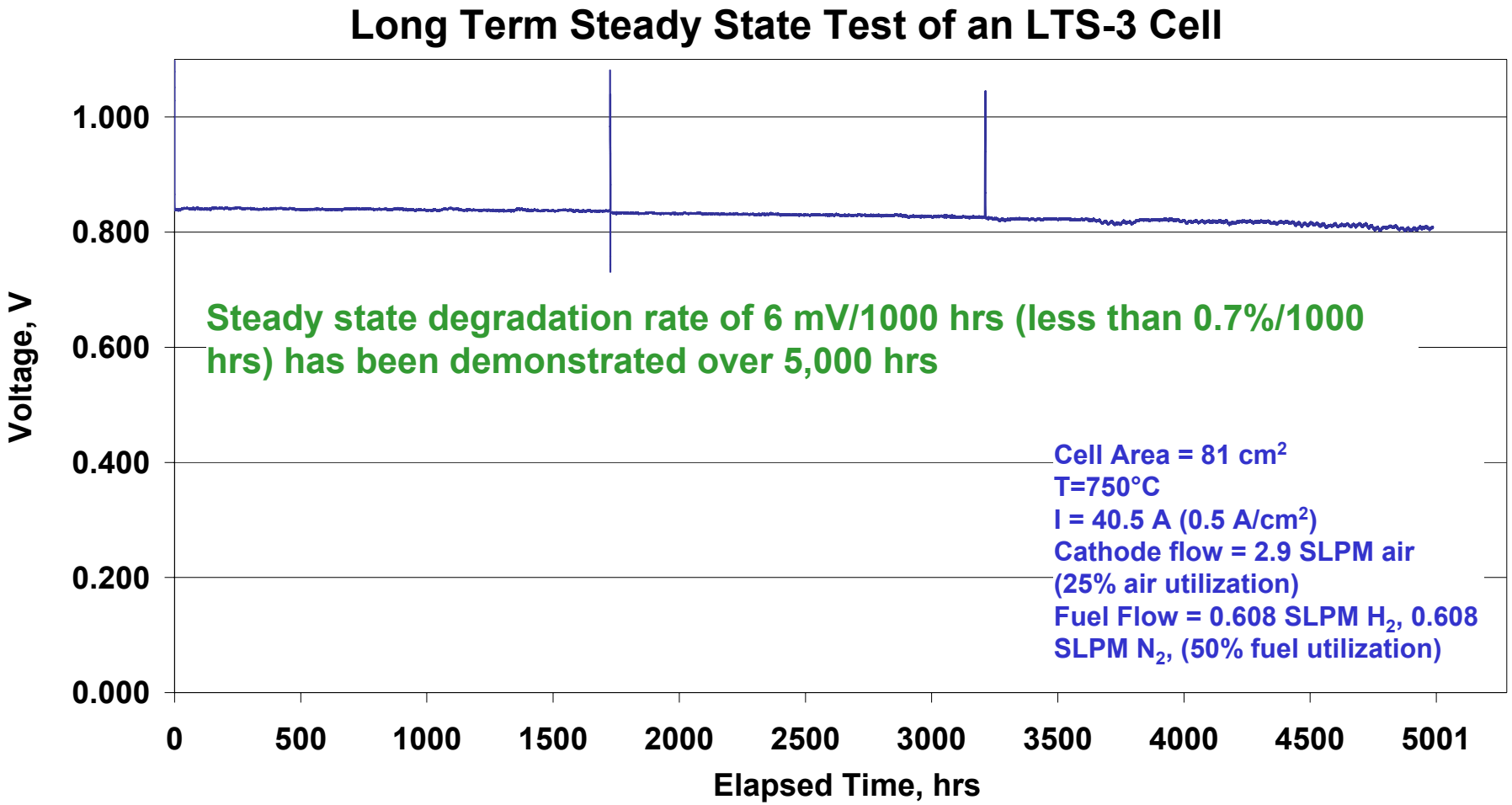
Cell Endurance Enhancement



Significant improvement in endurance (decreased degradation rate) has been shown in single cell testing with improved cell components.

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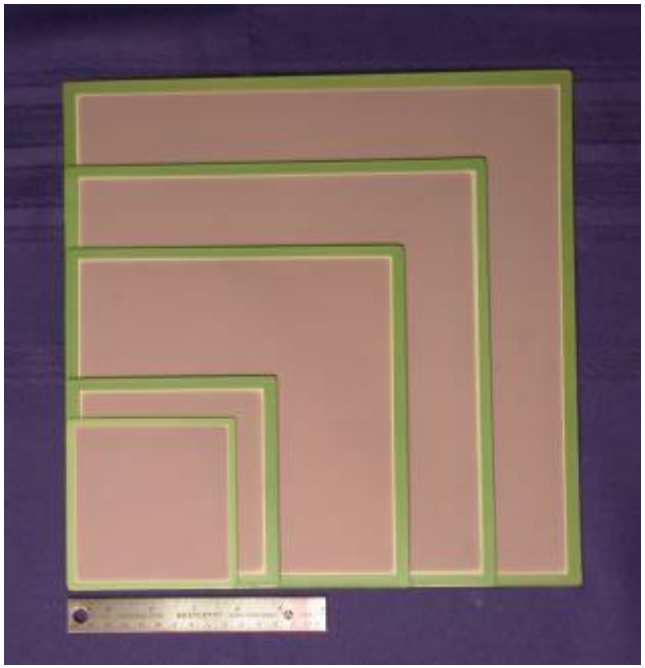
Cell Scale-Up Development

• **Cell Scale-Up Process Development:**

> **Cells up to 33 x 33 cm^2 were produced with baseline TSC II process to evaluate process capability**



• **Manufacturing, Tooling and Facility Development:**

> **All major manufacturing process equipment have been established for both size and volume scale-up**

> **Key equipment has been commissioned to handle cell production volume of 1 MW/year**

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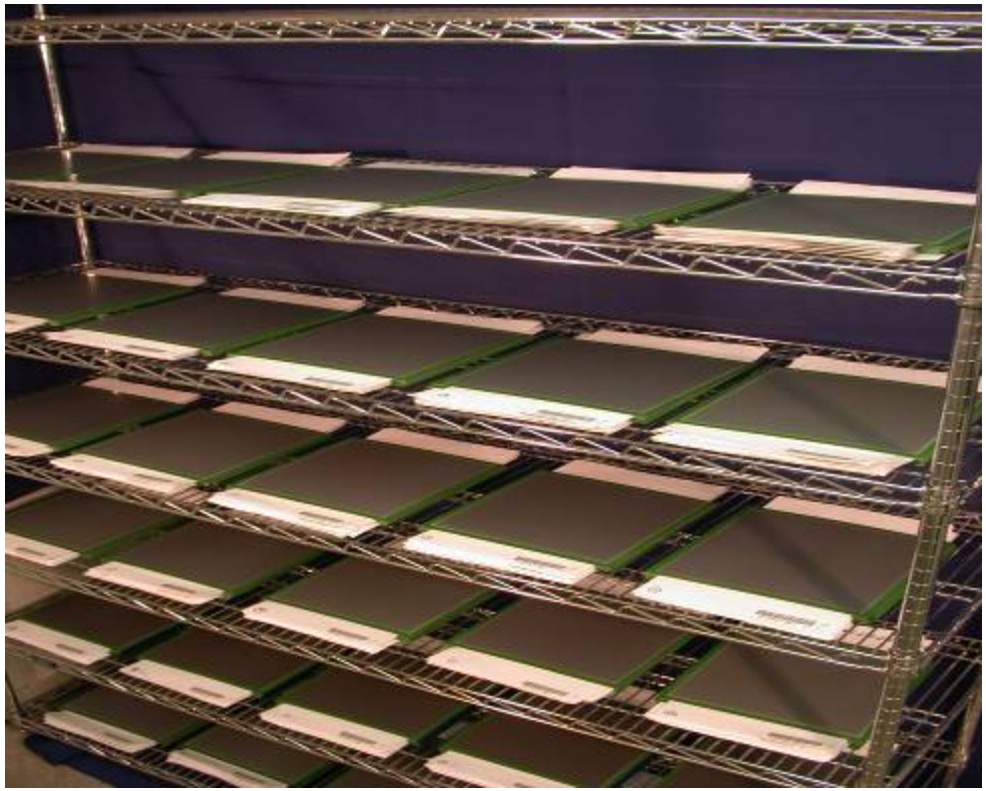
Cell Scale-Up Development

- 25 x 25 cm^2 cells with 550 cm^2 active area were selected for the 10 kW stack block.
- More than 1000 cells (25 x 25 cm^2) have been produced with a high level of process control. Production yields over 95% have been demonstrated.



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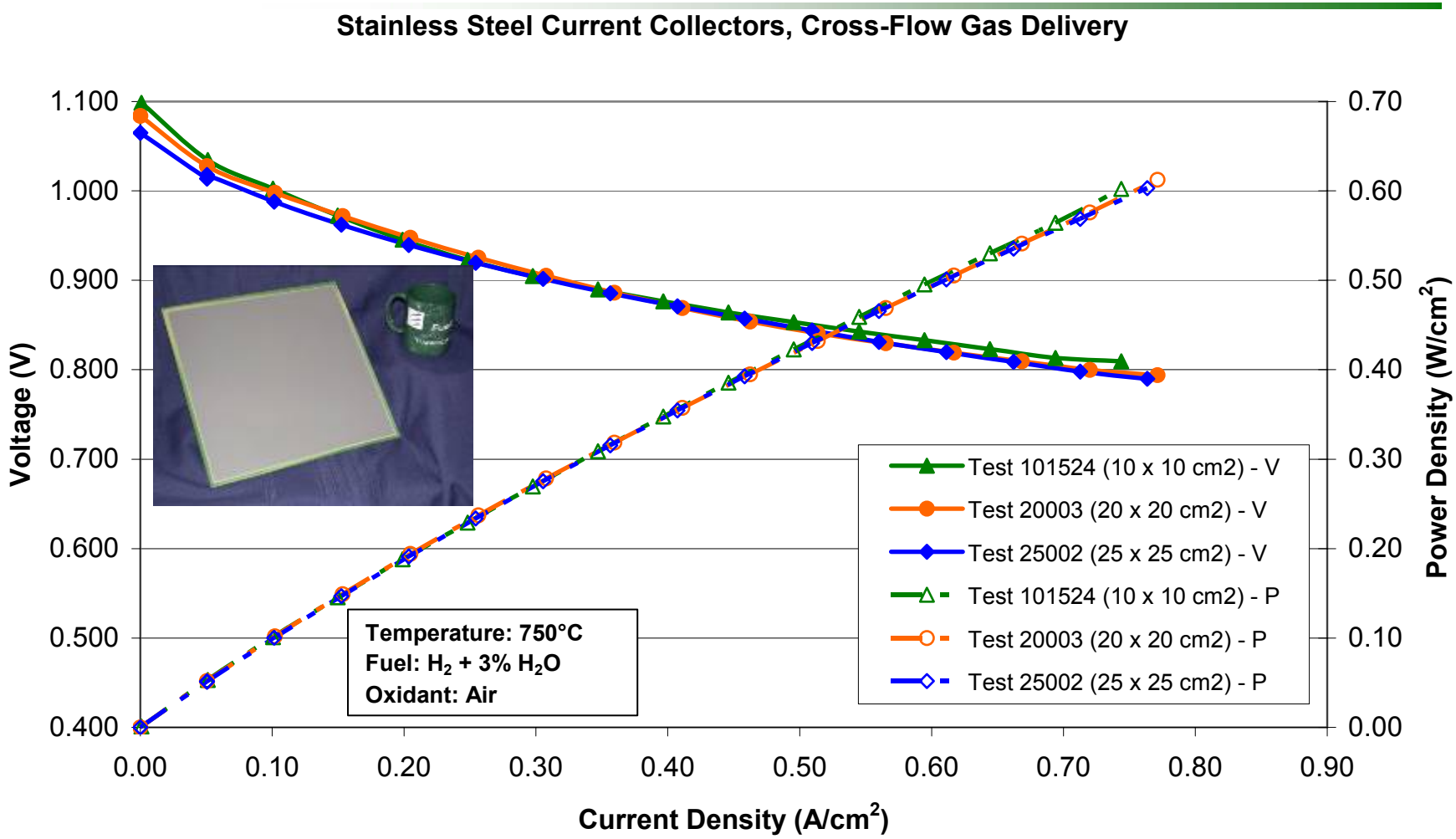
Scaled-Up Cell Area: Performance Validation



- **Single cell testing of large area components showed no significant performance difference as compared to the baseline size cells.**

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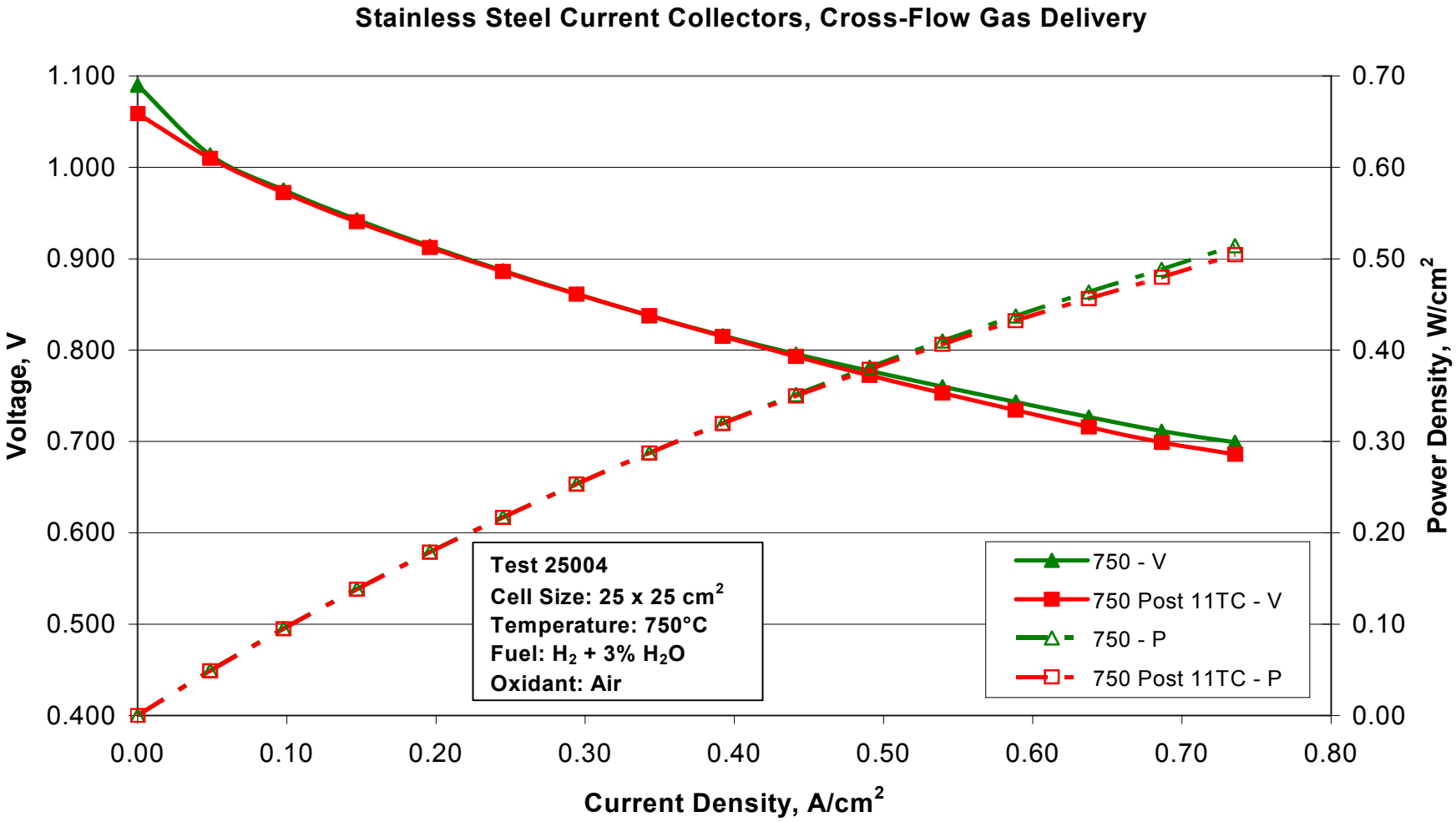
Scaled-Up Cell Area: Reliability (Thermal Cycle) Validation



- **Large area cell components showed good thermal cyclability.**

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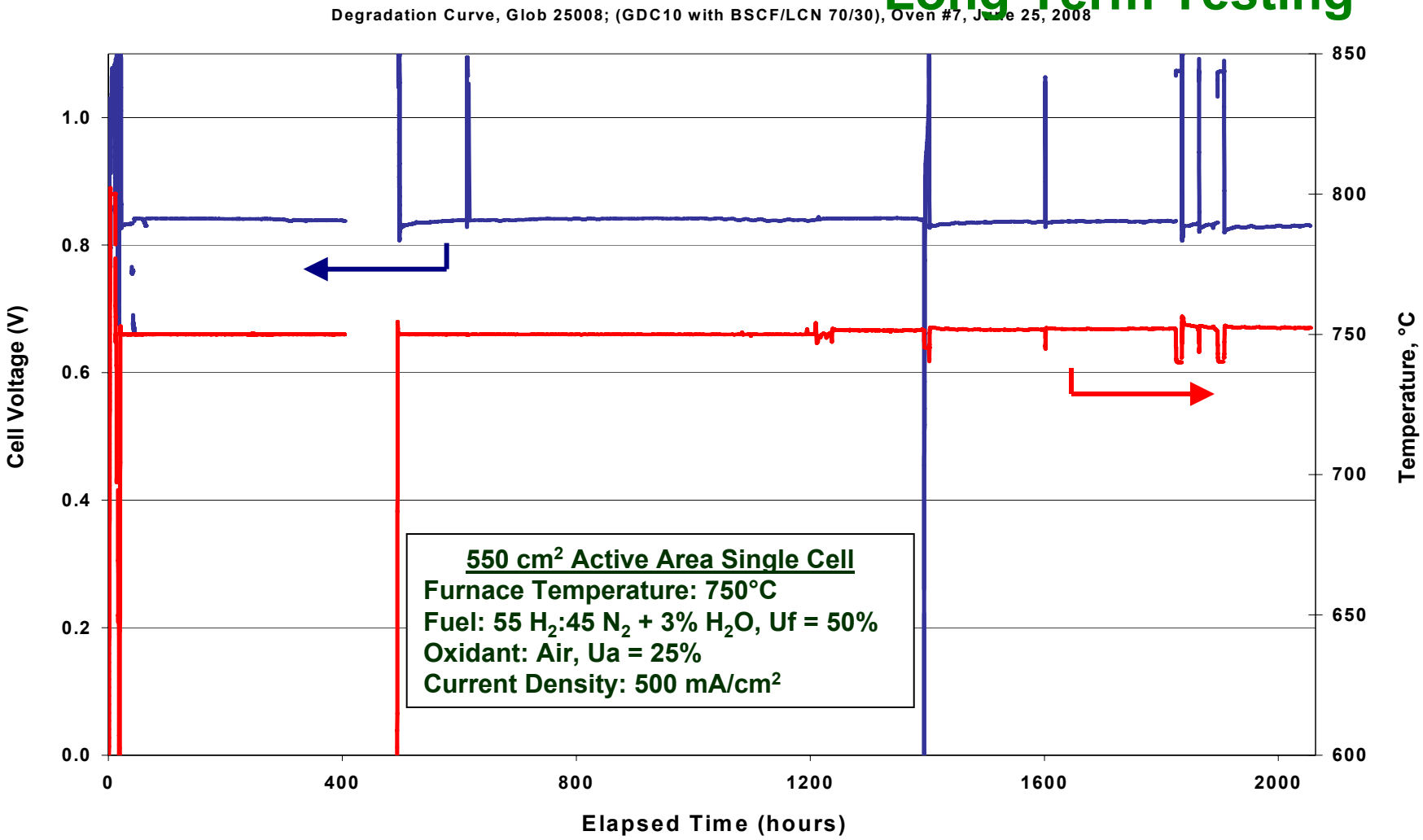
Scaled-Up Cell Area: Long-Term Testing



- **Large area cell components showed good steady-state endurance of 0.6% loss per 1000 hours**

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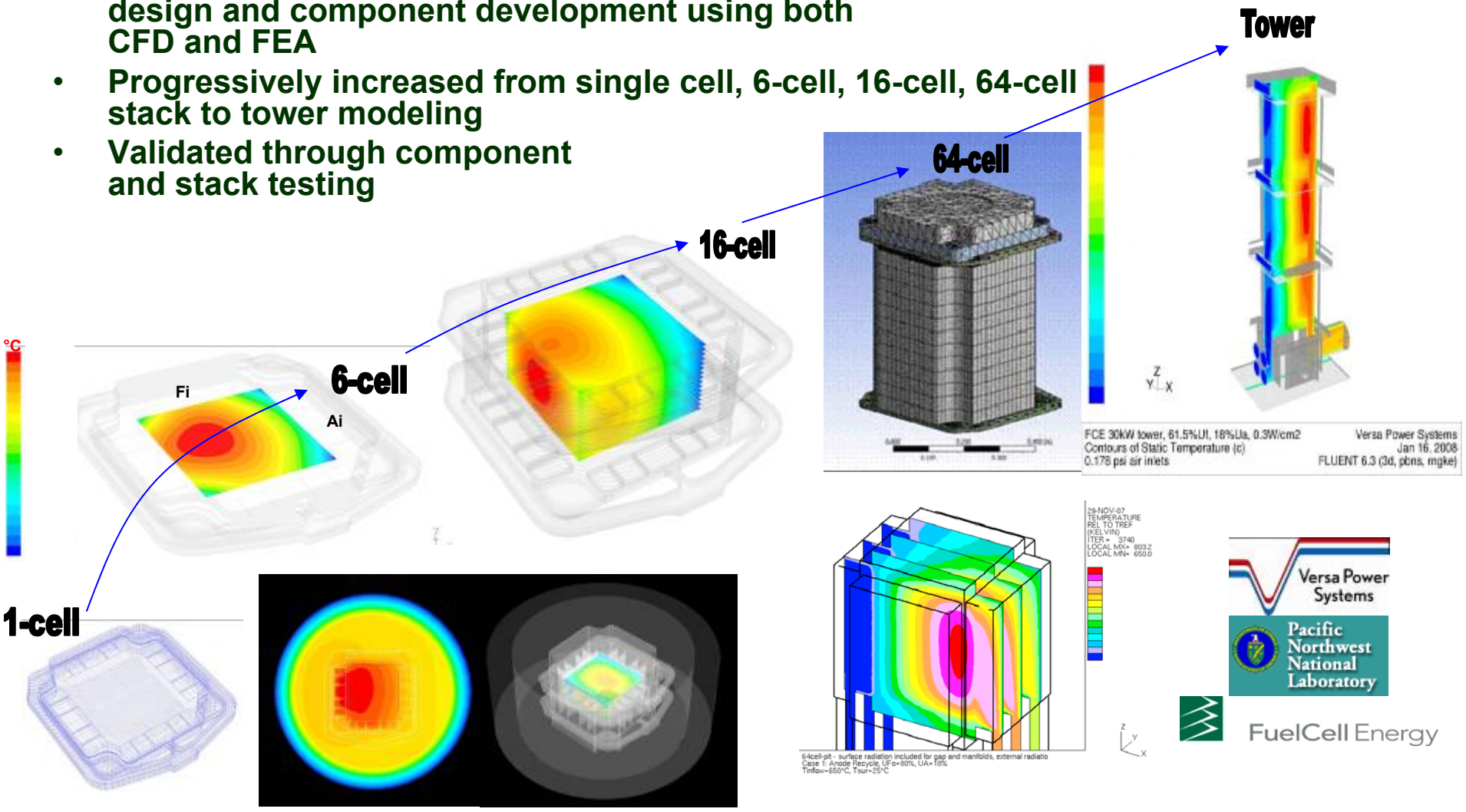
Stack Design Approach

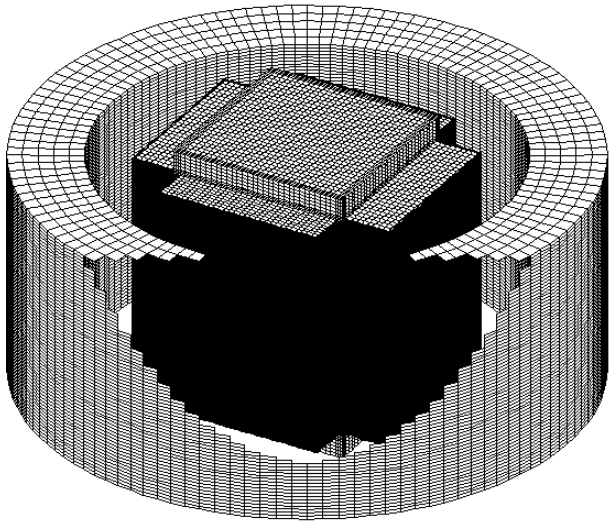
- Model-driven design approach is utilized for specific challenges
- Modeling has provided guidance to engineering design and component development using both CFD and FEA
- Progressively increased from single cell, 6-cell, 16-cell, 64-cell stack to tower modeling
- Validated through component and stack testing



Stack Modeling

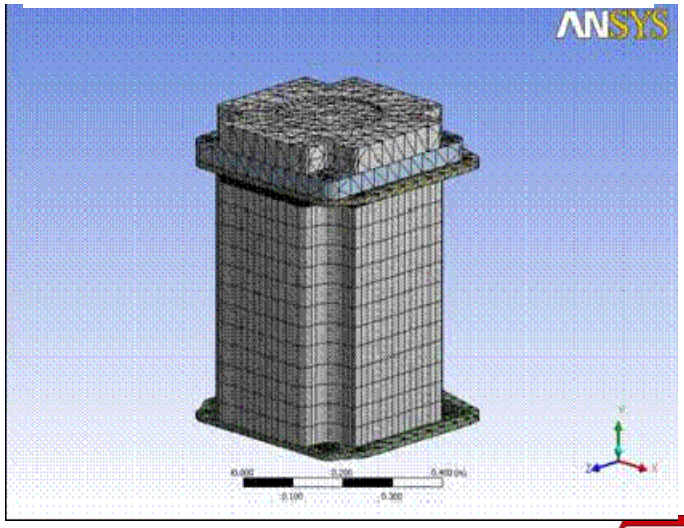
PNNL Modeling

- Generic 64-cell Stack CFD Modeling using PNNL super computer
- Largest SOFC model available with >5 million computational cells
- Used for Short and Tall Stack Structural Analysis



VPS/FCE In house Modeling

- Detailed Stack Mechanical Modeling
- Fuel Cell Stack Flow Modeling
- Module Configuration
- Reliability Studies



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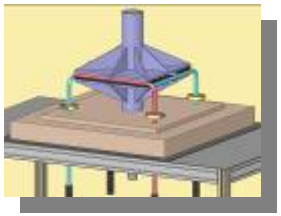
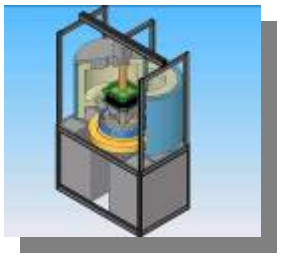
Stack Test Facility & Infrastructure





- ✓ **Modification of existing VPS single cell test stands to accommodate tests of scaled-up cells of up to 25X25 cm (550 cm^2 active area)**
- ✓ **Modification of two existing VPS stack test stands to accommodate short full-area stack testing of up to 2.5 kW**
- ✓ **Acquisition of 2 single cell test stands to accommodate tests of cell sizes up to 38X38 cm at VPS**
- ✓ **Acquisition of 3 large-area stack test stands to accommodate stack scale-up development of 10 – 25 kW at VPS**
- ✓ **Construction of a 10-30 kW test facility to accommodate SOFC stack tower testing at FCE**

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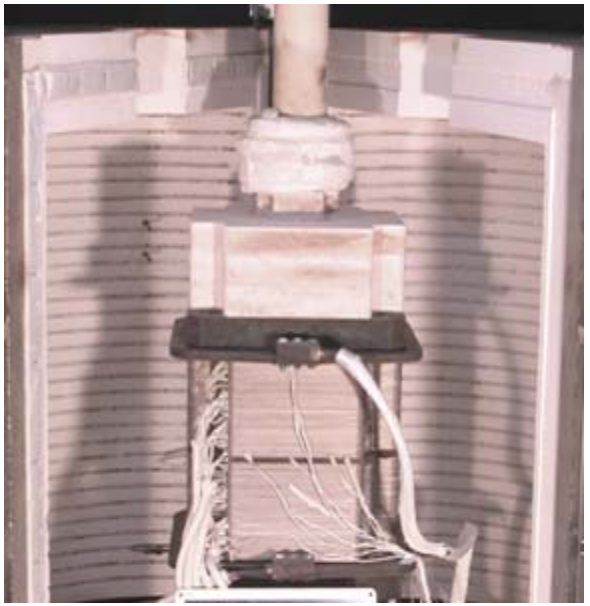
Large-Area Stack Tests

0.16 kW 1-cell → 1 kW 6-cell → 2.5 kW 16-cell → 10 kW 64-cell



Stack Design	Power (kW/stack)	Quantity	Total Power (kW)
6 cells	1	21	21
16 cells	2.5	18	45
64 cells	10	6	60
Total		45	126

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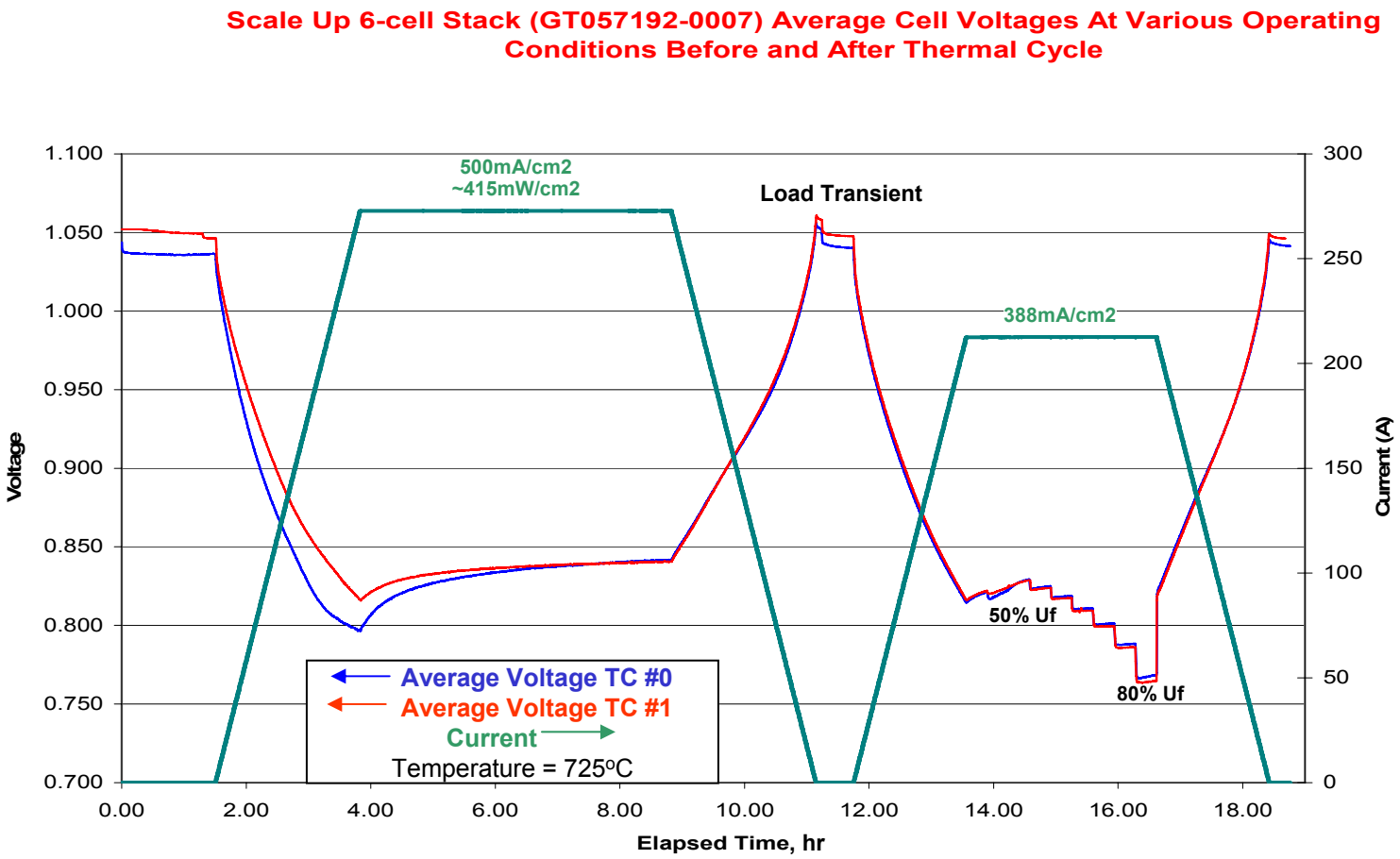
Large-Area 6-Cell Stack Performance



- **Excellent performance and transient characteristics achieved.**

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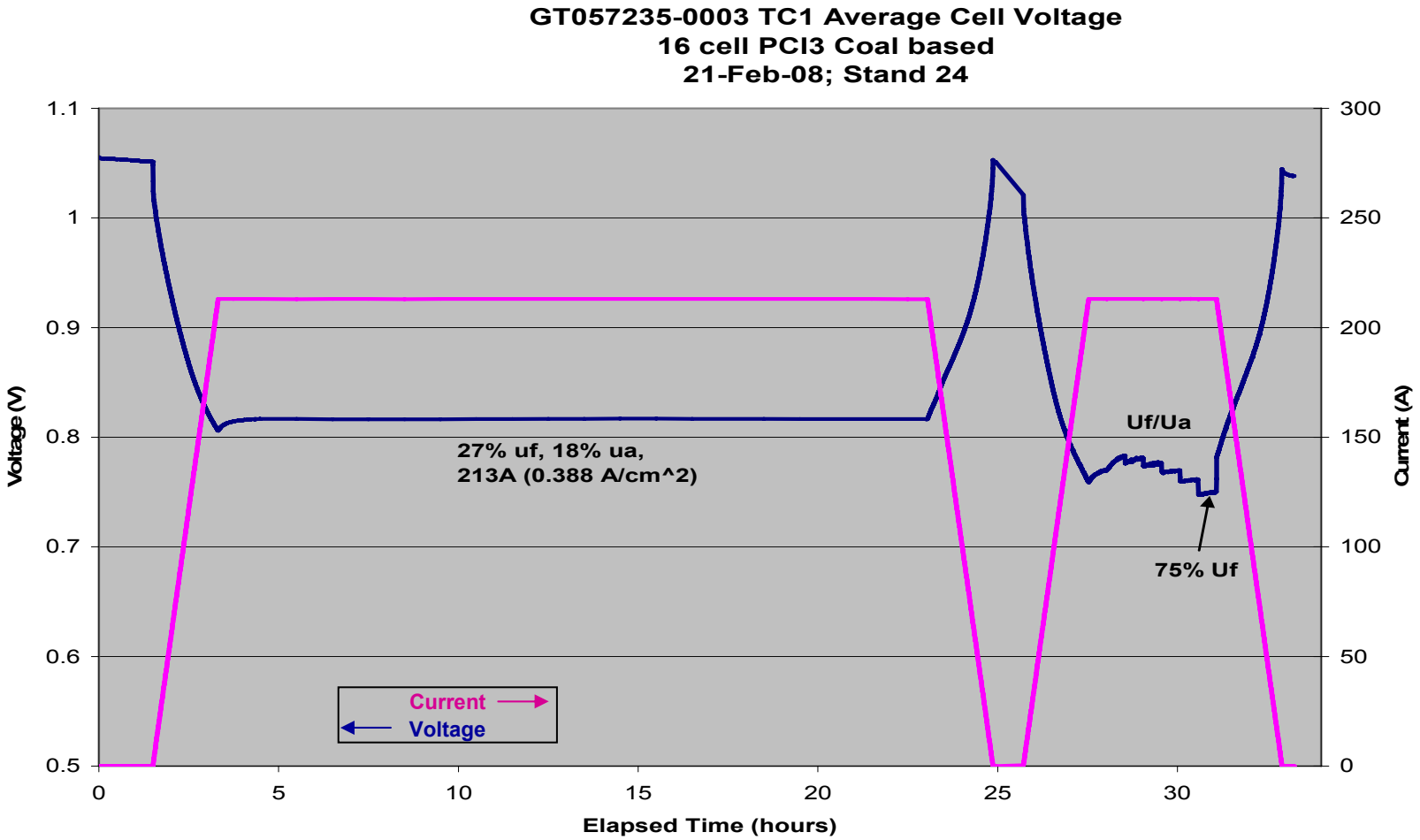
Large-Area 16-Cell (2.5 kW) Stack Performance



- **Excellent performance observed in short 16-cell stack testing of scaled-up area (550 cm^2 active area) cells.**

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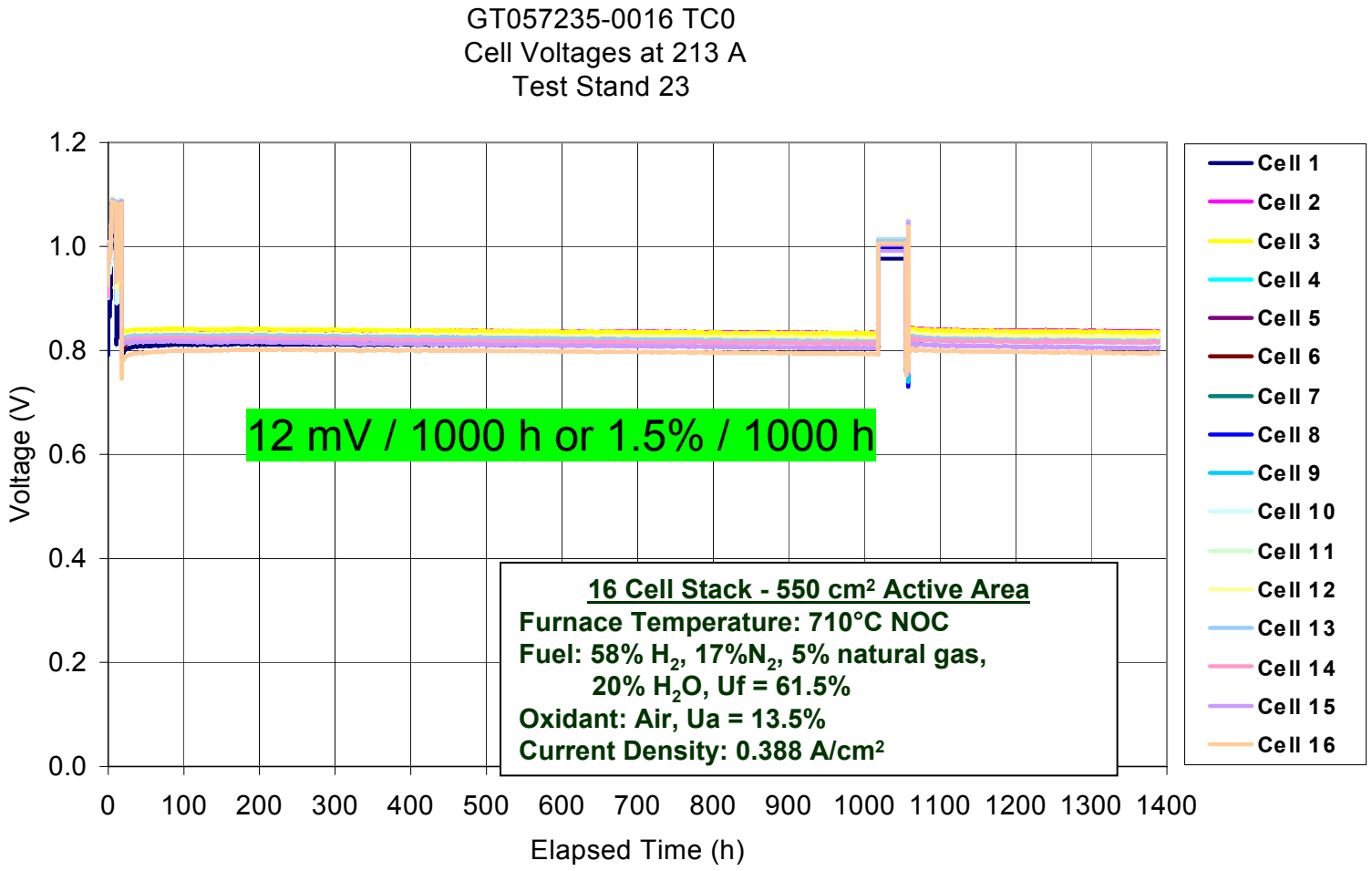
Large-Area 16-cell Stack (2.5 kW) Long-Term Testing



- **Long-term tests of the large-area 16-cell stack showed stable and uniform cell-to-cell performance.**

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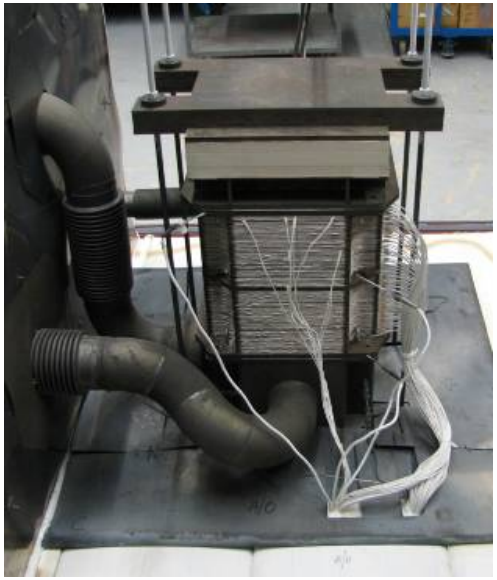
10-kW Stack Fabrication



GT057259-0001

V1-001 stack at FCE

GT057382-0001

V2-001 stack installed at FCE after tests at VPS

GT057382-0002

V2-002 stack at VPS

To date, six 10-kW stacks were fabricated for testing at VPS and FCE.

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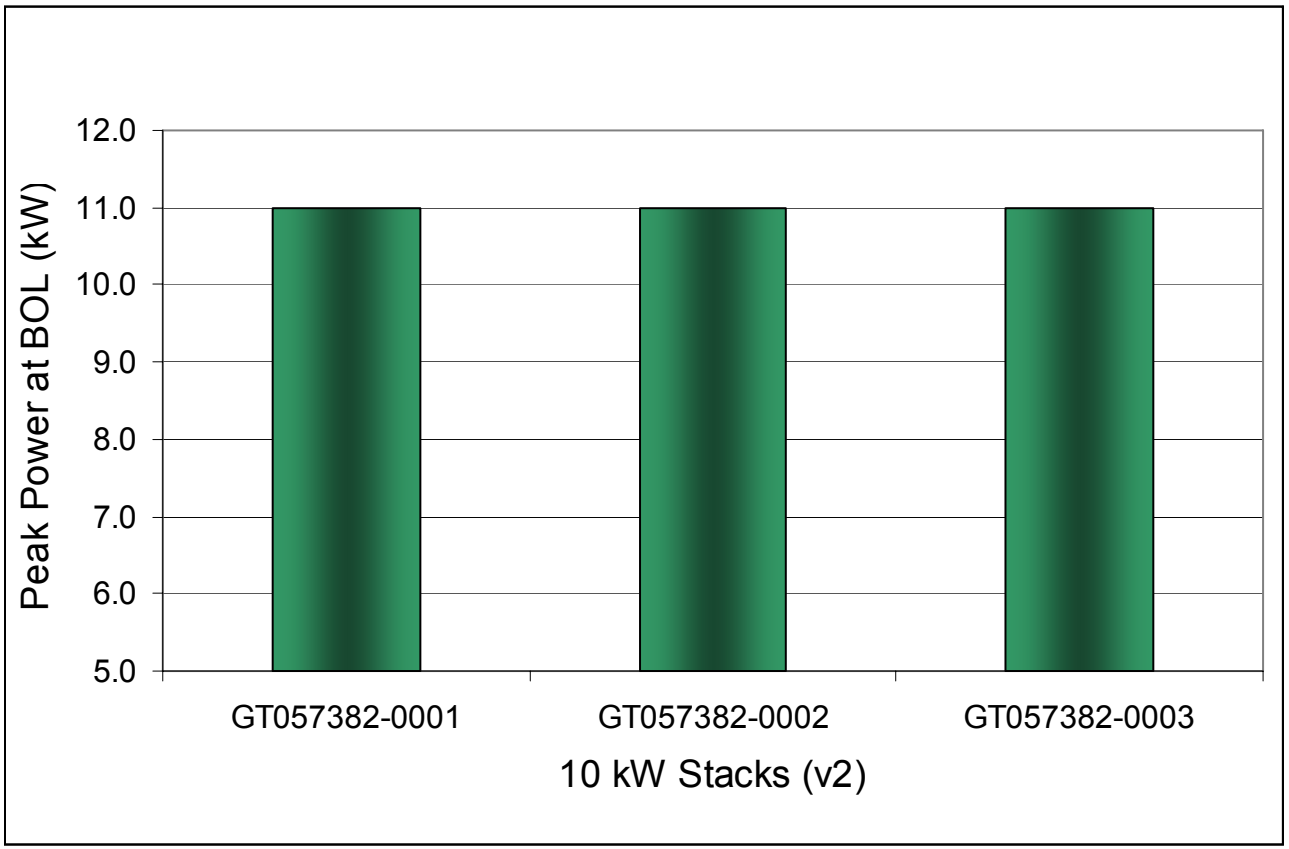
Peak Power Test Results of 10 kW Stacks



Version 2 stacks generate excellent repeatability at 213 A condition.

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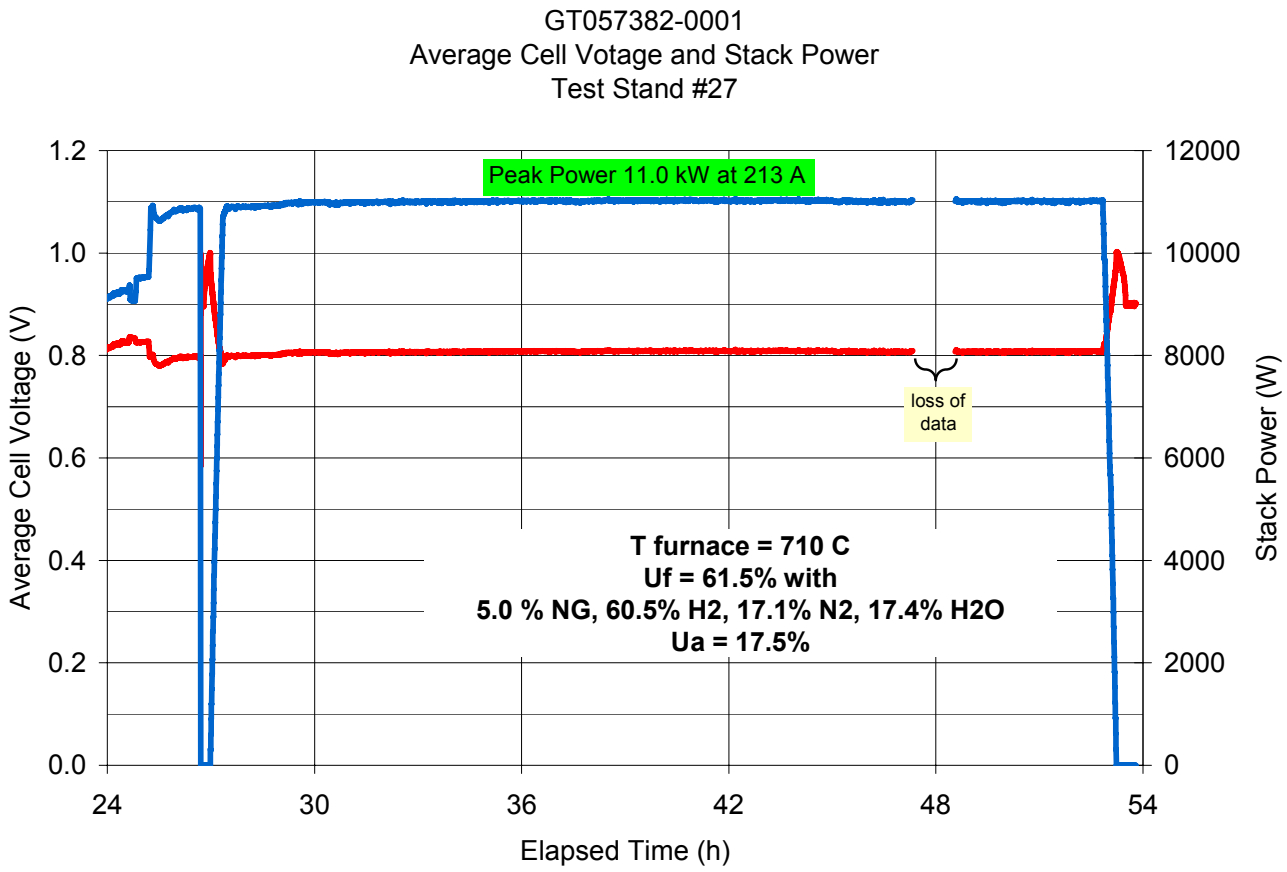
10 kW Stack (V2-001) Testing



Shipped to FCE for further testing

V2-001 stack exhibited stable performance at VPS facilities prior to shipment to FCE.

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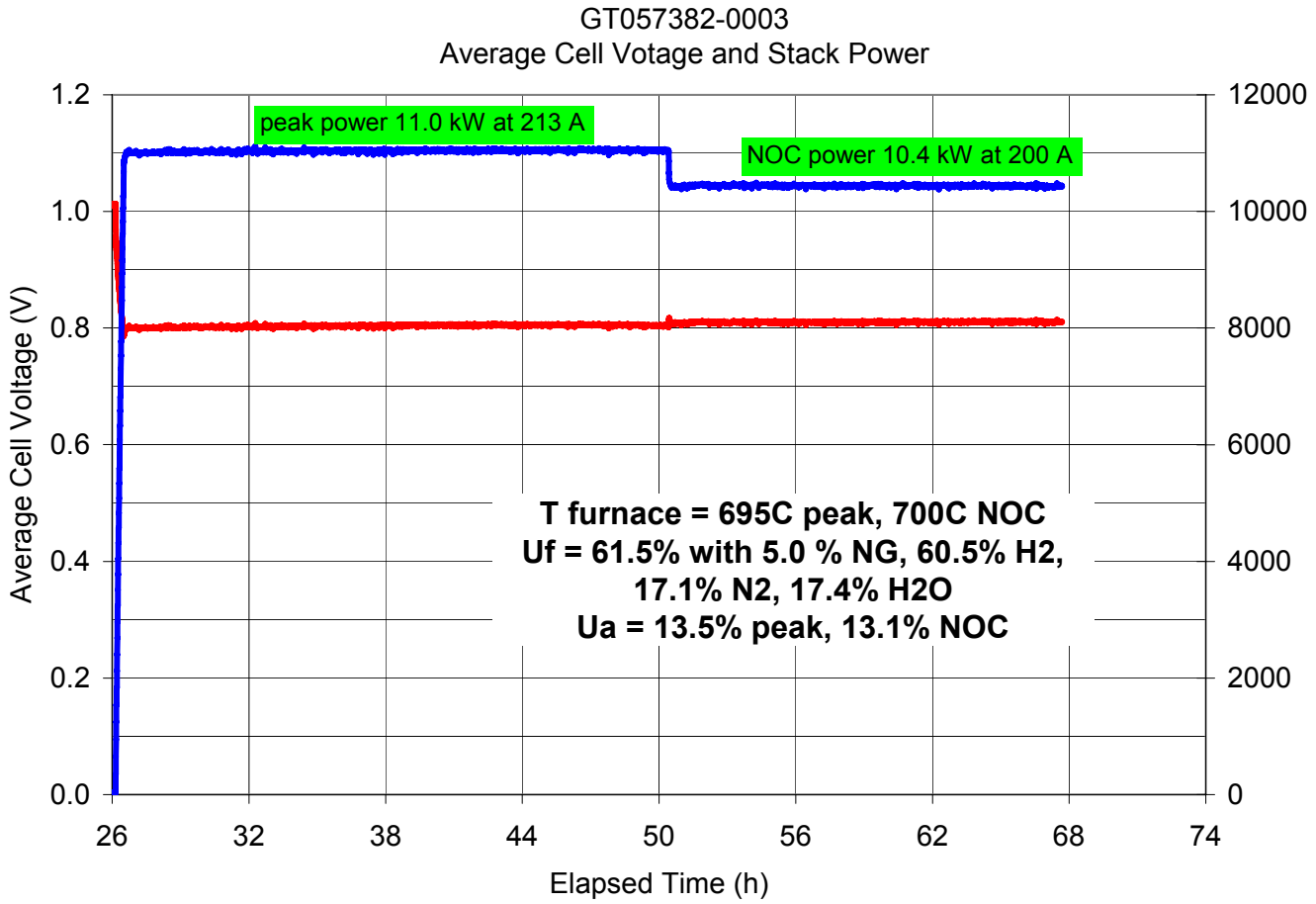
10-kW Stack (V2-003) Test at VPS



Continued tests at VPS

V2-003 stack shows stable performance at VPS facilities.

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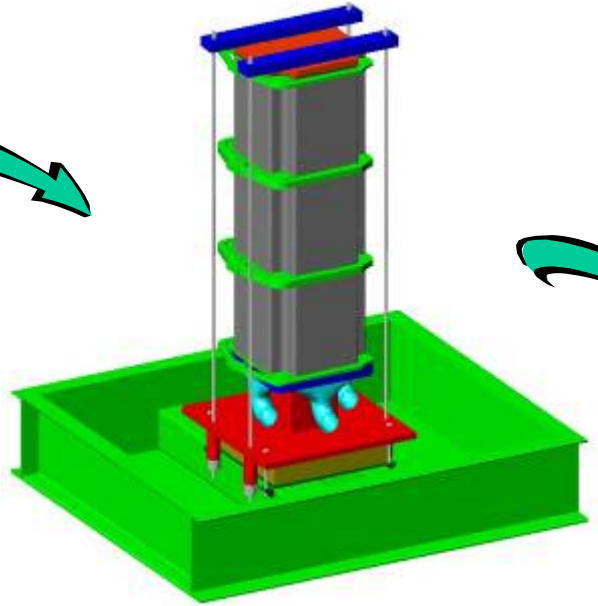
Building Block Approach

10 kW Stack

Building block for stack towers

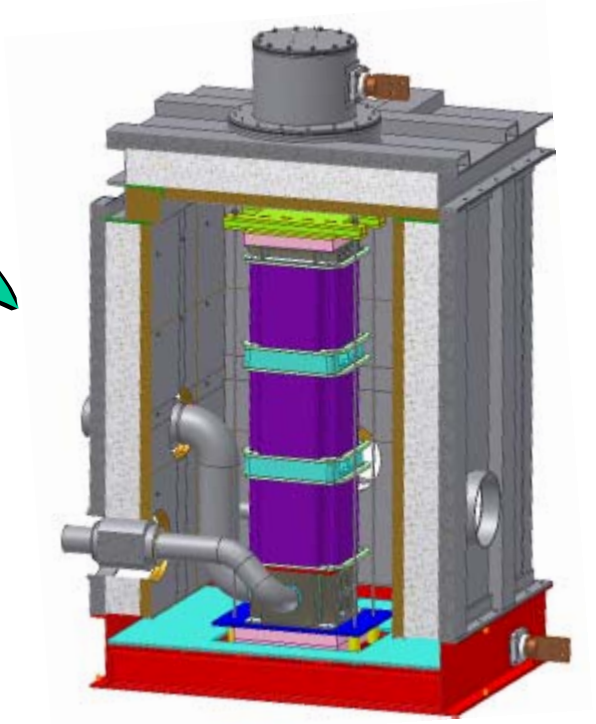
10- 50 kW

Stack Tower



Building block for stack modules of ≥ 250 kW

Stack Module



Building Block for a ≥100MWe Integrated Gasification Fuel Cell (IGFC) system

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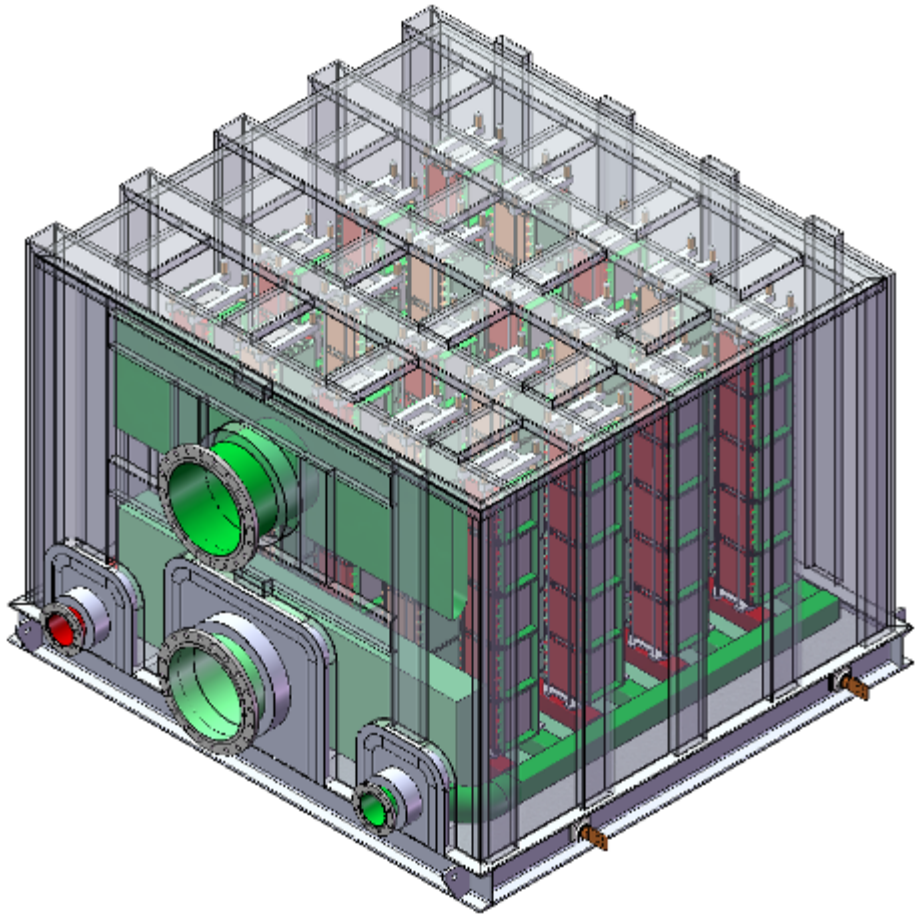
MW-Scale SOFC Stack Module



- **The SOFC MW module is built off lessons learned from FCE's commercial MW-scale products**

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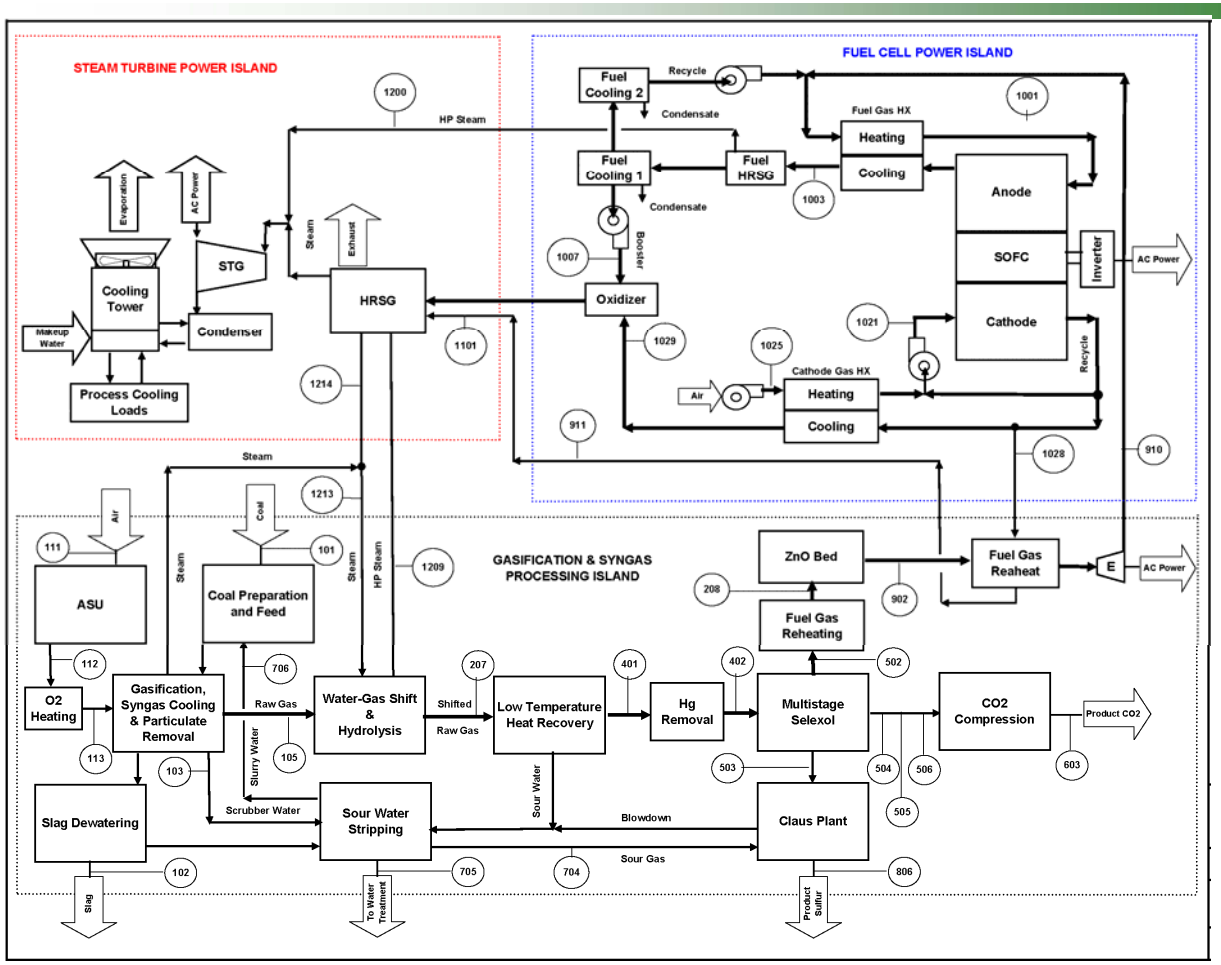
WorleyParsons
resources & energy

Integrated Gasification Fuel Cell System (IGFC)



➡ **System analysis has indicated that SOFC offers great potential for generation of highly efficient power with >90% carbon capture from coal using conventional gasification technologies.**

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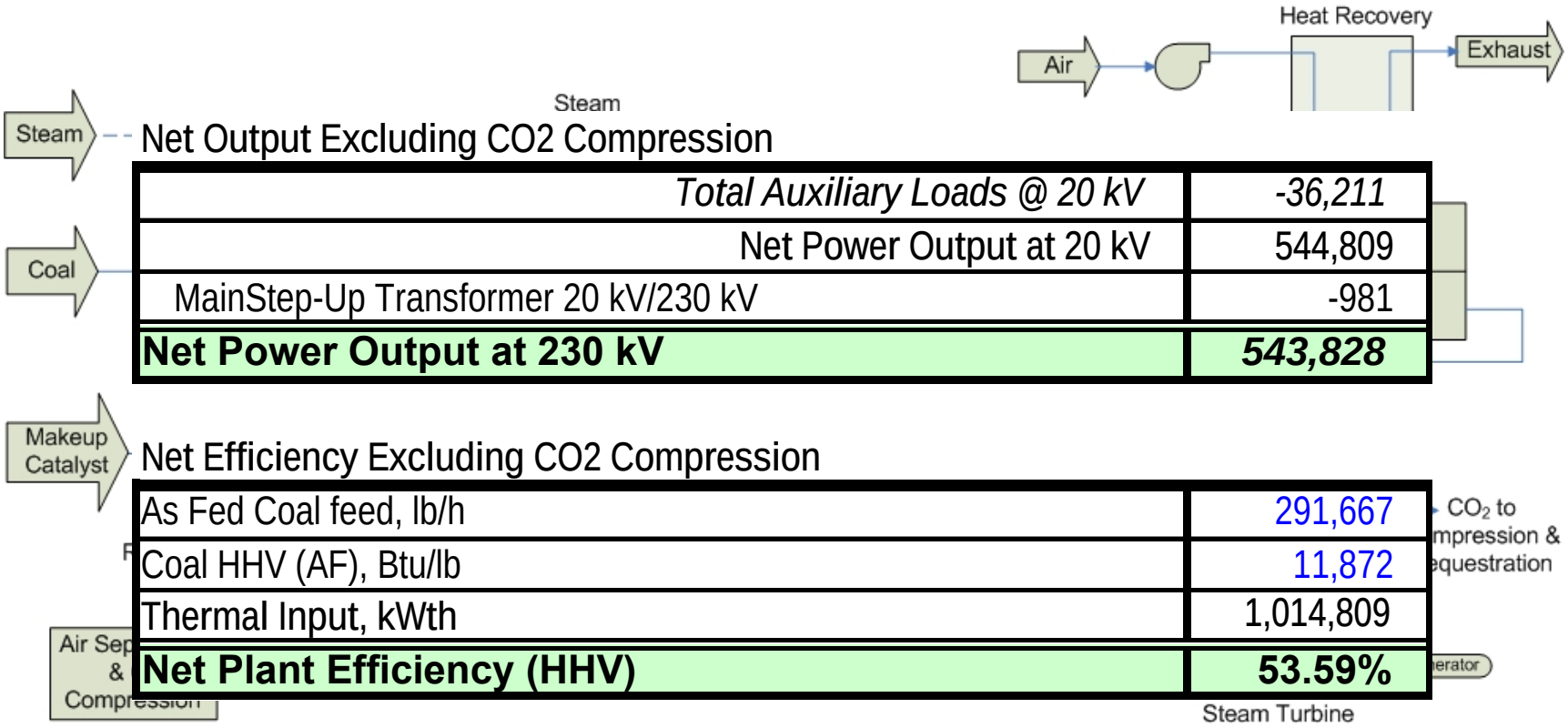
Advanced Coal-Based SOFC Systems



➡ **Combined with high methane producing gasification, coal based SOFC systems are capable of achieving >50% efficiency**

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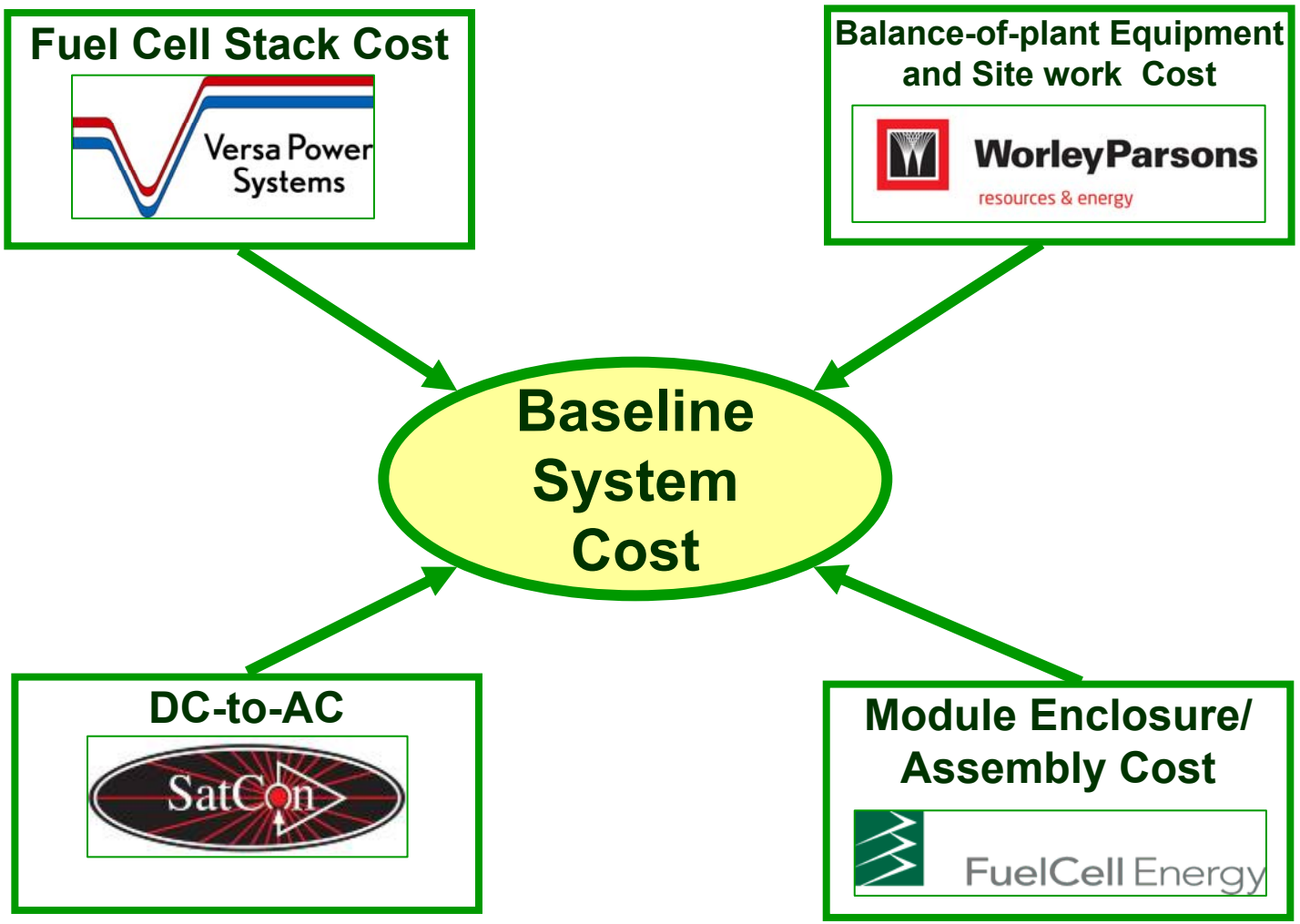
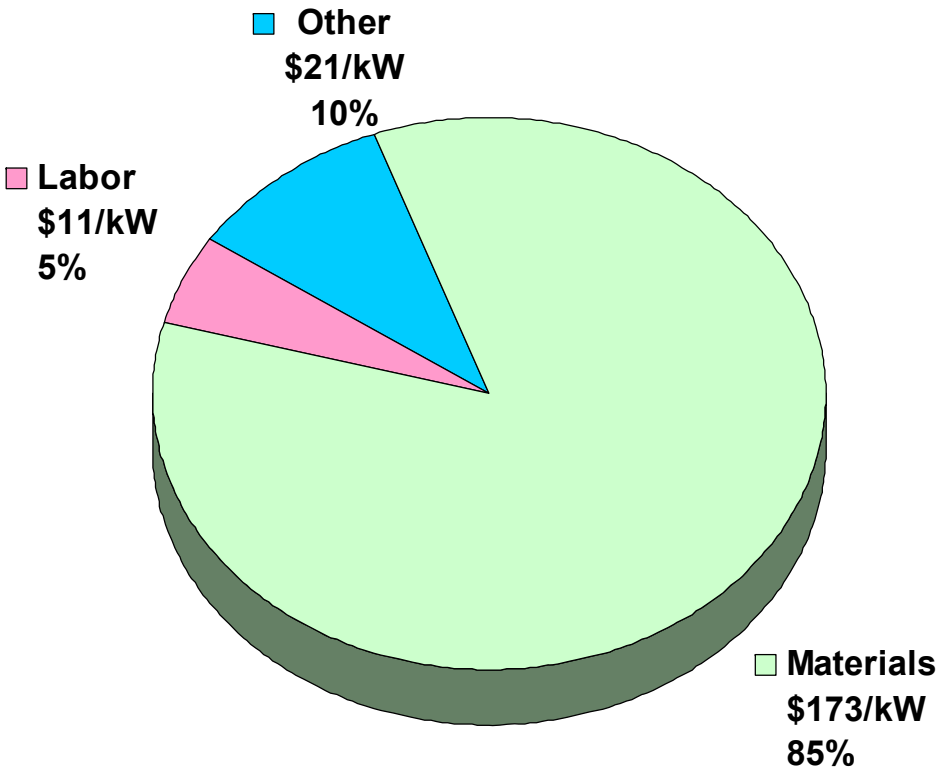
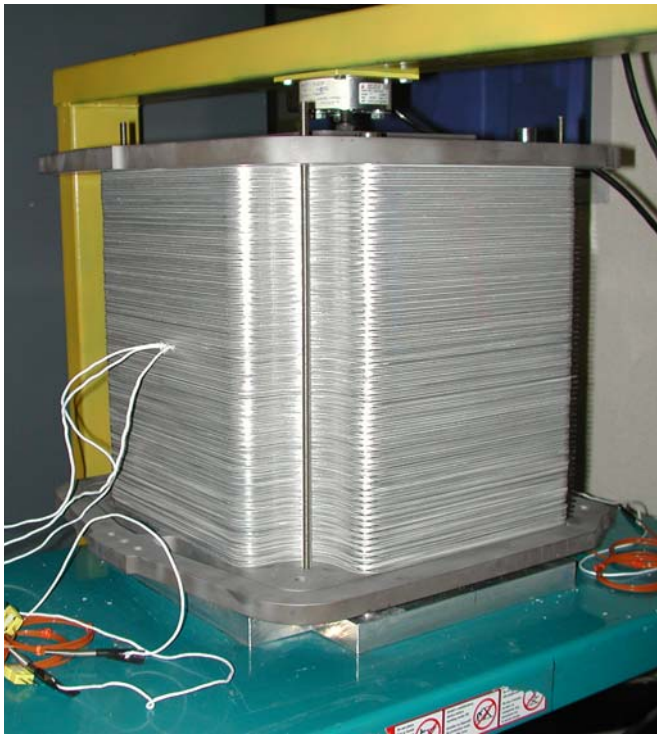
Baseline Power Plant Cost



Preliminary Stack Cost by Category





- The majority of stack cost is driven by the cost of materials.
- The relatively low labor cost is attributed to the many years of cell and stack process development at VPS.
- Stack cost estimates are planned to be audited by an independent auditor.

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System Cost Estimation Methodology

- WorleyParsons' in-house cost database and conceptual estimating tools based on:
  - > Past projects
  - > Recent quotes
  - > In-house parametric factoring methodology
- WorleyParsons' cost model uses bottoms-up reference estimates for key components that can be easily adjusted for system alternatives based on data provided by heat and mass balance calculations
- Costs are referenced to year 2002 USD
- Cost is based on a power plant size of 400MW and factory output capacity of 800MW/year.

This methodology provides a sound basis for the comparison of BOP and system design options.

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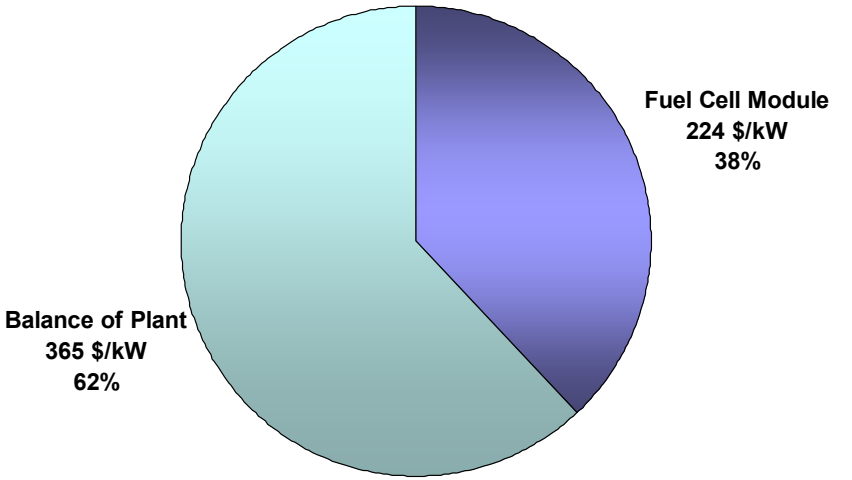
Preliminary Baseline System Cost

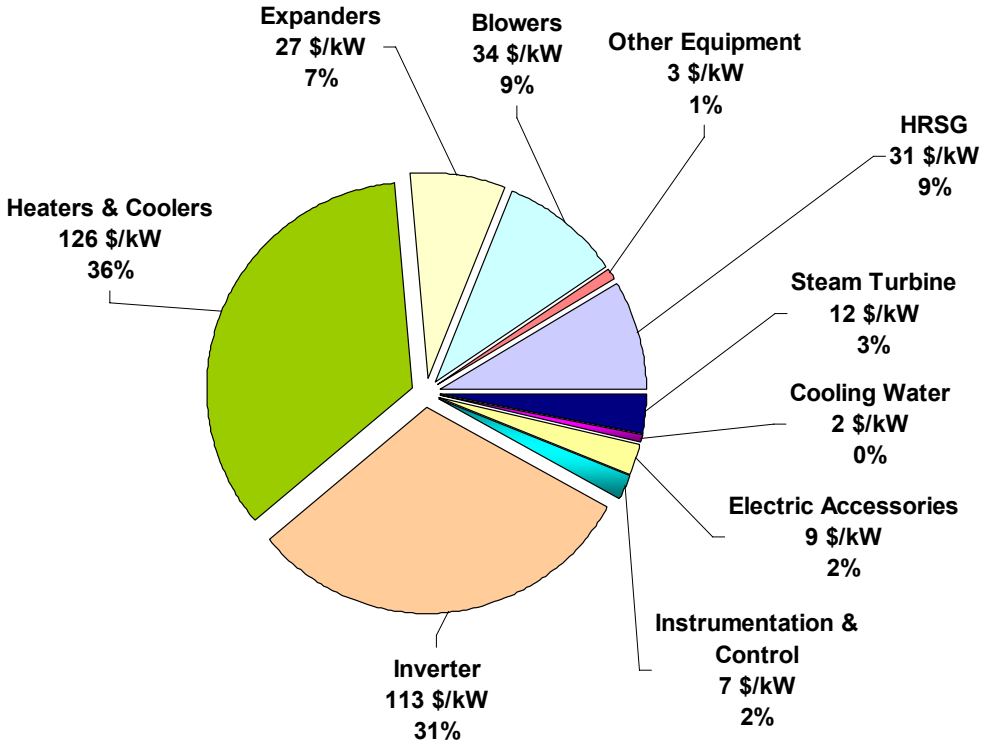
- **Cost estimation based on 5 x 400 MW manufacturing production has established that system equipment factory cost of < $600/kW is achievable.**

Total Factory Equipment Cost (2002 USD) = 589$/kW



Net power rating (kW) does not include CO_2 compression

Total BOP Cost (2002 USD) = 365 $/kW



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Presentation Outline

- **Introduction:**
  - FCE SECA program team members
  - SOFC cell and stack technology overview
- **SECA Coal-Based SOFC Program Outline**
- **Technical Approach and Status:**
  - Cell development (performance, endurance, area scale-up)
  - Stack development (performance, endurance, stack height scale-up)
  - MW module development
- **System and Cost Analyses:**
  - Integrated Gasification Fuel Cell (IGFC) System Configuration
  - Stack Cost Estimate
  - Baseline (400MW) Power Plant Cost Estimate
- **10 kW Stack Metric Test**
- **Conclusions**

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10-kW 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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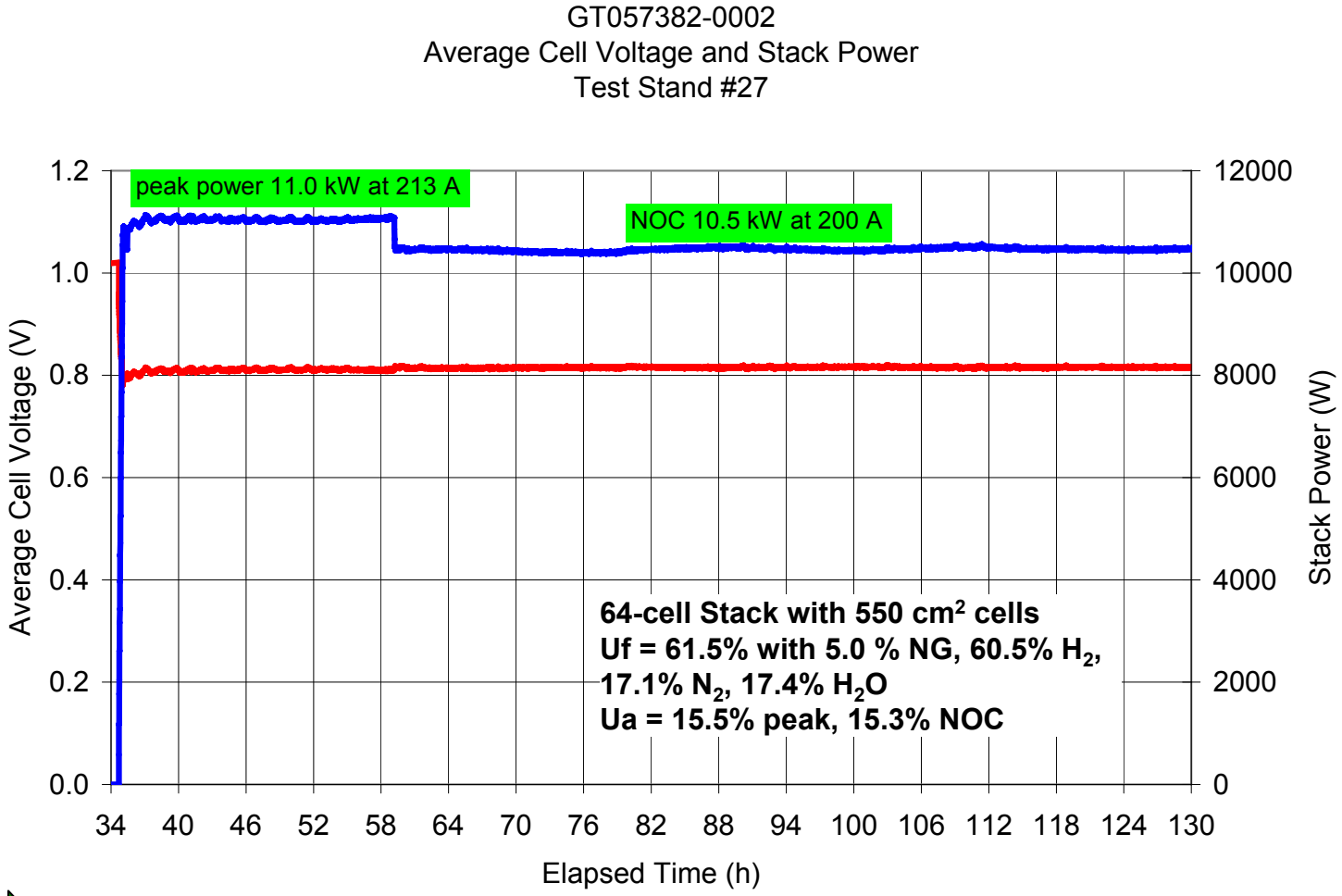
10-kW Stack Metric Test at VPS Performance



Continued operation of the 10 kW stack is planned to meet the 5000 hours of metric test requirements.

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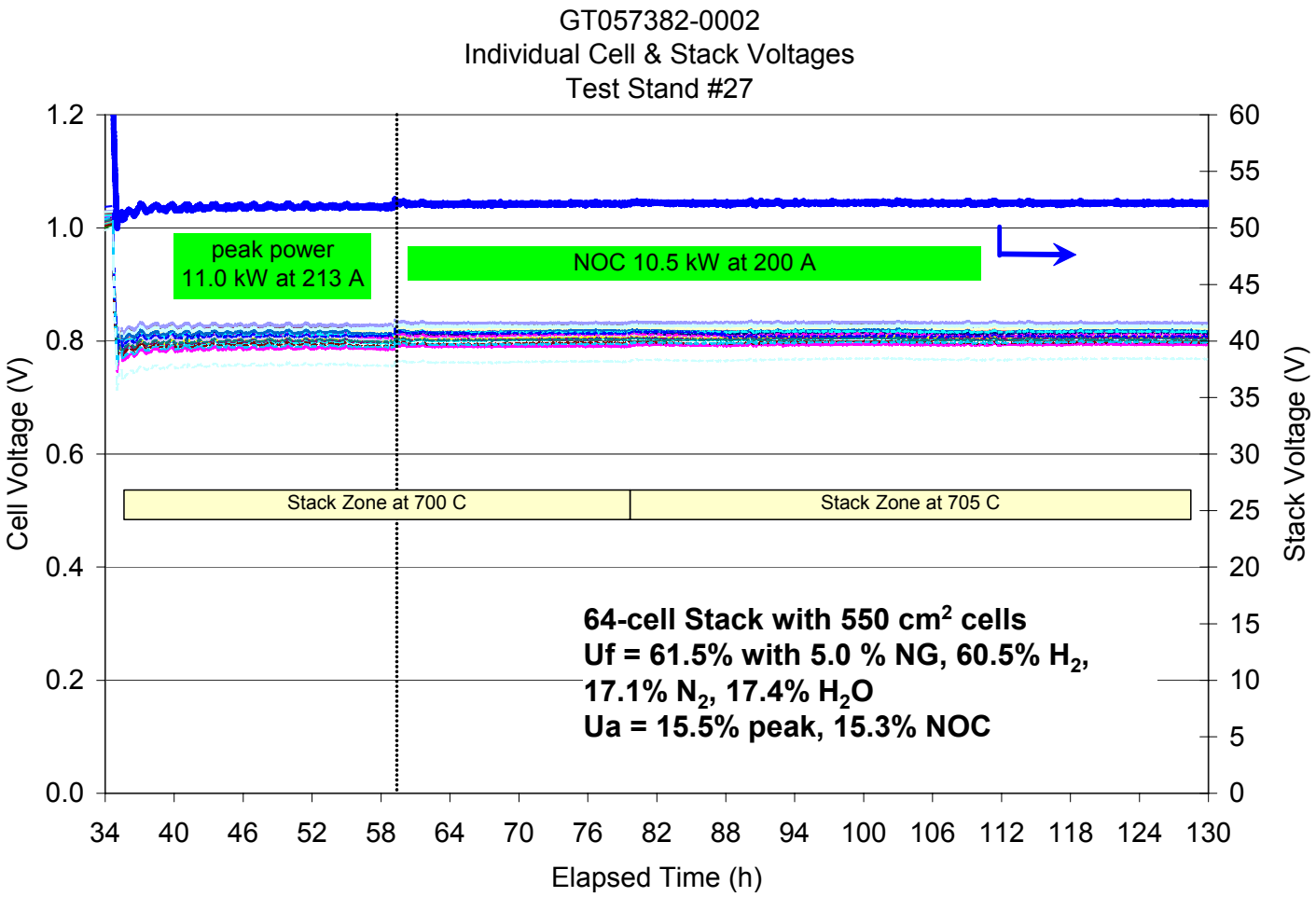
10-kW Stack Metric Test at VPS
Operational Data



64-cell stack has shown excellent cell-to-cell voltage uniformity.

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Stack Technology Progression

Cell Active Area (cm^2)	81
Number of Cells	16
Gross Power (W)	220

Cell Active Area (cm^2)	121
Number of Cells	28
Gross Power (W)	1,152

Cell Active Area (cm^2)	550
Number of Cells	64
Gross Power (W)	11,000

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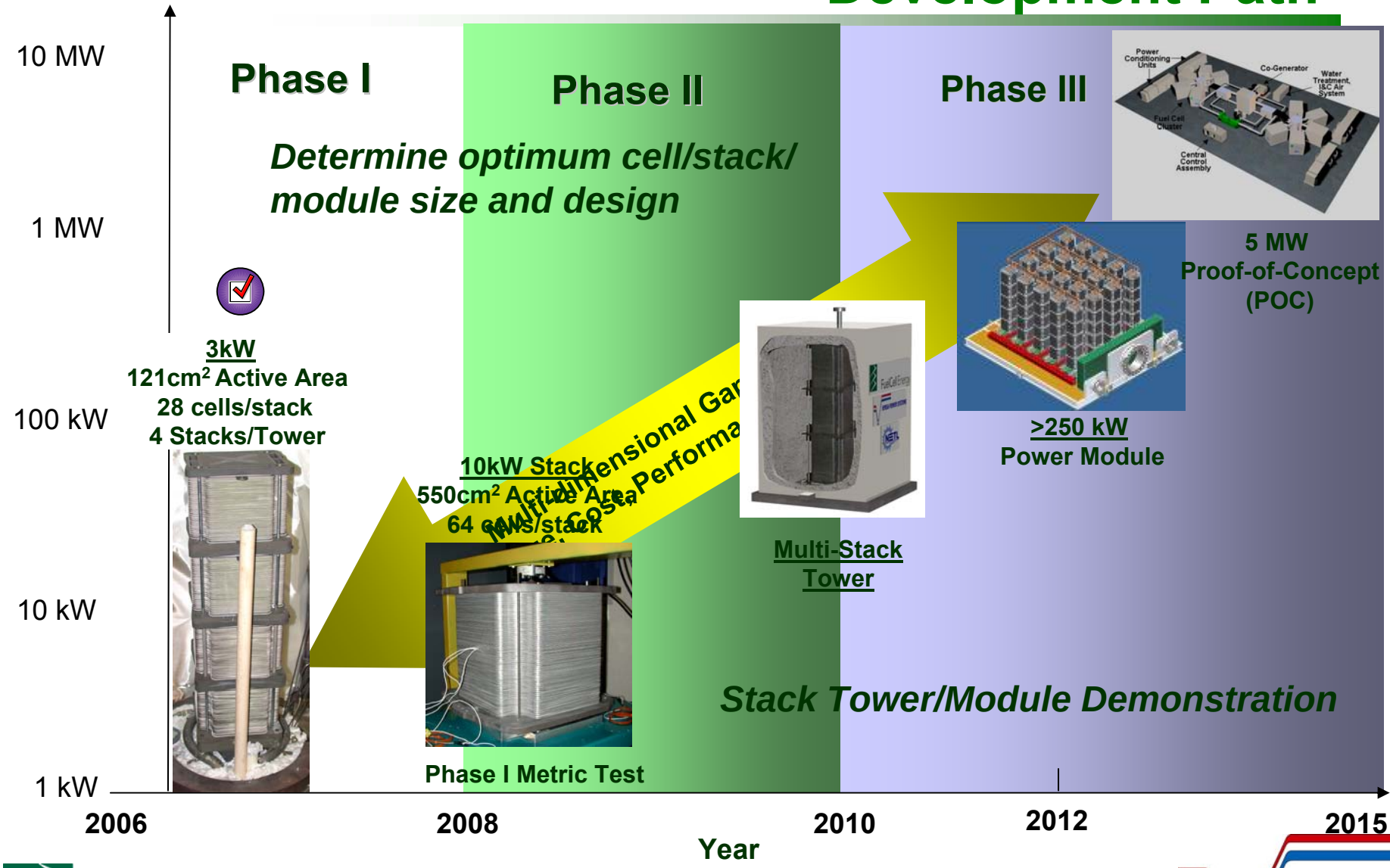
SOFC Stack Module Development Path



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Conclusions

- **Several significant technical milestones in cell and stack development have been achieved:**
  - SOFC manufacturing scale-up from the baseline size of 156cm^2 to greater than 1000cm^2 has been successfully demonstrated. Production capacity for scaled-up 625cm^2 (550cm^2 active area) components has been successfully validated.
  - Efforts are well underway to enhance stack manufacturing capacity to 500kW/year and cell manufacturing capacity to 1,000kW/year by the end of the Phase I program (October 2008).
  - Single cell testing of advanced cell components has demonstrated ~8-10% performance improvement over baseline cell components.
  - Advanced cell components also have shown significant improvement in endurance (decreased decay rate) over the baseline cells.
  - Stability and uniformity in operation of the scaled-up cells have been successfully demonstrated in several 10-kW stacks of 64 cells.
- **Preliminary cost analysis of the SOFC Multi-MW Baseline Power Plant System shows a clear path to achieving the SECA cost goals.**
- **Technical advances indicate that SOFC offers a viable option for clean, reliable, highly efficient and cost effective power generation from coal based fuel sources.**

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Acknowledgements

- The support provided by NETL is acknowledged and gratefully appreciated by the FCE team.
- Many thanks to Wayne Surdoval, Travis Shultz, and Heather Quedenfeld for their project and technical guidance.

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