Progress in SOFC Development at FuelCell Energy

13th Annual SECA Workshop
Pittsburgh, PA
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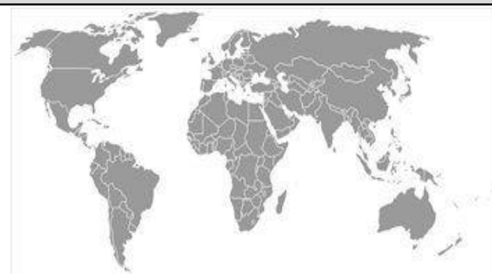
Versa Power Systems

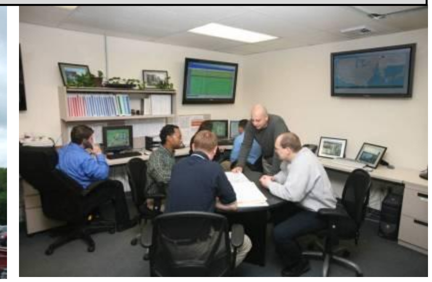
Presentation Outline

- **Introduction**
  - FCE SECA Program Team Members
  - SECA Coal-Based SOFC Program Overview
- **Progress in SOFC Technology**
  - Cell Development and Manufacturing
- **Stack Development**
  - Scale-up and Tower Tests
- **Proof-of-Concept Module (PCM) Development**
  - Stack Module
  - 60 kW PCM System
- **Baseline System Design and Cost Analyses**
  - Integrated Gasification Fuel Cell (IGFC) System Configuration
  - Updated Baseline Power Plant Cost Estimate
- **Conclusion and Future Plans**

FuelCell Energy, Inc.

Manufacture | **Sell** (direct & via partners) | **Install** | **Services**



- Premier developer of stationary fuel cells with >40 years of experience
- Delivering Direct FuelCell® (DFC®) power plants to commercial and industrial customers
  - 182 MW installed and in backlog (>80 power plants), plus 120 MW MOA
- Established commercial relationships with major distributors in the Americas, Europe, and Asia
- Developing large-scale coal-based power plants as well as natural gas distributed generation (DG) systems utilizing planar SOFC

Delivering ultra-clean baseload distributed generation globally

600 kW plant at a food processor

1.4 MW plant at a municipal building

2.4 MW plant owned by an Independent power producer

2.8 MW DFC3000 Wastewater Treatment Plant

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Large Scale Power Plants

Experience in large scale power plants will be utilized in design, fabrication, and operation of Coal-Based SOFC Plants

10.4MW Plant
(Yeosu, S. Korea)

11.2 MW Plant
(Daegu City, S. Korea)

60MW System in Development
(Hwaseong, S. Korea)

Proposed 15 MW fuel cell park
(Bridgeport, CT)

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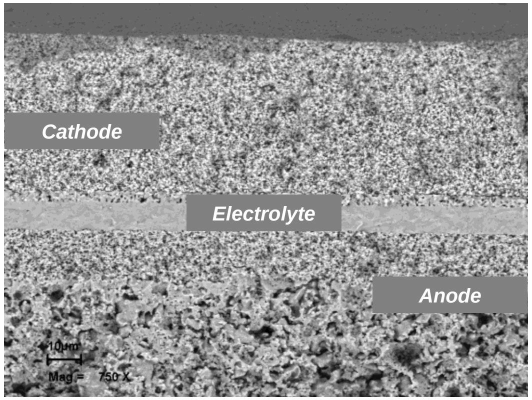
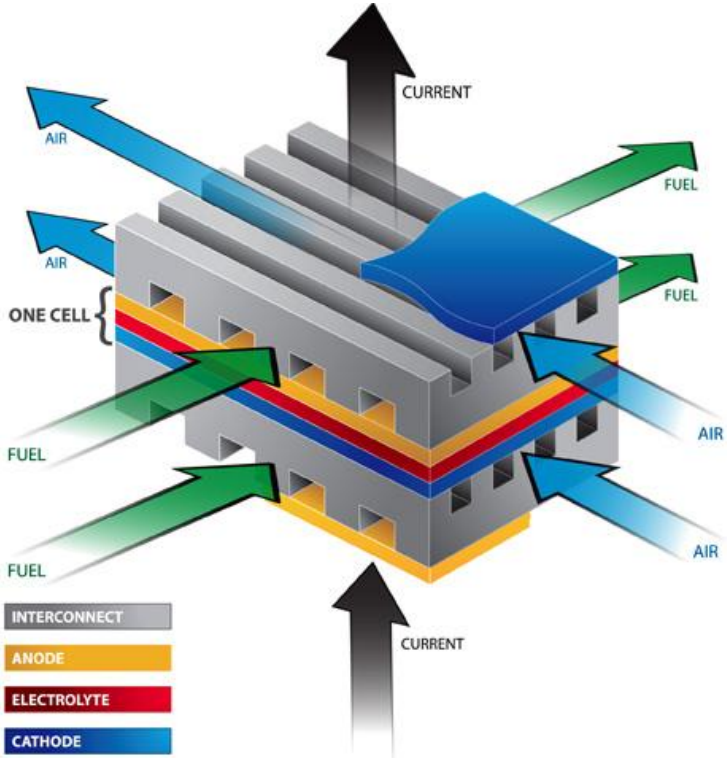
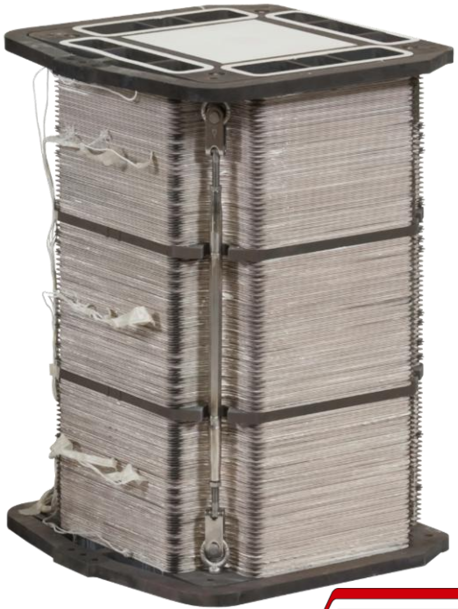
SOFC Cell and Stack Technology Background

- Planar anode supported cells (up to 1000 cm^2)
- Capable of operating from 650 C to 800°C
- Ferritic stainless steel sheet metal interconnect
- Cross-flow gas delivery, with integrated manifolding
- Standardized stack blocks configurable into stack towers for various power applications







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Versa Power Systems (VPS)

- **Privately held company**
  - > Founded as joint venture of Solid Oxide Fuel Cell Consortium in 2001
  - > Headquartered in Littleton, Colorado, United States
  - > Established SOFC development facility in Calgary, Alberta, Canada
- **Planar solid oxide fuel cell technology**
  - > Achieved high electrical power densities and long life using low-cost materials
  - > Developed manufacturing processes scalable to high volume production rates
  - > Established standardized SOFC stack products
  - > Extended R&D for defense and regenerative fuel cell applications

32,000 ft² research & pilot manufacturing Facilities in Calgary, CA

17,000 ft² facility in Littleton, Co

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Coal-Based SECA Program Status

Phase I

- Cell & stack scale-up
- Validation testing of 64-cell stack block (10 kW)
- Pilot manufacturing process development and yield increase

10 kW Stack

Phase II

- Increased cell performance and endurance combined with cost reduction
- Standardization of 96-cell stack block
- Demonstration of 2-stack tower (30 kW) operation
- Configuration of an IGFC system achieving DOE's performance and cost targets

30 kW Stack Tower

Phase III

- Increased cell and stack robustness and reliability
- Development of a >50kW Stack Module design
- Validation testing of 60 kW module non-repeat hardware in preparation for upcoming 60kW Stack Module testing

60 kW Stack Module

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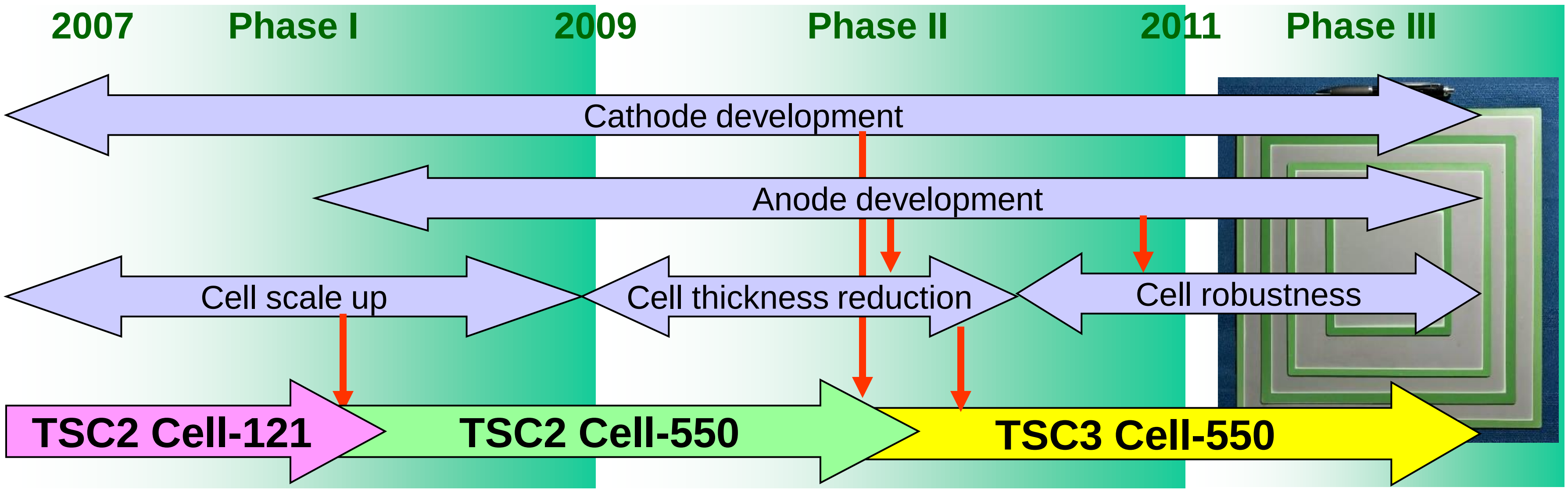
Cell Development Accomplishments



- **Cathode Development**
  - ☑ **Enhanced Performance and Endurance**
  - ☑ **Reduced Operating Temperature**
  - ☑ **Increased Operating Window**
- **Anode Development**
  - ☑ **Reduced Cell Thickness**
  - ☑ **Enhanced Performance at Higher Fuel Utilization and at Lower Temperature**
  - ☑ **Enhanced Cell Mechanical Properties and Robustness**
- **Scale Up & Manufacturing Development**
  - ☑ **Scaled up from 121 cm² → 550 cm² →1000 cm²**
  - ☑ **Established Manufacturing Processes for Baseline 550cm² Cells**
  - ☑ **Completed Process Integration and Validation in Transitioning from TSC2 → TSC3 technology**

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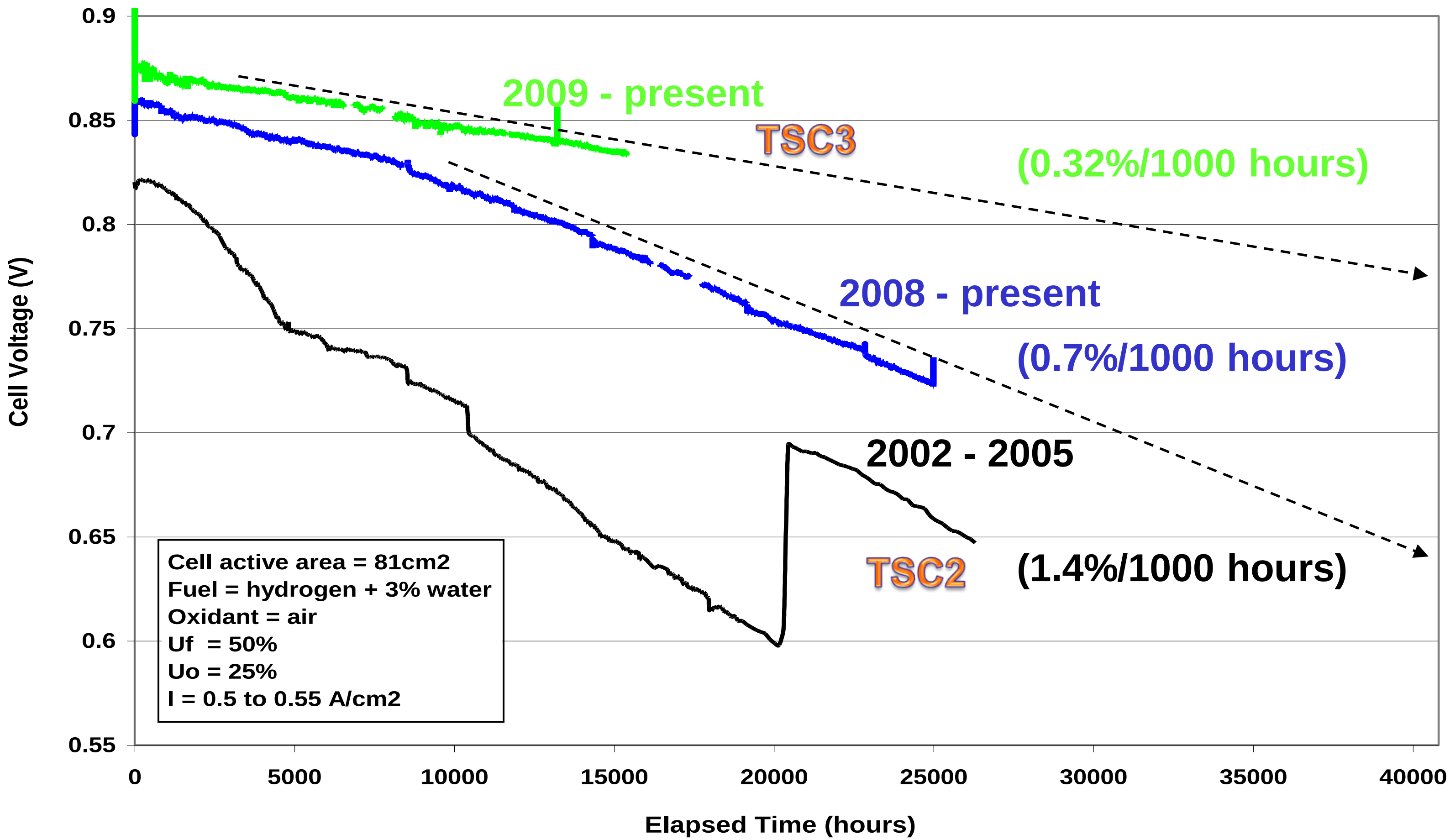
Cell Technology Evolution



Significant progress has been made toward enhancing cell performance and endurance.

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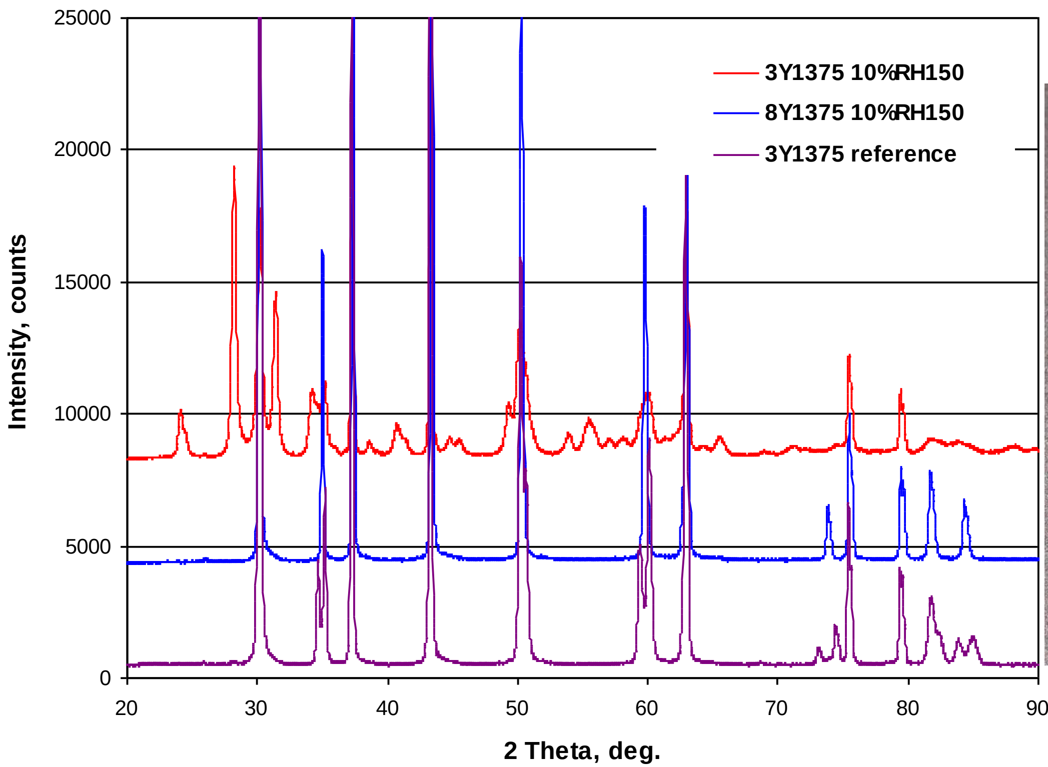
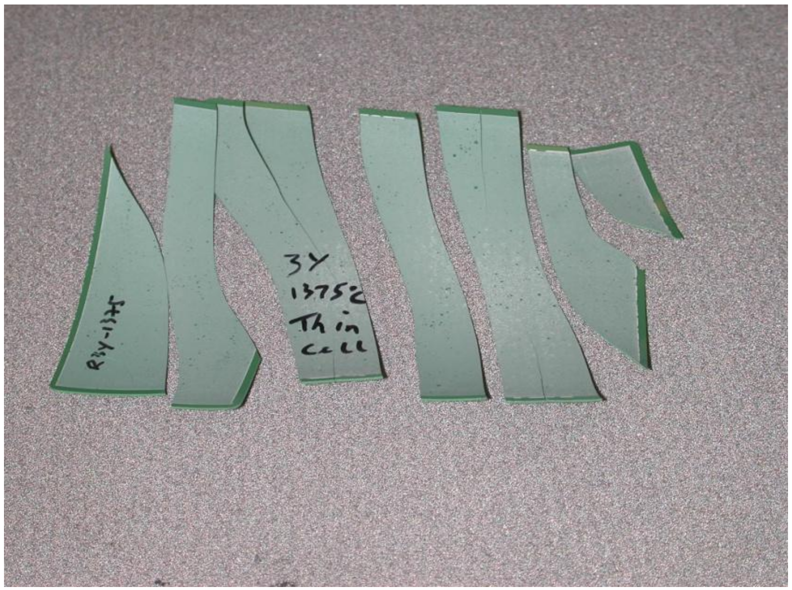
Development of Hydrothermal Stable Cell

- **Hydrothermal stability issues for thin cells**
  - > 3YSZ was initially used in anode substrate for thin (0.6 mm) TSC3 cells
  - > The anode made with 3YSZ exhibited hydrothermal stability issues due to monoclinic phase formation at 100 to 400 C with humidity
  - > Phase changes resulted in cell cracking due to anode substrate volume increase (up to 7%)





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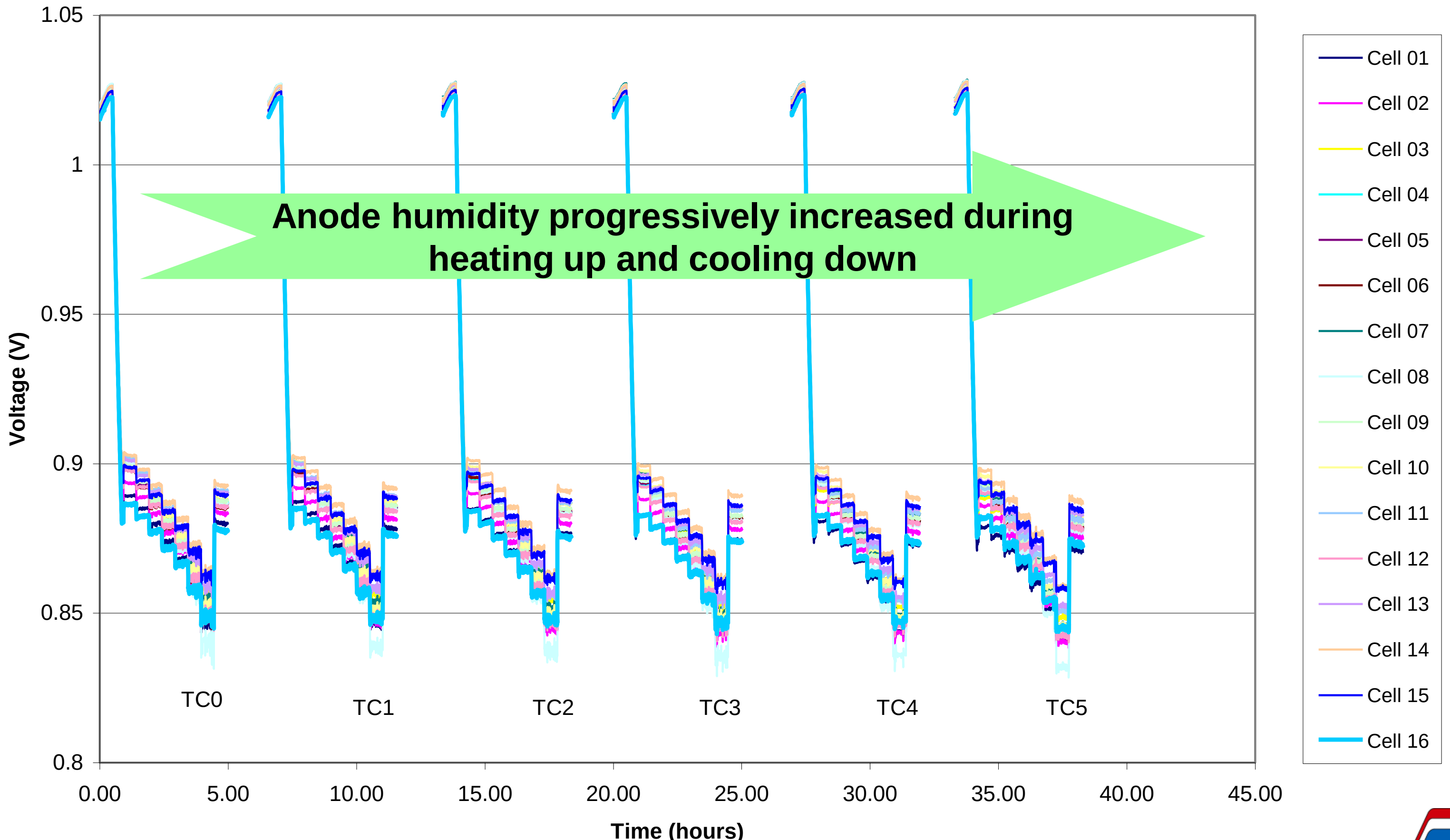
Development of Hydrothermal Stable Cell

- Over 20 anode substrate formulations were explored and tested
- A preferred solution was found and validated in stack testing
- Cell manufacturing process was re-developed to implement the changes



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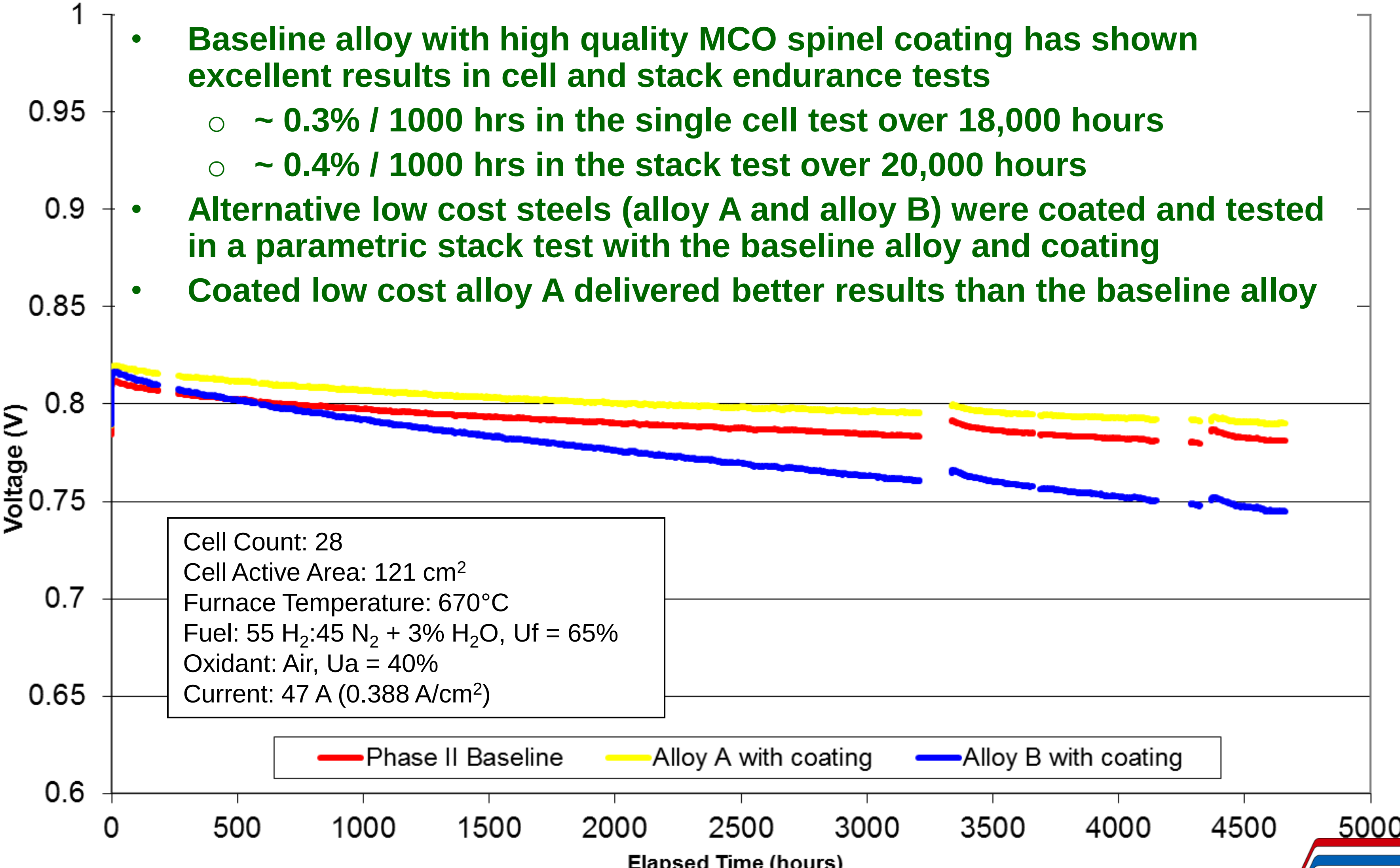
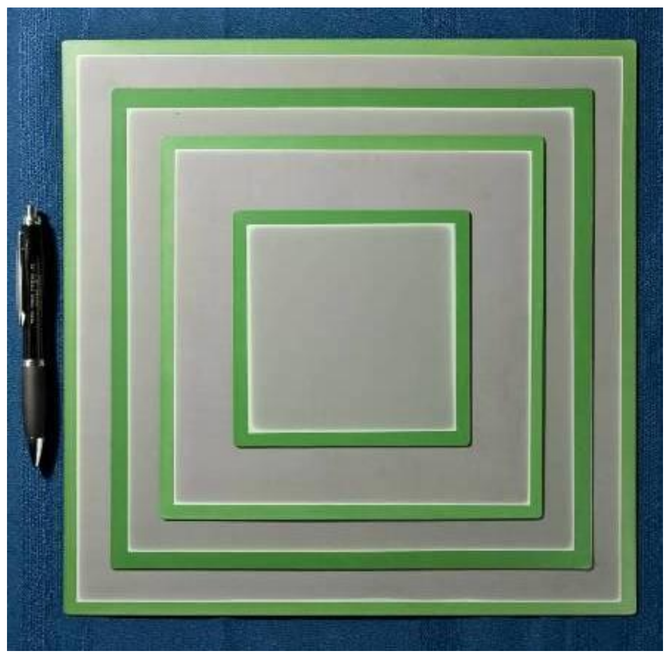
Interconnect Alloy and Coating Development

- **Baseline alloy with high quality MCO spinel coating has shown excellent results in cell and stack endurance tests**
  - **~ 0.3% / 1000 hrs in the single cell test over 18,000 hours**
  - **~ 0.4% / 1000 hrs in the stack test over 20,000 hours**
- **Alternative low cost steels (alloy A and alloy B) were coated and tested in a parametric stack test with the baseline alloy and coating**
- **Coated low cost alloy A delivered better results than the baseline alloy**



Cell Scale-Up Development

- VPS' established **T**ape casting/**S**creen Printing/**C**o-firing (TSC) process proved flexible enough to allow a > 8x increase in cell active area (121 → 1000 cm^2)
- Cell thickness was reduced from 1 mm to 0.6 mm
- 25 cm x 25 cm cells (550 cm^2 active area) are the focus for large area stack development



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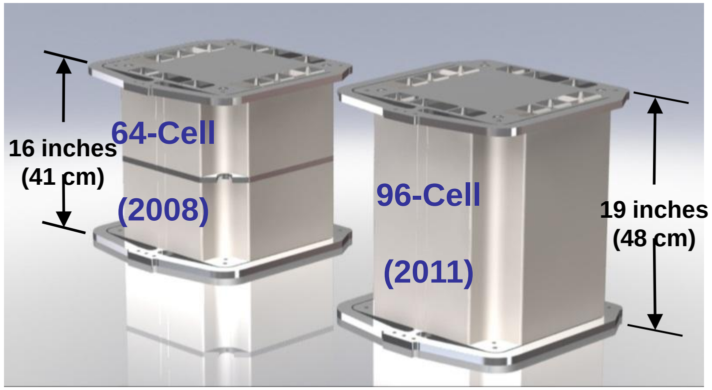
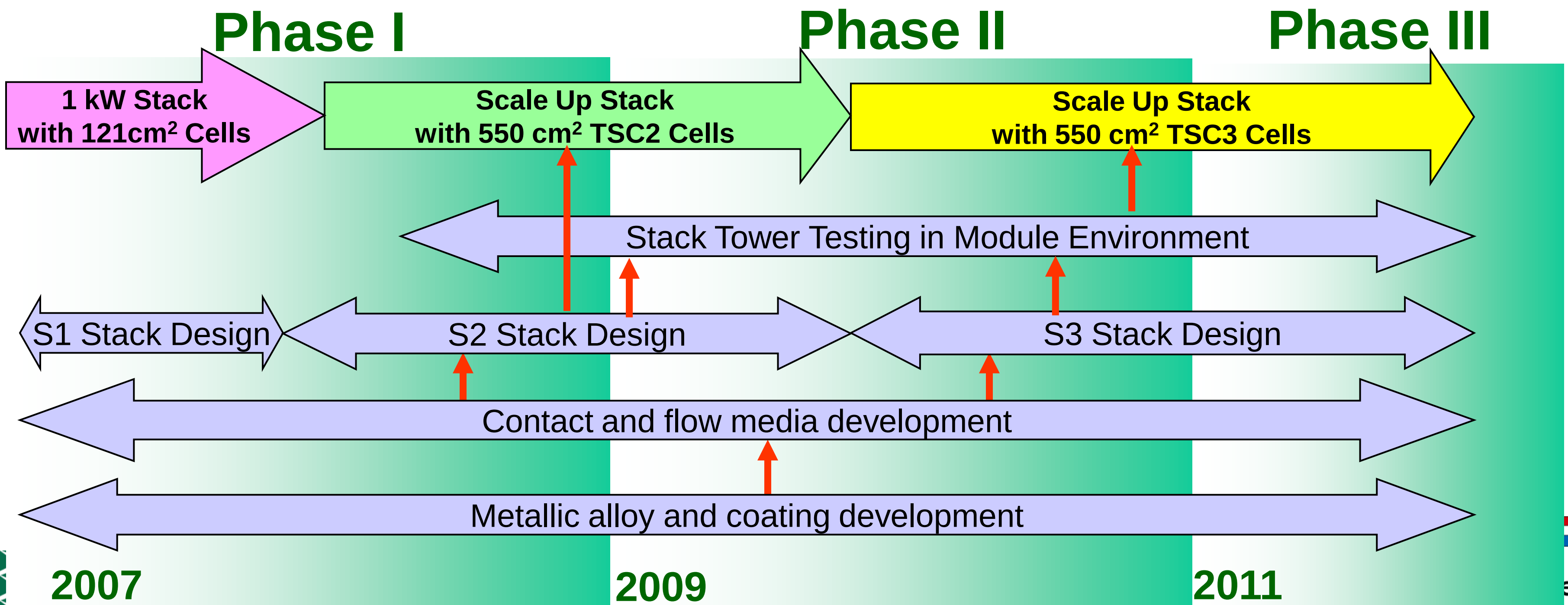
Stack Development Accomplishments



- **Improved stack performance**
  - > **Higher power density**
  - > **Higher fuel utilization**
  - > **Higher direct internal reforming**
- **Enhanced stack endurance**
  - > **Improved stack thermal and flow management**
  - > **Incorporated TSC3 cells**
  - > **Incorporated advanced metallic coating technology, contact and flow media**
- **Reduced stack cost to meet SECA cost targets**



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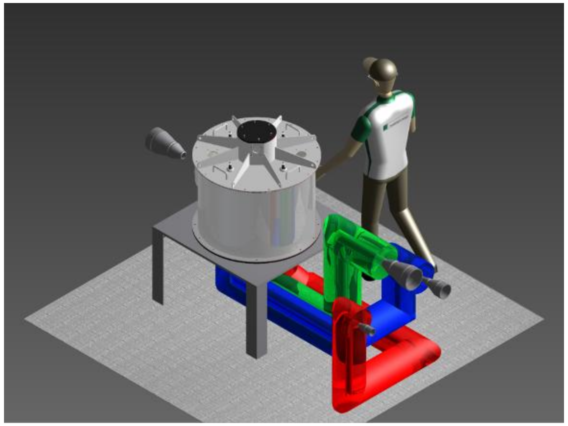
3-5 kW Module for Short-Stack Testing



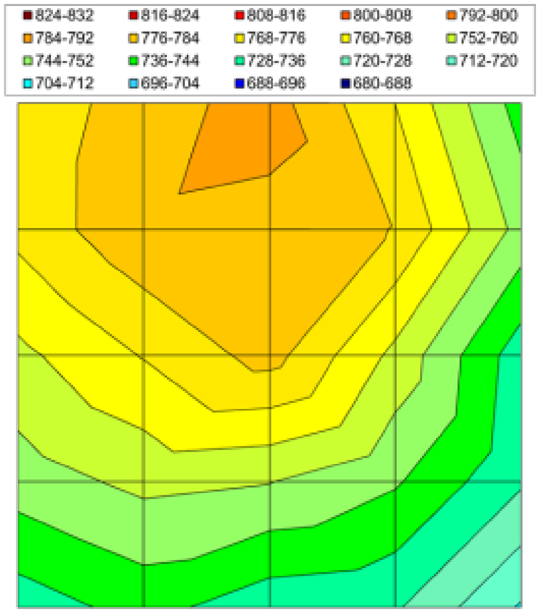
- Objective: Provide a platform for testing short stacks under various process conditions with reduced technical risk relative to large modules
- Benefits:
  - > Enables rapid stack change-out (less than 1 day)
  - > Test stacks under expected system conditions
  - > Study stack/module design alternatives under a thermally self-sustaining environment
  - > Investigate thermal cycling, start-up and shut-down procedures.
- Design Features:

Stack Change-out without the need for piping removal

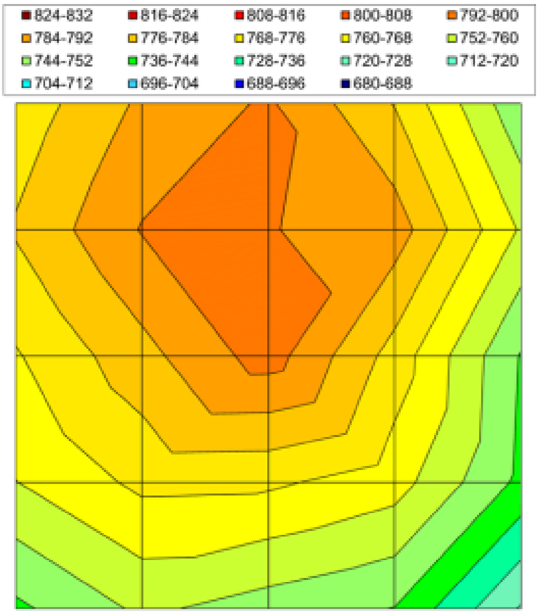
3-5kW Module Test Results Using 16-cell Stack

- Preferred system operating procedures and controls were identified using Sub-scale testing platform.
- Performance and thermal profiles were evaluated as function of fuel composition, extent of internal reforming, and fuel/air utilizations.
- System level heat-up/shut down procedures were tested with acceptable results.

Air Utilization = 13.5%
Maximum On-cell ΔT = 77°C
Average Cell Temp. = 753°C



Air Utilization = 25%
Maximum On-cell ΔT = 77°C
Average Cell Temp. = 760°C



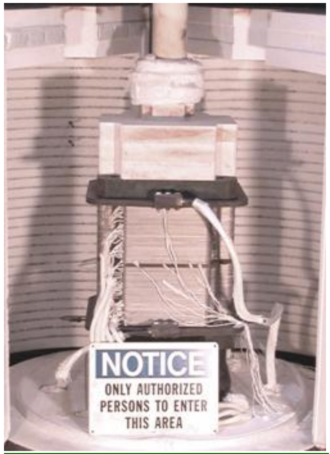
Stack Fabrication

Stack Size	Phase I Quantity	Phase II Quantity	Phase III Quantity	Total
Short Stacks 6 - 32 Cells	39	43	16	98
Full Size Stacks > 64 cells	6	9	15	30
Total Quantity	45	52	31	128
Total kW	126	255	262	643

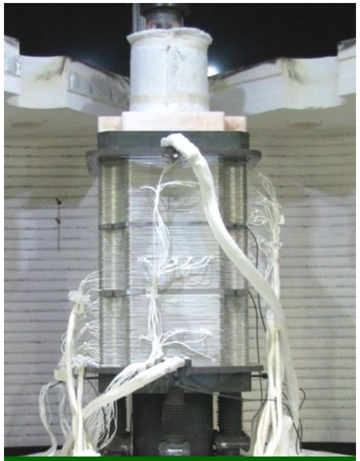
Phase III stack block (96-cell)

6-cell short stack

16-cell short stack

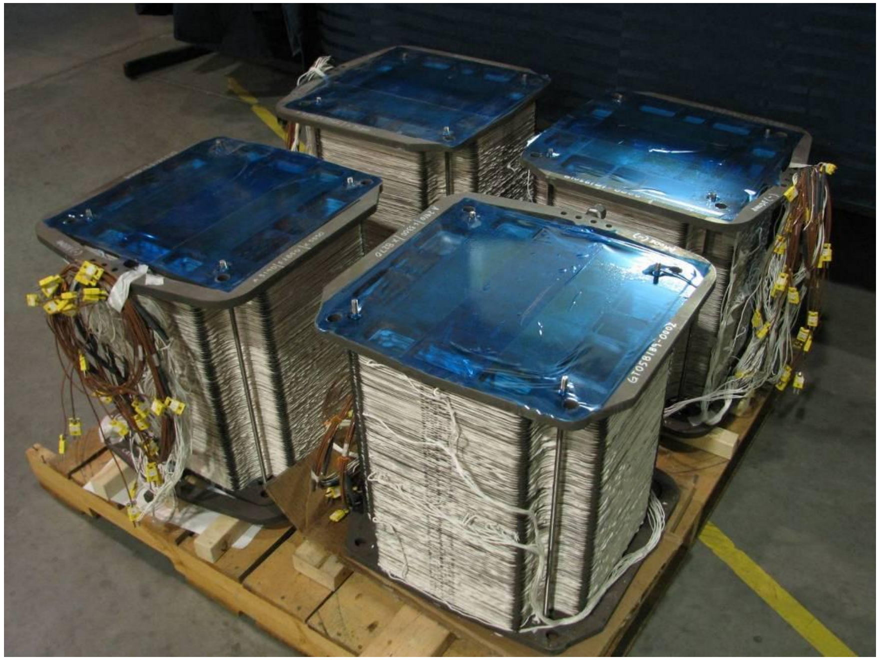


Phase I stack block (64-cell)



Phase II stack block (92-cell)

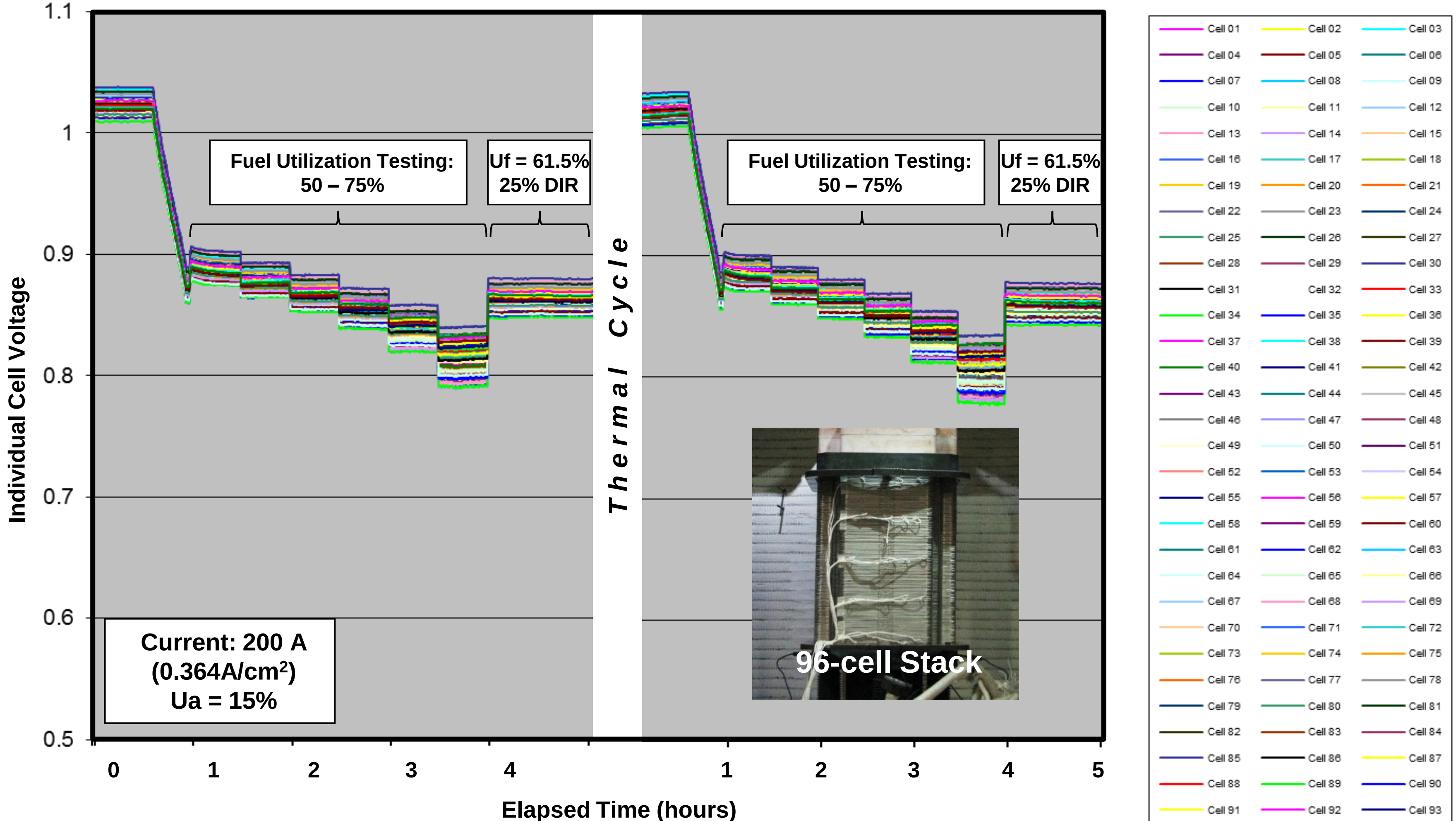
Standard 96-Cell Stack Block Development and Fabrication



4x 96-cell stacks to be integrated in a 60 kW module as shown on a shipping crate

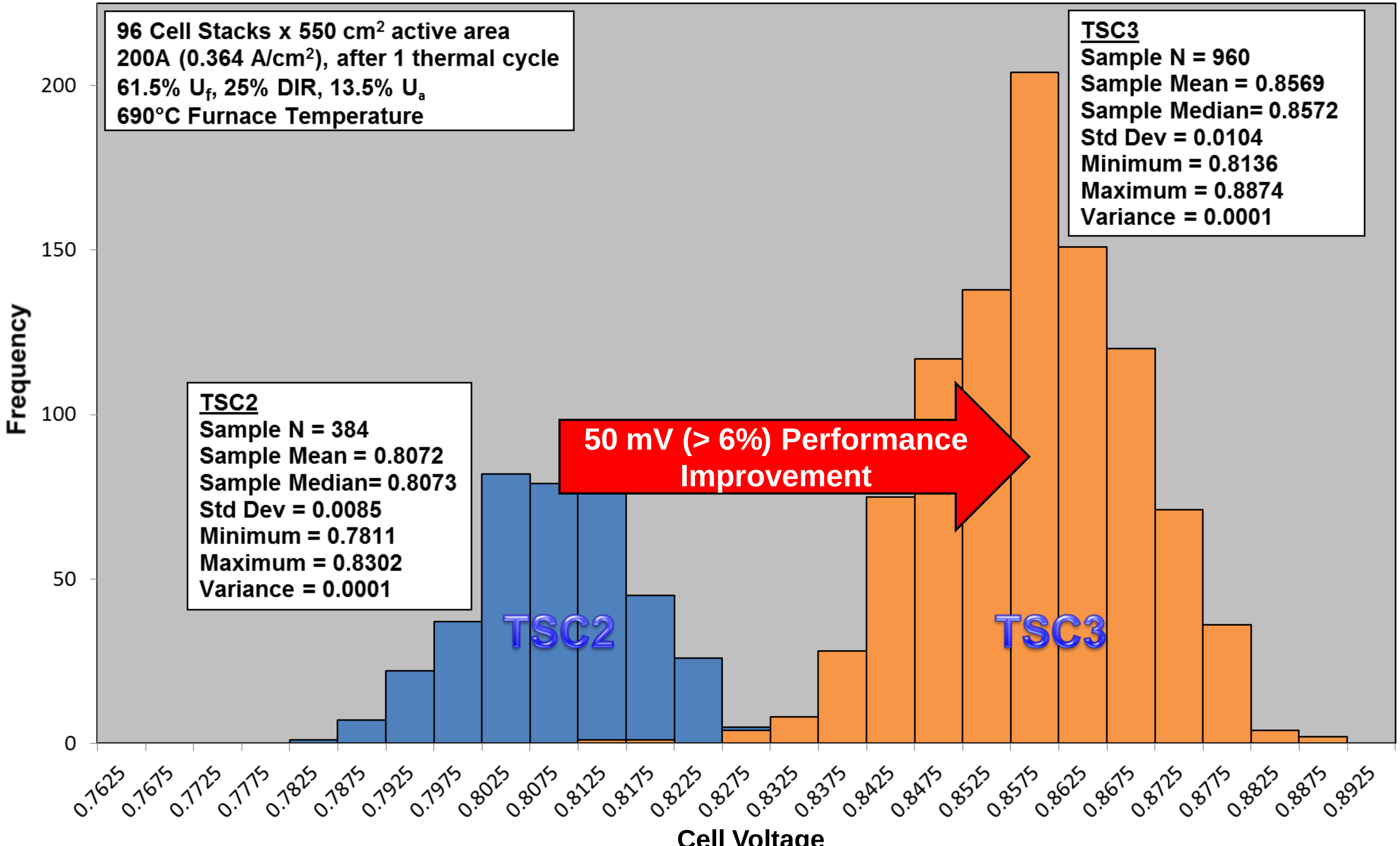
- Reduced stack heights through component reduction
- Reduced on-cell thermocouples
- Improved production tooling
- Implemented additional QA and QC steps for stack components
- Refined stack acceptance criteria
- Accomplished factory acceptance testing of 14 x 96-cell stacks with consistent results

Stack Acceptance Tests
Before and After Thermal Cycle



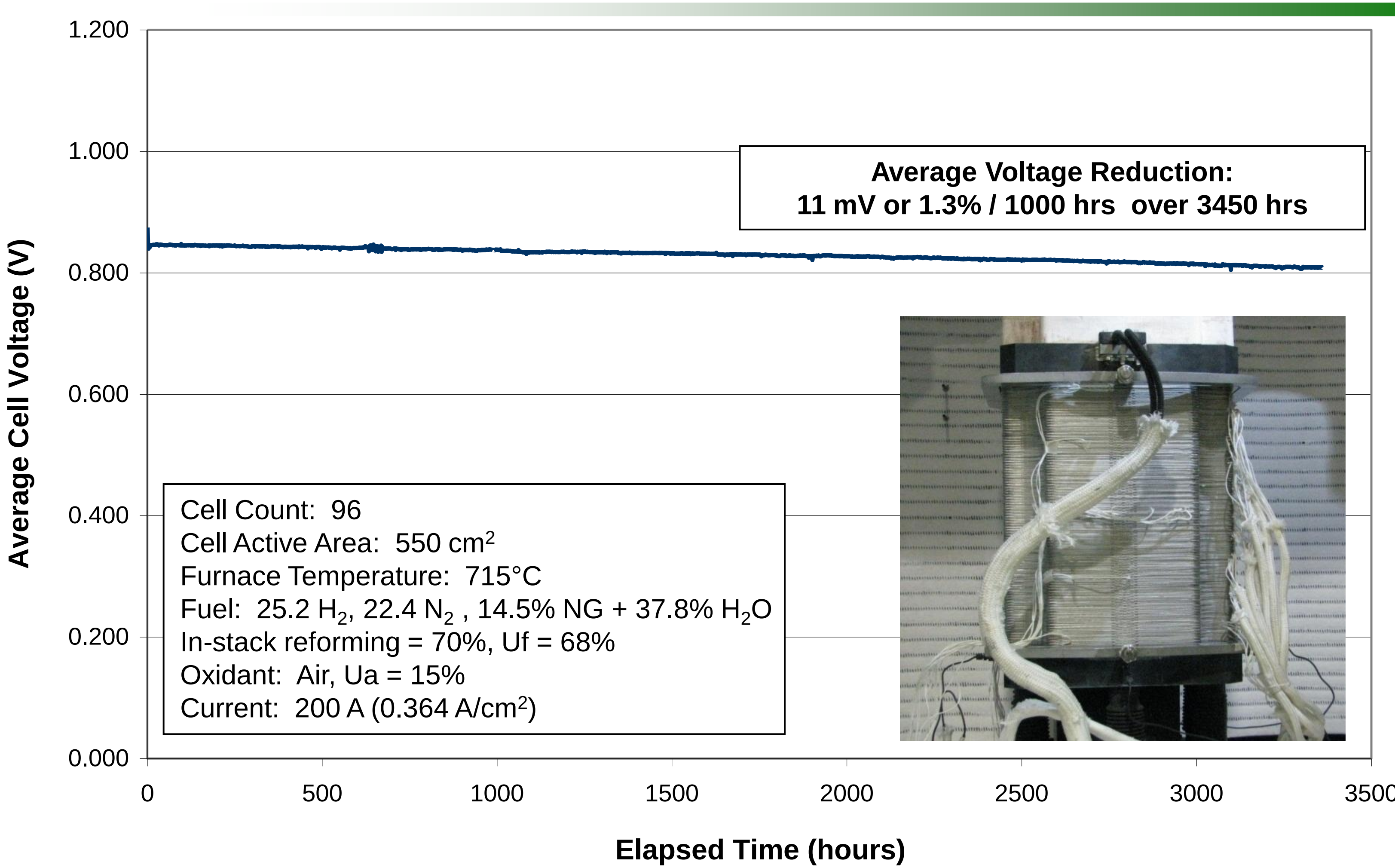
➡ **Stack Displays stable performance, even at high fuel utilization, after thermal cycling**

Performance Consistency of 96-cell Stacks



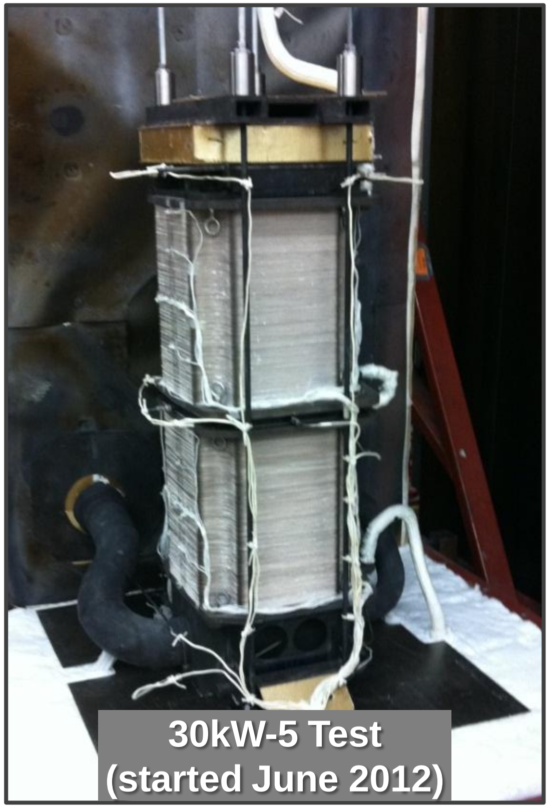
- **Ten 96-cell TSC3 stacks have been built, displaying consistently higher performance than previous TSC2 technology**

96-Cell Stack Endurance Testing



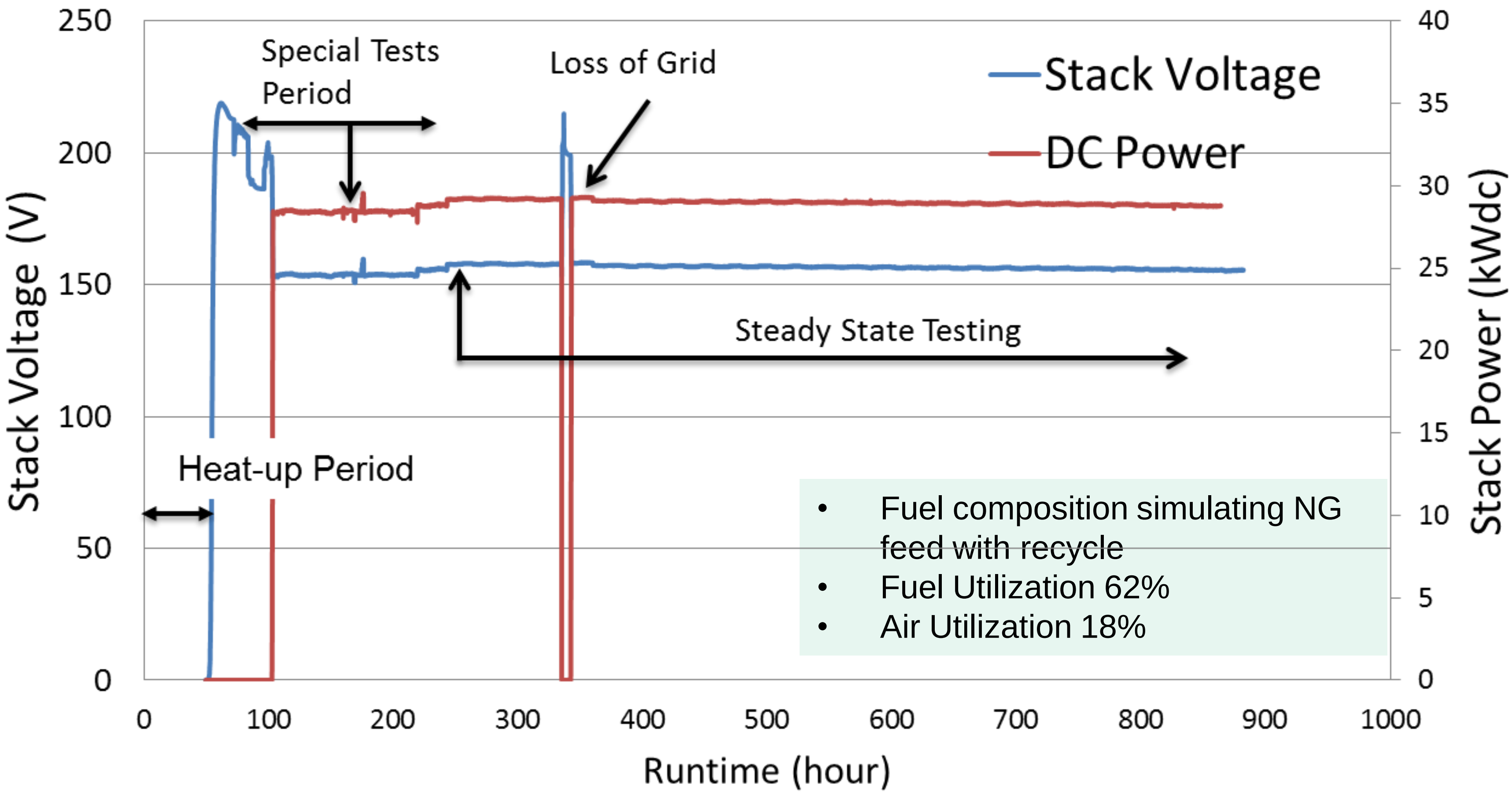
- **Recent stacks have been shown improved stability and reliability utilizing advanced components and materials developed in Phase III**

Stack Tower Testing



- Thermally self-sustaining test environment (gas preheated only)
- Provisions for simulated anode gas representative of both coal-derived syngas and natural gas fueled systems
- Simulates commercial system operation: Providing valuable lessons for future larger stack module designs

30kW-5 Stack Tower Test Results



- Fuel composition simulating NG feed with recycle
- Fuel Utilization 62%
- Air Utilization 18%

Tests of the 30 kW stack (30-5) tower is being continued under system operating conditions.

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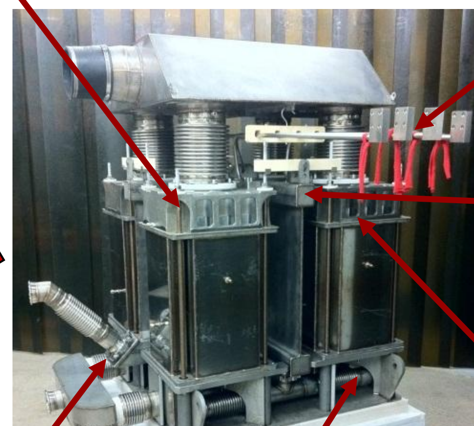
60 kW Stack Module Design Development

Complete Module

Compression Plate

Hot Buss Bars

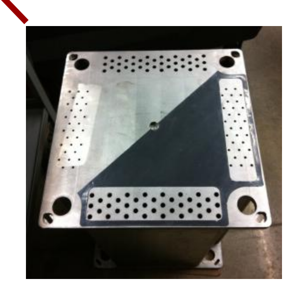


Internal Fuel Pre-Heater

Module Integration
and Instrumentation

High Temp. Flanges

Quad Base



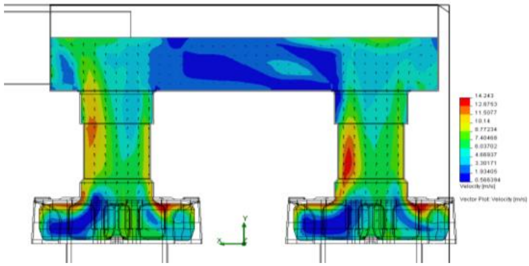
Conductive
Stack Gasket

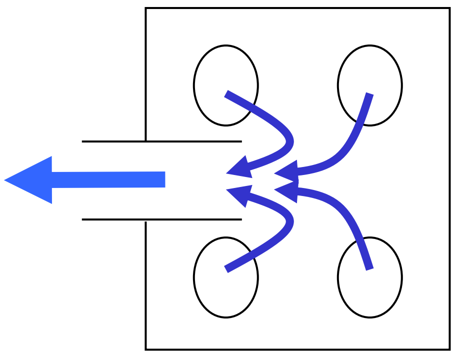
60 kW Module Hardware Testing

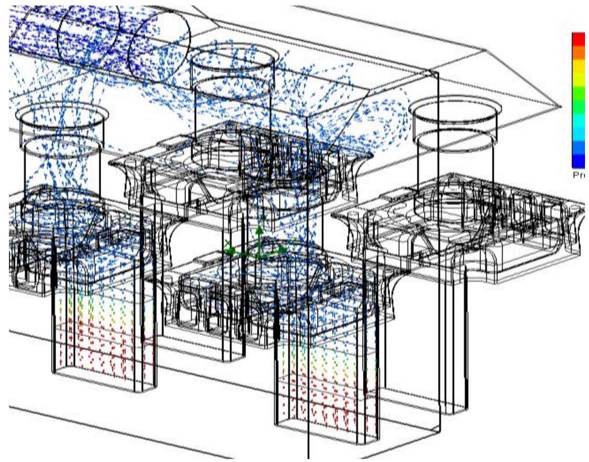
<u>Objective</u>: Validate all non-repeat module components in hot operation with inexpensive mock (non-real) stacks

- **Flow:**
  - > Validate CFD models for flow uniformity
  - > Verify pressure drop
- **Thermal:**
  - > Thermal balancing
  - > Symmetrical heat loss among stacks
  - > Vessel thermal performance
- **Electrical:**
  - > Determine hot buss bar IR losses
  - > Characterize conductive gasket performance
  - > Ensure dielectric isolation of key components
- **Mechanical:**
  - > Verify high-temperature integrity of ducting and mechanical connections
  - > Validate stack compression components
  - > Validate alloy selections and differential thermal expansions

60 kW Stack Module Flow Uniformity





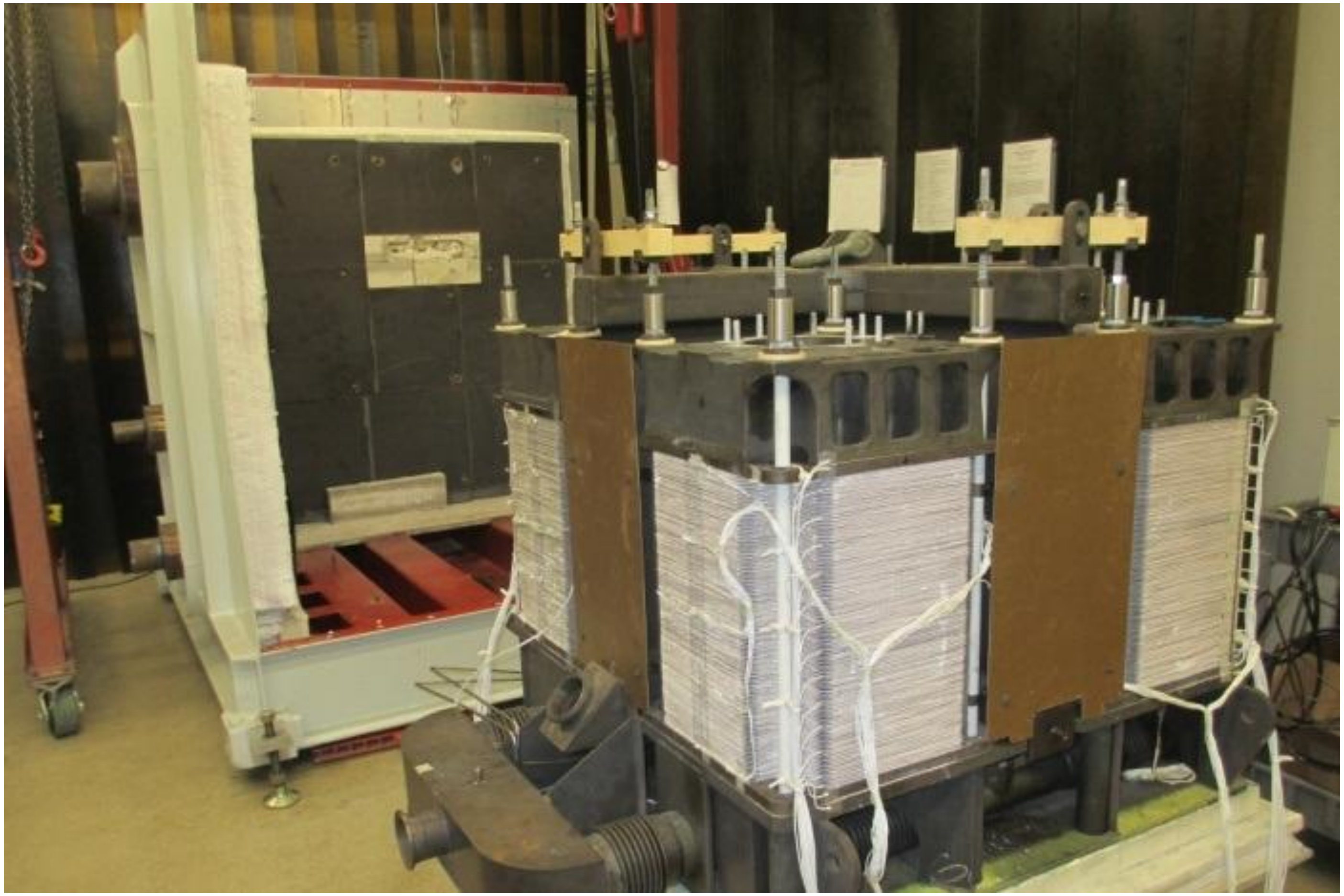


Cathode-Out Collector

Cold-Flow Test Setup

- CFD analysis utilized during design process to achieve uniform flow distribution
- Cold Flow testing performed to characterize flow distribution and validate CFD models and correct issues prior to Hot Testing
- Hot testing verified acceptable flow variation (+0.45% to -0.35% from the mean)

60 kW Stack Module Assembly



➡ **60 kW SOFC Module Assembly with Live Stacks is in Progress for August 2012 Test Start**

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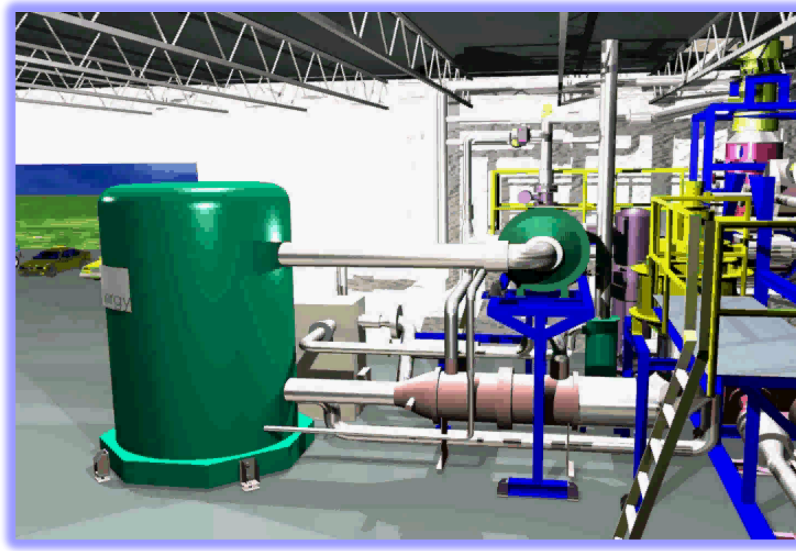
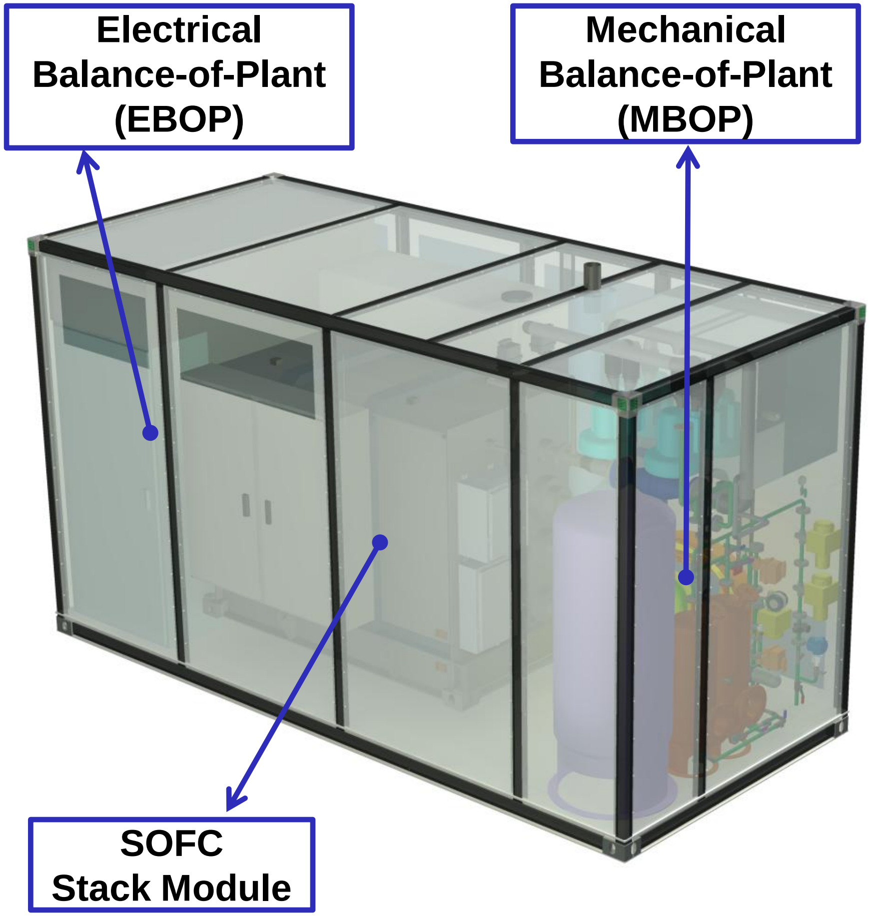
400 kW Power Plant Facility

60 kW module is planned to be tested in the existing 400 kW Power Plant Facility.



- 400 kW Power Plant Facility is equipped for testing of full scale fuel cell modules integrated in an actual system configuration:
  - Fully Automated Process Control
  - Anode & Cathode High Temperature Blowers (700 °C)
  - High Temperature Recupertors (750 °C)
  - Catalytic Oxidizer, Desulfurizers, and Reformer
  - DC-AC Inverter and Switch Gear for Utility Tie-In

60 kW PCM System Performance



System Performance Summary

SOFC Gross Power		
DC Power	**70.1**	**kW**
Energy & Water Input		
Natural Gas Fuel Flow	6.3	scfm
Fuel Energy (LHV)	103.4	kW
Water Consumption @ Full Power	0	gpm
Consumed Power		
AC Power Consumption	3.3	kW
Inverter Loss	3.2	kW
Total Parasitic Power Consumption	**6.5**	**kW**
Net Generation		
SOFC Plant Net AC Output	**63.6**	**kW**
Available Heat for CHP (to 120°F)	**22.6**	**kW**
Efficiency		
Electrical Efficiency (LHV)	**61.6**	**%**
Total CHP Efficiency (LHV) to 120°F	**83.4**	**%**

➡ **PCM system is designed to lay the foundation for market entry 60 kW SOFC product operating on natural gas and biogas.**

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Coal-Based SOFC System with Catalytic Gasification

POWER GENERATION SUMMARY	kW	% Q input	% MW gross
Fuel Gas Expandors Gross Power @ 20 kV	49,750	*7.04%*	*10.96%*
Fuel Cell Inverter AC Gross Power @ 20 kV	362,134	*51.28%*	*79.78%*
WGCU Off Gas Expander Gross Power @ 20 kV	7,024	*0.99%*	*1.55%*
Steam Turbine Gross Power at Generator Terminals @ 20 kV,	35,019	*4.96%*	*7.71%*
Total Gross Power Generation @ 20 kV	**453,927**	***64.27%***	***100.00%***
Total Auxiliary Load	**39,342**	***5.57%***	***8.67%***
Net Power Output at 345 kV	***414,585***	***58.70%***	***91.33%***

Net Efficiency Excluding CO_2 Compression & Thermal Input

Coal feed, lb/h	202,980		
Coal HHV (AF), Btu/lb	11,872		
Coal Thermal Input, kWth	**706,255**	***100.00%***	***155.59%***
Net Plant Efficiency (HHV)	**58.70%**		

Combined with high methane producing gasification, coal based atmospheric-pressure SOFC systems are capable of achieving ~ 59% efficiency and 99+% carbon capture.

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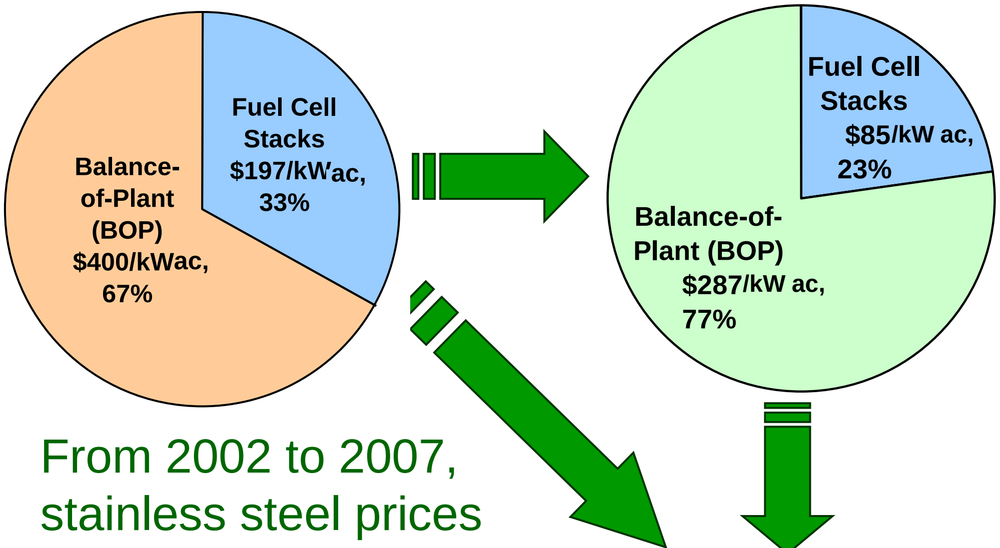
Factory Equipment Cost Estimate

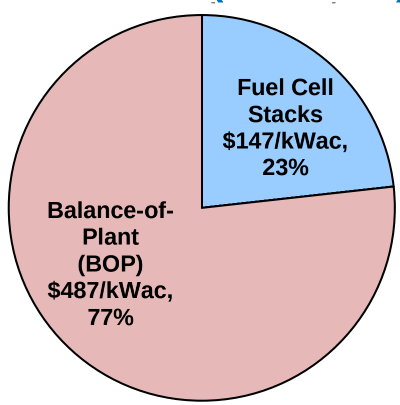
Phase I Estimate:
597 $/kW (2002 USD)

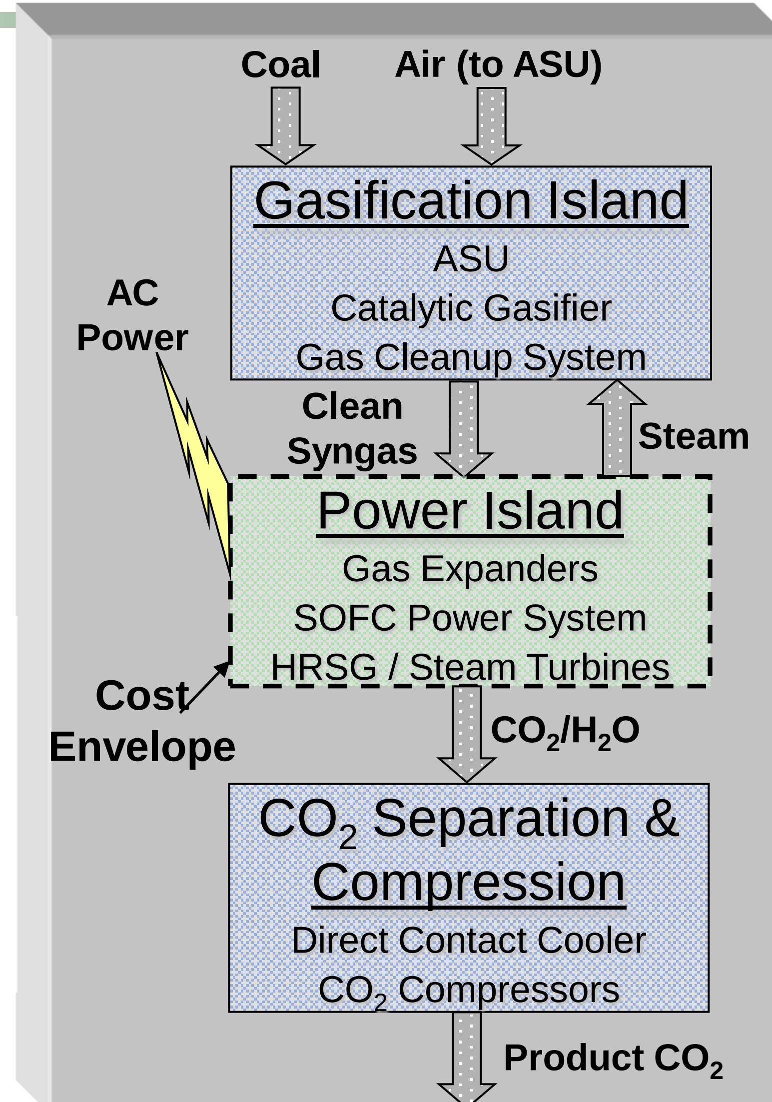
Phase II Estimate:
372 $/kW (2000 USD)



- From 2002 to 2007, stainless steel prices increased 97%, Ni increased 125%, and zirconia increased 118%
- Due to cost reduction efforts, cost estimate only increased 6% (38 $/kW) from 2002 to 2007.

Phase III Estimate:
635 $/kW (2007 USD)





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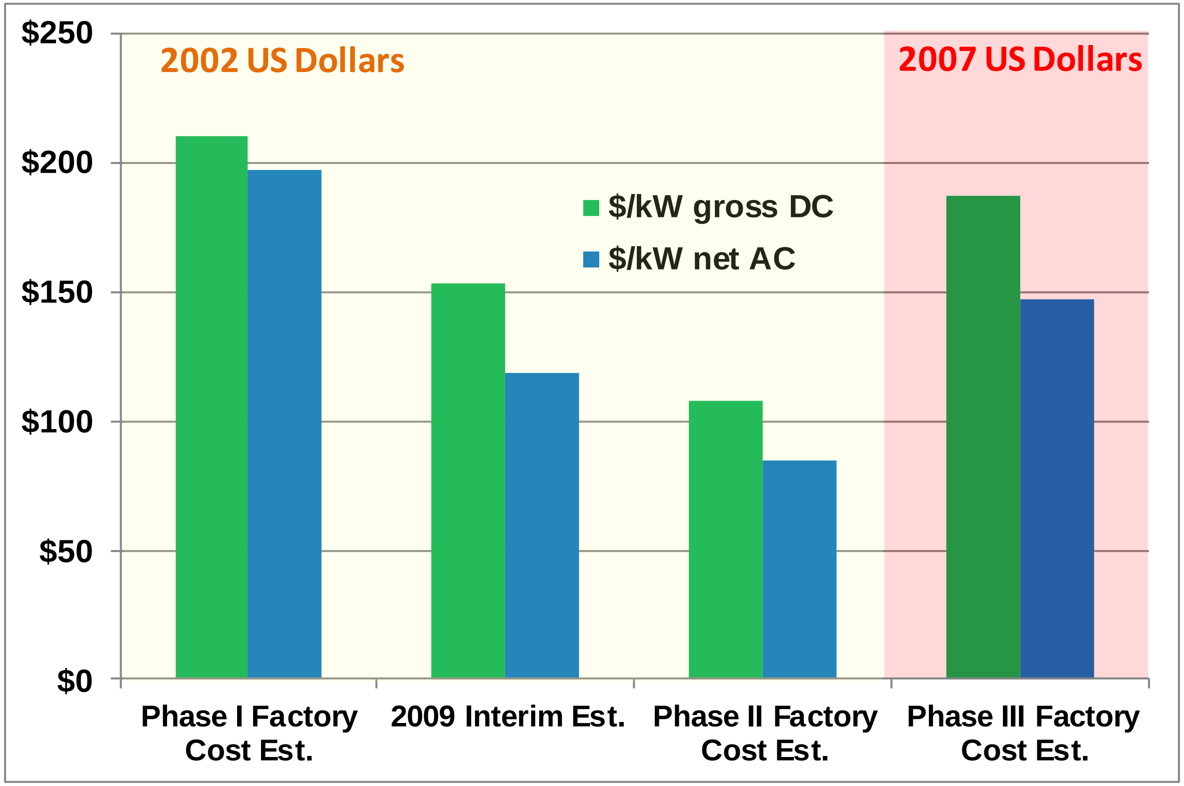
Stack Cost Reduction

Cost Reduction Focus Areas

1. **Stack Performance Increase**
   - Peak Power Increase
   - Improved thermal management
2. **Material Reduction:**
   - Thinner cells and stack components
   - Interconnect material reduction
   - Eliminated intermediate plates
3. **Manufacturing Process Changes & Optimization**
   - Interconnect manufacturing development
   - Improved material utilization
   - Automation
   - Elimination of process steps



The fuel cell stack cost have decreased substantially mainly due to the R&D activities in the SECA project.

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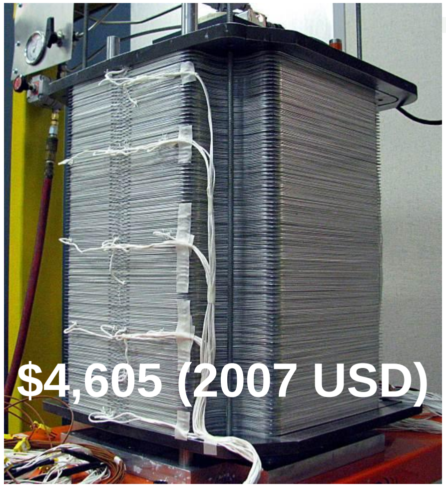
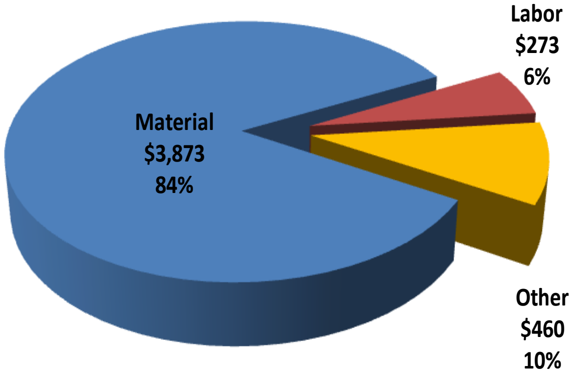
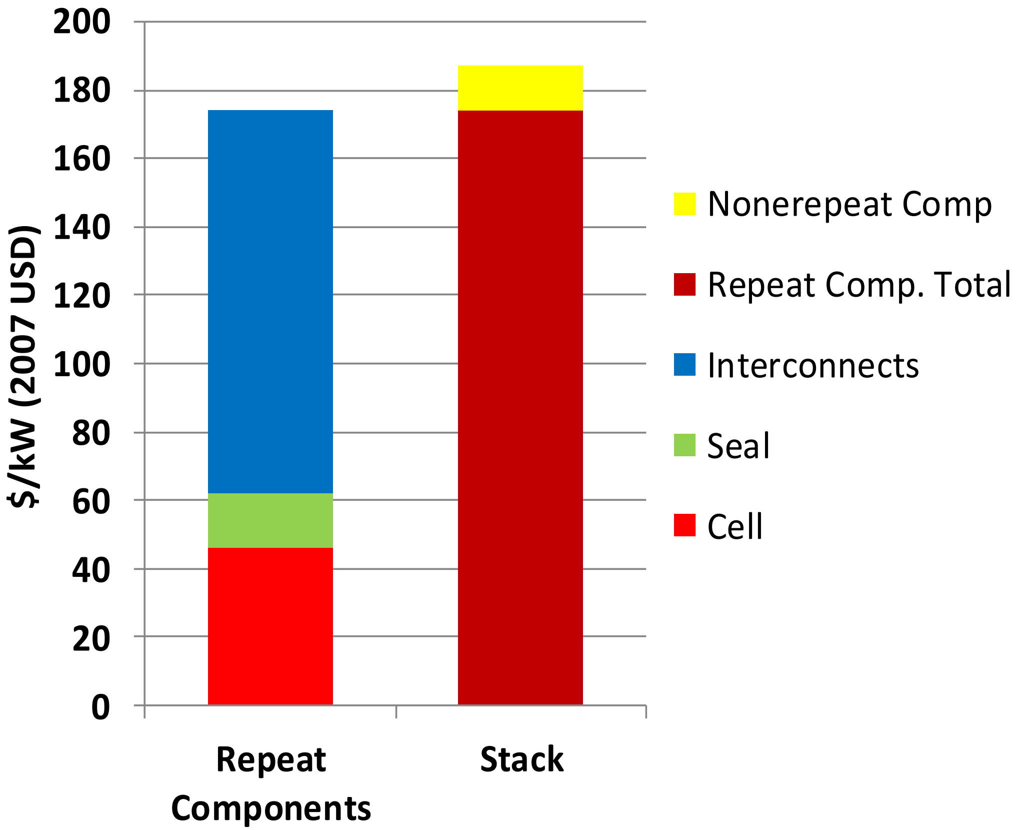
Stack Cost by Components and Category



43,008 units/per year production





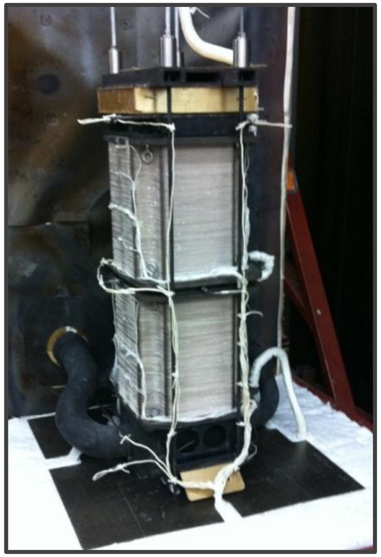
- **Majority of stack cost is driven by the cost of materials.**
- **Manufactured cell cost is < 25% of total stack cost.**

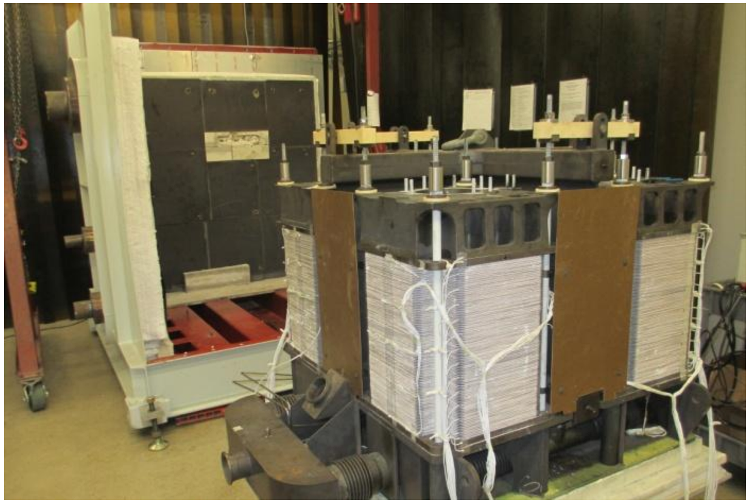
Presentation Outline

- **Introduction**
  - FCE SECA Program Team Members
  - SECA Coal-Based SOFC Program Overview
- **Progress in SOFC Technology**
  - Cell Development and Manufacturing
- **Stack Development**
  - Scale-up and Tower Tests
- **Proof-of-Concept Module (PCM) Development**
  - Stack Module
  - 60 kW PCM System
- **Baseline System Design and Cost Analyses**
  - Integrated Gasification Fuel Cell (IGFC) System Configuration
  - Updated Baseline Power Plant Cost Estimate
- **Conclusion and Future Plans**

Summary of Key Accomplishments

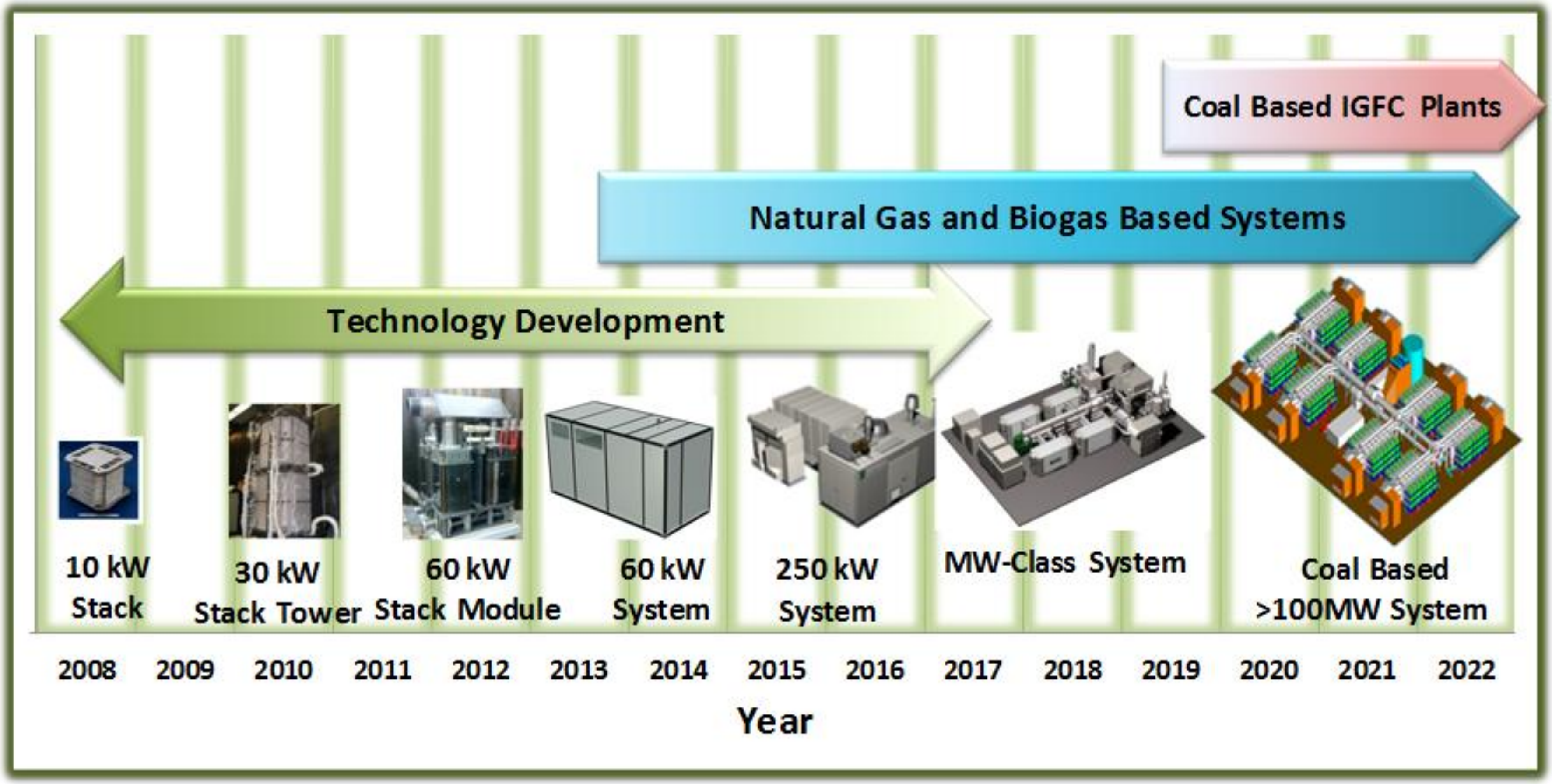
- Hydrothermally stable thin anode was developed and incorporated in 3rd generation TSC cells.
- Ten 96-cell stacks with advanced TSC3 cell technology were fabricated
  - TSC3 stacks achieved a 6% performance improvement over TSC2 stacks
  - Progress observed in increasing the reliability and robustness of stacks with each stacks built.





- Stack tower suitable for large-scale SOFC modules was successfully demonstrated by achieving power output of ~30 kWdc
- Validation testing of 60 kW module non-repeat hardware successfully completed in preparation for upcoming 60kW Stack Module testing (August 2012)

SOFC Commercialization Timeline



- **FCE's long-term plan is development of SOFC power plants capable of using a variety of fuels such as natural gas, biogas, and coal syngas.**

Acknowledgements

- Support for FCE's SECA Coal Based Program provided by the US Department of Energy (DOE) through the co-operative agreement DE-FC26-04NT41837
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Thank You!

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