FuelCell Energy

Advances in SOFC Development at FuelCell Energy

14th Annual SECA Workshop
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Hossein Ghezel-Ayagh

Ultra-Clean, Efficient, Reliable Power

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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
- **SOFC Technology Applications**
- **Summary**

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Integrated Fuel Cell Company

Design & Manufacture
Megawatt-class power generation solutions

Services
Over 80 DFC® plants operating at more than 50 sites – 1.6 billion kWh ultra-clean power produced

Direct Sales & via Partners
Installations/orders in 9 countries

Engineering / Construction
Over 300 megawatts installed and in backlog

Global Foundation for Growth

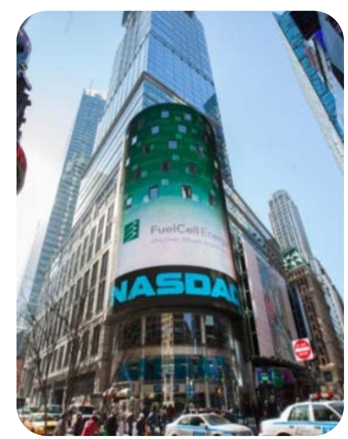
- **Global footprint solidified**
  - Asian market expansion / POSCO agreement ($181M)
  - FuelCell Energy Solutions (FCES), GmbH
    - JV partnership with Fraunhofer IKTS
- **Trend towards larger installations**
  - 14.9 MW Bridgeport fuel cell park
  - 59 MW fuel cell park in S. Korea
- **Increasing annual run-rate in USA by 25%**
  - Ramping in 2013 to 70 MW annually from 56 MW
- **Entered data center market - Microsoft project**
- **Versa Power Systems (SOFC) acquisition**
- **World's largest renewable biogas fuel cell plant now operating**
  - 2.8 MW plant operating at a wastewater treatment facility

POSCO ENERGY

FuelCell Energy Solutions
Saubere, effiziente, zuverlässige Energie.

Dominion

Microsoft



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Bridgeport Fuel Cell Park

- Five DFC3000 Powerplants produce 14 MW
- Waste heat from powerplants drives Organic Rankine Cycle (ORC) system which produces an additional 930 kW
- Total system nominal capacity 14.93 MW
- Nominal system LHV efficiency ~50%
- Construction in process, startup late 2013
- Project owner is Dominion
- Power purchased by CL&P under 15 year agreement

Dominion

CL&P

The United Illuminating Company

59 MW Fuel Cell Park

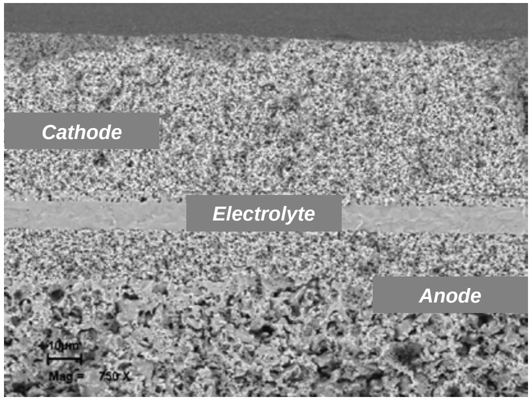
World's largest fuel cell installation

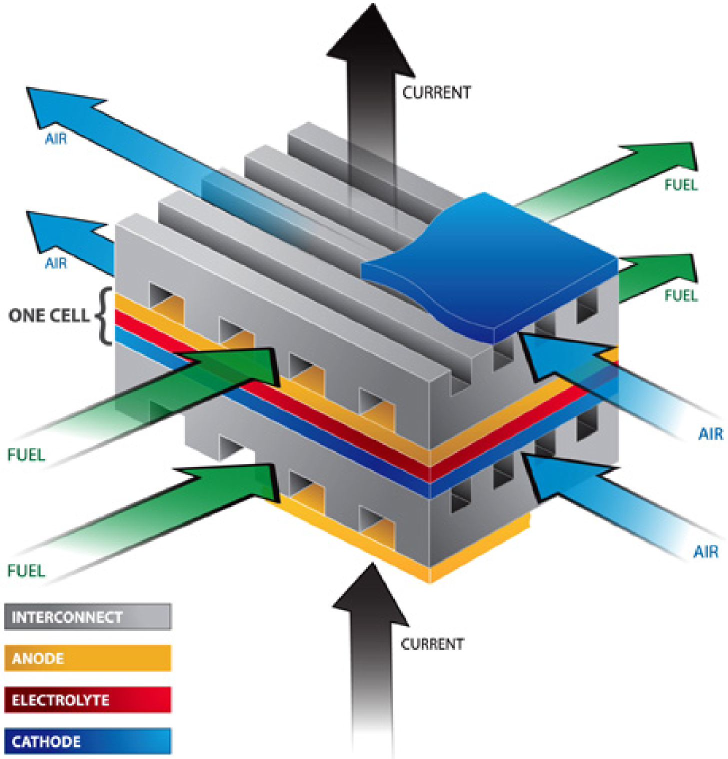
- Located in Hwasung City, S. Korea
- Comprised of 42 modules
- Expected to be fully operational in early 2014

Project being developed by POSCO, Korea Hydro Nuclear Power Co. (KHNP) and Samchully Gas Co in Hwaseong, South Korea

SOFC Cell and Stack Technology Background

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





Coal-Based SECA Program Status

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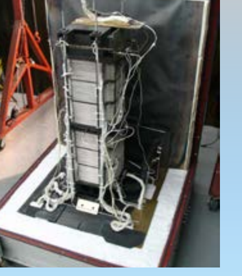
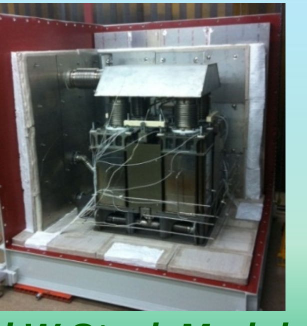
Phase I
- Cell & stack scale-up
- Validation testing of 64-cell stack block (10 kW)
- Pilot manufacturing process development and yield increase


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
- Design, fabrication and tests of a 60kW (peak) stack module
- Design of a natural gas fueled 50 kW Proof-of-Concept (POC) power plant underway


60 kW Stack Module

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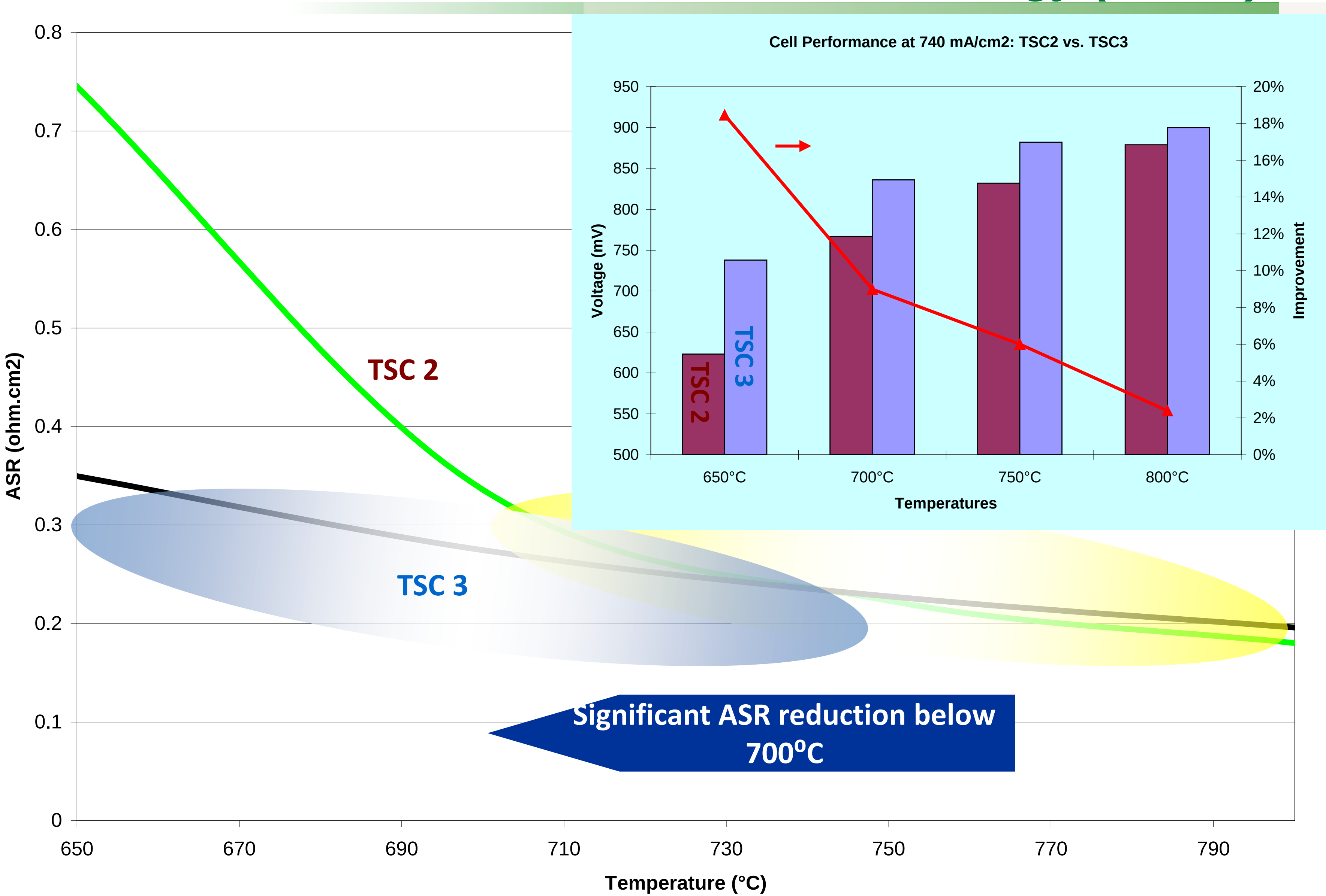
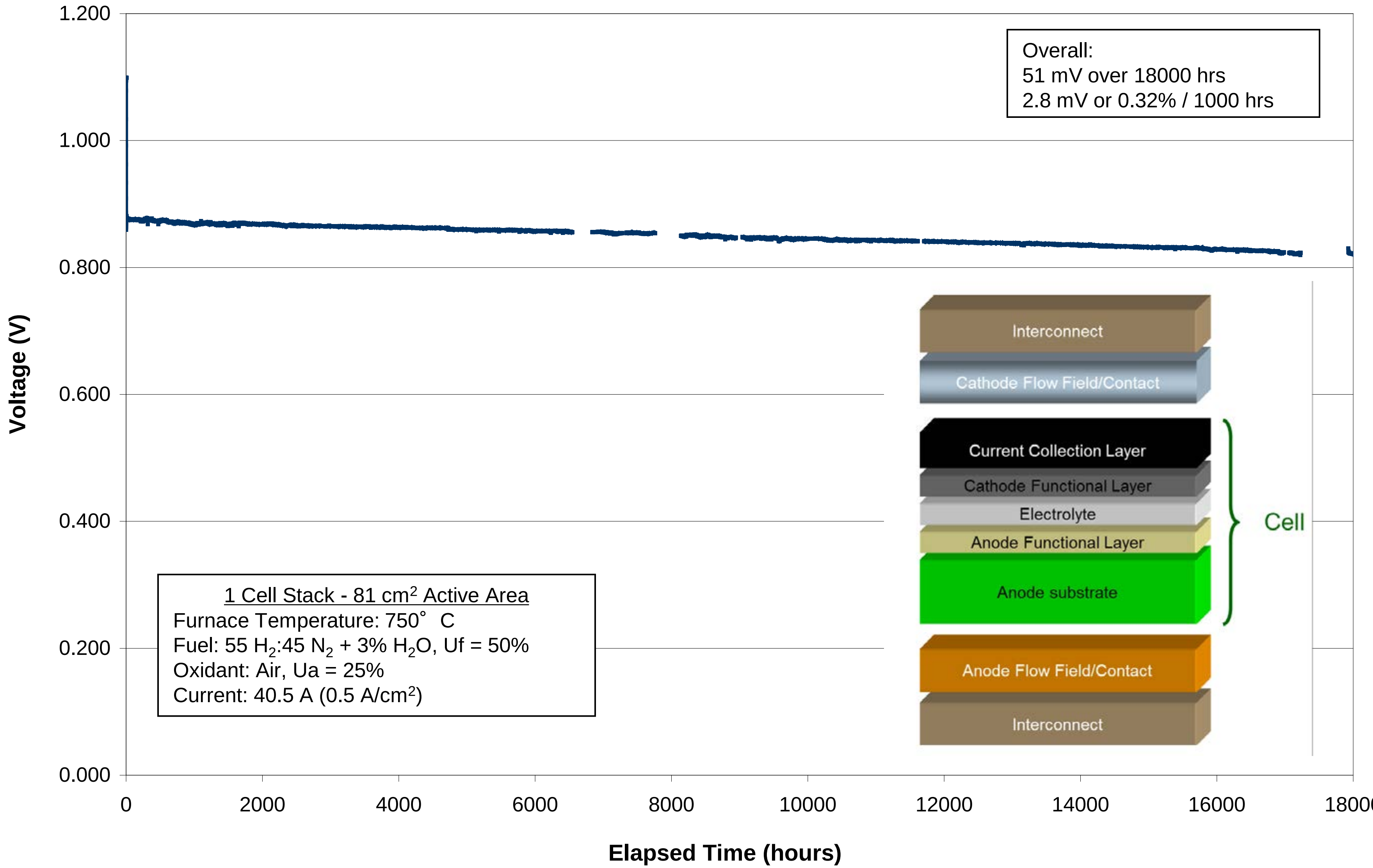
Cell Manufacturing

- Cell Scale Up
  - Tape casting/Screen Printing/Co-firing (TSC) process has proven flexible enough to allow for cells up to 33 x 33 cm^2
  - 25 x 25 cm^2 cells (550 cm^2 active area) are the focus for large area stack development
- Cell Process Development
  - Capital equipment for all major process units was added in order to accommodate increased cell size and volume
  - Thin (from 1 mm to 0.6 mm) TSC3 cell manufacturing process development was completed
- Cell Fabrication
  - More than 6000 cells (25 x 25 cm^2) have been fabricated
  - Production yield greater than 95% was obtained
  - Production volumes of 500 kW (annual) have been demonstrated

Third Generation of Cell Technology (TSC-3)

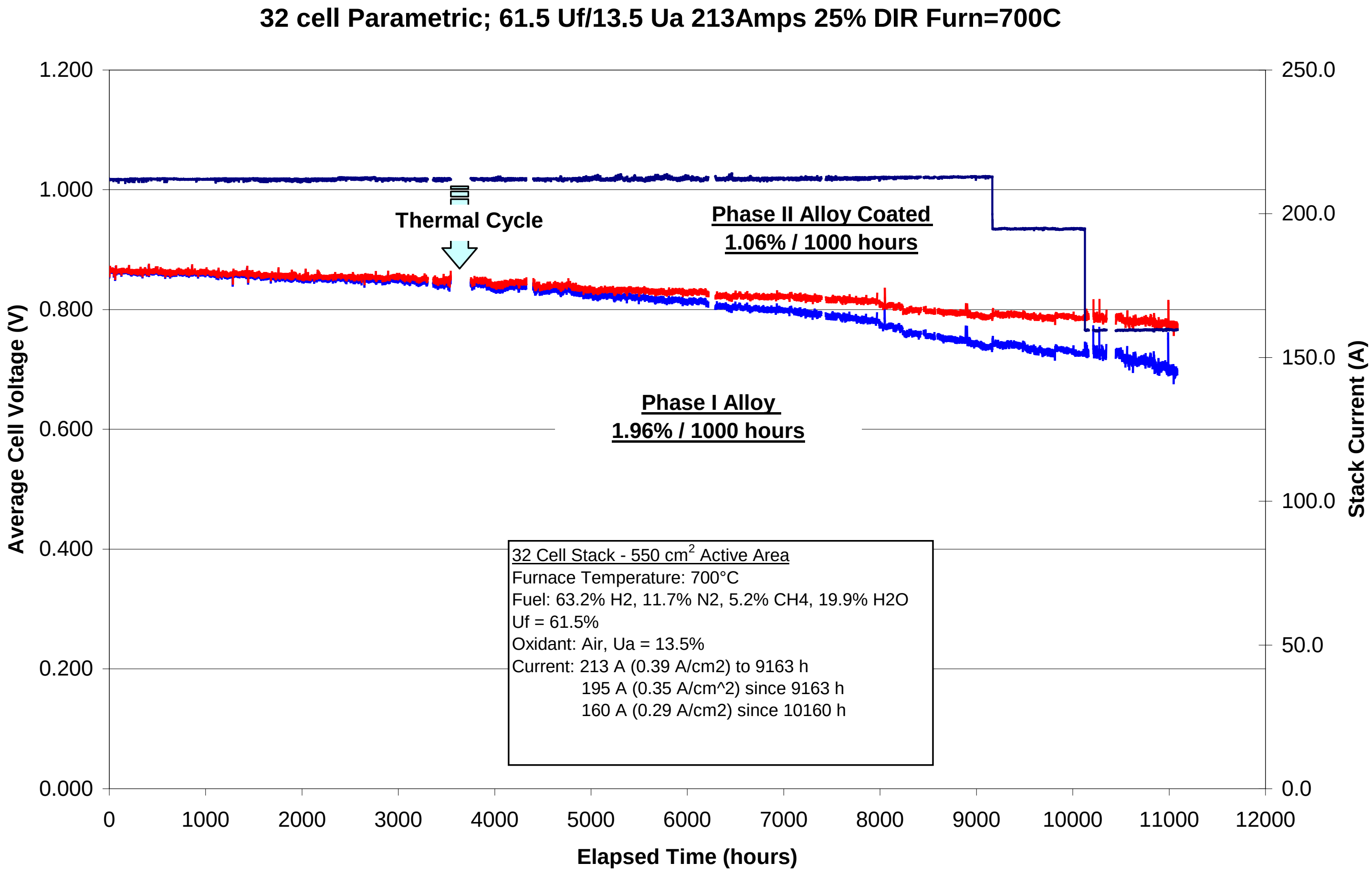


TSC3 Cell Performance Endurance



Interconnect Coating Studies Using a 32-Cell Stack

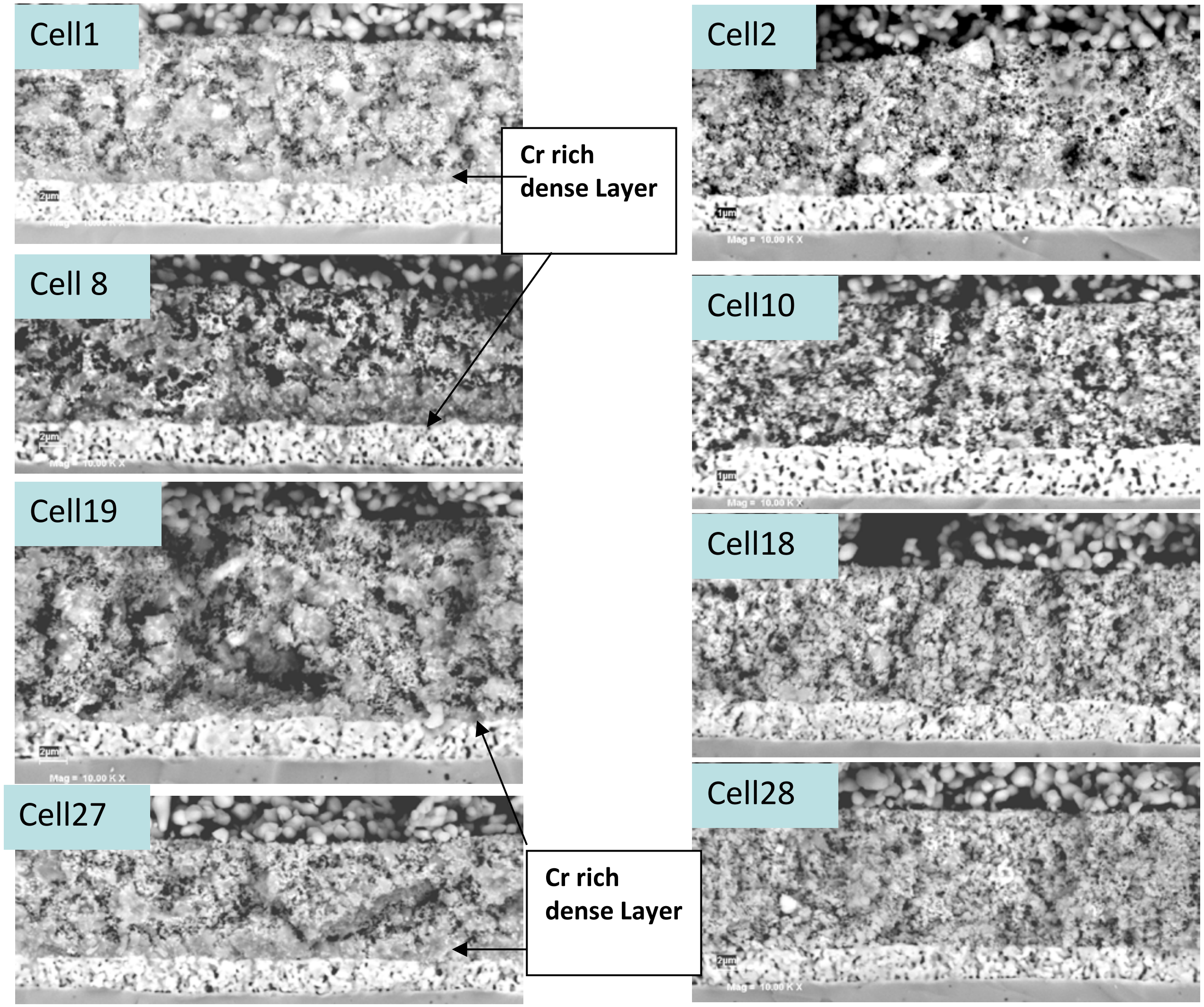
- Investigated the effect of chromium vapor species on cell degradation by testing a 32 cell stack consisting of both coated and uncoated Interconnects



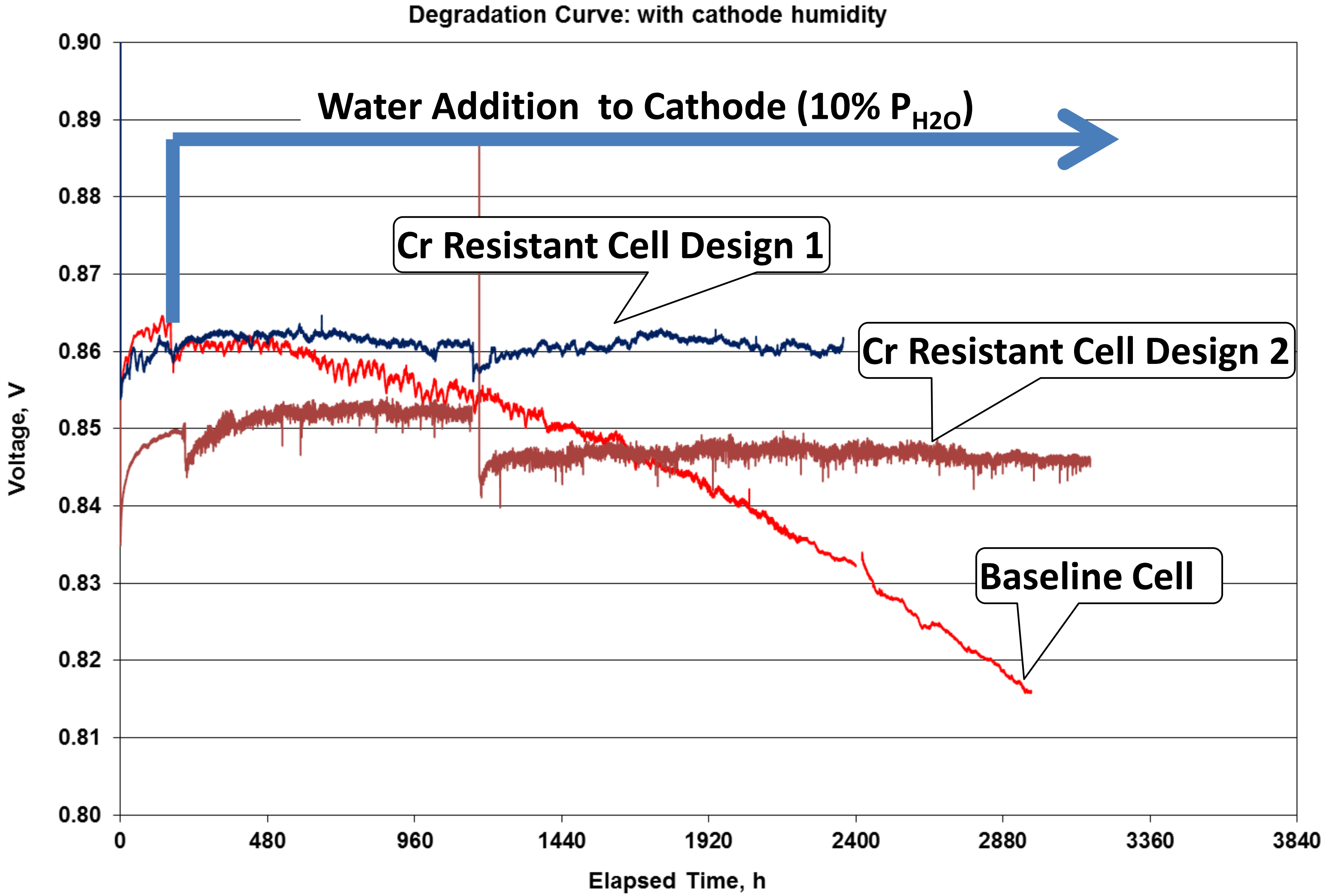
Post Test Analysis of the 32-Cell Stack

Non-coated Layers

Coated Layers

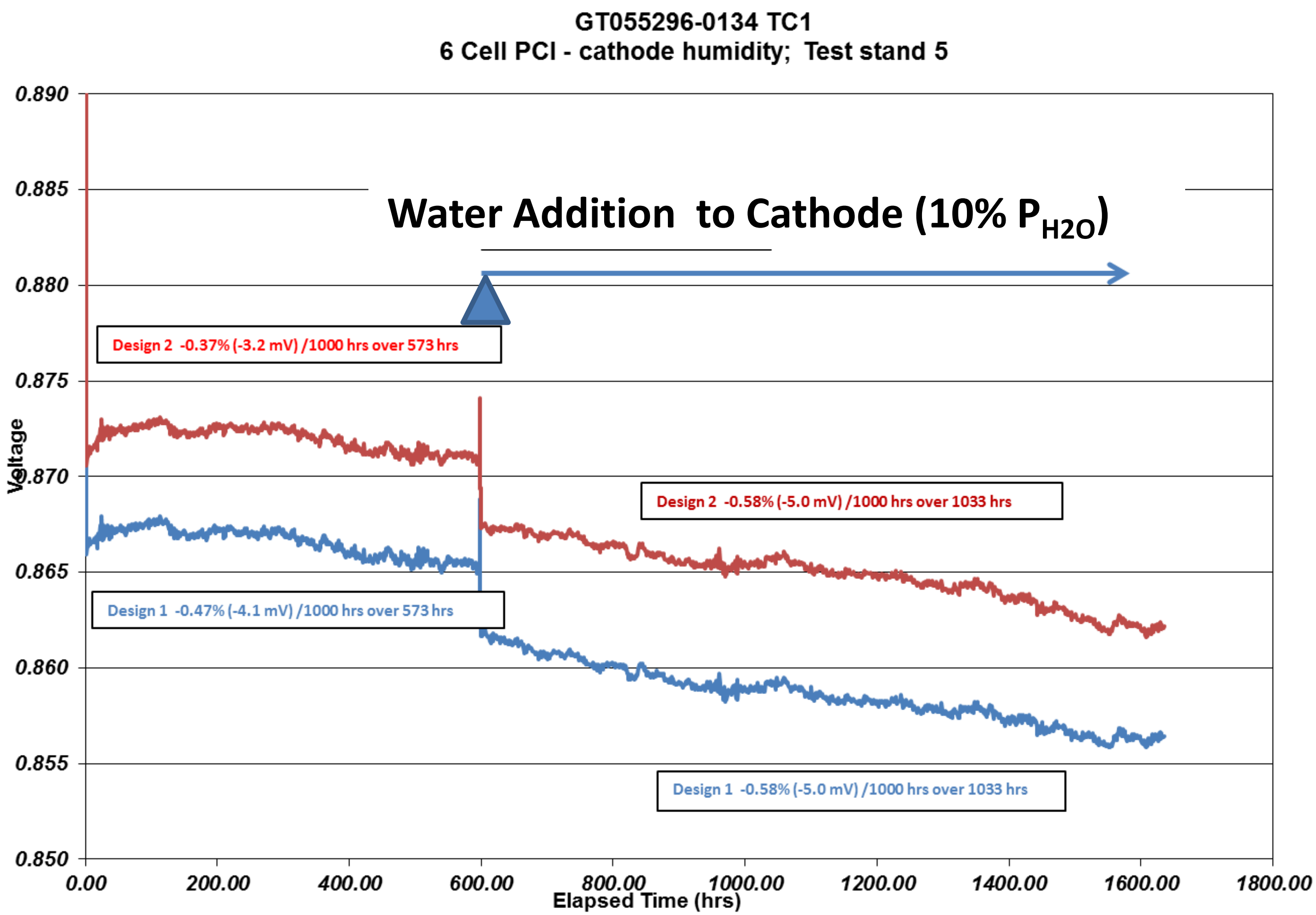


Cr Resistant Cell Technology



Cr resistant cell technology has shown promising stability in presence of high humidity

Parametric Stack Test of Blended Cr Resistant Cells



Cr resistant cell technology was implemented in short stacks with excellent performance stability and low degradation rates

Chromia Volatility Tests

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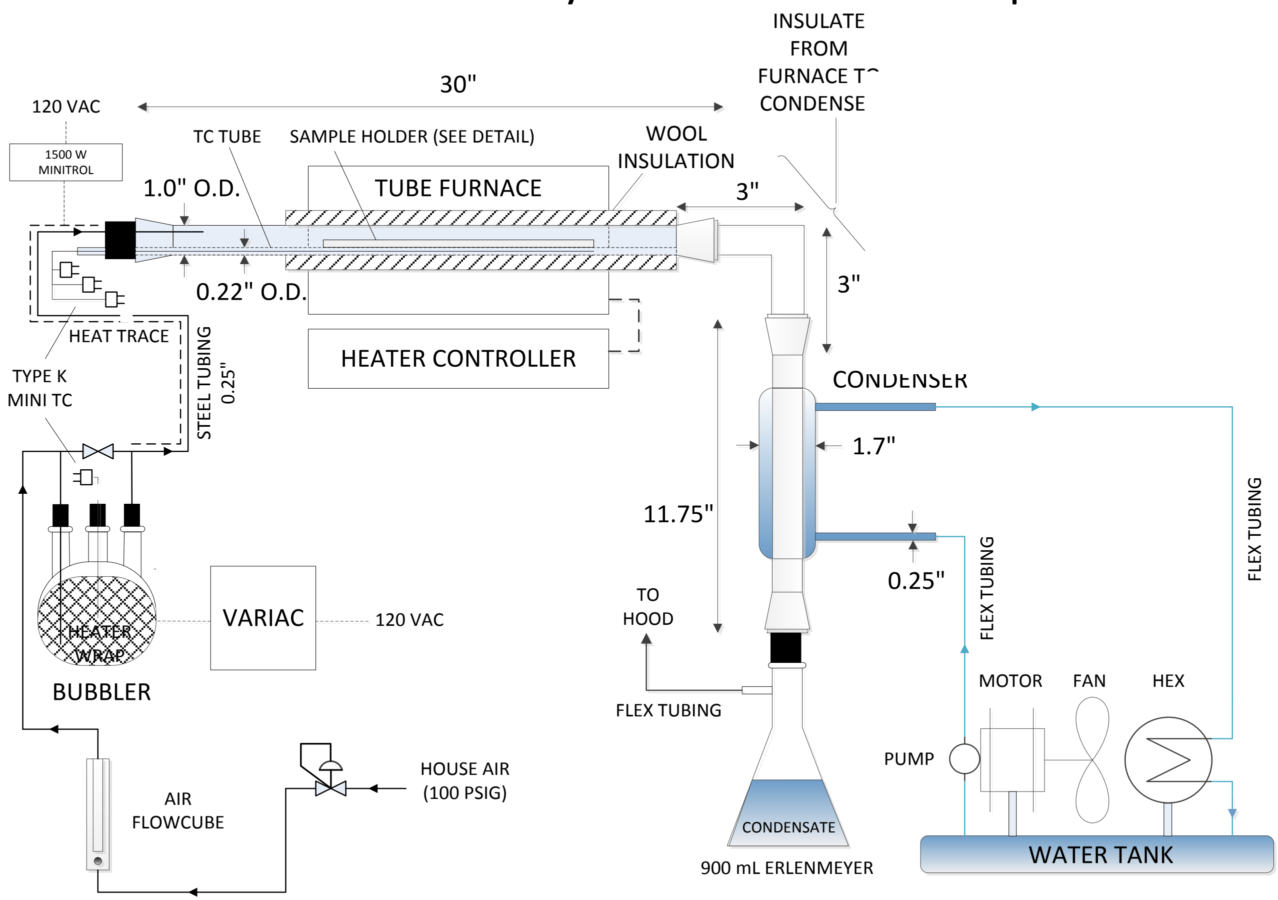
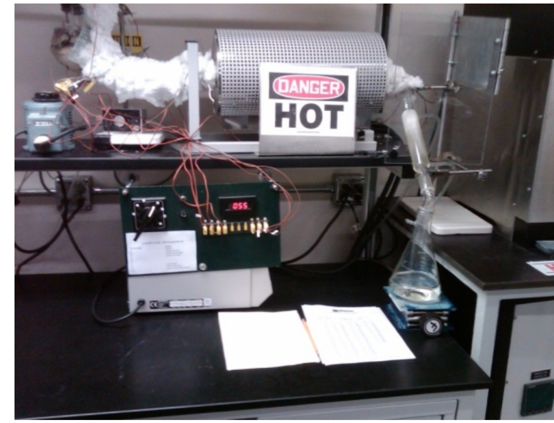
Chromia Volatility Evaluation Test Setup





Test Setup

Atomic Emission Spectrometer

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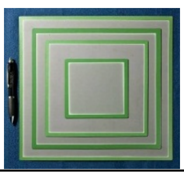
Power Module Scale-Up Using Building Block Approach

Lab-Scale Planar Cell

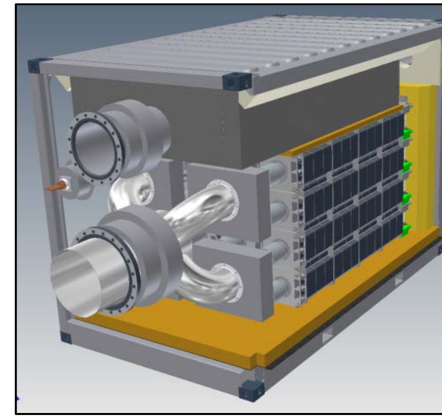


Scaled-up Cell

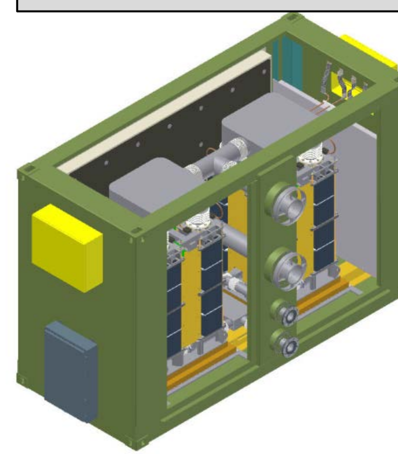
Stack Building Block for Large SOFC Plants

15 kW
96-Cell Stack

30 kW
Stack Tower
(2 Stacks)



1 MW Stack Module
16 Horizontal Towers
(4 Stacks Each)



250 kW Stack Module
8 Vertical Towers
(2 Stacks Each)

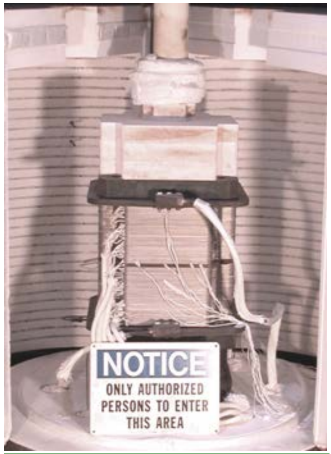
Stack Fabrication

Stack Size	2006-2008	2008-2010	2011-2013	Total
Short Stacks 6 - 32 Cells	39	43	29	111
Full Size Stacks > 64 cells	6	9	17	32
Total Quantity	45	52	46	143
Total kW	126	255	349	730


96-cell stack block


6-cell short stack


16-cell short stack



64-cell stack block

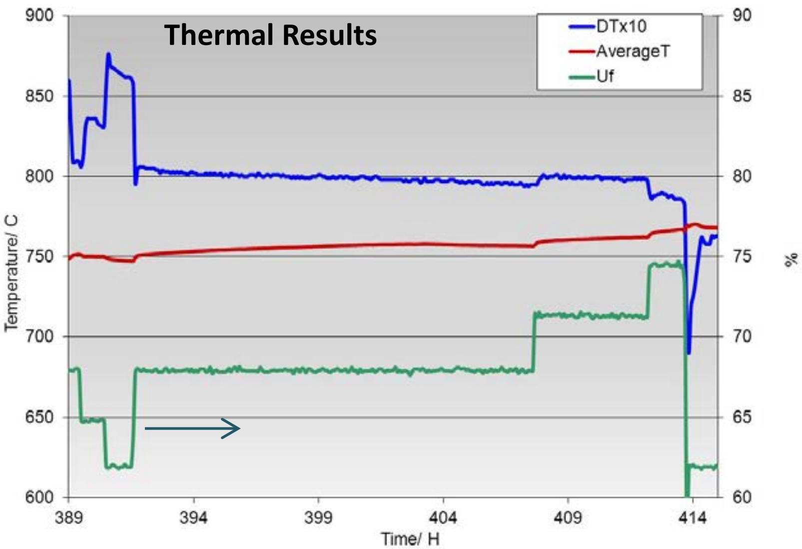

92-cell stack block

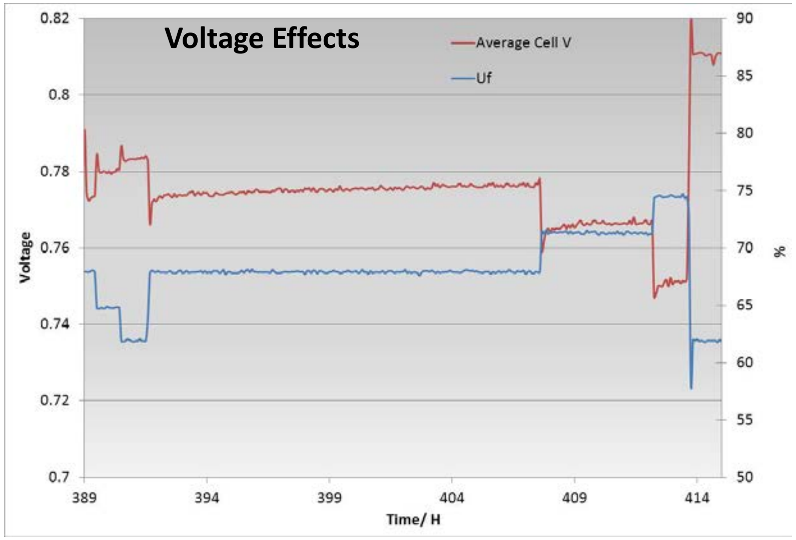
Self-Sustained 3-5kW Module Tests

- Rapid prototype tests subject to system conditions
- Identify preferred system operating conditions and controls
- Evaluate performance and thermal profiles as function of fuel composition, extent of internal reforming, and fuel/air utilizations
- Evaluate system level heat-up/shut down procedures during normal operation and forced power trip events
- Assess technology developments in a quick turn-around sub-scale testing platform

Thermally Self-Sustaining 3-5kW Module

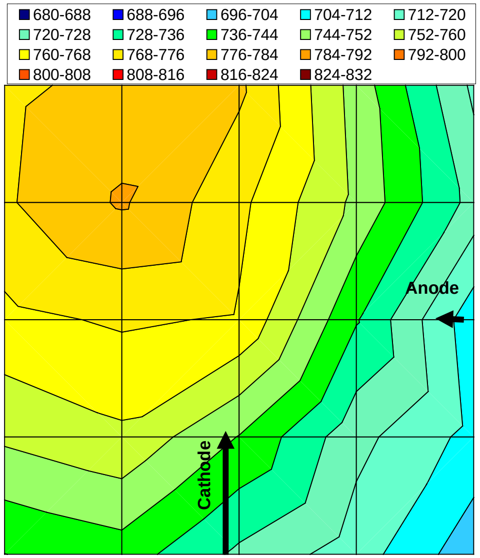
Fuel Utilization Study



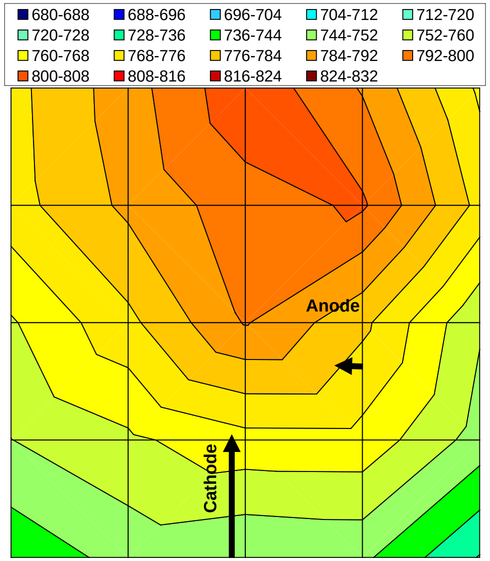


Lower per pass utilization resulted in:

- Significant on-cell dT increase due to increase in on-cell reforming
- Lower overall cell temperatures
- Significantly higher cell voltage (performance)



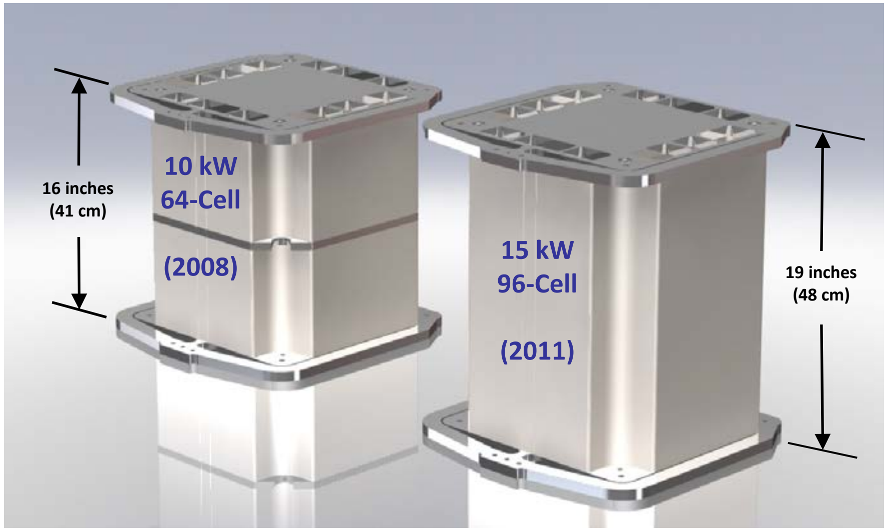
Fuel Utilization 62%

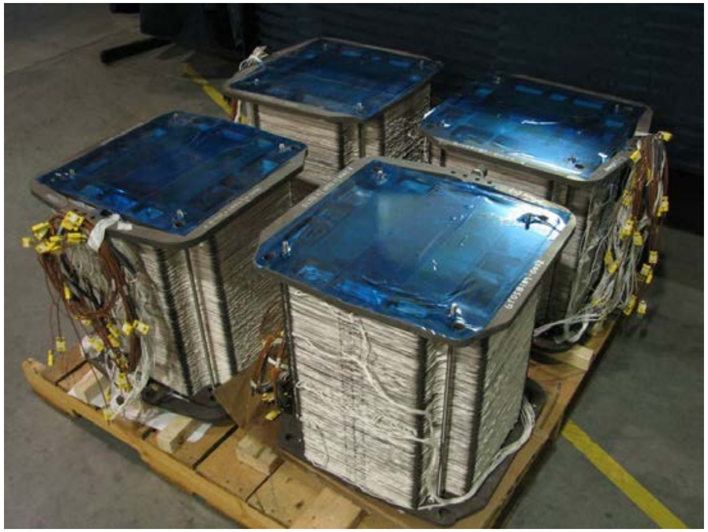


Fuel Utilization 75%

Phase III Stack Manufacturing

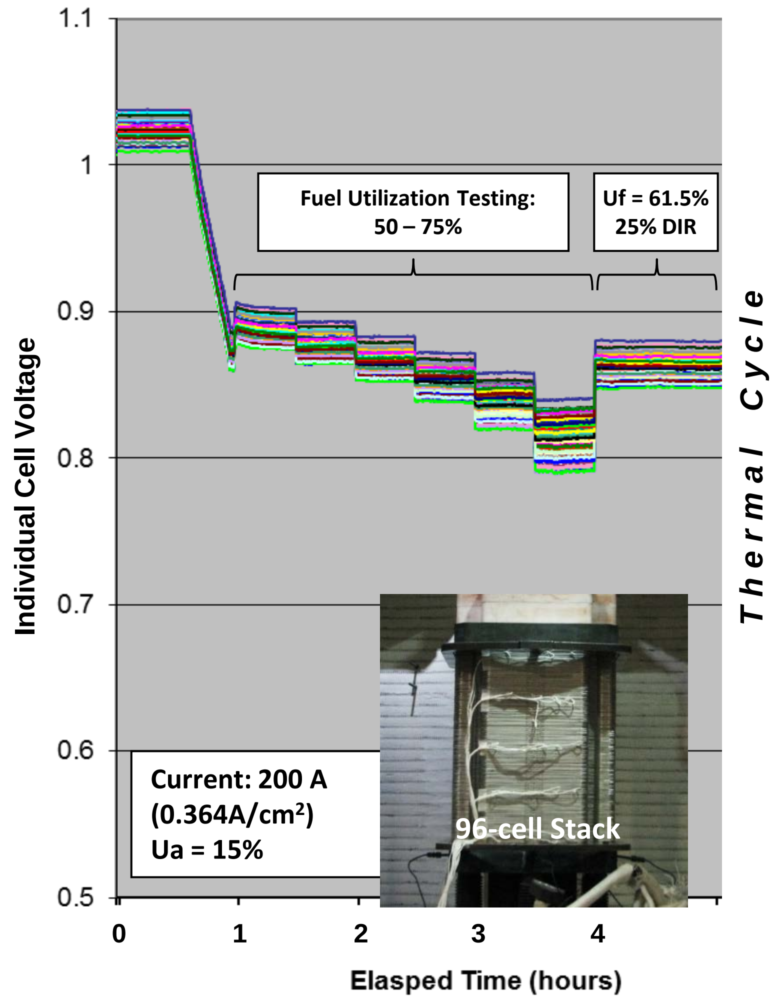
- 15 stack blocks (225 kW) were produced in Phase III
- Implemented additional QC steps in stack component preparation and stack build
- Implemented refined stack conditioning procedures
- Key design modifications
  - Decreased stack part counts
  - Eliminated instrumentation plate





Stack Quality Testing

- **Step 1: Fuel Utilization Curve (before thermal cycle)**
  - Load stack to 200 A (0.364 mA/cm²) at 25% in-stack reforming (DIR)
  - Test at 50% to 75% U_f in 5% increments
  - All cells greater than 0.7 V at 75% U_f
- **Step 2: Thermal Cycle**
  - Cool to < 150° C
  - Reheat to 750° C
- **Step 3: Utilizations are Repeated (after thermal cycle)**
  - Reload stack to 200 A (0.364 mA/cm²) at 25% DIR
  - Test at 50% to 75% U_f in 5% increments
  - < 10 mV decrease in cell voltage, compared to before thermal cycle
- **Step 4: Steady State Hold**
  - Stack is held at constant conditions for ≥ 50 hours to verify stable performance of all cells

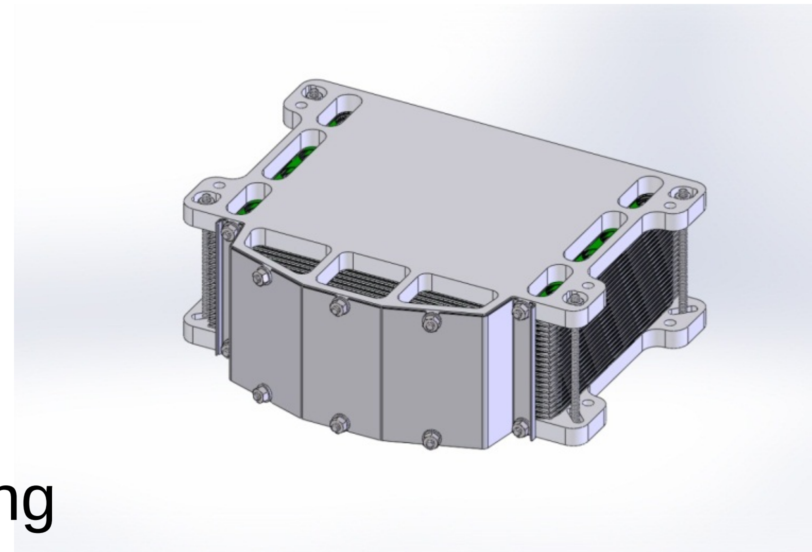


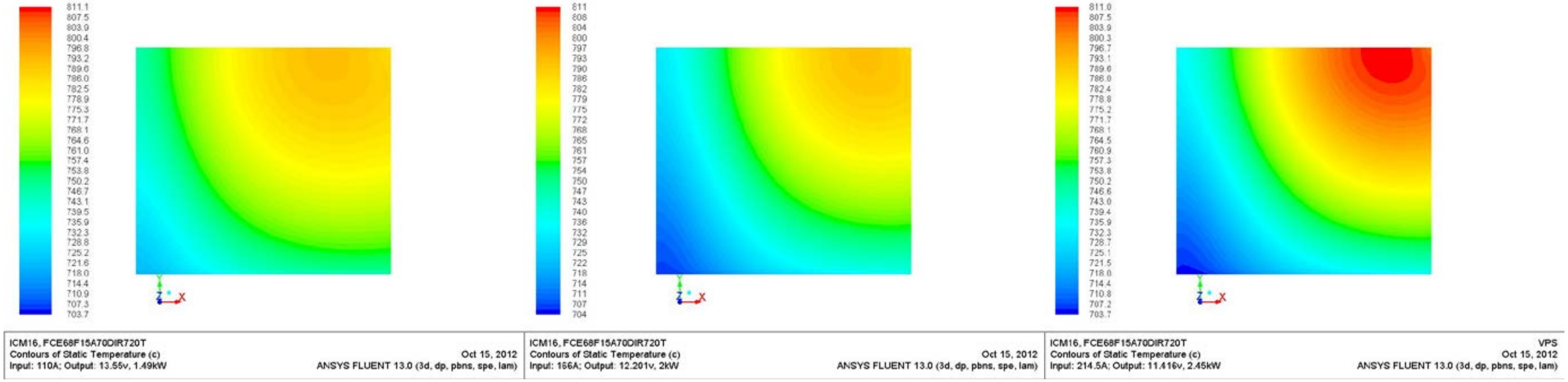
30kW Stack Tower Test

- Objectives:
  - Thermally self-sustaining test environment
  - Provisions for simulated anode gas representative of both coal-derived syngas and natural gas fueled systems
- Highlights:
  - 3,300 hours on load
  - 3,500 hours hot (>500ºC)
  - Max Power: 30.0kW
  - Electricity Generated: 75.2 MWh
  - Multi-stack tower configuration validated under system conditions

2nd Generation Stack Design

- Next generation stack design utilized anode in cell manifold to increase the reliability and robustness:
  - Contact improvement
  - Sealing improvement
  - Cost reduction
- Conceptual stack design including CFD modeling is underway

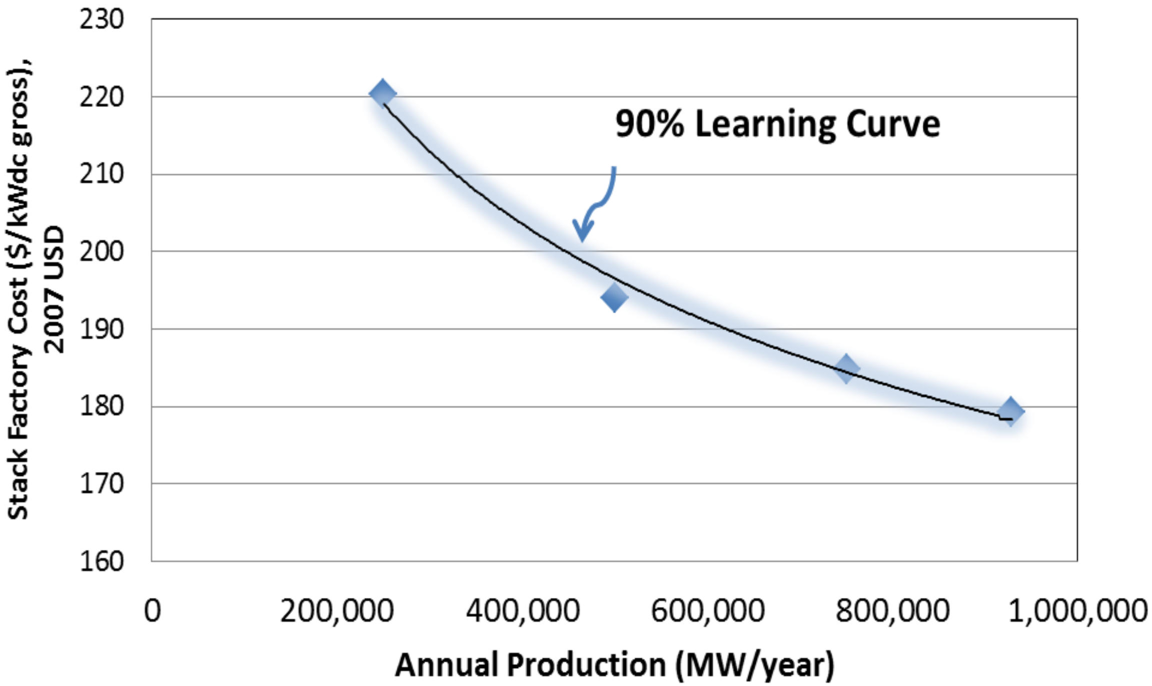




Stack Cost Reduction

<u>Cost Reduction Focus Areas</u>

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 has decreased substantially mainly due to the R&D activities in the SECA project.

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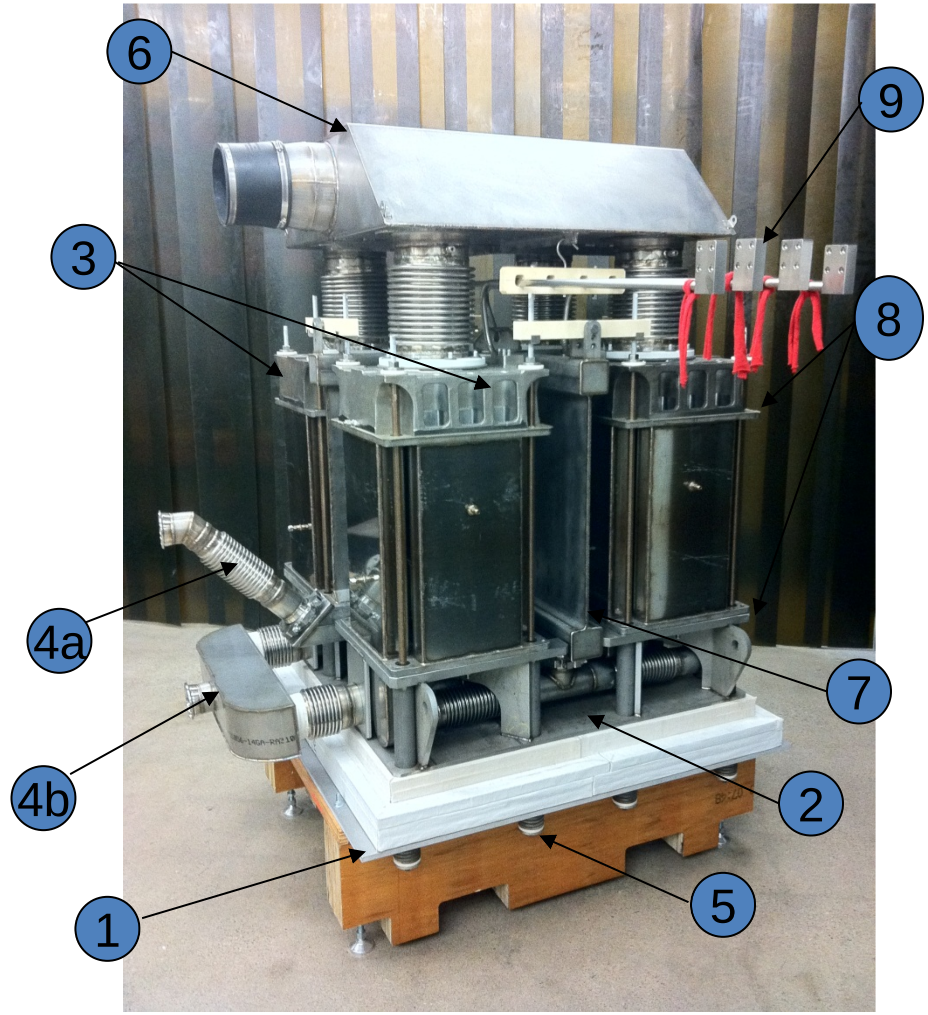
60kW Module Design and Hardware

1. Base
2. Towers on a single base forming a "Quad"
3. Compression plates
4. Anode nozzles
   A. Anode in
   B. Anode out
5. Insulation
6. Cathode-out collector
7. Fuel distributor
8. Conductive gaskets
9. Bus bars



400 kW Power Plant Facility

60 kW module tested in the existing 400 kW Power Plant Facility

- Major Equipment:
  - Anode & Cathode High Temperature Blowers (700ºC)
  - High Temperature Recupertors (750ºC)
  - Catalytic Oxidizer, Desulfurizers, and Reformer
  - DC-AC Inverter and Switch Gear for Utility Tie-in
- Designed and implemented new control system for 60kW SOFC operation

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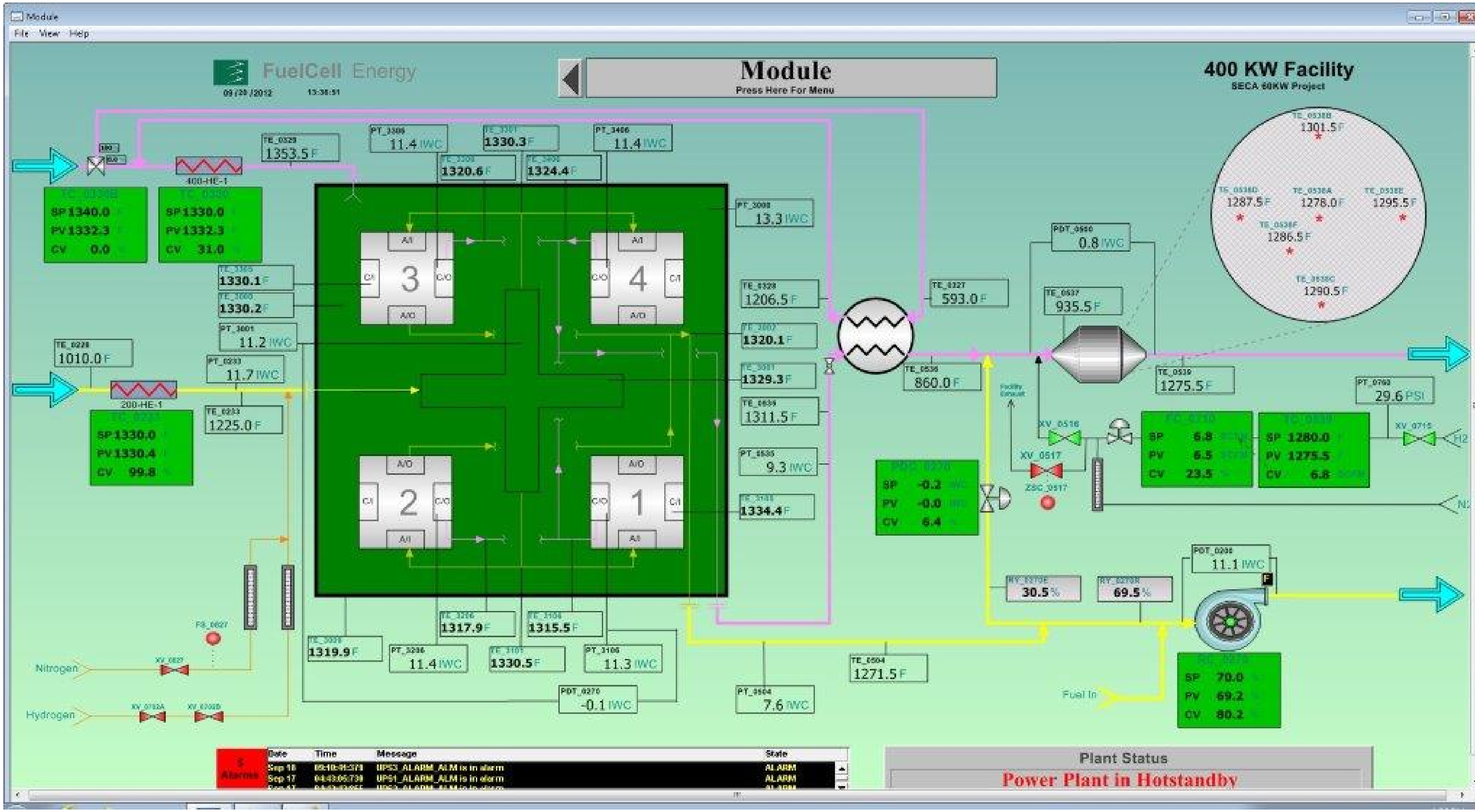
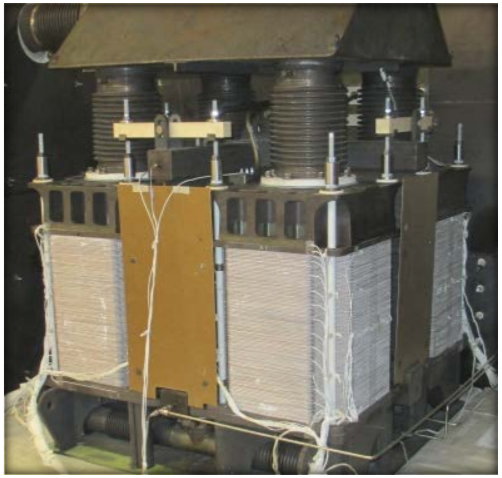
400kW Facility HMI



- Module screen shows all fuel cell module controls and measurements along with cathode and anode heaters and anode recycle blower
- More than 400 total instrument tags measured and recorded each minute

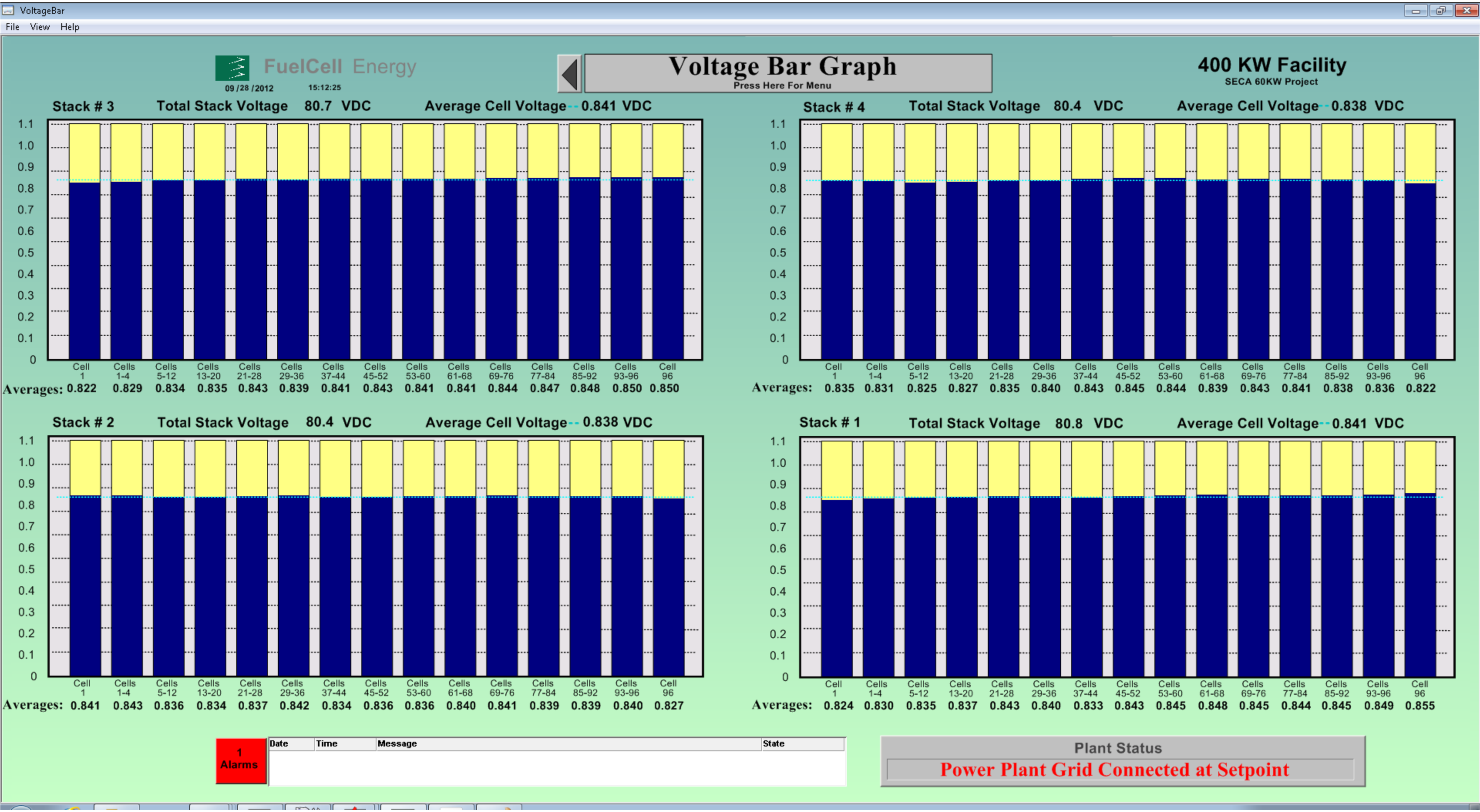
60 kW SOFC Module



- 60 kW SOFC module using four ~15 kW TSC3 stacks was installed in the grid-connected Power Plant Facility at Danbury, CT.
- 1,130 hours on load
- 1,645 hours hot (above 500° C/932° F)
- Max Power: 60.6 kW
- Electricity Generated: 51.2 MWh

	BOL Performance (100-hour average)
Stack Current	187.4 A
Cell Voltage	819 mV
Stack Voltage	78.64 V
Gross Module Power	58.96 kW
Fuel Utilization - System	81%
Module Efficiency (LHV)	64%

60 kW Stack Voltage Bar Graph



- **Uniform Voltage Distribution Confirmed the Outstanding 60 kW SOFC Module Design and Stack Blocks Performance.**

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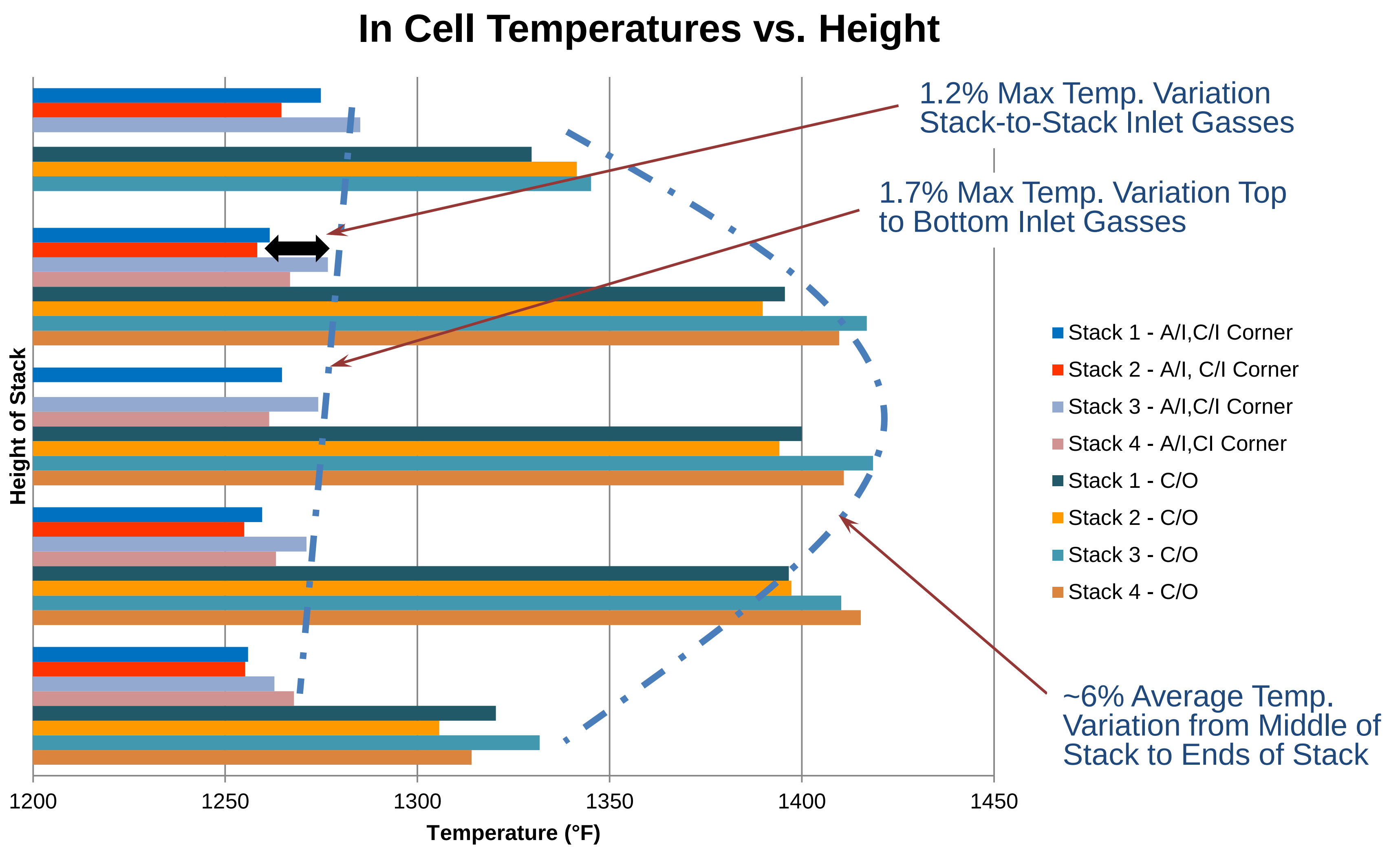
Inter and Intra-Stack Thermal Uniformity within 60 kW Module



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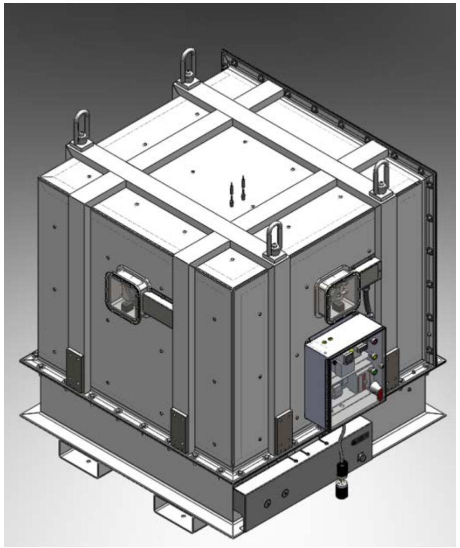
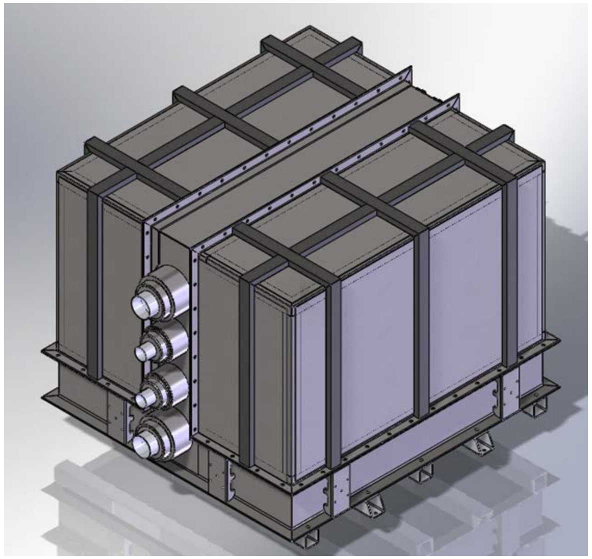
10 kW SOFC Module



- VPS fabricated and delivered a 10 kW SOFC module to VTT
- Integrated with VTT balance of system at Technical Research Centre of Finland in 2010 using one 10 kW TSC2 stack
- Restacked in 2012 using one 10 kW TSC3 stack

	Design - TSC2 cells -	100 h Average - TSC2 cells -	100 h Average - TSC3 cells -
Stack Current	200 A	200 A	200 A
Cell Voltage	780 mV	772 mV	843 mV
Stack Voltage	49.92 V	49.43 V	53.92 V
Module Power	9.984 kW	9.885 kW	10.785 kW
Fuel Utilization - System	80%	81%	80%
Module Efficiency (LHV)	60%	60%	65%

60 kW VPS SOFC Module – Design v. Performance



- Integrated with Wärtsilä balance of system in Finland in 2012 using four ~15 kW TSC2 stacks

	Design	100 h Average - TSC2 cells -
Stack Current	200 A	200 A
Cell Voltage	780 mV	784 mV
Stack Voltage	74.88 V	75.27 V
Module Power	59.90 kW	60.22 kW
Fuel Utilization - System	80%	76%
Module Efficiency (LHV)	59%	59%

WÄRTSILÄ

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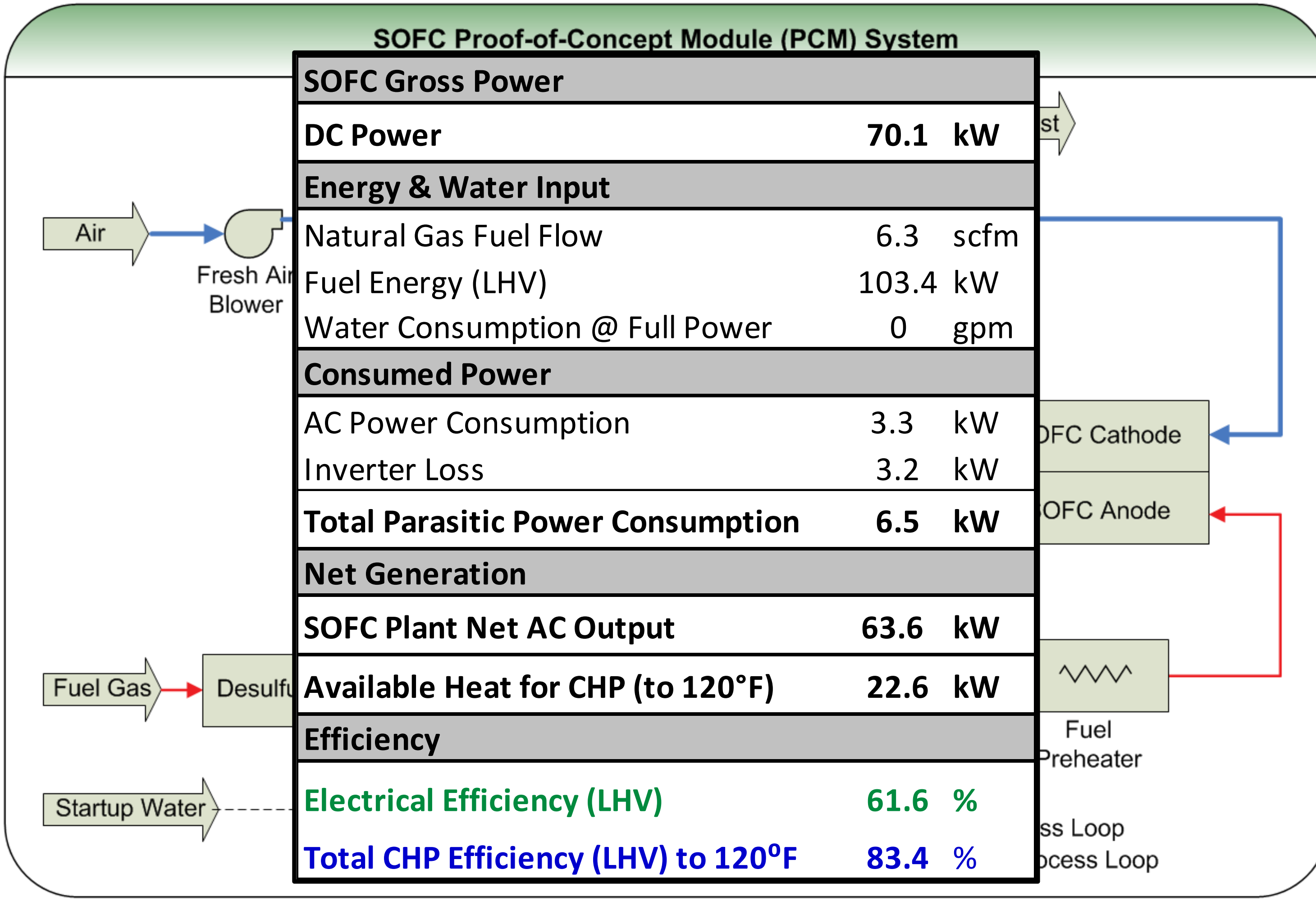
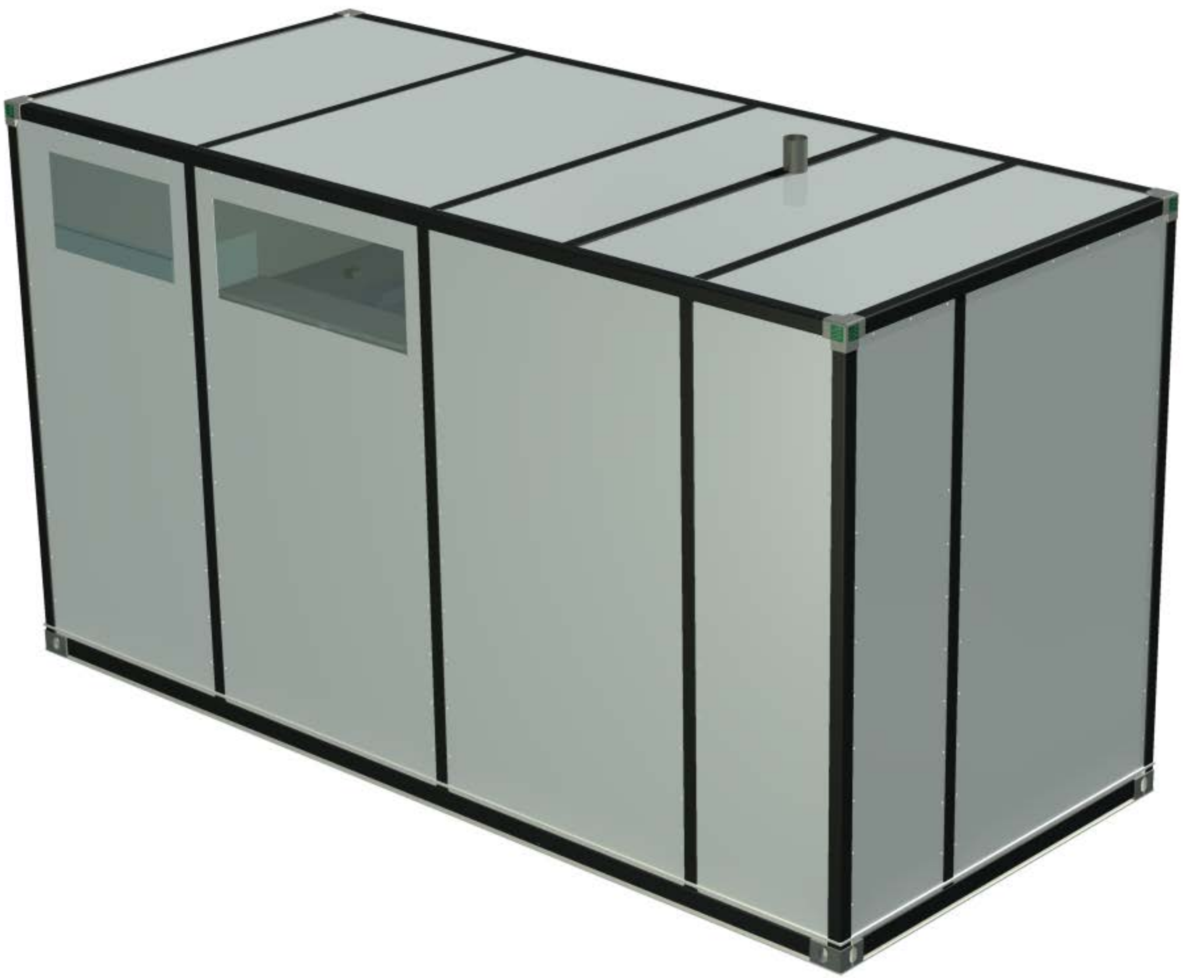
PCM System Block Flow Diagram & Performance



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 (peak) SOFC product operating on natural gas and biogas.**

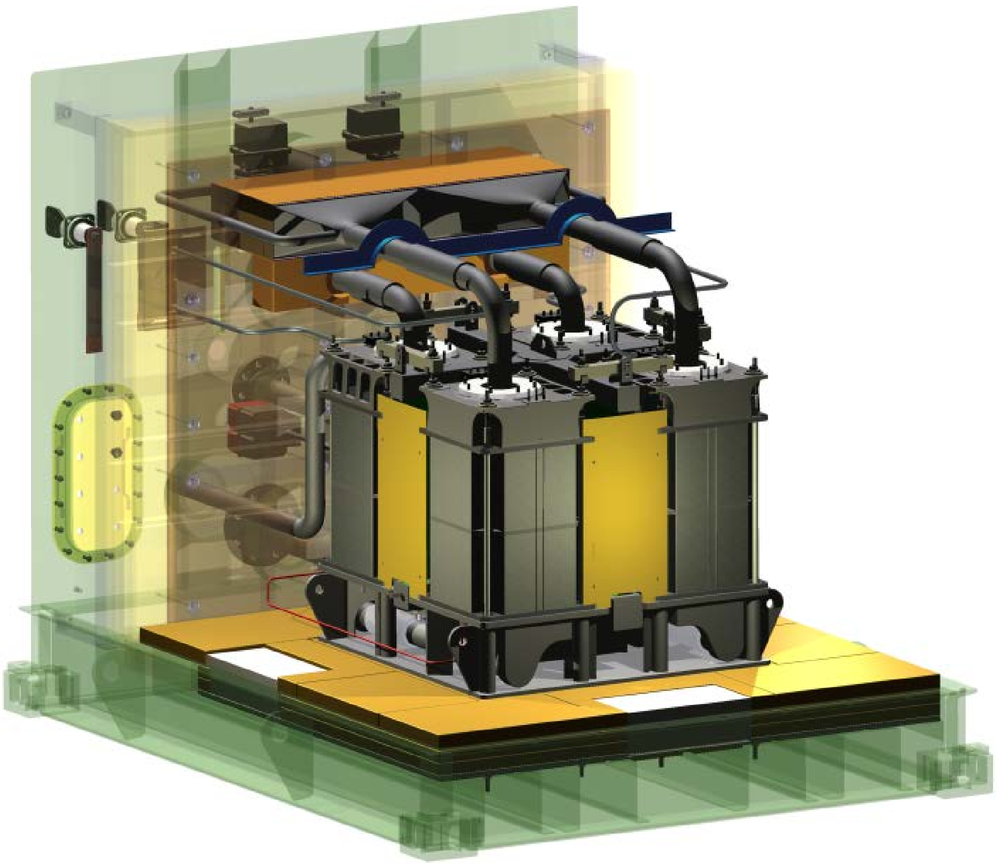
60kW PCM System BOP Layout



- 18’ L x 8’ W x 10’ H
- Stack Module, MBoP, & EBoP factory assembled: shipped as a single skid
- Field-removable enclosure
  - Protects equipment from the elements
  - Enables field maintenance access without returning the entire unit to the factory

2^{nd} Generation 60kW Module Design

- Utilizes proven designs which have been validated in testing
  - Quad base stack support
  - Fuel and oxidant distribution/collection system
- 2^{nd} generation design improvements for PCM
  - Integrated balance-of-plant components
  - Significant reduction in heat loss
  - Reduced plant cost



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3kW SOFC Power Generator

Net AC Output (Peak)	**3,138 W**
Efficiency (LHV)	**58.4%**

Small Footprint: 3.5’ x 3’ x 5’

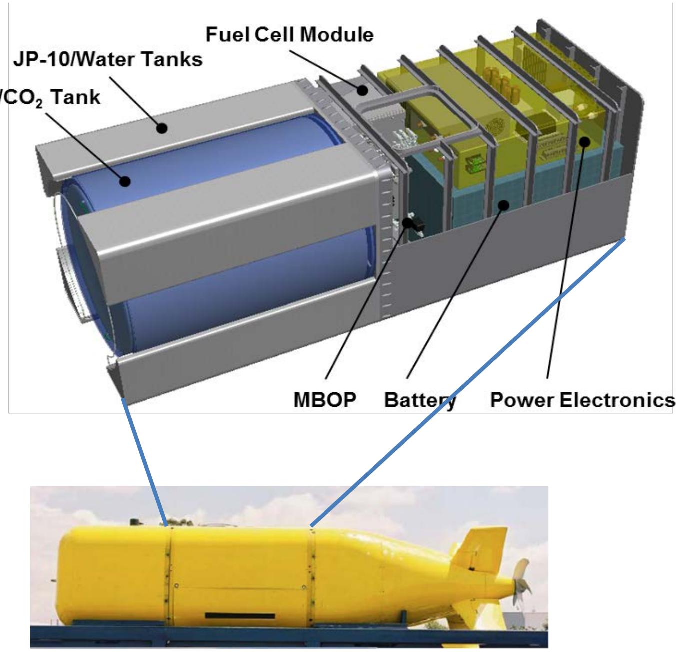
Project supported by US Department of Energy (DOE):

- Demonstration of 3 kW SOFC on a Dairy farm to operate with biogas from animal waste.
- Unattended operation
- Dual fuel (Natural gas & Biogas)
- Water self-sufficient
- Plug and Play with Remote monitoring

SMUD
SACRAMENTO MUNICIPAL UTILITY DISTRICT
The Power To Do More.℠

TDA Research

SOFC Defense Applications



Office of Naval Research (ONR):

- Develop a compact hybrid SOFC-battery system with high-energy density/high-peak power capabilities, specifically designed for Large Displacement Unmanned Underwater Vehicle (LDUUV) service
  - > SOFC provides base load power
  - > No discharge: CO_2 and water stored on board

DARPA/Boeing:

- DARPA Vulture II Project
  - > Develop a light-weight high-efficiency energy storage subsystem for uninterrupted intelligence and surveillance over an area of interest.

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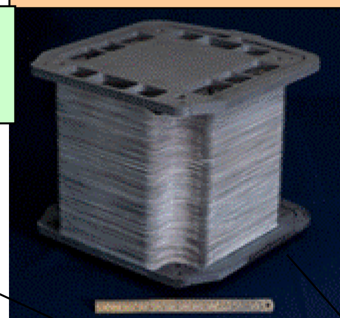
High Power Density Stack

Evolution of the planar SOFC stack technology:
From largest "power rating" in the world to super high "power density"

Distributed Generation (DG) Stacks (DOE SECA)

Residential (DG)/Mobile Stacks (DOE)



High Power density Stack

	Baseline 28-cell Stack (2006)	64-cell large scale (2008)	92 cell large scale (2010)
Gross Power (W)	1,200	11,000	18,000
Power to Weight Ratio (W/kg)	69	61	72
Power to Volume Ratio (W/L)	225	175	200

10 x

6.9x

225 cell HPD
1760
733
1546

- Achieved 10x improvement in specific power (W/kg)
- Demonstrated operational endurance of over 7000 hours in a 60 cell stack

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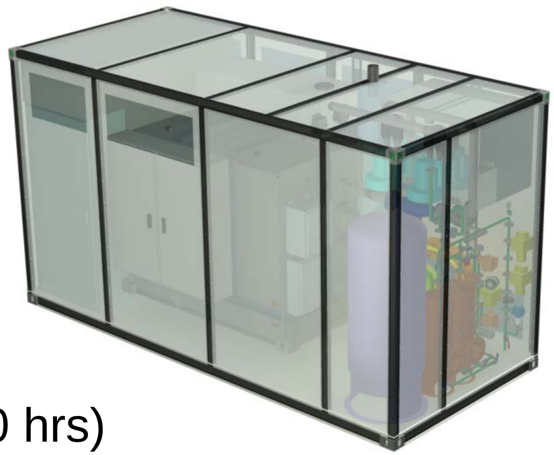
Presentation Outline

- **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
- **SOFC Technology Applications**
- **Summary**

Summary

Significant advances made in SOFC technology as the result of SECA Coal Based Program will increase the prospects for future natural gas system products.

- Cell Technology
  - Performance enhancement (18% increase at 650ºC)
  - Degradation reduction (1.4%/1000 hrs. → 0.3%/1000 hrs.)
  - Scale up (121 cm^2 → 1000 cm^2)
  - Low cost (1 mm → 0.57 mm)
  - Cr resistant technologies developed
- Stack Technology
  - Scale Up (1 kW → 15 kW)
  - Performance enhancement (7-8% increase)
  - Degradation reduction (2%/1000 hrs → 0.4%/1000 hrs)
  - Reduced Cost
- System Development
  - Largest anode supported SOFC module to date (60 kW) was designed, fabricated and tested in a self-sustaining grid-connected mode
  - Detailed design of a 60kW (peak) system is underway



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