SECA SOFC Programs At FuelCell Energy Inc.

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by

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FuelCell Energy

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FCE SECA SOFC Programs

- **FuelCell Energy, Inc. (FCE) has been engaged in a Department of Energy (DOE) sponsored SECA Cost Reduction Phase I program to develop a 3-10kW SOFC power plant system since April, 2003**
- **FCE has recently been selected by DOE to participate in the SECA Coal-Based Systems program. This programs objective is the development of very efficient coal-fueled large scale (multi-MW) power plants with near zero emissions to be demonstrated at FutureGen. Applicable elements of the existing SECA Cost Reduction project will be integrated into this new project's technical objectives, based on similarities in cell and stack development.**

The FCE SOFC Team

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

- **FuelCell Energy Inc. (FCE), Danbury, CT**
- **Versa Power Systems Inc. (VPS), Littleton, CO:**
  - **Versa Power Systems Ltd, Calgary, Alberta**
  - **Materials and Systems Research, Inc. (MSRI), Salt Lake City, UT**
  - **University Of Utah, Salt Lake City, UT**
  - **Gas Technology Institute (GTI), Des Plaines, IL**
- **Pacific Northwest National Laboratory (PNNL), Richland, WA**

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Presentation Overview

FCE's SECA SOFC Programs:

- **SECA Phase I 3-10kW SOFC System Development Program:**
  - Objectives - Status
  - Technology Developments
  - 3-1 System Test Results
  - Factory Cost Audit
  - Summary

- **SECA Phase I Coal Based, Multi-MW SOFC/Hybrid System Development Program:**
  - Objectives
  - Technical Approach

SECA Phase I, 3-10kW Development Program

Objectives:

Development of a kW-Class (3-10kW) SOFC Power Plant System With:

- 3-10kW Net Power Output.
- At least 35% overall efficiency from natural gas (stationary product requirement).
- Less than 4%/1000hours steady state performance degradation. Less that 1% performance degradation after DOE specified transient tests (load and thermal cycles).
- System Cost Less Than $800/kW.

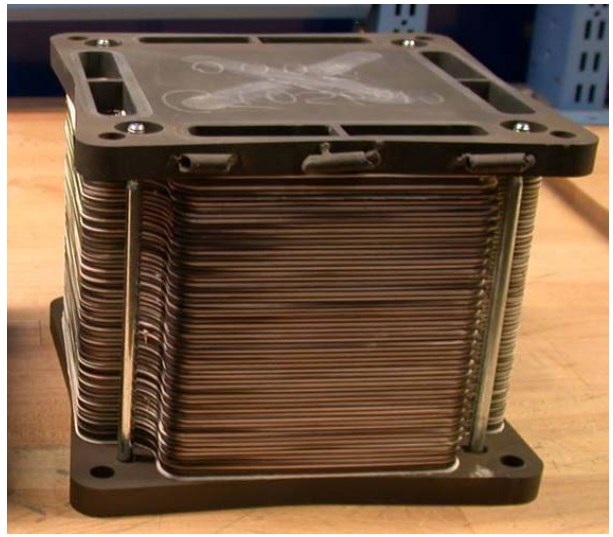
Status:

- ✓ Verified performance of scaled up cell area and stack size components.
- ✓ Completed 3-1 system test (DOE Program Metric).
- ✓ Completed system cost analysis and report for audit. 3rd party consultant has been selected and approved by DOE to conduct audit of system cost (DOE Program Metric).
- ✓ FCE on accelerated program schedule to end program early, to merge with Coal Based Program.

Cell And Stack Technology

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

- Anode Supported, Planar Cell Design



- Internally Manifolded Stacked Design
- 28 Cells Per Stack
- 121cm2 Cell Area

- Four Stacks Per 3kW Tower

Versa Power Systems is also the SOFC technology provider to the Cummins Power Generation (CPG) SECA team. Synergies and technical cooperation between FCE and CPG SECA industrial teams provides greater efficiency in development of this enabling SOFC technology.

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Versa Power Systems SOFC Manufacturing

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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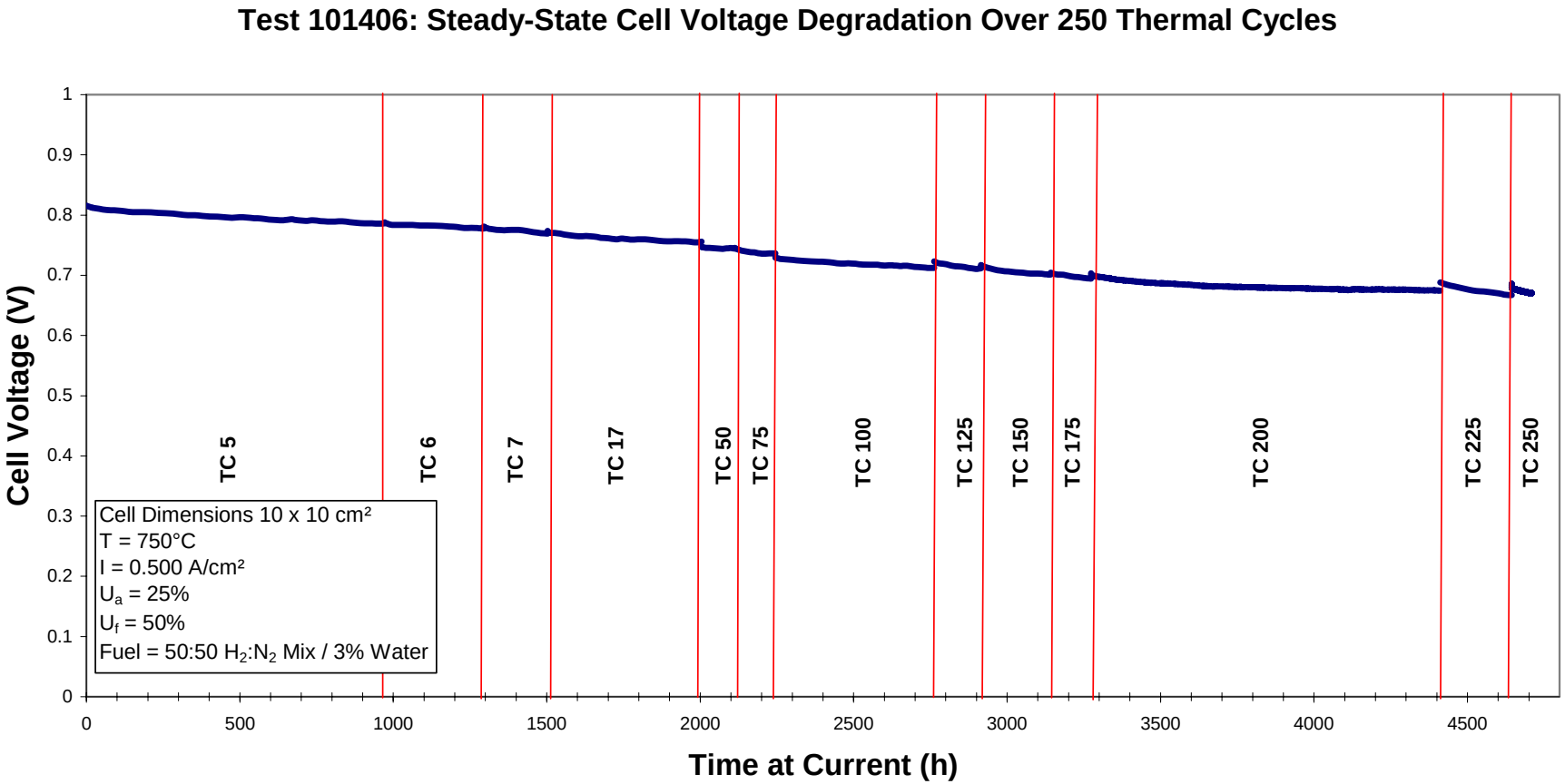
SECA Phase I Program Technical Highlights

- **FCE:**
  - Evaluated alternative gasket materials and designs for improved cell and stack sealing efficiency.
  - Lab tested internal reforming options for improved thermal management.
- **VPS:**
  - Successfully developed, tested and validated scaled-up cell area components and tall stack (number of cells) designs.
  - Developed manufacturing processes for scaled up components with improved yields and reduced cost.
  - Completed the development of the integrated stack & BOP for the 3kW Prototype System.
  - Completed the Phase 1 Prototype System Technical Metric: tested at VPS and now being demonstrated at NETL.
  - Completed Factory Cost analysis. Report submitted for 3rd party audit.
- **MSRI/UU:**
  - Analyzed and developed alternative anodes with improved strength, redox tolerance and resistance to sulfur poisoning.
  - Evaluated alternative electrolyte materials for improved performance.
  - Studied and developed a better understanding of charge transfer mechanism for reduced area specific resistance (ASR) of the active cell component.
- **GTI:**
  - Developed the sulfur cleanup subsystem for a 10kW NG system. Evaluated absorbent materials from alternative vendors. Analyzed ambient (low) temperature absorbent (ATA) materials for sulfur removal.
  - Characterized utility NG compositions at VPS, Calgary and NETL, Morgantown WV.
  - Developed heat exchange and thermal management subsystems for the advanced 10kW System
- **PNNL:**
  - Developed computational modeling tool that includes cell and stack thermomechanical, electromechanical and electrochemical properties. This provides a mechanistic tool to analyze stress and failure conditions of alternative designs considered for improved performance and scale-up.

VPS Cell Reliability



- **VPS single cells have demonstrated good durability as illustrated by the steady-state cell voltages after 250 thermal cycles and 4700 hours operation.**

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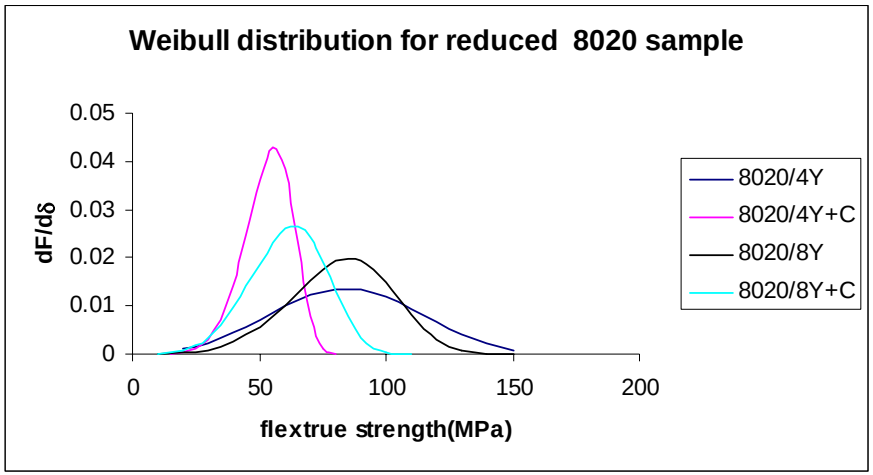
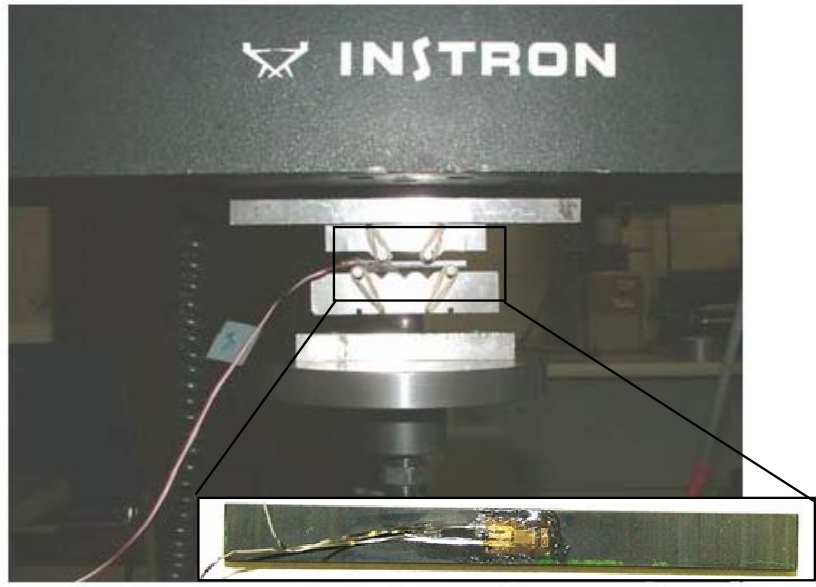
Core Cell Technology Development at MSRI/UU

	Flexural strength (Mpa)	Strain (%)	Young's Modulus (GPa)
6040/3Y	158 ± 9	0.088	170
6040/3Y + C	81 ± 6	0.122	70
7030/3Y	135 ± 17	0.128	106
7030/3Y + C	55 ± 5	0.117	50

Flexural strength, strain and Young's Modulus for various anode supports



4-point bending analysis enables flexural strength values of anode supports to be obtained by Weibull distribution analysis



Stress-strain Apparatus Used For Anode Strength Analysis

- **Innovative techniques developed by MSRI/UU provide quantitative tools to analyze key functional criteria of core cell components.**

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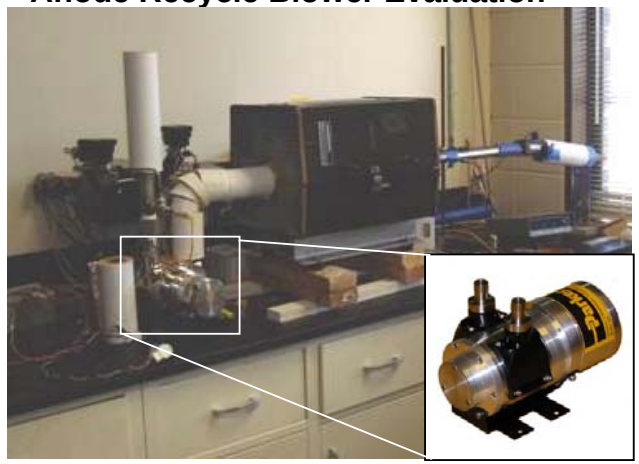
Subsystem Development at GTI for the Advanced 10kW System

	Natural Gas (NG)	Anode Recycle Gas (ARG)		Reactor Feed (NG+ARG)		Reactor Exit
	Dry	Dry	Wet	Dry	**Wet**	Dry
CH_4, vol%	92.12	--	--	89.11	**86.19**	ND
C_2H_6, vol%	2.98	--	--	2.88	**2.79**	ND
C_3H_8, vol%	0.39	--	--	0.38	**0.36**	ND
C_4+, vol%	0.13	--	--	0.12	**0.12**	ND
C_5+, vol%	0.04	--	--	0.04	**0.04**	ND
H_2, vol%	0.00	**31.50**	**15.52**	1.03	**1.00**	ND
CO_2, vol%	0.79	**54.70**	**26.90**	2.56	**2.47**	ND
CO, vol%	0.00	**13.80**	**6.82**	0.45	**0.44**	ND
N_2, vol%	3.55	--	--	3.43	**3.32**	ND
H_2O, vol%	ND	--	50.76	--	**3.27**	ND
H_2S, ppmv	**BDL**	--	--	**BDL**	**BDL**	**BDL**
COS, ppmv	**0.48**	--	--	**0.46**	**0.44**	**BDL**
DMS, ppmv	**2.15**	--	--	**2.08**	**2.01**	**BDL**
TBM, ppmv	**2.46**	--	--	**2.38**	**2.30**	**BDL**
THT, ppmv	**1.02**	--	--	**0.98**	**0.95**	**BDL**

Complete Odorant (Sulfur) Removed With Alternative Absorbent Materials

- **Developed the S-cleanup subsystem: evaluated HDS and ambient cleanup strategies.**
- **Developed the regenerative fuel heat exchange subsystem: validated new, regen HX (165 hours/10TCs)**
- **Evaluated anode recycle blowers for increased system efficiency :**
  - > evaluated 2 off- the-shelf blowers;
  - > selected candidate for >150°C use: factory tested; “system conditions” commissioning in process.

Test Facility For Regen HX and Anode Recycle Blower Evaluation



Lab Set-up For Anode Recycle Blower Testing

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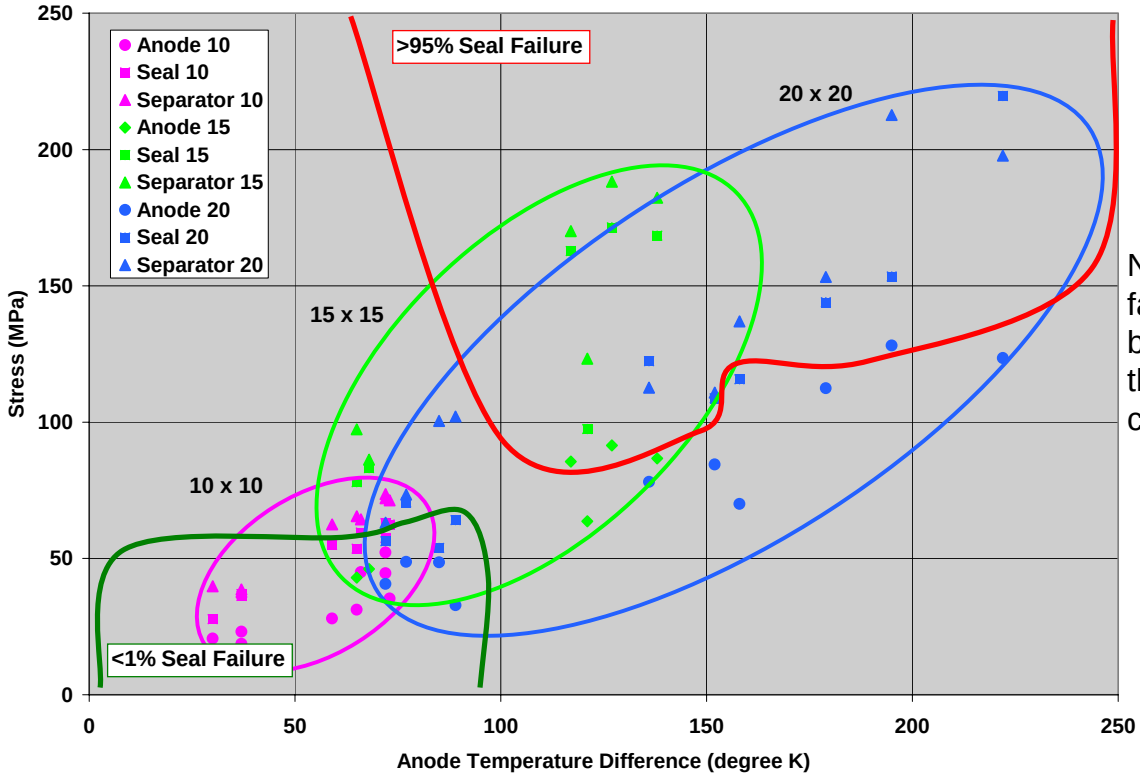
PNNL Modeling Analysis

CELL PRINCIPAL STRESS AS FUNCTION OF CELL SIZE AND TEMPERATURE GRADIENT



Note: Weibull probabilistic failure results presented are based on material test results that may not be comparable to current designs.

- **Computational model includes cell and stack thermomechanical and electrochemical conditions.**
- **Combined with material test results (Weibull analysis), this provides a mechanistic tool for predicting stress and failure analysis at various conditions for alternative designs being considered.**

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SECA 3kW SOFC Prototype System Demonstration (SECA Metric)

- Thermally integrated power system
- Pipeline natural gas fuel
- Autonomous control
- Grid connected (parallel)
- Designed towards applicable codes and standards compliance

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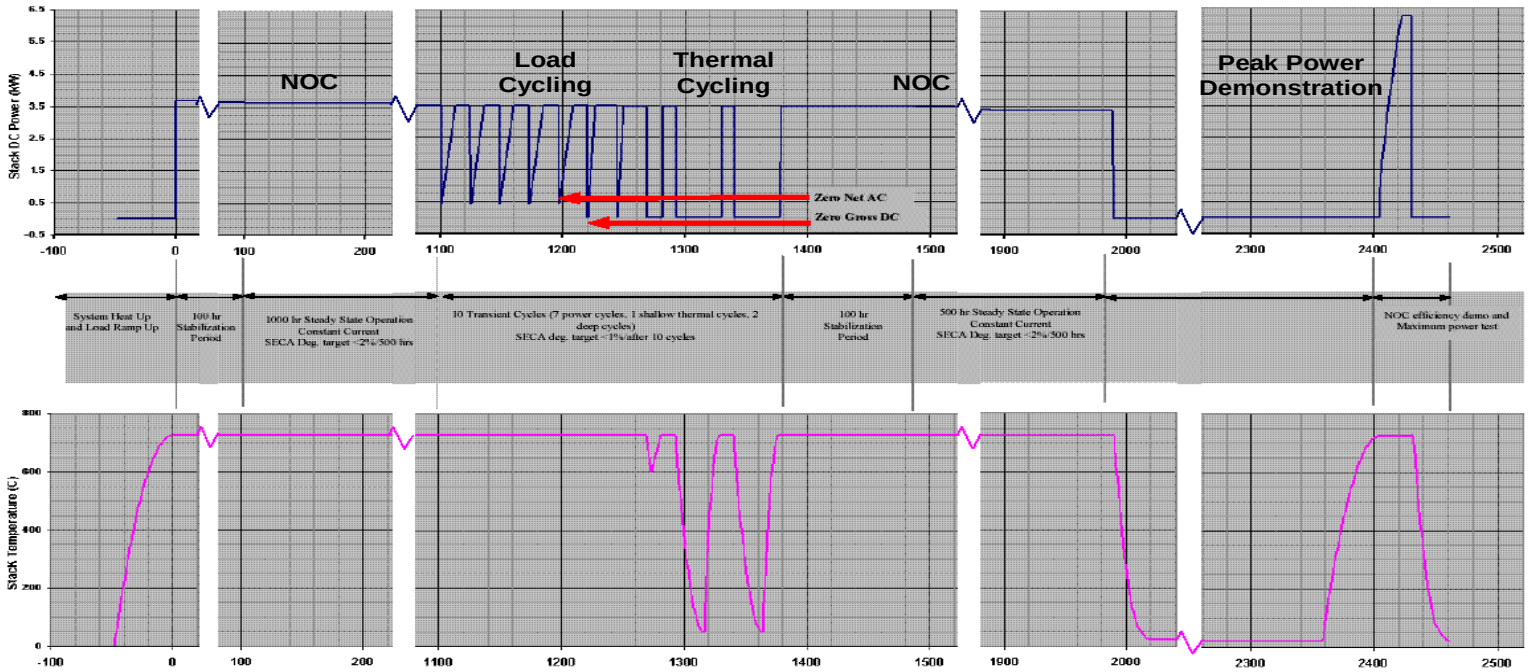
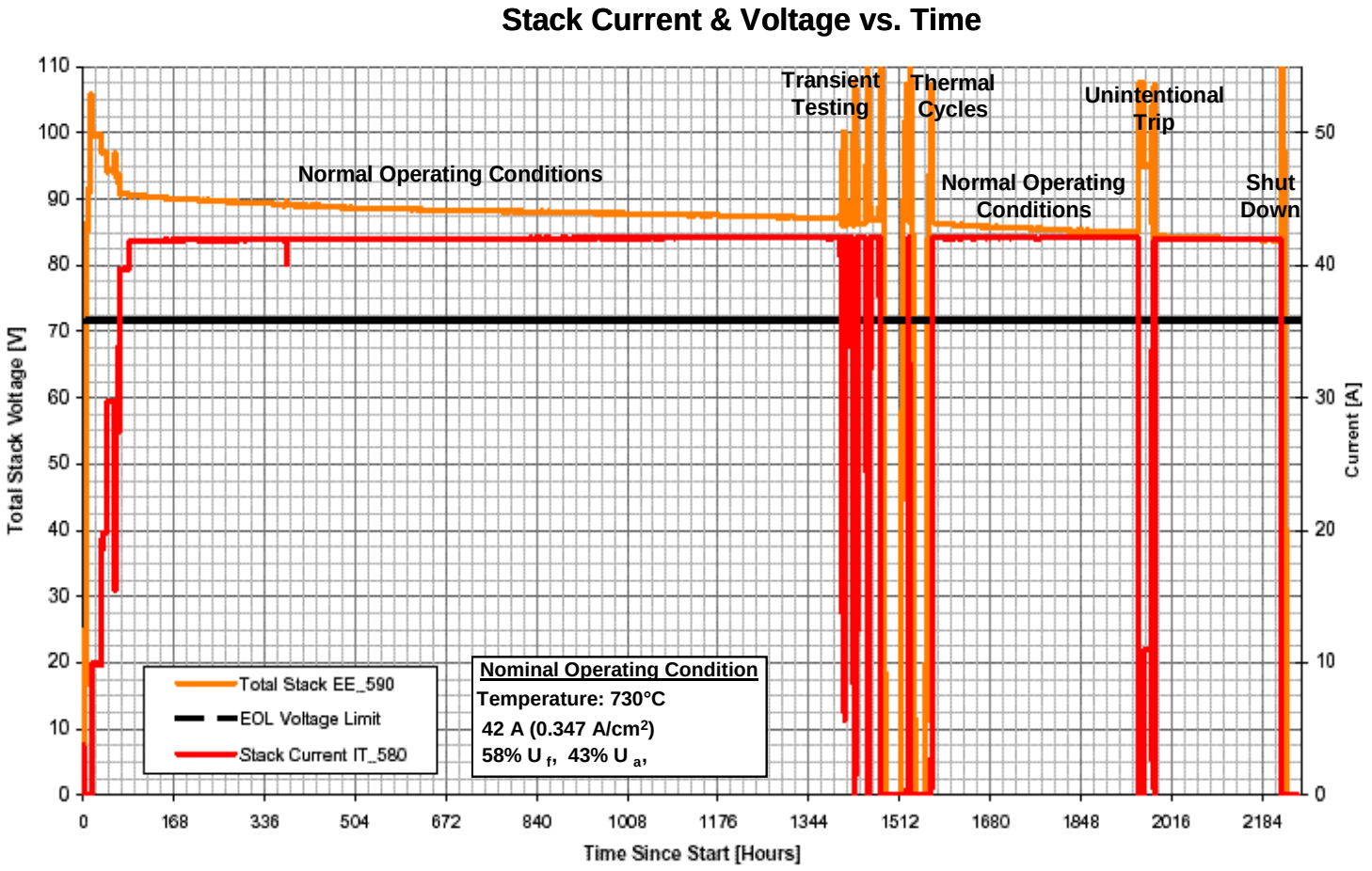
3-1 System Test (SECA Metric)



- **SECA Phase 1 Performance Test Conducted from December 2005 to March 2006:**
  - 1,000 hour steady-state operation at constant current
  - 5 “zero net” electrical transients (system supplies parasitic power requirements only, no net export of power to grid)
  - 2 “zero gross” electrical transients (also known as “open circuit, hot hold”)
  - 1 thermal cycle to 600°C
  - 2 thermal cycles to <50°C
  - 500 hour steady state operation at constant current
  - Peak power demonstration

SECA 3kW SOFC System Performance



- SECA Phase I program 3kW performance metrics have been demonstrated with the scaled up cell and stack configuration.

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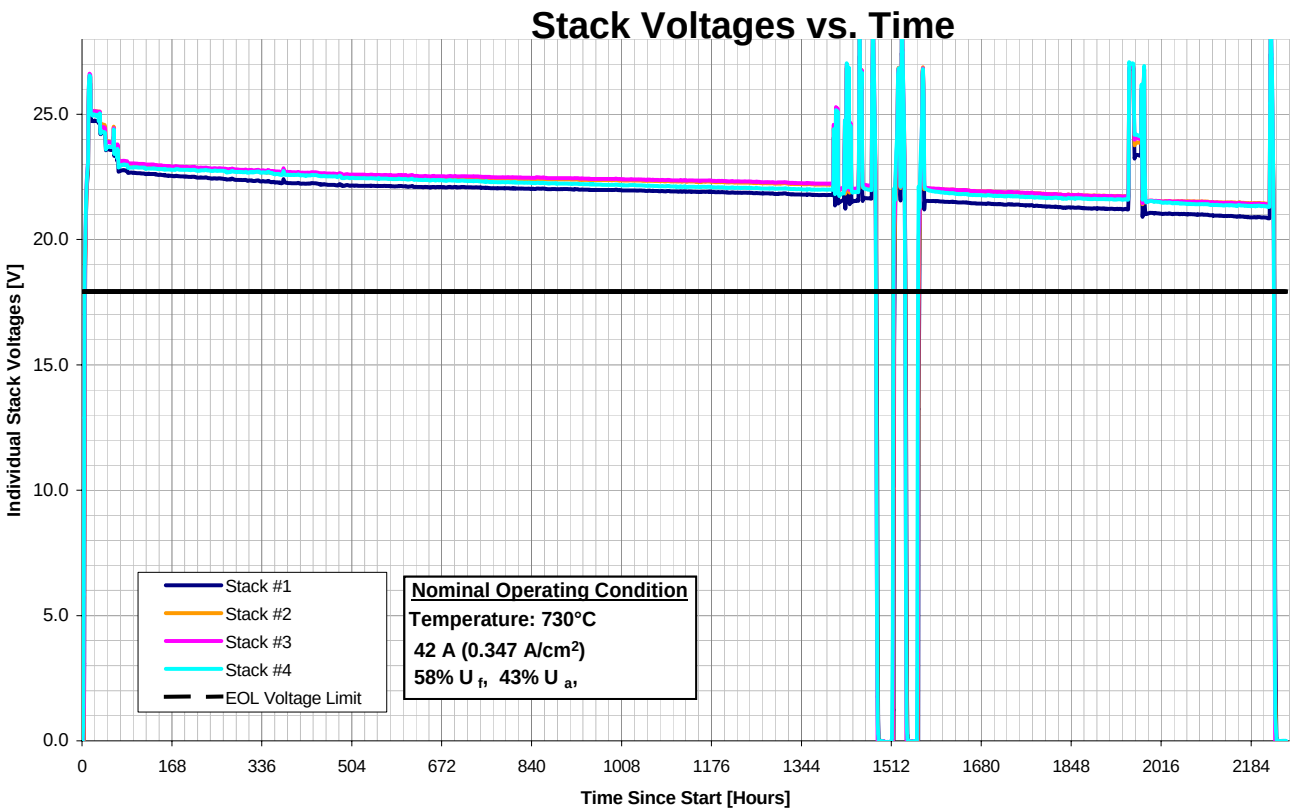
SECA 3kW SOFC System Performance



- **3-1 system tower showed uniform stack-to-stack performance throughout the test.**

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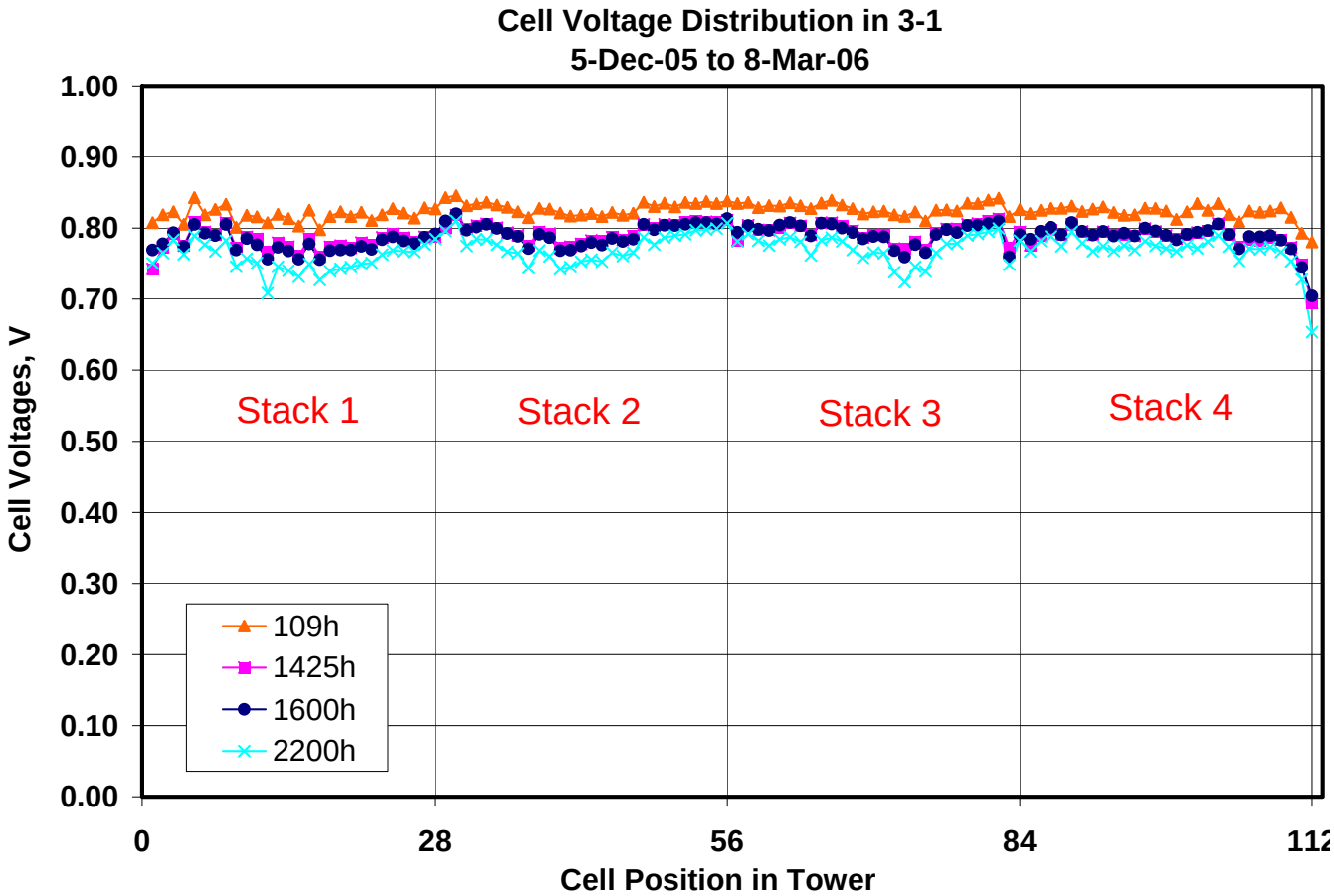
3-1 Cell Voltage Uniformity



- **3-1 system tower likewise showed uniform cell-to-cell performance throughout the test.**

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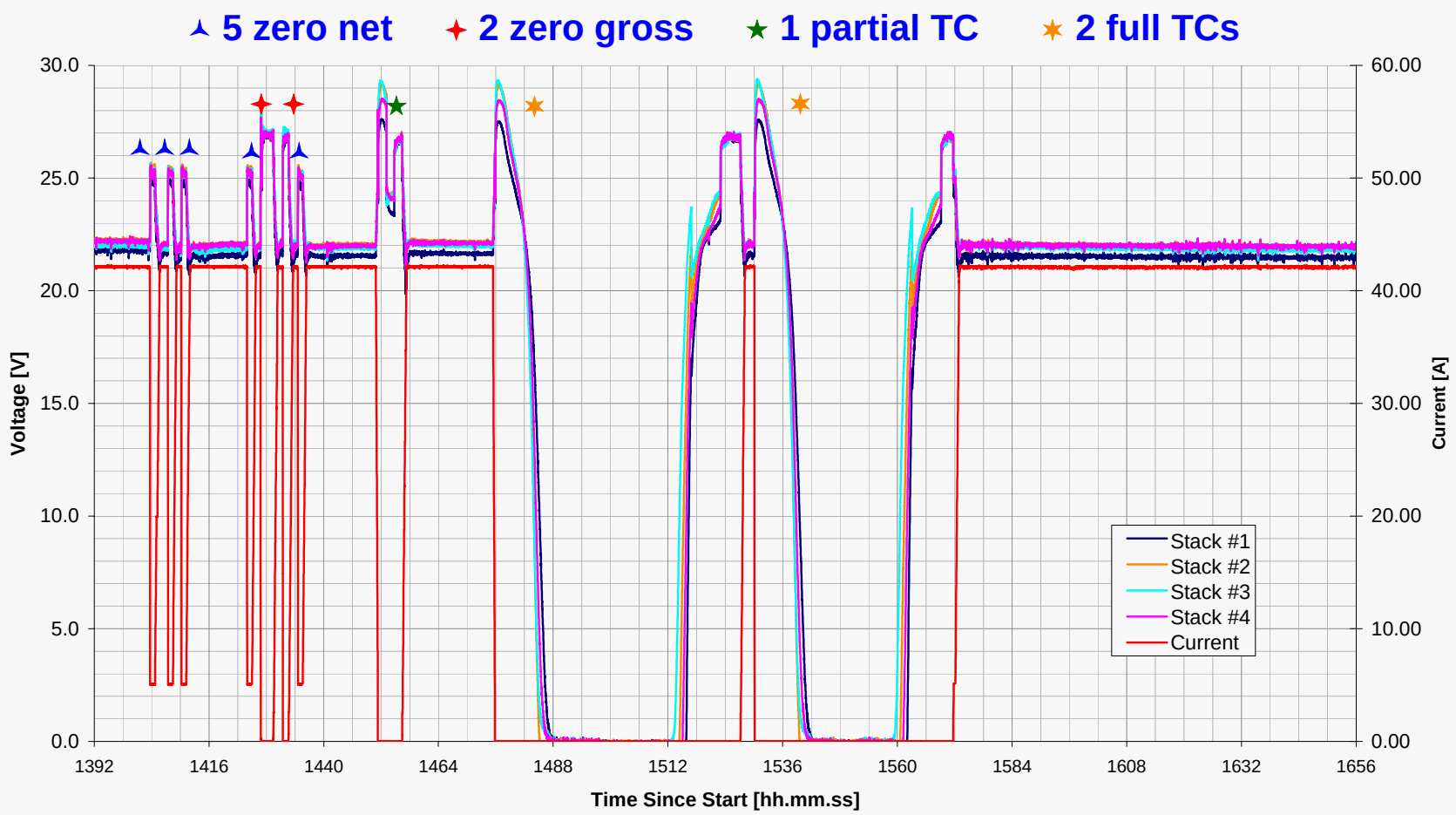
3-1 System Transient Testing



- 3-1 system completed transient test cycle with <1% performance degradation (SECA metric).

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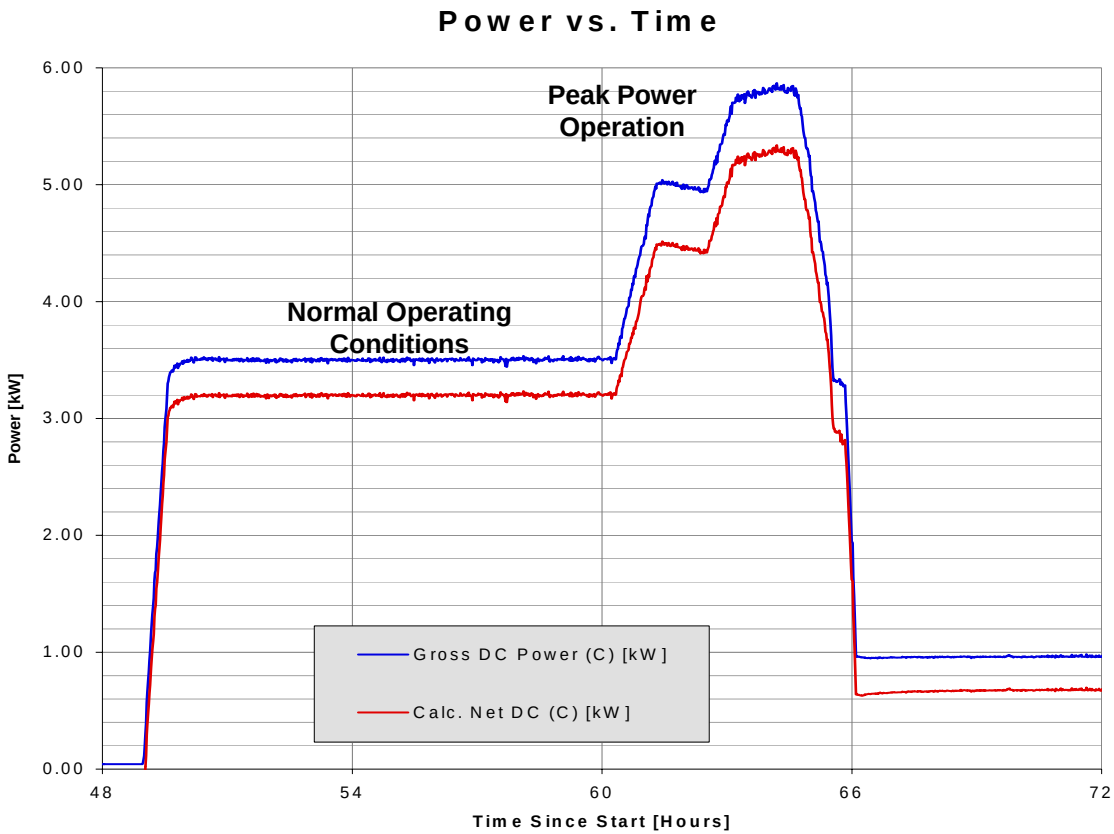
3-1 System Peak Power Testing



- Peak power (5.3kW net DC, 430mW/cm^2) was successfully demonstrated with the same 3-1 system (stacks and BOP) after completion of the SECA prescribed test plan (~2200hours operation including transient tests).

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3-1 kW System Test Summary

	MEASURED NOC - BOT	MEASURED NOC - EOT	PEAK POWER	SECA METRIC	
Net DC Electrical Power	3.39kW	3.13kW	5.26	3 to 10kW	✓
Net DC Electrical Efficiency	38.7%	36.4%	33.3%	>35% NOC	✓
Stack Current	42A ($347 mA/cm^2$)	42A ($347 mA/cm^2$)	80A ($661 mA/cm^2$)	N/A	
Fuel Utilization	58%	58%	60%	N/A	
Air Utilization	43%	43%	46%	N/A	
Steady State Degradation		1.2%/500hours	N/A	<2%/500hours	✓
Transient Degradation (7 load interruptions, 3 thermal cycles)		0.7%	N/A	<1.0%	✓
Availability		98.6%	N/A	>80%	✓

Notes: - Hourly averaged data
- Efficiencies based on LHV Calgary pipeline natural gas

- **All SECA performance metrics have been successfully demonstrated!**

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3-1 System Test Demonstration At NETL

- 3-1 System Test Demonstration at NETL, Morgantown is in progress.

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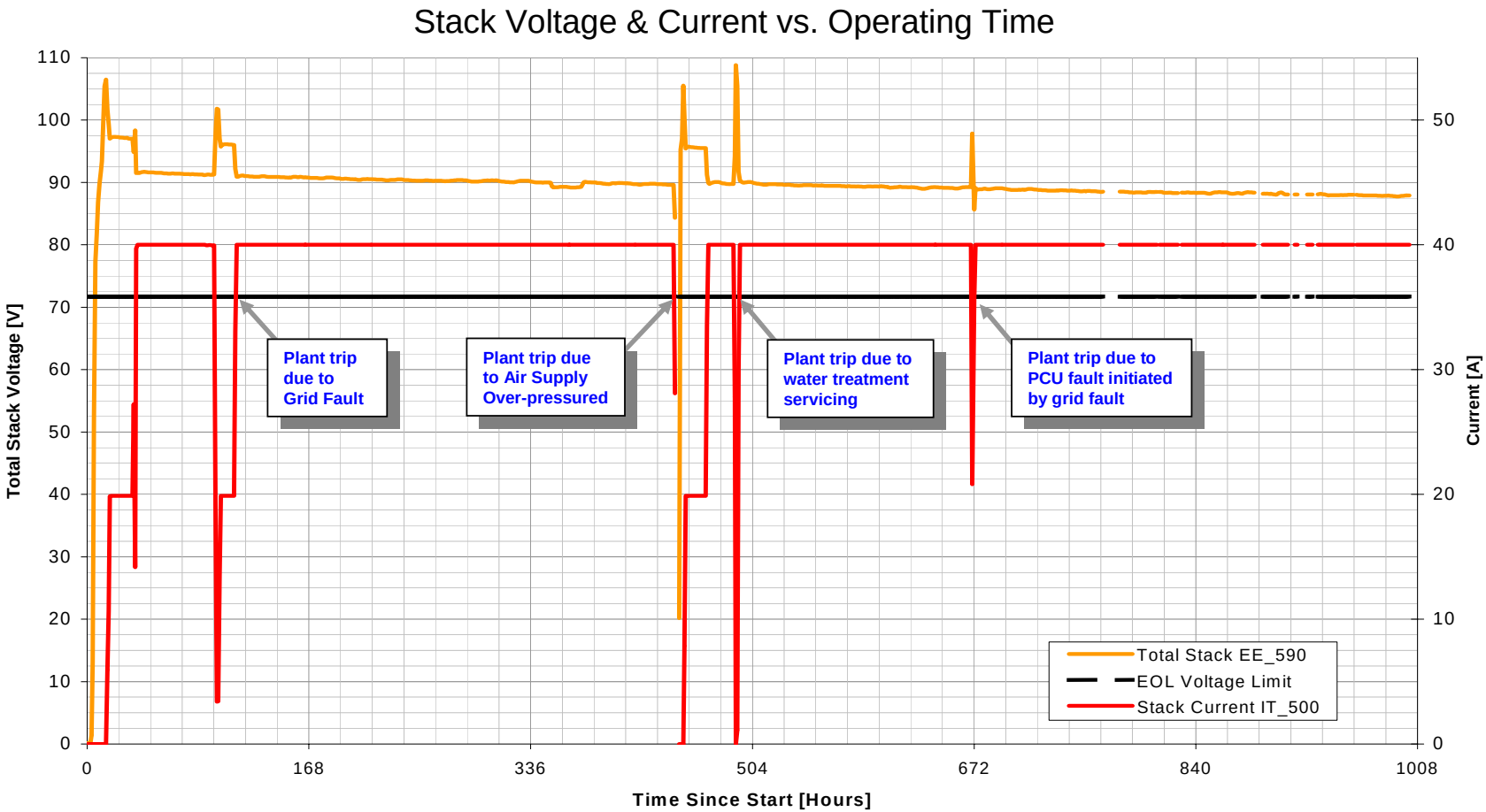
3-1 System Test Demonstration At NETL



- **3-1 System demonstration at NETL, Morgantown ongoing having operated over 1000 hours. No stack and system related issues identified under this real life, customer environment.**

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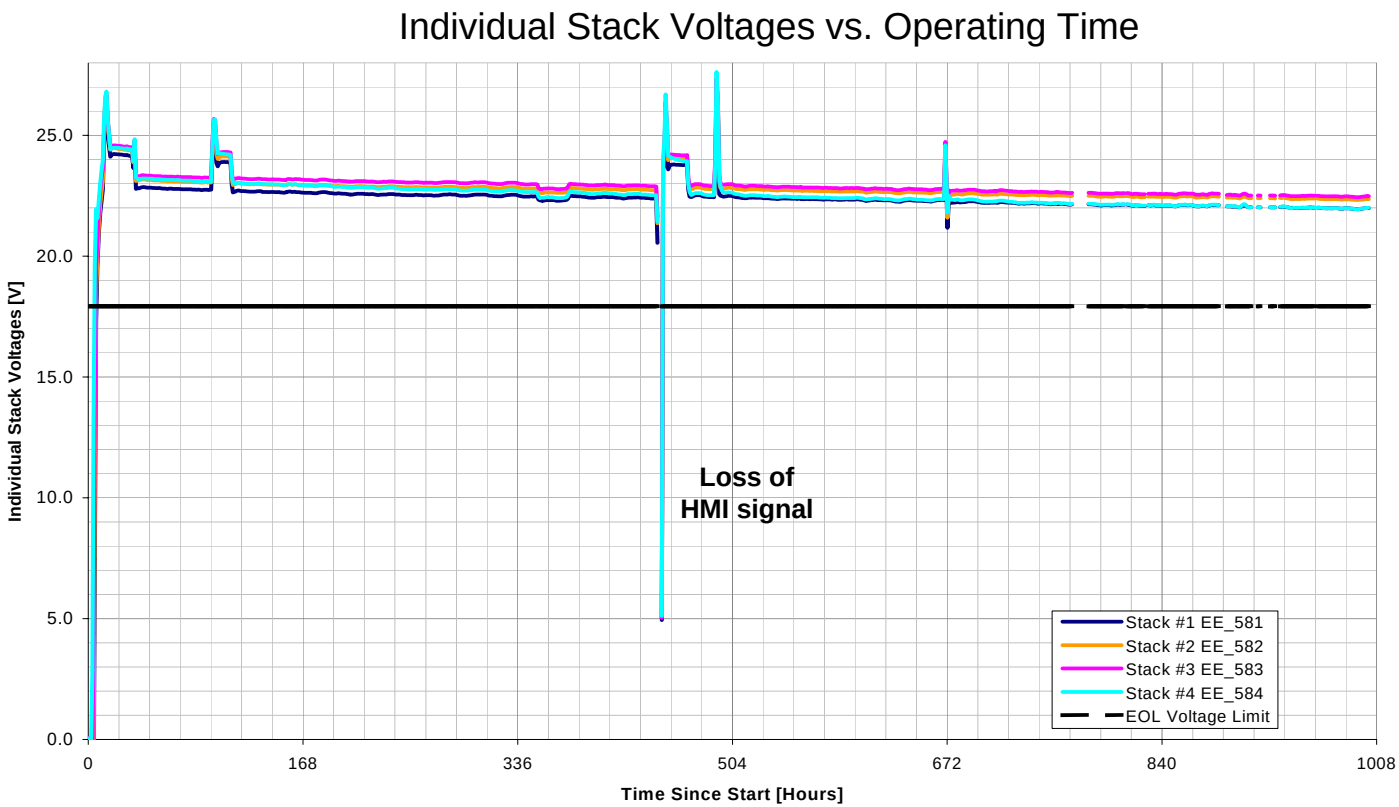
3-1 System Test Demonstration At NETL



- **System continues to demonstrate good stack-to-stack performance uniformity.**

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3-1 System Test Demonstration At NETL

NOC:

Total Test Run Time	1002h
Stack Operating Temperature	730.0°C
Fuel Utilization	57.5%
Air Utilization	42.5%
Direct Internal Reforming	~30. % [1]
Stack Current	40.0A
Power Density	260 mW/cm^2

[1] Based on Performance Test @ VPS Calgary

Gross DC Power (Peak)	3.66 kW
Gross DC Power (Average)	3.45 kW
Net DC Power (Peak)	3.22 kW
Net DC Power (Average)	3.01 kW
Net AC Power (Peak)	2.98 kW
Net AC Power (Average)	2.78 kW

Gross DC Efficiency (Peak)	45.8 %
Gross DC Efficiency (Average)	43.7 %
Net DC Efficiency (Peak)	40.2 %
Net DC Efficiency (Average)	38.1 %
Net AC Efficiency (Peak)	37.1 %
Net AC Efficiency (Average)	35.2 %

- **3-1 System Test Demonstration at NETL, Morgantown continues to operate well.**

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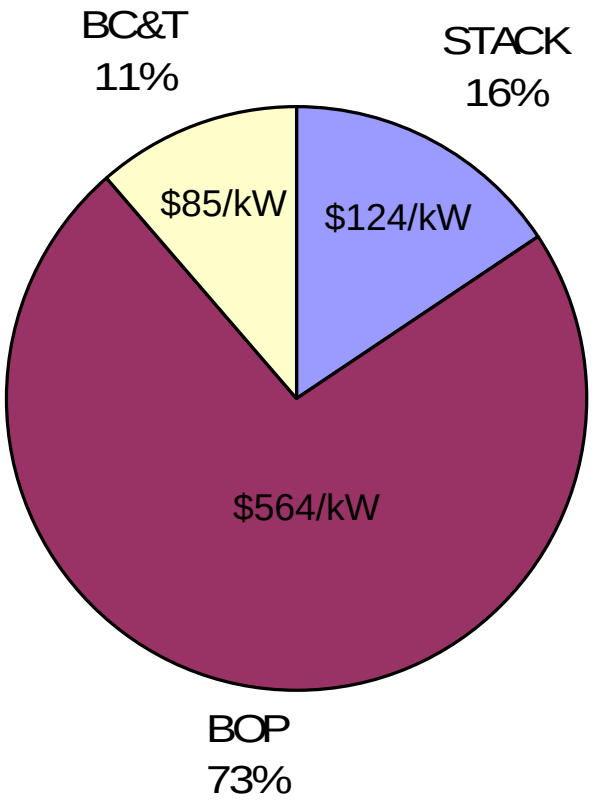
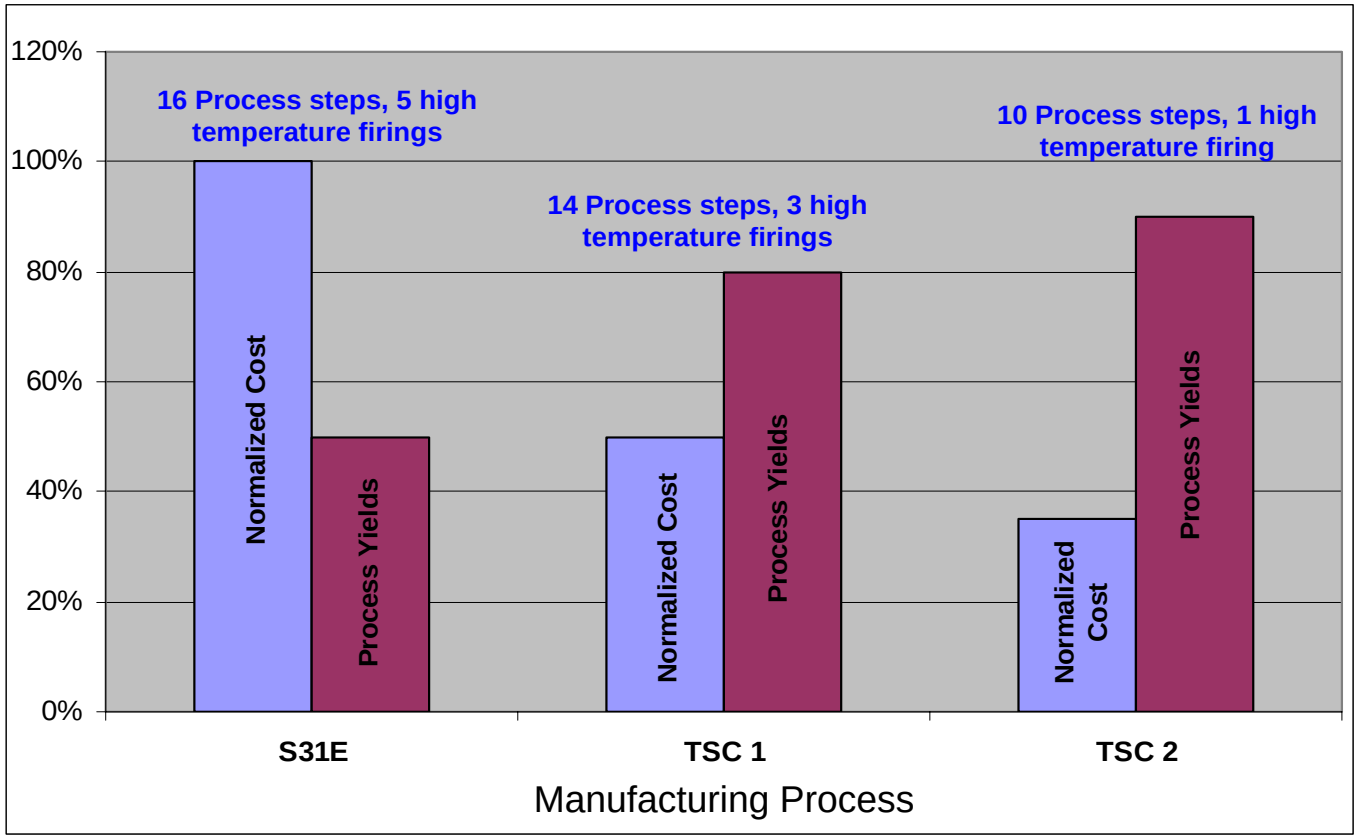
3-1 System Cost Analysis (SECA Metric)



- **Preliminary analysis indicated the total system cost mean to be $774/kW.**
- **The basis for this factory cost analysis is 50,000 units production rate per year.**
- **~3/4 of the cost is associated with the system BOP.**
- **Cost analysis needs to be audited by 3rd party independent consultant.**
- **3rd party consultant has been selected and approved by DOE to conduct audit of system cost.**

➢ **The SECA Phase I cost metric of <$800/kW has been achieved.**

Manufacturing Process Improvements



The low cost associated with the stack reflects the many years of process development and cost reduction activities at VPS. The TSC process is a fully integrated cell manufacturing process.

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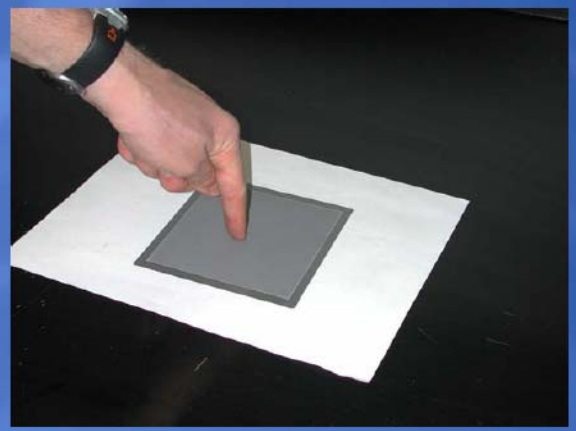
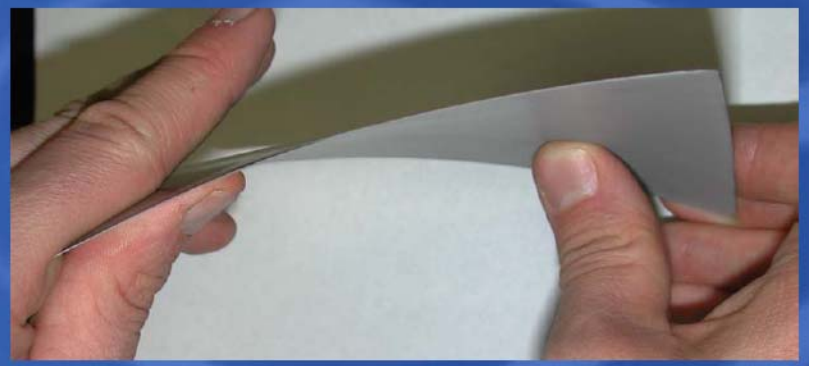
SOFC Active Component Cost Reduction

Thin Cell Development

Cell Thickness	Material Cost Reduction
1 mm	--
0.6 mm	29%
0.3 mm	51%





Reduced cost, increased power density per kg

- **SOFC Cell Thickness and Material Reduction has led to significant cost reduction achievements.**

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SOFC Scale-up Continued In SECA Phase I Program

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

Cell Active Area (cm^2)	121
Number of Cells	21
Gross Power (W)	864

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

- **Cell area and stack height (number of cells) scale-up has resulted in ~260% increase in area and ~5-fold increase in power.**

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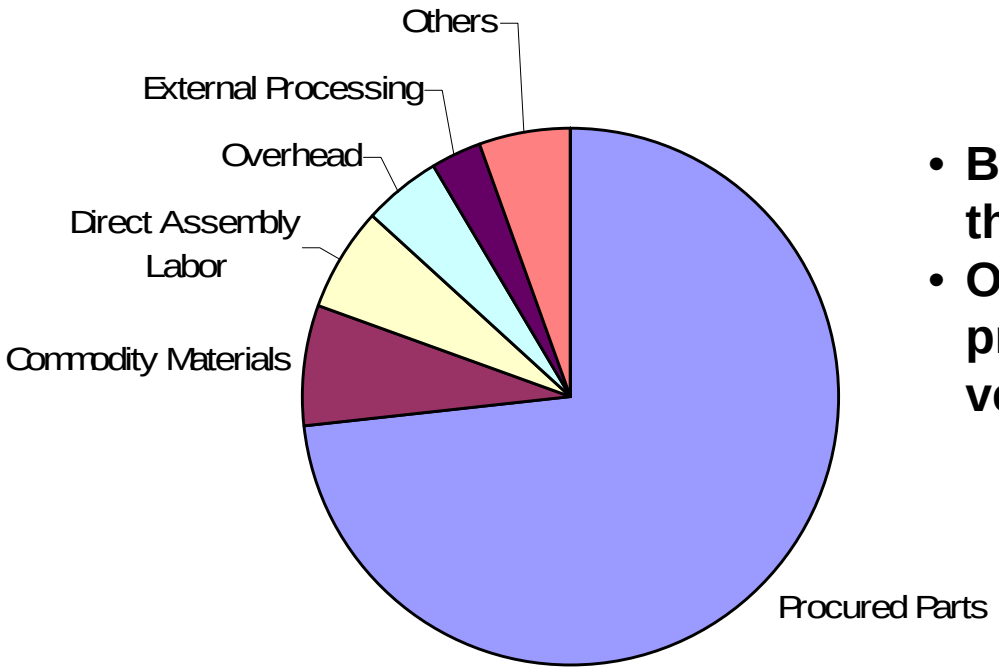
3-1 System BOP Costs



- **BOP components comprise ~73% of the total system costs.**
- **Of this, ~75% of the BOP costs are procured or fabricated by outside vendors.**

➢ **Significant cost reductions are anticipated in BOP components once design configurations are stabilized, multiple vendor sourcing is established and value engineering programs are in play.**

➢ **As power plant size increases, BOP costs will diminish on a cost-per-kilowatt basis.**

SECA Coal-Based, Multi-MW SOFC/Hybrid Power Plant Development

Program Objectives:

Development of large (>100 MWe) hybrid SOFC fuel cell power plant systems with:

- At least 50% overall efficiency from coal (higher heating value)
- Performance to meet DOE specified metrics for degradation, availability, transient testing, etc.
- Cost $400/kW
- Include 90% of CO_2 separation for carbon sequestration

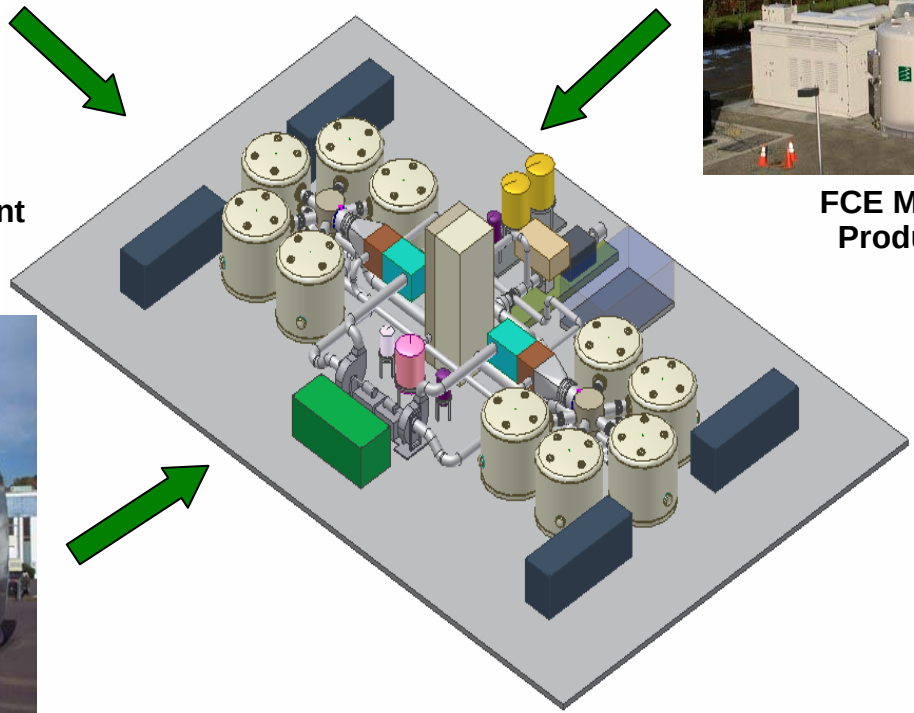
The Program has 3 Phases:

- **Phase I (2-3 years):** **80-100kW SOFC Stack Components and Design**
  - Design a baseline system.
  - Construct an 80-100kW fuel cell stack for validation (building block for MW power plants).
  - Initiate baseline and proof-of-concept power plant design.
- **Phase II (2 years):** **MW Scale SOFC Stack Module (~2MW)**
  - Develop detailed design and cost analysis of the proposed system.
  - Fabricate and test a fuel cell module (building block for multi-MW power plants).
  - Finalize proof-of-concept power plant design
- **Phase III (5 years):** **Multi-MW Scale Hybrid Demonstration (~10-12MW)**
  - Fabricate a proof-of-concept system (gas turbine >1 MW) integrated with a coal gasifier.
  - Conduct long-term tests (25000 hours) at FutureGen site.

SECA Coal-Based, Multi-MW SOFC/Hybrid Power Plant Development

3-10kW SOFC Product Development
(Versa Power Systems)

MULTI-MW SOFC/HYBRID POWER PLANT CONCEPTUAL DESIGN

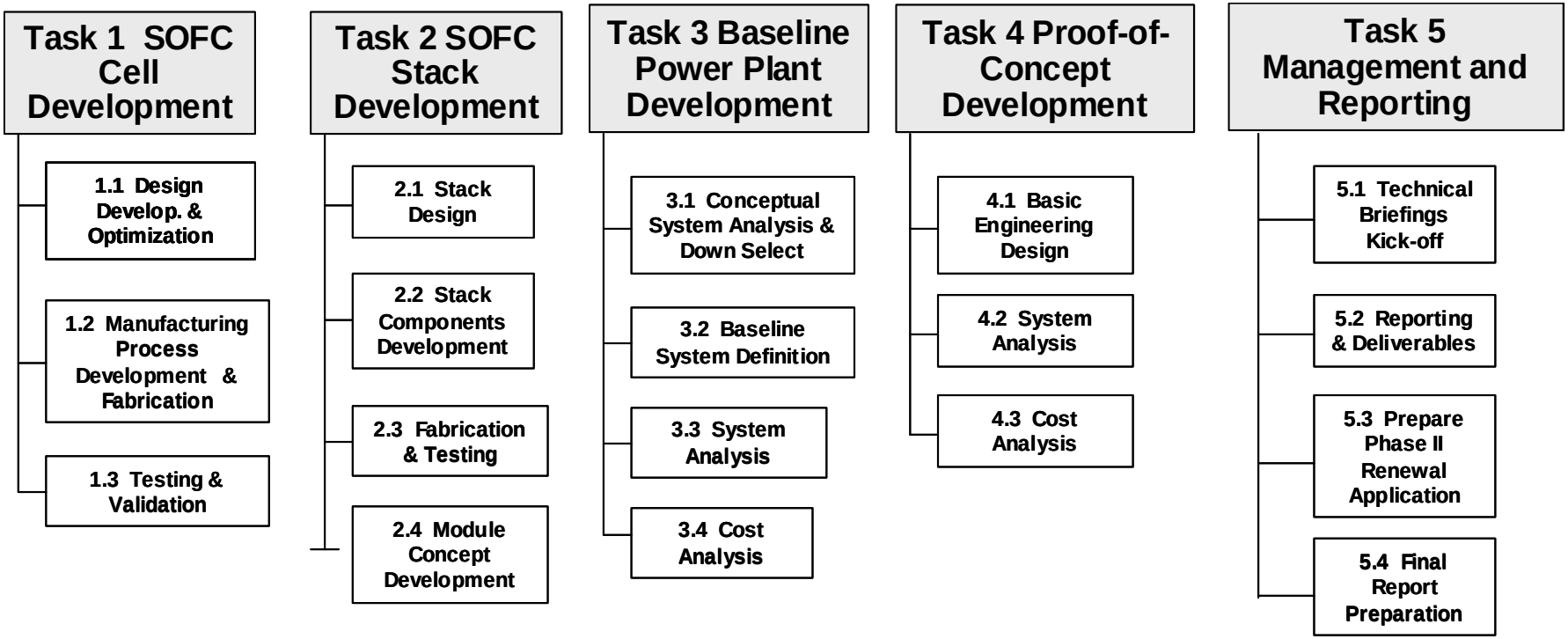


FCE MW Class Fuel Cell
Product Development

FCE High Efficiency Hybrid Fuel Cell–
Turbine Product Development

- **The FCE team's experience is ideally suited to development of multi-MW SOFC/hybrid power plant using coal derived fuels.**

SECA Coal-Based Program Work Breakdown Structure



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

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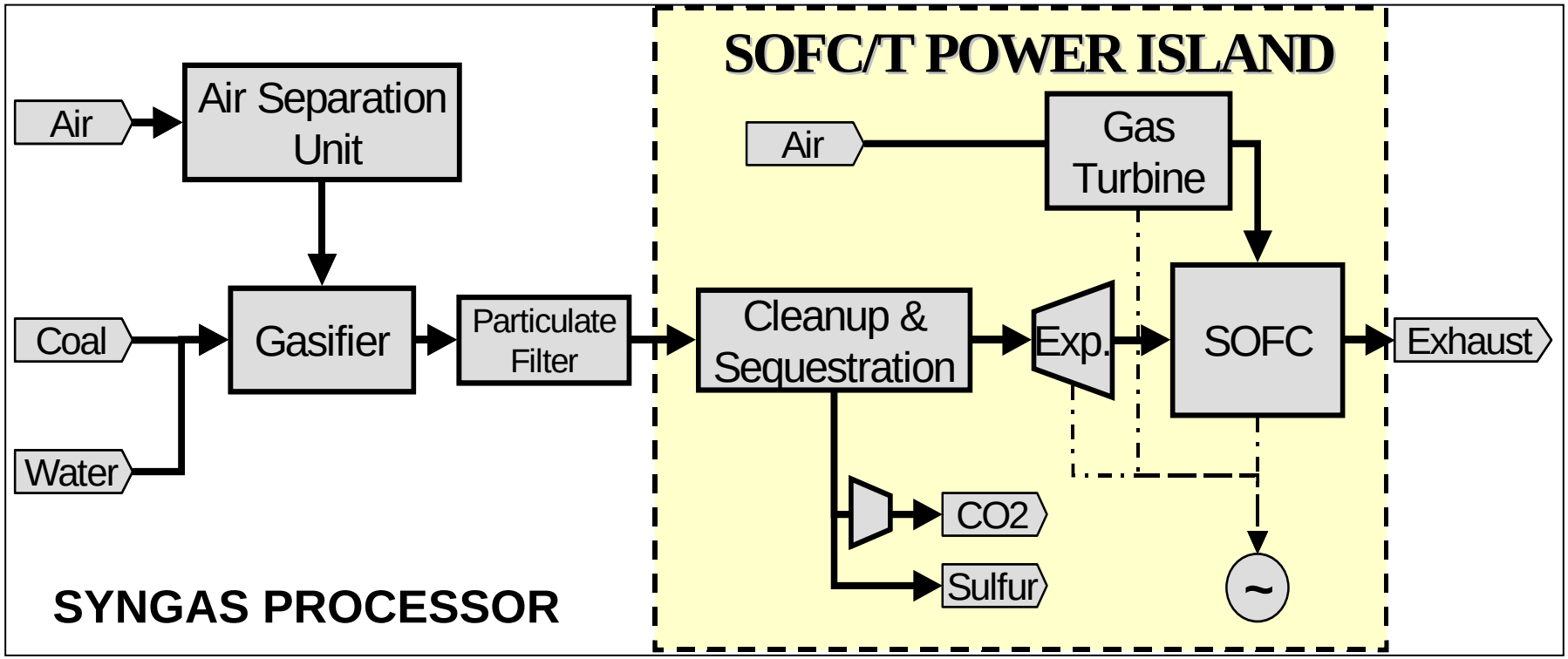
Coal-Based Hybrid SOFC-Turbine Simplified System PFD



- **This innovative SOFC/Turbine hybrid concept is anticipated to provide high system efficiencies approaching 60% (HHV) using coal derived fuels while sequestering CO2 for low emissions.**

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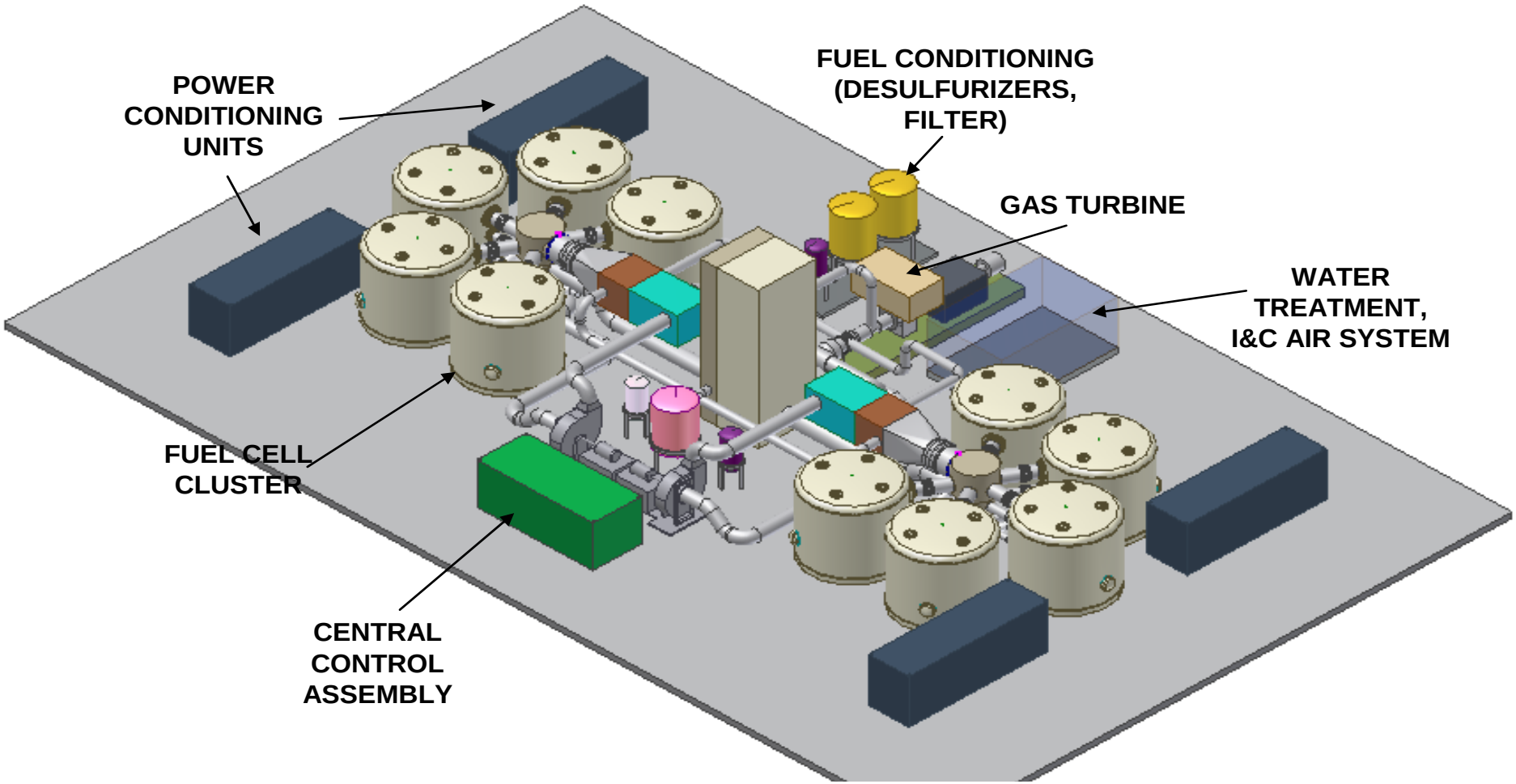
SOFC Stack Development Technical Approach



Phase III SECA Coal-Based program deliverable will be to build and test a large scale, multi-MW SOFC/Hybrid power plant on Coal syngas at a FutureGen site.

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Acknowledgements

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