SECA SOFC Programs At FuelCell Energy Inc.

Presented at the 8th Annual SECA Workshop

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by

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FuelCell Energy

Versa Power Systems

Who is FuelCell Energy Corporation (FCE)?

R & D

Danbury, CT

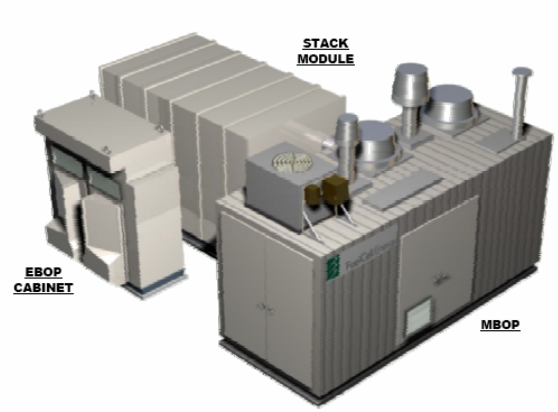
MANUFACTURING

Torrington, CT

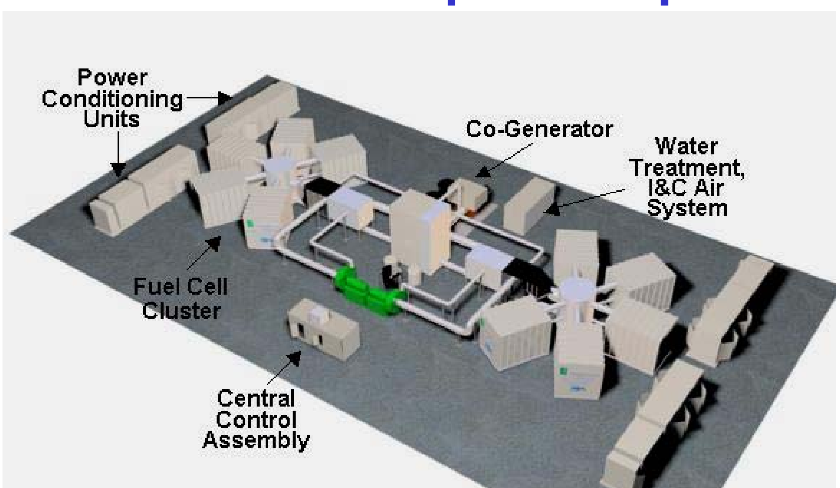
FuelCell Energy Corporation (FCE) is a high temperature fuel cell company that has been involved in development of fuel cells for stationary power applications for over 30 years. Much of this development work has been supported by DOE programs.

Why is FCE Interested In SOFC?

- **FCE is currently engaged in commercial deployment of it's DFC™ products in the sub-MW to multi-MW size ranges.**
- **Consistent with it's mission as a high temperature fuel cell company, FCE is also interested in large scale SOFC power plant development as a future product option to enhance it's fuel cell product portfolio.**



Direct FuelCell® DFC300MA™



Multi-MW SOFC Power Plant

Direct FuelCell® DFC3000

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FCE SECA SOFC Programs

- **FuelCell Energy Corporation (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 on Sept 2006, surpassing all DOE specified metrics for performance and cost.**

- **On 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. Final program deliverable will be a 5MW proof-of-concept (POC) power plant demonstration at FutureGen or other suitable SECA selected site. This POC system will be an embodiment of the Baseline (>100MWe) power plant designed for commercial applications.**

Presentation Overview

FCE's SECA SOFC Programs:

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

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

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Cell And Stack Technology

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

Anode Supported, Planar Cell Design

Internally Manifolded Stack Building Block Design

Stack Building Blocks Assembled Into Stack Tower

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Versa Power Systems SOFC Manufacturing

VPS has been developing cost effective SOFC manufacturing procedures since 1998 and has well establish processes, quality procedures and equipment for the manufacture of small to intermediate size 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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SECA Phase I

3-10kW Cost Reduction Program

- 3-1 System Metric Test Results
- Factory Cost Estimate

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SECA Phase I, 3-10kW
Cost Reduction 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.**

Accomplishments:

- ✓ **Completed 3-1 system test (Program Metric). Test operated for over 2,100 hours at VPS Ltd and successfully surpassed all performance targets for power output, efficiency, availability and endurance.**
- ✓ **Following the metric test, the prototype 3kW SOFC system was shipped to NETL and re-tested for another 1,700 hours validating the performance of the metric test conducted at VPS.**
- ✓ **A detail factory cost estimate analysis was completed (Program Metric). System cost was $776/kW including a stack cost of $133/kW. This surpasses (less than) the SECA Phase I metric of $800/kW.**
- ✓ **Both the metric system performance tests and the factory cost estimate were audited and confirmed by independent third party consultants approved by the DOE.**
- ✓ **FCE accelerated the program schedule to end early and merge with new Coal-Based SOFC Program.**

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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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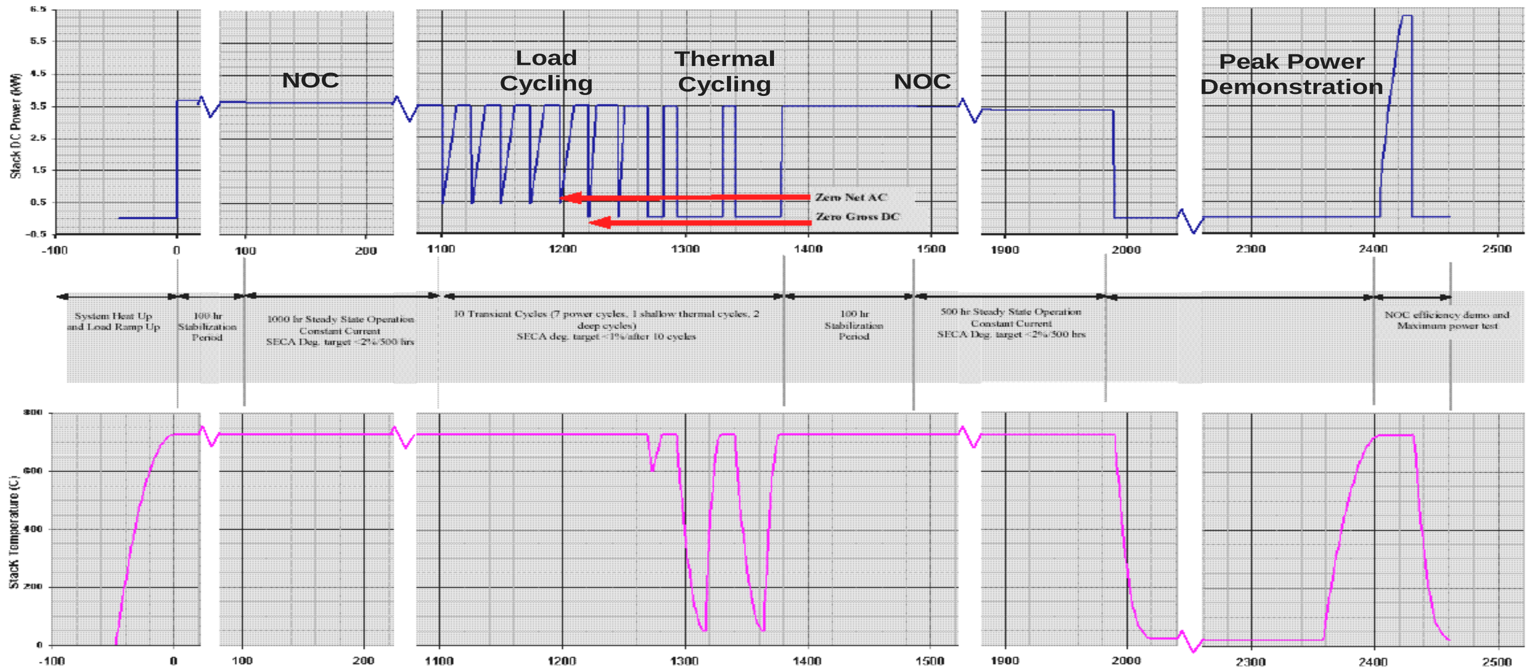
3-1 System Test Plan (SECA Metric)



- **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

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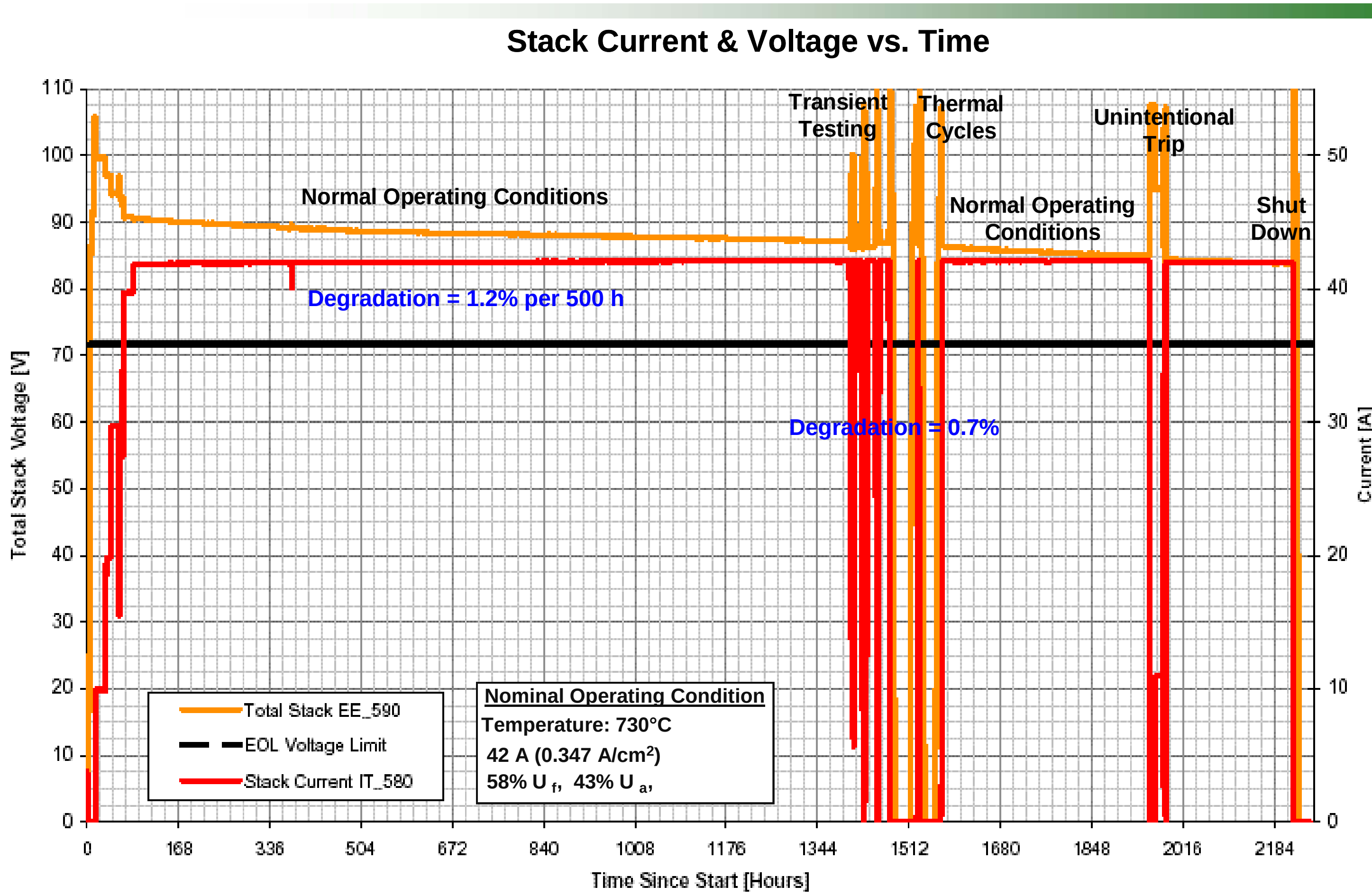
SECA 3kW SOFC System Performance



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

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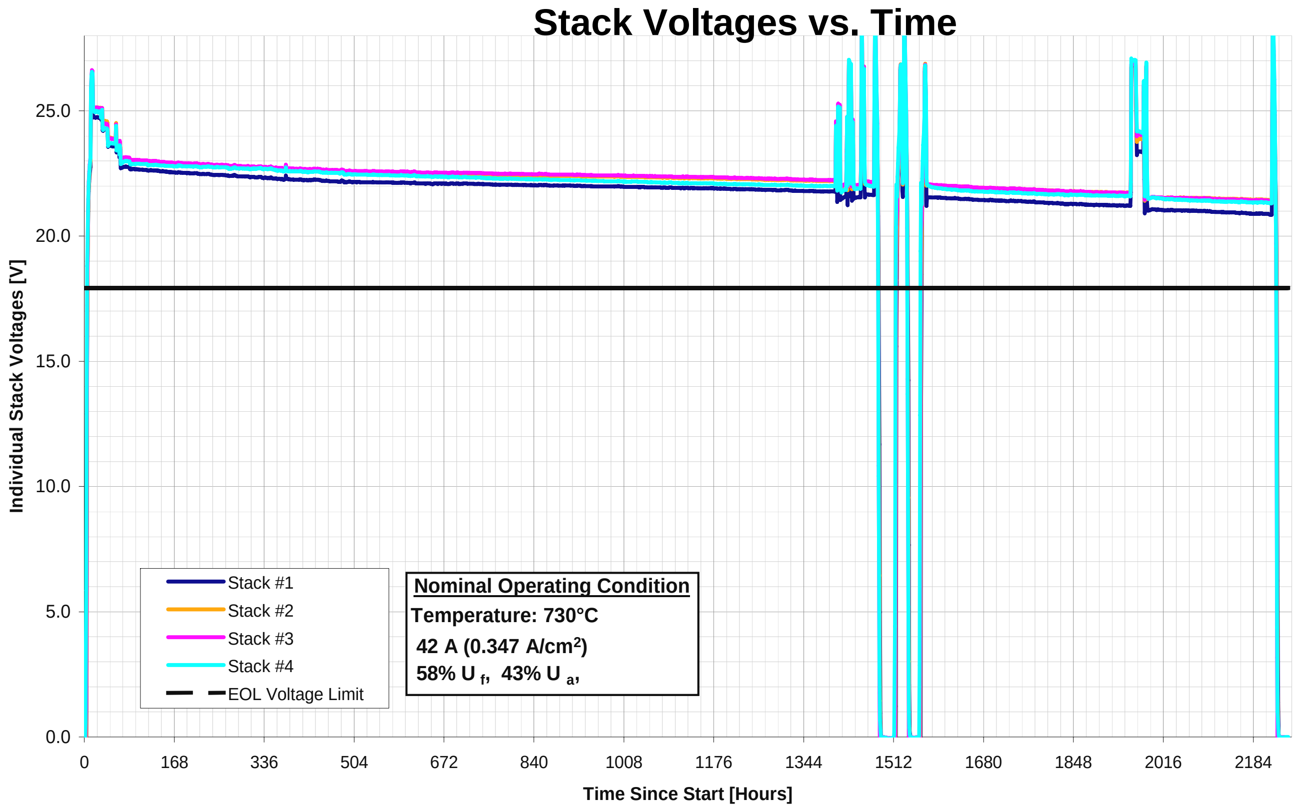
SECA 3kW SOFC System Performance



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

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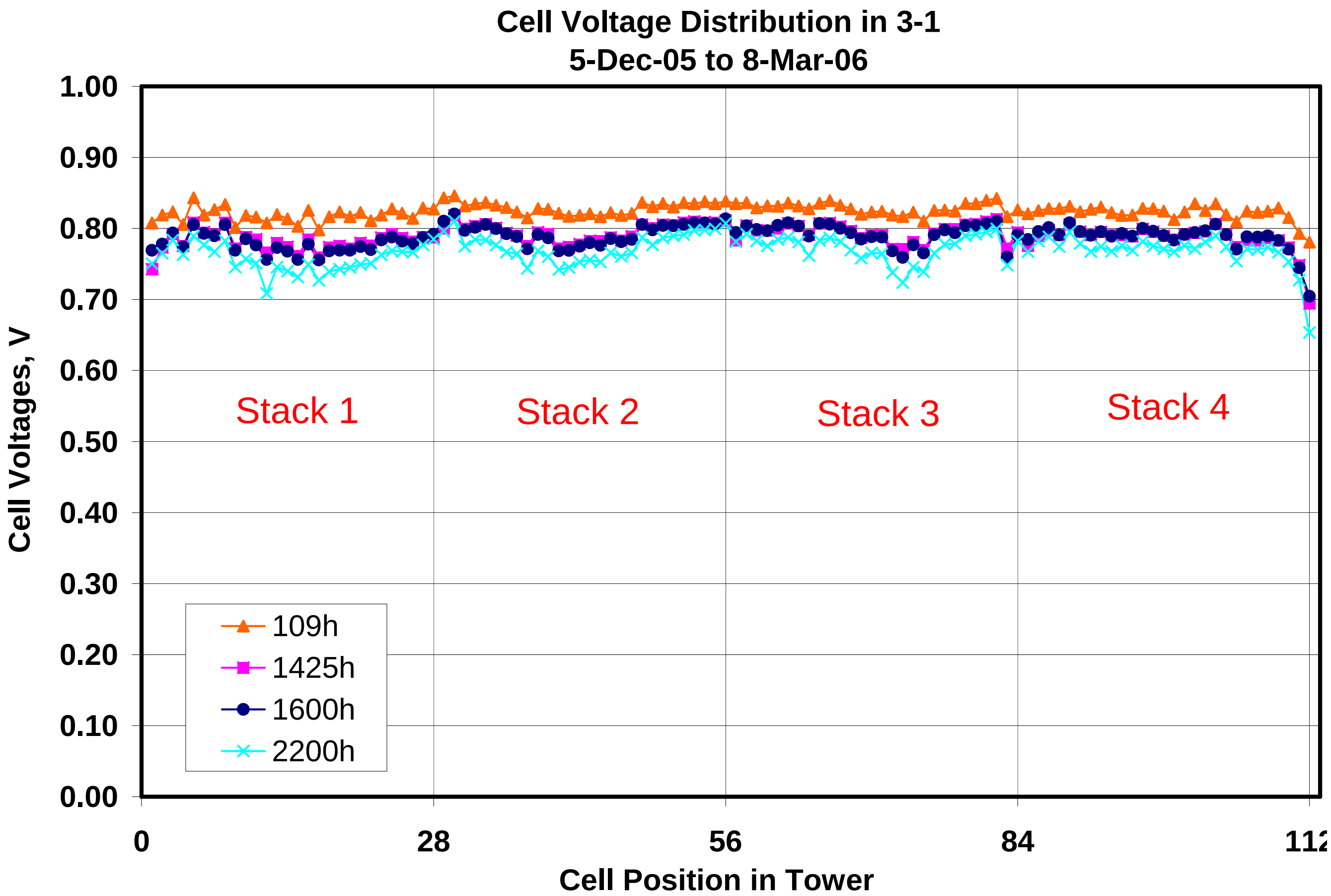
3-1 Cell Voltage Uniformity



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

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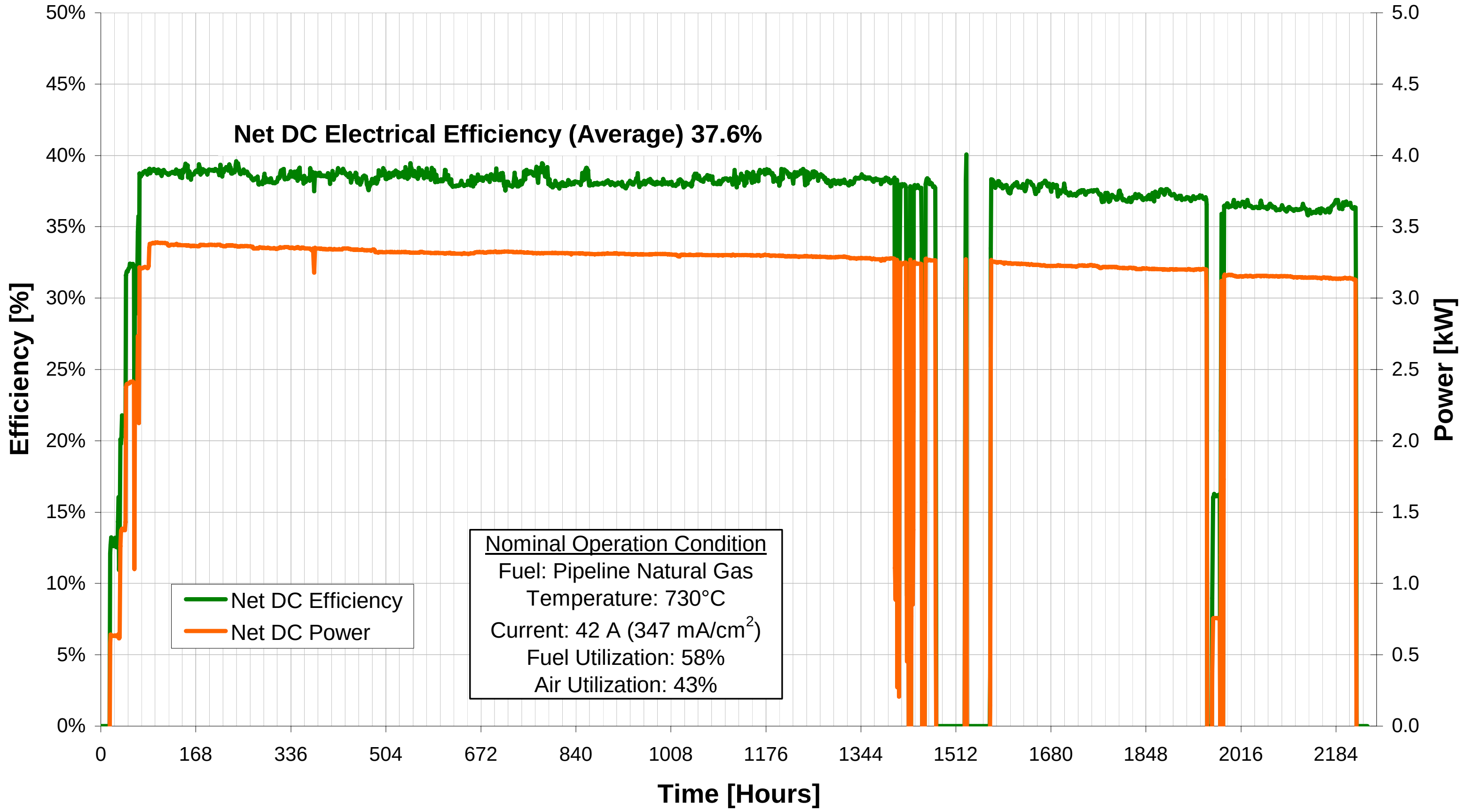
3-1 System Metric Test Efficiency



➢ **3-1 system efficiency was 37.6% during steady state operation, exceeding the SECA Phase I program metric of >35%.**

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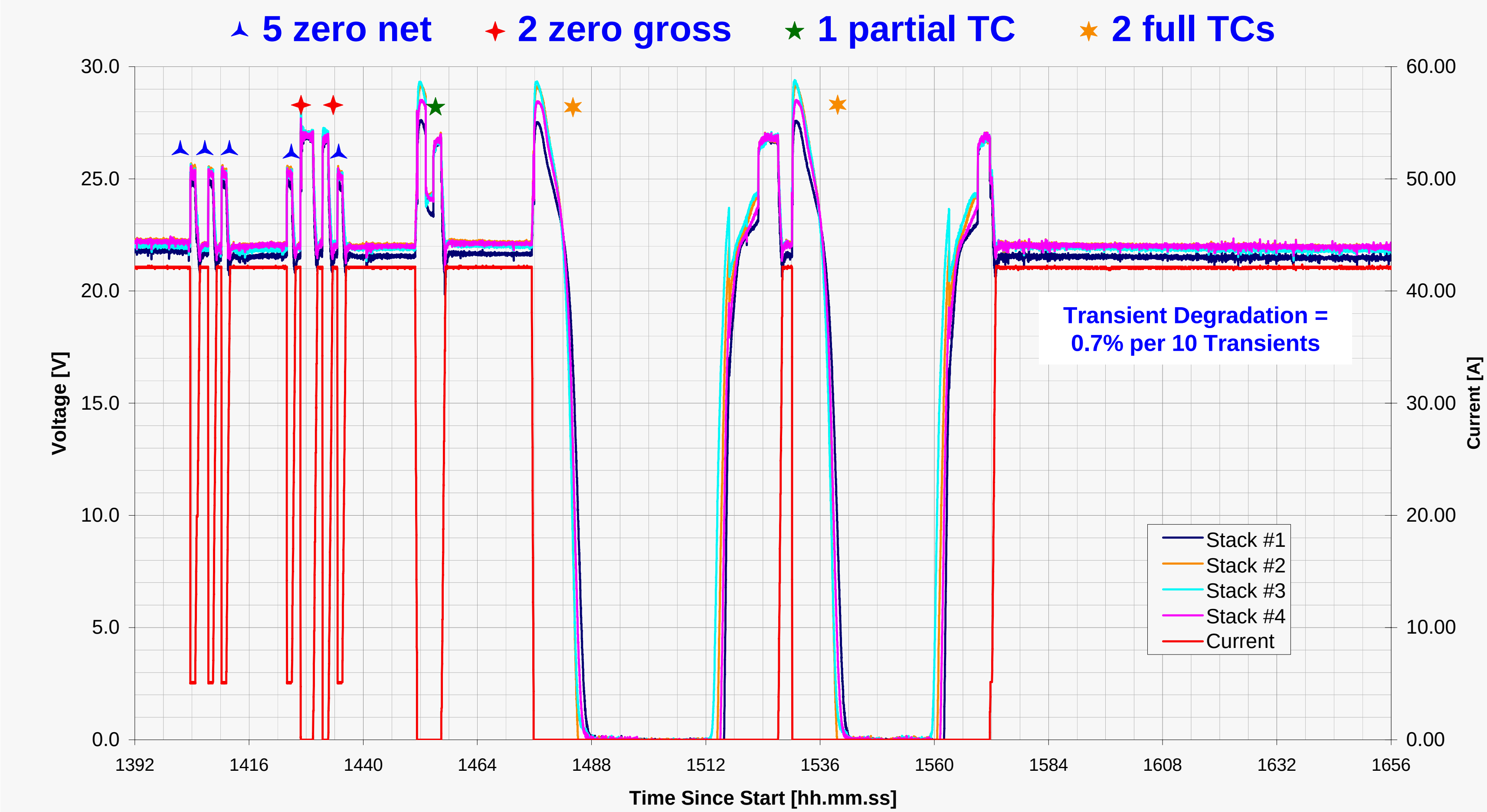
3-1 System Transient Testing



- 3-1 system completed transient test cycle with 0.7% performance degradation, less than SECA Phase I metric being <1.0%.

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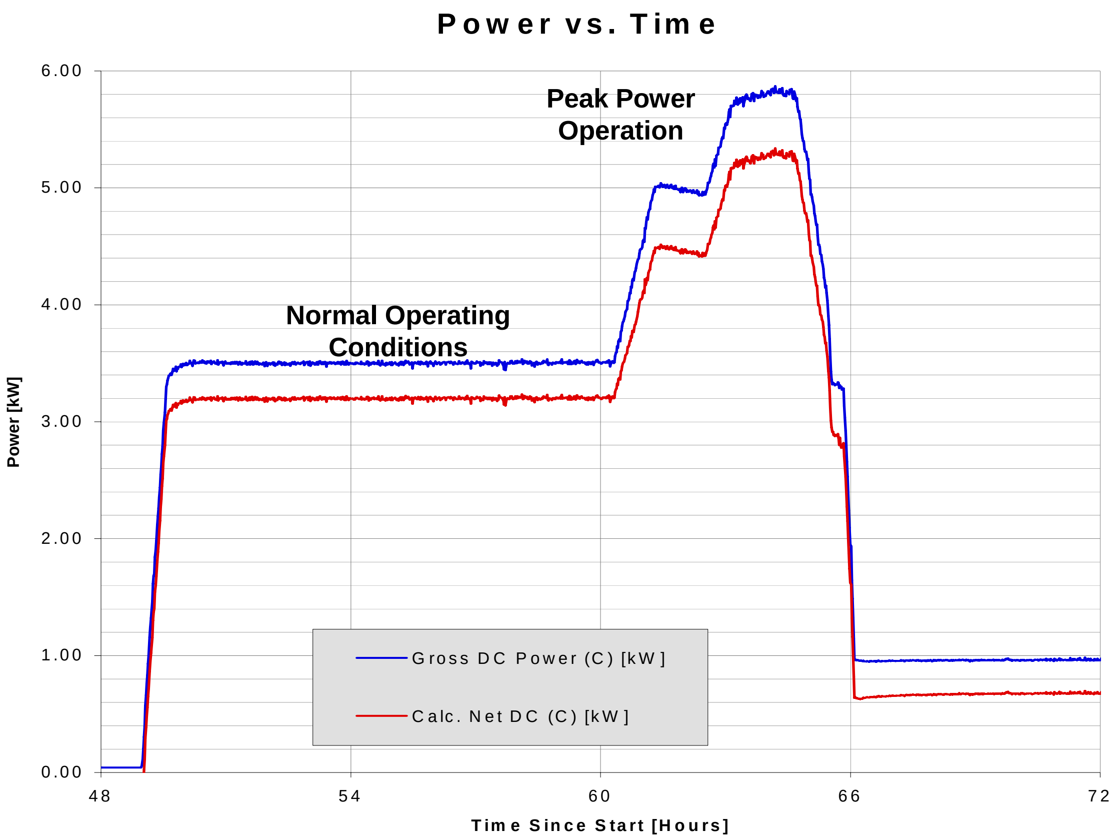
3-1 System Peak Power Testing



- **Peak power (5.1kW 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

	STEADY STATE OPERATION (BOT)	STEADY STATE OPERATION (EOT)	PEAK POWER OPERATION	SECA METRIC	
Net DC Electrical Power	3.39kW	3.13kW	5.26kW	3 to 10kW	✓
Net DC Electrical Efficiency	38.7%	36.4%	33.3%	>35% (Steady State)	✓
Stack Power Density	280mW/cm^2	260mW/cm^2	430mW/cm^2	N/A	
Steady State Degradation		1.2%/500hrs	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!**

3-1 System Test Demonstration At NETL

3-1 System Test Demonstration at DOE NETL, Morgantown during July to October, 2006.

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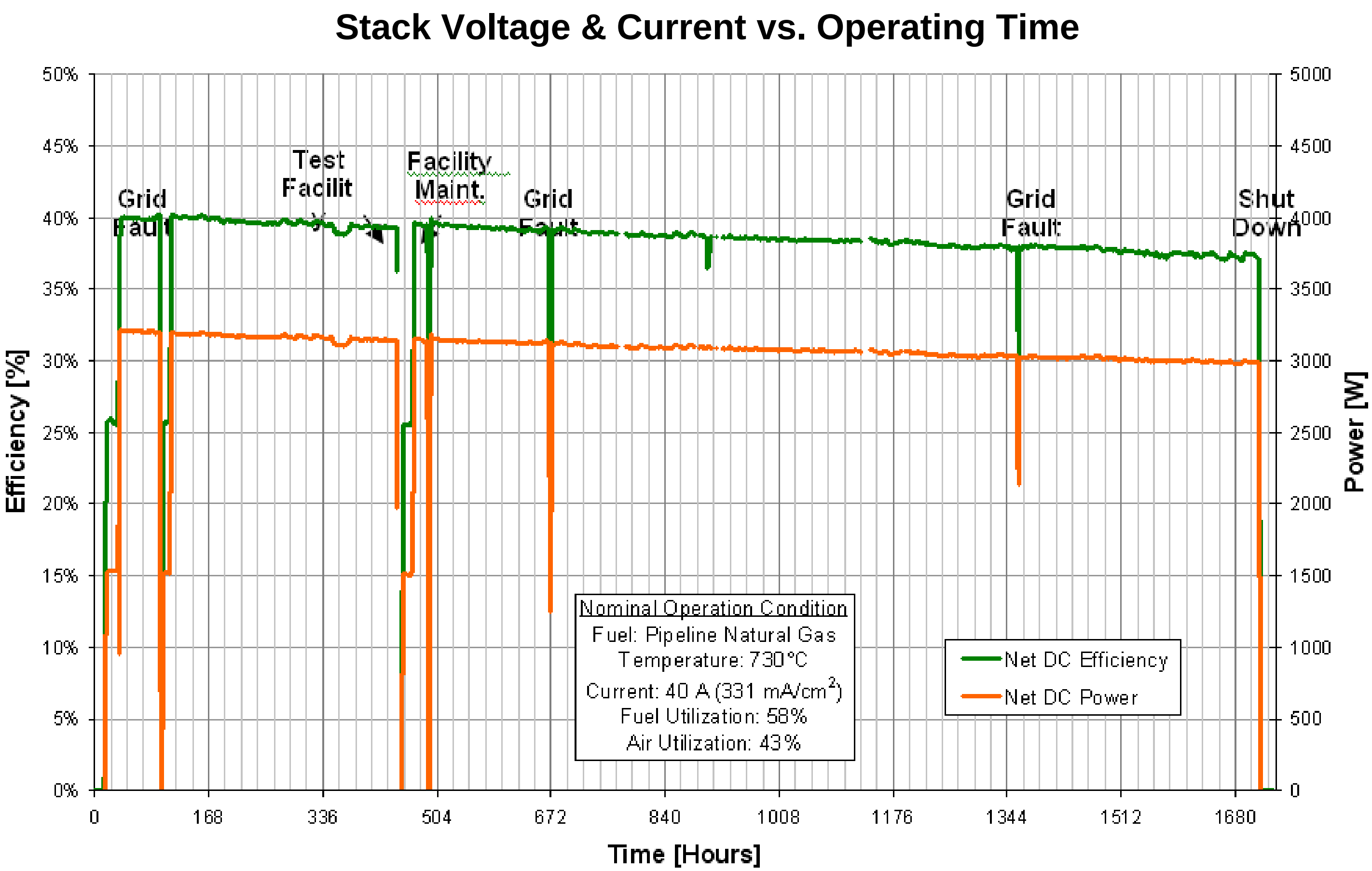
3-1 System Test Demonstration At NETL



➢ **3-1 System demonstration at NETL, Morgantown operated for ~1700 hours. Test results validated SECA metric test results obtained during operation at VPS.**

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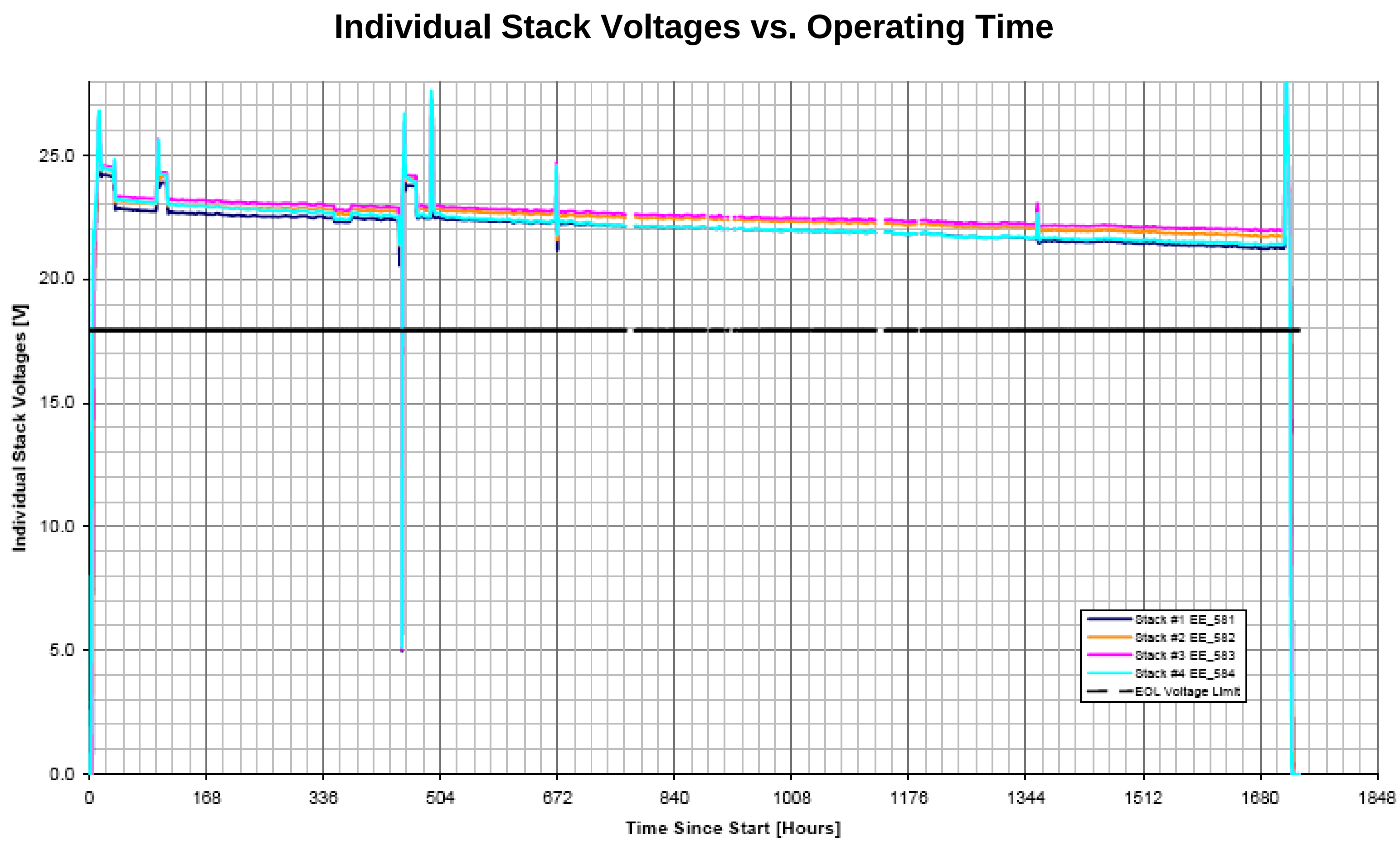
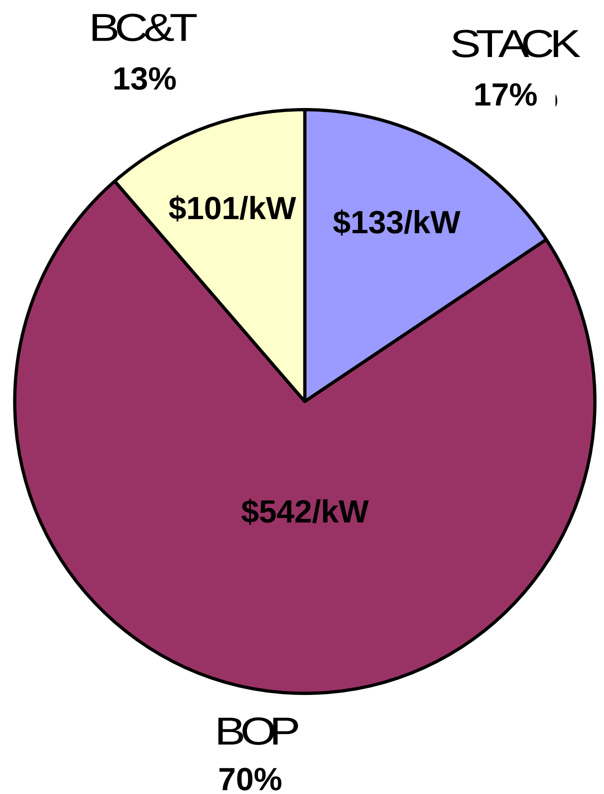
3-1 System Test Demonstration At NETL



- System demonstrated good stack-to-stack performance uniformity.

3-1 System Cost Analysis (SECA Metric)



Total System Cost = $776/kW

- **SECA Phase I system factory cost estimate is $776/kW.**
- **The basis for this factory cost analysis is 50,000 units production rate per year.**
- **Approximately 70% of the system cost is associated with the system BOP.**
- **The low stack cost is attributed to the many years of cell and stack manufacturing development at VPS.**
- **The cost analysis was audited and confirmed by 3rd party, independent consultant.**

➢ ***SECA program phase I factory cost estimate metric (<$800/kW) was successfully met!***

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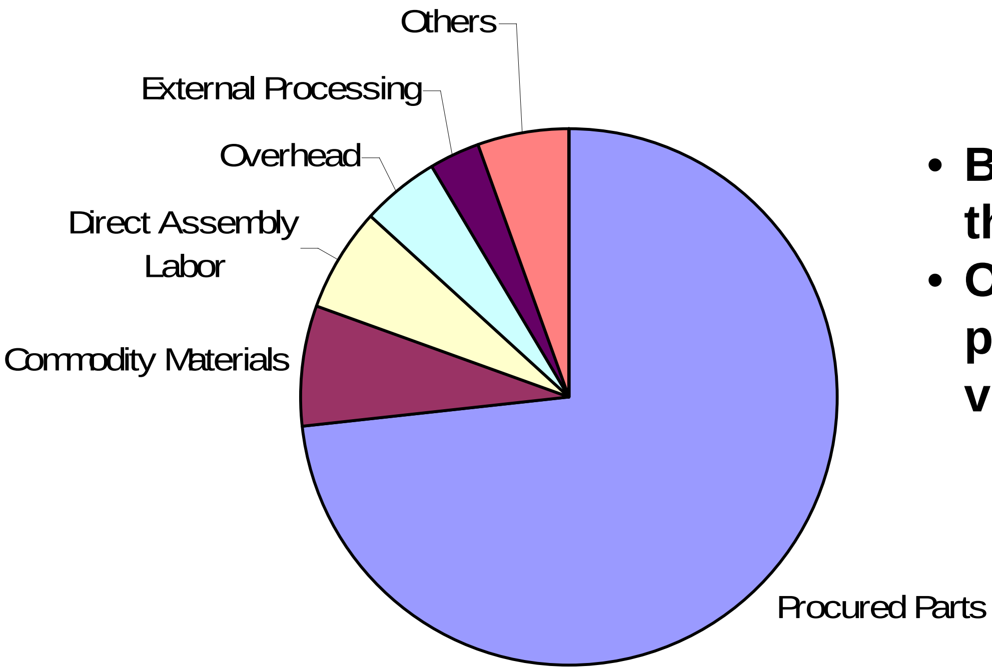
3-1 System BOP Costs



- **BOP components comprise ~70% of the total system costs.**
- **Of this, ~75% of the BOP costs are procured or fabricated by outside vendors.**

➢ **Significant cost reductions can be 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.**

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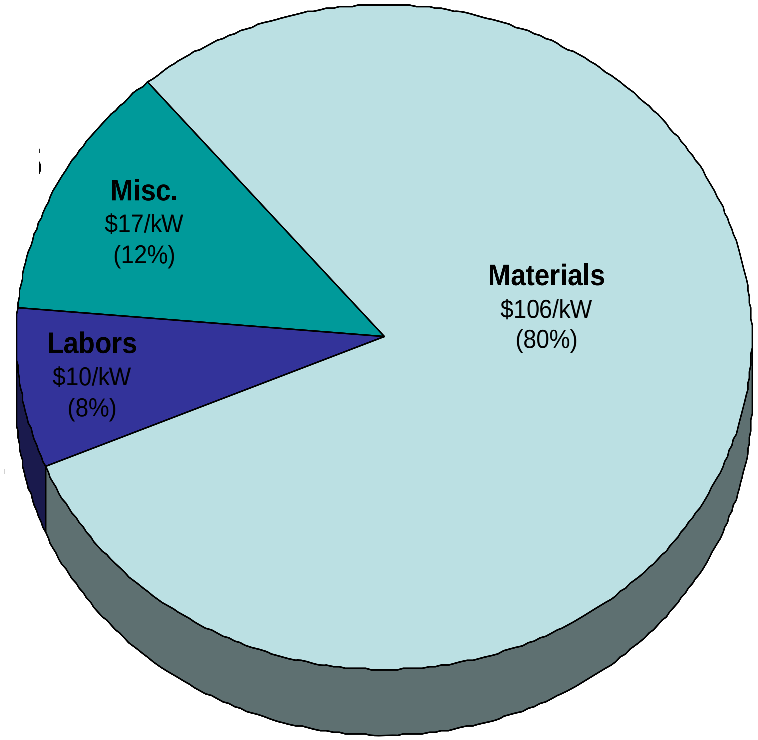
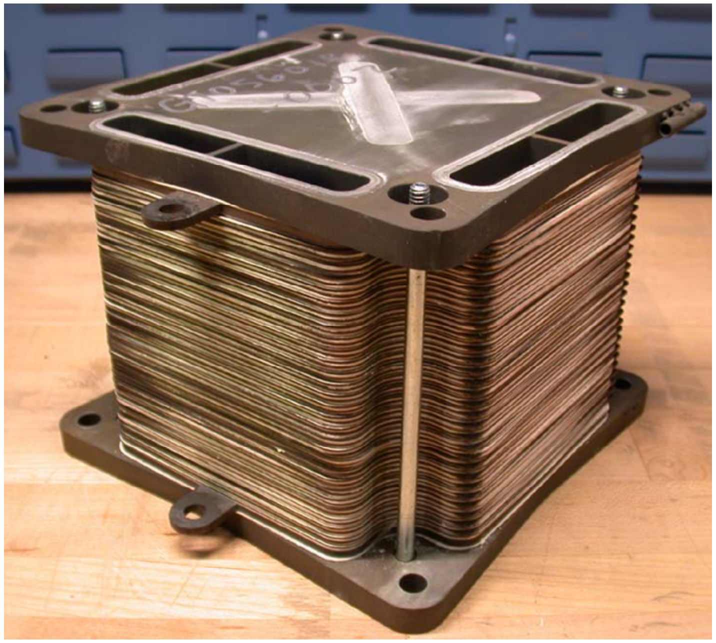
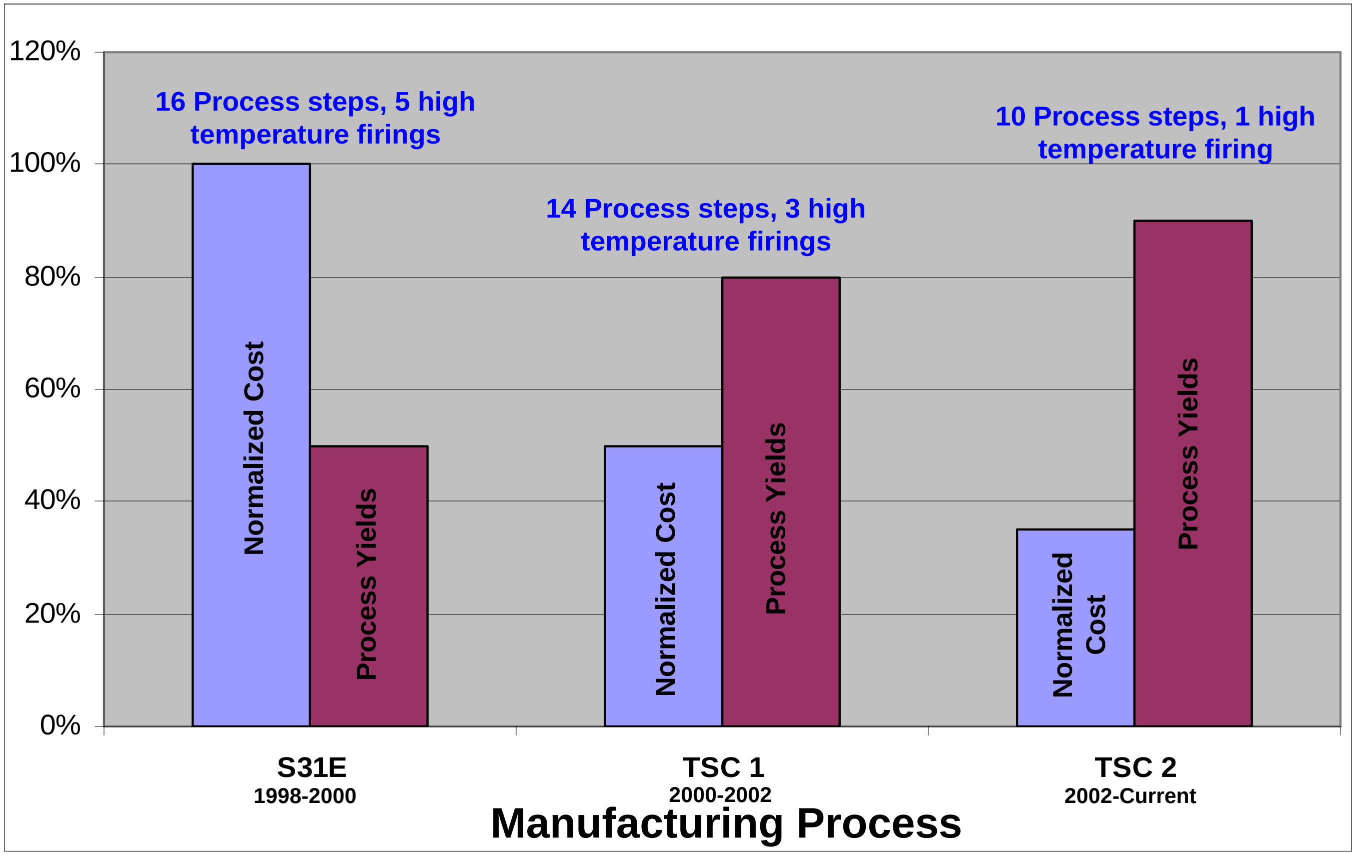
Stack Cost by Category





- 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.

Cell Manufacturing Process Improvements



The "TSC" process is a fully integrated cell manufacturing process. The "TSC" process has proven to be cost effective with high yields and excellent quality.

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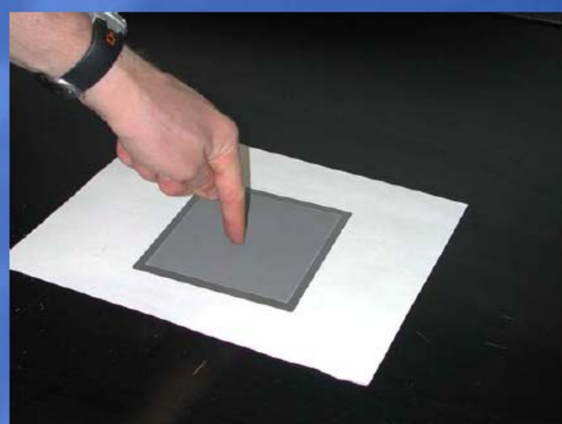
SOFC Active Component Cost Reduction

Thin Cell Development

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

Used as basis for SECA Phase I Factory Cost Estimate → 0.6 mm



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

2000 - 2002

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

2002 - 2004

2004 - 2006

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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Cost Auditor's Comment

"VPS is the only SECA team that has a production-scale cell production line using the same processing parameters as would be used in a commercial plant. Their experience and its translation to production cost in this cost report confirms DOE's belief that stack cost need not be a bottleneck to cost reduction for planar-supported SOFC, even at the current level of power density and production".

Tape Cast

Screen Print

Co-Fire

The "TSC" SOFC Cell Production Process

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SECA Phase I

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

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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 years): **SOFC Stack Components and Design**

- Scale-up SOFC cell area and stack size (number of cells), improve cell/stack performance (power, efficiency)
- Initiate SOFC manufacturing capacity development to meet Phase II & III program production requirements.
- Conduct preliminary engineering design and analysis for multi-MW power plant systems.
- Test demonstrate a scaled-up size SOFC stack building block unit that is representative of a MW class module on simulated coal syngas.

Phase II (2 years): **MW Scale SOFC Stack Module**

- Continue cell/stack scale-up and performance improvements, manufacturing capacity development to meet Phase II & III program production requirements.
- Design, fabricate and test a MW class SOFC module on simulated coal syngas (building block for multi-MW power plants).
- Conduct detailed design engineering and cost analysis for multi-MW power plant systems
- Finalize proof-of-concept power plant design

Phase III (5 years): **Multi-MW Scale Hybrid Demonstration (~5MW)**

- Fabricate a proof-of-concept (POC) system integrated with a coal gasifier.
- POC system will be an embodiment of the Baseline (>100MWe) system design.
- Conduct long-term tests (25000 hours) at FutureGen site or other suitable SECA selected site.

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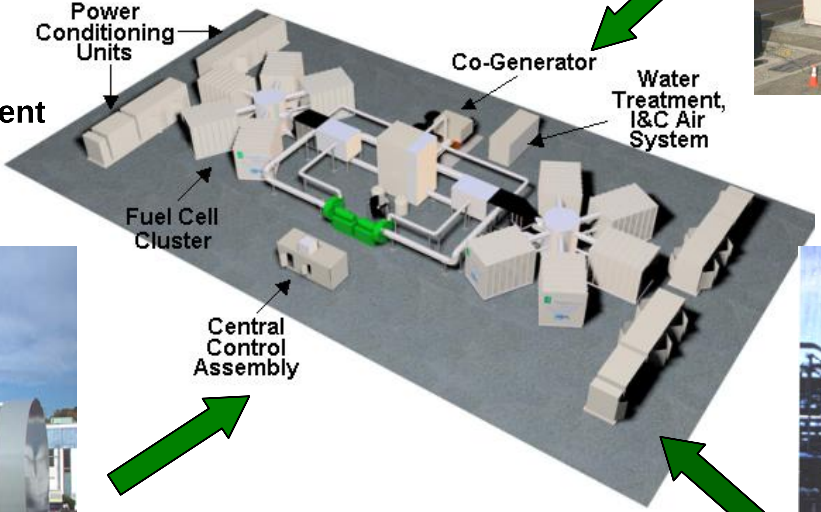
SECA Coal-Based, Multi-MW SOFC/Hybrid Power Plant Development

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

FCE MW Class Fuel Cell Product Development
DOE PDI

MULTI-MW SOFC/HYBRID POWER PLANT CONCEPTUAL DESIGN



FCE High Efficiency Hybrid Fuel Cell–Turbine Product Development
DOE Vision 21

20kW DFC Operating on Destec Coal Syngas (4,000 hours)
DOE-EPRI (1990-1991)

The FCE team's experience is ideally suited to development of a high efficiency, low emissions multi-MW SOFC power plant using coal derived fuels.

The FCE Team

The FCE team is comprised of organizations with expertise in key functional area's:

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 Can.
- Power control and conditioning systems.

SECA Coal-Based Program Work Breakdown Structure

VPS Technical Lead
Eric Tang

- **Task 1 SOFC Cell Development**
  - 1.1 Design Develop. & Optimization
  - 1.2 Manufacturing Process Development & Fabrication
  - 1.3 Testing & Validation
- **Task 2 SOFC Stack Development**
  - 2.1 Stack Design
  - 2.2 Stack Components Development
  - 2.3 Fabrication & Testing
  - 2.4 Module Concept Development

FCE Technical Lead
Hossein Ghezel-Ayagh

- **Task 3 Baseline Power Plant Development**
  - 3.1 Conceptual System Analysis & Down Select
  - 3.2 Baseline System Definition
  - 3.3 System Analysis
  - 3.4 Cost Analysis
- **Task 4 Proof-of-Concept Development**
  - 4.1 Basic Engineering Design
  - 4.2 System Analysis
  - 4.3 Cost Analysis

FCE: Jody Doyon
VPS: Randy Petri

- **Task 5 Management and Reporting**
  - 5.1 Technical Briefings Kick-off
  - 5.2 Reporting & Deliverables
  - 5.3 Prepare Phase II Renewal Application
  - 5.4 Final Report Preparation

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

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Tasks 1 and 2 Technical Approach and Status Overview

Cell and Stack Development

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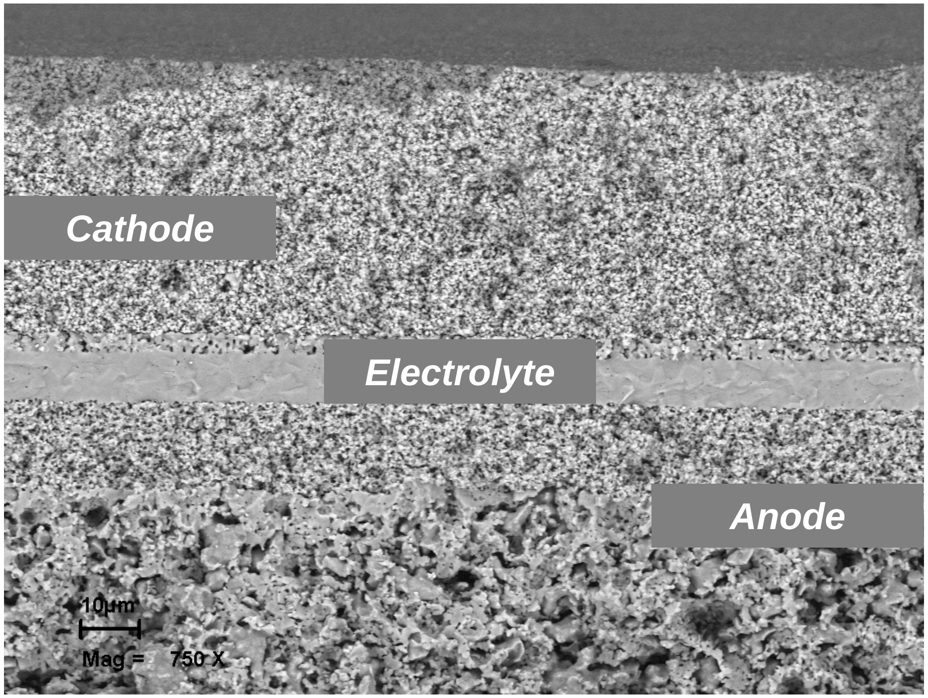
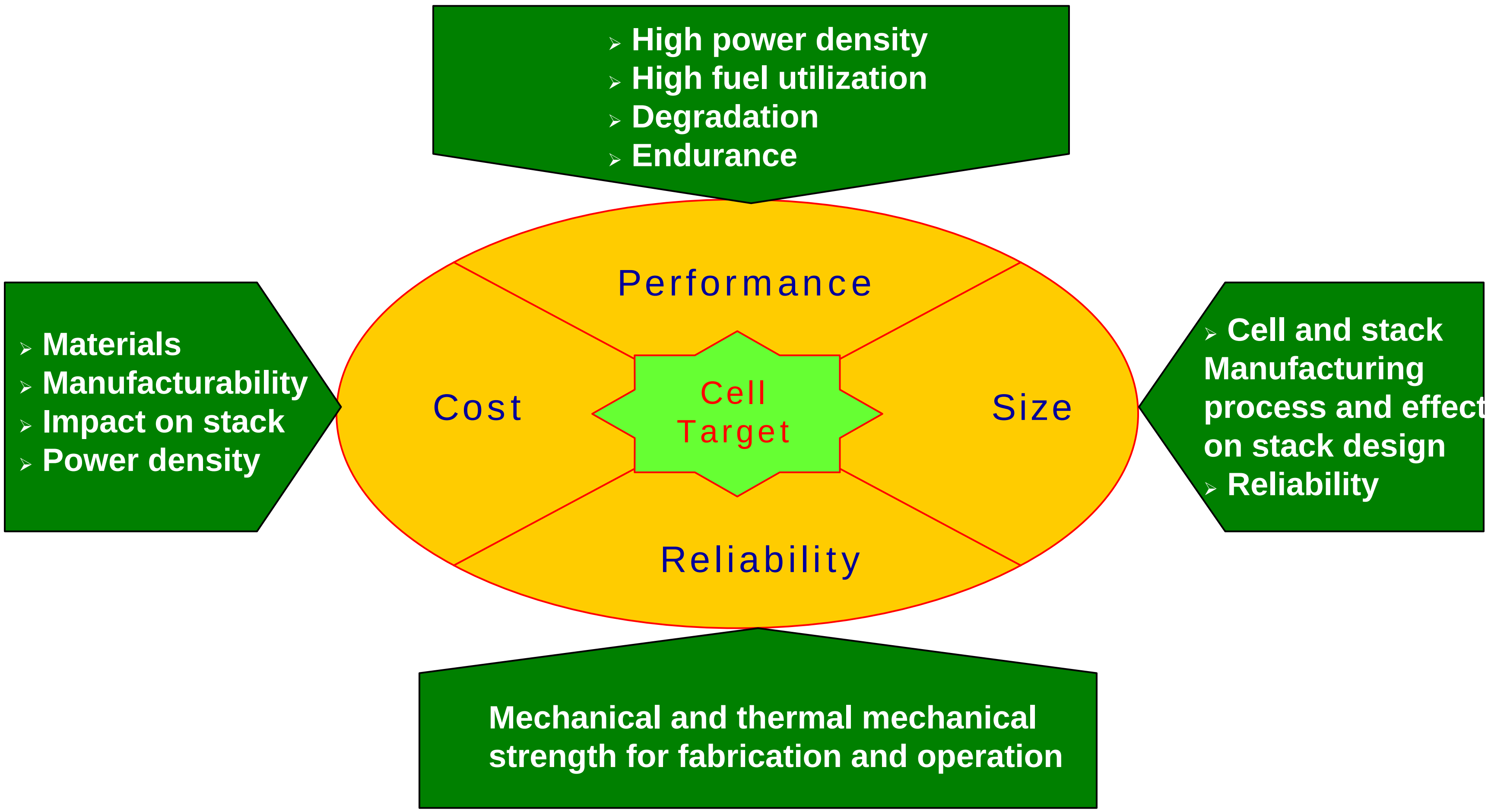
Baseline VPS Cell Technology



- *Anode – nickel-zirconia cermet*
- *Electrolyte – yttria-stabilized zirconia (YSZ)*
- *Cathode – conducting ceramic*

Anode supported planar cell design consists of conventional SOFC active component materials.

Cell Technology Gap Analysis



Cell technology development is a multi-dimensional challenge that will require a multi-faceted approach.

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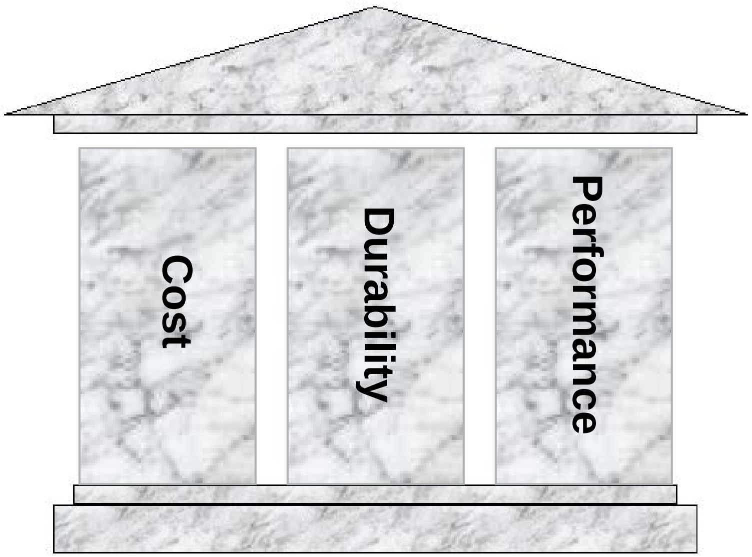
Cell and Stack Development Approaches



Three pillars for success!

- Enhance operating temperature windows
- Reduce average operating temperature
- Enhance cell performance
- Enhance mechanical strength
- Enhance thermal mechanical strength
- Scale-up cell process technologies
- Reduce cell manufacturing cost
- Improve endurance at both steady state and transient conditions

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Development Highlights

- **Cell Development for Improved Performance** (key to reduce cost, improve endurance and increase efficiency):
  - Cell voltages of 870mV was demonstrated at 0.5A/cm^2 / 50% Uf / 25%Ua / 750°C with humidified hydrogen in single-cells containing high performance components (HPC).
  - Stability of the high performance cells were tested between 650 to 750°C for over 1000 hours.

- **Cell and Stack Scale-Up**
  - Active cell components of up to 1090cm^2 have been successfully manufactured by the TSC process.
  - Pilot production batches of 625cm^2 scaled-up area cell components were produced to evaluate the repeatability of the TSC process.
  - Single cell tests of 400cm^2 scaled-up area cell components have been conducted to evaluate the cell performance at steady-state and transient conditions.

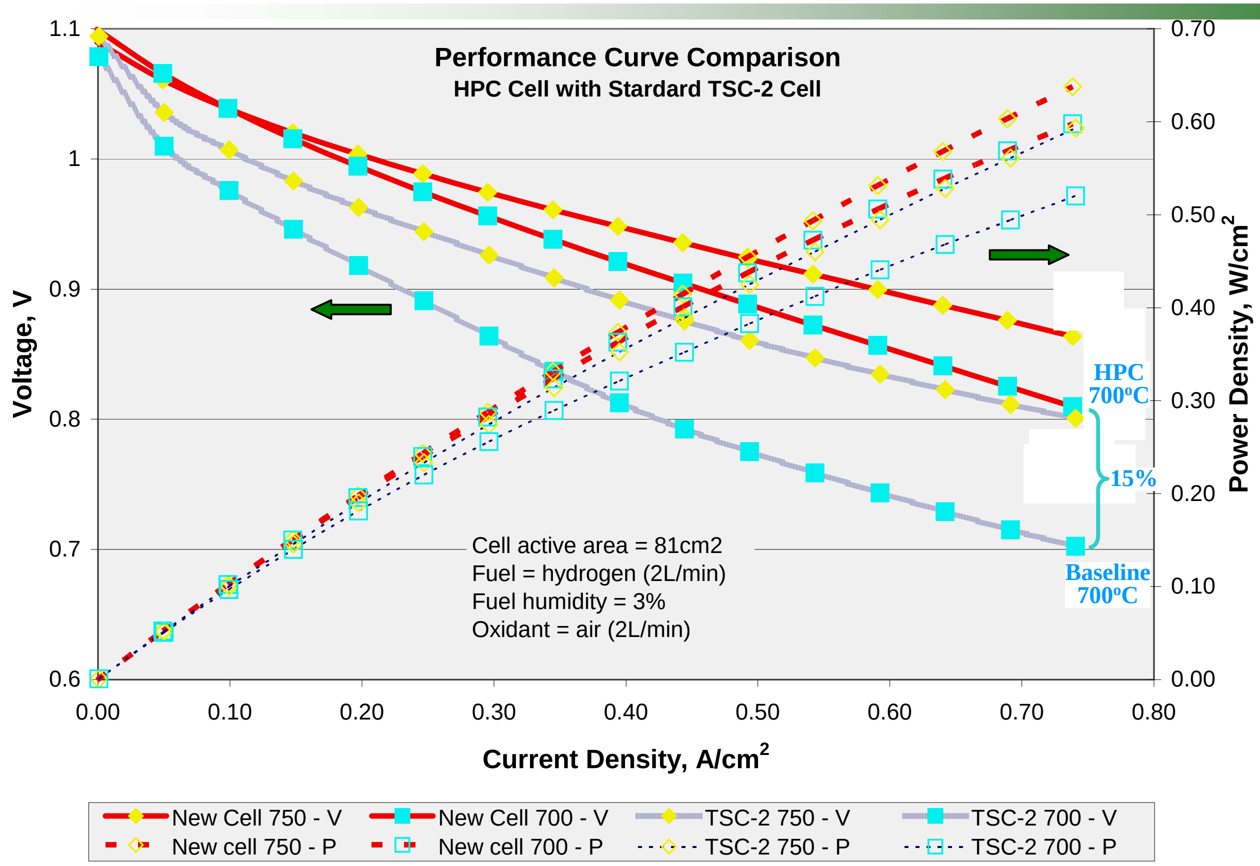
Performance Improvement Accomplishments

	Start Voltage at 750°C, 0.5A/cm^2	Peak Voltage at 750°C, 0.5A/cm^2	Performance gain from baseline	Degradation rate per 1000 hrs	Testing Duration
101567	855 mV	857 mV	5.8%	9 mV	3,188 hrs
101570	858 mV	858 mV	5.9%	14 mV	1,873 hrs
101571	865 mV	871 mV	7.5%	12 mV	2,682 hrs
TSC II Baseline	810 mV	810 mV	--	11 mV	26,000 hrs

Cost: Higher power density per unit active area
Life: Less thermal management issues in stack
Efficiency: Better electrochemical efficiency

Single cell testing of high performance components (HPC) show a potential performance gain of 6-8%. Stack test verification is planned.

Low Temperature Cell Performance



New high performance components show significant voltage improvement at lower SOFC operating temperatures:

- **8% performance improvement at 750°C as compared to baseline cell components.**
- **15% performance improvement at 700°C as compared to baseline cell components.**

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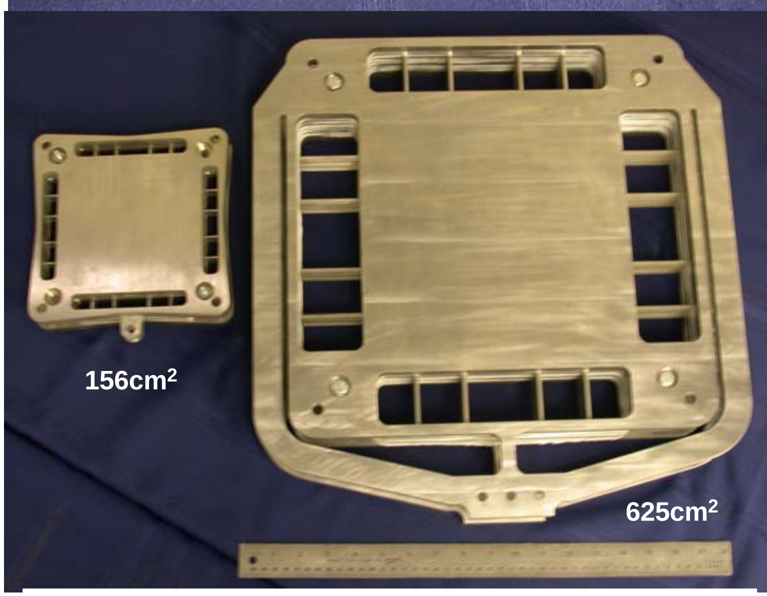
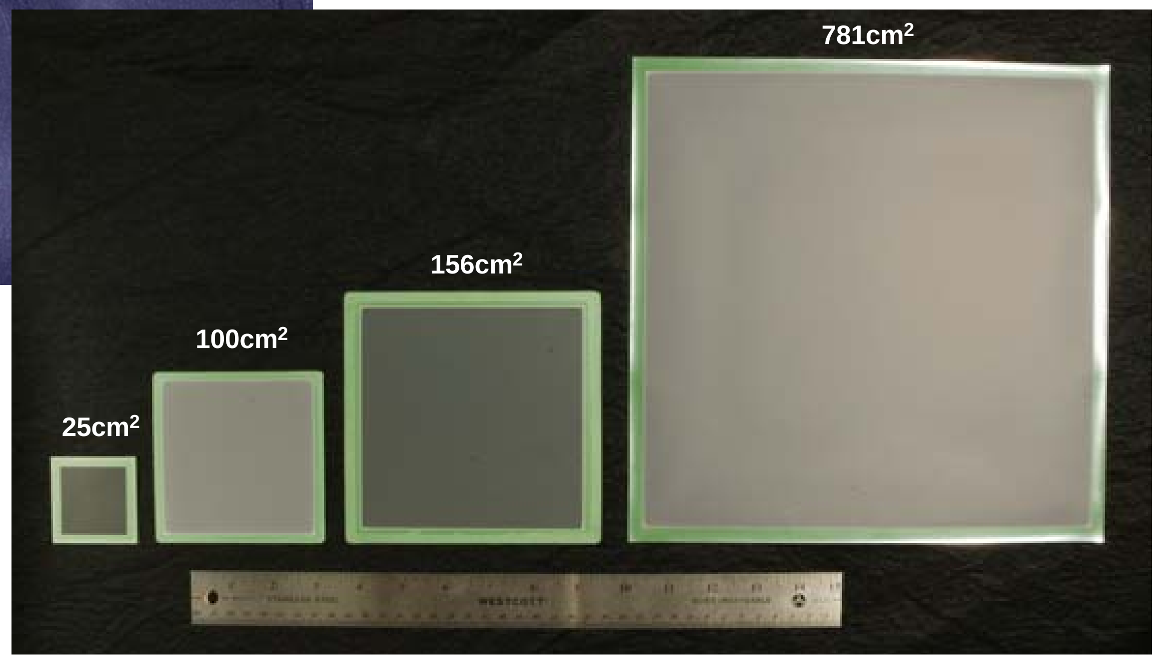
Cell & Stack Scale-up

Cells up to 1090cm^2 have been produced by the baseline cell manufacturing process (TSC II)



Short Stack Assemblies



Cell Tri-layer Component Scale-up

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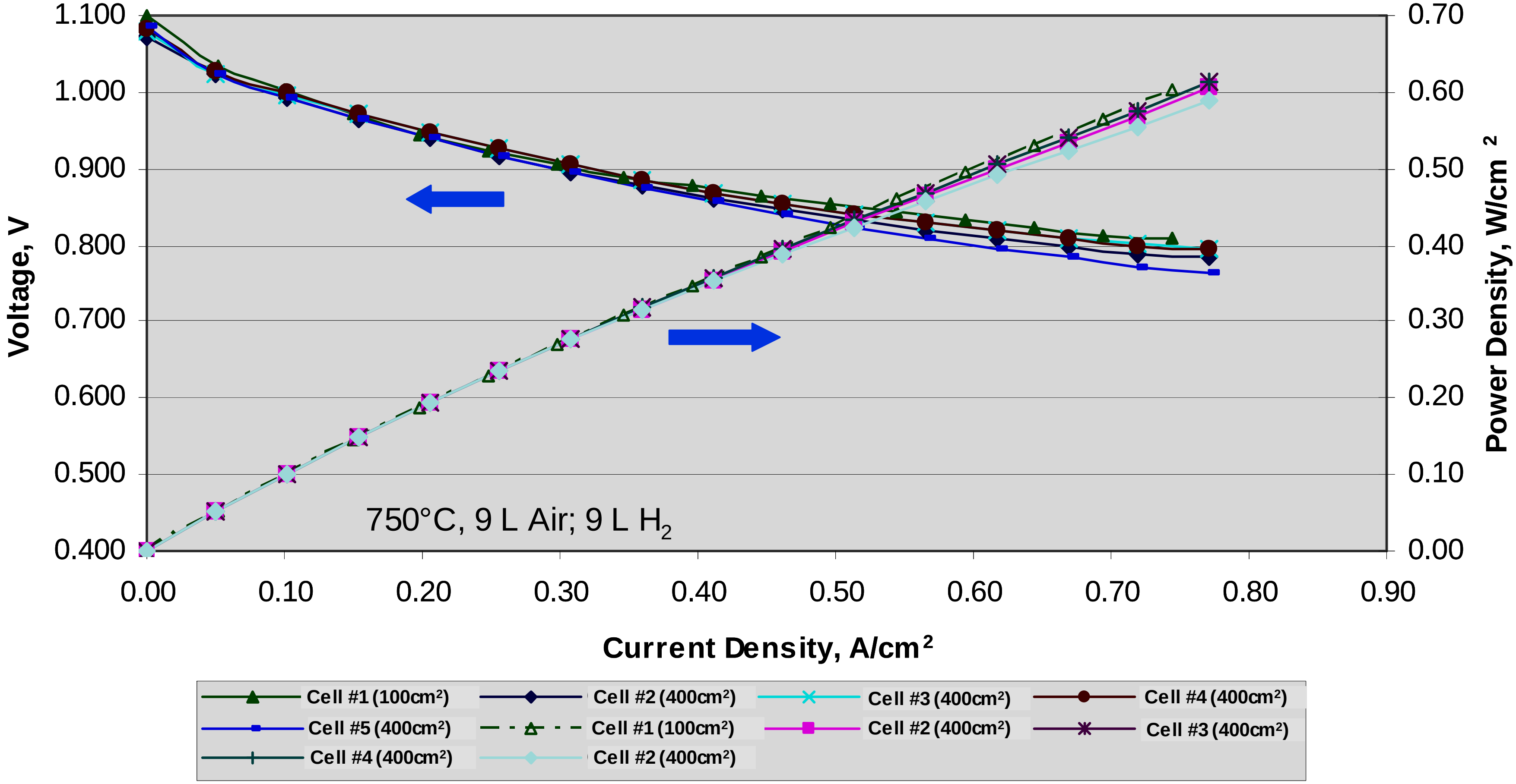
Single Cell Performance Reproducibility of Scaled-up Components



- **No electrochemical performance loss in single cell tests from four-times scale-up in cell active area.**

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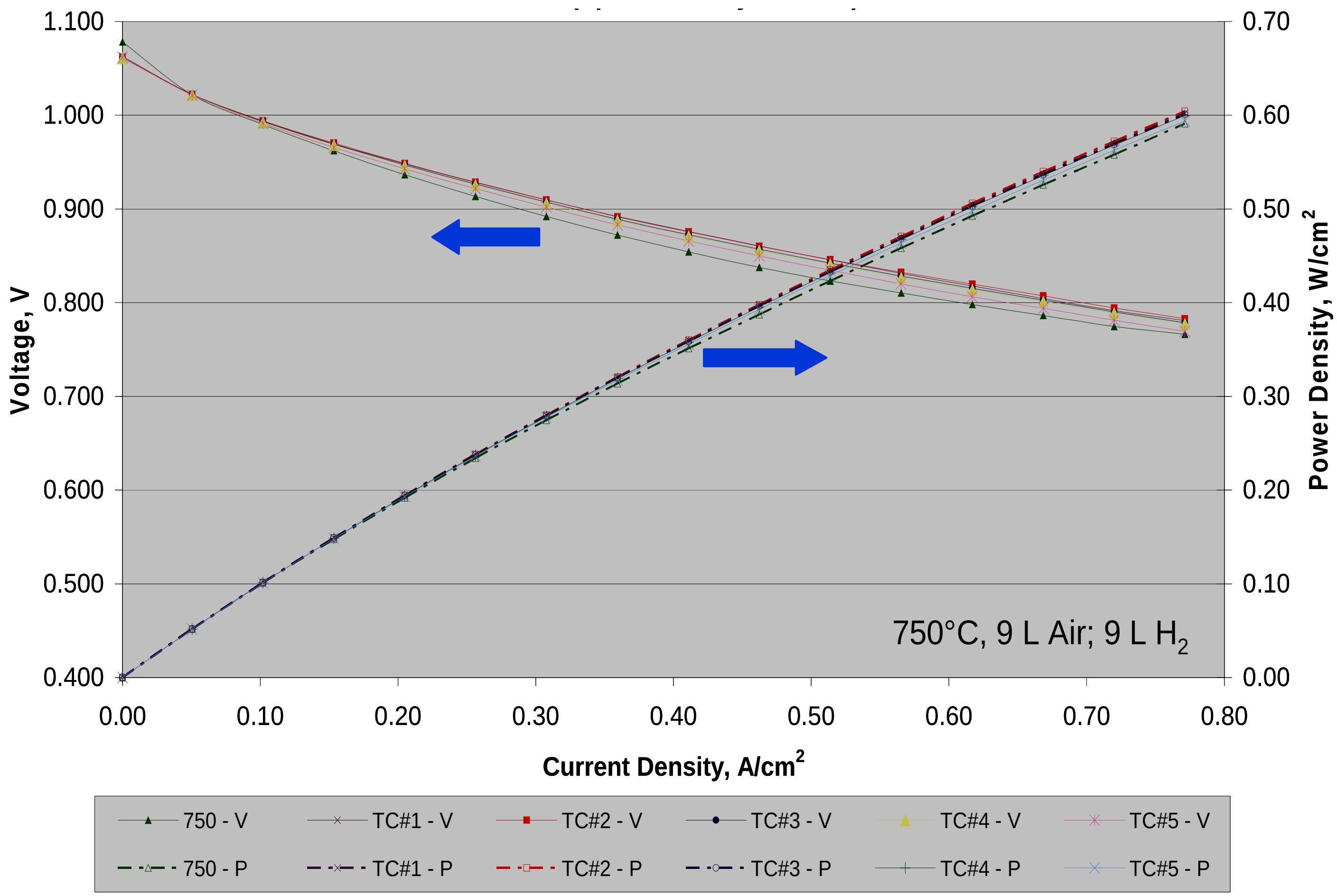
Scale-Up Cell Thermal Cycle Testing



- **Single cell thermal cycle testing of scale-up (400cm²) cell components indicate good durability and reliability.**

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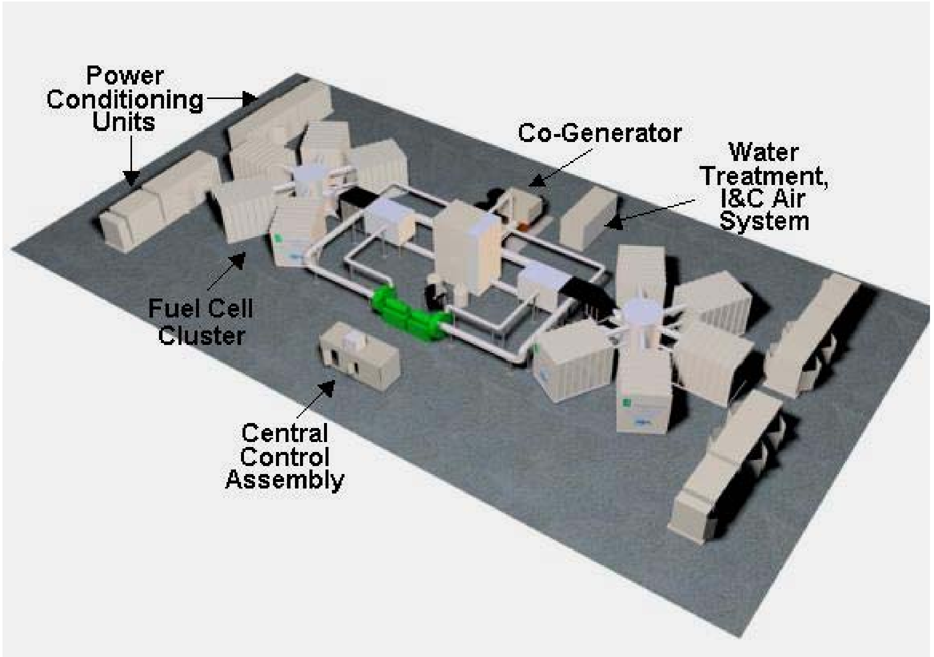
SOFC Stack Development
Technical Approach

Phase II Coal Based Program
(MW Demonstration)

- MW Module Development
- Performance Improvement
- Manufacturing Capacity Development
- Cost Reduction

Phase III Coal Based Program
(Multi-MW Demonstration)



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 or other SECA site.

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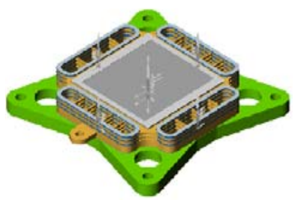
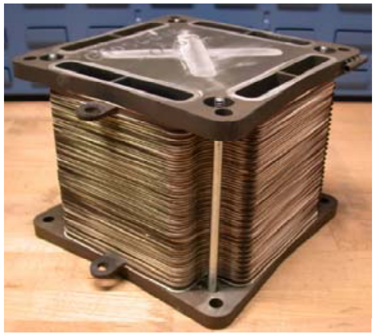
Stack Development Path

Component Development

Stack Engineering Integration



- Cell
- Seal
- Interconnect
- Contacts
- Current Collection
- Flow Management
- Thermal Management
- Manufacturability
- Repeatability
- Tolerance



Technology Development

Stack Manufacturing Process Development

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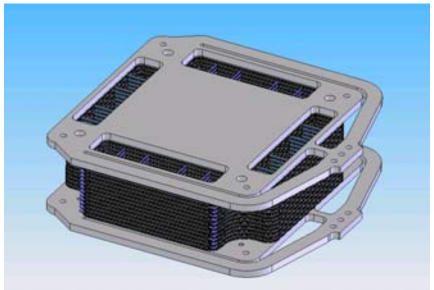
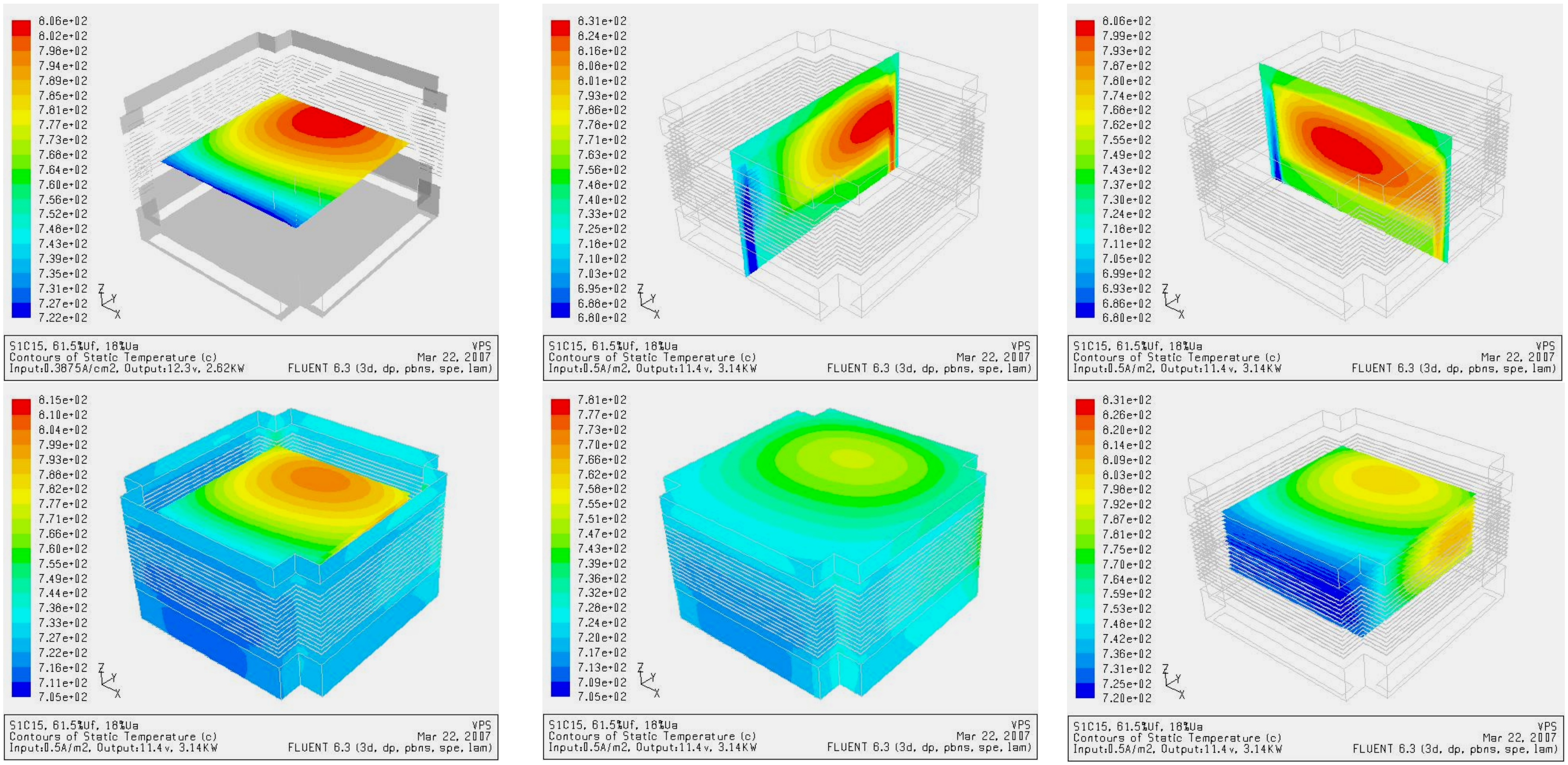


Stack Modeling



➢ **Detailed 3-D computational stack modeling is being conducted at FCE, VPS and PNNL. This will provide input and direction to the detailed scaled-up stack design.**

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Stack Design Thermal Management Targets

Index	Threshold	Target	Ideal	Notes
Tmax (°C)	850	800	800	Maximum temperature in stack limited by metallic components
Tmin (°C)	600	650	700	Minimum temperature in stack limited by cell electrochemical performance
dT (°C)	250	150	100	On cell (in x and y directions) temperature gradient limited by thermal-mechanical stress
dTz (°C)	150	100	50	In stack (z direction) temperature gradient Limit by stack operating conditions

- **Stack modeling analysis coupled with cell and stack test verification has enabled the specification of key temperature parameters.**

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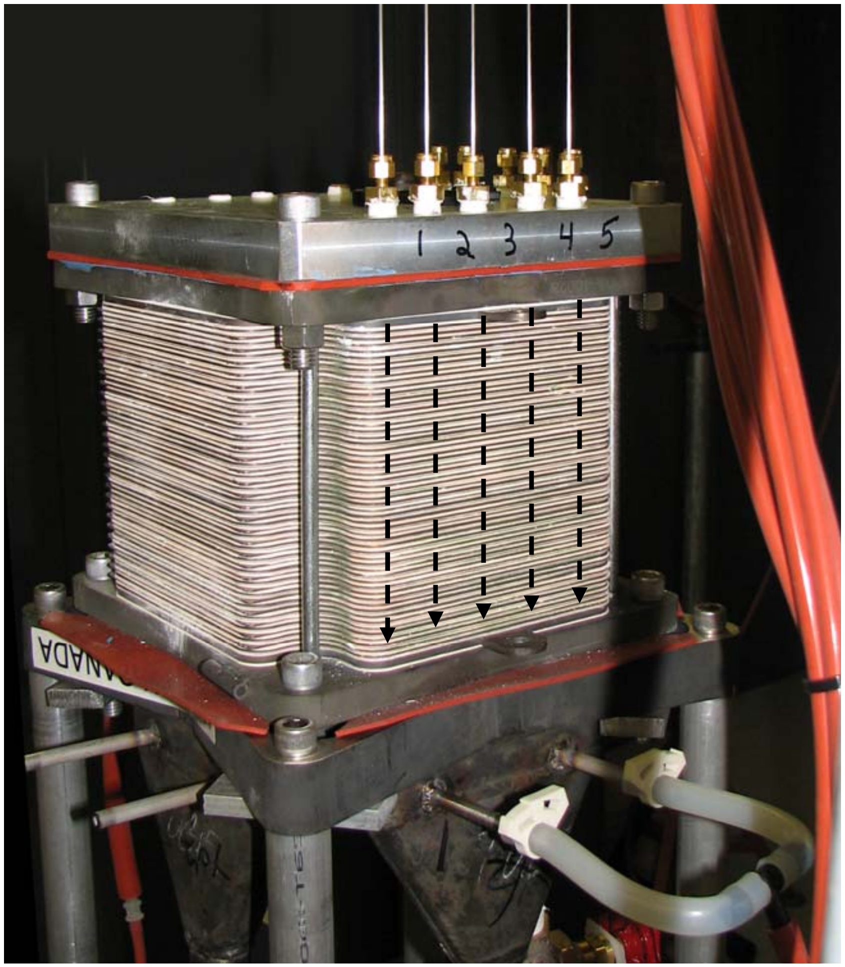
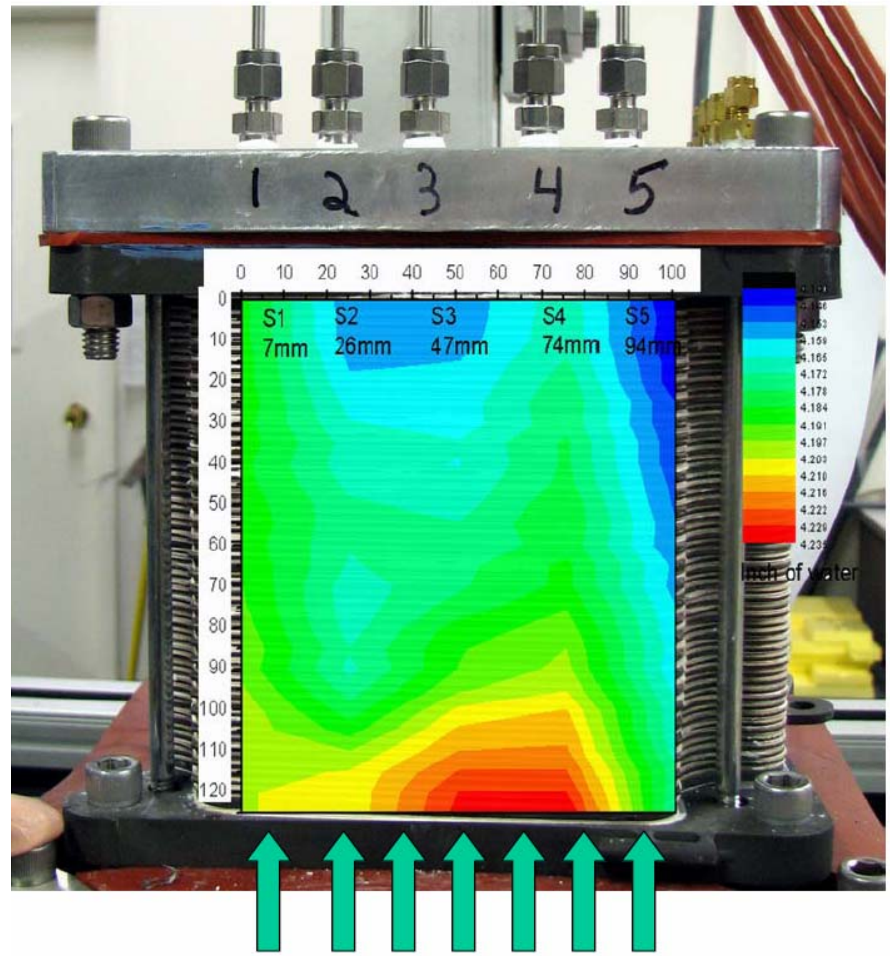
SOFC Stack Manifold Flow Uniformity Analysis





- Apparatus to measure manifold flow uniformity of a SOFC stack has been designed and validated on current baseline stacks. This will be used for quantitative analysis of scaled-up stack component designs.

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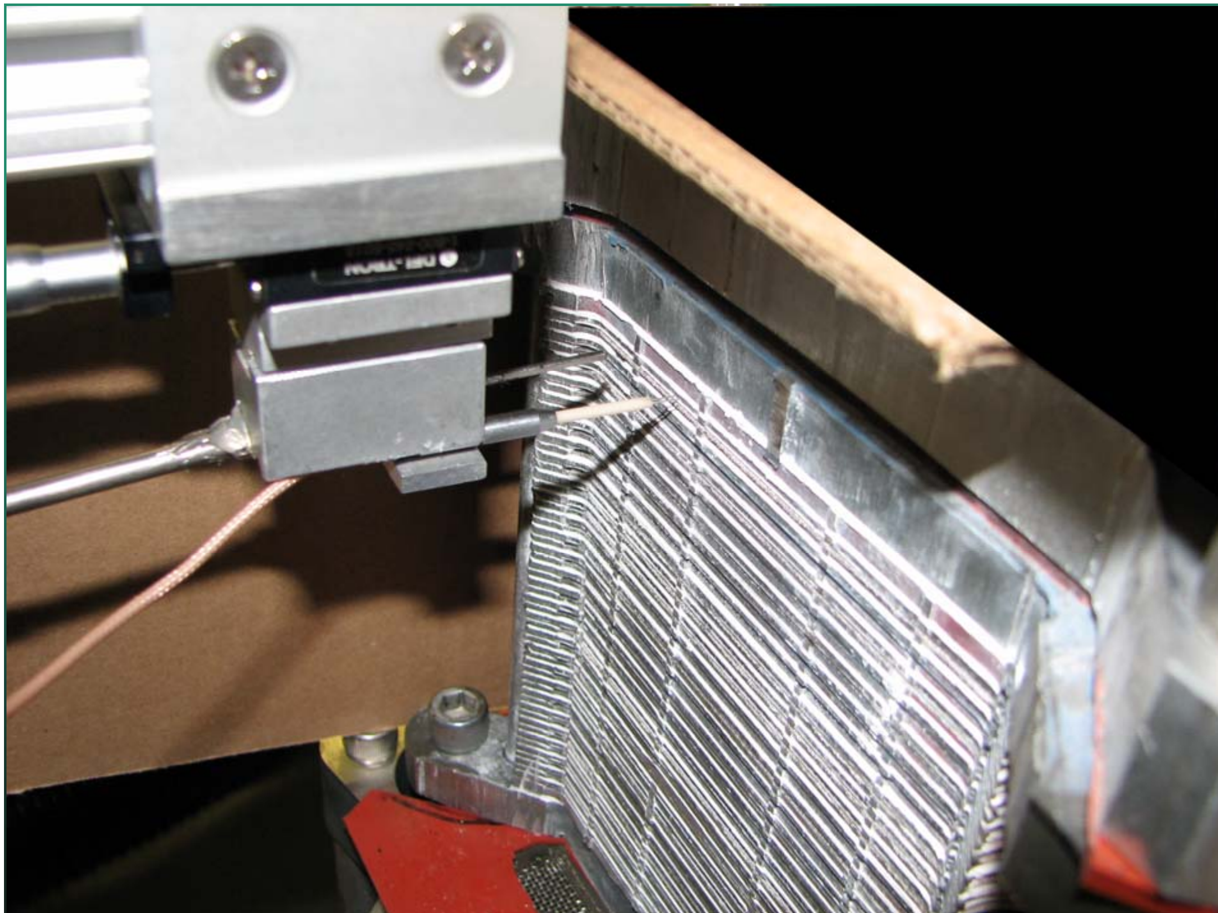
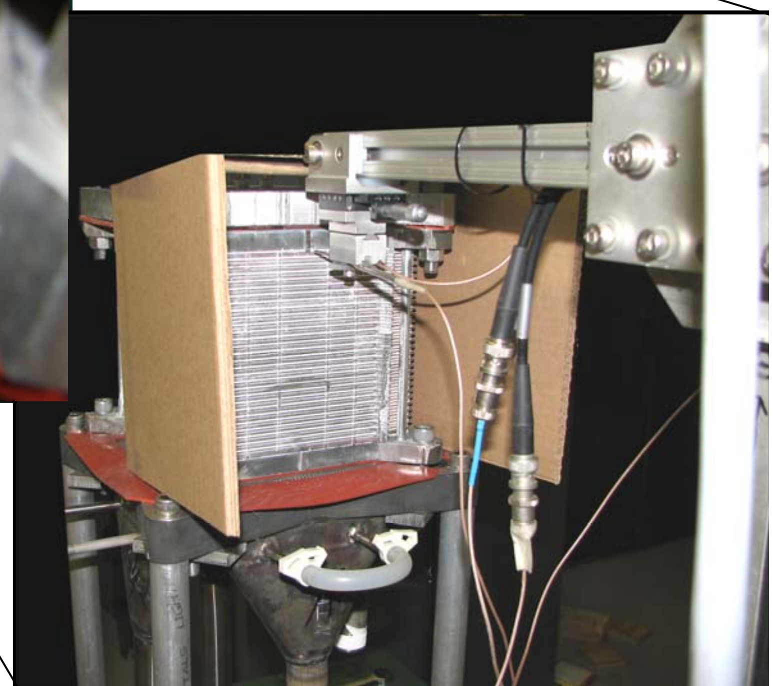
Cell-To-Cell Flow Uniformity Analysis Within a SOFC Stack





- **Hot Wire Anemometer Apparatus set-up for cell-to-cell flow uniformity analysis within a scaled-up SOFC stack**

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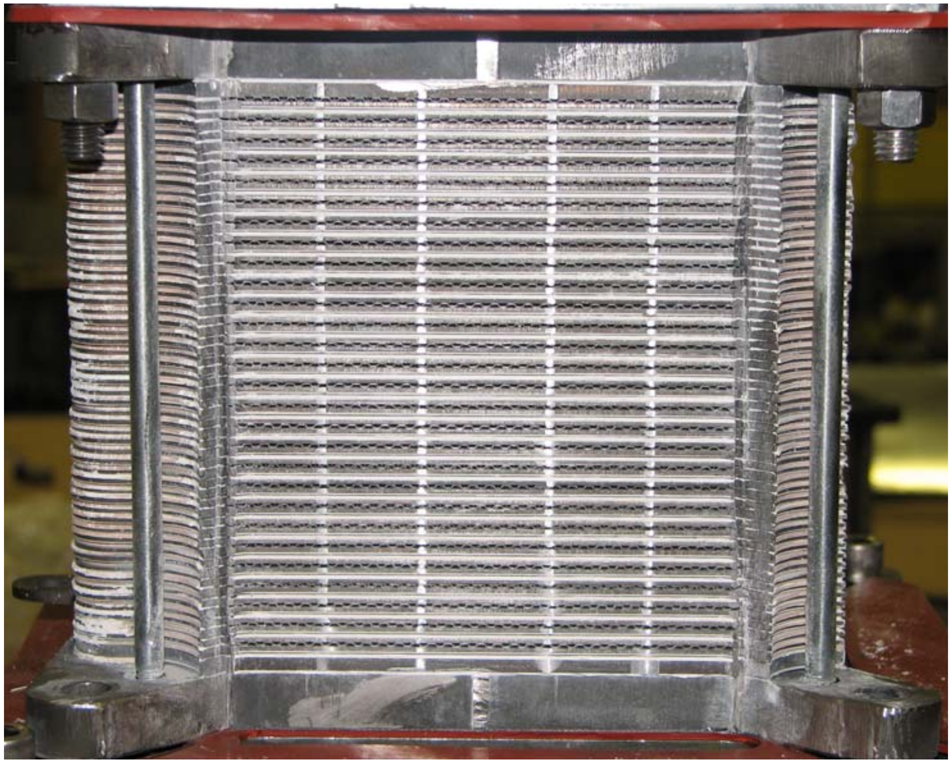
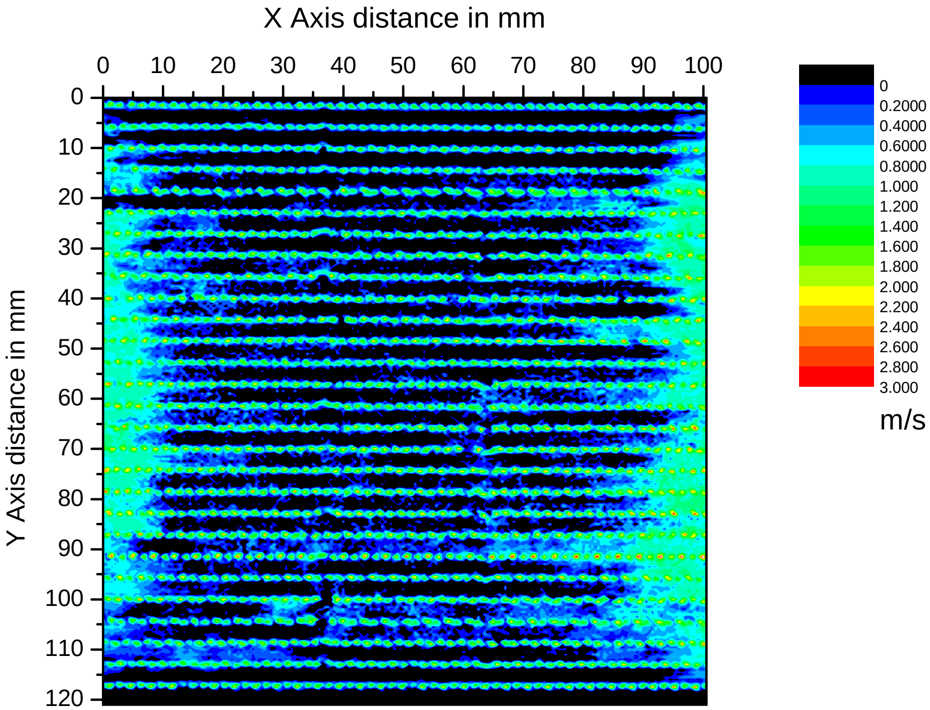
Cell-To-Cell Flow Uniformity Analysis Within a SOFC Stack





Flow is 160 lpm, Wire is vert,stack 104, cathode out side

- **Apparatus to measure cell-to-cell flow uniformity within a SOFC stack has been validated on current baseline stacks. This will be used for quantitative analysis of scaled-up component designs.**

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Tasks 3 and 4 Technical Approach and Status Overview

Baseline and Proof-of-Concept Power Plant Development

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Tasks 3 & 4 – Scope of Work Overview

- **Baseline power plant development:**
  - > Define power plant size
  - > Downselect major processes/subsystems
  - > Lead development of preliminary engineering package
  - > Generate preliminary grade cost estimate
  - > Generate the System Analysis documentation for DOE/NETL review
- **POC power plant design:**
  - > The POC power plant will be an embodiment of the Baseline Power Plant design.
  - > Define size based on the down selected Baseline power plant
  - > Lead development of basic engineering package
  - > Generate preliminary grade cost estimate
  - > Generate System Analysis documentation for DOE/NETL review

System and BOP Technical Approach

Improved Gasification and Cleanup Technologies → Design of Fuel Cell Power Island → Integration of Advanced Turbines → 50% HHV System

Baseline (>100MWe) Advanced Coal-Based SOFC Systems

Phase III SECA Proof-of-Concept

- The SECA Program Phase III 5MW SOFC power plant system demonstration will be an embodiment of the Baseline >100MWe power plant system.

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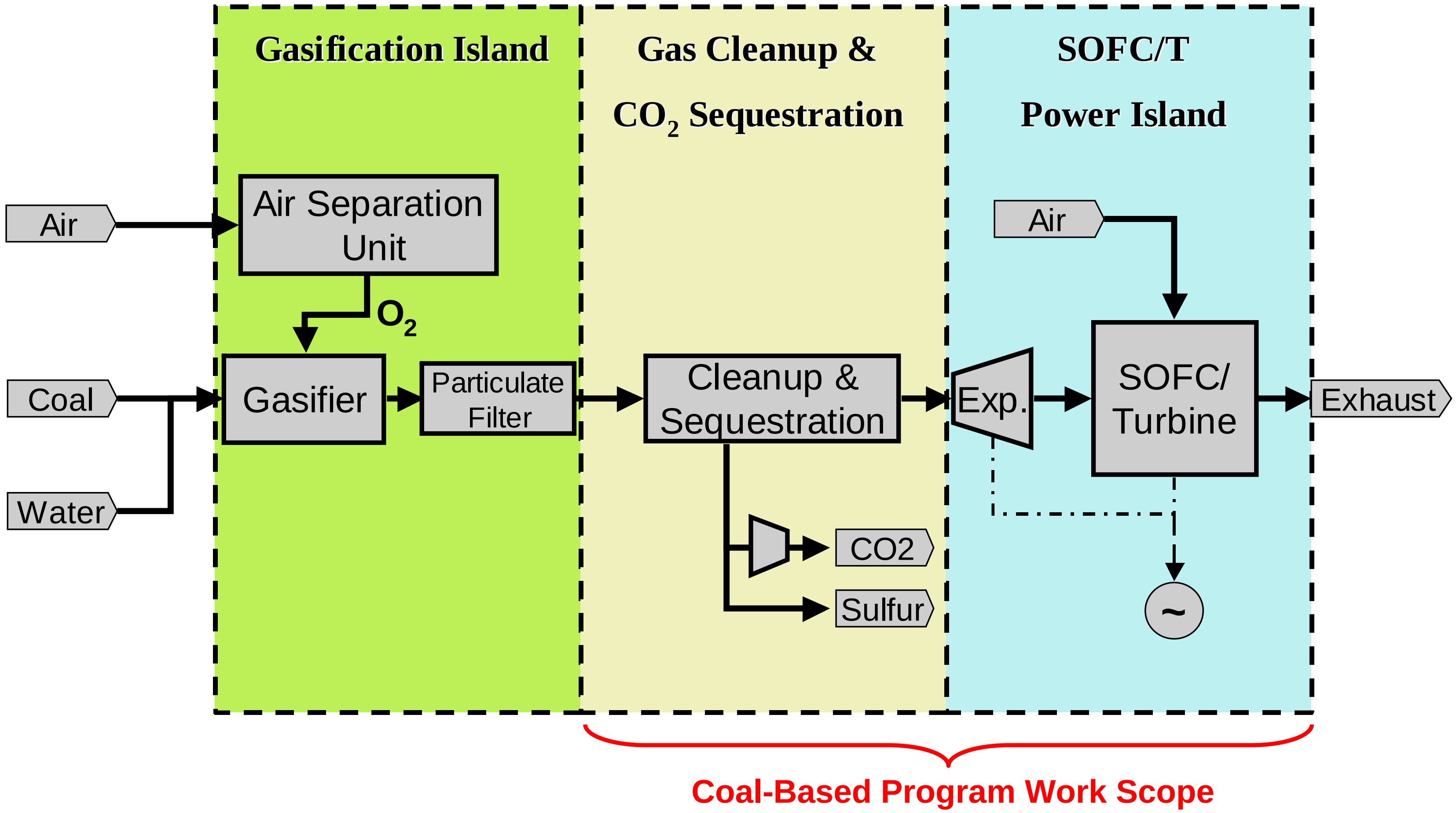
Coal-Based Hybrid SOFC-Turbine Simplified System PFD



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

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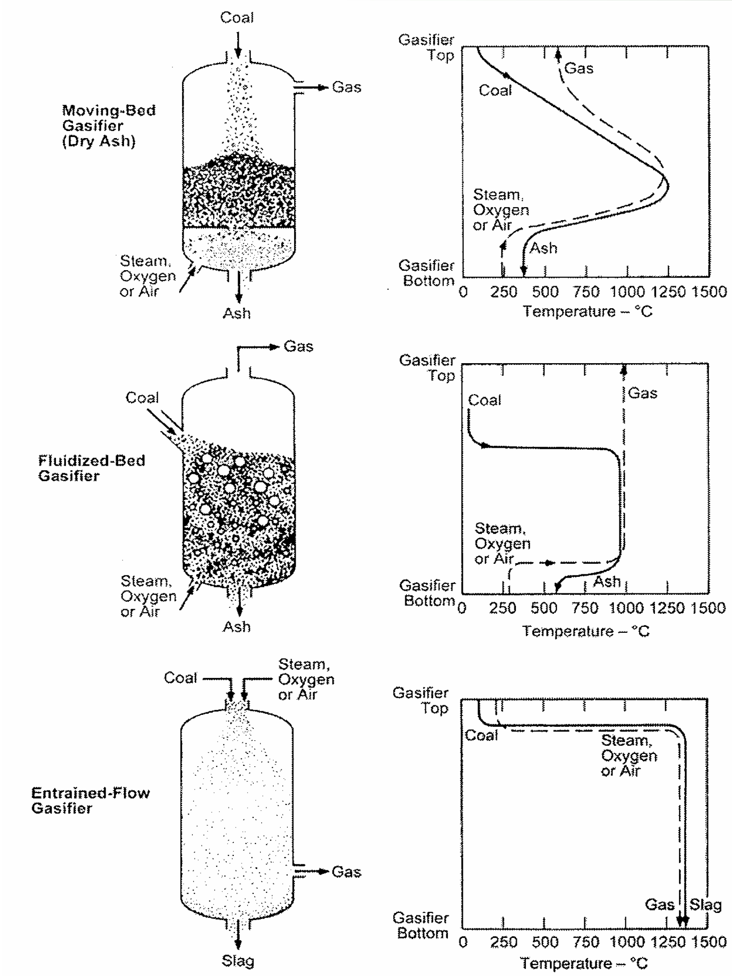
Gasification Technologies Being Considered



- **Moving-Bed**
  - > **Lurgi**
  - > **BGL**
- **Fluidized Bed**
  - > **High Temp Winkler**
  - > **Transport (KBR)**
- **Entrained-Flow**
  - > **ConocoPhilips (CoP)**
  - > **Shell**
  - > **General Electric (GE)**
  - > **Koppler Totzek (KT)**

➢ **Engineering analysis in progress to evaluate and down select preferred system option with respect to cost, efficiency and carbon capture complexity.**

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Acid Gas Removal Technologies Under Evaluation

> **Physical Absorption (molecular solvation)**
  - » Rectisol (Linde)- uses methanol
  - » Selexol (UOP) –uses DIEPG
    (dimethyl ether of polyethylene glycol)

> **Chemical Absorption (ionic solvation)**
  - » Ucarsol (Dow Chemical Company) - uses MDEA
    (methyldiethanolamine)

> **Hybrid Absorption**
  - » Sulfinol (Shell) – uses DIPA (di-isoproponalamine)
  - » FLEXSORB (Exxon-Mobil) - uses a hindered amine

> **All are Commercial, Low-Temperature, Regenerable Liquid Solvents.**

➢ **Analysis in progress to evaluate and down select preferred system option with respect to cost, efficiency and carbon capture efficiency.**

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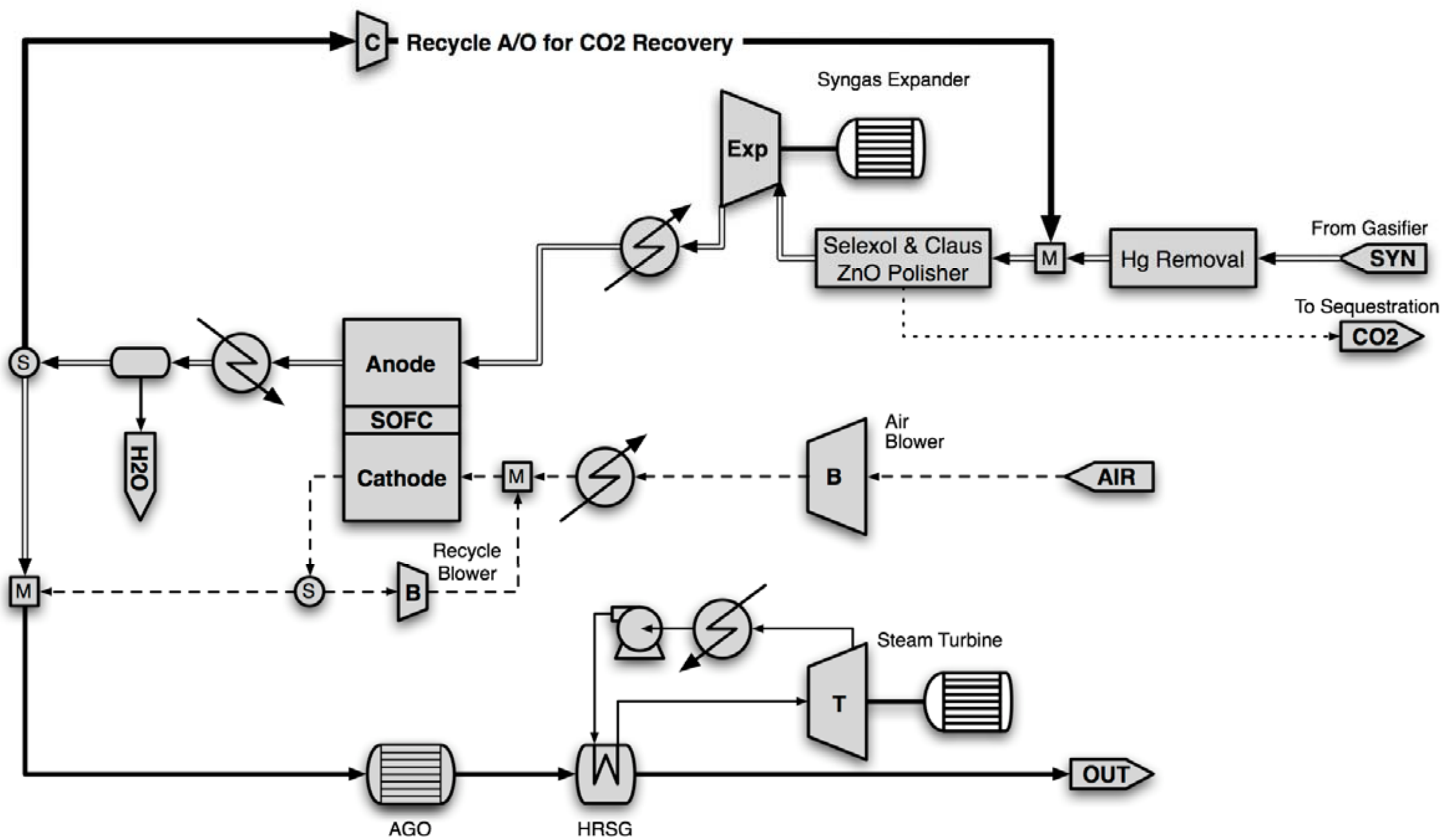
Fuel Cell - Turbine Combined Cycle System



Fuel cell power blocks enable simplified system designs with high efficiencies, >90% carbon capture and no emissions.

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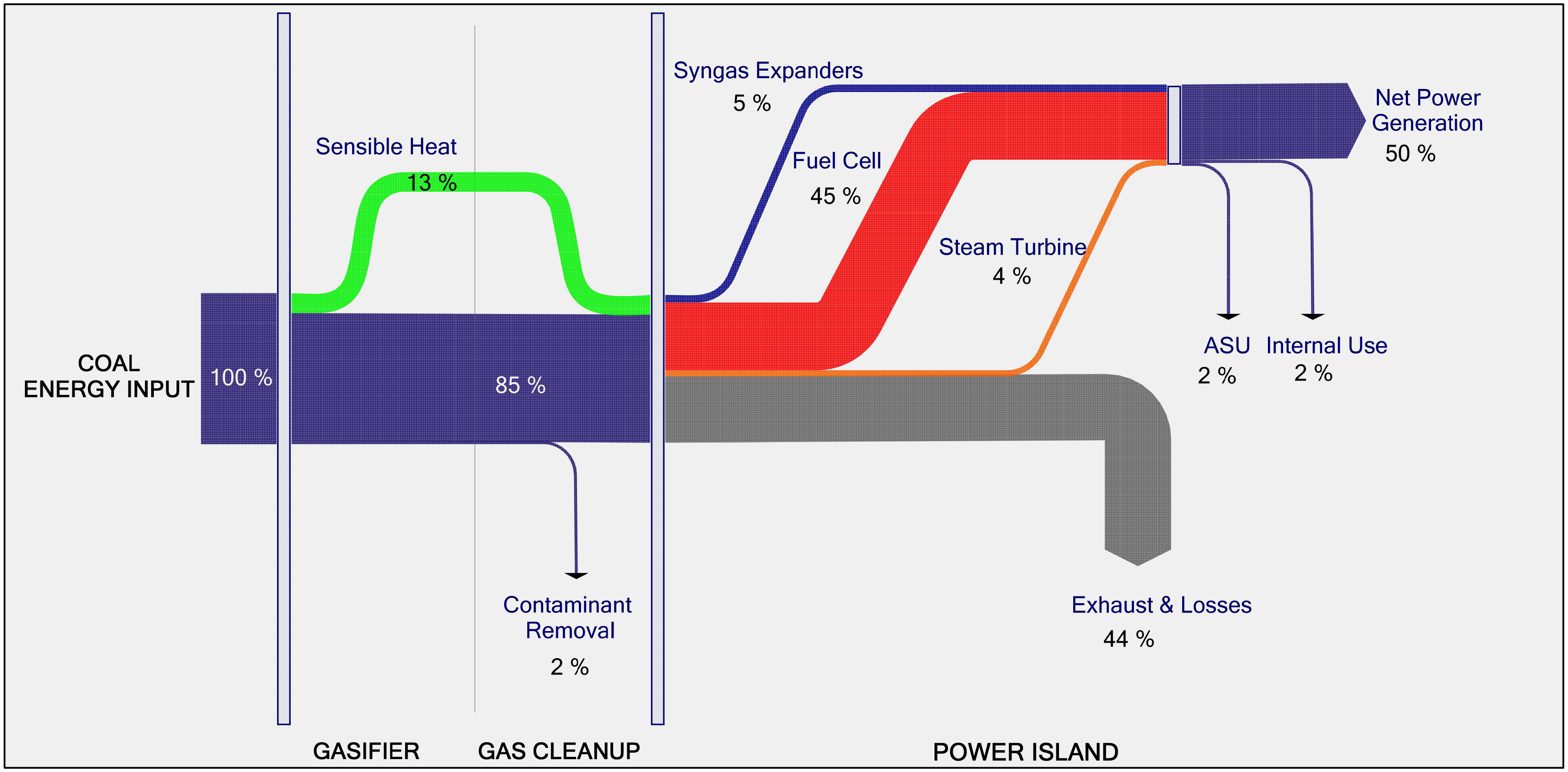
Estimated Energy Flow Diagram



Unlike conventional IGCC where the turbine is the prime mover producing ~60-70% of the net power generated, with IGFC, the fuel cell is the prime mover producing ~90% of the power output.

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FutureGen Readiness

Based on our experience with high temperature fuel cells, combined cycle systems and coal-based syngas testing, the FCE team sees no technical barriers and is confident that it can meet the objectives of the SECA program to be ready for the FutureGen demonstration.

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Acknowledgements

The support and guidance provided by the Department of Energy is acknowledged and gratefully appreciated by the FCE team, most notably Wayne Surdoval, Travis Shultz and Don Collins.

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