Solid Oxide Fuel Cell Program
at
FuelCell Energy Inc.

10th Annual SECA Workshop
Pittsburgh, PA
July 14-16, 2009

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FuelCell Energy

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Presentation Outline

- **Introduction:**
  - FCE SECA program and team members
- **SECA Coal-Based SOFC Program Outline**
- **Stack Metric Testing**
  - 10 kW Metric Test Results
  - 30 kW Stack Testing
- **MW-class Module Demonstration Unit Development**
- **Baseline (500 MW) System Design and Cost Analyses**
  - Integrated Gasification Fuel Cell (IGFC) System Configuration
  - Baseline Power Plant Cost Estimate
- **Conclusions**

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FuelCell Energy (FCE)

- Premier developer of stationary fuel cell technology
- Headquarters in Danbury, CT (USA), with 65,000 square foot manufacturing facility in Torrington, CT (USA)
- Delivering Ultra-Clean Direct FuelCell power plants to commercial and industrial customers
- Developing multi-megawatt coal power plants based on planar SOFC
- Established commercial relationships with major distributors in the Americas, Europe, and Asia

Danbury, CT – Headquarters, R&D, Stack Conditioning

Torrington, CT - Manufacturing Facility

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FCE's 40th Anniversary (1969-2009)

1969 – Led by Dr. Bernard Baker, Energy Research Corp is established as a subsidiary of Consolidated Controls in Bethel, CT to conduct research in fuel cells and high energy batteries

1976 – First carbonate fuel cell tested

1992 – ERC becomes a public company with $6.5 million IPO

1993 – First 2' x 3', 8kW field demonstration stack shipped to Elkraft (Denmark)

1993 – Production of stacks for 2MW proof of concept demonstration project begins

2008 – Began shipments of advanced DFC1500 and DFC3000 power plant design with MW-class module

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SECA Coal Based Program

Program Objectives

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

- At least 50% overall efficiency from coal (higher heating value)
- Performance to meet DOE specified metrics for power output, degradation, availability, and reliability
- Factory cost <$400/kW (2002 USD)
- Greater than 90% of carbon capture from coal syngas for sequestration
- Reduced water consumption as compared to the existing coal power plant technologies

Program Status

- **FCE team successfully completed Phase I of the Coal Based SECA Program in December 2009.**
- **Phase II work has been initiated to further the development of an affordable, multi-MW size SOFC power plant system to operate on coal syngas fuel, with near zero emissions.**

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Phase II SECA Coal-Based Team

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

FuelCell Energy Inc. (FCE), Danbury, CT

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

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

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

Pacific Northwest National Laboratory (PNNL), Richland, WA

- SOFC cell and stack computational modeling.

WorleyParsons Inc. (WP), Reading, PA

- Design of the power plant, including: integration with gasifier and syngas clean-up technologies, system level costing, and system performance analysis.

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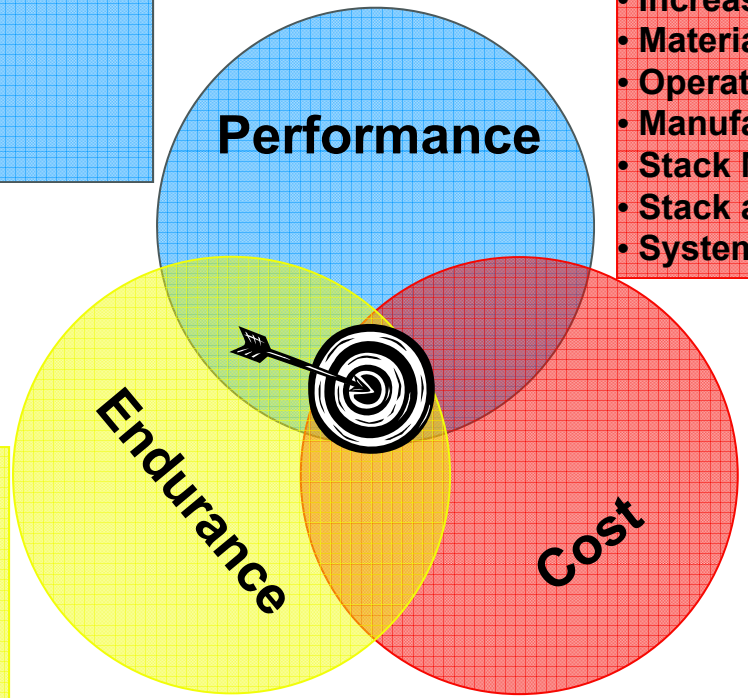
Progress Towards Achieving Project Goals

- Increased Voltage
- Increased Fuel Utilization
- Materials Selection
- Fabrication Processes
- Stack Design
- Flow Distribution
- Stack Thermal Profile



- Increased Power Density
- Materials Selection and Quantity
- Operating Temperature
- Manufacturing Process & Yield
- Stack Manifold Design
- Stack and Module Designs
- System Design

- Electrode Materials
- Interconnect Materials
- Temperature Reduction
- Stack Deign and Thermal Profile

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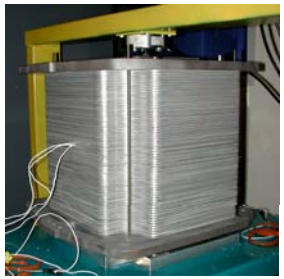
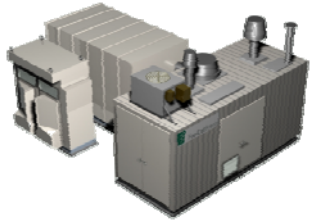
SECA Coal Based Multi-Phase Program Plan

10 kW Stack

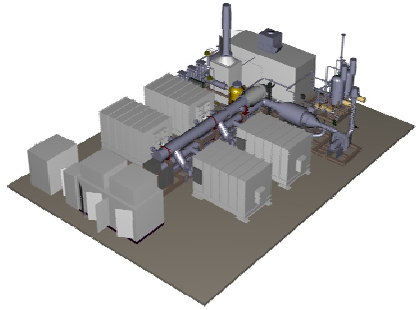


Multi-Stack Tower

≥ 250 kW Module Demonstration Unit



5 MW Proof of Concept



2008 2010 2012 2015

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

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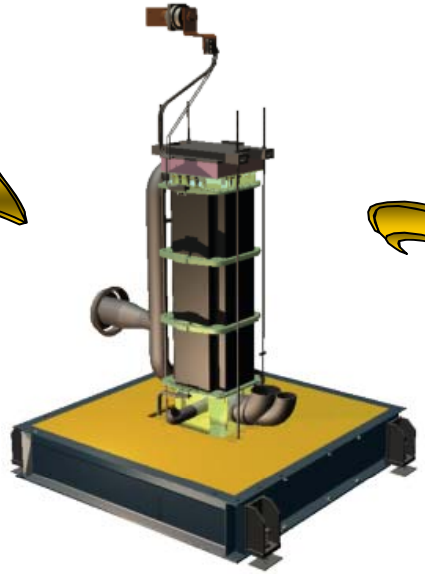
Building Block Approach

10 kW Stack

Building block for stack towers

30-50 kW

Stack Tower



Building block for stack modules of ≥ 250 kW

Stack Module

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

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Phase I Metric Tests

PHASE I Metric Test SECA Coal-Based Systems	
DELIVERABLE POWER RATING	≥10kW
STEADY STATE TEST (Normal Operating Conditions)	5000 hours
	Δ Power < 4.0% degradation/1000 hours
TEST SEQUENCE	1) Start-up 2) Peak Power Test 3) Steady State Test 4) Shut-down
FUEL TYPE	Simulated (subject to DOE concurrence, up to 25% CH_4, dry basis)
MAINTENANCE INTERVALS	Design aspects should not require maintenance at intervals more frequent than annually.

Successful Phase I Project was predicated upon operation of a >10 kW SOFC stack for at least 1500 hours with a degradation of <4%/ 1000hr, followed by additional tests in Phase II for a total of 5000 hours.

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10 kW Stack Block for Metric Tests

➡ **Two 10 kW Stack Blocks Met Phase I Metric Test Minimum Requirements.**

	Normal Operating Conditions – BOL
Fuel Utilization (system)	61.5% (80%)
Air Utilization (system)	10 to 18% (35%)
Stack Current	200 A (364 mA/cm^2)
Cathode Outlet Temperature	730-750 °C
Gross DC Electrical Power	~10,000 W

- **64-cells**
- **550 cm^2 active area**
- **0.313 W/ cm^2 Peak Power Density @ 11 kW**

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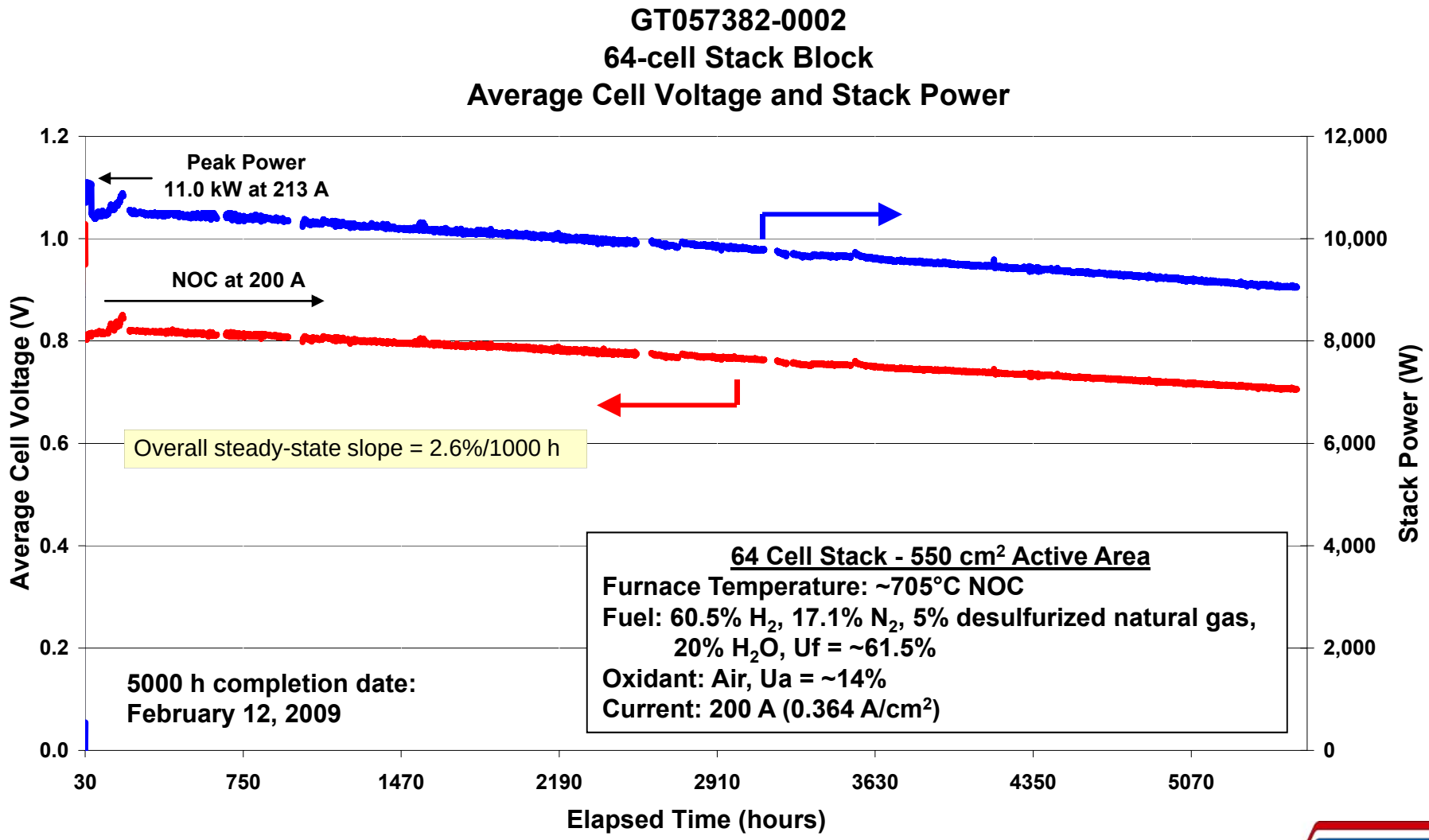
64-cell Stack (GT057382-0002)
Long Term Testing



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64-cell Stack (GT057382-0003)
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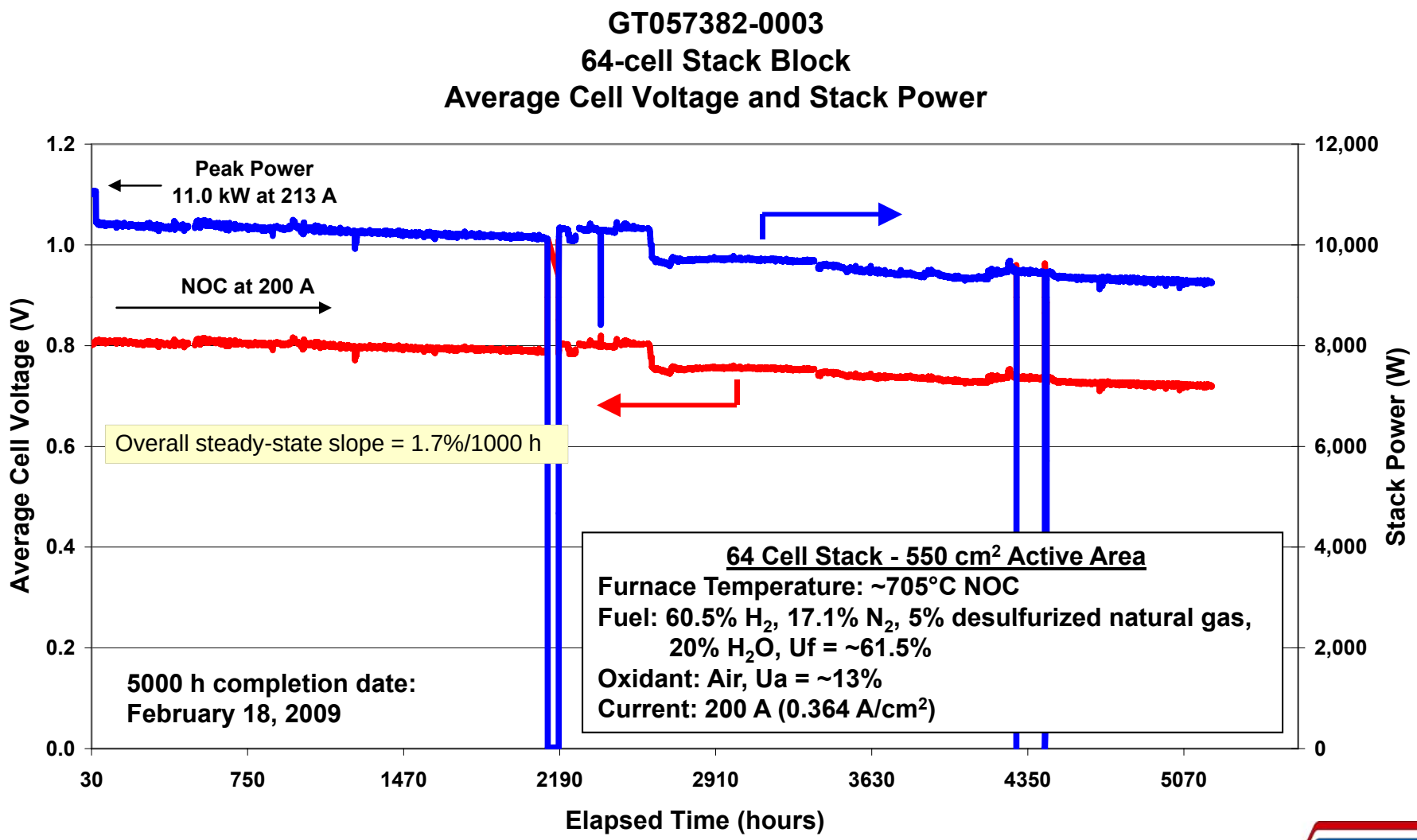

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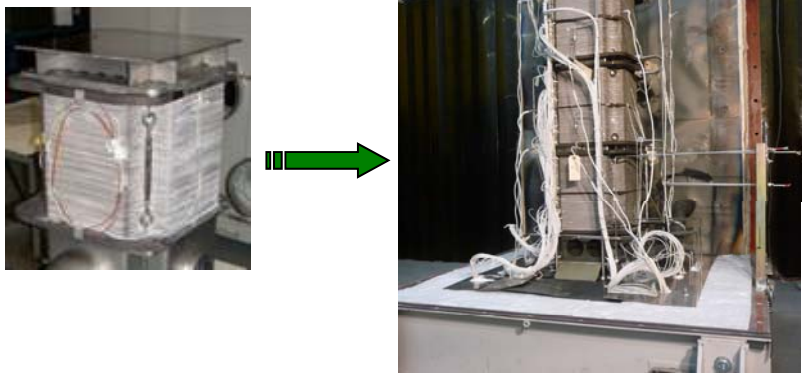
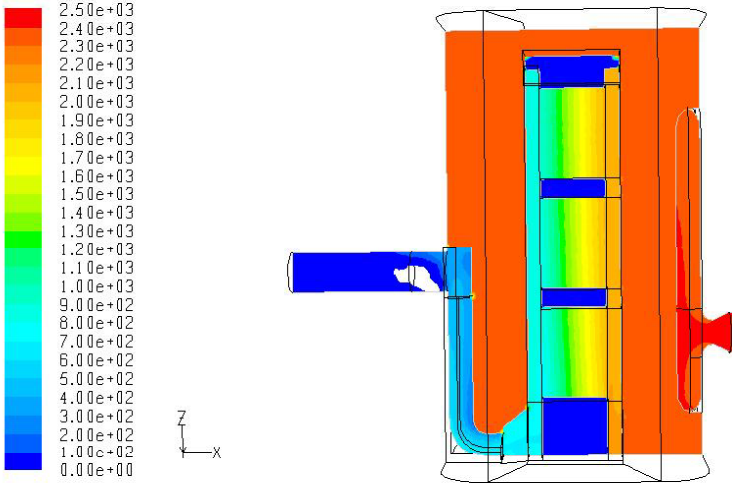
30 kW Stack Tower Design Development

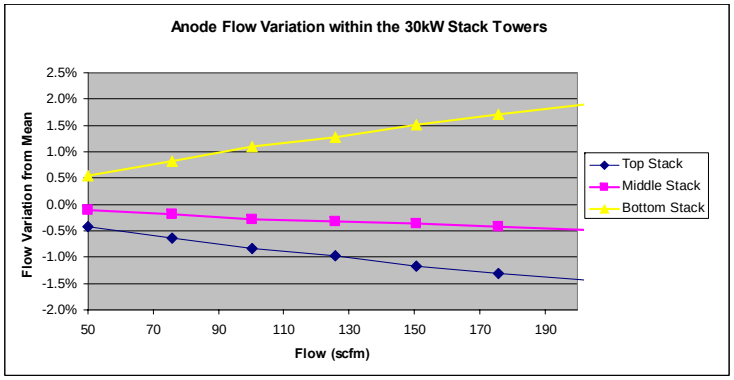
➢ **Design and integration of 3 stack blocks of 10kW each into 30kW stack module was completed.**



➢ **CFD modeling of the 30kW stack tower confirmed flow distribution and pressure map are acceptable.**



➢ **Cold-flow testing of stacks proved excellent flow distribution among the stack blocks resulting from design of manifolds and flow fields.**



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30 kW Stack Tower Tests

- **Next step is demonstration of 30 kW stack tower operation in a simulated power plant environment**

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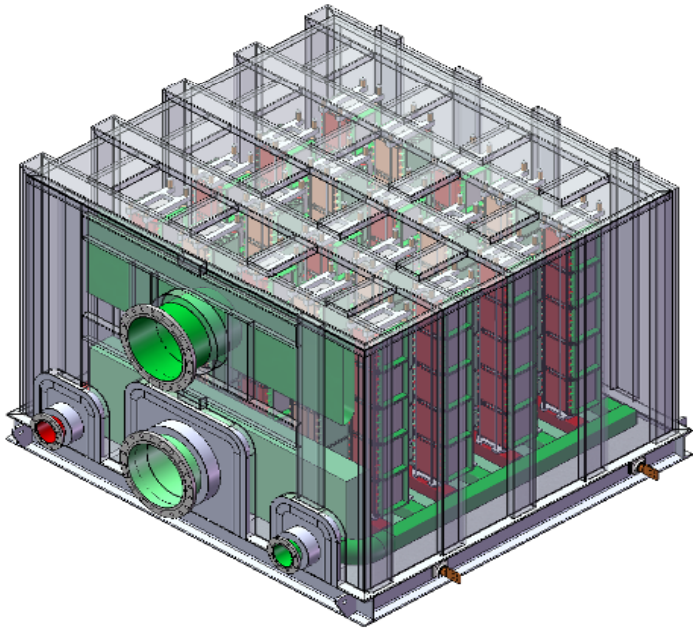
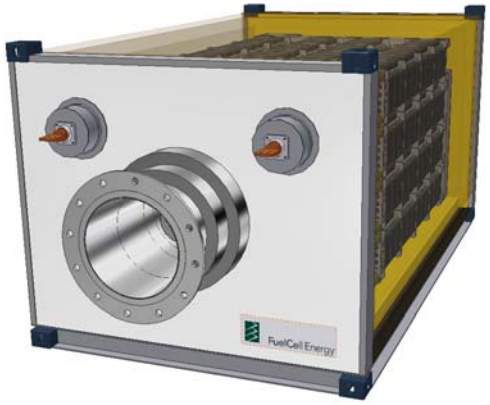
MW-Scale SOFC Stack Module

- 2008 Design



- 2009 Improved Design



Design Parameters		
	2008 Design	2009 Design
Towers/ Module	20	16
Cells/ Tower	320	~400
Module Volume	2400 ft^3	780 ft^3
Module Power Output	1.1 MW	1.3-1.6 MW

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Improved Coal-Based SOFC System with Catalytic Gasification

POWER GENERATION SUMMARY	kW	% Q input	% MW gross
Fuel Gas Expandors Gross Power @ 20 kV	52,307	5.15%	8.49%
Fuel Cell Inverter AC Gross Power @ 20 kV	515,126	50.76%	83.57%
WGCU Off Gas Expander Gross Power @ 20 kV	9,361	0.92%	1.54%
Steam Turbine Gross Power at Generator Terminals @ 20 kV,	39,599	3.90%	6.42%
Total Gross Power Generation @ 20 kV	616,393	60.74%	100.00%
Total Auxiliary Load	56,152	5.53%	9.11%
Net Power Output at 230 kV	***560,241***	***55.21%***	***90.89%***

Net Efficiency Excluding CO2 Compression & Thermal Input			
As Fed Coal feed, lb/h	291,667		
HHV (AF), Btu/lb	11,872		
Thermal Input, kWth	1,014,809	100.00%	164.64%
Net Plant Efficiency (HHV)	**55.21%**		

➡ **Combined with high methane producing gasification, coal based SOFC systems are capable of achieving ~ 55% efficiency and 98% carbon capture.**

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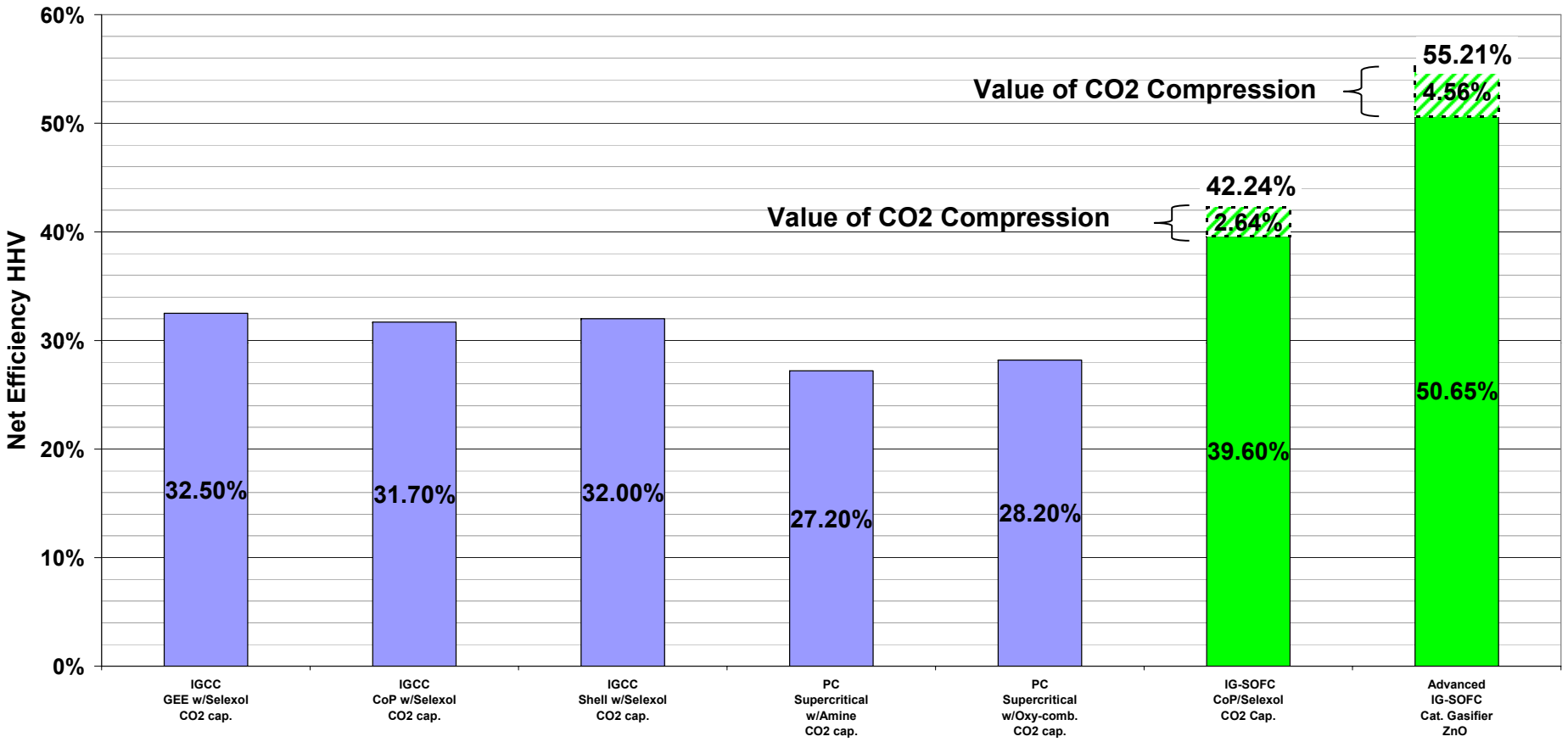
Baseline SOFC Power Plant Efficiency vs. Competing Technologies



Baseline coal based SOFC system is >18 percentage points more efficient than IGCCs and Pulverized Coal (PC) Steam plants.

References for Competing Technologies:

* Cost and Performance Baseline for Fossil Energy Plants, Volume 1 - Bituminous Coal and Natural Gas to Electricity, DOE/NETL-2007/1281, Revision 1, August 2007

** Pulverized Coal Oxycombustion Power Plants, Volume 1 - Bituminous Coal to Electricity, DOE/NETL-2007/1291, Final Report, August 2007

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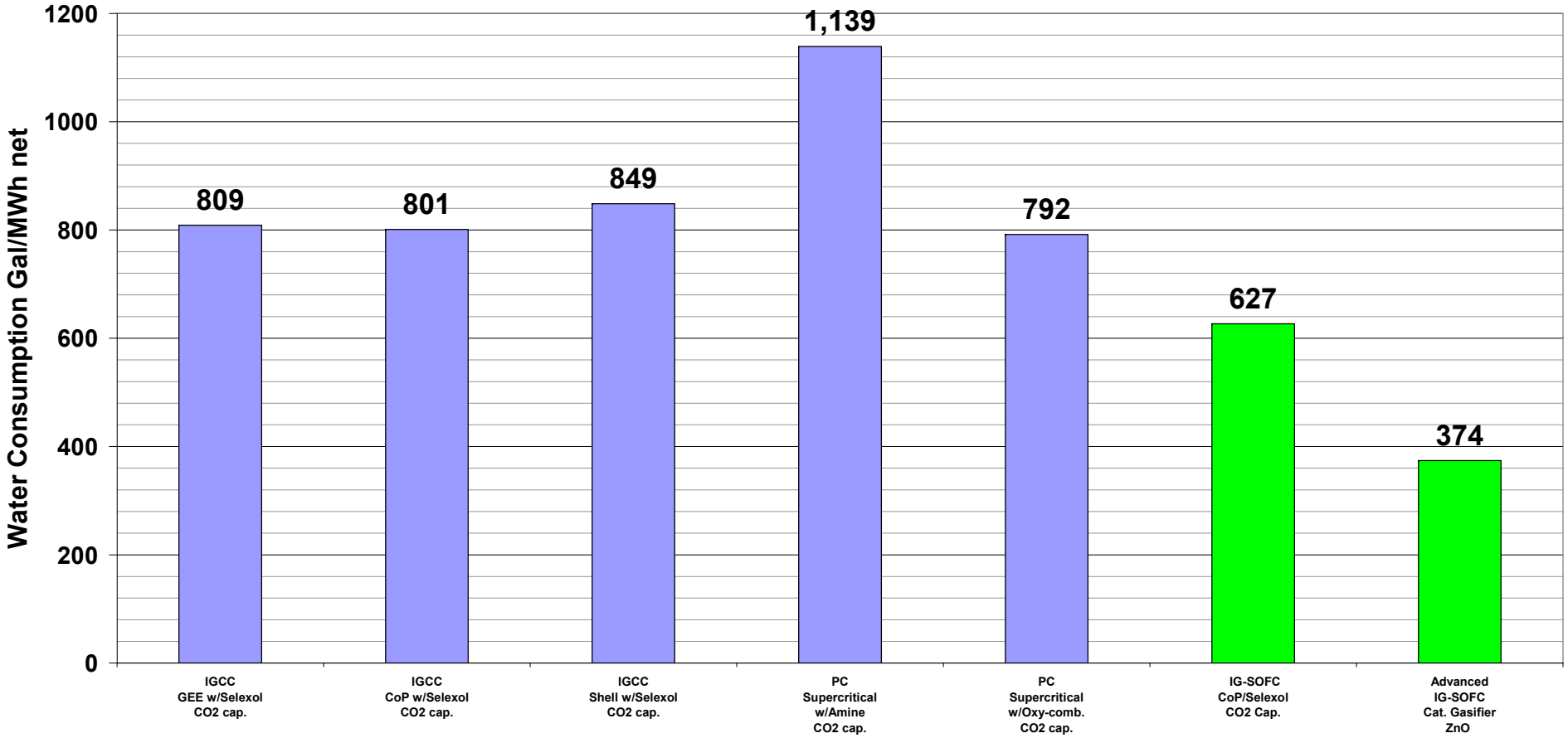
Baseline SOFC Power Plant Water Consumption vs. Competing Technologies



Baseline coal based SOFC system requires significantly less water than IGCCs and Pulverized Coal (PC) Steam Turbine Power Plants.

References for Competing Technologies:

* Cost and Performance Baseline for Fossil Energy Plants, Volume 1 - Bituminous Coal and Natural Gas to Electricity, DOE/NETL-2007/1281, Revision 1, August 2007

** Pulverized Coal Oxycombustion Power Plants, Volume 1 - Bituminous Coal to Electricity, DOE/NETL-2007/1291, Final Report, August 2007

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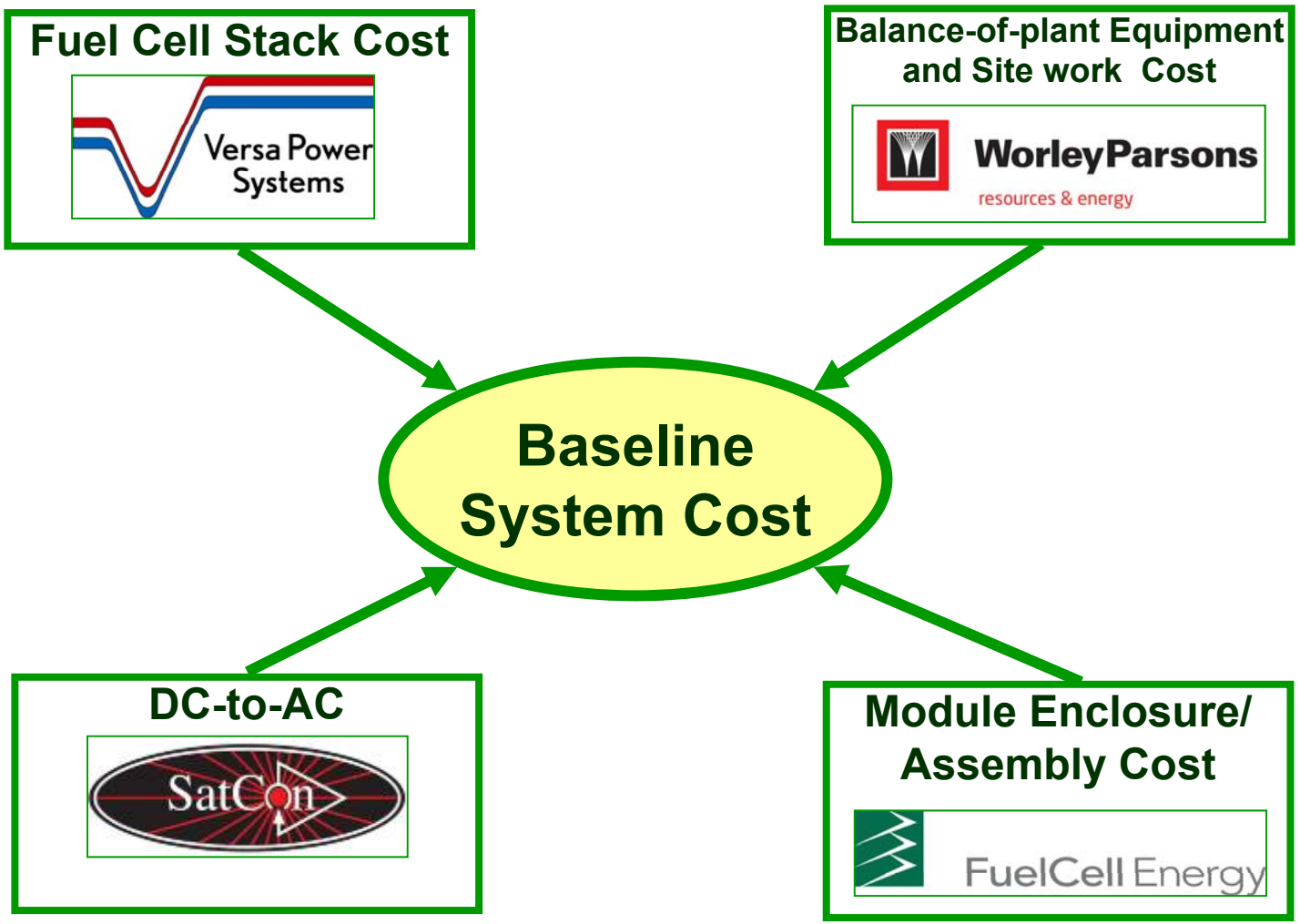
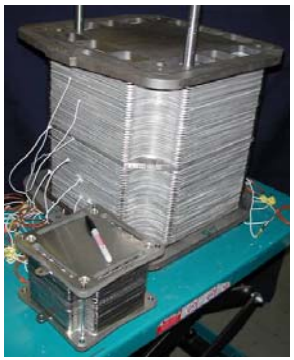
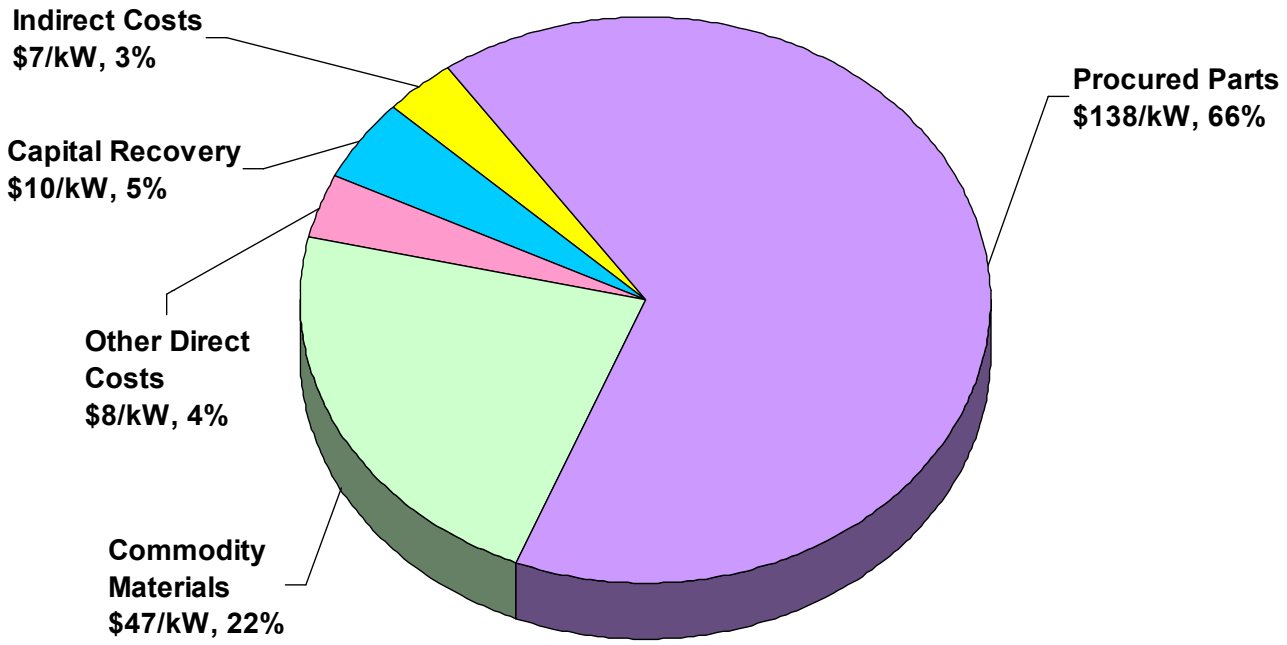
Baseline Power Plant Cost



Stack Cost by Category



- 64-cell stack, 11 kW
- Cell dimensions
  - > 550 cm^2 active area
  - > 645 cm^2 cell substrate
- 1003 MW/yr production volume
  - > 91,200 stack blocks
  - > 5,836,800 cell repeat units
  - > 376,600 m^2
  - > 1,885,000 kg, cells



- Cost shown are in $/kWdc based on 11kW dc peak power rating.
- The majority of stack cost is driven by cost of materials.
- The relatively low labor cost is attributed to cell and stack simple and automated manufacturing processes developed at VPS.
- Cost analysis audited by independent consultant.

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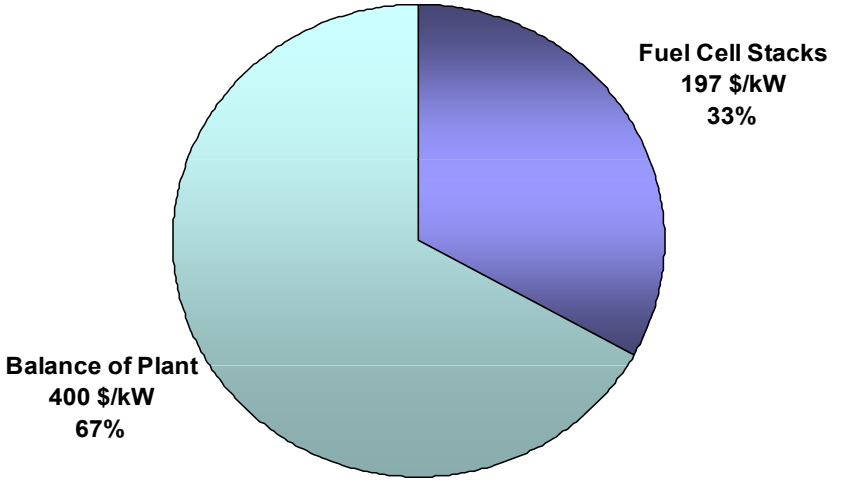
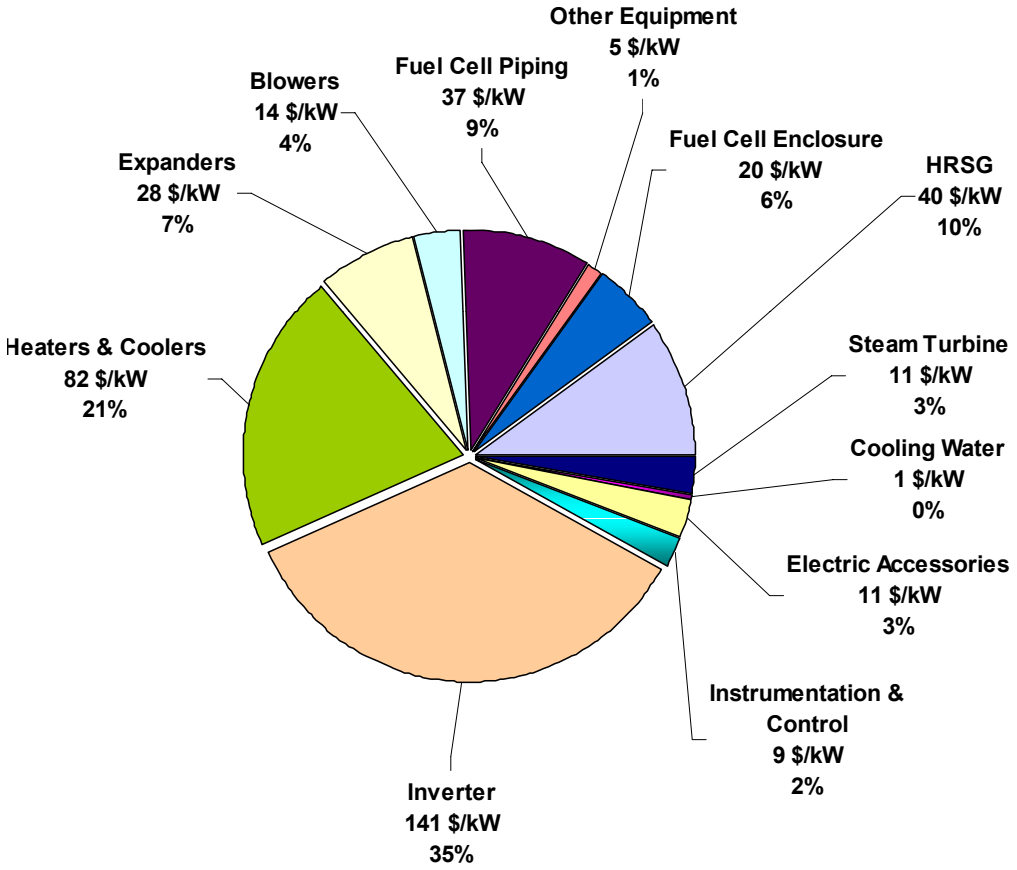
Factory Equipment Cost Estimate

Total Factory Equipment Cost (2002 USD) = 597 $/kW



Total BOP Cost (2002 USD) = 400 $/kW



- **Cost estimation, based on two nominal 500 MW power plants manufactured per year, established that system equipment factory cost of < $600/kW is achievable.**

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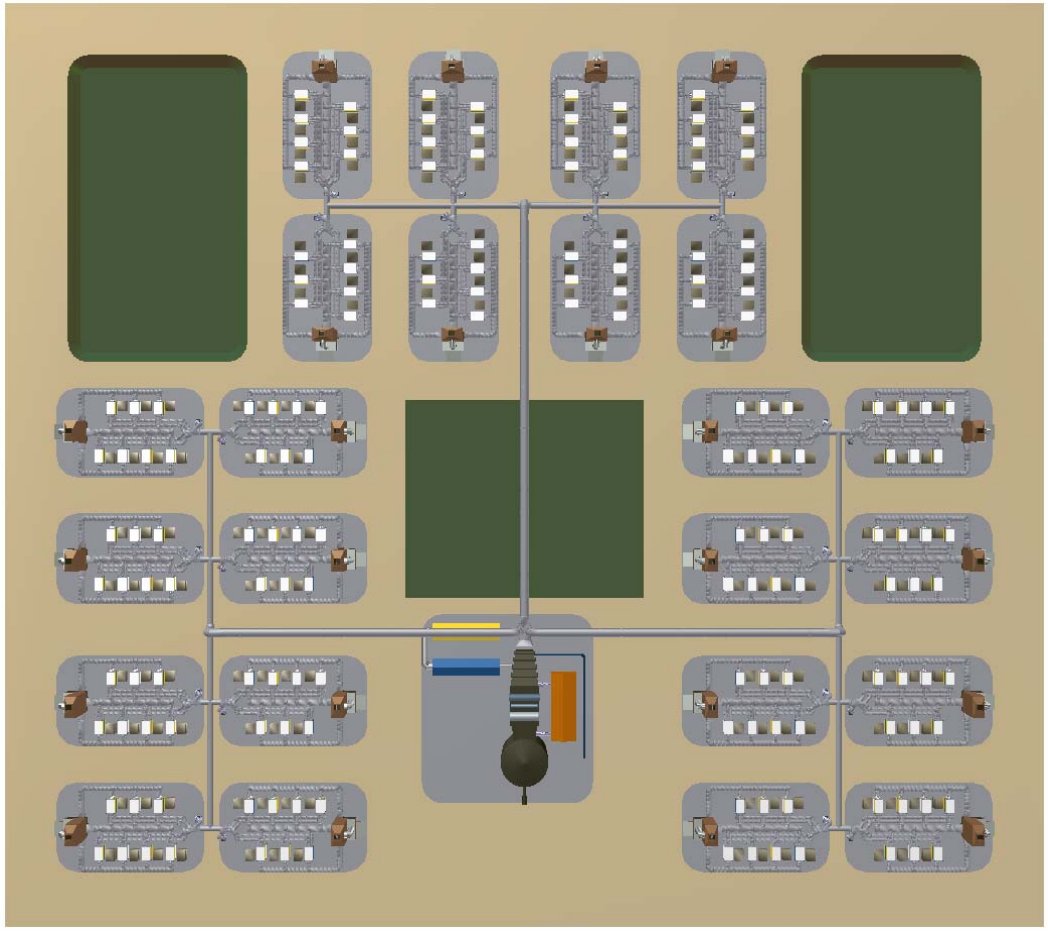
Baseline SOFC Power Island



- SOFC power island includes 24 clusters of 14 MW-scale fuel cell stack modules and a steam bottoming cycle for a net power generation of 500 MWac.

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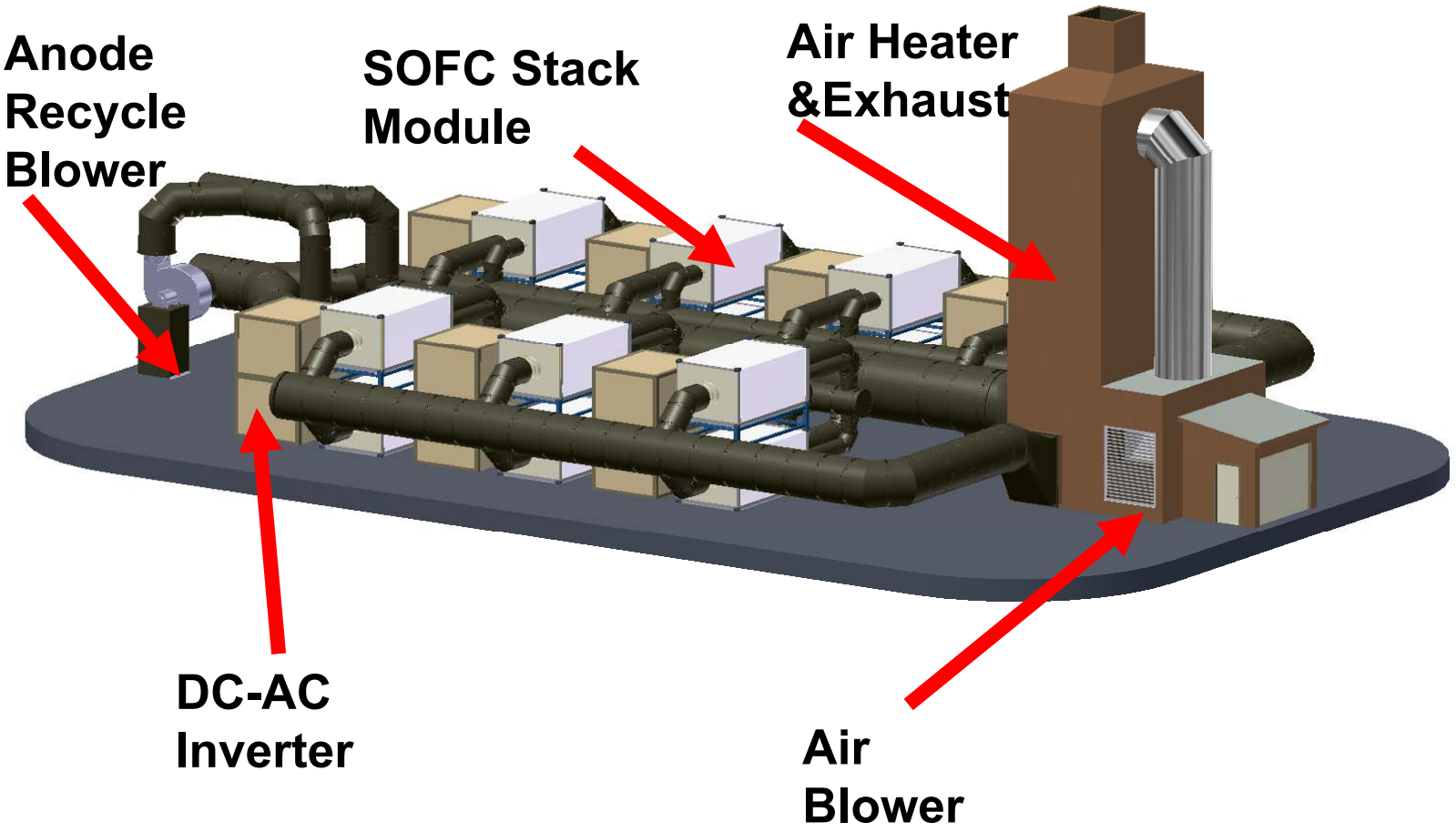
Layout of 14-Module SOFC Cluster



➡ SOFC cluster design takes advantage of modularity of fuel cells.

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Summary of Recent Achievements

- **Cell Technology:**
  - Advanced cell components with significant improvement in endurance over the baseline cells and reduced cell degradation rate by more than 50%.
  - Enhanced cell performance, especially at lower operating temperature, by greater than 10%.
  - Fuel cell manufacturing processes were developed to support the new scaled-up baseline cell (25 cm x 25 cm). The processes for stack manufacturing capacity of 500 kW/year and cell manufacturing capacity of 1,000 kW/year were implemented.
- **Scale-up of stack size to 10kW:**
  - Manufacturing of the scaled-up 10kW stack blocks was accomplished to establish the building block for multi-MW power plants.
  - Improved stack design and component advancements to meet the Phase I targets of performance and endurance criteria were developed.
  - Phase I metric tests were completed by two 10kW stacks, in accordance with SECA Minimum Requirements of >5000 hours of operation, with degradation of <2.6%/1000 hours.
- **Baseline IGFC System:**
  - Baseline Systems with Catalytic Gasifier were developed which could achieve efficiency (HHV) of 55% and be able to remove greater than 98% carbon from syngas.
  - Baseline 500MW power plant layout and Factory Cost Estimates were developed resulting in a cost estimate of $597/kW (in 2002 dollars) for the SOFC power block.

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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

- Support and guidance by the management team at NETL:
  Wayne Surdoval, Travis Shultz, and Heather Quedenfeld

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