Coal-Based SECA Program - FuelCell Energy Inc.

11th Annual SECA Workshop
Pittsburgh, PA
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Brian Borglum, *Versa Power Systems*

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Presentation Outline

- **Introduction**
  - FCE SECA program team members
- **SECA Coal-Based SOFC Program Outline**
- **Progress in SOFC Technology**
- **Stack Development**
  - Metric Tests
- **Module Demonstration Unit Development**
- **Baseline 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 fuel cell technology for stationary power applications
- Headquarters in Danbury, CT (USA), with 65,000 ft^2 manufacturing facility in Torrington, CT (USA)
- Delivering Direct FuelCell power plants to commercial, industrial and utility customers
- Developing large-scale coal-based power plants as well as natural gas distributed generation (DG) systems utilizing planar SOFC
- Established commercial relationships with major distributors in the Americas, Europe, and Asia

Torrington, CT - Manufacturing Facility

MW-Class Fuel Cell Products

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SECA Coal-Based Systems Program

Program Objectives

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

- At least 50% electrical efficiency from coal (higher heating value)
- Performance to meet DOE specified metrics for power output, degradation, availability, and reliability
- Fuel cell power island factory cost <$400/kW (2002 USD)
- More than 90% of carbon capture from coal syngas as CO_2, 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 2008.**
- **Phase II work is focused on further development of cost-effective, 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 Program 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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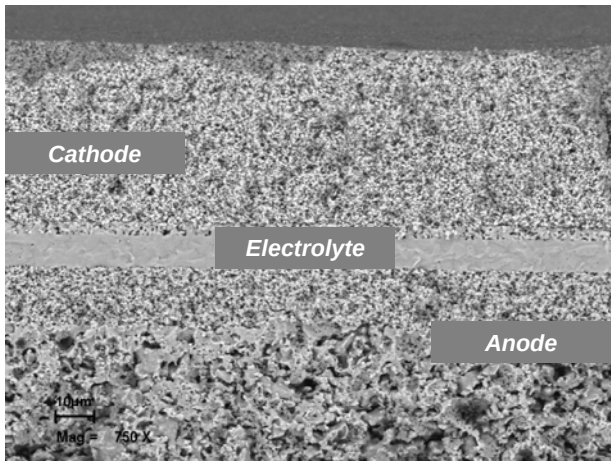
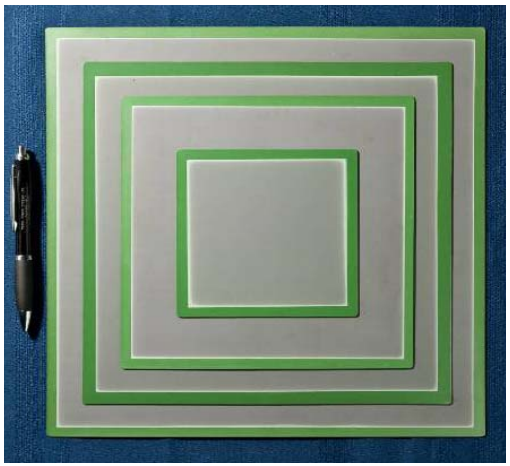
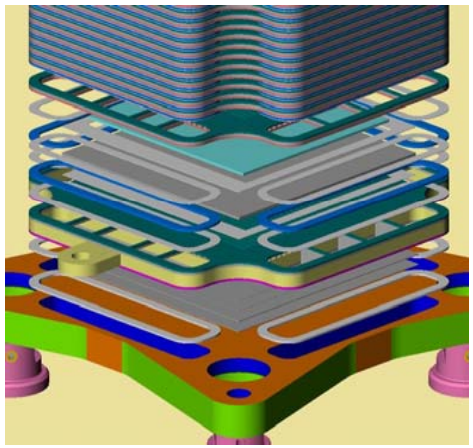
VPS Planar SOFC Cell and Stack Technology

- Anode supported cells (up to 33 x 33 cm^2)
- Capable of operating from 650°C to 800°C
- Ferritic stainless steel sheet metal interconnect
- Cross-flow gas delivery with manifolds integrated into the interconnect but not through the cell
- Compressible ceramic gasket seals
- Standardized stack blocks configurable into stack towers for various power applications







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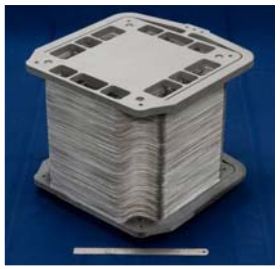
SECA Coal Based Program Plan for IGFC Development

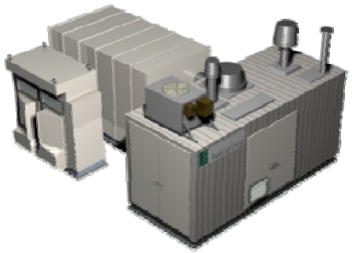
• FCE is currently engaged in development of stack tower and SOFC power module configurations suitable for large scale coal based power plants.

10 kW Stack

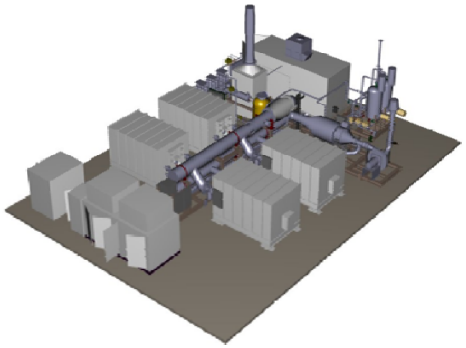


>25 kW Stack Tower

≥ 250 kW Module Demonstration Unit



5 MW Proof of Concept



2008 2010 2012 2015

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

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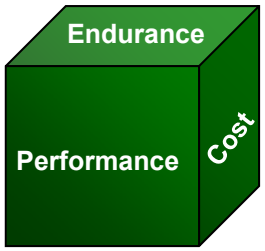
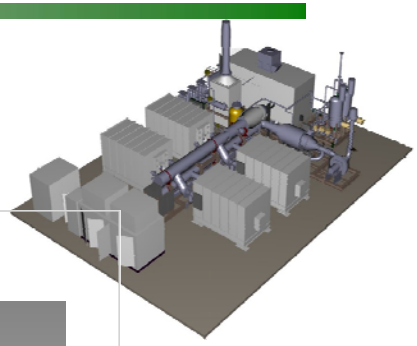
SECA SOFC Development Path



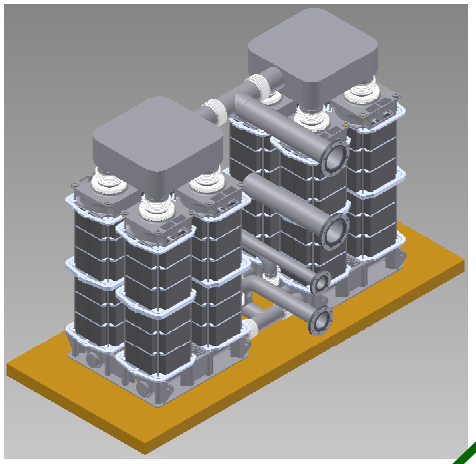
Develop SOFC stack technology that meets the performance & cost objectives, is scalable, and is used as the building block for assembling stack towers and large-scale power modules.



MW-scale Proof-of-Concept Plant

2010

Stack Tower



SOFC Stack Module

Scalable

2008

10-20 kW Stack

2006

1 kW Stack

Modular

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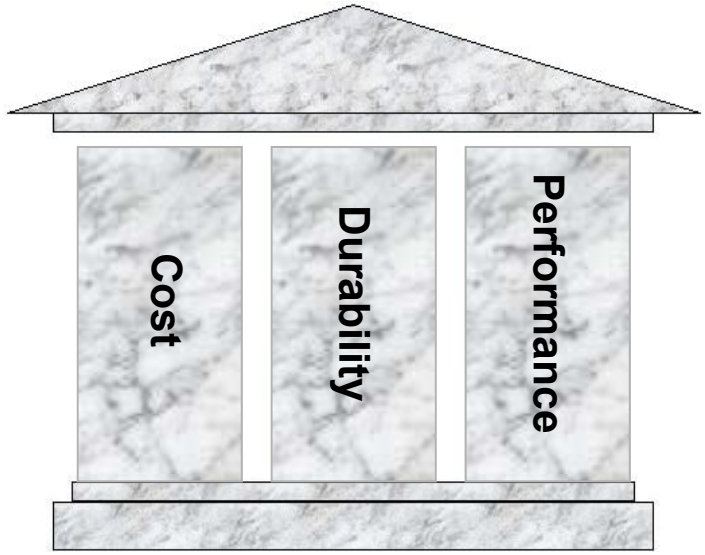
Cell Development Objectives

- **Performance:**
  - > High performance over a wide operating window
  - > Capability for in-stack reforming (DIR)
  - > Accommodation of load following
- **Durability:**
  - > Degradation rate of less than 0.2% per 1000 hours over a wide operating window (temperature, fuel utilization and current density)
  - > Robustness for thermal cycles and rapid load transients
- **Cost:**
  - > Scalability to facilitate large stack and power module
  - > Reduction of materials usage
  - > Improvements in cell fabrication process technology



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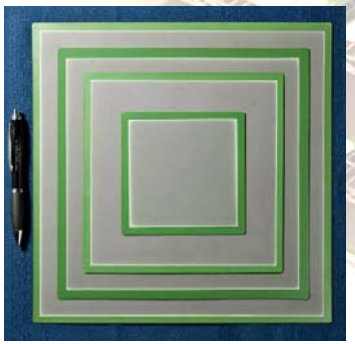
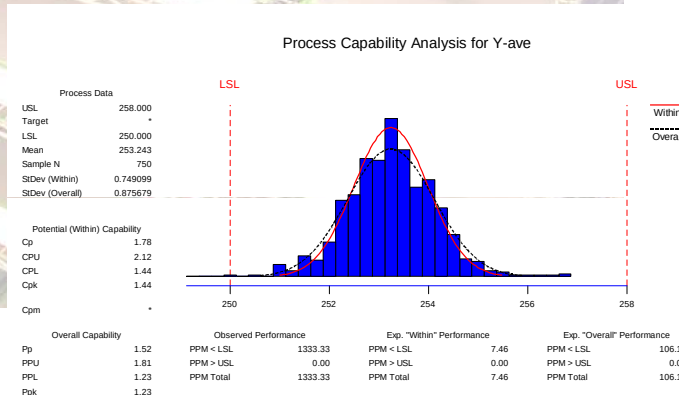
Recent Achievements in Cell Fabrication Process

- **Established fabrication process capabilities for large area cells**
  - > **Cells up to 1000 cm^2 (33 x 33 cm^2) in size were produced using TSC cell manufacturing process**
- **Developed and implemented the next generation of cell fabrication processes**
  - > **Cell thickness was reduced by more than 40%**
- **Fabricated > 4000 cells (25 x 25 cm^2)**
  - > **Production volume of 500 kW (annual) was established**





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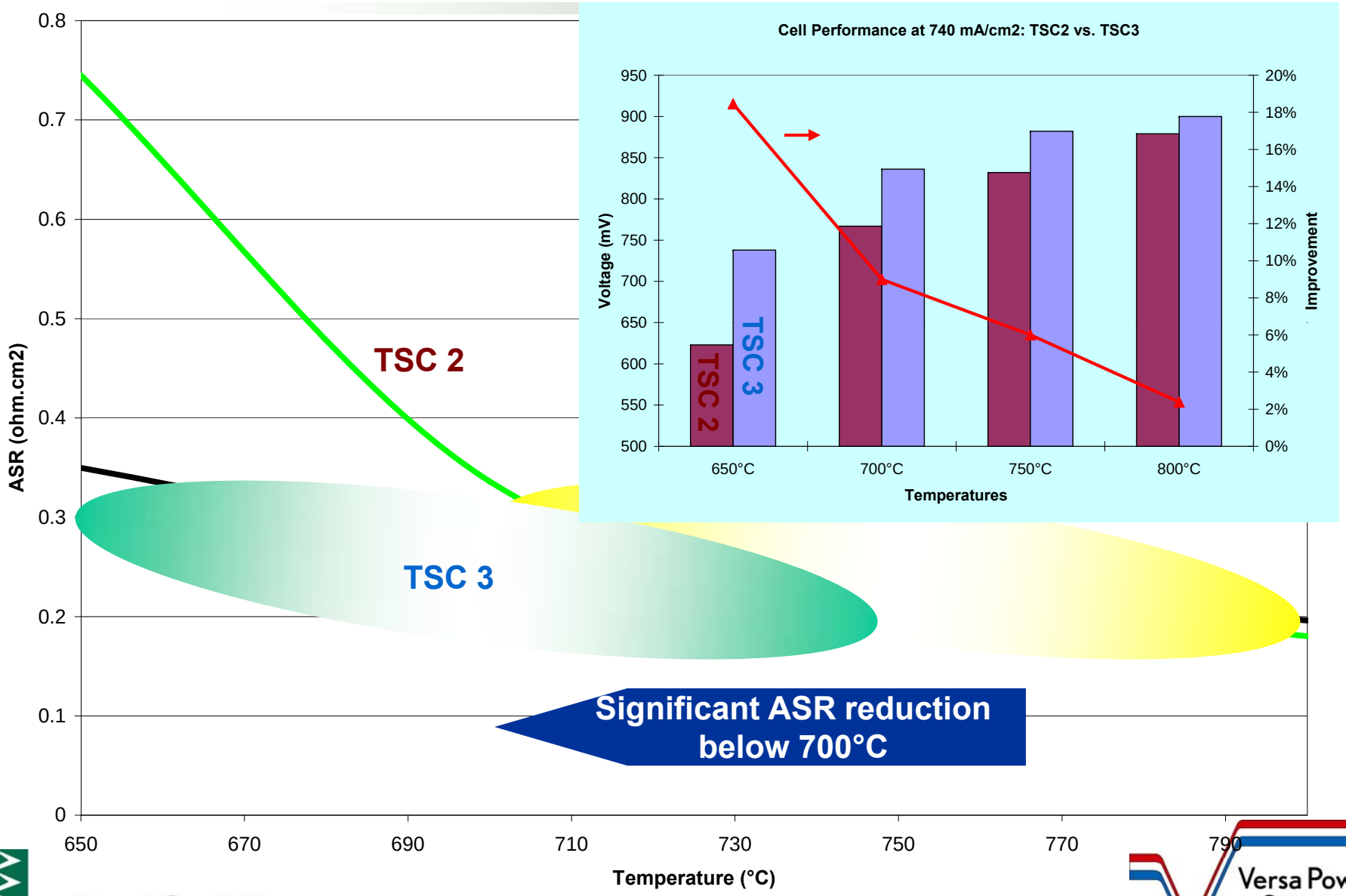
Third Generation of Cell Technology (TSC-3)



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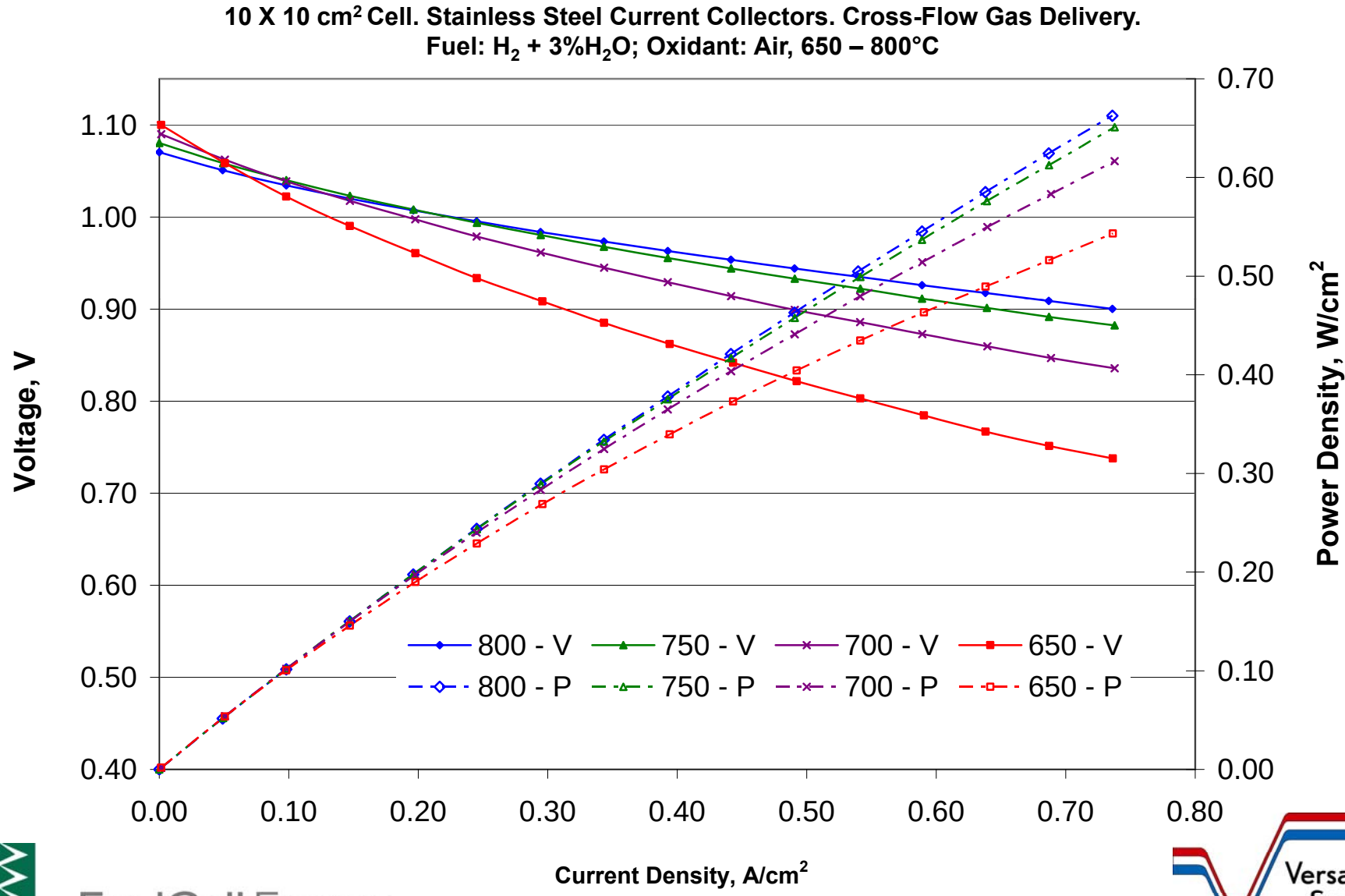
Single Cell Performance Enhancement



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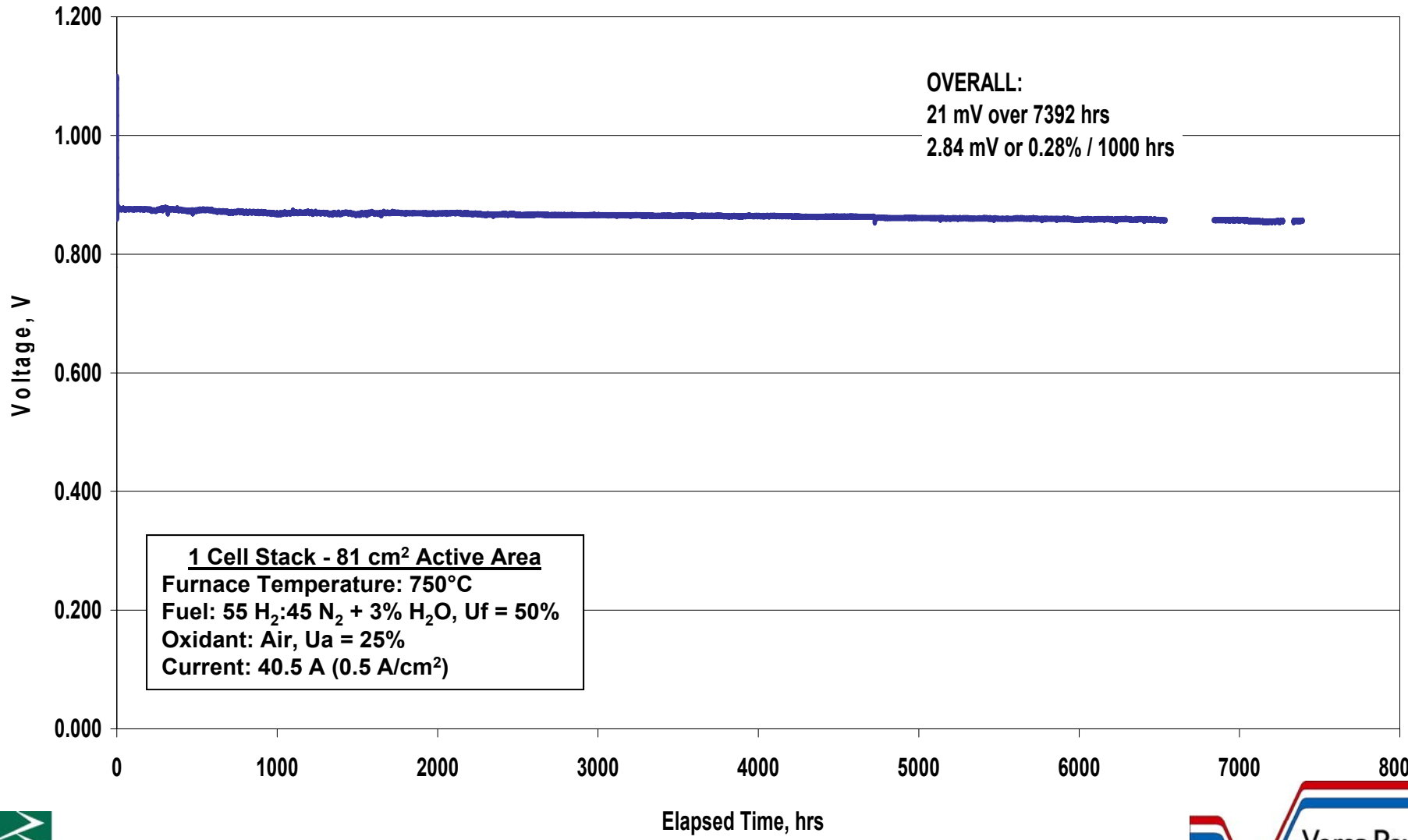
Single Cell Stability Achievements



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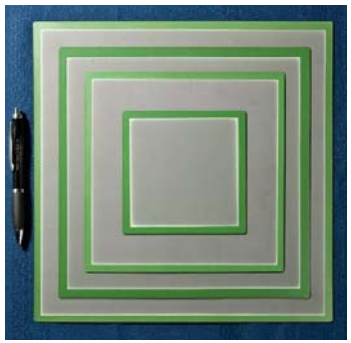
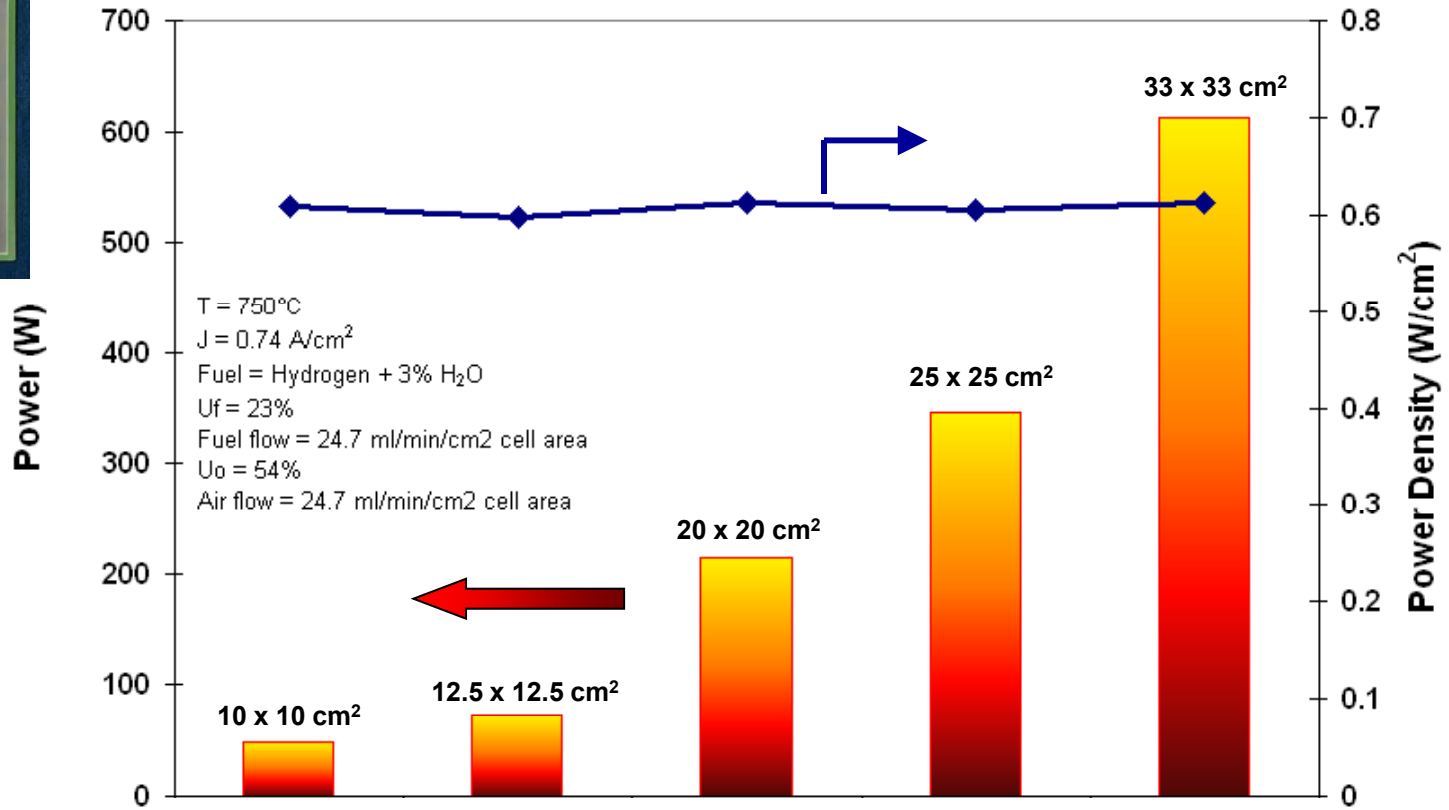
Progress in Cell Scale-Up





Power	49	72	214	346	612
Power Density	0.608	0.598	0.612	0.606	0.612

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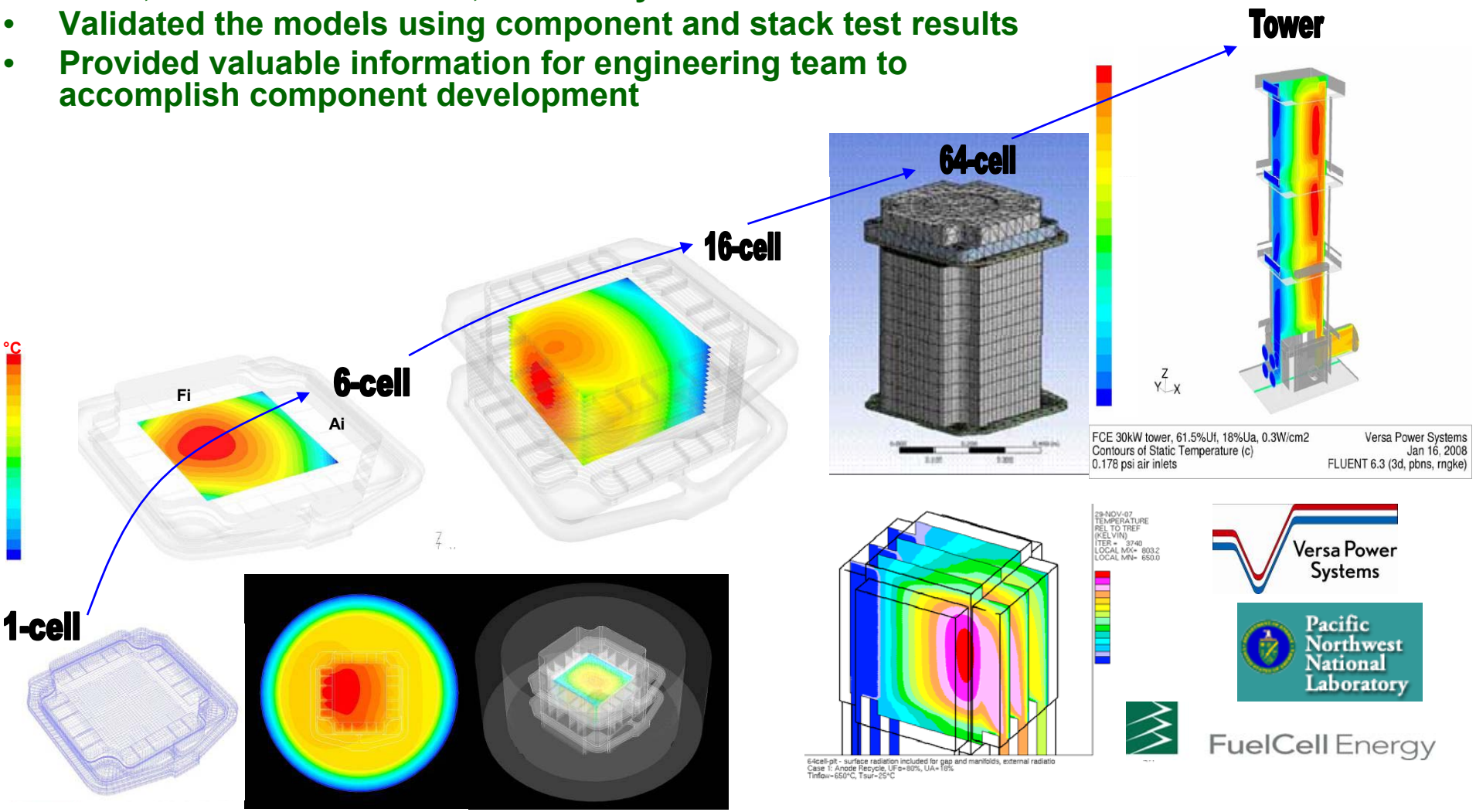
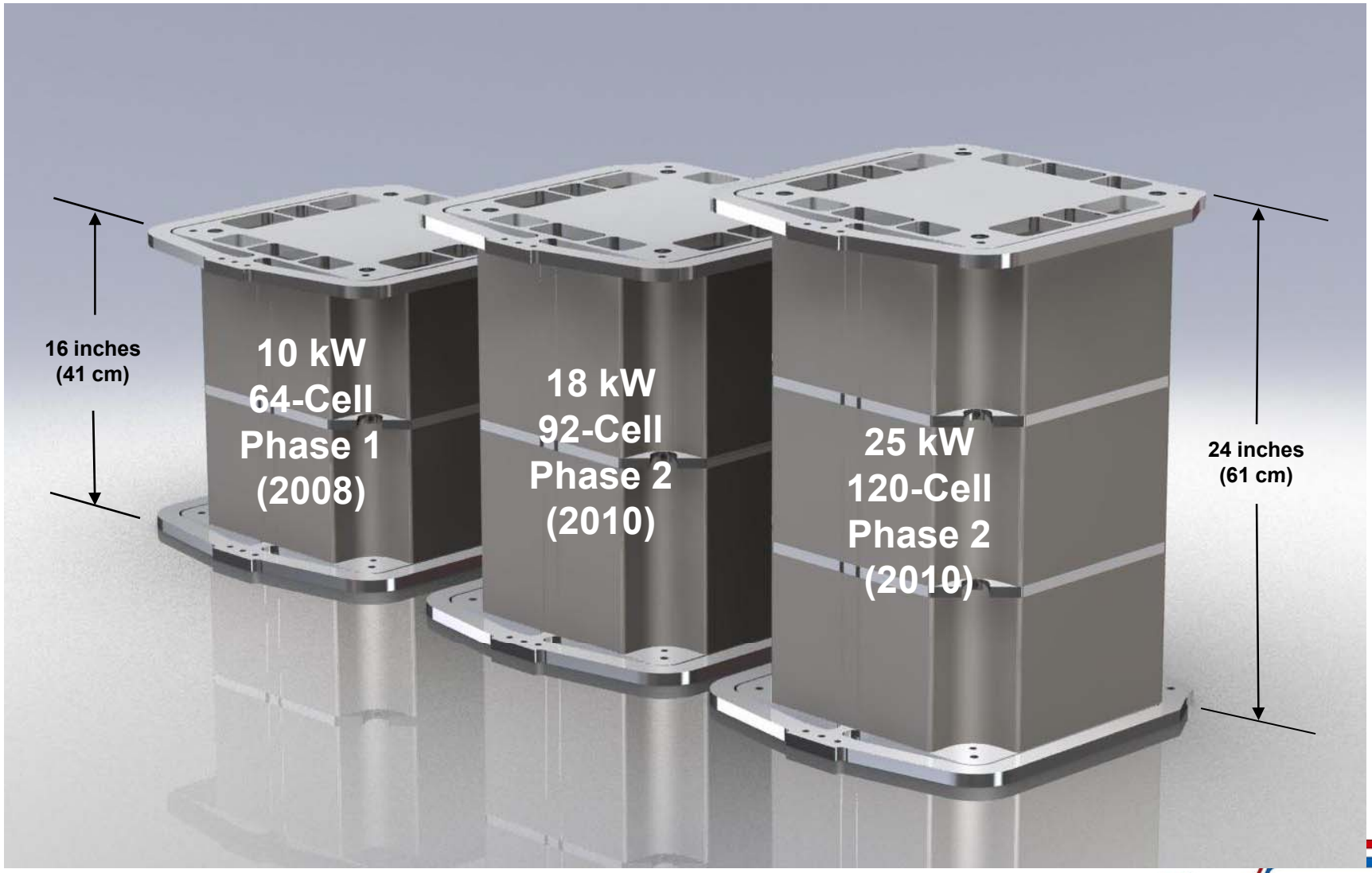
Stack Design Approach

- Utilized a model-driven design approach using both CFD and FEA to resolve thermo-mechanical challenges
- Followed a progressive modeling path from single cell, short stack, full size stack block, and finally to stack tower
- Validated the models using component and stack test results
- Provided valuable information for engineering team to accomplish component development



SOFC Stack Evolution



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Stack Scale-up and Maufacturing Progression

Stack Size	Power (kW/stack)	Quantity	Total Power (kW)
6 cells	1	21	21
16 cells	2.5	18	45
64 cells	10	6	60
Total		45	126

Phase 1

1 kW 6-cell

2.5 kW 16-cell

10 kW 64-cell

18 kW 92-cell

25 kW 120-cell

Stack Size	Power (kW/stack)	Quantity	Total Power (kW)
16 cells	2.5	42	105
32 cells	5	1	5
92 cells	18	7	126
120 cells	25	1	25
Total		51	261

Phase 2

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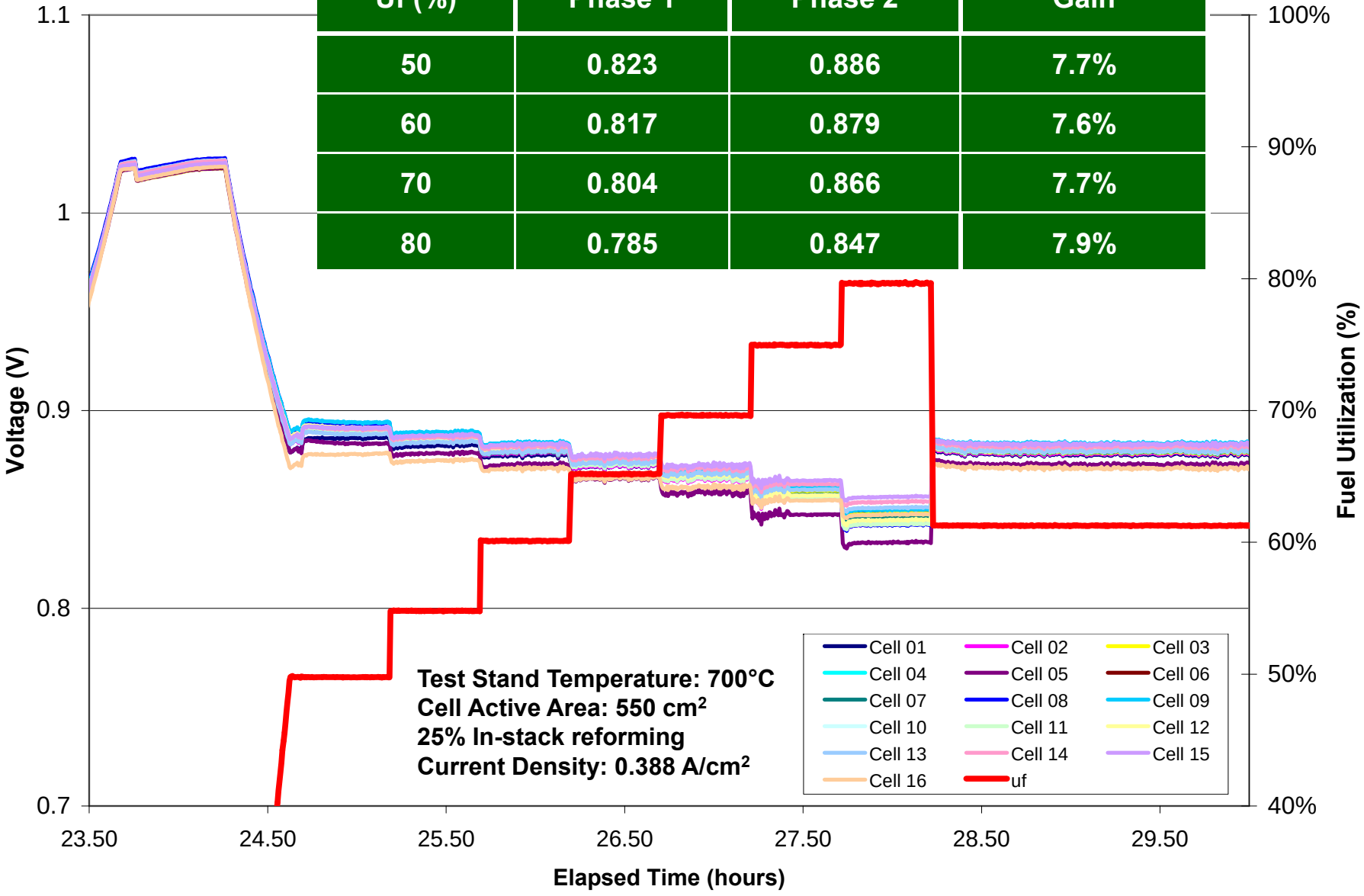
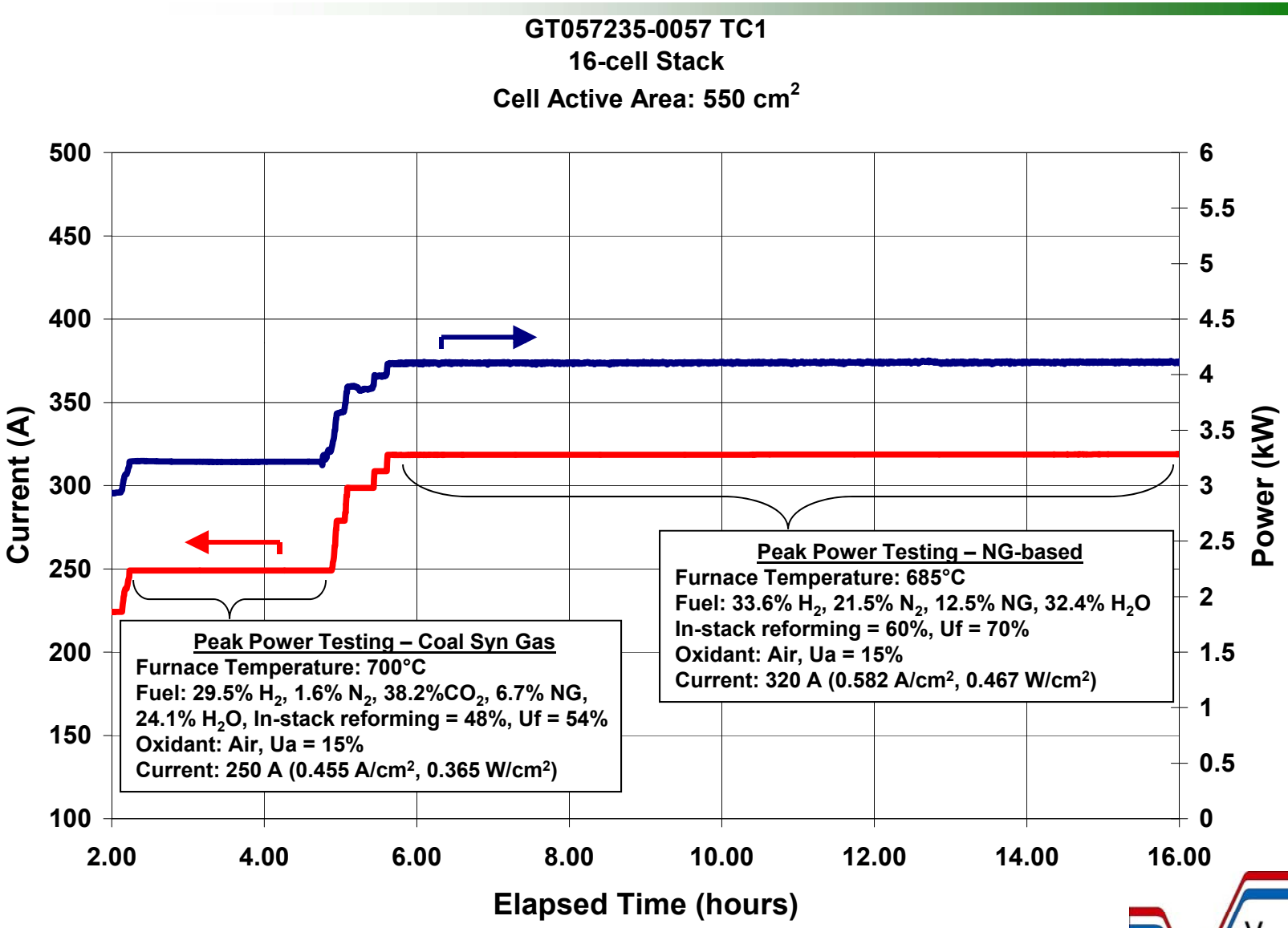
Stack Performance Enhancement
16-Cell Stack

Uf (%)	Phase 1	Phase 2	Gain
50	0.823	0.886	7.7%
60	0.817	0.879	7.6%
70	0.804	0.866	7.7%
80	0.785	0.847	7.9%



Stack Peak Power Achievement



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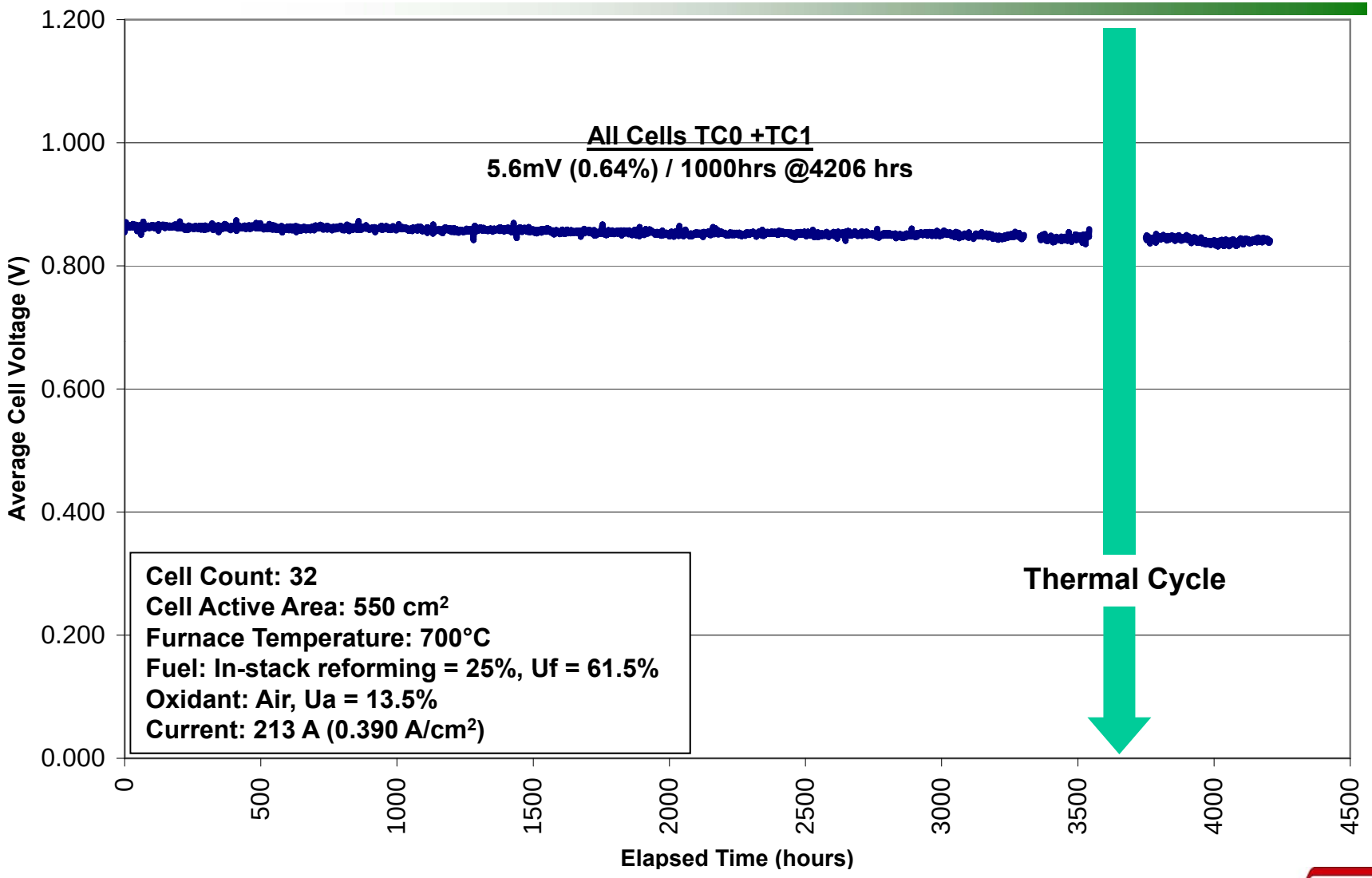
Stack Endurance Achievement



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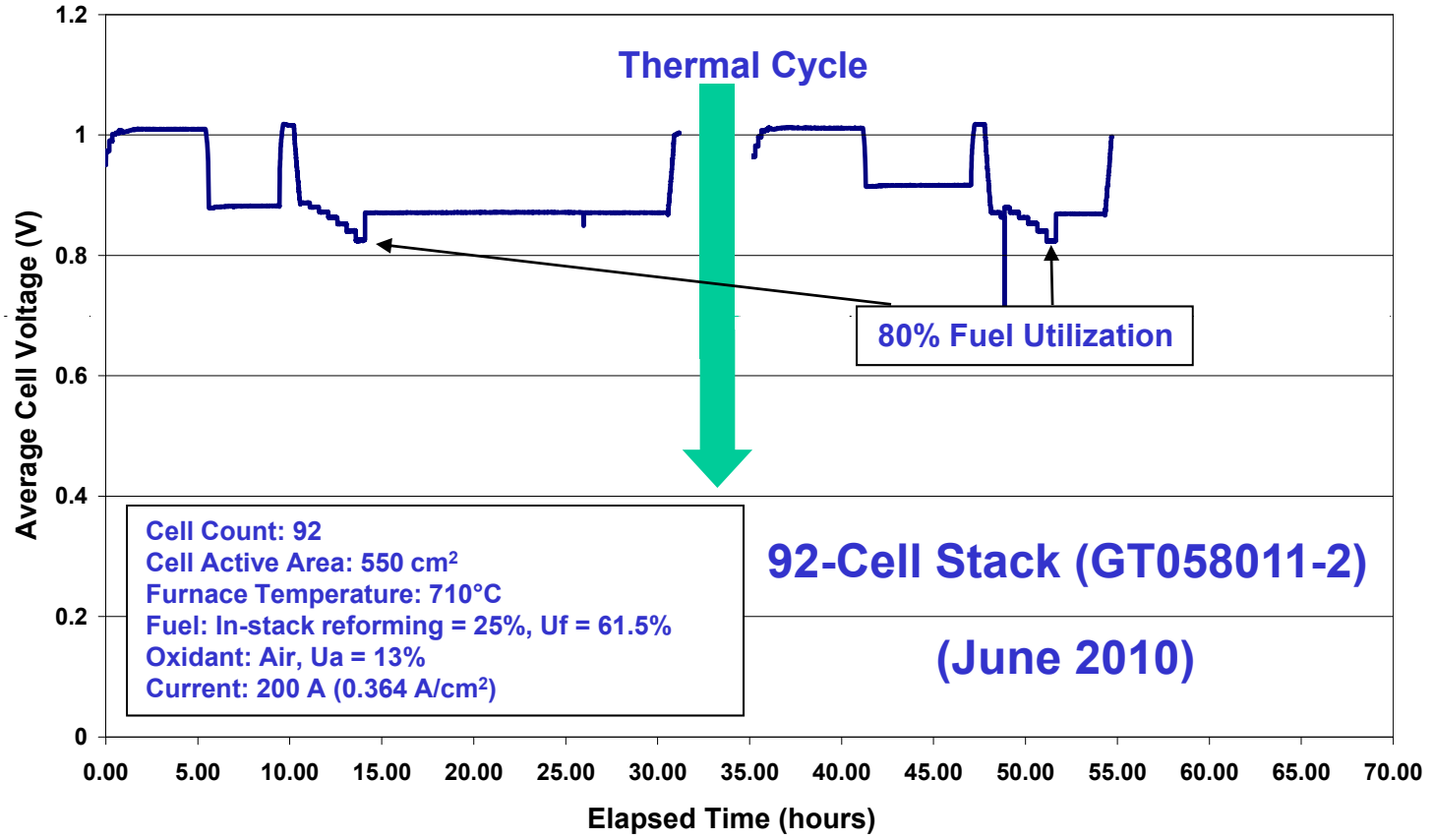
Stack Scale-Up Status (Phase II)
92-Cell Stack (GT058011-1)

Cell Size	25 x 25 cm
Active Area	550 cm²
Number of Cells	92



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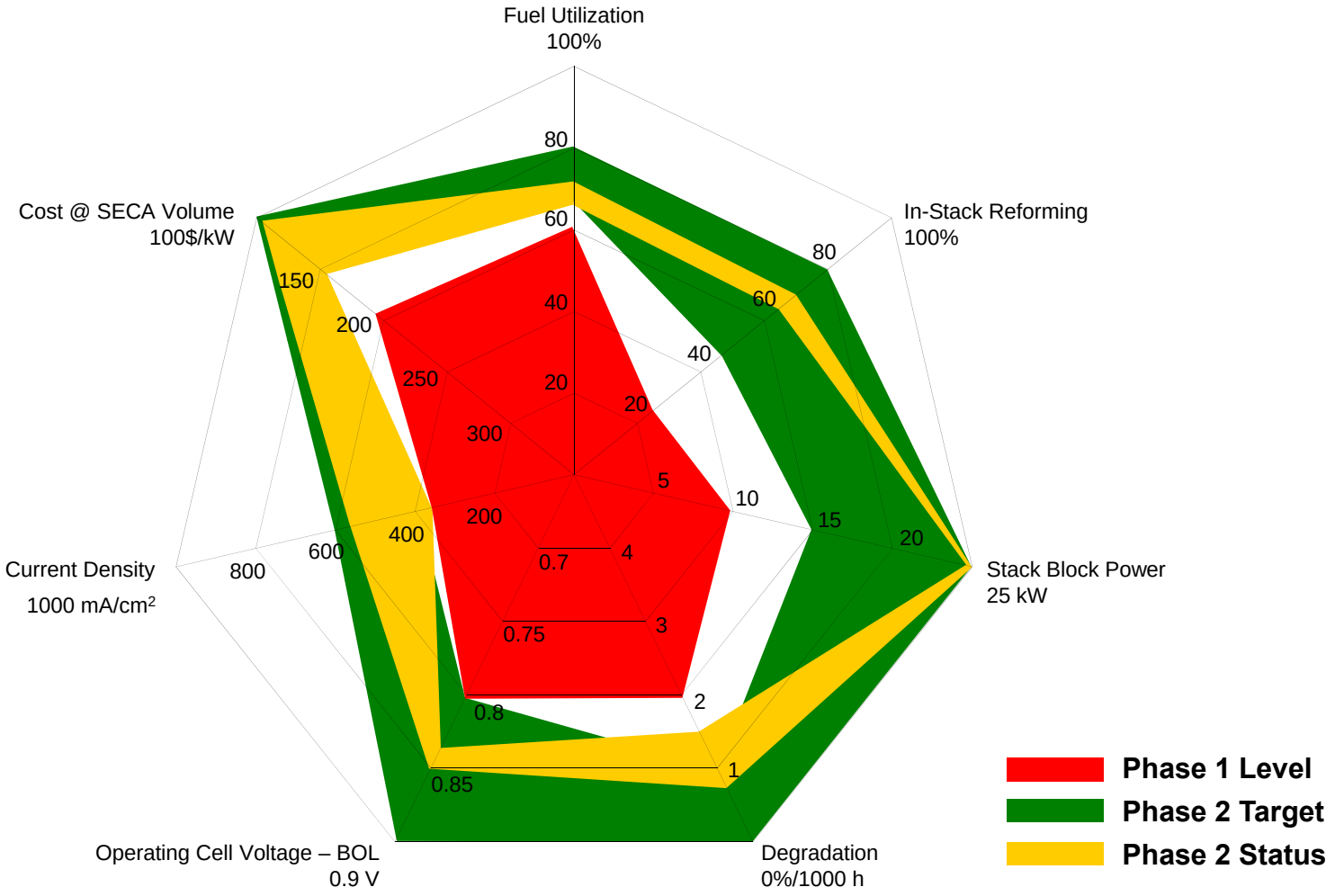
Stack Development Status



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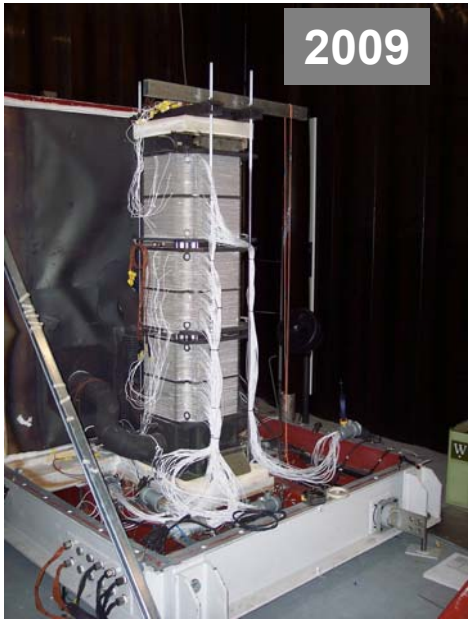
Stack Tower Testing

3 x 64-cell stacks



SO-30-1 Tower Assembly

2 x 92-cell stacks

SO-30-3 Tower Assembly

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

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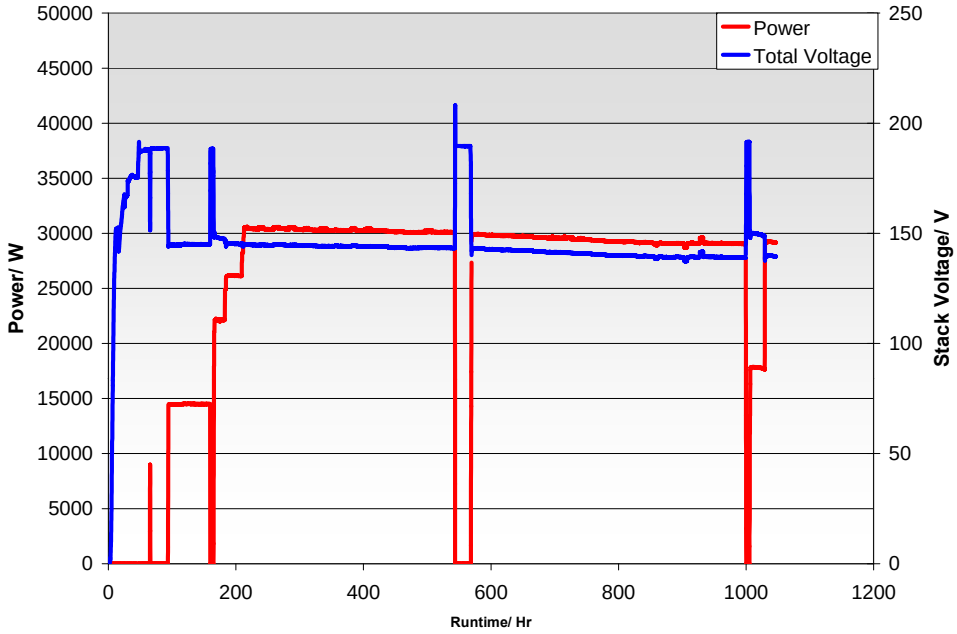
Stack Tower (SO-30-3) Test



- **Demonstration of stack tower operation in a simulated power plant environment, using 2x92-cell stack blocks.**
- **A Power Rating of 30 kW was established during the operation.**

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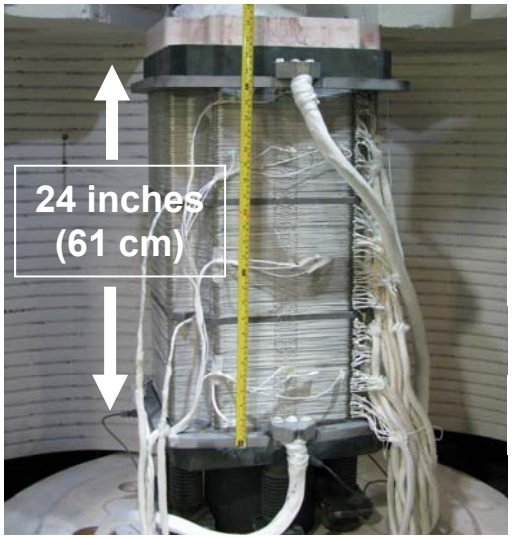
Next Steps – Metric Tests

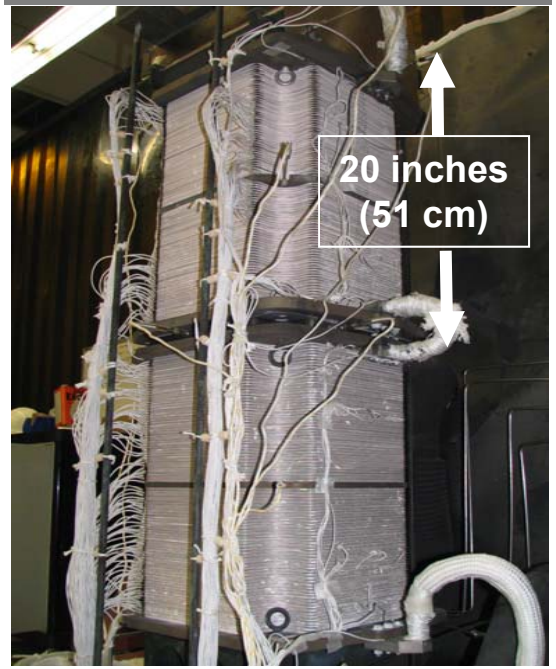
SECA Phase II Metric Test Minimum Requirements:

- Stack power rating ≥25 kW
- Degradation rate < 2%/1000 hrs
- Endurance tests: 1,500h in Phase II plus 3,500h in Phase III (5000h total)

120-Cell Stack



2x92-Cell Stack Tower



Two pronged approach:

A 120-cell stack block at VPS and a 2x92-cell stack tower at FCE

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Initial Performance (June 2010)
120-Cell Stack (GT058027-1)

GT058027-0001
120-cell Stack
Cell Active Area: 550 cm^2

Stack Current (A)

Power (kW)

Elapsed Time (hours)

Peak Power Testing
Furnace Temperature: 700°C
Fuel: 33.6% H_2, 21.5% N_2, 12.5% NG, 32.4% H_2O
In-stack reforming = 60%, Uf = 65%
Oxidant: Air, Ua = 15%
Current: 250 A (0.455 A/cm^2)

Normal Operating Conditions (NOC)
Furnace Temperature: 715°C
Fuel: 25.2% H_2, 22.4% N_2, 14.5% NG, 37.8% H_2O
In-stack reforming = 70%, Uf = 68%
Oxidant: Air, Ua = 15%
Current: 200 A (0.364 A/cm^2)

Future
5000 hr Tests

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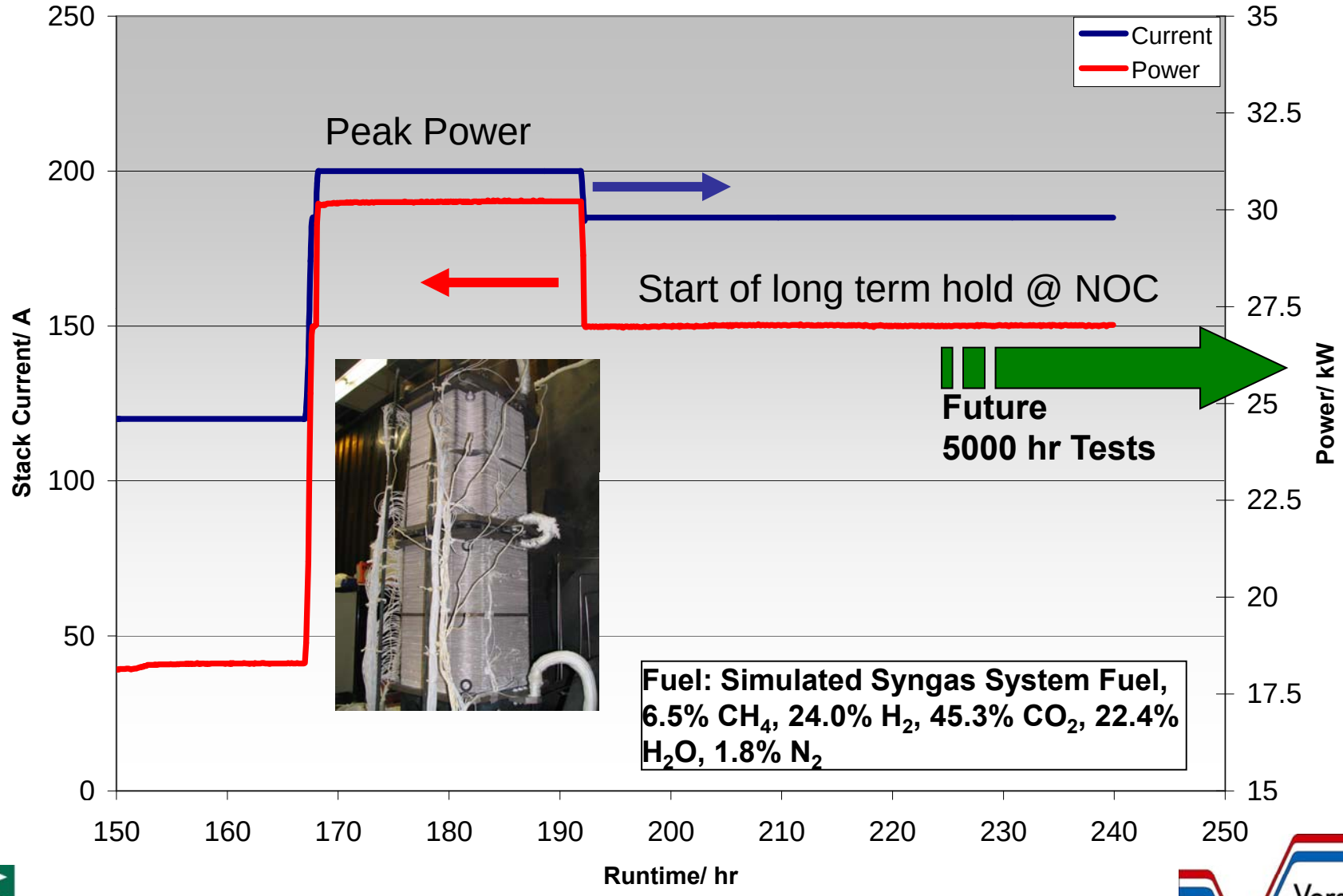
Phase II Stack Tower Metric Test at FCE



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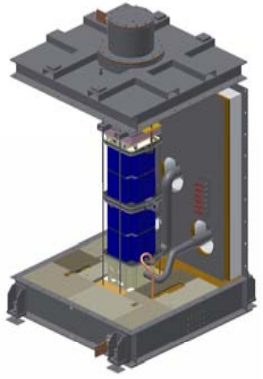
SOFC Module Evolution

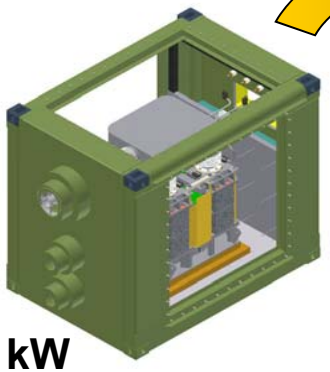
30-kW Tower Assembly (Phase II)

Stack Block

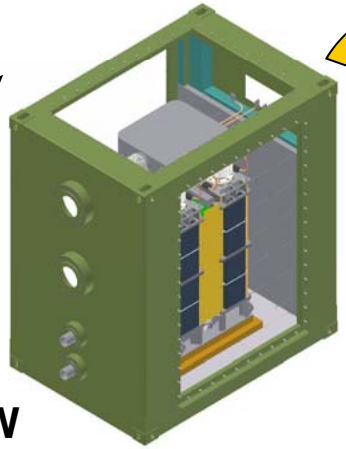


30 kW
2-Stack Tower

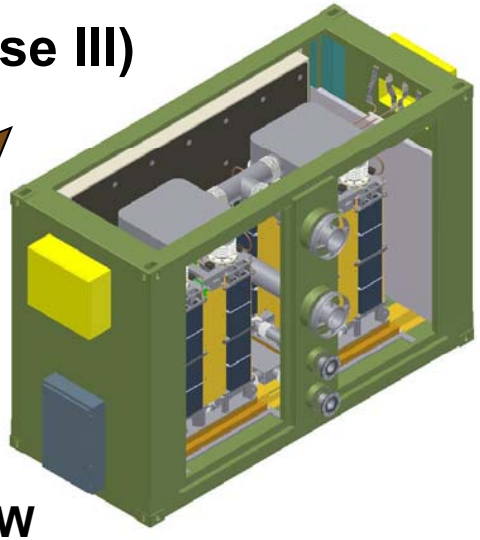
SOFC Stack Modules Assembly (Phase III)



60 kW
4-Stack
Quad



125 kW
4-Stack Tower
Quad



250 kW
2-Quad
Module

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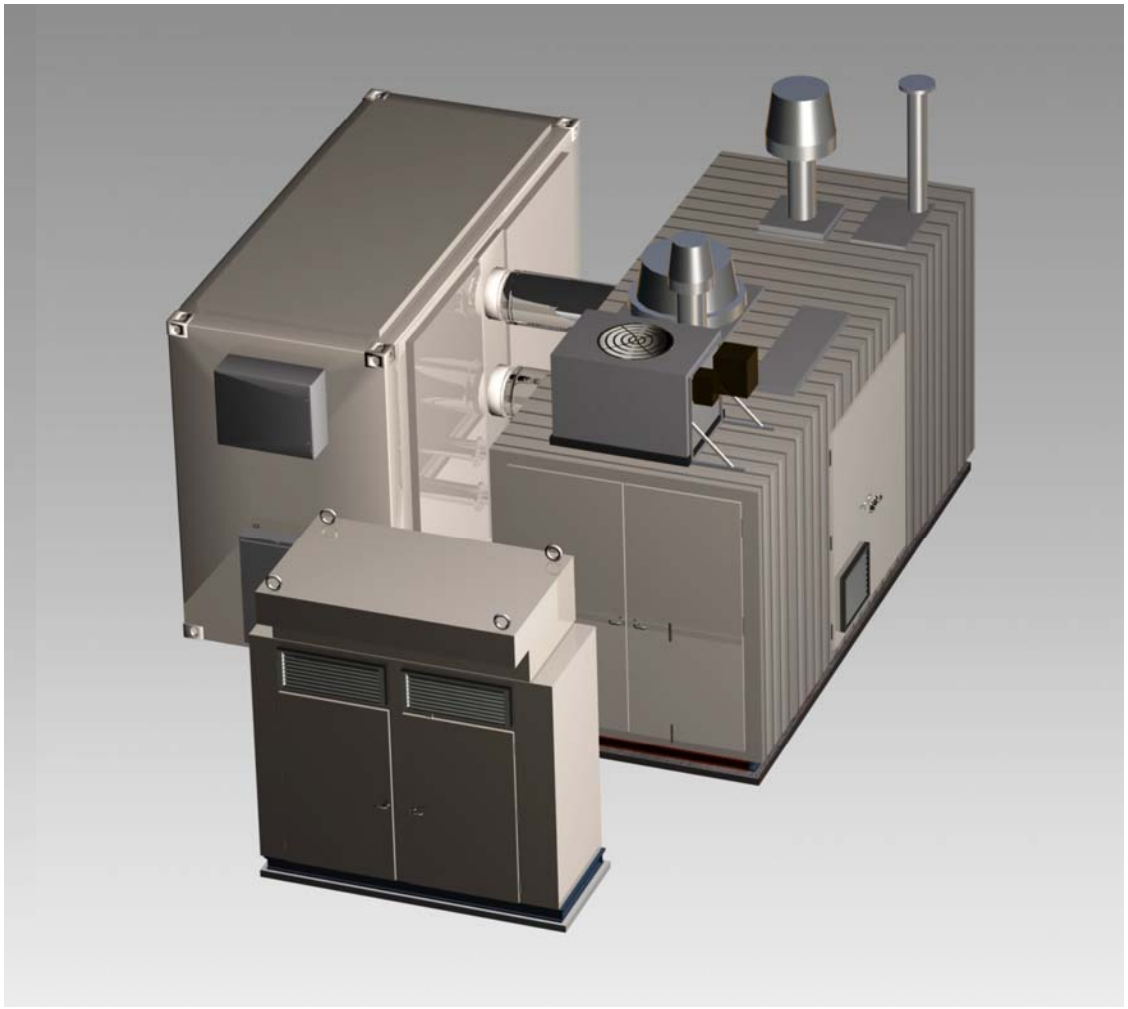
250kW SOFC Power Plant



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MW-Class SOFC Module Design

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

Net Efficiency Excluding CO_2 Compression & Thermal Input

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

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

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WorleyParsons
resources & energy

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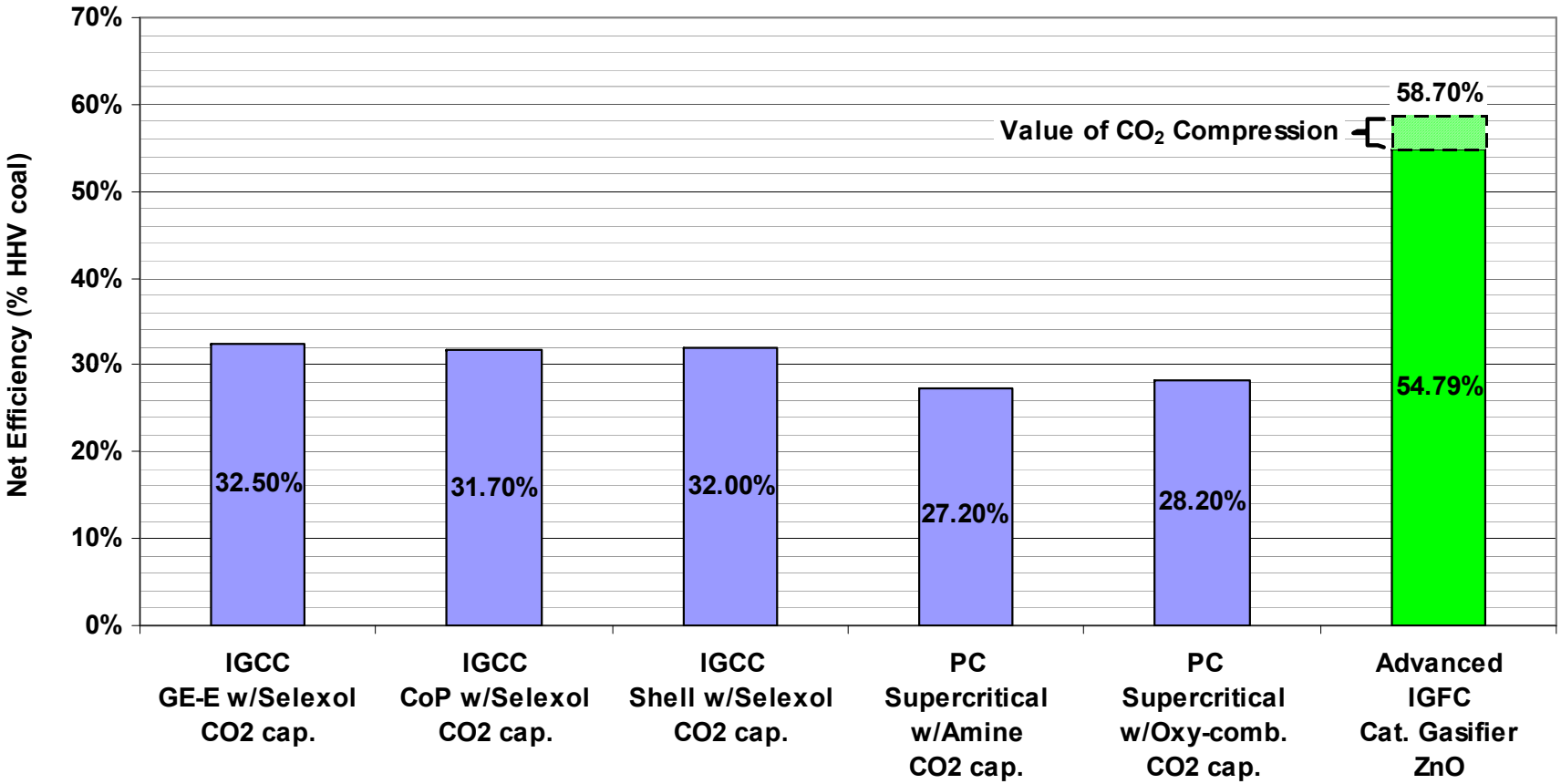
Baseline SOFC Power Plant Electrical Efficiency vs. Competing Technologies



Baseline coal based SOFC system is >22 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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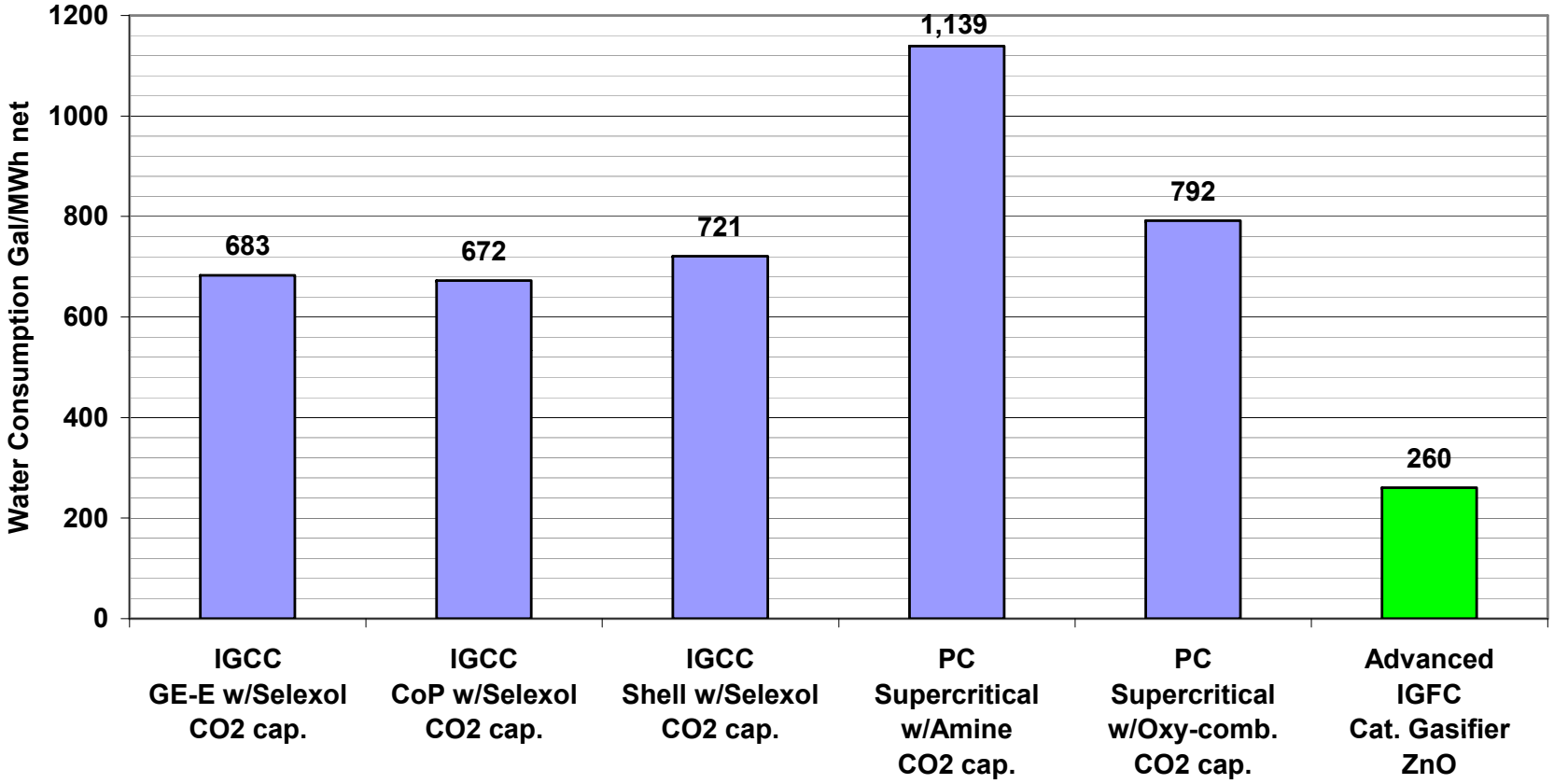
Baseline SOFC Power Plant Water Consumption vs. Competing Technologies



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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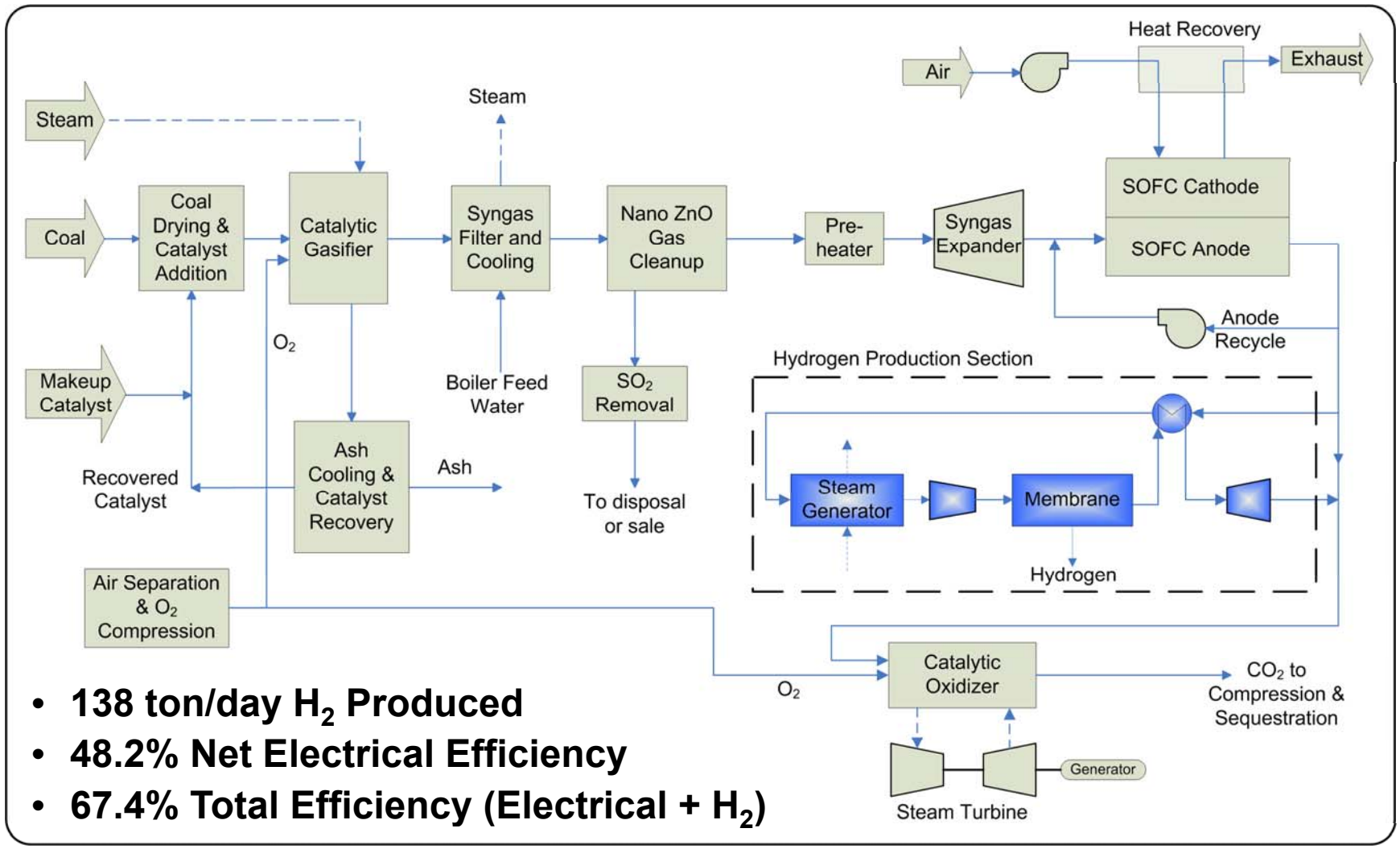
H2 Co-Generation System Concept



- **138 ton/day H_2 Produced**
- **48.2% Net Electrical Efficiency**
- **67.4% Total Efficiency (Electrical + H_2)**

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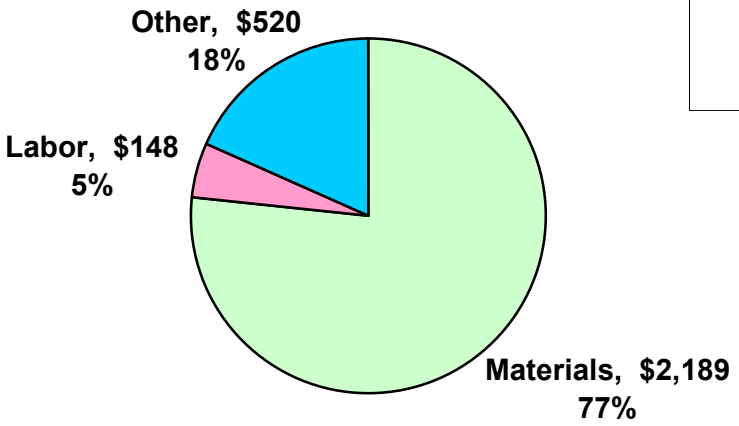
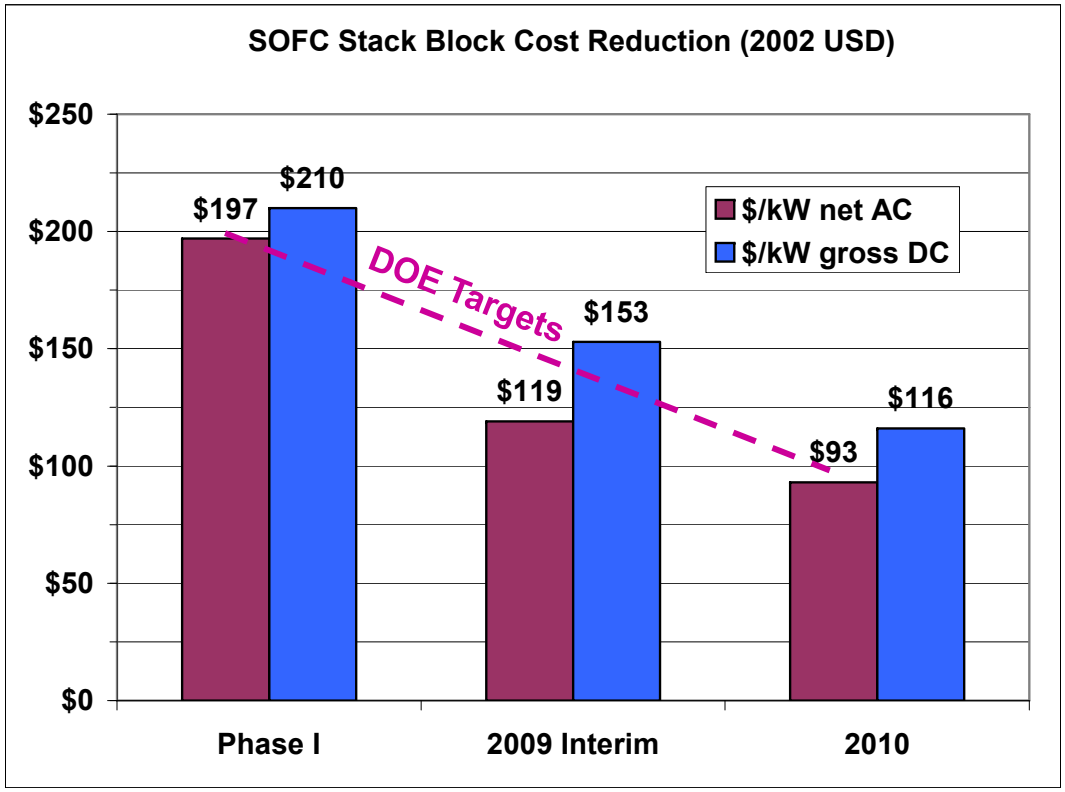
Stack Cost Reduction

96-cell Stack:

$2,857 (2002 USD)





Thin Cell Development

Stack Materials Reduction

Stack Block Scale Up

Power Density Improvements

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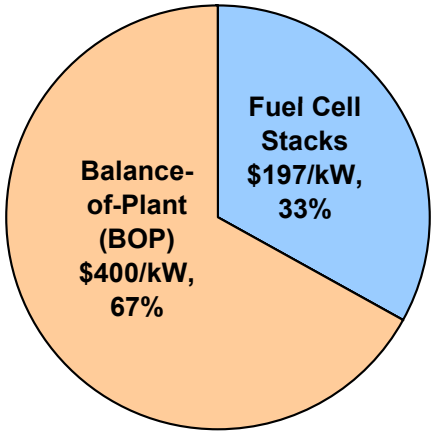
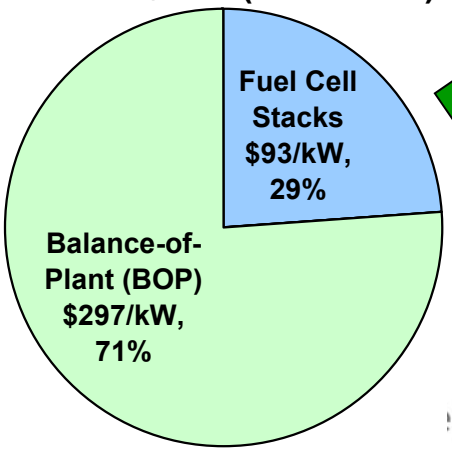
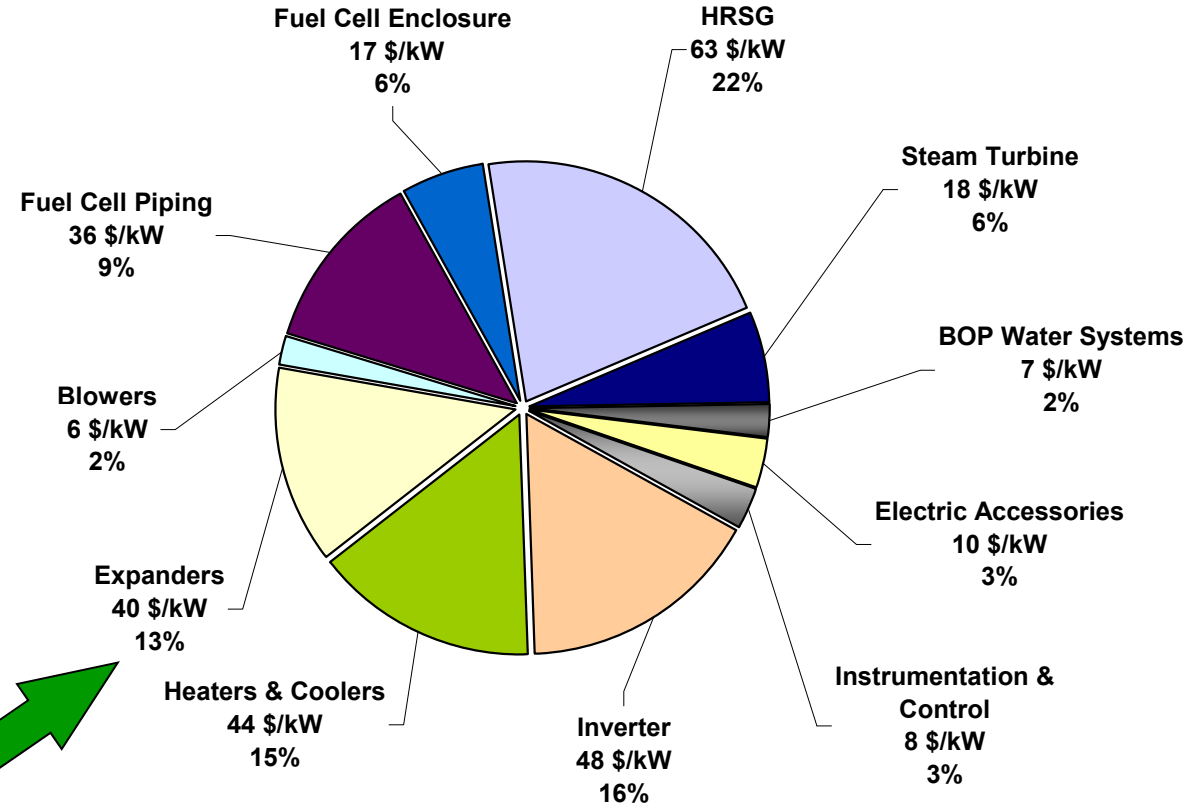
Factory Equipment Cost Estimate

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



Phase II Interim Cost Estimate:
390 $/kW (2002 USD)





- Cost estimation is based on two 570 MW nominal power plants manufactured per year (2002 USD).
- Estimate includes Factory Equipment costs for the Power Island, exclusive of gasification, syngas cleanup, and CO_2 separation/compression systems.

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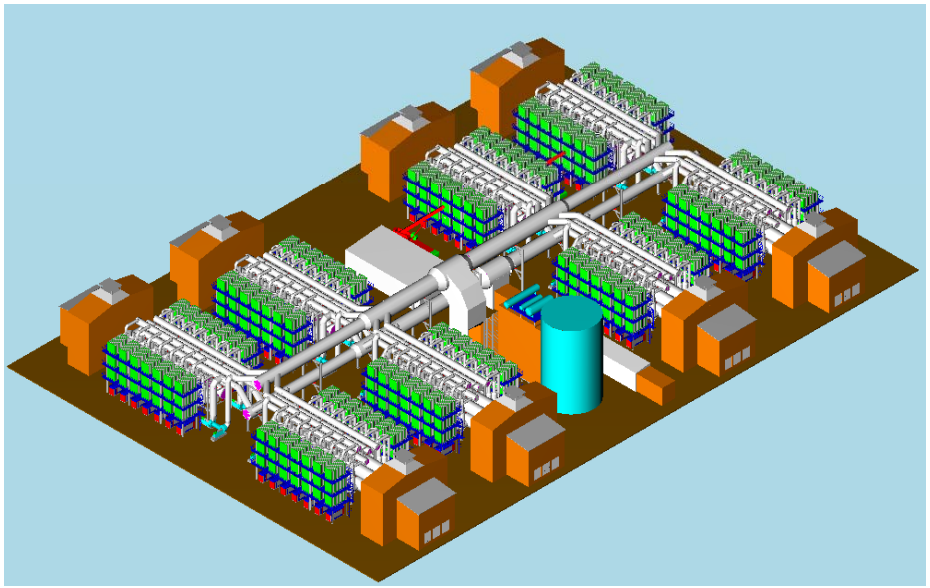
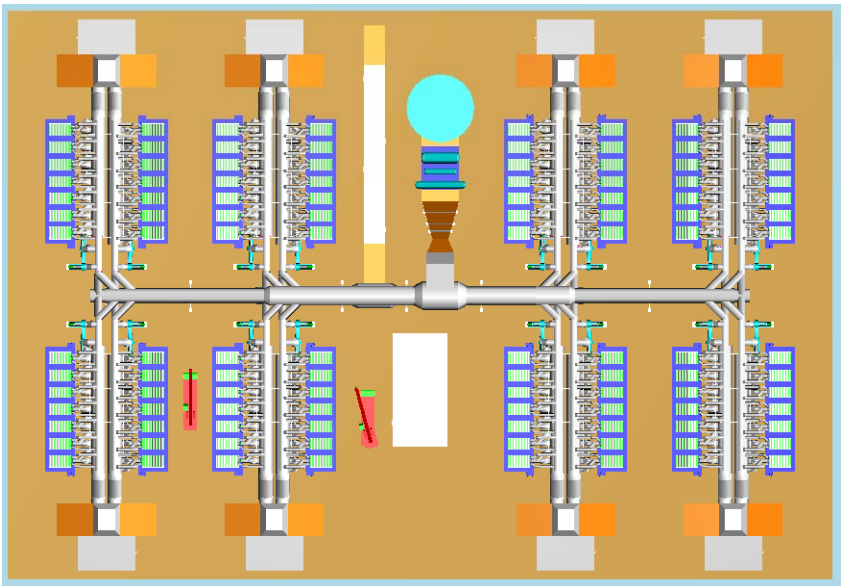
Baseline SOFC Power Island

- SOFC power island includes:
  - > 8 Sections of 42 fuel cell stack modules
  - > Steam turbine
  - > Two syngas expanders





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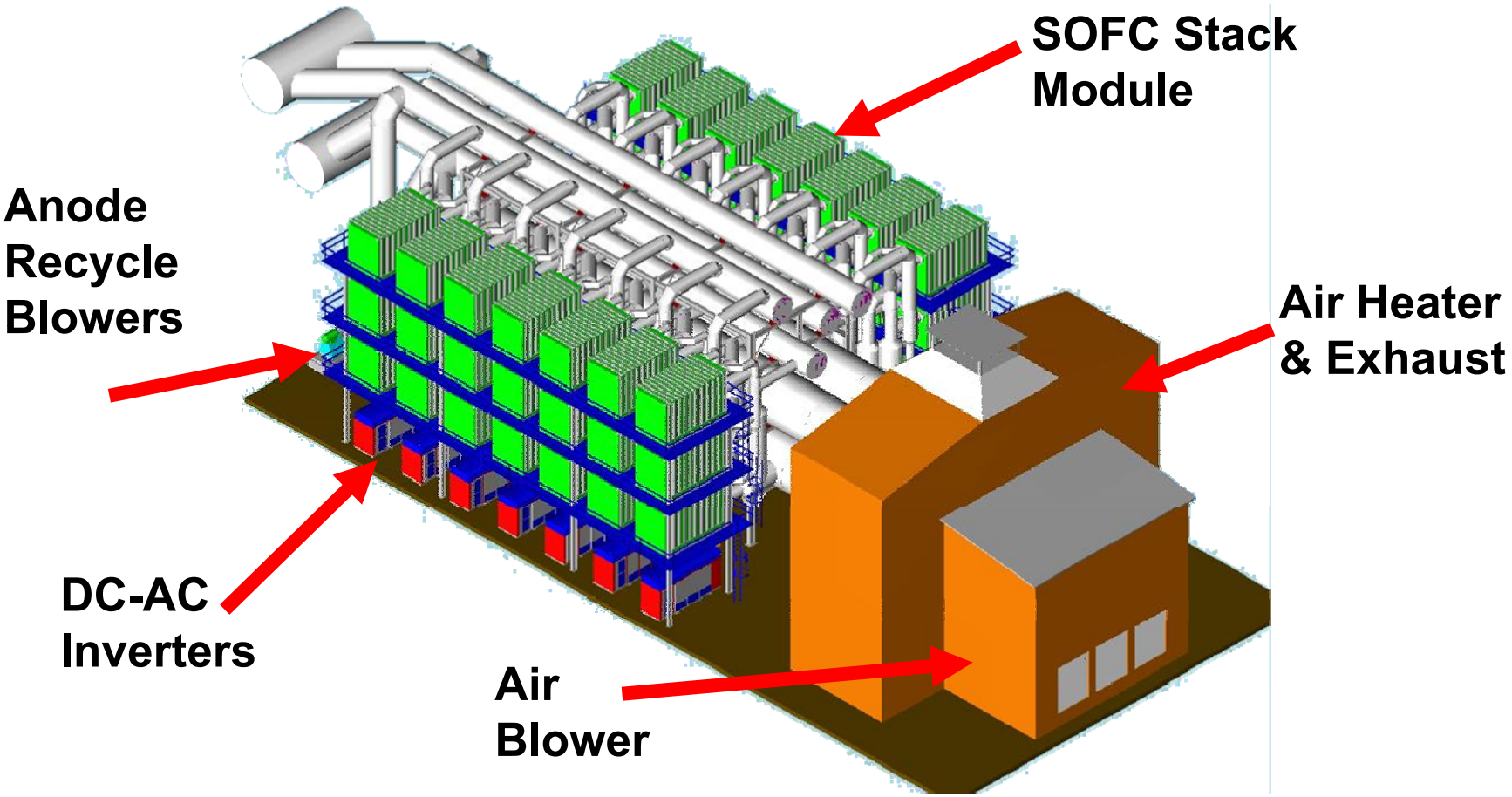
Layout of 42-Module SOFC Cluster



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

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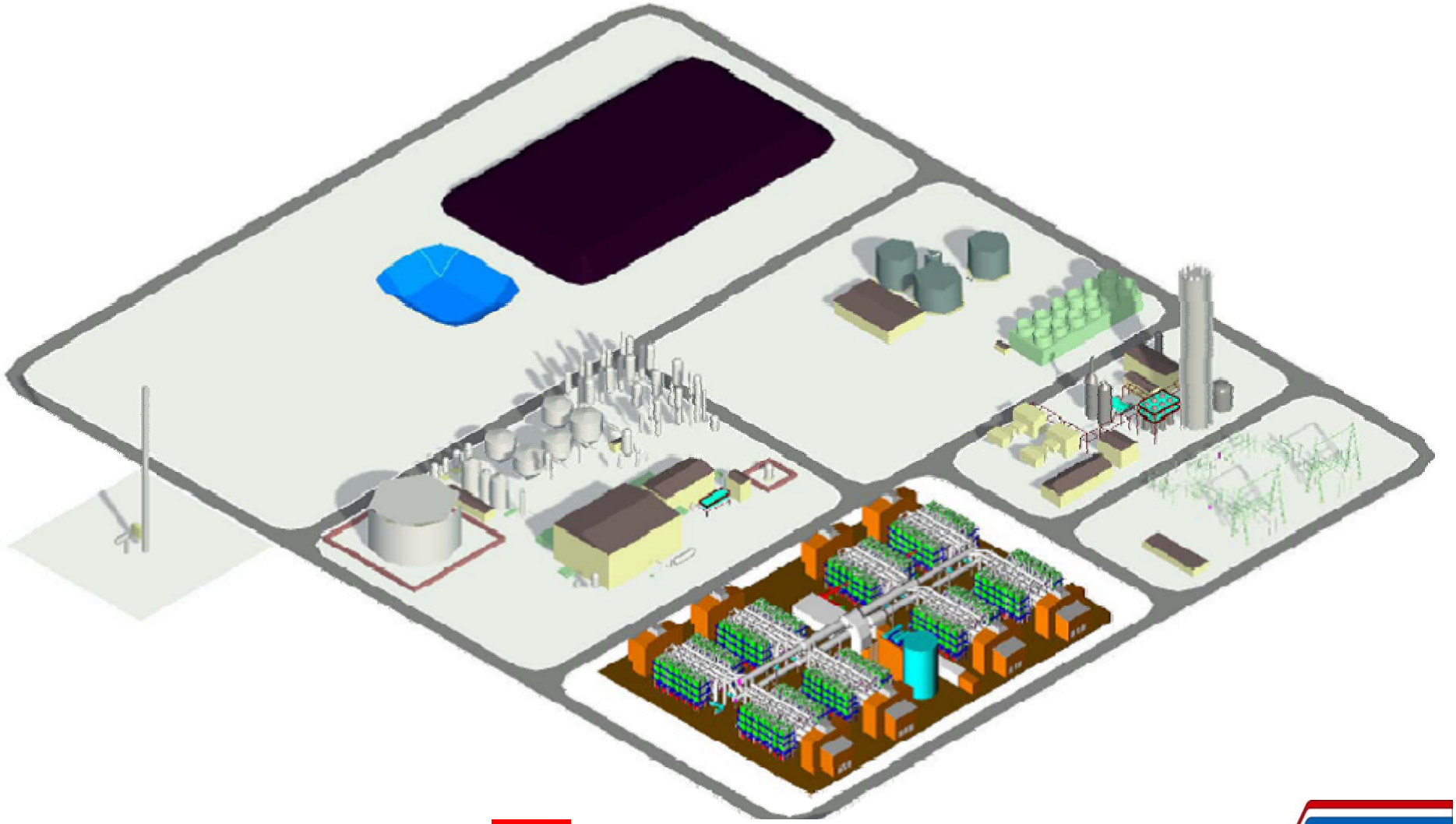
IGFC Site Layout



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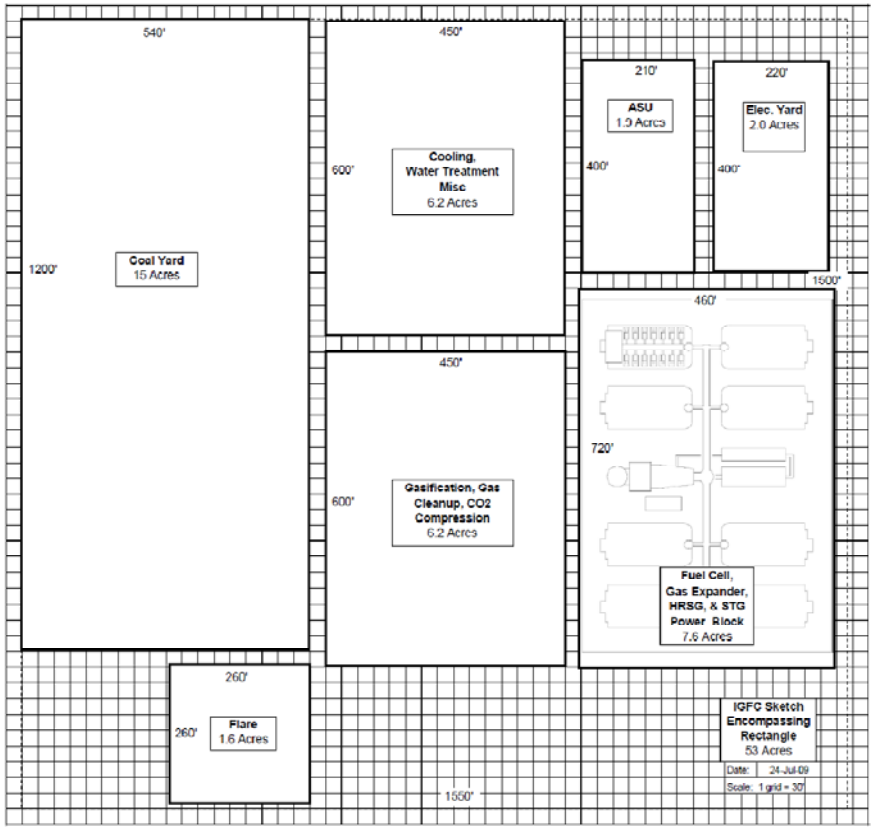
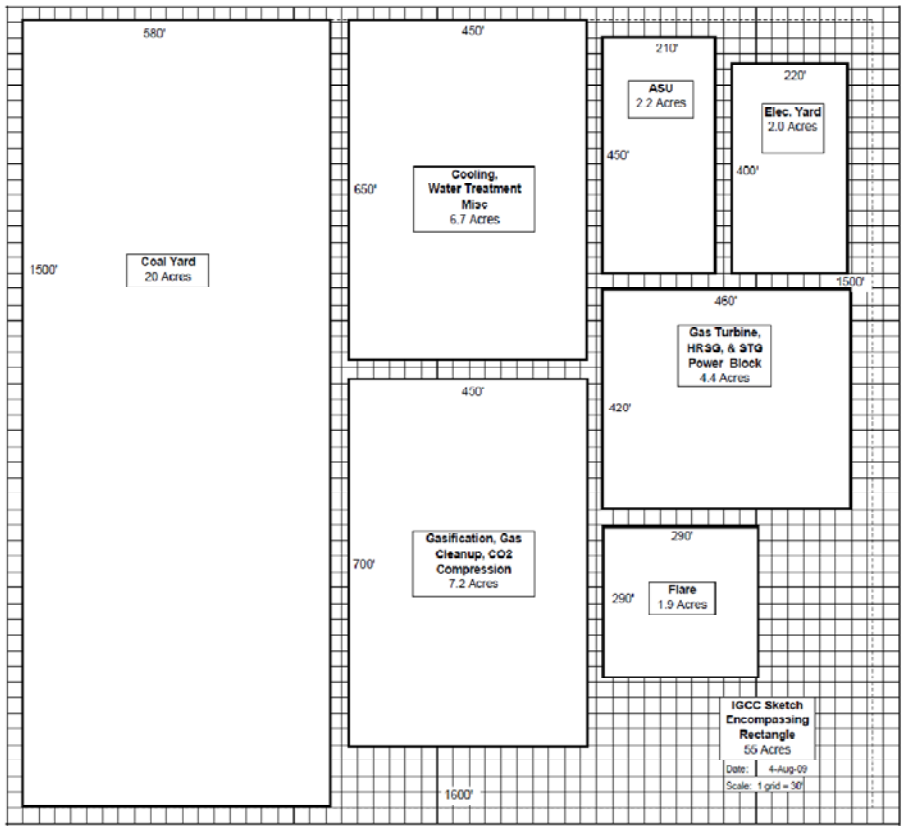
Representative Foot Print Comparison: IGFC & IGCC

IGFC



IGCC



- **A similarly sized (MW) IGCC and IGFC will be comparable in real estate requirement.**

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Presentation Outline

- Introduction
  - FCE SECA program team members
- SECA Coal-Based SOFC Program Outline
- Progress in SOFC Technology
- Stack Development
  - Metric Tests
- Module Demonstration Unit Development
- Baseline System Design and Cost Analyses
  - Integrated Gasification Fuel Cell (IGFC) System Configuration
  - Baseline Power Plant Cost Estimate
- **Conclusions**

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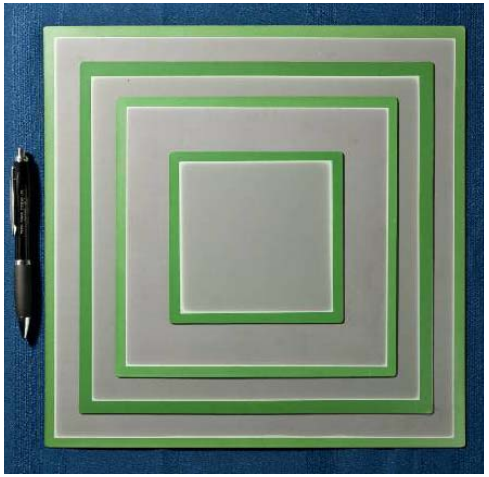
Summary of Recent Achievements



- Demonstrated new TSC3 cell with ASR less than 0.35 ohm·cm^2 at 650°C and a degradation rate of less than 0.3% per 1000 h at 750°C (on-going test of over 7,000 h)
- Established cell manufacturing processes for the new baseline TSC3 cell with an active area of 550 cm^2 (25 x 25 cm^2)

- Demonstrated performance and endurance improvements in scaled up stacks with TSC3 cells
- Developed a 92-cell stack block that produces 18 kW and has been successfully tested in a 2 x 92-cell stack tower
- Demonstrated 25 kW from a 120-cell stack

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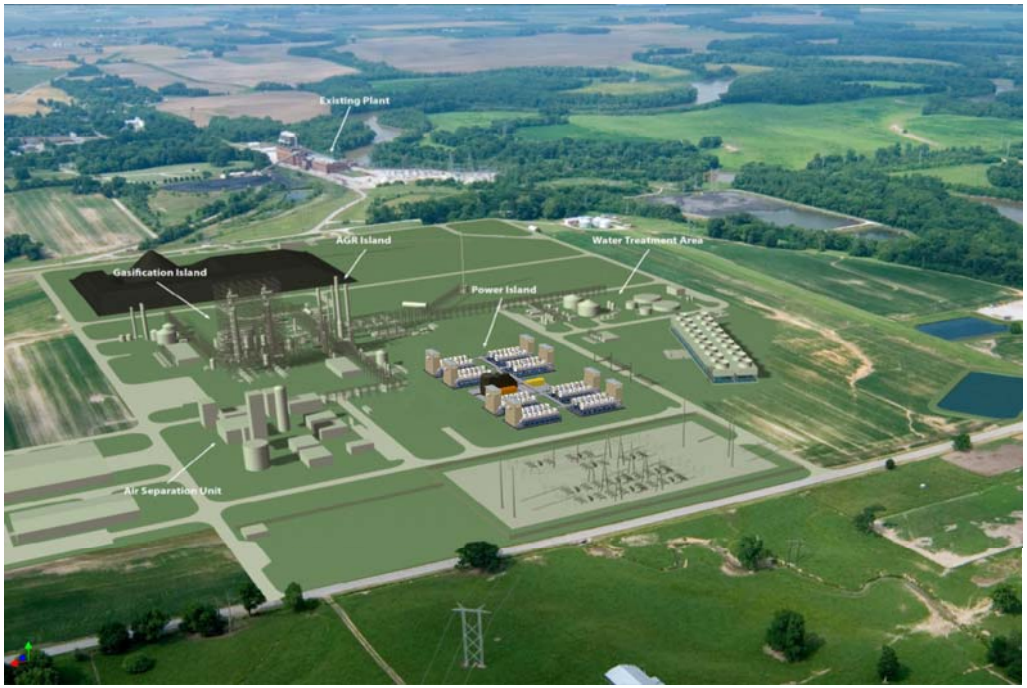
Summary of Recent Achievements

- Baseline Systems with Catalytic Gasifier were developed which could achieve electrical efficiency (HHV) of 59% and remove more than 99% carbon from syngas.
- Baseline 400-600MW power plant layout and Factory Cost Estimates were developed resulting in an interim cost estimate of $390/kW (in 2002 dollars) for the SOFC power island.
- The developed IGFC system showed significantly lower water consumption as compared to IGCC and other coal fueled power plants.



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- Support and guidance by the management team at NETL

Thank You!

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