Progress in SECA Coal-Based Program

12th Annual SECA Workshop
Pittsburgh, PA
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FuelCell Energy

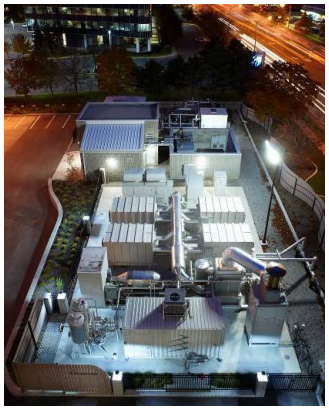
Versa Power Systems

Presentation Outline

- **Introduction**
  - FCE SECA Program Team Members
- **SECA Coal-Based SOFC Program Overview**
- **Progress in SOFC Technology**
  - Cell Development and Manufacturing
- **Stack Development**
  - Scale-up and Metric Tests
- **Proof-of-Concept Module (PCM) Development**
  - Stack Module
- **Baseline System Design and Cost Analyses**
  - Integrated Gasification Fuel Cell (IGFC) System Configuration
  - Baseline Power Plant Cost Estimate
- **Conclusion and Future Plans**

FuelCell Energy (FCE)

- Premier developer of stationary fuel cells with >40 years of experience
- Headquarters and R&D in Danbury, CT (USA), with 65,000 ft^2 manufacturing facility in Torrington, CT (USA)
- Delivering Direct FuelCell® (DFC®) power plants to commercial and industrial customers
  - 182 MW installed and in backlog
  - Over 80 plants generating power at more than 50 sites globally
- Product sales and service backlog in excess of $200 million
- Established commercial relationships with major distributors in the Americas, Europe, and Asia
- Developing large-scale coal-based power plants as well as natural gas distributed generation (DG) systems utilizing planar SOFC



Multi- MW DFC-ERG in Toronto, Canada

600 kW plant at a food processor

1.4 MW at a municipal building

2.4 MW plant owned by an IPP

11.2 MW plant owned by an IPP

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Versa Power Systems (VPS)

- **Privately held company**
  - > Founded as joint venture of Solid Oxide Fuel Cell Consortium in 2001
  - > Headquartered in Littleton, Colorado, United States
  - > SOFC development facility in Calgary, Alberta, Canada
- **Planar solid oxide fuel cell technology**
  - > Achieved high electrical power densities and long life using low-cost materials
  - > Established manufacturing processes scalable to high volume production rates
- **Current product effort focus on SECA stacks**
  - > Developed and verified modular approach providing size flexibility
  - > Existing 32,000 ft^2 facility has capacity for initial market production

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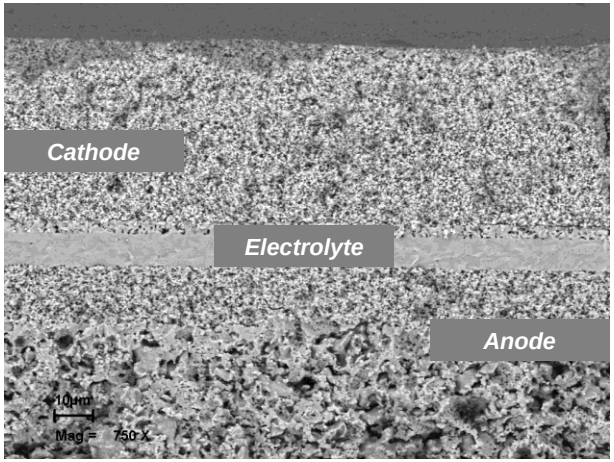
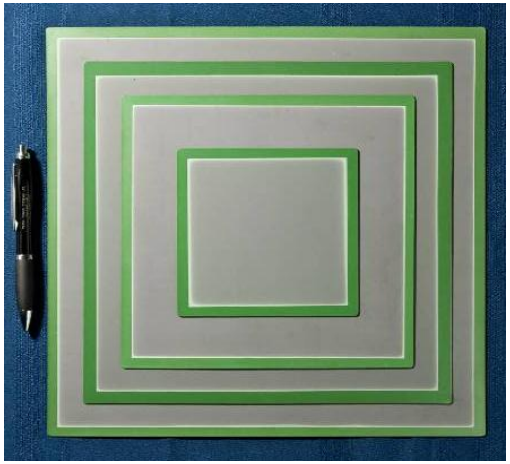
SOFC Cell and Stack Technology Background

- Planar 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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Program Technology Area

FCE's program focuses on the development of solid oxide fuel cell (SOFC) cell and stack technology suitable for use in highly-efficient, economically-competitive central generation power plant facilities fueled by coal derived synthesis gas (syngas).

Program Goals

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 (2000 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

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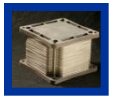
Coal-Based SECA Program Status

- **FCE team successfully completed Phase II of the Coal with Based SECA Program in April 2011 with development of a new generation of low-cost high-performance cell technology.**
- **SECA Phase III Project is to enhance stack robustness and reliability for development of a >50kW Stack Module.**

2006

1 kW Stack



Phase I

2008

10 kW Stack

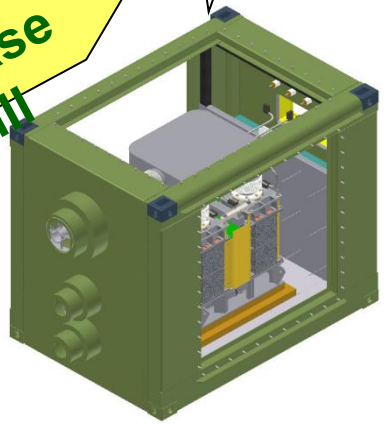
Phase II

2010

30 kW Stack Tower

Phase III

2012



60 kW Stack Module

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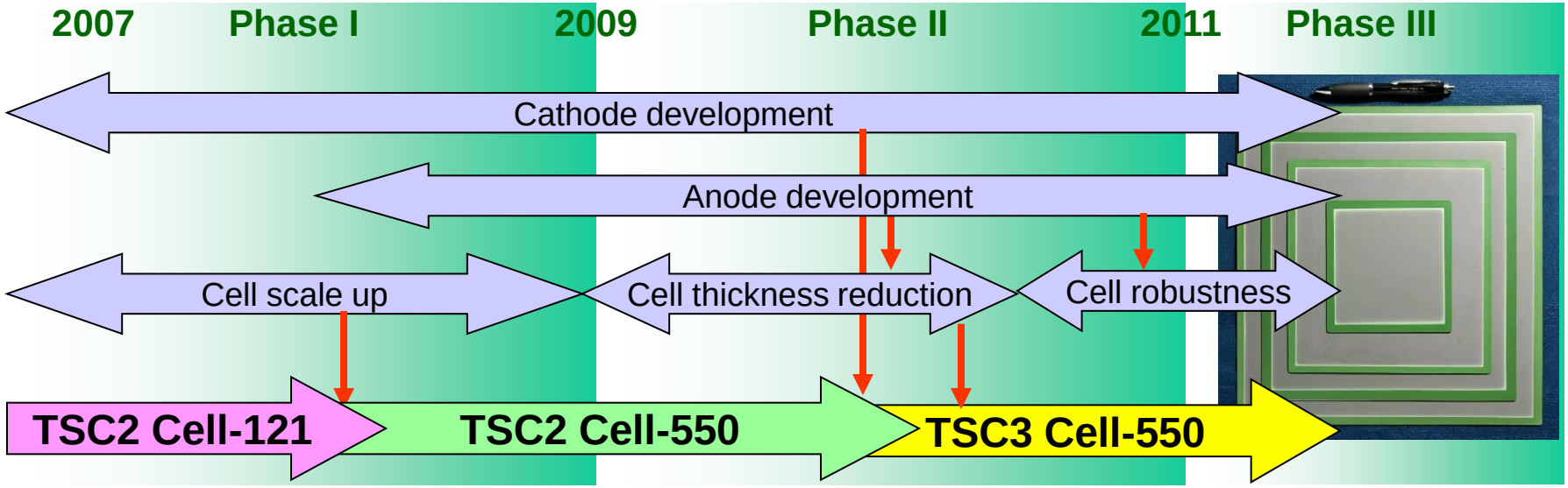
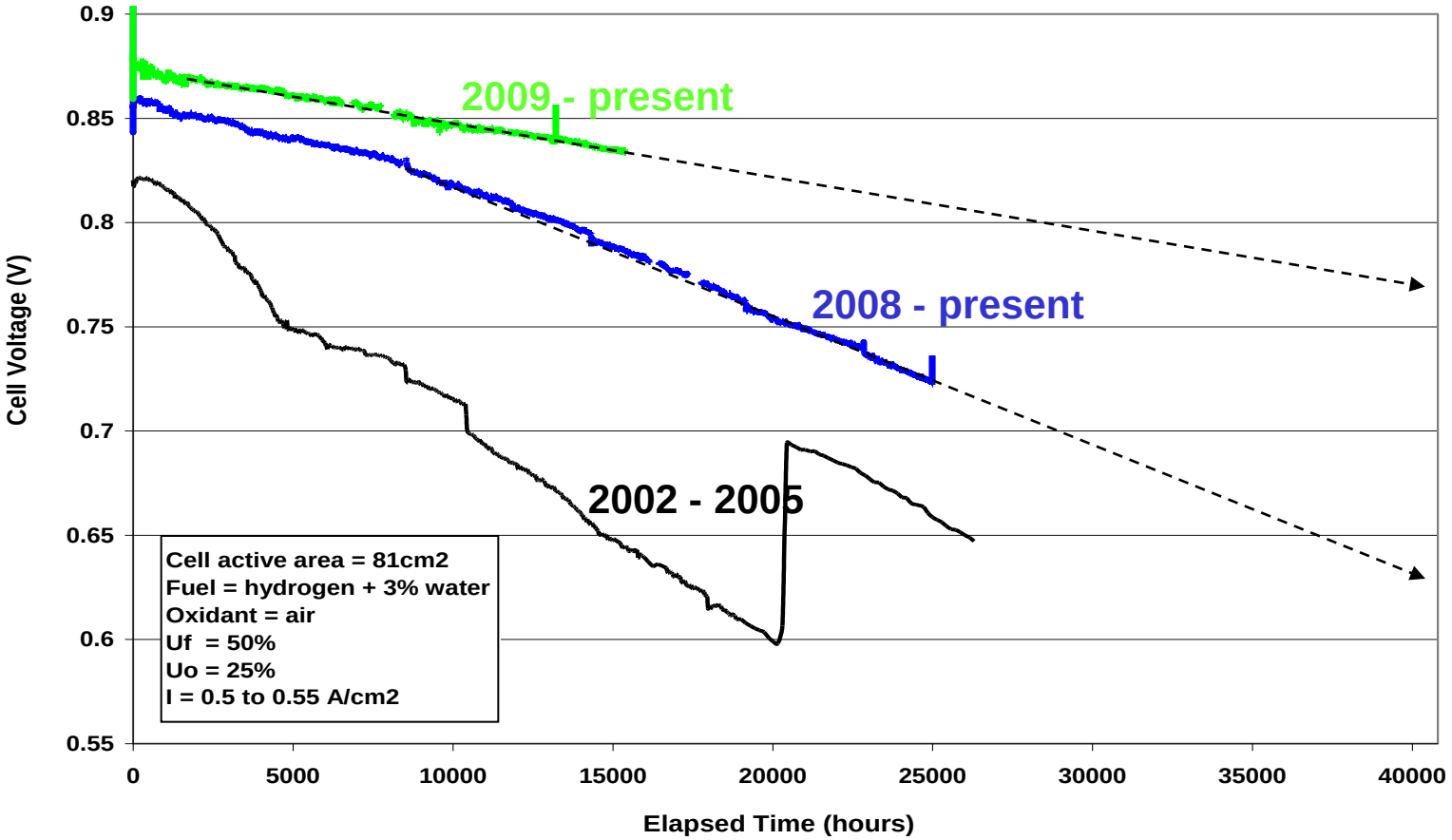
Cell Development Accomplishments



- **Cathode Development**
  - ☑ Enhanced Performance and Endurance
  - ☑ Reduced Operating Temperature
  - ☑ Increased Operating Window
- **Anode Development**
  - ☑ Reduced Cell Thickness
  - ☑ Enhanced Performance at Higher Fuel Utilization and at Lower Temperature
  - ☑ Enhanced Cell Mechanical Properties and Robustness
- **Scale Up & Manufacturing Development**
  - ☑ Scaled up from 121 cm^2 → 550 cm^2 →1000 cm^2
  - ☑ Established Manufacturing Processes for Baseline 550cm^2 Cells
  - ☑ Completed Process Integration and Validation in Transitioning from TSC2 → TSC3 technology

The Evolution of Cell Technology



➡ **Significant progress has been made toward enhancing cell performance and endurance.**

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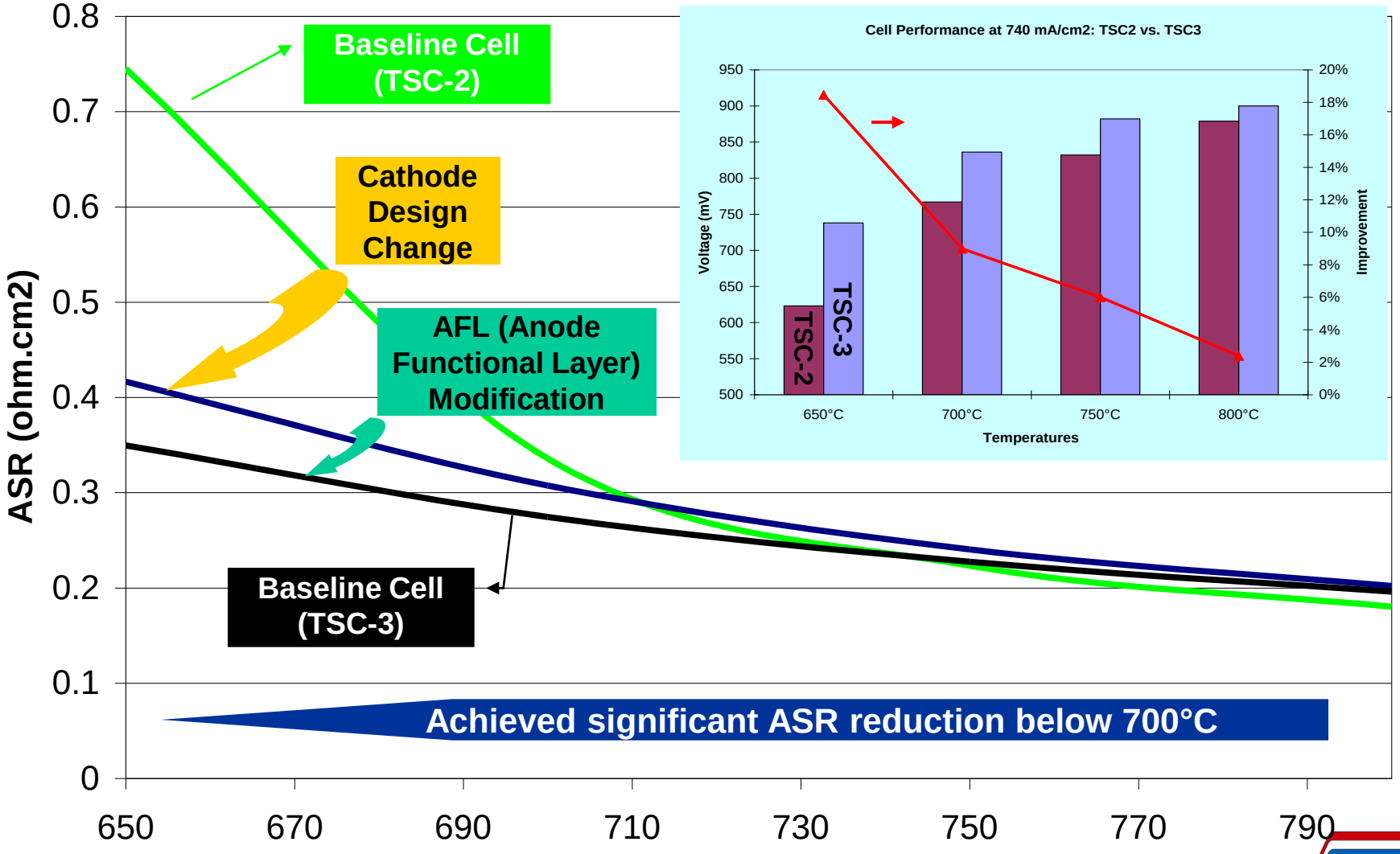
ASR (Area Specific Resistance) Reduction and Performance Improvement



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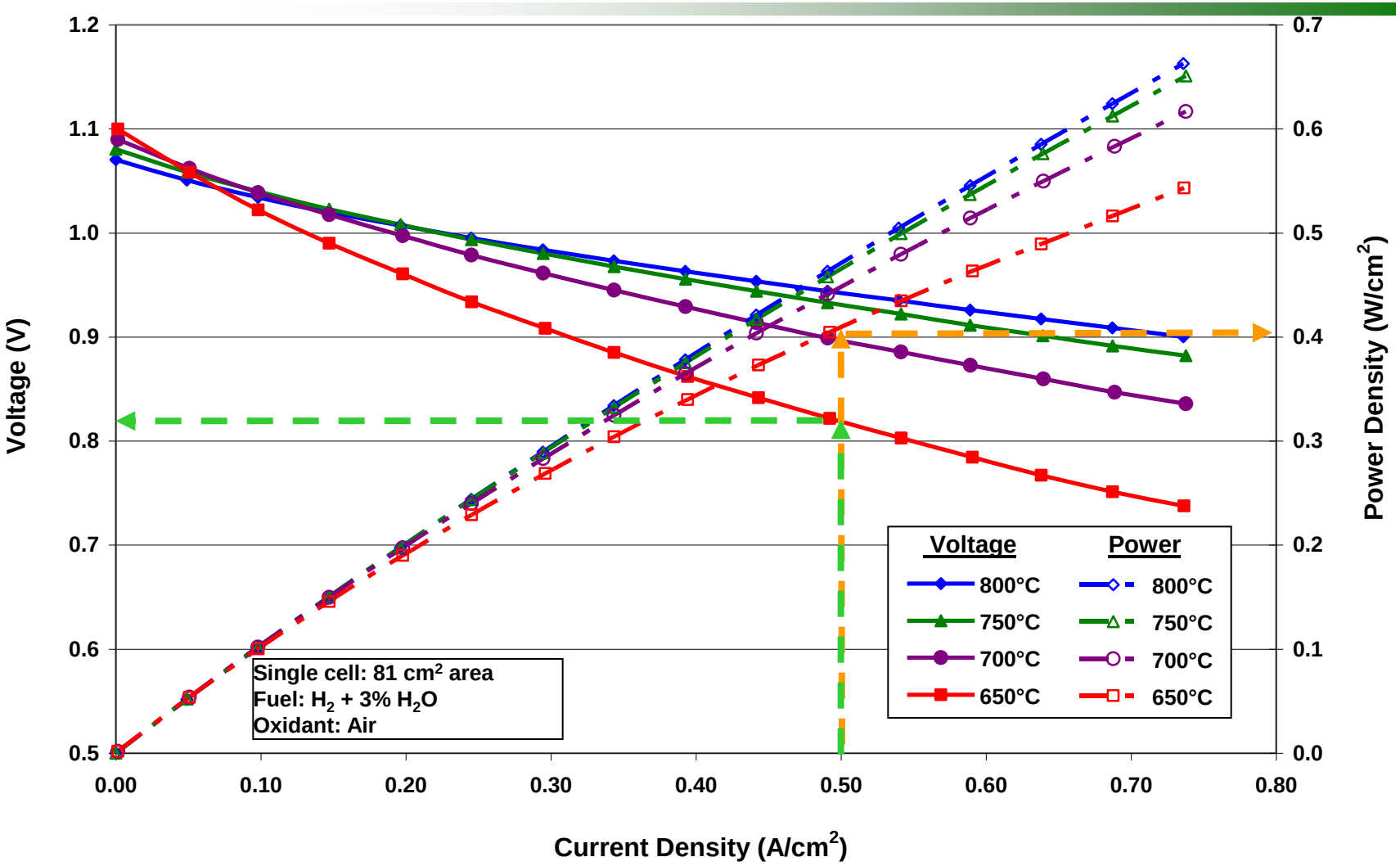
Performance of Improved Cells



➡ **Cell voltage of >800 mV and power density of 400 mW/cm² at 650 C were achieved.**

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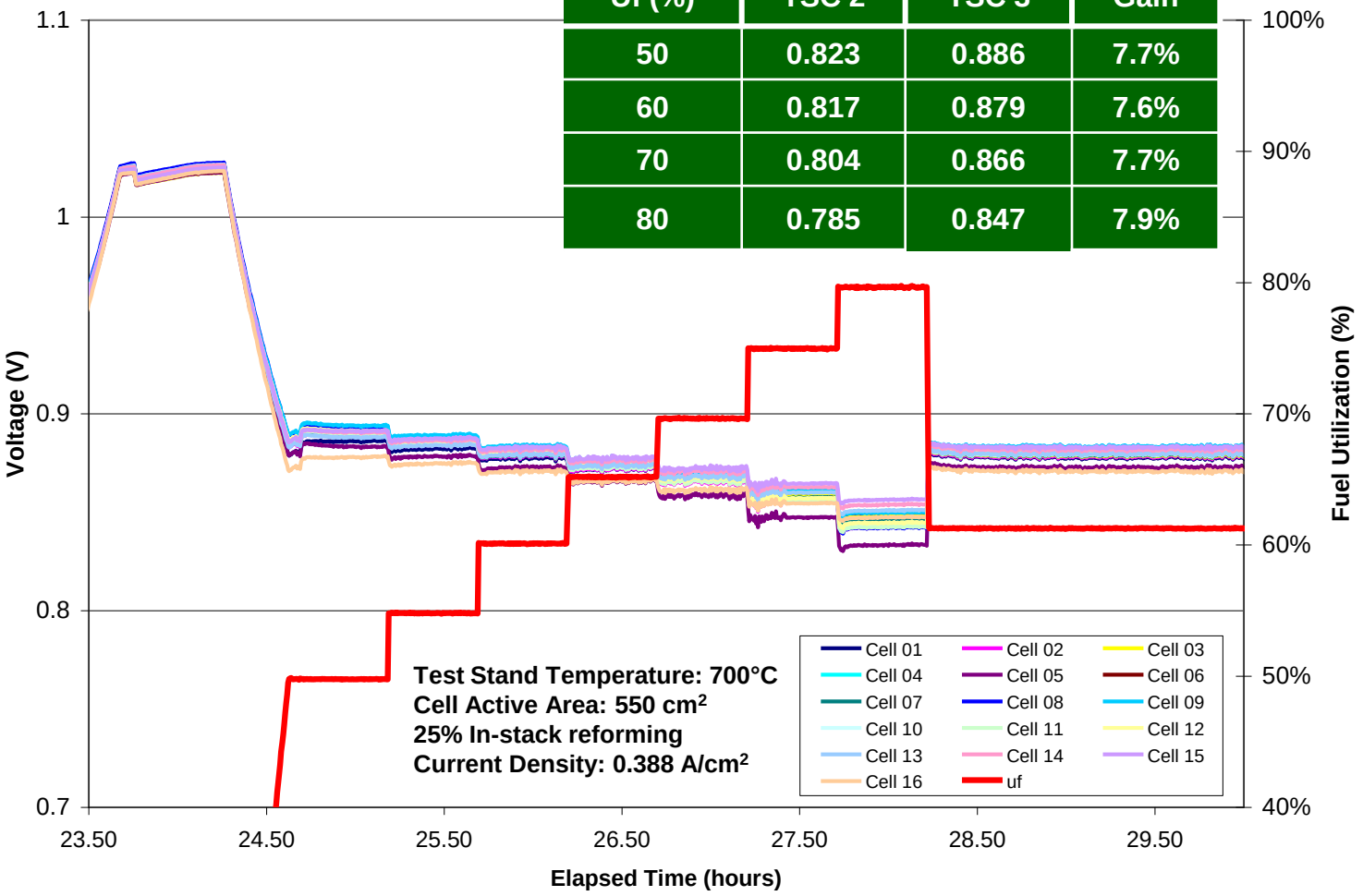
Cell Performance Enhancement in Stack

Uf (%)	TSC 2	TSC 3	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%



➡ **Scale-up TSC-3 cells with thin anodes have shown high performance at high fuel utilizations in a 16-cell stack.**

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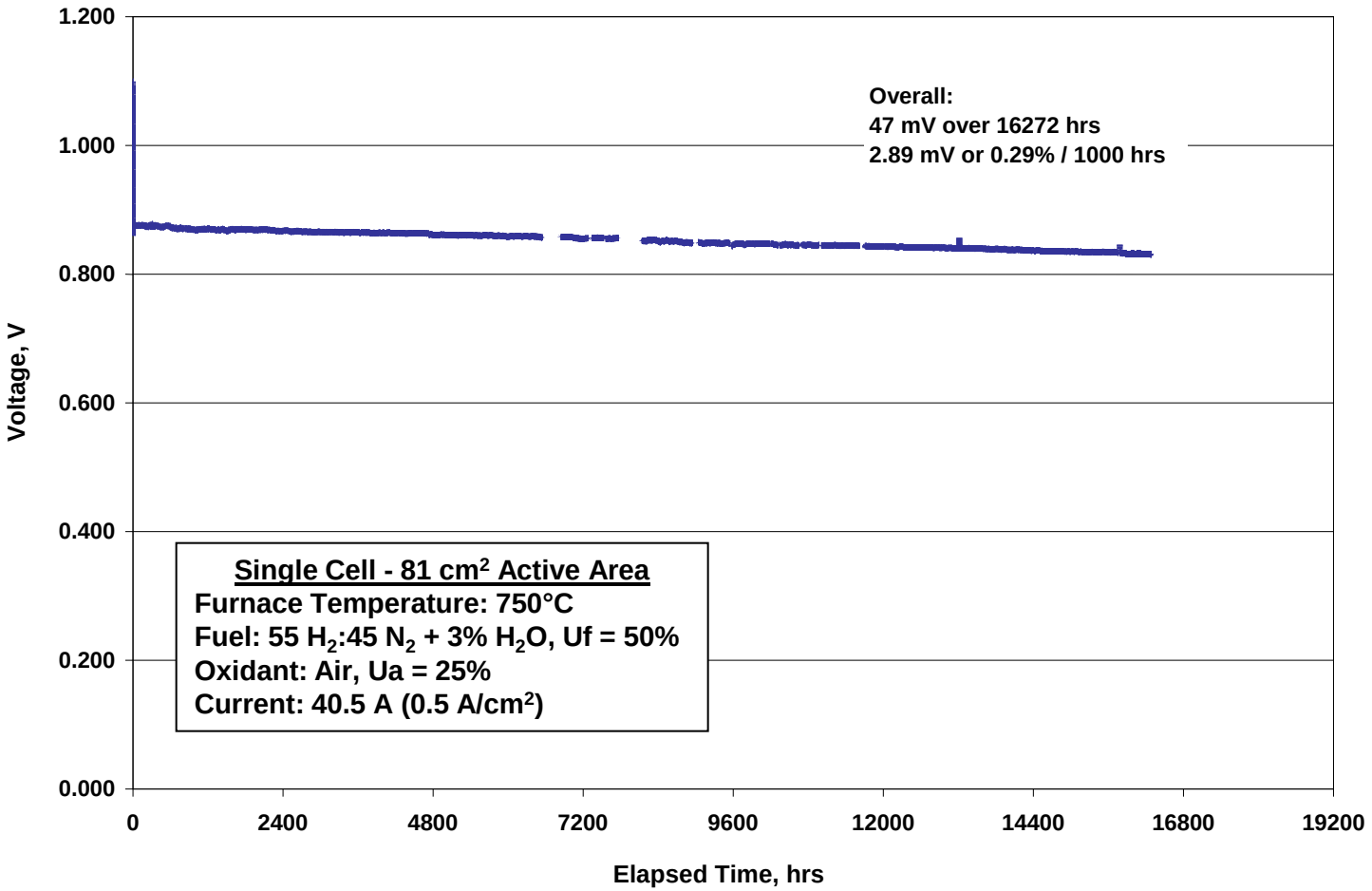
Single Cell Stability Achievements (750 C)



- **Performance degradation rate of <0.3%/1000 h was achieved in 17,000 h of operation using new generation TSC-3 cell technology and interconnect alloy.**

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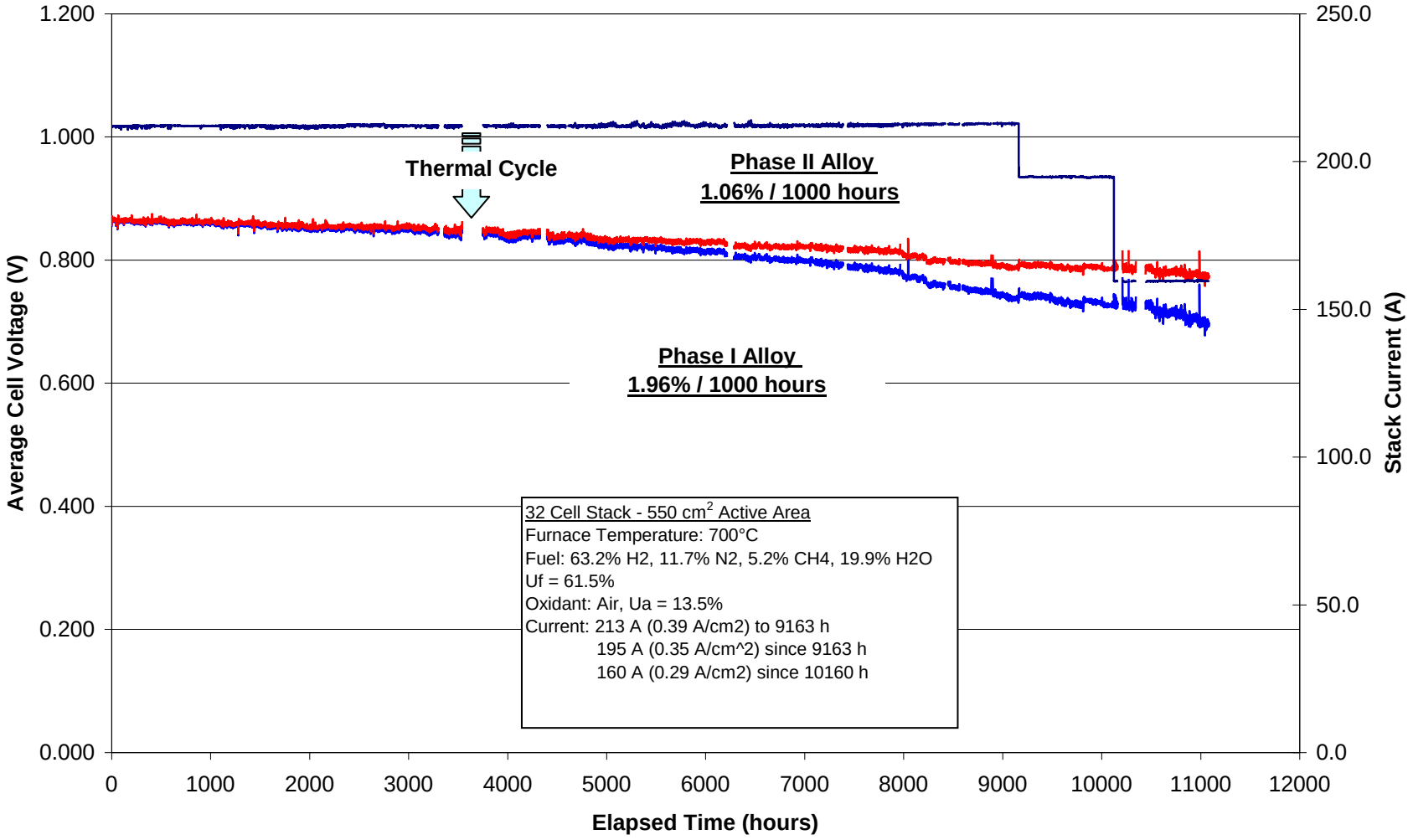
Parametric Testing of Alloys in a 32-cell Stack



➡ **Phase II research has identified a superior alloy, offering higher oxidation resistance and a lower performance degradation rate.**

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Recent Achievements in Cell Fabrication Process


Tape Casting


Screen Printing


Co-sintering

- 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
  - > Capital equipment for all major process units was added in order to accommodate increased cell size and volume
- Developed and implemented the next generation of cell fabrication processes
  - > Cell thickness was reduced by more than 40%
- Fabricated > 5000 cells (25 x 25 cm^2)
  - > Production volume of 500 kW (annual) was established and yield greater than 95% was demonstrated

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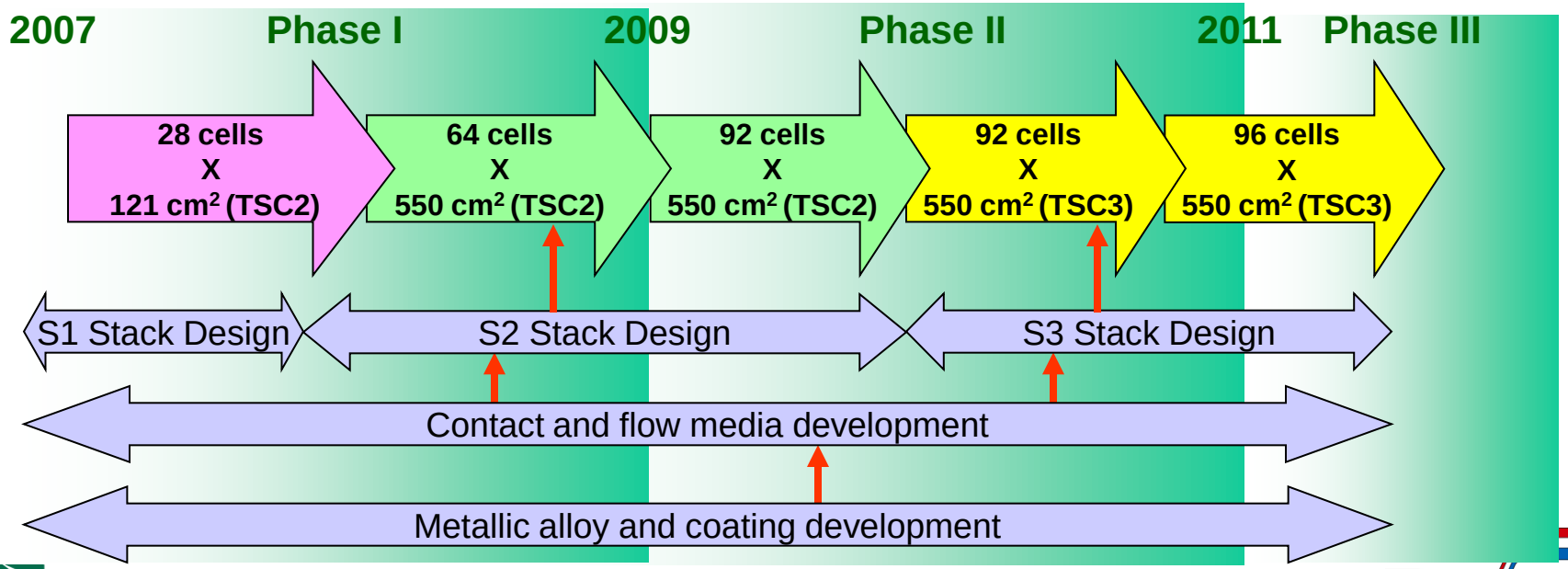
Stack Development Accomplishments

- **Improved stack performance**
  - ☑ Higher power density
  - ☑ Higher fuel utilization
  - ☑ Higher direct internal reforming
- **Enhanced stack endurance**
  - ☑ Improved stack thermal and flow management
  - ☑ Incorporated TSC3 cells
  - ☑ Incorporated advanced interconnect alloy, contact and flow media
- **Reduced stack cost**

Cell Size	25 x 25 cm^2
Active Area	550 cm^2
Number of Cells	92



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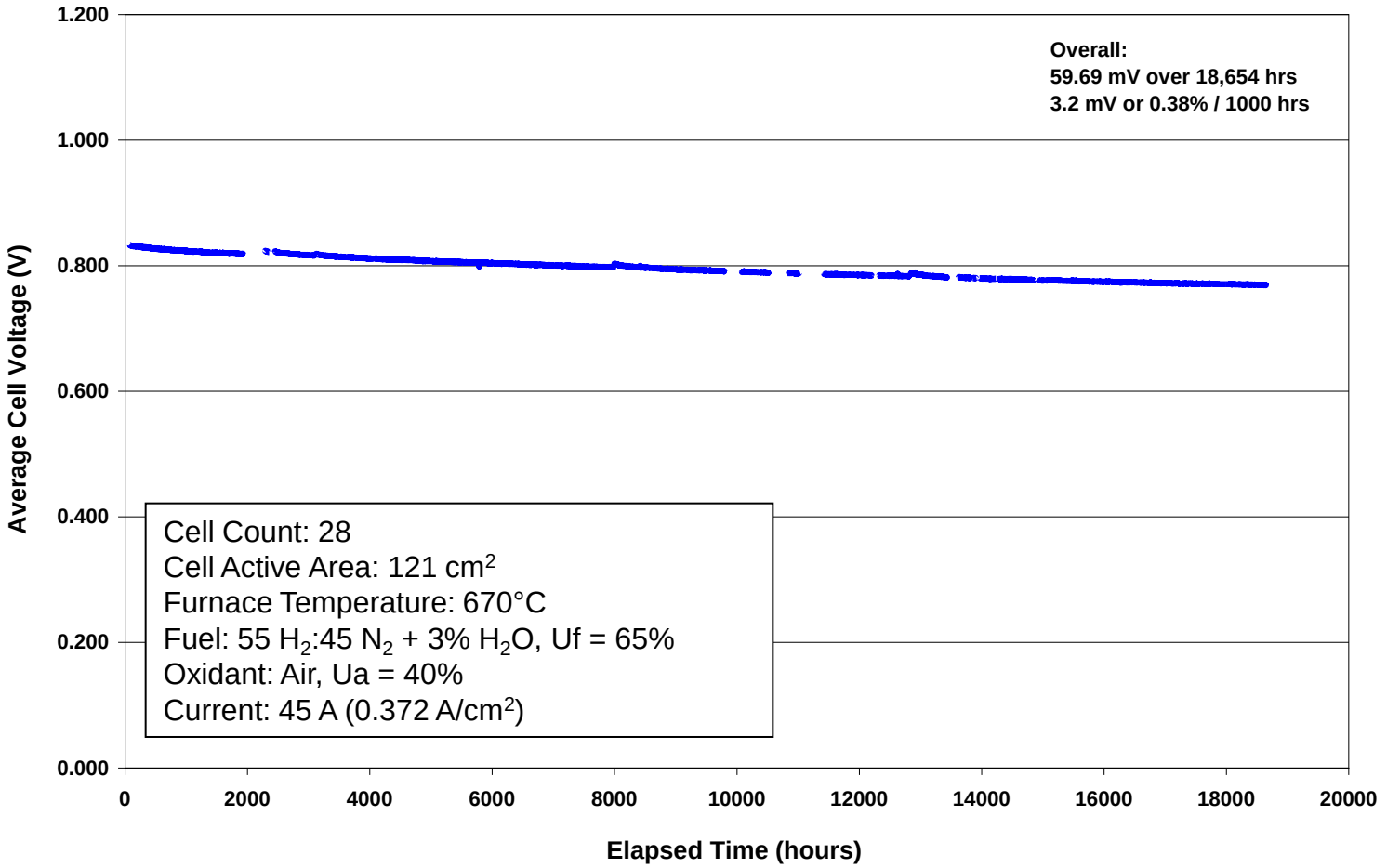
Stack Endurance Tests



➡ **Low performance degradation rate (~0.4% /1000 hr) is demonstrated in a sub-scale stack with > 2 years of operation.**

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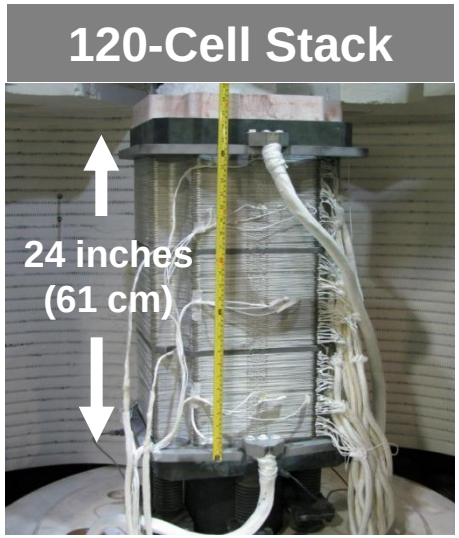
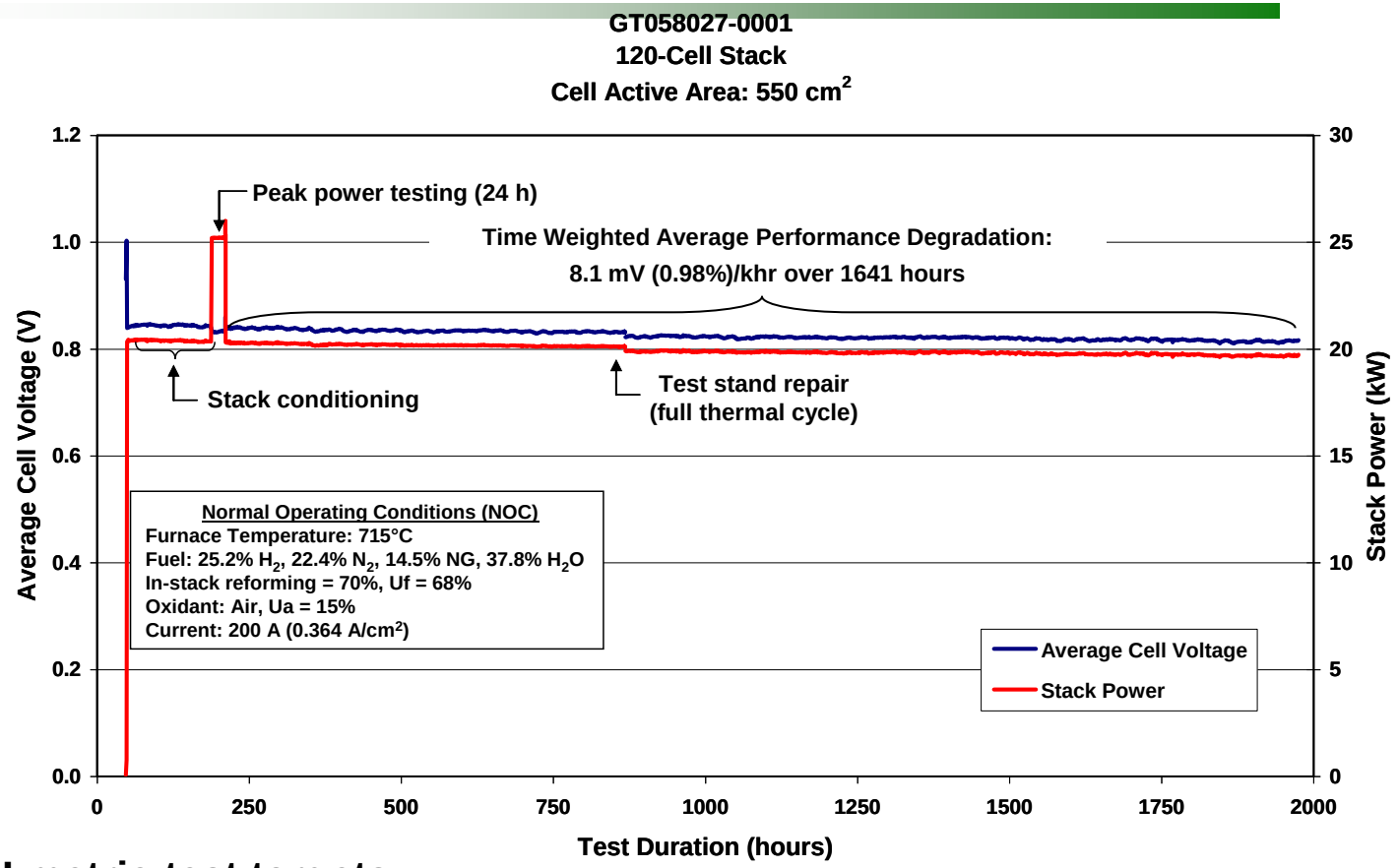
120-Cell Stack Metric Test





- **Stack met Phase II metric test targets:**
  - **Peak power rating of 25.2 kW**
  - **>1,500 hours of operation**
  - **Performance degradation rate < 1%/1000 h (surpassing 2%/1000 h DOE target)**

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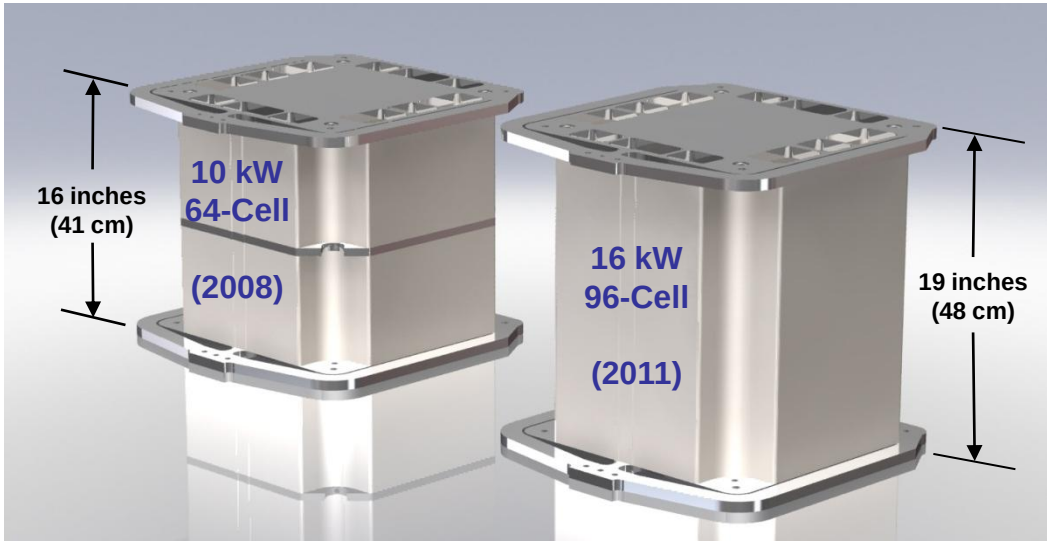
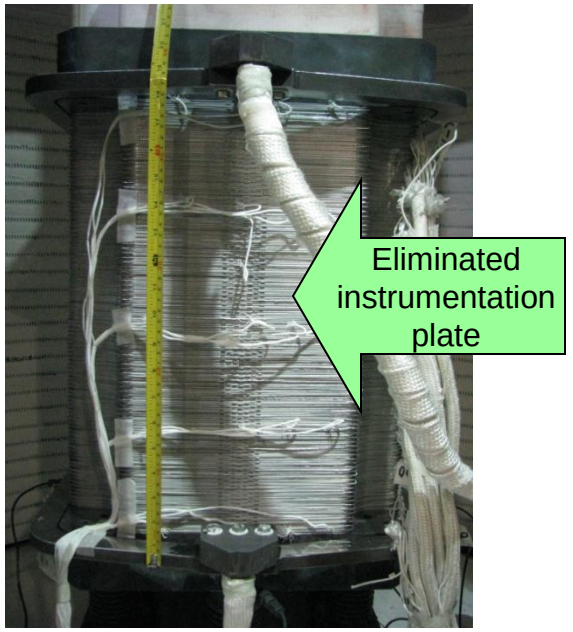
Next Generation 96-Cell Stack Block

- **Stack Instrumentation**
  - > **Eliminate instrumentation plates**
  - > **Reduce on-cell thermocouples**
- **Improve stack block flow management with enhanced manifold and flow medium designs**
- **Stack Manufacturing**
  - > **Develop production tooling**
  - > **Refine stack acceptance criteria**





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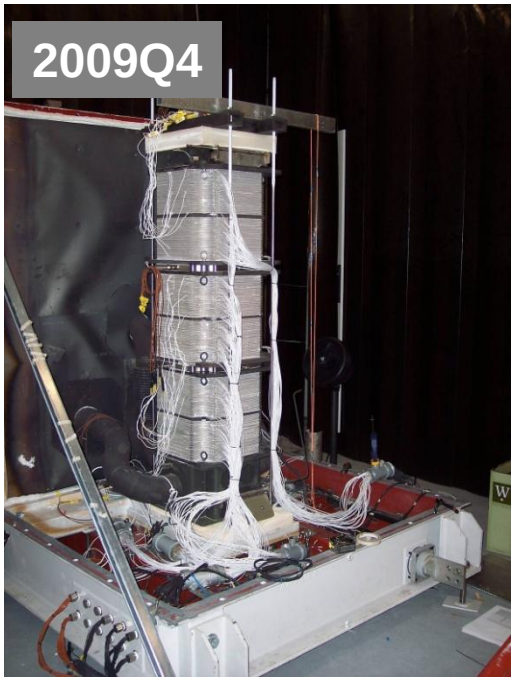
Stack Tower Testing

3 x 64-cell stack tower

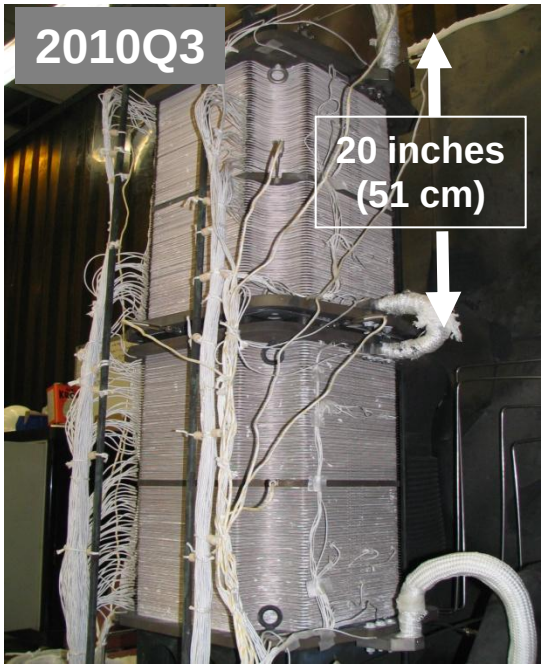


SO-30-1 Tower Assembly

2 x 92-cell stack tower

SO-30-3 Tower Assembly

2 x 92-cell stack tower



SO-30-4 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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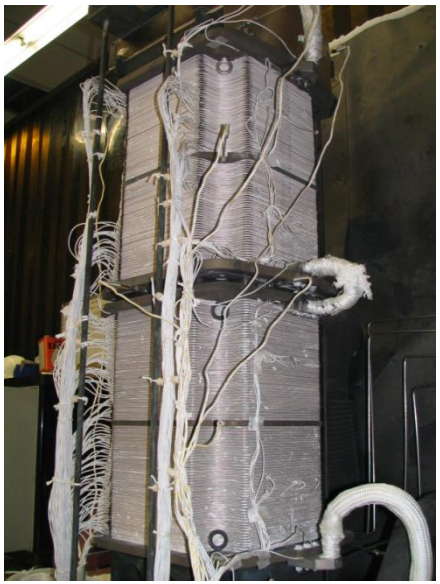
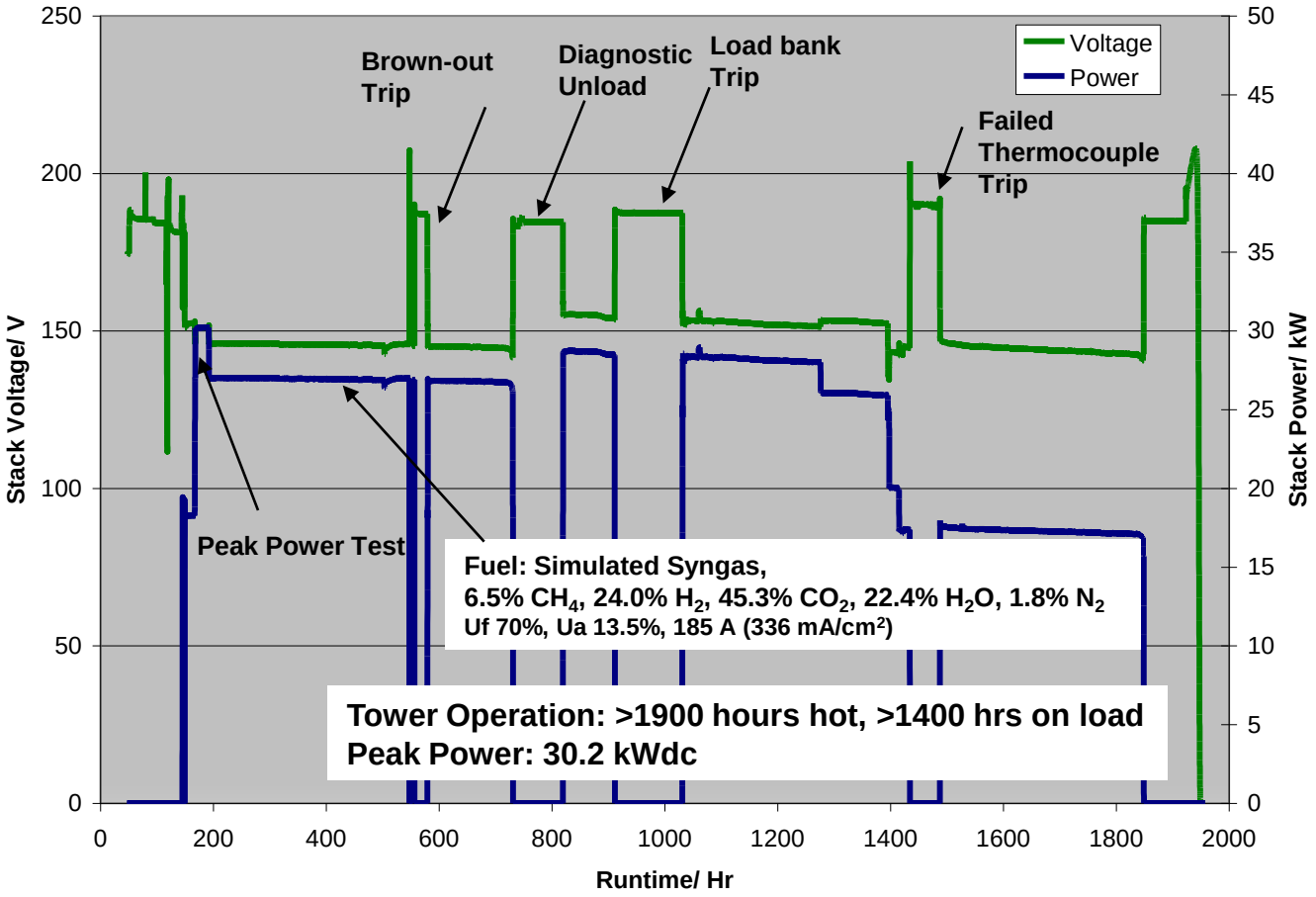
Stack Tower (SO-30-4) Test





➡ **Confirmed Operation on Simulated Coal Syngas with High Methane Gas Composition from an Advanced Catalytic Gasifier.**

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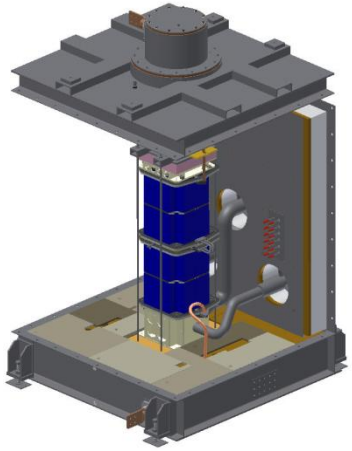
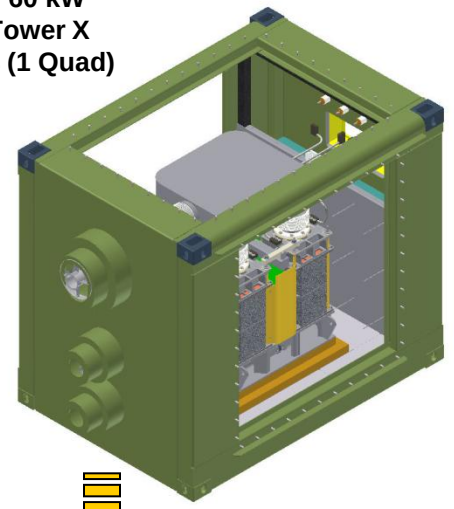
SOFC Module Evolution



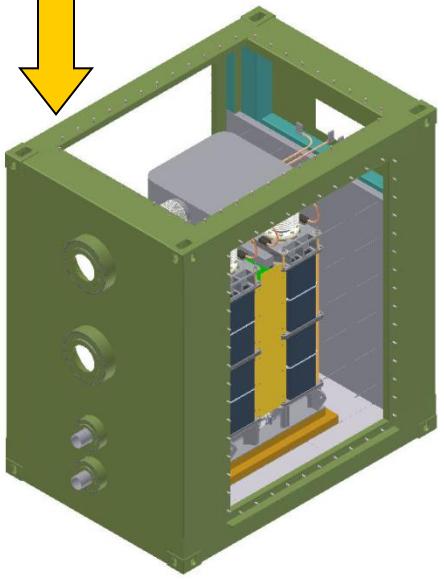
Phase II: 30 kW
2-Stack Tower

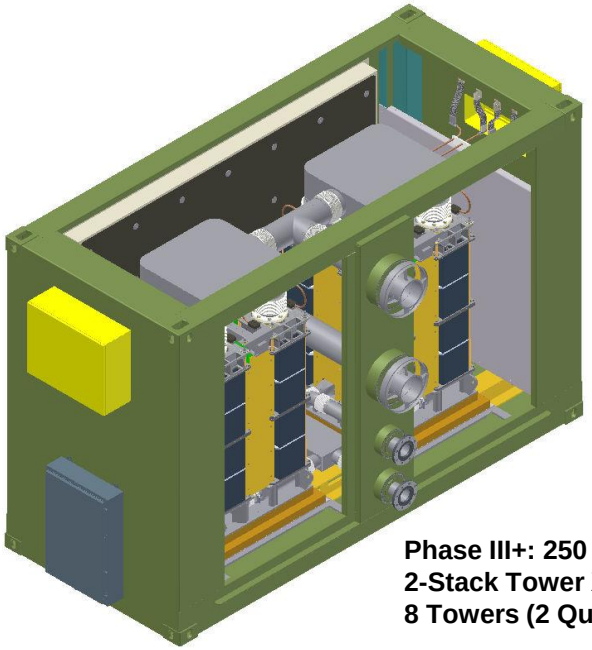
Phase III: 60 kW
1-Stack Tower X
4 Towers (1 Quad)



Rapid Module Development:

Over 90% of the same parts used each time the size doubles from 60-125-250 kW.

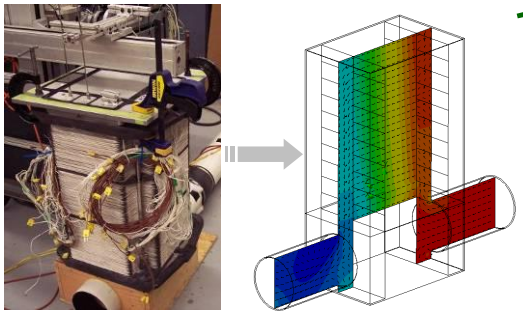




Phase III+: 250 kW
2-Stack Tower X
8 Towers (2 Quads)

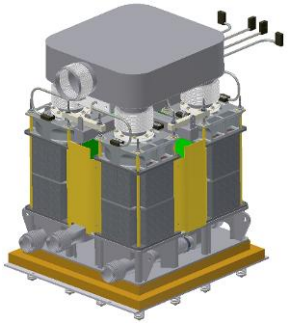
Phase III+: 125 kW
2-Stack Tower X
4 Towers (1 Quad)

60 kW Module Development Cycle

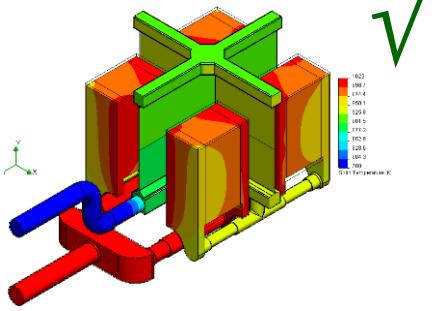


SubScale Testing & Modeling

√ **PHASE II** √

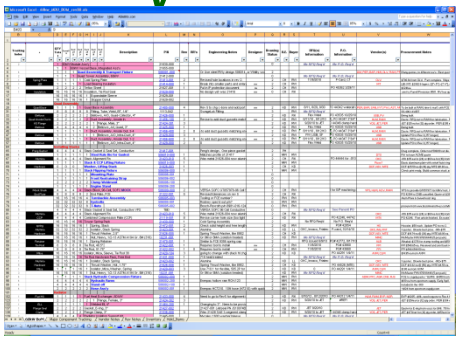


Scale-Up Design

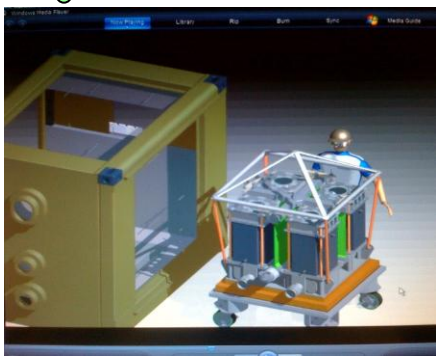


Detailed Modeling:
CFD & FEA

√ **PHASE III**



Detailed Engineering Drawings,
RFQ's, BOM, Procurement & Part
Accumulation



Build Module

Validation Test in FCE's
400 kW Test Facility

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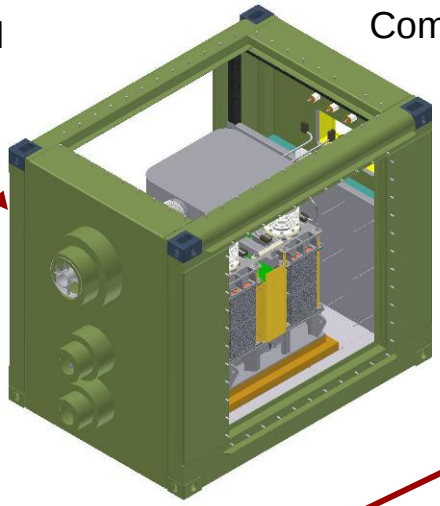
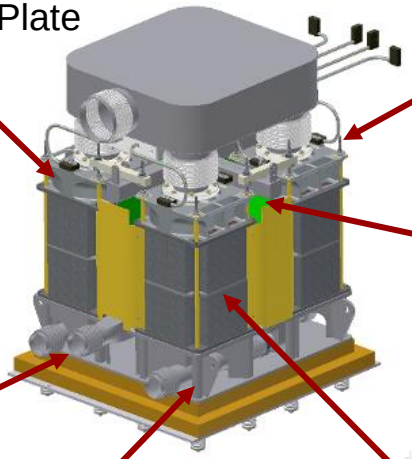
60 kW Stack Module Hardware Fabrication

60 kW Vessel

Compression Plate

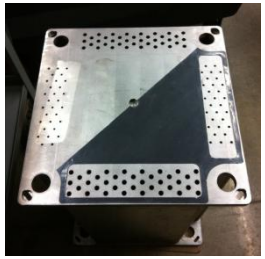
Buss Bars





Internal Radiator

Conductive Stack Gasket



High Temp. Flanges

Quad Base

Stack Simulator

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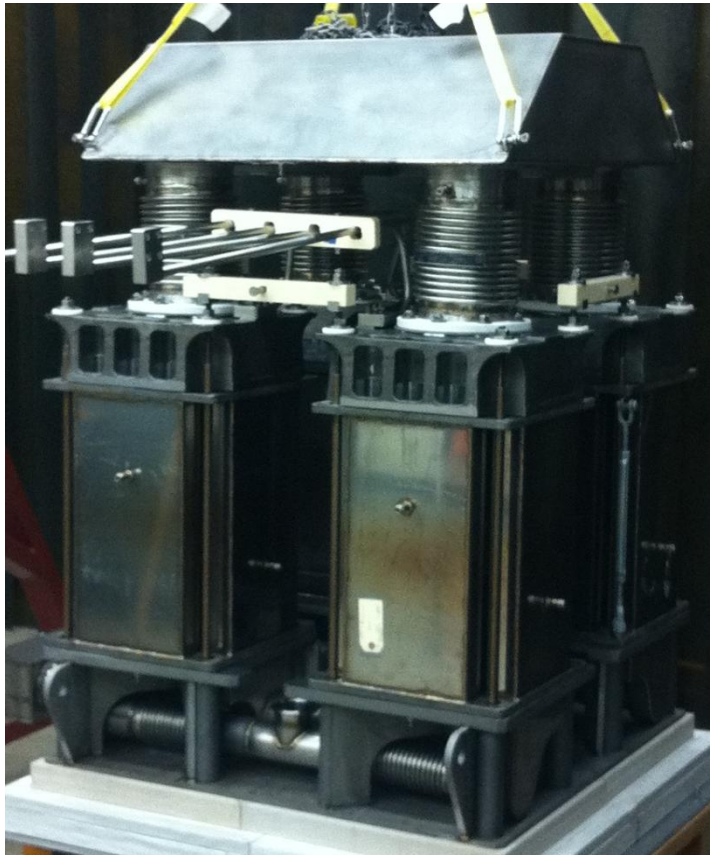
60 kW Module Hardware Assembly



➡ **SOFC Module Hardware Assembly is in Progress for Future Tests**

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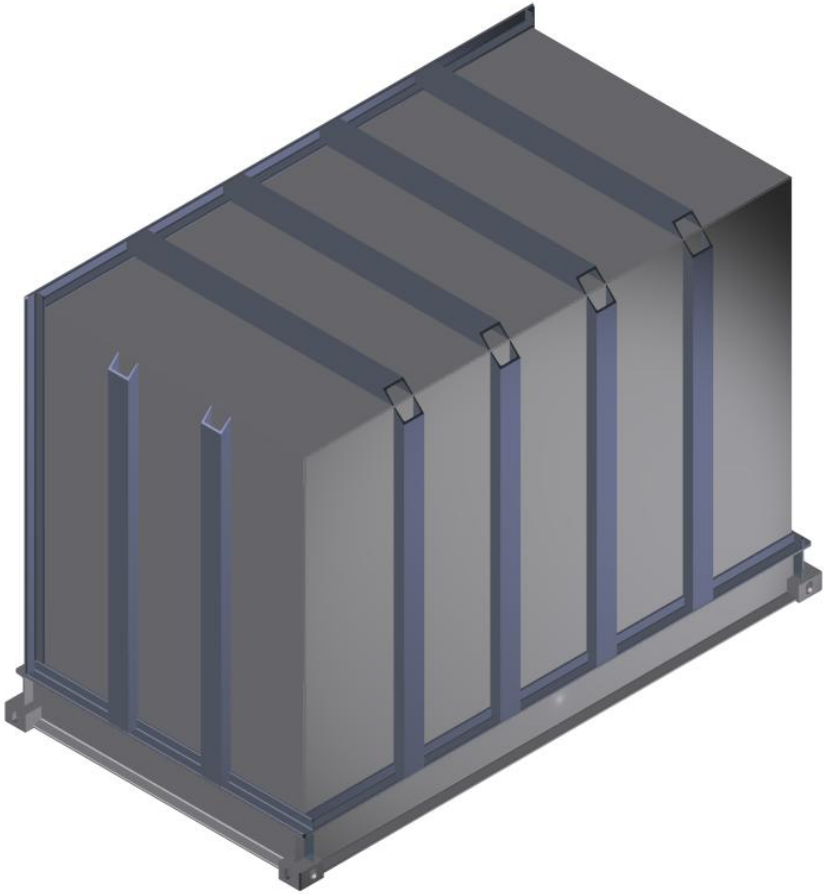
250 kW Module Design



- **Implement lessons learned from FCE's current commercial DFC product, in the areas of: detailed design, manufacturing, value engineering, cost reduction, serviceability, and shipping.**

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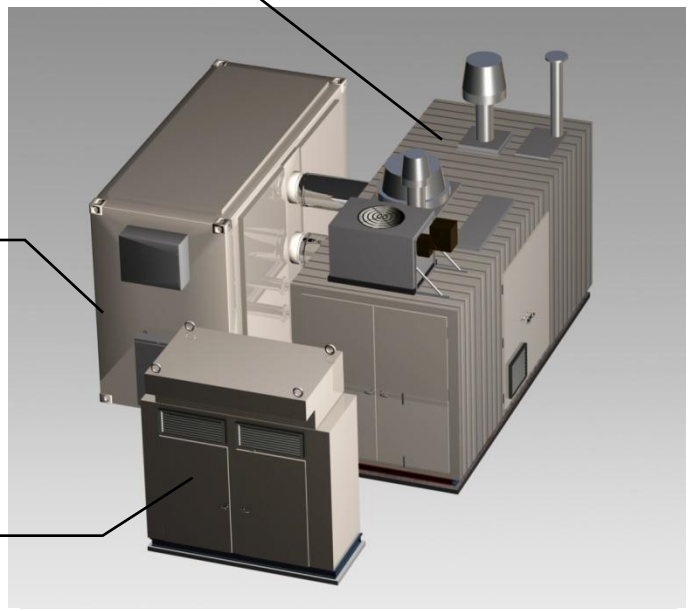
PCM System Performance

Mechanical Balance-of-Plant (MBOP)

SOFC Stack Module

Electrical Balance-of-Plant (EBOP)



System Performance Summary: Normal Operating Conditions

Fuel Cell		
DC Power	277.2	kW
Inverter Loss	13.9	kW
SOFC Gross AC Power	**263.3**	**kW**

CONSUMED POWER

AC Power	**8.9**	**kW**

Net Generation

Plant Net AC Output	**254.4**	**kW**
Efficiency (HHV)	55.5	%
Efficiency (LHV)	**61.5**	**%**

➡ **MDU system is designed to lay the foundation for market entry 250 kW SOFC product operating on natural gas and biogas.**

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  - Scale-up and Metric Tests
- Proof-of-Concept Module (PCM) Development
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- **Baseline System Design and Cost Analyses**
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  - Baseline Power Plant Cost Estimate
- Conclusion and Future Plans

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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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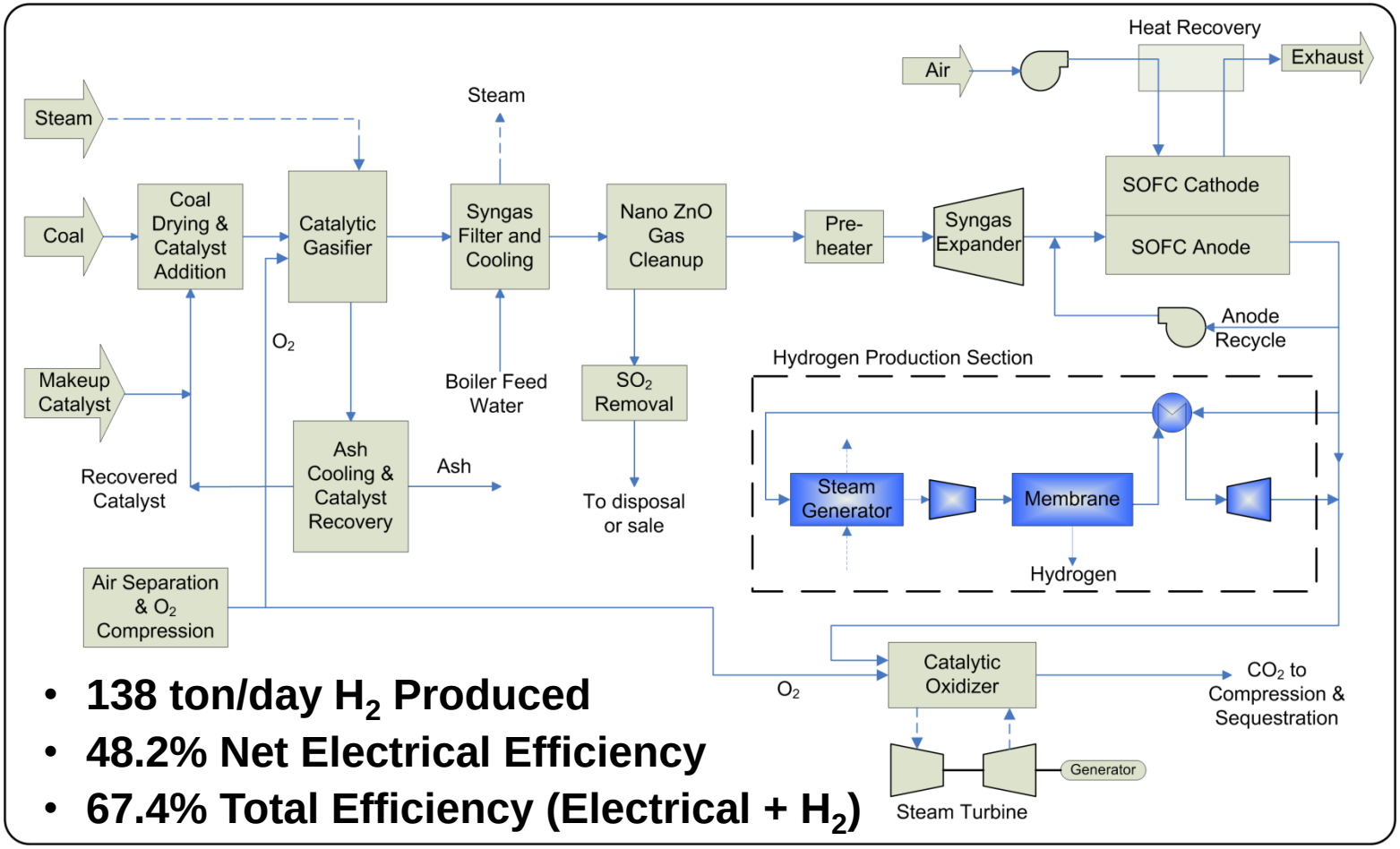
H_2 Co-Generation System Concept

- **IGFC systems have the flexibility for hydrogen co-production at a very attractive overall efficiency.**



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

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MW-class Module Development Approach

FCE's DFC MW Module

SOFC MW Class Module
(scale: similar)

➡ **Use lessons learned in FCE DFC MW-scale commercialization to optimize design for SOFC MW Class System.**

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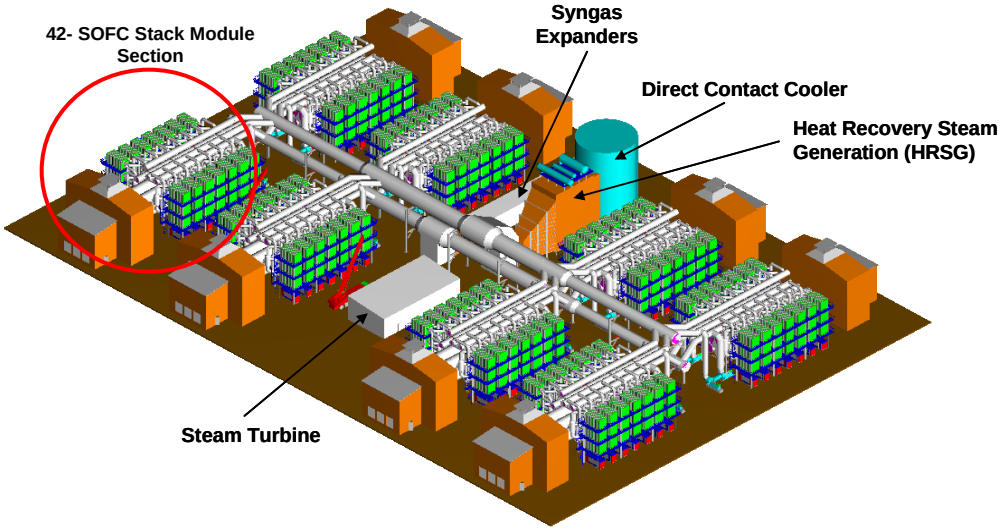
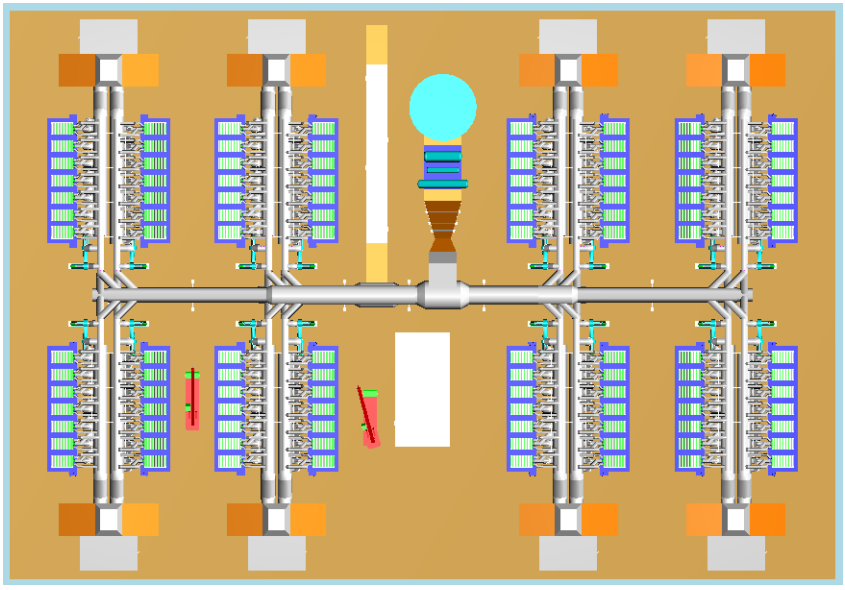
Baseline SOFC Power Island

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





- **SOFC power island lay-out takes advantage of well-thought clustering concept using repeated arrangements of grouped components.**

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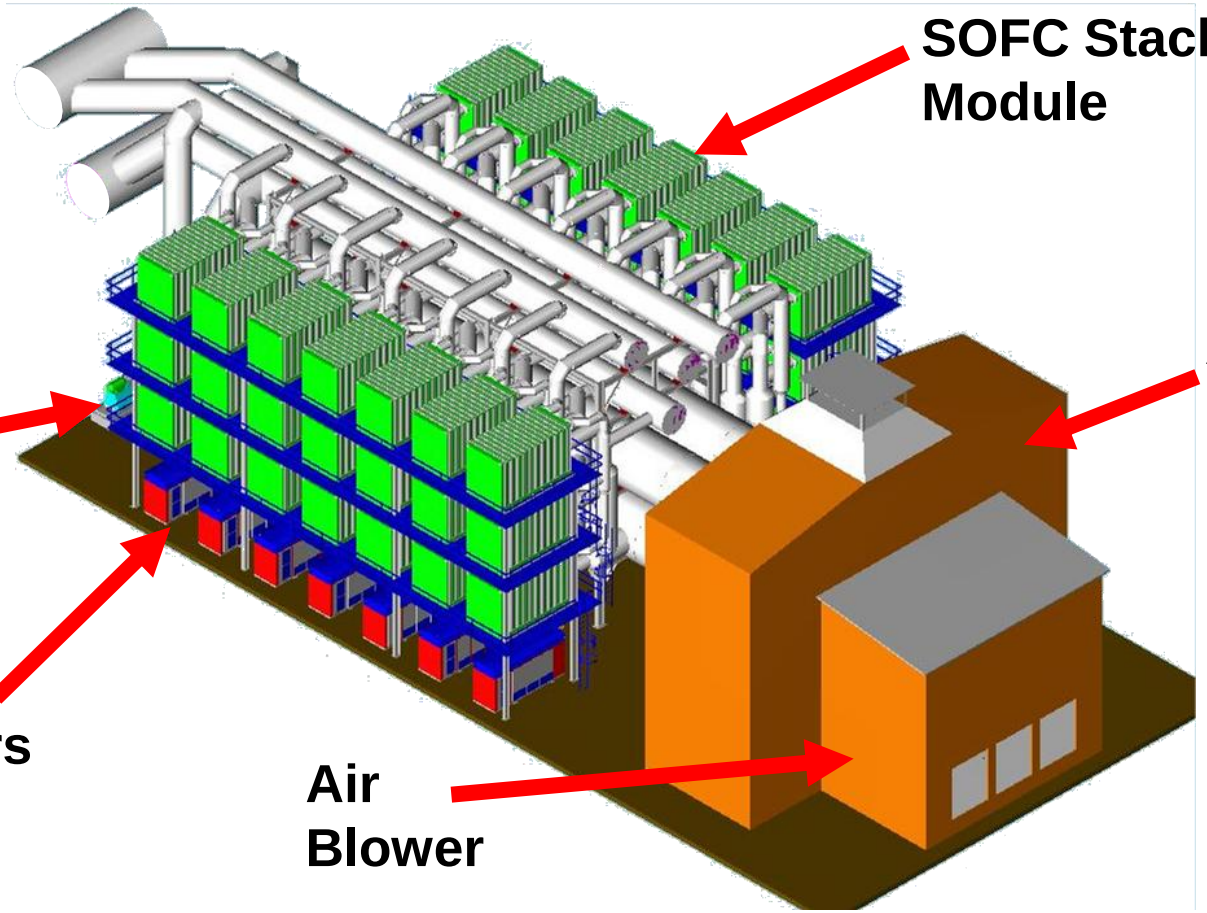
Layout of 42-Module SOFC Cluster



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

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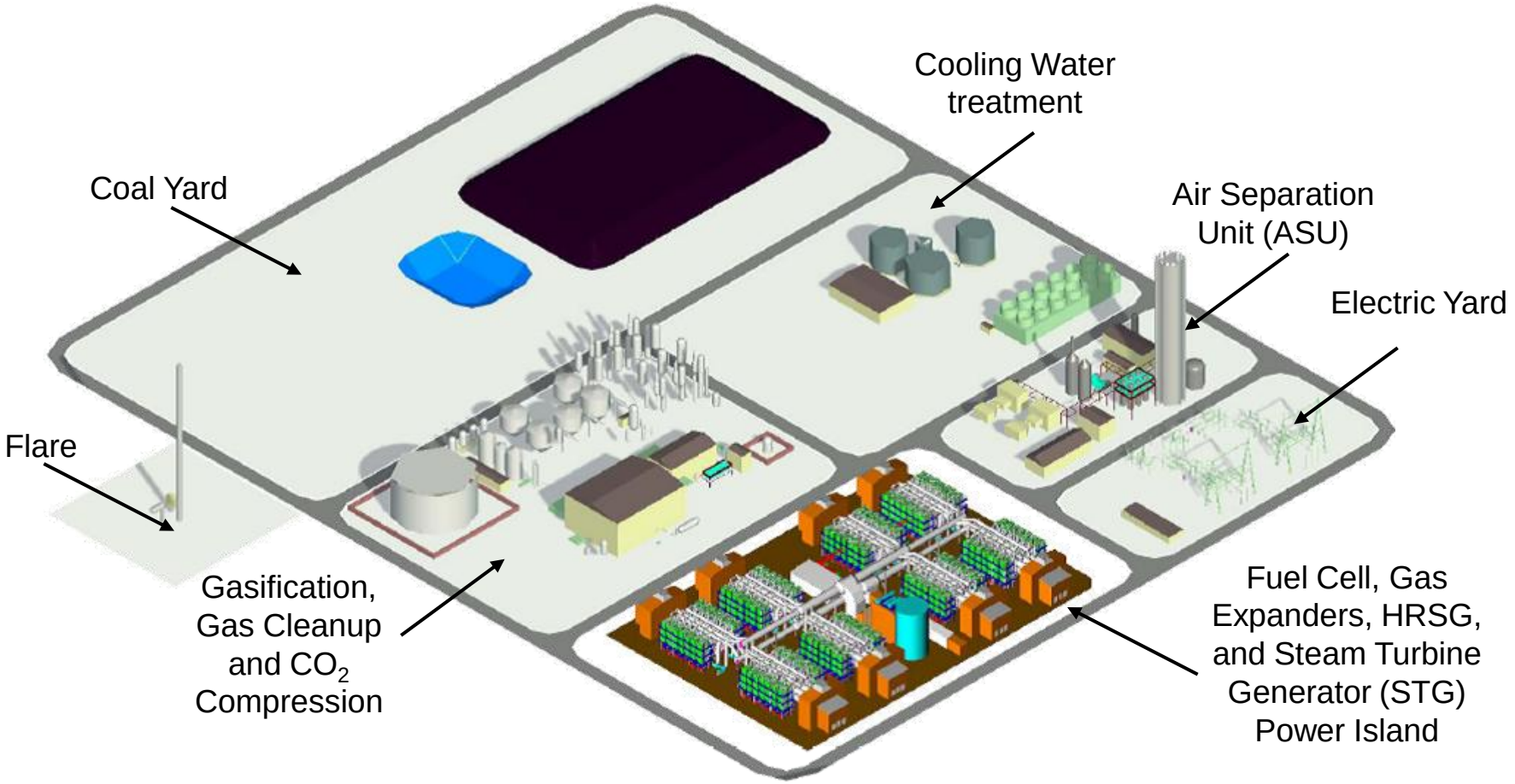
IGFC Site Layout



➡ **Lay-out of 670 MWac IGFC plant includes 336 SOFC stack modules, two syngas expanders, and a steam bottoming cycle.**

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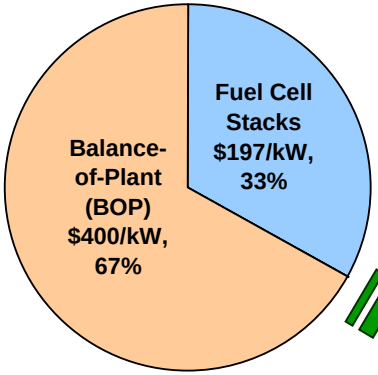
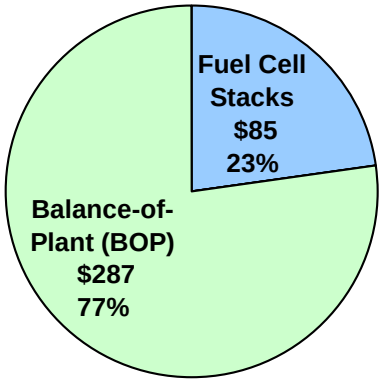
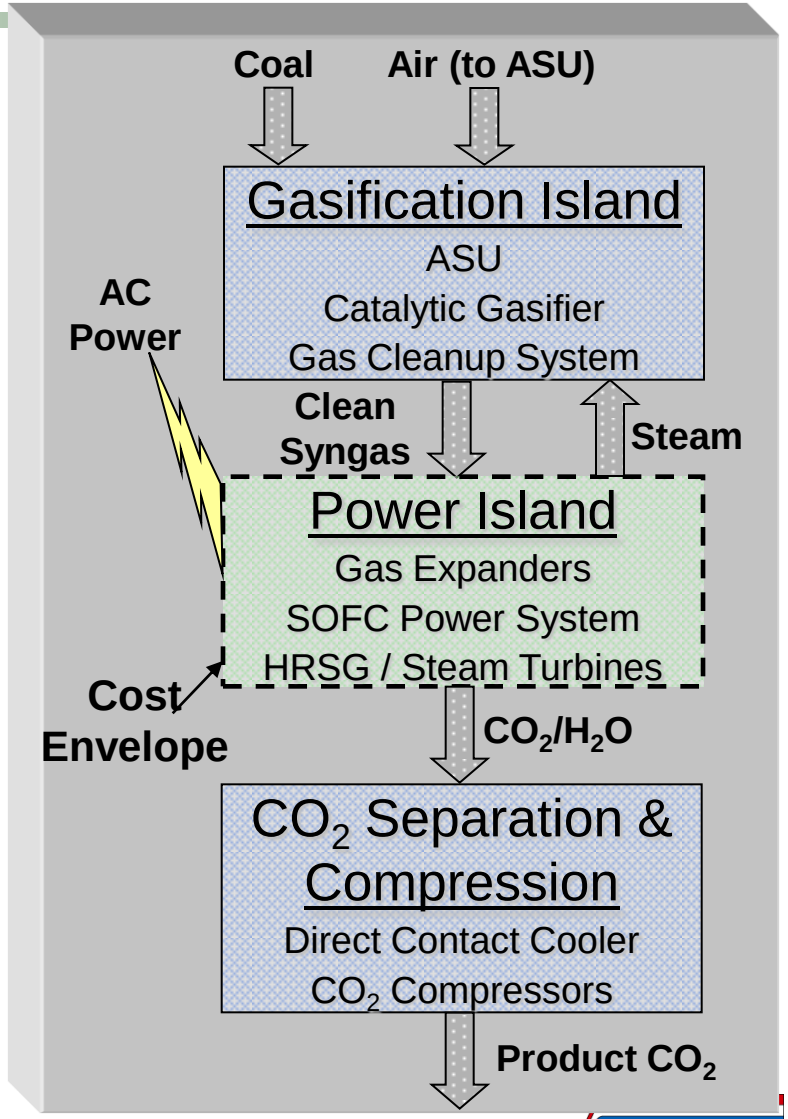
Factory Equipment Cost Estimate

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



Phase II Factory Cost Estimate:
372 $/kW (2000 USD)





Cost Reductions were achieved via:

- Stack cost reductions and performance improvements
- Integrated system performance optimizations
- Value engineering of BOP components

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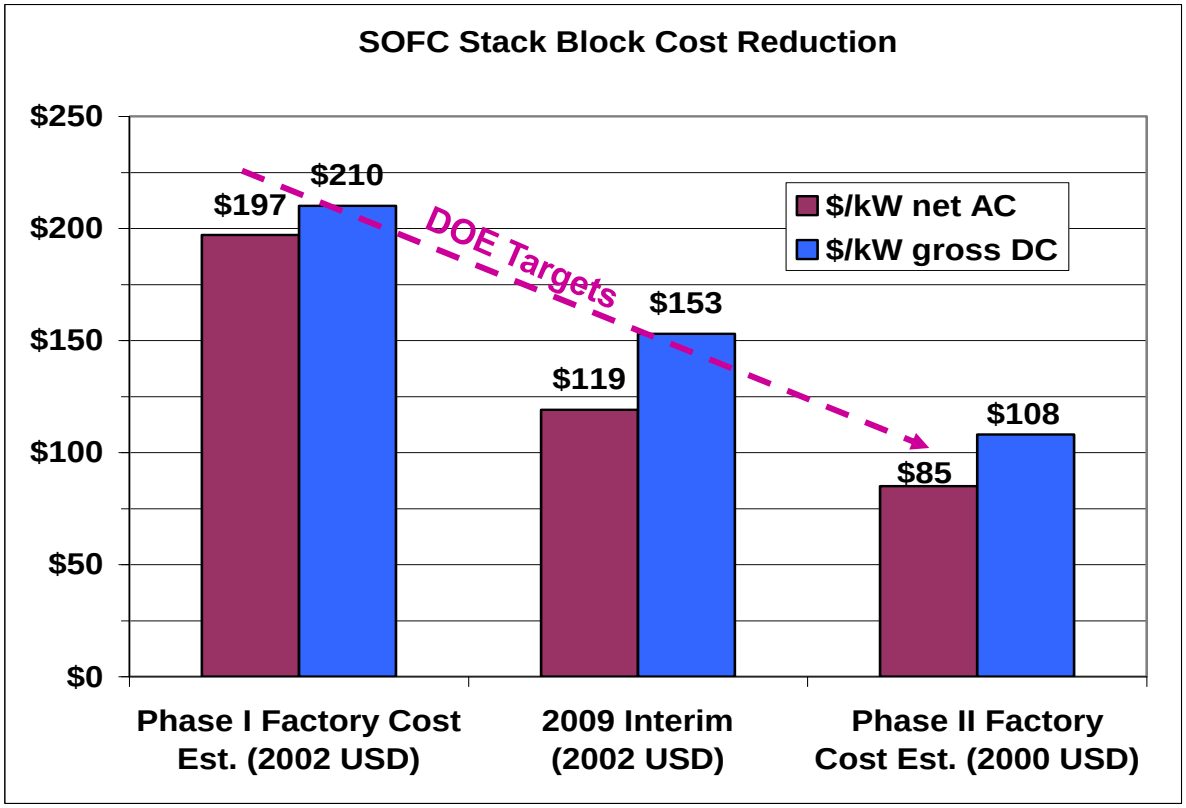
Stack Cost Reduction

Cost Reduction Focus Areas

1. Stack Performance Increase
   - Peak Power Increase
     - ➢ Resolved thermal management issues
2. Material Reduction:
   - Thinner stack components
   - Interconnect material reduction
   - Reduced number of intermediate plates
3. Manufacturing Process Changes
   - Improved material utilization
   - Automation
   - Elimination of process steps
   - Interconnect manufacturing development



➡ **The fuel cell stack cost have decreased substantially mainly due to the R&D activities in the SECA Phase II project.**

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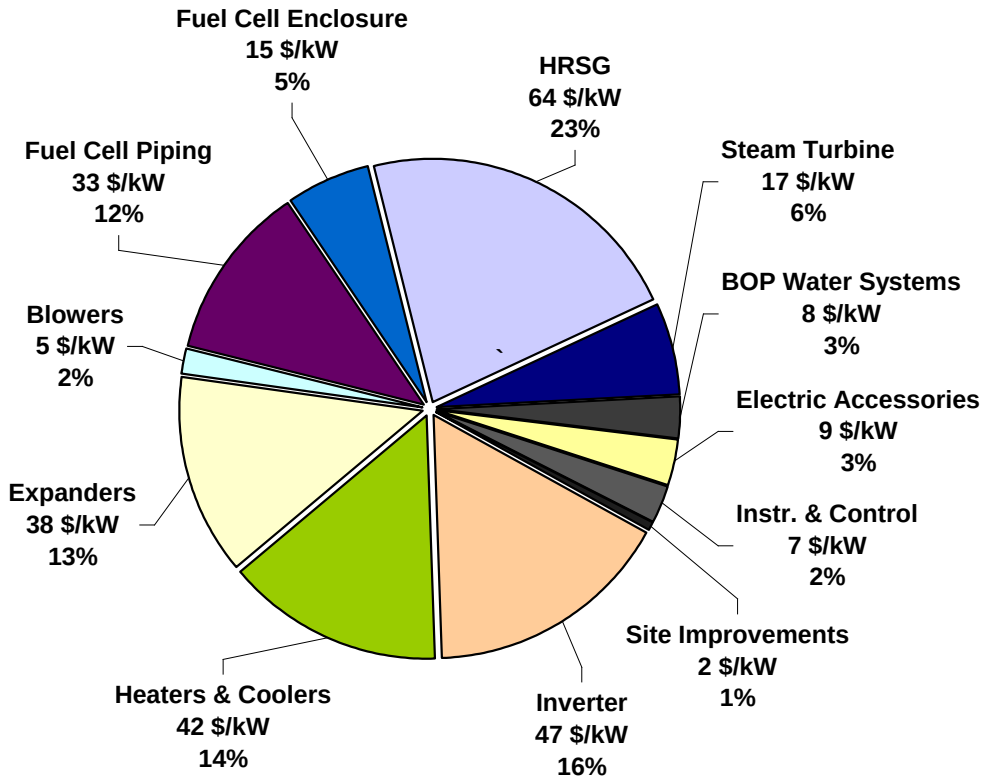
Balance-of-Plant Factory Equipment Cost Estimate



BOP Factory Cost Estimate:
287 $/kW (2000 USD)

- **Costs were estimated by WorleyParsons, based on extensive in-house cost database in addition to budgetary vendor quotations**
- **Cost estimation is based on two 670 MW nominal power plants manufactured per year (2000 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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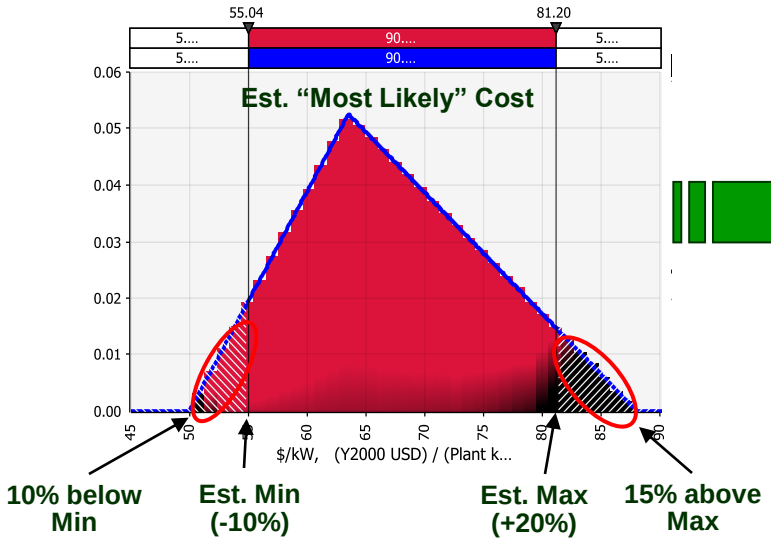
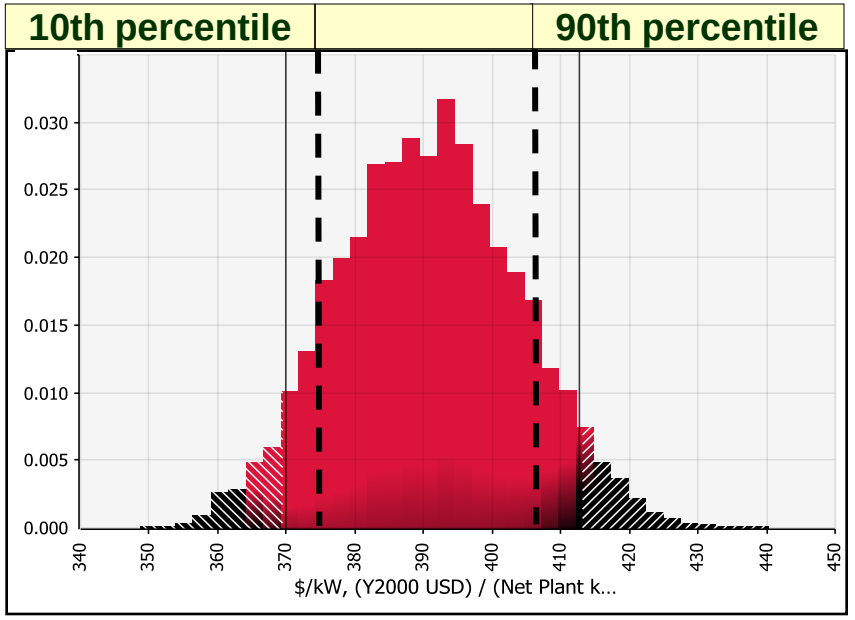
Factory Cost Estimate Sensitivity Results

➡ **Monte Carlo Simulation was performed to predict Probability Distribution Function (PDF) of Estimated System Cost.**

Cost Distribution Inputs



SOFC Power Island Cost ($/kW)



- **Mean = $390.8/kW, with a range of $348.8 to $440.2/kW**
- **The range between the 10th and 90th percentiles is from $374.0 to $407.8 or within $17/kw from the mean**

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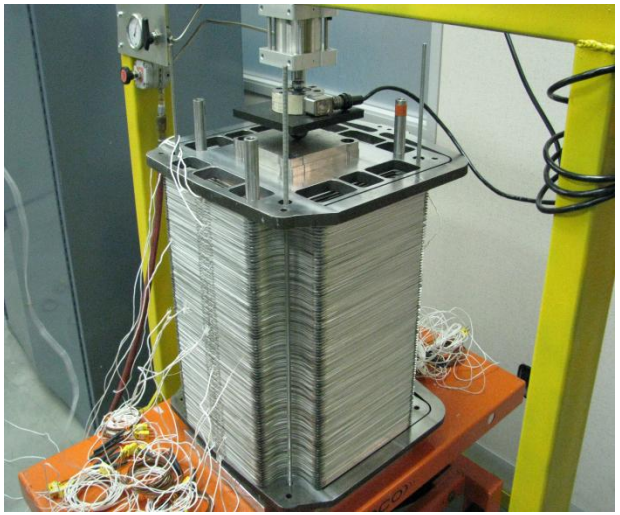
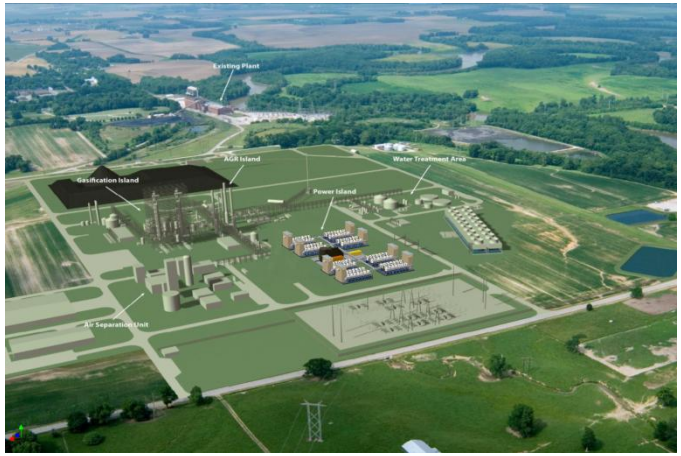
Summary Accomplishments

- Modifications in cell materials have enhanced cell performance and reduced degradation rate to <0.3%/1000 h.
- Third generation manufacturing processes (TSC-3) were developed for scaled-up 550 cm^2 active area (25 cm x 25 cm) cells based on high-performance thin cell technology.
- Over 5000 cells of 25 cm x 25 cm cell size (550 cm^2 active area) have been fabricated in the pilot manufacturing facility, with >95% product yield.
- A 120-cell stack metric test successfully met DOE's requirement of completing 1500 h of testing before the end-of-Phase II, demonstrating a peak power of 25.2 kW and achieving a steady state average power degradation rate of 0.9%/1000 h (well below the Phase II DOE requirement of ≤ 2%/1000 h).

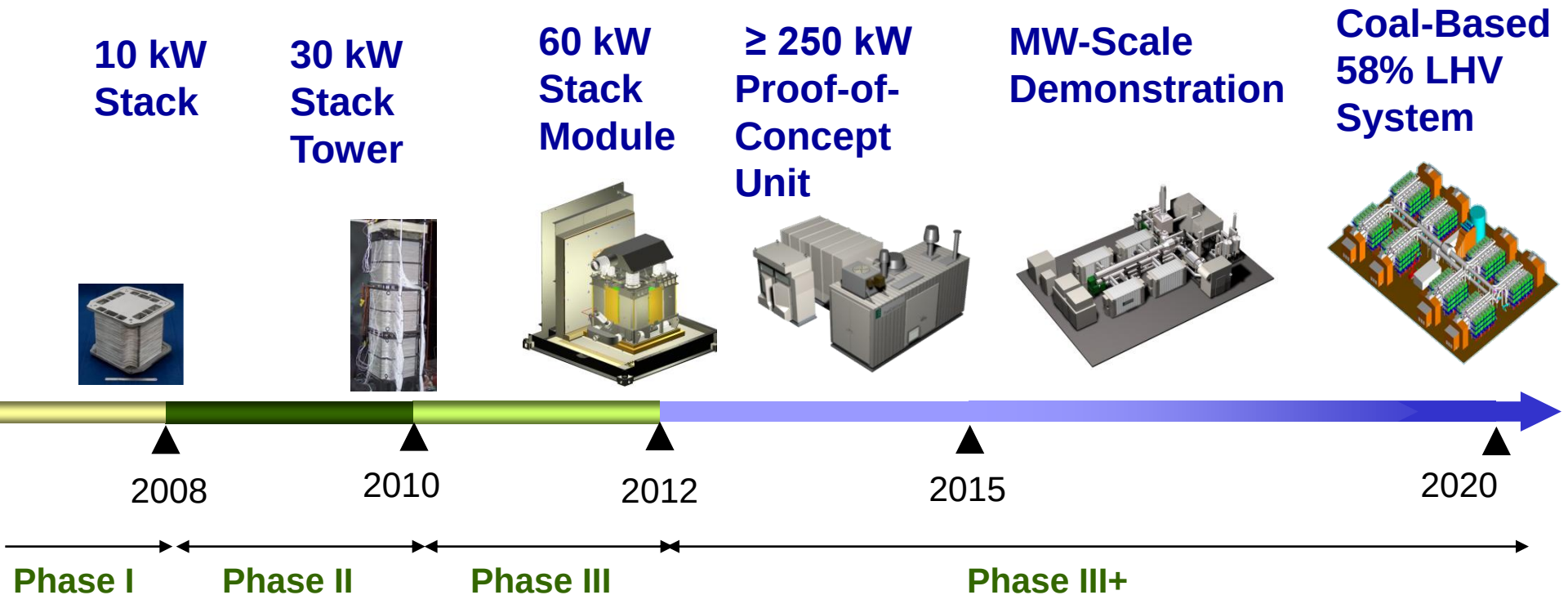




- Stack tower concept suitable for large-scale SOFC modules was successfully demonstrated by achieving power output of >30 kWdc and operating on simulated coal-derived syngas.
- A Baseline IGFC System (~670 MW nominal) utilizing catalytic gasification and capturing > 99% of carbon (as CO2) in the syngas was developed with an electrical efficiency of 58.7% (high heating value of coal).
- SOFC stack Factory Cost was estimated at $85/kW (Year 2000 dollars), meeting the Phase II target of ≤$100/kW.
- The Baseline Power Plant system Factory Cost Estimate, audited by an independent party, achieved a cost of $372/kW (2000 USD) for the SOFC power island meeting the DOE metric of <$400/kW.

FCE's Coal-Based SECA Program Plan

- FCE's long-term plan is development of SOFC power plants capable of using a variety of fuels such as natural gas, biogas, and coal syngas.



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- Support for FCE's SECA Coal Based Program provided by the US Department of Energy (DOE) through the co-operative agreement DE-FC26-04NT41837
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Thank You!

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