COAL-BASED IGFC PROJECT PHASE I

FC26-08NT0003894

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July 26-28, 2011

Sheraton Station Square Hotel

Pittsburgh, PA

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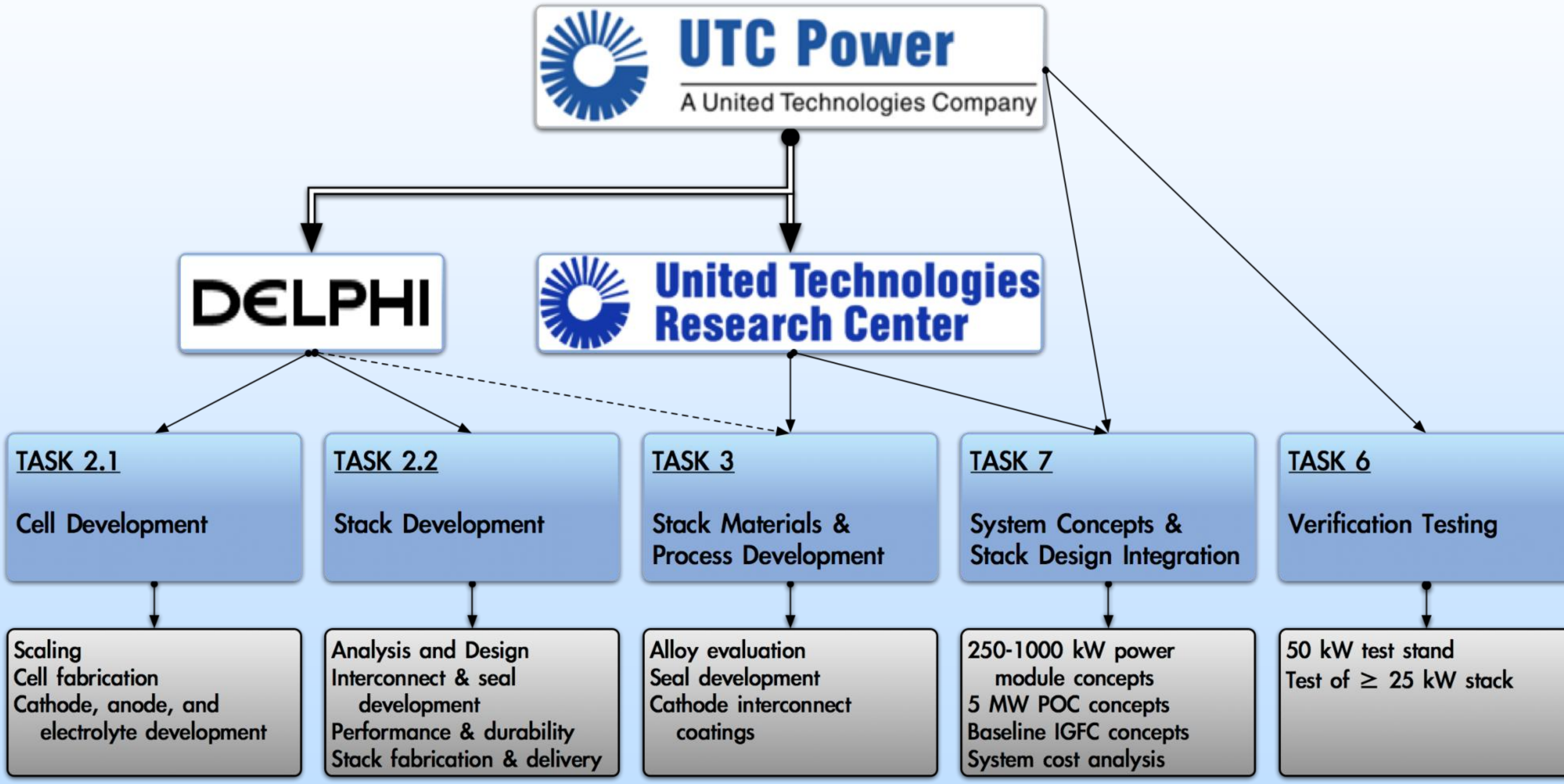
SECA OBJECTIVES

- Reduce SOFC-based electrical power generation system cost to ≤ $700/kWe (2007 dollars) for a >100MW Integrated Gasification Fuel Cell (IGFC) power plant, exclusive of coal gasification and CO_2 separation subsystem costs
- Achieve an overall IGFC power plant efficiency of ≥50%, from coal (HHV) to AC power (inclusive of coal gasification and carbon separation processes)
- Reduce the release of CO_2 to the environment in an IGFC power plant to ≤ 10% of the carbon in the coal feedstock
- Increase SOFC stack reliability to achieve a design life of >40,000 hours

SOFC TEAM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TASK 2.1
Cell Development
TASK 2.2
Stack Development
TASK 3
Stack Materials & Process Development
TASK 7
System Concepts & Stack Design Integration
TASK 6
Verification Testing
Scaling
Cell fabrication
Cathode, anode, and electrolyte development
Analysis and Design
Interconnect & seal development
Performance & durability
Stack fabrication & delivery
Alloy evaluation
Seal development
Cathode interconnect coatings
250-1000 kW power module concepts
5 MW POC concepts
Baseline IGFC concepts
System cost analysis
50 kW test stand
Test of ≥ 25 kW stack

OUTLINE

Stack

- Summary Highlights
- Cells
  - Scale up
  - Cost Reduction
- Gen 4 Stack performance
  - Electrochemical performance of Gen 4
  - Comparison of Gen 4 performance data to Gen 3 data
  - Gen 4 max power performance on SECA coal gas blend
- Durability
  - Constant current
  - Stack tested with actual hydrocarbon fuel reformate
  - Thermal cycling of Gen 4 stack
- Modeling
  - Scale up to larger power systems

Systems

- 50kW Test Stand
- 1500hr Stack Module Endurance Testing
- Power Module
- IGFC Systems

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SUMMARY HIGHLIGHTS - STACK

- Scaled up cells from 105 cm^2 (active area) cells to 403 cm^2 for Gen 4 stacks
- Expanded cell and stack fabrication and testing capability for large footprint Gen 4 stacks
- Developed low cost, high volume manufacturable processes for Gen 4 stack components. Fabricated and tested more than 40 Gen 4 stacks.
- Demonstrated maximum power of 6.4 kW on a 40-cell Gen 4 stack with SECA simulated coal gas blend
  - Power density of 398 mW/cm2
  - Average cell voltage of 0.7V
- Demonstrated up to 9,700 hours continuous durability on Gen 3.2 stack. Demonstrated 3,000 hours on Gen 4 stack.
- Completed 60 full thermal cycles on Gen 4 stack, with less than 5% voltage degradation

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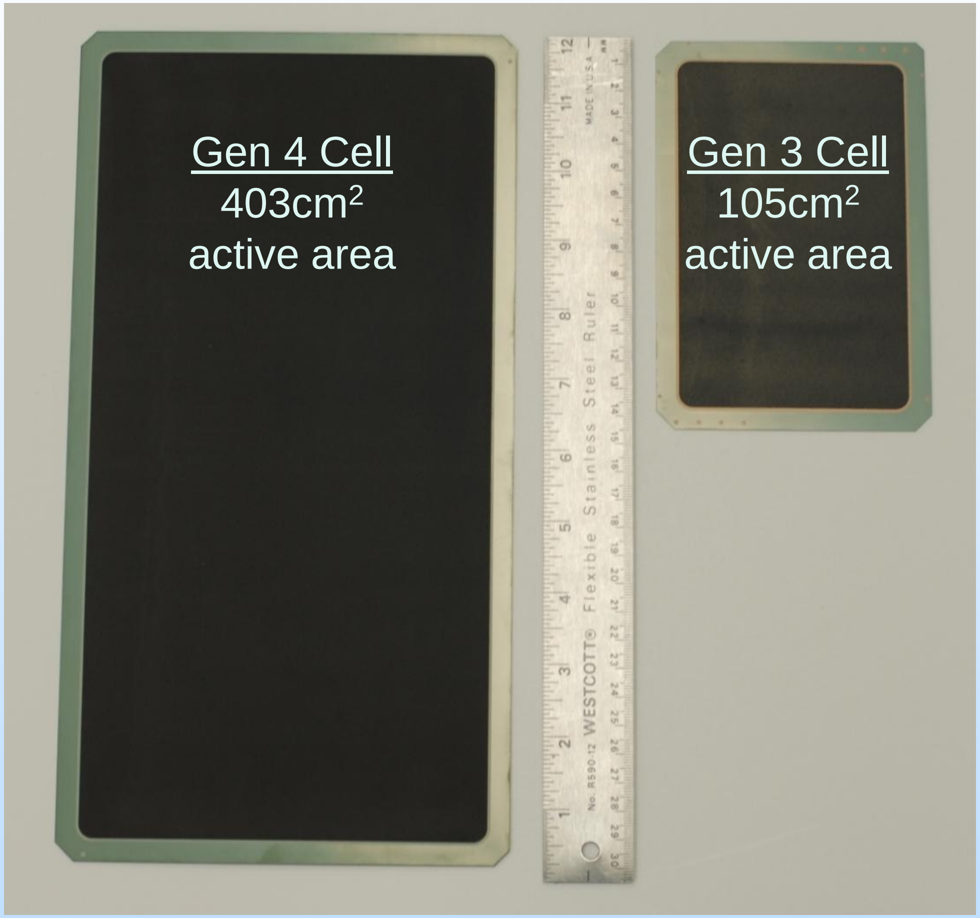
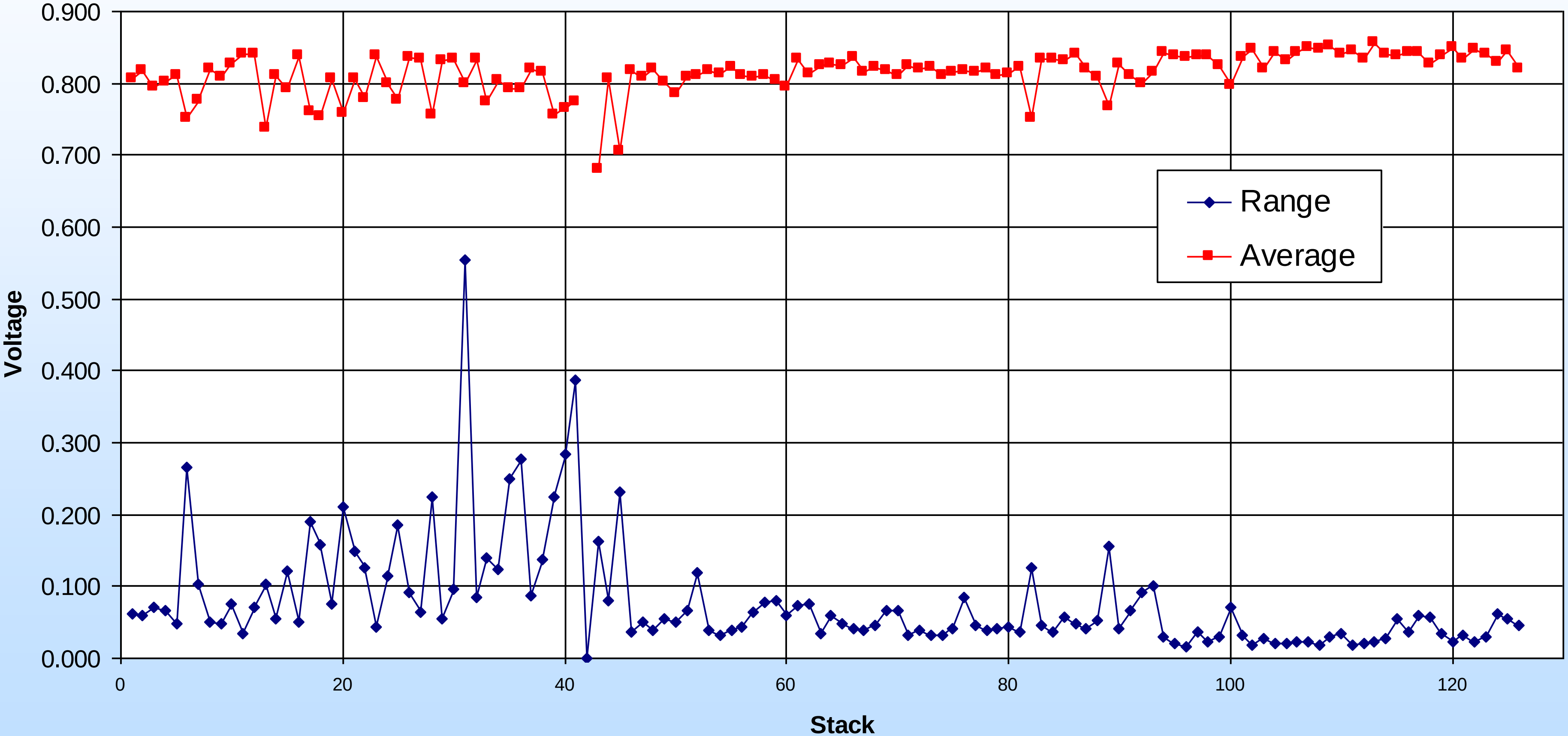
CELL SCALE-UP

- Scaled up to a larger cell without increasing cell thickness
- Gen 4 stacks being fabricated with the large footprint cell



STACK MANUFACTURING

- Delphi manufacturing system design processes reduce stack build variation



Gen 3.2 is baseline platform for evaluation of technology and components to scale up into Gen 4

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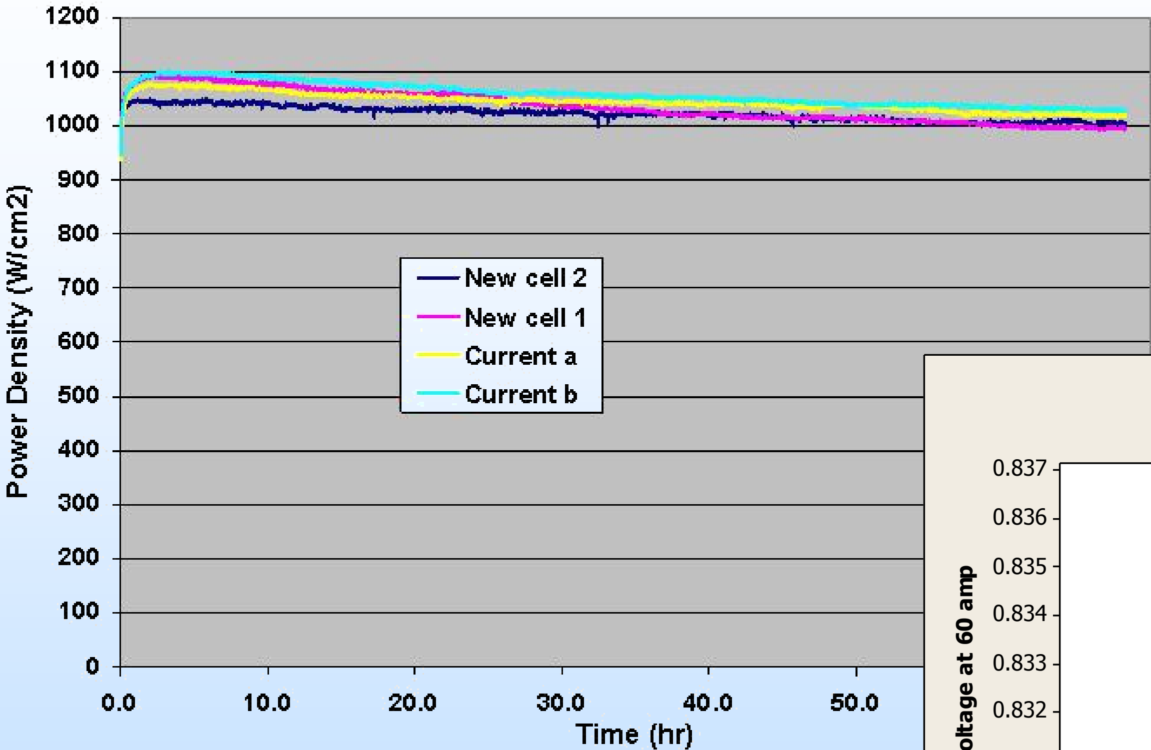
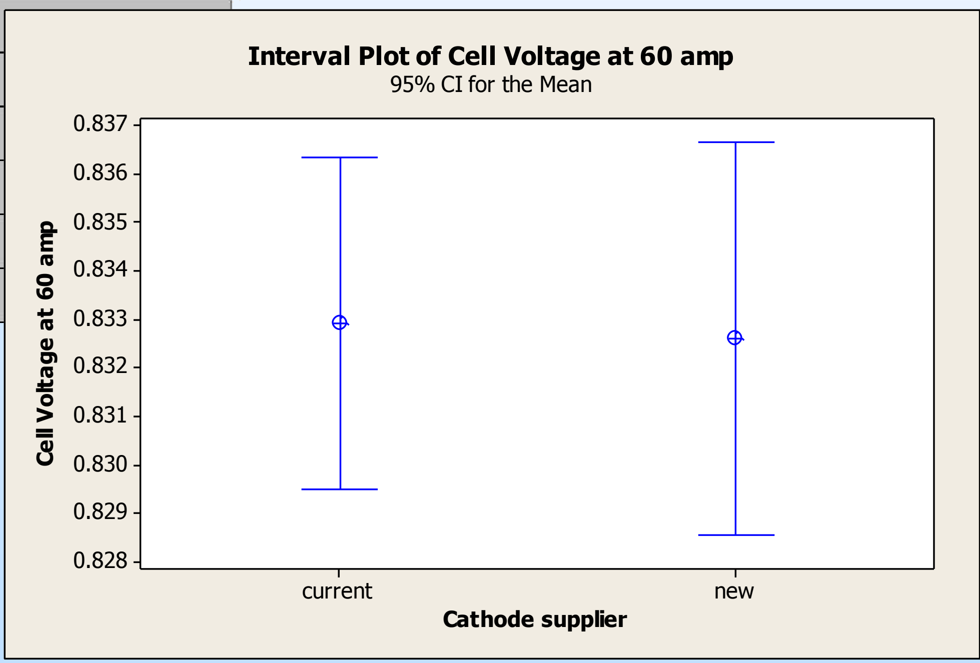
COMMERCIAL, LOW COST CATHODE SUPPLY

Button Cell Results @ 750C/0.7V/502:50N2



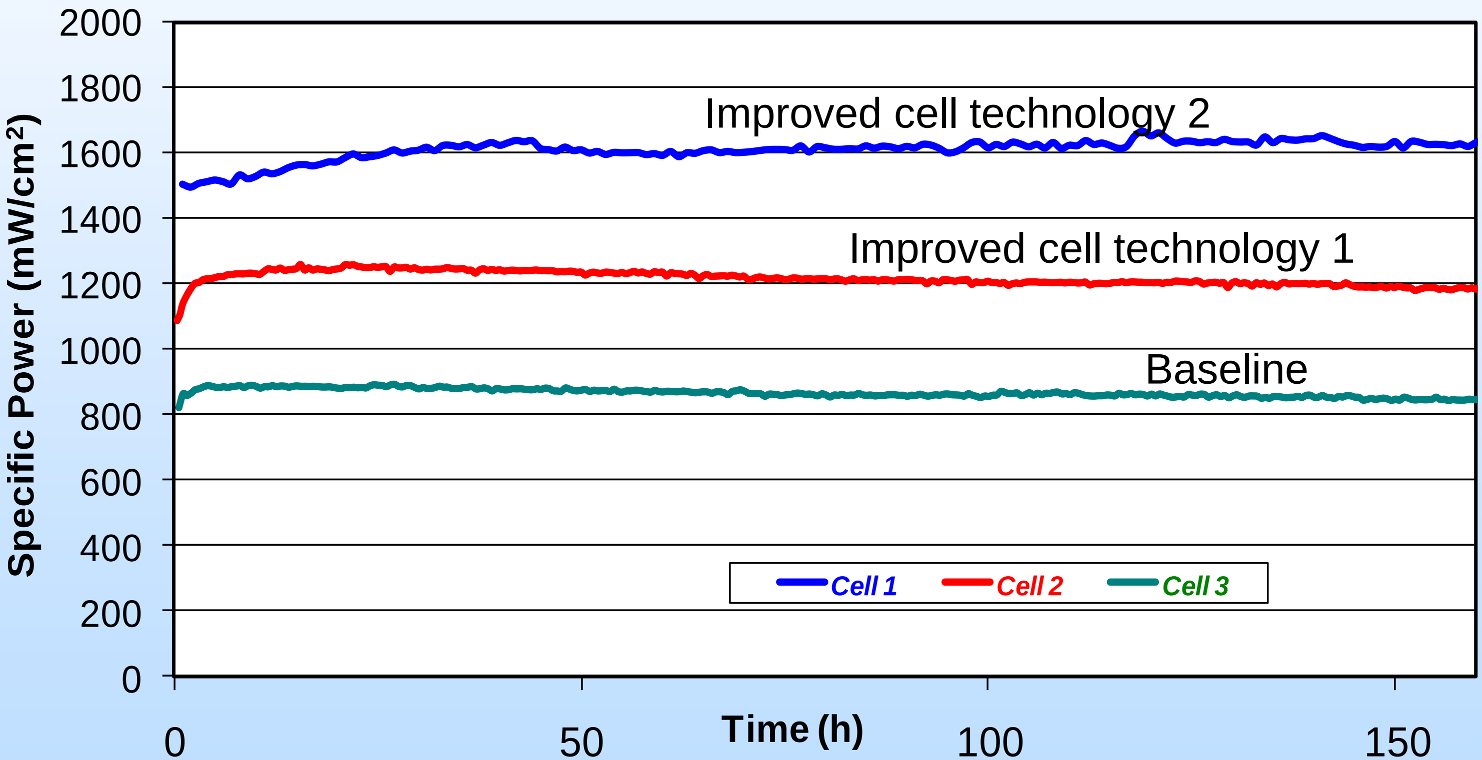
Stack Results @ 750C/60A/50H2:47N2: 3H2O



Cells fabricated with a low cost supply of cathode powder have statistically the same electrochemical performance as cells made from current cathode powder

CELL PERFORMANCE IMPROVEMENTS

- Cathode and anode materials development have demonstrated improved power density in button cell tests
- Further testing ongoing at a stack level



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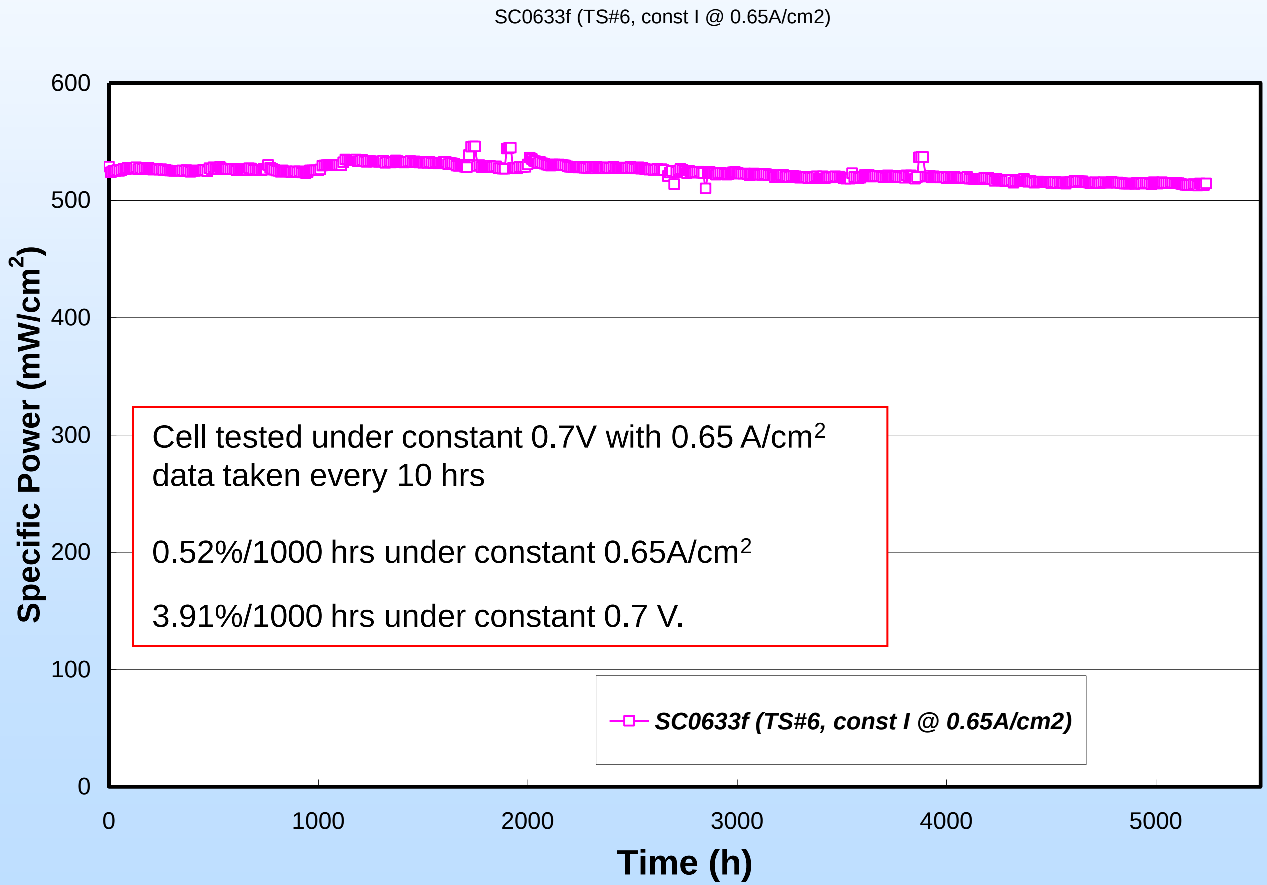
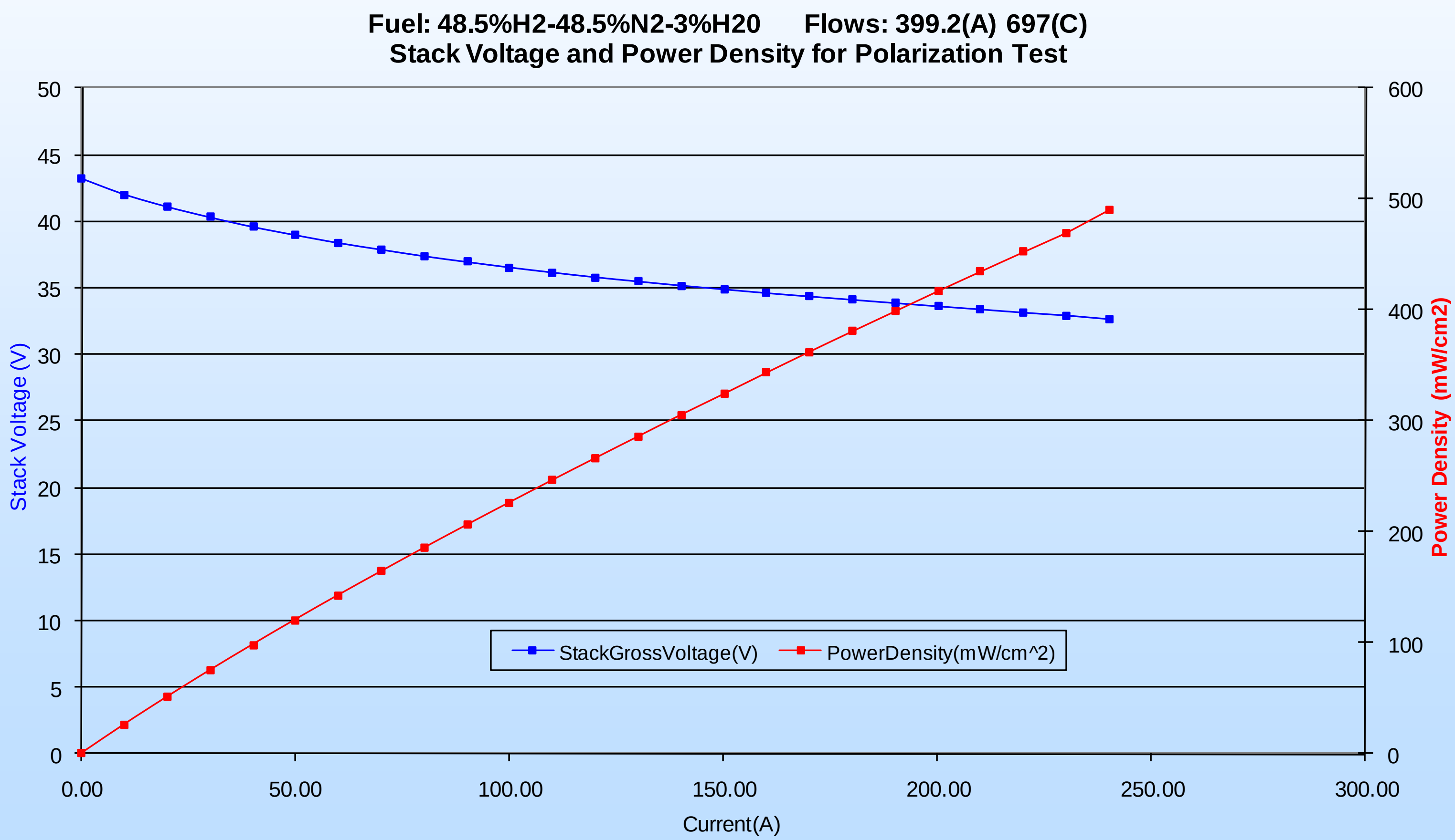
DURABILITY OF LSCF CATHODE

- Data from button cell durability test of current cells with LSCF cathode -demonstrating stable performance
- Greater than 5000 hours of test



GEN 4 STACK ELECTROCHEMICAL PERFORMANCE

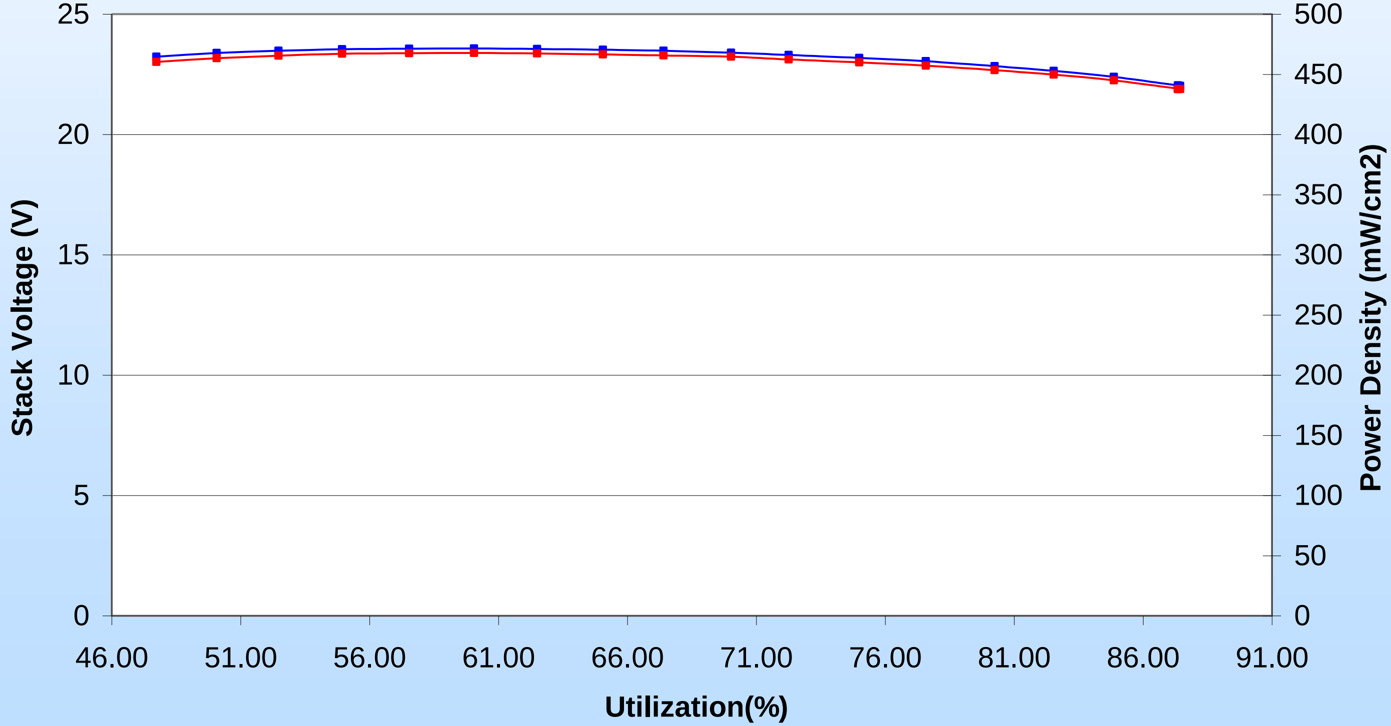
- Recent 30-cell Gen 4 stack performance
- Produced 5.76 kW (476 mW per cm2) @ 0.80 Volts per cell with 48.5% H2, 3% H2O, rest N2



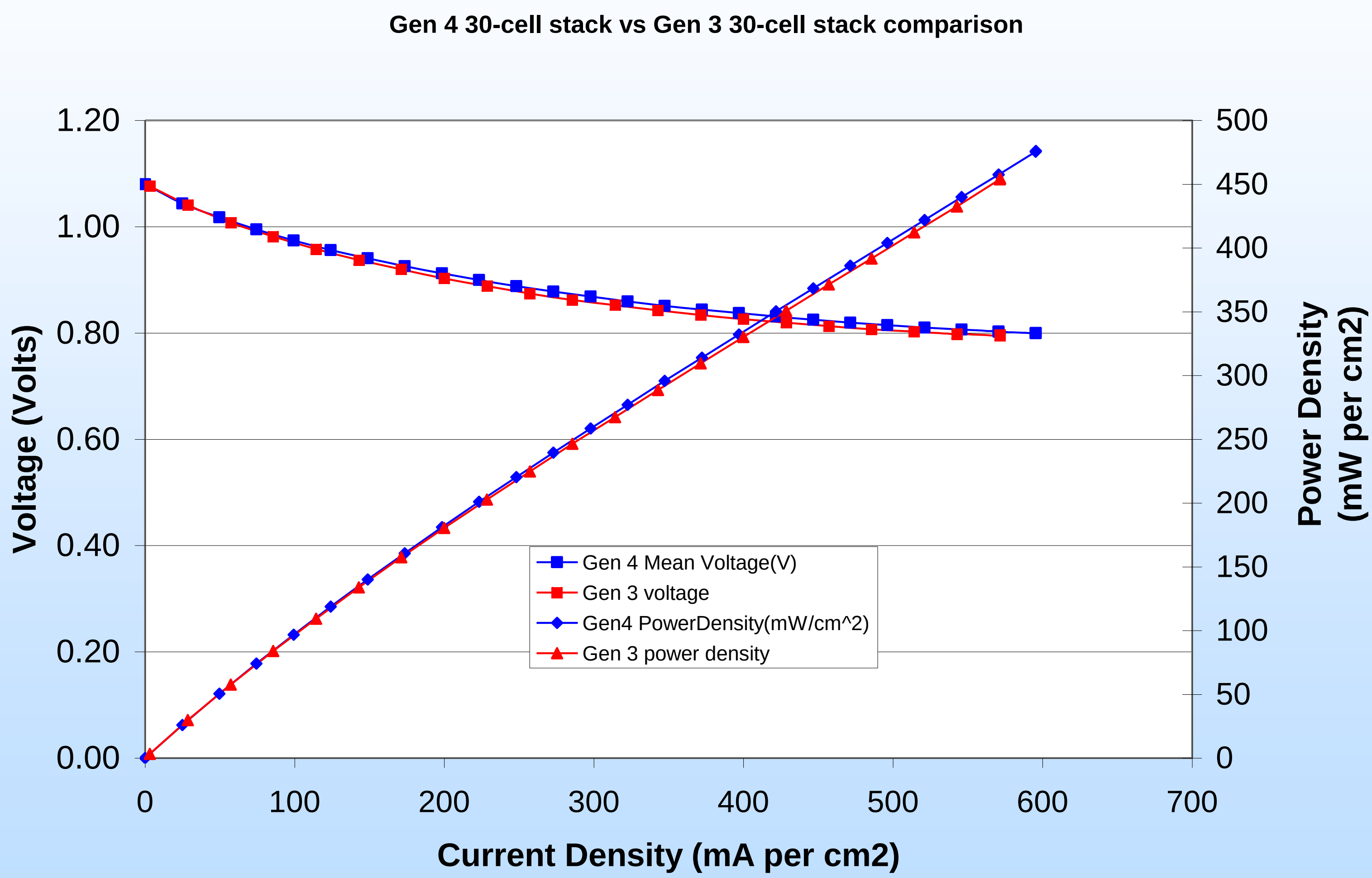
GENERATION 4 STACK PERFORMANCE

- Recent Gen 4 stack fuel utilization

- Current density of 600 mA per cm^2
  - Minimal lowering of power density up to 85% utilization (Fuel 48.5% H_2,3% H_2O, rest N_2)
  - Power density of 460 mW per cm^2 at 70% fuel utilization



GENERATION 4 VERSUS GEN 3 STACK PERFORMANCE



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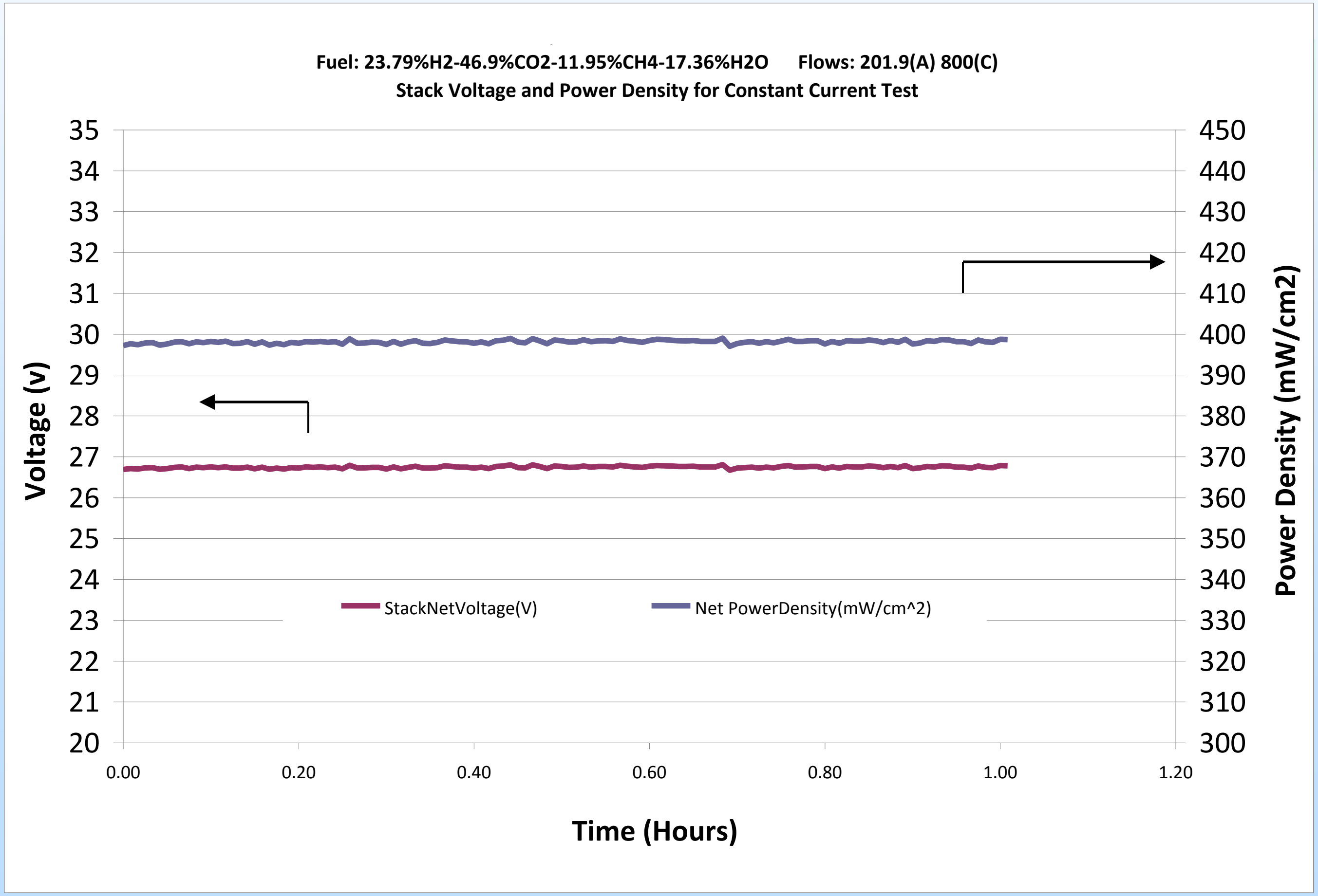
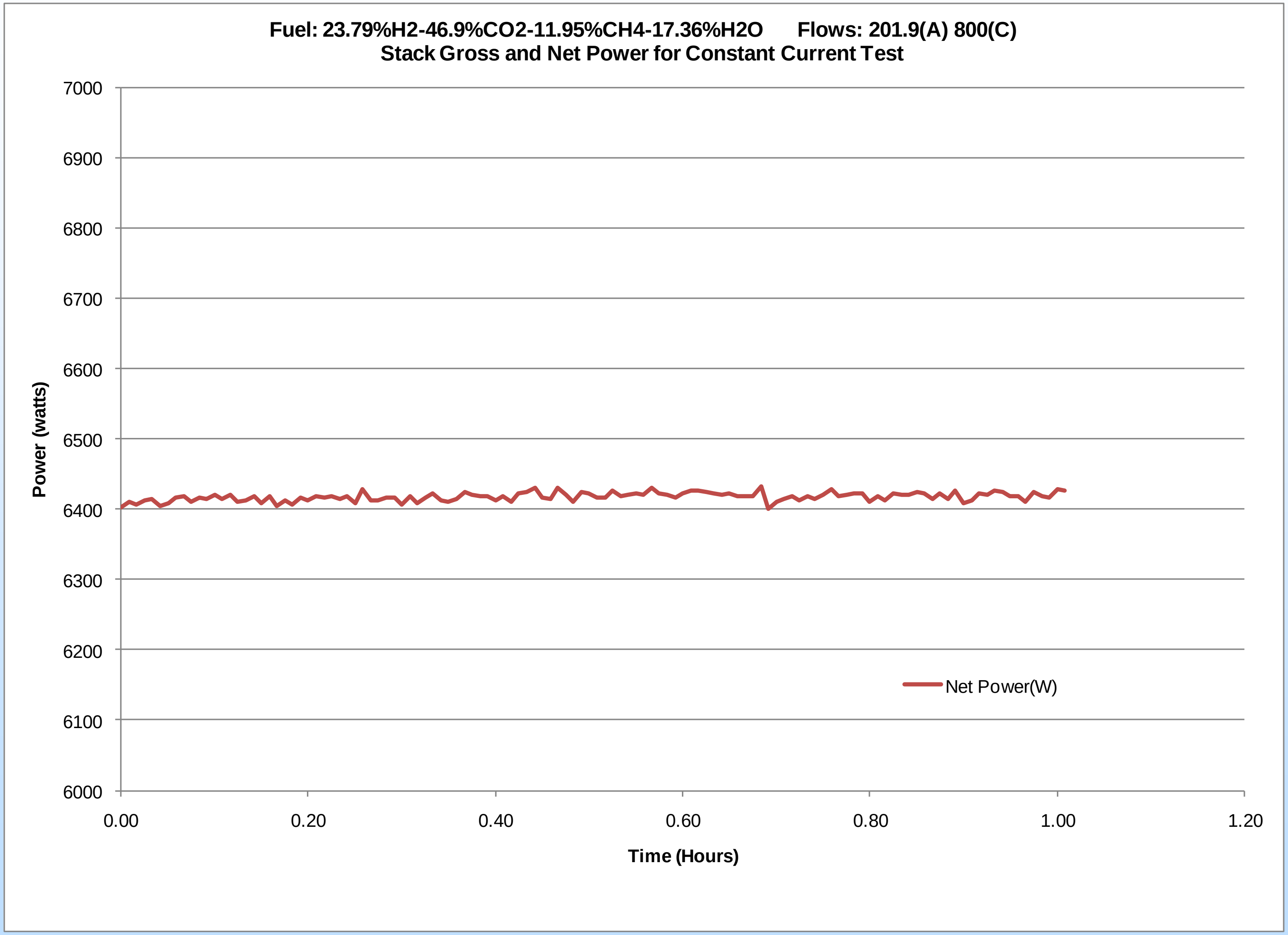
GEN 4 STACK TESTED WITH SIMULATED COAL GAS REFORMATE-SECA MAX POWER TEST

- Generation 4 40-cell stack evaluated with simulated coal gas reformate – one hour steady state at maximum power
  - Produced a power density of 398 mW per cm^2 (6.4 kW per 40-cell stack) at an average voltage of 0.7 Volts per cell

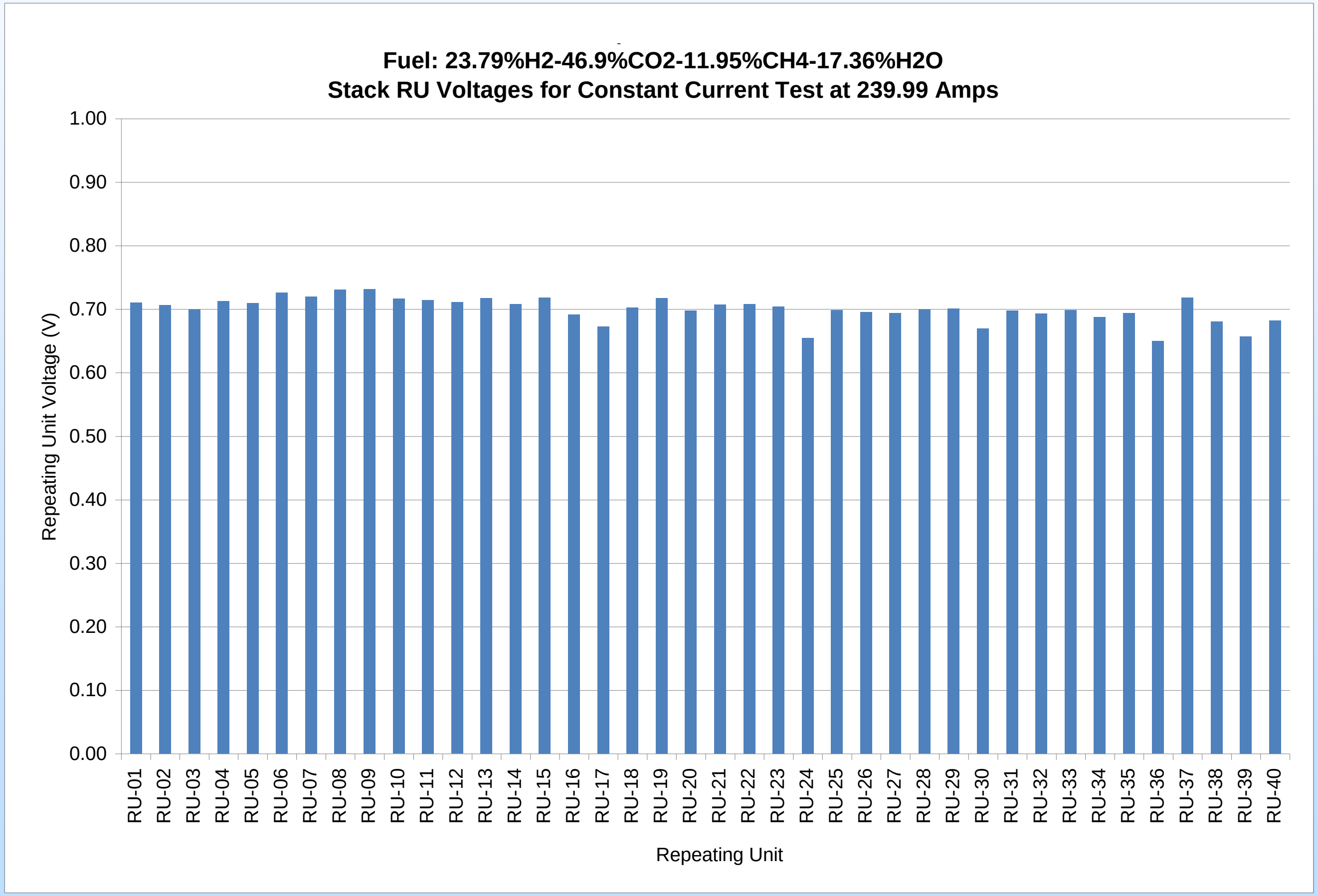


GEN 4 STACK MAX POWER ON SECA COAL GAS BLEND



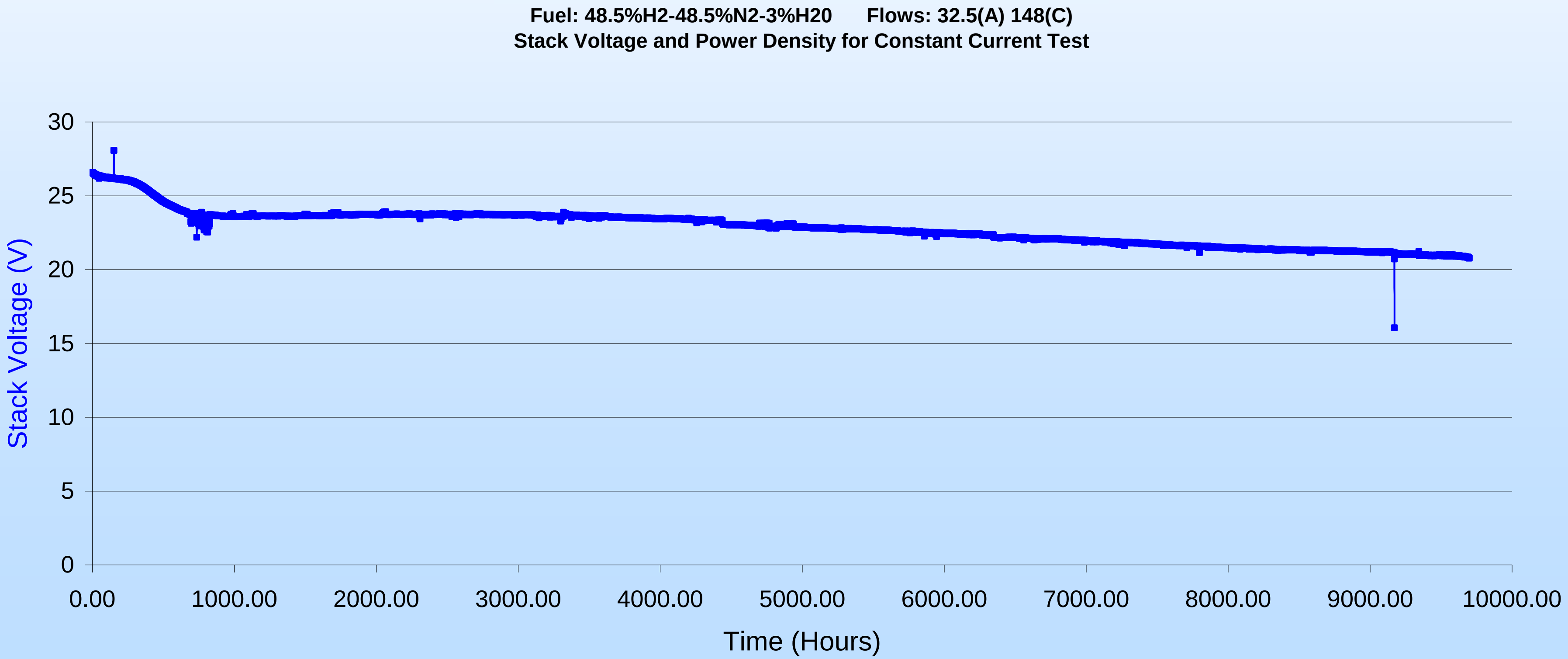
GEN 4 STACK TESTED WITH SIMULATED COAL GAS REFORMATE- SECA MAX POWER TEST

- Generation 4 40-cell stack evaluated with simulated coal gas reformate – one hour steady state at maximum power output
- Minimal Cell to cell voltage variation (0.08 V) under max power conditions



GENERATION 3 30-CELL STACK DURABILITY

- 9700 hours of durability test on Generation 3 30-cell stack
  - Fuel = 48.5% H_2, 3% H_2O, rest N_2; current = 333 mA/cm^2
  - Total degradation is 1.12% per 500 hours
  - Degradation mechanism during initial 1000 hours and after 5000 hours is understood and technology solutions are being implemented
  - Test stopped due to facility failure



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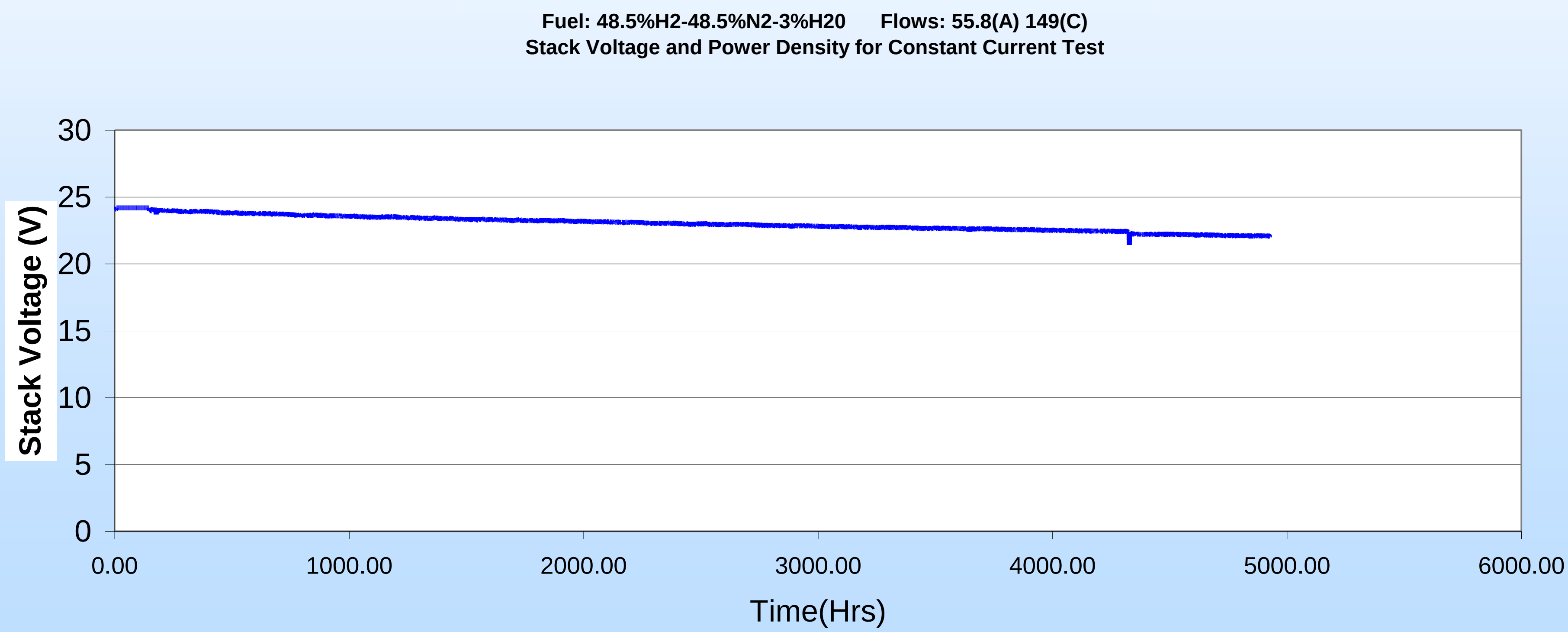
GENERATION 3 30-CELL STACK DURABILITY WITH IMPROVED TECHNOLOGY

- Ongoing durability test with improved technology solutions show minimal initial degradation in the first 1000 hours
  - Fuel = 48.5% H_2, 3% H_2O, rest N_2; current = 570 mA/cm^2
  - 5000+ hours completed, test continuing
  - Total degradation is 0.88% per 500 hours



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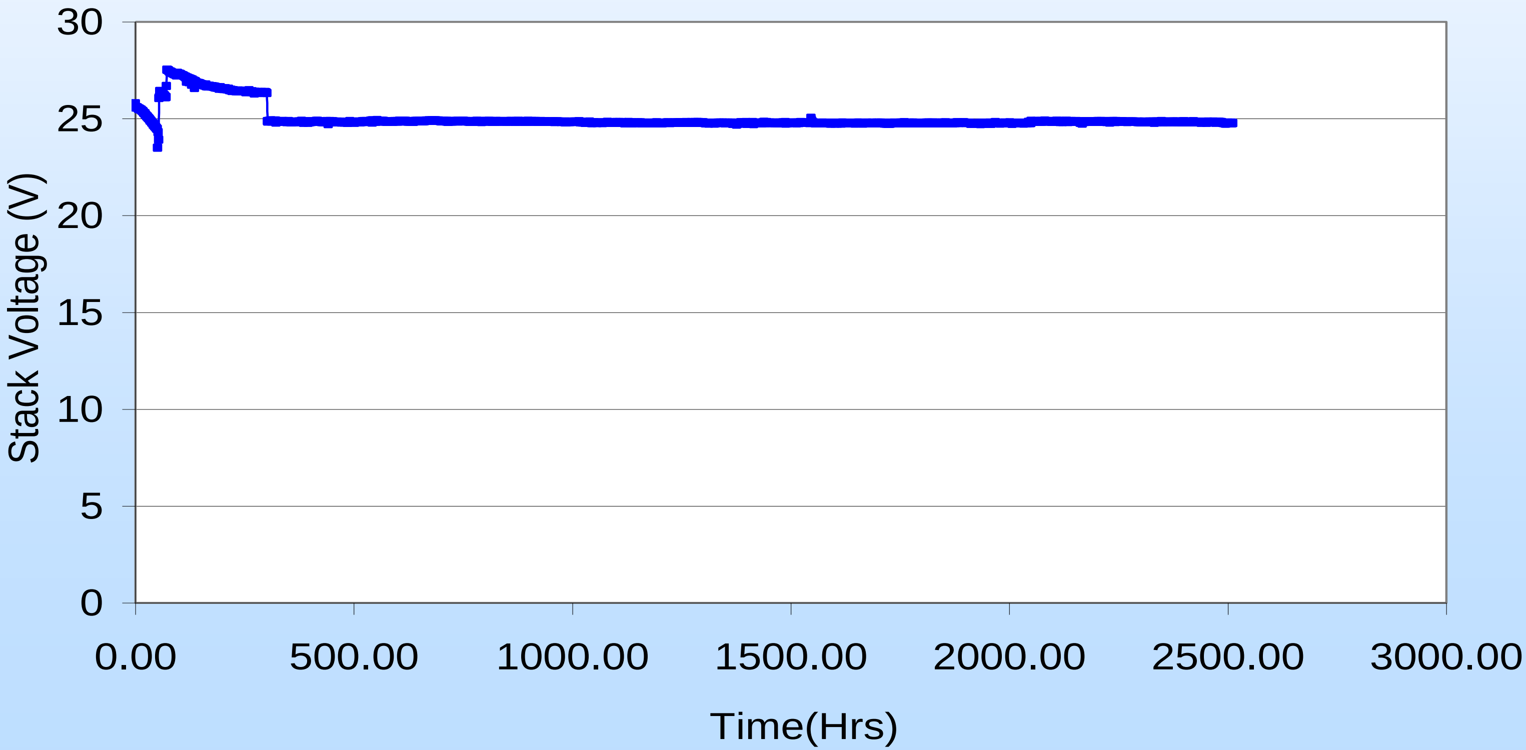
GENERATION 4 30-CELL STACK DURABILITY TEST

- Ongoing durability test with Gen 4 30-cell stack
  - Fuel = 48.5% H_2, 3% H_2O, rest N_2; current = 153 mA/cm^2
  - After the first 300 hours (4% degradation), minimal degradation rate observed (less than 0.5%)
  - 2500+ hours completed, test continuing



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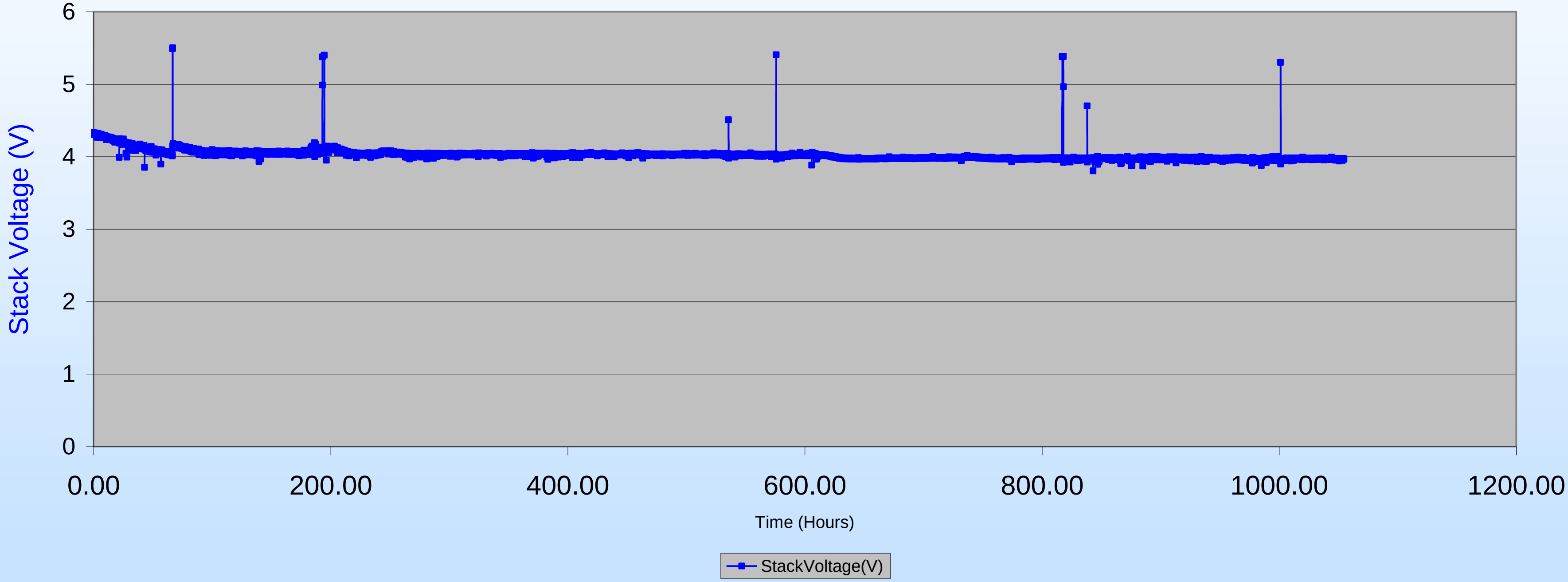
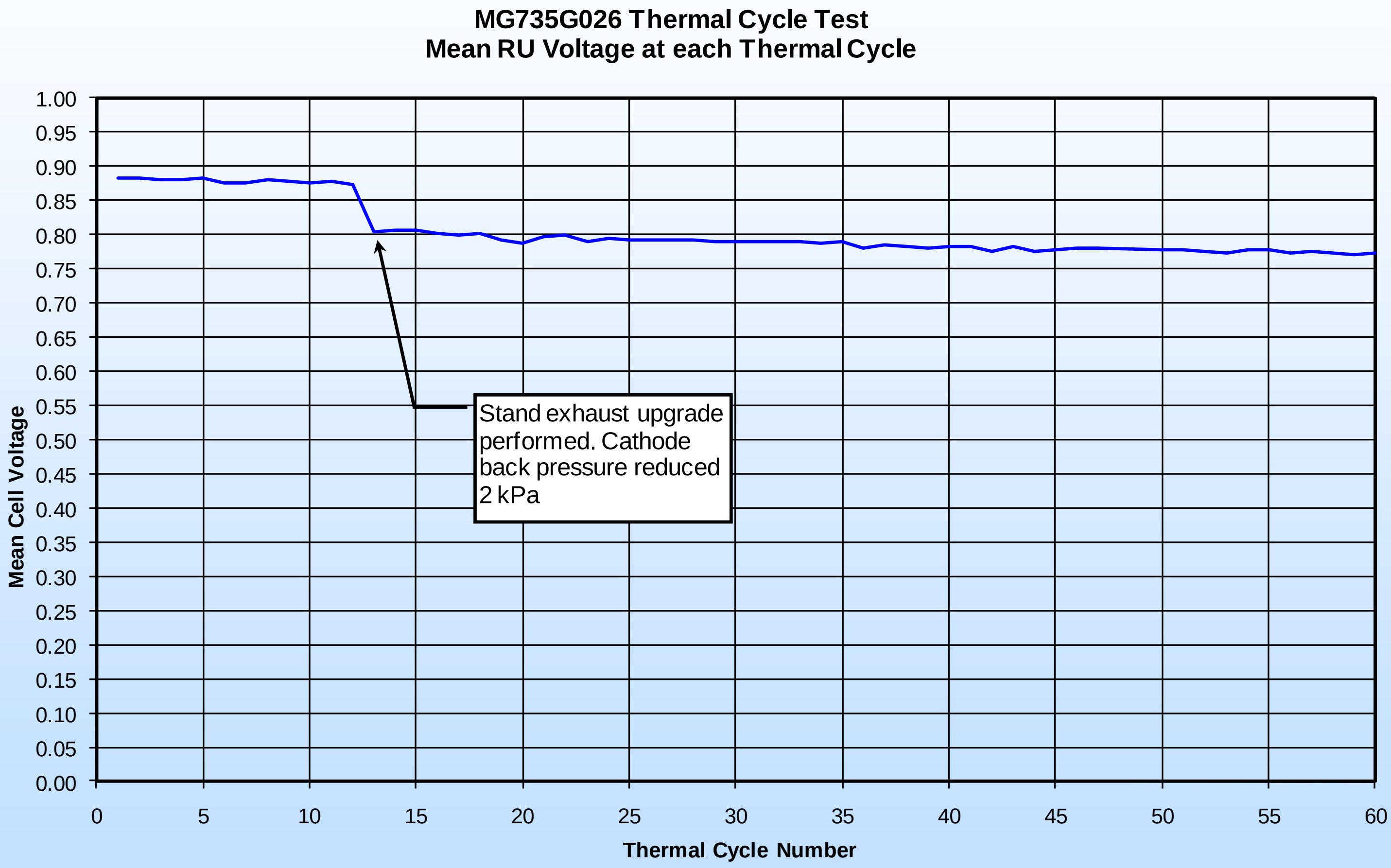
STACK TESTED WITH REFORMATE

- Gen 3.2 5-cell stack evaluated with hydrocarbon fuel reformate
- 1000 + hours of stable performance (voltage and pressure)
- Initial degradation due to sulfur in hydrocarbon fuel



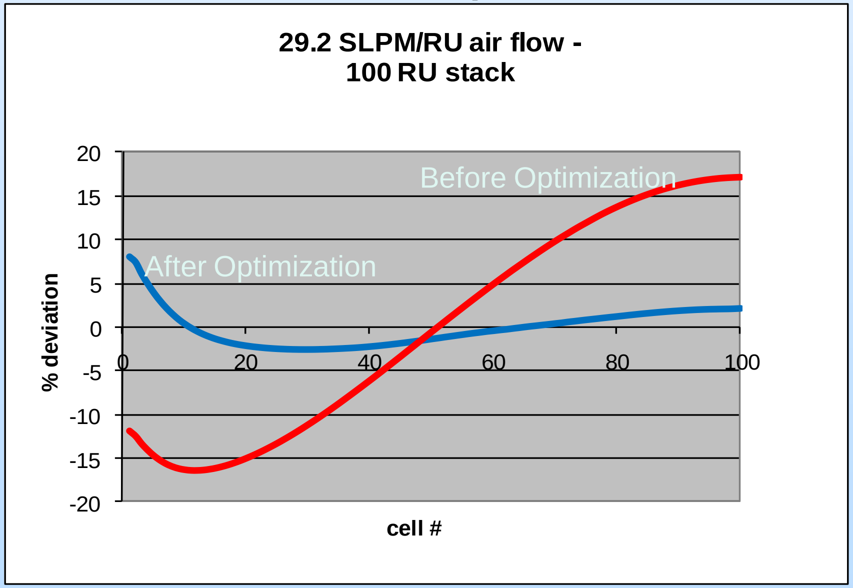
10-CELL GEN 4 STACK COMPLETED 60 DEEP THERMAL CYCLES



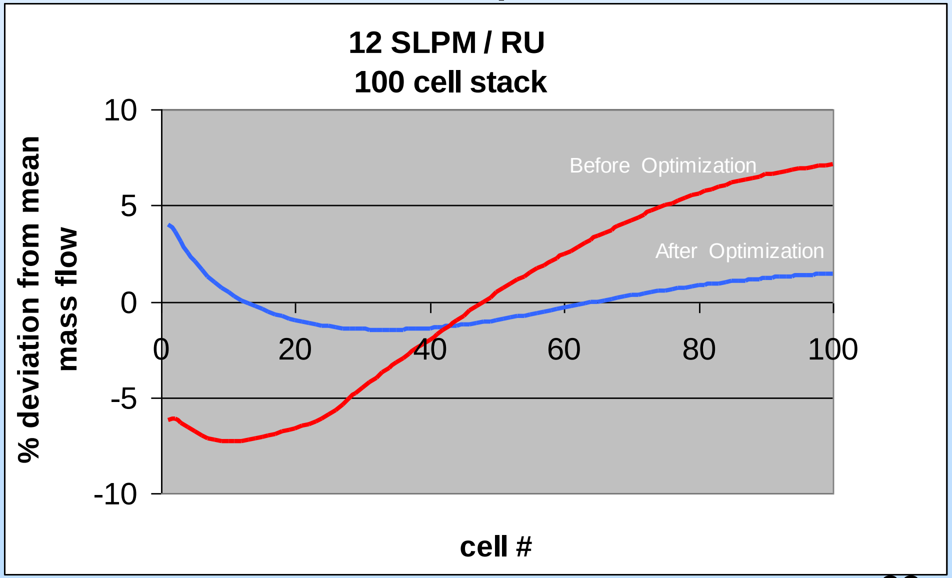
CFD MODELING OF GEN 4 STACK

- Detailed CFD modeling of Gen 4 stack completed to optimize for 100 repeating units
  - Detailed geometry of Gen 4 repeating unit captured in computational mesh
  - 30-RU to 100-RU stack model developed
  - Pressure drop analyzed for Gen 4 with varied fuel and air flow rates
  - Pressure drop prediction validated with actual Gen 4 stack flow data
  - Robust engineering project completed to optimize stack design for robustness to mass flow distribution between cassettes in 30 to 100 RU stacks
    - ± 0.5 slpm for fuel, ± 1.0 slpm for air

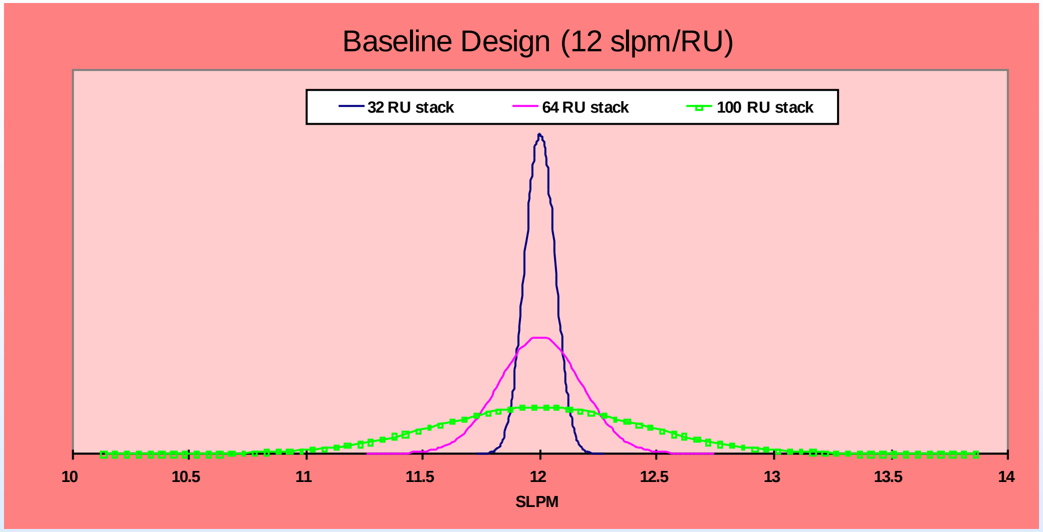
Cathode Flow Optimization



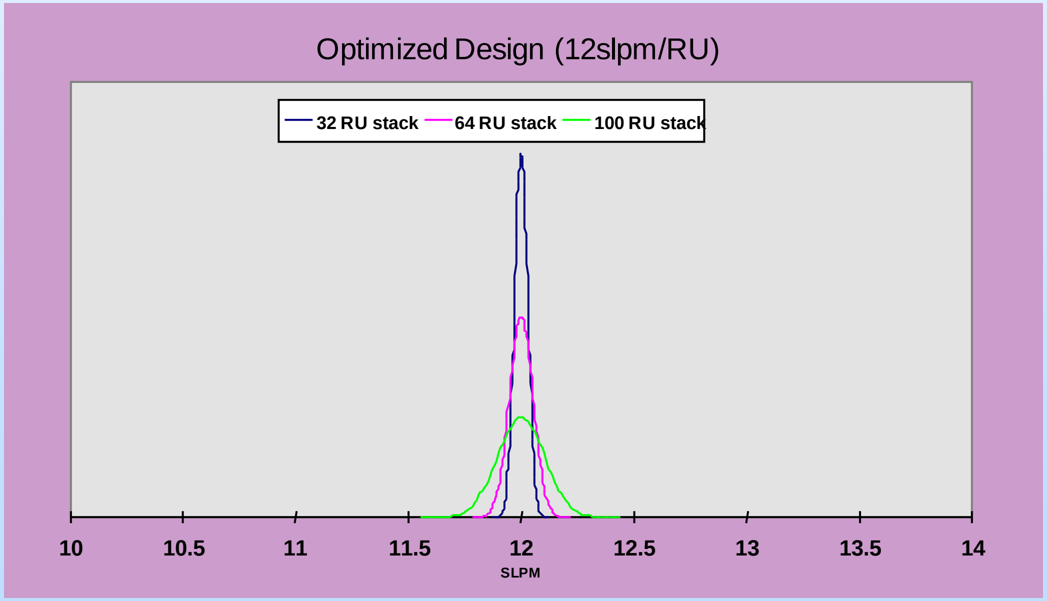
Anode Flow Optimization



STACK MASS FLOW DIST. OPTIMIZED FOR FUEL FLOW



32 RU -100 % within limits
64 RU- 100% within limits
100 RU - 38% within limits



32 RU - 100% within limits
64 RU - 100% within limits
100 RU- 100% within limits

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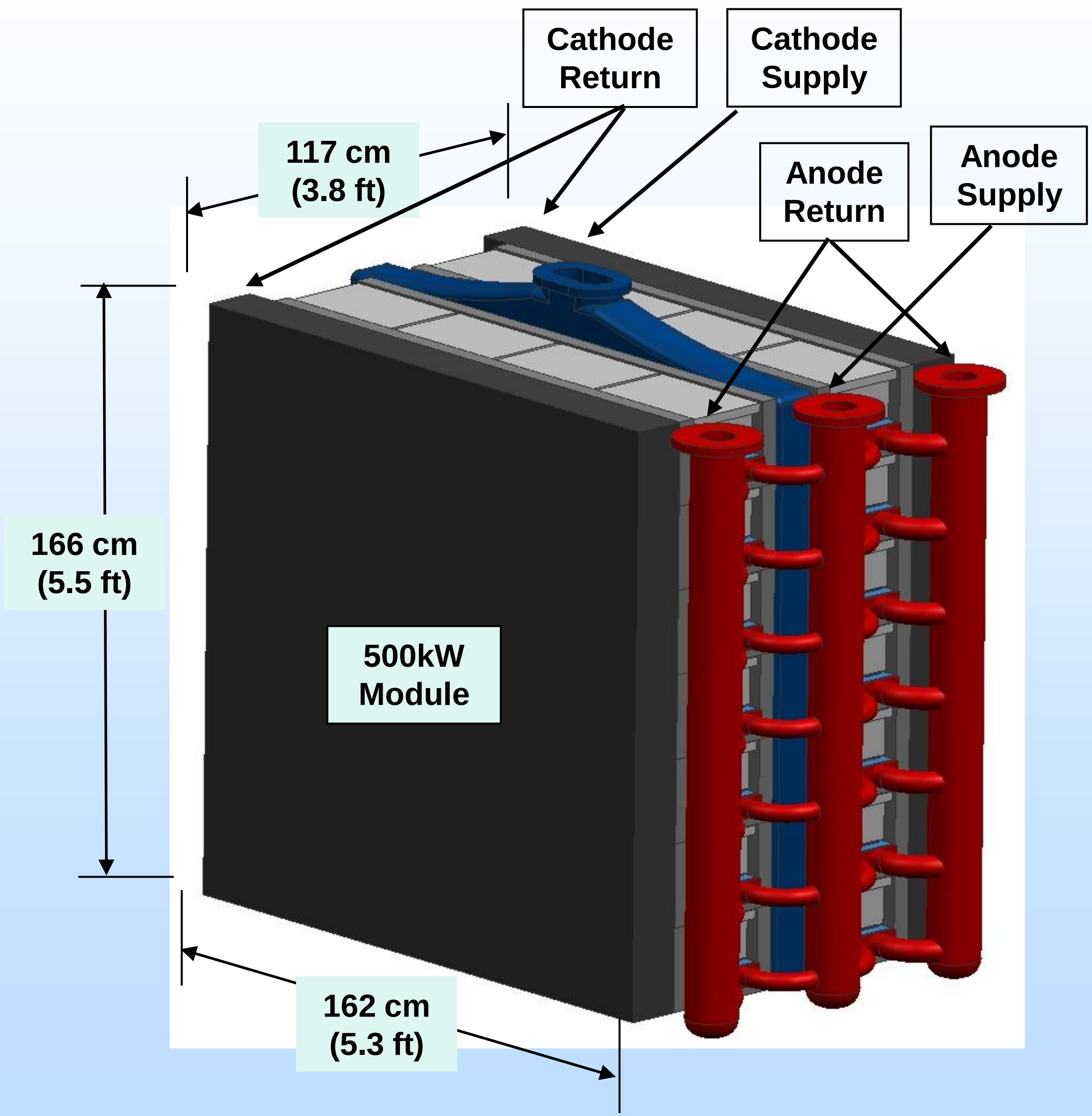
STACK ASSEMBLY FOR STATIONARY POWER PLANTS

- Modular array design
- Simplified fuel manifolding
- Plenum Air Supply and Return
- Volume ~ 111ft³ (500kW)



PHASE I ACHIEVEMENTS - SYSTEMS

- Commissioned the 50 kW capable test stand at UTC Power.
- Started 1500 hr endurance testing of stack module.
- Developed multiple Power Module concepts for 400 kW net AC and $\eta \geq 60\%$ (LHV).
- Developed multiple IGFC designs for > 100 MW net AC power, $\eta \geq 50\%$ (HHV), and ≥ 90% carbon capture.

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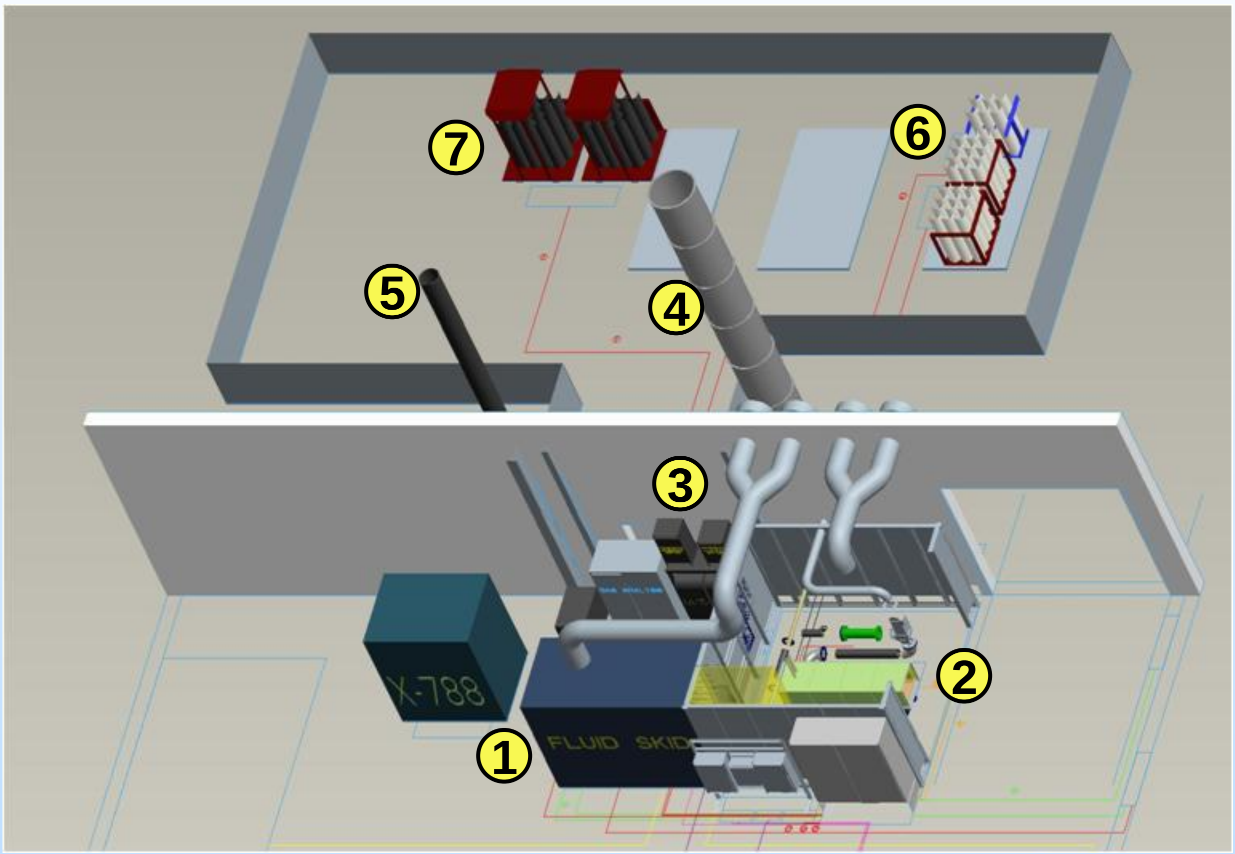
TASK 6

50kW Test Stand

- Automated operation
- Provide anode/cathode gases
  - Forming gas, 50%/50% H_2/N_2,Coal syngas
  - 750°C-775°C process gas temperature
- Provide loads up to 50kW
  - 400 amperes/600 volts
- Tested/commissioned in Q2, 2011 using extensive testing on debug stack
- Currently testing Delphi stack module for 1500 hr endurance

50KW TEST STAND

Test Facility



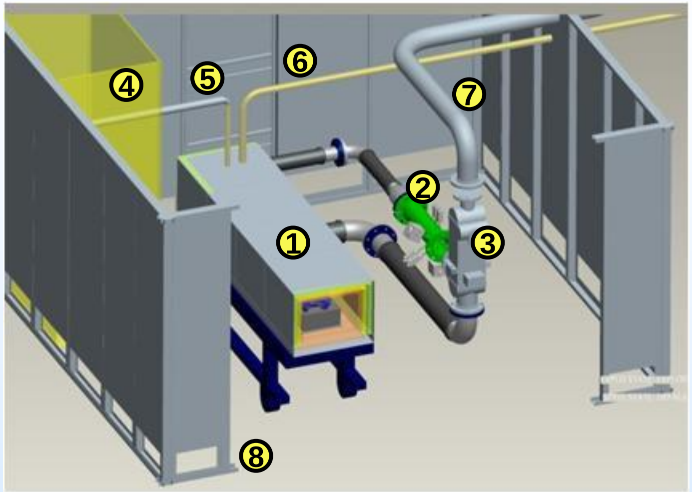
Piping, heat exchanger and heater insulation not shown

❶ Fluid Management Skid
❷ Test Room
❸ Load Bank
❹ Afterburner
❺ Cathode Exhaust
❻ Emergency air, 4%H2 bottles
❼ Methane Bottles

50KW TEST STAND

Test Room

- ❶ Test Article (in Hot Box)
- ❷ Cathode Heater
- ❸ Cathode Recuperative Heat Exchanger
- ❹ Anode Constituent Heaters
- ❺ Anode Supply
- ❻ Anode Exhaust
- ❼ Cathode Exhaust
- ❽ Test Article Room

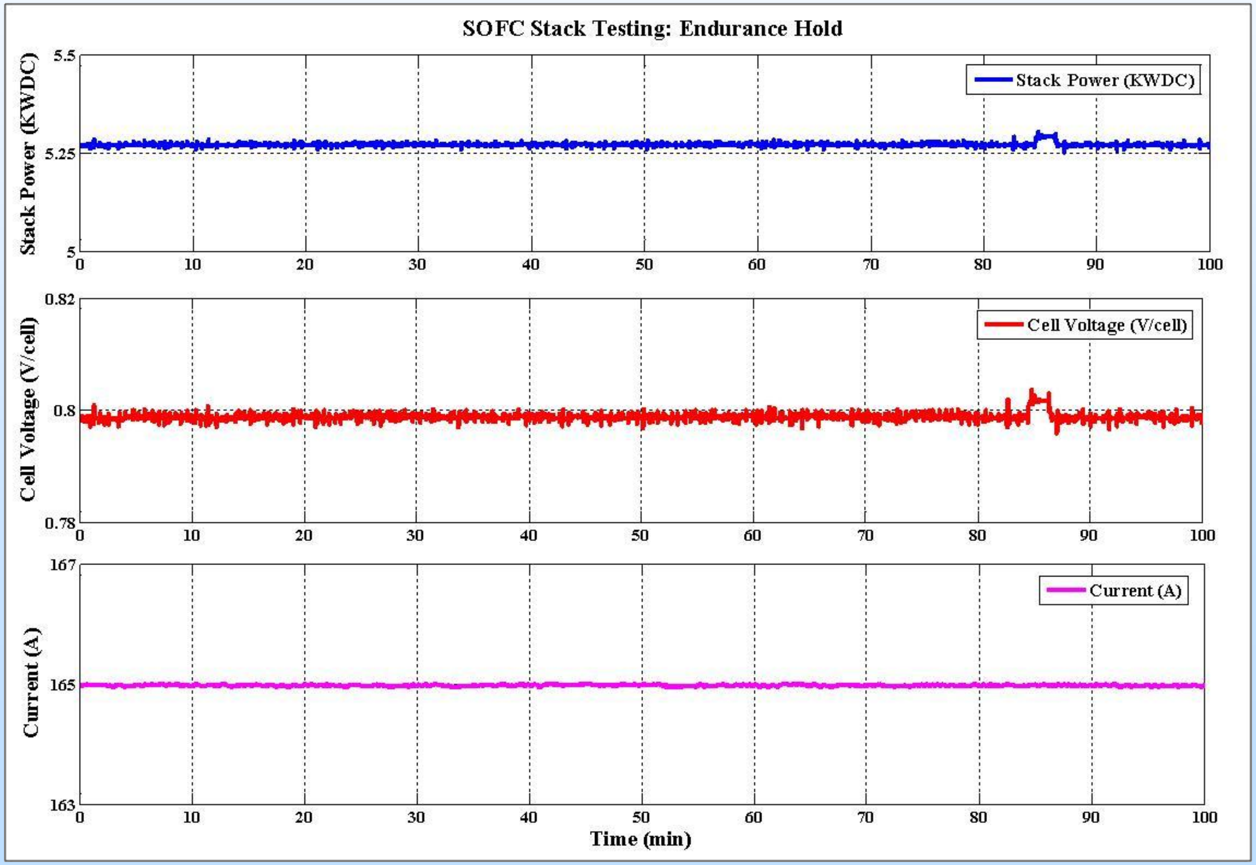


Test Room

Test Room with Test Article

1500 HR ENDURANCE HOLD

- Started 1500 hr endurance hold with 2-stack module
  - Coal gas: (23.79%H_2-46.9%CO_2-11.95%CH_4-7.36%H_2O)
  - NOC point: 0.8V/cell at 165A & 5.2kW
  - Stack performance stable



TASK 7

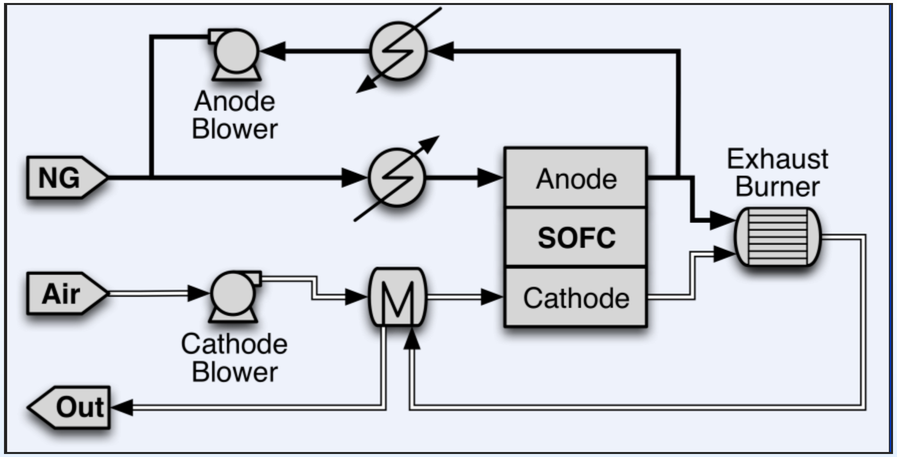
Power Module Design

- **12 systems designed and analyzed**
  - Categorized into 4 groups
- **All systems designed for 400 kW net AC and $\eta \geq 60\%$ (LHV)**
- **Heat-up and power ramp studies were performed**
- **Conceptual design decisions based on**
  - Customer value drivers: **C**ost, **E**fficiency, **R**eliability, **O**perability
  - Technology Readiness Level (TRL) for critical components: Blowers, HEX, Desulfurizer
- **Design decisions driven by**
  - System design simplification
  - Component interface conditions: Lower recycle blower inlet temperature, Improve desulfurization step, Meet stack interface conditions

COAL-GAS POWER MODULE

Design Features:

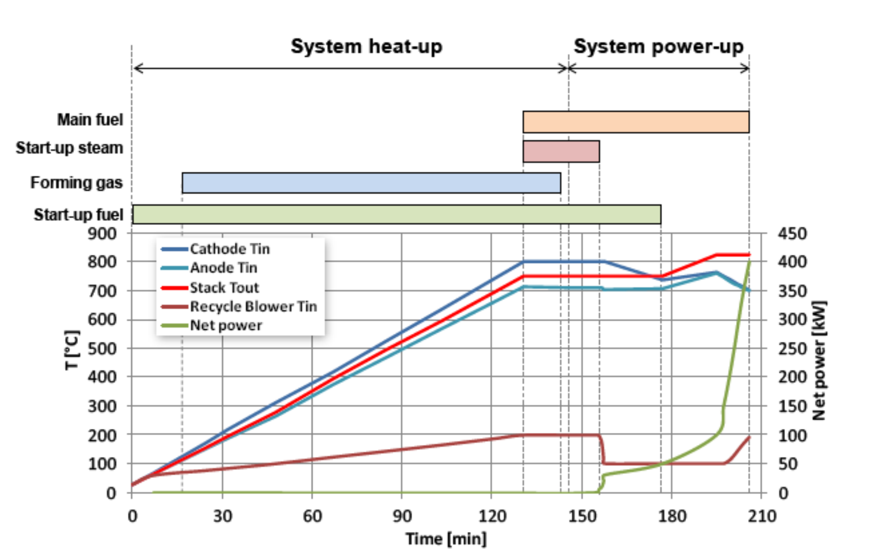
- Simplified FPS
- Fuel recycle for efficiency and fuel pre-heat
- Anode HEX for lower blower temp, pre-heat coal gas
- Cat burner for emissions management and air pre-heat



Coal-gas (CG) Power Module concept

Net AC power	400	[kW]
System electrical efficiency (LHV of CG)	60.3	[%]
Cell voltage	800	[mV]
Stack inlet temperature	700	[°C]
Stack outlet temperature	825	[°C]
Single pass fuel utilization	80.0	[%]
Overall fuel utilization	90.0	[%]
Steam/Carbon at anode inlet	2.0	[-]
Anode exhaust recycle ratio	55.8	[%]
Recycle blower inlet temperature	193	[°C]
Stack oxygen utilization	27.1	[%]

Key Power Module Requirements



Simulation results of CG system start-up

POWER MODULE CONCEPTS

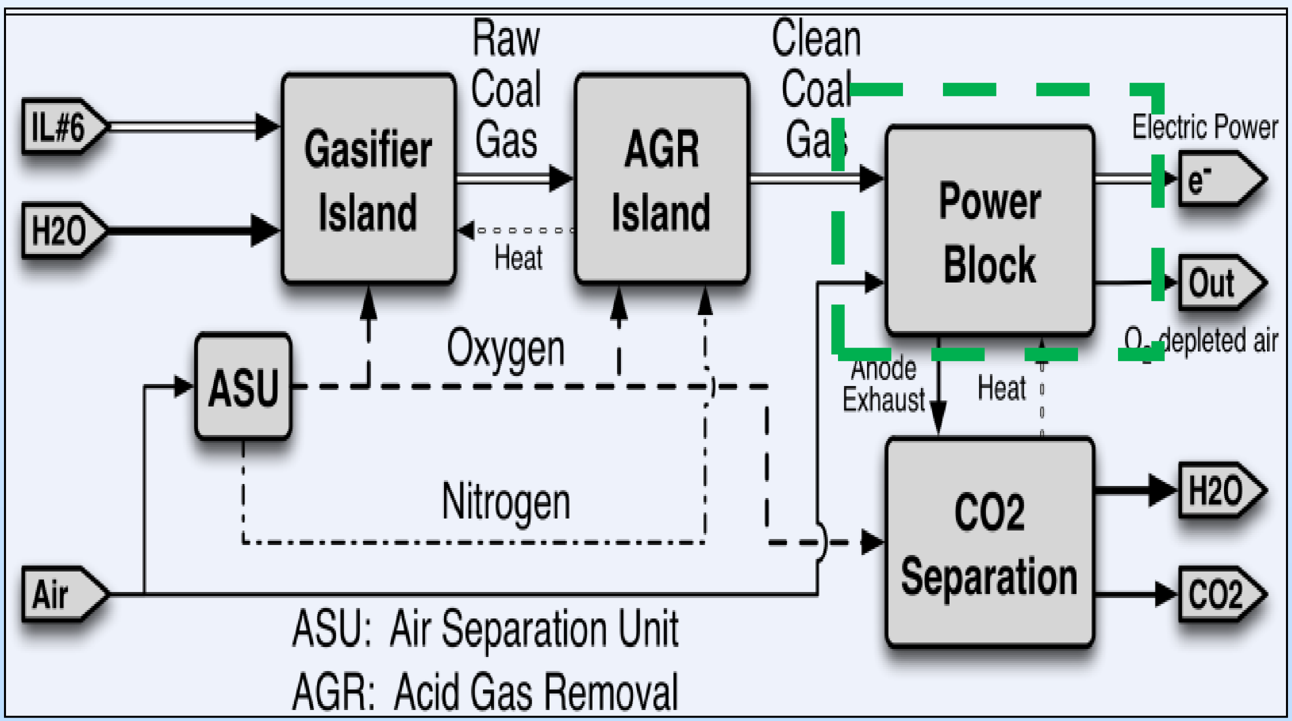
Preliminary Concept Down-select

Concepts / Metrics	Concept 1	Concept 2	Concept 3	Concept 4
	Integrated FPS-CB with Anode Recycle	Integrated APS-CB with Anode Recycle	Integrated APS-CB with Anode and FPS Recycle	Integrated APS-CB-Boiler with Anode and FPS Recycle
Efficiency **($\eta \geq$ 60% (LHV))**				
Reliability **(Relative Scale)**				
Operability **(Relative Scale)**				
Cost **(<700 $/kWe)**				
TRL **(> TRL6)**				

FPS – Fuel Processing System; APS – Air Processing System; CB – Catalytic Burner

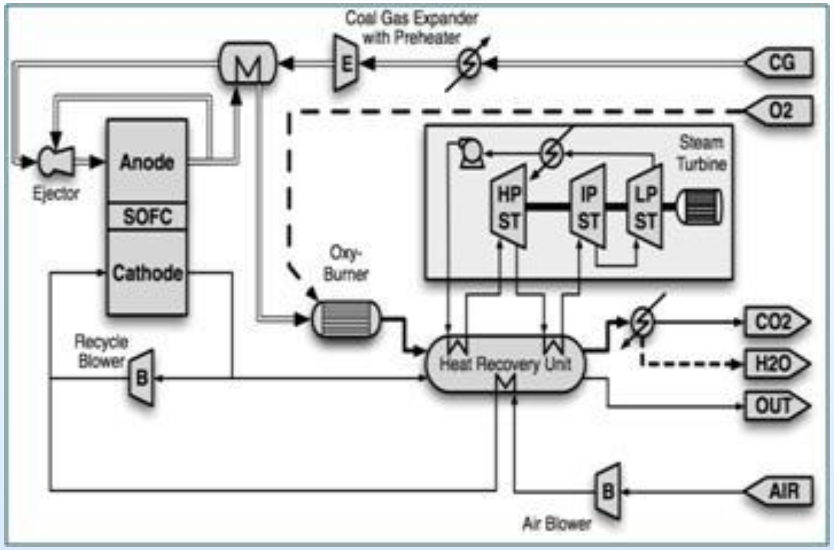
IGFC SYSTEM DESIGN

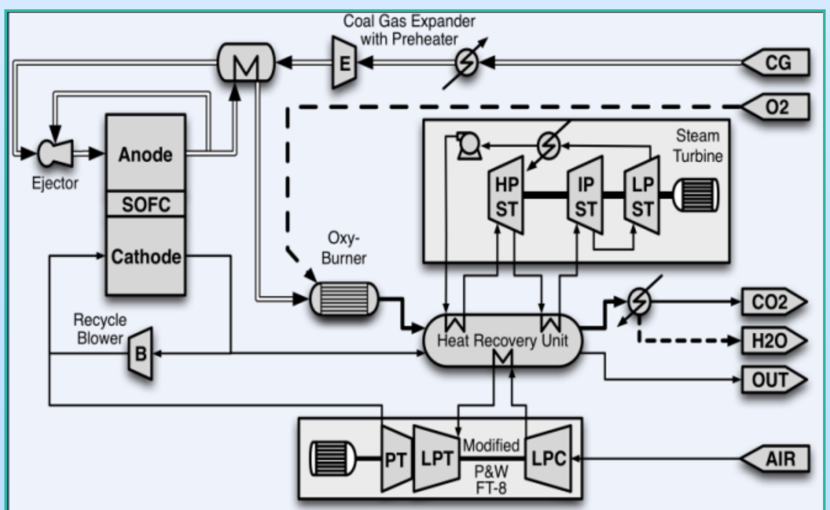
- **3 system concepts designed and analyzed**
  - Atmospheric SOFC/ST system with air blower
  - Atmospheric SOFC/ST system with gas turbine
  - Pressurized SOFC/ST system with gas turbine
- **All concepts designed for 100 MW net AC power, η ≥ 50% (HHV), and ≥ 90% carbon capture**



IGFC POWER BLOCK DESIGN

Atm. SOFC/ST/GT - Performance Comparison





	Atmospheric	
	SOFC/ST $U_{f,p}$ = 80%	SOFC/ST/GT $U_{f,p}$ = 80%
Net Efficiency* [%, HHV]	**51.0**	**57.0**
Net AC Power [MW]	**108.0**	**122.0**
SOFC AC [% gross]	87.7	80.0
Steam Cycle [% gross]	9.0	5.7
Coal-gas Expander [% gross]	3.3	3.2
Gas Turbine [% gross]	—	11.1

Model Assumptions

Cell voltage= 0.8V/cell

Per pass fuel utilization = 80%

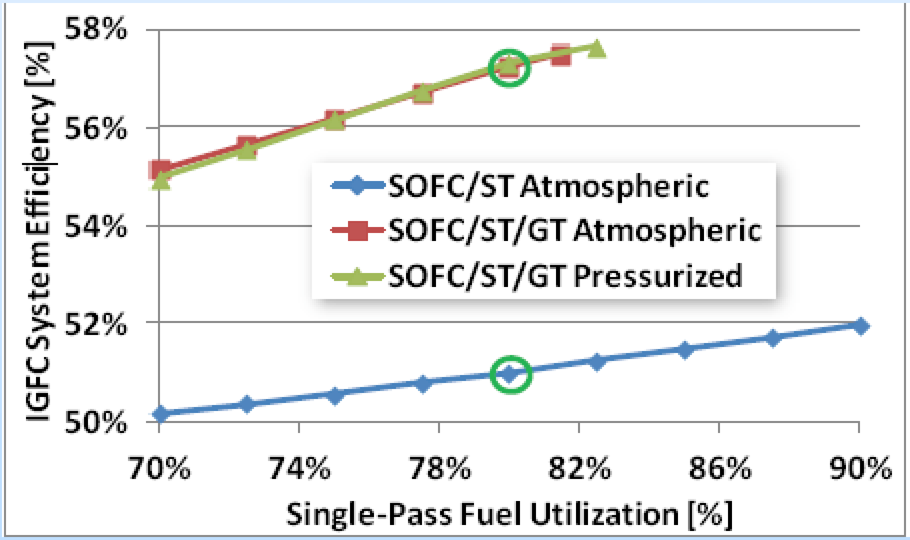
Overall fuel utilization = 90%

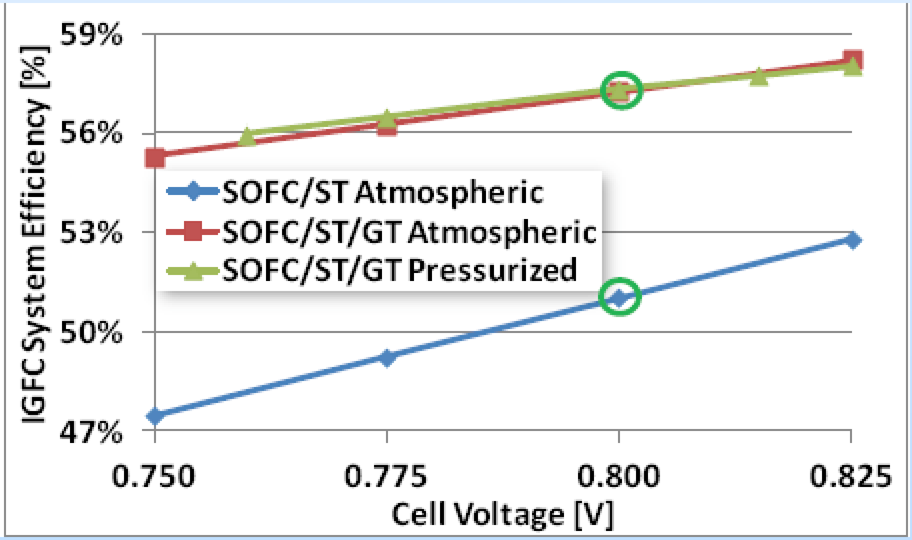
Inverter efficiency = 97%

IGFC POWER BLOCK DESIGN

IGFC Performance – Sensitivity Analysis

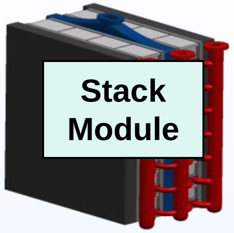
- 1-D sensitivity analyses performed with key system parameters
- 3 IGFC designs meet DOE requirements over broad range of parameters
- Studied operating variables to be modified to maintain performance



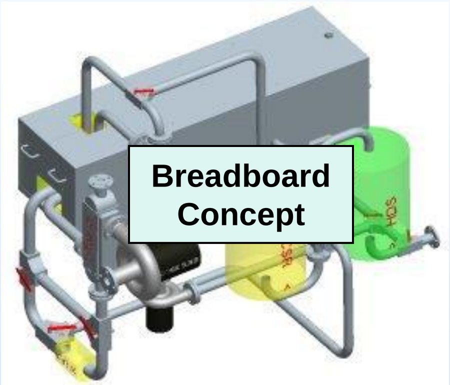


FUTURE WORK

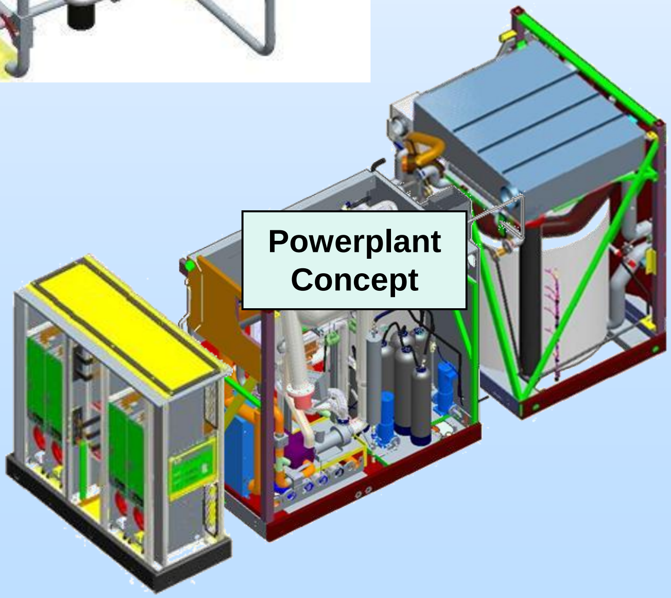
Phase II



- Continue cost reduction of stack and power plant components



- Design high power stack module utilizing results of stack array testing
- Focus on system development leveraging existing stationary platforms
- Develop breadboard to test power plant components at 25 kW scale
- Demonstrate scalable 100+kW power plant



ACKNOWLEDGEMENTS

Battelle
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Thanks to Shailesh Vora, Joe Stoffa, Briggs White, and Heather Quedenfeld of the DOE for their support and technical guidance

BACKUP SLIDES

PHASE I OBJECTIVES

Task 6

- Design, build and commission a test stand capable of testing SOFC stacks up to 50 kW
- Complete 1500 hours of stack module operation

Task 7

- 250-1000kW power module design
- 5MW proof of concept design
- IGFC system development

GEN 4 STACK MAXIMUM POWER CELL PERFORMANCE