SOFC Program Review

11th Annual SECA Workshop

Pittsburgh, PA

27 July 2010

David Brengel - Project Manager

UTC Power

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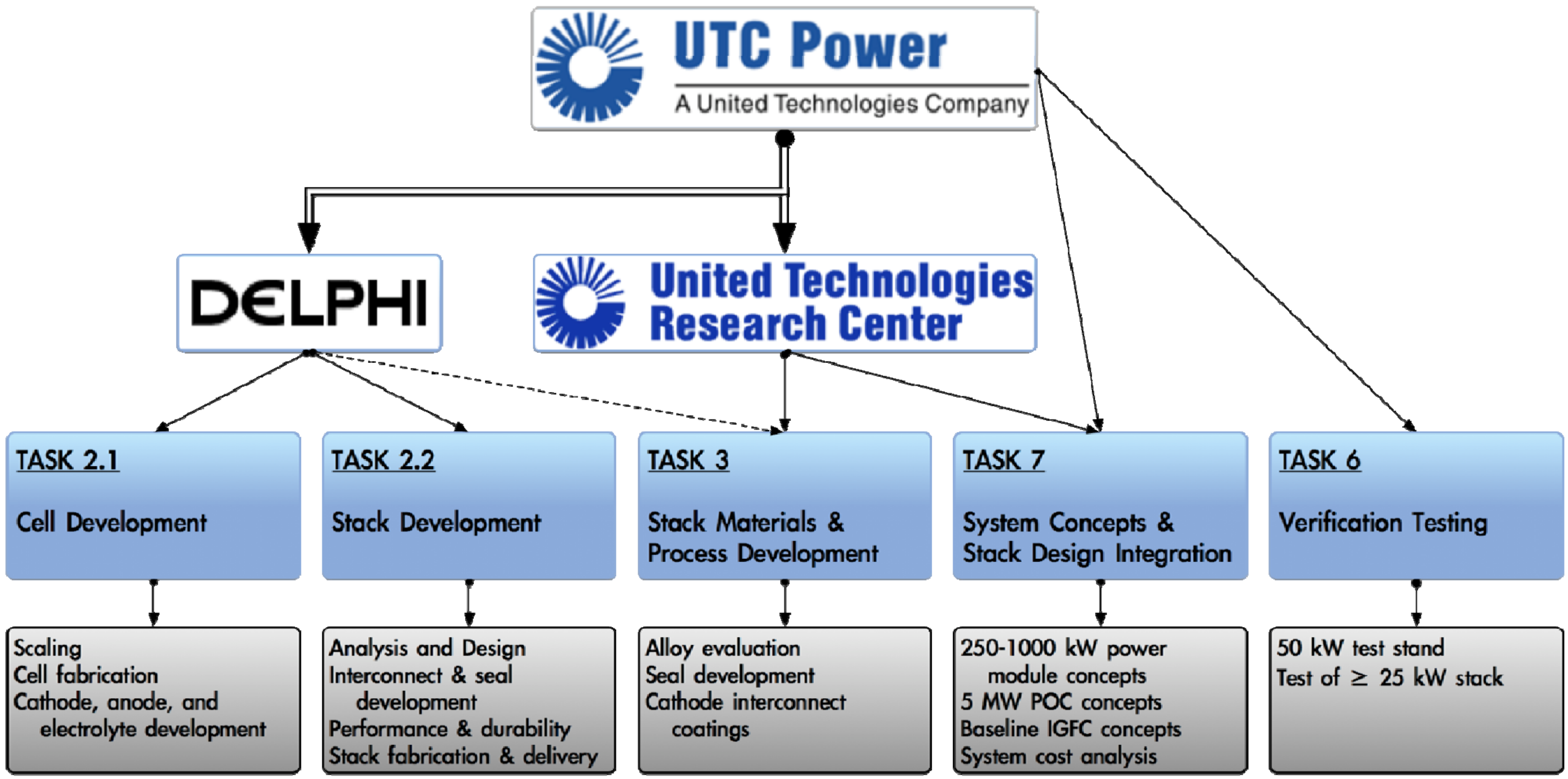
SECA Objectives

- Reduce SOFC-based electrical power generation system cost to ≤ \$400/kWe (2002 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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United Technologies Research Center
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

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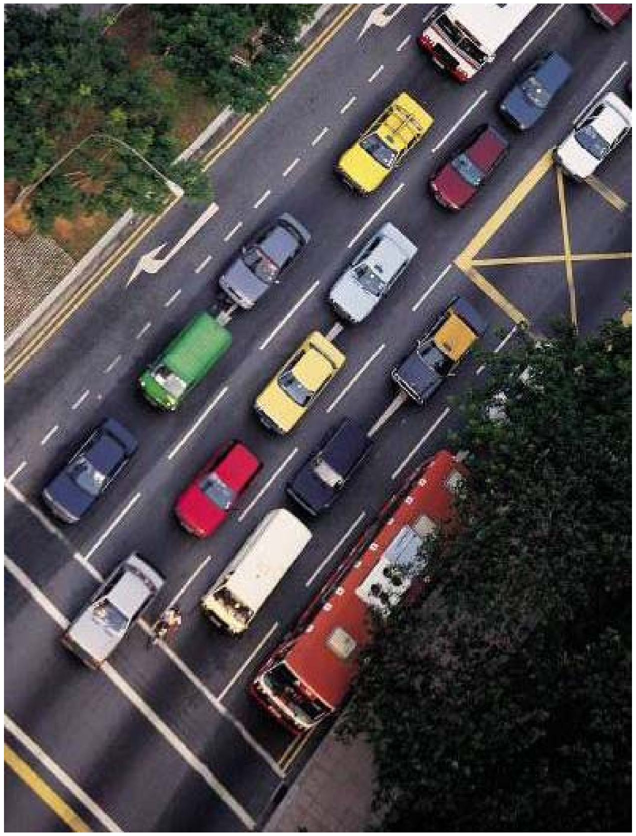
Markets: Buildings & Transportation

A world leader in developing and producing fuel cells that generate energy for buildings and transportation



Stationary Fuel Cell Solutions

Successful track record around the world

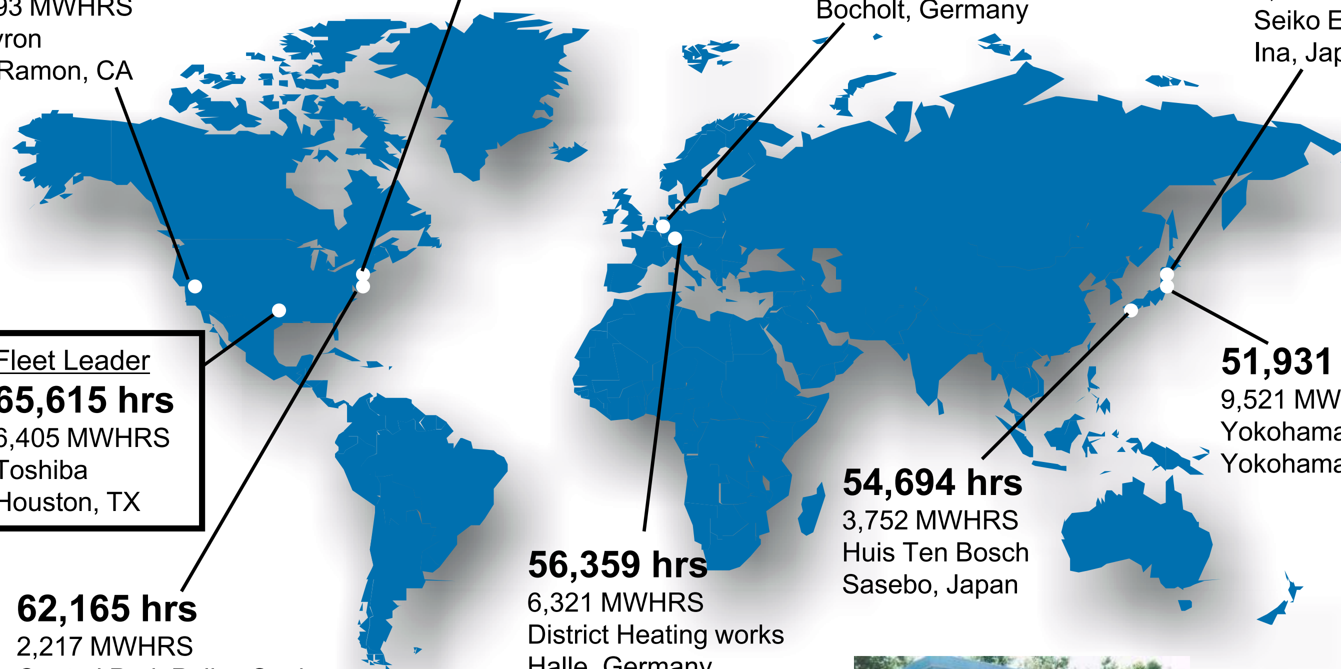
61,040 hrs &
11,897 MWHRS
Casino
Uncasville, CT

57,640 hrs
11,033 MWHRS

61,950 hrs
11,457 MWHRS
Hospital
Bocholt, Germany

56,573 hrs
10,793 MWHRS
Chevron
San Ramon, CA

51,277 hrs
9,141 MWHRS
Seiko Epson Ina Works
Ina, Japan



Fleet Leader
65,615 hrs
6,405 MWHRS
Toshiba
Houston, TX

51,931 hrs
9,521 MWHRS
Yokohama Sewage Plant
Yokohama, Japan

54,694 hrs
3,752 MWHRS
Huis Ten Bosch
Sasebo, Japan

56,359 hrs
6,321 MWHRS
District Heating works
Halle, Germany

62,165 hrs
2,217 MWHRS
Central Park Police Station
New York City, NY

200 kW systems

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Stationary Fuel Cell Solutions

400 kW PureCell® system advantages

- **400 kW electric output**
- **Natural gas**
- **42% electrical efficiency***
- **1.7 MMBtu/hr heat output†**
- **Up to 90% system efficiency**
- **Designed to meet CARB 2007 standard±**
- **20-year powerplant life****
- **“Dual Mode” capability**
- **Modular approach for MW-size applications**

* At beginning of life
** With overhaul at end of year 10
† ~ 500 kW
± California Air Resources Board 2007 emissions standard

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Driving Global Innovation-
In Close Collaboration with Our Customers

Key Global Technical Centers

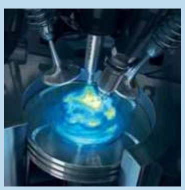
24 Technical Centers ■ 21 Countries ■ 16,000 Scientists & Engineers

Core Innovations = Future Possibilities

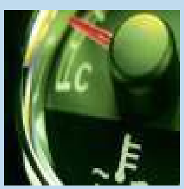
Core Automotive Markets

Electrical/Electronic Architecture

Electronics & Safety



Powertrain Systems



Thermal Systems

Aftermarket

Adjacent Markets

Residential/Commercial Heating and Cooling

Commercial Vehicles

Military/Aerospace

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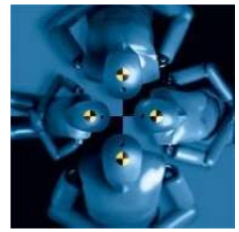
Delphi: Committed to Innovation and Excellence

- Superior Engineering and Systems Integration
- Leading-Edge Technology
- Quality Products and Services
- World-Class Customer Support
- Global, Precision Manufacturing Capabilities
- Collaborative Innovation
- Award Winning Performance



Safe.

Green.

Connected.

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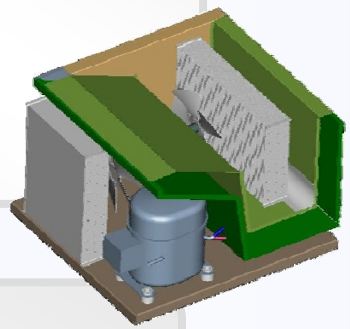
Technical Capabilities

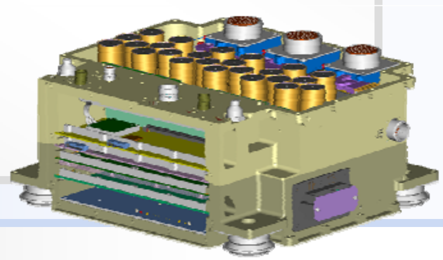
Physical Sciences...

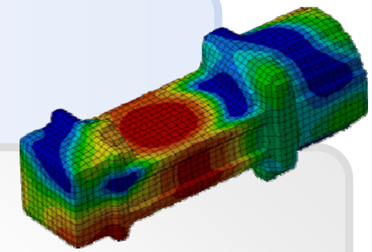
- Chemical engineering
- High temperature materials
- Materials analysis
- Applied mechanics



Systems...

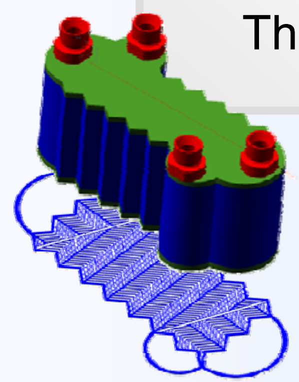
- Cyber physical systems
- Control modeling
- Embedded intelligence
- Decision support
- Power electronics

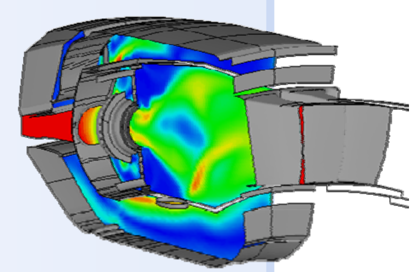




Thermal & Fluid Sciences...

- Acoustics
- Combustion
- Applied fluid dynamics
- Thermal management





Outline

- Phase I Accomplishments Summary
- System concepts & stack design integration
  - 250-1000kW Power Module
  - IGFC concepts
    - Atmospheric SOFC/ST
    - Atmospheric SOFC/GT/ST
- Verification testing
  - 50kW Test Stand
  - Test of Delphi ≥ 25kW stack

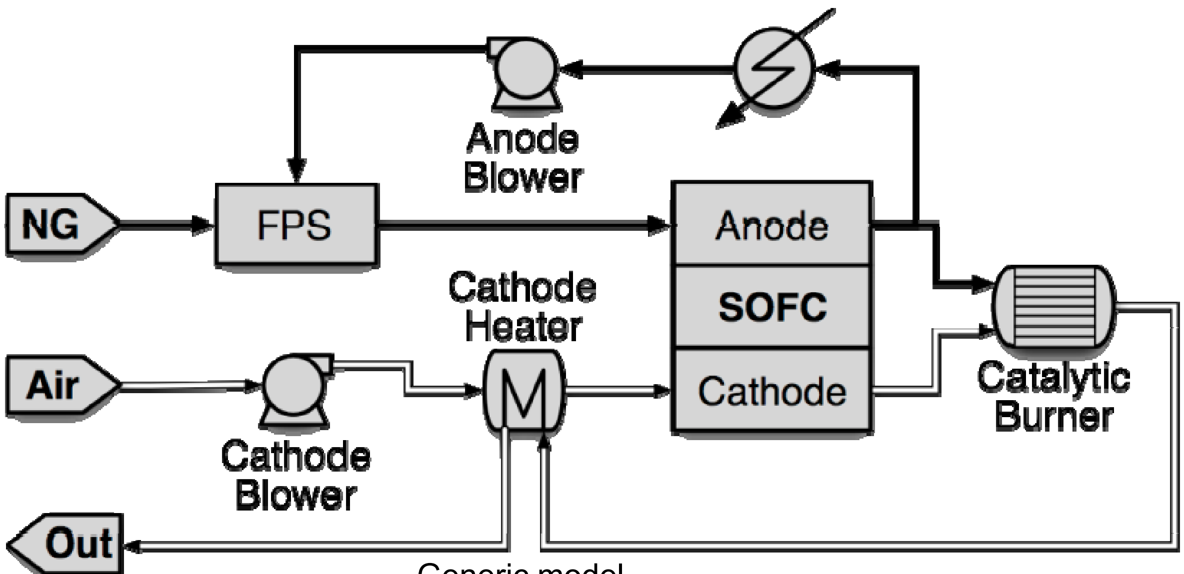
Phase I Accomplishments Summary

- Completed the detailed design, including an FMEA and Hazard Analysis, of a Test Stand capable of testing stacks up to 50 kW
- Procured all major components, including the fully completed fluid skid, and initated the final assembly of the 50kW Test Stand
- Completed an initial downselect of the 250-1000 kW SOFC Power Module operating on pre-reformed natural gas
- Developed a conceptual design for atmospheric IGFC systems with an SOFC/GT/ST cycle achieving 57 percent (HHV) efficiency

250-1000kW Power Module

- Developing systems based on
  - Cost
  - Efficiency
  - Reliability
  - Operability

Value proposition for customers



Generic model

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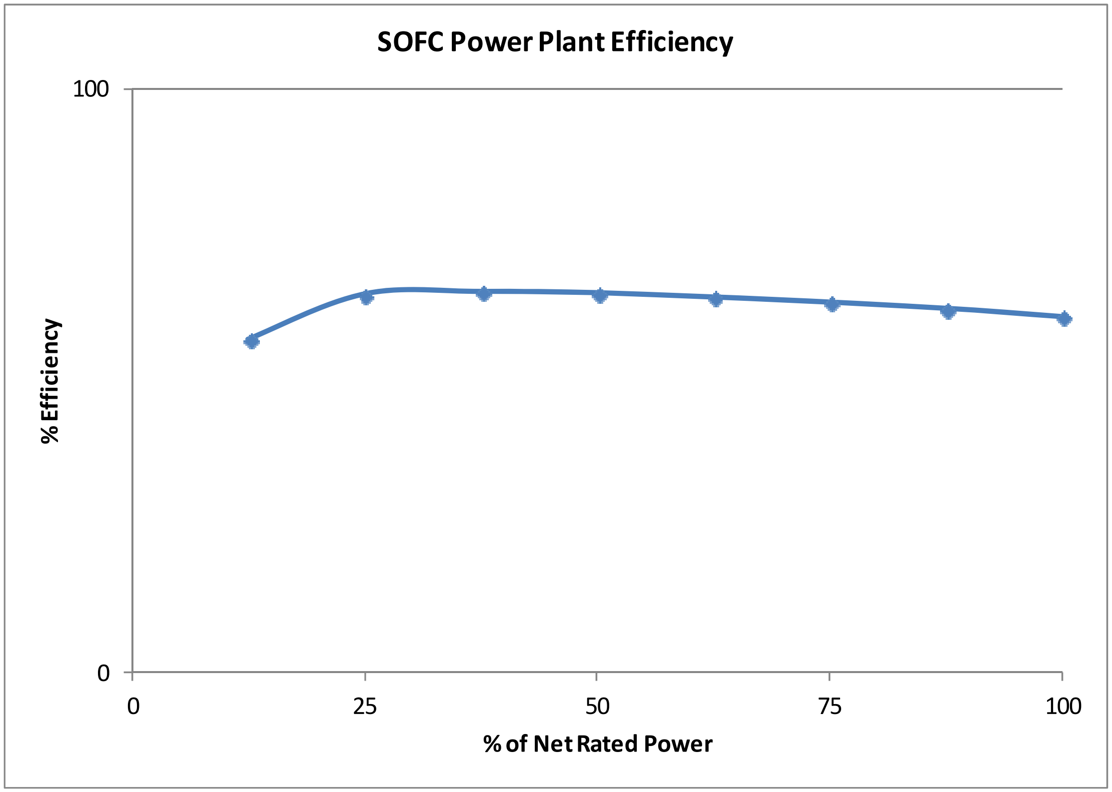
250-1000kW Power Module

- Efficiencies > 60% (LHV)
  - Largely invariant when operated at reduced load



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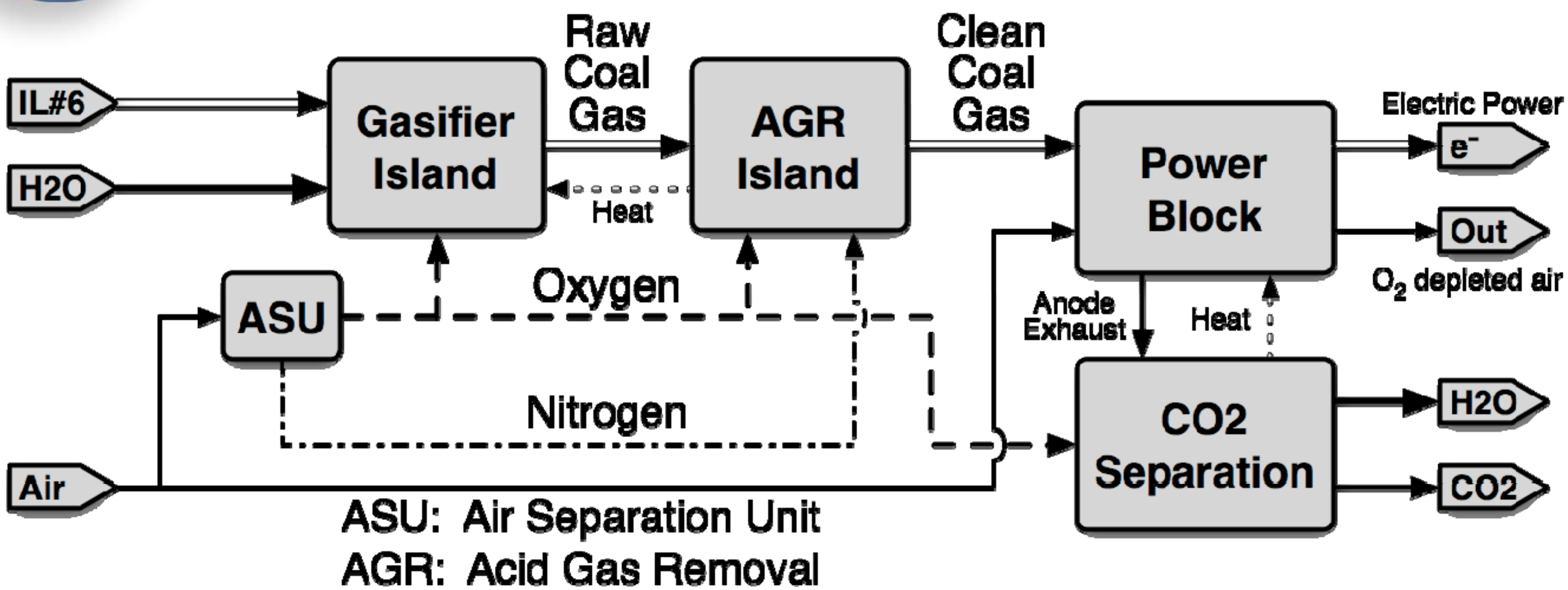
IGFC Overview

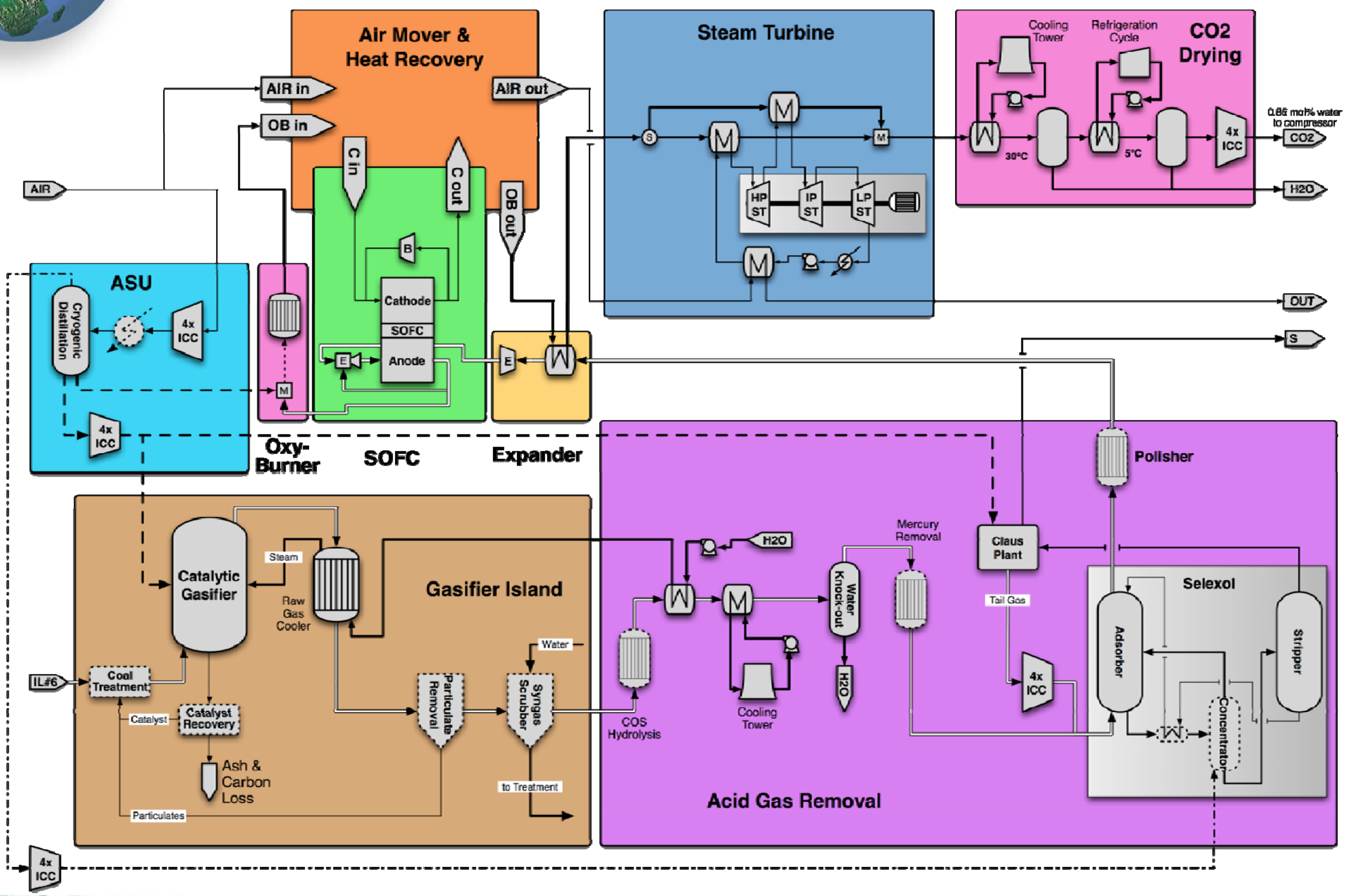
Block representation



- Catalytic gasification: High cold gas efficiency & methane content
- Oxygen generation via cryogenic distillation (ASU)
- Sulphur removal via Selexol or warm-gas clean-up
- CO_2 separation via oxy-combustion

IGFC Overview

Component representation

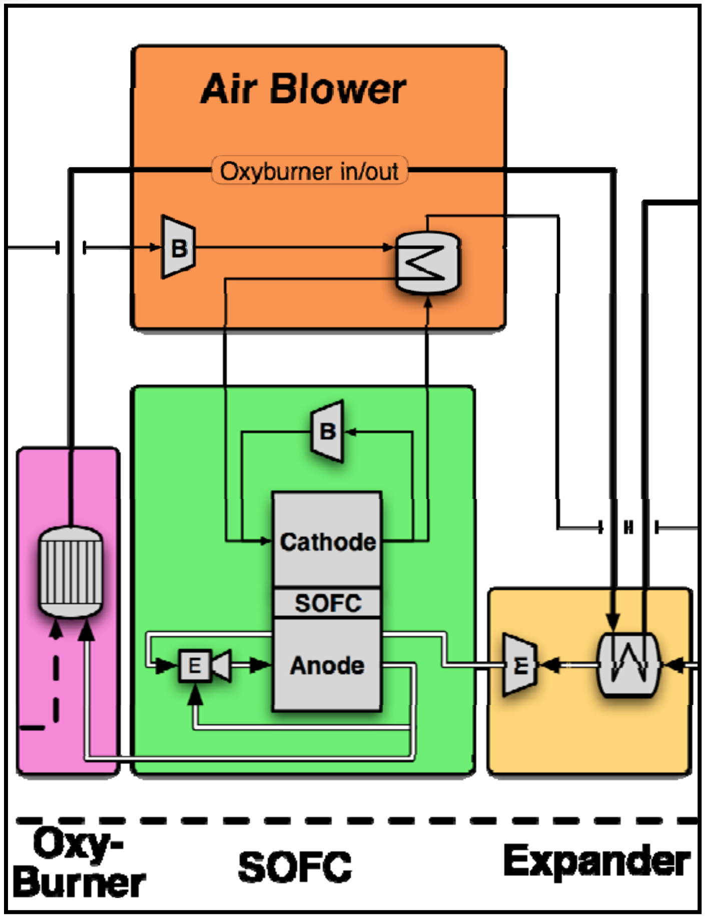


IGFC Power Block Design

- Systems of increasing sophistication and efficiency have been developed
  - Atmospheric SOFC with Steam Turbine Cycle
  - Atmospheric SOFC with Gas and Steam Turbine Cycle
  - Pressurized SOFC with Gas and Steam Turbine Cycle
- Steam cycle with reheat: [1800 psig ,1050°F]
- Gas turbine: Modified P&W FT-8 at 5 atm
- Heat recovery unit maximizes re-use of waste heat from cathode exhaust and oxyburner
  - Steam generator, re-heater
  - Cathode pre-heat
  - Indirectly heated gas turbine

IGFC Power Block Design

Atmospheric SOFC/ST



	$U_{f,p}$ = 70%	$U_{f,p}$ = 80%
SOFC AC power [MW]	106.6	106.6
Steam cycle net power[MW]	16.3	9.7
Expander power [MW]	9.7	8.1
Total produced power [MW]	**132.5**	**124.4**
Air blower [MW]	-1.7	-1.9
Recycle blower [MW]	-1.9	-2.1
Refrigeration [MW]	-0.7	-0.7
Cooling [MW]	-1.8	-1.7
Parasitic ASU [MW]	-8.0	-5.9
Parasitic other [MW]	-1.6	-1.5
Total parasitics	**-15.7**	**-13.6**
Net AC Power [MW]	**116.9**	**110.8**
Coal massflow (dry) [kg/h]	27511	25005
Gross coal input power [MW]	233.3	212.1
IGFC efficiency [HHV %]	**50.1**	**52.2**

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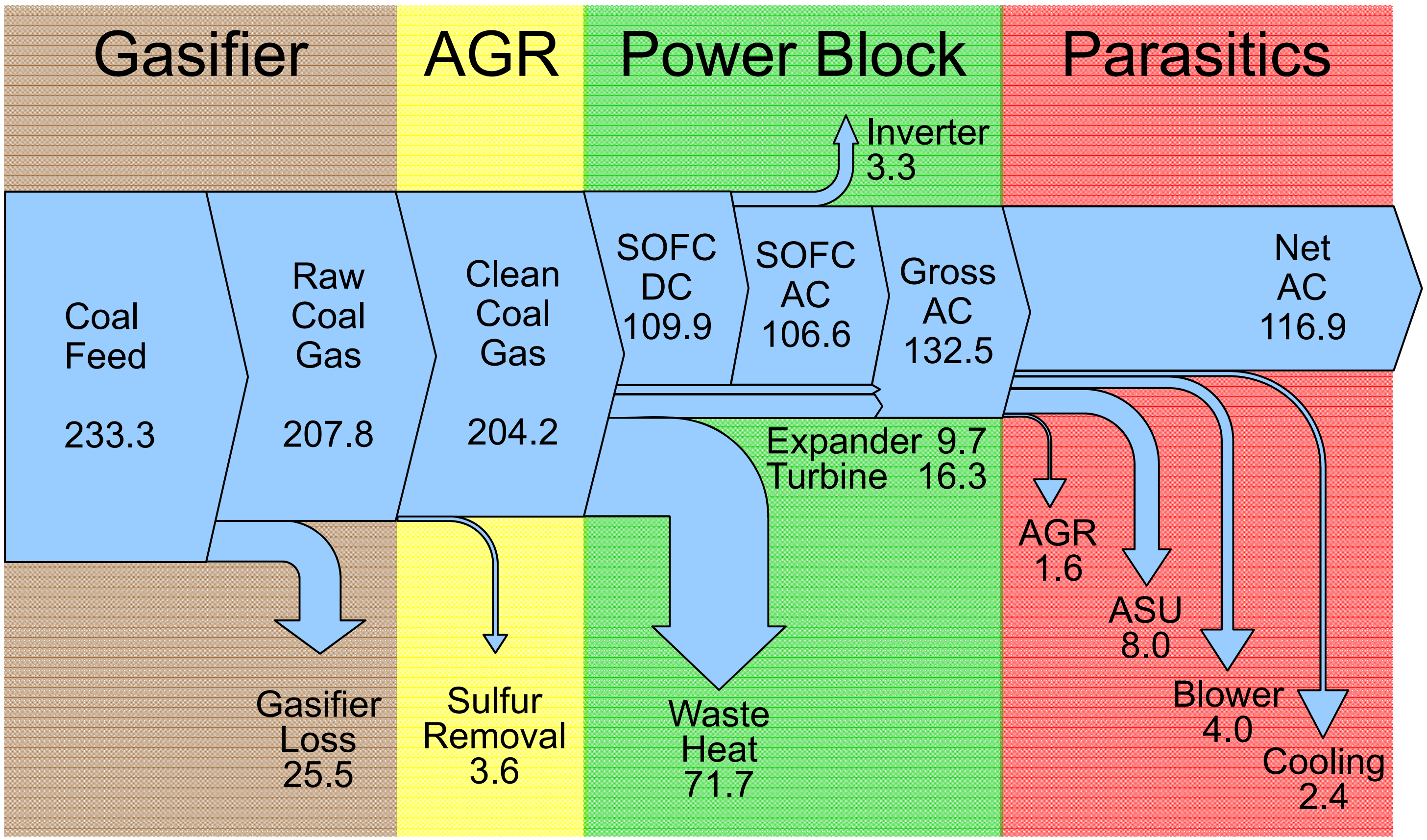
IGFC Power Block Design

Atmospheric SOFC/ST



Efficiency (HHV)
- **50.1% net**
- **56.8% gross**

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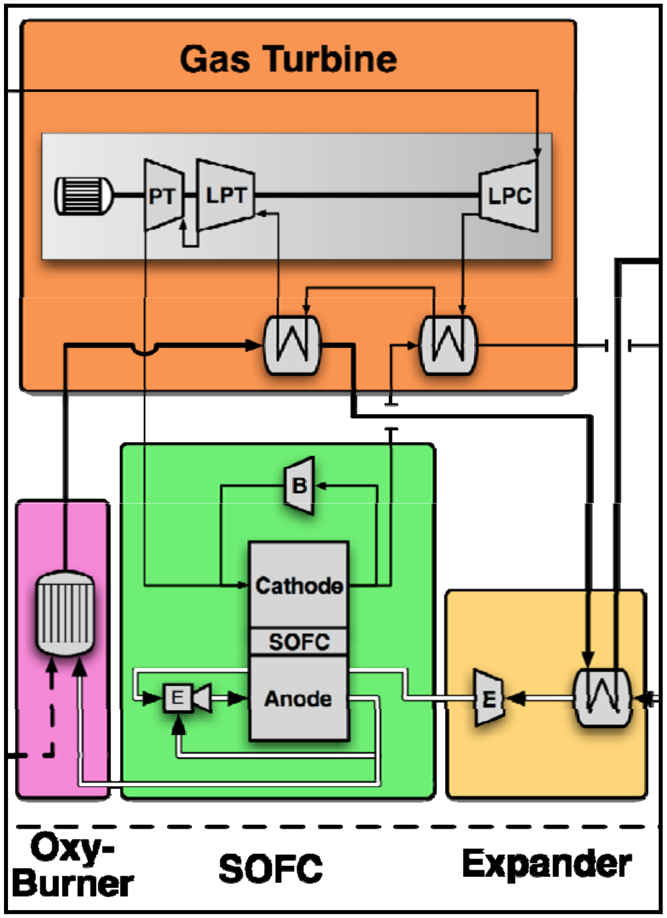
IGFC Power Block Design

Atmospheric SOFC/GT/ST



	Results
SOFC AC power [MW]	107.1
FT8 net power [MW]	14.9
Steam cycle net power[MW]	7.6
Expander power [MW]	4.2
Total produced power [MW]	**133.8**
Recycle blower [MW]	-2.1
Refrigeration [MW]	-0.7
Cooling [MW]	-1.7
Parasitic ASU [MW]	-5.9
Parasitic other [MW]	-1.5
Total parasitics	**-11.8**
Net AC Power [MW]	**122.0**
Coal mass flow (dry) [kg/h]	25141
Gross coal input power [MW]	213.2
IGFC efficiency [HHV %]	**57.2**

Gas turbine integration offers significant efficiency gain

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IGFC Power Block Design

Performance Comparison

	Atmospheric		
	SOFC/ST $U_{f,p}$ = 70%	SOFC/ST $U_{f,p}$ = 80%	SOFC/GT/ST $U_{f,p}$ = 80%
Net Efficiency* [%, HHV]	**50.1**	**52.2**	**57.2**
Net AC Power [MW]	**116.9**	**110.8**	**122.0**
SOFC DC [% gross]	80.4	85.7	80.1
Steam Cycle [% gross]	12.3	7.8	5.7
Coal-gas Expander [% gross]	7.3	6.5	4.2
Gas Turbine [% gross]	—	—	11.2

Model Assumptions

- Cold gas efficiency = 89.1%
- Steam turbine efficiency** = 34.3%
- Gas turbine efficiency = 85%
- Inverter efficiency = 97%

* Efficiency includes CO_2 separation (but not compression) parasitics
** Based on utilized heat. Based on available heat, efficiency is 19.6%

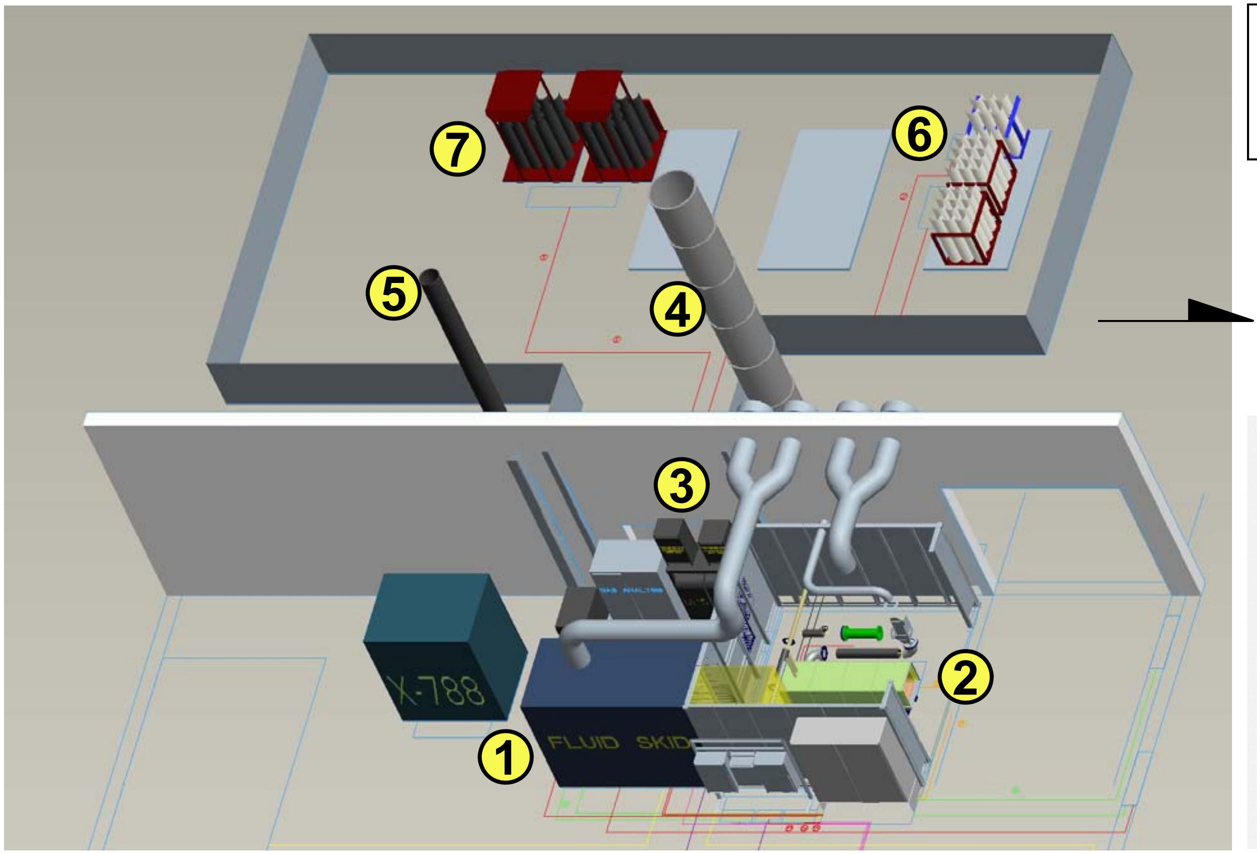
50kW Test Stand

Capabilities

- Fully automated, lights-out operation
- Provide anode gases up to
  - 50kW using coal syngas, or
    30 kW using 50%/50% H_2/N_2
    - 70% fuel utilization and up to 775°C
  - 5000 sl/min cathode air up to 775°C and -40°C dewpoint
- Provide loads up to 60kW
  - Up to 400 amperes
  - Up to 600 volts
- Recuperate up to 52kW cathode energy

50kW Test Stand

Test Facility

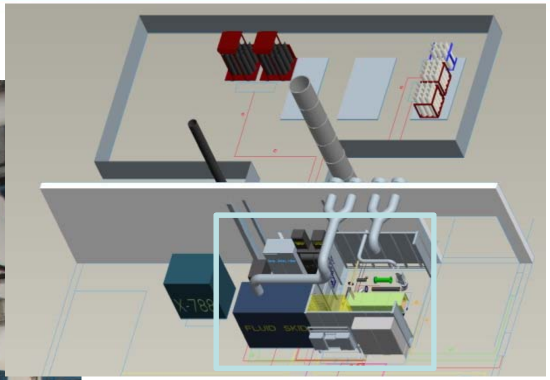


Piping, heat exchanger and heater insulation not shown

1. Fluid Management Skid
2. Test Room
3. Load Bank
4. Afterburner
5. Cathode Exhaust
6. Emergency air, 4%H2 bottles
7. Methane Bottles

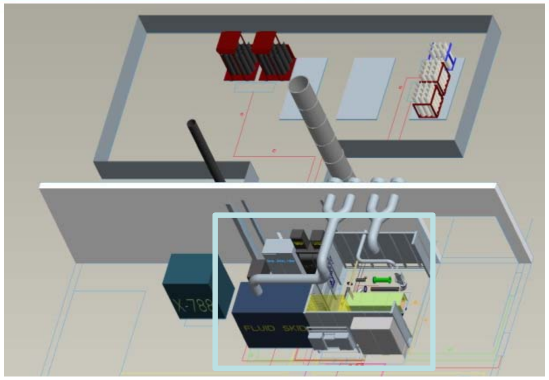
50kW Test Stand

Test Facility



50kW Test Stand

Test Facility



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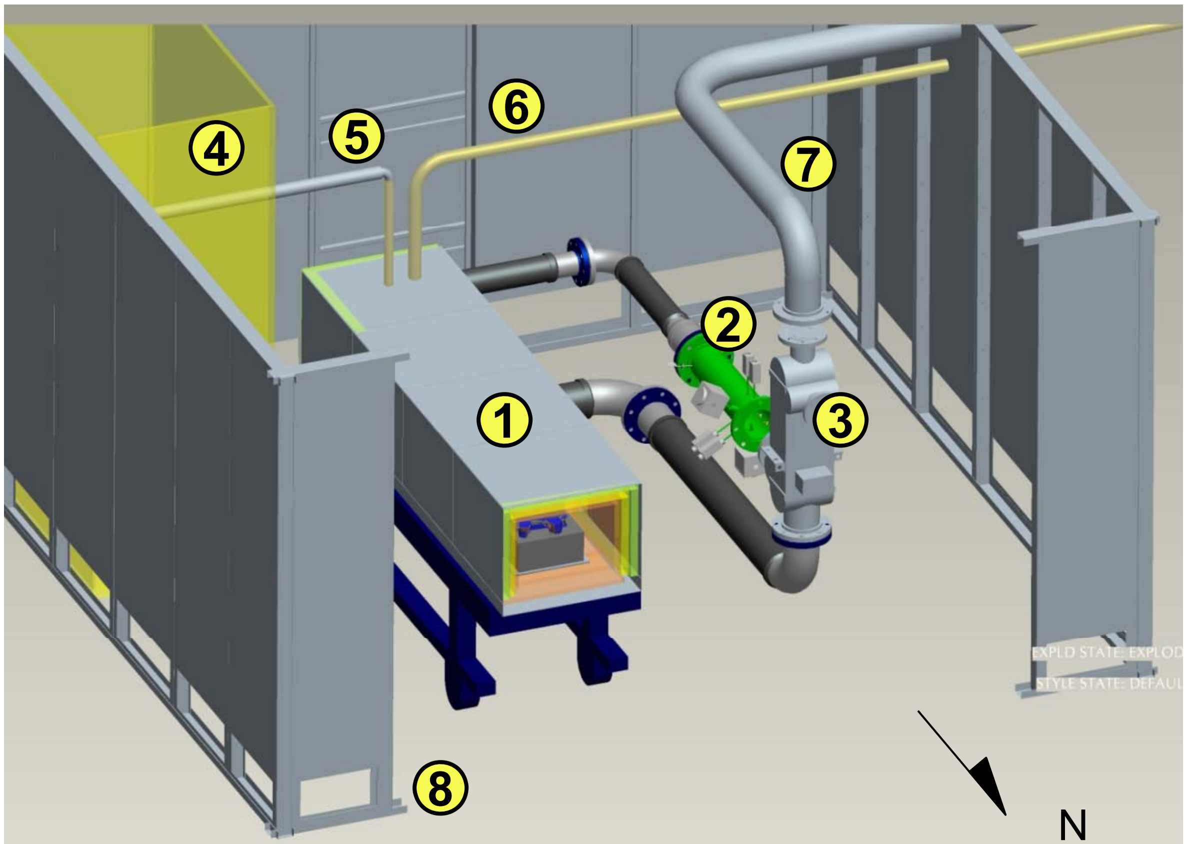
50kW Test Stand

Test Room

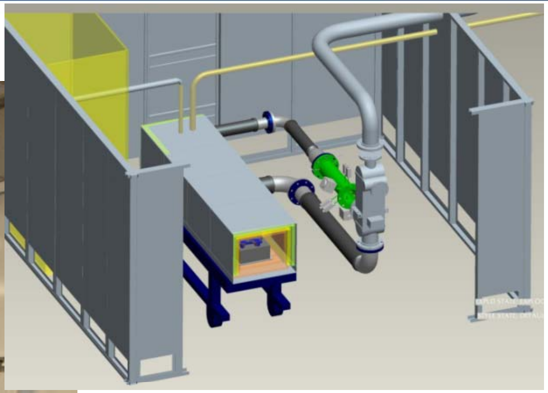


Piping, heat exchanger and heater insulation not shown

❶ Test Article (in Hot Box)
❷ Cathode Heater
❸ Cathode Recuperative Heat Exchanger
❹ Anode Constituent Heaters (obscured)
❺ Anode Supply
❻ Anode Exhaust
❼ Cathode Exhaust
❽ Test Article Room (doors not shown)

50kW Test Stand

Test Room



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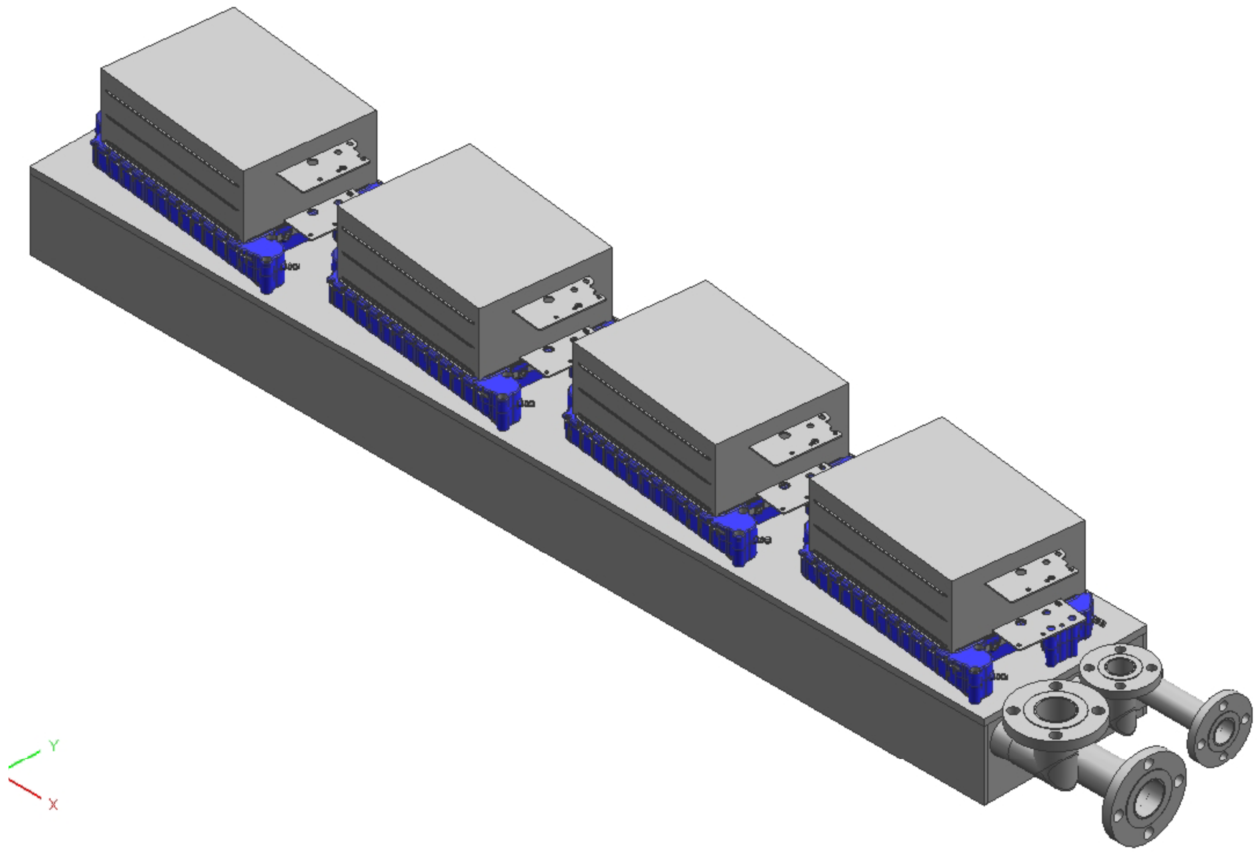
Test of Delphi ≥ 25kW Stack

- Comprises four 40-cell stacks using the Gen 4 cassette



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Verification Testing Goals

PHASE I MINIMUM REQUIREMENTS SECA Coal-Based Systems	
DELIVERABLE POWER RATING	≥ 25kW
COST (fuel cell system, 2002 dollars)	$400 / kW
STEADY STATE TEST (Normal Operating Conditions)	Δ Power < 2.0% degradation/1000 hours
TEST SEQUENCE	1) Start-up 2) Peak Power Test 3) Steady State Test 4) Shut-down
TEST DURATION	5000 hours (1500 hours in Phase I)
FUEL TYPE	Simulated (subject to DOE concurrence, up to 25% CH_4, dry basis)

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Outline

- Summary Highlights
- Cells
  - Scale up
  - Cell microstructure
  - Process improvements
  - DFMEA-based accelerated test development
  - Cathode development
- Gen 4 and Gen 3 stacks
  - Electrochemical performance of Gen 4
  - Comparison of Gen 4 performance data to Gen 3 data
  - Stack voltage tracking run chart
- Durability
  - Constant current durability test
  - Thermal cycling
  - Stack tested with real hydrocarbon fuel reformate

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Performance Highlights Summary for SECA Coal Based System Stack Development

- Continued scale up of cells from 105 cm^2 (active area) cells to 403 cm^2 without increasing cell thickness for Gen 4 stacks
- Expanded cell and stack fabrication and testing capability for large footprint Generation 4 stacks
- Fabricated and tested Gen 4 stacks
- Completed design for 25 kW SECA Phase 1 test article
- Demonstrated 5kW Gen 4 stack module
  - Produced 5064 Watts (506 mW per cm^2) @ 0.81 Volts per cell
  - Fuel = 48.5% H_2, 3% H_2O, rest N_2
- Developed low cost, high volume manufacturable processes for Gen 4 stack components – stamping, laser welding
- Demonstrated greater than 8000 hours continuous durability in Gen 3.2 stack
- Demonstrated 200 thermal cycles in Gen 3.2 stack

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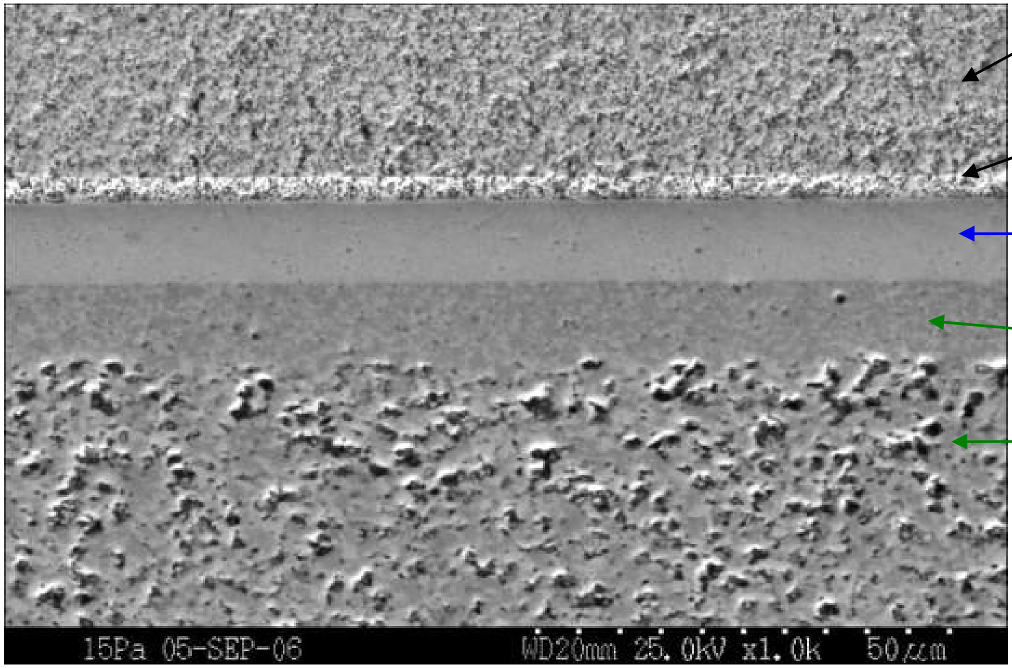
Delphi SOFC Unreduced Cell Microstructure

- Gen 3.2 cell footprint is 140 mm x 98 mm (105 cm2 active area)
- Gen 4 cell footprint is 300 mm x 158 mm (403 cm2 active area)



Cathode: LSCF (~30 μm)

Interlayer: Ceria Based Layer (~4 μm)

Electrolyte: 8 mol. YSZ (~10 μm)

Active Anode: NiO – YSZ (~10 μm)

Bulk Anode: NiO – YSZ (~500 μm)

Cell Process Engineering Achievements Using Quality Tools

- **Design for Six Sigma – Includes Functional Modeling, Axiomatic Design, FMEA, Designed Experiments**
  - Optimized cell firing techniques to improve cell electrochemical performance by about 7%
  - Implementing cell manufacturing processes that reduce raw material costs by about 35% and capital investment by about 60%
  - Devised improved lamination method that incorporated high volume manufacturing process, significantly reducing lamination cycle time
  - Developed optimized process strategy for controlling screen printed thick film cell layers
  - Developed cell to retainer seal material, process, and design approach using axiomatic design principles that increases durability and eliminates active degradation mechanisms
- **Shainin Red X – Strategy for Cell Defect Reduction**
  - Identified defect sources, elimination strategies currently under evaluation to increase first time quality

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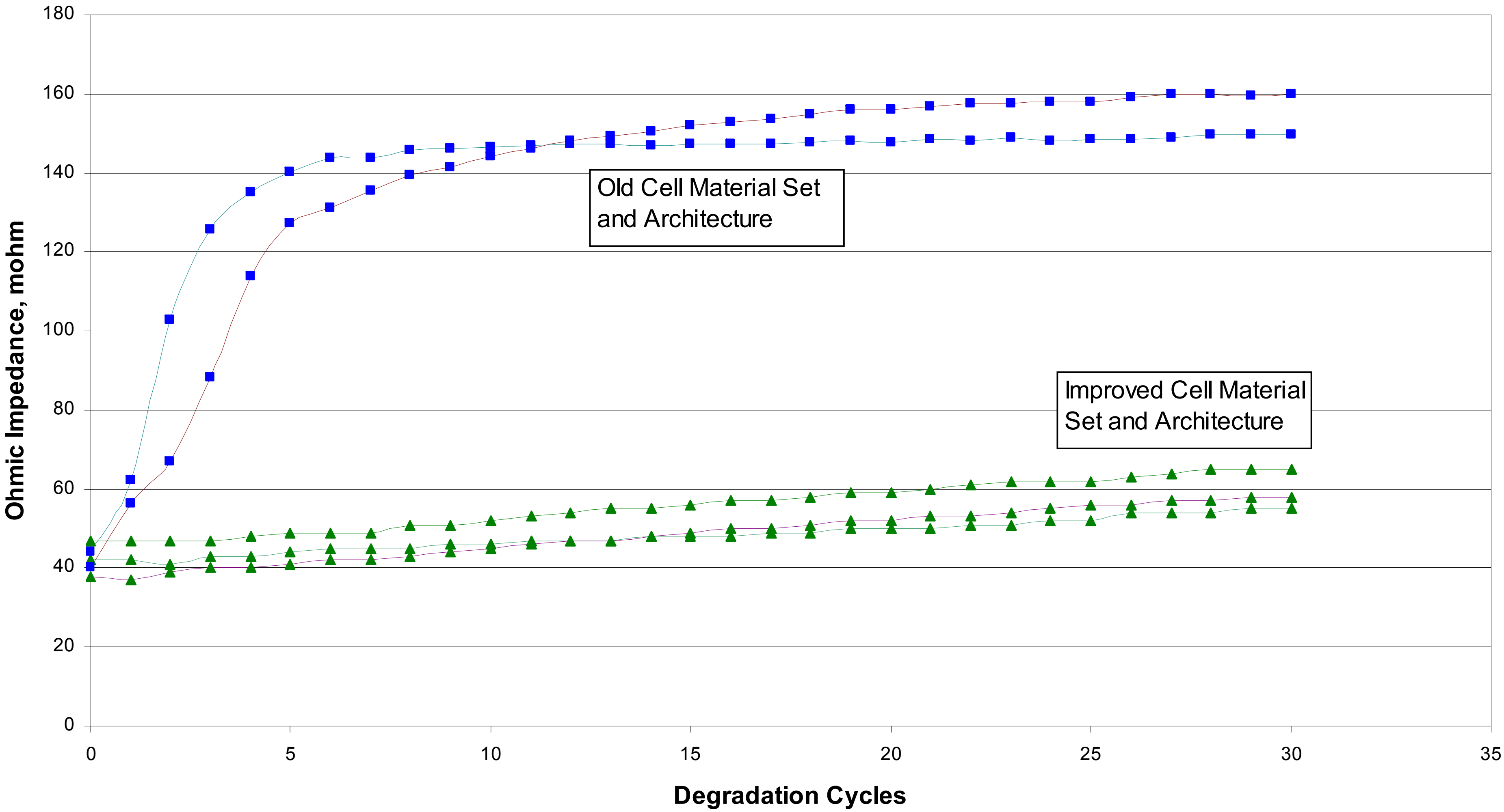
Accelerated Test Development

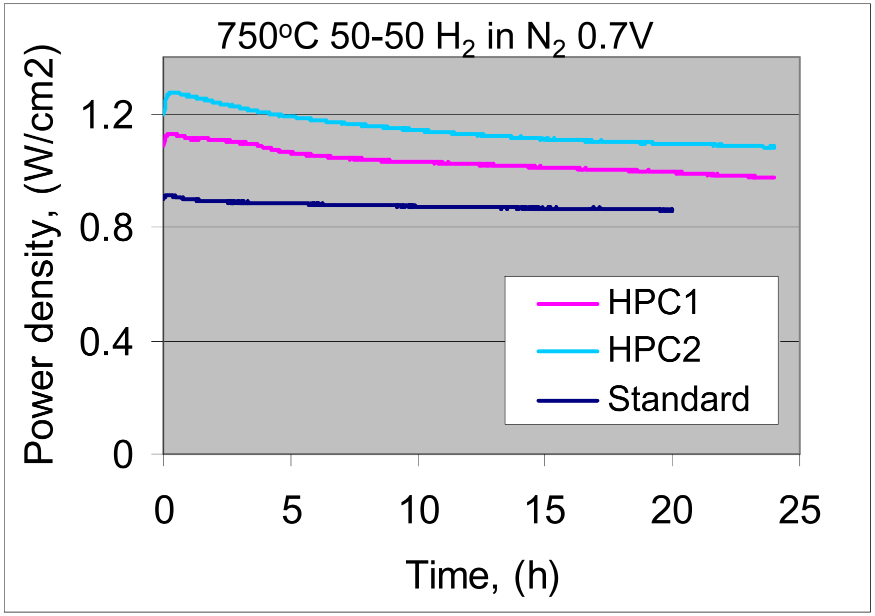
Develop DFMEA → Develop Validation Testing Plan to Address DFMEA Issues and Observations from Stack Testing → Develop Accelerated Testing to Address Failure Mechanisms Identified in DFMEA and Stack Testing

Cell Accelerated Degradation Testing



Cathode Development

Cathode	Power (From Button Cell Performance Testing)
Standard	Standard
Cathode Improvement 1 (HPC1)	Typically > 25% Higher Than Standard Cathode
Cathode Improvement 2 (HPC2)	Additional 20% Higher Than Cathode Improvement 1
Cathode Improvement 3 (HPC3)	Additional 10% Higher Than Cathode Improvement 2 in 4ppmv H_2S



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Seal and Interconnect Development

- Improvements in glass/ceramic seals and substrate coatings have demonstrated good results for repeating unit to repeating unit sealing in a stack
  - Coupon level testing has demonstrated higher shear strength and thermal cycling stability
  - Multiple stacks tested with the improved repeating unit to repeating unit seals confirmed improved thermal cycling capability with no measurable leakage in the seals

- Low cost coatings and interconnects have been developed and implemented in stacks
  - Coupon level tests have demonstrated stable and acceptable ASR
  - Tested for > 8000 hours in Gen 3.2 stack durability
  - Tested for thermal cycling
  - Process improvements ongoing

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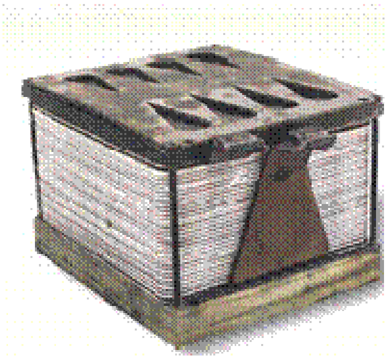
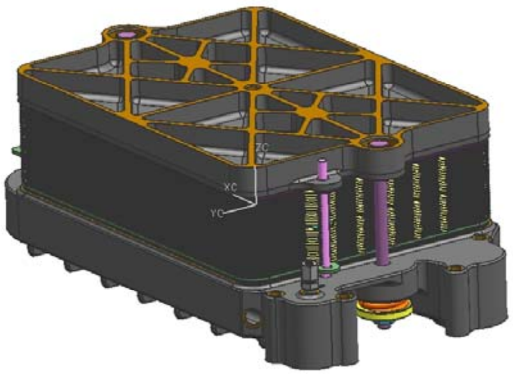
Gen 4 Stack

- Delphi is developing its Generation 4 stack with larger footprint cell
- Key stack features are:
  - 4x active area increase
  - Very low pressure drop (less than 4kPa, anode and cathode)
  - Laser welded cassette repeating unit configuration
  - Stamped metallic cassette components including interconnects
  - Reduced part count
  - Low cost, conventionally processed balance of stack components



Gen 3.2 stack



Gen 4 stack

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Gen 4 Stack

- Gen 4 stack fabrication ongoing for meeting SECA requirements

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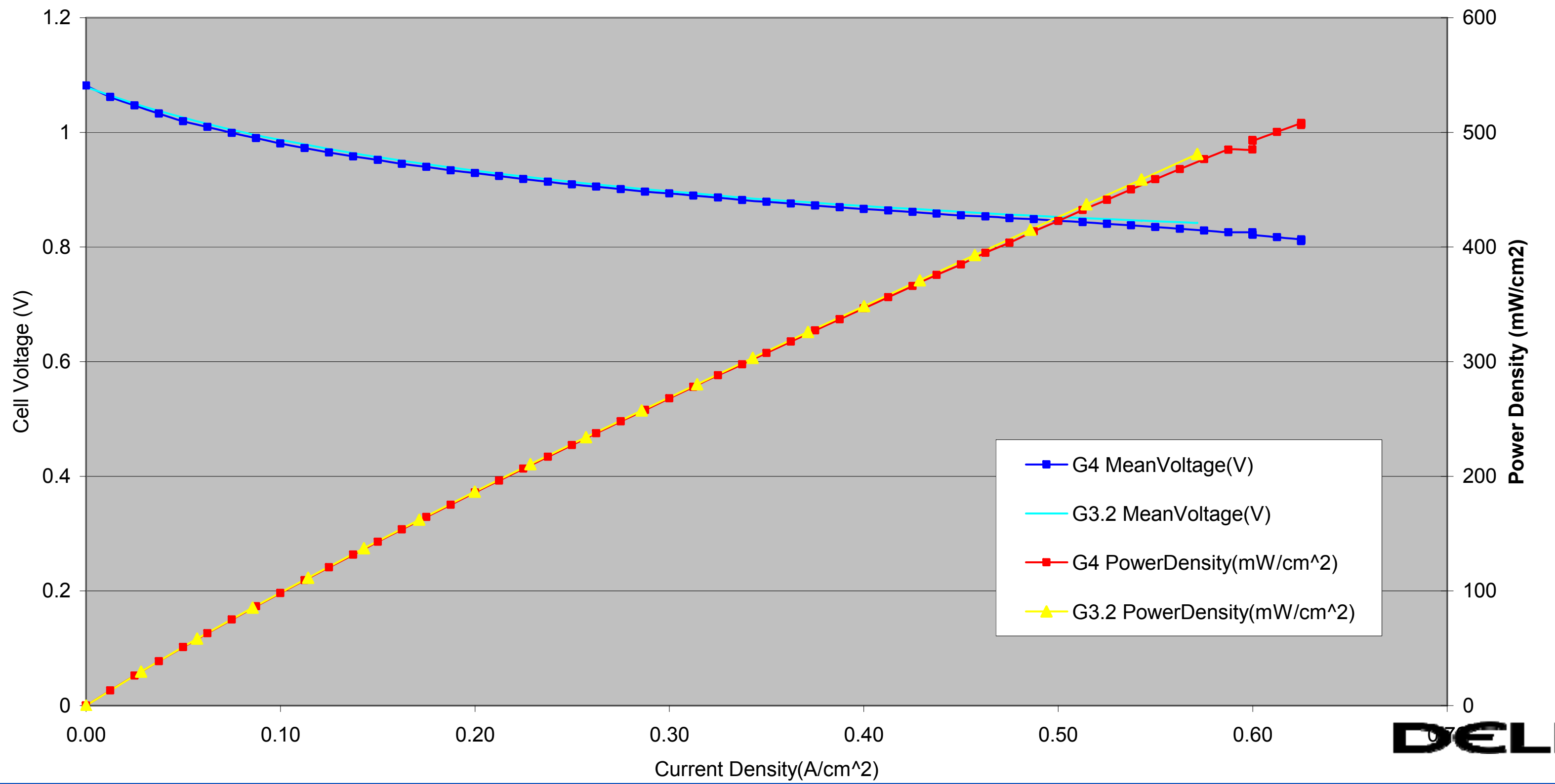
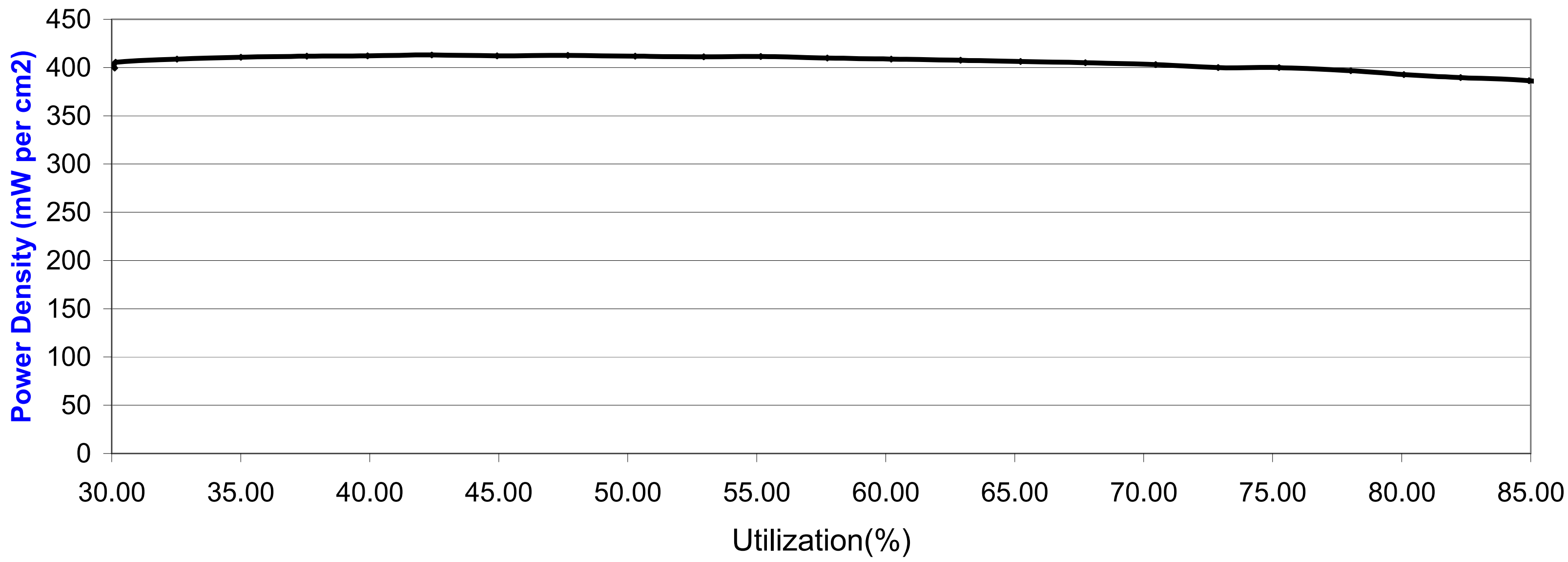
Gen 4 Stack Performance

- 25-cell Gen 4 stack demonstrated predicted power density
  - Produced 5.064 kW (506 mW per cm^2) @ 0.81 Volts per cell with 48.5% H_2, 3% H_2O, rest N_2
  - Data shows comparison of Gen 3.2 and Gen 4 electrochemical performance



Gen 4 Stack Performance

- Fuel utilization evaluation has demonstrated good results
- Current density of 600 mA per cm^2
- Fuel 48.5% H_2,3% H_2O, rest N_2
  - Data below shows minimal lowering of power density up to 85% utilization
  - Data shows a power density of 403 mW per cm^2 at 70% fuel utilization



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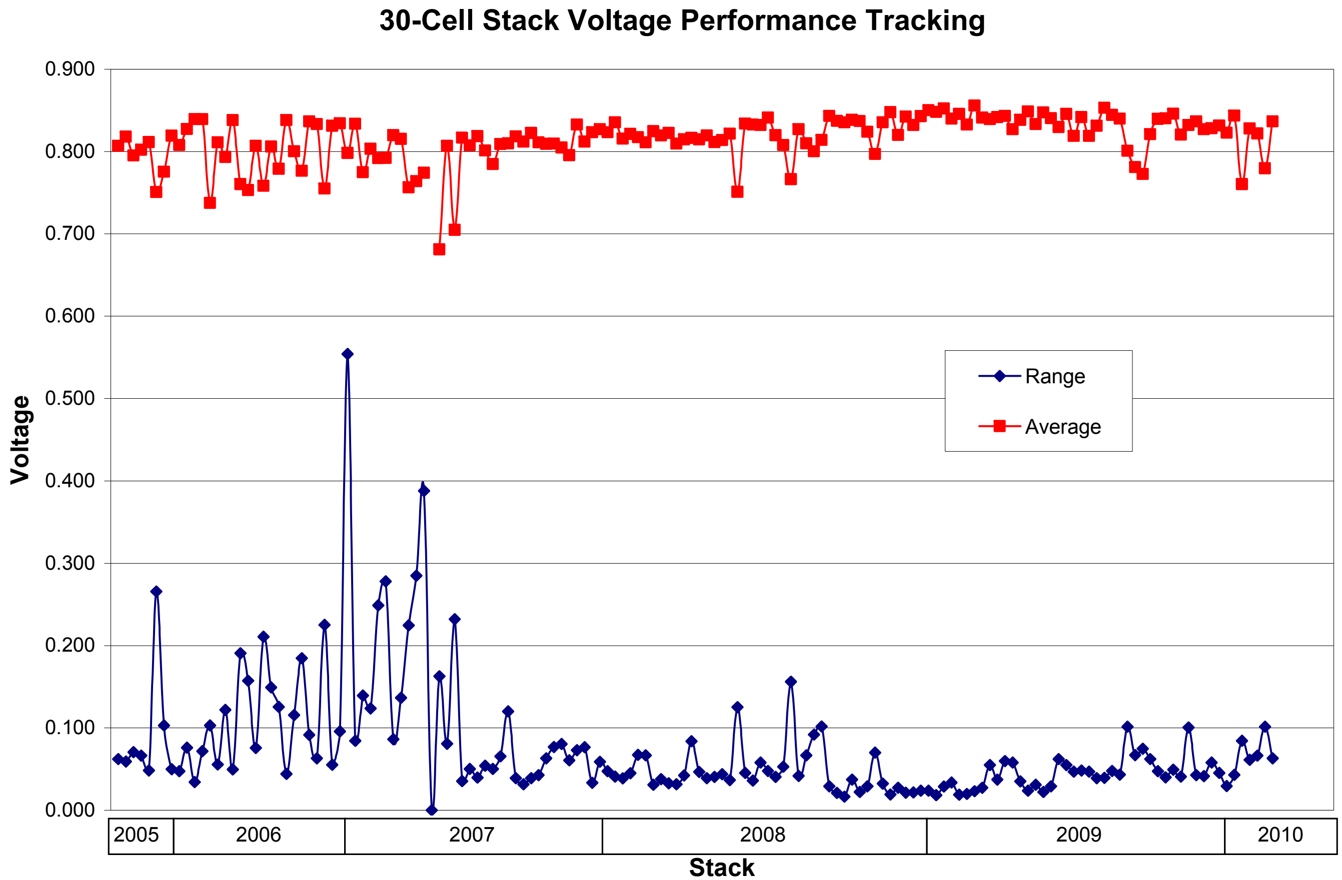
Generation 3.2 30-Cell Stack Run Chart

- Gen 3.2 stacks is our baseline platform for evaluation of technology and components as we scale up Gen 4 fabrication
- Improvements in design and process parameters have led to consistent performance in stack to stack builds – translates to lessons learned for Gen 4



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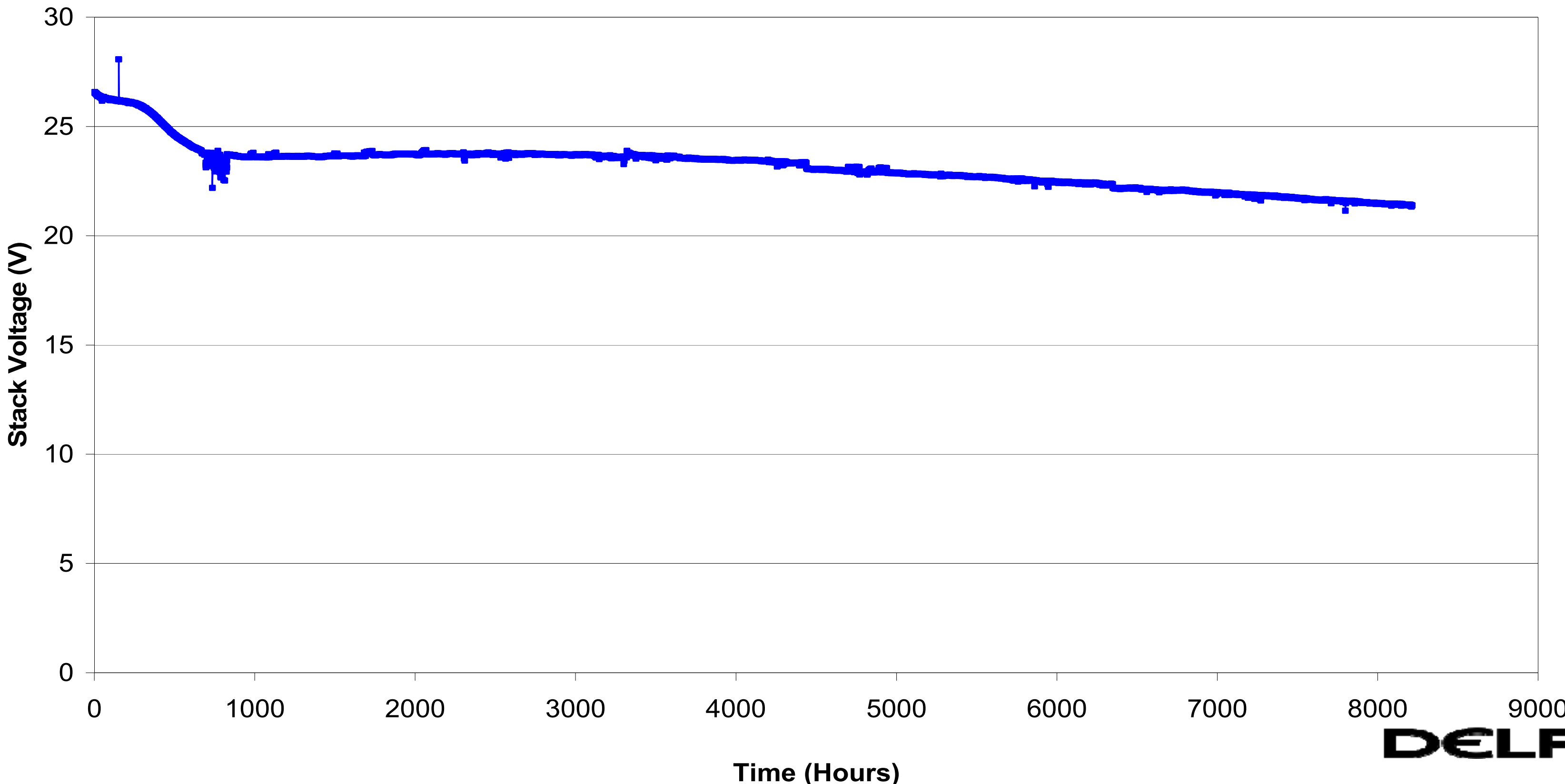
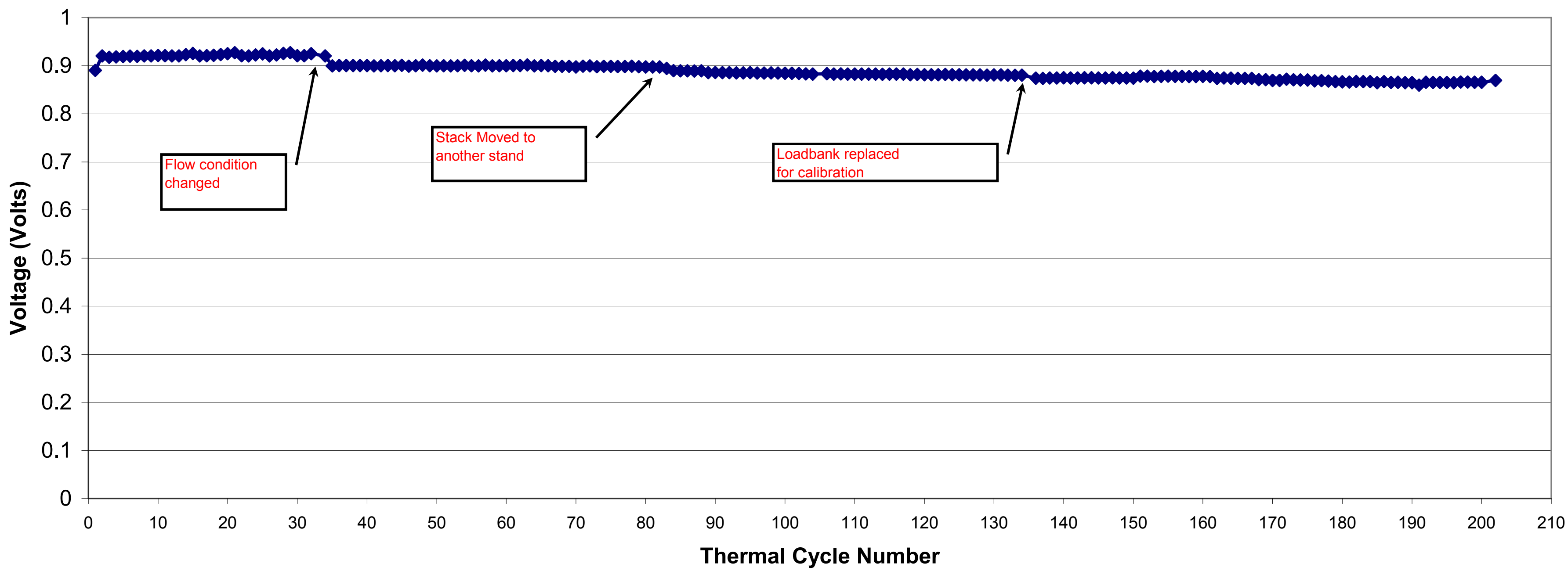
Gen 3.2 30-Cell Stack Durability

- Fuel = 48.5% H_2, 3% H_2O, rest N_2; current = 333 mA per cm^2
- > 8200 hours, continuing to run
- Total degradation is 1.20% per 500 hours
- Degradation after initial lowering of power and stabilization is 0.66% per 500 hours
- Implementing solution to mitigate initial lowering of power



Thermal Cycling

- Gen 3.2 30-cell stacks evaluated for thermal cycling with improved seals
- 200 thermal cycles demonstrated with minimal degradation
  - 2 hour heat-up
  - Performance evaluated at each thermal cycle
  - Constant current load of 285 mA per cm^2 at operating temperature
  - Fuel of 48.5% H_2, 3% H_2O, rest N_2



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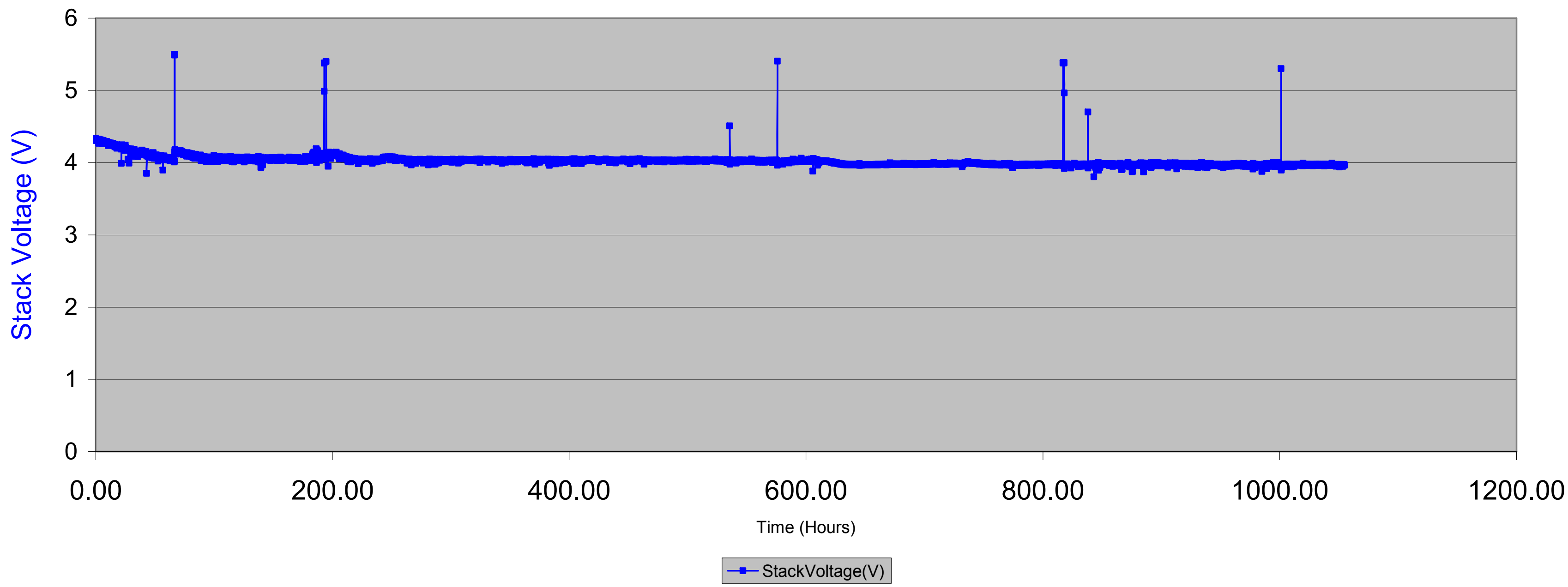
Stack tested with real hydrocarbon reformate

- Gen 3.2 5-cell stack evaluated with real reformate based on different O:C mapping from hydrocarbon fuel reforming
- 1000+ hours on actual hydrocarbon fuel reformate (20% H_2, 24% CO, 7% H_2O, 6% CO_2, rest N_2) at optimized operating conditions
- Voltages and pressure drop stable



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