Development Update on Delphi's Solid Oxide Fuel Cell Power System

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2006 SECA Review Meeting

Acknowledgements

Battelle

Pacific Northwest National Laboratory
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Fuel Cell Development Team

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA ·

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Outline

- Market Opportunities
- Systems Development
- Cell and Stack Development
- Reformer Development
- Cost Analysis
- Summary

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SOFC Market Opportunities

European micro –CHP & CHCP
Natural Gas

US Stationary – APU & CHP
Natural Gas, LPG

Commercial Power
Natural Gas

FutureGen Powerplant
Coal Gas

derivatives

Heavy Duty Truck
Diesel

Recreational Vehicles
Diesel, LPG

Truck and Trailer Refrigeration
Diesel

US Military
JP-8

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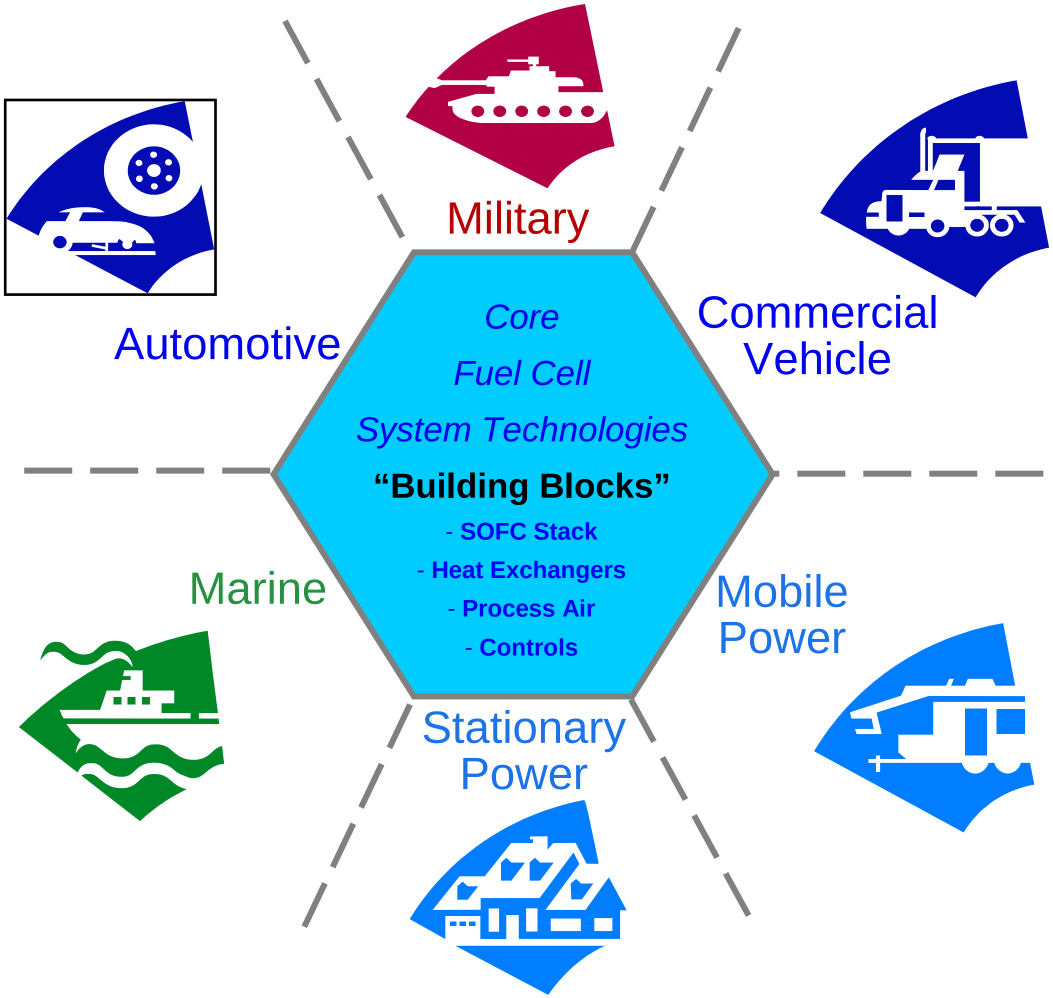
Development Strategy



<u>Each application adjusted for</u>:

- **Fuel Type**
- **Electrical Configuration**
- **Application Environment**
- **User Interface**

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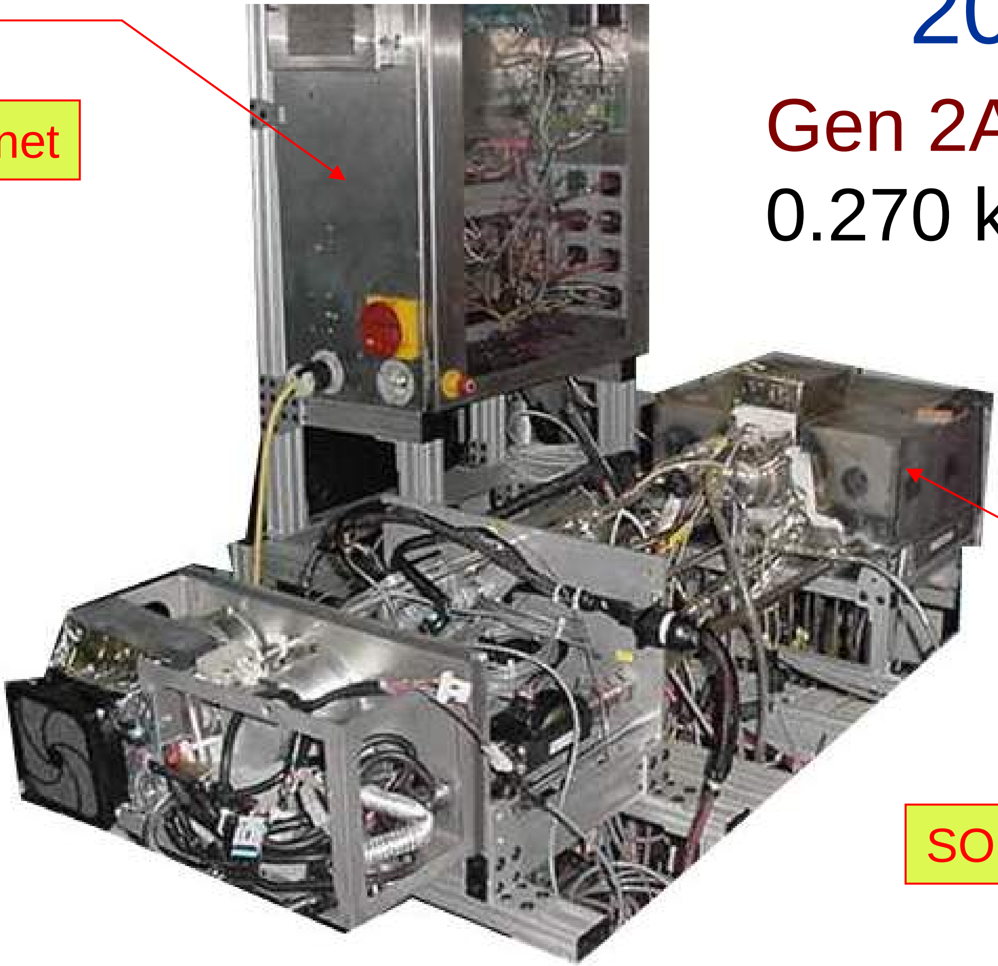
SECA Phase I Starting Point



Control Cabinet

SOFC Hot-Zone Module

2002

Gen 2A (Level 0)

0.270 kW_{gross}

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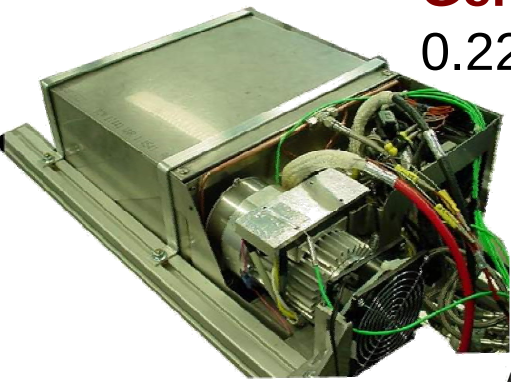
Delphi Systems Developed During Phase I

Gen 2A
0.220 kW_{gross}



2003

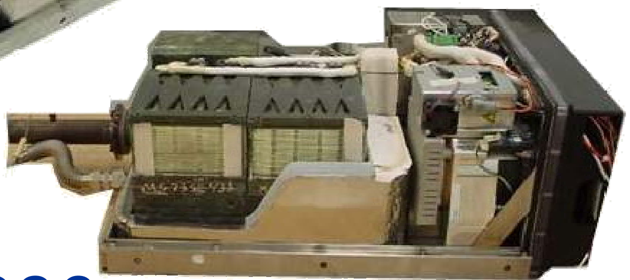
Gen 2B/2C
0.423 kW,
3.3% efficiency

2004

SPU 1A
1.18 kW,
17% efficiency

2005

SPU 1B
2.16 kW,
38% efficiency



2006

Phase I Progress

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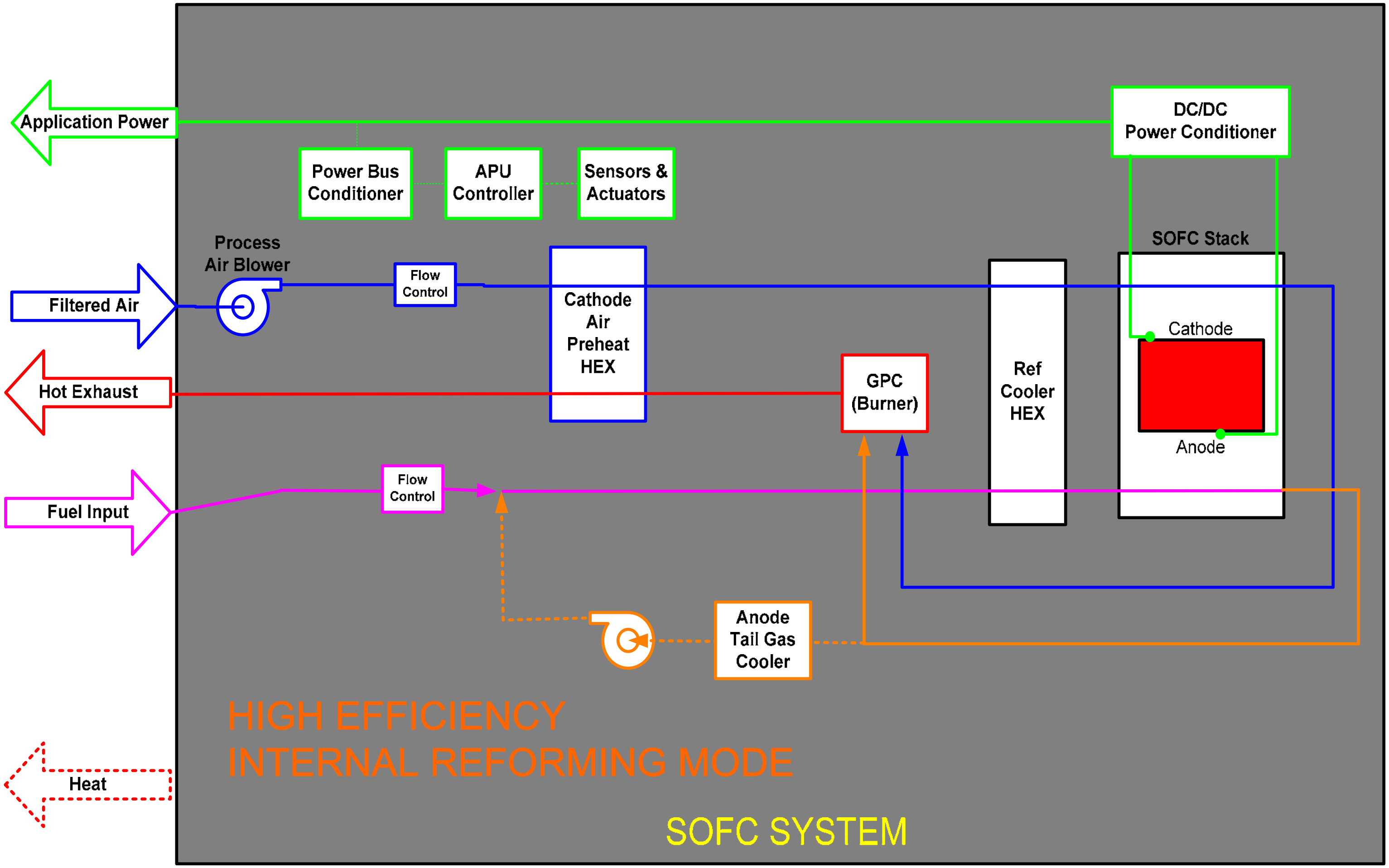
SOFC System Mechanization



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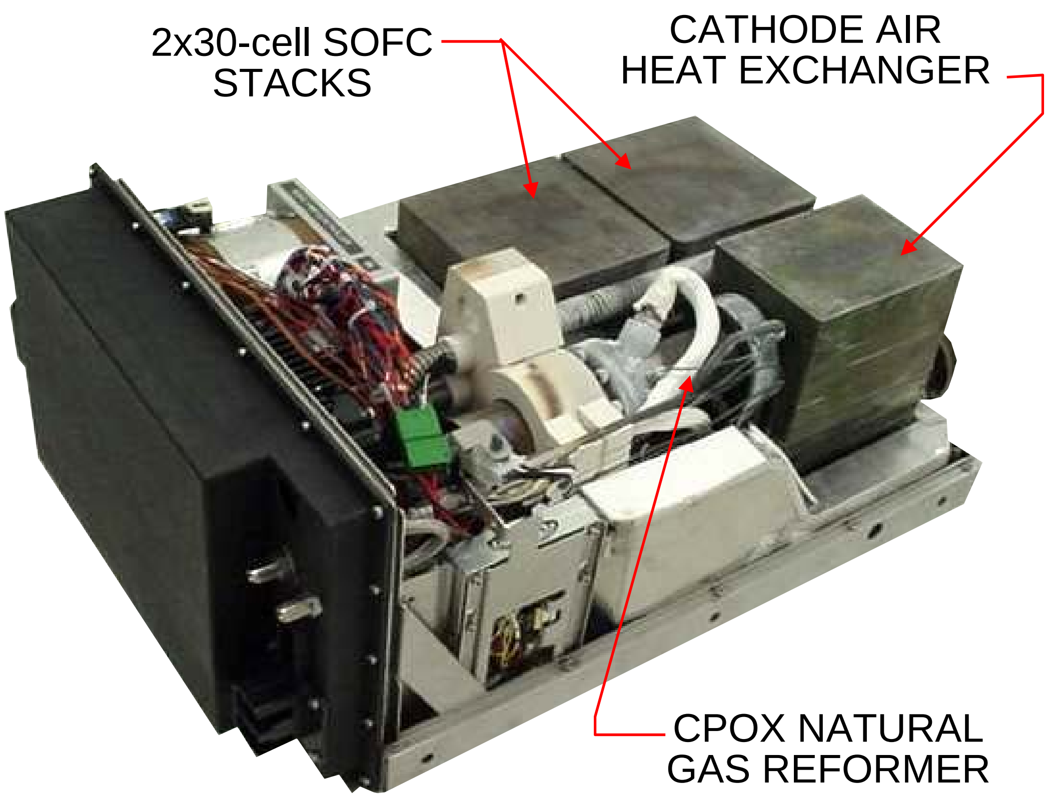
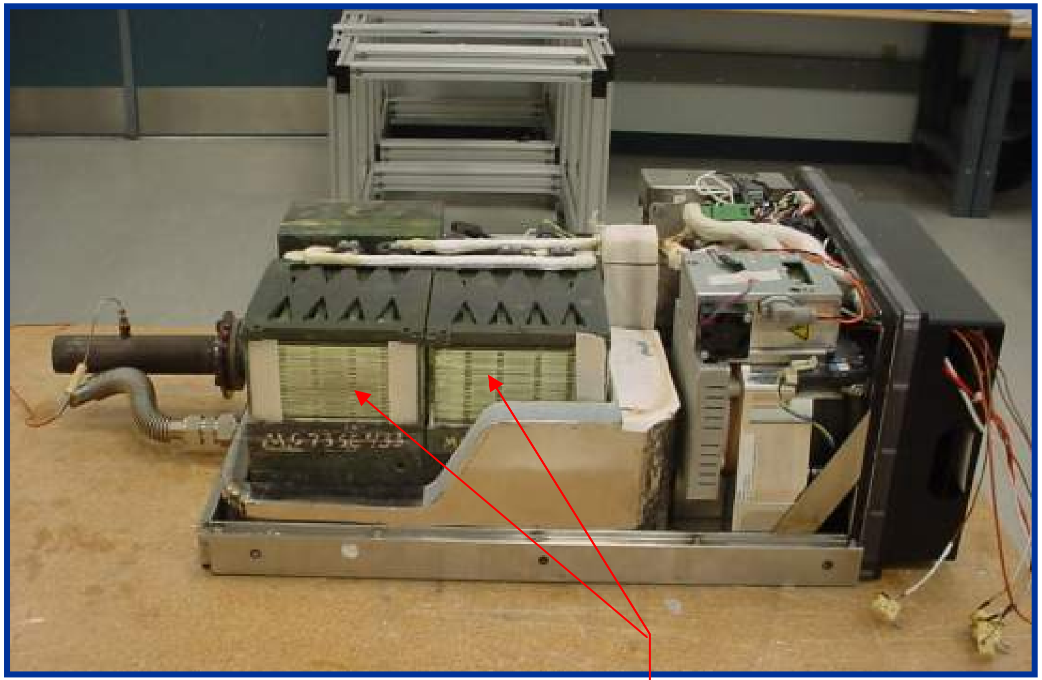
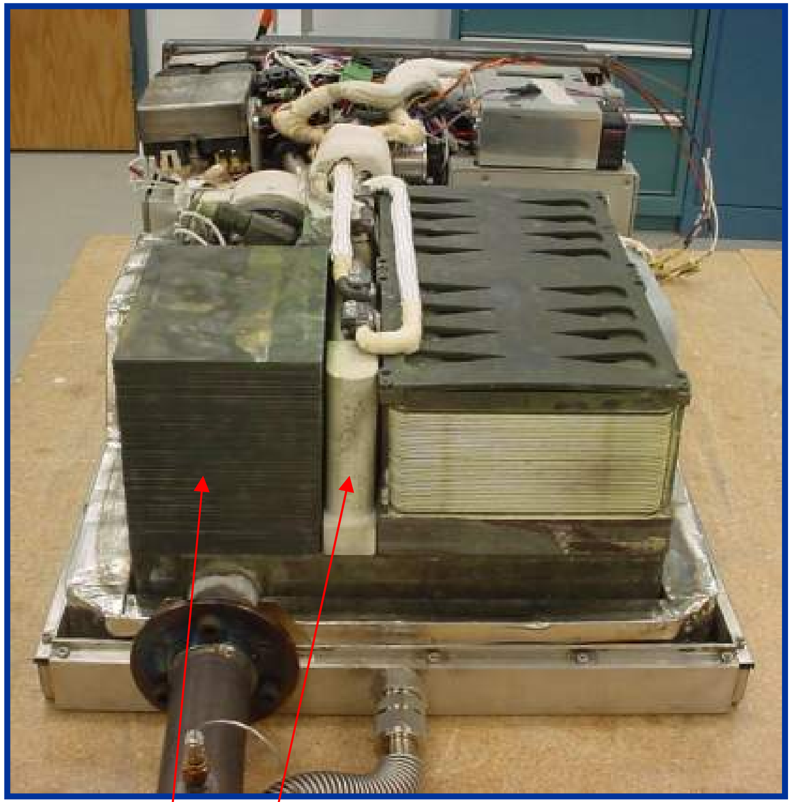
Integration of SPU 1B SOFC System



SPU 1B SOFC System





2x30-cell SOFC Stacks

Cathode Air Heat Exchanger

Recycle Cooler

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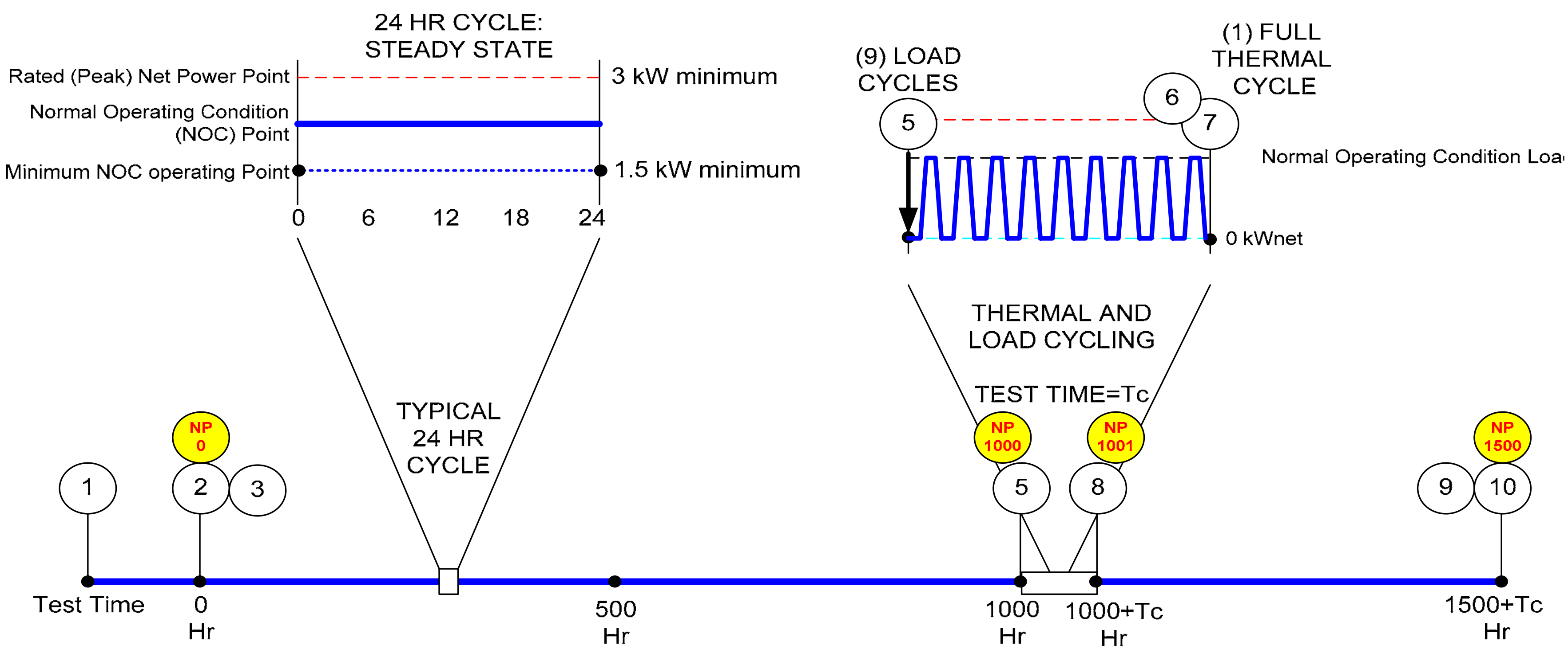
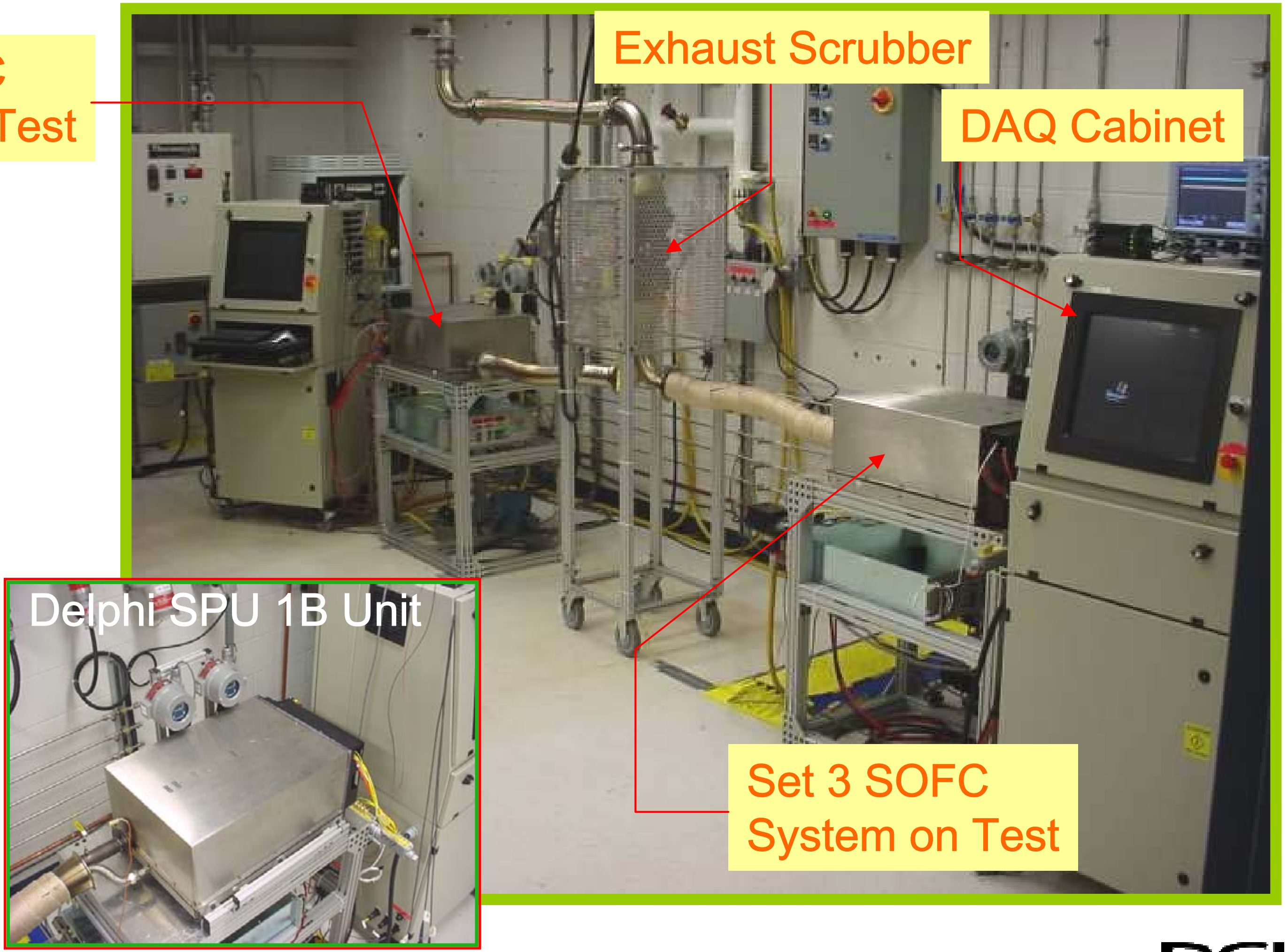
SECA Phase I Test Plan



Delphi Phase I Demo System A Test



Delphi Phase I System Performance

		Delphi System Performance		
System Metrics	Target	Set 2	Set 3	2 & 3 Combined
Rated Net Power	3 kW	2.08	2.16	4.24
System Efficiency (Peak)	35%	35.1%	38.9%	37.0%
Factory Cost	$800/kW			$767
Durability Test	1500 hours	4660	2240	>1500
Temp Cycles	1 cycle	2	2	1
Power Cycles	9 cycles	10	10	10
Net Power Degradation	7% / 1500 hours	4.5%	10.1%	7.3%
Operational Availability	80%	99%	99%	99%

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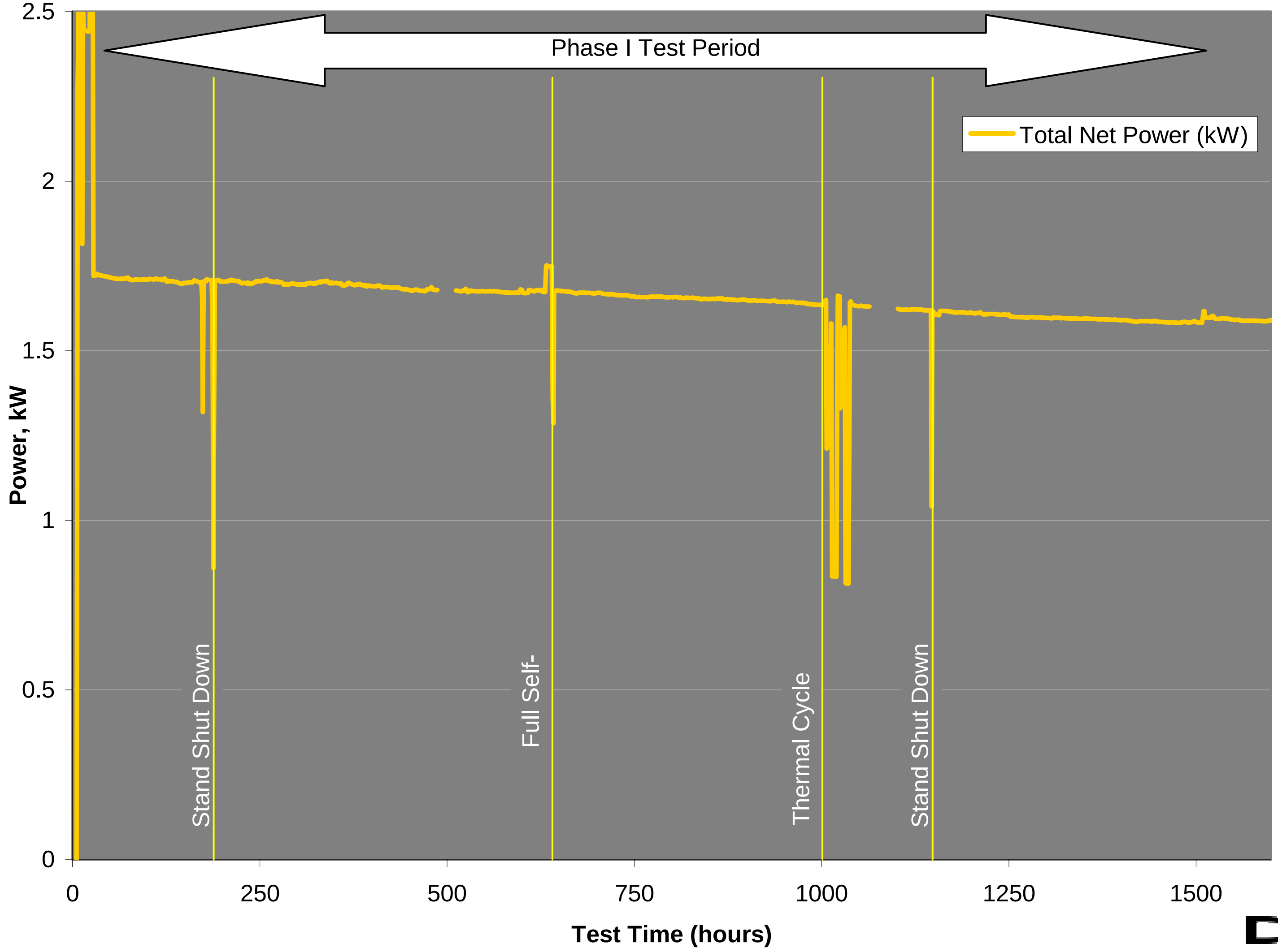
Delphi Phase I Durability Performance Demonstration System



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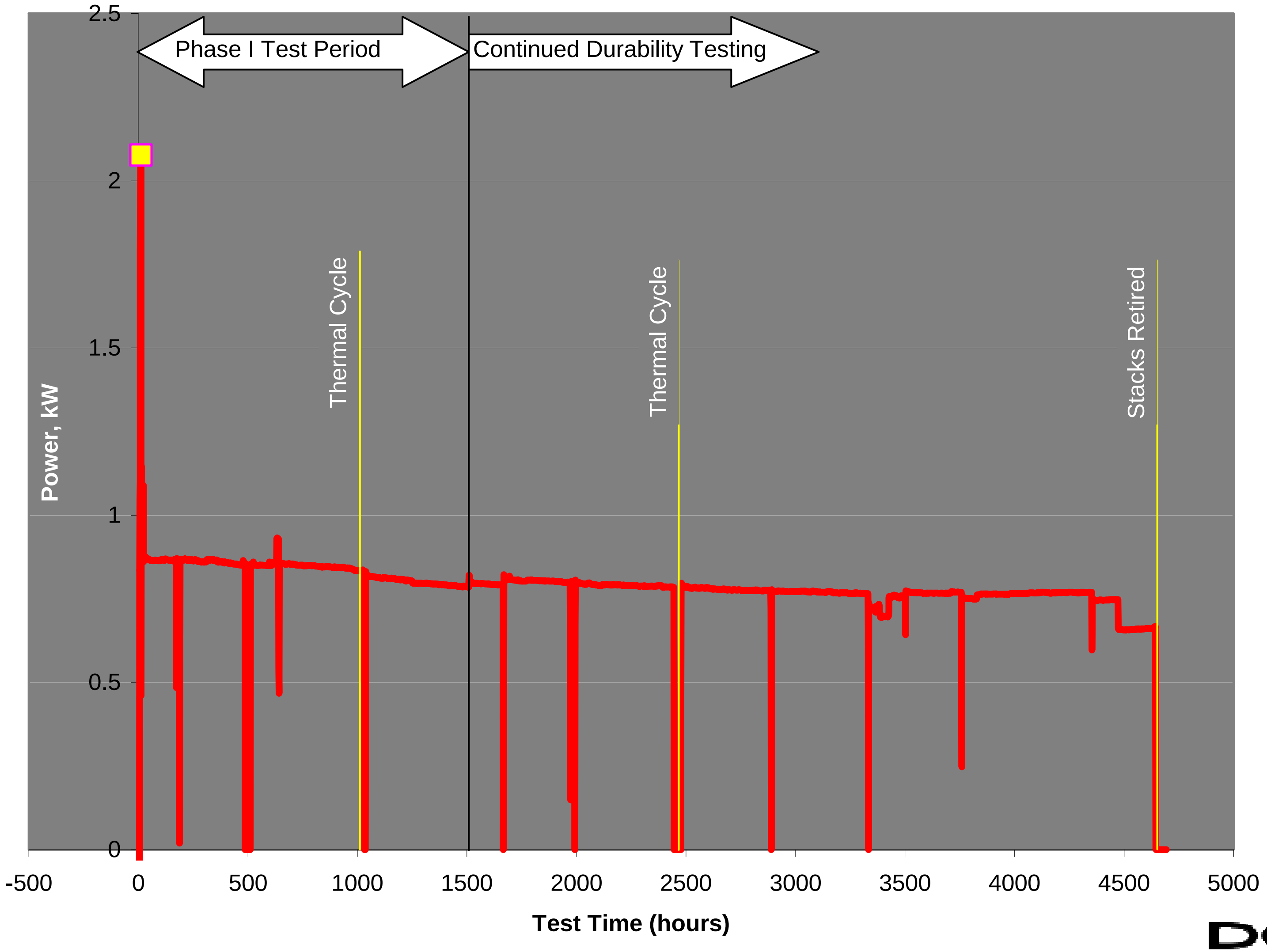
Delphi Phase I Durability Performance
SPU 1B – Set 2



Delphi Team SECA Phase I Success

SECA Phase I Goals		Delphi Demonstration Unit
Power	3 to 10 kW	4.24 kW
Cost	< $800/kW	$767/kW
Efficiency	35 – 55%	37% LHV- DC
Degradation	<7%/1500 hours	7.3%/1500 hours

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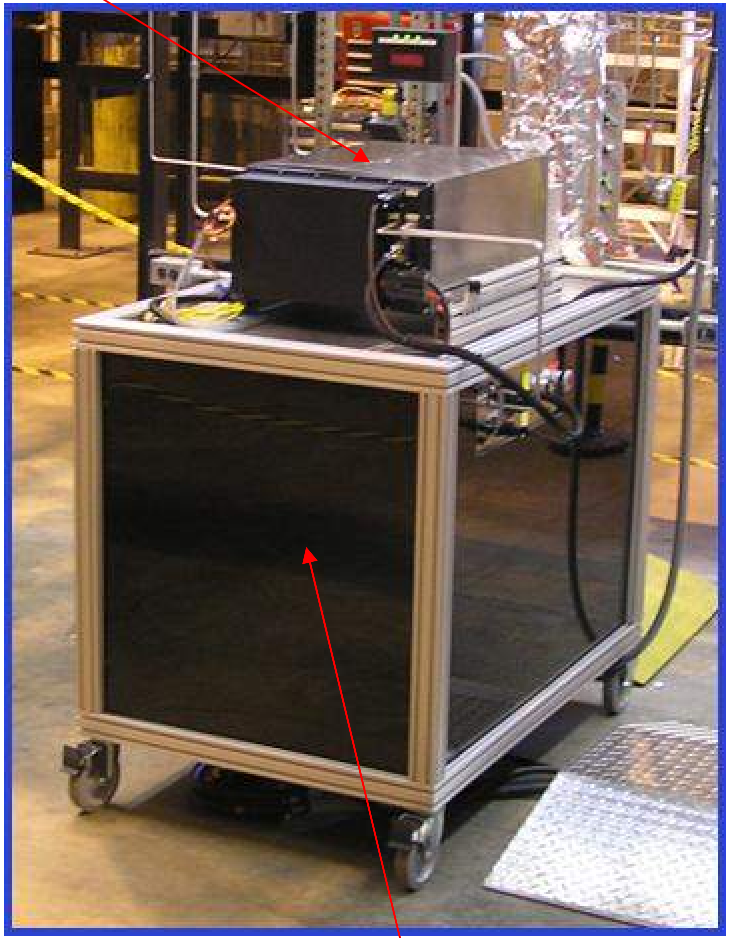
Delphi SOFC Power System Operation at NETL

Delphi SOFC Power System



Laboratory Test Platform

- Delphi SOFC Power System operated at NETL Test Facility in Morgantown, WV from May 2, 2006 through June 17, 2006
- Testing conducted at Normal Operating Condition of 1.0 kW, average net electrical output
- 610 hours of operation using methane

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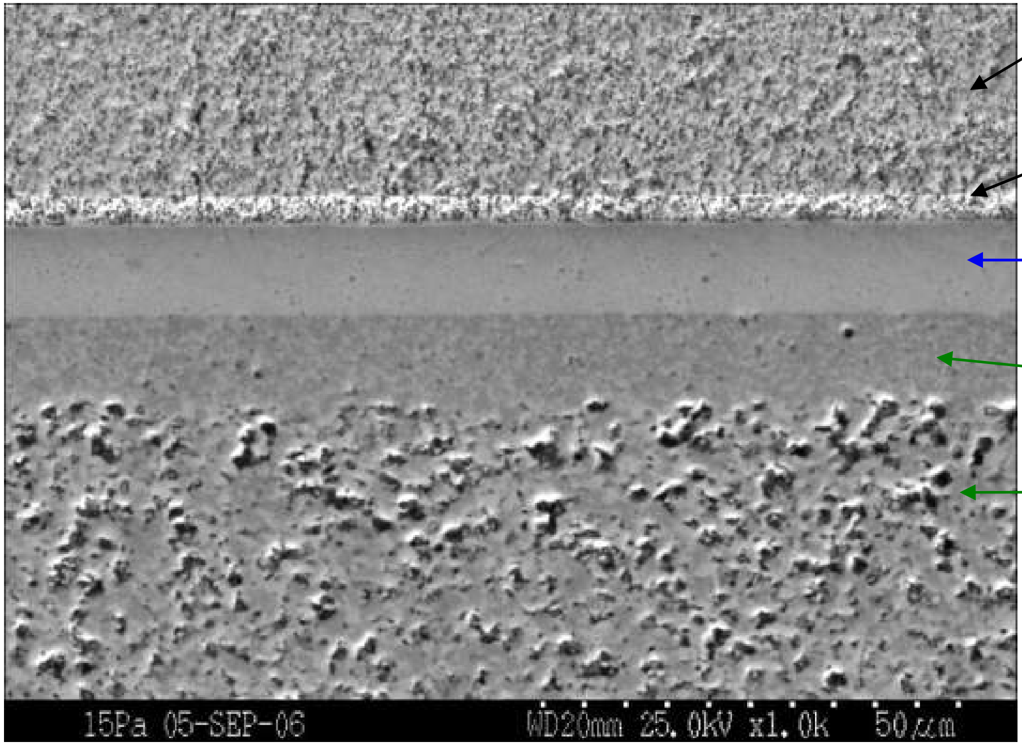
Anode Supported Cell Microstructure

- Delphi is fabricating anode supported cells with LSCF cathode
- Current footprint is 140mm x 98mm (active area 105 sq cm)
- Currently producing ~80 cells per week
- A typical microstructure is shown below



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)

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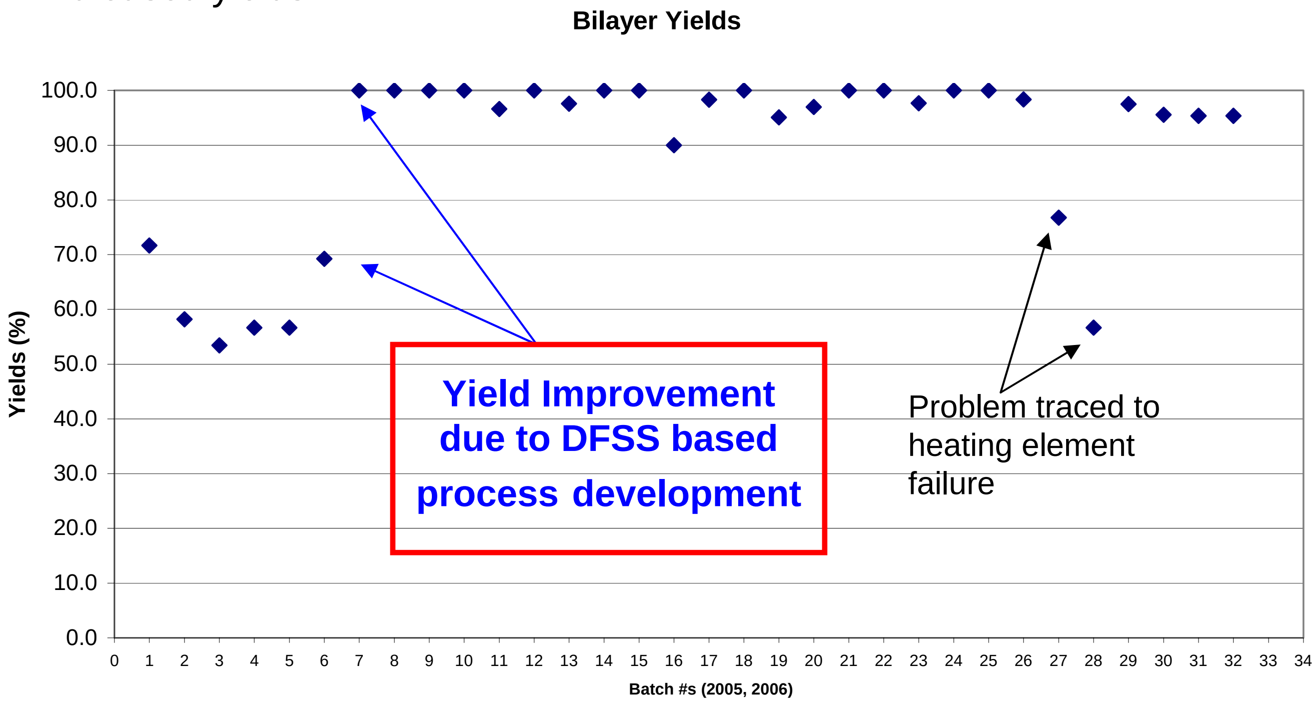
Cell Process Development

- Key process development for cells have included:
  - Improved tape characterization, improvement of lamination parameters
  - Electrolyte processing optimization (solids loading optimized)
  - Bi-layer sintering operation development using Design for Six Sigma (DFSS) - significantly increased yields



- Key focus on developing specification for materials, tapes and inks for high volume manufacturing – includes identifying and developing relationship with high volume manufacturing suppliers
- Delphi is also exploring viability of manufacturing cells with larger footprints for application in large power plants for stationary markets

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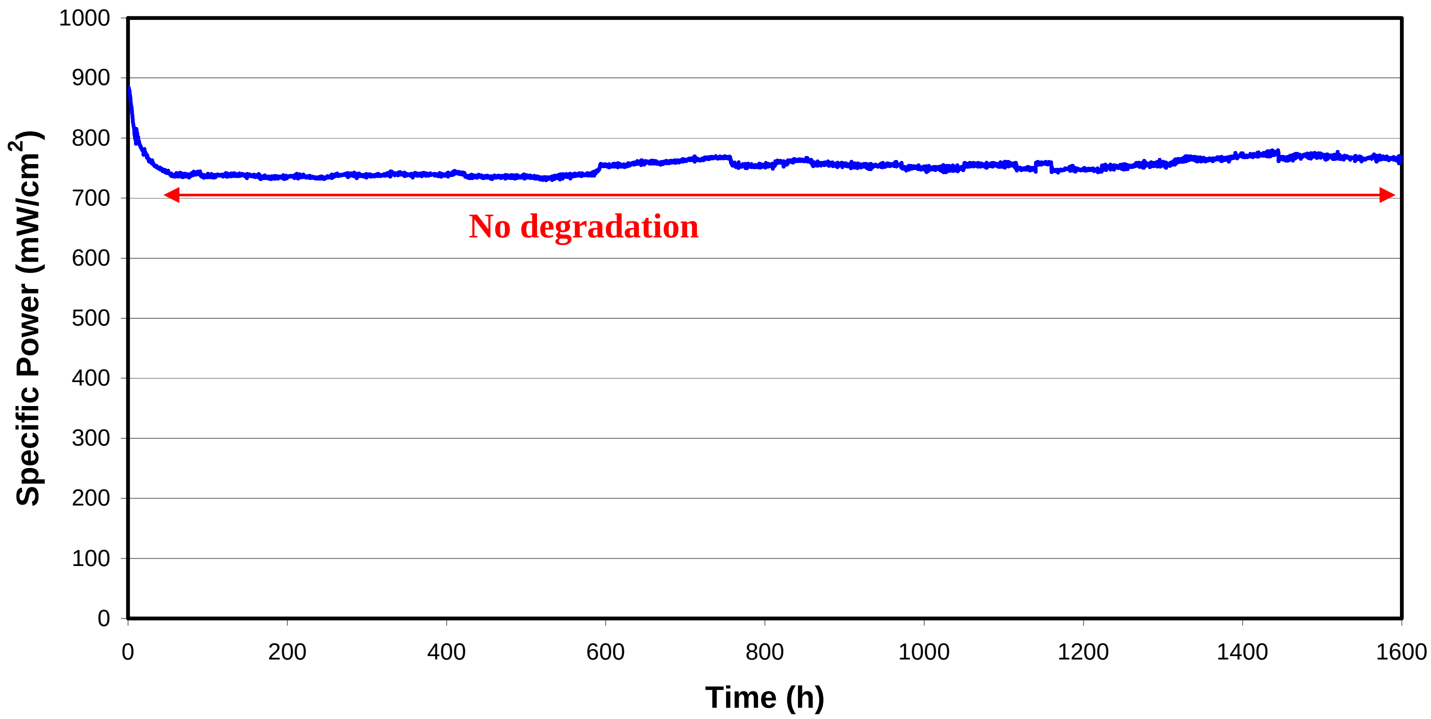
Long Term Stability of Cell Materials

- Button cell tests ongoing for materials development
- Stable performance from LSCF cathode based cell demonstrated
- No degradation in 1500 hours after initial stabilization



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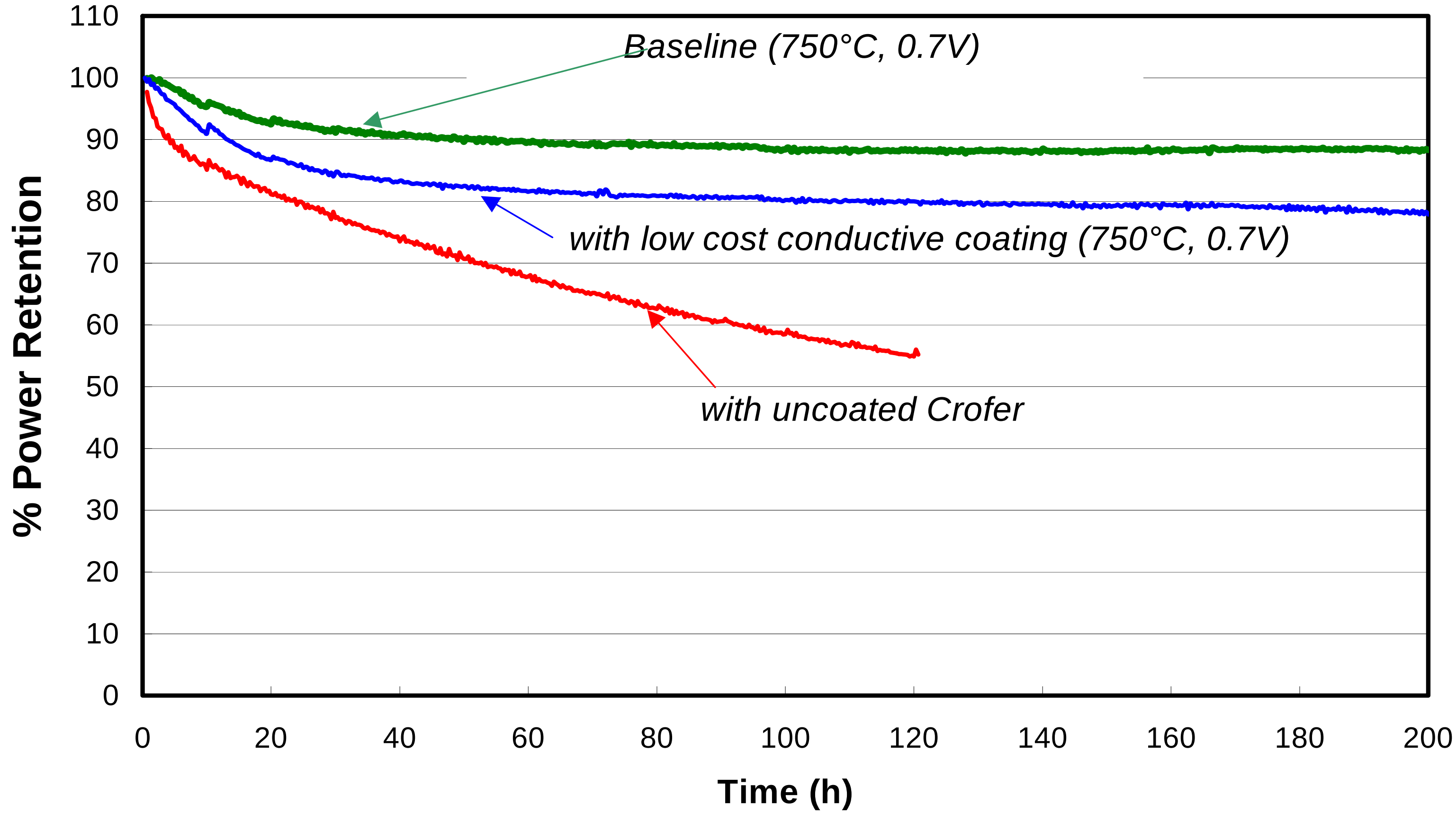
Coating Development for Interconnects

- Low cost coating being developed for Cr retention – data shown below on a button cell test with Crofer 22 sample (coated and uncoated) in the cathode environment



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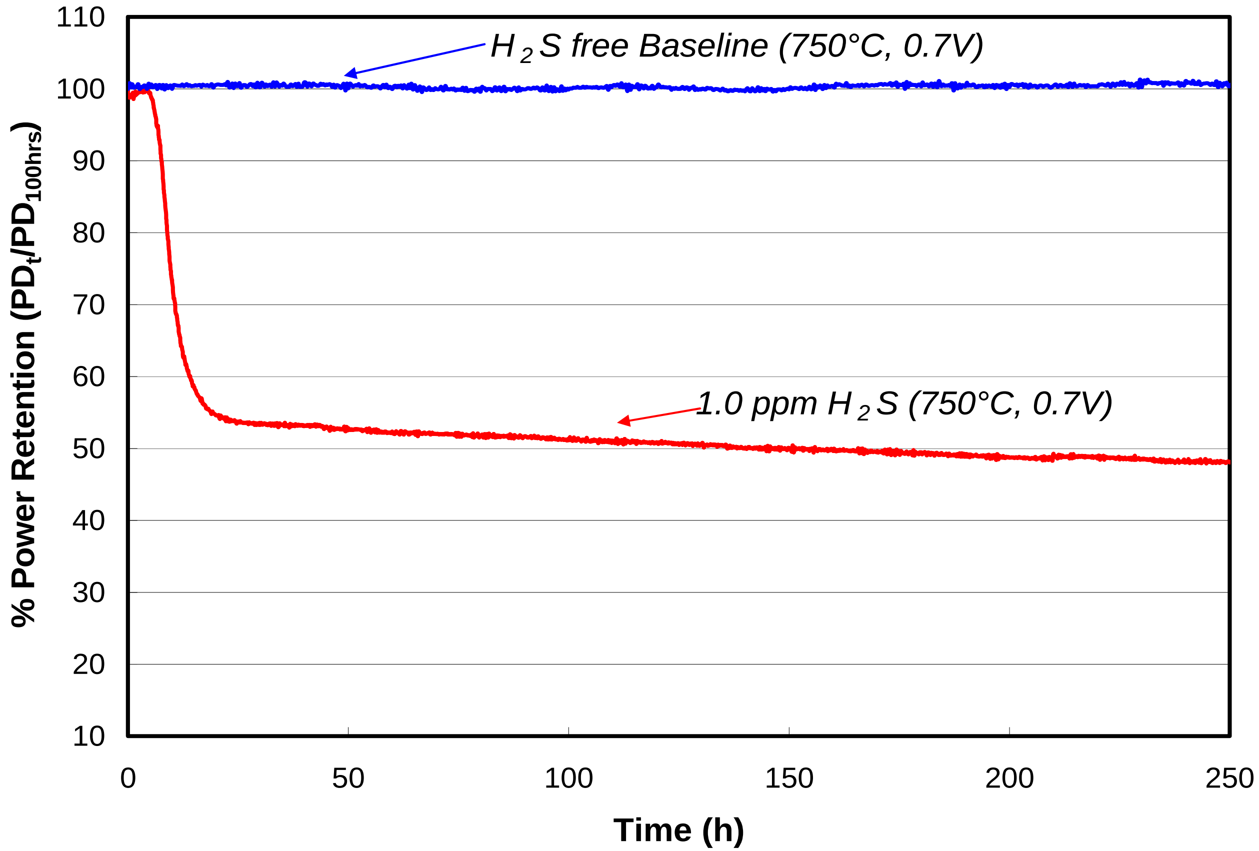
Effect of 1.0 ppm H_2S on Standard Cell

- Development ongoing to understand and minimize degradation mechanisms due to H_2S
- Data below shows lowering in power due to addition of 1ppm H_2S in hydrogen at 750°C



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Generation 3.1 30-Cell Stack

Generation 3.1 30-cell stack
(2.5 liters, 9 Kg)

- 30-cell modules are the building blocks for Delphi's power systems
- These 30-cell modules were integrated into the system and operated to meet SECA Phase 1 targets

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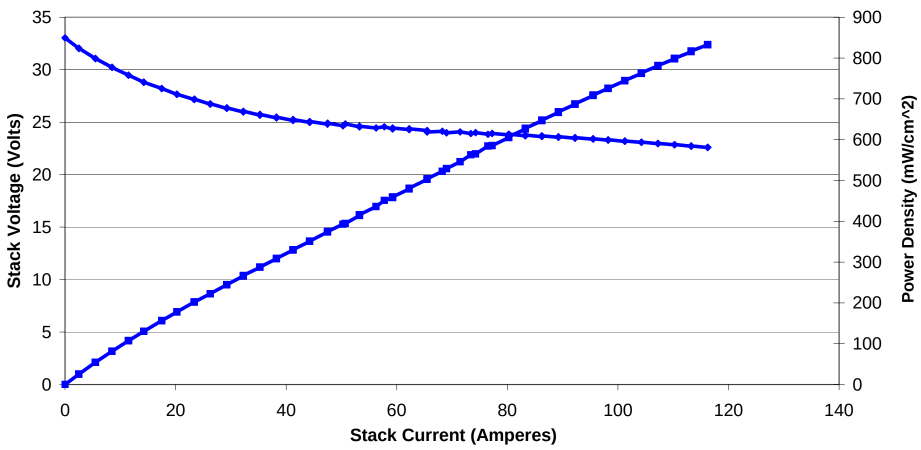
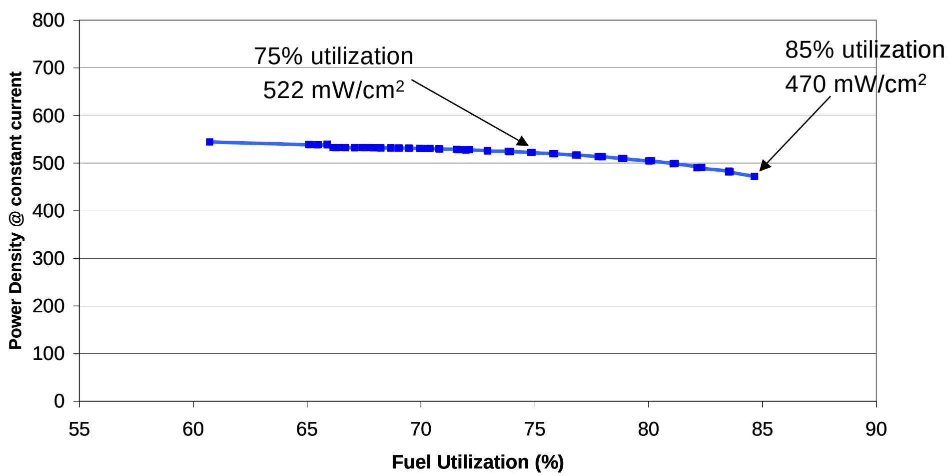
Generation 3.1 30-Cell Stack Data

- Power
  - Data below shows a 30-cell Generation 3.1 stack tested in the stack laboratory (furnace, no insulation)
  - Produced max power of 2.62 kW (833 mW/cm^2) @ 22.6 Volts with 48.5% H_2, 3% H_2O, rest N_2 (53 % utilization, measured anode outlet temperature: 800ºC)
    - » Current development ongoing to map cell temperature and optimize conditions for adequate internal cooling of stack for high power operation in systems
  - Fuel utilization studies show a 30-cell stack producing 522 mW/cm^2 @ 75% utilization @ 0.8 V per cell, power density of 470 mW/cm^2 @ 85% utilization @ 0.8 V per cell





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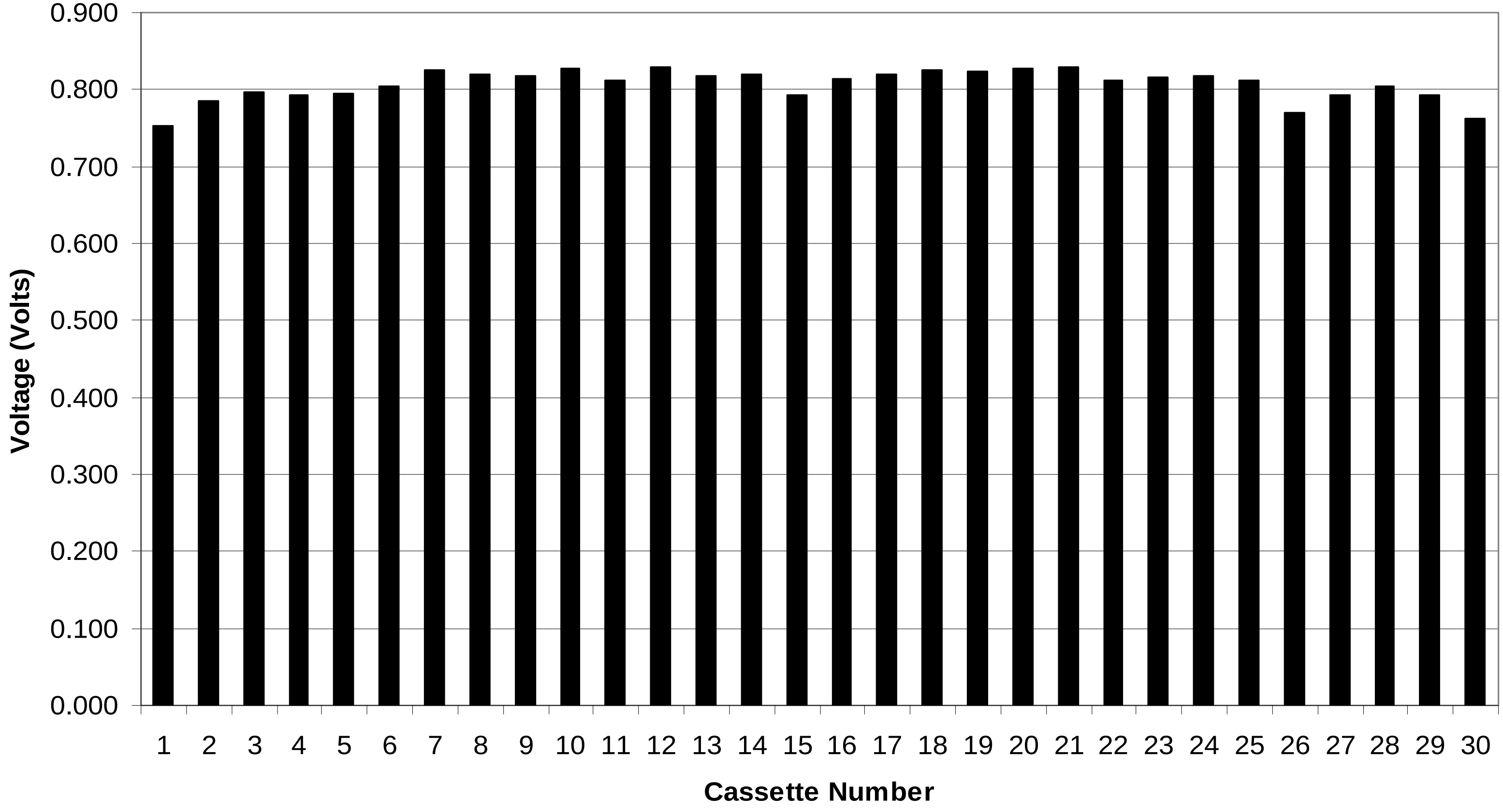
Cassette Variation in a 30-Cell Stack

- Consistent performance between cassettes in a 30-cell stack (@ 60 Amps, 48.5% H_2, 3% H_2O, rest N_2)
  - Voltage difference between best and worst cassette is 0.07Volts



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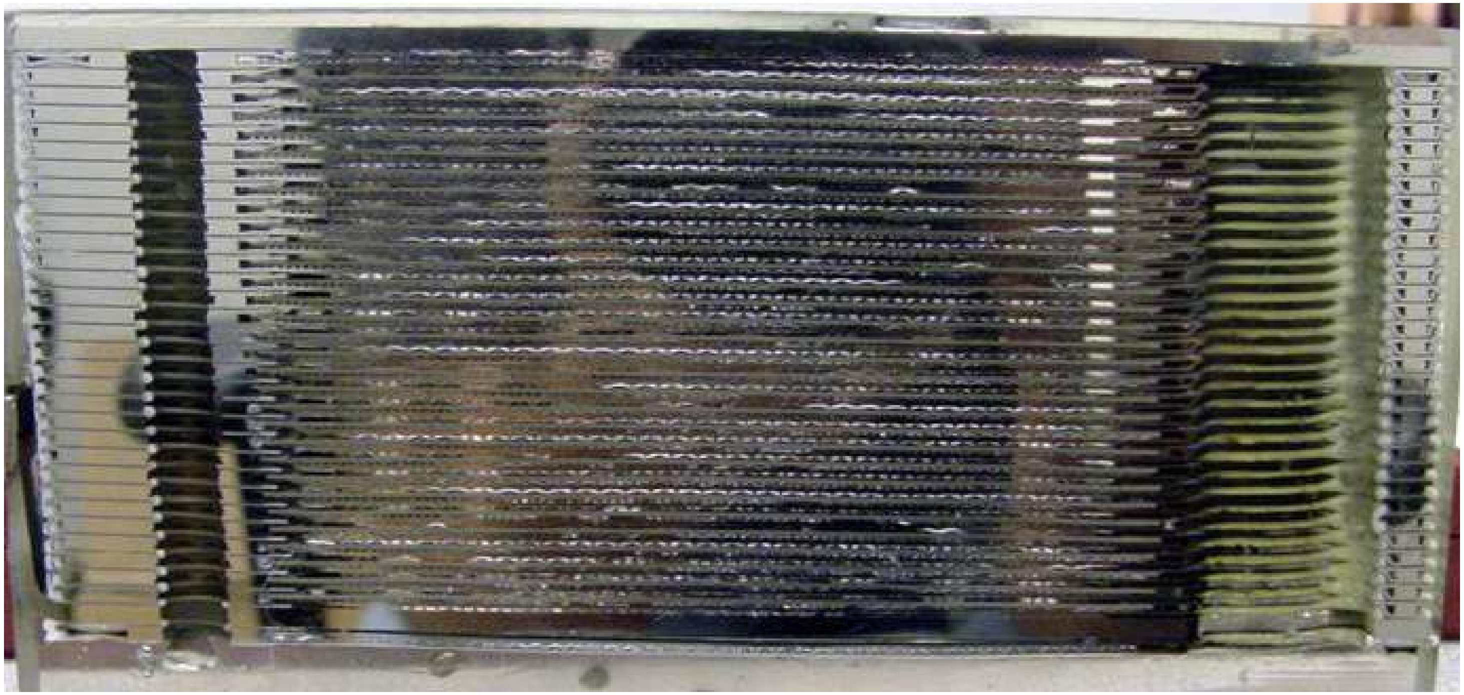
Post-Mortem Analysis of Stacks

- Focus is on understanding degradation and failure mechanisms from autopsy of stacks after long term operation in the system
- Key lessons learned on seals, interconnects and cell durability
- Picture below shows an optical micrograph of center slice of 30-cell stack prior to SEM examination.



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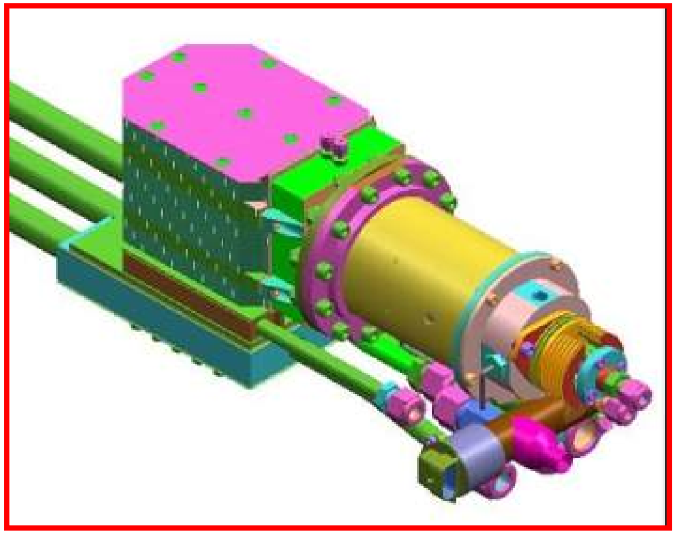
Fuel Reformer Development

- Delphi is developing reforming technology for Natural Gas, Gasoline and Diesel/JP-8 for SOFC applications
- Two main designs are being developed:
  - **CPOx Reformer**
    - Moderate efficiency
    - Simplicity of design
    - Not recycle capable
  - **Recycle Based (Endothermic) Reformer**
    - High efficiency
    - Use of water in anode tailgas to accommodate steam reforming
    - Recycle capable



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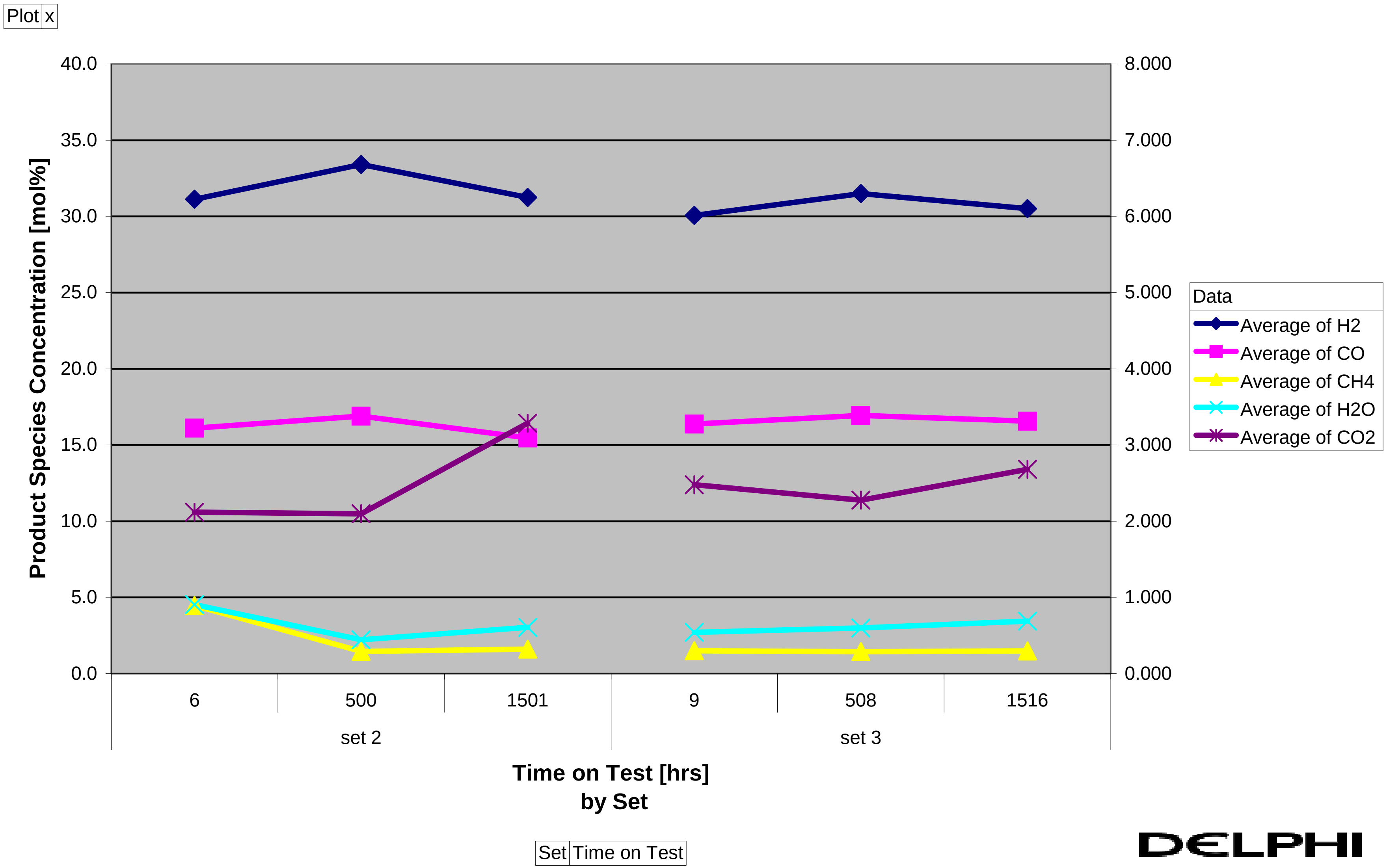
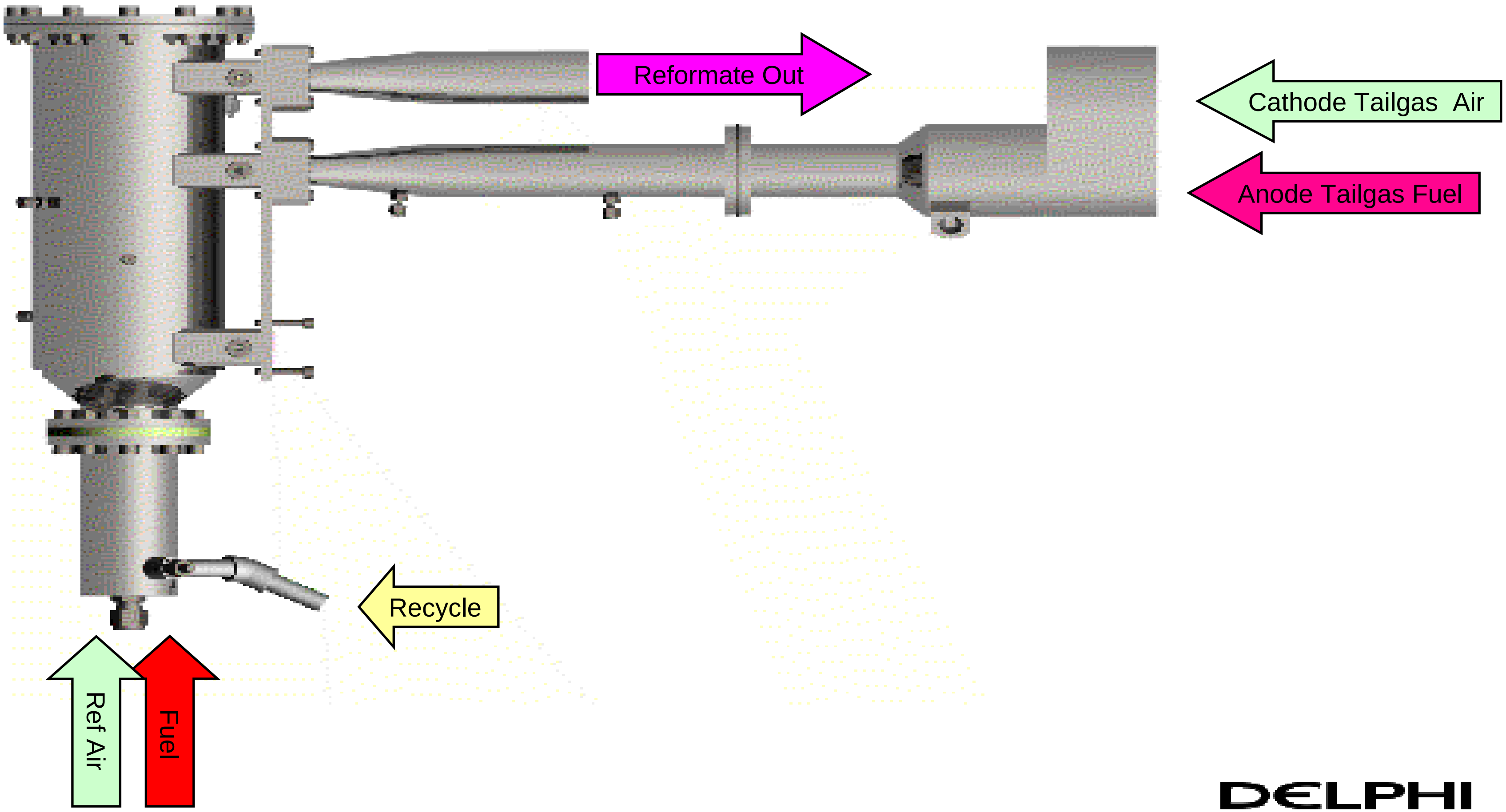
CPOx Fuel Reformer Durability on Systems Test – Reformate Composition



Tubular Endothermic Fuel Reformer



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Delphi Factory Cost Analysis

- Establish a standard Bill of Material
- Perform Component Review Meetings (These meetings identify the differences between prototype and production intent designs)
- Identify and Document Assumptions and Justifications
- Submit Quote Request Forms through Delphi's Supply Management Team for all purchased components
- Estimates were developed for all manufactured and assembled parts using Delphi's extensive manufacturing experience
- Cost analysis audited by outside consultant
- Audited Phase I Cost Analysis submitted to SECA

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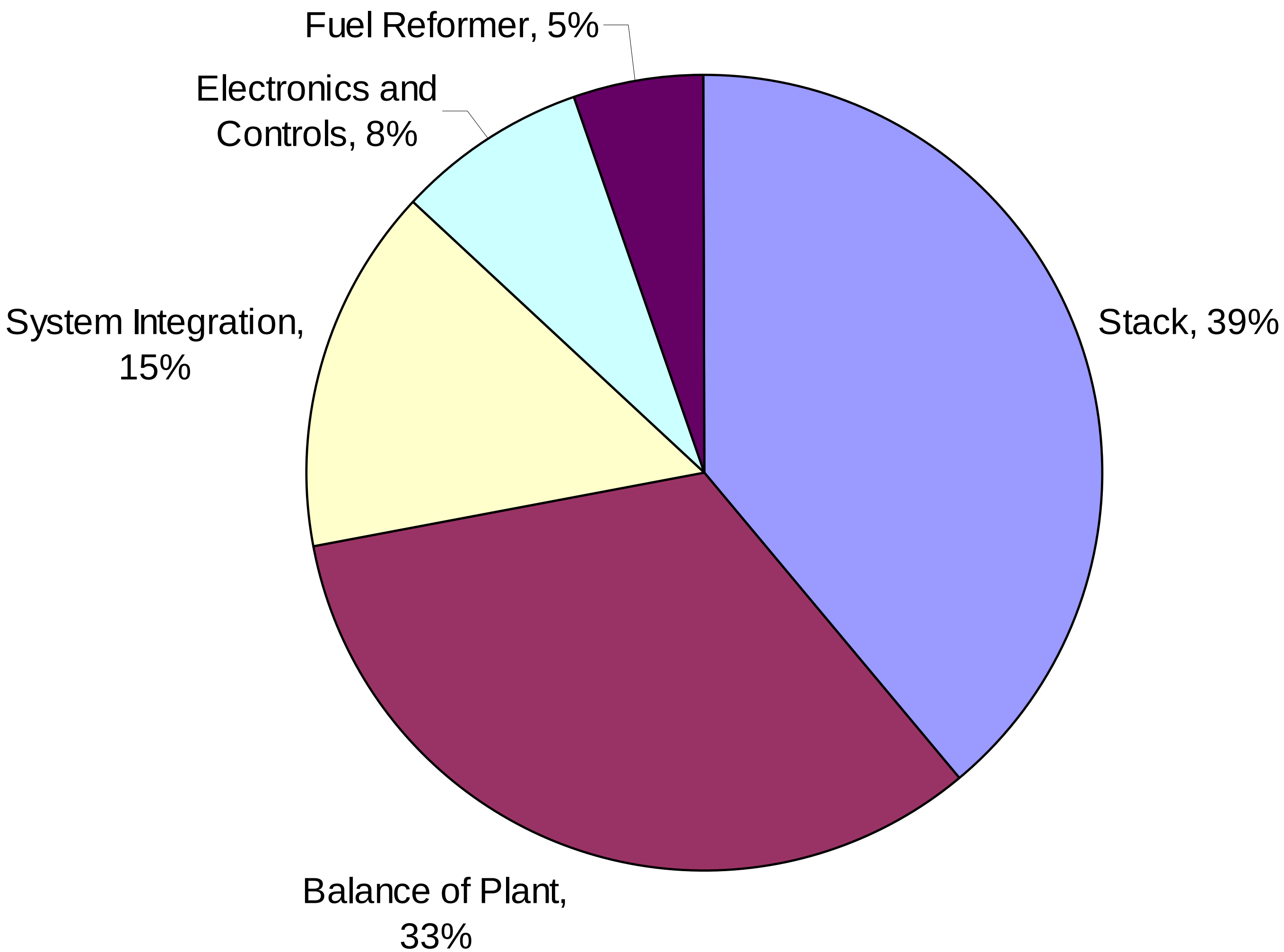
Cost Breakdown by Subsystem



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Next Steps:

- SECA Phase II:
  - Conversion to Line Natural Gas with Fuel Desulfurizer
  - System integration of output power electronics including A/C inverter
  - Aggressive cost reduction and manufacturability improvement
  - Continued improvement in power, efficiency, and reliability
  - Diesel-fueled APU System Development
  - Improve thermal cycle capability of Stack and System
  - Meet Phase II targets

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SECA Phase II System Target Metrics

Target Metric		Current SPU 1B	DOE/SECA Ph I (CONTRACT)	DOE/SECA Ph II (CONTRACT)
"Production" Date		2005	2005/2006	2008
Fuel		Methane	Methane	Nat Gas
Net Rated Power	kW	2.2	3-10	3-10
Fuel to Electric Efficiency (Peak)	%	38%	35%	40%
System Start-Up Time (25C - 750C)	min	180	N/A	N/A
Cycle Durability	cycles	2	1	50
Operation Life	hrs	4660	1500*	1500*
		-1.5% / 500 hours	-2% / 500 hours	-1% / 500 hours

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