Development Update on Delphi's Solid Oxide Fuel Cell Systems

Steven Shaffer
Chief Engineer – Fuel Cell Development

San Antonio, TX
2007 SECA Annual Review Meeting

Acknowledgements

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Fuel Cell Development Team

Battelle

Pacific Northwest National Laboratory
...delivering breakthrough science and technology

United Technologies Research Center

Department of Energy · United States of America

SECA

NETL

Solid Oxide Fuel Cell Market Opportunity

Heavy Duty Truck
Diesel

Recreational Vehicles
Diesel, LPG

Truck and Trailer Refrigeration
Diesel

US Military
JP-8

derivatives

European micro –CHP & CHCP
Natural Gas

US Stationary – APU & CHP
Natural Gas, LPG

Commercial Power
Natural Gas

FutureGen Powerplant
Coal Gas

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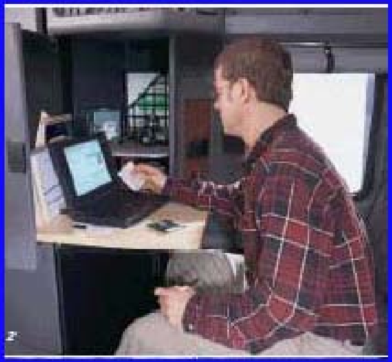
Truck Cabs are Getting More Advanced



Margaret Sullivan, PACCAR
Trucks: Truck of the Future
2003 Conference Proceedings
Fourth Annual SECA Meeting - Seattle, WA
April 15-16, 2003

PACCAR Inc

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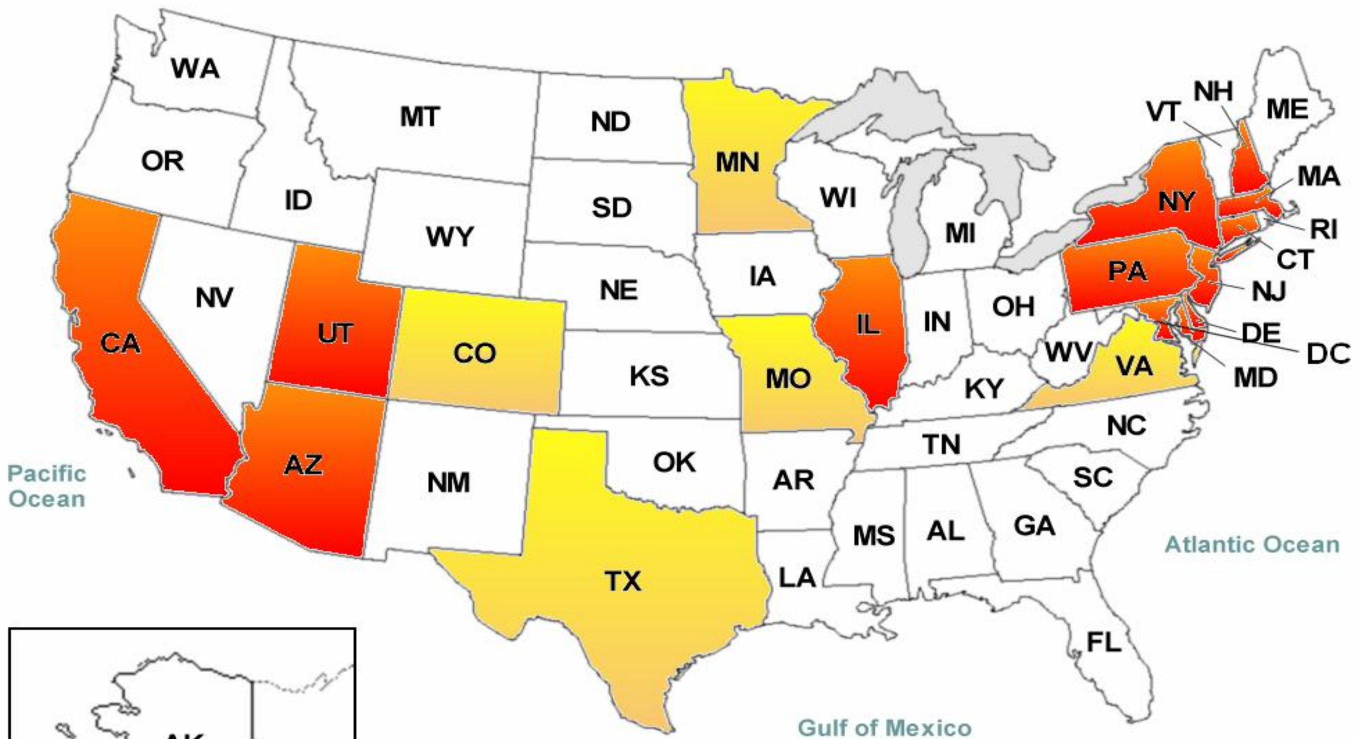
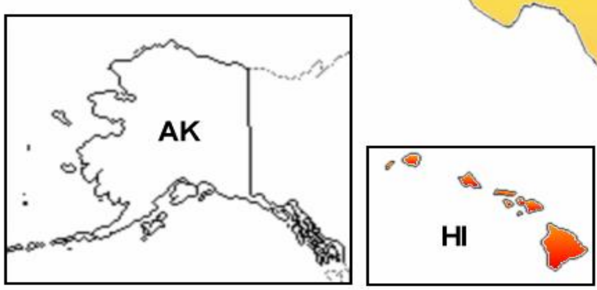
Anti-idling Regulations - State & Local





State-wide idling regulation

Limited to specific areas, cities or counties

No anti-idling regulation

In 22 States Anti-Idling laws are adopted

(Total Number of States, Counties, Urban areas and Cities which have anti-idling laws in place is 34)

Source and Details: http://www.atri-online.org/2005.ATRI.IdlingCompendium.pdf

http://www.epa.gov/smartway

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Internal Combustion Engine APUs (Diesel)

Courtesy of Idle-Aire

Margaret Sullivan, PACCAR
Trucks: Truck of the Future
2003 Conference Proceedings
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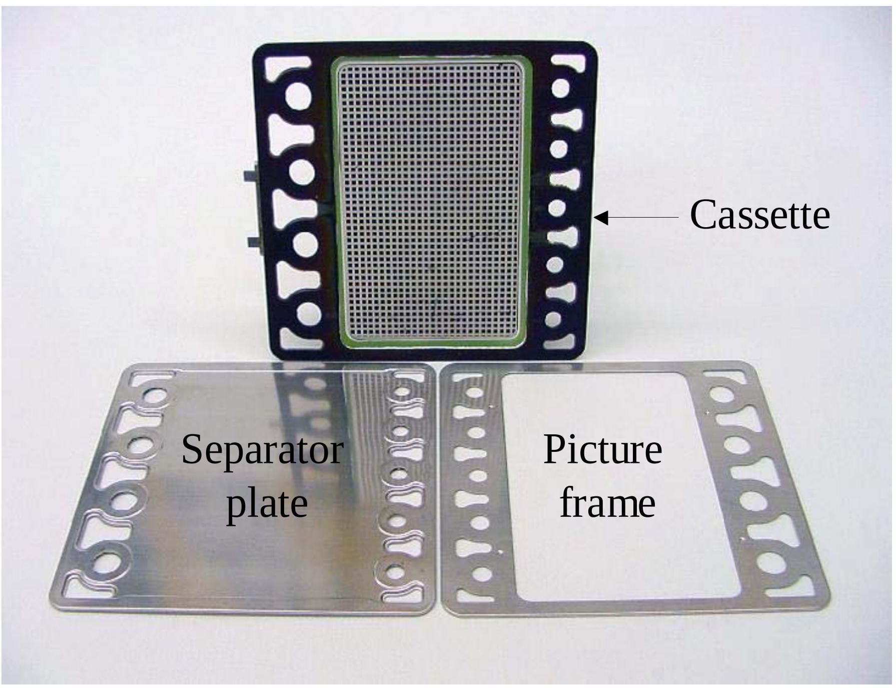
SOFC Subsystem Development
Stack

Generation 3 Stack
Key Features

- Key Stack characteristics
  - Cassette repeating unit configuration
  - High volume manufacturable processes (stamping, laser-welding, etc)
  - Integrated manifold and compact load frame
  - Low mass and volume



Generation 3 (30 cell),
9 Kg, 2.5 L

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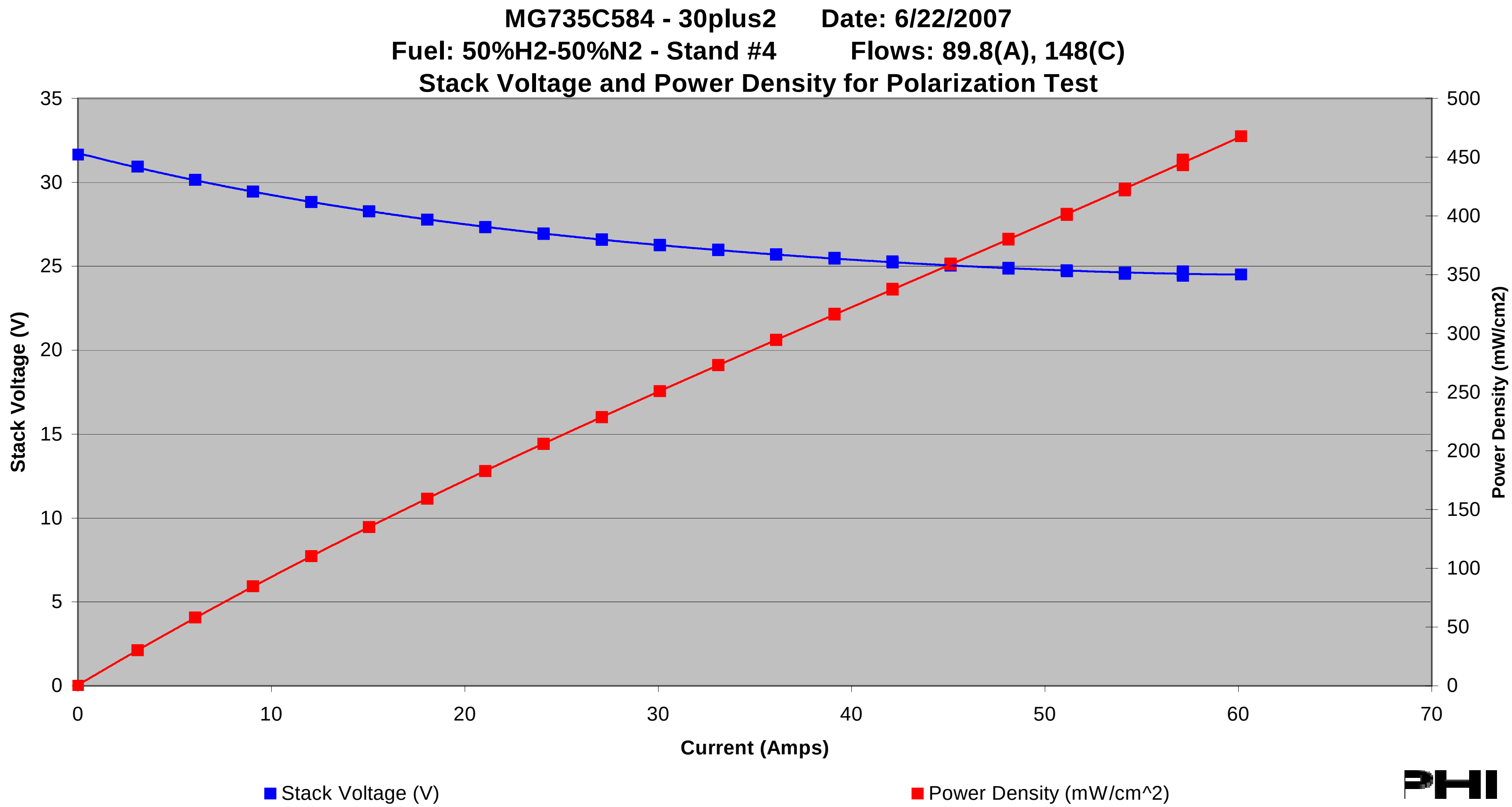
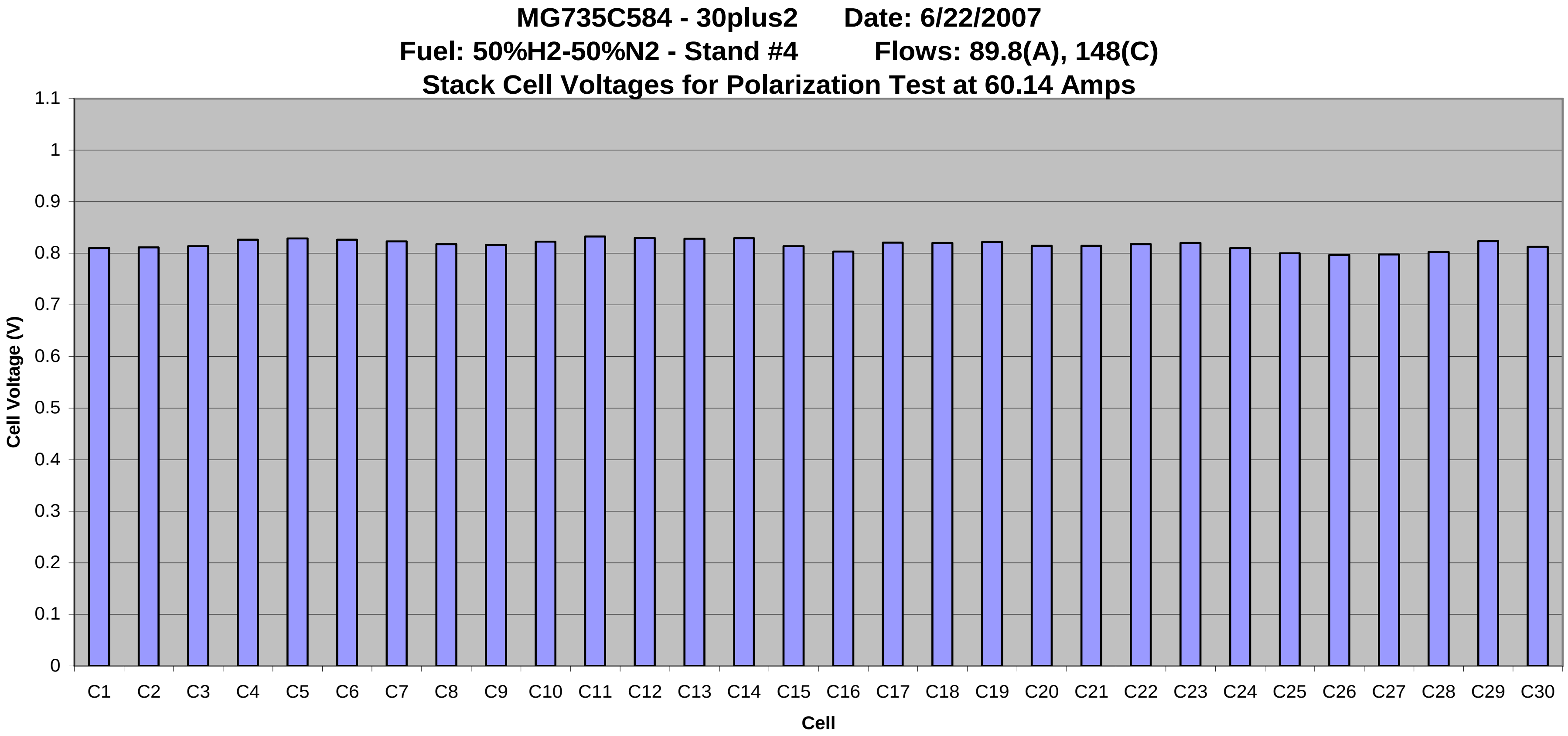
Generation 3 30-Cell Stack Data

- Data below shows a typical 30-cell Generation 3.2 stack tested in the stack laboratory
  - Produced greater than 450 mW/cm^2 at 0.8V per cell with 48.5% H_2, 3% H_2O, rest N_2



Cassette to Cassette Variation in a 30-Cell Stack

- Consistent performance between cassettes in a Gen 3.2 30-cell stack
  - 570 mA/cm^2, 48.5% H_2, 3% H_2O, rest N_2
  - Maximum voltage difference is 0.04 Volts



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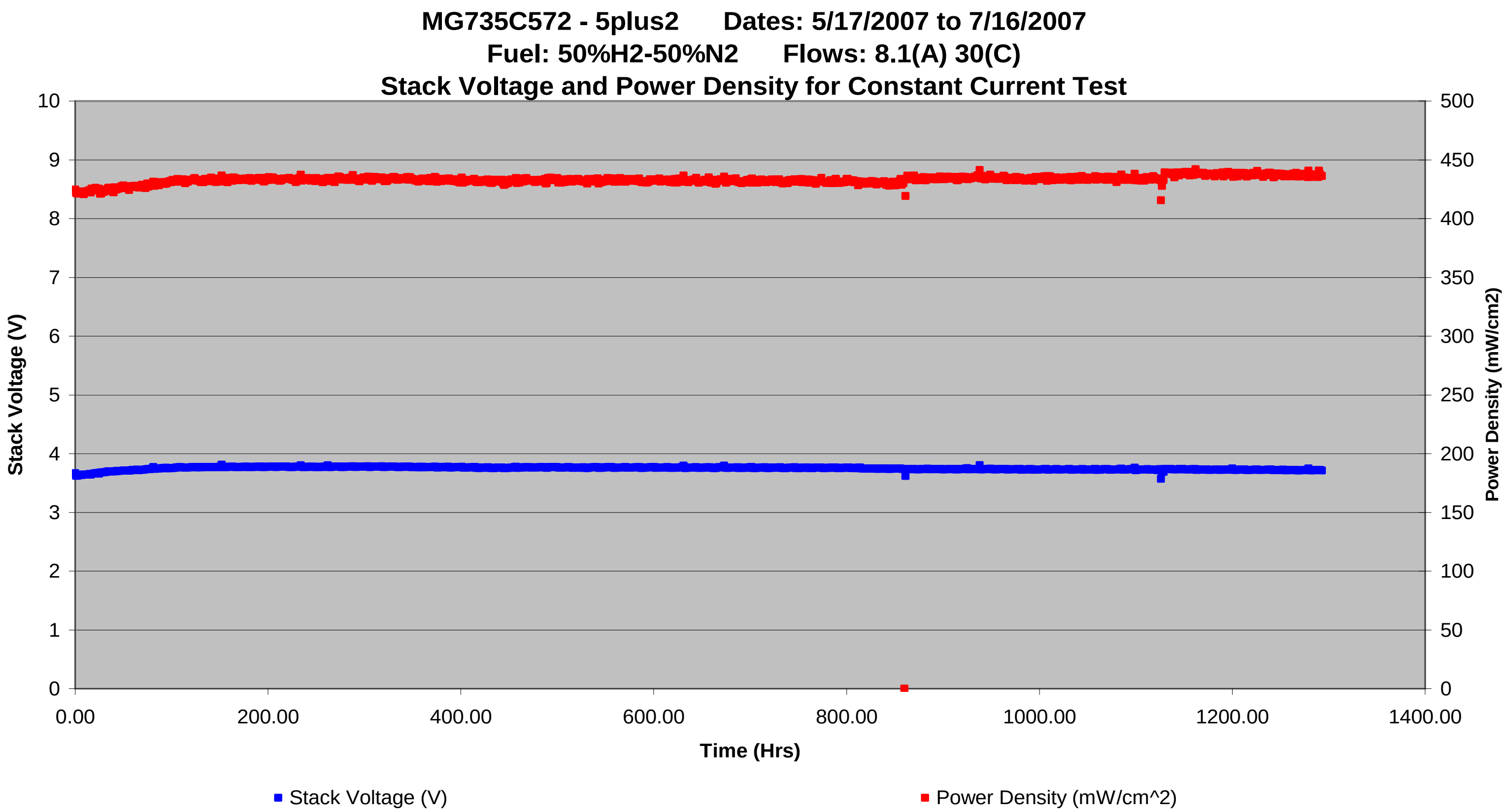
5-cell Stack on Durability Test

- Data from 5-cell stack tested for continuous durability
  - 35% H_2, 30% H_2O, rest N_2, 50% fuel utilization
  - 570 mA/cm^2
  - No degradation in 1300 hours – test continuing



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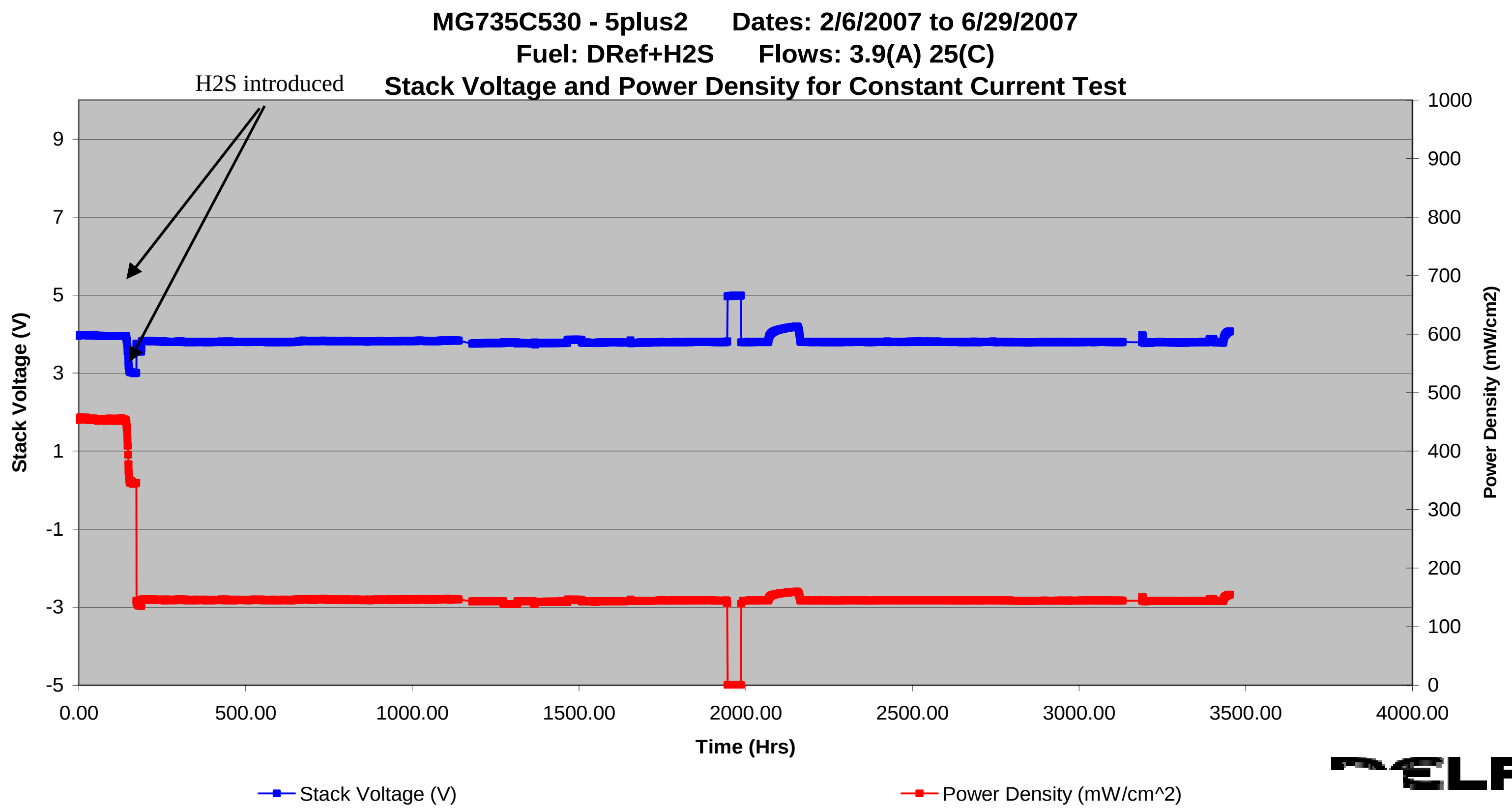
5-cell Stack on Simulated Diesel Reformate (including 2.5 ppmv H_2S) – 3500 Hours

- Data from 5-cell stack being tested on simulated diesel reformate at 750ºC with 2.5 ppmv H_2S
  - 28% H_2, 30% CO, 6% H_2O, 2.5 ppmv H_2S
  - Initial H_2S added at constant current density of 570 mA/cm², 26% drop in performance observed
  - Current density re-set at 190 mA/cm² at the nominal operating point
  - No secondary degradation



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Key Cell Scale-up Developments

- Increased tape cast width capability of TCF tape caster
- Developed machine specifications for higher volume cell production processing
- Developed timing plan for progression to higher volume cell production
- Successfully demonstrated capability for fabricating larger footprint bilayers (up to 350 cm2 active area)
- Added larger screen printer capable of printing very large cells

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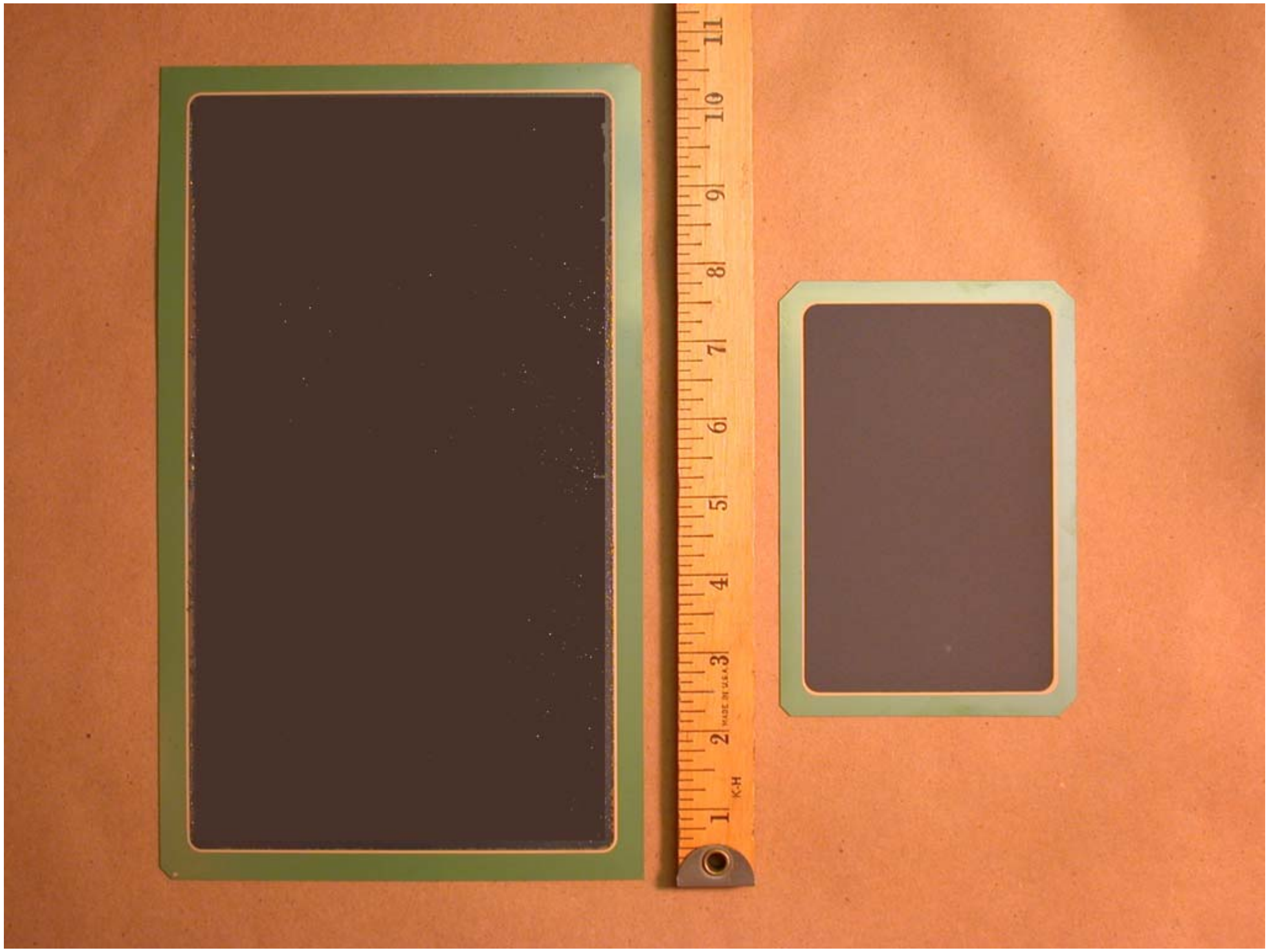
Scale-Up of Cell Active Area



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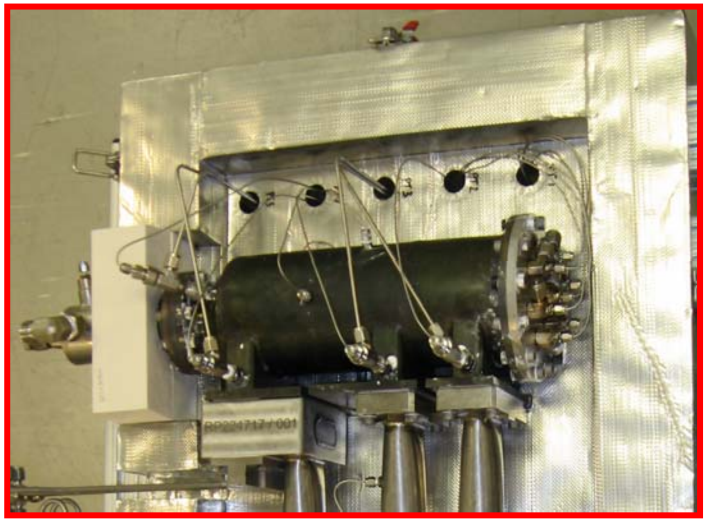
SOFC Subsystem Development

Reformer

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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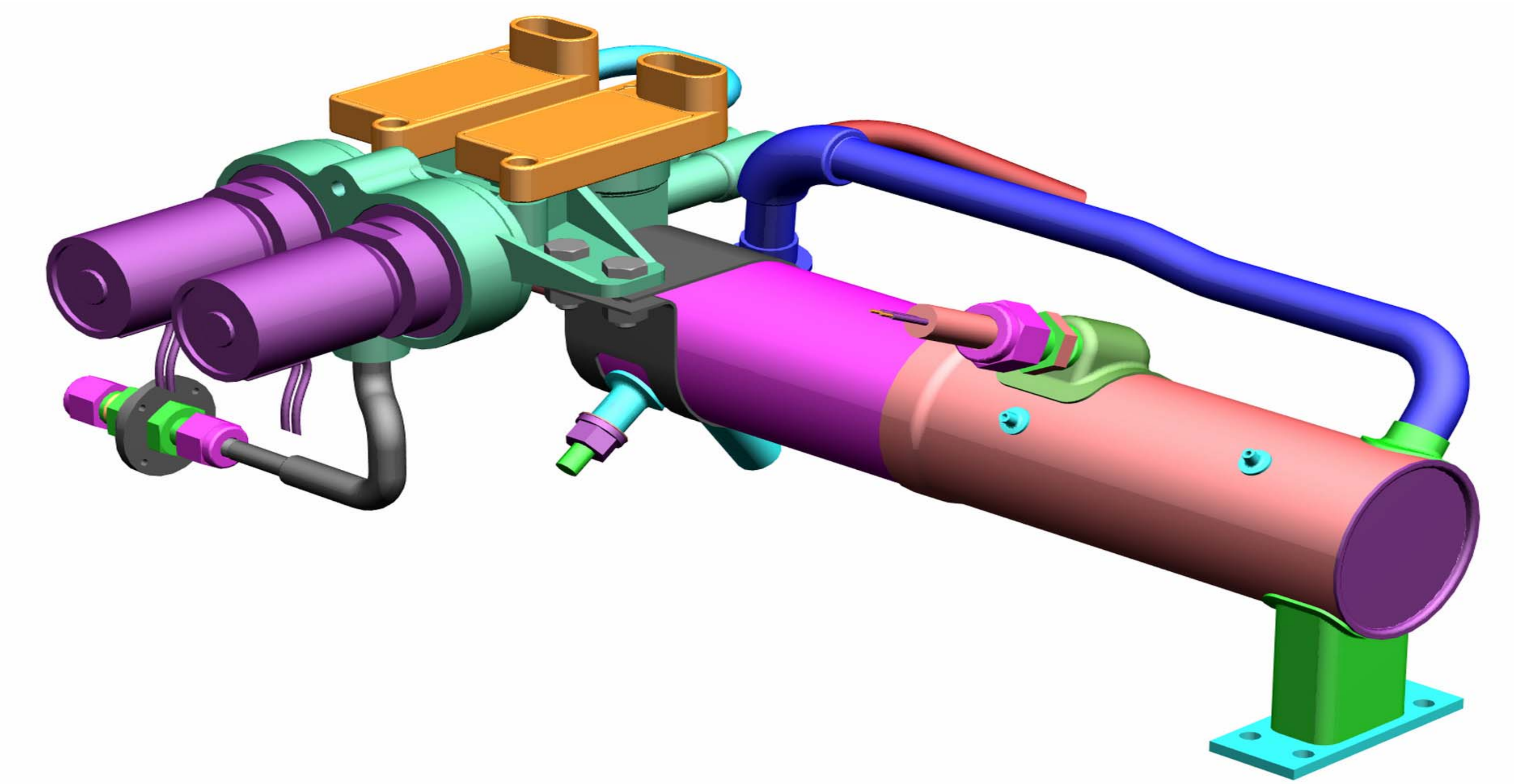
CPOx Reformer (productive concept)



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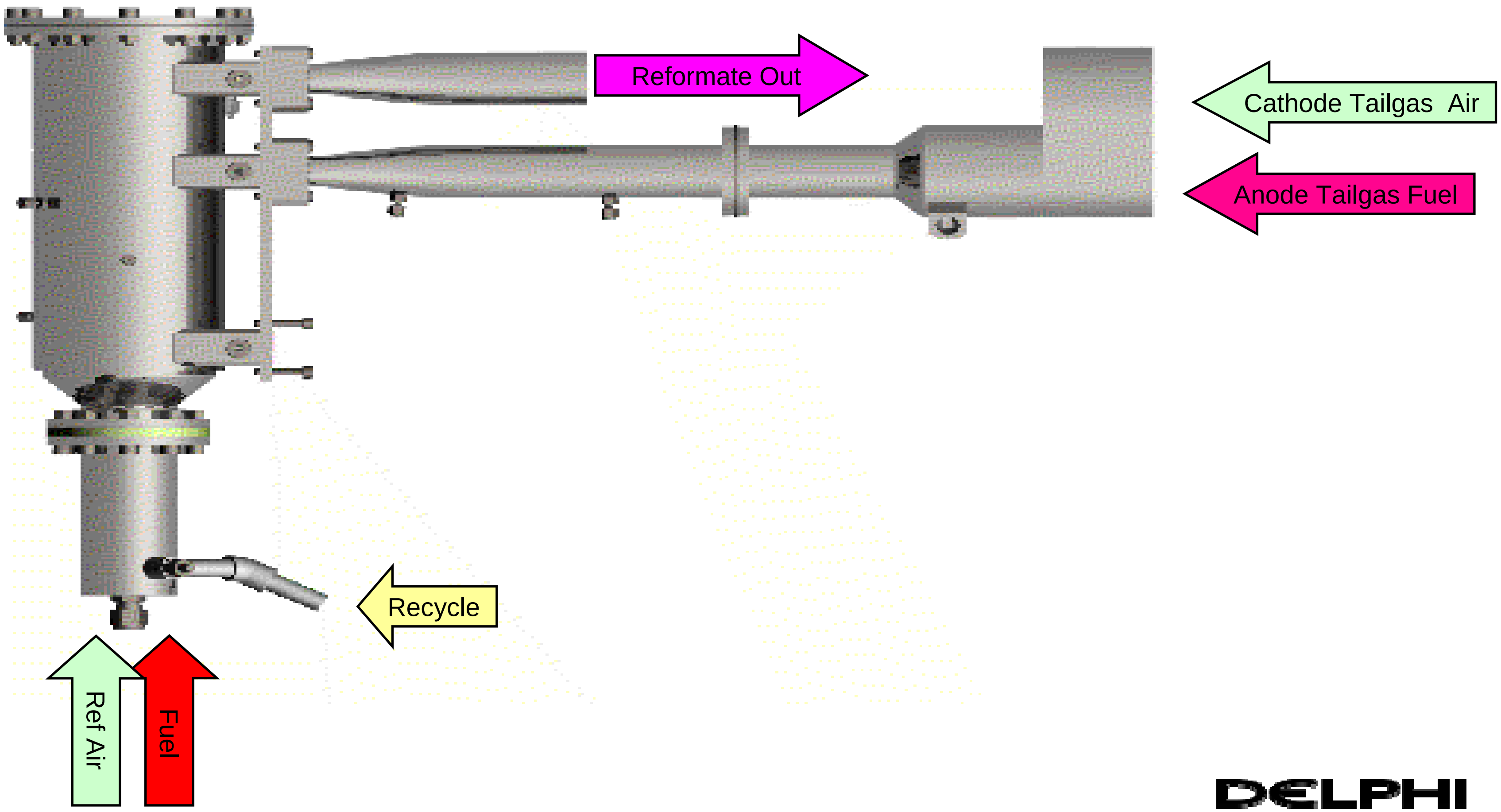
Tubular Endothermic Fuel Reformer



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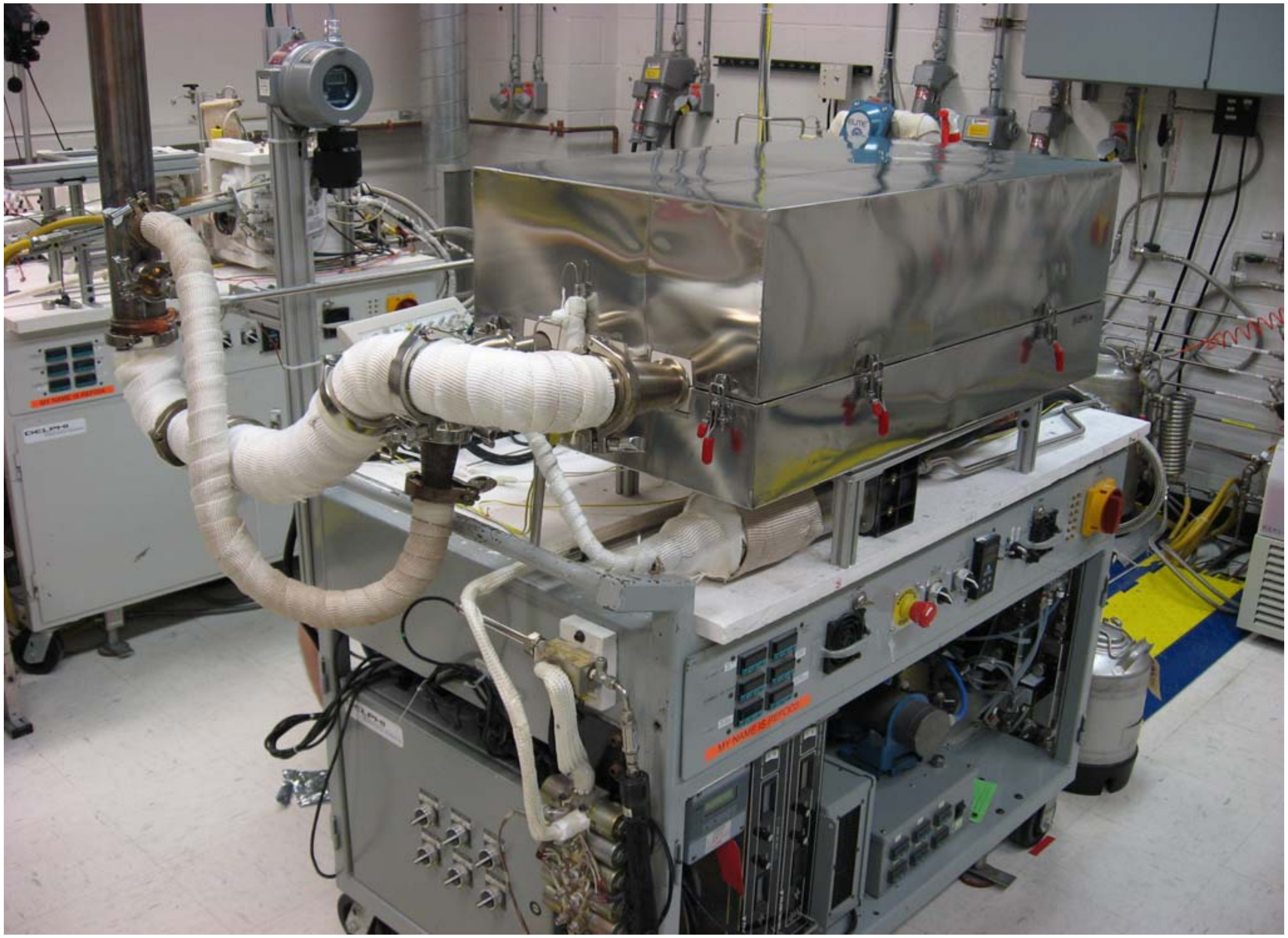
Endothermic Reformer on Test Stand



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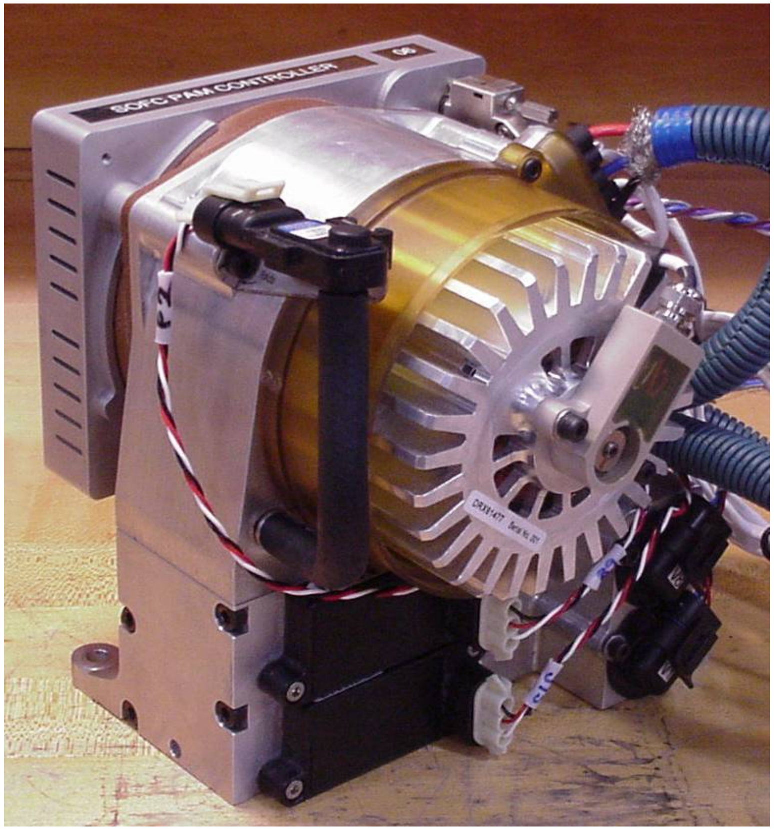
SOFC Subsystem Development
Balance of Plant

Blowers/Pumps



- Process Air Module (PAM)
- Anode Tailgas Recycle Pump

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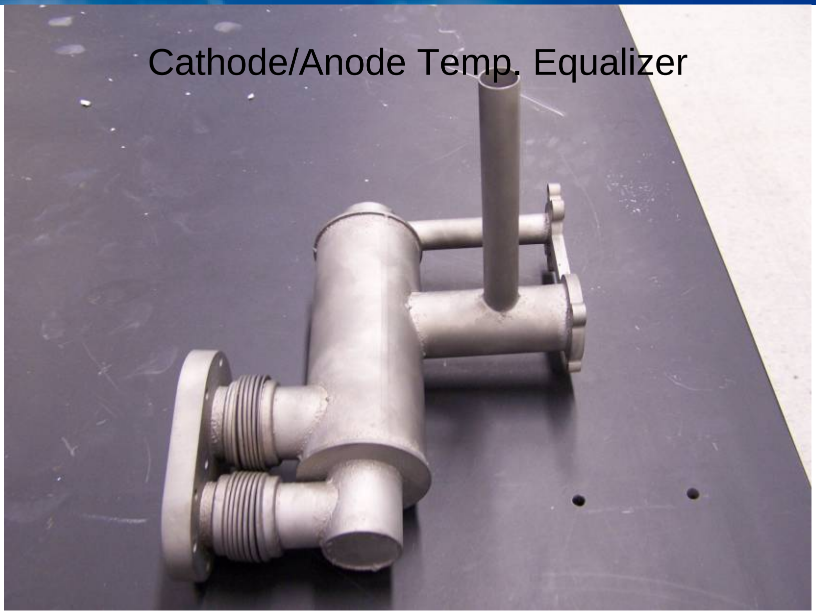
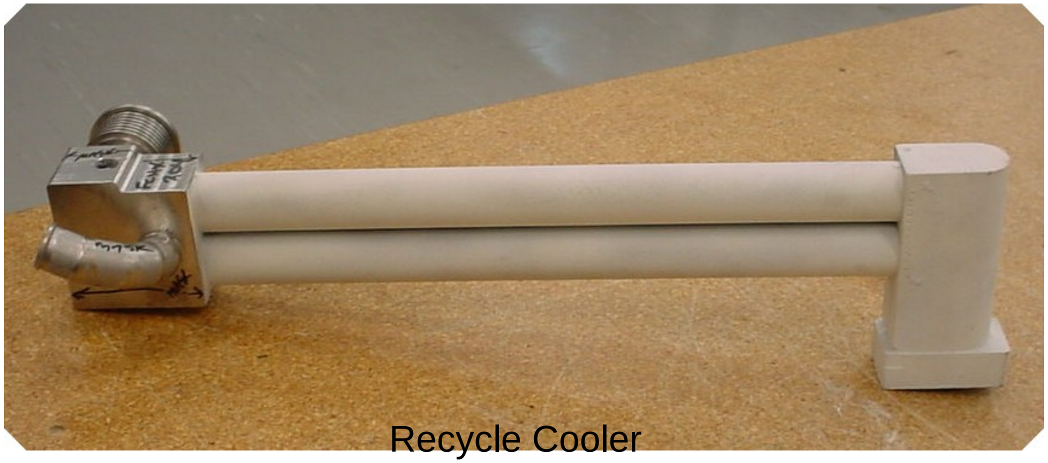
High Temperature Compact Heat Exchangers

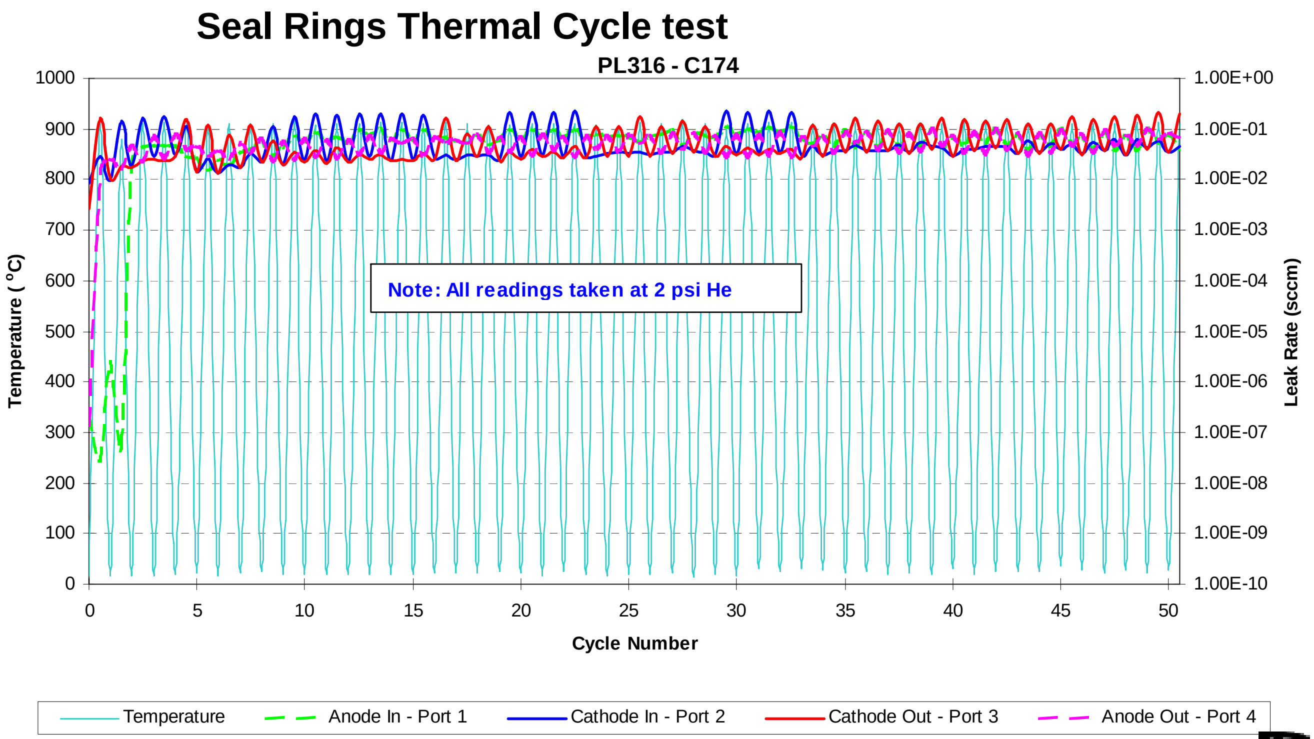

Cathode Air Heat Exchanger


Cathode/Anode Temp. Equalizer


Recycle Cooler

BOP High Temperature Seal – Thermal cycling

- Background :
  - High temperature seals between Stack base manifold, Heat exchanger and Reformer to Integrated Component Manifold.
  - 50 Thermal Cycles (25C to 900C)
  - Leak rates < .01 sccm; Helium @ 2psi



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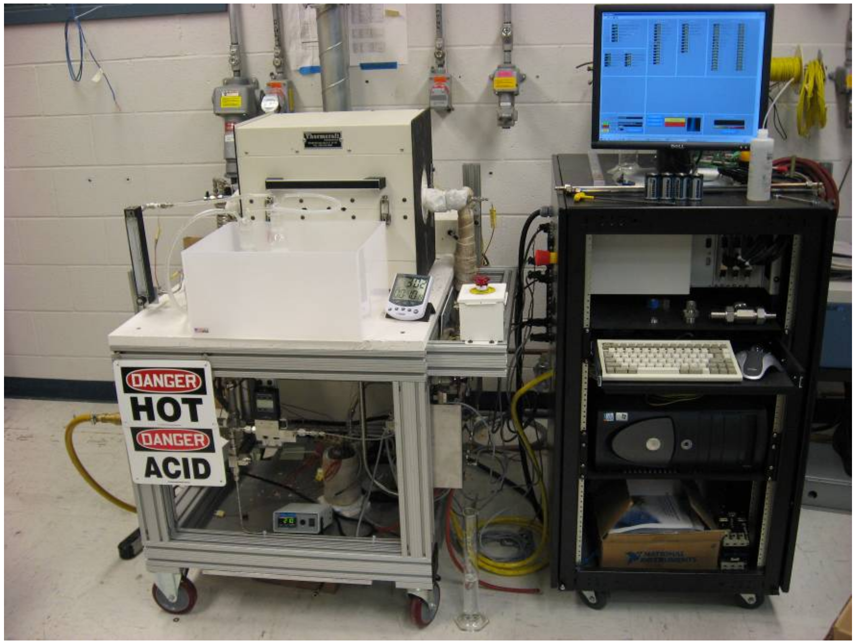
Chromium Vaporization Testing

- A test method has been established to measure the rate of chromium vaporization
  - Materials are being tested for the rate of chromium vaporization
  - Coatings for materials and other methods for mitigating chromium vaporization are being evaluated.
  - Test methodology also applied to SOFC System and data collected during system operation



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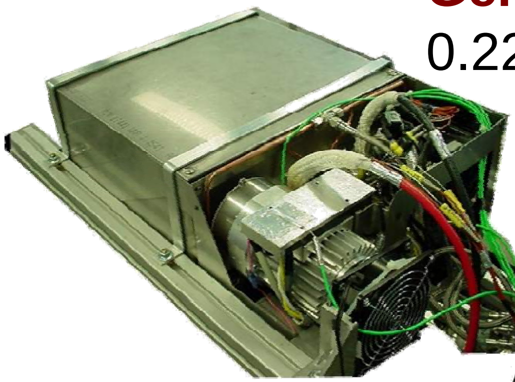
SOFC System Integration

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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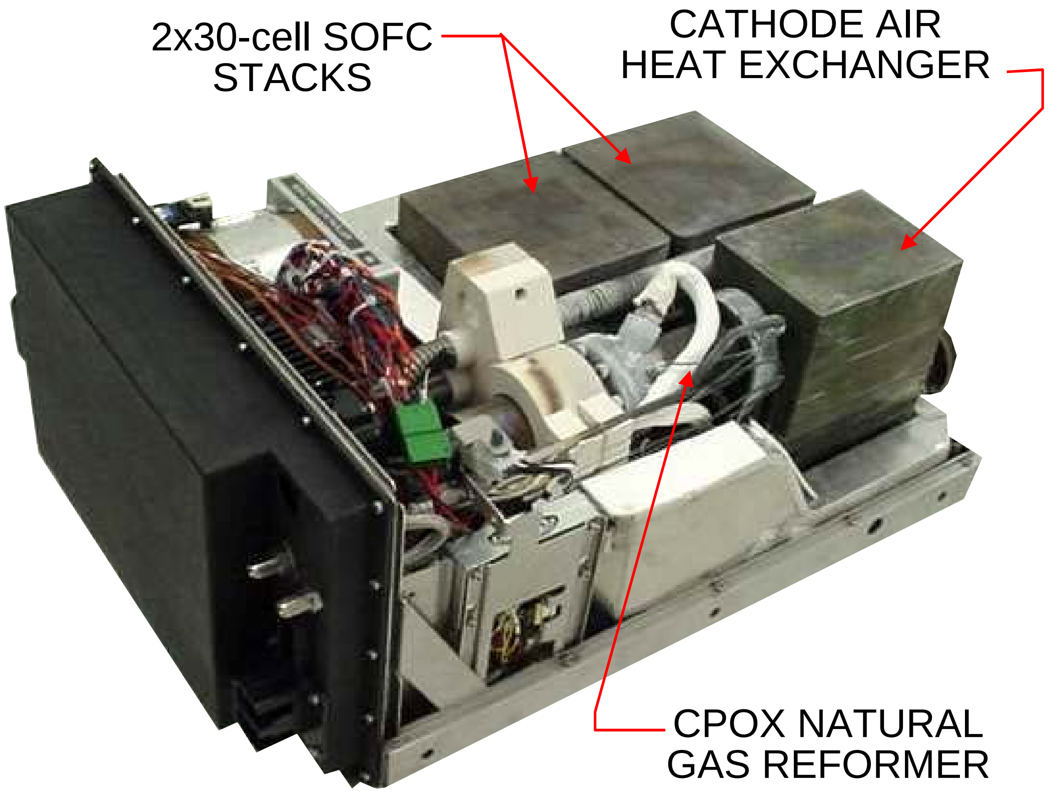
SPU 1 SOFC System
(NG Stationary & Diesel APU)



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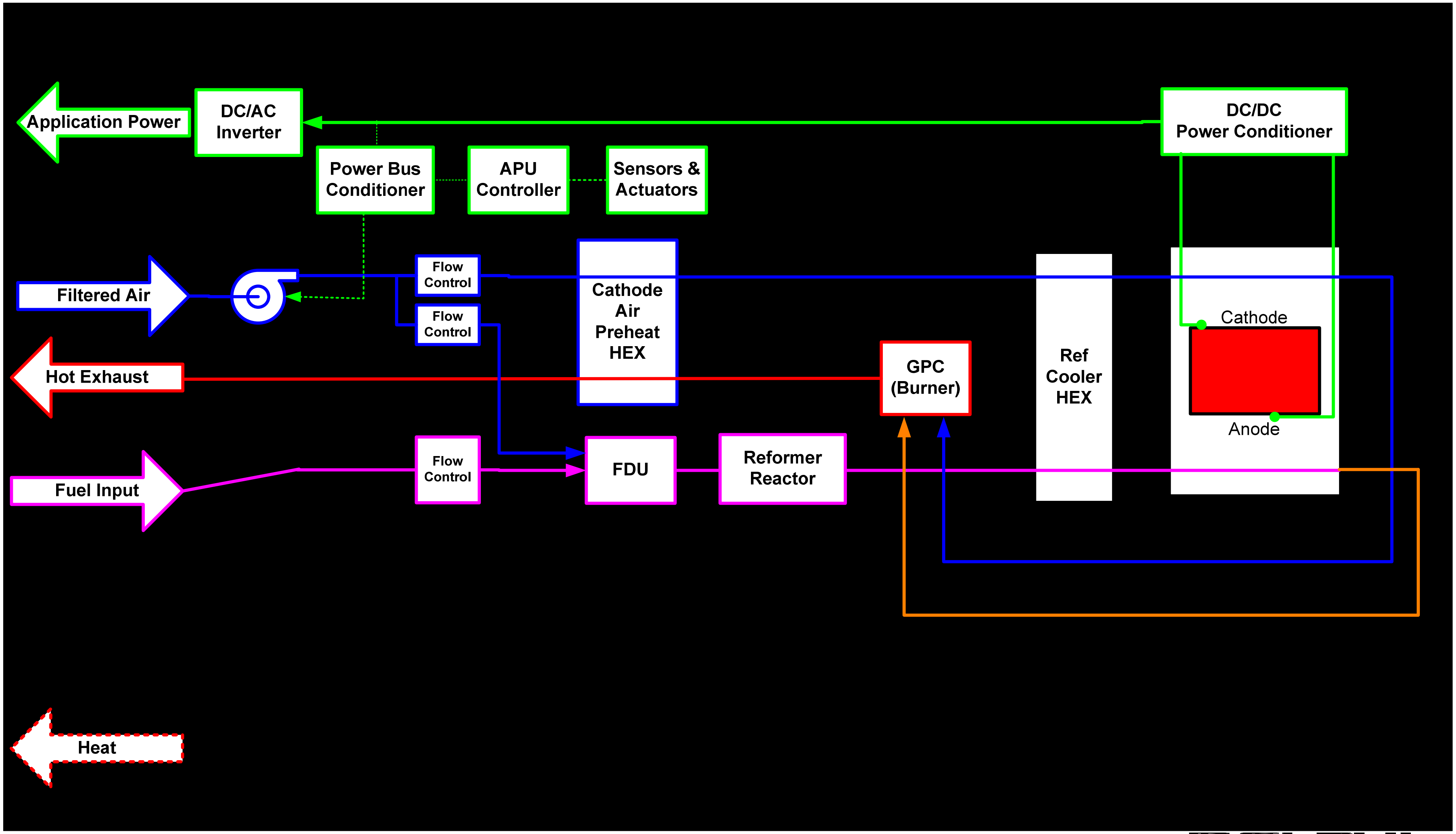
SOFC System Mechanization-CPOx



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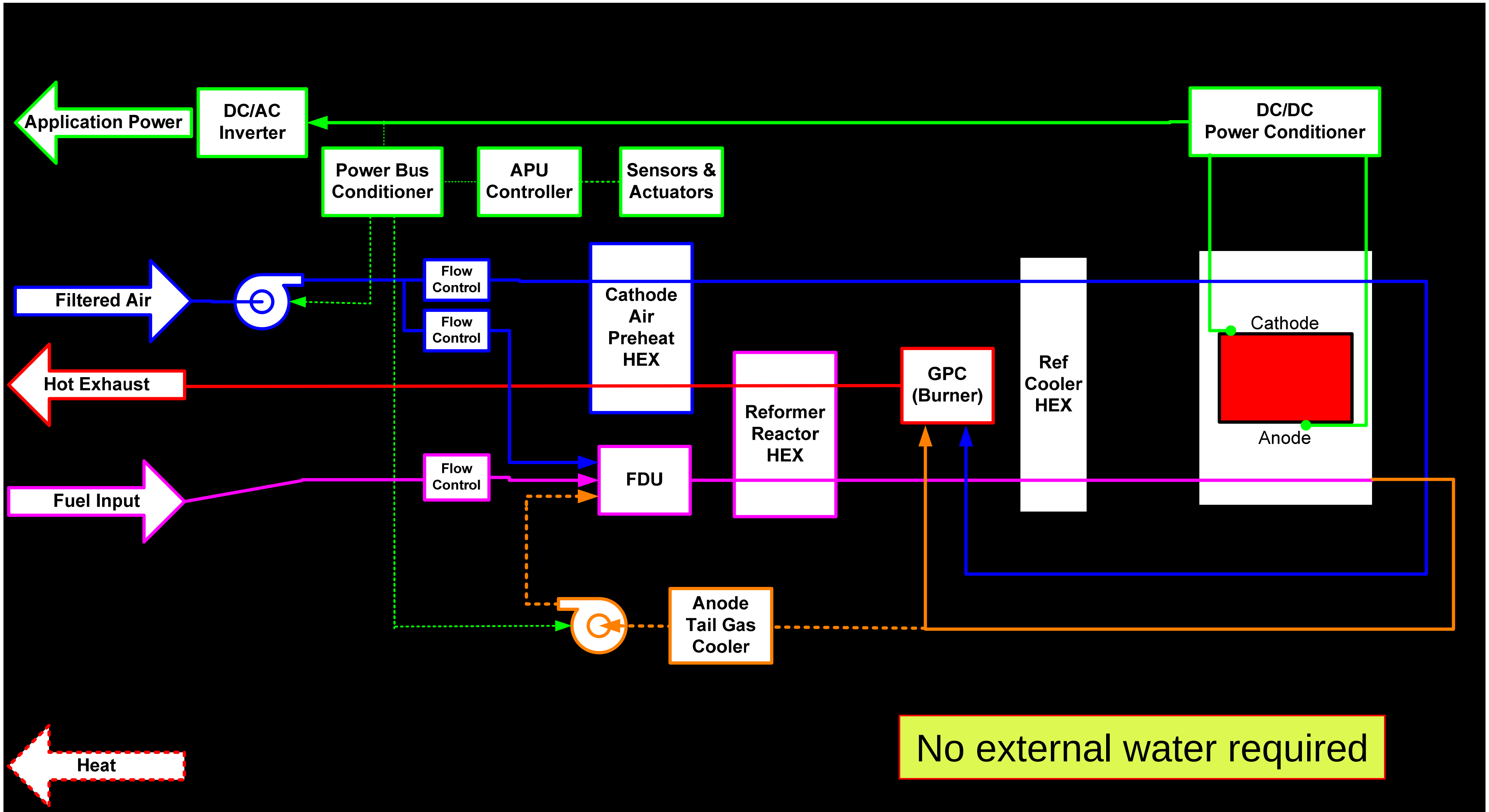
SOFC System Mechanization-Anode Tail Gas Recycle



No external water required

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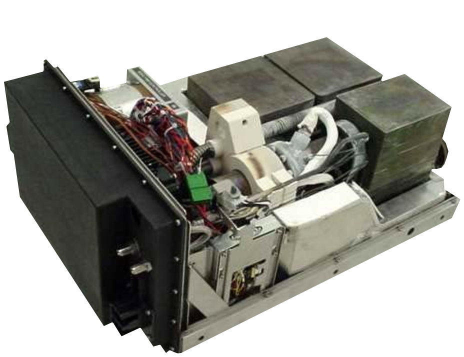
Delphi SOFC System Development Platforms

Set 00

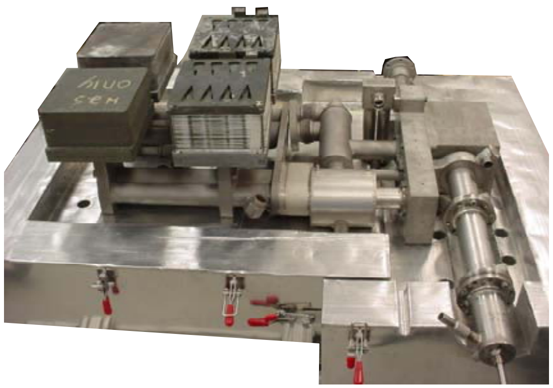
3 kW Development System

SPU 1



3 kW Auxiliary Power Unit

SPU 2



5 kW Stationary Power Unit

NG	**Q1&Q2 2007**	**Q1&Q2 2007**	**Q4 2007***
Diesel	**Q3 2007**	**Q3 2007**	**Q1 2008***

*Pending

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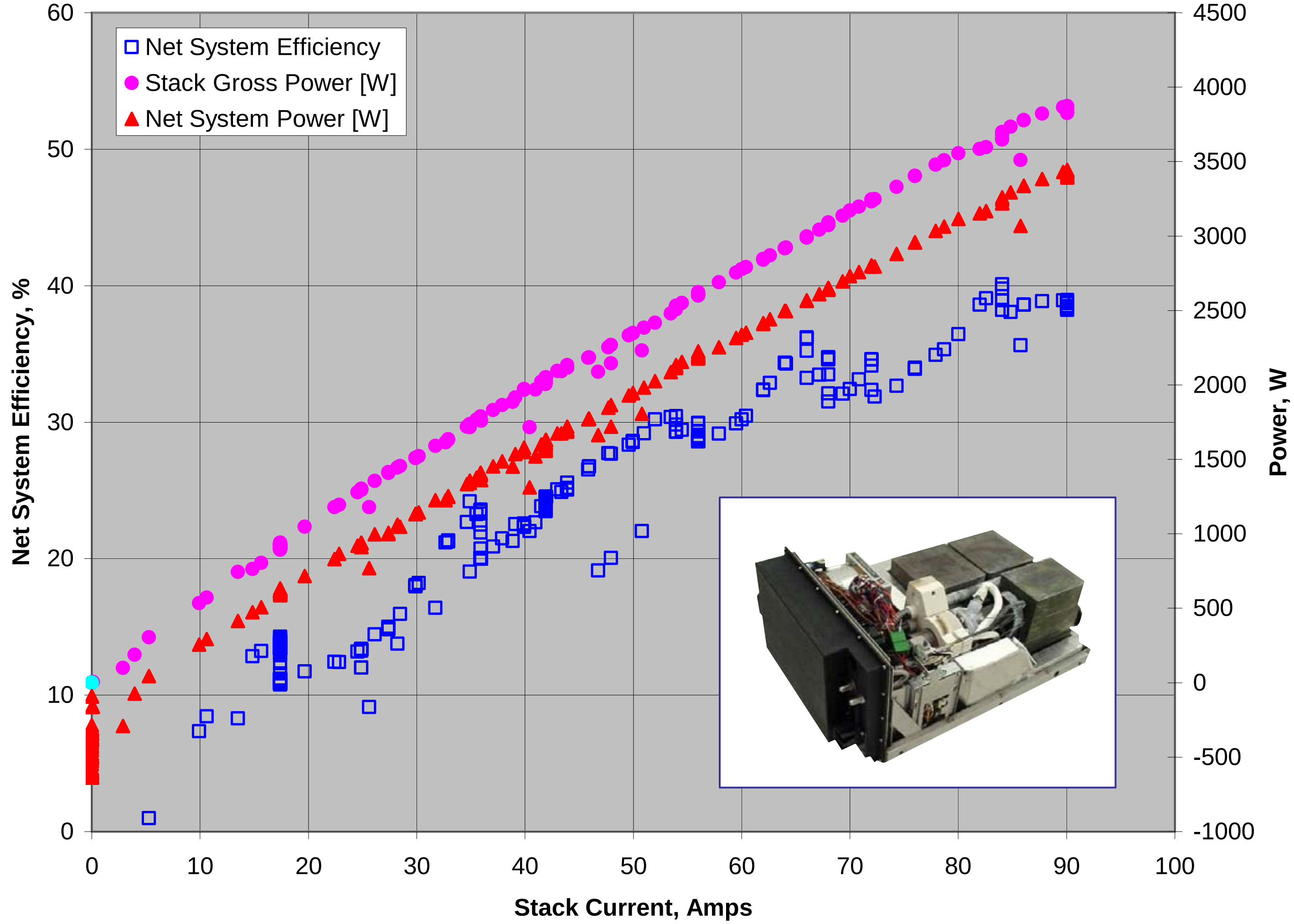
SPU 1 System Performance with Improved Stack Temperature Profile



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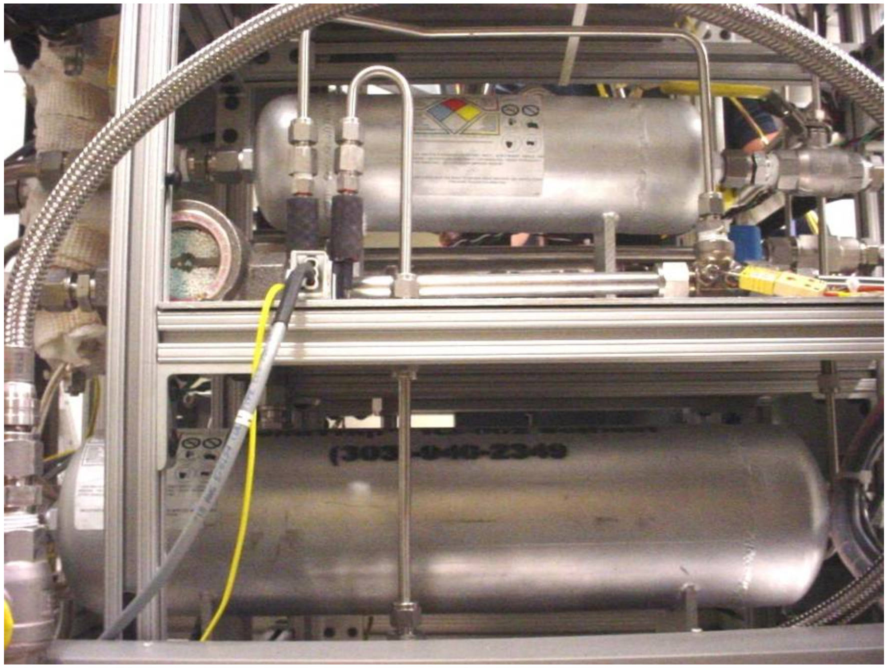
Natural Gas (NG) Desulfurization

- Prototype desulfurizers provided by supplier
- Successfully demonstrated over 1000 hrs on system test
  - Consists of a combo-sorbent bed



Sulfur species present in RGE NG at Delphi SOFC Test Facility

Suldur species	ppmv
Hydrogen sulfide	0.355
Carbonyl sulfide	0.065
Methyl Mercaptan	0.125
Ethyl Mercaptan	0.048
Dimethyl sulfide	0.047
Iso-Propyl Mercaptan	0.571
T-Butyl Mercaptan	2.163
N-Propyl Mercaptan	0.083
Butyl Mercaptan	0.000
Thiophene	0.037
Total sulfur	3.494

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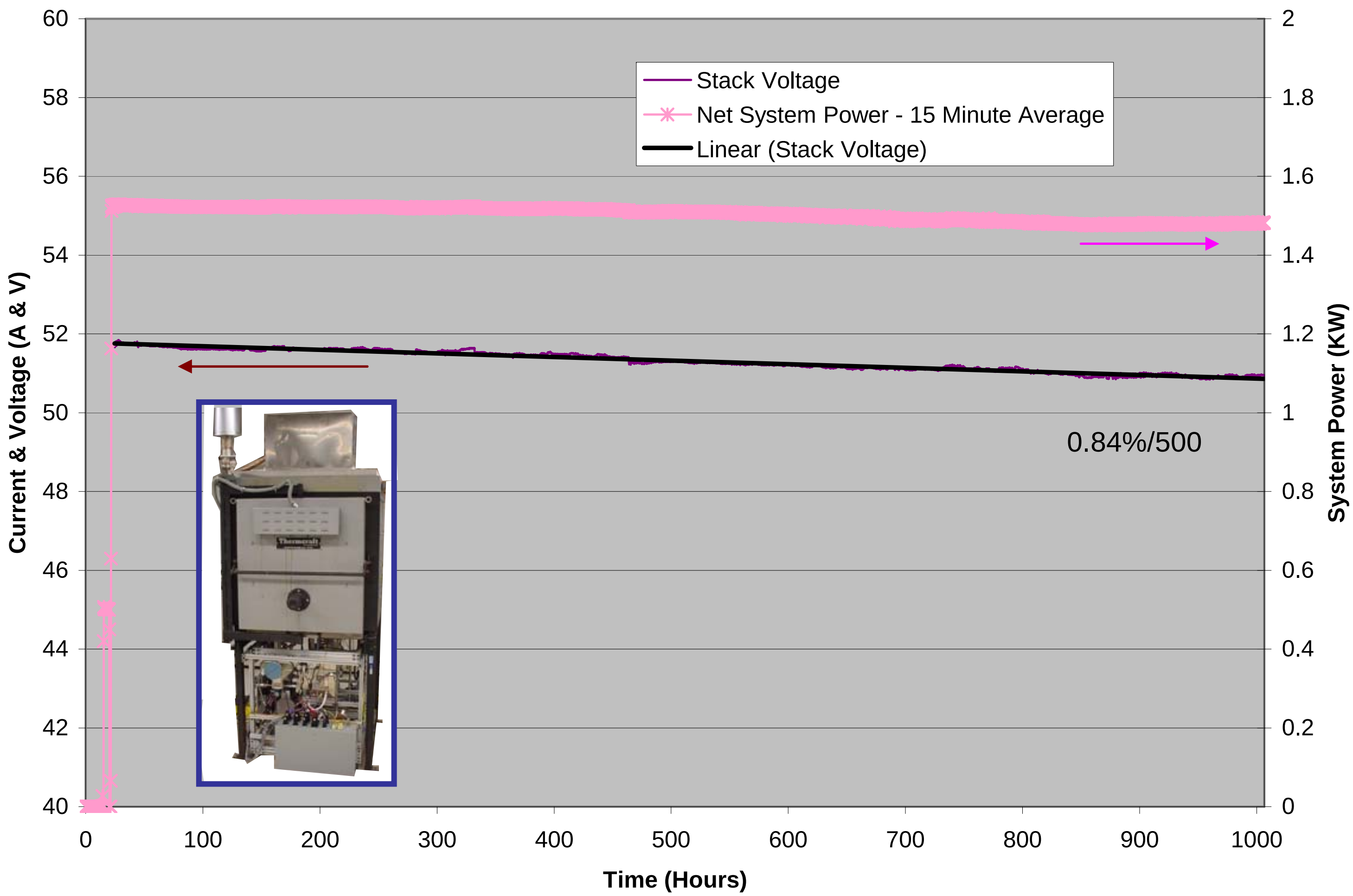
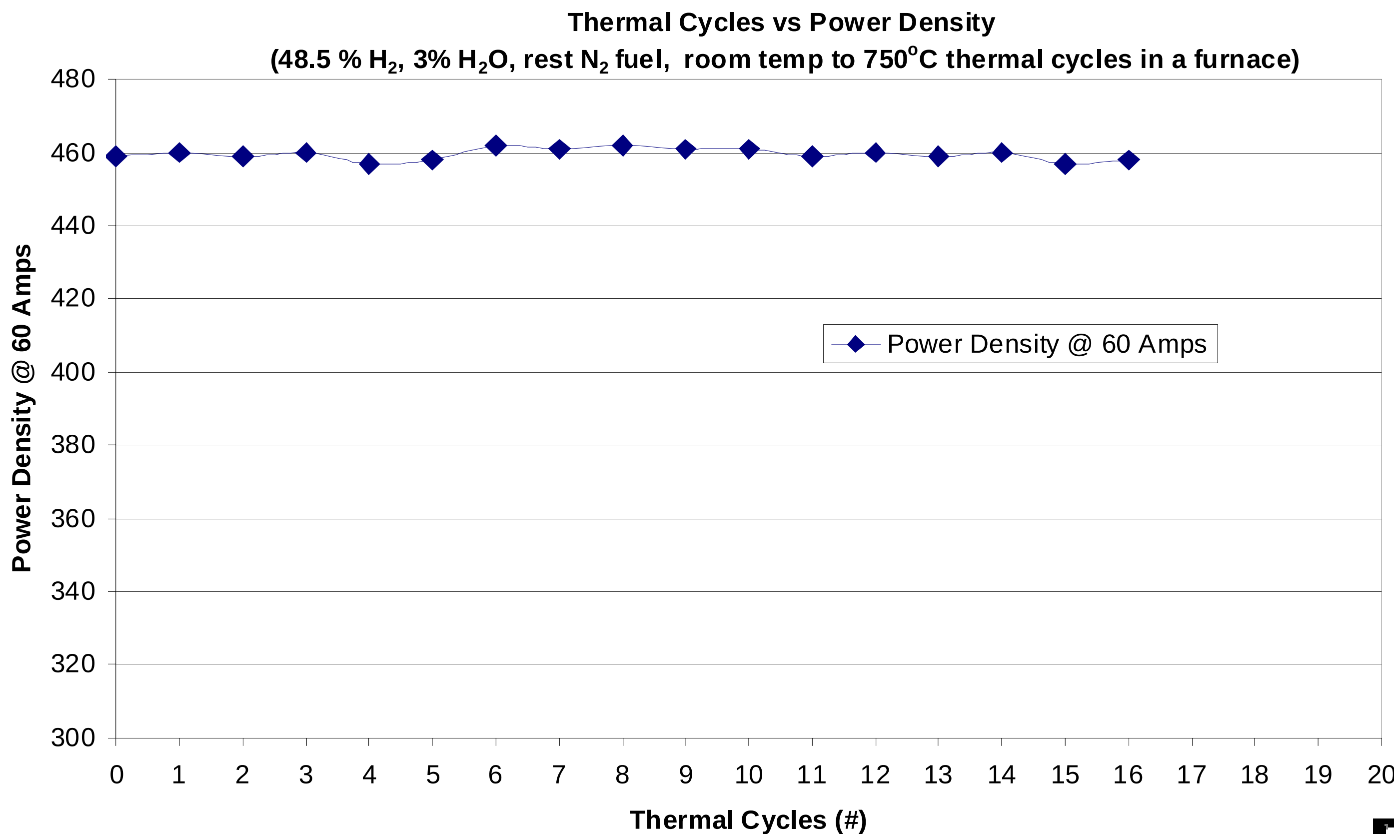
Set 00 System Performance
1000 Hour Stability on Natural Gas (CPOx)



Thermal Cycling of Stacks

- 10-cell stack thermally cycled in a furnace 16 times
  - Room temperature to operating temperature in ~90 mins
  - No loss of power -16 cycles



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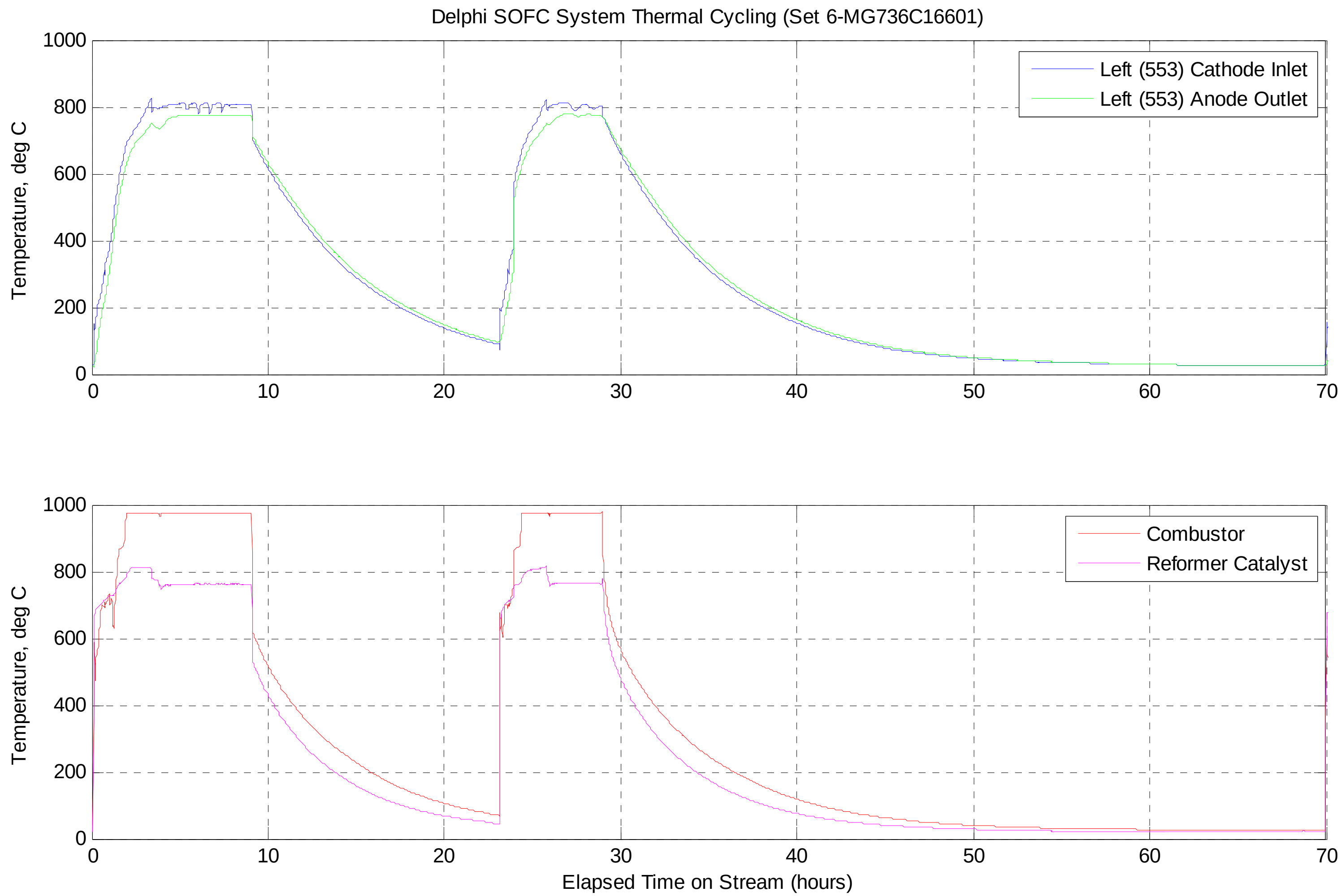
SPU 1 System Performance
Typical Thermal Cycle



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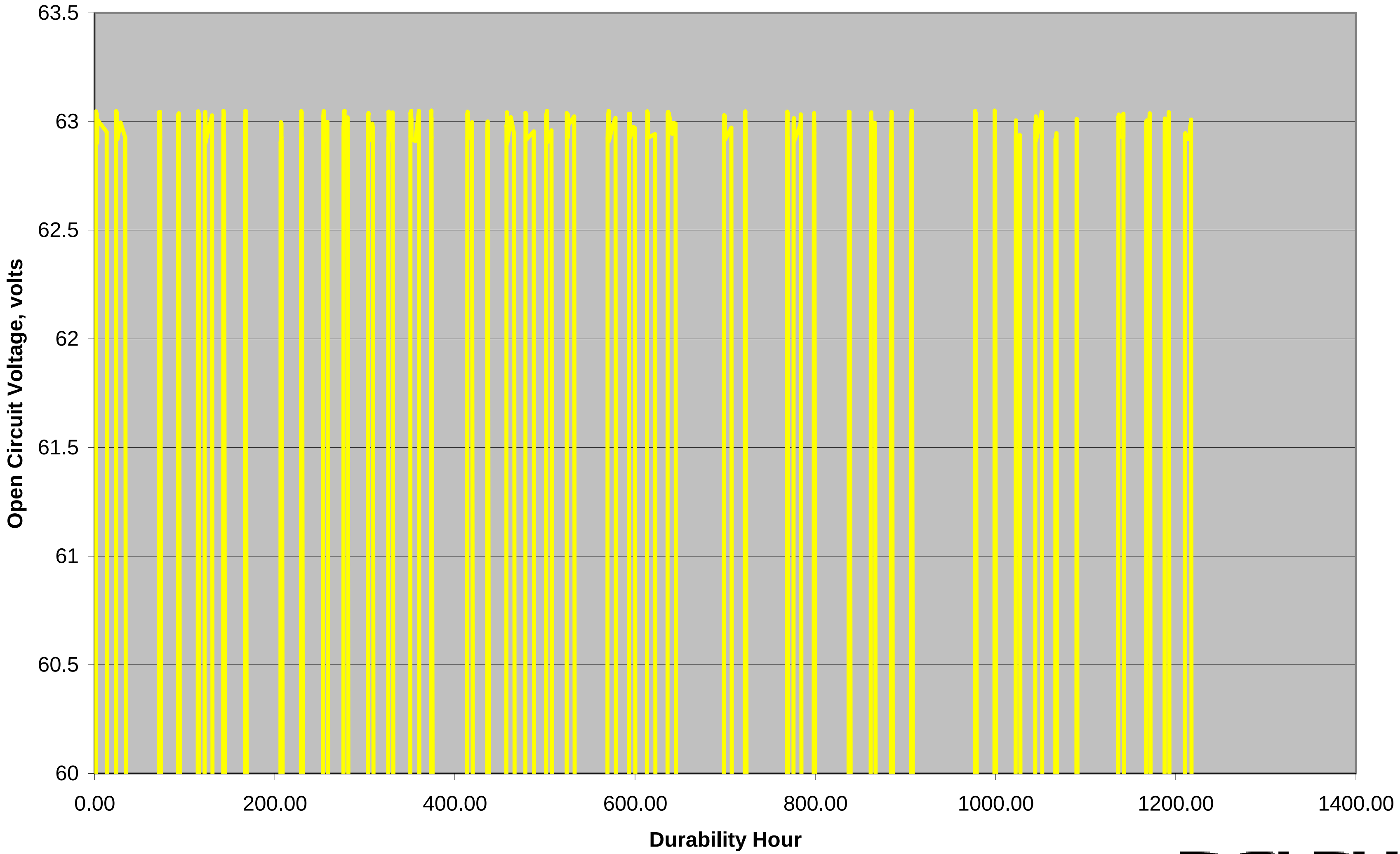
SPU 1 System Performance
45 Thermal Cycles Completed



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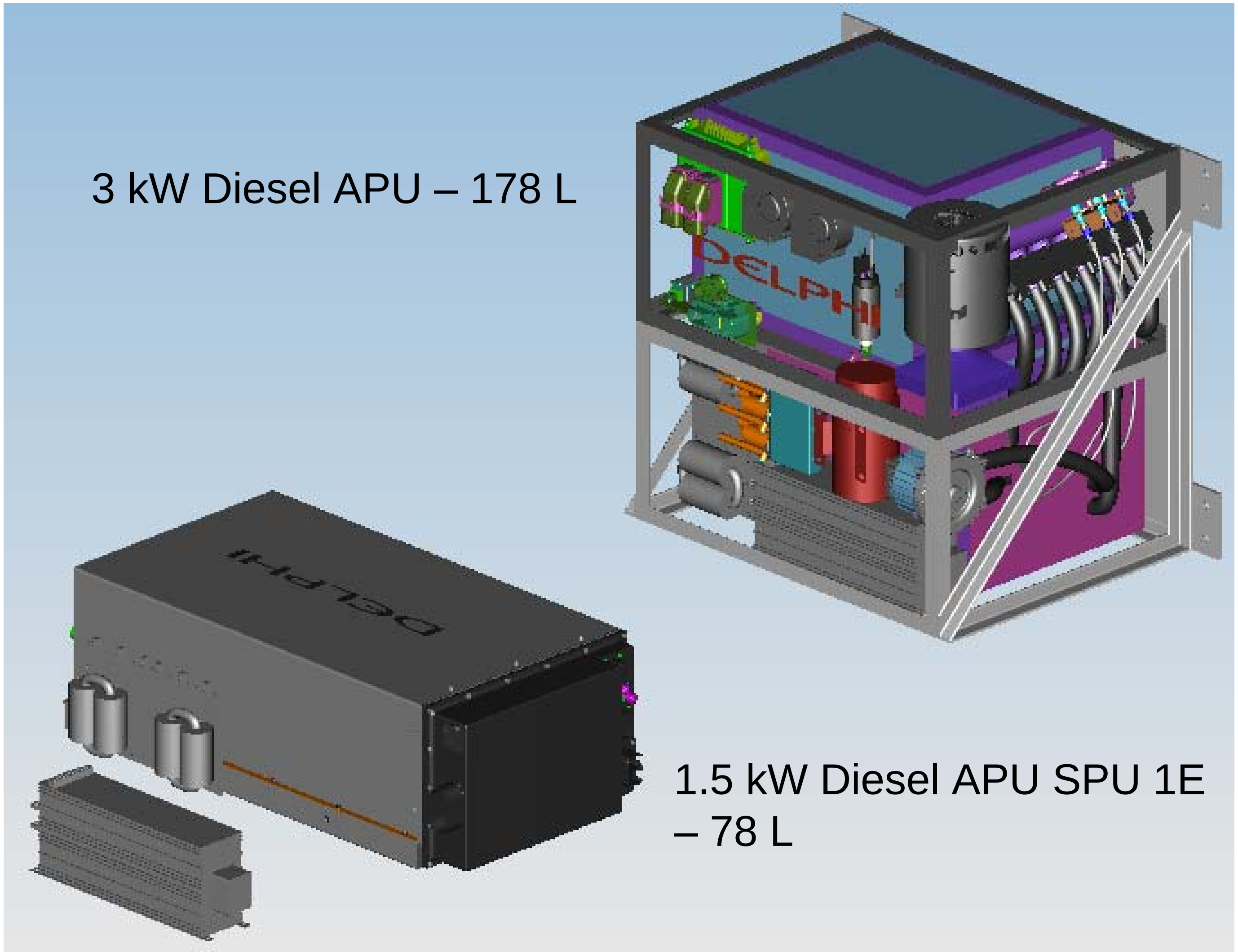
Phase II Next Steps:

Next Steps:
Design of New Diesel APU Platform



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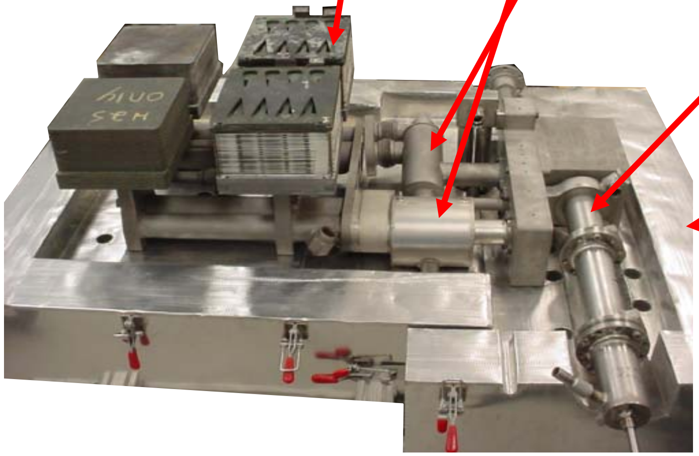
Next Steps:
Phase II Performance Testing of SPU 2 System

4x30-cell Gen 3.1 SOFC Stacks in electrical and flow series/parallel configuration

Combustor

Recycle cooler heat exchanger

Gen 4.2T Natural Gas Reformer



Insulation shell

Targets:
5 kW Net
45% Efficiency

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System Analysis and Conceptual Stack Design

Provided to Delphi by UTRC

SOFC-Gas Turbine Hybrid Power Plant

150 MW system concept reaches efficiencies >53% (HHV) w/ CO_2 capture

- System efficiency include CO_2 capture and compression to sequestration-ready pipeline conditions
- System efficiency approaches 60% without counting CO_2 capture and compression
- System based on pressurized SOFC integrated with a Twin Pack of UTC Pratt & Whitney's FT8-3 Gas Turbines
- Operate on gasified coal composition as specified by NETL
- Modify existing FT8-3 engine is more cost effective than beginning a new engine design program. Design changes can result in 15% reduction in FT8 capital cost

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SOFC with Bottoming Rankine Cycle Power Plant

1 MW demo system concept reaches efficiency >43% (HHV) w/ CO_2 capture

- System efficiency include CO_2 capture and compression to sequestration-ready pipeline conditions
- System efficiency approaches 47% without counting CO_2 capture and compression
- System based on **ambient** SOFC integrated with a bottoming Organic Rankine Cycle
- ~35 stacks in the system and ~ 300 cells per stack
- Required cell power density in the range of 0.27 -0.3 W/cm^2

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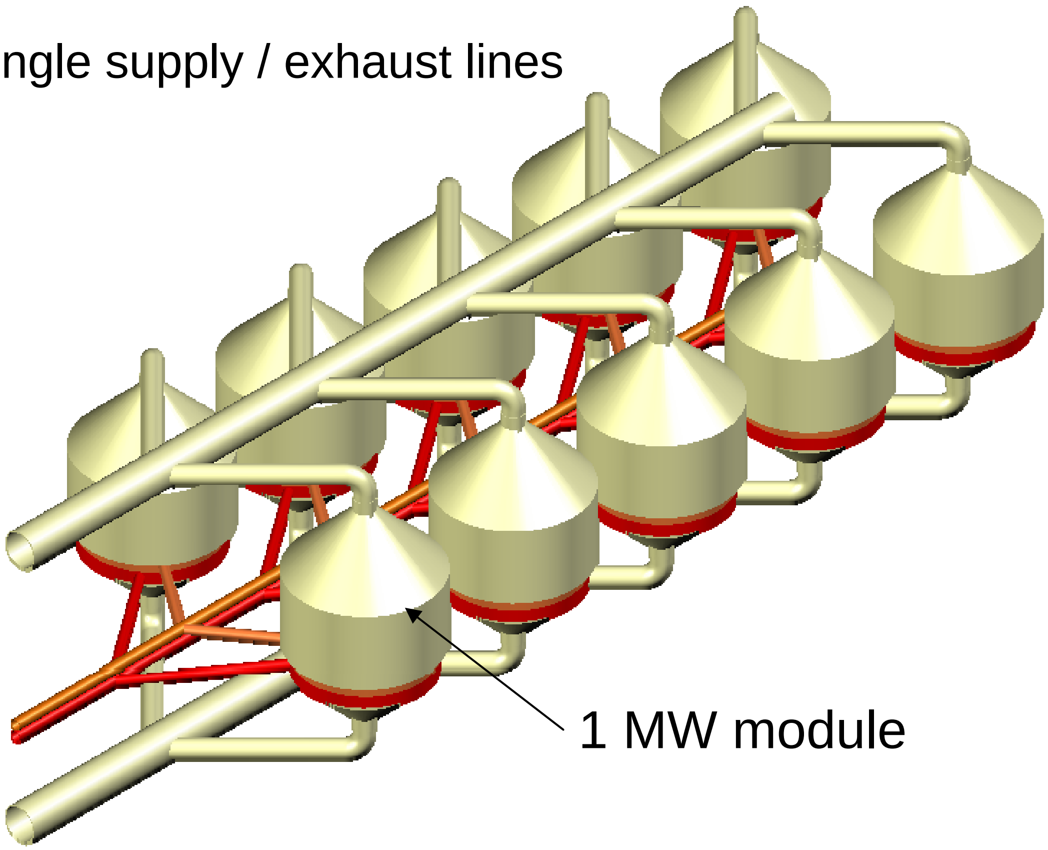
SOFC Stack Module Concept

Annular stack module design

- 10 MW module array with single supply / exhaust lines
- Module power 1MW
- Module diameter ~250 cm
- Stack power 50 kW
- Cell active area 360 cm^2
- Power density 0.45 W/cm^2
- ~280 cells per stack



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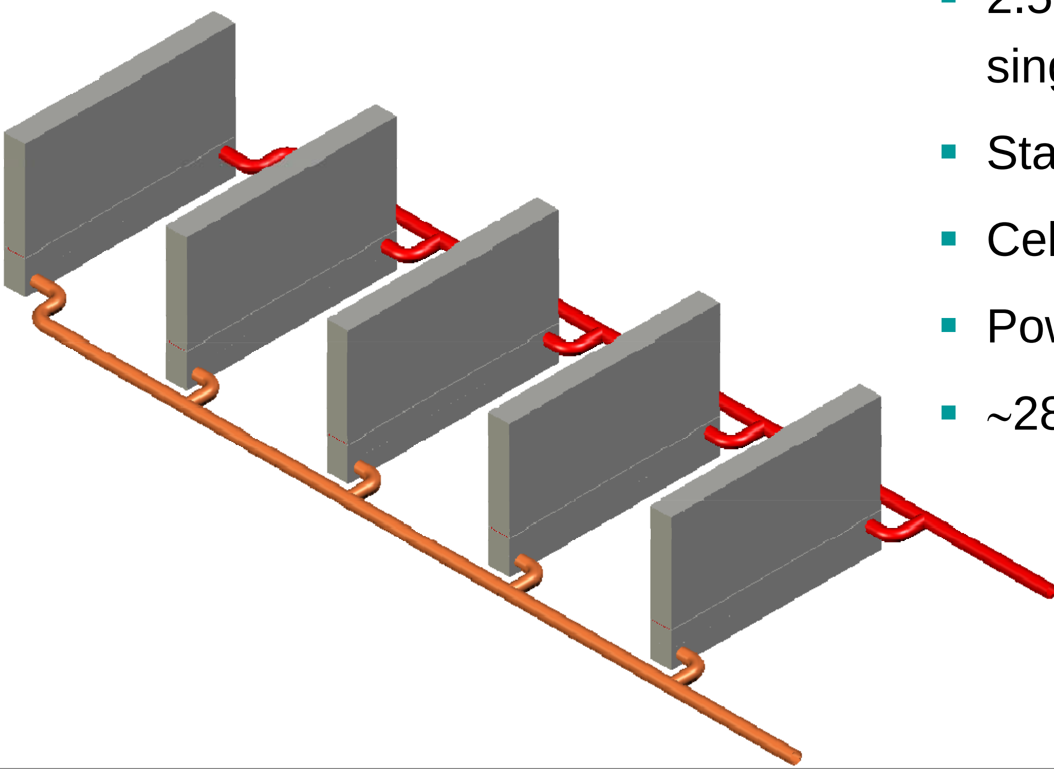
SOFC Stack Module Concept

Linear stack module design



- 2.5 MW module array with single supply / exhaust lines
- Stack power 500 kW
- Cell active area 360 cm^2
- Power density 0.45 W/cm^2
- ~2800 cells per stack

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Summary of Phase II Progress:

7/24/2007 0:00

Target Metric		DOE/SECA Ph II (CONTRACT)	Current Status	
Target Date		4Q 2008	3Q 2007	
Fuel		Nat Gas	Nat Gas	
Net Rated Power	kW	3-10	3.4	SPU 1
Fuel to Electric Efficiency (Peak)	%	40%	38%	SPU 1
Cost	$/kW	$600	$670	Projected SPU 2
Cycle Durability	cycles	50	36	Completed SPU 1
Operation Life	hrs	1500*	1000	Set 00
Degradation Rate	%/500 hrs	1.0%	0.84%	Set 00

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