Development Update on Delphi's Solid Oxide Fuel Cell System

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Pacific Grove, CA
2005 SECA Review Meeting

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Solid Oxide Fuel Cell Potential Markets

Automotive APU

Residential Power Units with Combined Heat and Power.

Heavy Duty Truck APU to eliminate long term idling or EPU as part of Electric Truck Architecture

Military uses are similar to that in mobile applications with modifications for High Sulfur fuels: JP8

Pension und Cafe S. Simon

Commercial Power Units

Market Drivers

STATIONARY SYSTEMS

Efficiency

Continuous operation/long life

Fuels: Natural gas, Coal based syngas

TRANSPORTATION SYSTEMS

Compact size and low mass

On-Off Cycling

Fast start-up time

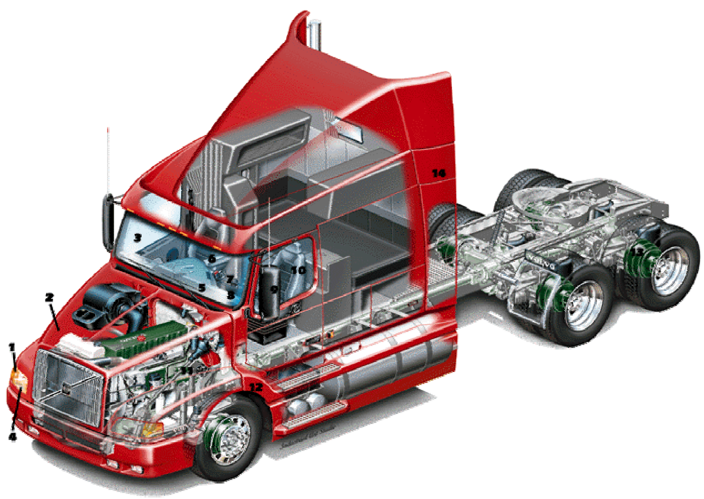
Fuels : Gasoline, Diesel, JP-8

Project Overview

- Program: Solid Oxide Fuel Cell (SOFC) for Auxiliary Power in Heavy Duty Vehicle Applications
  - Program Objective: To demonstrate, in a laboratory environment, a SOFC APU capable of operating on low sulfur diesel fuel, for the Commercial Trucking Industry
- Sponsor: U.S. DOE – Hydrogen, Fuel Cells and Infrastructure Technologies
- Project Duration: 48 months
- Leverage Delphi's technology development and investment in SOFC technologies to meet APU commercial trucking application requirements

DOE-Delphi APU Industry Collaboration

- Delphi has teamed with OEM's PACCAR Incorporated and Volvo Trucks North America (VTNA) to define system level requirements for a Fuel Cell (SOFC) based Auxiliary Power Unit (APU) for the commercial trucking industry. Delphi has enlisted Electricore to provide administrative assistance.



Volvo Trucks North America (VTNA), Greensboro, NC

PACCAR, Mt. Vernon, WA

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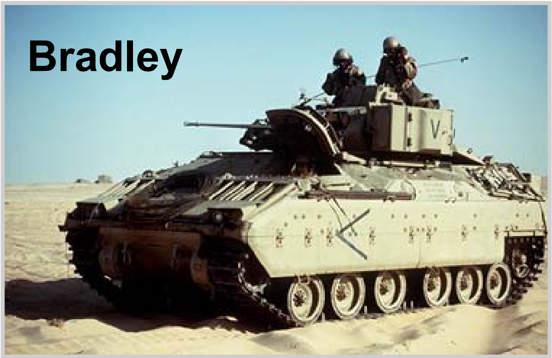
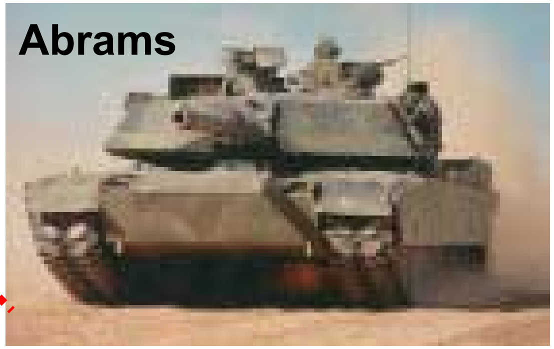
Project Overview

- Program: Fuel Cell Based Ground Vehicle APU's
- Sponsor: TACOM
- Technology program to support development of SOFC APU's for military vehicle usage in "Silent Watch" mode
- Focus of the program is development and laboratory demonstration of a reformer operation on JP-8 world-wide logistic fuel
- TACOM/TARDEC's primary interest is in three Military Ground Vehicles:
  - **Bradley**
  - **Stryker**
  - **Abrams**





Delphi SOFC APU Development Progression

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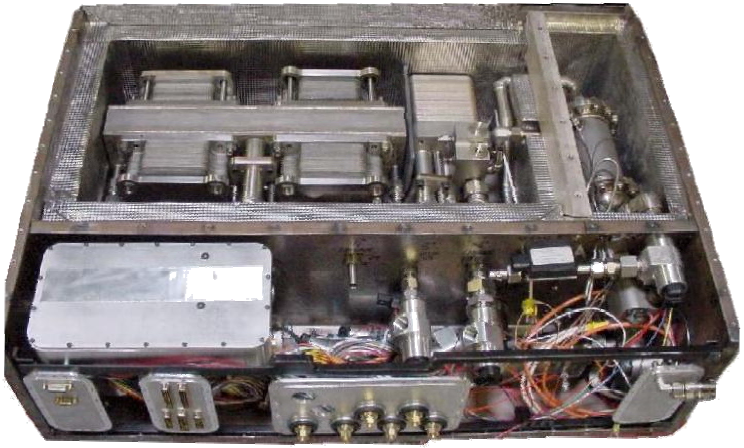
- APU development progression from the Proof Of Concept unit to a Generation 3 APU design that will be the building block for the transportation markets

Generation 1 SOFC APU	Generation 2 SOFC APU	Generation 3 SOFC APU
	 	
155 Liters *204 kg*	*70 Liters* *70 kg*	*63 Liters* *70 kg*
2000	2002-2004	2005

- Introduction
- **Stack Development**
- Fuel Reformer Development
- Balance of Plant Development
- Electronics and Controls Development
- System Integration and Testing
- Summary and Conclusion

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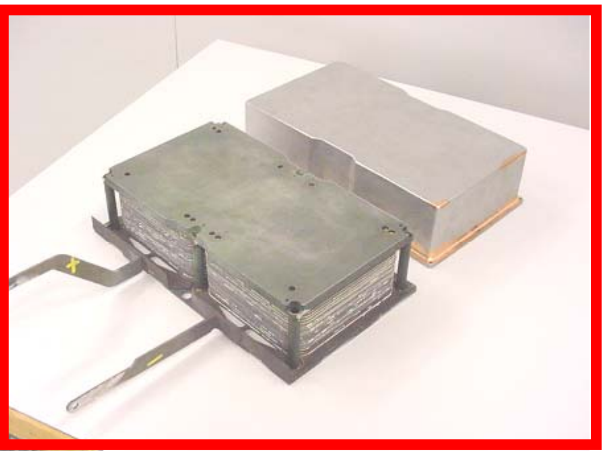
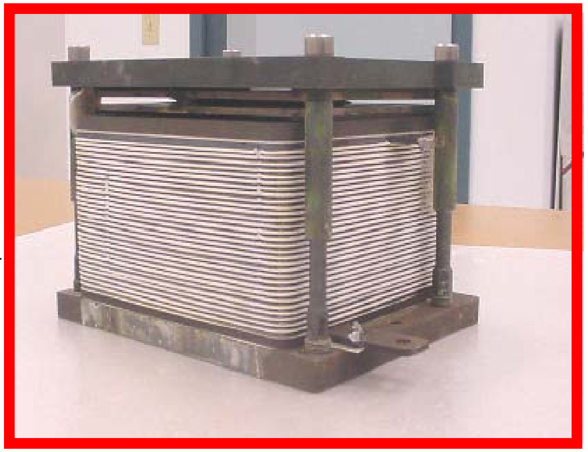
Stack Introduction

- Delphi is developing SOFC stack technology for transportation and stationary markets
- Delphi is working with Battelle- Pacific Northwest National Laboratory (PNNL) for the development of the SOFC technology under DOE's SECA program
- The development history from Delphi's Generation 2 stacks to the current Generation 3.1 stack sub-system is shown below



Generation 2 (2x15-cell), >20 Kg, 6 L
2002 - 2003

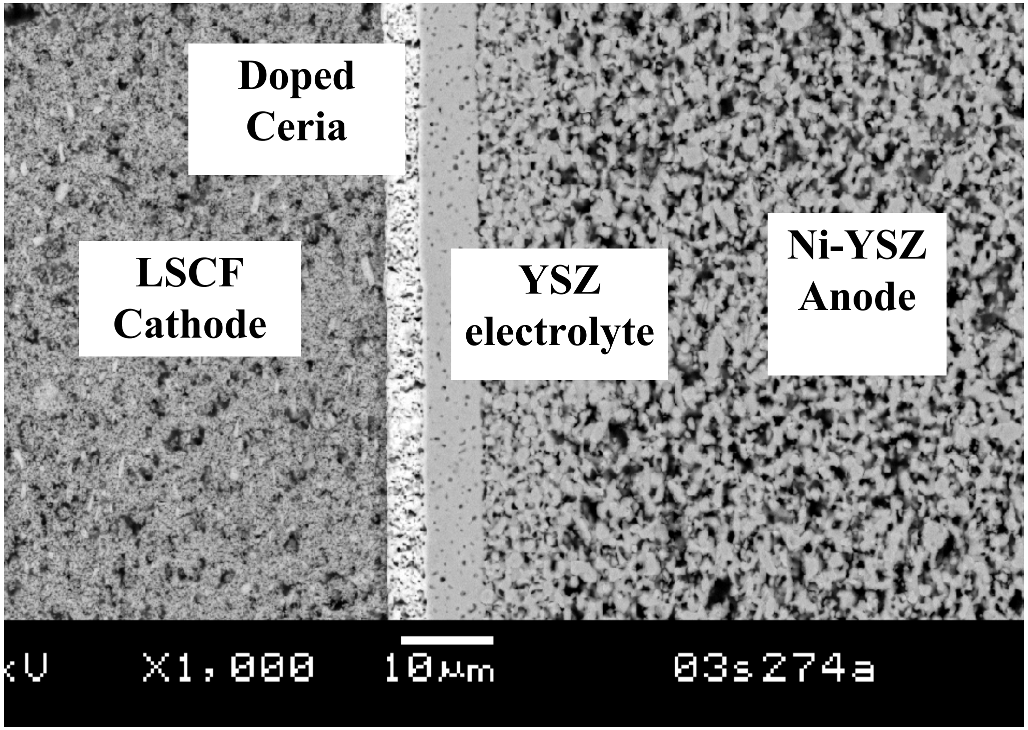


Generation 3 (30-cell), 13 Kg, 3.5 L
2004

Generation 3.1 (30 cell), 9 Kg, 2.5 L
2005

Generation 3.1 Stack Cell Characteristics

- Delphi is developing and fabricating its own SOFC cell with the characteristic electrode-electrolyte layers shown below
- Cell fabrication includes tape-casting, screen-printing and sintering processes
- Current focus is on process development and capital investment for increasing the volumes of cell manufacturing to pilot line levels



Generation 3.1 Stack Cell Characteristics

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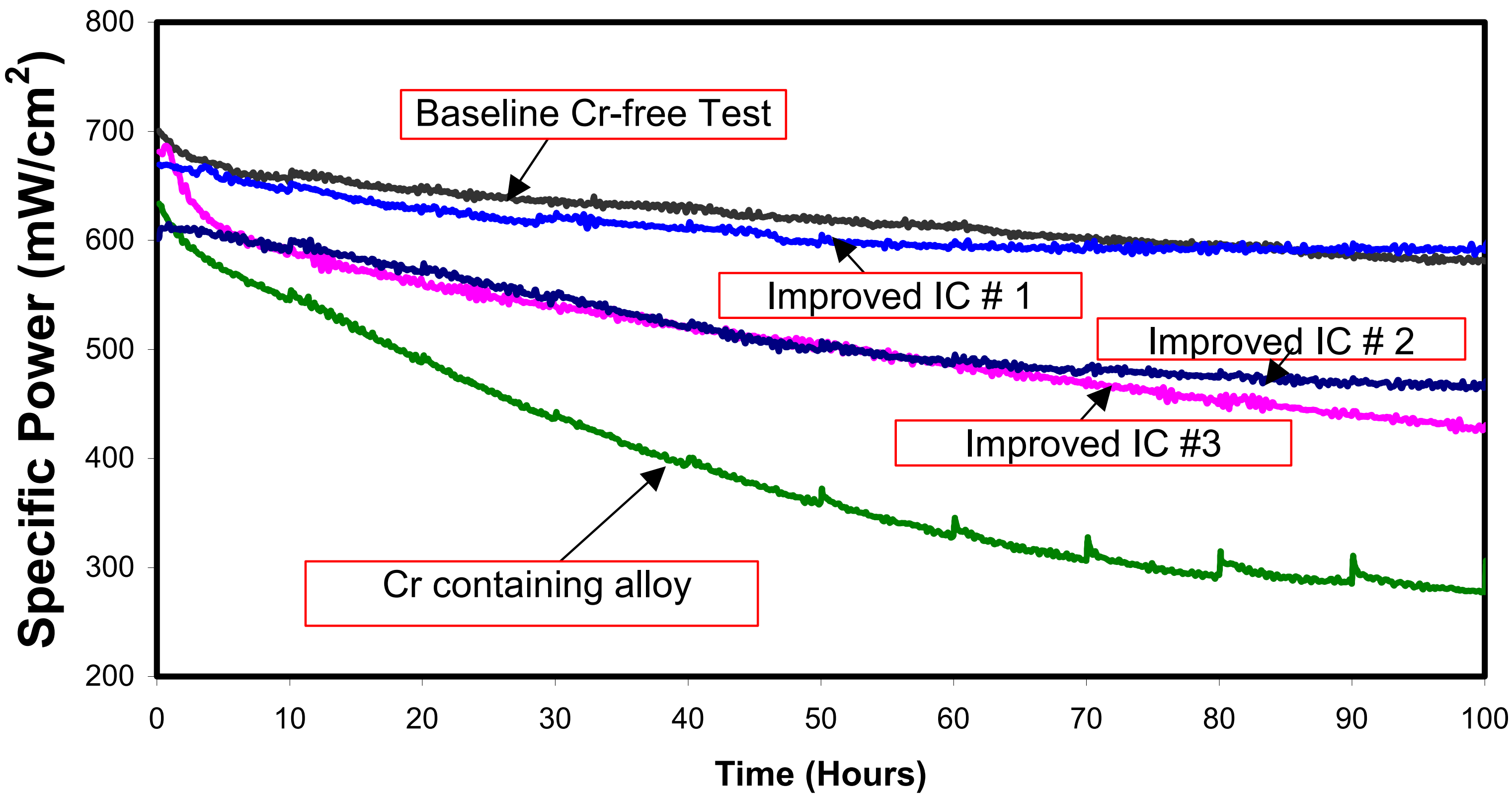
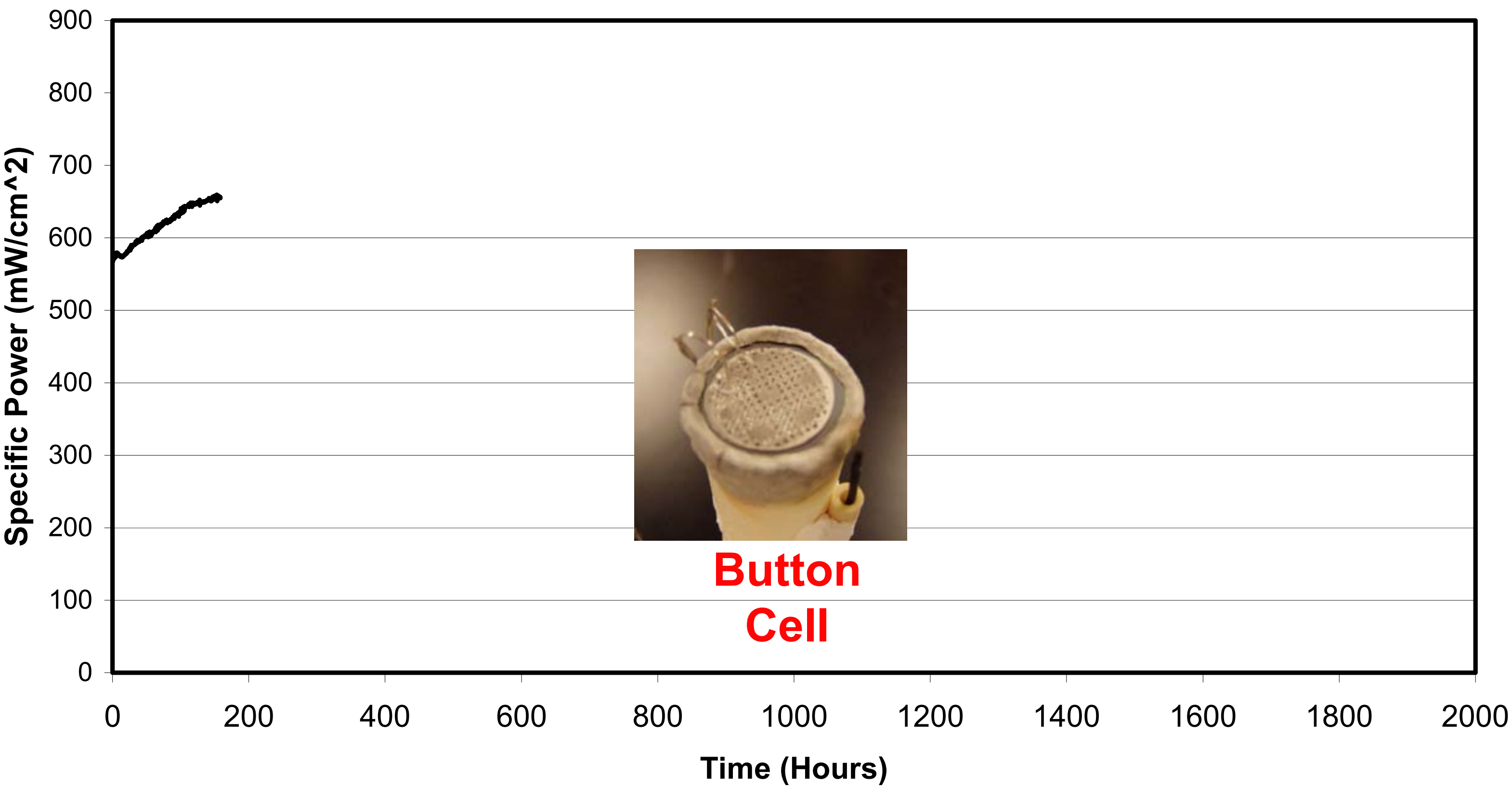
- Button cell testing demonstrated the effect of Cr (in vapor phase) in degradation of cathode
- Improved interconnects are being developed to overcome this degradation in the stack



Generation 3.1 Stack Cell Characteristics

- Button cell testing of current cell configuration demonstrated no degradation for greater than 2000 hours (48.5% H_2, 3% H_2O, rest N_2, 750°C)



Generation 3.1 Stack Key Design Features

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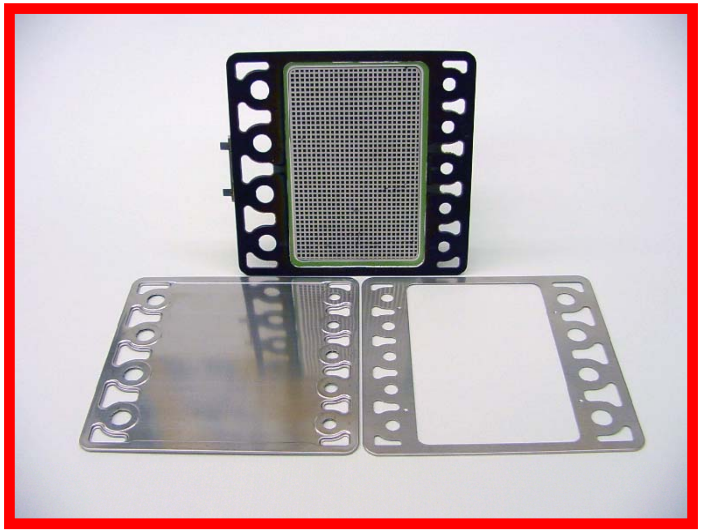
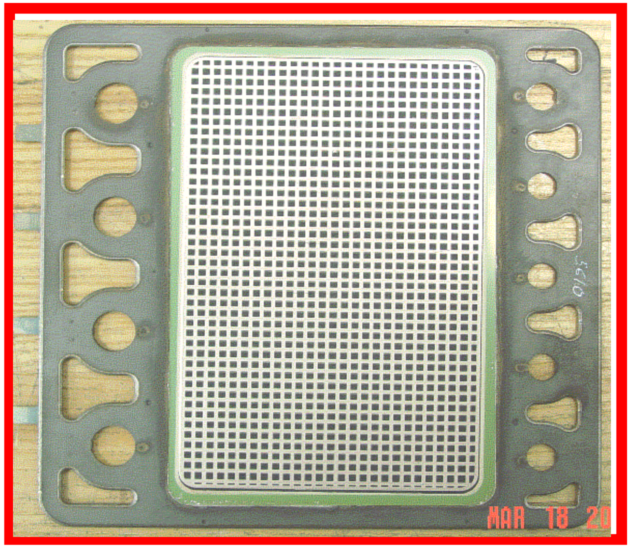
- The new Generation 3.1 stack has evolutionary improvements over Delphi's Generation 3.0 stack design
- Key Generation 3.1 stack characteristics
  - Co-flow cassette configuration
  - Integrated manifold
  - Compact load frame
  - Improved interconnect
  - Low mass
  - Low volume
  - Improved manufacturability of stack sub-system





Generation 3.1 Stack
30-Cell Stack

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

- 30-cell stacks of Generation 3.1 design have been successfully fabricated and tested
- 30-cell modules are the building blocks for Delphi's power systems
- Currently being tested in the system

Generation 3.1 Stack
30-Cell Stack Data

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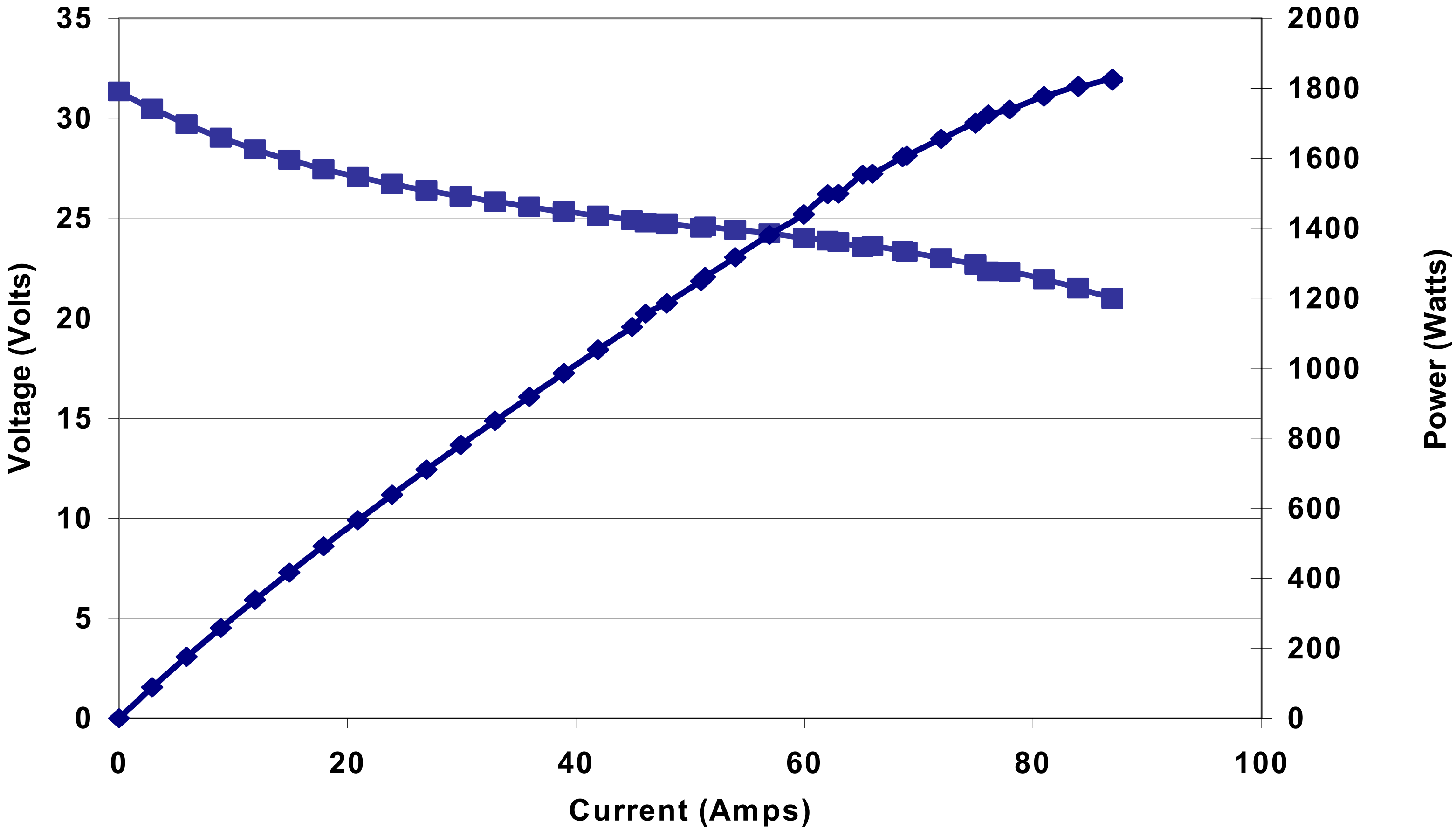
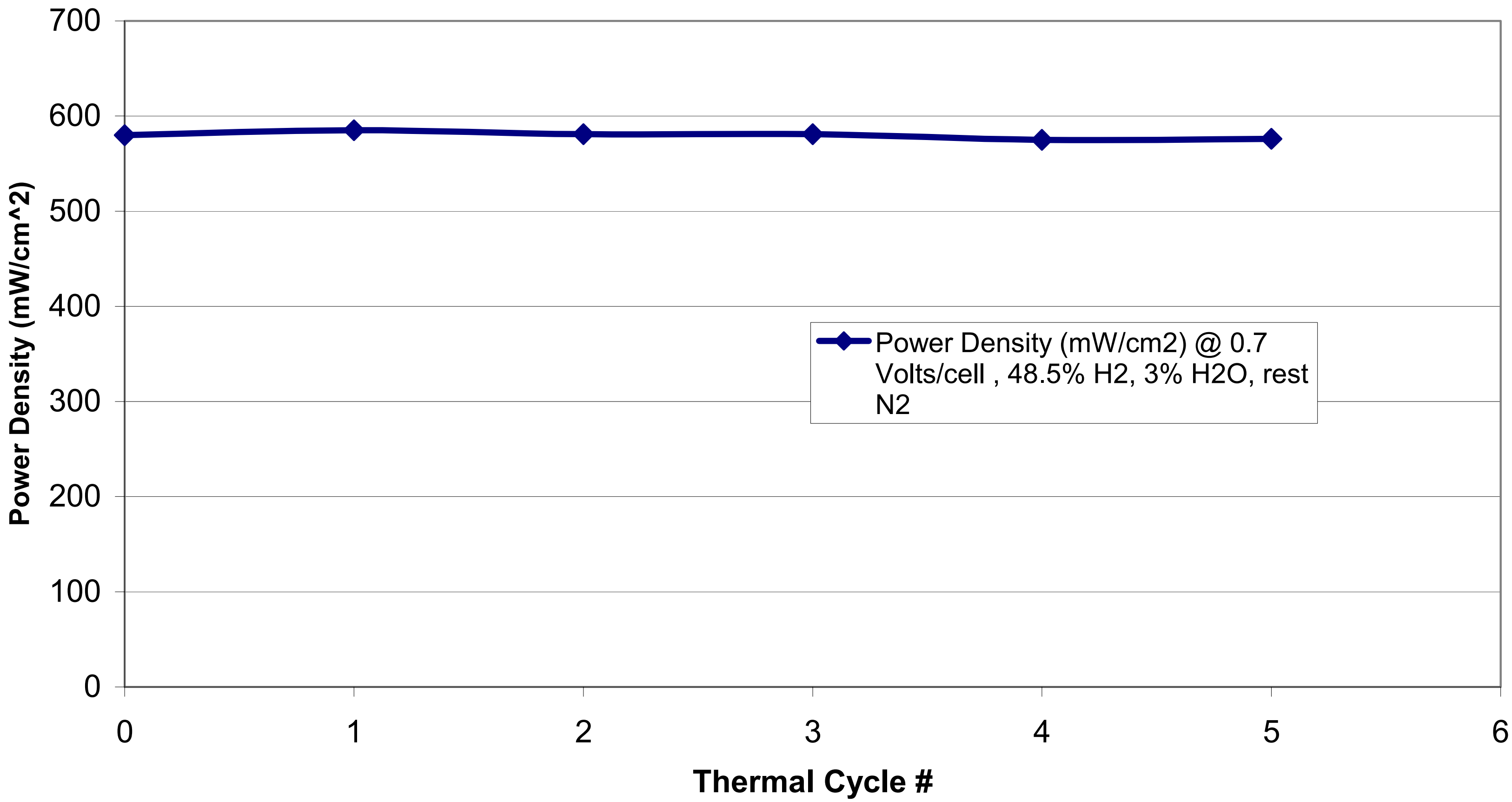
- Power
  - Data below shows a 30-cell Generation 3.1 stack producing **1821 Watts at 21 Volts** (0.7 Volts/cell) with 48.5% H_2, 3% H_2O, rest N_2 simulated reformate (power density of 578 mW/cm^2, 42% fuel utilization)



Generation 3.1 Stack Thermal Cycling

- Thermal Cycling
  - Data below shows a 10-cell Gen 3.1 stack showing no degradation in power after 5 thermal cycles
    - 90 minute heat-up in a furnace (limited by fastest possible heat-up rate of the furnace)



Generation 3.1 Stack Continuous Durability

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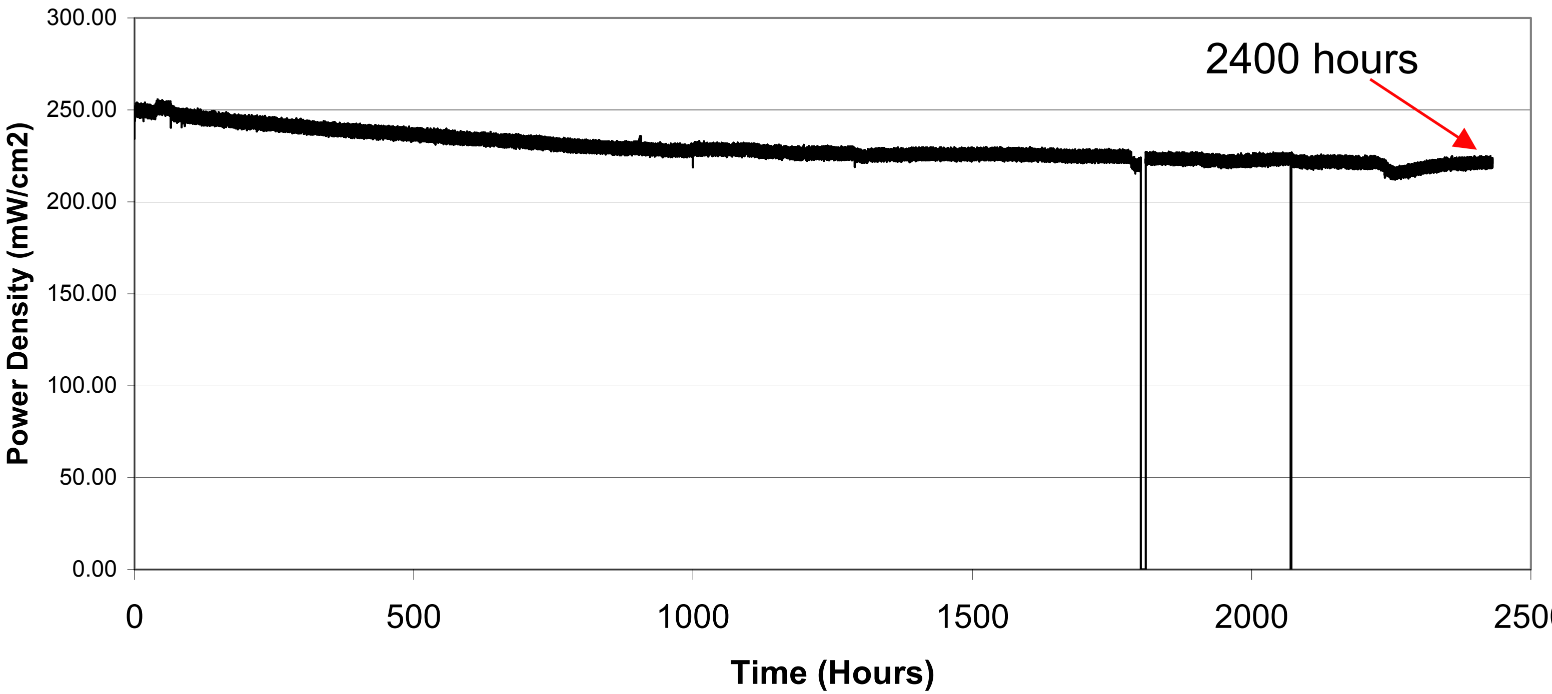
- Continuous Durability
  - Data below shows a 5-cell stack showing <10% degradation in **2400 hours** (constant current of 32 Amperes) – test stopped intentionally due to facilities shutdown
    - Minimal degradation in the last 1000 hours (~1%)



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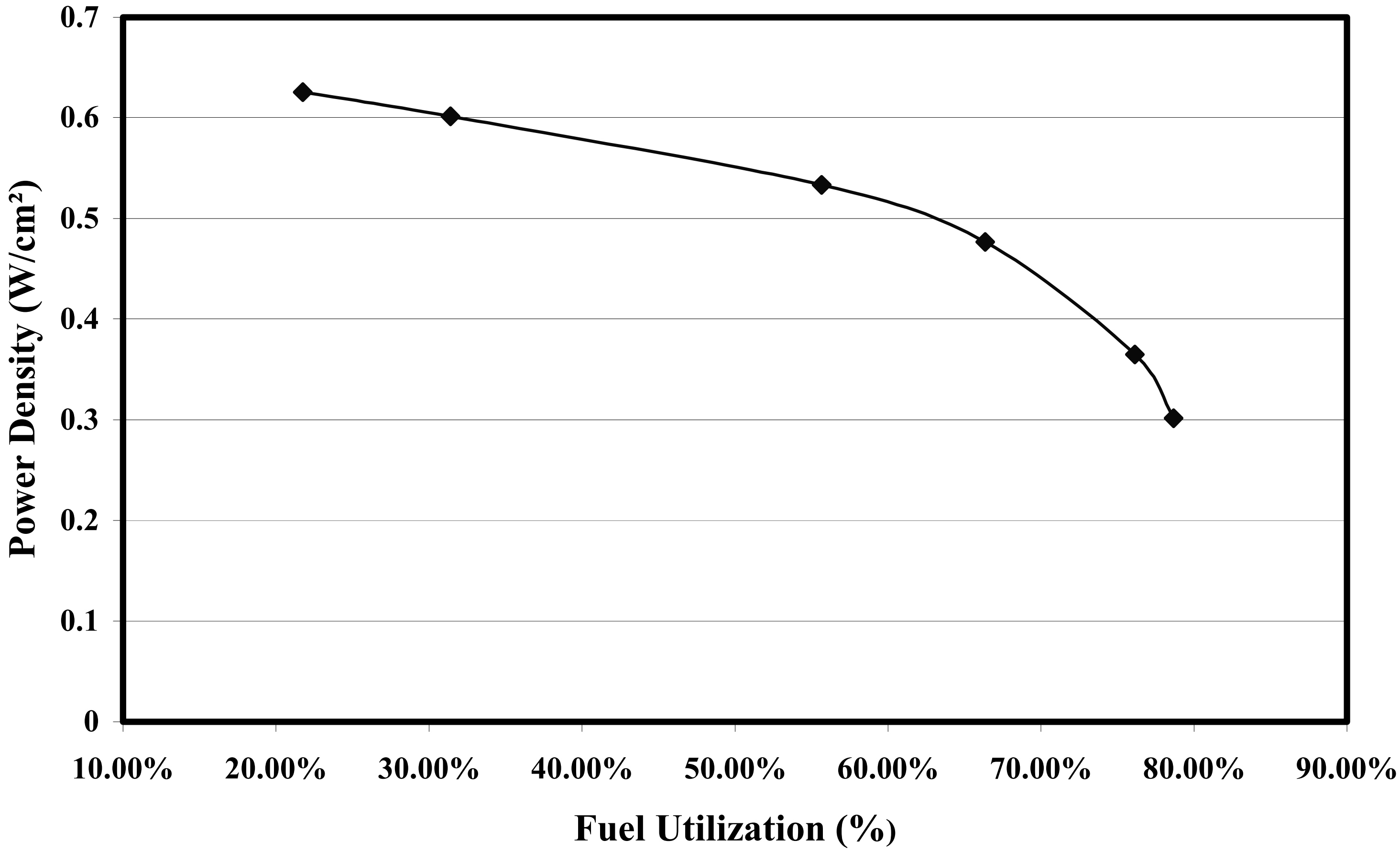
- Fuel Utilization
  - Data below shows a utilization curve of a Generation 3 single cell on 48.5% H_2, 3% H_2O, and balance N_2



Stack Summary

- Key progress has been made in stack technology to meet SECA and eventually production targets

Stack Metrics	Performance Demonstrated (March 05)
Power*	1800 Watts (580 mW/cm^2)
Mass (30-cell stack)	9 Kg (including load frame & base manifold)
Volume (30-cell stack)	2.5 liters (including load frame & base manifold)
Continuous Durability	> 2400 hours
Thermal Cycles	> 5 cycles (furnace)
Start-up time	75 minutes (system)

*, 48.5% H2, 3% H2O, rest N2 @ 0.7 V/cell, @ 42% FU

Outline

- Introduction
- Stack Development
- **Fuel Reformer Development**
- Balance of Plant Development
- Electronics and Controls Development
- System Integration and Testing
- Summary and Conclusion

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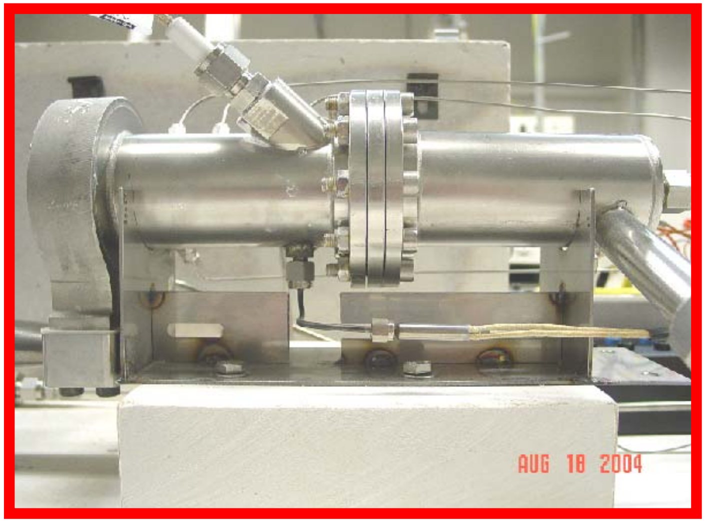
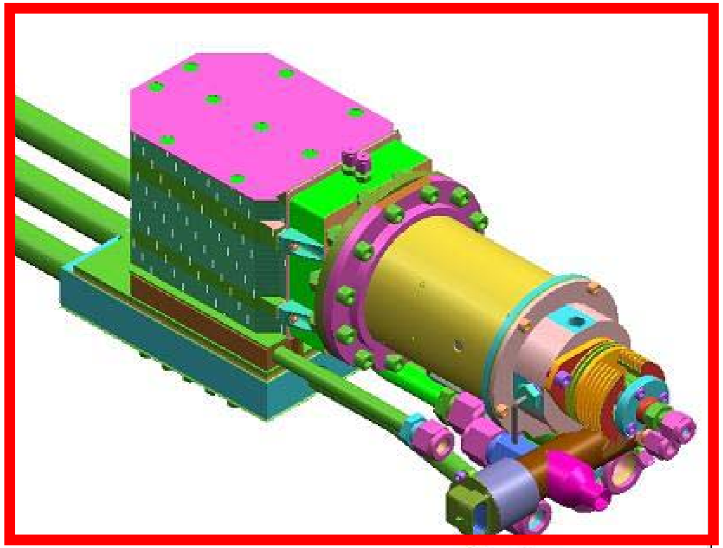
Fuel Reformer Development

- 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
    - » No recycle
  - **Endothermic Reformer**
    - » High efficiency
    - » Use of water for endothermic reaction
    - » Efficient thermal management
    - » Recycle capable





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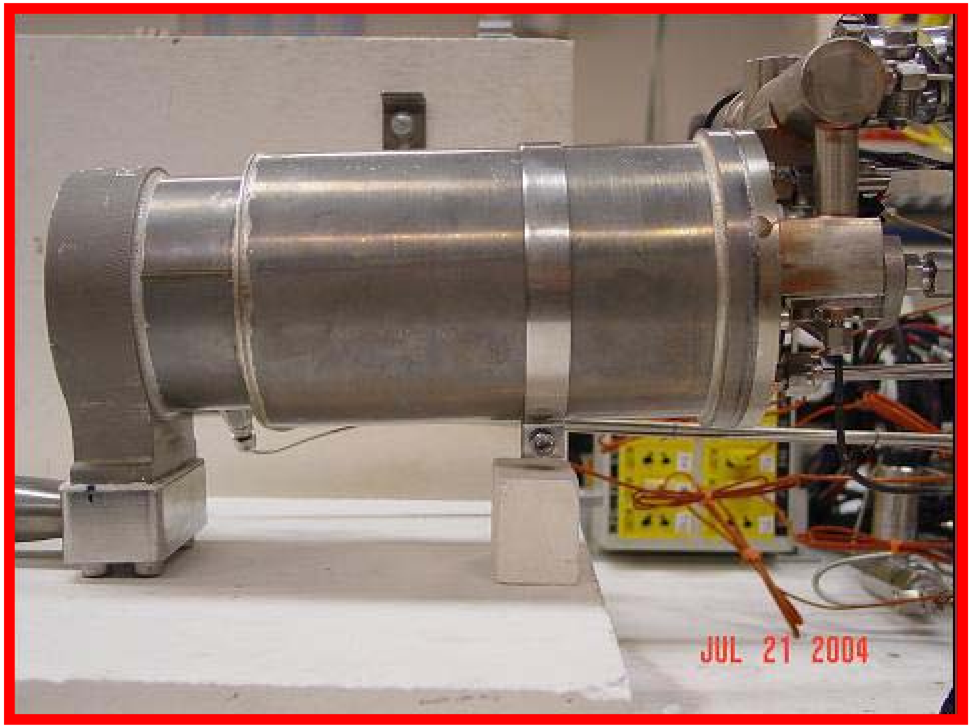
Gasoline CPOx Reformer Development Status

- Reformer Efficiency
  - No short term issues (>78% efficiency)
- Reformate Quality
  - Meeting requirements
- Carbon Avoidance
  - Several refinements in design and controls
- Durability
  - Demonstrated to 100 hrs
- Start Time
  - <3 min start demonstrated



Gasoline CPOx Reformer Assembly

Natural Gas CPOx Reformer Development Status

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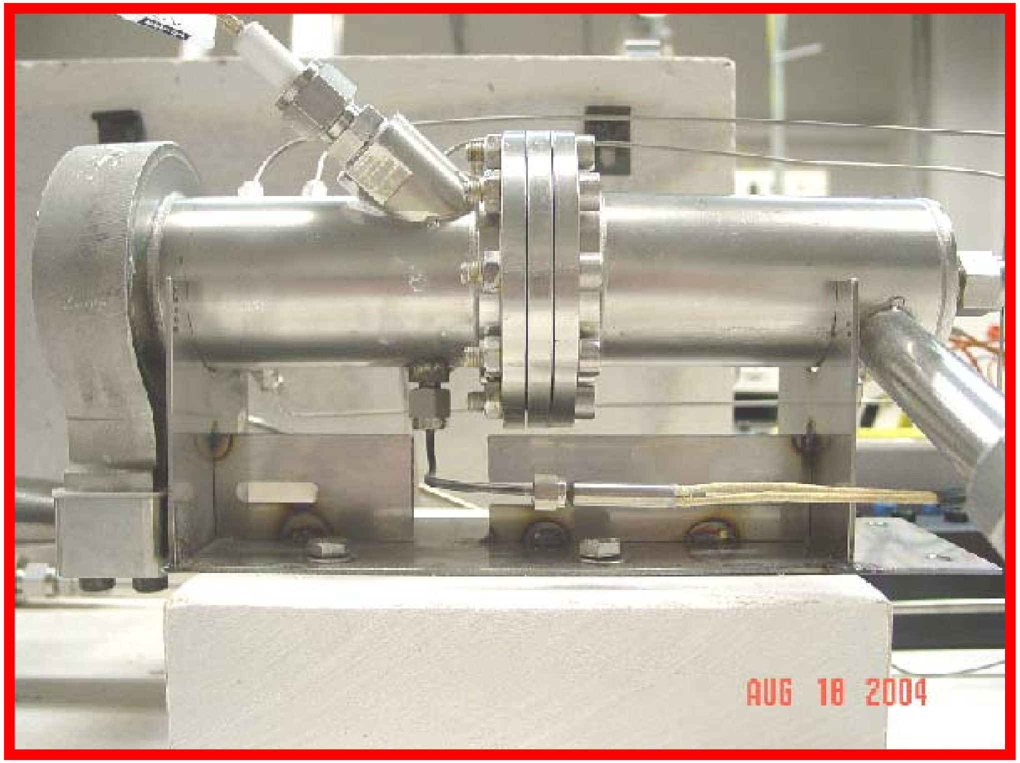
- Reformer Efficiency
  - POx mode > 84%
- Reformate Quality
  - Meeting requirements
- Carbon Avoidance
  - under study
- Durability
  - Demonstrated to 310 hrs
- Start Time
  - < 3 min start demonstrated



Natural Gas CPOx Reformer Assembly

Natural Gas CPOx
Composition over Turndown on Methane

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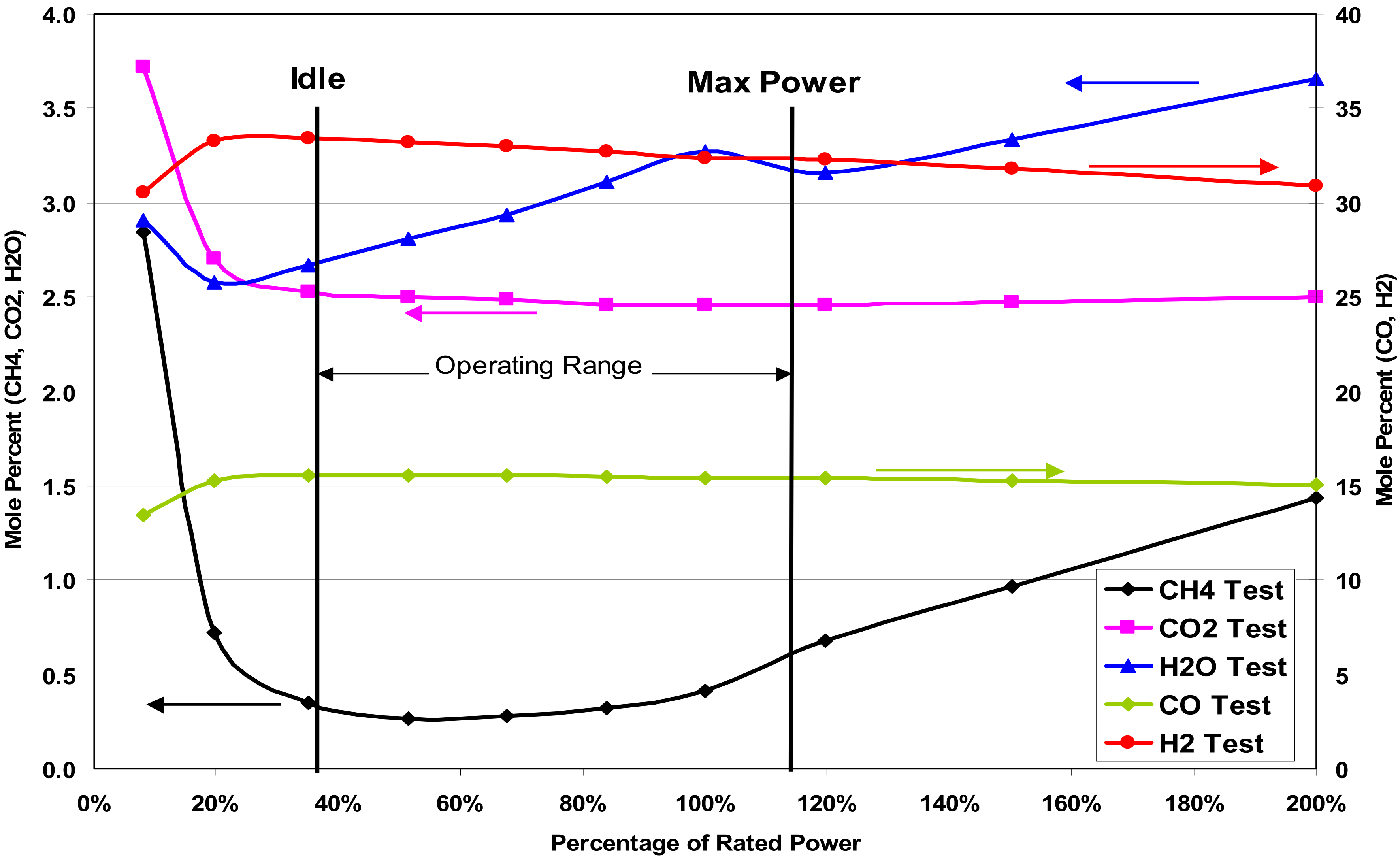

Natural Gas CPOx Reformer Durability on Methane

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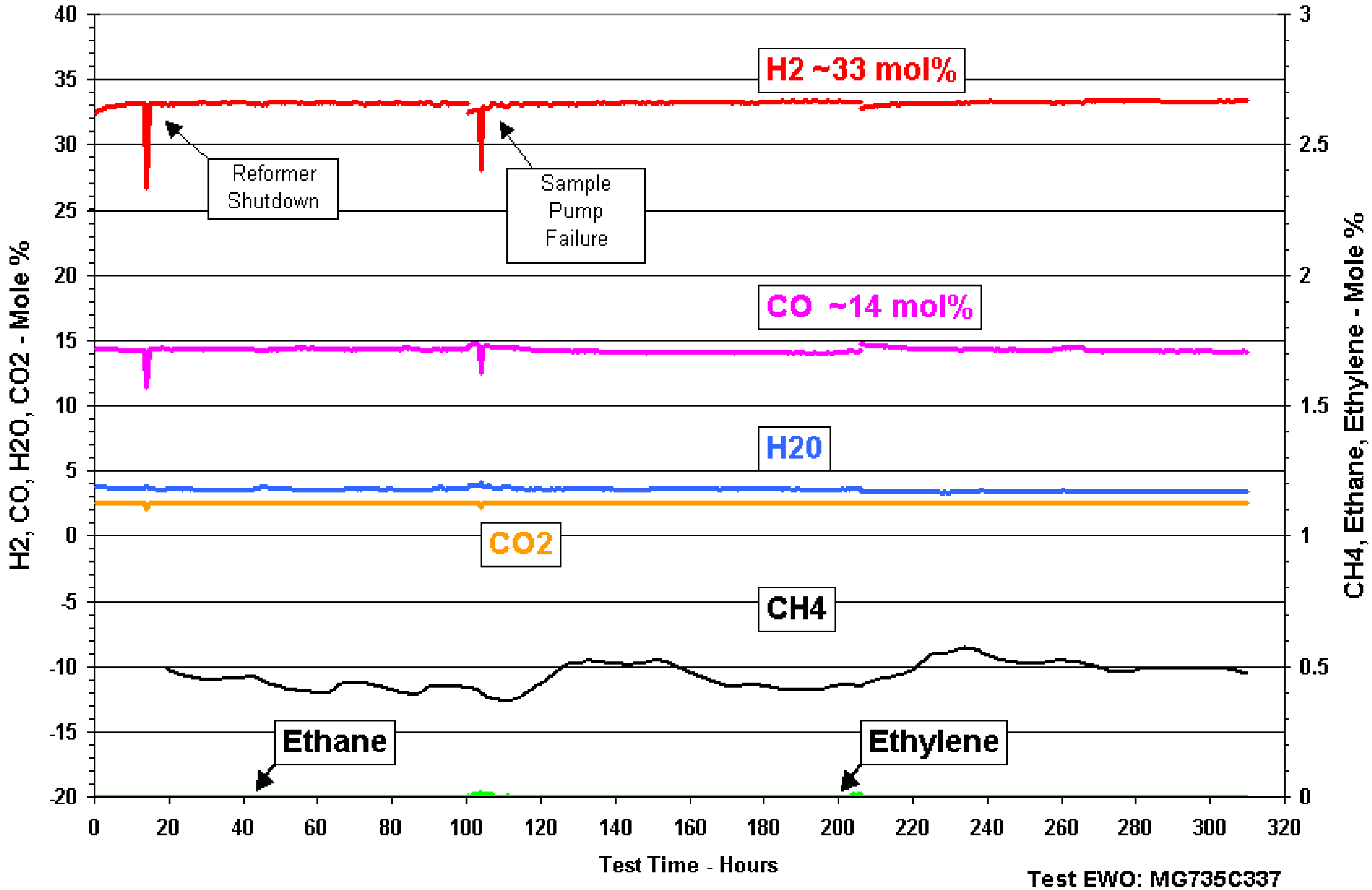
- Durability test on reformer showing encouraging results
  - 300 hours test data shown below



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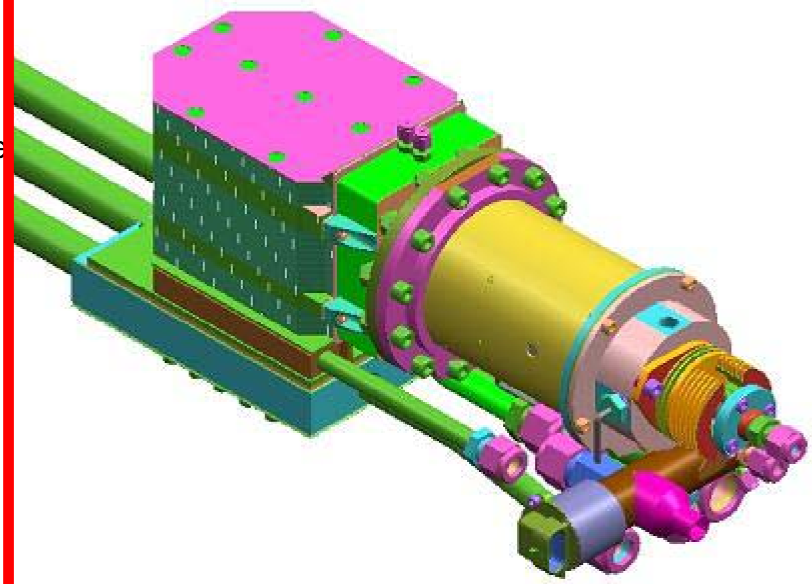
Endothermic Reformer Development Status

- Gains in reformer efficiency over CPOx achieved
  - Gross Reforming efficiency > 120 %
    (accounting for LHV of liquid fuel only in the input in an anode recycle mechanism for endothermic reforming)
- Consistent reformate quality demonstrated
  - Methane less than 1%
  - Higher hydrocarbons less than 0.1%
- Improved thermal management features incorporated
  - Lower mass design
  - New combustor design
  - Reduced package size



Endothermic Planar Reformer

CPOx / Endothermic Reforming Test Results - Summary

	Units	NG CPOx Reformer	NG Endothermic Reactor Single Planar	Gasoline CPOx Reformer	Gasoline Endothermic Reformer
Fuel	-	Methane	Methane	CARBPh2 Gasoline	CARBPh2 Gasoline
H_2	mol %	32.7	33.0	21.0	29.9
CO	mol %	15.5	17.3	22.2	27.2
CH_4	mol %	0.32	0.59	0.58	0.53
HC's > C_2	mol %	0.02	un-detectable	0.06	0.08
Gross Reforming Efficiency w/ CH4	%	85	137	80	122

- Introduction
- Stack Development
- Fuel Reformer Development
- **Balance of Plant Development**
- Electronics and Controls Development
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Balance of Plant Development

- Development of all required Balance of Plant components based on system requirements
- SOFC Balance of Plant components based on automotive industry components and automotive industry manufacturing include:
  - Fuel injection system (fuel fittings, fuel injector, fuel line)
  - Air meters
  - Flow control valves
  - Electronic Control Unit
  - Heat exchangers
  - Air filtration
  - Cathode tubes

Heat Exchangers

Air Meters

Fuel Metering

Cathode Air Tubes

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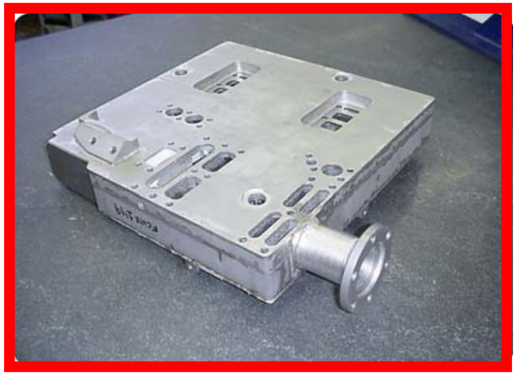
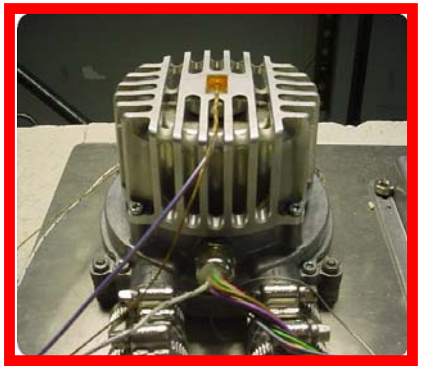
Balance of Plant Development

- Custom developed hardware

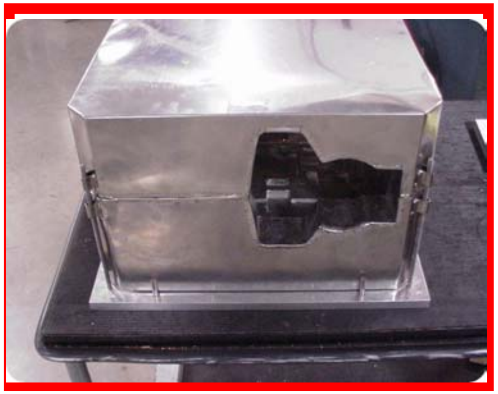
Integrated Component Manifold



Air Delivery System



Anode Recycle Pump



Hot Zone Insulation

- Introduction
- Stack Development
- Fuel Reformer Development
- Balance of Plant Development
- **Electronics and Controls Development**
- System Integration and Testing
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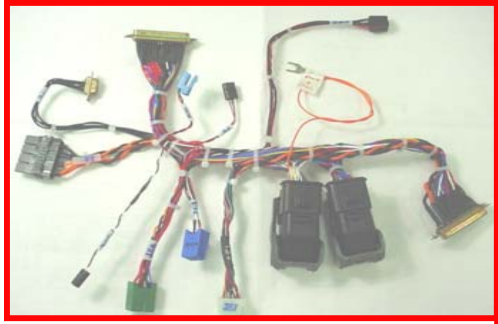
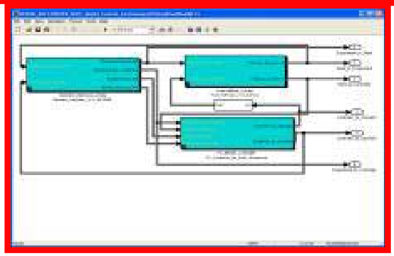
Electronics and Controls Development

- **Electrical Architectures**
  - Transportation Auxiliary Power Unit
  - Stationary Power Unit
- **Power Electronics**
  - Auxiliary Power Unit (APU)
    - DCDC Converters
  - Stationary Power Unit (SPU)
    - DCAC Inverter
    - DCDC Converters
  - 3000 kVA AC Load Bank
- **Power and Signal Distribution**
  - Bussed Electrical Center (BEC)
  - System wiring harness
    - Power harness
    - Signal harness
- **Control**
  - Hardware Design Update
  - Rapid Algorithm Development
  - Flexible System Control Algorithm/Software





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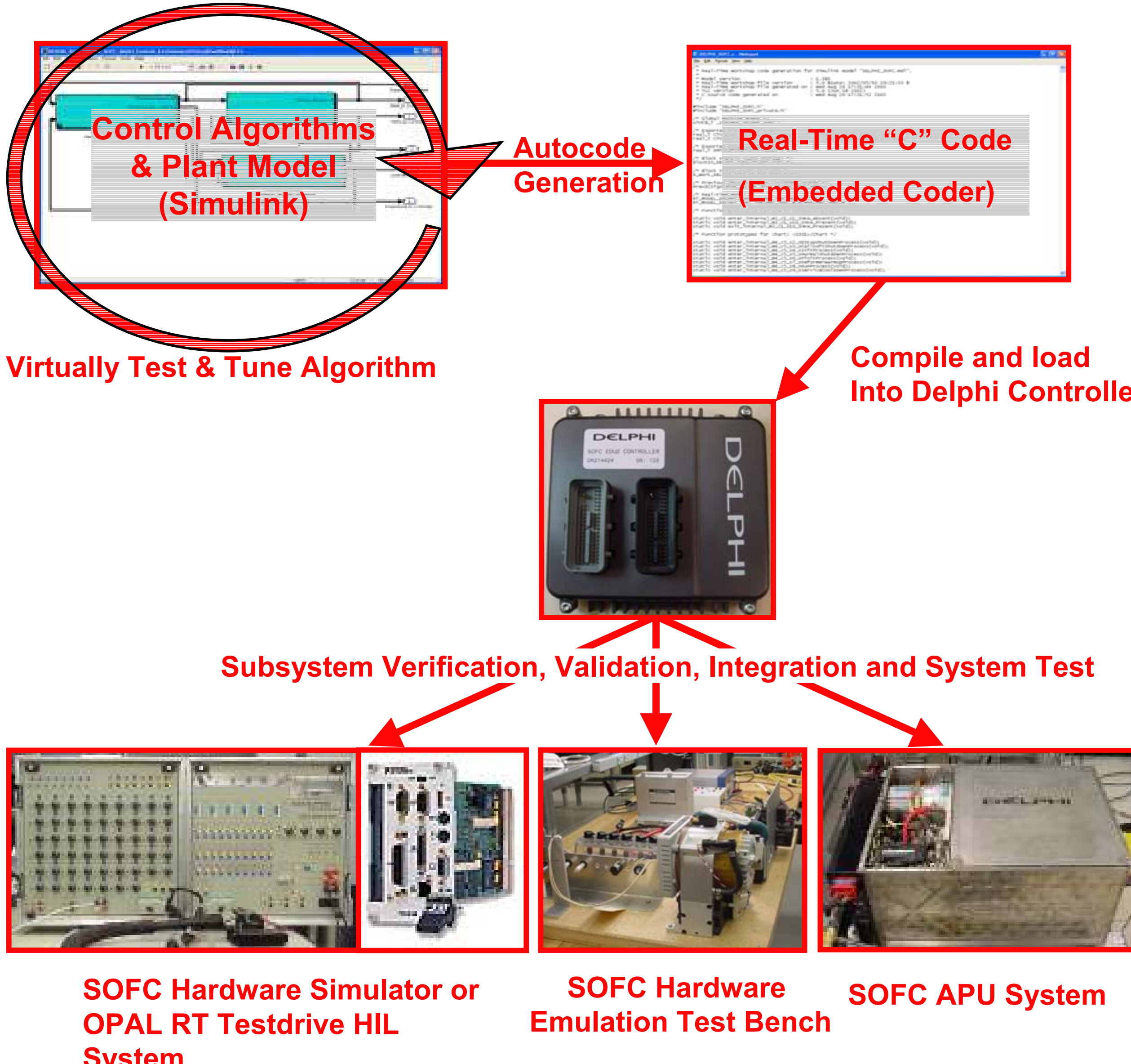
SOFC System Control Development: Rapid Algorithm Development Process

- **State-of-the-Art Development**
  - Entire model is auto-coded
  - Two OSEK-compliant operating systems
  - CAN Communication
  - Flash over CAN capable
- **Size and Complexity**
  - Large/Complex algorithm set
  - High input/output count
  - 436K Code, 125K Calibration
- **Savings**
  - MicroAutoBox
  - Signal conditioning
  - $20k savings per system
  - No software engineer
- **Development Speed**
  - Algorithm modifications to code and test (< 30 minutes)



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Generation 3 System
SECA Test Profile Targets

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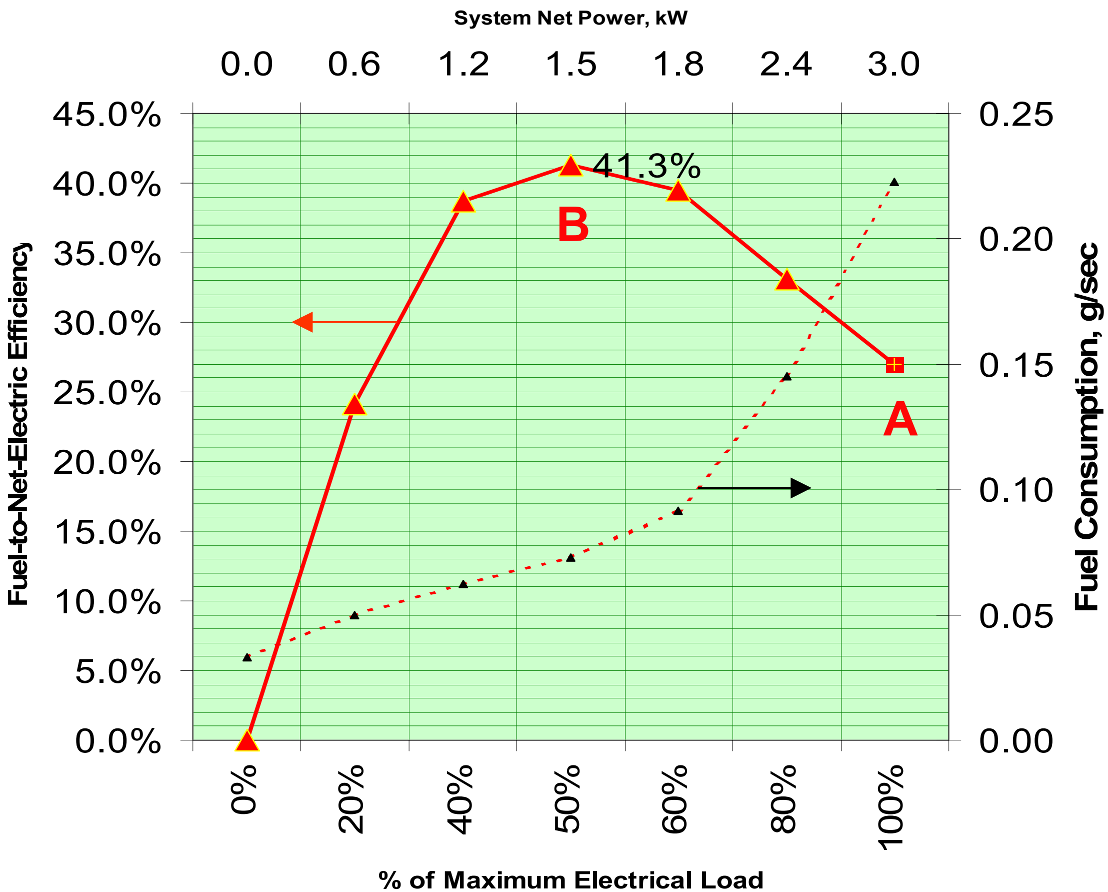
- Delphi's Generation 3 System will be operated at the rated conditions shown below to meet SECA's Phase 1 targets



A : Rated Power, 3 kW Minimum

B : Nominal Operating Condition (NOC): Peak System Efficiency: Min 35%

Generation 3 SOFC System

Generation 3 System

63 Liters, 70 Kg

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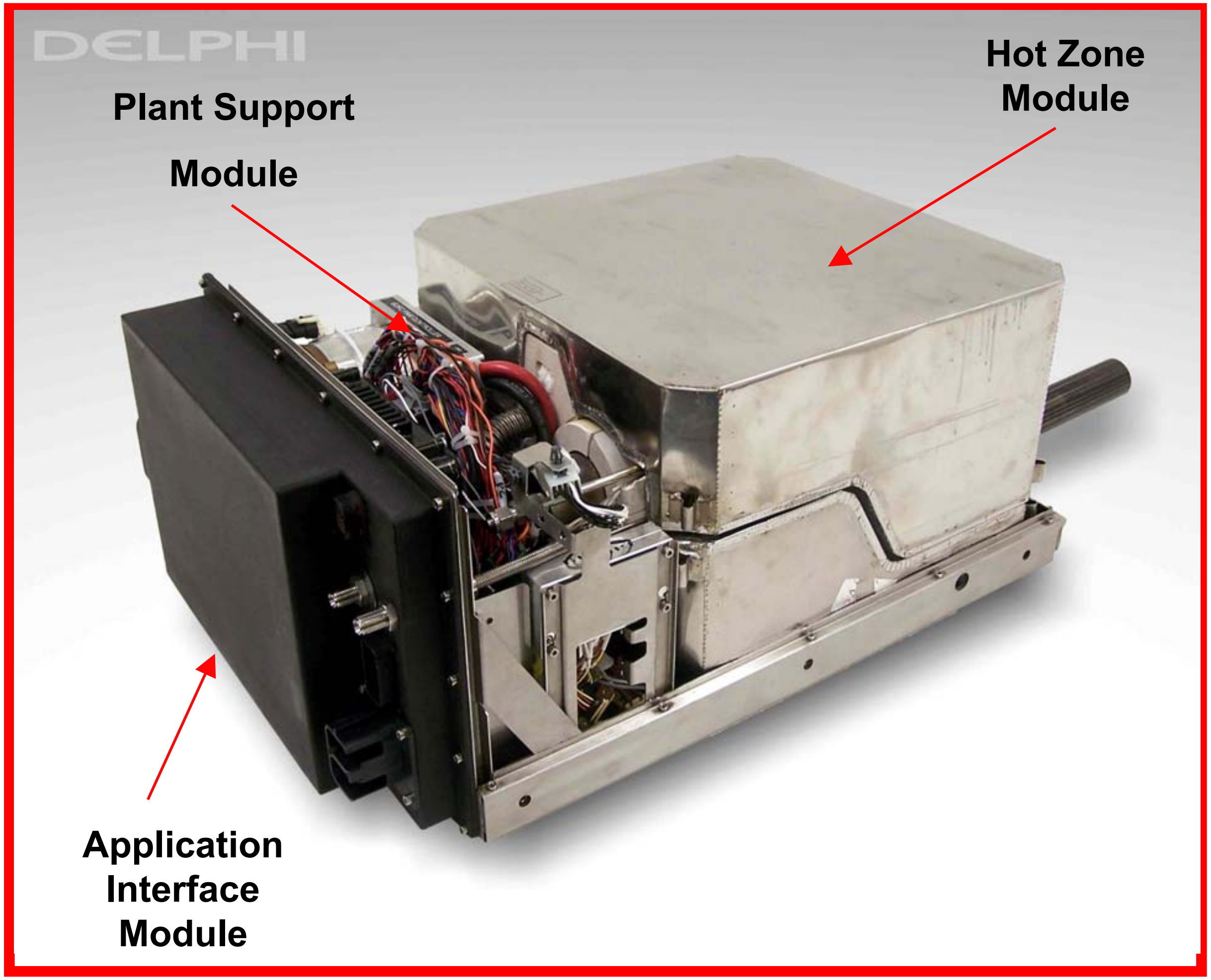
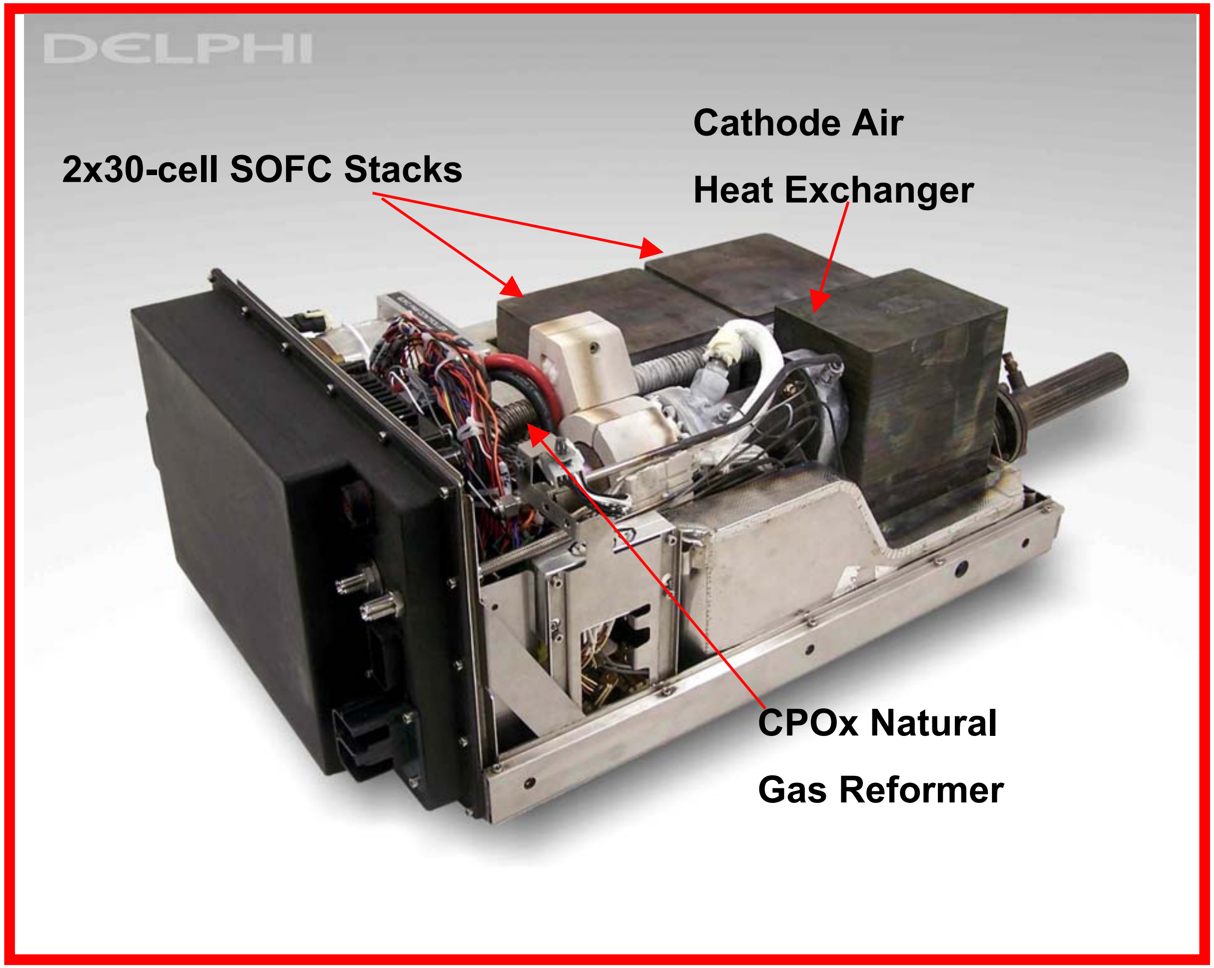
Generation 3 SOFC System

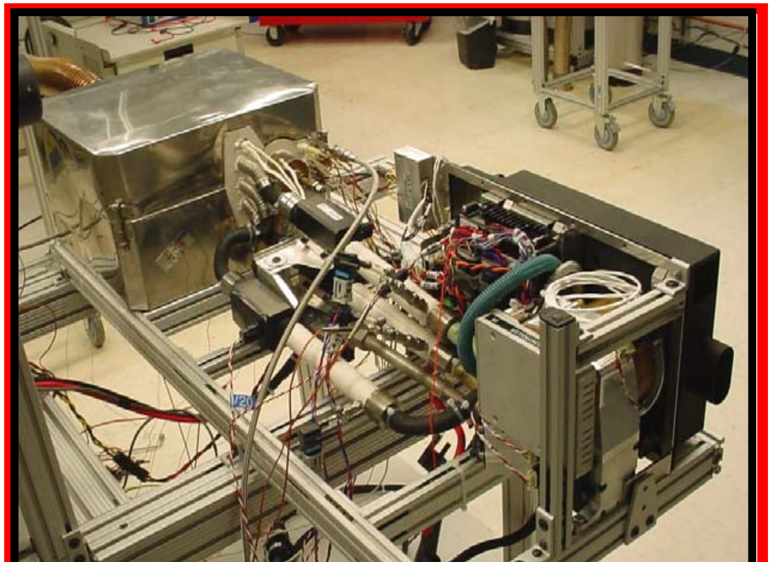


Generation 3 SOFC System



Generation 3 SOFC System Test

From Methane to Electric Power



- **First test of Generation 3 System completed**
  - Methane fuel
  - 2x30 cell Gen 3.1 stacks
  - CPOx reformer
- **Test demonstrated**
  - Automated Start-up
  - Good quality CPOx reformate
  - 1500 Watts net power (1931 Watts stack gross power)
  - 3 Thermal Cycles
- **Next Steps**
  - Durability testing and validation per SECA profile

Summary and Conclusions

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- A "Generation 3 SOFC System" has been demonstrated and is currently being tested with methane fuel
- Key sub-systems have been developed and successfully integrated into the Generation 3 system
  - Generation 3.1 stack sub-system with 30-cell stacks
  - Natural Gas CPOx reformer
  - Balance of Plant and Power Electronics
- Current focus is to demonstrate the Generation 3 system to SECA targets
- Further advanced development is focused on improving performance and reducing life cycle cost:
  - Continuous durability, improved efficiency, thermal cycling
  - Fast start-up (for transportation applications)
- Delphi is committed to working with DOE and its partners to bring this novel technology to market

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Acknowledgements

DEPARTMENT OF ENERGY • UNITED STATES OF AMERICA

NETL

SECA

Battelle

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

DELPHI
Fuel Cell Tech Team