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Development Update on Delphi's Solid Oxide Fuel Cell System

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Battelle

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Primary Stationary Applications

- Residential
  - Residential (2 to 5 kW) grid augmentation with Combined Heat and Power: Liquid or gaseous fuels

- Commercial
  - Commercial (25 kW) grid augmentation : Liquid or gaseous fuels

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Primary Mobile Applications

- Passenger Car
  - Primary Application to satisfy increased electrical demand on vehicles
  - Integration with ICE, utilizing reformate to reduce ICE emissions
  - Other opportunity - range extension on electric vehicle (Hybrid)

- Heavy & Medium Duty Truck
  - Application of Engine-off electrical power on Long Haul Trucks
  - Applications on Short Haul and Smaller Trucks
  - Development of Essential Power Unit (EPU) for Long Haul Class 8 Truck
  - Satisfy increasing electrical demand
  - Worksite Electrical

- Other Mobile
  - Military Vehicles, Aircraft APUs, Ship Board Distributed Power, Other Portable Power

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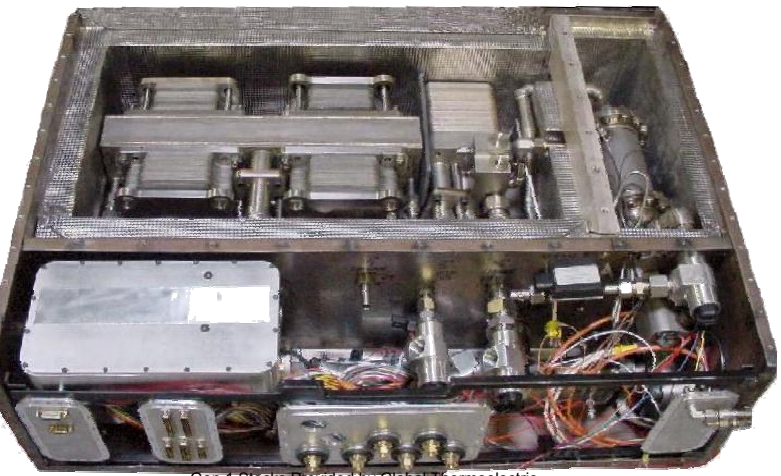
SOFC APU Concept Evolution

Generation 1 SOFC APU



Gen 1 Stacks Provided by Global Thermoelectric

155 Liters
204 kg

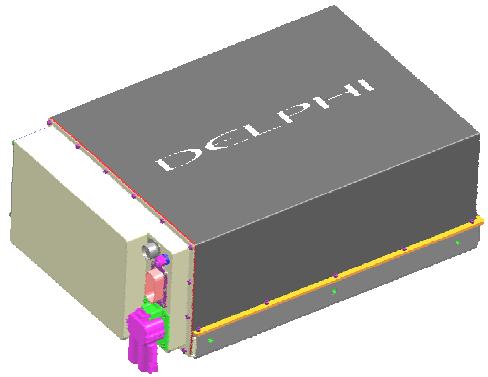
12/2000

Generation 2 SOFC APU

60 Liters
70 kg

12/2002

Generation 3 SOFC APU



Under Development

200X

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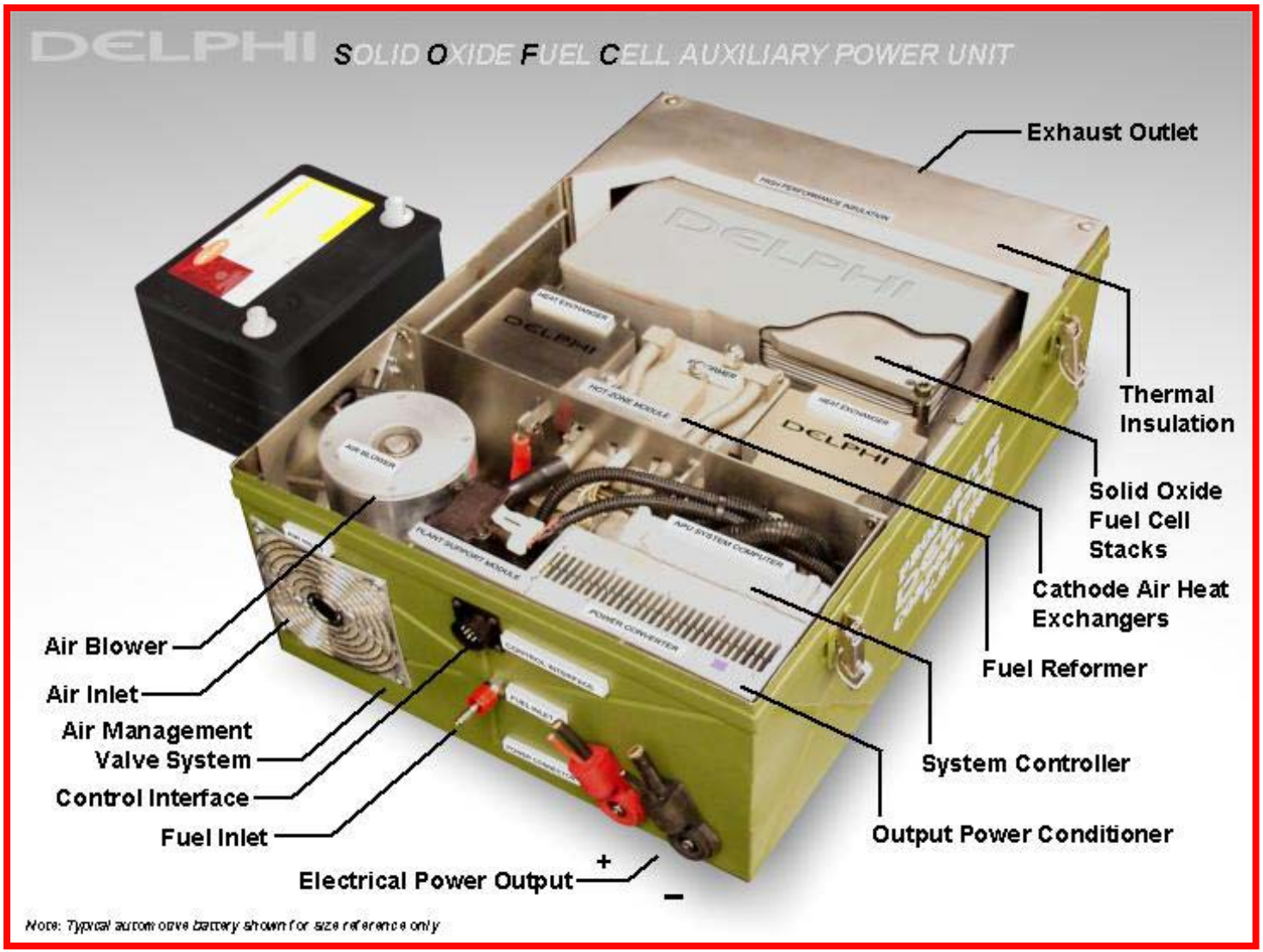
SOFC APU Concept Evolution

- Gen 1 - 12/2000
  - Proof of Concept
  - First demonstration of gasoline-fueled SOFC APU
- Gen 2A
  - Revised package, integrated design
  - First cold-start, warm-up, and power from a system
- Gen 2B
  - Improved reliability, controls, and assembly (integration)
  - First APU run in full enclosure
- Gen 2C
  - Gen 2B APU modified to use Gen 3 stacks (2 x 30 cell)
  - First systems test with 2x30 cell stack
  - Under test
- Gen 3 – current
  - Under development
  - APU redesign with improved features
  - Gen 3 Stacks
  - Anode Tail Gas Recycle (TGR) deployed for increased system efficiency

Delphi SOFC APU
Main Subsystems / Components



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Stack Development

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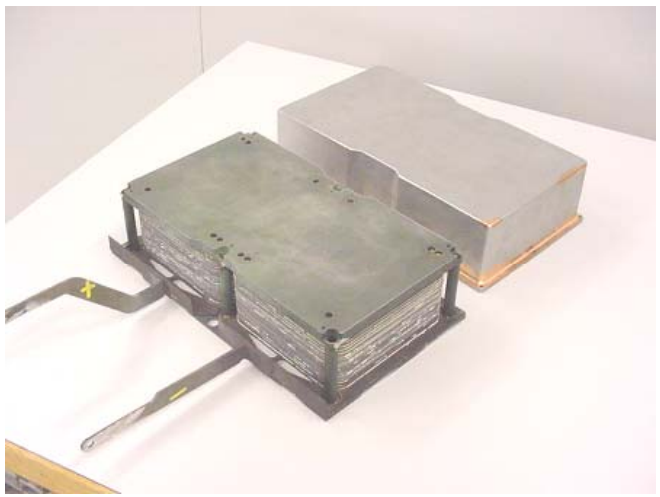
SOFC Stack Development Status

- Delphi-Battelle team developed and demonstrated limited functionality of the Generation 2 stack technology
  - Multiple stack sub-systems were built and tested
  - Produced greater than 400 mW/cm^2 power density
  - Additional development needed to overcome critical technical barriers
- Current development focus is on an improved “Generation 3” stack technology, aiming at improved functionality. Generation 3 stack technology is viewed as a major step toward product viability.



Generation 2 (2x15-cell),
2003

Generation 3 (30-cell),
2004

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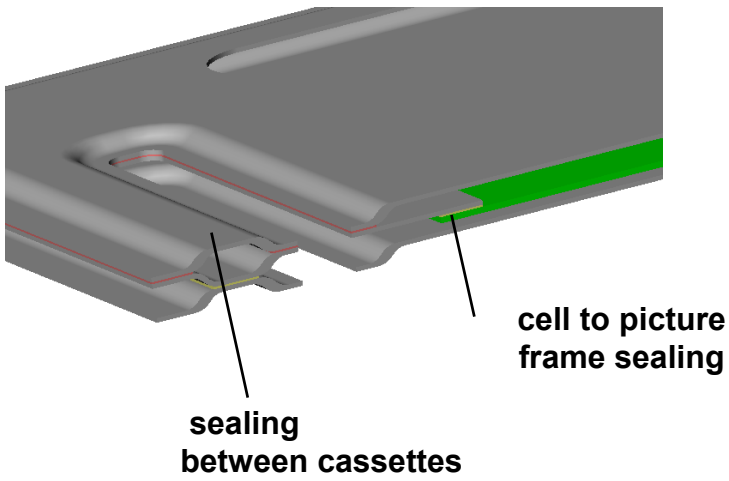
Generation 2 Stack Key Features

- Generation 2 stack characteristics :
  - 750 °C operating temperature
  - Anode supported cells
  - Ferritic steel based interconnect
  - Glass seals
  - “Cassette” based repeating unit (4-piece design)



Metal cassette (without cell)

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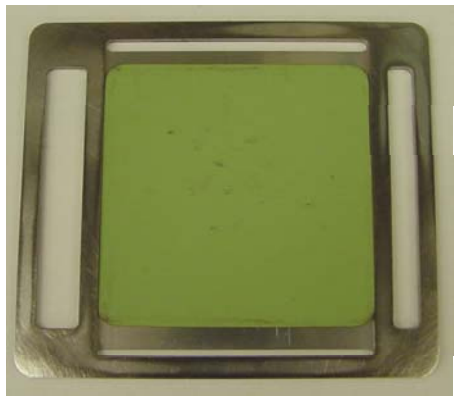
Generation 2 Stack
Cell and Stack Development Scale Up

Button Cell

Primarily for cathode, electrolyte and anode materials development



Intermediate-Scale

Small active area repeating unit for stack – for design and performance optimization and development

Full-Scale

Full active area repeating unit for stack –for design and performance optimization and development

Cell Development
Power Density Improvements

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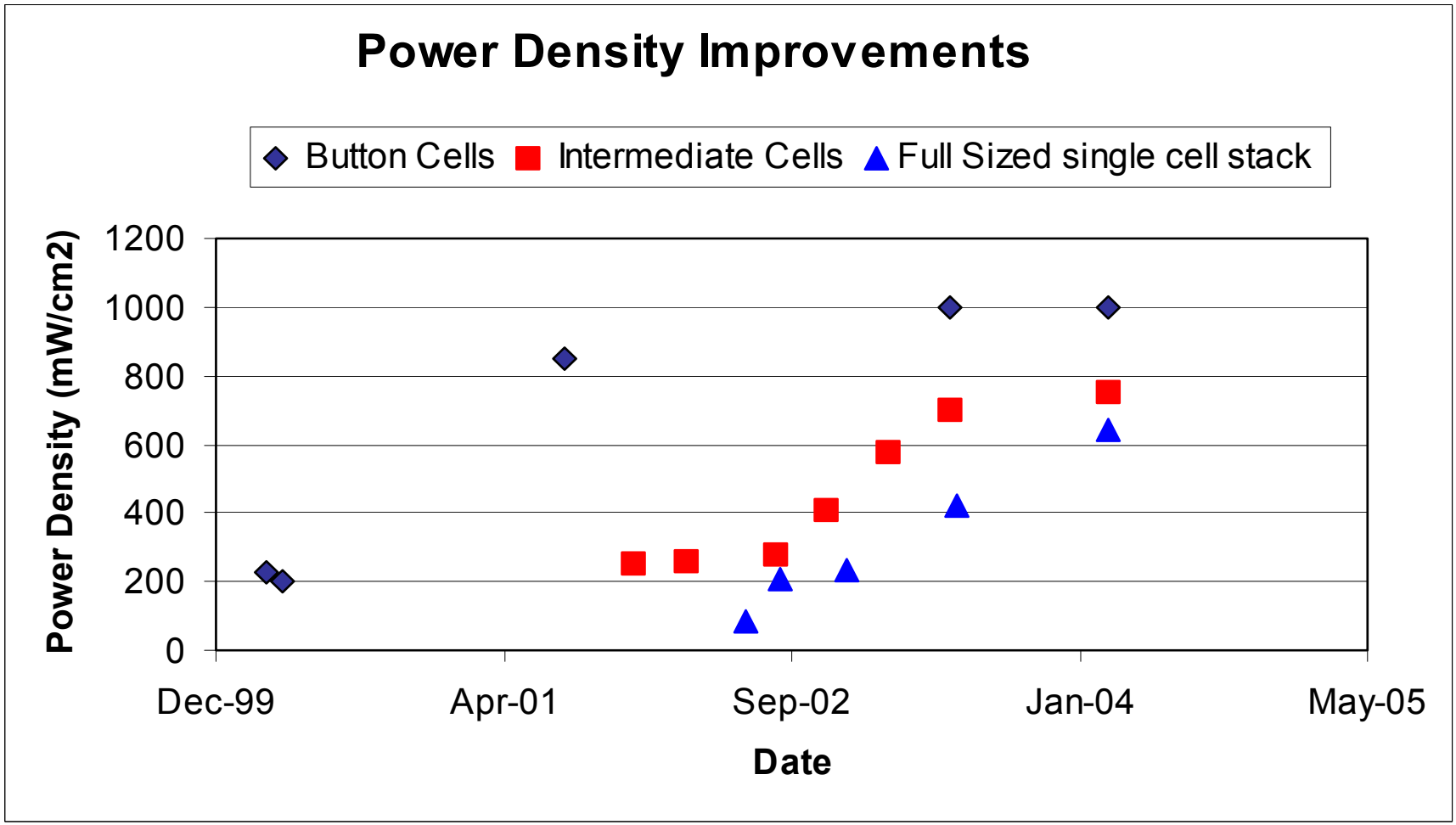

Generation 2 Stack
2x15-Cell Integrated Stack Module

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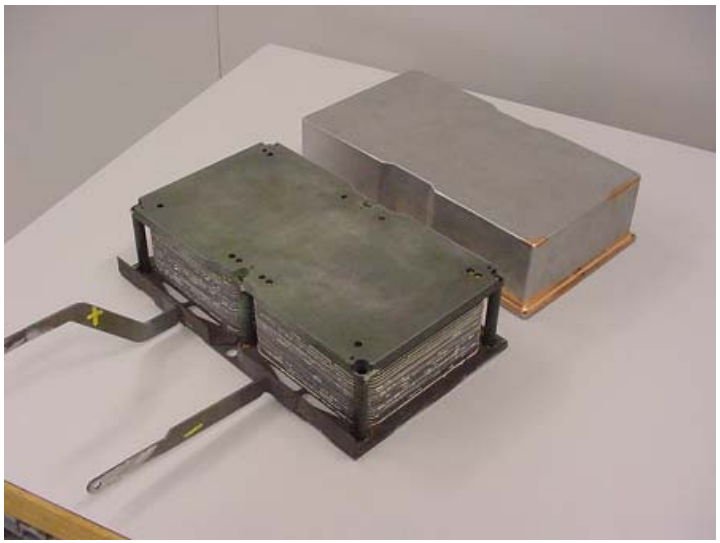
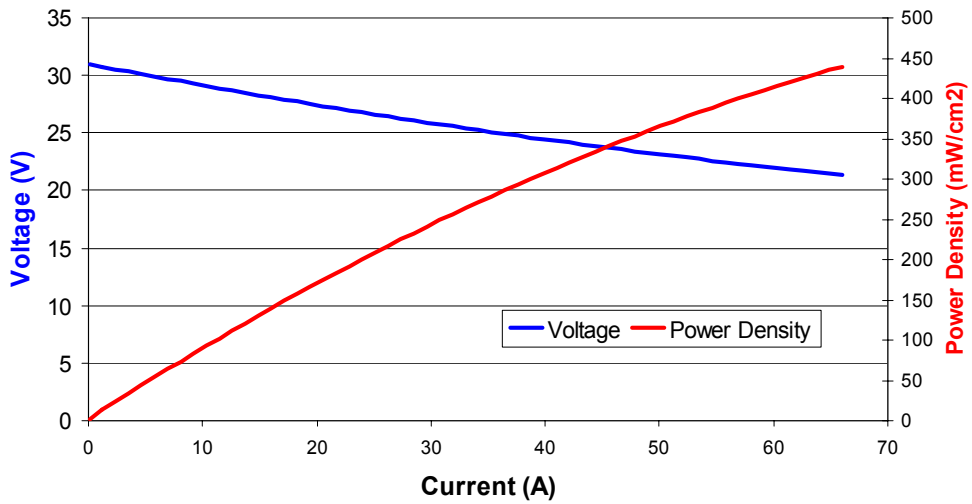


Generation-2, 2x15-cell stack
(> 20 Kg, 6 L)



- Produced 1.39 kW (436 mW/cm2) @ 21 V with simulated recycle reformate (35% H2, 40% CO, 3% H2O, rest N2) at 750oC, 25% fuel utilization

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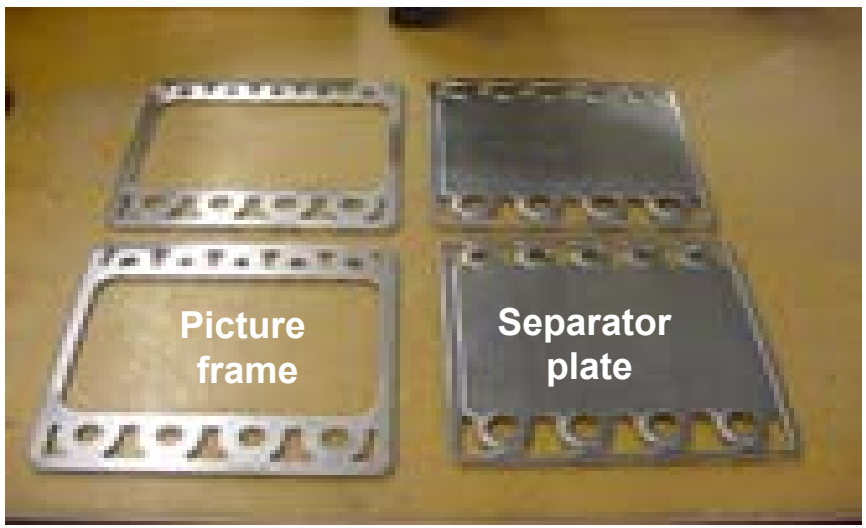
Generation 3 Stack Key Features

- Generation 3 stack characteristics :
  - Co-flow design
  - Stamped metal parts (2 pc) (CroFer 22 APU alloy)
  - Cell brazed to picture frame
  - Laser weld for bonding cell-picture frame to separator plate
  - Low mass and volume utilizing high volume manufacturing processes



Generation 3 Stack
30-Cell Stack Module

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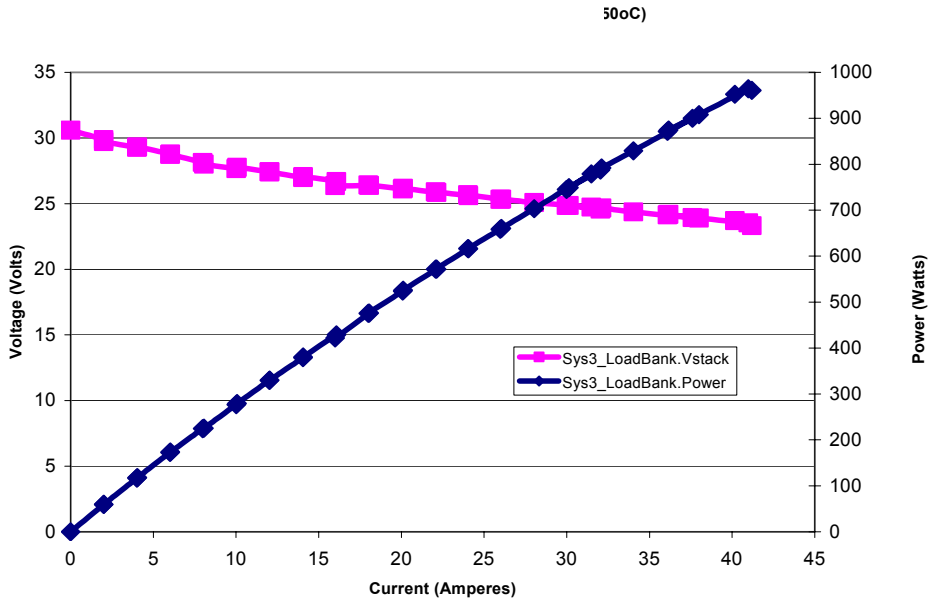
Generation 3 30-cell stack
(3.5 liter, 13 Kg)



- Produced 980 Watts (308 mW/cm^2) with simulated CPOx reformate (20% H_2, 23% CO, 3% H_2O, rest N_2) at 22 Volts at 750^{o}C, 25% fuel utilization

Stack Development - Thermal Cycling, Durability and Fuel Utilization

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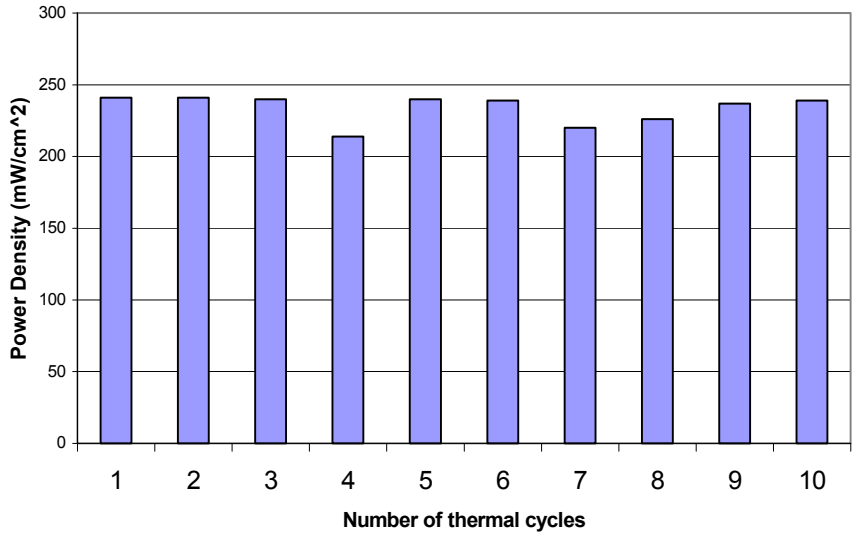
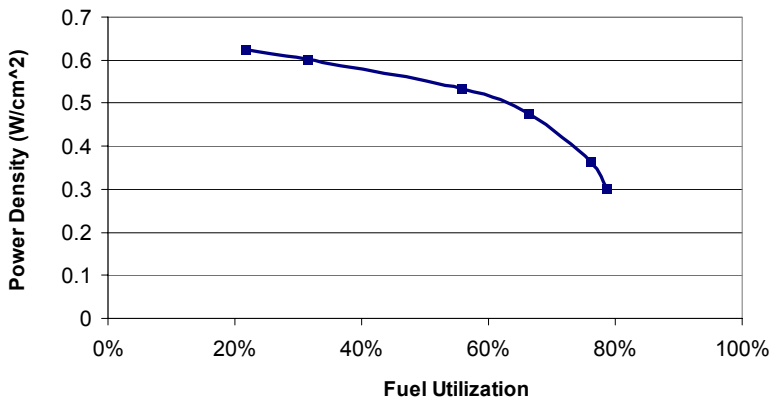
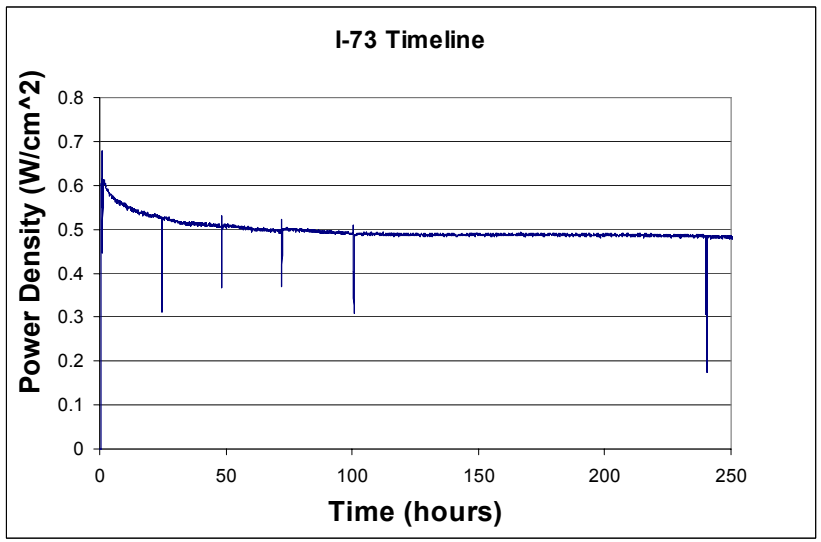
- **Thermal Cycling**
  - 15-cell Gen 3 stacks have been thermally cycled 10 times in a furnace (from ambient to 750°C) with minimal power degradation
- **Continuous Durability**
  - CroFer based interconnects exhibiting greater than 10% degradation due to interaction of chromia with cathode (1600 hours test)
  - Improved interconnects in 1-cell stack tests showing minimal degradation rate after initial ~50 hours (250 hours completed)
- **Fuel Utilization**
  - 1-cell Gen 3 stacks demonstrating greater than 400 mW/cm^2 at 70% fuel utilization







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Reformer Development

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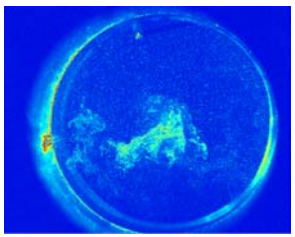
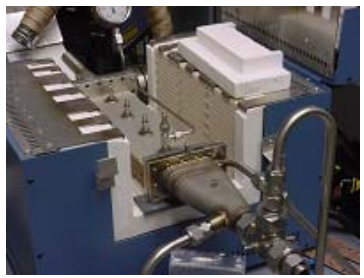
Reformer Development

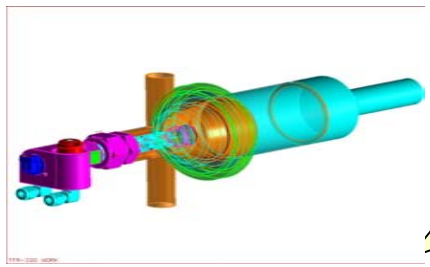
- Delphi is developing reformer technology for reforming gasoline, diesel, and natural gas.
- Fundamental research, catalyst development, computer aided engineering, controls development and extensive testing is leading to robust, manufacturable product designs.



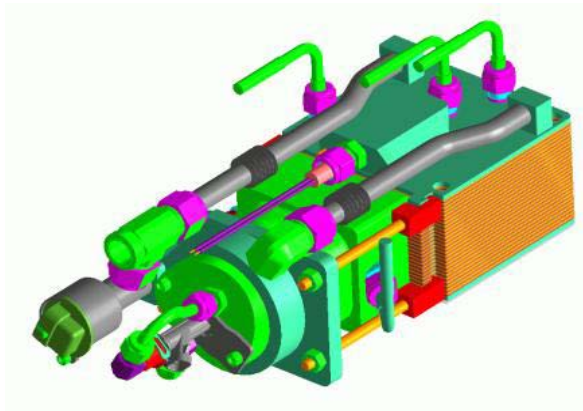
Fundamental Development



Controls Development and Validation



Computer Aided Design



Delphi Reformer

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Reformer Development Design Parameters

- Reformer (POx and Endothermic)
  - Operate at required Reformate Power & Efficiency (kWlhv)
  - Operate under non-Carbon forming conditions
  - Operate with minimum CH4 and Emissions levels
  - Tolerance to fuel sulfur content

- Endothermic
  - Combine functions of reformer and energy recovery unit into one device
  - Utilize system heat sources to match with Reformer System heat requirements (improve efficiency)

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Reformer Development
Tubular CPOx Reformer Assembly

Tubular CPOx Reformer Development Status

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Tubular CPOx Reformer

- 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 / Start Emissions
  - <3 min start demonstrated; emissions monitored and steadily improved

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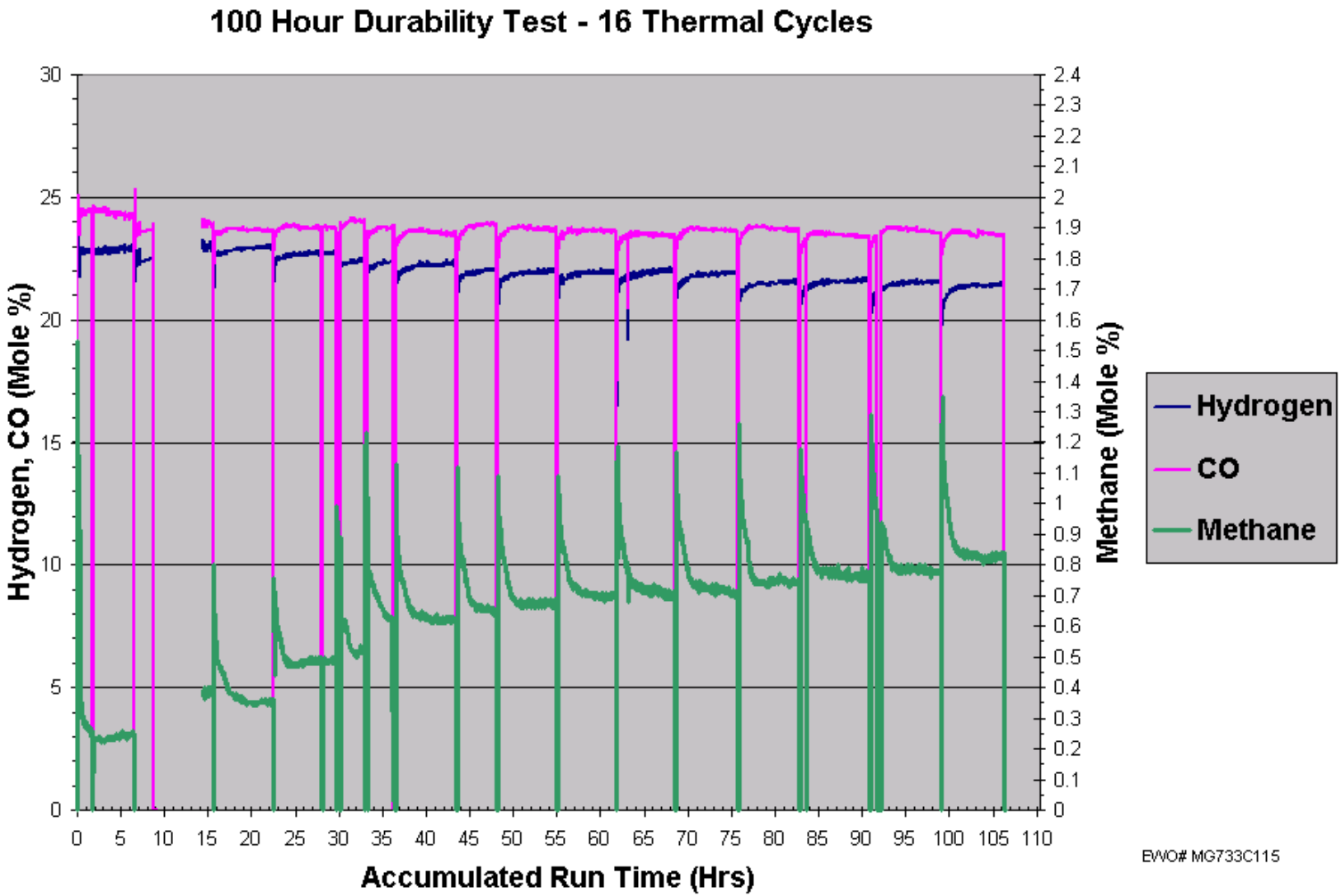
Tubular Reformer Durability



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Endothermic Reformer Development Status

- Gains in reformer efficiency over CPOx
- Consistent reformate quality
- Reforming efficiency > 100
- Improved thermal management / distribution
- Ongoing
  - Improve thermal integration
  - New combustor design
  - Reduced package size

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Balance of Plant Development

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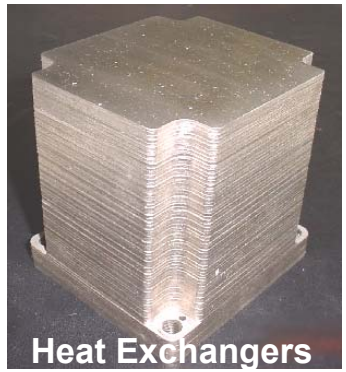
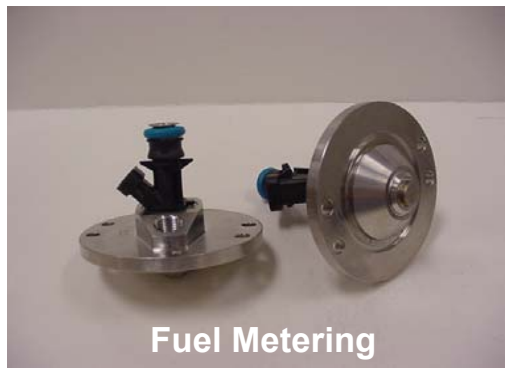
Balance of Plant

- SOFC Balance of Plant Components based on automotive industry components and automotive industry manufacturing
  - Fuel injection system (fuel fittings, fuel injector, fuel line)
  - Air Meters
  - Flow control valves
  - Electronic Control Unit
  - Heat exchangers
  - Air Filtration
- Integrated Manifold
- Insulation


Heat Exchangers


Air Meters


Fuel Metering


Integrated Manifold and Insulation

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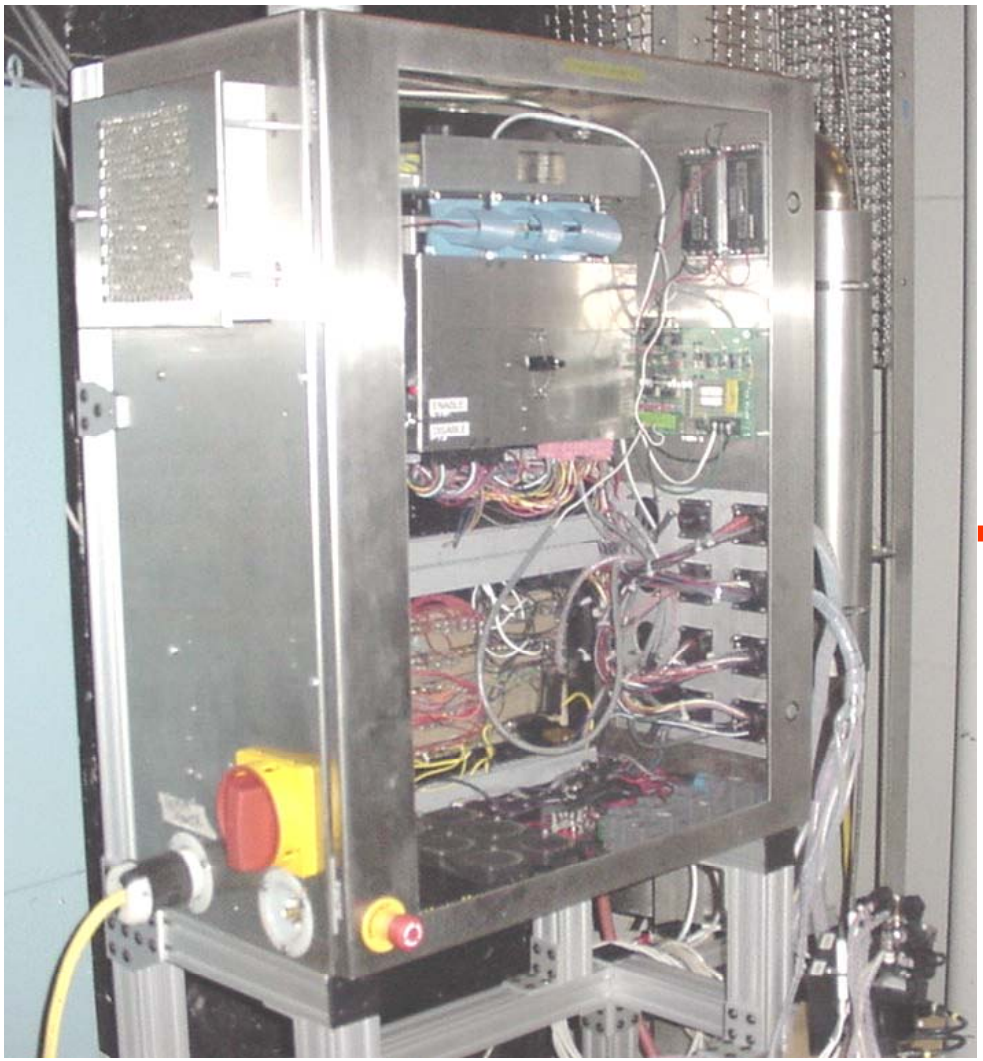
Control System Development

System Electronic Control Unit (ECU)



Development Controller and Supporting Circuitry

Electronic Control Unit

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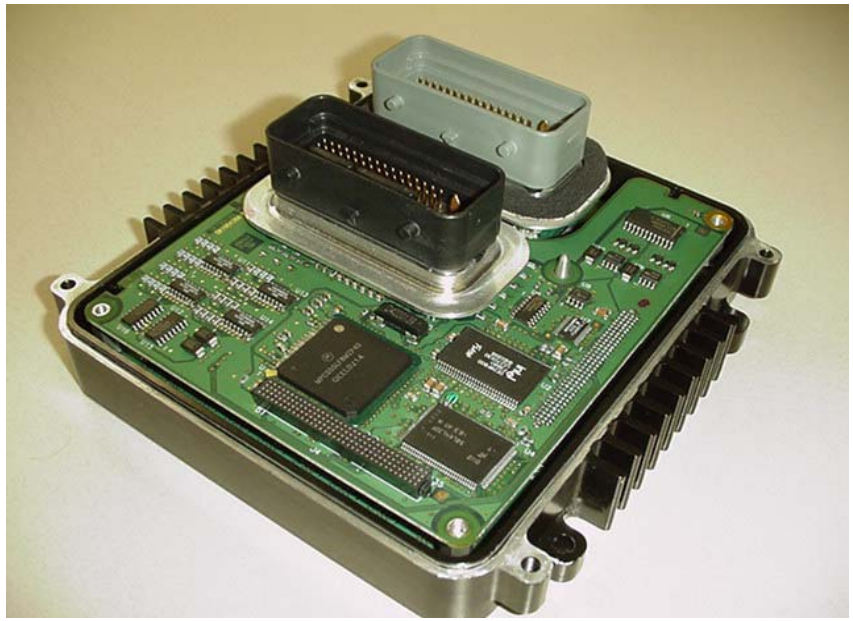
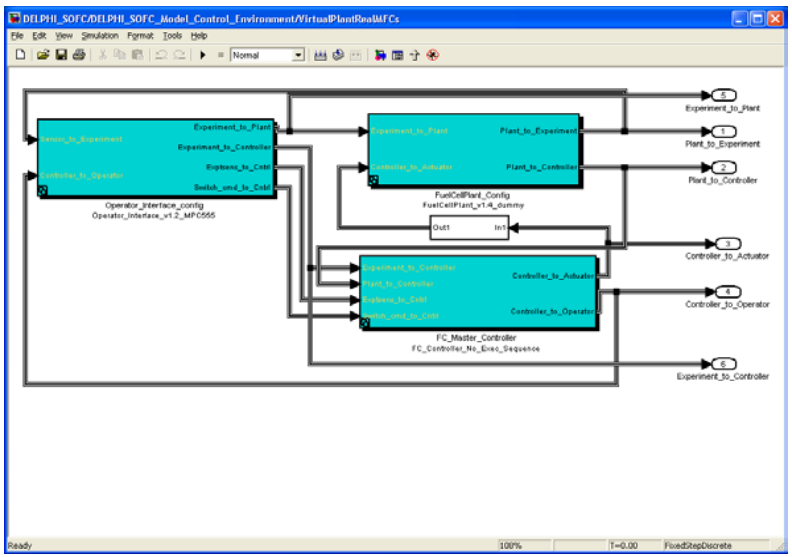
System Electronic Control Unit (ECU)

- Electronic Control Unit (ECU) developed by Delphi and based on robust automotive controller designs
- Located inside APU
- Designed for operational temperature of 125 ºC

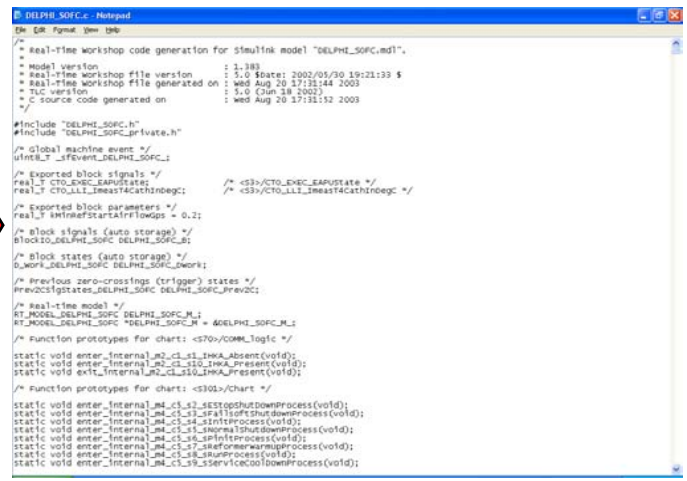


Automatic Code Generation Tools

- Coder creates production C-code to run on SOFC ECU with the targeted processor
- Allows flexible code configuration and optimization
- Real-time debugger capabilities through WindRiver Single Step



Ecoder



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System Build and Test

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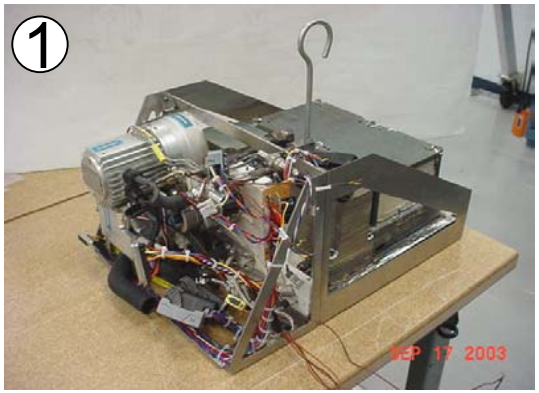
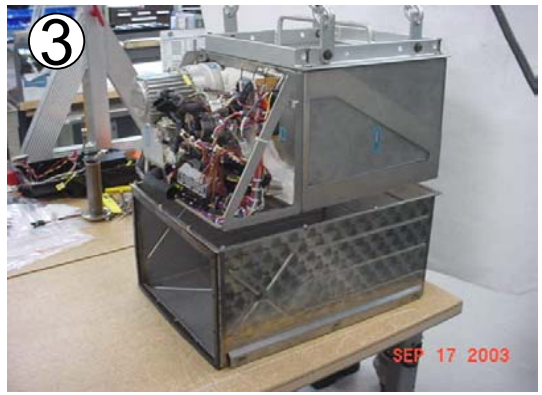
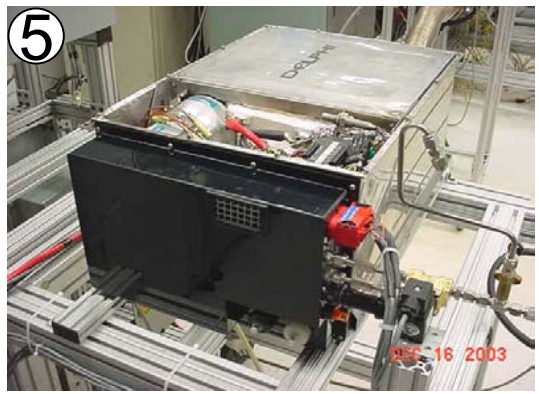
APU System Build

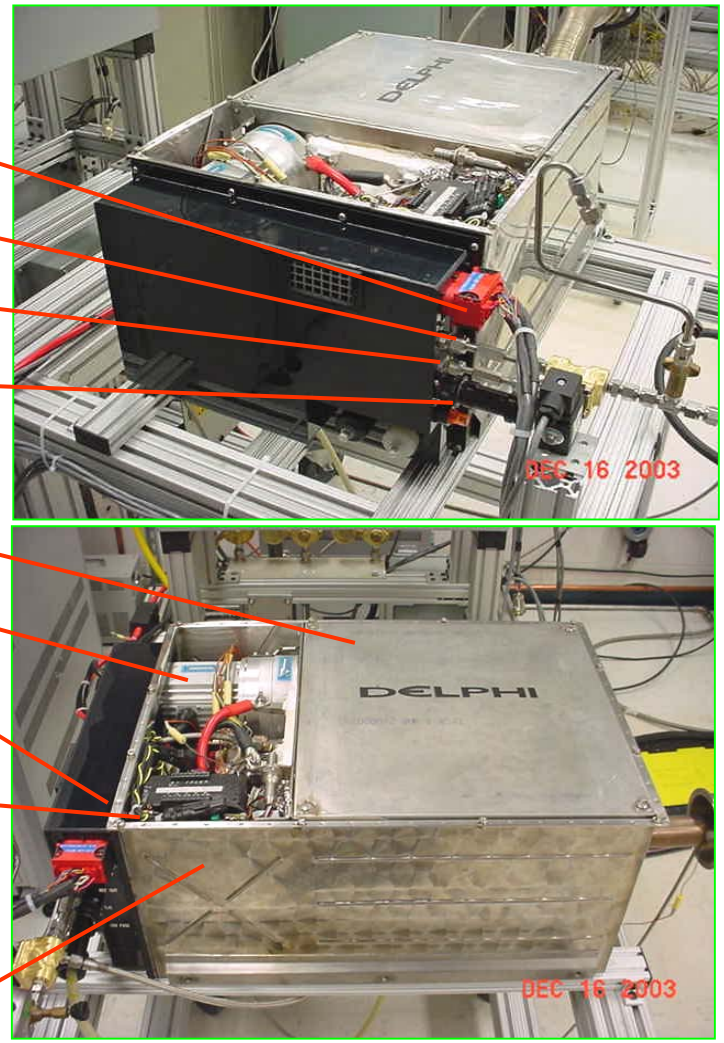






System Build and Test

SOFC APU Gen 2



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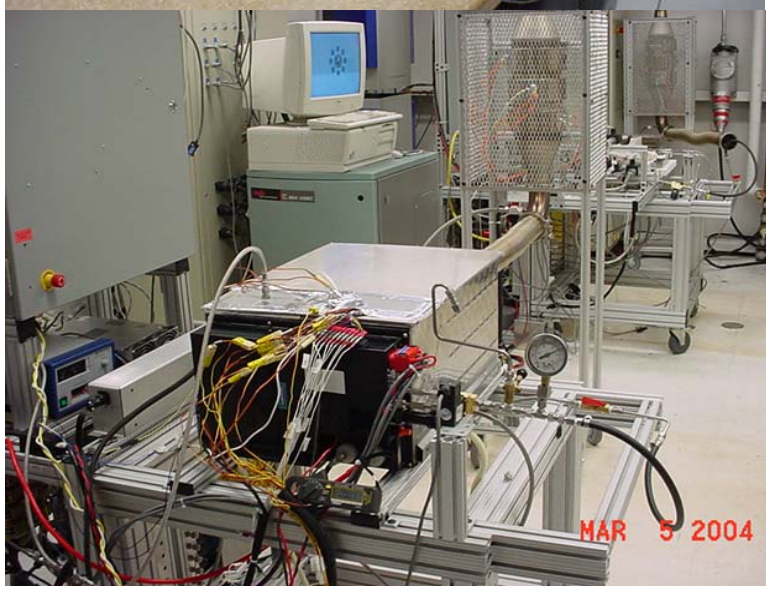
System Build and Test



- First test of Gen 2 Auxiliary Power Unit with POx reformer and 2 x 30 cell Gen 3 Stacks
- Fully automatic cold-start, warm-up, and run modes (CARB Ph-2 gasoline)
  - POx reformer produced good quality reformate
  - 1617 W Indicated Stack Power
- Demonstrated the viability of Generation 3 stacks in the APU system
- Further development and testing ongoing to improve performance and durability

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Summary and Conclusions

- SOFC based power systems are a paradigm shift in the supply of electric power for transportation, stationary and other applications
- Delphi fundamental developments have targeted transportation, stationary and other application's functional requirements
- Delphi is currently working on:
  - Advanced generation stack subsystem
  - Endothermic reformer for increasing overall system efficiency
  - Anode tail gas recycle
- A "Generation 2 APU" has been developed and is being tested
- A "Generation 3 APU" is currently under development
- Current research and advanced development is focused on improving performance and reducing life cycle cost:
  - Continuous durability, Thermal cycling , Power Density, Improved efficiency
  - Fast start-up (for transportation applications)

Acknowledgements

- US-Department of Energy, Solid State Energy Conversion Alliance (SECA)
- Delphi management and development team members