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

From Gasoline to Electric Power

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Introduction

- Delphi is developing Solid Oxide Fuel Cell (SOFC) technology for transportation and stationary applications.
- Delphi is currently developing a **second generation** SOFC APU that is more robust and consistent with market requirements.
- In the following slides we will discuss:
  - Introduction to Delphi's fuel cell activity
  - Transition from Proof of Concept to Generation 2 SOFC APU
  - Generation 2 SOFC APU design and key features
  - Development of Generation 2 stack and reformer
  - Development and testing of Generation 2 APU

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SOFC Power Unit Applications

Luxury automotive APU for Engine-off power: Gasoline and Diesel fuel

Residential grid-augmentation with Combined Heat and Power : Natural Gas fuel

Commercial (25 kW) grid augmentation : Natural Gas fuel

Heavy Duty Truck APU to eliminate long term idling: Diesel fuel

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

Aerospace is for use as an APU for redundant electric power supply : Jet Fuel

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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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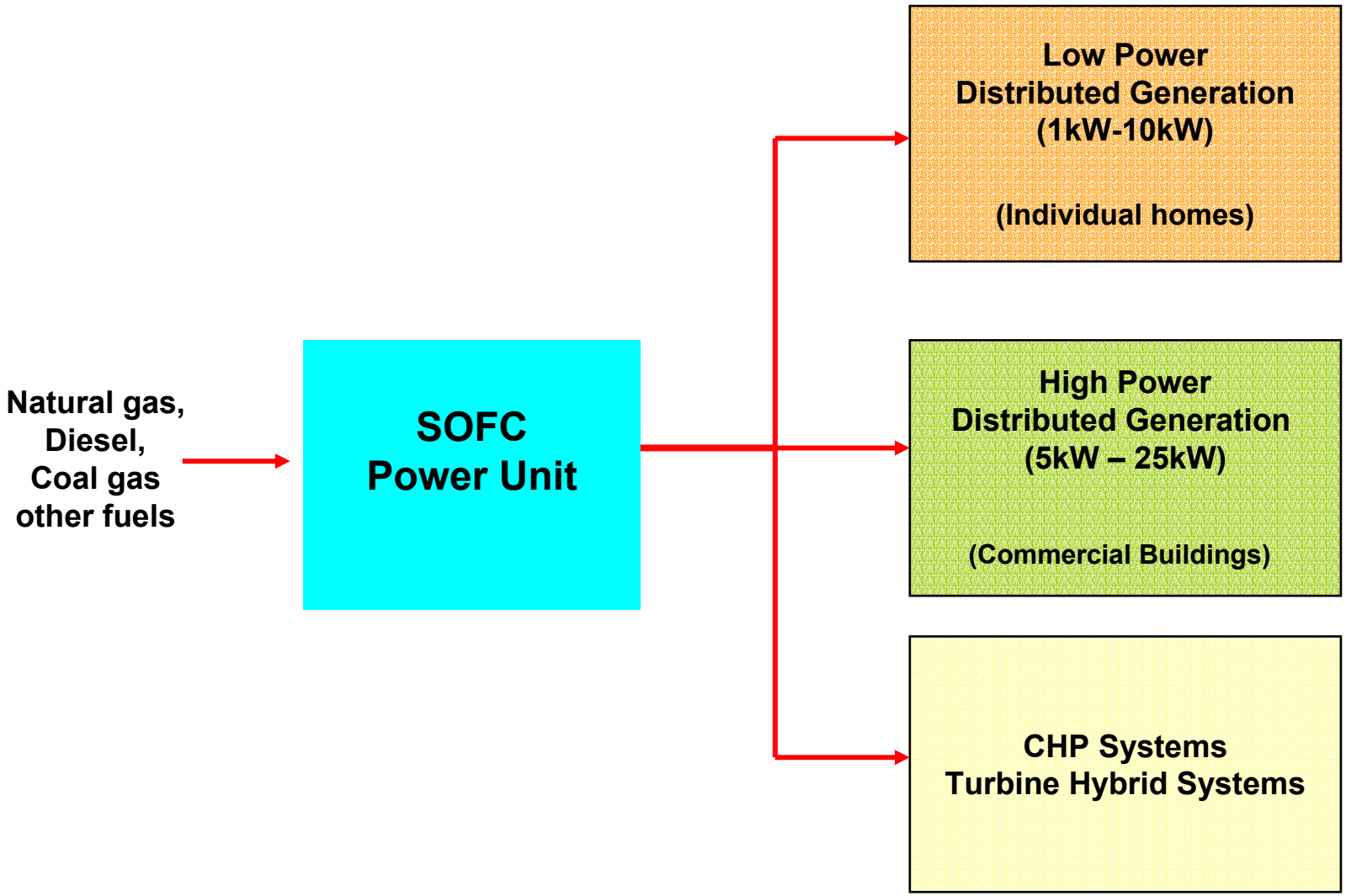
Stationary Applications



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Delphi's Generation 2 SOFC APU Key Features

- Delphi is currently focused on developing a Generation 2 SOFC APU that is more consistent with automotive requirements and customer needs

- Key features of the Generation 2 APU System are:
  - The design has been optimized as a more functionally integrated system in order to reduce weight and volume of the unit.
  - The weight and volume of the generation 2 APU is reduced by 75% from the Proof of Concept APU.
  - A Generation 2 Integrated Stack Module (two stack modules in electrical series) has been designed, built and integrated into the APU.
  - A tubular as well as a flat plate reformer has been designed. The tubular reformer has been built, tested and integrated into the APU. Development and testing is ongoing on the flat plate reformer.

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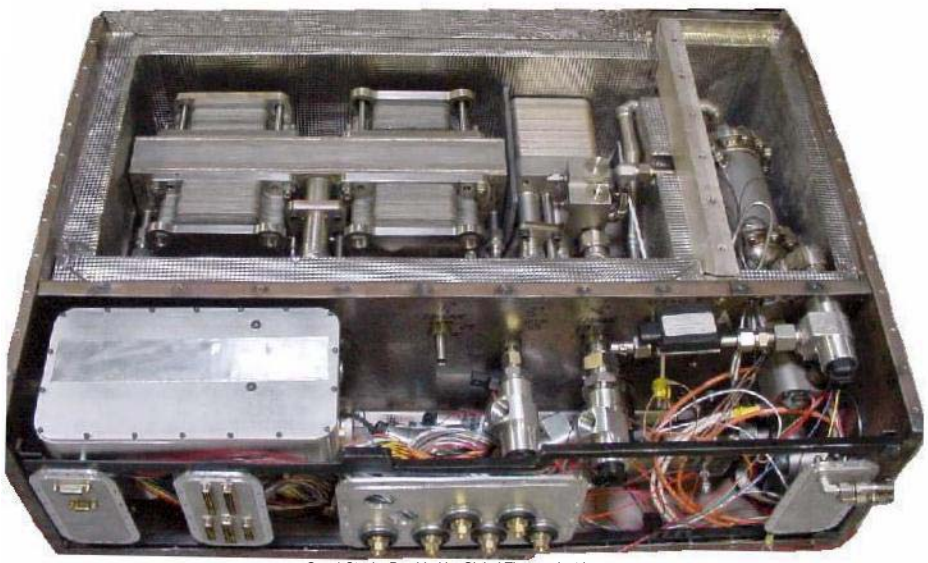
Generation 2 SOFC APU
From Proof Of Concept to Gen 2

SOFC APU System Evolution

Generation 1 SOFC APU



Gen 1 Stacks Provided by Global Thermoelectric

155 Liters
204 kg

12/2000

Generation 2 SOFC APU

44 Liters
70 kg

12/2002

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Generation 2 SOFC APU Design Features and Packaging

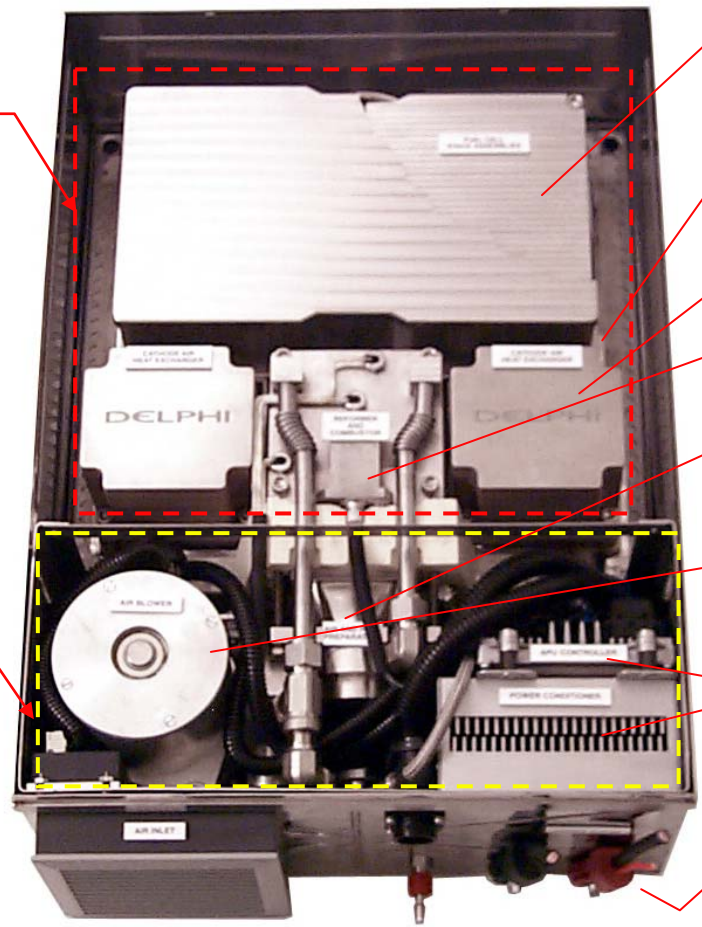
APU = HZM + PSM

Hot-Zone Module (HZM)

- high-temperature subsystems (700-950 C)
- Surrounded by high-performance thermal insulation
- "Core" of the SOFC plant

Plant Support Module (PSM)

- Low-temperature subsystems (40-125C)
- Inlet-air cooled electronic components
- Balance of plant
  - sensors, actuators, electronics, harness



Integrated Stack Module (ISM)

Integrated Component Manifold (ICM)

Cathode Air Preheat HEX

ReforWER

Fuel/Air Prep & Start Burner

High-Output Blower

Power & Control Electronics

Output Terminals

Fuel & Air Interface

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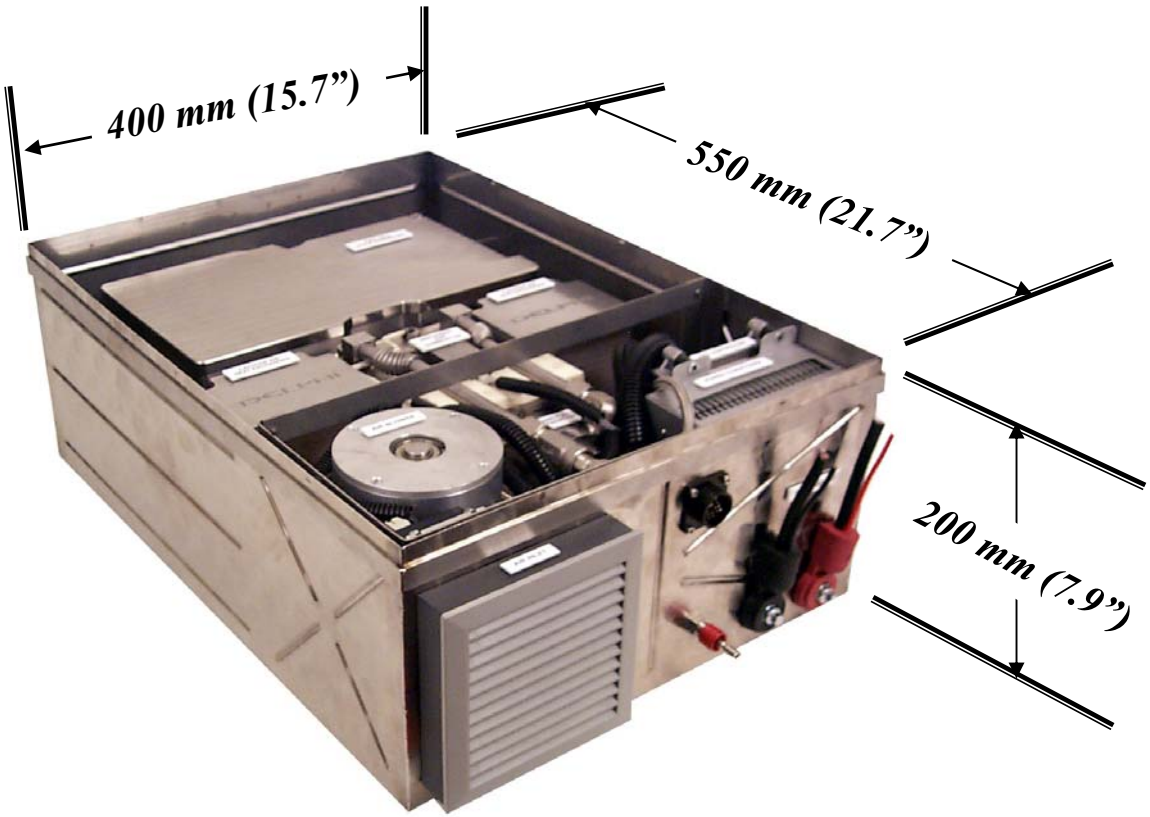
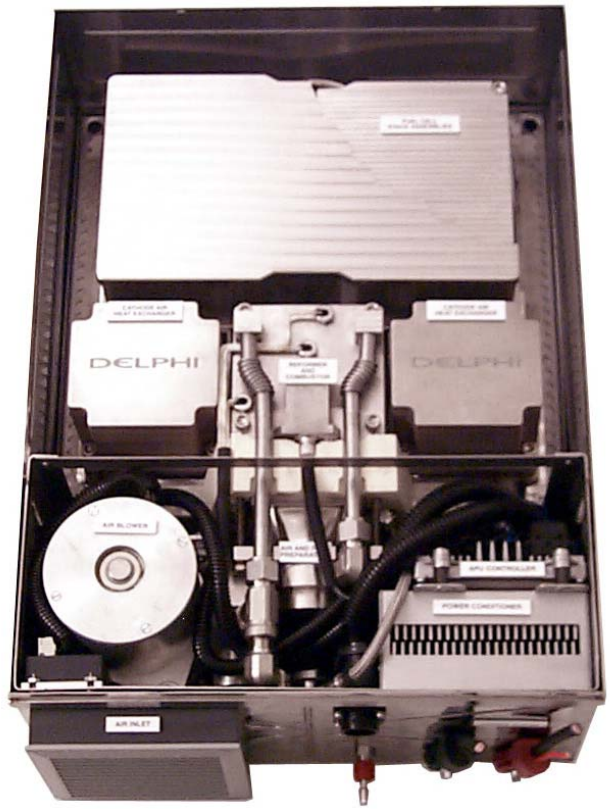
Generation 2 SOFC APU
Design Features and Packaging





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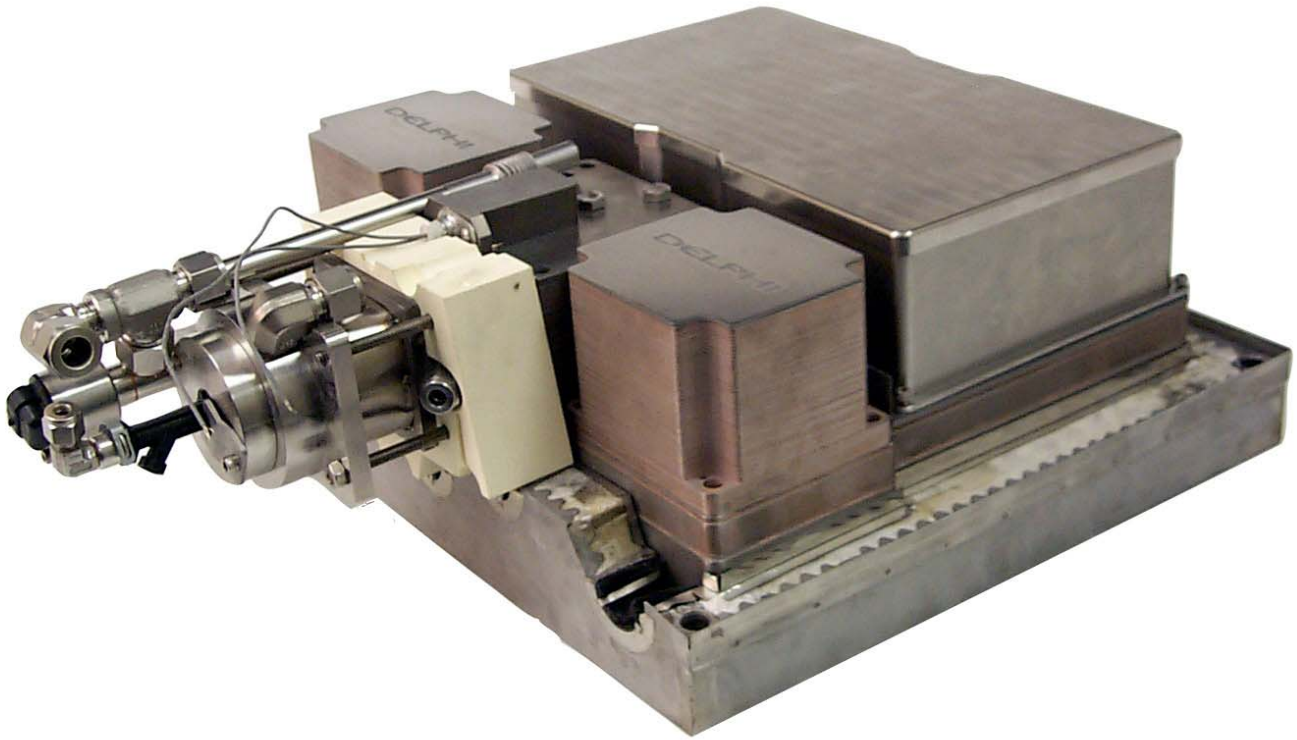
Generation 2 SOFC APU
Design Features and Packaging

Core Module without Insulation



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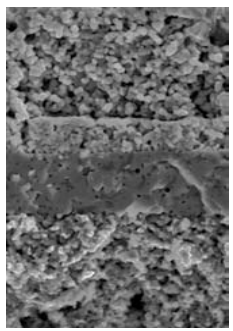
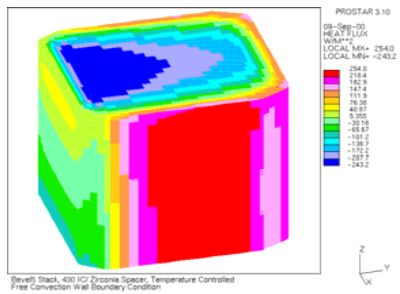
Generation 2 Stack Introduction

- Delphi is internally developing Generation 2 stack technology.
- Fundamental component development,computer aided engineering and extensive testing is leading to robust, manufacturable product designs.



Fundamental Research

Validation



Modeling

Gen 2 Delphi stack

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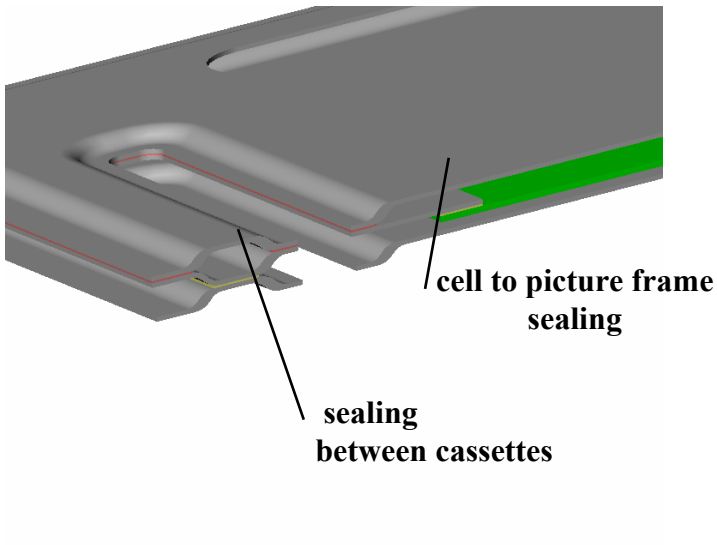
Generation 2 Stack Key Features

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



Metal cassette (without cell)

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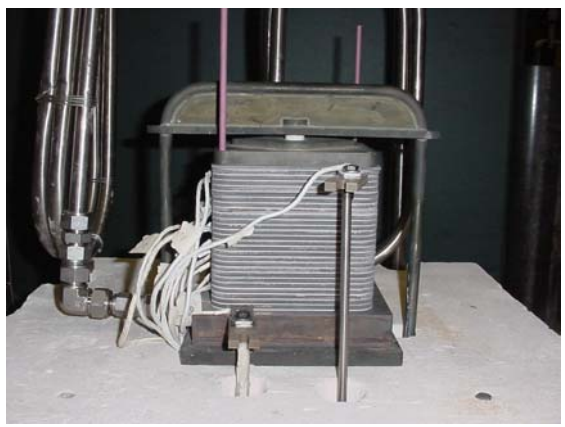
Generation 2 Stack Development Summary

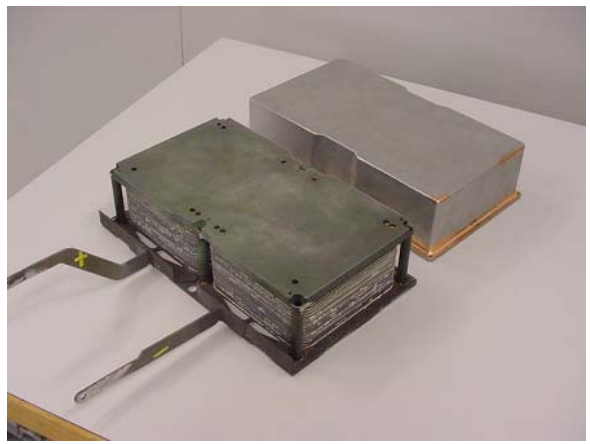
- Multiple sintered cells (12 cm x 12 cm) have been successfully fabricated.
  - Research and development is being done in collaboration with Battelle.
  - Process development being done internally at Delphi.

- Multiple stacks from 1-cell to 30-cell have been fabricated. 2X15-cell ISMs (Integrated stack module) have also been fabricated and are being tested in the APU systems.

Cassette with cell (repeating unit)



30-cell stack under test



Integrated stack module-ISM

(Two 15-cell stacks+ current collector + load frame)

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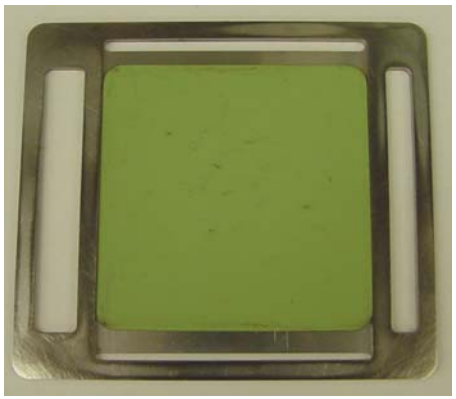
Generation 2 Stack
Cell and Stack Development Scale Up

106 cm^2 Active Area

34 cm^2 Active Area



3.5 cm^2

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

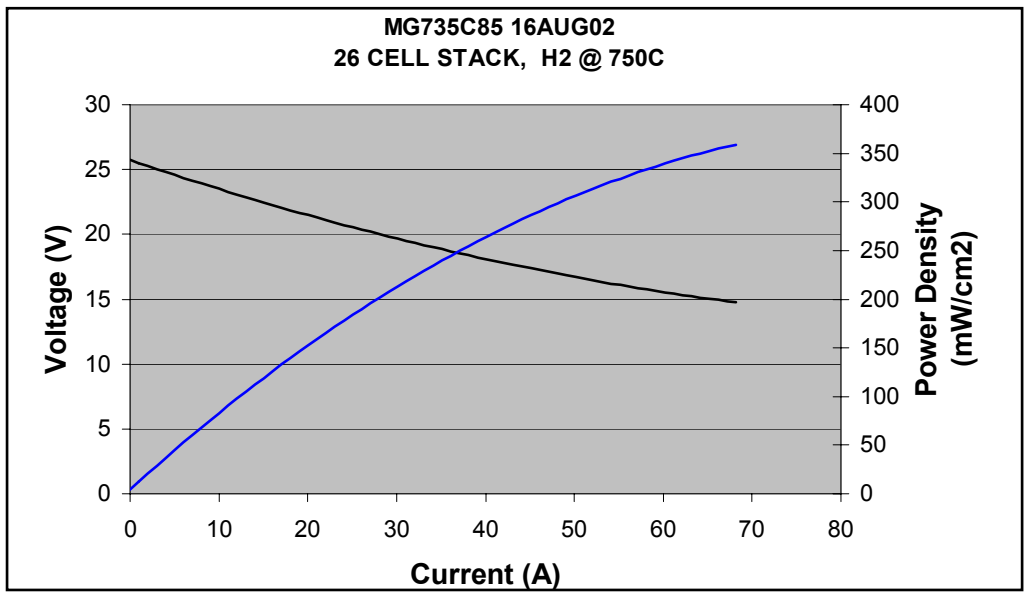
Full-Scale

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

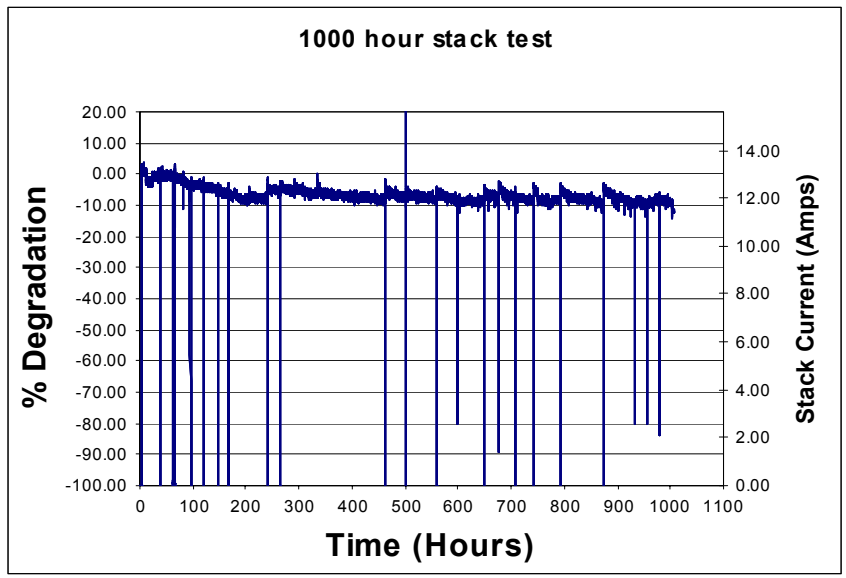
Generation 2 Stack
Stack Test Results

- Cell power density (coupon sized cell) : > 0.9 W/cm^2 at 750°C and 0.7 V (H_2) (1.4 W/cm^2)
- 1-cell stack power density (7cm x 7cm cell) : 0.6 W/cm^2 at 750oC and 0.7 V(H_2)
- 1000h test completed on 3-cell stack (7cm X 7cm cell) at 750^{o}C (H_2)
- 20 thermal cycles demonstrated on 1-cell stack (12cm x 12 cm cell); 5 cycles on 3-cell stack
- 26-cell-stack (12cm x 12cm cell): 350 mW/cm^2 at 750°C, 0.6V/ cell (H_2)

26-cell stack (12cm X 12cm) cell



3-cell stack (7cm X 7cm) cell, 1000 hours



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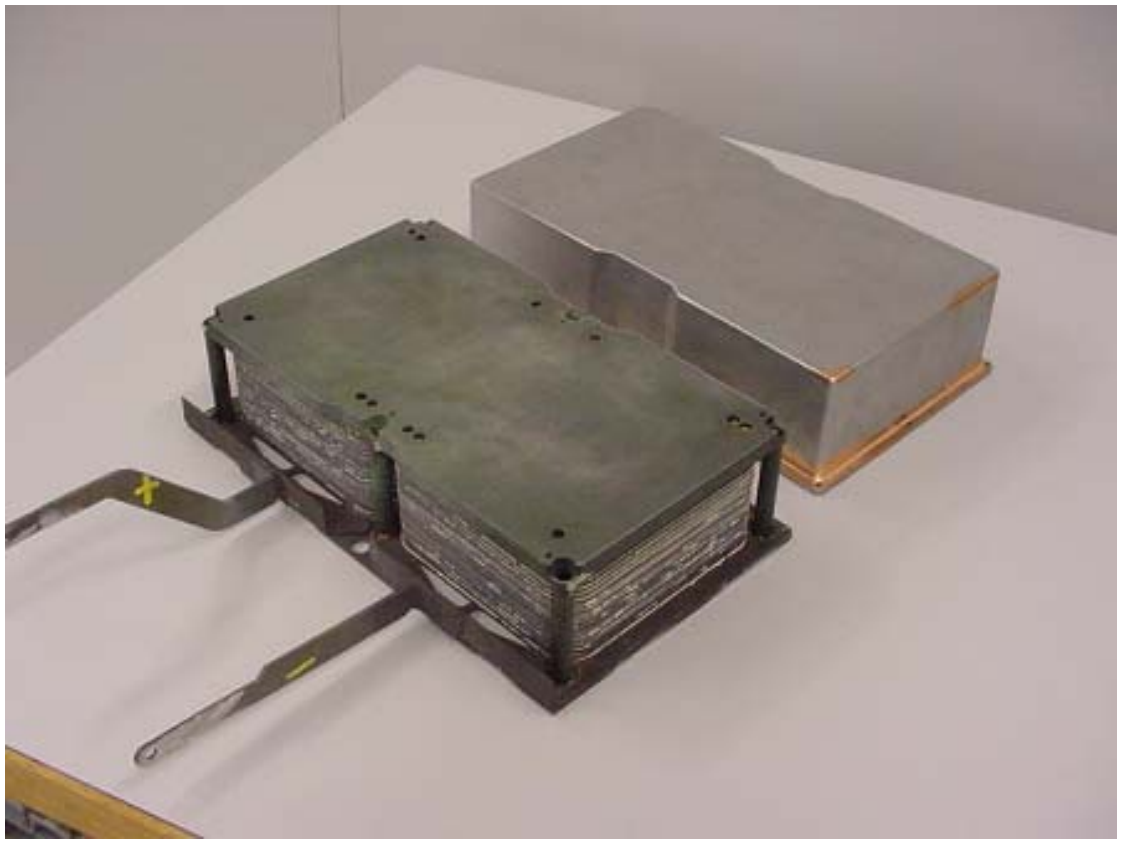
Generation 2 Stack
Integrated Stack Module



- 2x15-cell stacks on a manifold (load frame, current collectors included) after sealing and initial electrochemical testing .
- Ready for integration to the APU.

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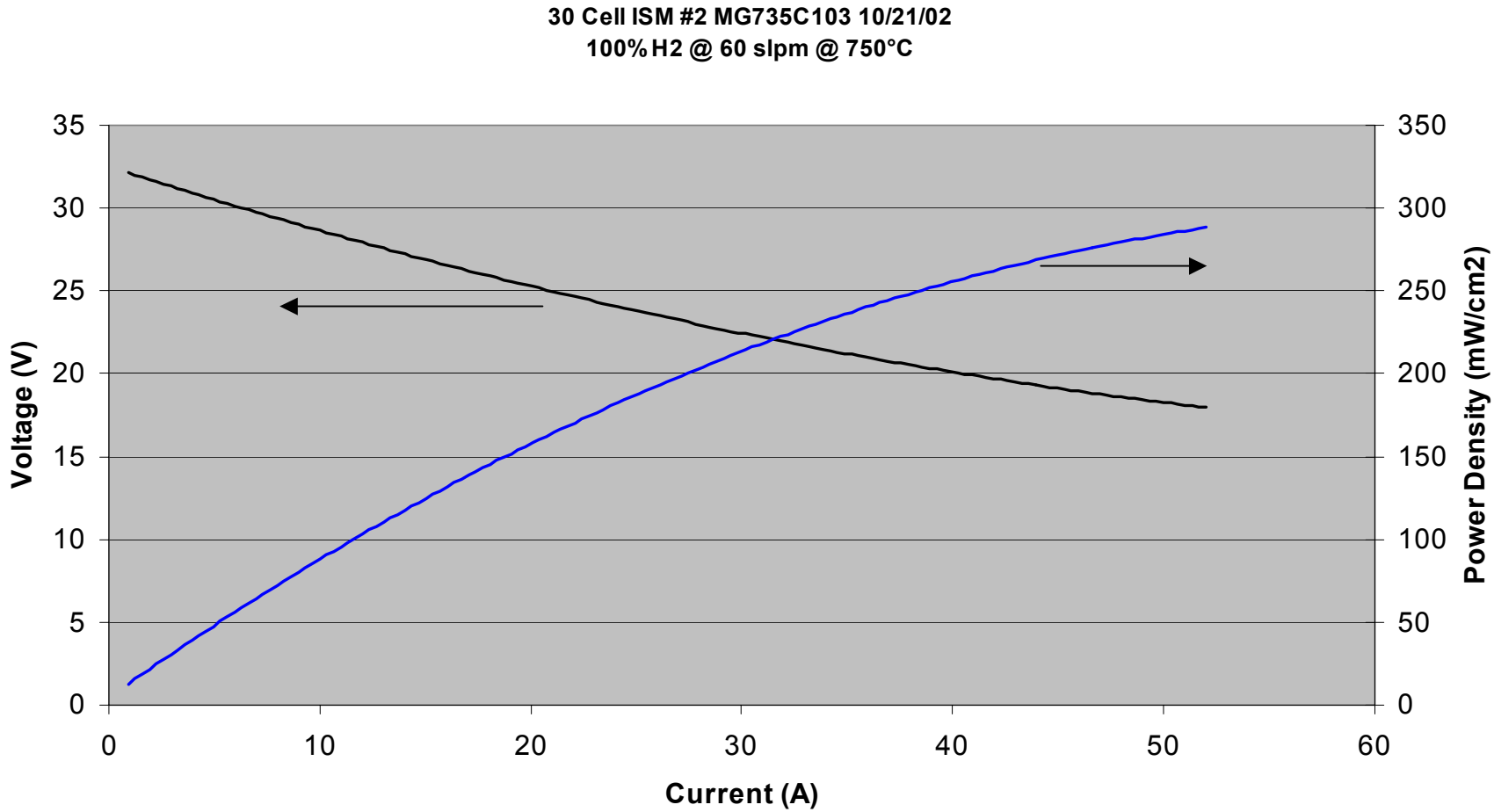
Generation 2 Stack
ISM -2x15 cell stack



- Produced 918 Watts @ 18 V (750°C, H_2).

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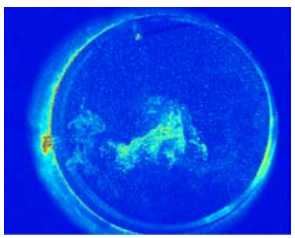
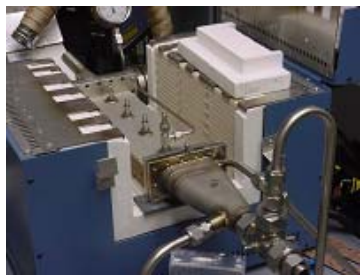
Generation 2 Reformer Introduction

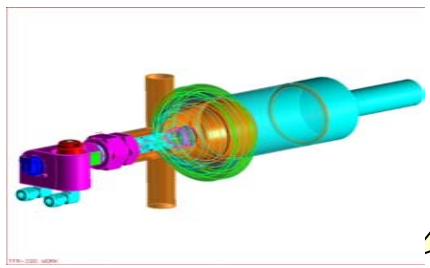
- Delphi is developing reformer technology for reforming gasoline, diesel and natural gas.
- Fundamental research, catalyst development, computer aided engineering, controls development and extensive testing is leading to robust, manufacturable product designs.



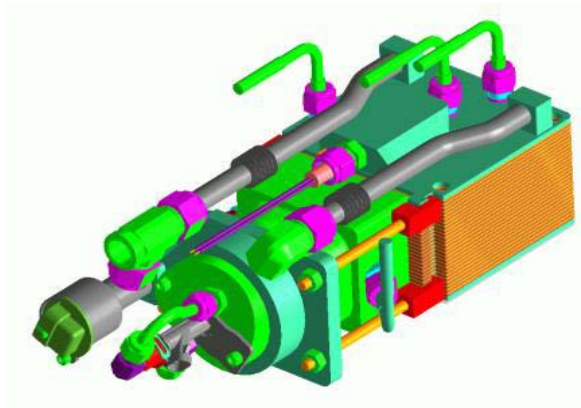
Fundamental Development



Controls development and validation



Computer aided design



Generation 2 Delphi reformer

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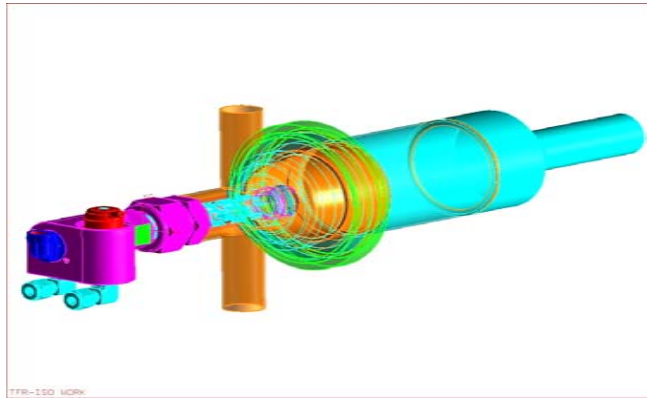
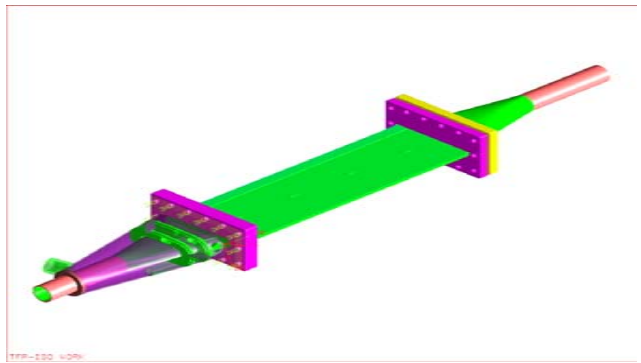
Generation 2 Reformer
Reformer Design Parameters

- Operate at required Reformate Power & Efficiency (kW_{lhv})
- Operate under non-Carbon forming conditions
- Operate with minimum CH_4 and Emissions levels
- Tolerance to fuel sulfur content
- Combine functions of reformer and energy recovery unit into one device (ReforWER)
- Utilize system heat sources to match with Reformer System heat requirements



Tubular



Planar

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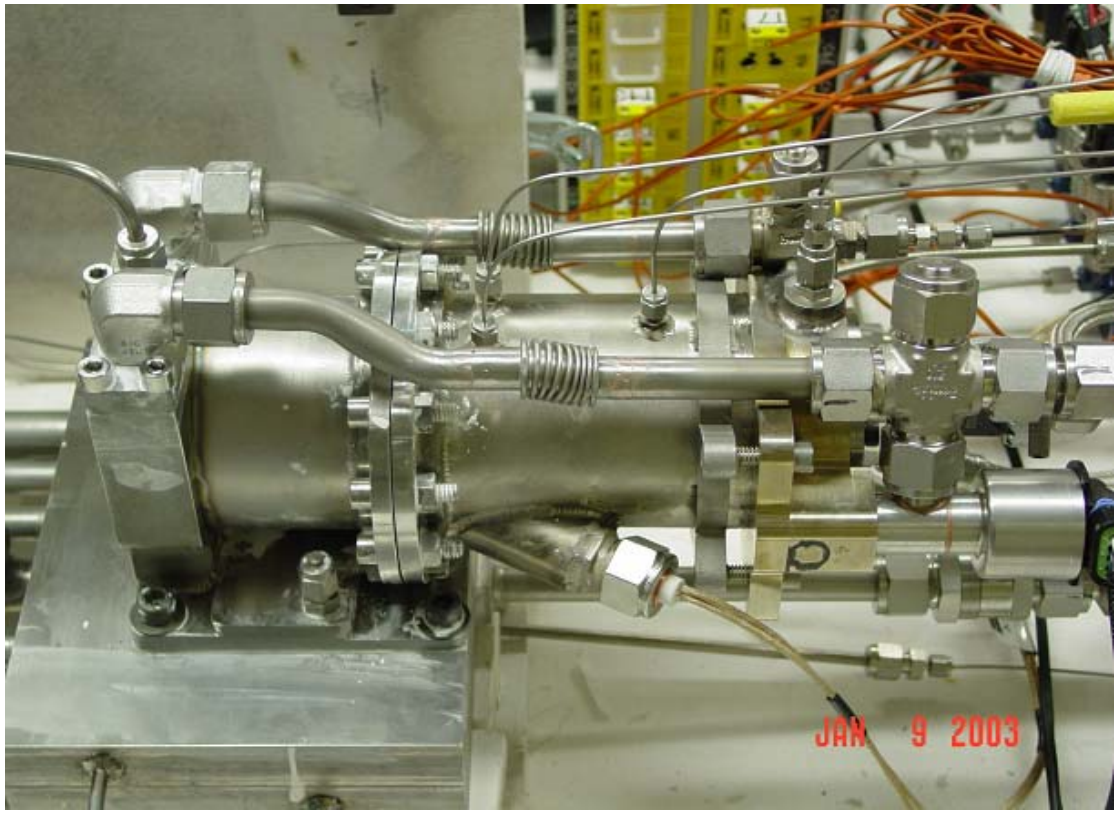
Generation 2 Reformer
Tubular Reformer Assembly



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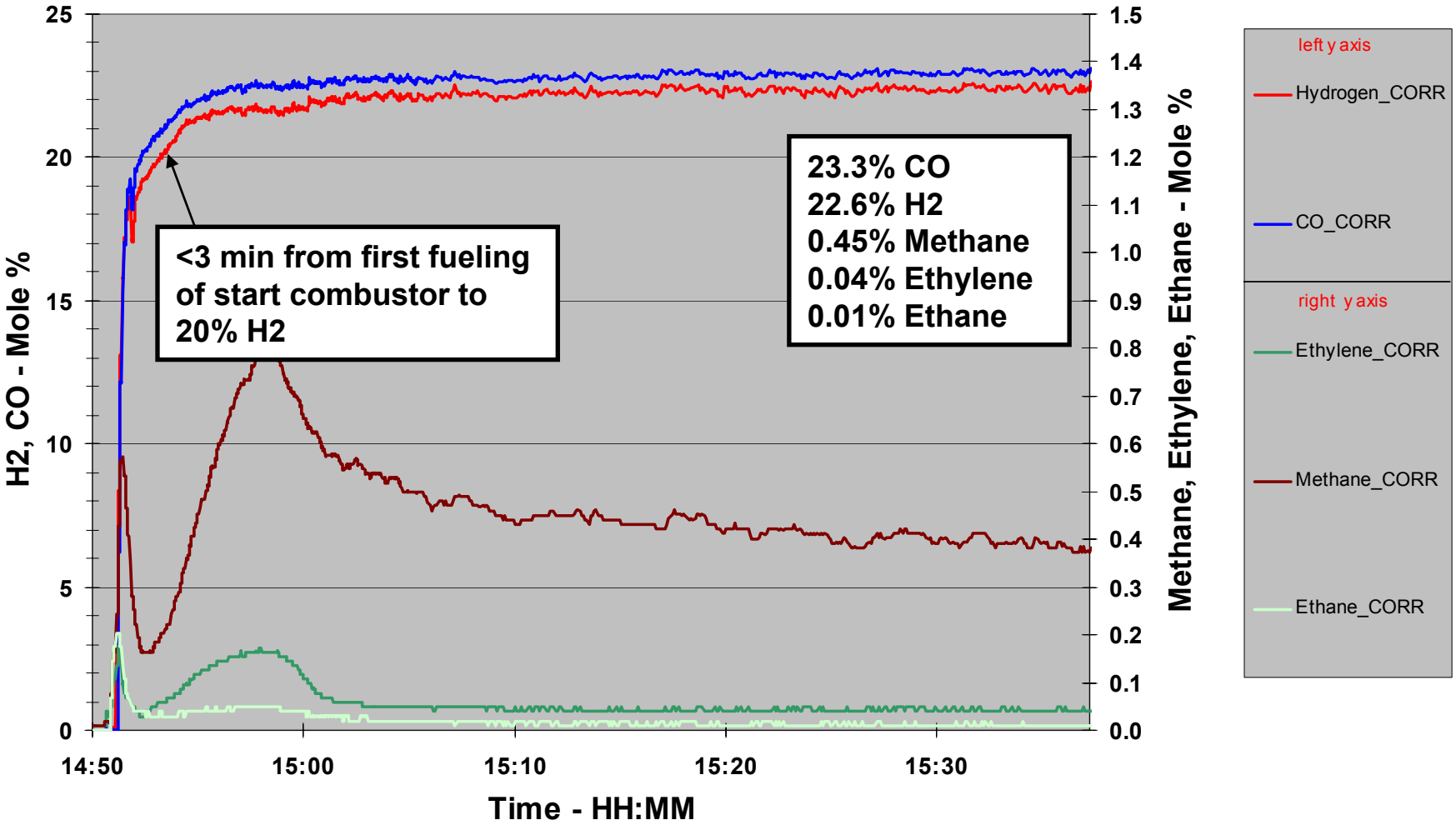
Generation 2 Tubular Reformer Time vs Composition



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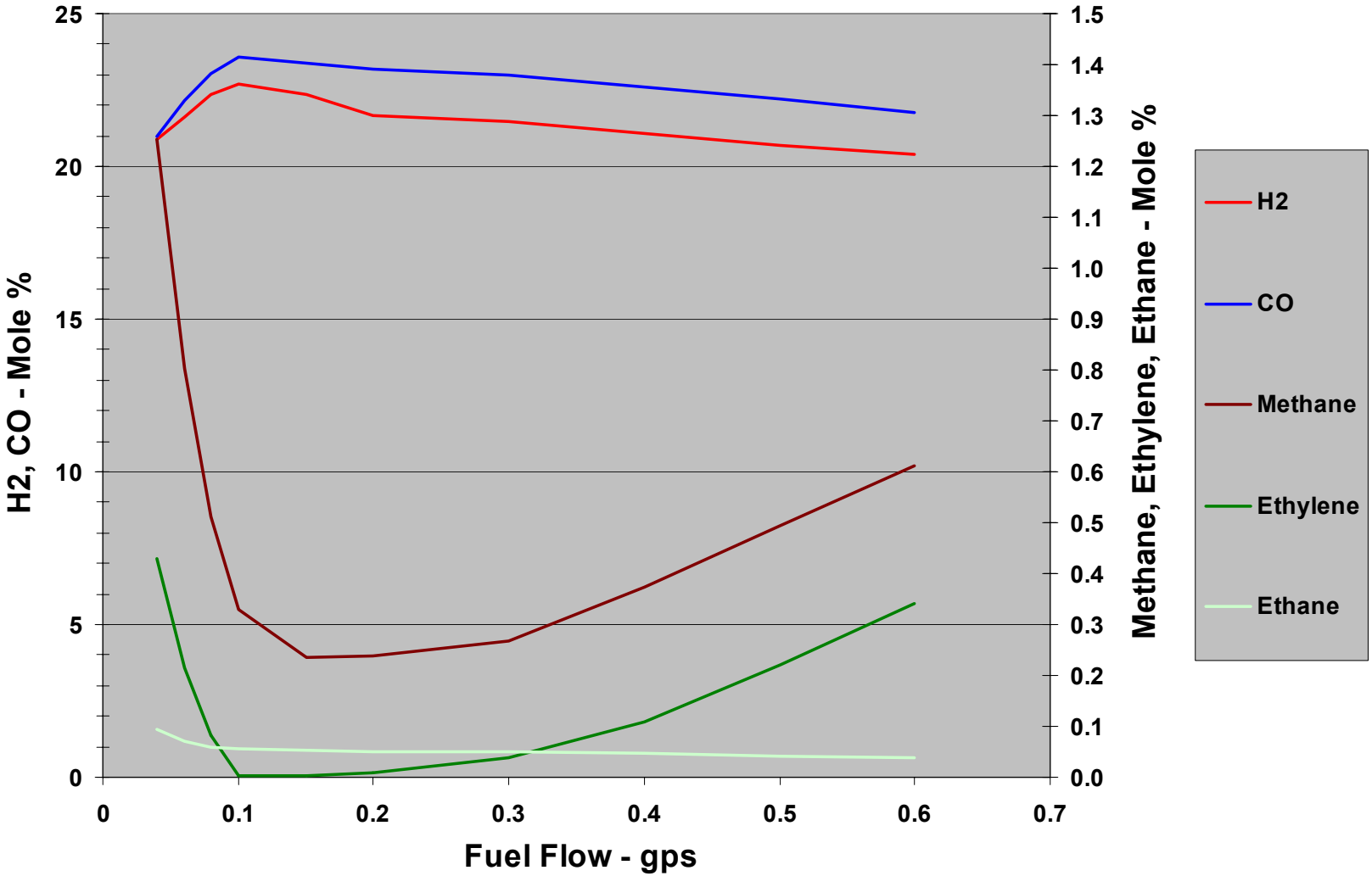
Tubular Reformer
Fuel Flow vs Composition



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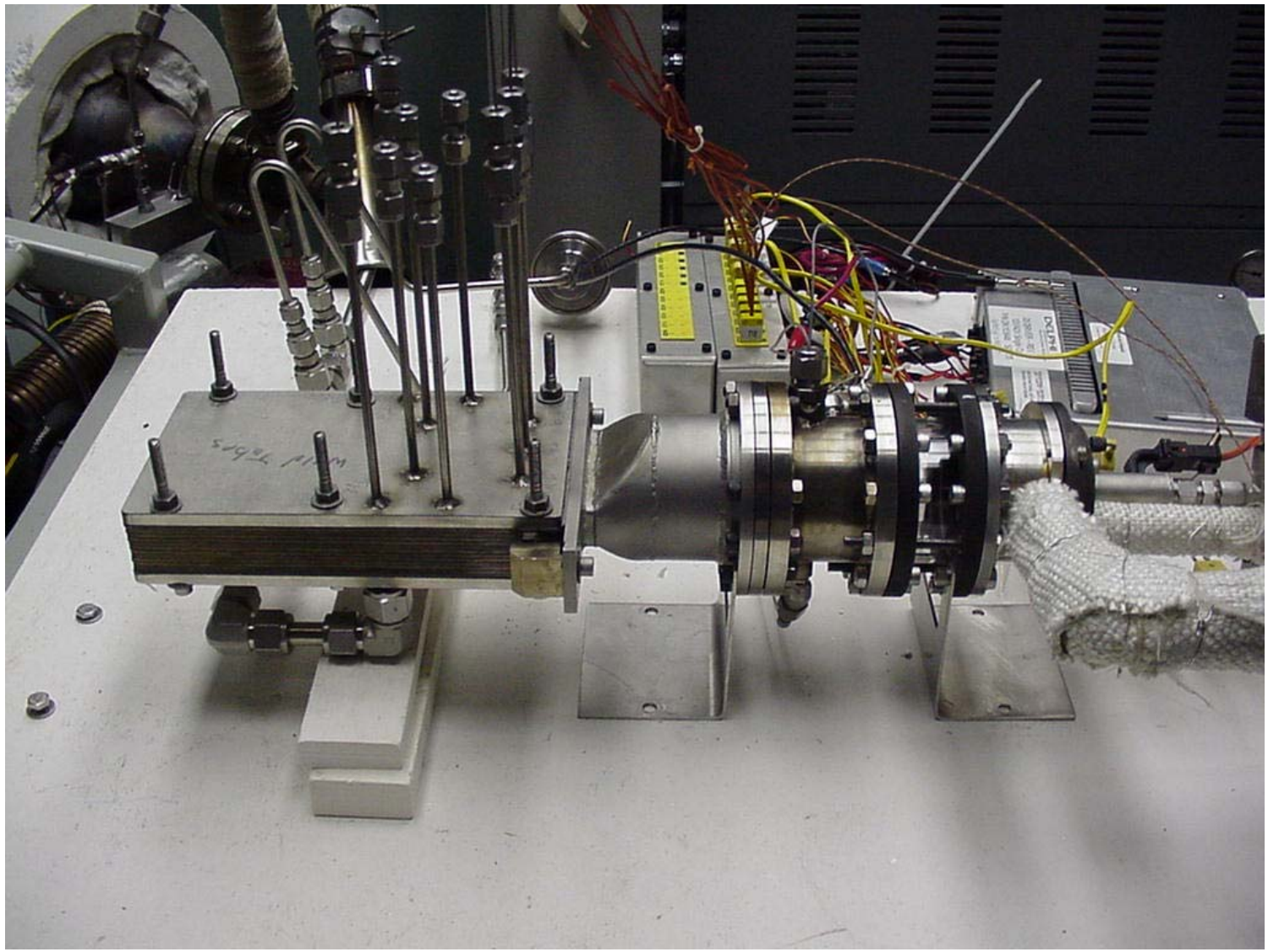
Generation 2 Reformer
10 plate ReforWER



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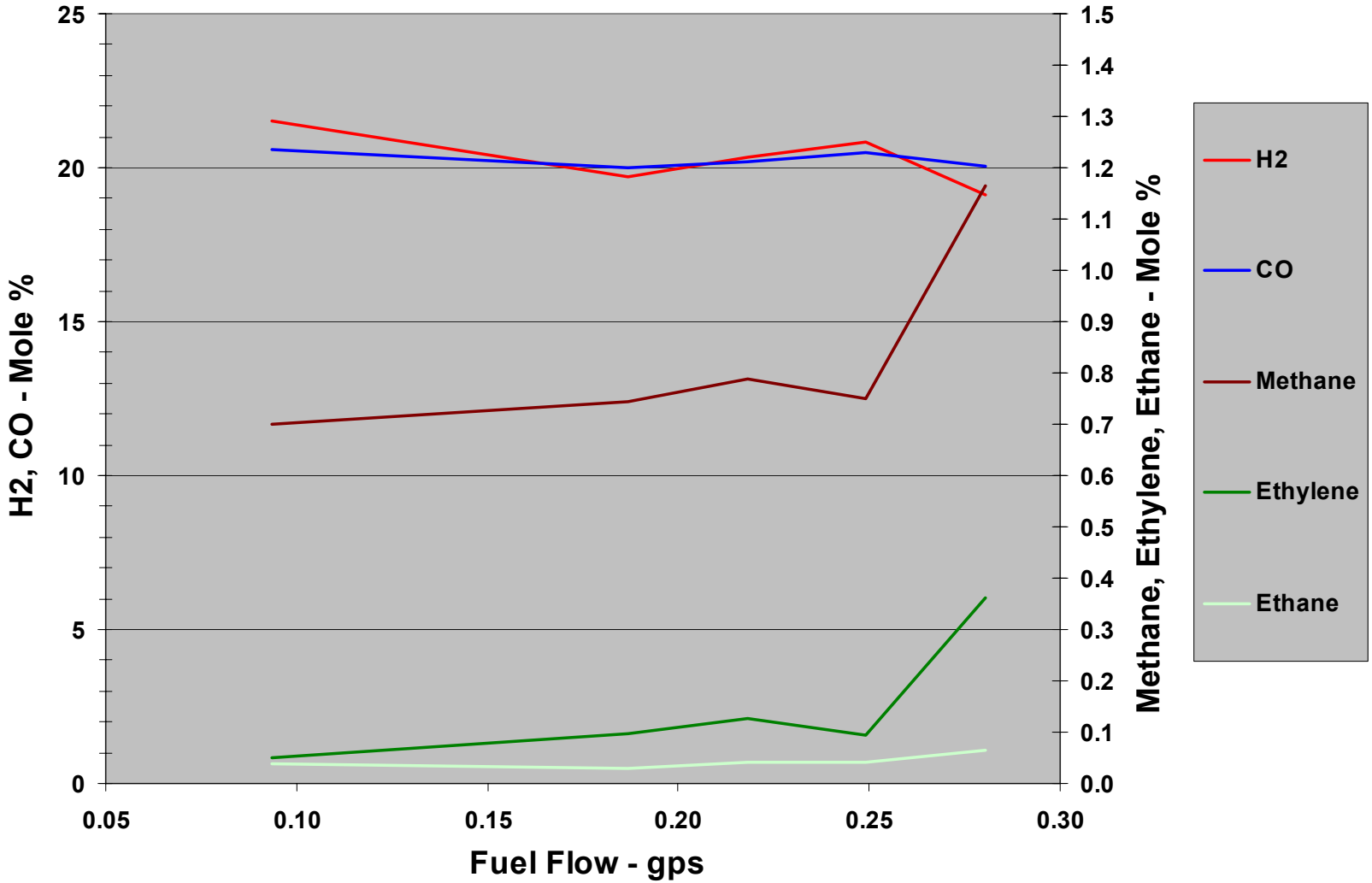
H1 10 Plate ReforWER
Fuel Flow vs Composition



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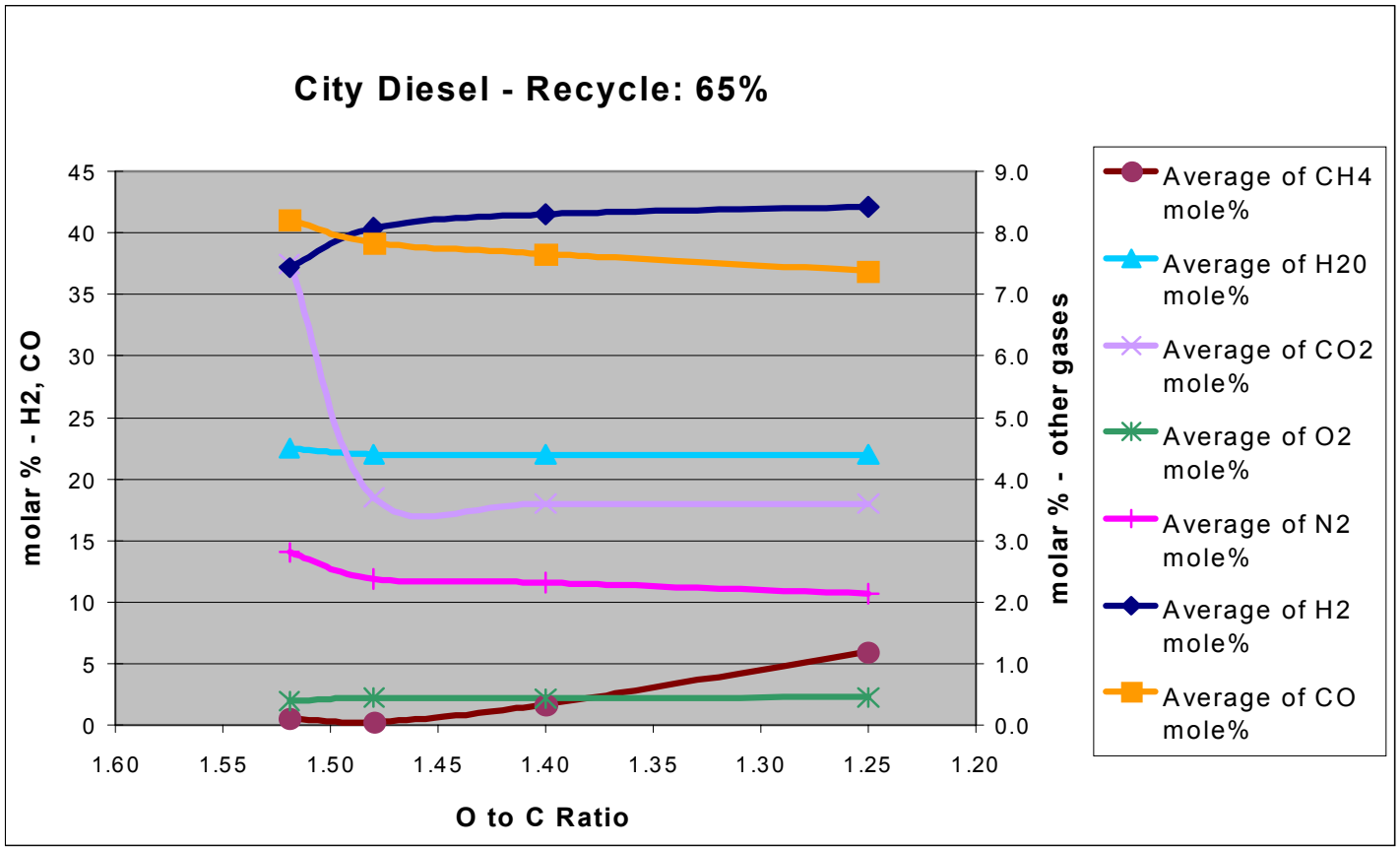
Generation 2 Reformer
1 Plate Reformer Test Data with Diesel

- Single Planar laboratory reformer on City “Swedish” Diesel fuel:
  - 65% Anode recycle condition typical for high efficiency operation of system



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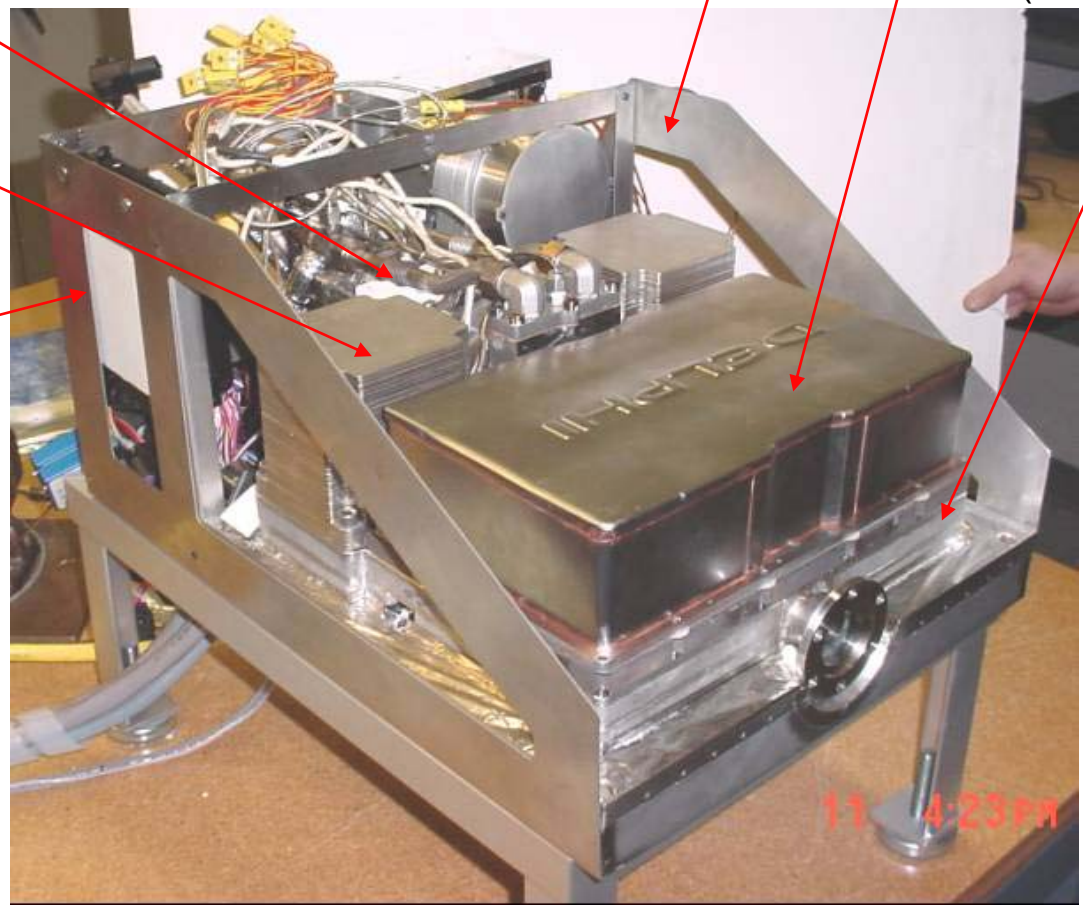
Generation 2 SOFC APU
SOFC APU Integration



- Successful integration and build of SOFC APU

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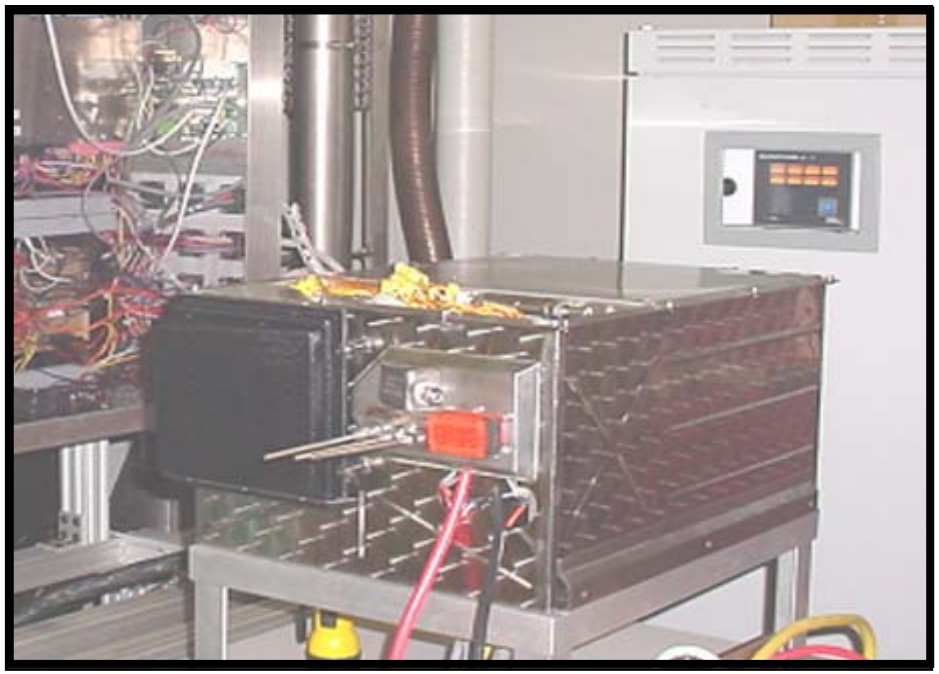
Generation 2 SOFC APU From Gasoline to Power

Successful heat-up and production of electric power from gasoline



All components in the APU sized for 5kW net electric power

- Multiple tests carried out
- Successful cold start on gasoline
- Fastest heat-up in ~60 minutes (to date)
- Tubular reformer produced good quality POx reformate from gasoline
- 2 x15-cell ISM produced OCV and power (30.8 V OCV, 486 Watts @ 15.2 V power)
- Further optimization ongoing
- Key milestone in the development of Generation 2 APU

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Status and Technical Challenges

- The Generation 2 SOFC APU addresses many of the key challenges discussed in the Proof of Concept system.

  The current status of development is:

Cost	
Volume and Mass (Packaging)	
Power density	
Efficiency Projection	
Fast Startup	
Thermal Cycling	
Robustness	

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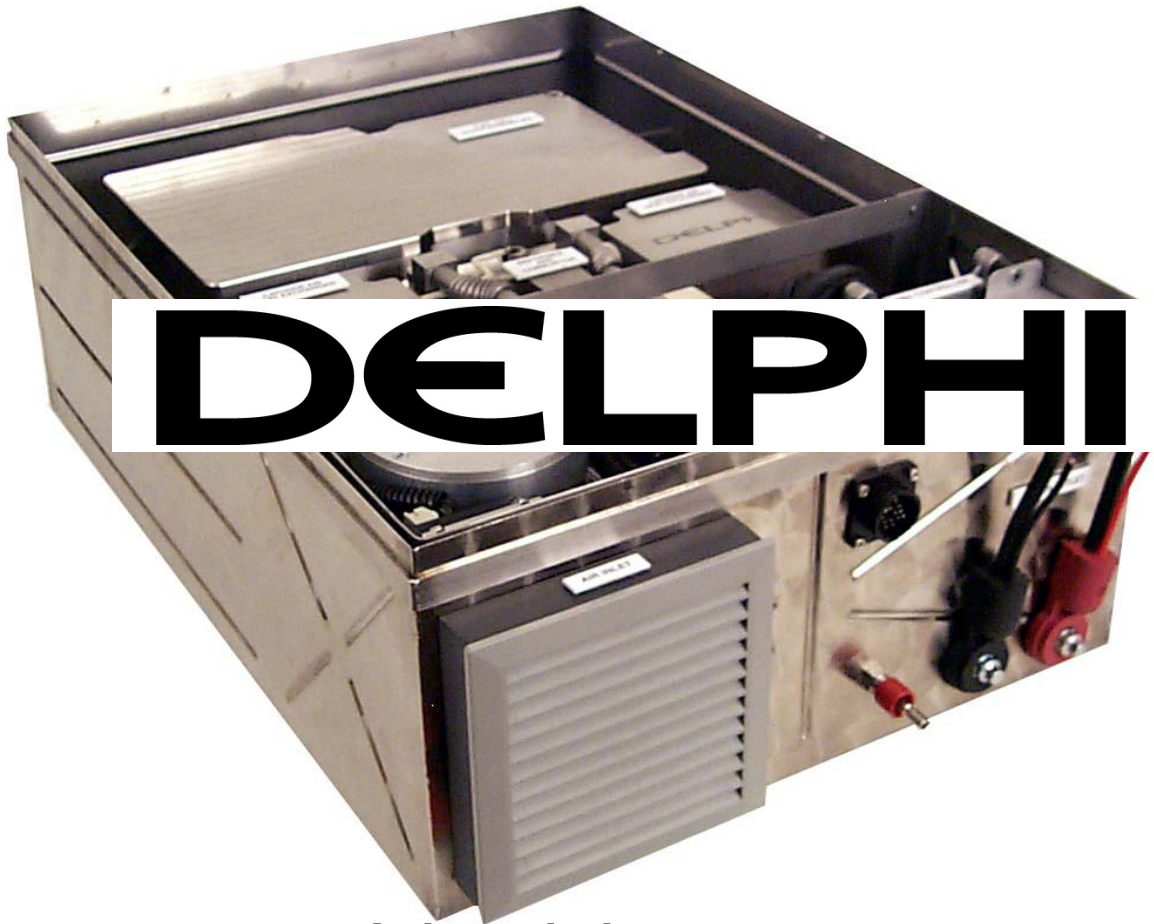
Summary and Conclusions

- SOFC based power systems is a paradigm shift in the supply of electric power for transportation and stationary applications.
- Its applications in transportation include premium class automobiles, work trucks, recreational vehicles, fire-rescue vehicles, military vehicles, ships and aircraft. Its stationary applications include distributed power generation systems and CHP systems.
- Delphi has pioneered its application as an APU for transportation. It is also pursuing complimentary stationary applications.
- A Generation 2 APU has been developed and is being tested. Current development is focused on addressing the challenges to improve performance and robustness of this system. Work is ongoing on improving durability, power density, efficiency and fast start-up. Work is also focused on lowering cost.
- Delphi is committed to working with customers and partners to bring this novel technology to market.



Acknowledgement

- **US-Department of Energy, Solid State Energy Conversion Alliance (SECA)**