
# Delphi SOFC Development Update

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Chief Engineer – Fuel Cell Development

Pittsburgh, PA
2008 SECA Annual Review Meeting

# Outline

- Cell and Stack Development
- Reformer Development
- Balance of Plant Development
- Systems Development
- Programs Leveraging SECA Activities

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# SOFC Subsystem Development
# Cells and Stacks

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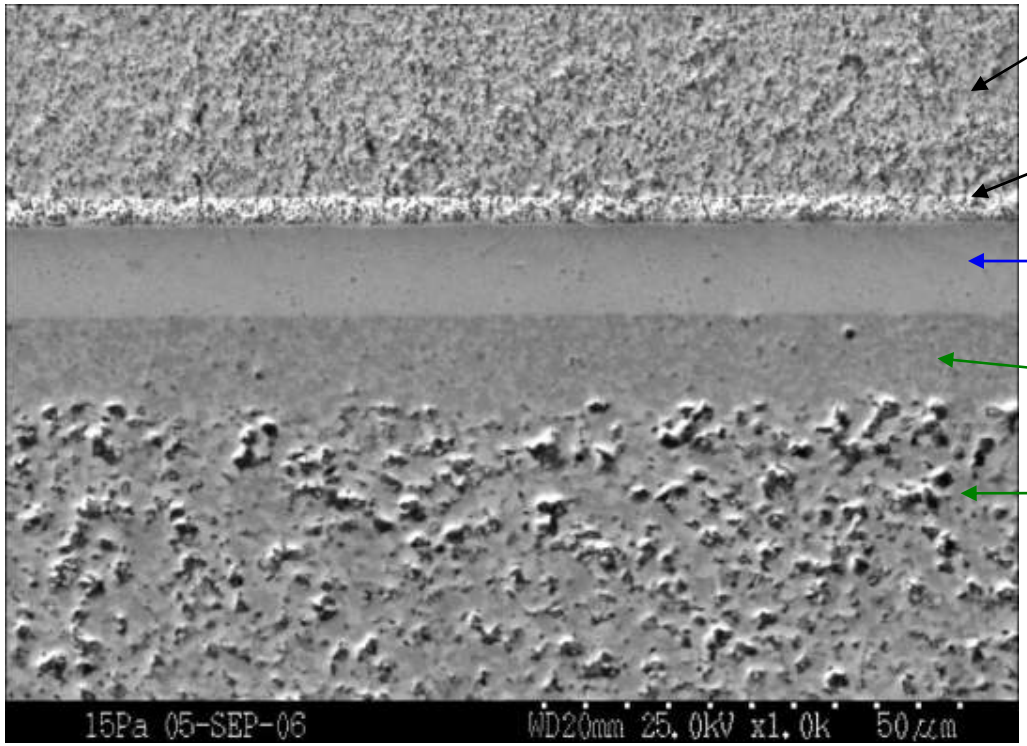
# Anode Supported Cell Microstructure

- Delphi is fabricating anode supported cells with LSCF cathode
- Current footprint is 140mm x 98mm (active area 105 sq cm)
- 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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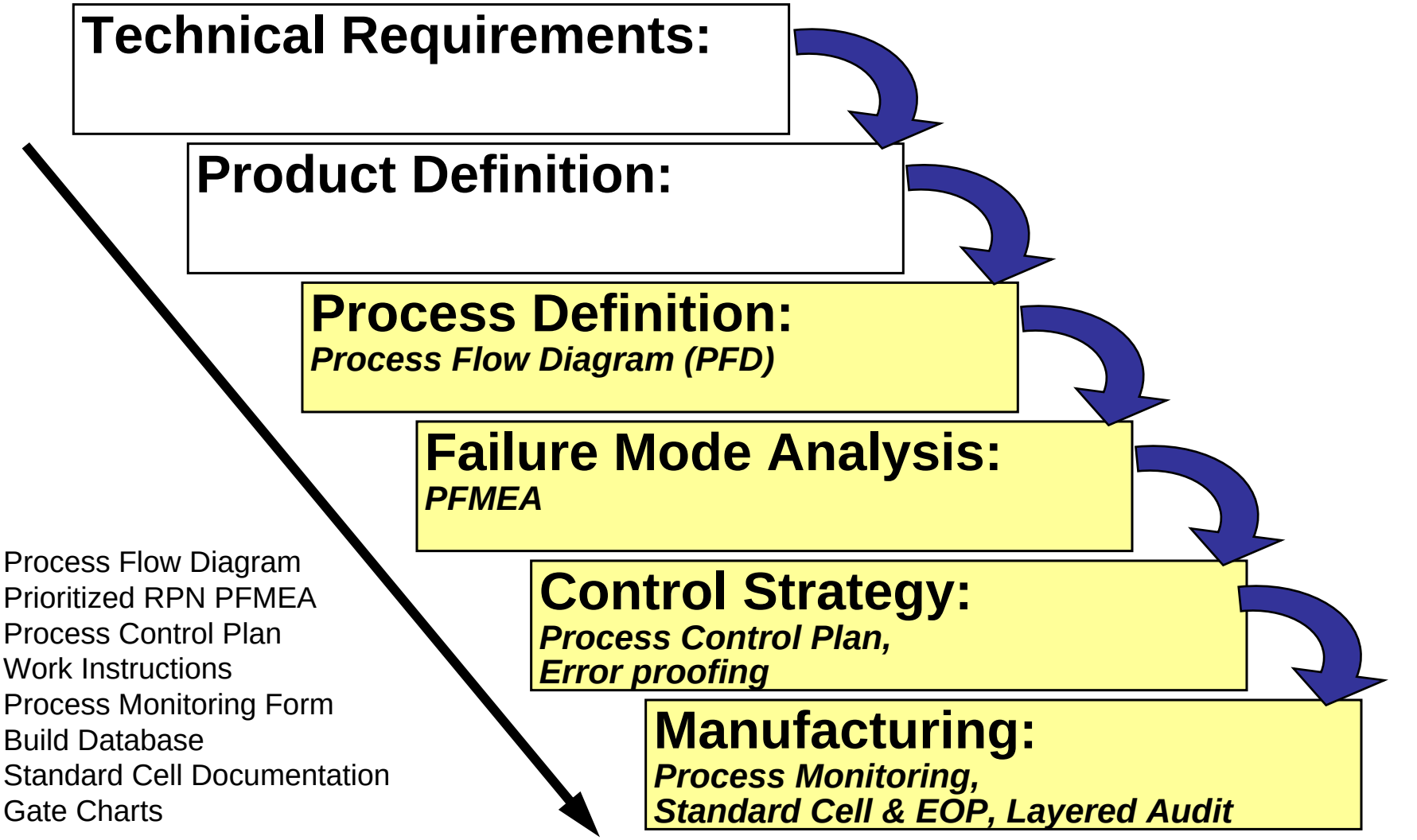
# Manufacturing System Development




Process Flow Diagram
Prioritized RPN PFMEA
Process Control Plan
Work Instructions
Process Monitoring Form
Build Database
Standard Cell Documentation
Gate Charts

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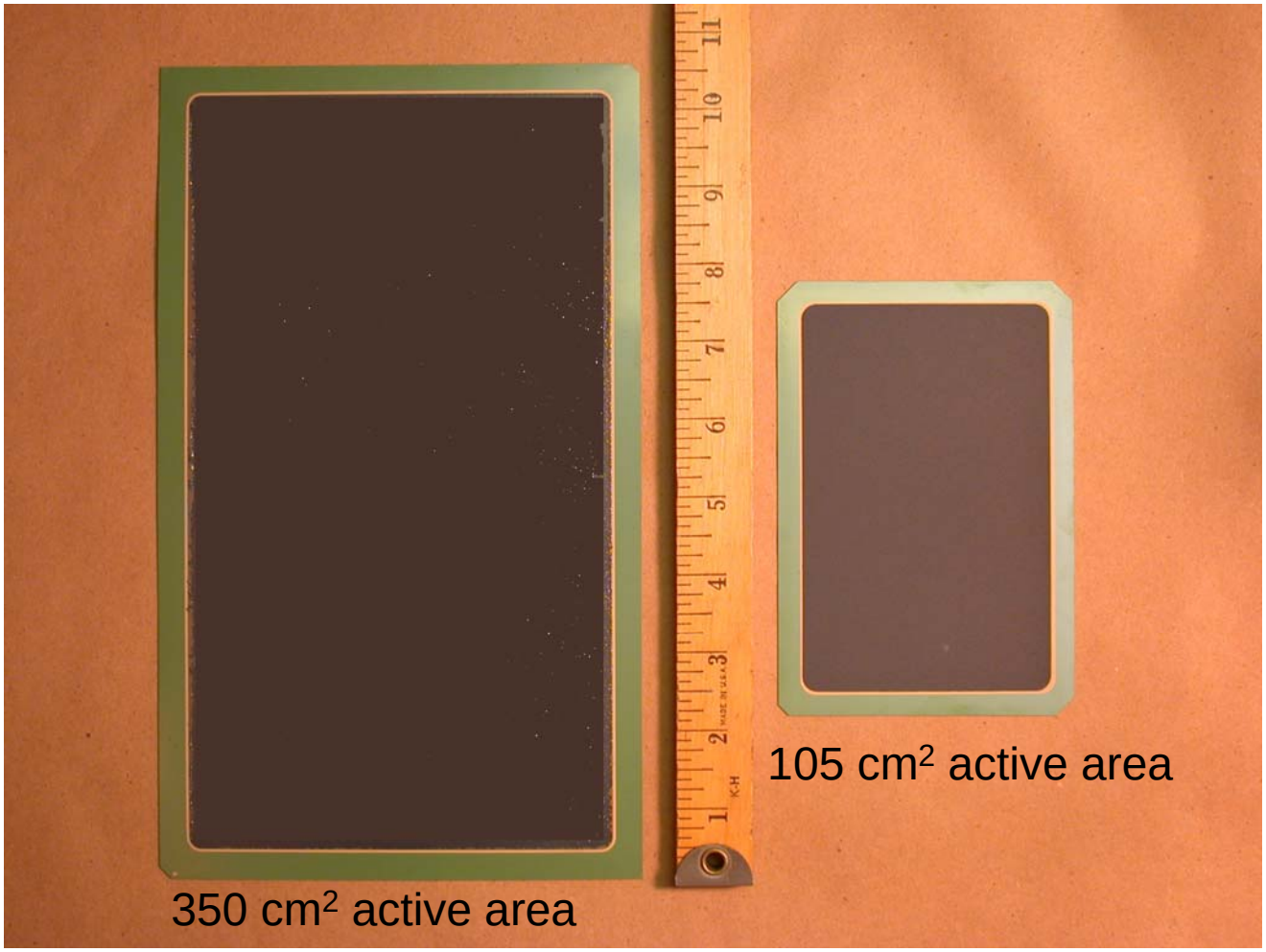
# Large Footprint Cell Fabrication

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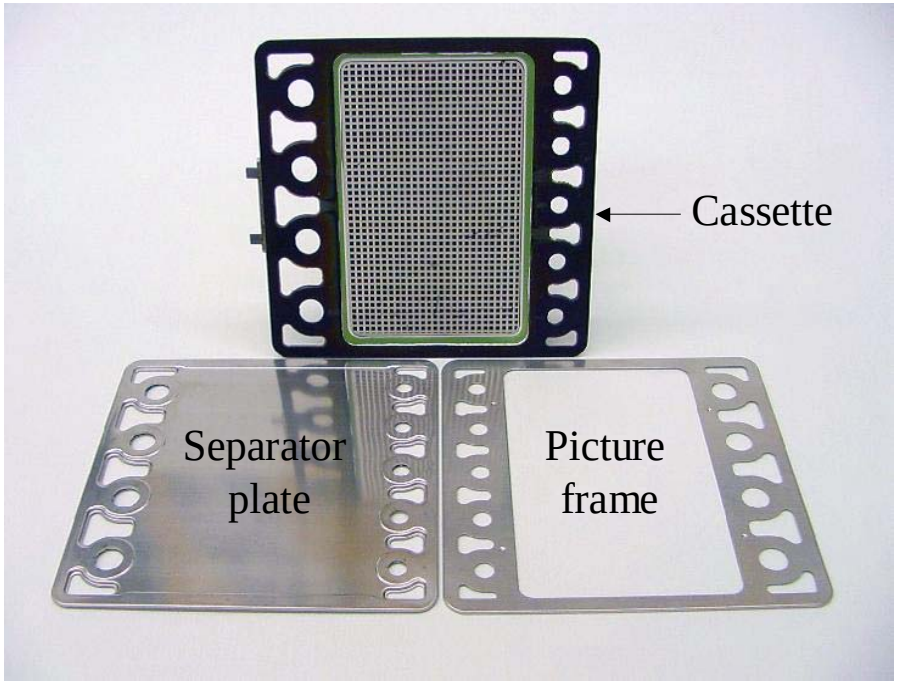
# Generation 3 Stack
# Key Features

- 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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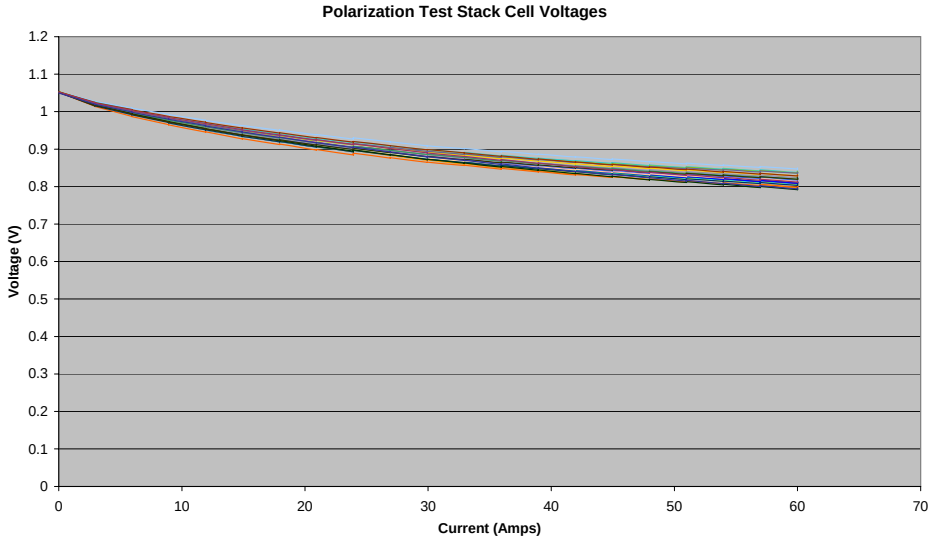
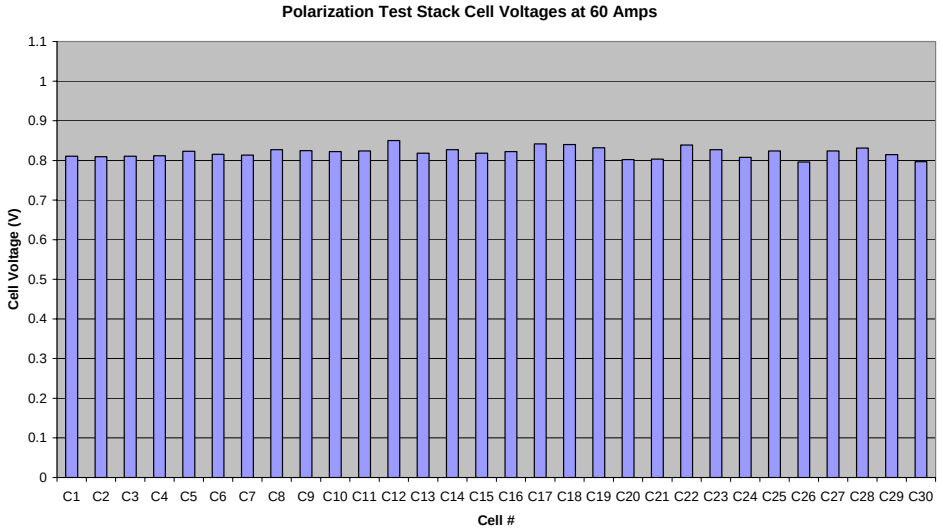
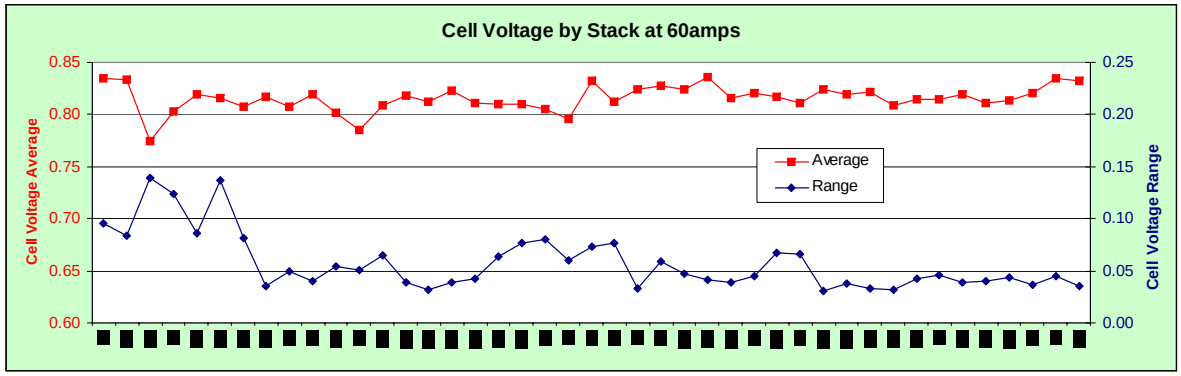
# Cassette Variation in a 30-Cell Stack

- Consistent performance between cassettes in a 30-cell stack
  - Voltage difference between best and worst cassette is 0.05V or less
  - Achieved by application of high volume manufacturing process control methods

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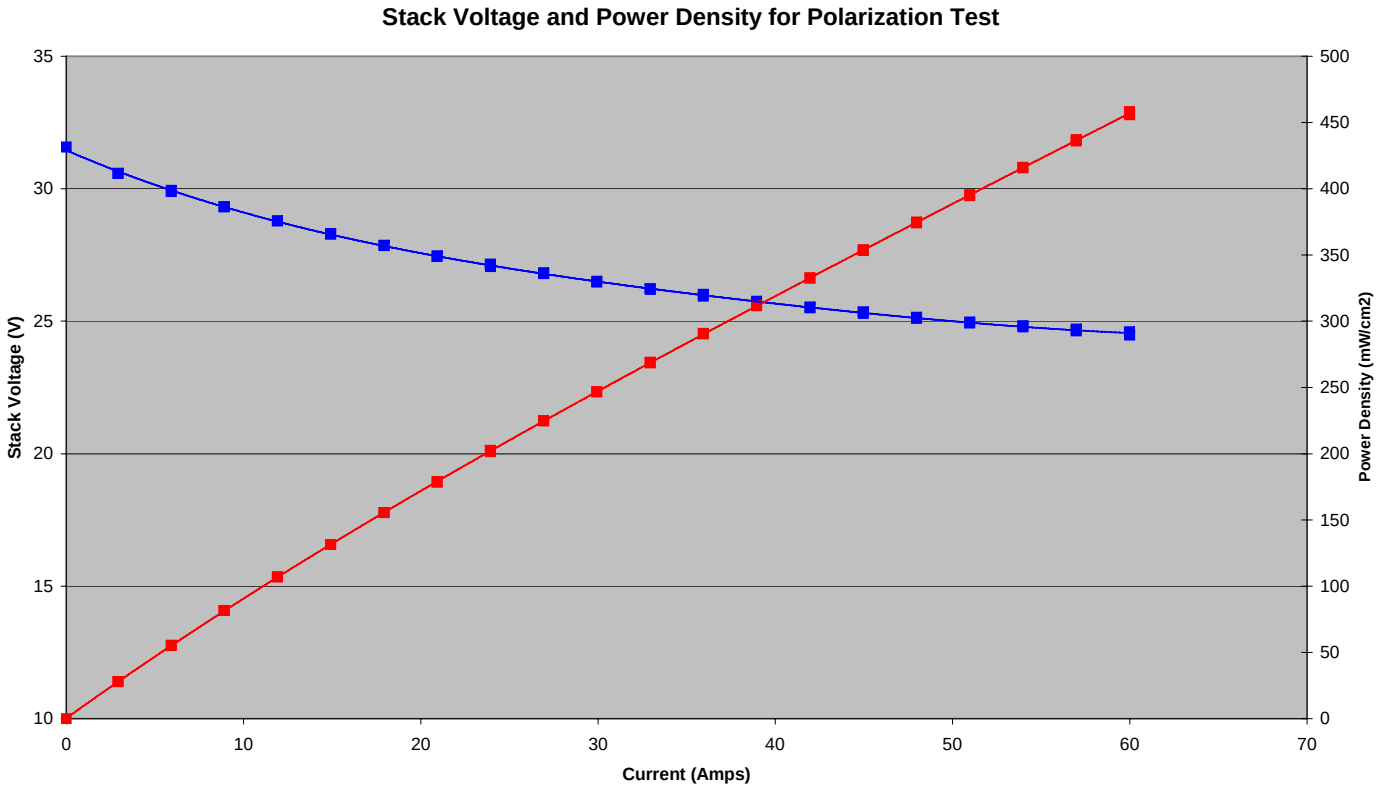
# Generation 3 30-Cell Stack Data

- Data shows a typical 30-cell Gen 3 stack tested in the stack laboratory furnace
- Power: 1.44 kW (450 mW/cm$^2$) @ 60A (570 mA per cm2), 24.6 V (0.82V / cell avg), fuel 48.5% H2 (3% H2O, rest N2), 750$^o$C

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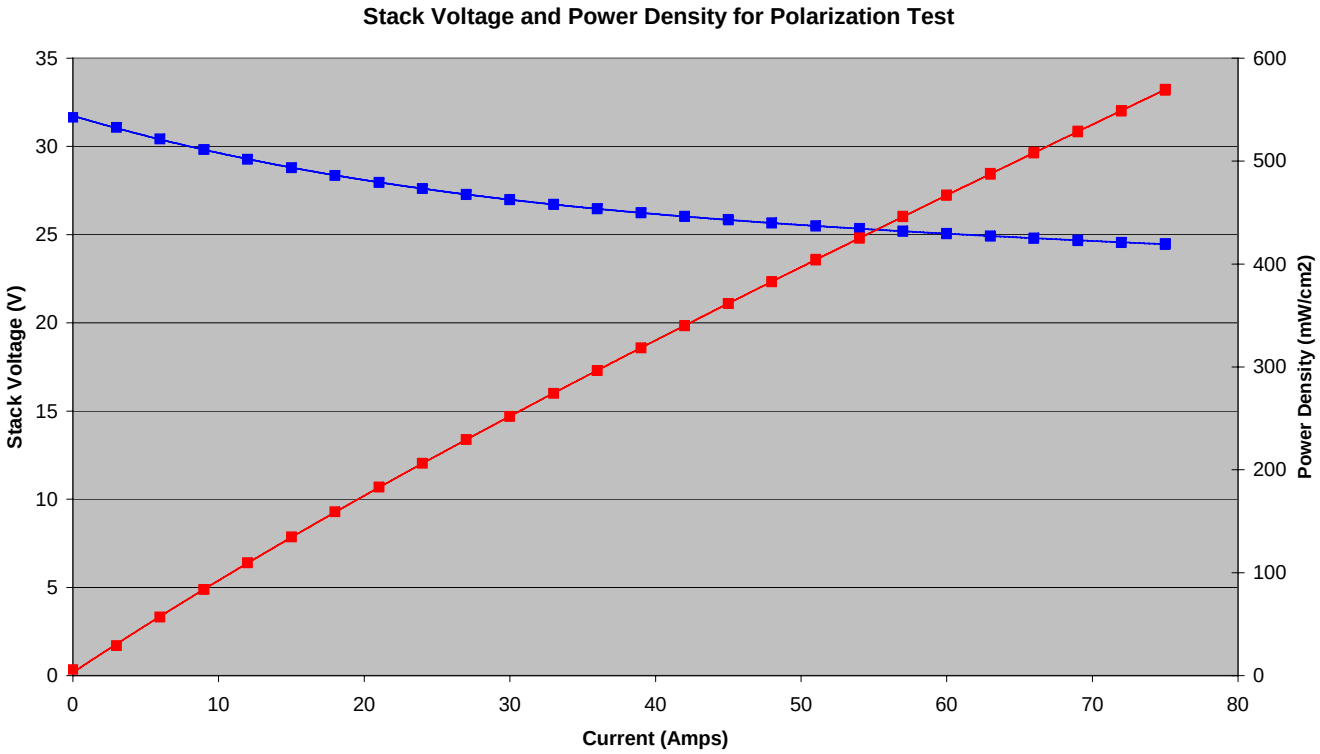
# Generation 3 Stack Recent Improvements

- Interconnect development
  - Data for a 30-cell Generation 3 stack tested in a stack laboratory furnace
  - Demonstrated 1.8kW (570 mW/cm$^2$) @ 75A (0.71 mA/cm$^2$), 24.5V (0.82 V / cell), fuel 48.5% $H_2$ (3% $H_2O$, rest $N_2$), 750$^o$C (800$^o$C avg stack internal temp)
  - Demonstrated comparable thermal cycling capability and stability

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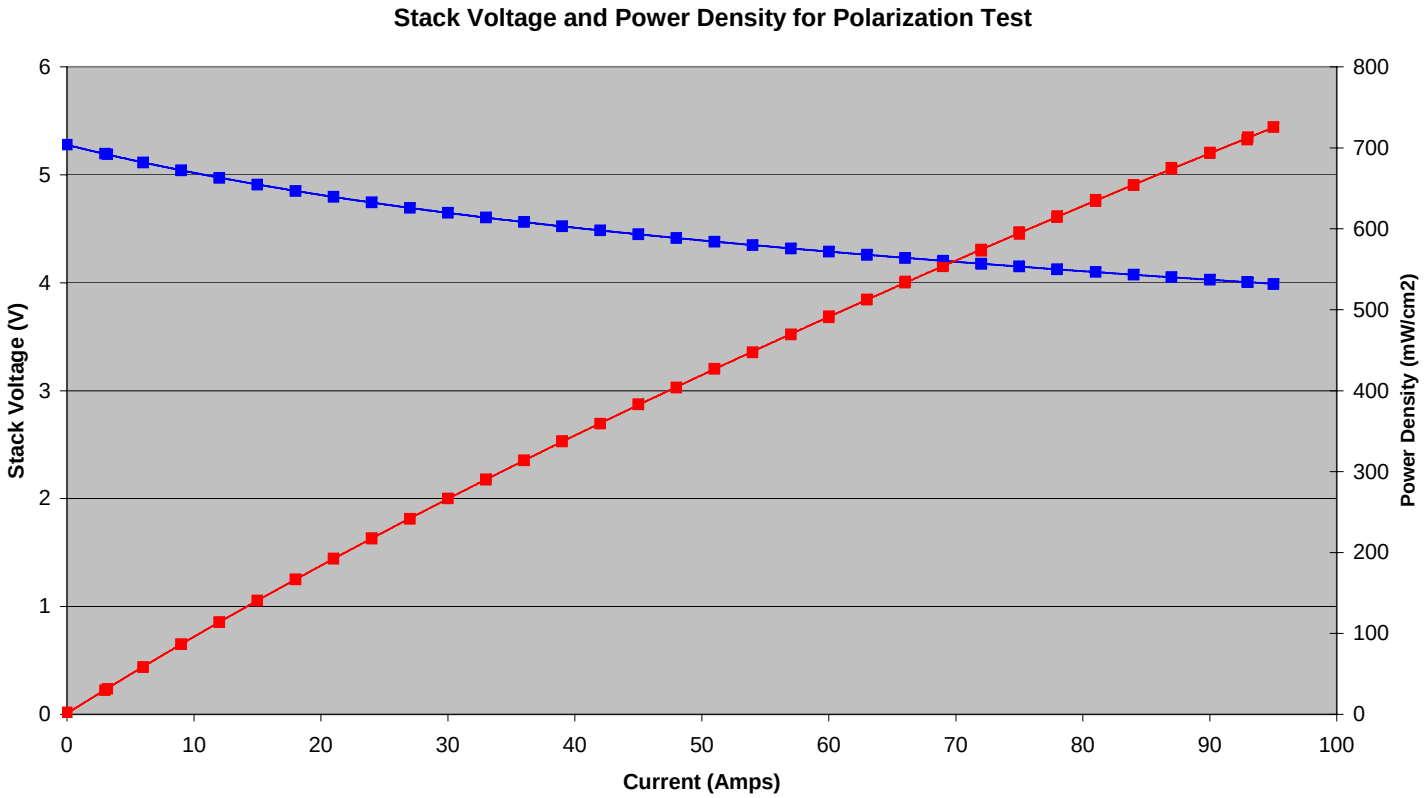
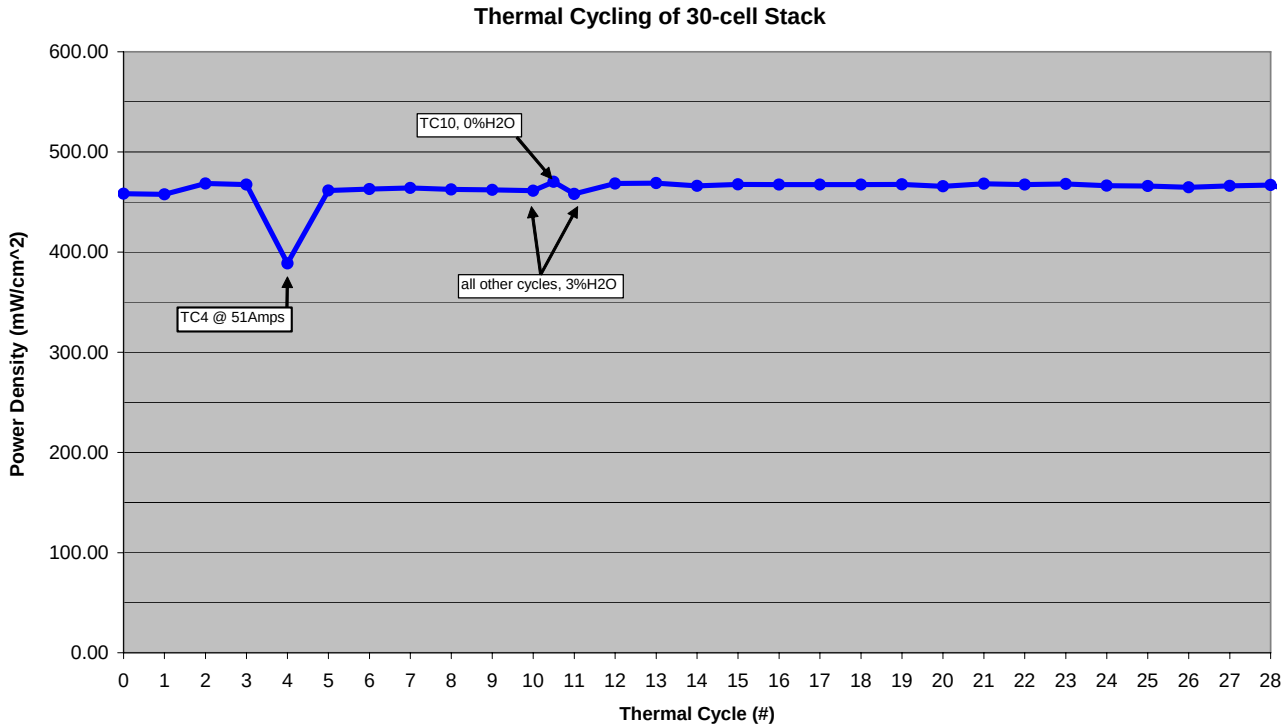
# Generation 3 Stack Recent Improvements

- Improvements to cathode material
  - Data for a 5-cell Generation 3 stack tested in a stack laboratory furnace
  - Demonstrated 725 mW/cm$^2$ @ 0.80V / cell (48.5% $H_2$, 3% $H_2O$, rest $N_2$), 750$^o$C
  - Currently evaluating thermal cycling capability and stability – results to date comparable to current cathode material set



# Thermal Cycling of Stacks

- Stable thermal cycling performance demonstrated
  - Data shown for 30-cell stack, 2 hour heat-up
  - Robust interconnect system and cells
  - Mechanical integrity with improved seal technology




**Thermal Cycle Leak Data**

| Cycle | Leak (SCCM) | | |
|---|---|---|---|
| | Anode | Cathode | Crossover |
| Initial | 47.0 | 27.0 | 0.0 |
| TC5 | 40.0 | 36.0 | 0.0 |
| TC10 | 26.0 | 13.0 | 0.0 |
| TC15 | 39.0 | 26.0 | 0.0 |
| TC20 | 52.0 | 32.0 | 0.0 |
| TC25 | 48.0 | 40.0 | 0.0 |

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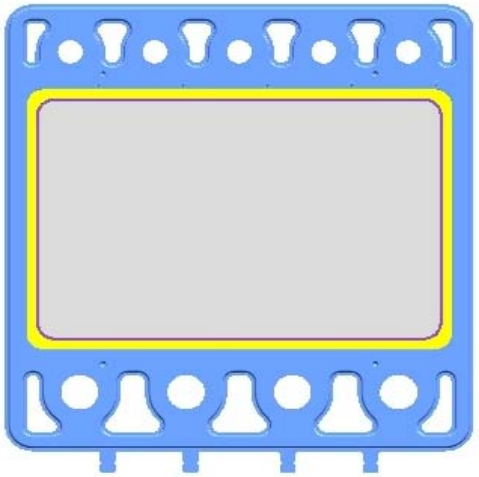
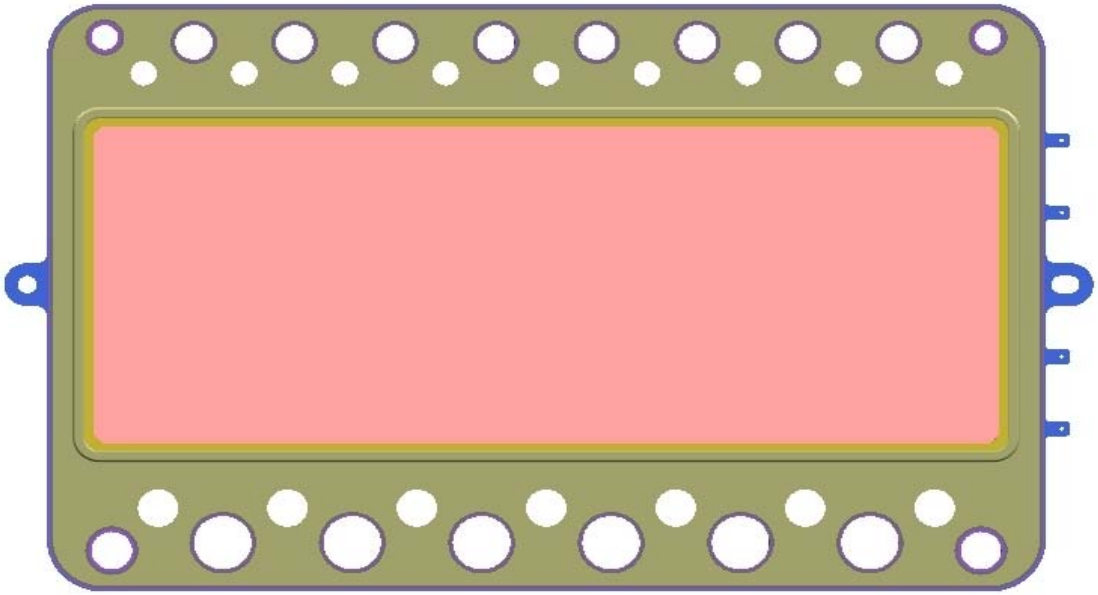
# Next Generation Single Cell Repeating Unit

Gen3.2



Next Generation Cassette



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# SOFC Subsystem Development
# Reformer

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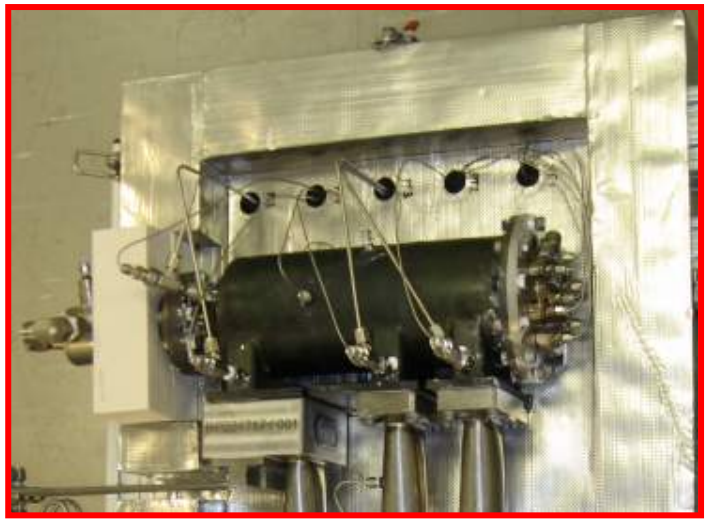
# Fuel Reformer Development

- 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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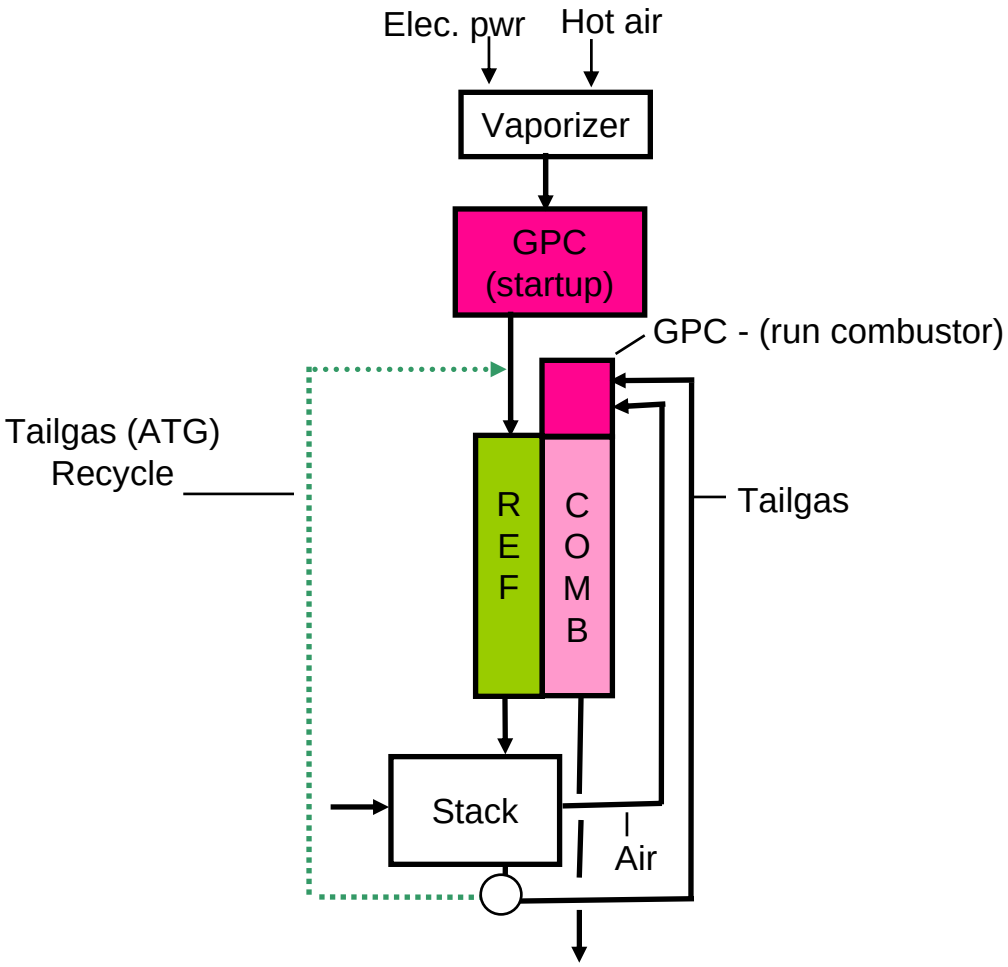
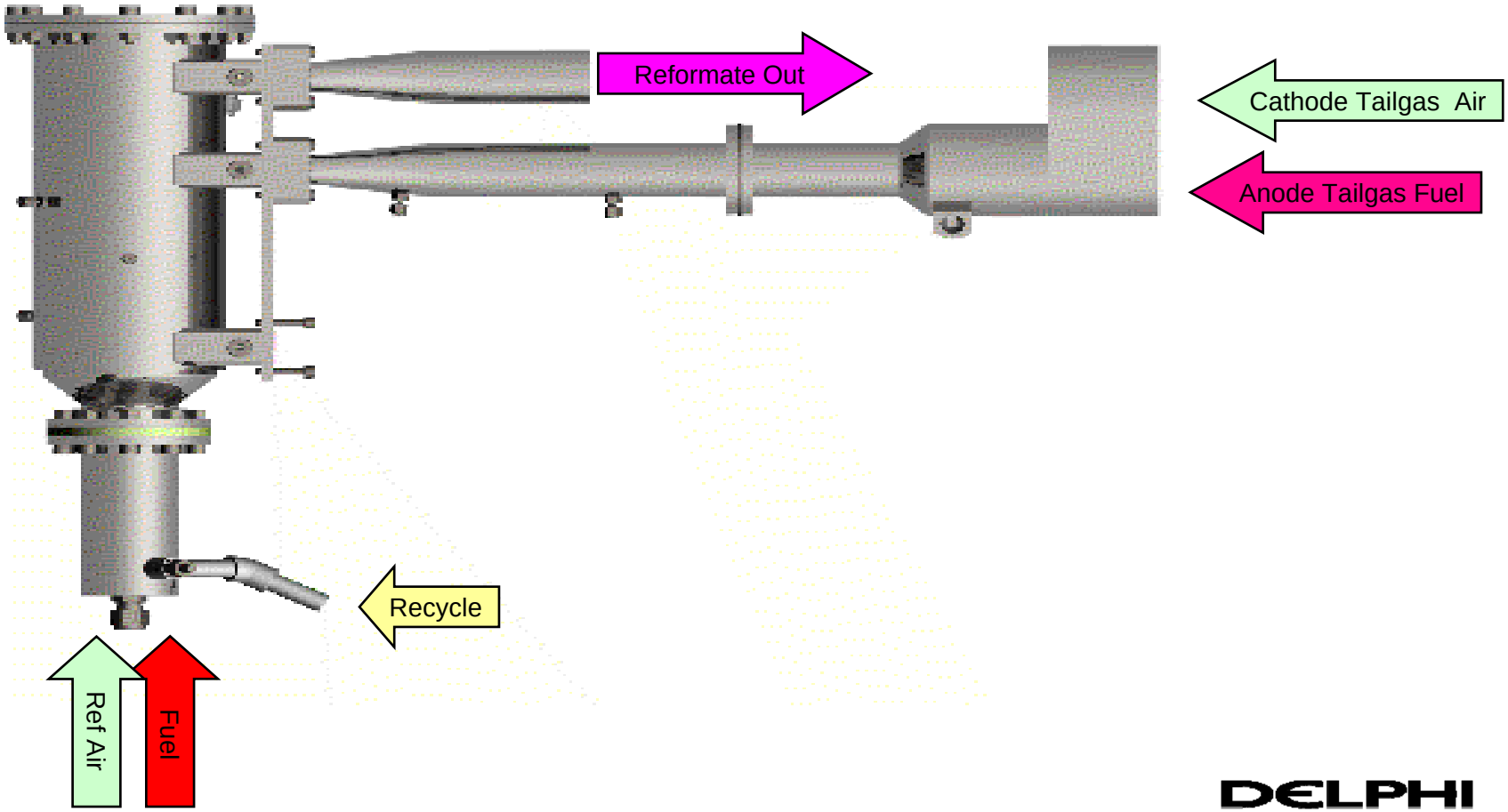
# Reformer Recycle Flow



# Tubular Endothermic Fuel Reformer

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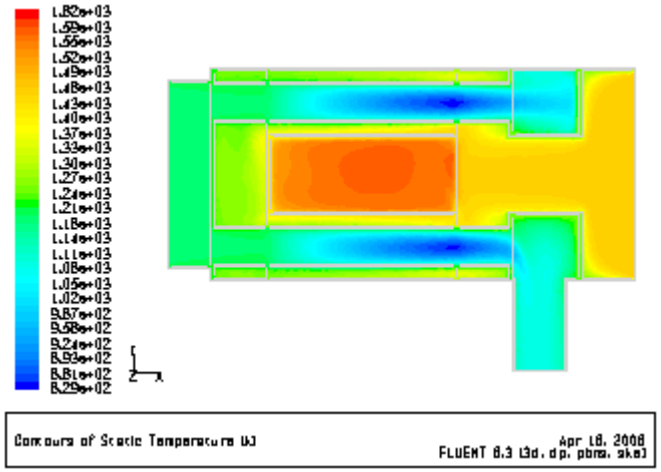
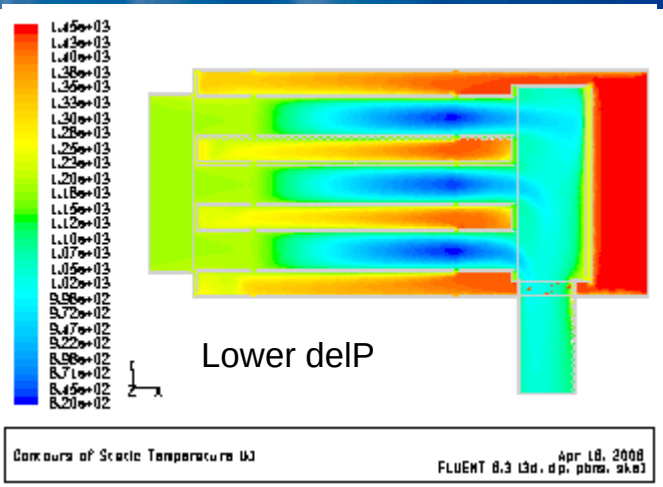
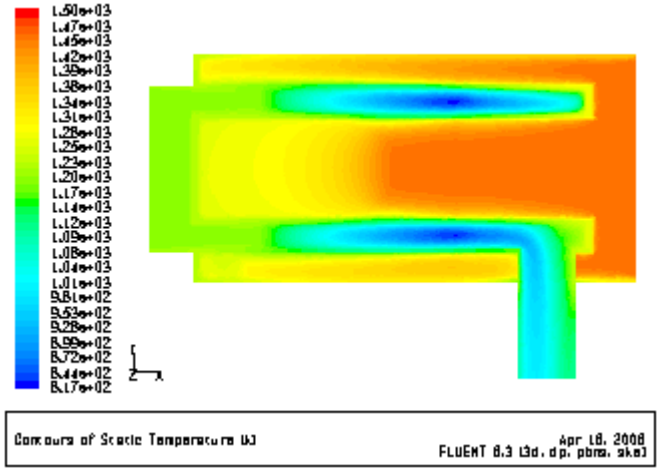
# Reactor Modeling -Temperature



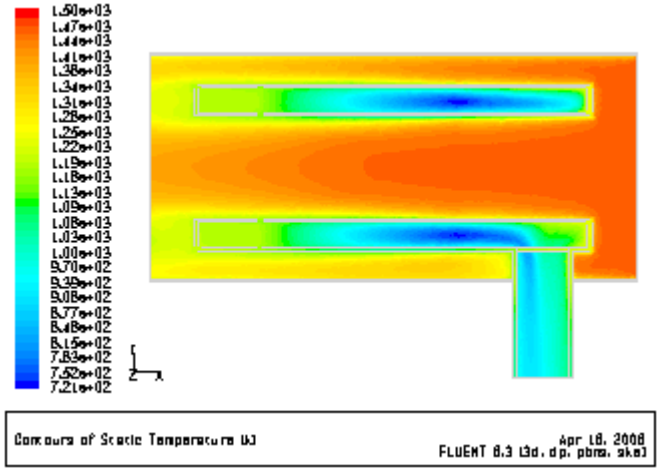

Concept A1




Concept B1




Concept C1




Concept D1

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# SOFC Subsystem Development
# Balance of Plant

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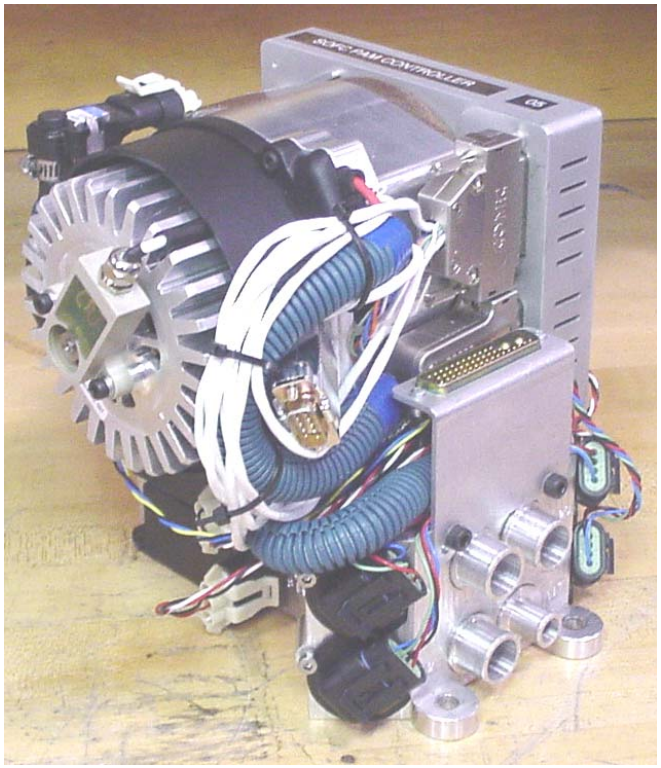
# Process Air

- Current Blower and Manifold Asm.



- New Process Air Blower by R & D Dynamics

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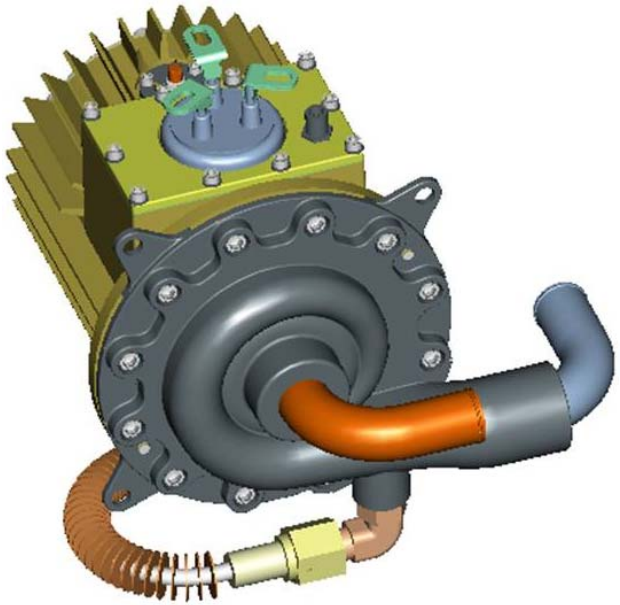
# Anode Tail Gas Recycle Pump

- Current Recycle Pump

- New Recycle Pump by R & D Dynamics



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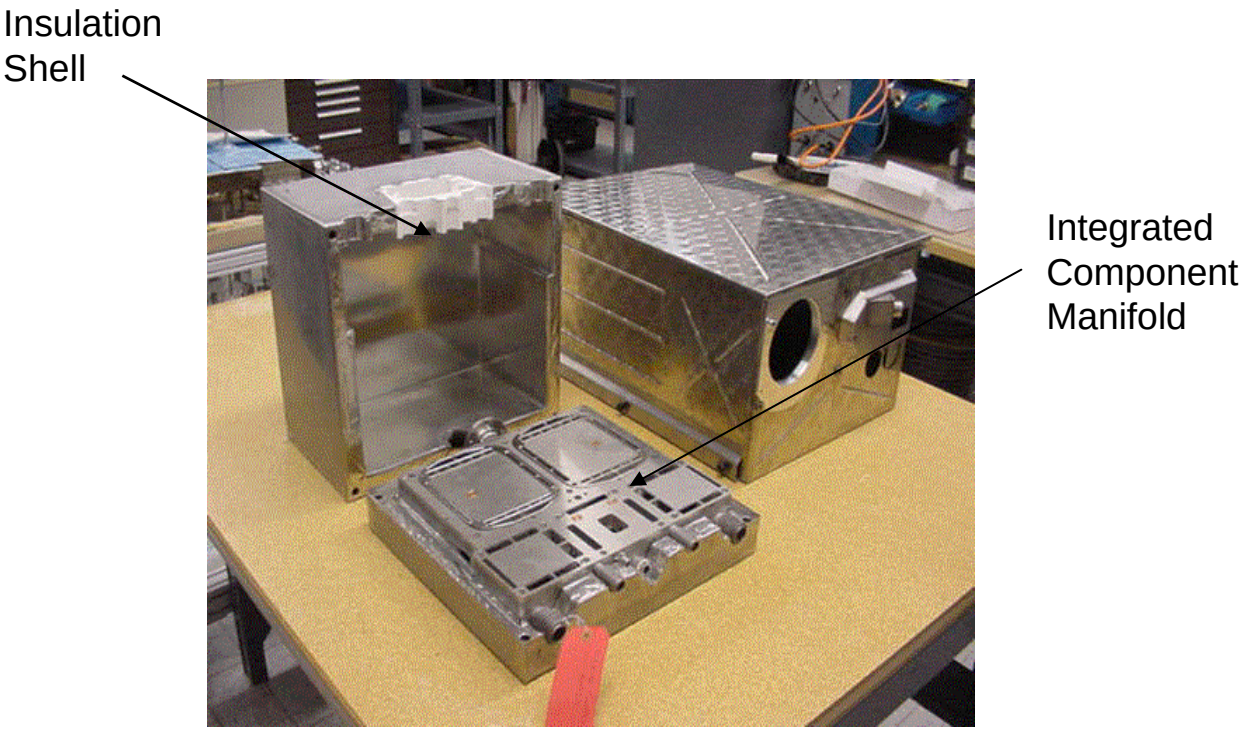
# High Temperature Insulation

- Thermal Insulation
  - Currently using micro-porous insulation
  - Insulation is metal wrapped using standard manufacturing process

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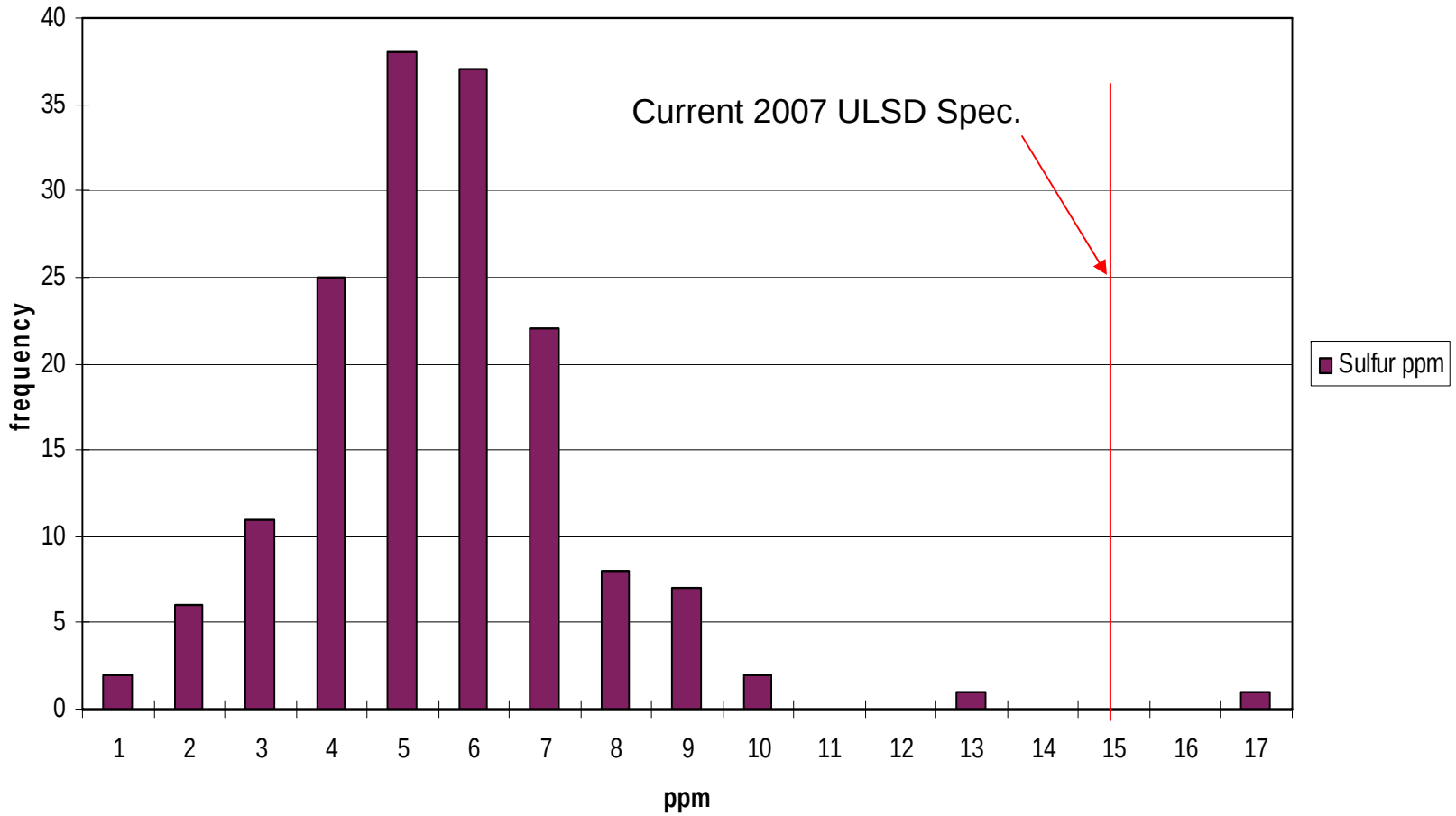
# Diesel Fuel Survey Results
# Summer 2007 – Sulfur Levels




Source: Alliance of Automobile Manufacturers (US and Canada, 160 samples)

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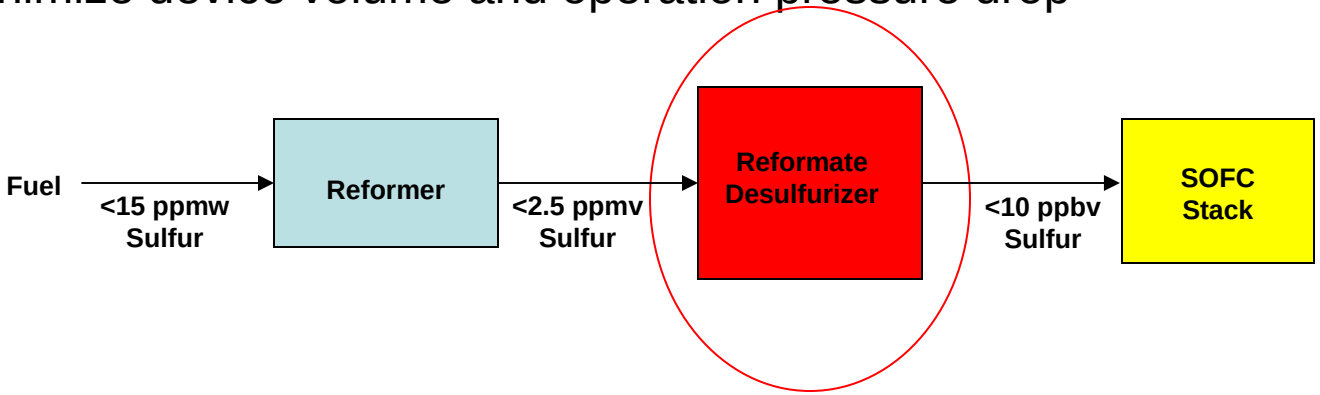
# Delphi Solid Oxide Fuel Cells
# Hot Reformate De-Sulfurization

- **Hot Reformate De-Sulfurization Development**
  - Remove $H_2S$ to levels below 10 ppbv (parts per billion volume) from an input of 2.5 ppmv (parts per million volume)
    - » Sulfur acts as a poison to SOFC
  - Operate from ambient start up conditions to 800°C
  - Maximize operation time between sorbent exchanges
  - Minimize device volume and operation pressure drop

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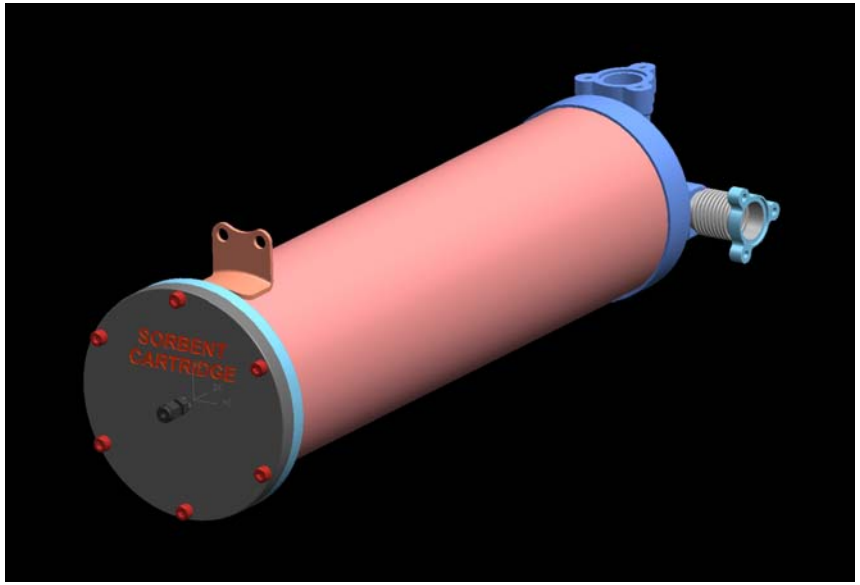
# Delphi Solid Oxide Fuel Cells
# Hot Reformate De-Sulfurization

- A non-regenerating sorbent has been selected that:
  - Meets maximum 10 ppbv output
  - Meets operating temperature requirements
  - Capacity is such that a bed operates for at least 6 months prior to requiring bed exchange
  - System pressure drop requirements were met at full system reformate flow

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# SOFC Power System Development

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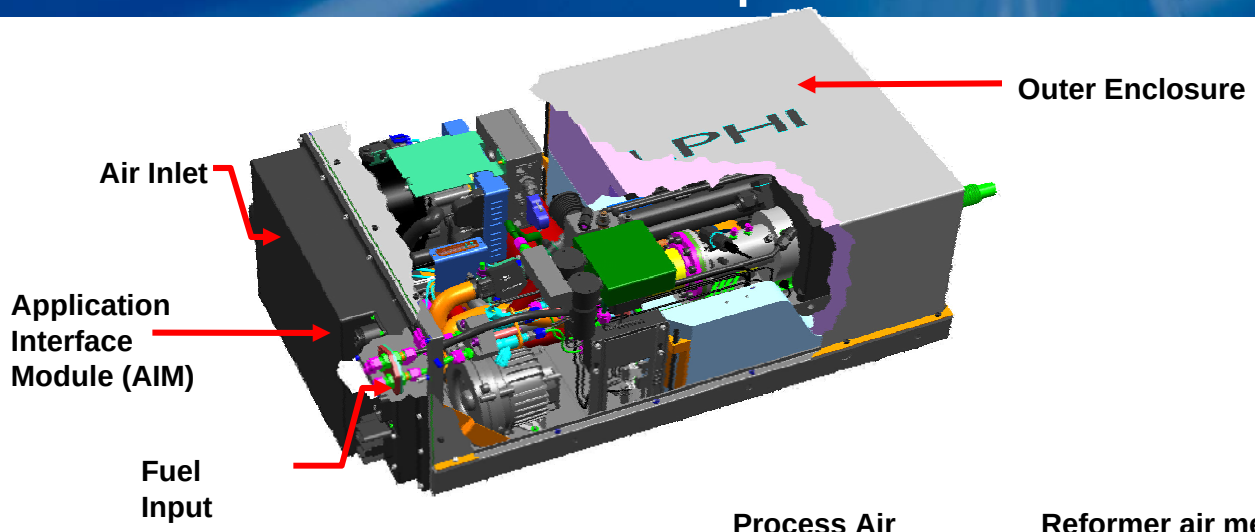
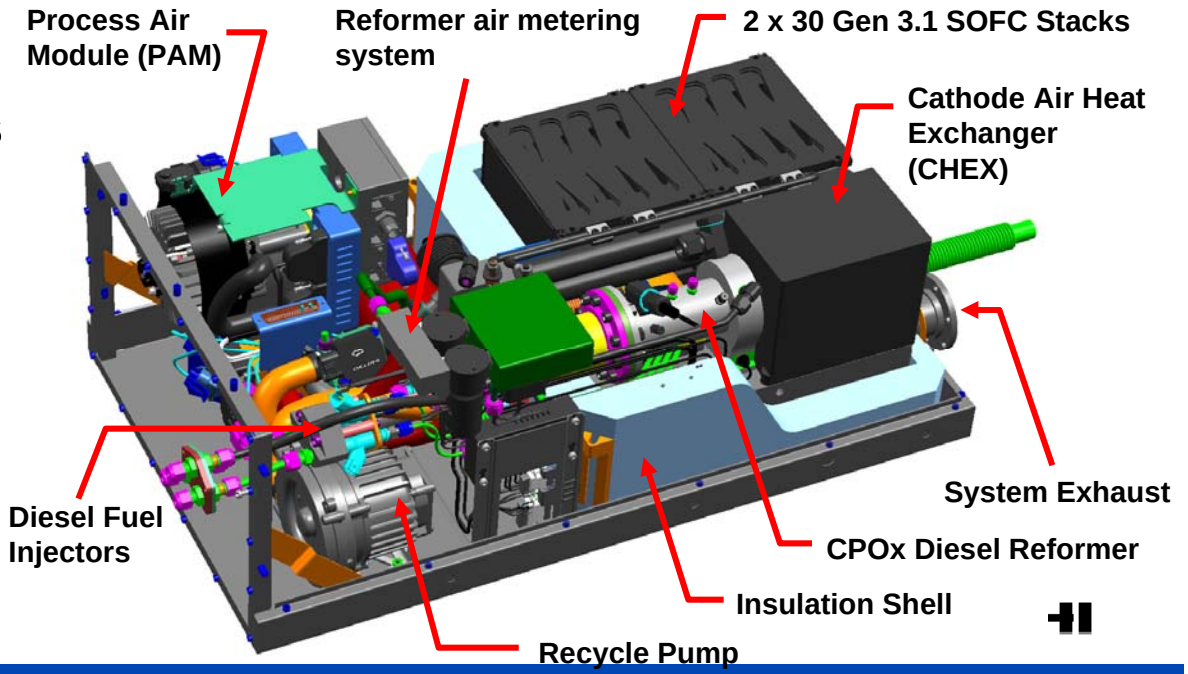
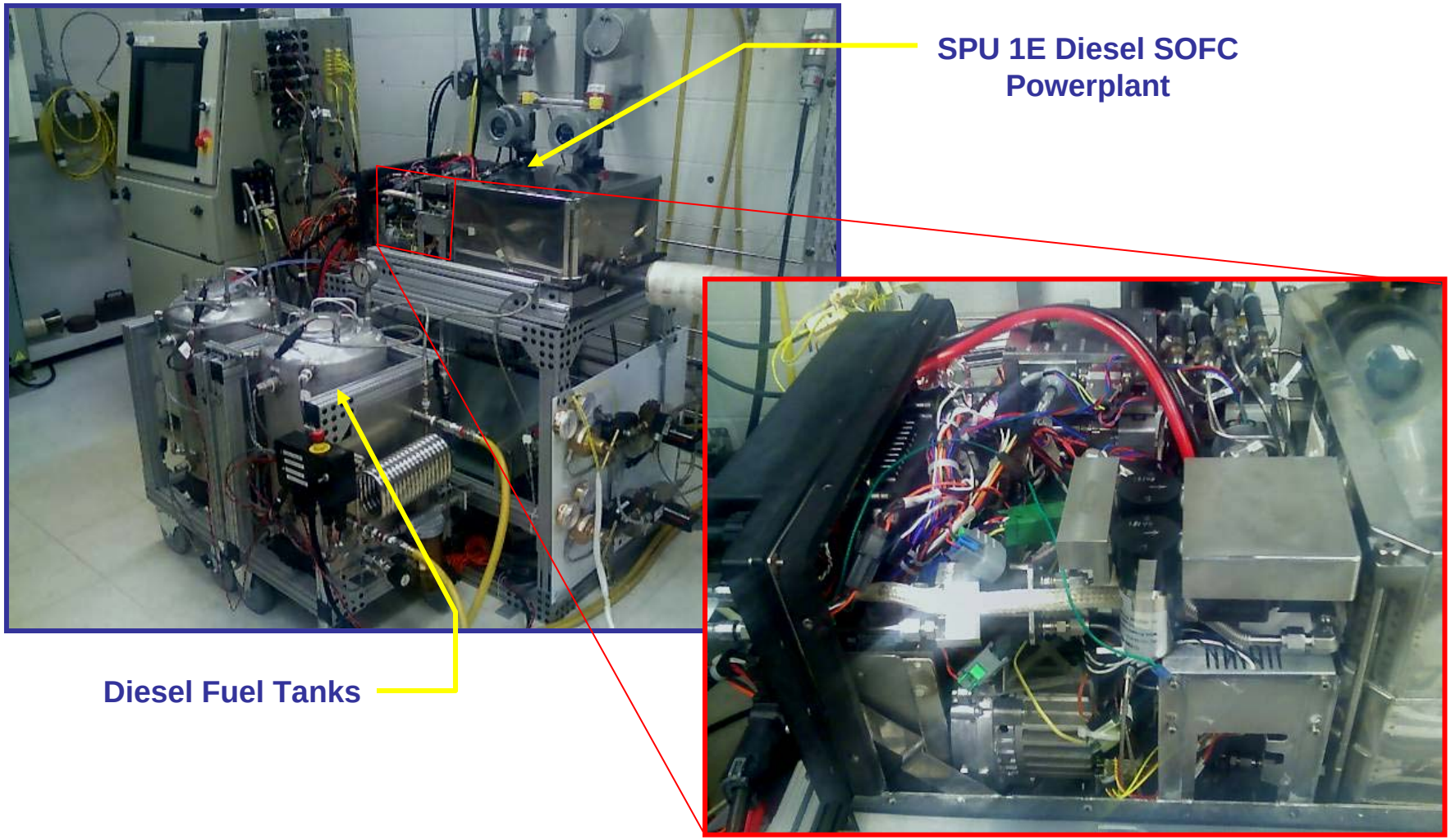
# Delphi Solid Oxide Fuel Cells
# Diesel SOFC Powerplant




- **Additions to Natural Gas System for Diesel Capability (no sulfur):**
  - Diesel fuel vaporizer
  - Electric start vaporizer
  - Carrier air pump
  - Carrier air control manifold
  - Injection air controller
  - Check valve assembly
  - Fuel pump and filter asm



# Diesel SOFC Powerplant

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# Delphi Solid Oxide Fuel Cells
# Truck Technology Demo Enhancements

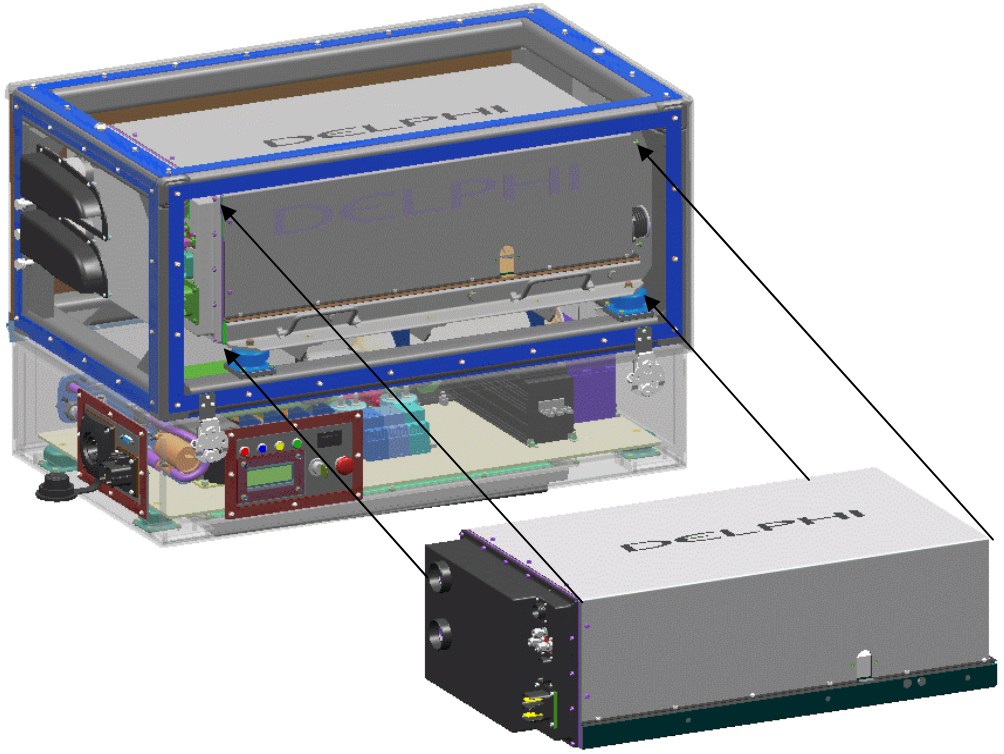
- **Additions for Truck Demonstrator:**
  - Truck output power converter
  - Truck input power converter
  - AC input power converter
  - Power interface controller
  - Truck mounting frame and enclosure with vibration isolators
  - Electronics housing with vibration isolators
  - Reducing gas supply asm and controller
  - User interface panel
  - Remote user interface head
  - Wireless remote PC monitoring system

**Demonstrator Chassis (362 Liters)**

**Q1-2008**

1.25 kW / 16% Efficiency (No Sulfur Diesel)

39 in long x 21 in wide x 27 in tall



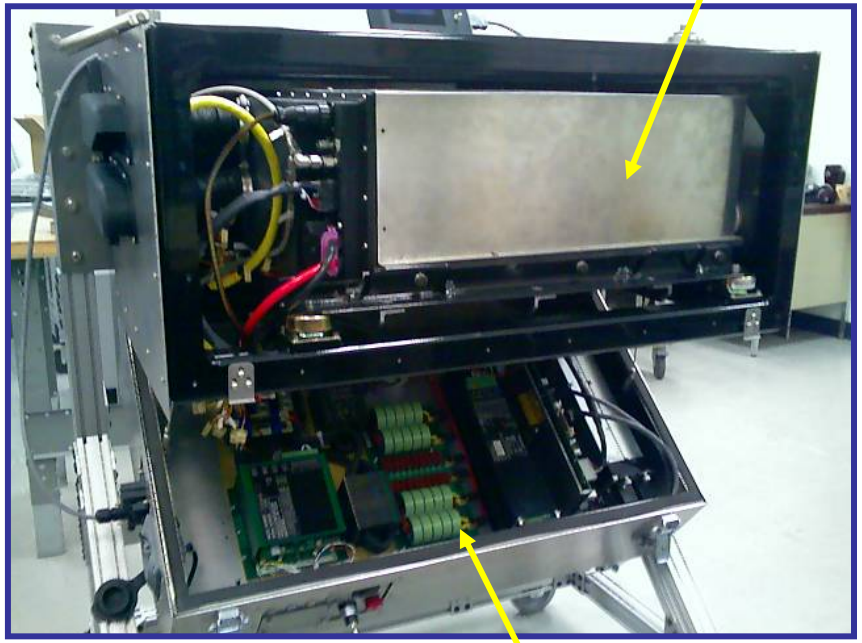

**SPU 1E Powerplant (79 Liters)**

**Q4-2007**

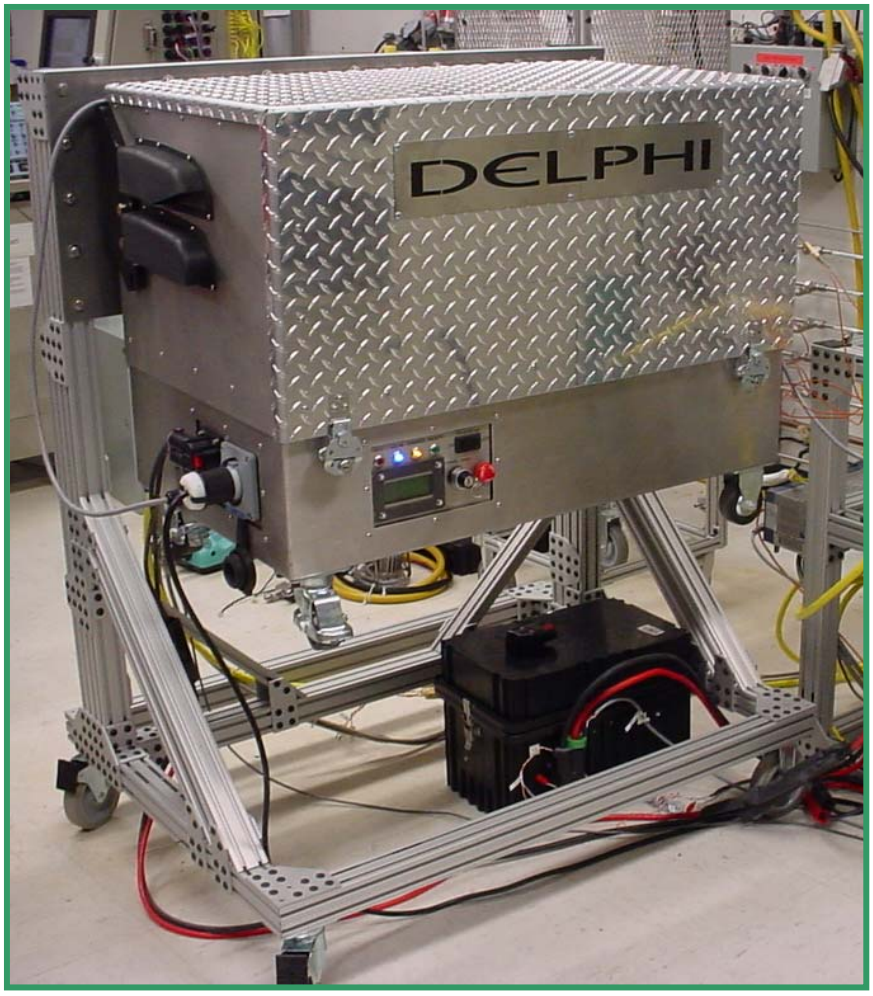
31 in long x 15.8 in wide x 9.8 in tall

# Class 8 Truck Diesel System Demonstrator

SPU 1E Powerplant



Electronics Tray

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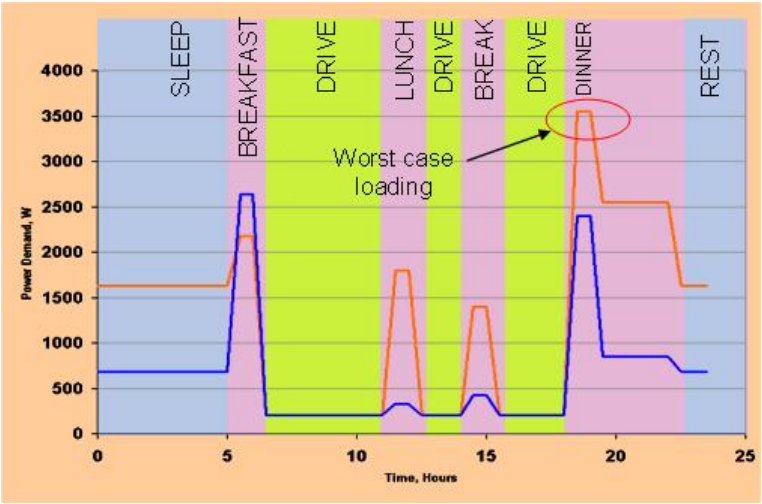
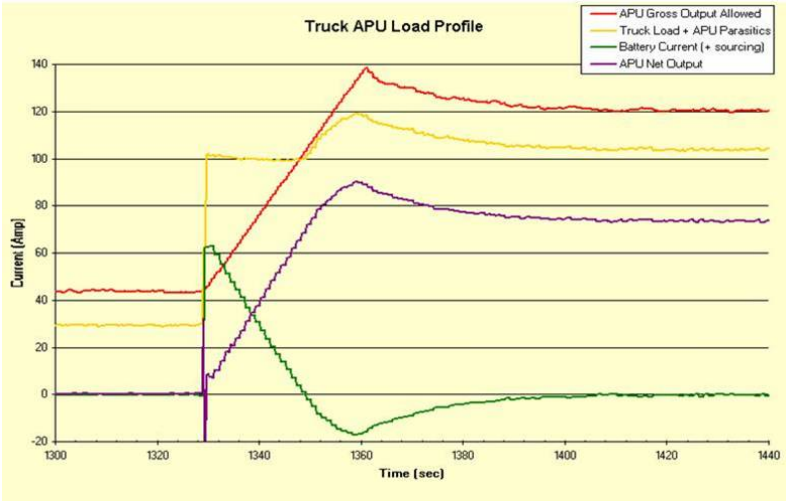
# APU Load Profile Implementation




- Simulates Morning, Afternoon, and Evening loads
  - Food & Entertainment
  - HVAC system
  - MISC AC power loads
- Utilizes battery for load spikes, while subsequently charging
- Approximate sharing rate 50W/s with room for improvement
- Electronics & Software developed internally with off-the-shelf hardware

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# Delphi Diesel SOFC Systems

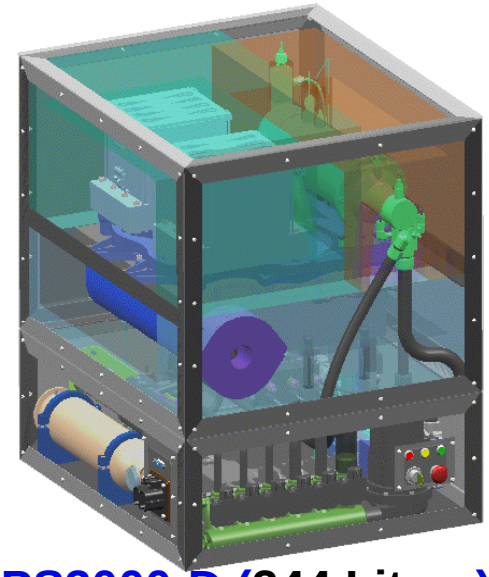
## Demonstrator Chassis (362 Liters)

**Q1-2008**

1.25 kW / 14% Efficiency (No Sulfur Diesel)

991 mm long x 533 mm wide x 686 mm tall

39 in long x 21 in wide x 27 in tall



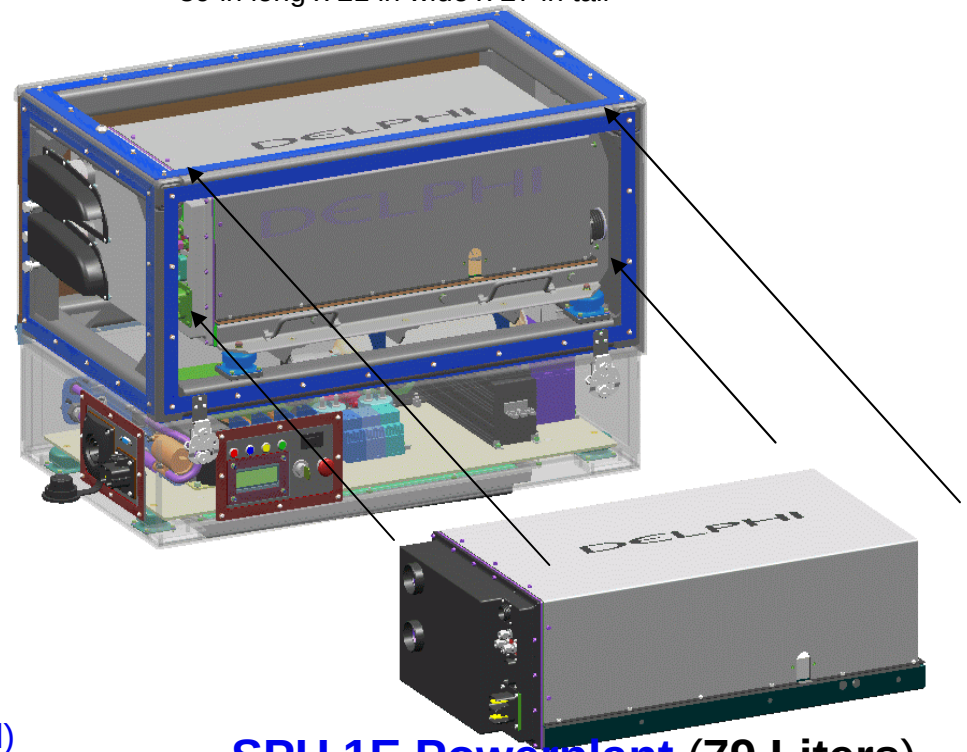
## DPS3000-D (244 Liters)

**Q1-2009**

3.5 kW / 25% Efficiency (US07 Diesel)

626 mm long x 549 mm wide x 676 mm tall

25 in long x 22 in wide x 27 in tall




## SPU 1E Powerplant (79 Liters)

**Q4-2007**

1.25 kW / 14% Efficiency (No Sulfur Diesel)

790 mm long x 400 mm wide x 250 mm tall

31 in long x 15.8 in wide x 9.8 in tall

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# Diesel SOFC APU Conceptual Design


**DPS3000-D**

626 mm long x 549 mm wide x 676 mm tall (244 Liters)

150 Kg

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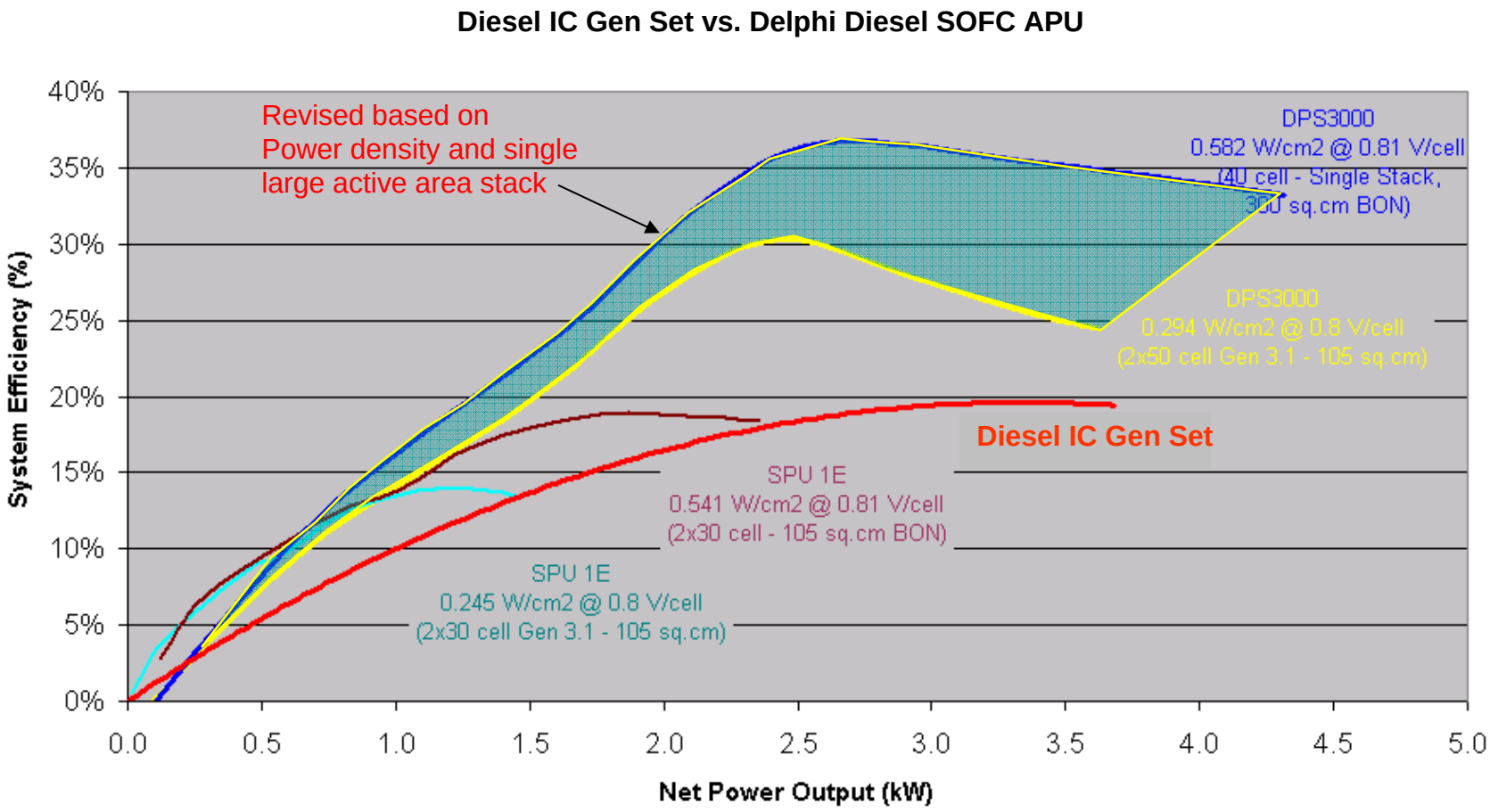
# Projected Performance Comparison

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# Programs Leveraging SECA Activities

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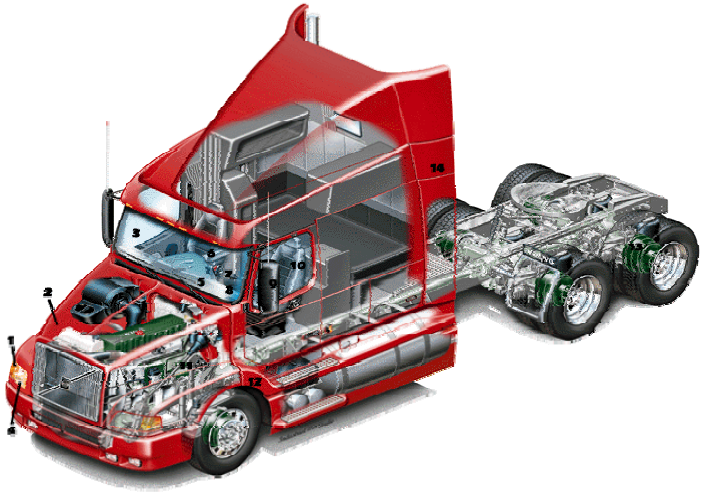
# Government Programs Leveraging SECA Heavy Duty Truck Fuel Cell APU

- Delphi has teamed with DOE EERE and 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 operating on diesel fuel.

VOLVO



***Volvo Trucks North America (VTNA), Greensboro, NC***

PACCAR

KENWORTH

Peterbilt

DAF

Foden Trucks

***PACCAR, Mt. Vernon, WA***

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# Delphi Diesel SOFC APU Demonstrator Chassis

Accomplishments:

- First operation of Delphi SOFC outside of a laboratory
- First complete start-up on truck generator power
- Automatic transition of truck loads to fuel cell system (truck engine off)
- SOFC Fuel Cell System support of truck loads (860$W_{net}$):
  - HVAC Blower
  - Radio
  - Interior lights and dashboard lights
  - Headlamps & running lights
  - Windshield wipers
  - Battery charging
  - Fuel pump
  - 12V cooler accessory


April 25th, 2008

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# Delphi Diesel SOFC APU Peterbilt Demonstration

- 06/03/08: System start-up on truck power. 10 hour operation running approximately 800 W net (HVAC blower, radio, CB, dome light, battery pack).

- <u>Specifications:</u>
  - Fuel: "Zero Sulfur" diesel (1.2 ppmw S max)
  - Peak power 1300 W
  - Conditioned 12 Volt output
  - 39 in long x 21 in wide x 27 in tall
  - 600 lbs,
  - Start time: 3 hours


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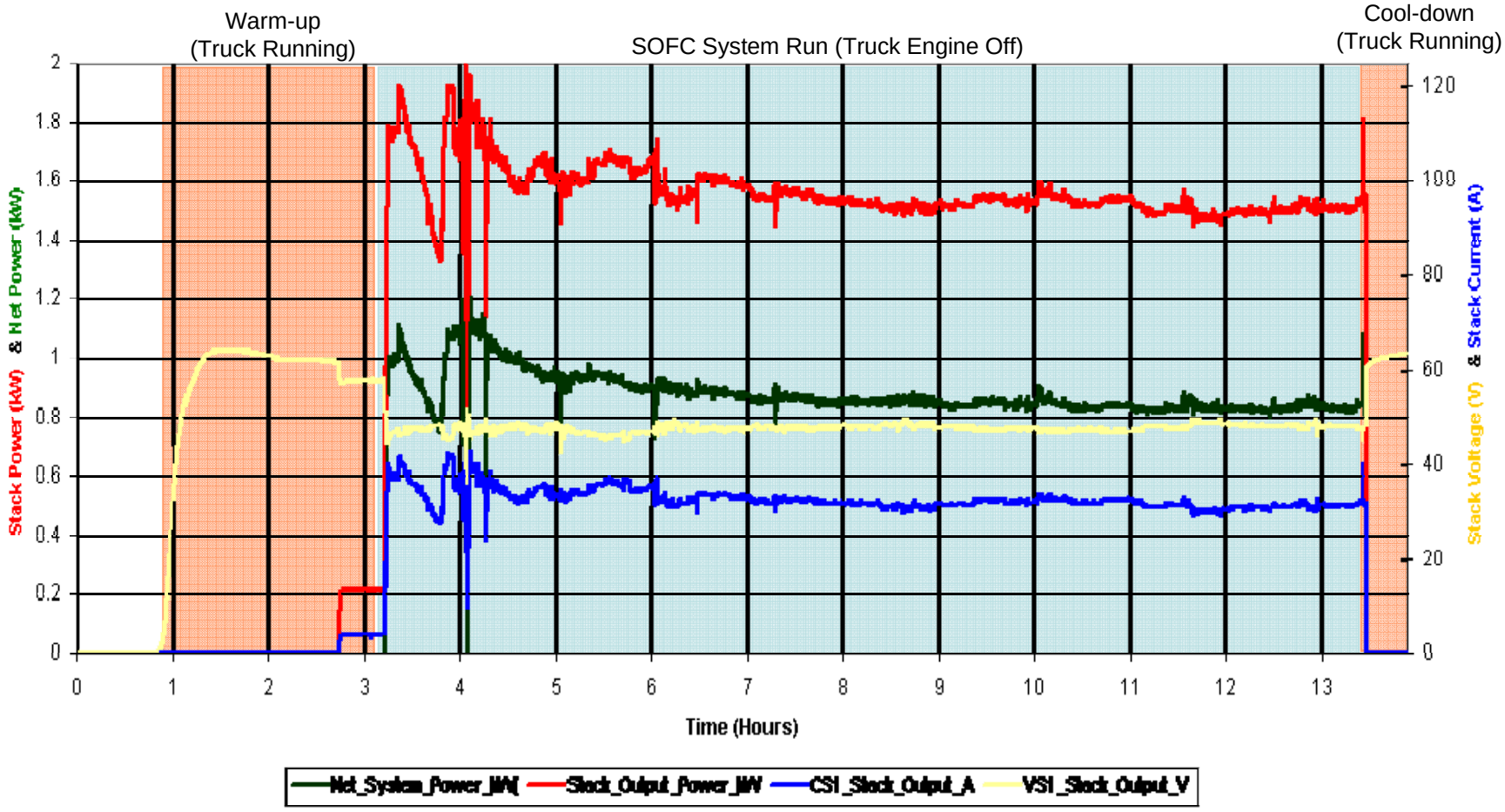
# Diesel SOFC System Operation on Class 8 Truck

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# Stack Testing at NUWC

- Delphi, SECA (Dept. of Energy) and the Navy are collaborating for Solid Oxide Fuel Cell technology development for Undersea Naval applications
- A Delphi 10-cell stack developed under the SECA program was tested at the Naval Undersea Warfare Center (NUWC) under simulated conditions specific for this application
- Stack produced very encouraging performance
  - Demonstrated excellent reproducibility during the offsite test
  - Demonstrated and met power density requirement that was set for this specific application test (see next slide)
  - Testing included performance evaluation with pure oxygen on the cathode side and actual reformate on the anode side
- Next step is to test a stack at higher power levels

NAVSEA WARFARE CENTERS NEWPORT

ONR

**Ref: Solid Oxide Fuel Cells for Undersea Naval Applications**

10th Electrochemical Power Sources R&D Symposium

Alan Burke, Ph.D.; Louis G. Carreiro, Ph.D.

Naval Undersea Warfare Center (NUWC), Division Newport

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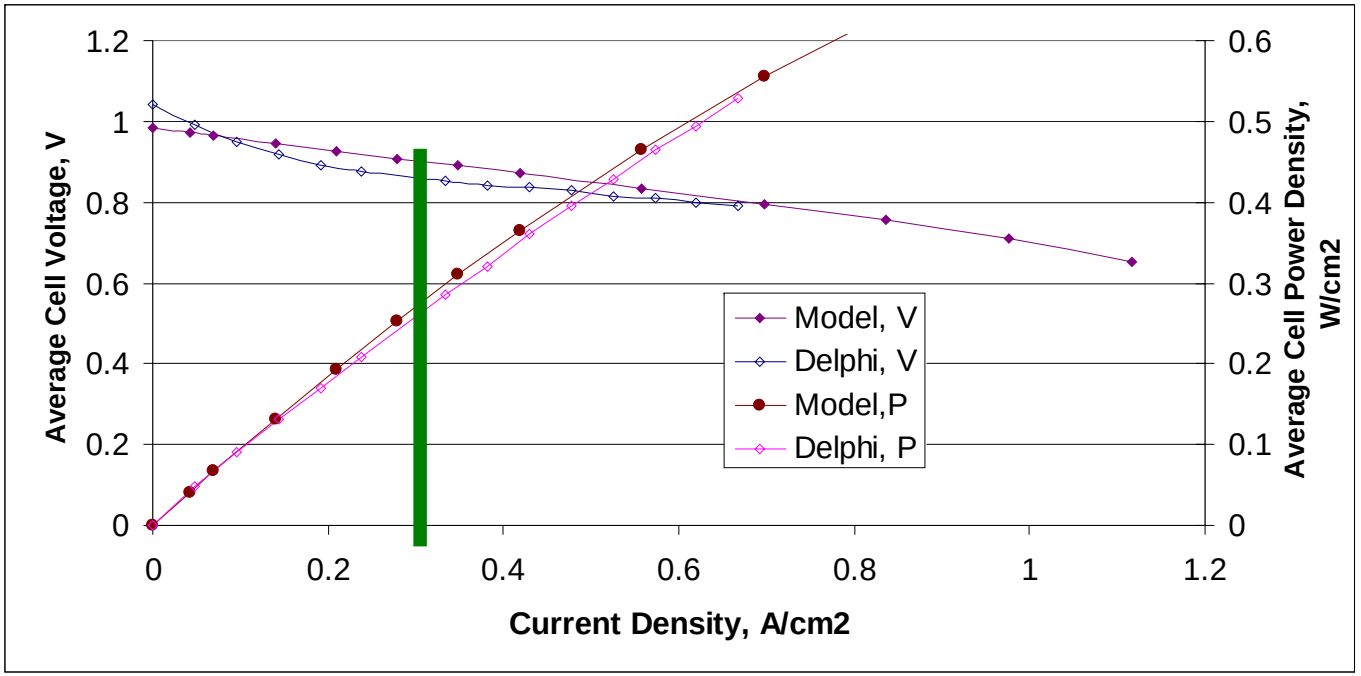
# SOFC Stack Performance Under Simulated UUV Operating Conditions (1 atm, 725º C)




**Targeted Steady State operating point: 0.8 V/cell at 0.3 A/cm²**

**Model does not consider methane reformation at the cell surface, localized cooling from methane reforming could explain higher OCV & lower voltage at low current density**


**Ref: Solid Oxide Fuel Cells for Undersea Naval Applications**

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