Solid Oxide Fuel Cell and Power System Development at PNNL

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Content

- Development of SOFC Technology
- Fuel Reforming and System Design
- Power and Efficiency

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SOFC Technology Development at PNNL

- **PNNL is the leading US DOE laboratory for SOFC research and development.**
  - Active in SOFC development since 1987
  - Over $100M of SOFC-related funding since 1999
  - Mostly DOE Office of Fossil Energy
  - Solid State Energy Conversion Alliance (SECA)
- **PNNL developed anode-supported, thin electrolyte technology.**
- **Transferred technology to Delphi Corp. starting in 2000.**
- **Delphi is now supplying SOFC stacks for projects developing power systems at PNNL.**

Solid Oxide Fuel Cell Characteristics

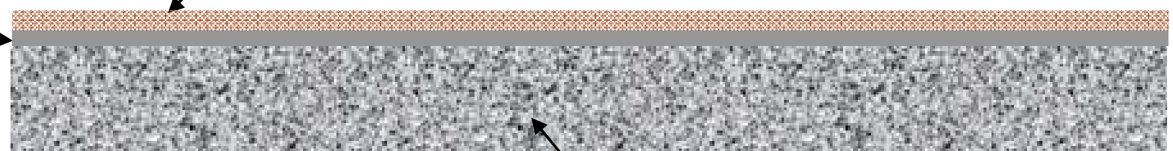
- **High temperature (~700 – 800°C)**
- **Can use H_2, CO and CH_4 as fuel, so can run directly on reformed liquid hydrocarbons.**
- **Fuel must have very low sulfur levels (<1 ppm to avoid performance loss).**

Anode-Supported Thin-Electrolyte Cell Structure

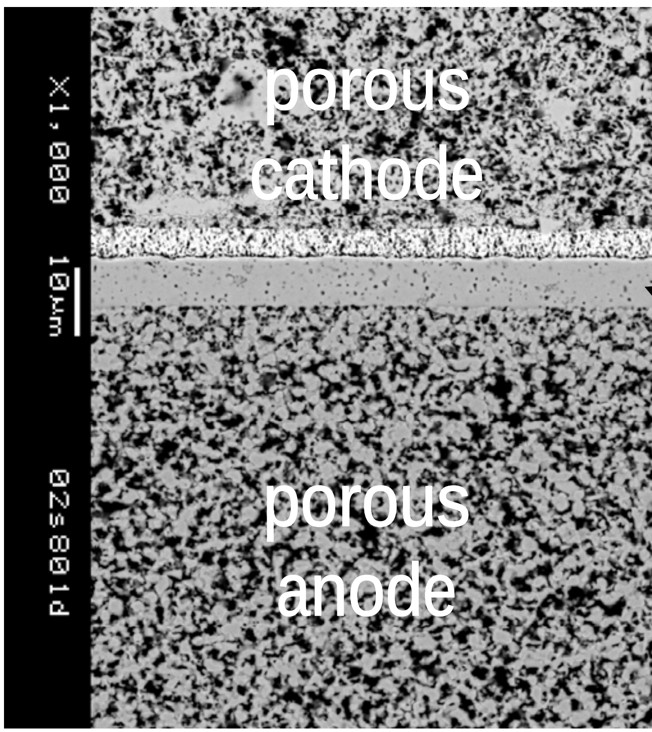
Cathode:
Thin (30-40 micron), porous electrically conductive ceramic

"LSCF 6428"
$(La_{0.6}Sr_{0.4})_{1-d}(Co_{0.2}Fe_{0.8})O_3$

Electrolyte:
Very thin (<10 micron) YSZ
Conducts oxygen ions, not electrons



Anode:
Thick (~500 micron), porous Ni metal-YSZ "cermet". Structural support for cell



CeO_2 "barrier" layer

dense YSZ electrolyte

electron micrograph of SOFC in cross section

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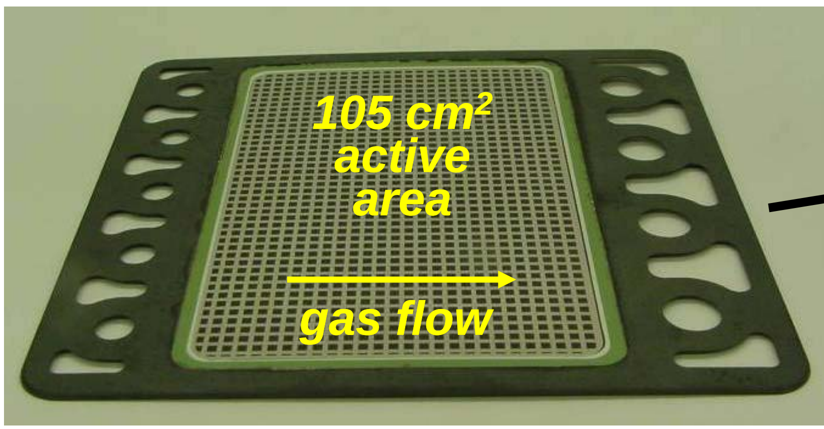
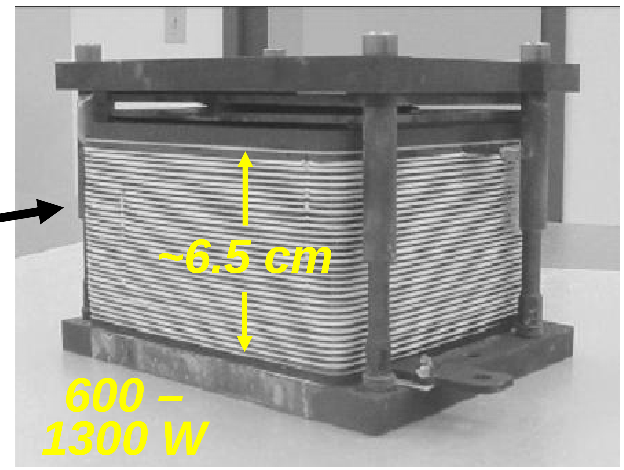
PNNL-Delphi Technology

- Thin electrolyte allows good performance at low enough temperatures so that stainless steels can be used as cell frame and separator plate.

Cassettes are glass sealed together to form stack.



Single Cell in Co-flow Cassette



30-Cell Stack in Frame

PNNL-Delphi SECA Team

2.8 cm^2

Button Cell

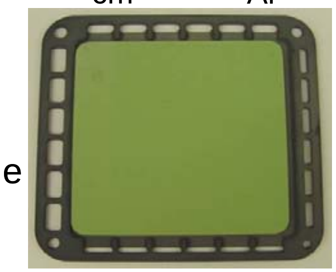
Feb 2000 -present

34 cm^2

Intermediate-Scale

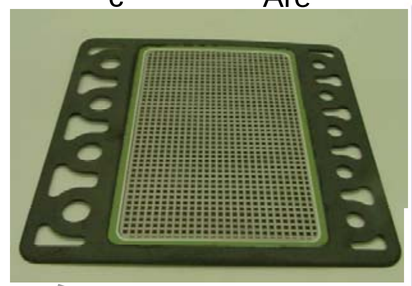
Nov 2001 -present

Gen 2
106 cm^2 Active Area



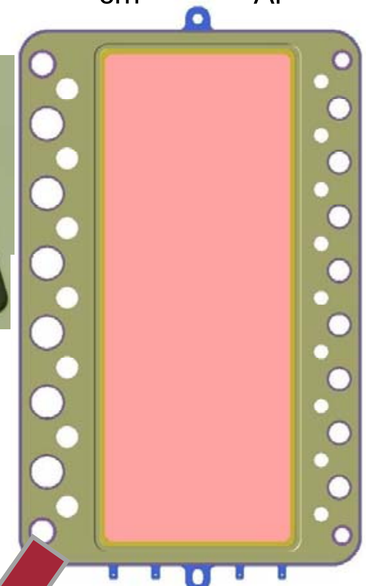
Jan 2002   2003

Gen 3
105 cm^2 Active Area



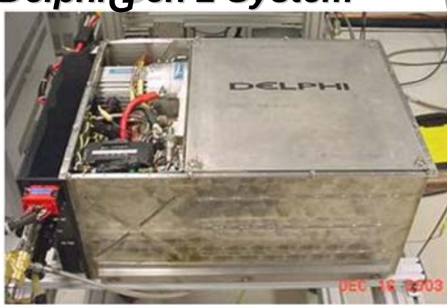
July 2003 -

Gen 4 *
403 cm^2 Active Area



June 2008 -

Delphi Gen 2 System



Dec 2002

Delphi Gen 3 APU

June 2008

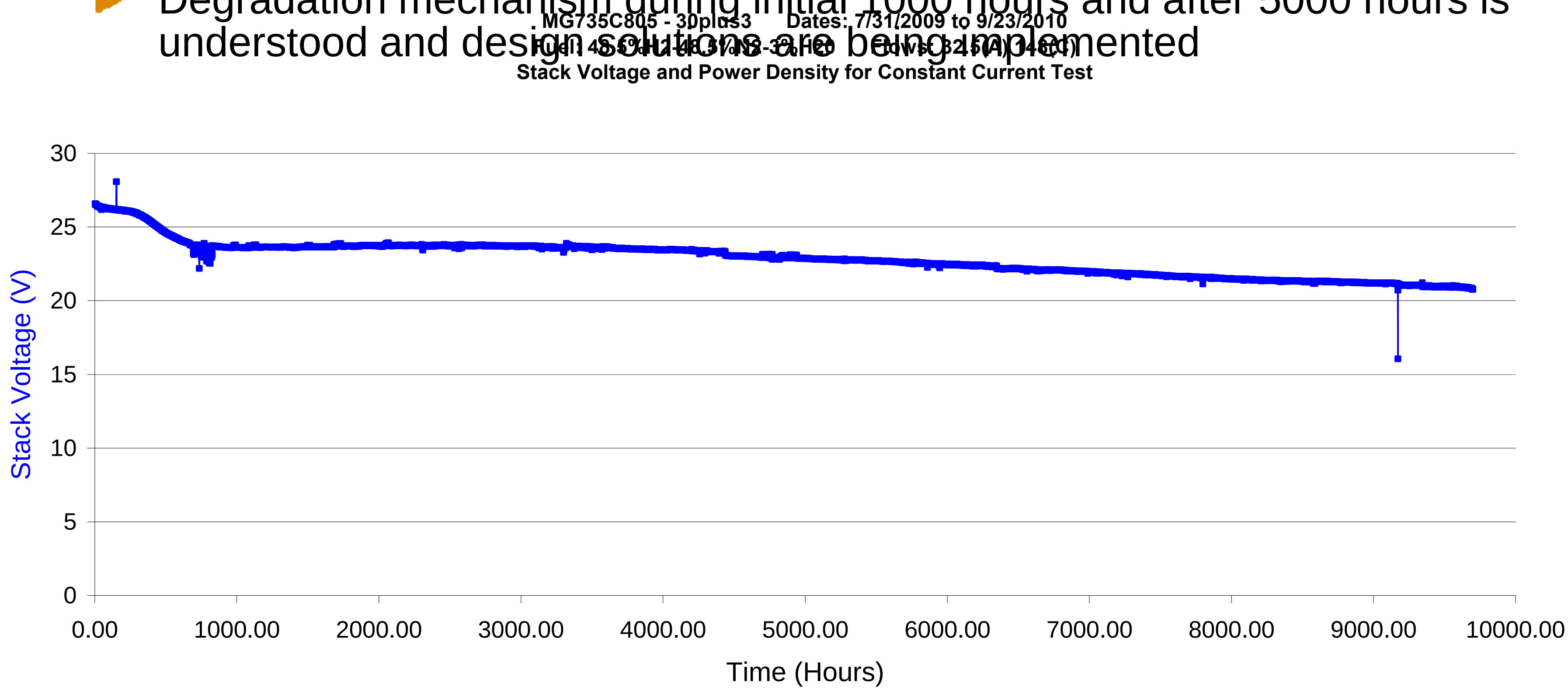
Delphi DPS3000-D

Delphi's First Commercial Market: APU for Long-Haul Trucks

- Supports "hotel load" so ICU can be shut down at night.
- APU is started up on Monday morning, shut down Friday night.

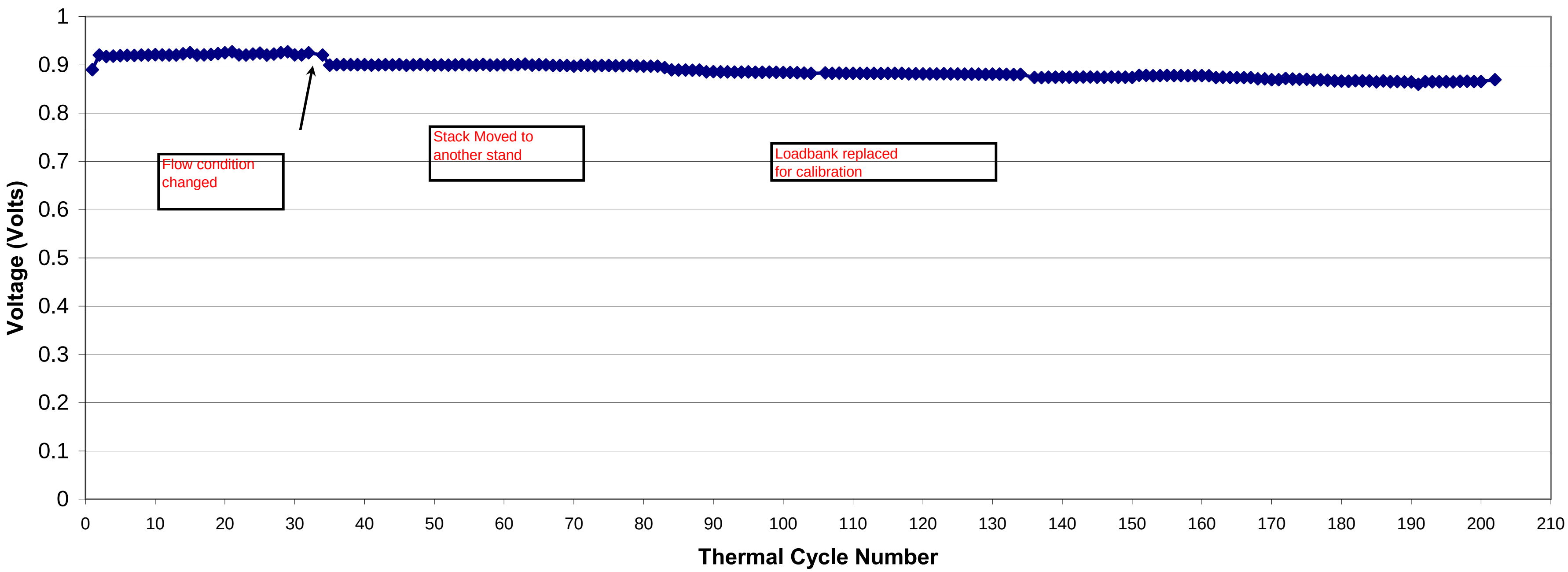
Delphi Stack Performance

- 9700 hours
- Total degradation is 1.12% per 500 hours
- Degradation mechanism during initial 1000 hours and after 5000 hours is understood and design solutions are being implemented



Delphi Stack Performance

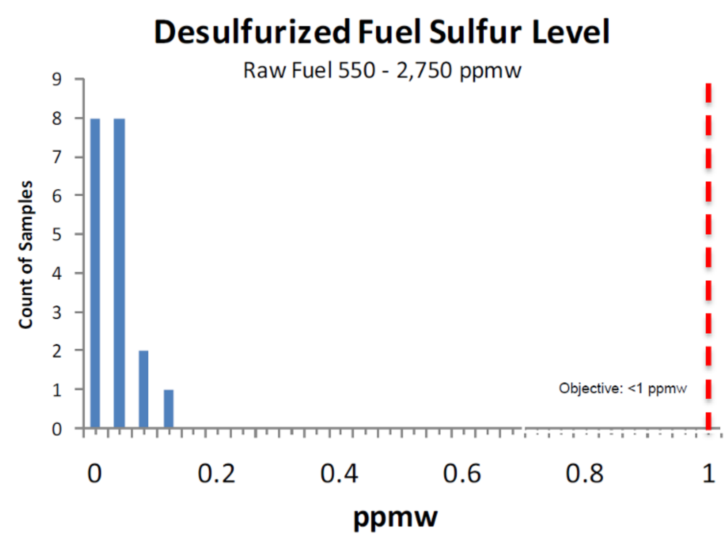
- Stack endured 200 thermal cycles with minimal degradation



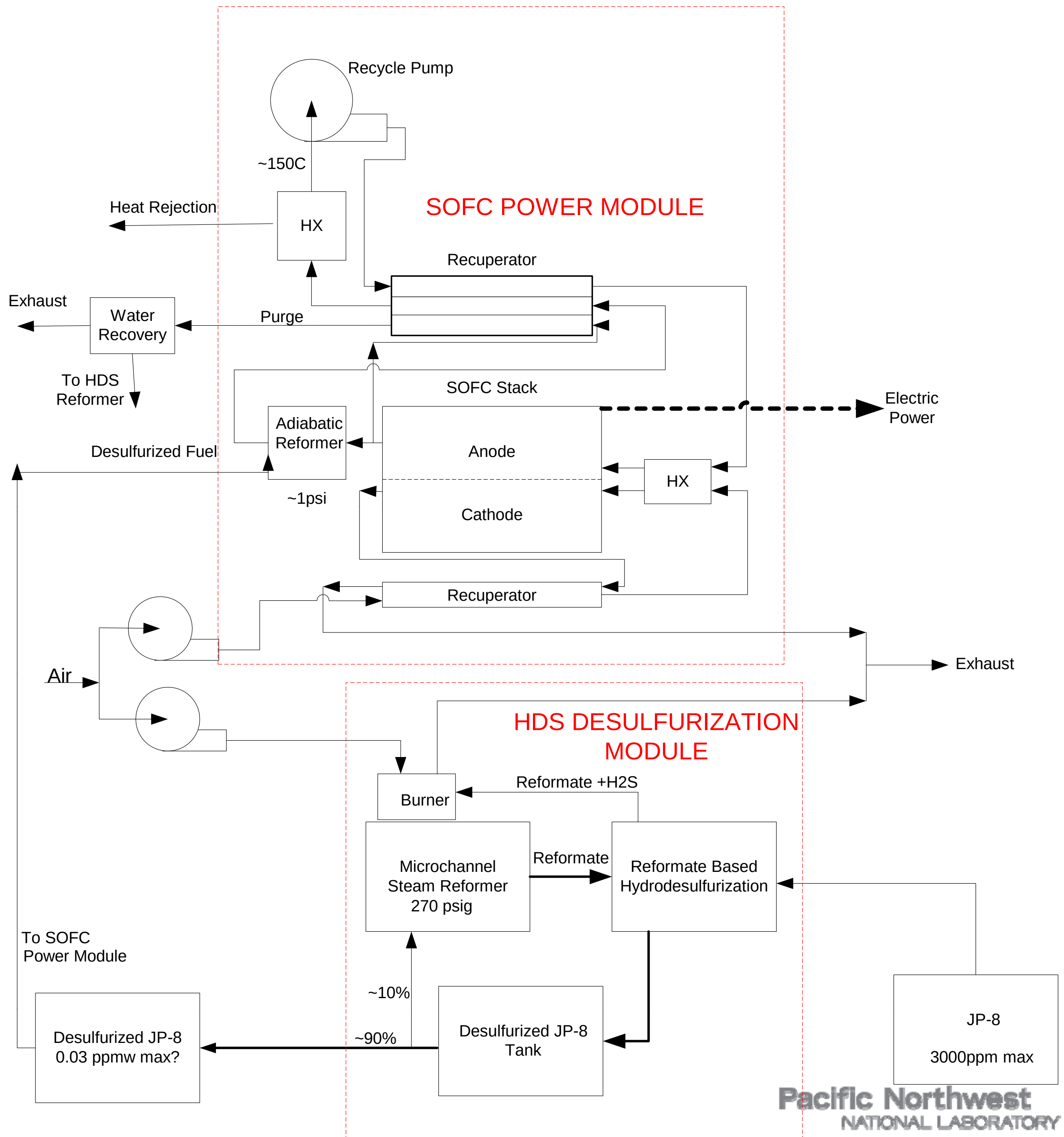
- Development of SOFC Technology
- **Fuel Reforming and System Design**
- Power and Efficiency

Hydro-Desulfurization Technology

- Funded by Army TARDEC
- Brass board, transportable system
- Ran 10 kW PEM fuel cell
- Demonstrated on JP-8 with 2750 ppm sulfur.
  - Very similar to Jet A, but higher sulfur.
  - Could use JP-5.
  - Bunker fuel would be problematic.



Conceptual Flow Diagram to Integrate Hydro-desulfuration with SOFC Power System



Efficiency Boost from Steam Reforming

- **Steam reforming is endothermic**

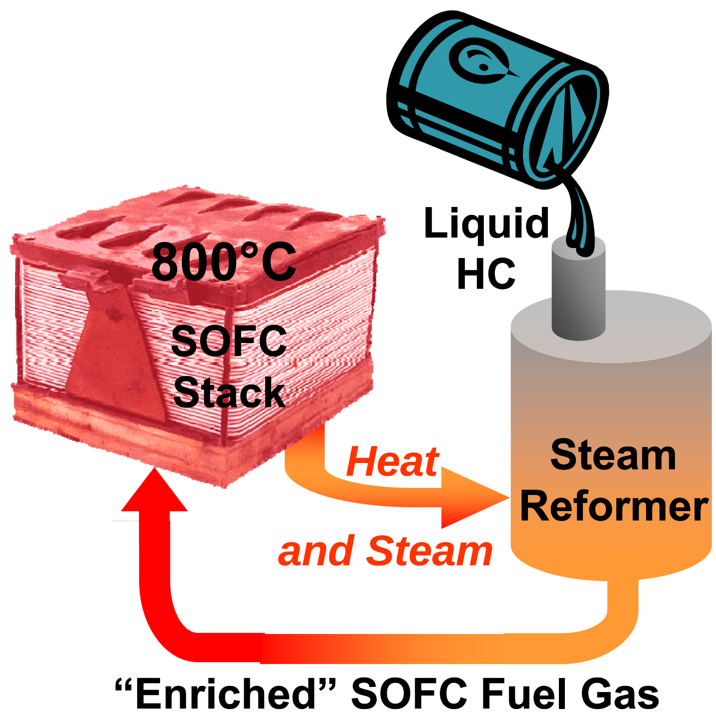
- **Heat from SOFC stack is converted into ~25% *increased* chemical energy of reformate:**

<u>Steam Reformation of *n*-Dodecane:</u>

$C_{12}H_{26} + 12H_2O + \text{heat} \rightarrow 12CO + 25H_2$

7552 kJ/mole (for $C_{12}H_{26}$)

9421 kJ/mole (125%) (for $12CO + 25H_2$)



- ***System yields >60% net efficiency***

- **Steam and heat for reforming obtained from SOFC stack exhaust**

Partial Oxidation (POx) Reforming

- Some systems use POx reforming.
- POx is exothermic.
- POx reformate has *less* chemical energy than original fuel.
- Example, dodecane: $\underbrace{C_{12}H_{26}}_{\substack{\textbf{7552}\\ \textbf{kJ/mole}}} + 6O_2 = \underbrace{12CO + 13H_2}_{\substack{\textbf{6618}\\ \textbf{kJ/mole (87\%)}}} + \text{heat}$

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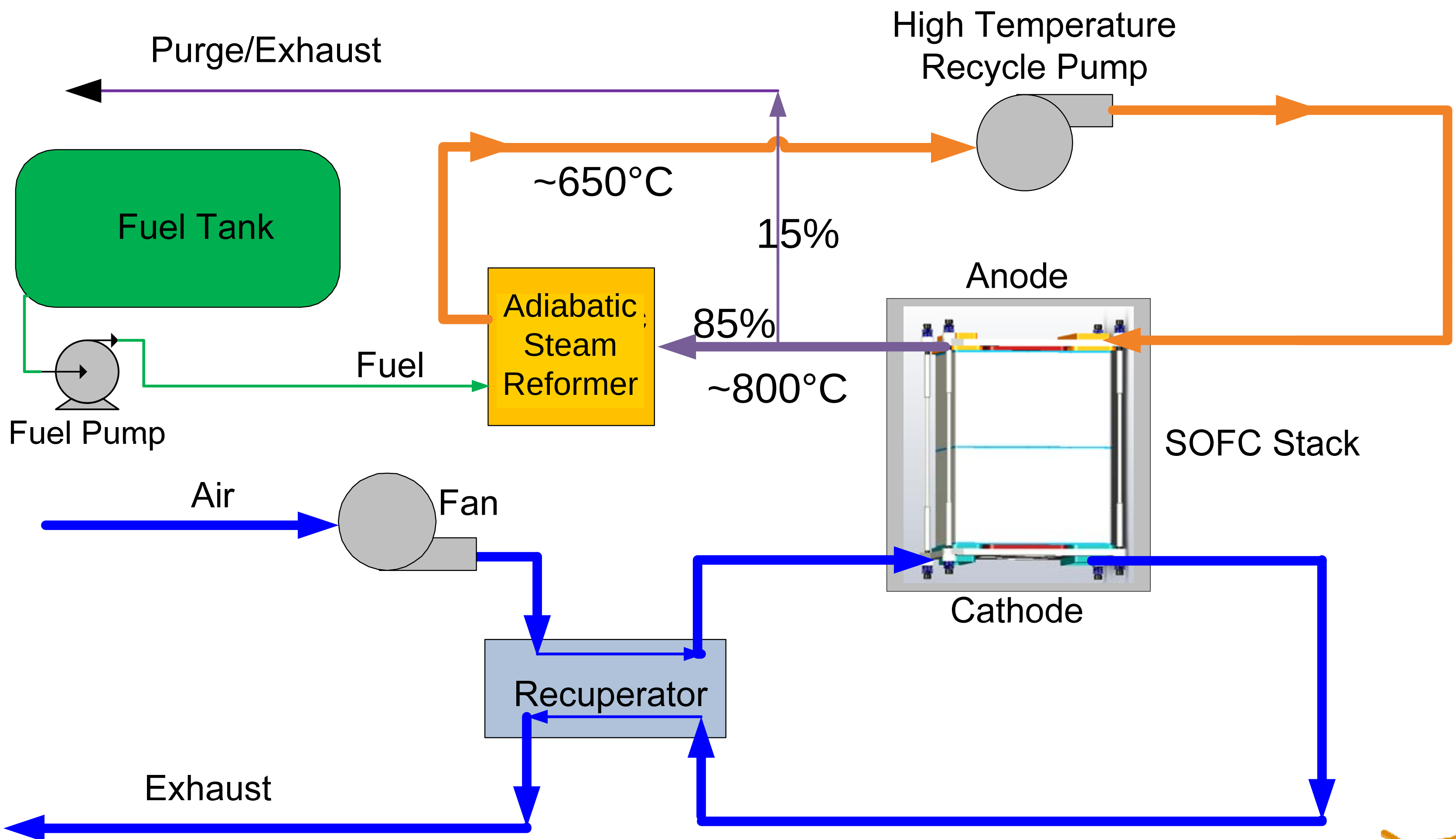
SOFC Power System with Steam Reforming and Anode Recycle



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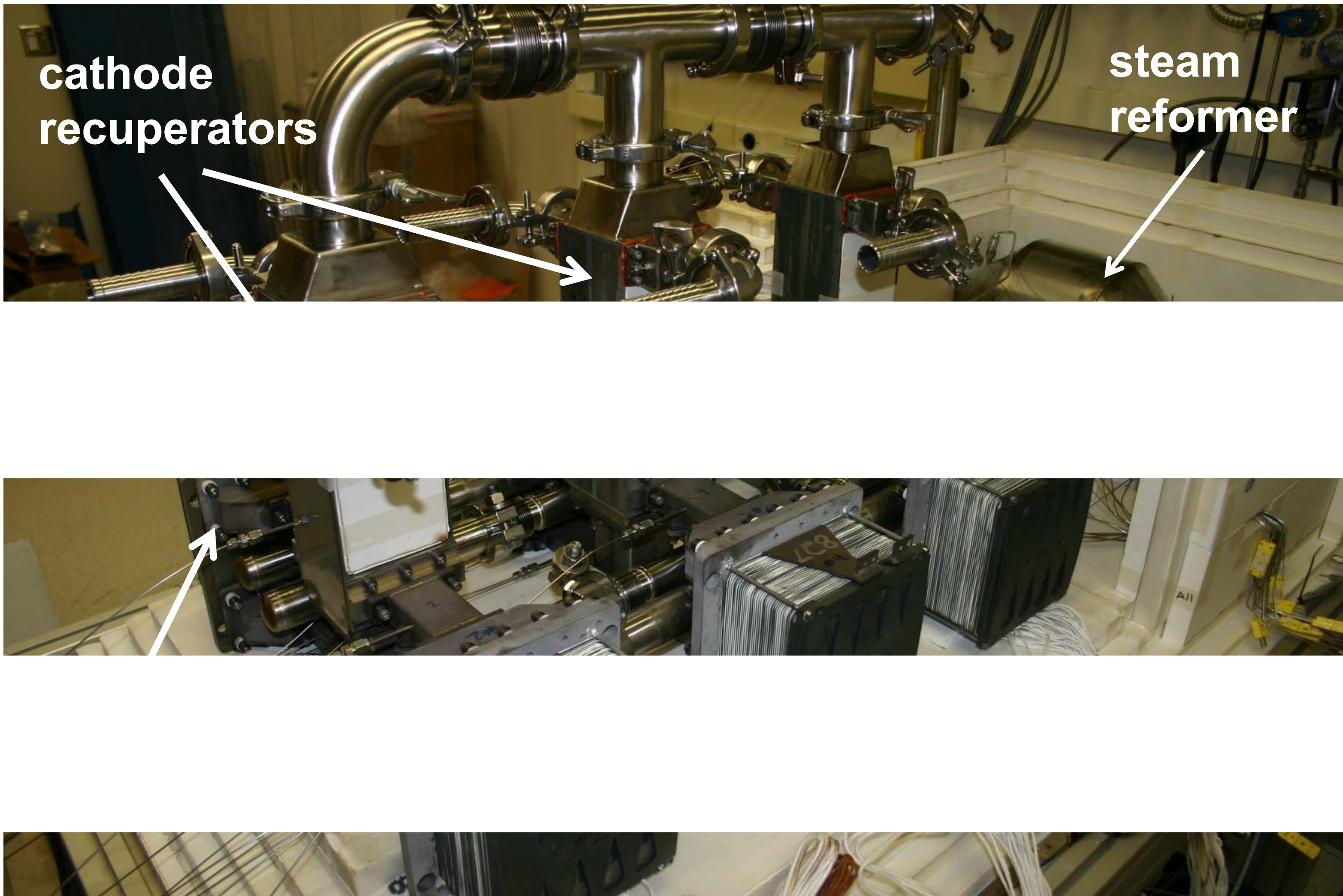
TRL-4 Demonstration System with Steam Reforming and Anode Recycle



- Development of SOFC Technology
- Fuel Reforming and System Design
- **Power and Efficiency**

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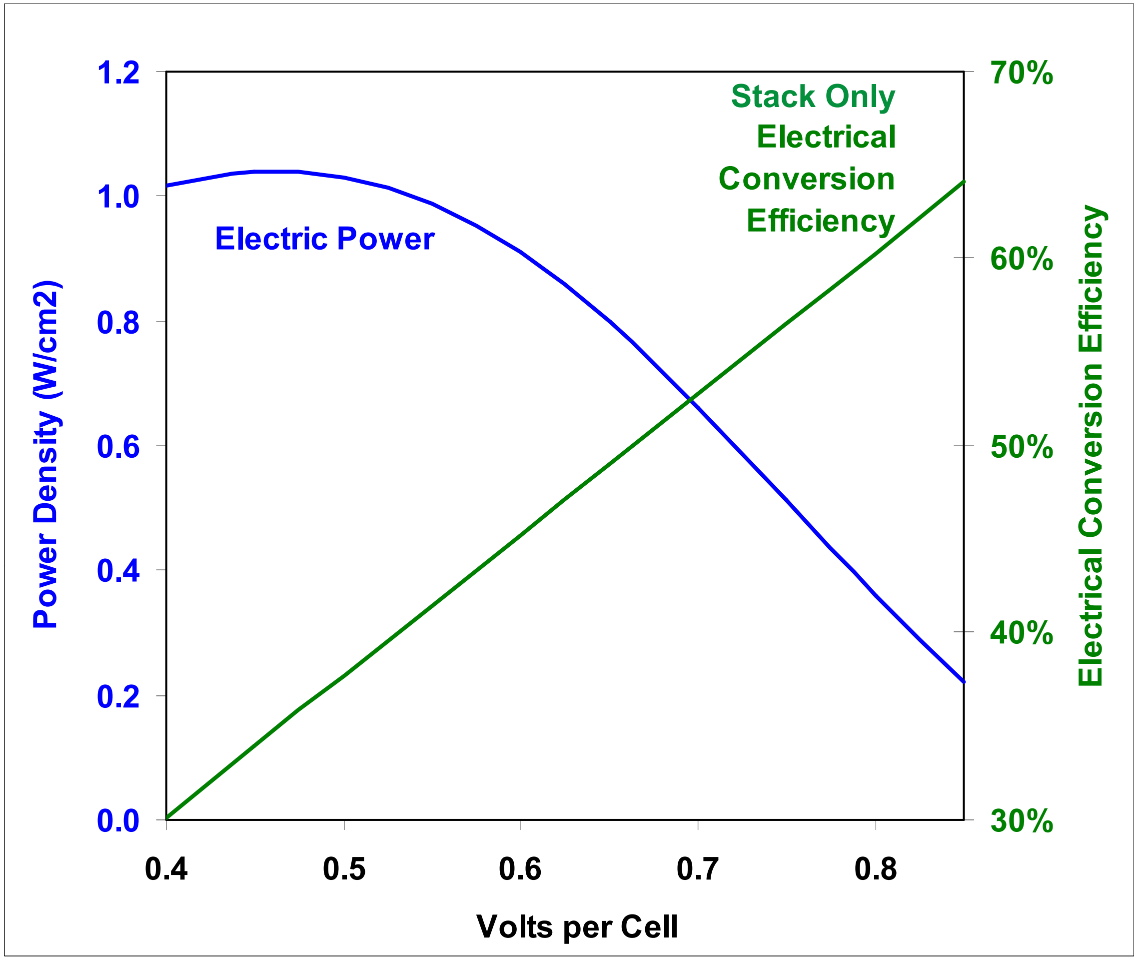
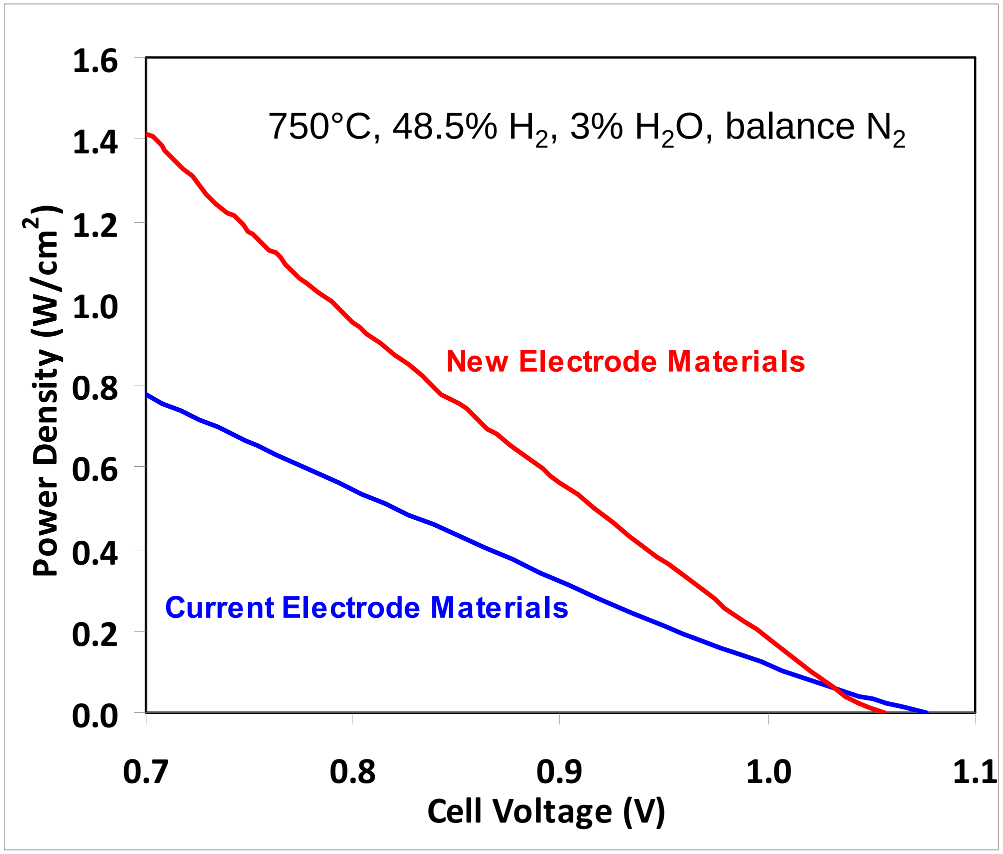
Higher Power Density Comes with Lower Efficiency



Factors Affecting Power Density (Stack Size)

- **Voltage**
- **Temperature**
- **Pressure**
- **Concentration of H_2, CO and CH_4 in anode gas (reformate)**
- **Cell materials**

Electrochemical Activity is About to Improve



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787 is a More Electric Airplane (MEA)

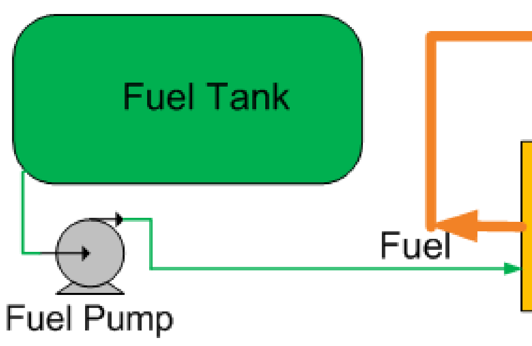
- Efficiency changes in 787 due to:
  - Composite airframe
  - Efficient no-bleed engines
- Transition in power sources in the MEA
  - Increase in electric power to ~1 MW

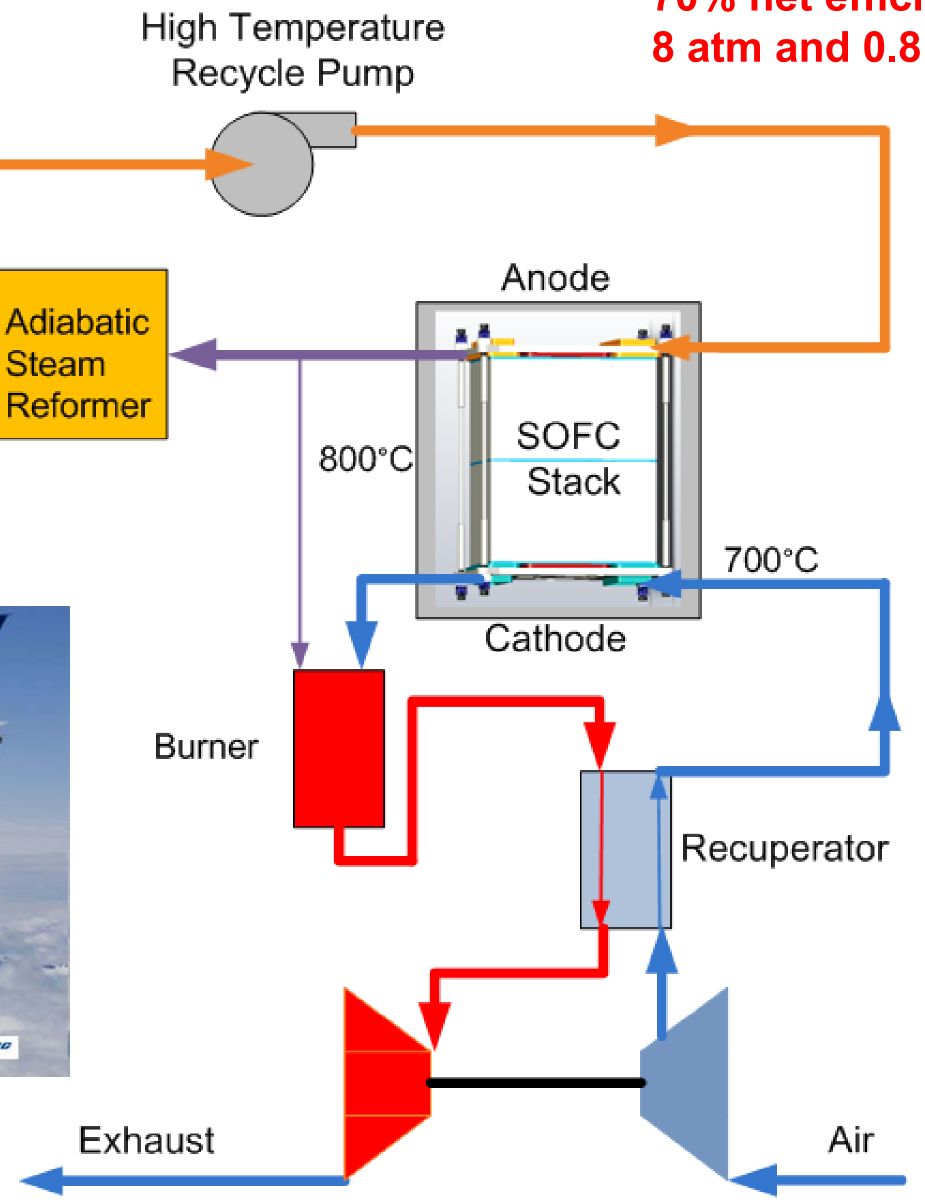
Efficient No-Bleed Engines

Power Source	Bleed	No Bleed + MEA
Electrical	Cabin Lighting Avionics, Fuel Pumps, etc.	Engine start, De-Ice ECS & Pressurization, Cabin Lighting, Avionics, Fuel Pumps, Brakes, Flight Controls, etc.
Hydraulic	Brakes, Flight Controls, Landing Gear, etc.	Flight Controls, Landing Gear
Pneumatic	Engine start, De-Ice ECS & Pressurization	Cowl De-Ice

Anode Recycle Steam Reformer System with Compressor/Expander

70% net efficiency at 8 atm and 0.8 V/cell

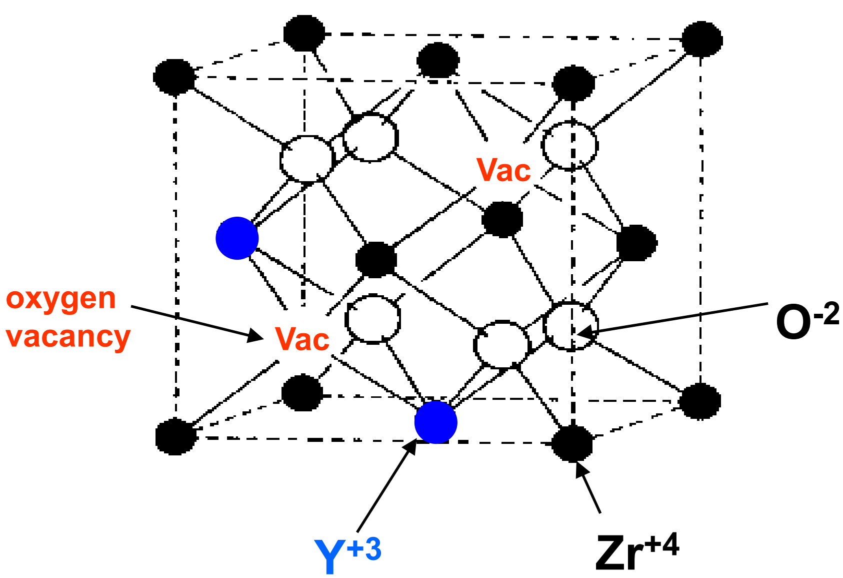


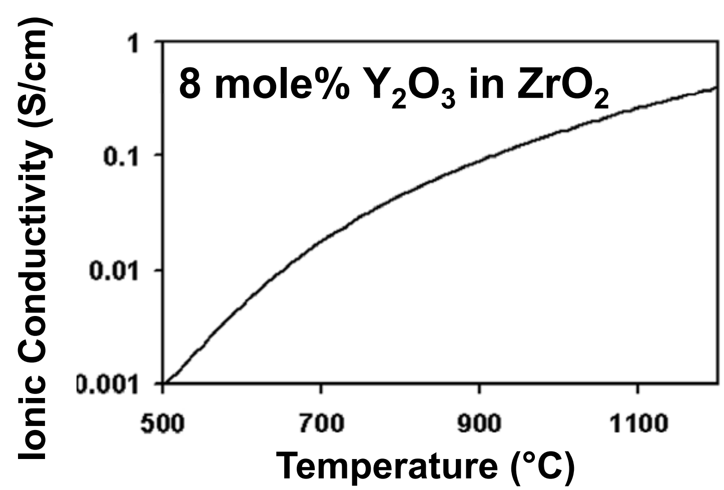


Back-Up Slides

When $Y^{(3+)}$ is substituted into ZrO_2:

- The material is called yttria-stabilized zirconia (YSZ) because the substitution "locks" the material into the cubic structure.
- For every two yttrium ions, one oxygen vacancy is created.
- The oxygen vacancies facilitate ionic conductivity; thermally activated oxygen ions can "hop" from vacancy to vacancy.



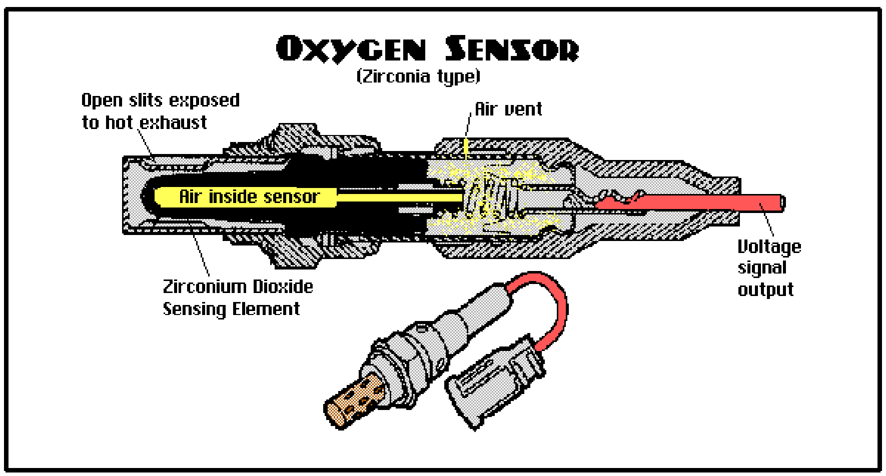


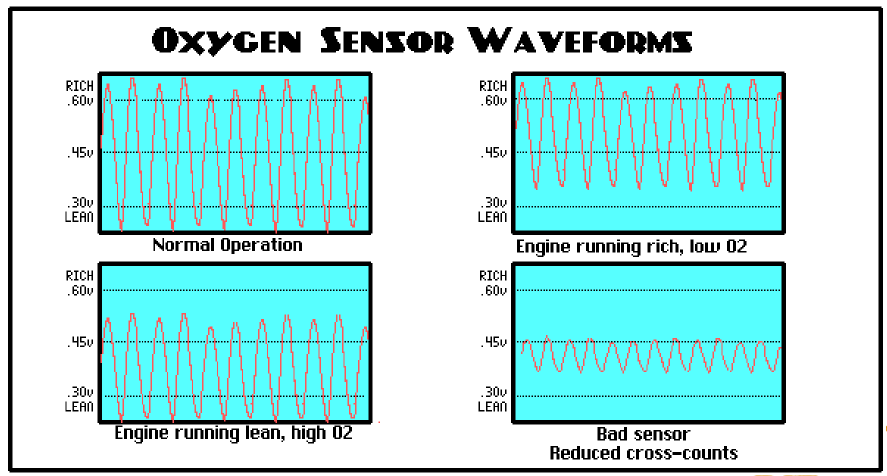
➢Every modern car contains a solid oxide cell in the form of a zirconia oxygen sensor.

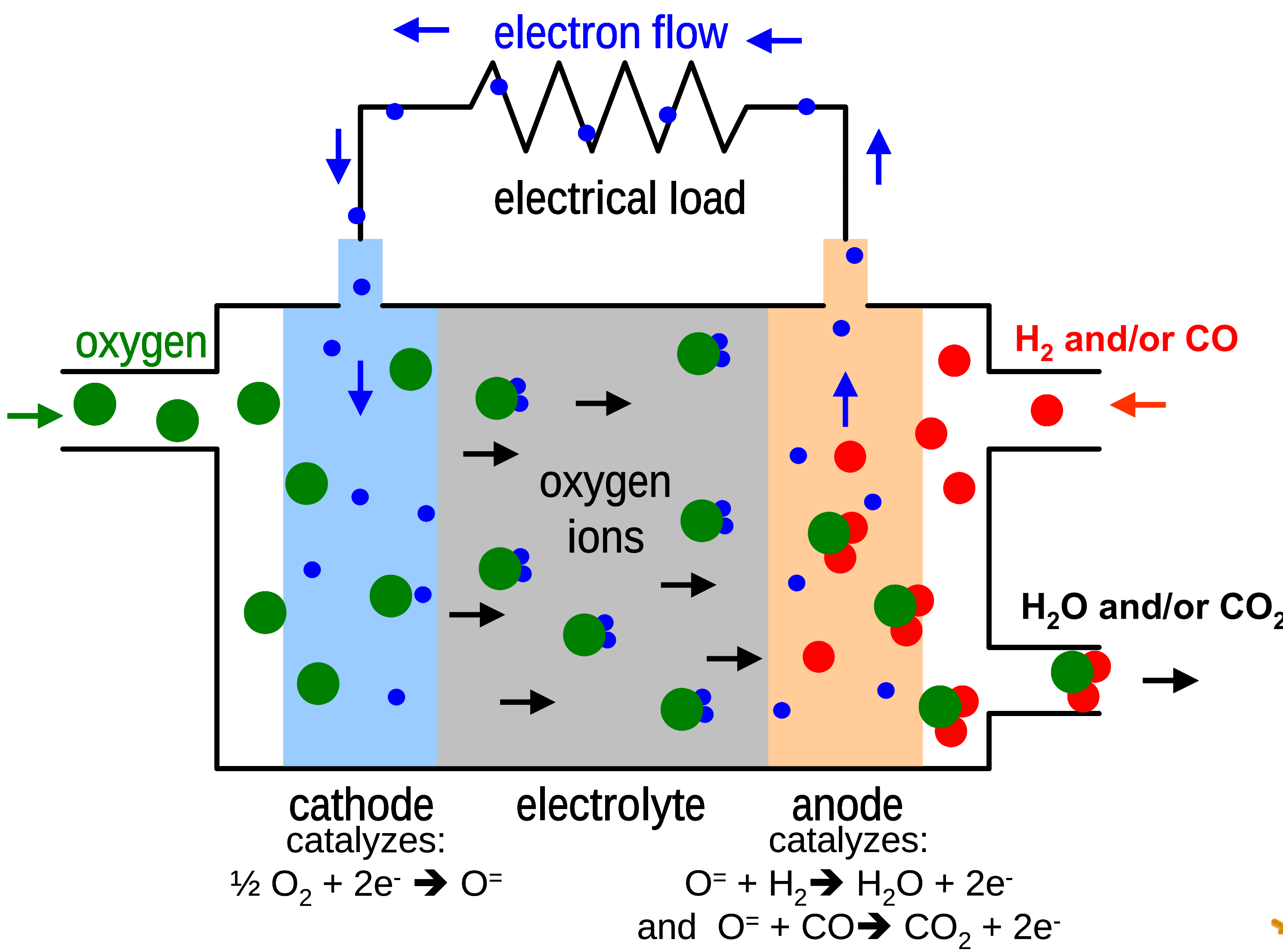
➢The output voltage is governed by the Nernst equation:

$$Voltage = \frac{RT}{4F} \ln \frac{P_{O_2(air)}}{P_{O_2(exhaust)}}$$

➢Current is near zero.







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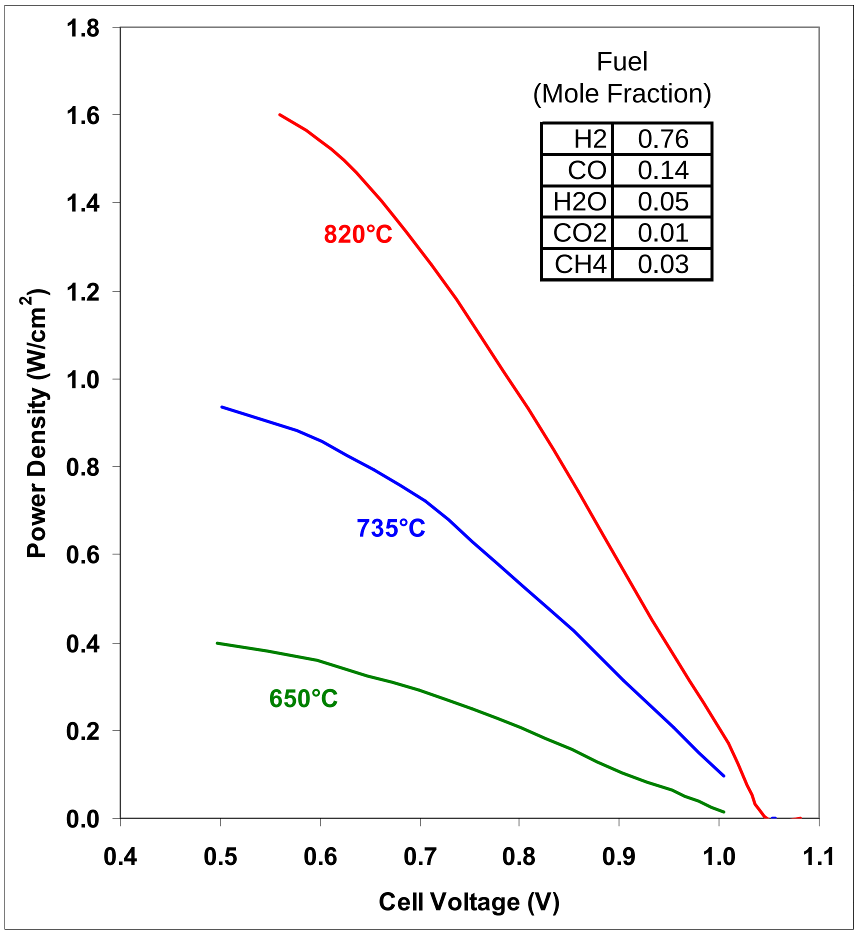
Upper Limit for Steel Framed Planar SOFC Technology: ~850°C



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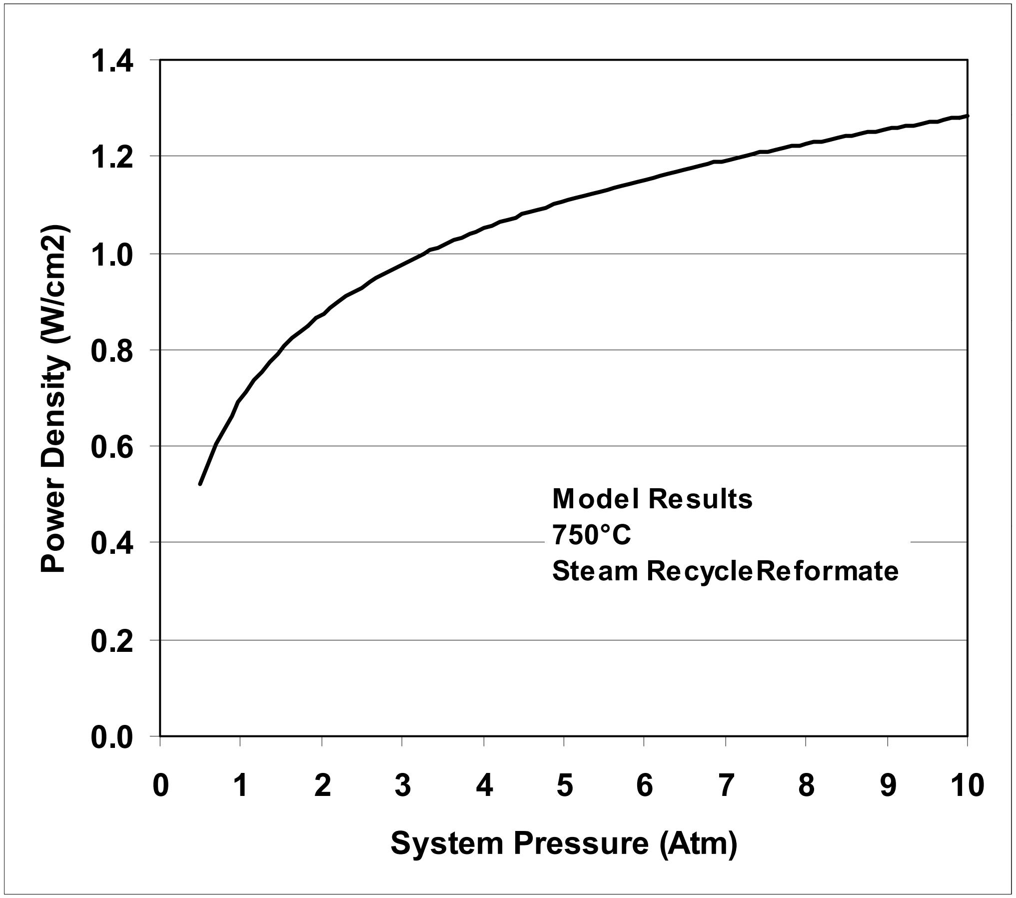
Effect of Pressure on SOFC Power Density



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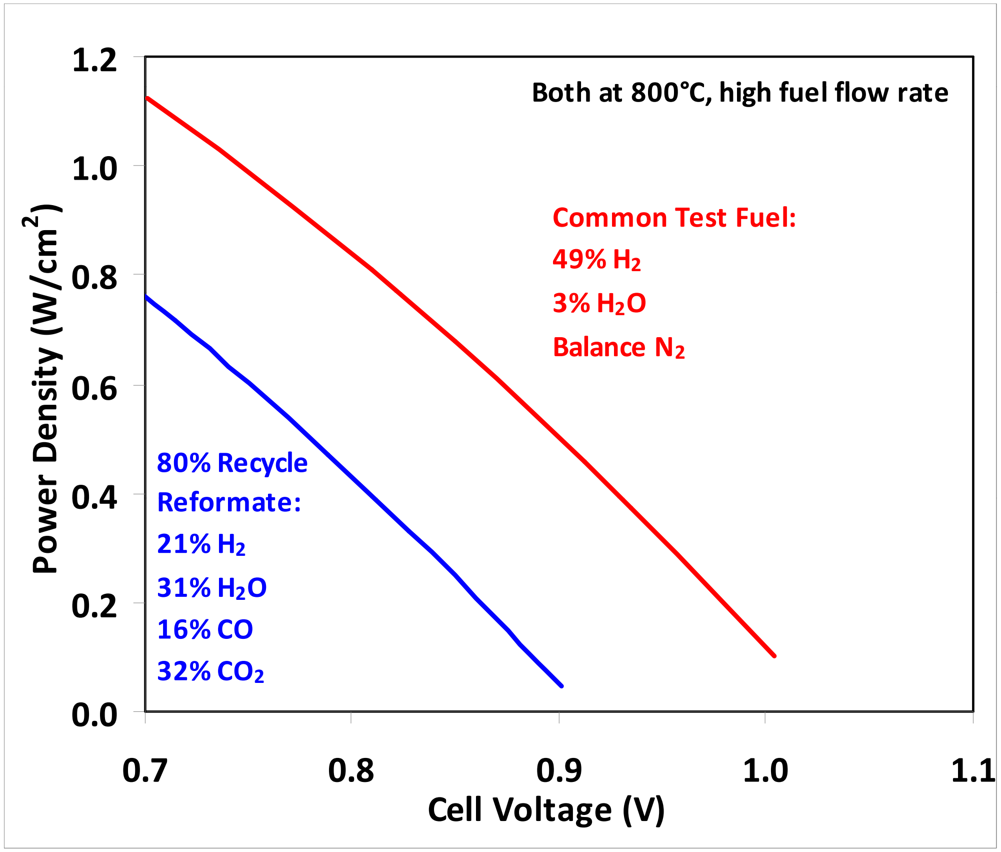
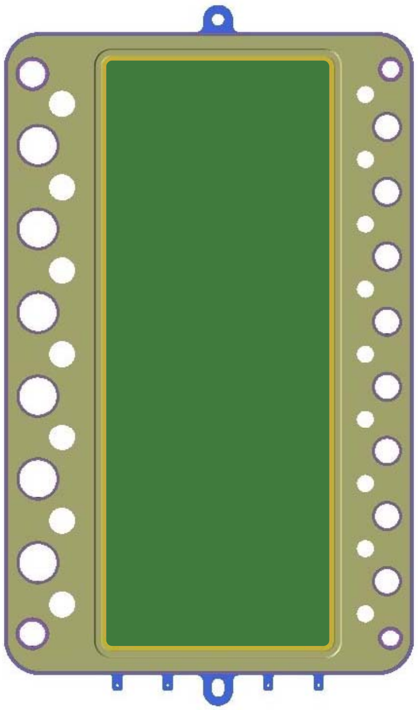
Reformate Gives Lower Power than Moist Hydrogen



Delphi Generation 4 SOFC Technology

Delphi Gen 4 Cassette
403 cm^2 Active Area



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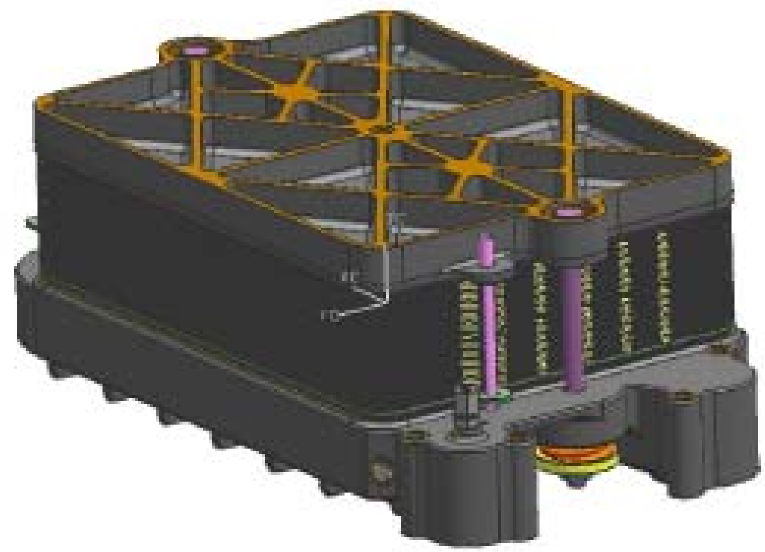

Manifold, load plate and
current collectors = 33.5 kg

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Predicted Effects of Pressure and Cell Voltage on System Efficiency and Stack Mass

For SOFC System with Steam Reformer, Anode Recycle and Compressor/Expander

Efficiency/Mass*

	SOFC Cell Voltage			
Pressure	**0.85**	**0.80**	**0.75**	**0.70**
0.8 atm	75%/7455	71%/3358	68%/2168	64%/1608
3 atm	75%/4291	70%/1933	66%/1404	61%/1120
8 atm	75%/2959	70%/1333	65%/1034	61%/859

Efficiency = Net Electrical Energy Supplied to Bus / LHV of Kerosene

*Mass is for cassettes needed to generate 821 kW gross power.