Solid Oxide Fuel Cell (SOFC) Technology for Greener Airplanes

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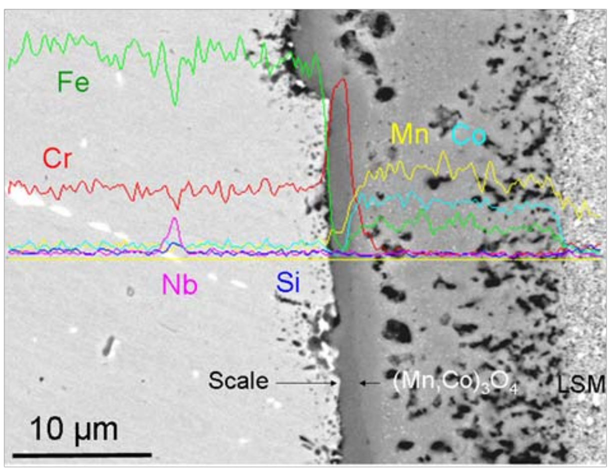
SOFC Technology Development at PNNL

- **PNNL has been active in SOFC development since 1987.**

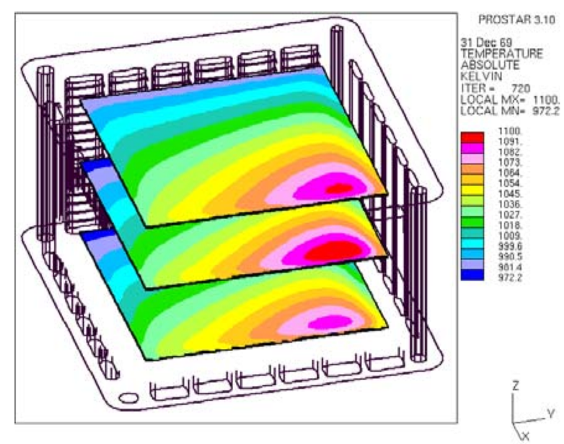
Glycine – nitrate powder synthesis of $La_{0.7}Ca_{0.31}CrO_3$

- **Major participant in SECA Core Technology Program since 2000.**



Development of electrically conductive coatings to prevent Cr volatility from SS

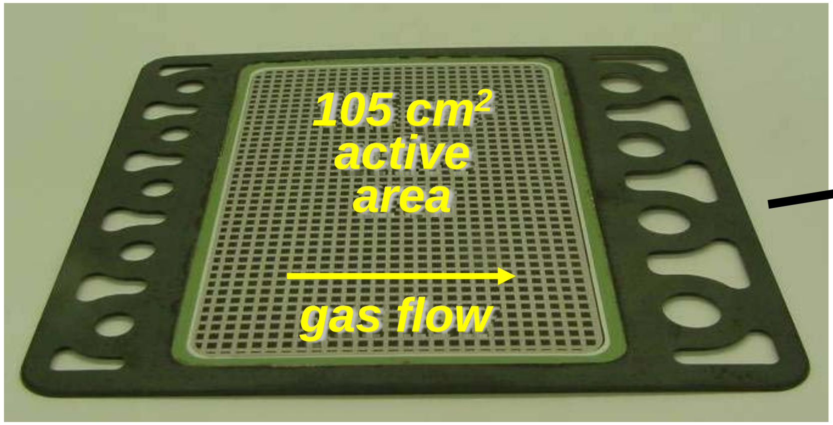
SOFC stack electrochemical-thermal modeling



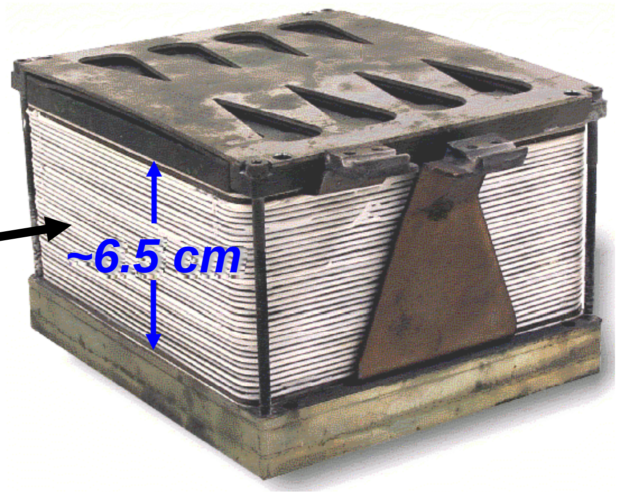
PNNL-Delphi SECA Team

• Transferred SOFC technology to Delphi starting in 1999.

• PNNL now purchases stacks from Delphi for integration into specialty systems.



Single Cell in Co-flow Cassette



30-Cell Stack in Frame
700-2300 watts, 9 kg, 2.5 L

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Delphi is Developing Auxiliary Power Unit (APU) for Long Haul Trucks

- Supports “hotel load” so ICE can be shut down at night.
- Runs on low-sulfur diesel (<15 ppm S)

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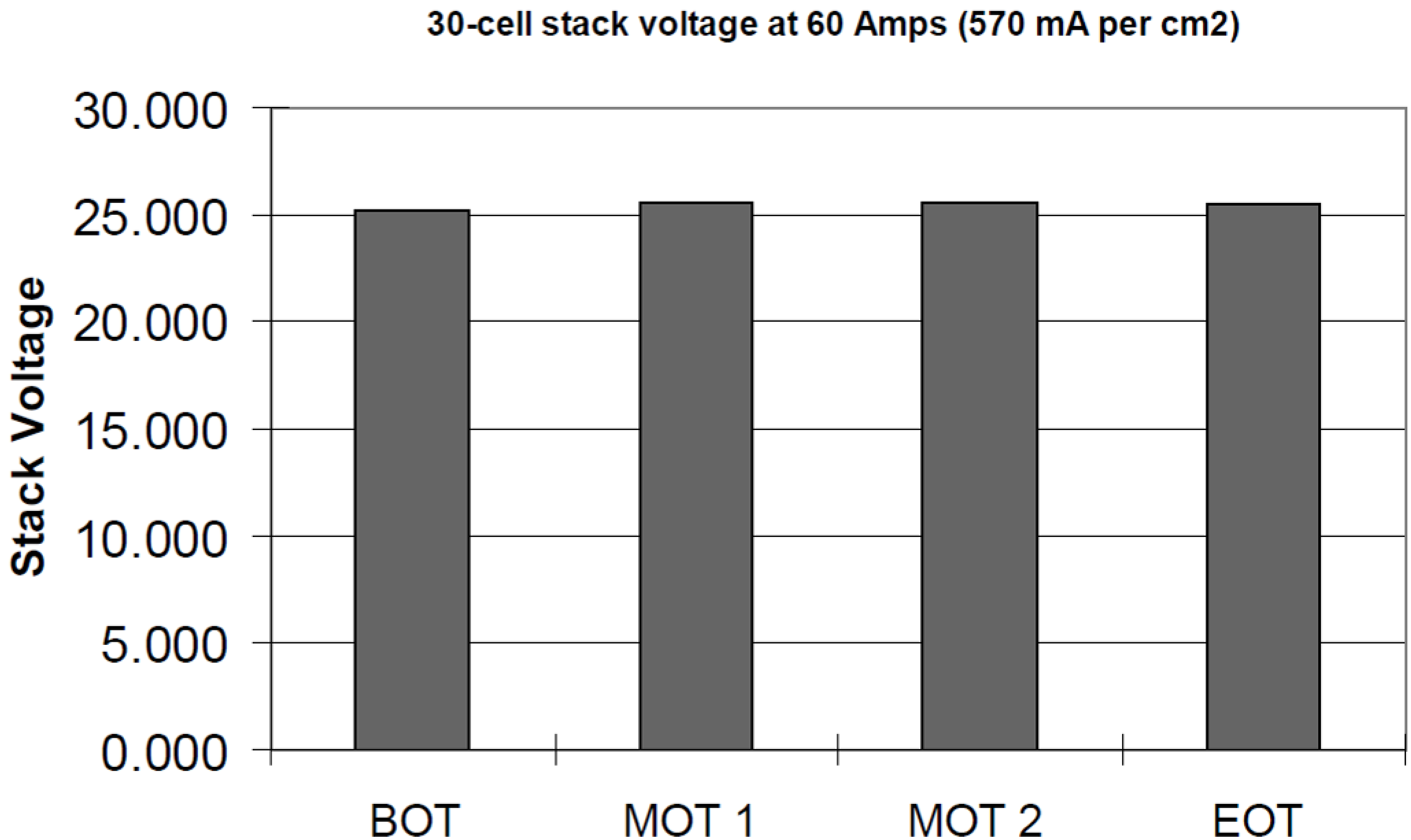
Vibration Testing of 30-Cell Stack - Delphi



- Military Standard d 810G Method 514.6 Annex C “Truck and Transportation Over US Highways”
- 10-800 Hz, 3 Axes
- Simulated 750,000 miles of driving

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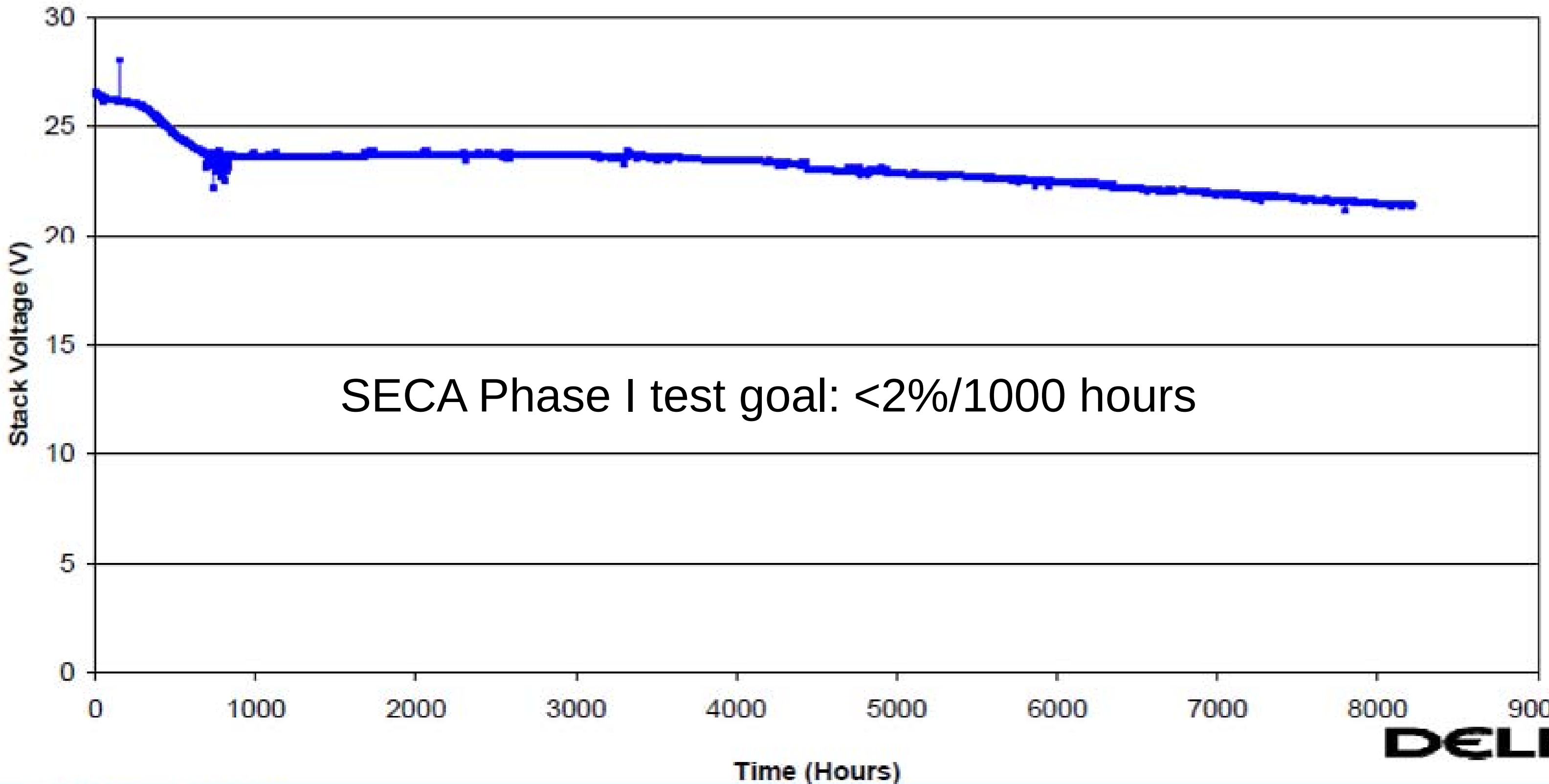
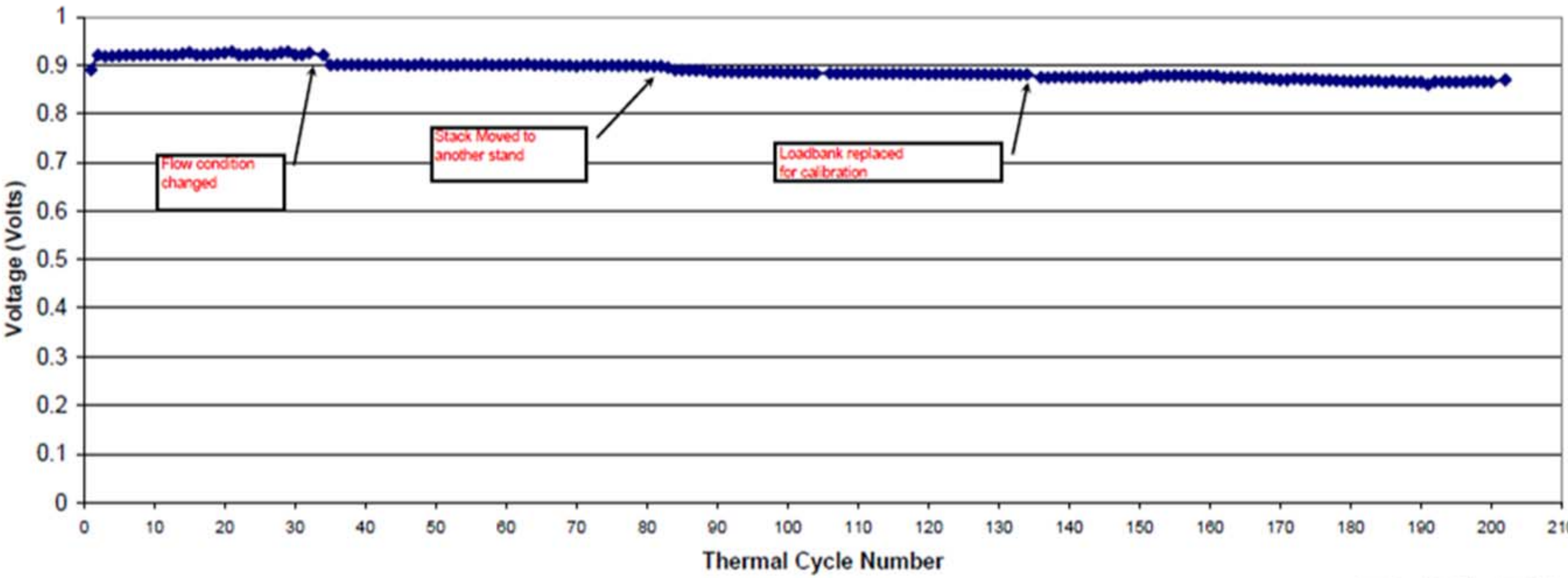
Gen 3.2 30-Cell Stack Durability

- Fuel = 48.5% H_2, 3% H_2O, rest N_2; current = 333 mA per cm^2
- > 8200 hours, continuing to run
- Total degradation is 1.20% per 500 hours
- Degradation after initial lowering of power and stabilization is 0.66% per 500 hours
- Implementing solution to mitigate initial lowering of power



Thermal Cycling

- Gen 3.2 30-cell stacks evaluated for thermal cycling with improved seals
- 200 thermal cycles demonstrated with minimal degradation
  - 2 hour heat-up
  - Performance evaluated at each thermal cycle
  - Constant current load of 285 mA per cm^2 at operating temperature
  - Fuel of 48.5% H_2, 3% H_2O, rest N_2



Key Advantages of SOFC for Aircraft

- H_2, CO and CH_4 can be directly supplied to the anode as fuels, so an SOFC system can more easily use liquid hydrocarbons.

- High temperature supports steam reforming, which boosts system efficiency.

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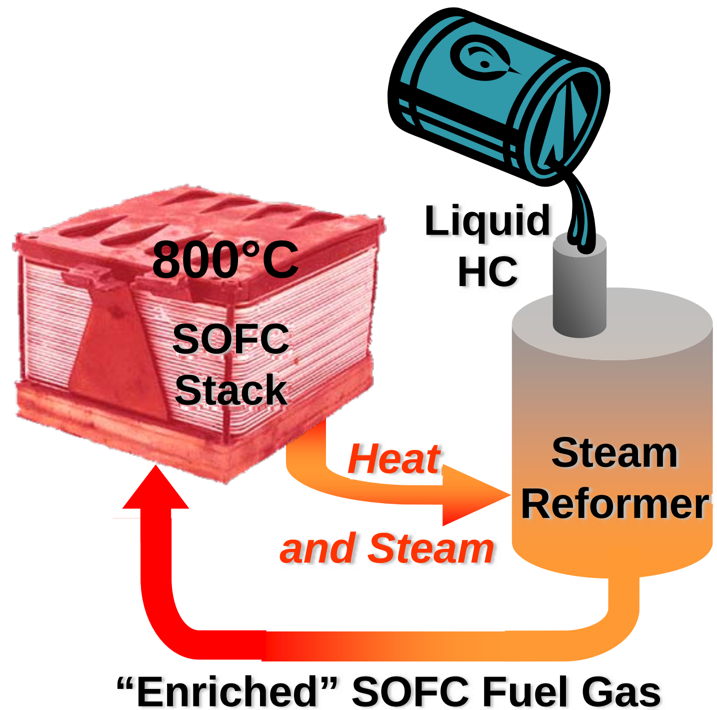
Efficiency Boost from Steam Reforming

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

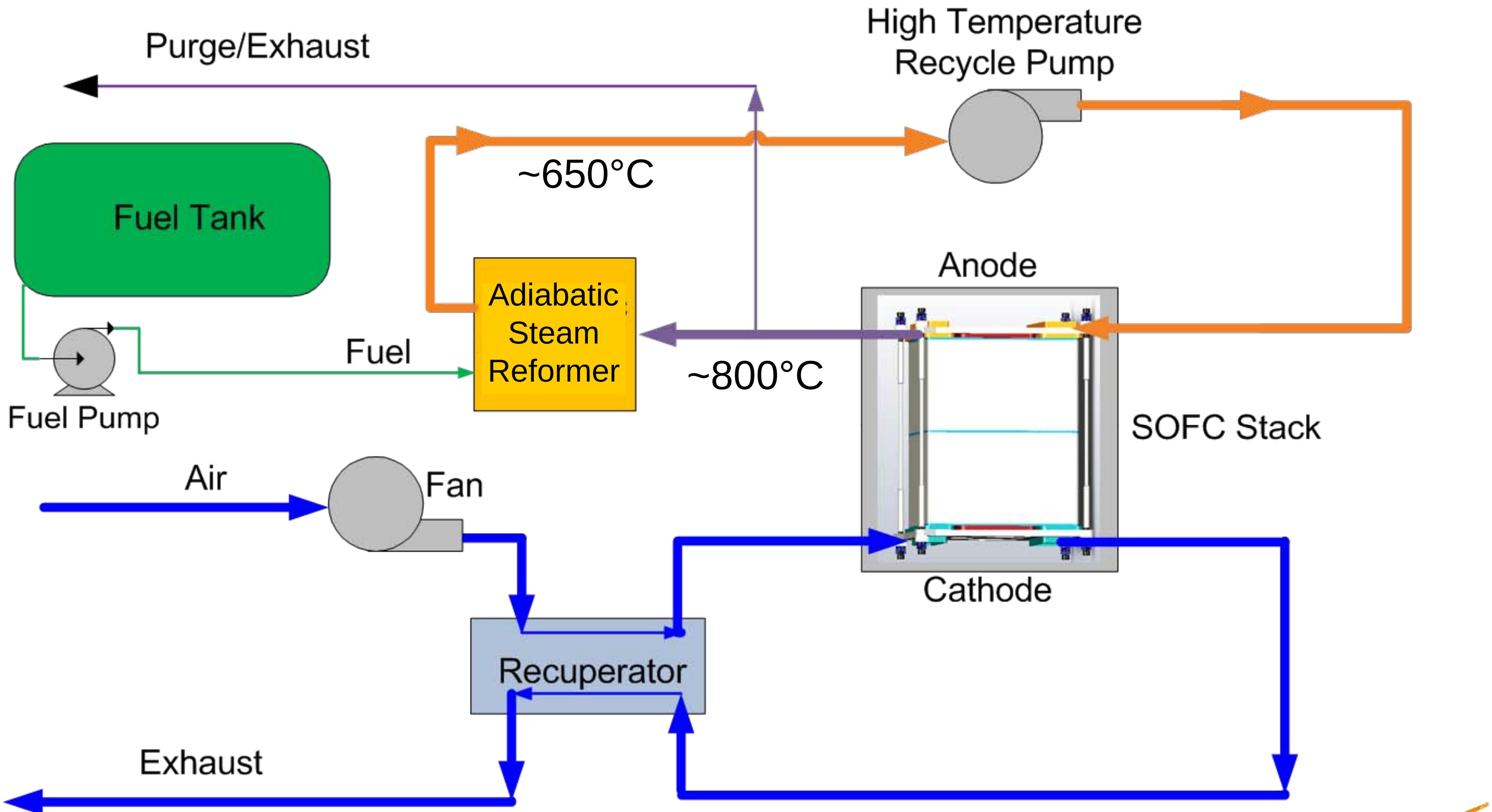
Steam Reformation of *n*-Dodecane:

$$\underbrace{C_{12}H_{26}}_{\text{7552 kJ/mole}} + 12H_2O + \text{heat} \rightarrow \underbrace{12CO + 25H_2}_{\text{9421 kJ/mole}}$$

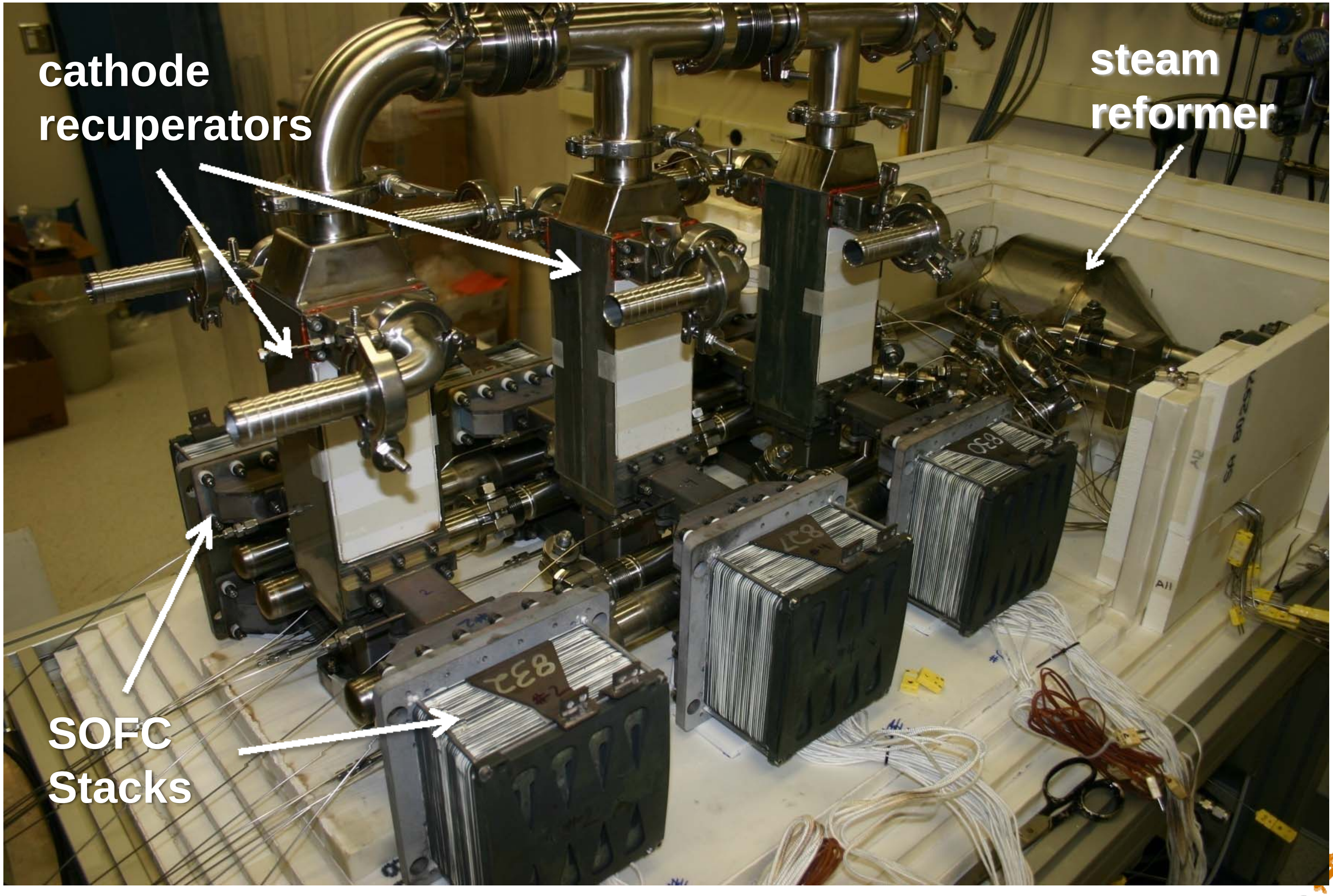
- ***System can yield 65% net efficiency***
- **Steam and heat for reforming obtained from SOFC stack exhaust**



SOFC Power System with Steam Reforming and Anode Recycle



Demonstration System with Steam Reforming and Anode Recycle



Key Challenge for SOFC in Aircraft

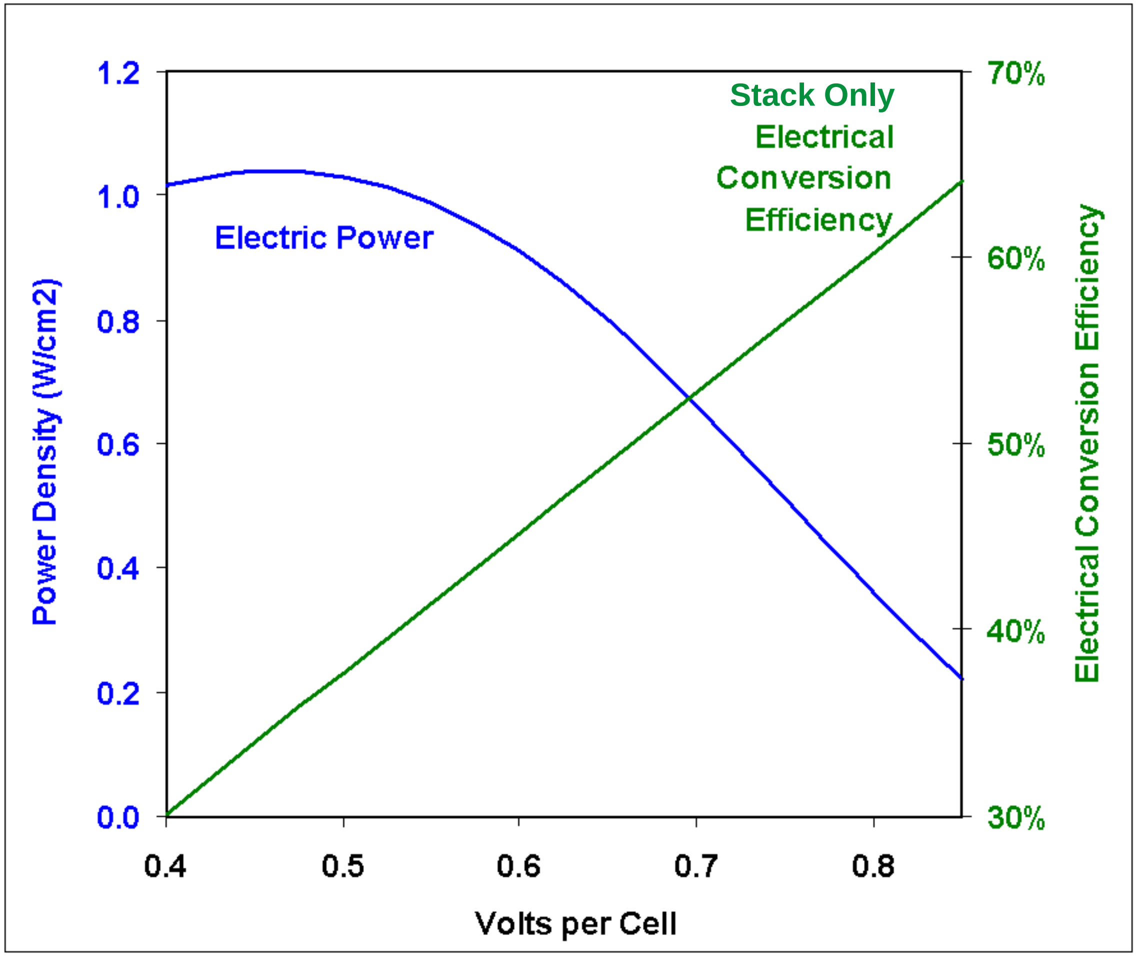
$$\frac{\textbf{kW}}{\textbf{kg}}$$

Must increase specific power!

The Numerator: Factors Affecting Power Density

- Voltage
- Temperature
- Fuel Concentration
- Electrochemical Activity

High Power Density Comes with Lower Efficiency



- Operation below ~0.7 volts may accelerate degradation.

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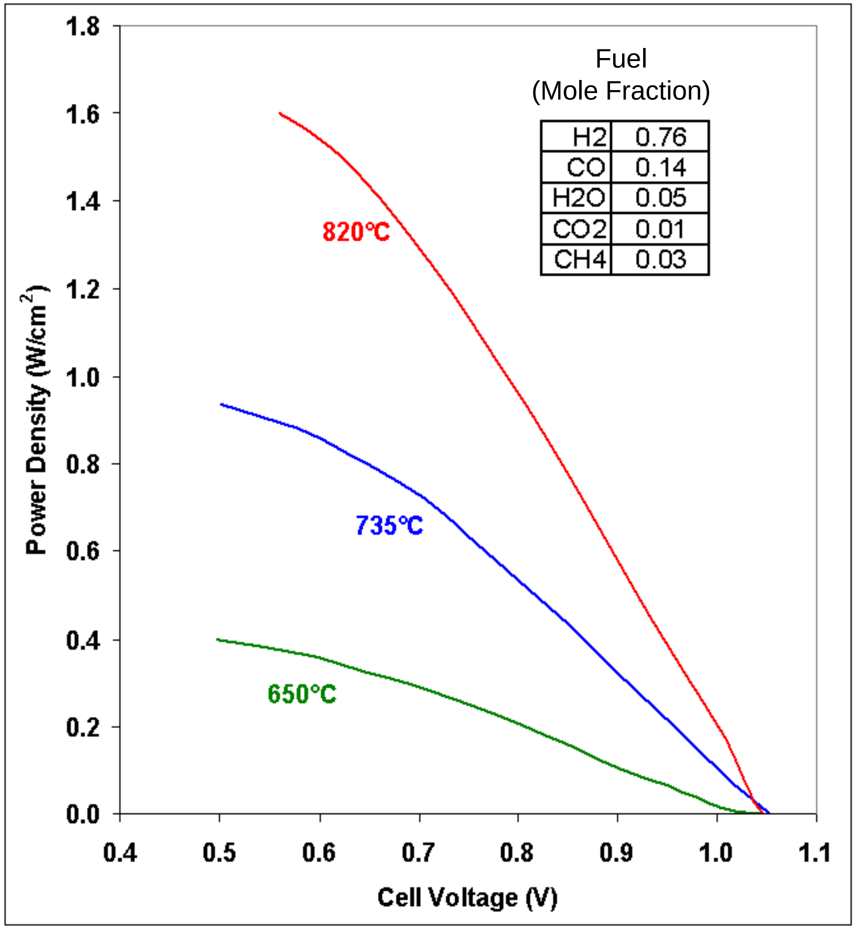
Upper Limit for Steel Framed Planar SOFC Technology: ~850°C



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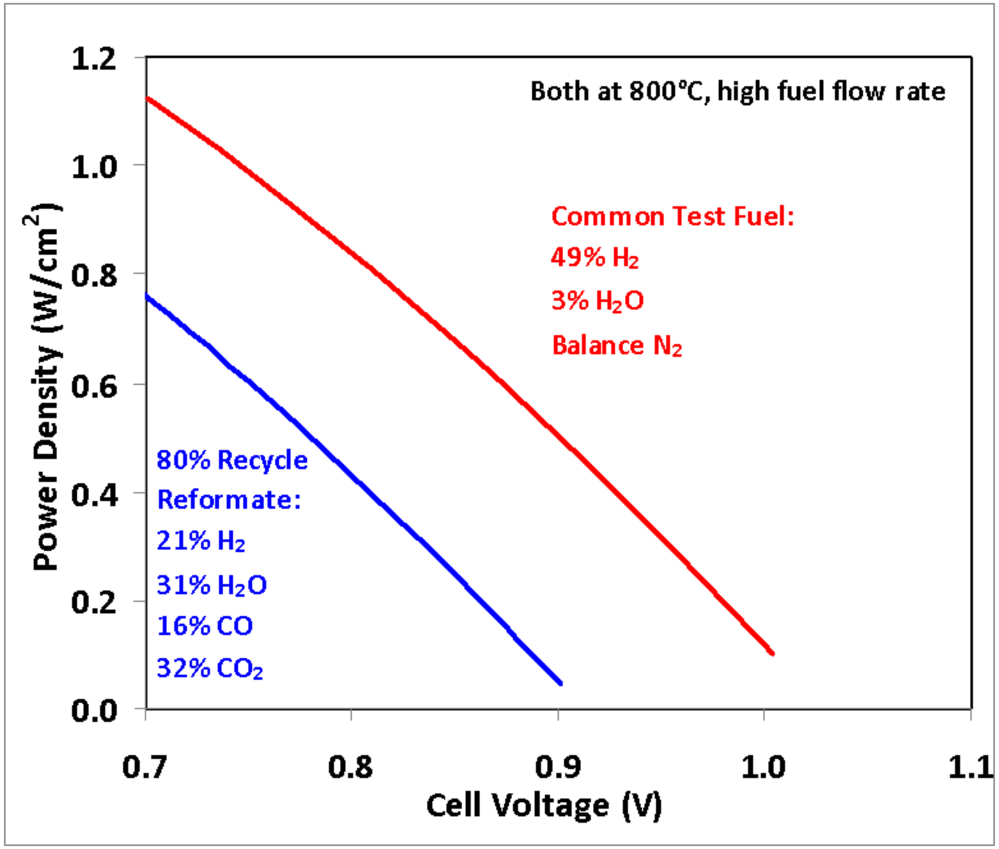
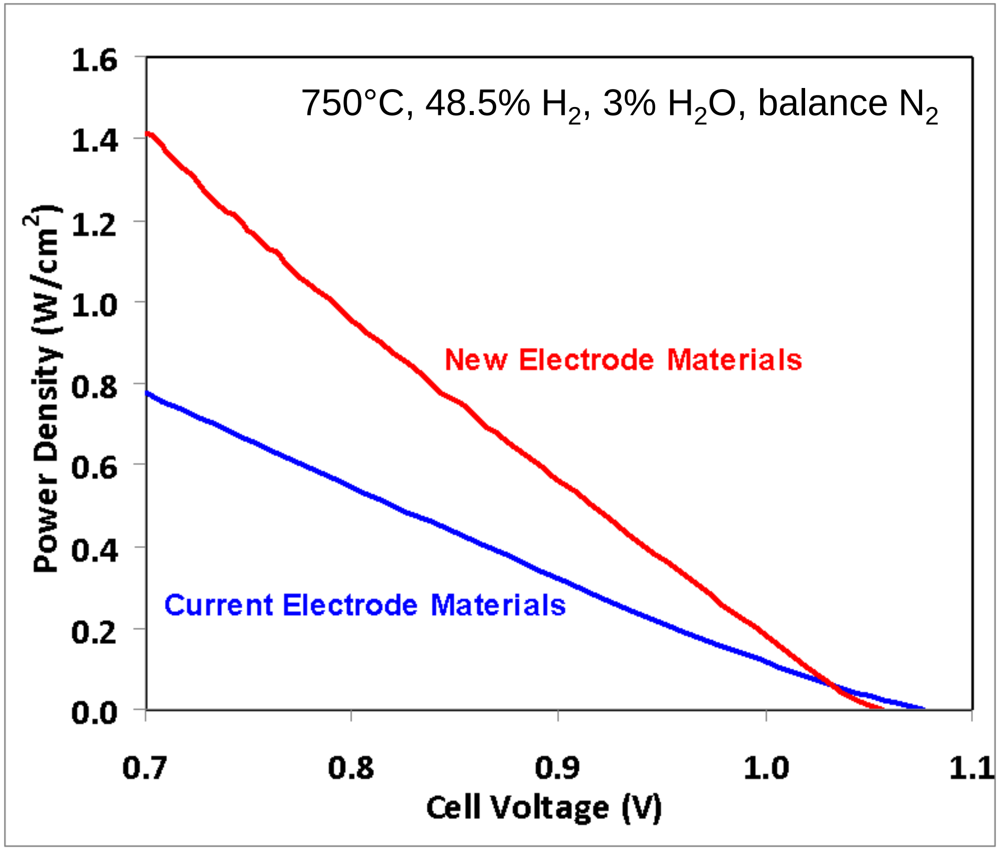
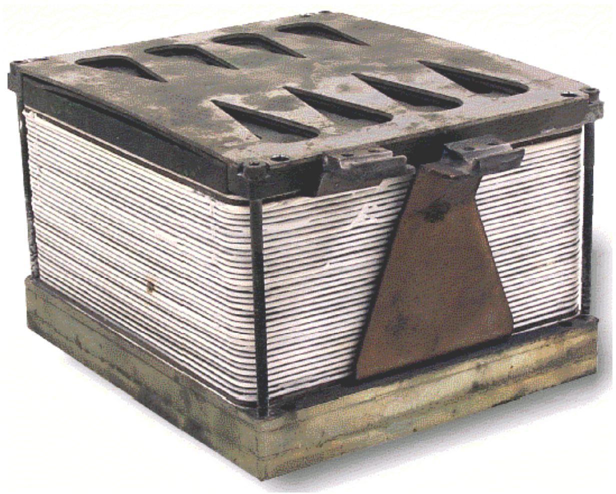
Reformate Gives Lower Power than Moist Hydrogen



Better Times are Ahead: Electrochemical Activity is Improving



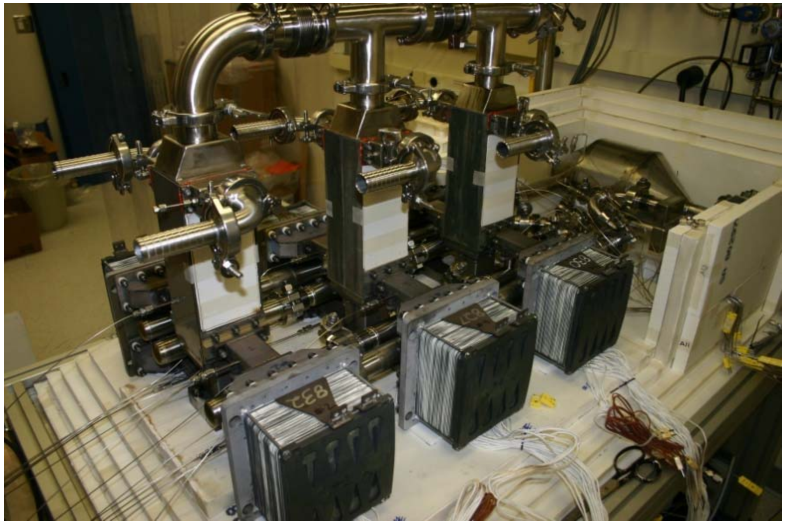
Stack Weight

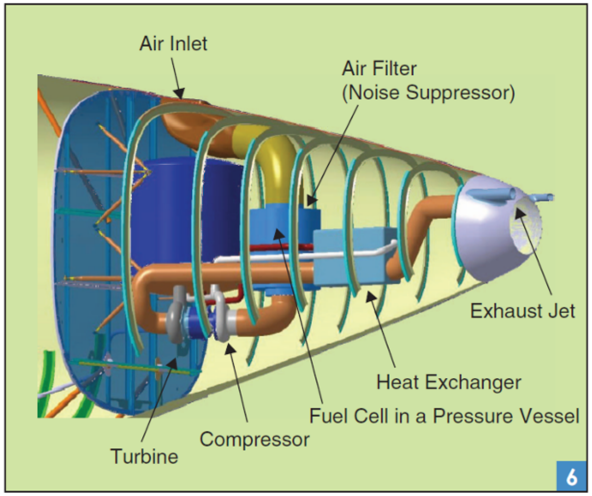


- Current technology:
  ~1.5 kW, 9 kg
  ~ 0.17 kW/kg

- Specific power required for aircraft stack:
  ~ 1.0 – 1.5 kW/kg

System Weight



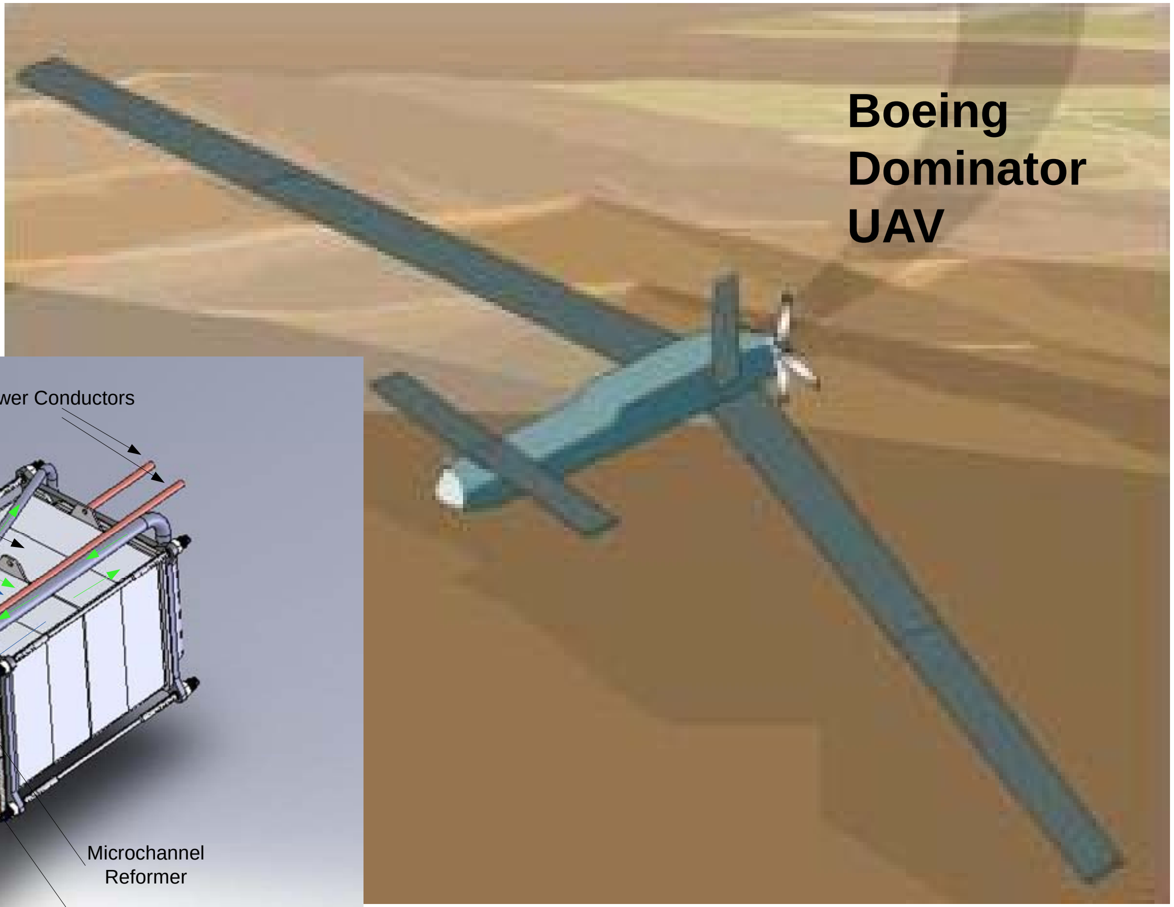


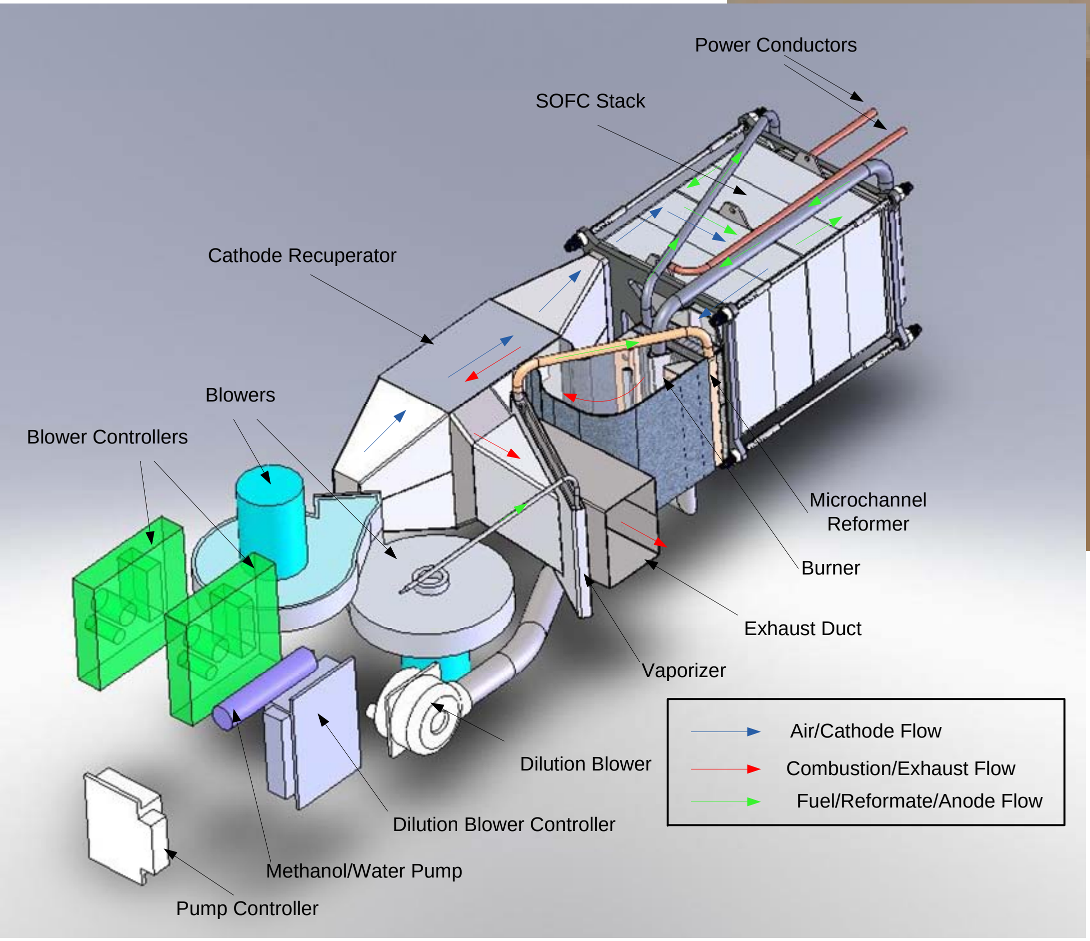
K. Rajashekara, J. Grieve and D. Daggett, IEEE Industry Applications Magazine, July-August, 2008

- Current technology not designed for low mass:
  6 kW, ~170 kg
  ~ 0.035 kW/kg

- Specific power required for aircraft system:
  ~ 0.4 to 0.5 kW/kg

Demonstration System for UAV (AFRL)





- Short flight, methanol-water fuel
- 0.55 volts/cell, low efficiency
- 3 kW, 12.3 kg ➔ 0.24 kW/kg

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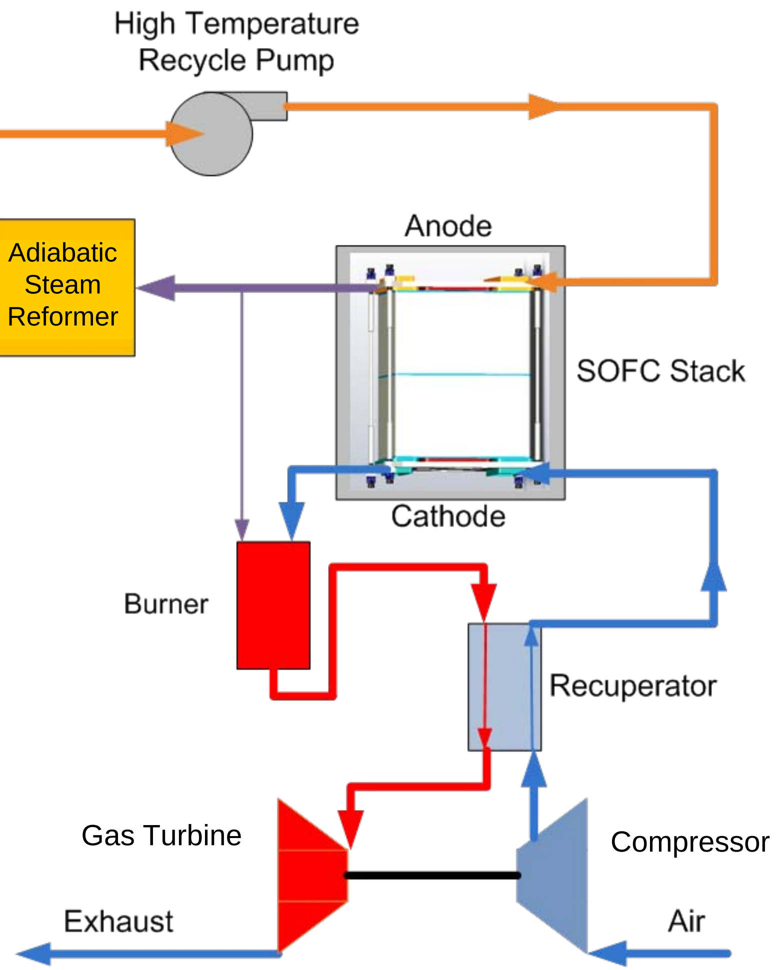
Possible Configuration for Aircraft



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Greener Airplane Study

Assumptions:

- Reference airplane will be the more electric 787.
- SOFC to supply base load.
- Metrics are overall airplane fuel efficiency and emissions.

Questions to be addressed:

- Determine load profile for 787 (have made a good start with Joe Briet's help)

- What size and configuration for SOFC base-load system?
  - Combine with turbine-compressor?
  - Run at elevated pressure?
  - How much anode recycle?
  - What voltage (power vs. efficiency)?
  - Two SOFC systems for redundancy?

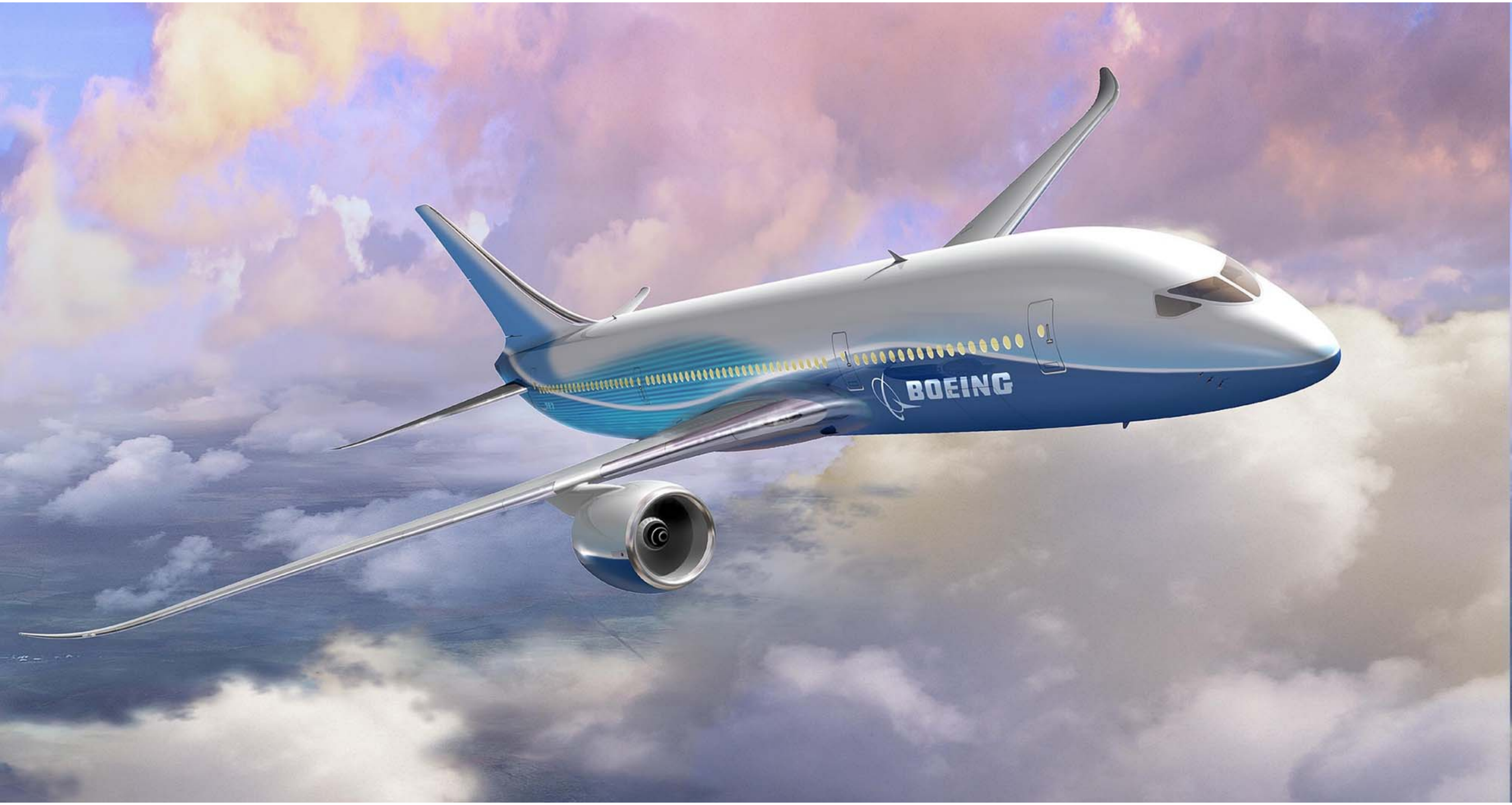
- What technologies for peak loads?
  - Turn up SOFC
  - PEM, HTPEM
  - Turbine
  - Batteries, ultra-capacitors
  - Combinations

Greener Airplane Study, Cont.

<u>Questions, continued:</u>

- De-sulfurization on-board or at airports?
- If PEMFC used for peaking power, how should H2 be supplied?
  - Storage in tanks
  - Metal hydrides
  - Obtain by membrane separation from SOFC system reformate
- Assume water will be condensed and collected. How to use it?
  - Cabin air humidification
  - Lavatories
  - Injection into jet turbines to reduce emissions
- Can waste heat be used for de-icing or…?
- Should CO_2 be separated for fuel tank inerting?
- Assess benefits of optimum system over existing (787) technology using overall airplane fuel economy and emissions as metrics.
- Assess technology readiness levels and pathway to deployment.

Thank you!



Questions?

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