Assessment of Solid Oxide Fuel Cell Power System for Greener Commercial Aircraft

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Project MT001

Overview

Timeline

- Start: July 19, 2010
- End: September 30, 2011
- Percent complete: *45%*

Barriers

- Identify and quantify barriers to deployment of fuel cell power systems on commercial aircraft.

Budget

- Total project funding
  - DOE share: $400K
  - Contractor share: $0
- Funding received in FY10: $400K
- Funding for FY11: $150K

Partners

- Collaborator: Boeing Commercial Aircraft Division
- Project Lead: PNNL

Objectives-Relevance

- Assess approaches to provide electrical power from solid oxide fuel cells (SOFC) on board commercial aircraft.

- Focus on more-electric airplanes, with the Boeing 787 as a case study for comparison.

- Assess optimum sizing, location and configuration of the SOFC power system.

- Identify and quantify barriers to deployment of fuel cell power systems on commercial aircraft.

Approach

- Obtain detailed understanding of current 787 electrical system, including generators, power conversion and loads.
  - Milestone: Determine reference load profile. Completed Q1, FY11

- Develop a model to determine the expected performance and fuel efficiency of various SOFC power system configurations. Use PNNL stack performance model and ChemCAD.
  - Milestone: Complete system model. Completed Q1, FY11

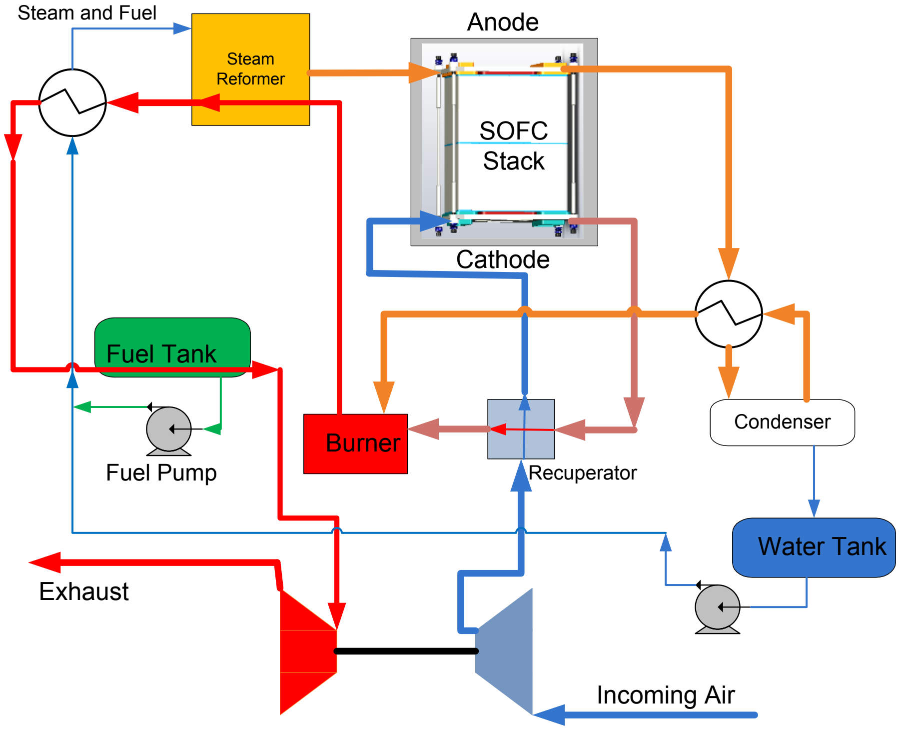
- Perform a trade study using the modeling tool. Assess various SOFC system configurations. Assess optimum system operating conditions, including stack voltage, system pressure and single-pass fuel utilization.
  - Milestone: Complete trade study Q3, FY11. On schedule.

Approach, cont.

- Quantify the benefits of the optimum fuel cell power system relative to fuel savings and emissions reduction.
  - Milestone: Quantify benefits of fuel cell system, Q4, FY11. On schedule.

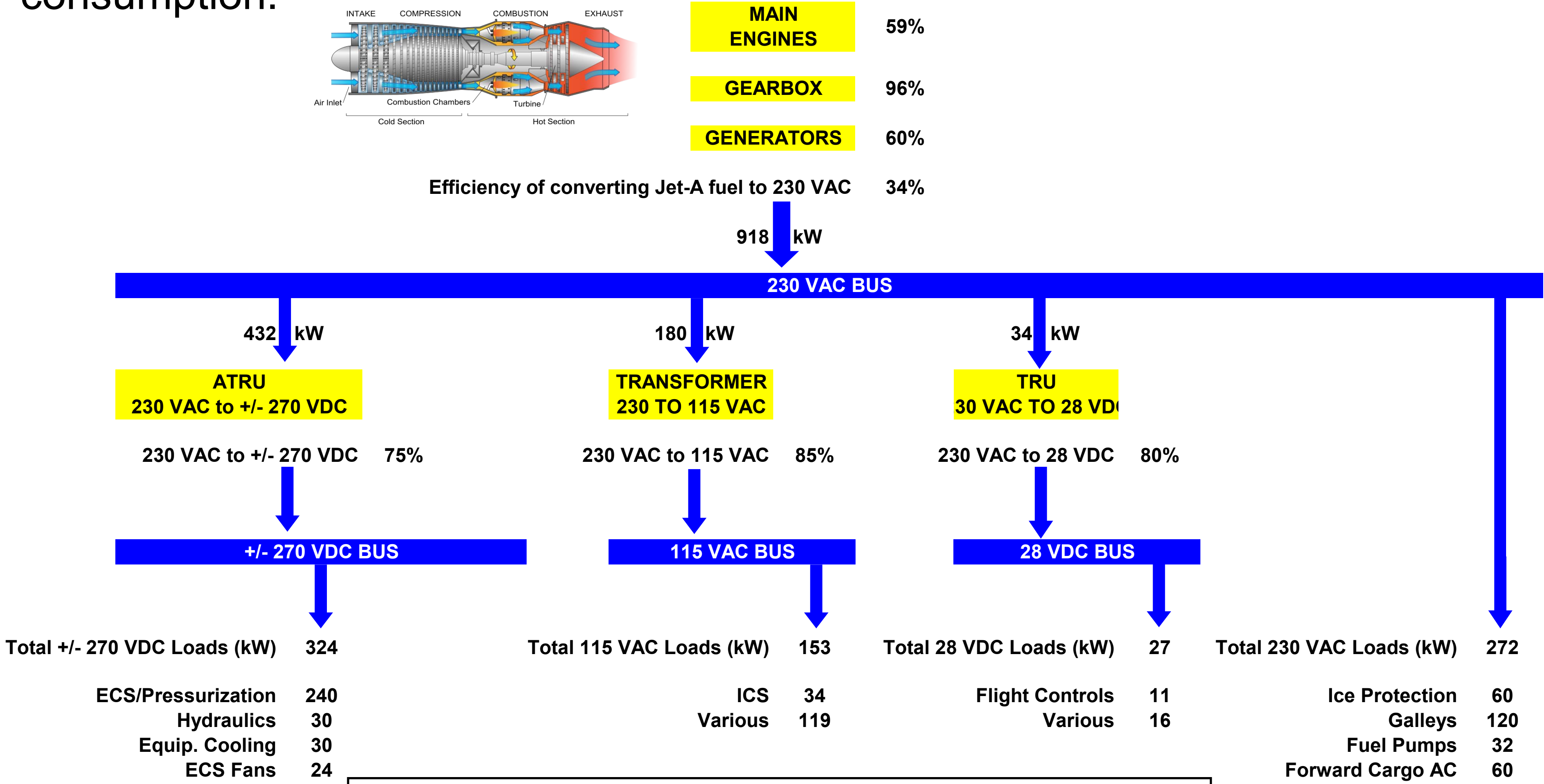
- Identify near-term demonstration project(s) that would decrease barriers to commercial use on airplanes.
  - Milestone: Demonstration project(s) identified, Q3, FY11. Not yet started.

- Prepare a final report to DOE.
  - Milestone: Complete final report Q4, FY11. Not yet started.



Technical Accomplishments and Progress

- Obtained extensive information from Boeing on the 787 electrical system, including generation and distribution systems, load profiles and fuel consumption.



MAIN ENGINES	59%
GEARBOX	96%
GENERATORS	60%
Efficiency of converting Jet-A fuel to 230 VAC	34%

918 kW

230 VAC BUS

432 kW

ATRU
230 VAC to +/- 270 VDC

230 VAC to +/- 270 VDC 75%

+/- 270 VDC BUS

180 kW

TRANSFORMER
230 TO 115 VAC

230 VAC to 115 VAC 85%

115 VAC BUS

34 kW

TRU
30 VAC TO 28 VD

230 VAC to 28 VDC 80%

28 VDC BUS

Total +/- 270 VDC Loads (kW)	**324**
ECS/Pressurization	240
Hydraulics	30
Equip. Cooling	30
ECS Fans	24

Total 115 VAC Loads (kW)	**153**
ICS	34
Various	119

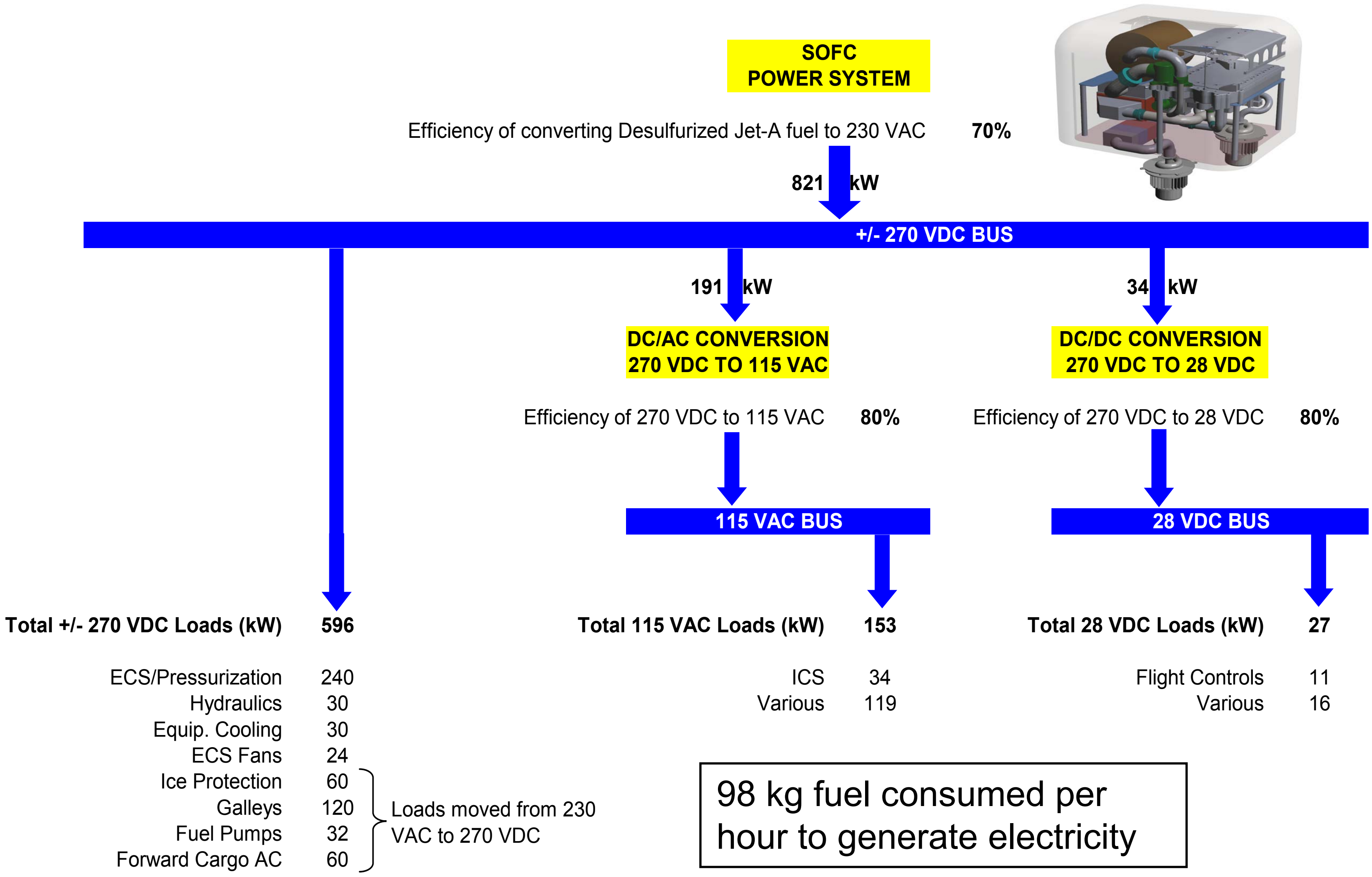
Total 28 VDC Loads (kW)	**27**
Flight Controls	11
Various	16

Total 230 VAC Loads (kW)	**272**
Ice Protection	60
Galleys	120
Fuel Pumps	32
Forward Cargo AC	60

226 kg fuel consumed per hour to generate electricity (~5% of fuel used for propulsion at 40,000 feet).

Technical Accomplishments and Progress

- Conceived electrical system using SOFC on DC bus that will save ~100 kW in power conversion losses and almost 200 kg in conversion equipment.



SOFC POWER SYSTEM

Efficiency of converting Desulfurized Jet-A fuel to 230 VAC **70%**

821 kW

+/- 270 VDC BUS

191 kW

DC/AC CONVERSION 270 VDC TO 115 VAC

Efficiency of 270 VDC to 115 VAC **80%**

115 VAC BUS

34 kW

DC/DC CONVERSION 270 VDC TO 28 VDC

Efficiency of 270 VDC to 28 VDC **80%**

28 VDC BUS

Total +/- 270 VDC Loads (kW)	**596**
ECS/Pressurization	240
Hydraulics	30
Equip. Cooling	30
ECS Fans	24
Ice Protection	60
Galleys	120
Fuel Pumps	32
Forward Cargo AC	60

Ice Protection, Galleys, Fuel Pumps, Forward Cargo AC: Loads moved from 230 VAC to 270 VDC

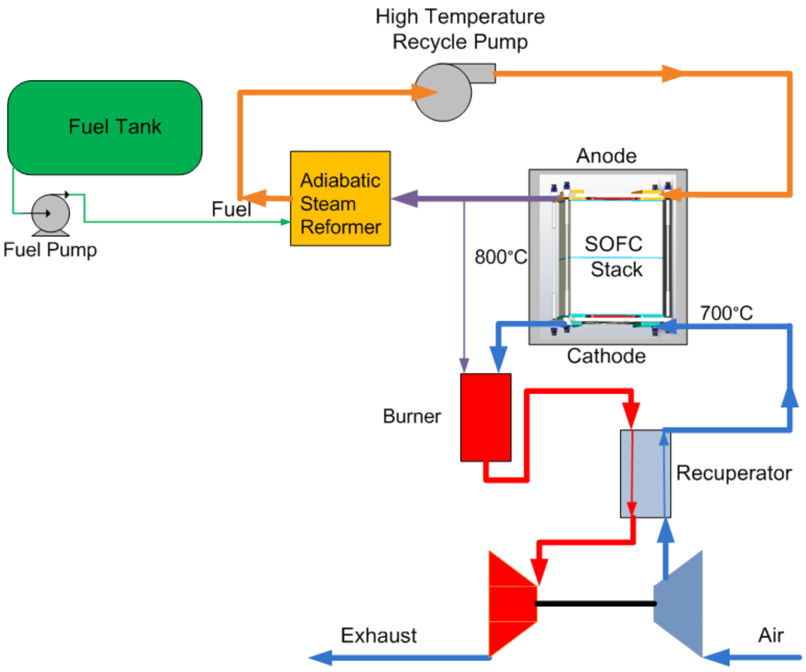
Total 115 VAC Loads (kW)	**153**
ICS	34
Various	119

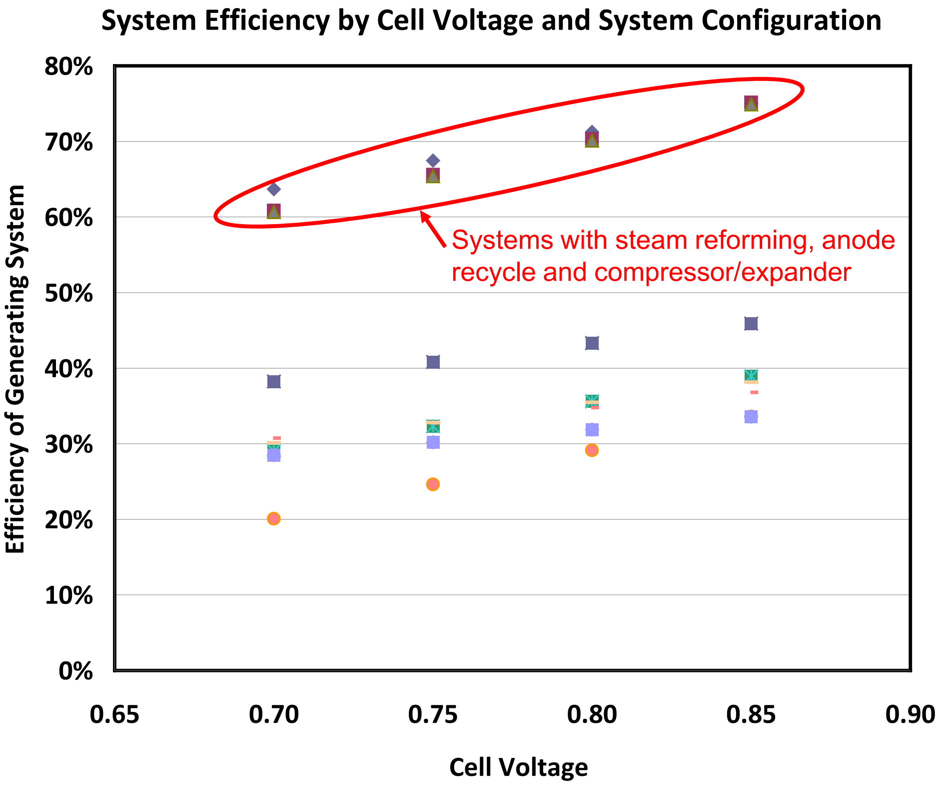
Total 28 VDC Loads (kW)	**27**
Flight Controls	11
Various	16

98 kg fuel consumed per hour to generate electricity

Technical Accomplishments and Progress

- Modeled a matrix of SOFC power systems to determine anticipated fuel efficiencies. Most promising system uses steam reforming, anode recycle and compressor/expander.

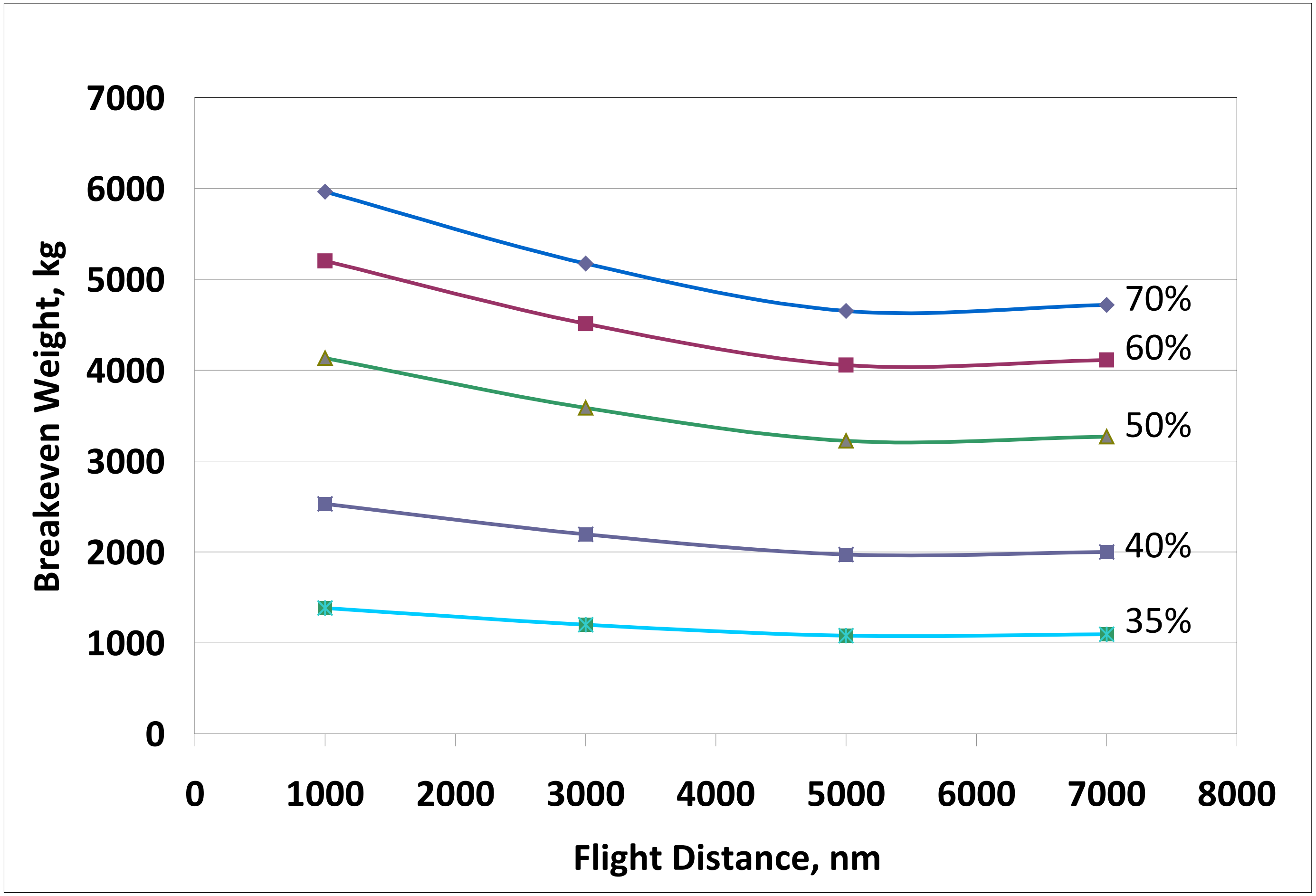




Systems with steam reforming, anode recycle and compressor/expander

Technical Accomplishments and Progress

- Determined breakeven weight change vs flight distance for various SOFC system efficiencies: A system with 70% conversion efficiency can add up to 4600 kg and still break even on fuel consumed.



Technical Accomplishments and Progress

- Generated estimates of system weights (not yet complete) for SOFC system with steam reformer, anode recycle and compressor/expander.

Efficiency*/Added Mass (kg)**

	SOFC Cell Voltage			
Pressure	**0.85**	**0.80**	**0.75**	**0.70**
0.8 atm	75%/9130	71%/5336	68%/4464	64%/4235
3 atm	75%/5961	70%/3973	66%/3802	61%/3897
8 atm	75%/4652	70%/3401	65%/3463	61%/3673

- Efficiency increases with cell voltage, not much affected by pressure.
- Stack mass decreases as pressure increases because power density increases.
- Below 0.8 volts/cell BoP mass increases because gas flow rates increase.

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

**Net change in aircraft mass does not yet include insulation, supporting structure, piping, ducting or instrumentation.

Proposed Future Work

(Now till 9/30/2011)

- Develop pre-conceptual design for most promising system and refine weight estimates based on this design. Split total load between 2 or 3 systems for redundancy.
- Develop weight estimate for on-board de-sulfurization system. Current estimates assume low sulfur fuel is available at airports.
- Test effect of elevated pressure on state-of-the-art SOFC performance. Publish the results.
- Compare alternatives to provide peaking power.
- Assess benefits of condensing water for lavatories from SOFC system.
- Identify opportunities for reducing weight of SOFC power systems.

Collaborations

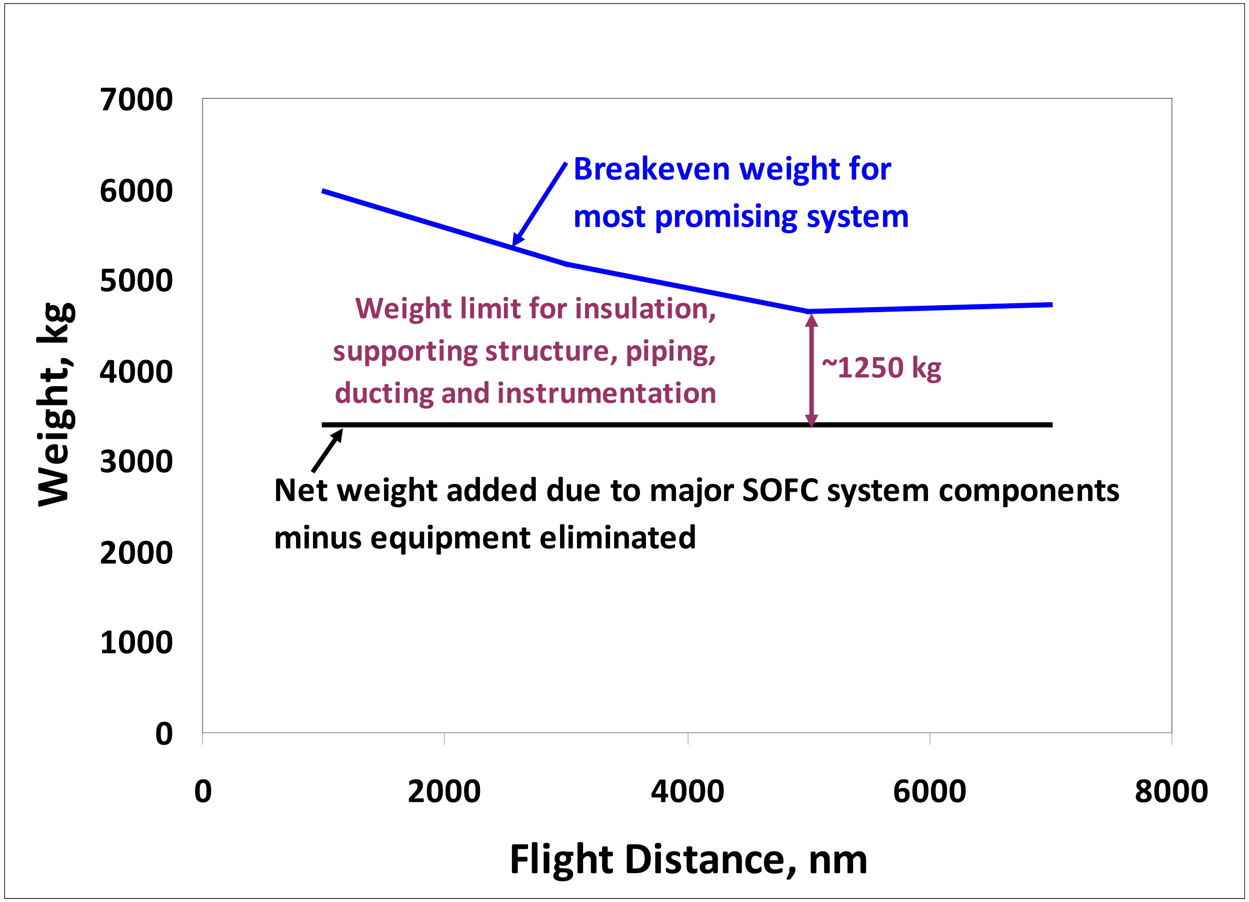
- Boeing has been very helpful in explaining how modern airplane electrical systems work with relevance to fuel cell applications and in providing data on loads, power conversions and system efficiencies.

- Williams International has offered (as of 3/31) to develop a conceptual design for a custom turbo expander/compressor.

- Aviation Working Group, with members from Boeing, Cessna, Airbus and others has provided useful information.

Summary

- ➢ Preliminary analysis indicates current state-of-the-art technology is near or just under breakeven weight.
- ➢Weight reduction has potential to increase fuel savings to significant levels.



Technical Back-Up Slides

Efficiency Boost from Steam Reforming

- **Steam reforming is endothermic**

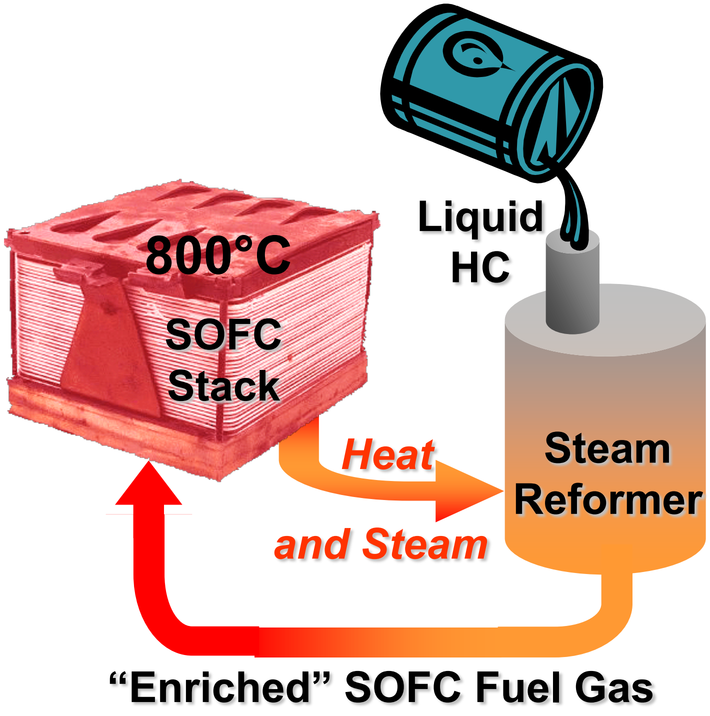
- **Heat from SOFC stack is converted into ~25% *increased* chemical energy of reformate:**

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

$$\underbrace{C_{12}H_{26}}_{\substack{\textbf{7552}\\ \textbf{kJ/mole}}} + 12H_2O + \text{heat} \rightarrow \underbrace{12CO + 25H_2}_{\substack{\textbf{9421}\\ \textbf{kJ/mole (125\%)}}}$$

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

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



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Partial Oxidation (POx) Reforming

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

Preliminary Mass Estimate

- Number of cells based on required gross power and state-of-the-art cell power density at pressure.

- Mass of anode recuperator, reformer and anode blower based on fuel consumption rate and scaled to 3.6 kW system.

- Mass of cathode recuperator based on air flow rate and scaled to 3.6 kW system.

- Compressor/Expander mass based on small jet engine specifications (Williams International) and scaled to number of compressor stages required.

- Mass of pressure vessel based on actual design calculation. Assumes titanium.

- Mass of supporting structure, insulation, piping and ducting to be determined based on pre-conceptual design.

Preliminary Mass Estimate, cont.

- Calculation of “net mass added to aircraft”:
  - Mass of SOFC power system components
  - Minus mass of AC/DC power converters (196 kg)
  - Minus mass of turbine APUs (245 kg)
- Existing generators cannot be removed because they also serve to start the main engines.

***Preliminary* Mass (kg) Estimate for Most Promising Configuration at 8 atm. and 0.8 volts/cell**

SOFC cells	1333
cathode recuperator	770
anode recuperator	392
reformer	510
anode blower	760
compressor/expander	45
pressure vessel	31
subtotal for major system components	**3842**
credit for elimination of conversion equipment	-196
credit for elimination of turbine APU	-245
net change in aircraft mass	**3401**

Too high. Artifact of preliminary scaling method.