A Heavy Fuel Solid Oxide Fuel Cell-Enabled Power System for Electric Flight

Transformational Vertical Flight Workshop

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Nicholas Borer, NASA Langley Research Center

Systems Analysis & Concepts Directorate/Aeronautics Systems Analysis Branch

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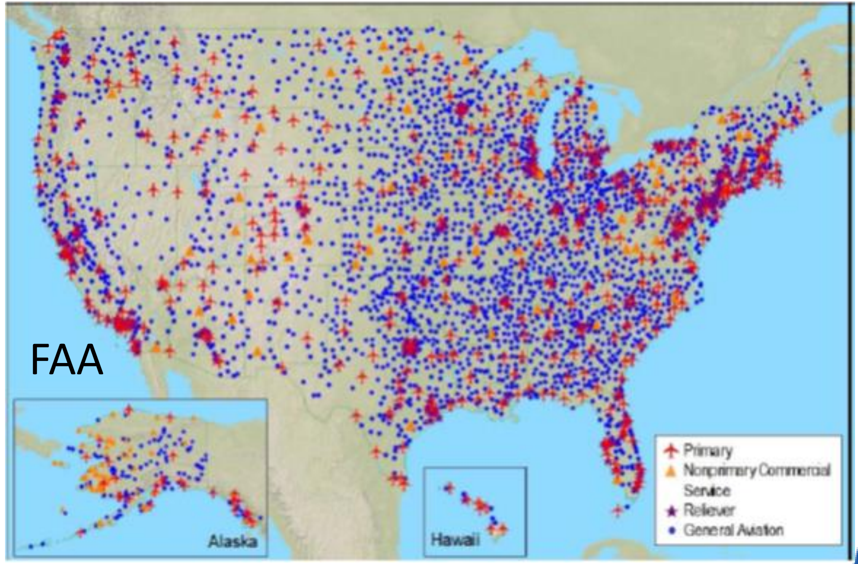
- Team members:
  - NASA Langley: Craig Nickol, Rick Yasky, Frank Jones, Kurt Woodham, Mark Cagle, Jared Fell, Brandon Litherland
  - NASA Glenn: Andy Provenza, Lee Kohlman, Pat Loyselle
  - NASA Armstrong: Aamod Samuel
  - Boeing: Tina Stoia, Shailesh Atreya, Pat O’Neil

nicholas.k.borer@nasa.gov

Three “Barriers” to Adoption of Electric Propulsion

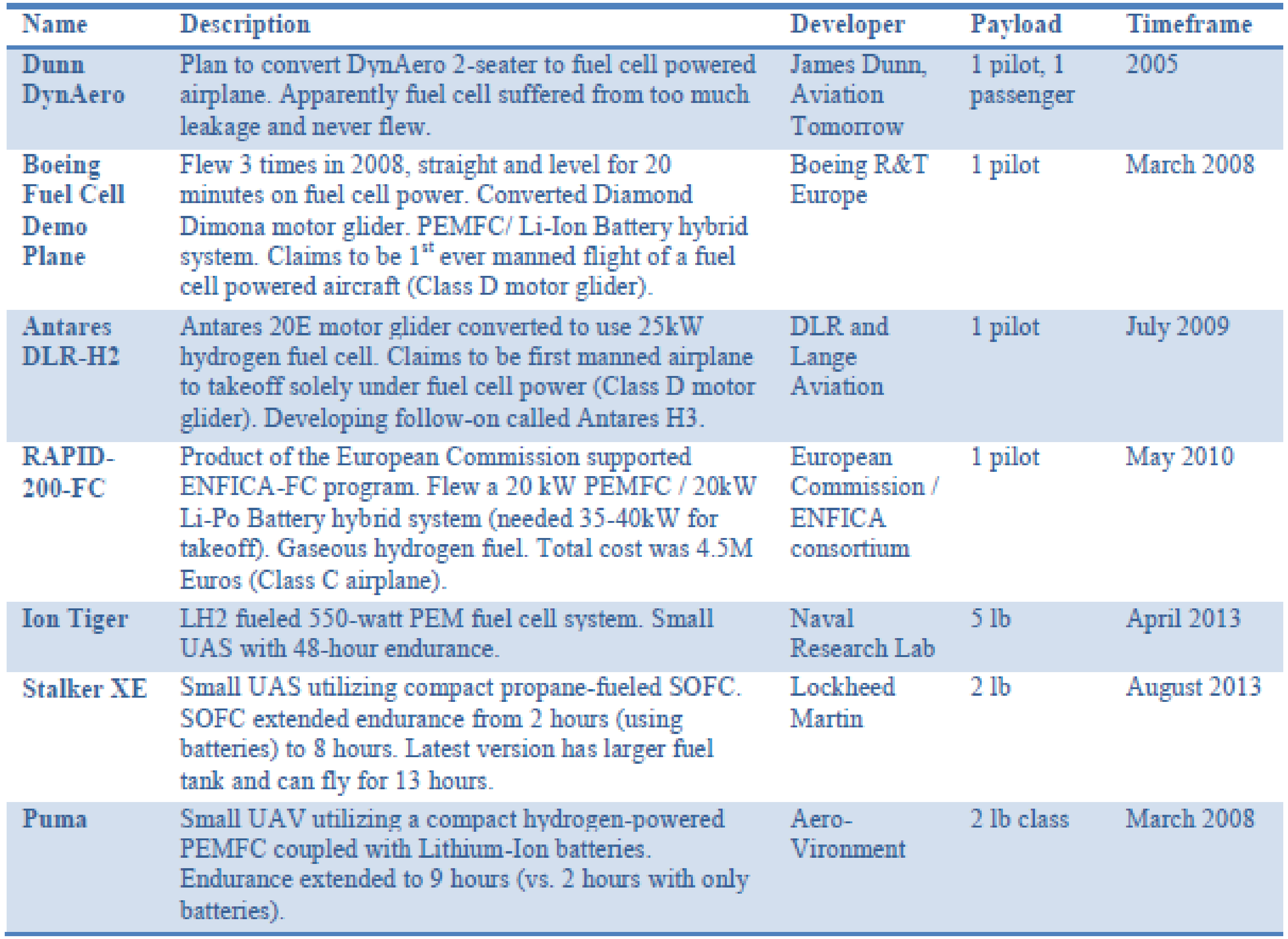
- Electric propulsion offers compelling efficiency, but is blunted by three barriers:
  - State-of-the-art batteries have 60x less energy per unit mass than current fuels
  - No public-use airports have charging stations or other non-conventional fueling infrastructure, thousands of airports in the US have conventional refueling facilities
  - Risk-aversion in commercial operations (1 failure per billion flight hours) precludes adoption of new technology without extensive data to justify safety



FAA

Fuel Cells for Airborne Electric Power

- Fuel cells have been used for airborne electric power generation, with limited success
- Lightweight, small, slow platforms, some optimized for endurance
- No fuel cell-powered aircraft to date have utilized “infrastructure-friendly” fuels



Name	Description	Developer	Payload	Timeframe
Dunn DynAero	Plan to convert DynAero 2-seater to fuel cell powered airplane. Apparently fuel cell suffered from too much leakage and never flew.	James Dunn, Aviation Tomorrow	1 pilot, 1 passenger	2005
Boeing Fuel Cell Demo Plane	Flew 3 times in 2008, straight and level for 20 minutes on fuel cell power. Converted Diamond Dimona motor glider. PEMFC/ Li-Ion Battery hybrid system. Claims to be 1st ever manned flight of a fuel cell powered aircraft (Class D motor glider).	Boeing R&T Europe	1 pilot	March 2008
Antares DLR-H2	Antares 20E motor glider converted to use 25kW hydrogen fuel cell. Claims to be first manned airplane to takeoff solely under fuel cell power (Class D motor glider). Developing follow-on called Antares H3.	DLR and Lange Aviation	1 pilot	July 2009
RAPID-200-FC	Product of the European Commission supported ENFICA-FC program. Flew a 20 kW PEMFC / 20kW Li-Po Battery hybrid system (needed 35-40kW for takeoff). Gaseous hydrogen fuel. Total cost was 4.5M Euros (Class C airplane).	European Commission / ENFICA consortium	1 pilot	May 2010
Ion Tiger	LH2 fueled 550-watt PEM fuel cell system. Small UAS with 48-hour endurance.	Naval Research Lab	5 lb	April 2013
Stalker XE	Small UAS utilizing compact propane-fueled SOFC. SOFC extended endurance from 2 hours (using batteries) to 8 hours. Latest version has larger fuel tank and can fly for 13 hours.	Lockheed Martin	2 lb	August 2013
Puma	Small UAV utilizing a compact hydrogen-powered PEMFC coupled with Lithium-Ion batteries. Endurance extended to 9 hours (vs. 2 hours with only batteries).	Aero-Vironment	2 lb class	March 2008

Recent Research into Airborne Fuel Cells

- DARPA awarded Vulture II (flight demonstration phase) to Boeing-led team in 2010 to develop an ultra-long endurance UAS
  - Program included regenerative solar power system with fuel cells to power aircraft through night
  - Vulture II is winding down, but power system hardware has been developed & tested on ground
- NASA awarded an ARMD Team Seedling award in 2015 to investigate a transformative airborne demonstrator that would tackle the "three barriers" to electric flight
  - Plan to use Boeing fuel cell paired with a reformer to use traditional fuels as energy source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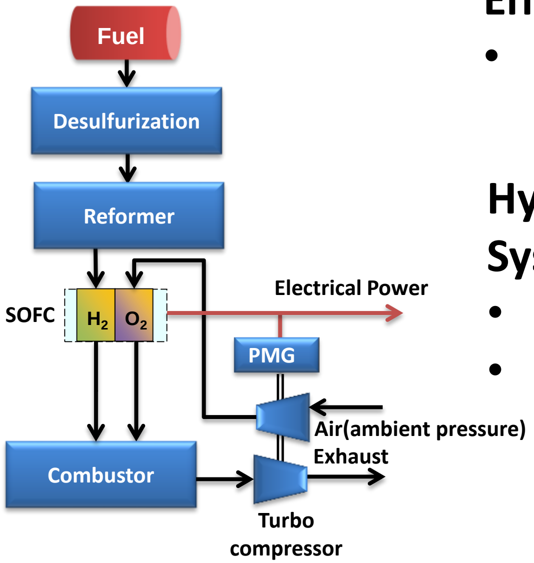
nicholas.k.borer@nasa.gov

Technology and Performance Discriminators

- Integration of key (yet proven) technologies to yield compelling performance to early adopters
  - "Useful" payload, speed, range for point-to-point transportation
  - Energy system that uses infrastructure-compatible reactants, allowing for immediate integration
  - High efficiency for compelling reduction in operating cost
- Early adopters as gateway to larger commercial market

High-Performance Baseline

- 160-190 knots cruise on 130-190kW
- 1100+ pounds for motor & energy system



Efficient Powertrain

- Turbine-like power-to-weight ratio at 90+% efficiency

Hybrid Solid Oxide Fuel Cell Energy System

- >60% fuel-to-electricity efficiency
- Designed for cruise power; overdrive with moderate efficiency hit at takeoff and climb power

Primary Objective: **Demonstrate a 50% reduction in fuel cost** for an appropriate light aircraft cruise profile (payload, range, speed, and altitude).

nicholas.k.borer@nasa.gov

Fuel Cell Trade

- Several types of fuel cells exist and have been used in a variety of different applications
- Solid Oxide Fuel Cells (SOFC) appear to be the best choice for use with a reformed hydrocarbon fuel
- Boeing SOFC stacks & plant have been conducting ground testing, currently advancing TRL

FC Type	Key Attributes
Alkaline Fuel Cell	▪ Operating Temp – 95°C ▪ Requires pure O2 ▪ TRL 9
Molten Carbonate Fuel Cell	▪ Operating Temp - 650°C ▪ Low specific energy ▪ TRL 9
Phosphoric Acid Fuel Cell	▪ Operating Temp - 200°C ▪ Low specific energy ▪ TRL 9
Proton Exchange Membrane (PEM) Fuel Cell	▪ Operating Temp- 80°C ▪ No tolerance to sulfur and CO ▪ Ideal for operation with H2 ▪ TRL 9
Solid Oxide Fuel Cell (SOFC) Boeing	▪ Catalyst – Nickel ▪ Operating Temp - 700°C ▪ Higher sulfur tolerance permits operation with JP8 ▪ H2 and CO are both fuels

nicholas.k.borer@nasa.gov

Power System Sizing

- Currently investigating candidate demonstrator aircraft, COTS or near-COTS motors, and power system design
- Considered power levels for three common light aircraft power systems
- Can size the power system for takeoff, climb, or cruise, with overdrive or buffer battery to handle high power requirements
    - De-rated max power levels by ~10% (3% for accessory drive, flat-rated to ~2,000 ft density altitude)

Replacement Class	Rotax 912S (Nominally 73.5kW)	Lycoming O-360-A4M (Nominally 134.3kW)	Continental IO-550-N (Nominally 231kW)
Takeoff Power (2-5 min)	66kW	121kW	208kW
Climb Power (10+ min)	56kW	103kW	176kW
Cruise (indefinite)	40kW	79kW	135kW
Height	404mm	650mm	518mm
Width	576mm	848mm	865mm
Length	708mm	738mm	975mm
Mass	61.3kg	133.6kg	204.3kg

nicholas.k.borer@nasa.gov

Initial Power System Integration & Scaling Studies

- Multiple trades ongoing for design of balance of plant
- Need to keep specific power of total power system (SOFC stack, reformer, plumbing, battery, pressurization equipment, etc.) low while keeping efficiency high
  - Specific power: 250-375 W/kg
  - Effective* specific power: 430-530 W/kg
  - Fuel-to-electricity efficiency: >60%
    - Fuel-to-shaft power: >54% @ 90% motor/controller efficiency
- Example: Lancair Columbia 300 (GTOM: 1545 kg)
  - Useful load: -468 kg (includes 267 kg 100LL fuel)
  - Crew & instrumentation: +200 kg
  - Effective power: 231 kW
    - Exchange mass: -240 kg
    - Power system mass: +436-537 kg
    - Powerplant mass: +60-120 kg
  - Net change in mass before fuel: -12 kg to +149 kg
    - Can get same (max) range on <138 kg of fuel (52% mass, 46% volume)
  - Net in change in mass for max range fuel: +126 to +287 kg

*Effective refers to specific power reference to replacement IC engine rated power

nicholas.k.borer@nasa.gov

Infrastructure Integration

- SOFCs are sulfur-tolerant, but cannot handle the very high sulfur levels in typical jet fuels
- Will focus on use of road diesel or ground cart desulfurization for demonstrator study
- Opportunity for creation of flight-weight desulfurization equipment, particularly for large commercial aircraft (APU)

Fuel	Fuel Spec (ppmw max)	Specification
Avgas (100/100LL)	500	ASTM D 910
Diesel (Low Sulfur)	500	ASTM D975
Diesel (Ultra Low Sulfur)	15	ASTM D975
Gasoline (current)	• 80 max (refinery) • 95 max (downstream) • 30 avg (refinery)	EPA Tier 2 Gasoline Sulfur Program
Gasoline (2017)	10 avg (refinery)	EPA Tier 3 Gasoline Sulfur Program
Jet A	3,000	ASTM D 1655
Jet A-1	3,000	DEF STAN 91-91
JP-5	3,000	MIL-DTL-5624U
JP-8	3,000	MIL-DTL-83133
Kerosene (1-K)	400	ASTM D 3699
Kerosene (K-2)	3,000	ASTM D 3699
Kerosene (Ultra Low Sulfur)*	15	

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nicholas.k.borer@nasa.gov

Other Integration/Operations Effects

- Throttle response time
  - SOFC power system scales fuel flow quickly, but battery handles immediate transients to enable better efficiency
- Startup time
  - SOFC stack takes time to come up to temperature
  - Make startup part of early preflight sequence, use batteries for taxi
  - More, smaller stacks = less startup time
- Electric taxi options
  - Wheel motors may provide more efficient taxi, increased safety
- Volume/mass distribution
  - Electric motor is lighter, but power system is heavier (can be distributed)
  - Need to find best way to distribute mass & volume as to not violate CG range or other safety requirements on demonstrator aircraft
- Fuel exhaustion/power system issues
  - Hybrid battery-SOFC system can be architected to provide emergency power capability if one side (battery or SOFC) fails

nicholas.k.borer@nasa.gov

Conclusions

- Adoption of electric propulsion will be slowed by three barriers:
    - Onboard energy storage system mass
    - Creation of appropriate service infrastructure
    - Certification, in particular for commercial operations
- Need to consider how to manage the transition to electric away from today's liquid hydrocarbon paradigm
- High-efficiency APUs or reformer fuel cell architectures offer "drop-in" solutions to the transition to electric propulsion, but don't close the door to alternative fuel/energy storage media
- Need to offer compelling performance to early adopters to establish a certification basis

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