SOFC Development for Aircraft Application

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Outline

- Introduction
- Operational Requirement of Aircraft Power Sources
- Aircraft Fuel Cell System Concepts
- Fuel Cell Development at Airbus
- Fuel Cell Development at Boeing
- Conclusion

Fuel Cells for Aircraft Application

In principle, there are 2 options for fuel cell application in airplanes:

- **fuel cells for propulsion**
- **fuel cells as electrical energy generator**

In both cases of application:

The industrialization of fuel cell systems and its integration is in the very beginning.

Fuel Cells for Propulsion

Development of an unmanned aircraft vehicle (Pathfinder Plus) by NASA for observation missions

- Operation with solar-generated hydrogen to be used in a regenerative propulsion system
- Combination of a solar array for electricity generation with an electrolyzer and a fuel cell for a continuous operation of the electric motor of the propulsion system

Development of a fuel cell powered piloted electric airplane by Boeing

- Integration of a PEM fuel cell system in an electric demonstrator airplane (motor glider)
- Flight tests of the fuel cell-powered motor glider
- On commercial transports fuel cells and electric motor will not replace jet engines. Fuel cells can replace gas turbine APU while on ground and for back up use in flight

Future Power Optimised Aircraft Configuration

- The aircraft industry has to accomplish the continuously growing requirements of low emissions and low operating costs
- One approach is a more electric aircraft configuration in a new system architecture
- Kerosene supplied fuel cell systems are a promising alternative as secondary/primary power source in a more electric aircraft configuration
- In order to achieve the challenging aims the aircraft development has to investigate and to apply technologies such as:
  - further replacement of pneumatic and hydraulic routings by electric wires
  - increase of electrical power as primary source
  - new electrical system components, e. g. electrical powered air conditioning
  - electric wing anti ice
  - application of fuel cell systems as a power source
  - main engines optimised for propulsion generation only

Possible Aircraft Fuel Cell System Concepts

Main characteristics:

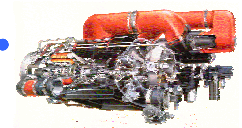
	PEM	SOFC
Operating Temperature	approx 60 – 80 °C	approx. 800 – 1000 °C
Efficiency	up to 40 %	up to 60 %
Fuel	kerosene	kerosene
Fuel Processing	no residual contamination	residual contamination tolerable
Carbon monoxide	CO must be removed	less susceptible to CO
Sulfur	sulfur must be removed	less susceptible to sulfur
Power density	< 1 kg/kW	< 1 kg/kW
Maturity level	pending on system concept	improvement necessary

Conventional Aircraft Power Architecture

Aircraft Power ***Sources***:

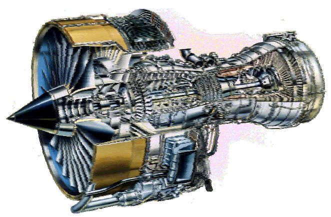
- Bleed Air power (e.g. for cabin air conditioning, main engine start)
- Electrical power (e.g. for lights, cabin entertainment)
- Hydraulic Power (e.g. flight controls)

Ram Air Turbine (RAT)
Emergency hydraulic and electrical power (AC)



Auxiliary Power Unit (APU)
Bleed air and / or electrical power (AC)

Aircraft Batteries
Electrical power (DC)

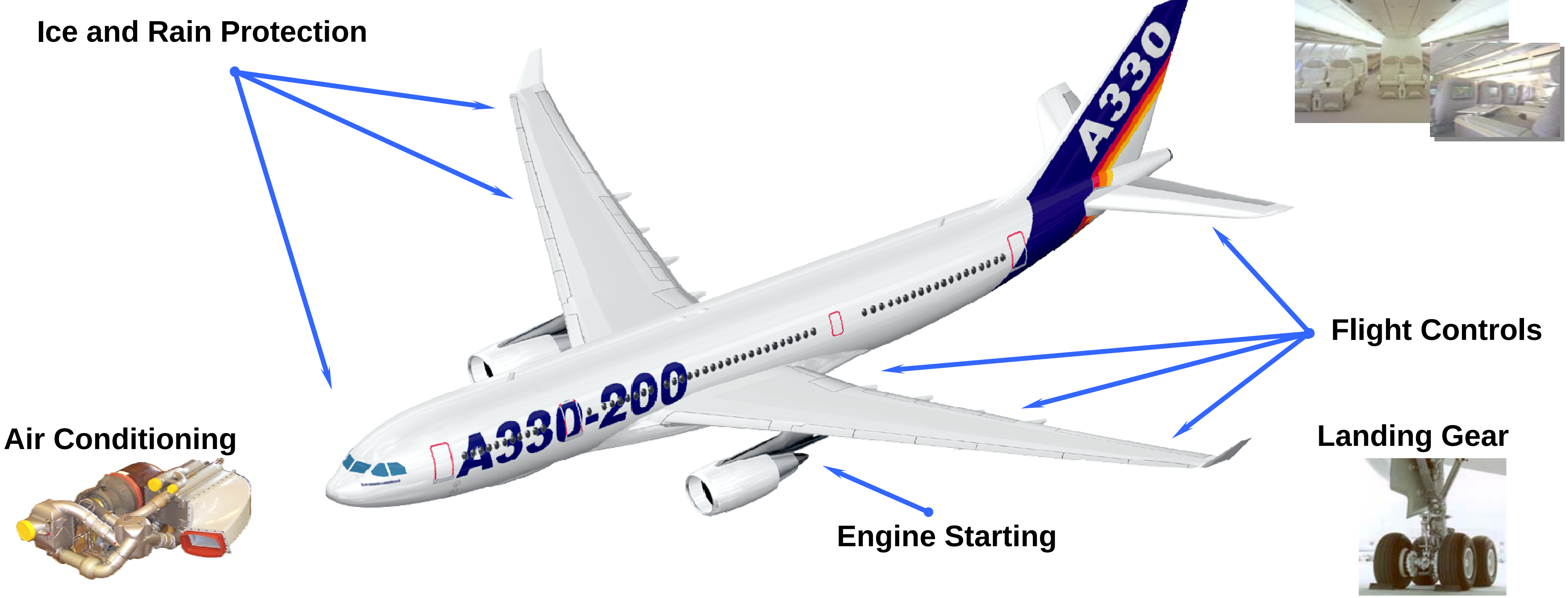


Main Engines
Hydraulic, bleed air and electrical power (AC)

Electrical, Hydraulic and Bleed Air Power (kW)	Main Engines	APU	RAT	Battery
	~ 1000	~ 550 (ground)	~ 25	~ 3

Conventional Aircraft Power Architecture

Aircraft Main Power *Consumers* (peak values):

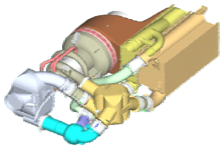


Max. Power Consumption (kW)	Air Conditioning	Ice and Rain Protection	Cabin Systems	Engine Starting	Landing Gear	Flight Controls
	~ 500	~ 250	~ 100	~ 300	~ 50	~ 150

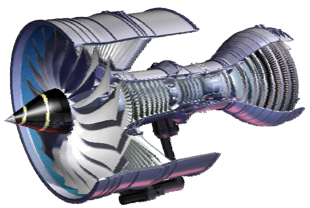
Future Power Optimized Aircraft Configuration

New technologies – opportunities:

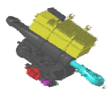
Fuel Cell System



Electrical Powered Air Conditioning



Advanced Main Engines



Electrical Actuators

Future Power Optimized Aircraft Configuration

Expected benefits of fuel cell system application:

✓ **Low Emissions**

- **significant NOx reduction on ground and in flight**

✓ **High Efficiency**

- **Efficiency increase due to applied technologies**

✓ **Fuel Economy**

- **up to 75 % Fuel Reduction on ground**
- **30 % Fuel Reduction in flight**

✓ **Noise Reduction**

- **excellent potential for a significant on ground noise reduction**

Fuel Saving Opportunity

On ground:

Typical turbine powered APU	Future 2015 SOFC APU (Boeing)
15 % efficient	60 % efficient
over average operating cycle	at std. sea-level conditions

→ **75 % less fuel used**

In-Flight:

Typical turbine-powered APU	Future 2015 SOFC APU (Boeing)
40-45 % efficient	~ 75 % efficient
Jet-A to electrical during cruise	overall system at cruise

→ **40 % less fuel used**

Source: Boeing

DLR

APU Configurations

In principle, fuel cells can replace the existing emergency generation and batteries, the existing APU and the generators.

Aircraft batteries provide:
- Start up power
- fill-in power for short-term interruptions
- electrical noise filtering
- emergency power

Evaluation of fuel cells for this application by Boeing and Cessna Aircraft Company (Design study)

Cessna Citation X: 10-passenger business jet

Boeing 737: 108-passenger airliner

Operational Requirements of a Battery

- Performance characteristics for steady-state, short circuit and fault clearing conditions
- Ambient Temperature range: -40 °C – +70 °C (start up)
-55 °C – +40 °C (operation)
- Altitude: 1.000 ft – 51.000 ft
- Tolerance of humidity, vibration and contamination
- Emergency power for 30 – 60 minutes
- Power: 2.4 kW 85 A at 28 VDC

Main Characteristics of Emergency Generation and Batteries

- **electrical power: about 50 kW**
- **minimum current: > 1 mA**
- **time to start in flight: immediately when needed in emergency case**
- **time to start on ground: no more than 1 min**
- **overload capability: 2 In/5s or 1.5 In/5 mn**
- **stand alone running time in flight: 30 min**
- **stand alone running time on ground: 1 hour**
- **environmental condition: -55 °C/+85 °C**

Main Characteristics of APU system

- start time: less than 120 seconds
- electrical output: 115 kVA, 110 kVA in 41.000 ft altitude
- electrical overload capability: 155 kVA for 5 minutes
218 kVA for 5 seconds
up to 35.000 ft altitude
- the system is self-controlled by its own electronic controller
- the system has to be started from a/c electrical system (batteries included)
- the system shall be capable to deliver the required performance after a deterioration time of 10.000 hours
- the APU is installed in a fire proofed compartment (withstand ca. 1.100 °C for 15 min)
- specific fuel consumption is below 0.4 kg fuel/kWh

Possible Aircraft Fuel Cell System Concepts

Aircraft specific features have to be considered for a fuel cell system integration:

- **On board fuel processing including desulphurisation and kerosene reforming**
- **Aeronautical requirements and standards**
  - low installation weight/high power density
  - system monitoring and controlling
  - high reliability and system robustness
- **Environmental operating conditions**
  - Varying outside pressures and temperature, e. g. at 41.000 ft 0.18 bar, -57 °C
  - aircraft manoeuvre loads
- **Turbo-machinery is an optimum supplement at high altitude ambient conditions for fuel cell systems**
- **Fuel cell hybrid systems are smaller, lighter and have a better dynamic response compared to non-hybrid fuel cell systems**
- **Fuel cell hybrid systems have a high power density and offer a better fuel efficiency than non-pressurized fuel cell systems**

Operating Conditions

Change of the ambient state during the mission

- **Ambient pressure and temperature reduction is a function of the flight altitude**

Flight altitude of 36.000 ft ⇒ 0.2 bar ambient pressure
70 K temperature reduction

⇒ **Decrease of Nernst voltage from 0.79 V to 0.74 V during atmospheric operation**
from 0.86 V to 0.82 V during pressurised operation

Decrease of efficiency of 5 – 6 %

⇒ **Increased air flow required to obtain the same amount of oxygen which is needed at sealevel**

Performance Requirements for Aircraft Application

Requirements by the aircraft application (SECA program)

Attributes	Current capability	Goal
Total power	-5 kW (planar) > 100 kW (tubular) > 1 MW (planned)	5 kW for early aviation demo 145 kW for 100 passenger 450 kW for 305 passenger 3-10 kW (SECA transportation)
Specific power for entire SOFC system incl. BOP	0.02 – 0.04 kW/kg	0.5 kW/kg (NASA/DOD) 0.1 kW/kg (DOE-SECA)
Area specific power density	0.5-1 W/cm² cell 0.4 W/cm² stack	2 W/cm² cell > 1 W/cm² stack
Fuel reformation	Mature at the industrial scale	Compact, lightweight system with high conversion efficiency
Sulfur tolerance	Limited exp. with logistic fuels	300 – 700 ppm current jet fuel sulfur level Aircraft life 40,000 hrs

Airbus General Approach

Airbus energy source approach is a step by step approach for Fuel Cell System Application:

- **Ram air turbine (RAT) substitution for early application**
- **Kerosene supplied fuel cell system to replace the APU**
- **Primary power source towards more electric aircraft**
- **Hydrogen based future aircraft**

Airbus General Approach

Step by Step approach

Under Study

- H2 Bottle – RAT Replacement
- APU Replacement
- Primary Power Supply
- H2 Tank – Fuel Cell System ?

Time: 2010 – 2013/15 – 20xx – 20yy

Legend: Hydrogen (blue) · Kerosene (yellow)

SOFC Spray Concept of DLR

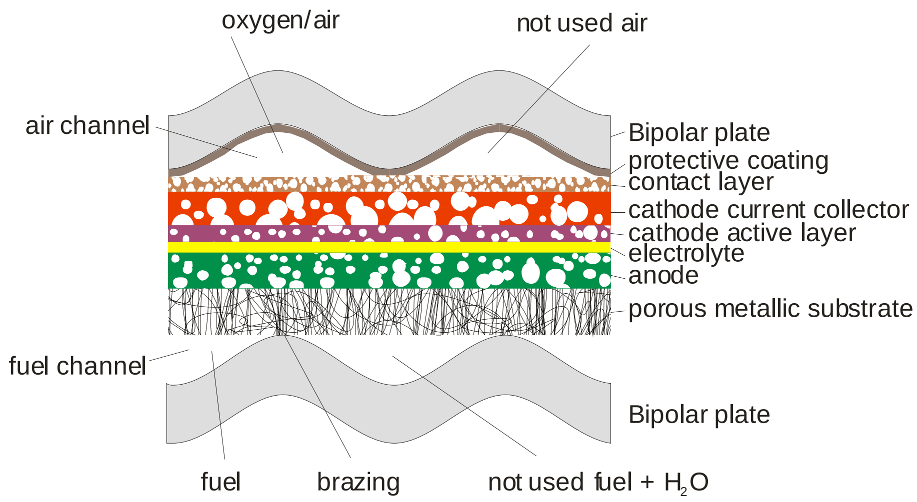
Plasma Deposition Technology

Thin-Film Cells

Ferritic Substrates and Interconnects

Compact Design with Thin Metal Sheet Substrates

Brazing, Welding and Glass Seal as Joining and Sealing Technology



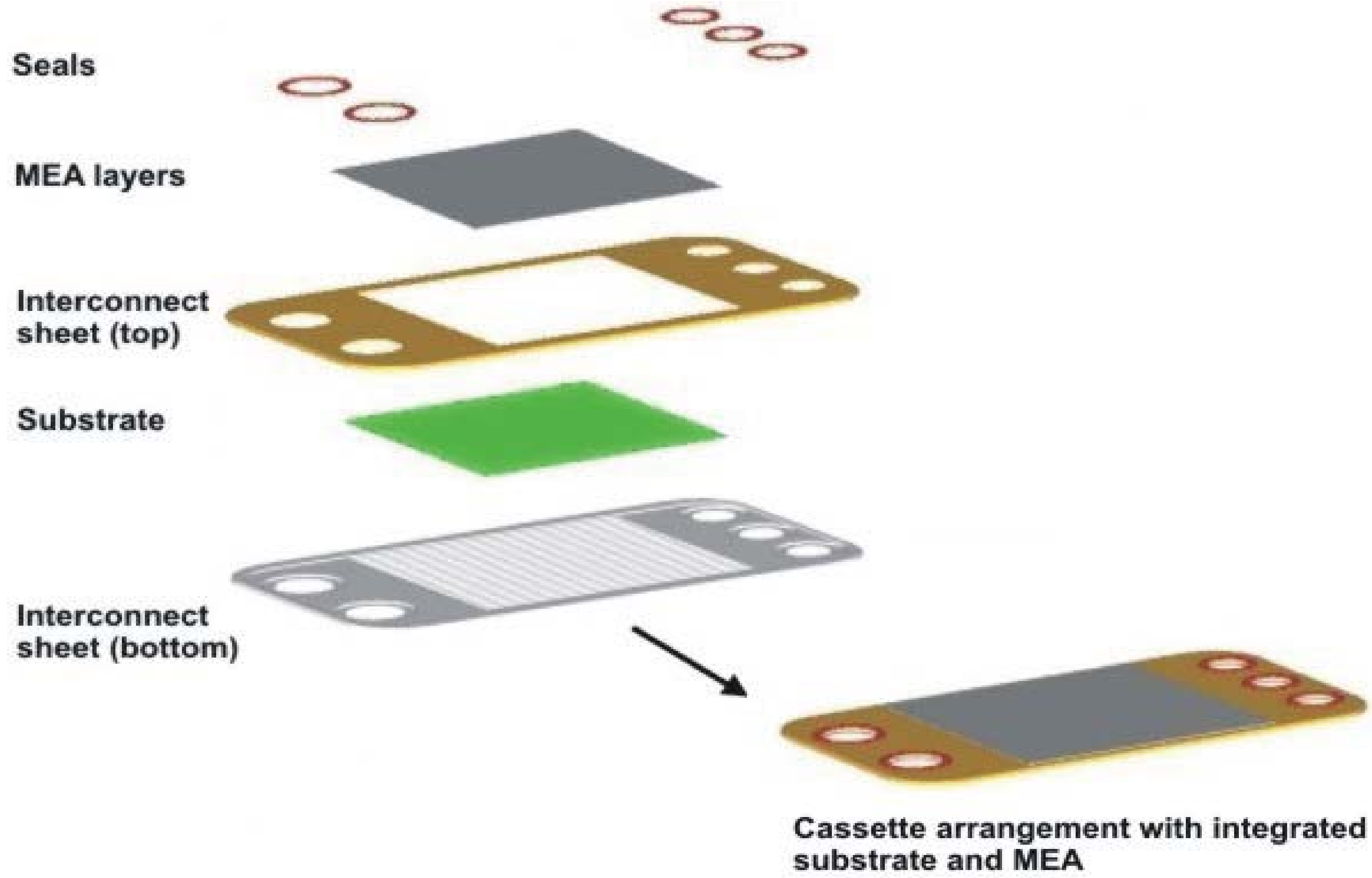
(not in scale)

Schematic of DLR-SOFC Design with Metallic Substrate

Objective of DLR Development:

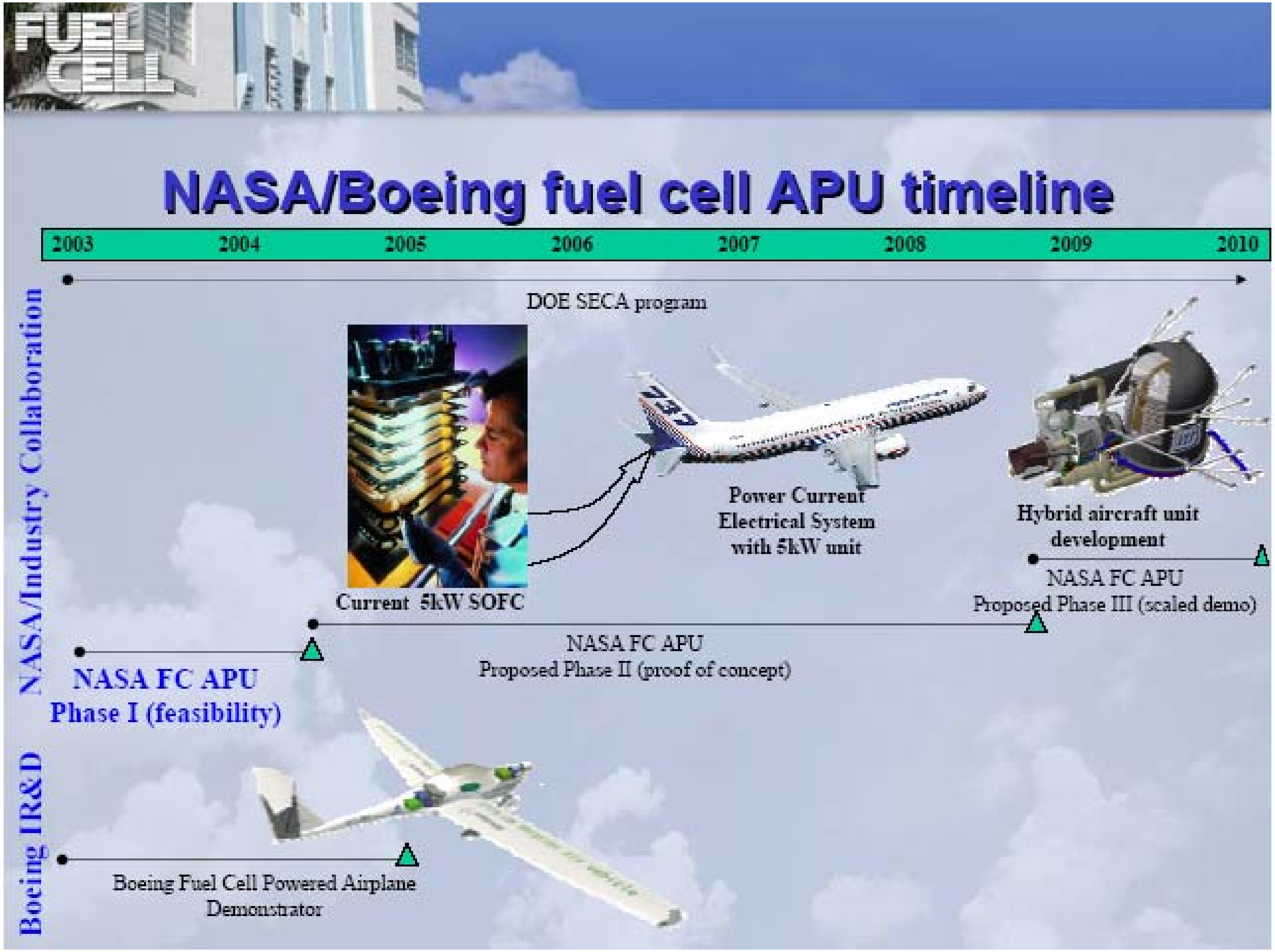
Light-weight stack of 5 kW power with high performance, rapid heat-up and good thermal cycling properties

Cell Design for APU Application



SOFC APU Challenges at Boeing

- Technology ready by 2010 (enables a 2015 entry into service)
- High system power density (0.5 kW/kg system goal)
- Ability to reform Jet-A fuel (1000 ppm fuel sulfur level tolerance goal)
- 40.000 hour life in airplane environment



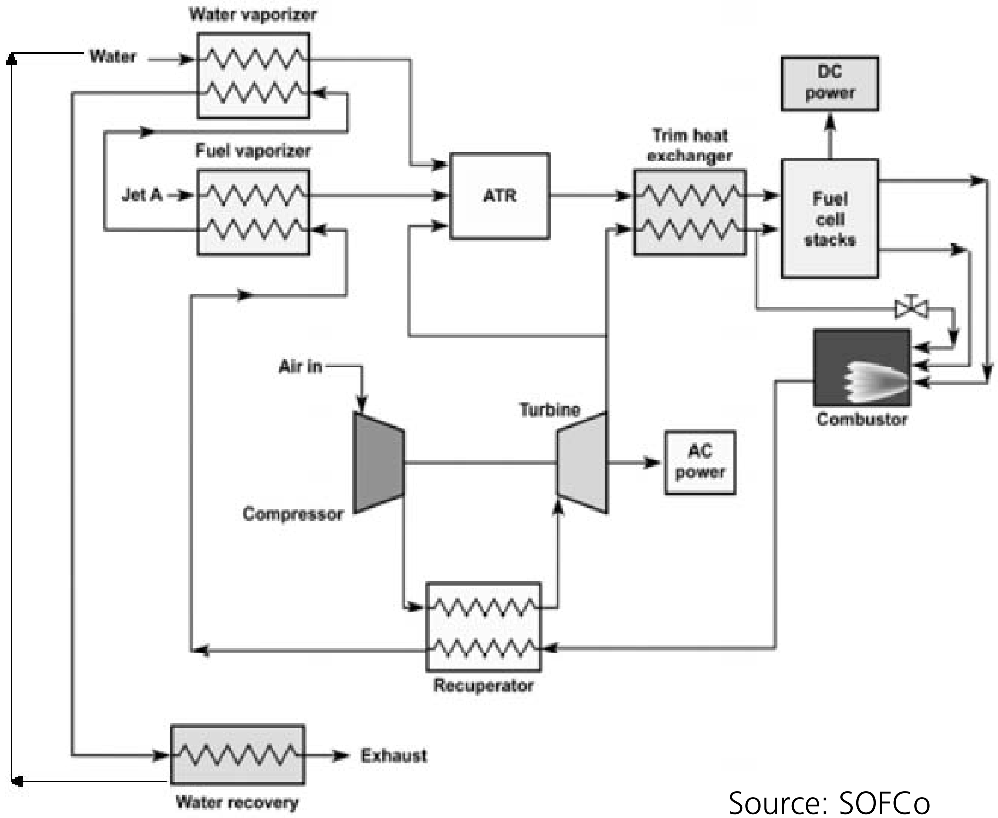
Source: Boeing

Study of a Hybrid SOFC for APU Replacement

Design of a hybrid SOFC system that incorporates jet fuel reformers

- **Pure enough source of H_2 for PEM fuel cell is impractical because of the complex nature of jet fuel**
- **Airplane platform: 777-200 ER-sized aircraft**
  440 kW of electrical power in flight as well as on the ground

SOFCo design: 440 kW hybrid APU using:
- a planar SOFC
- single stage turbo-compressor
- autothermal reformer (ATR)



SOFCo hybrid fuel cell APU concept

Source: SOFCo

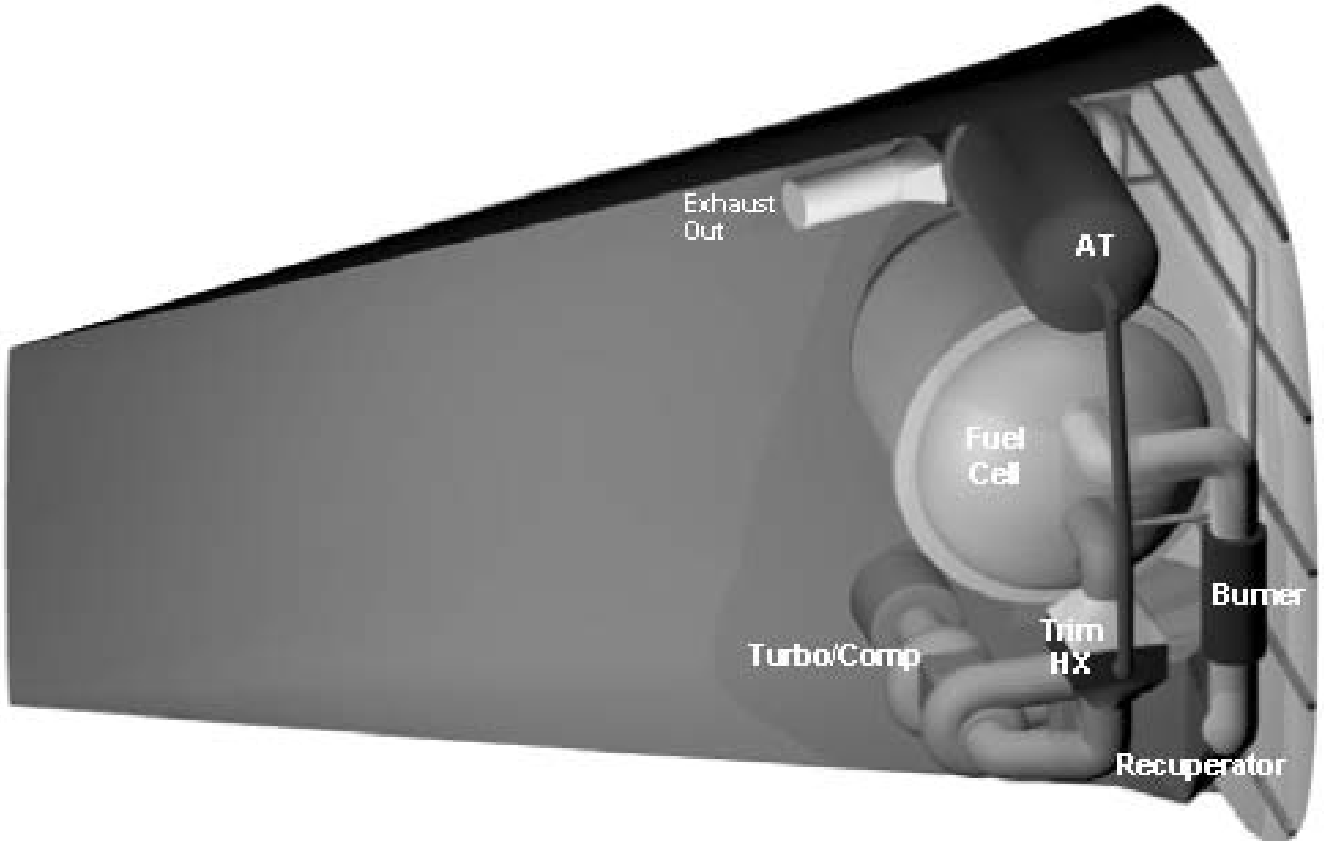
Study of a Hybrid SOFC for APU Replacement

	Cruise	Ground
Total Power, kW	440.4	432.1
Fuel Cell DC Power, kW	404.9	347.0
Turbine AC Power, kW	35.5	84.2

SOFC fuel cell APU estimated performances

Source: SOFCo

Study of a Hybrid SOFC for APU Replacement



Fuel cell APU concept in aft end of study aircraft

Source: Boeing

APU Application

- Replacement of APU by fuel cells is still in the stage of system studies
- 1:1 replacement is not feasible ⇨ completely new aircraft architecture is required
- More electric aircraft (MEA): electricity instead of pneumatic energy (→ environmental control)
- System studies are performed to determine concept feasibility, assess system-level benefits and identify technology gaps
- Study of fuel processing alternatives, fuel desulphurisation, water recovery system (“gray water”)
- Evaluation of best system configuration in terms of overall system performance, weight and size

Aircraft Specific Tasks

- **Development of kerosene reformer and means to prevent detrimental Sulphur effects**
- **Development of reformer and cells with higher impurity tolerance**
- **Study of low temperature and cold-start influence on fuel cells**
- **Study of influence of oxygen pressure reduction**
- **Study of product water quality**
- **Design, tests and optimization of the system with the components Reformer, Fuel Cell, Micro gas turbine and Air compression**
- **Study of influence of mechanical stress due to vibrations and shocks**

Synergy Effects with Automotive / Maritime Technologies