Fuel Cell Systems For Aeronautic Applications
A Clean Way from Kerosene to Energy
Hamburg, September 04 2006

Presented by
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Senior Manager Engineering
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Step 4: Fuel Cell as Primary Source

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Industrialization

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Airbus Activities

- Airbus is one driver of industrialization and early application of fuel cell systems.

- Airbus is leading or involved in national and international projects to encourage the fuel cell technology progress.

- Airbus supports Joint Ventures of companies, authorities, universities and associations.

- Airbus supports the system supplier in design and development of airworthy qualified fuel cell systems.

- High level Aircraft requirements result in synergy effects on similar transportation applications.
Introduction

Synergy Effects

<table>
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<tr>
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<th>Automotive</th>
<th>Aircraft</th>
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</thead>
<tbody>
<tr>
<td>Specific System Weight Targets</td>
<td>3 kg/kW</td>
<td>1 kg/kW</td>
</tr>
<tr>
<td>Specific System Volume Targets</td>
<td>2.5 l/kW</td>
<td>1.5 l/kW</td>
</tr>
</tbody>
</table>
Introduction

System Requirements and Environmental Conditions

• Variable outside pressures and temperatures, varying between –2000 ft / +43000 ft and -72°C / +56°C
• Aircraft maneuver loads
• Vibrations
• Installation area (pressurized / unpressurized)
• Transient requirements incl. starting
• Fuel supply (kerosene vs. hydrogen)
• Cooling
• Mission - profiles and safety

For each application on board of an Aircraft the most suitable fuel cell system configuration must be defined.
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Fuel Cell System

**Fuel Cell Operation**
Continuously change of chemical energy (hydrogen and oxygen) **directly** to electrical energy and heat without combustion

**Anode:** 2 H₂ → 4 H⁺ + 4 e⁻

H₂ = Hydrogen Molecule  
H⁺ = Proton  
e⁻ = Electron

**Cathode:** O₂ + 4 e⁻ → 2O²⁻  
2 O²⁻ + 4 H⁺ → 2 H₂O

O₂ = Oxygen Molecule  
O²⁻ = Oxygen Ion  
H₂O = Water

**Overall Reaction:** 2 H₂ + O₂ → 2 H₂O + Electrical Energy + Heat
Fuel Cell System

Comparison – Fuel Cell vs. Heat Engine

With $T_1=540°C; T_2=36°C$

$$\eta_C = 1 - \frac{T_2}{T_1} \approx 62\%$$

$$\eta_{Rev} = \frac{\Delta_r G^0}{\Delta_r H^0} \approx 83\%$$

$\eta_{Fuel\ Cell} = \eta_{Rev} = \frac{-237,13 kJ \cdot mol^{-1}}{-285,8 kJ \cdot mol^{-1}} = 0,8297 = \sim 83\%$

$\eta_{Heat\ Engine} = \eta_{Rev} \cdot \eta_C \cdot \eta_{el} = 0,83 \cdot 0,62 \cdot 0,9 = 0,46 = \sim 46\%$

Theoretical maximal achievable Efficiency: $\sim 83\%$
Fuel Cell System

Development and Technical Targets

Development and Targets for Specific Weight and Volume of Mobile Fuel Cell Stacks and Systems

Stacks:
- Specific Volume GM Stack (Power increased from 37 kW – 102 kW)
- Specific Weight GM Stack (Power increased from 37 kW – 102 kW)
- Specific Volume Ballard Stack (based on net System Power 85 kW)

Systems:
- Specific Weight and Volume DOE-PNGV FC System (Power 50 kW, gasoline fuelled)
- Specific Weight and Volume DOE-PNGV FC System (Power 50 kW, H2 fuelled)
- Airbus Target for System Volume Density
- Airbus Target for System Weight Density

- Ballard Xcellsis Hy-80 Fuel Cell Engine (68 kW)
- Delphi SOFC-APU Gen.2 (2002) 5 kW System
- Delphi SOFC-APU Gen.1 (2000) 5 kW System

GM St 3 – 1997 (37 kW)
Current Stack (102 kW)
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Motivation for Fuel Cell System Application

Ecological and Economical Aircraft Operation Aspects

Ecological Aspects:
- Noise reduction
- Emission reduction
- Higher fuel economy

Economical Aspects:
- Weight Reduction
- Low Maintenance
- Mission Improvements
- Elimination of RAT and APU
- Battery Reduction
- Potential for on-board water generation
Motivation for Fuel Cell System Application

Conventional Electrical Power Generation vs. Fuel Cell System

**NO\textsubscript{X} (Nitrogen Oxides)** Emission Reduction
- Total NO\textsubscript{X} reduction on ground and in flight

**CO\textsubscript{2} (Carbon Dioxide)** Emission Reduction
- 20% – 60% CO\textsubscript{2} reduction in flight and on ground
Motivation for Fuel Cell System Application

Aircraft Mission

Example: A330-300:

- ~100 000 L per flight of ~10 000 km (Average Fuel Consumption)
- Fuel Use: 3%* Aircraft Systems
  97% Propulsion

~ 3000 L per flight for Aircraft Systems operation
### Motivation for Fuel Cell System Application

#### Fuel Savings

<table>
<thead>
<tr>
<th></th>
<th>Conventional Electrical Power Generation</th>
<th>Fuel Cell System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>~40%</td>
<td>~60% (Target)</td>
</tr>
<tr>
<td>(Maximum possible)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Use per Flight (10,000 km)</td>
<td>~3,000 Liter</td>
<td>~2,100 Liter</td>
</tr>
</tbody>
</table>

#### Kerosene Savings

~900 Liter per Flight

#### Annual Savings for a fleet of 30 Aircraft A330-300

- On average 377 trips per year
- Assumed Kerosene Costs for 2020: 125 $/barrel (0.79 $/L)

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**Fuel Savings:** ~10 Mio L per Year  
**Money Savings:** ~8 Mio $ per Year  
**+ Emission Fees**
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- Fuel Processing
- Fuel Cell Principle
- Comparison PEMFC – SOFC

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Fuel Cell Systems Architecture

System Architecture Overview

- **Kerosene**
  - \( m \approx 60 \text{ kg/h} \)

- **Air**
  - \( m \approx 900 \text{ kg/h} \)

- **Fuel Processing**
  - \( m \approx 880 \text{ kg/h} \)

- **Fuel Cell**
  - \( m \approx 80 \text{ kg/h} \)
  - \( P_{el} \approx 400 \text{ kW} \)

- **Heat Management**
  - \( P_{th} \approx 160 \text{ kW} \)
Fuel Cell Systems Architecture

Key Challenge Fuel Processing

Fuel Processing is the Conversion of Kerosene into a hydrogen rich gas. Three Parts are normally necessary:

- **Desulfurization**: Removal of sulfur from kerosene.
- **Reforming**: Conversion of kerosene into a hydrogen rich gas (Reformat).
- **Gas Cleaning**: Cleaning of the reformat (depending on fuel cell).

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**Fuel Processing**

- **Desulfurization**: Adsorption
- **Reforming**: Steam reforming, Partial Oxidation, Autothermal Reforming
- **Gas Cleaning**: Shift Reactor, Membrane, Preferential Oxidation

**Input**
- Kerosene
- Air
- Water

**Output**
- Hydrogen (+ Rest)
Fuel Cell Systems Architecture

**Challenge:**
Standard Fuel Processing Methods are too complex.
⇒ A simple, lightweight and robust solution must be found!

**Dehydrogenation**

- Desulfurization
  - Adsorption
- Reforming
  - Steam reforming
  - Partial Oxidation
  - Autothermal Reforming
- Gas Cleaning
  - Shift Reactor
  - Membrane Preferential Oxidation

Fuel Processing

- Reforming
- Dehydrogenation of Kerosene

Kerosene

Dehydrogenation could be one possible solution
A **Fuel Cell** is an electrochemical device that continuously changes the electrical energy of hydrogen and oxygen from air **directly** to electrical energy and heat without combustion.

The overall chemical reaction:

\[ 2 \text{H}_2 + \text{O}_2 \rightarrow 2 \text{H}_2\text{O} \]

Different types of fuel cells with different working conditions are available:

- **PEMFC** (Protone Exchange Membrane Fuel Cell)
- **SOFC** (Solid Oxide Fuel Cell)
## Fuel Cell Systems Architecture

### Comparison PEMFC – SOFC

<table>
<thead>
<tr>
<th></th>
<th>Proton Exchange Membrane Fuel Cell (PEMFC)</th>
<th>Solid Oxide Fuel Cell (SOFC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fuel Cell with polymer (sulfonyl acid polymer $\rightarrow$ Nafion) as electrolyte.</td>
<td>Fuel Cell with ceramic ($Y_2O_3$-stabilized $ZrO_2$ $\rightarrow$ Yttria-stabilized zirconia) as electrolyte.</td>
</tr>
</tbody>
</table>
| **Advantages**         | - High development status (>100 kW$_{el}$)  
- Many thermal cycles possible  
- Water generation at cathode side | - High working temperature (~800°C)  
- Simple Cooling System  
- Insensitive against Gas Impurities  
- Simple Fuel Processing  
- Highest efficiencies  
- No humidification needed |
| **Challenges**         | - Low working temperature (~80°C)  
- Complex cooling system  
- Sensitive against CO  
- Complex Fuel Processing  
- Humidification needed | - Only few thermal cycles possible  
- Low development status for mobile application (20 kW$_{el}$)  
- Water generation at anode side |
Fuel Cell Systems Architecture

Comparison PEMFC – SOFC System
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**Airbus Fuel Cell System Strategy**
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Airbus Fuel Cell System Strategy

Step by Step Approach

Step 1
- Flying Test Bed
- H₂ Vessel
- 2007

Step 2
- Fuel Cell Emergency Power System
- mid of next decade

Step 3
- Fuel Cell Power Unit
- end of next decade

Step 4
- Primary Power Supply
- Kerosene
- 20XX

Step 5
- Alternative Fuels

Time
Airbus Fuel Cell System Strategy

Industrialization Approach

- Kerosene Reforming
- SOFC Integration
- PEM Integration
- Concepts

Overall Airbus Fuel Cell Activities

Research & Technology

Application to Programs

mid of next decade
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## Ongoing Projects and Activities

### Overview on Fuel Cell related research projects in Airbus

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<th>Project</th>
<th>Content</th>
<th>Target</th>
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<tbody>
<tr>
<td>POA</td>
<td>- Power optimization strategies</td>
<td>- SOFC functionality Demonstrator (1 kW)</td>
</tr>
<tr>
<td>Power Optimized Aircraft</td>
<td>- Kerosene fuelled SOFC system</td>
<td></td>
</tr>
<tr>
<td>APAWAGS</td>
<td>- Kerosene fuelled FC system</td>
<td>- SOFC and PEMFC System ground demonstrator for power and water generation (5 kW)</td>
</tr>
<tr>
<td>Advanced Power And Water Generation System</td>
<td>- Water Generation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- PEM and SOFC technology</td>
<td></td>
</tr>
<tr>
<td>CELINA</td>
<td>- Kerosene fuelled FC system</td>
<td>- Dynamic system simulation</td>
</tr>
<tr>
<td>Fuel Cell In A New Configured Aircraft</td>
<td>- Aircraft application investigation</td>
<td>- Extensive testing of PEMFC stack</td>
</tr>
<tr>
<td>FuCAp/FCEPS</td>
<td>- FC emergency power system</td>
<td>- Flying test bed demonstrator 20 kW (2007)</td>
</tr>
<tr>
<td>Fuel Cell Application (Demonstrator)</td>
<td>- H₂/O₂-Technology</td>
<td>- Integrated system flight tests</td>
</tr>
<tr>
<td>Fuel Cell Emergency Power System</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOET</td>
<td>- Electrical generation and distribution on Aircraft level</td>
<td>- Architecture assessment</td>
</tr>
<tr>
<td>More Open Electric Technology</td>
<td>- Kerosene fuelled SOFC system</td>
<td>- SOFC system simulation</td>
</tr>
<tr>
<td>A/C SOFC</td>
<td>- Kerosene fuelled SOFC system</td>
<td>- 400 kW SOFC System</td>
</tr>
<tr>
<td>Aircraft Solid Oxide Fuel Cell</td>
<td></td>
<td>- Testing and benchmarking</td>
</tr>
<tr>
<td>KING</td>
<td>- Fuel Processor development</td>
<td>- Dehydrogenation lab demonstrator (2006)</td>
</tr>
<tr>
<td>Kerosene Reforming</td>
<td>- Desulfurization by adsorption</td>
<td>- 50-100 kW Fuel Processor (2009)</td>
</tr>
<tr>
<td></td>
<td>- Autothermal Reformer</td>
<td>- 400 kW Fuel Processor</td>
</tr>
<tr>
<td></td>
<td>- Dehydrogenation of kerosene</td>
<td></td>
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- Test Data Collection

Step 2: Fuel Cell Emergency Power System
Step 3: Fuel Cell Power Unit
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Industrialization

Conclusion
Step 1: Demonstrator

Overview

Target (2007)
- Build Up of a Fuel Cell System Demonstrator
- Flight Test of the Fuel Cell System

Motivation
- First Safe Fuel Cell System operation on board
- Flight Test Data Collection, dynamic, heat, loads etc.

System Specification
- Power: $20 \text{ kW}_{el}$
- Fuel Cell: PEMFC
- Fuel: Pressurized Hydrogen and Oxygen
Step 1: Demonstrator

Installation Area

- Cooler
- Power Electronics
- Fuel Cell
- H₂-Storage
- O₂-Storage
- Storing Position 4
- Cargo Door
Step 1: Demonstrator

System Architecture

Aircraft Bus -130"

Fuel Cell System (FCS)

Safety System (Connections to ALL other systems)

Electronic Control Box (ECB)

FSC Control Panel / Internal

Power Conversion "EMP"

Power Conversion "ABD"

Fuel Cell & Auxiliaries

Oxygen Supply

Hydrogen Supply

H₂/O₂ Bottle

Cooling Loop

Battery System

Ventilation

Discharge O₂

Discharge H₂

Air In

Air Out

Filling Port O₂

Filling Port H₂

AC three phase 1
115V/400 Hz

AC three phase 2
115V/400 Hz

EMG Relay on Aircraft

Phase Unbalanced Detection

EMP

EMP Control

Switchbox Equipment

Fuel Cell System Equipment

Switchbox Equipment

FCS Observer Station - Laptop (FOS)

Ground System

"1XP"

Integrated Switchbox Switches

Electronic Control Box (ECB)

Battery System

Air In

Cooling Loop

Load Benches

Aircraft Equipment

Mechanic Connection

Electrical Connection

Blue Hydraulic Line

Blue Emergency Hydraulic Line

i.e. CSMG, Needed Slats, Flaps, ...
Step 1: Demonstrator

Test Data Collection

Flight Test Engineering Station
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Step 2: Fuel Cell Emergency Power System

Overview

Target (mid of next decade)

- Substitution of the Ram Air Turbine (RAT) by Fuel Cell Emergency Power System (FCEPS)

Advantages

- Support of the All Electric Aircraft Concept
- Weight Reduction
- Short System Starting Time
- Low Maintenance Costs
- Health Monitoring possible
Step 2: Fuel Cell Emergency Power System

Proposed Installation Area

Installation area
Ram Air Turbine

Proposed Fuel Cell Emergency Power System installation area

Proposed Electrical Motor Pump installation area
Step 2: Fuel Cell Emergency Power System

Installation Concept

View from aft cargo compartment into Aircraft lining
Step 2: Fuel Cell Emergency Power System

System Architecture
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Overview

Target (end of next decade)
- Power Generation by Fuel Cell System

Advantages
- Support of the All Electric Aircraft Concept
- Weight Reduction
- Mission Improvements
- Elimination of RAT and APU and battery reduction
- Potential for on-board water generation
- Emission Reduction

System Specification
- Power Output: 400 kW<sub>el</sub>
- Fuel: Kerosene
- Specific Weight: 1 kg/kW
- Specific Volume: 1,5 L/kW
Step 3: Fuel Cell Power Unit

System Concept

- Fuel Cell Stack
- Reformers
- Heat Exchanger
- Gas Cleaning
- Desulfurization
- Condenser
- Vaporiser
- Exhaust Turbine
- Exhaust Line
Step 3: Fuel Cell Power Unit

Tail Cone Integration Concept
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Step 4: Fuel Cell as Primary Power Source

Overview

Target (20XX)
- Primary Power Generation by Fuel Cell System

System Specification
- Power Output: 1000 kW_{el}
- Fuel: Kerosene

High Mature, Reliable and Safe Fuel Cell System!
Step 4: Fuel Cell as Primary Power Source

Advanced Aircraft System Configurations

- Electrical Powered Air Conditioning
- Advanced Main Engines
- Fuel Cell System

Emerging technologies:

- Optimized electrical and mechanical systems
- Power supply by fuel cell systems
- Advanced cabin system concepts
- New Aircraft system architectures

Electrical Actuators
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Overview

Target (20XX)
Power Generation by Fuel Cell System with Alternative Fuels

CO₂-Uptake = CO₂-Emissions

Renewable Biomass
Conversion
New Tank System

Alternative Fuels:
- Desulfurized Kerosene
- Hydrogen
- Ethanol/Methanol
- Biofuels
- Sunfuels

New Aircraft Generation
- Hydrogen Fuelled Aircraft
- New Tank System
- Fuel Cell System without Fuel Processing
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- Industrialization
  - Partners
  - Airbus Growing Systems Test Lab
  - hycity – Landesinitiative Brennstoffzellen und Wasserstofftechnologie Hamburg
- Conclusion
Industrialization

Growing Systems Test Lab in Hamburg

Test Rig with Reformer for SOFC Application

Test Rig with Integrated PEM Fuel Cell

Test Rig for SOFC
Airbus is founding member of the Landesinitiative Brennstoffzellen und Wasserstofftechnologie Hamburg. Targets of the Initiative:

- Promotion of fuel cell and hydrogen technology in Hamburg
- Reduction of CO₂ emissions
- Integration of renewable energies
- Secure of the Life Quality in Hamburg
- Stimulation of the Economy and Science in Hamburg
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Conclusion

- Airbus is involved/driving projects and tasks to bring forward the fuel cell industrialization with major suppliers especially in aeronautical applications.

- Airbus will gain an early integration with the step by step approach.
  - Soon experience with applied hardware.
  - Fundamental basis for further development.

- Airbus is committed to apply fuel cell systems with strong support by industrial partners and system suppliers.

- Airbus is at the forefront of fuel cell technology and innovation.

- Our advanced, environmental friendly and economical products will ensure an excellent competitiveness.
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