Fuel Cell Systems For Aeronautic Applications
A Clean Way from Kerosene to Energy
Hamburg, 10th of May 2007
Introduction

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>
<thead>
<tr>
<th></th>
<th>Automotive</th>
<th>Aircraft</th>
</tr>
</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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- Introduction

- **Fuel Cell System**
  - Fuel Cell Operation
  - Comparison Fuel Cell vs. Heat Engine
  - Development and Technical Targets

- Motivation for Fuel Cell System Application

- Fuel Cell Systems Architecture

- Airbus Fuel Cell System Strategy

- Step 1: Demonstrator

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- Step 3: Fuel Cell Power Unit

- Step 4: Fuel Cell as Primary Source

- Step 5: Alternative Fuels

- Industrialization

- Conclusion
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 $T_1 = 540°C; T_2 = 36°C$

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

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

\[
\eta_{el} = \frac{P_{el}}{P_{mech}} = \approx 90\%
\]

\[
\eta_{Fuel\ Cell} = \eta_{Rev} = (-237,13 \text{ kJ} \cdot \text{mol}^{-1})/(-285,8 \text{ kJ} \cdot \text{mol}^{-1}) = 0,8297 = \approx 83\%
\]

\[
\eta_{Heat\ Engine} = \eta_{Rev} \cdot \eta_C \cdot \eta_{el} = 0,83 \cdot 0,62 \cdot 0,9 = 0,46 = \approx 46\%
\]

Theoretical maximal achievable Efficiency: \( \approx 83\% \)
Fuel Cell System

Development and Technical Targets

![Graph showing the development and technical targets for fuel cell systems. The graph compares the DOE System fueled with gasoline and hydrogen, with an Airbus target for system specific weight.](image-url)
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  - Ecological and Economical Aircraft Operation Aspects
  - Conventional Electrical Power Generation vs. Fuel Cell System
  - Aircraft Mission
  - Fuel and Money Savings
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- Airbus Fuel Cell System Strategy
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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

APU | Engine | No Bleed/Electric Engine | Fuel Cell System

$\text{NO}_x$ (Nitrogen Oxides) Emission Reduction
Total $\text{NO}_x$ reduction on ground and in flight

$\text{CO}_2$ (Carbon Dioxide) Emission Reduction
20% – 60% $\text{CO}_2$ 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: up to 5%* Aircraft Systems
- 95 - 97% Propulsion

up to 5000 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% (Maximum possible today)</td>
<td>~60% (Target)</td>
</tr>
<tr>
<td>Fuel Use per Flight (10,000 km)</td>
<td>~5,000 Liter</td>
<td>~3,500 Liter</td>
</tr>
</tbody>
</table>

Kerosene Savings up to 1.500 Liter per Flight

Annual Savings for a fleet of 30 Aircraft A330-300

- On average ~ 380 trips per year
- Assumed Kerosene Costs for 2020: 125 $/barrel (0.79 $/L)

Fuel Savings: ~16 Mio L per Year
Money Savings: ~13 Mio $ per Year
+ Emission Fees
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- Motivation for Fuel Cell System Application

**Fuel Cell Systems Architecture**
- System Architecture Overview
- Fuel Processing
- Comparison PEMFC – SOFC

Airbus Fuel Cell System Strategy
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- Step 2: Fuel Cell Emergency Power System
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Fuel Cell Systems Architecture

System Architecture Overview

System Integration

System Control

Fuel Processing

Fuel Cell

Heat Management

Water

m = ~60 kg/h

Kerosene

m = ~900 kg/h

Air

m = ~880 kg/h

Electricity

P_{el} = ~400 kW

m = ~80 kg/h

Exhaust

P_{th} = ~160 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 Diagram**

- **Air**
- **Kerosene**
- **Water**

**Desulfurization**
- Adsorption

**Reforming**
- Steam reforming
- Partial Oxidation
- Autothermal Reforming

**Gas Cleaning**
- Shift Reactor
- Membrane
- Preferential Oxidation

**Hydrogen (+ Rest)**
**Dehydrogenation**

**Challenge:**
Standard Fuel Processing Methods are too complex.

⇒ A simple, lightweight and robust solution must be found!

Dehydrogenation could be one possible solution

**Fuel Processing**

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

**Kerosene**

- Dehydrogenation of Kerosene
  - m = ~1.200 kg/h

**Rest Kerosene**

- m = ~1.183 kg/h

**Hydrogen**

- m = ~17 kg/h
Fuel Cell Systems Architecture

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

**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 (sulfonic acid polymer → Nafion) as electrolyte.</td>
<td>Fuel Cell with ceramic ($\text{Y}_2\text{O}_3$-stabilized $\text{ZrO}_2$ → Yttria-stabilized zirconia) as electrolyte.</td>
</tr>
<tr>
<td>Advantages</td>
<td>- <strong>High development status (&gt;100 kW$_{el}$)</strong>&lt;br&gt;- Many thermal cycles possible&lt;br&gt;- Water generation at cathode side</td>
<td>- High working temperature (~800°C)&lt;br&gt;- Simple Cooling System&lt;br&gt;- Insensitive against Gas Impurities&lt;br&gt;- Simple Fuel Processing&lt;br&gt;- <strong>Highest efficiencies</strong>&lt;br&gt;- No humidification needed</td>
</tr>
<tr>
<td>Challenges</td>
<td>- Low working temperature (~80°C)&lt;br&gt;- Complex cooling system&lt;br&gt;- Sensitive against CO&lt;br&gt;- Complex Fuel Processing&lt;br&gt;- Humidification needed</td>
<td>- Only few thermal cycles possible&lt;br&gt;- Low development status for mobile application (20 kW$_{el}$)&lt;br&gt;- Water generation at anode side</td>
</tr>
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## Airbus Fuel Cell System Strategy

- Step by Step Approach
- Industrialization Approach

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Airbus Fuel Cell System Strategy

**Step by Step Approach**

**Step 1**
- H₂ Vessel
- Flying Test Bed
- 2007

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

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

**Step 4**
- Primary Power Supply
- Kerosene
- 20XX

**Step 5**
- Alternative Fuels

**Time**
Airbus Fuel Cell System Strategy

Industrialization Approach

Overall Airbus Fuel Cell Activities

Research & Technology

Application to Programs

Concepts

Kerosene Reforming

SOFC Integration

PEM Integration

mid of next decade

2004
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  - Overview
  - Installation Area
  - Test Data Collection

- Step 2: Fuel Cell Emergency Power System
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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: $20 \text{ kW}_\text{el}$
- Fuel Cell: PEMFC
- Fuel: Pressurized Hydrogen and Oxygen
Step 1: Demonstrator

Installation Area

Storing Position 4

Cooler
Power Electronics
Fuel Cell
H₂-Storage
O₂-Storage

Cargo Door
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

- Motor controller and AC/DC Converter
- Fuel Cell Stack
- Cooling Pump
- Existing Water Tank
- Oxygen Vessels

View from aft cargo compartment into Aircraft lining
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- System Concept
- Tail Cone Integration Concept
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Step 3: Fuel Cell Power Unit

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_{el} (possible configuration: 4*100 kW-System)
- Fuel: Kerosene
- Specific Weight: 1 kg/kW
- Specific Volume: 1.5 L/kW
Step 3: Fuel Cell Power Unit

System Concept

- Fuel Cell Stack
- Exhaust
- Condenser
- Vaporiser
- Exhaust Turbine
- Gas Cleaning
- Desulfurization
- Reformer
- Heat Exchanger
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
- Electrical Actuators
- Fuel Cell System

Emerging technologies:

- Optimized electrical and mechanical systems
- Power supply by fuel cell systems
- Advanced cabin system concepts
- New Aircraft system architectures
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Step 5: Alternative Fuels

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

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

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Industrialization

Partners:

Universities and Institutes:

Companies:

Industrialisation Partners:
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
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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.
THANK YOU FOR YOUR ATTENTION!