Lightweight Solid Oxide Fuel Cells for Aviation

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Central Research and Technology • Electrification Technologies • Materials

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Central R & T / Electrification Technologies

ZAL Center of Applied Aeronautical Research / Hamburg

Contents

Objectives

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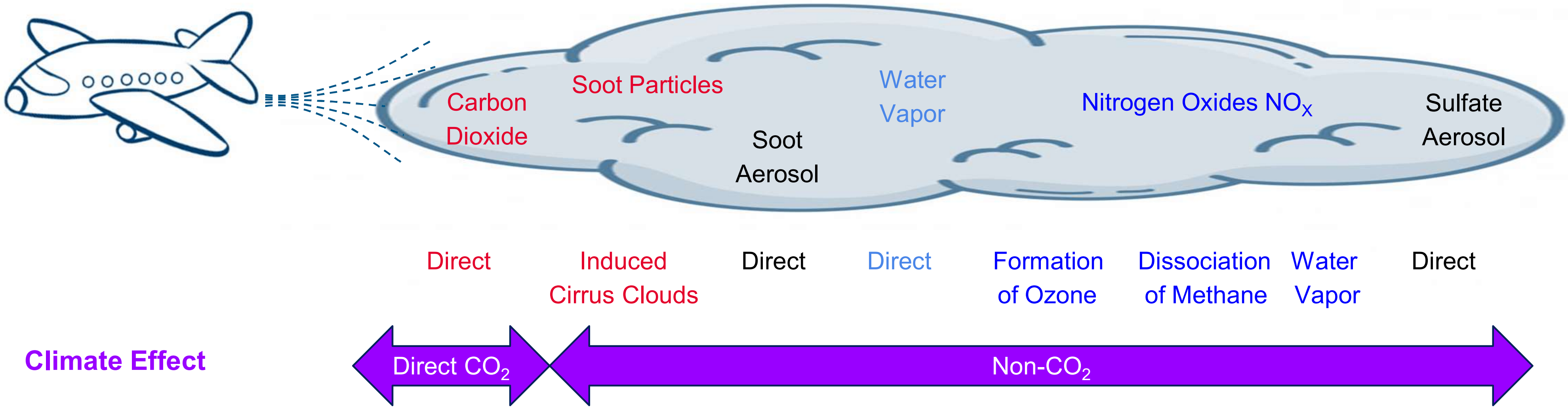

"Since CO_2 is well mixed throughout the atmosphere,
emission reductions in the fuel production process have the same benefit as emission reductions over the flight cycle."

(Source.: D. Lee et al. / Transport impacts on atmosphere and climate: Aviation / Atmospheric Environment 44 (2010) 4678–4734)

Ambition - ZEROe

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Turbofan design

- 120-200 passengers
- 2,000+ nautical miles range
- Powered by hybrid-hydrogen turbofan engines

Turboprop design

- 100 passengers max
- 1,000+ nautical miles range
- Powered by hybrid-hydrogen turboprop engines

"Blended-wing body" design

- 200 passengers max
- 2,000+ nautical miles range
- Powered by hybrid-hydrogen turbofan engines
- Multiple options for hydrogen storage and distribution, and for cabin layout.

Our Mission for 2035

…to bring a hydrogen powered commercial aircraft to market!

Fuel Cell Types

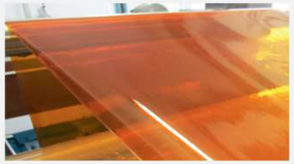
Low **T**emperature
Proton **E**xchange **M**embrane

LT-PEM / **60°- 80°C**
Polymer Electrolyte: Sulfonic Acid

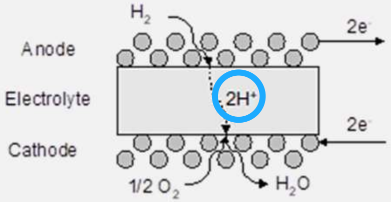
- **Hydrogen only** can be
- Carbon monoxide is a c

High **T**emperature
Proton **E**xchange **M**embrane

HT-PEM / **120°- 180°C**
Polymer Electrolyte: Phosphoric Acid



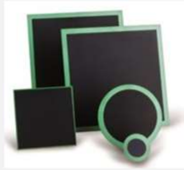
- Electrolyte is conductive for **protons (H^+)** that are formed on the fuel side



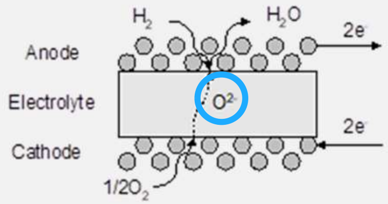
- **Hydrogen only** can be used as fuel
- Carbon monoxide tolerance around 1%

Solid **O**xide **F**uel **C**ell

SOFC / **650°C - 900°C**
Ceramic Electrolyte: Yttria Stabilized Zirconia



- Electrolyte is conductive for **oxides (O^{2-})** that are formed on the air side



- **Hydrogen, carbon monoxide** and **methane** can be used as fuel

Fuel Cell Types - Ready to Fly?

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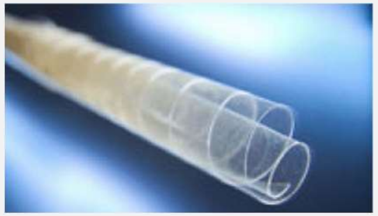
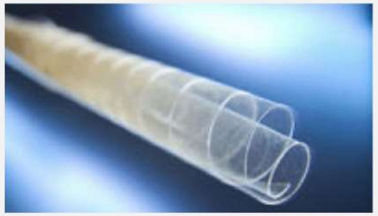
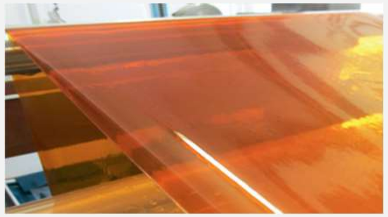
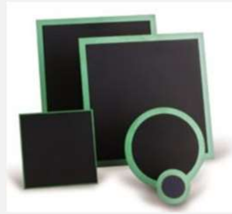
Direct Methanol Fuel Cell	Low Temperature Proton Exchange Membrane	High Temperature Proton Exchange Membrane	Solid Oxide Fuel Cell
DMFC / 30°- 130°C	LT-PEM / 60°- 80°C	HT-PEM / 120°- 180°C	SOFC / 650°C-900°C
			
State of the Art			
• Electrical Efficiency: 20-40% • Grav. Power Density: < 0.5 kW/kg • Cooling: Liquid (60°C-90°C)	• Electrical Efficiency: 40-60% • Grav. Power Density: 2-3 kW/kg • Cooling: Liquid (80°C)	• Electrical Efficiency: 40-50% • Grav. Power Density: 0.5 kW/kg • Cooling: Liquid (120°C-180°C) / Gaseous	• Electrical Efficiency: 60-70% (with GT) • Grav. Power Density: 0.1-0.5 kW/kg • Cooling: Gaseous • Efficient integrated reforming of H_xC_y
General R&D Objectives			
“Fundamental electrochemical research required to improve IV characteristics!”	**“Optimizing the performance!”**	**“Fundamental electrochemical research of materials and mechanisms!”**	**“Pushing the power density by novel manufacturing processes, enabling lighter cell designs!”**

Airbus & ElringKlinger Joint Venture “Aerostack GmbH”

“ElringKlinger has 20 years of experience in Proton Exchange Membrane Technology”

Fuel Cell - System Aspects

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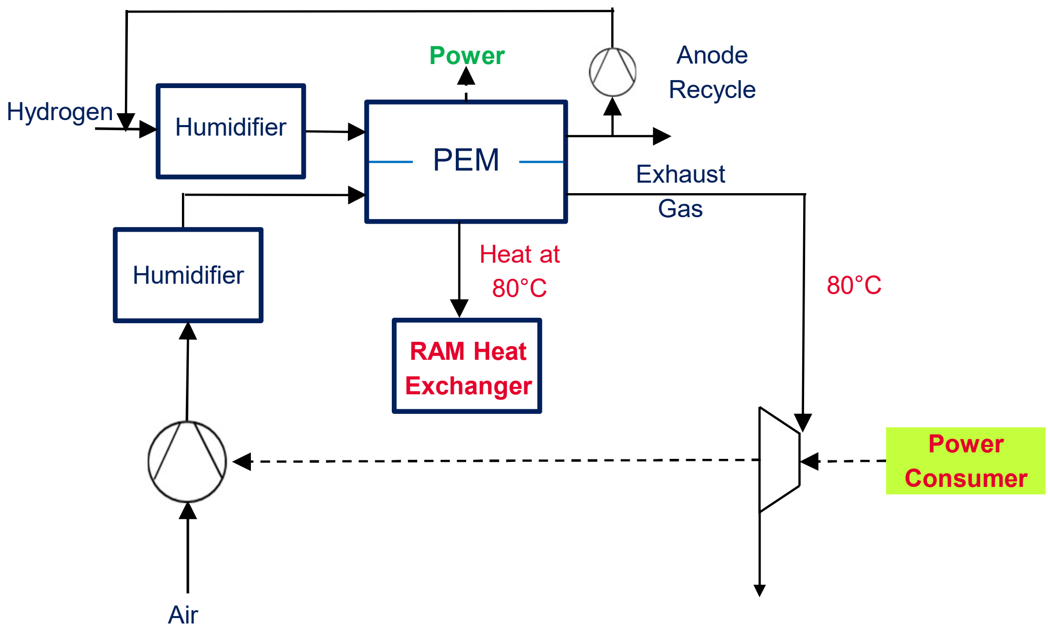
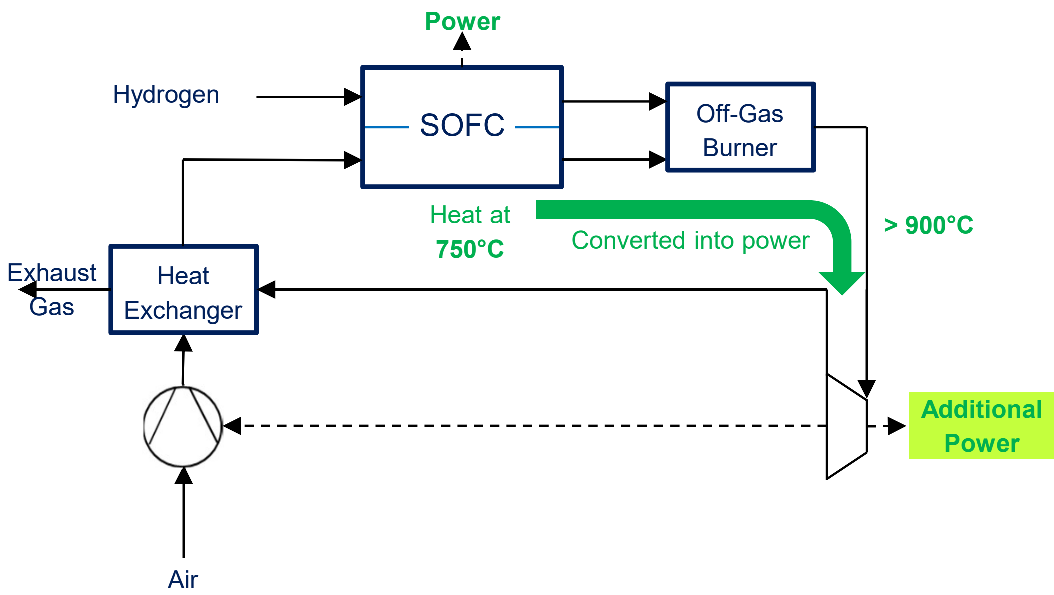
LT-PEM System



SOFC System

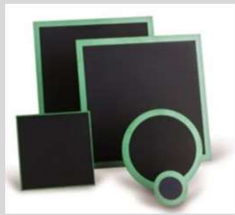
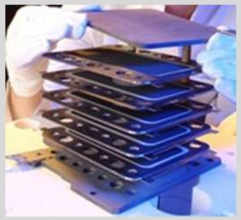
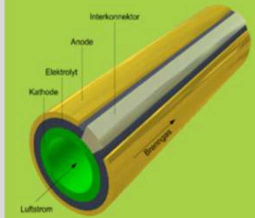
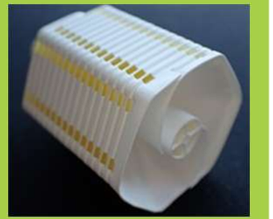


Win-Win by SOFC-GT coupling

Electrical efficiency: +10%-points (60% to 70% electrical)

Power density of SOFC: +10% to 20% by pressurization (at equal cell voltage)

Solid Oxide Fuel Cell

	Planar SOFC  	(Micro) Tubular SOFC  	Monolithic SOFC  
Grav. power density (kW/kg)	poor	good	good (presumably)
Startup and shutdown time	good (cell), poor (stack)	good	medium (presumably)
Thermal shock resistance	good (cell), poor (stack)	good	medium (presumably)
Additional cooling possibilities	poor	good	good - medium
Current collection losses	low	development required	development required
Gas manifold integration	easy	medium	medium
Stacking & Modularization (MW_{el})	medium	development required	development required
Maturity & Commercialization	high	medium - low	low

Solid Oxide Fuel Cells

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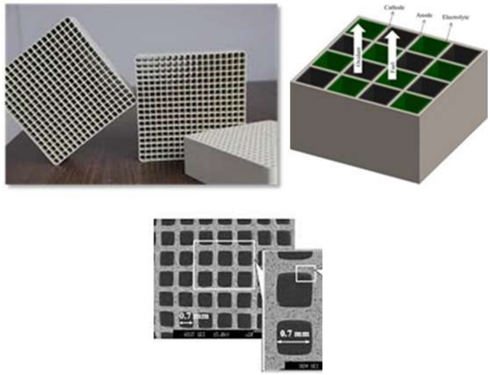
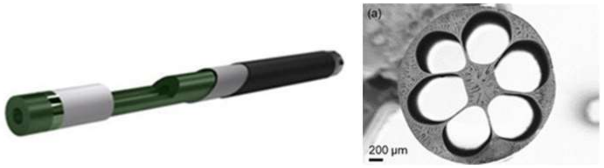
Area to Volume Ratio

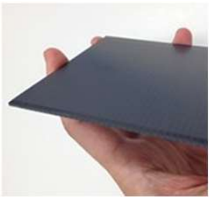
Monolithic



Micro Tubular



Flat Planar



Planar

Complexity of Manufacturing & Current Collection

Planar SOFC

- Large contact area for the current collection
- Mature manufacturing
- Limited area to volume ratio by the thickness of interconnect-plates
- Sensitive towards thermal gradients

Micro Tubular SOFC

- High area to volume ratio at small diameters
- High thermal shock resistance
- Challenging current collection

Monolithic SOFC

- Highest area to volume ratio
- Can make use of novel manufacturing technologies
- Challenging current collection

Project Objective • Our Journey

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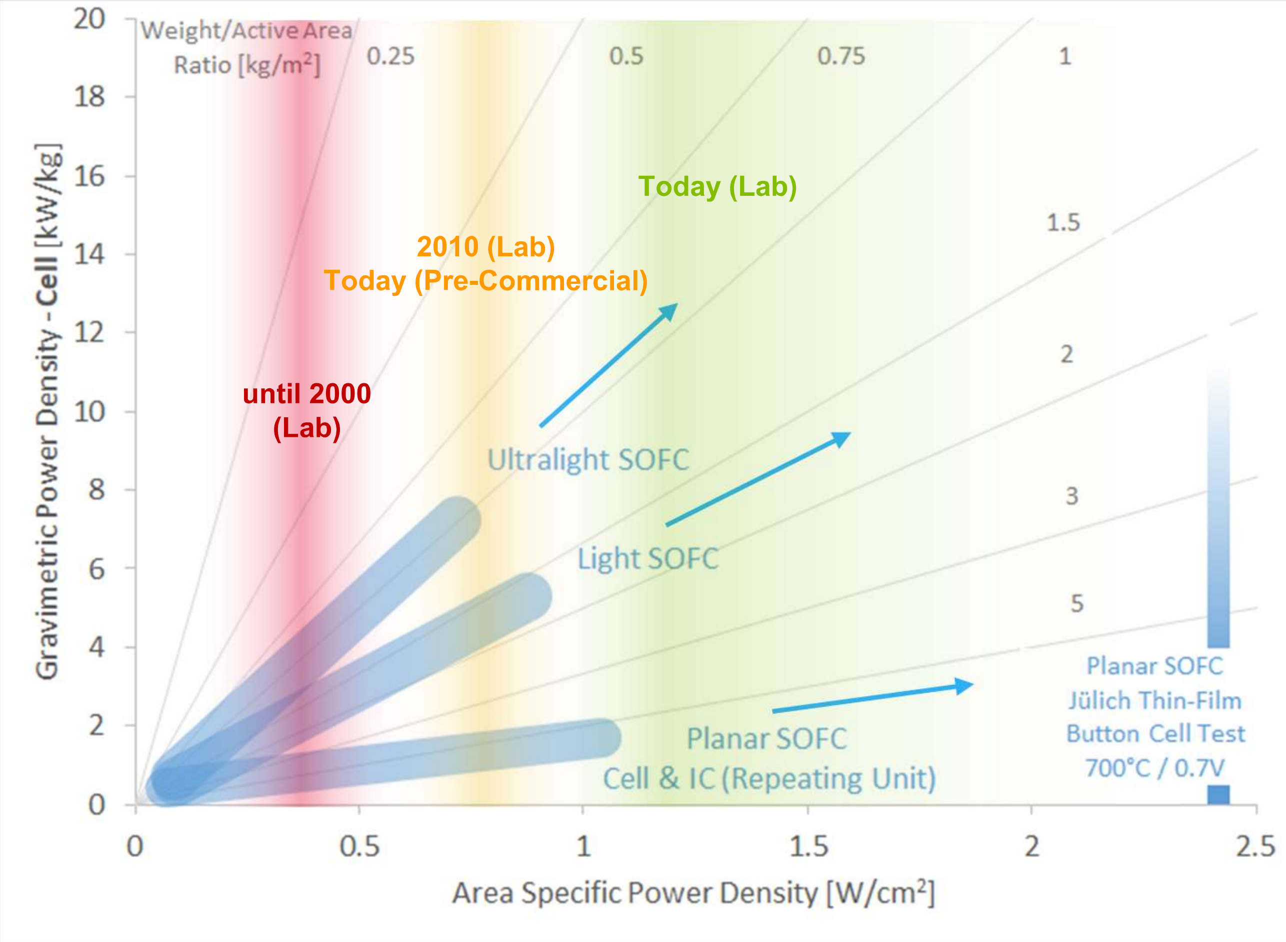


Target

- Higher Area to Volume Ratios
- Light Cell Support Structures
- Thin Electrolytes
- Efficient Current Collection

4-7 kW/kg on a cell level seems feasible in the near future!

Achievements in manufacturing of thin-film electrolytes demonstrated a power density of 2.45 W/cm² *

* Source: Performance Benchmark of Planar Solid Oxide Cells Based on Material Development and Designs / David Udomsilp, Christian Lenser, Olivier Guillon, Norbert H. Menzler (2021)

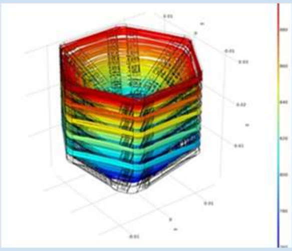
Research Activities at Airbus

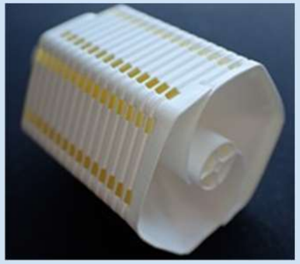
MONOBLOC Project

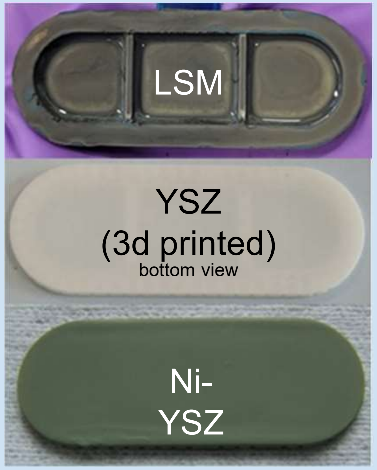
3D Printed SOFC

Feasibility of Manufacturing Process

- ➢ **3D printing and coating of functioning simple geometry proven!** ✓





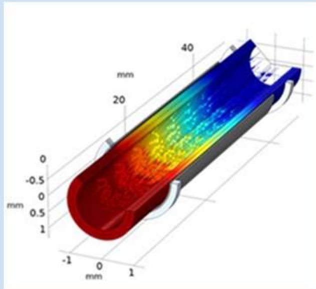


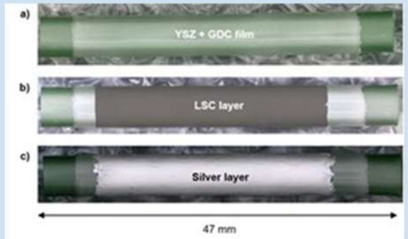
Light-Weight Tubular SOFC Project

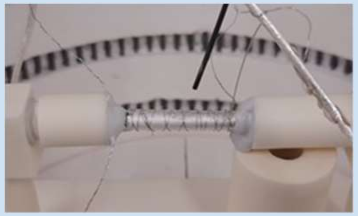
Micro Tubular SOFC

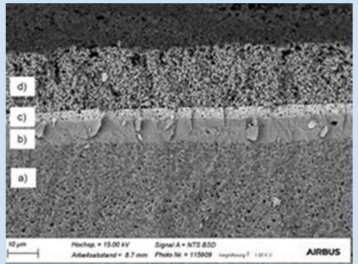
Lighter and more Porous Support Structure

- ➢ **2 kW_{el}/kg_{Cell} achieved for both-end current collection!** ✓

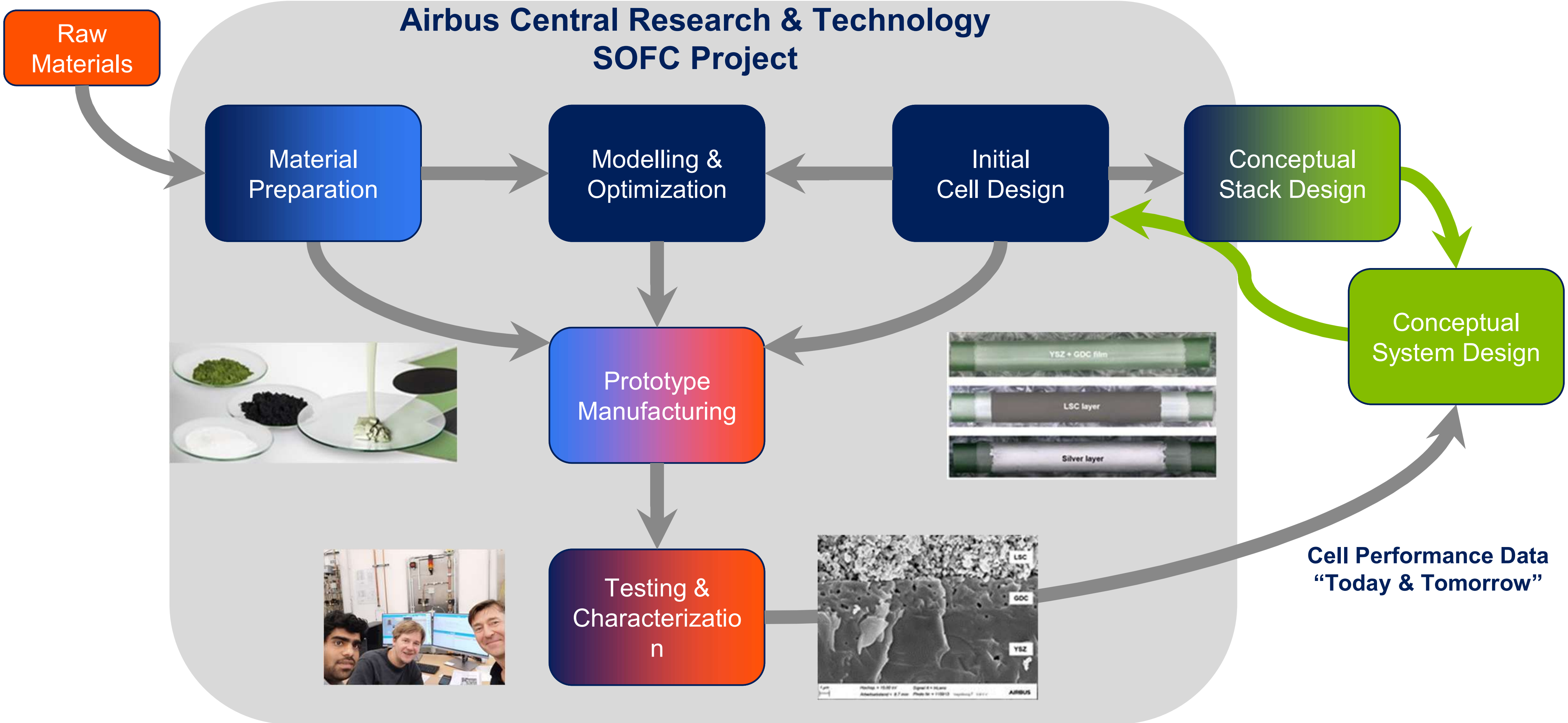








Research Activities at Airbus



Research Activities at Airbus - Micro Tubular ASC

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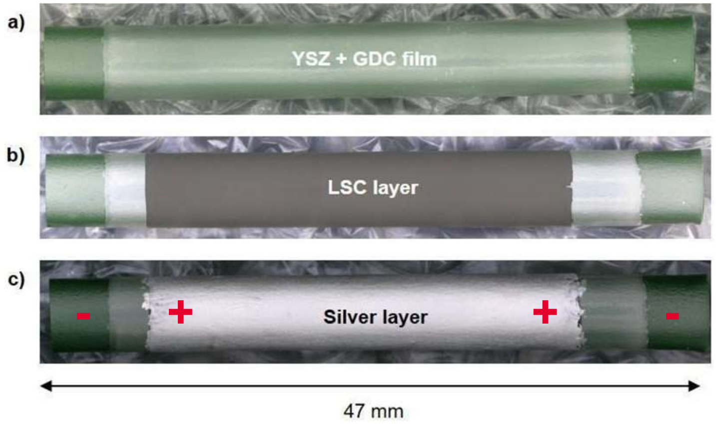
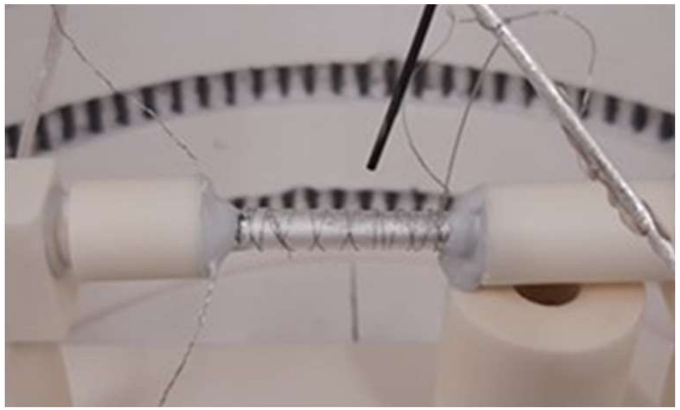
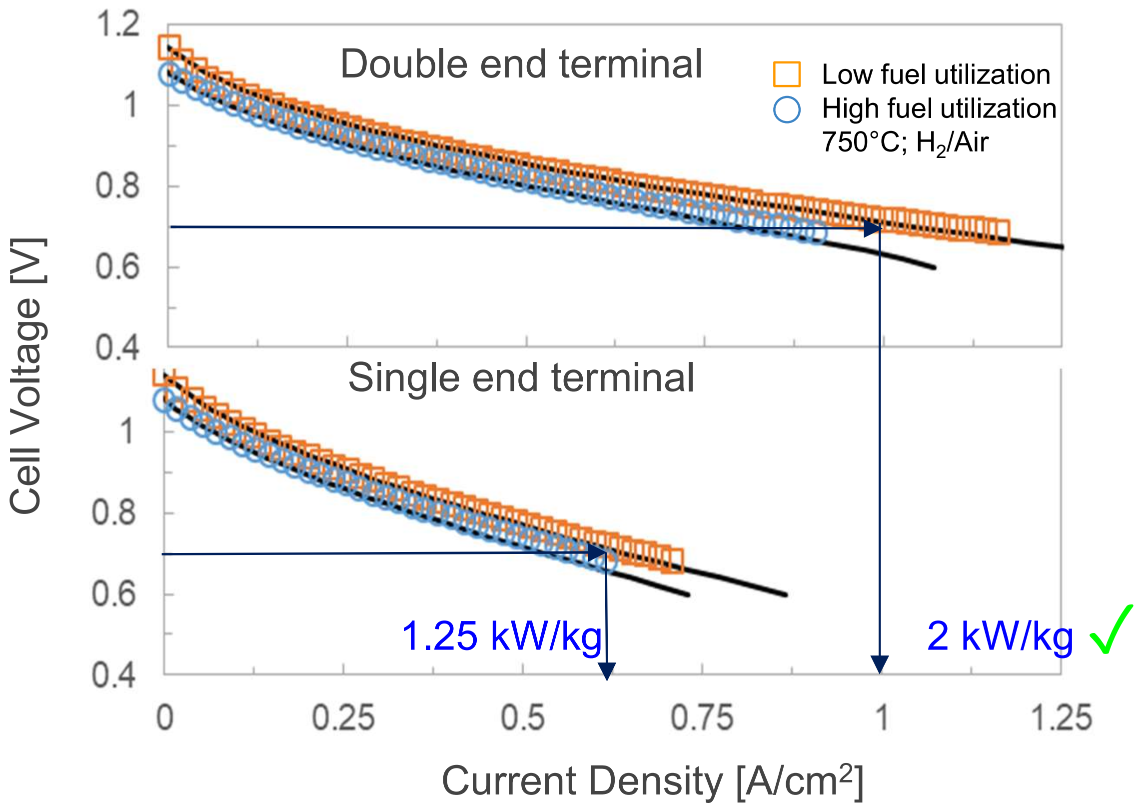
Anode Supported Tubular SOFC







Research Activities at Airbus

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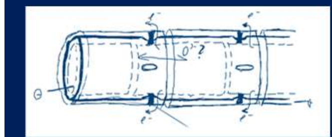
Light-Weight Tubular SOFC Project

Micro Tubular SOFC

Lighter and more Porous Support Structure

- ➢ **2 kW_{el}/kg_{Cell} achieved for both-end current collection!** ✓

NET-SOFC Project (2022-2024)

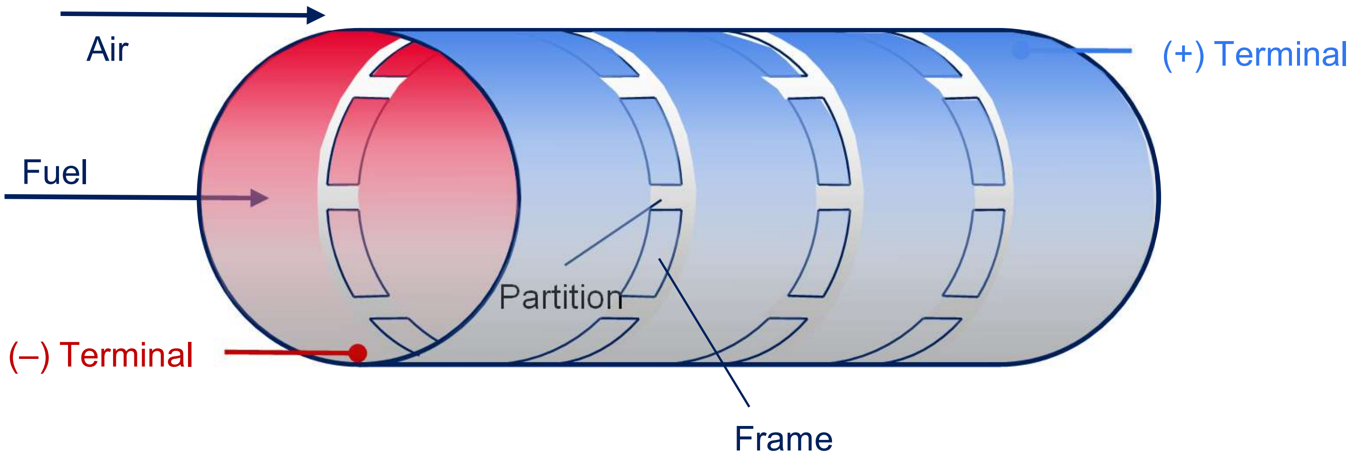


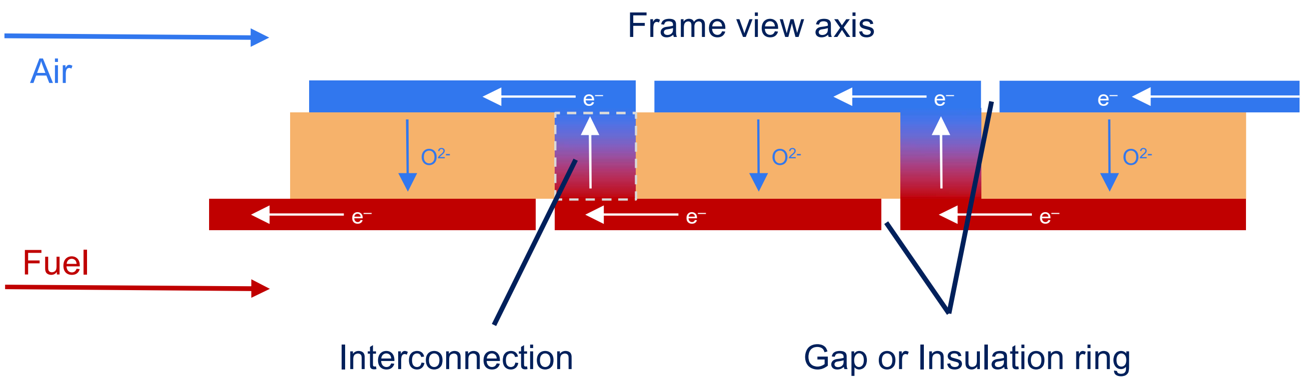
Networking SOFC

- ➢ **Reducing the distance of current collection!**
- ➢ **Target: > 3 kW_{el}/kg_{Cell}**

Research Activities at Airbus - ESC

Networking Tubular Electrolyte Supported Cell (ESC)





Networking-ESC

Pro

- Electrolyte support can be sintered as one of the first steps at highest temperatures
- Presumably high mechanical stability
- Potential: > 3 kW_{el}/kg_{Cell} based on ScSZ

Con

- 3D printing possibility to be checked
- Order of coating and sintering steps
- Gas tight interconnection

Research Activities at Airbus - ESC

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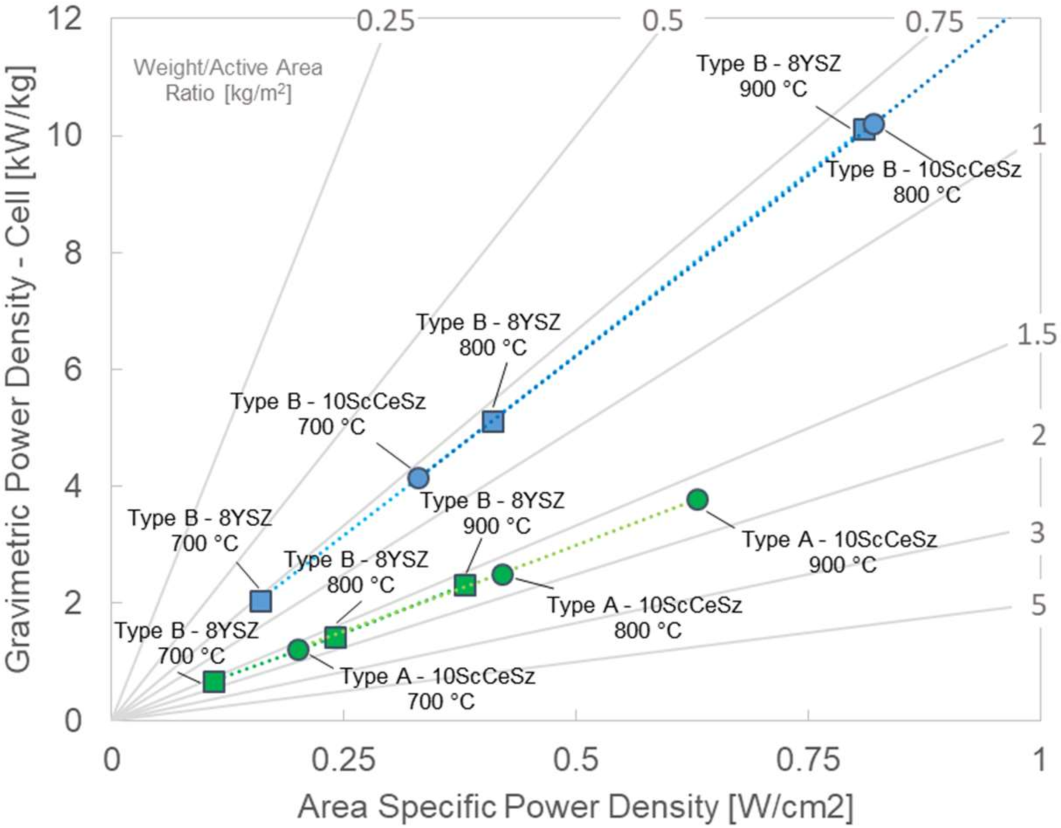
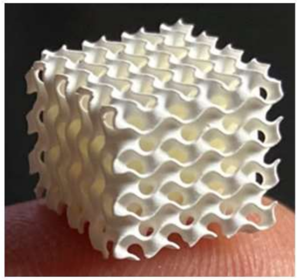
Monolithic **E**lectrolyte **S**upported **C**ell **(ESC)**





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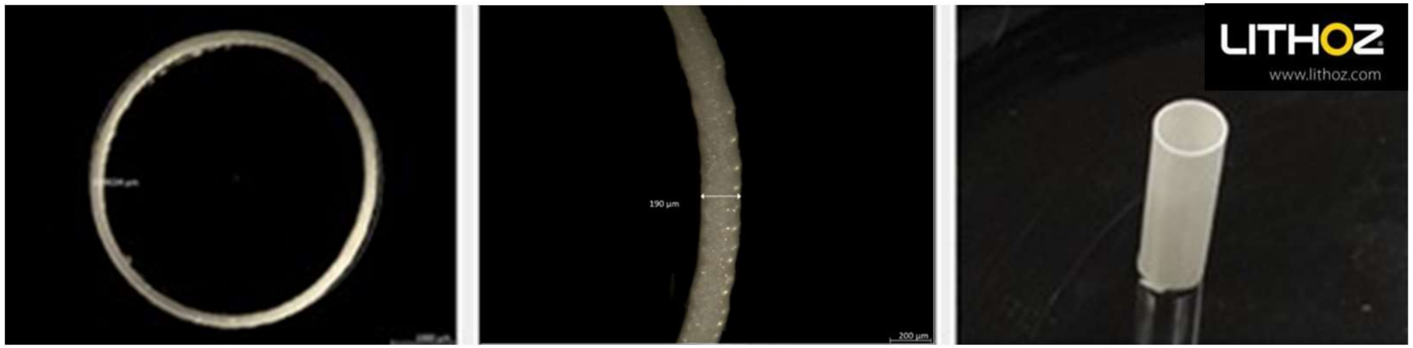
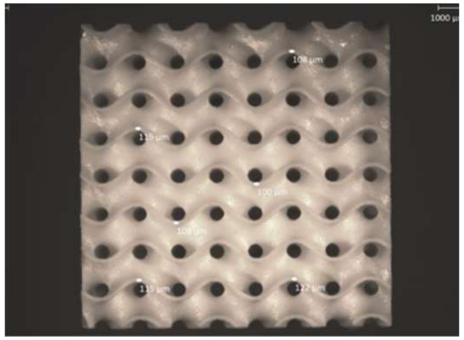
Research Activities at Airbus - ESC

3D Printing Samples - Thin Wall Tubes

by LCM - lithography based ceramic manufacturing



…wall thicknesses 158 – 221 µm after sintering!



…wall thicknesses 100µm after sintering!

Networking-ESC

(Patent application: 309.0381EP / 18080-EP-EPA)

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Research Activities at Airbus - ESC

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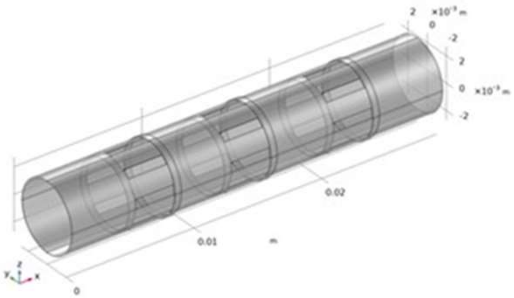
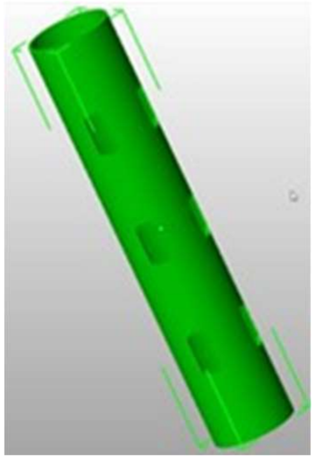
Initial Design



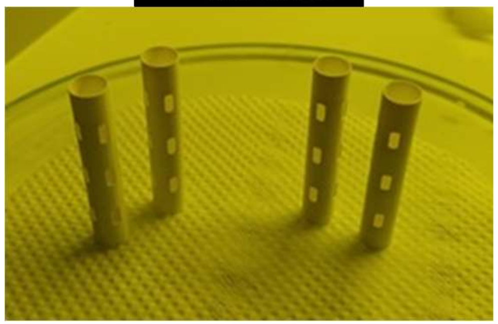
Optimized Design for 3D Printing



3D Printing Samples

by LCM - lithography based ceramic manufacturing

LITHOZ
www.lithoz.com



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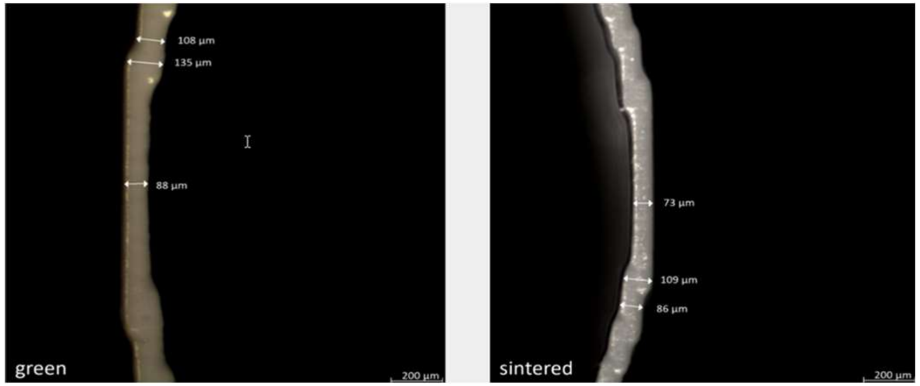
Research Activities at Airbus - ESC

3D Printing Samples - Thin Wall Tubes

by LCM - lithography based ceramic manufacturing

…wall thicknesses optimized down to 100 µm after sintering!



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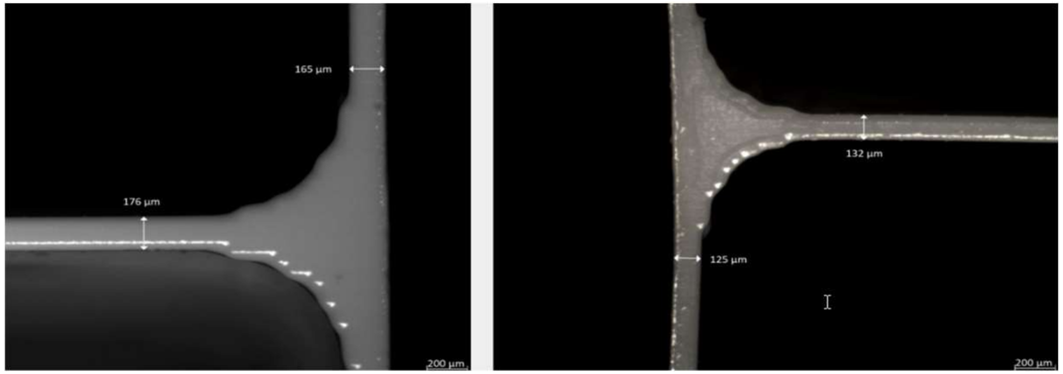
Research Activities at Airbus - ESC

3D Printing Samples - Thin Wall Flat Tubes

by LCM - lithography based ceramic manufacturing

…wall thicknesses optimized down to 150 µm after sintering!



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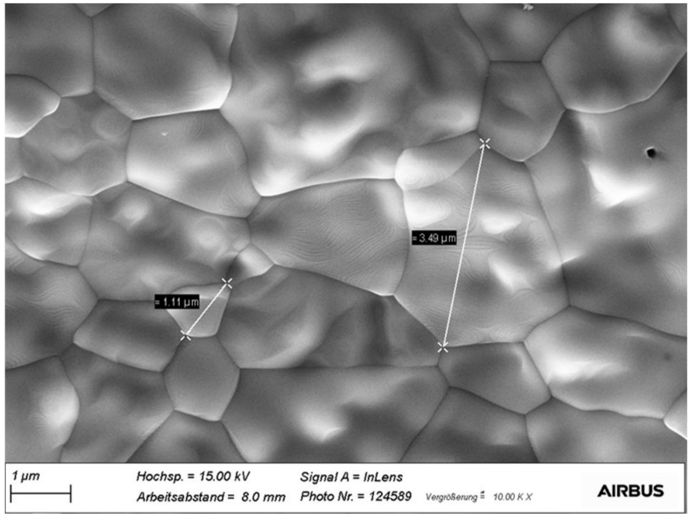
Research Activities at Airbus - ESC

Morphological Structure

Sample

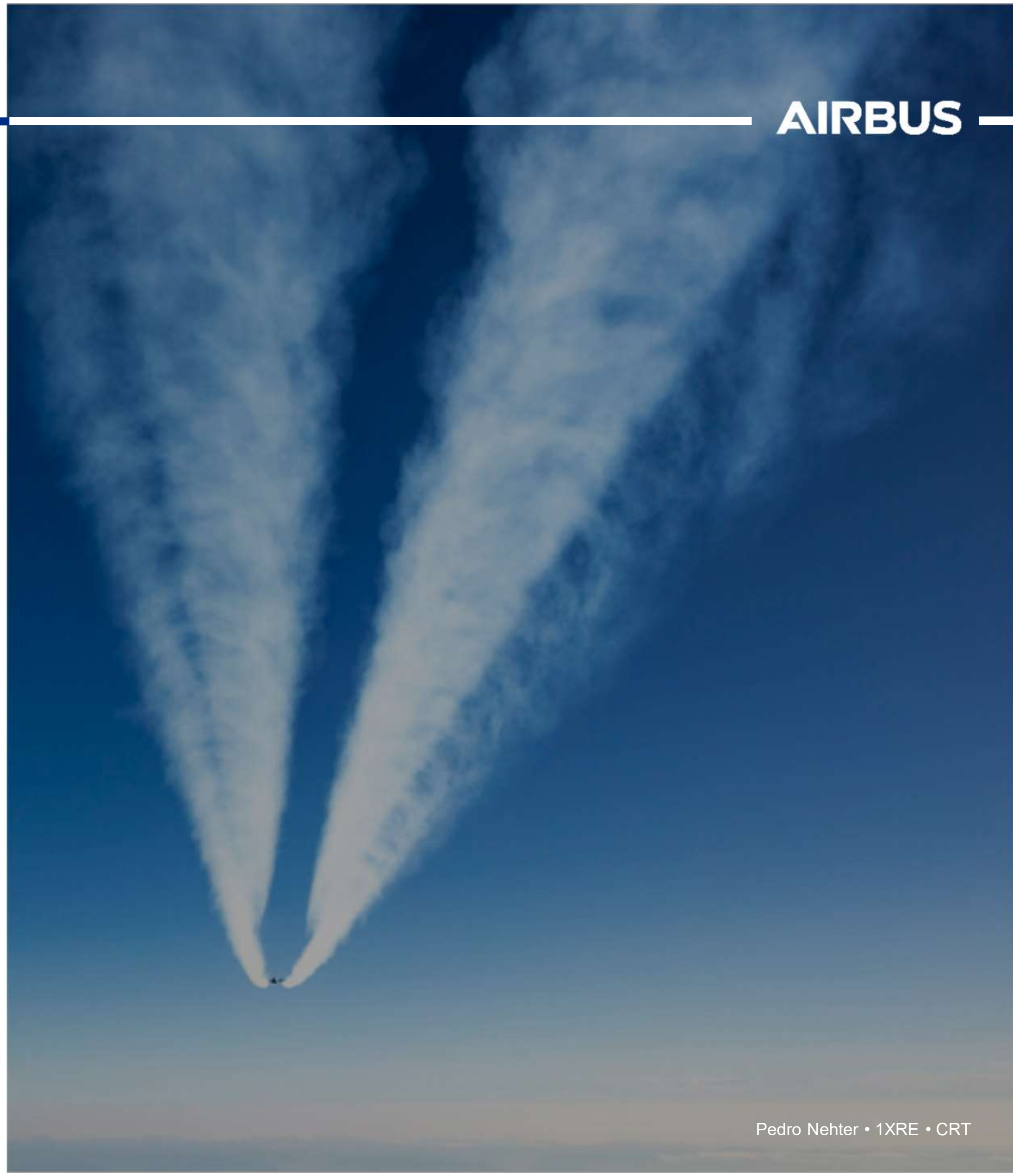
Grain Boundaries



SEM Results

- Thickness is uniform throughout the length and it is matches with supplied CAD models ✓
- Grain boundaries are tightly connected in the inner, outer surface and in cross-section and no pin holes observed in the interface of ScSZ particles ✓

Summary



- Airbus **C**entral **R**esearch and **T**echnology is exploring long term technology bricks to enable highly efficient propulsion.

- The **S**olid **O**xide **F**uel **C**ell offers **highest efficiencies** in combination with a gas turbine for hydrogen as well as for light hydrocarbons as fuel.

- The **SOFC**, currently **pre-commercialized** for stationary applications, has a rather low maturity for mobile applications. In particular, the gravimetric power density of today's planar stacks is far too low.

- Grametric cell power densities of **> 3 kW_{el}/kg_{Cell}** for **tubular** and **monolithic SOFC** concepts seem feasible in the near future.

Thank you

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