

Stack- und Zellkonzepte für die SOFC

André Weber

Institut für Angewandte Materialien – Elektrochemische Technologien (IAM-ET)

Adenauerring 20b, Geb. 50.40 (FZU), Raum 314

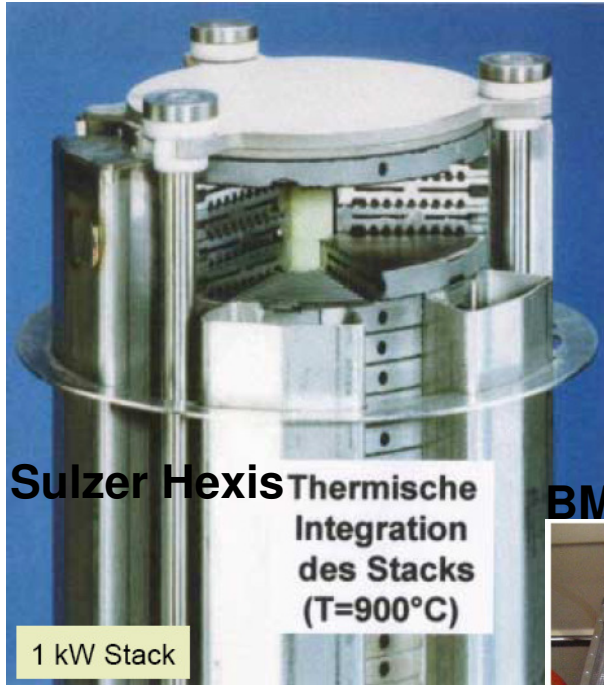
phone: 0721/608-7572, fax: 0721/608-7492

andre.weber@kit.edu

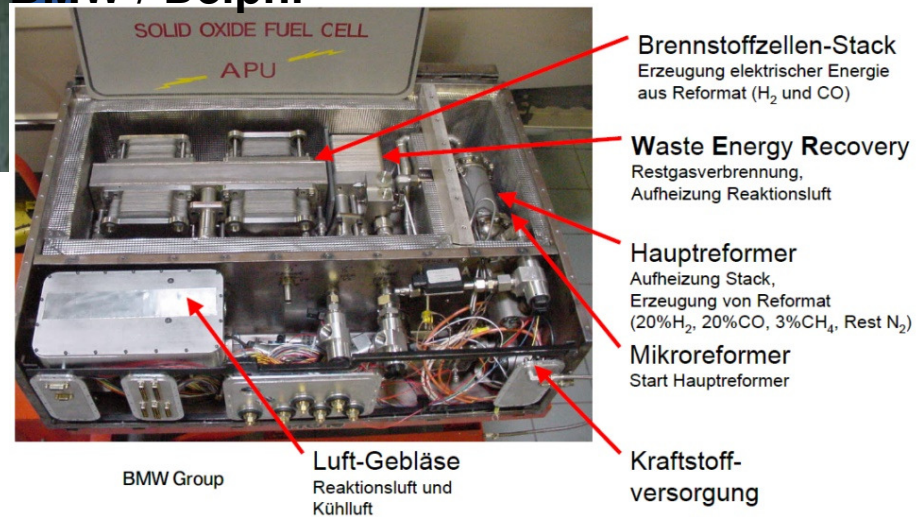
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Stack- und Zellkonzepte



BMW / Delphi



Siemens-Westinghouse

Fuel Cells

Cell Voltage, Internal Resistance and Fuel Cell Efficiencies

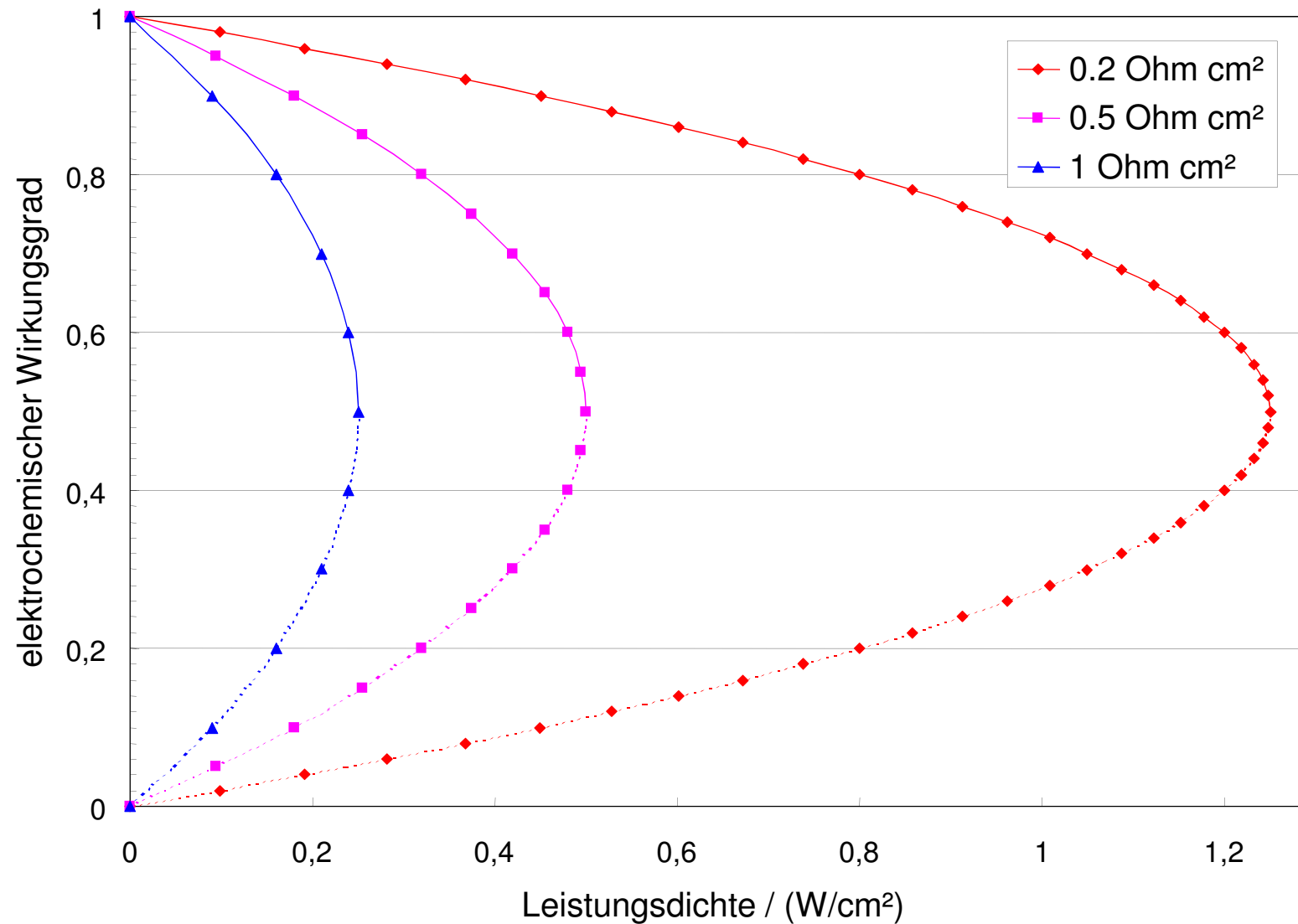
thermodynamic efficiency	$\eta_{th} = \frac{\Delta G}{\Delta H} = 1 - \frac{T\Delta S}{\Delta H}$	cell voltage and internal resistance $U_{cell} = U_0 - R_{cell} \cdot I_{cell} = U_0 - I_{cell} \cdot \sum_k R_{cell,k}$ $\sum_k R_{cell,k} = R_{cathode} + R_{electrolyte} + R_{anode} + R_{contact}$	single cell ... stack	
electrochemical efficiency	$\eta_{el} = \frac{U_{cell}}{U_{th}} = -\frac{nFU_{cell}}{\Delta G}$			
fuel utilization	$\beta_f = \frac{\text{used fuel}}{\text{provided fuel}}$	fuel efficiency		$\eta_f = \frac{I}{I_m}$
reforming efficiency	$\eta_{ref} = \frac{\Delta H}{\Delta H_{fuel}}$	el. system efficiency	$\eta_{elS} = \frac{W_{el}}{nFU_{cell}}$	system (el. p.)
electrical system efficiency	$\eta_{electrical} = \eta_{th} \cdot \eta_{el} \cdot \eta_f \cdot \beta_f \cdot \eta_{Ref} \cdot \eta_{elS} = \frac{\text{produced electrical energy}}{\text{provided chemical energy}}$			
thermal system efficiency	$\eta_{thermal} = \frac{\text{usable heat}}{\text{provided chemical energy}}$		CHP-system	
total efficiency	$\eta_{tot} = \eta_{electrical} + \eta_{thermal}$			

Fuel Cells

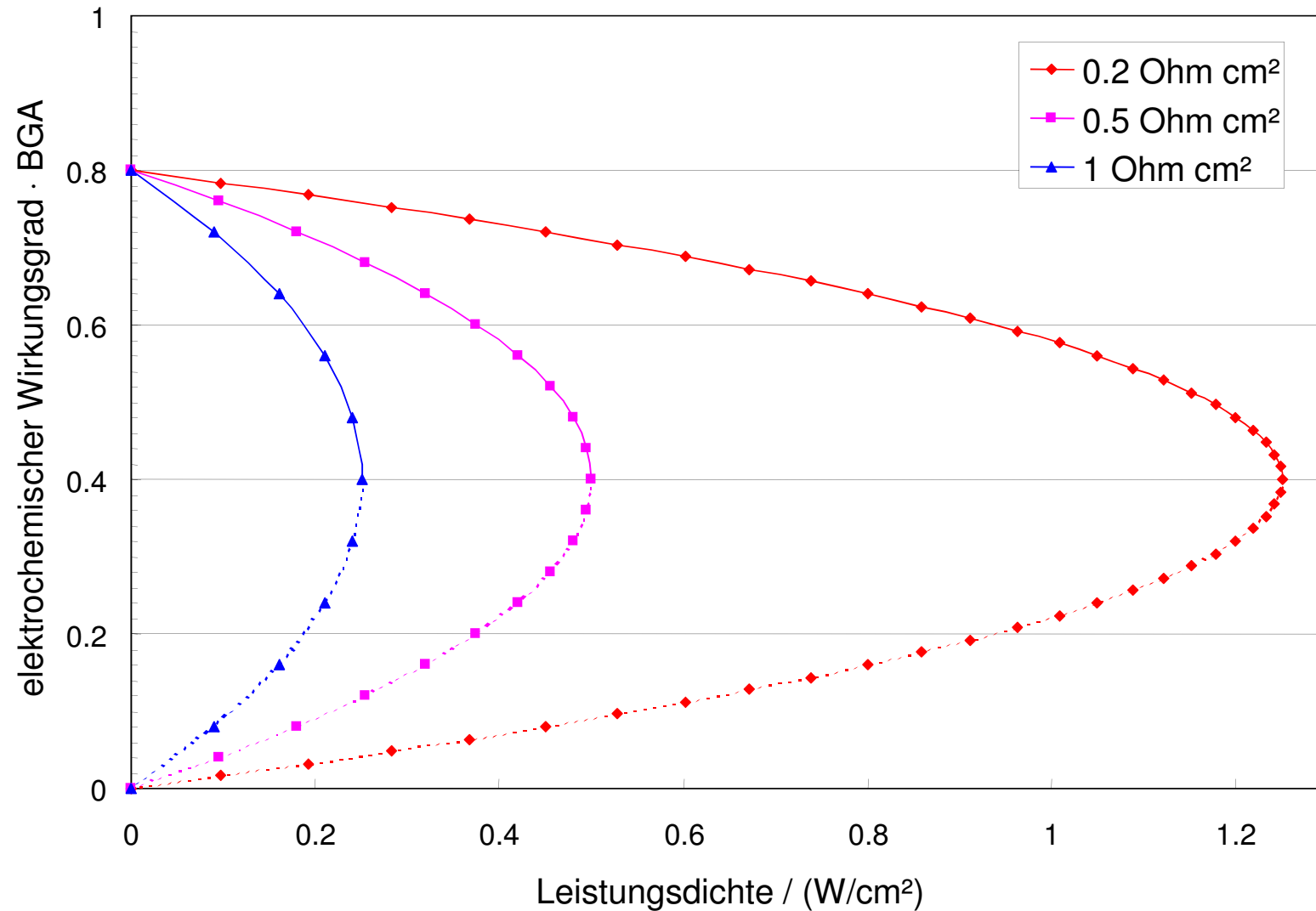
Cell Voltage, Internal Resistance and Fuel Cell Efficiencies

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total efficiency	$\eta_{tot} = \eta_{electrical} + \eta_{thermal}$			

Elektrochemischer Wirkungsgrad in Abhängigkeit der Leistungsdichte



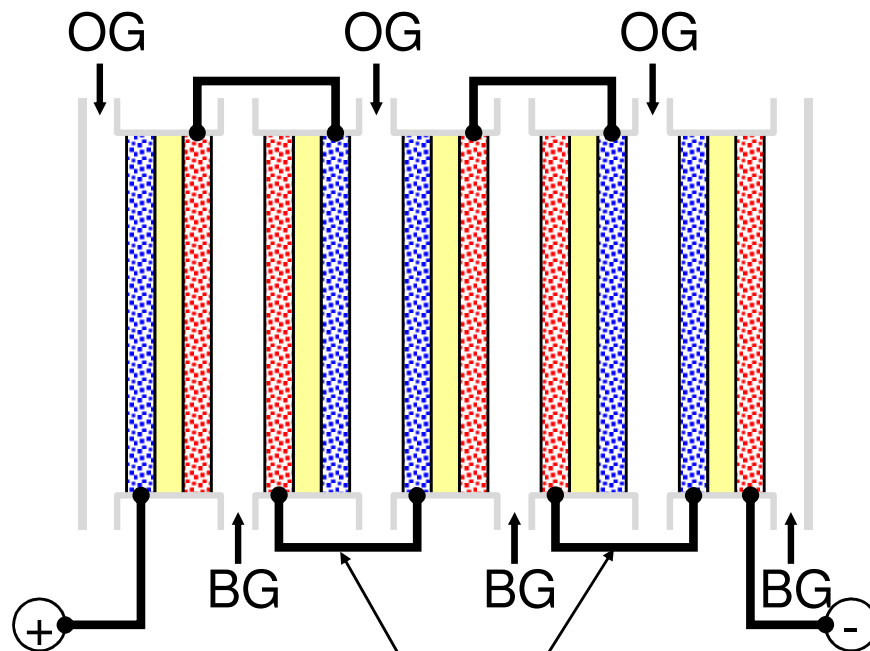
Stack-Wirkungsgrad ($\beta_f \cdot \eta_{el}$) in Abhängigkeit der Leistungsdichte



**Brenngas-
ausnutzung: 80%**
($\eta_f = 1$)

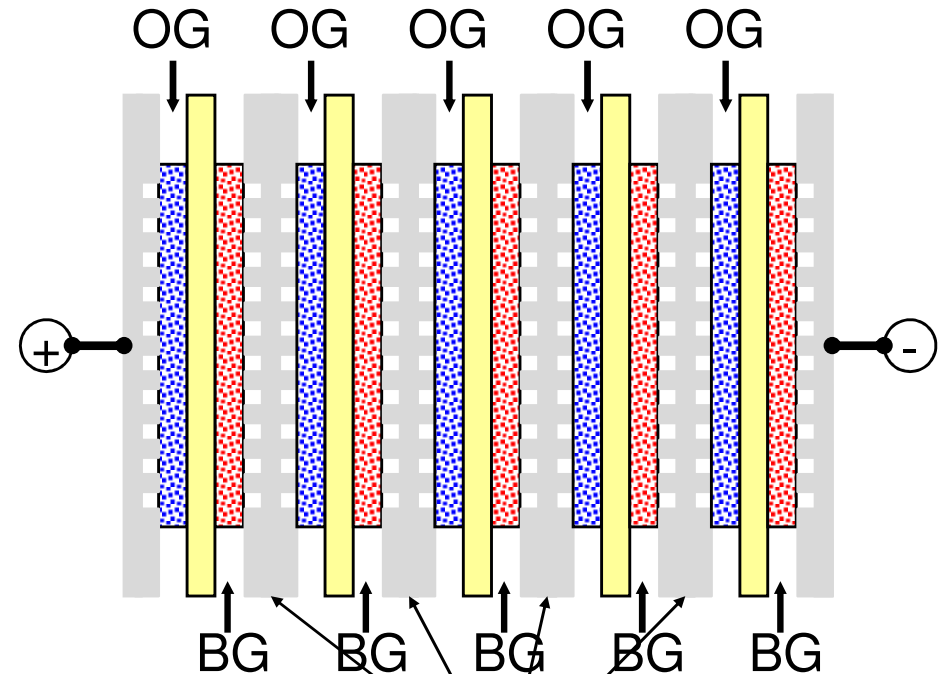
Baukonzepte für Brennstoffzellenstacks

monopolar



Stromfahnen

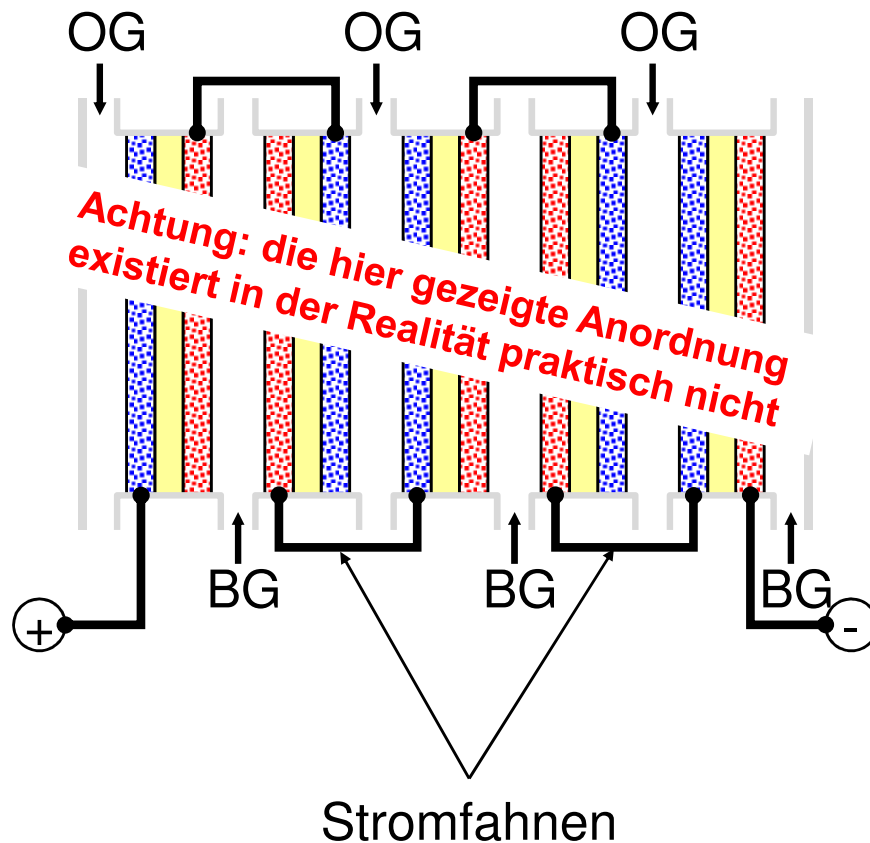
bipolar



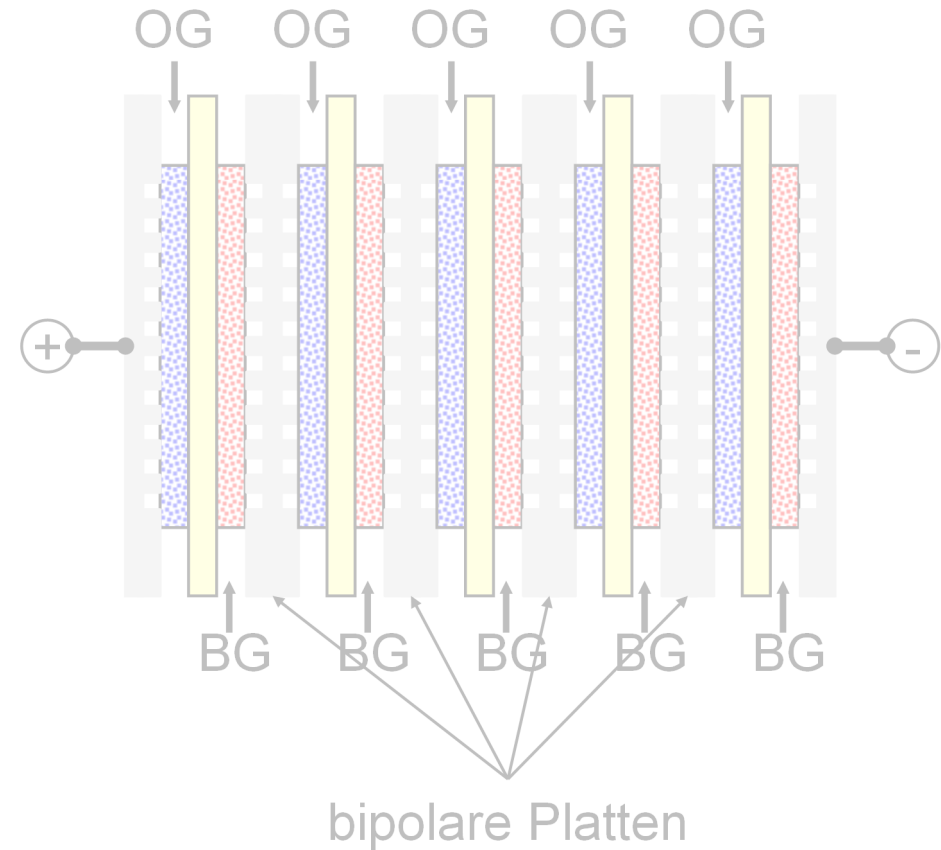
bipolare Platten

Baukonzepte für Brennstoffzellenstacks

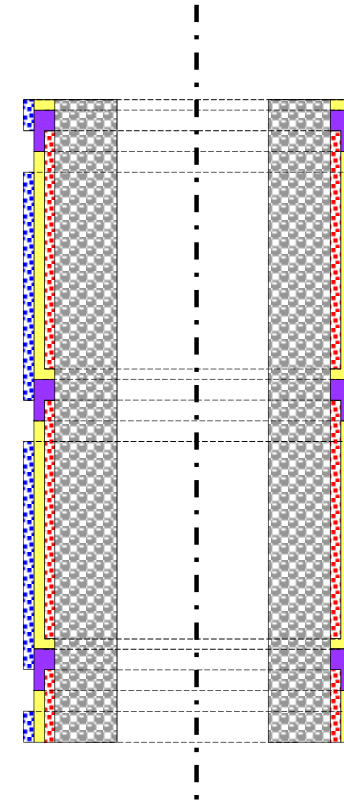
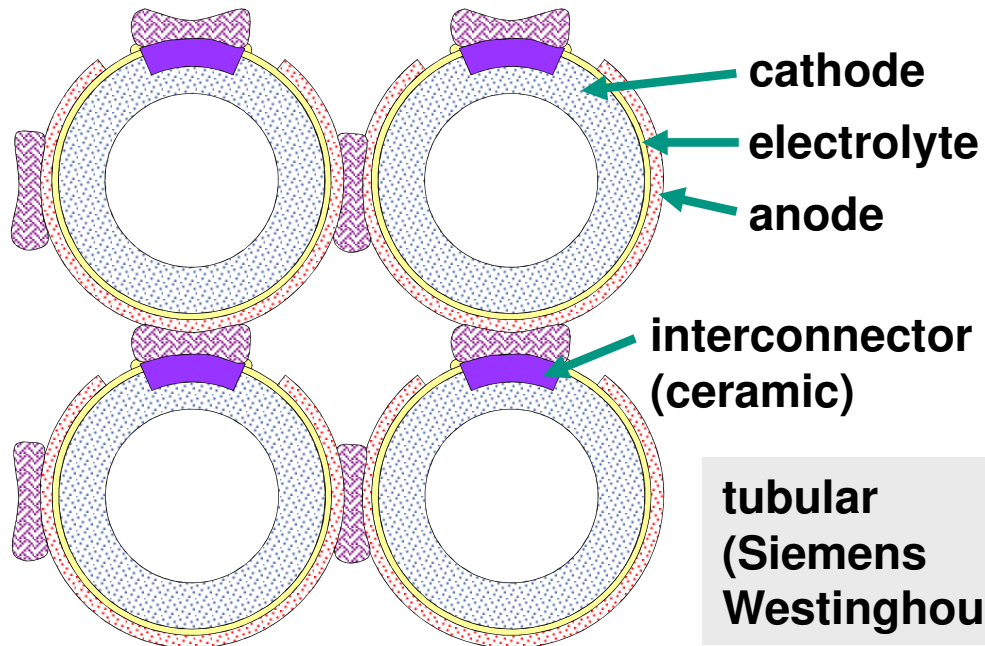
monopolar



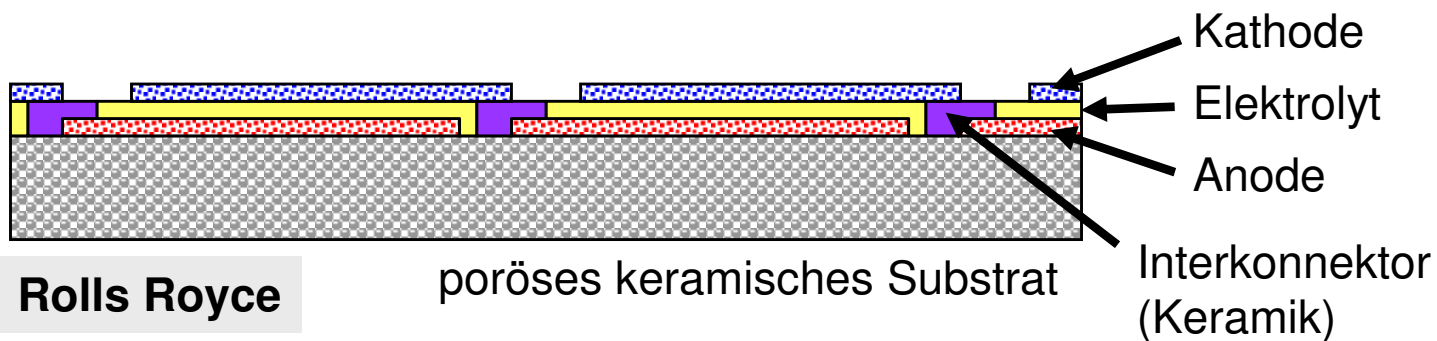
bipolar



SOFC Stack-Designs („monopolar“)



tubular
(Mitsubishi
Heavy
Industries)

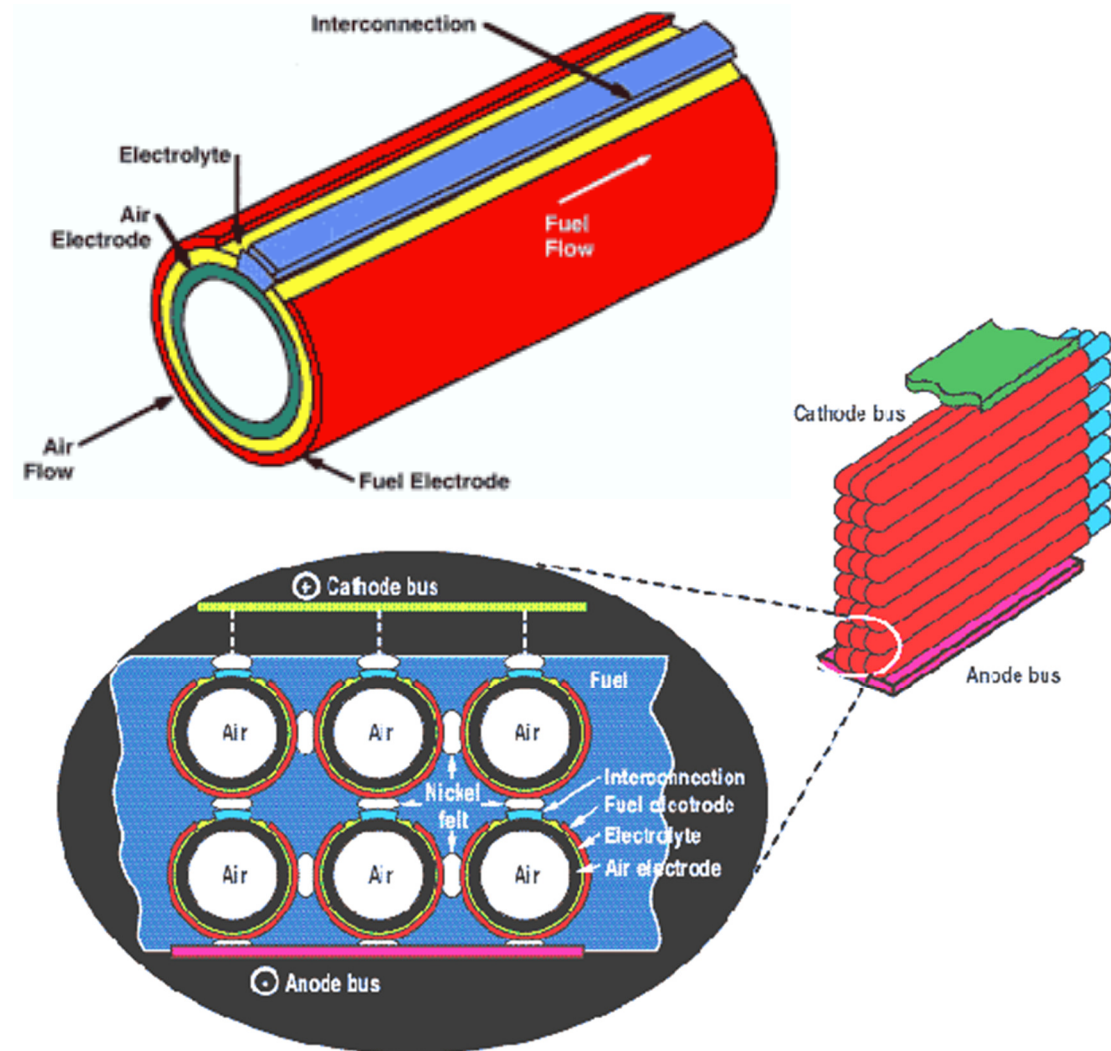
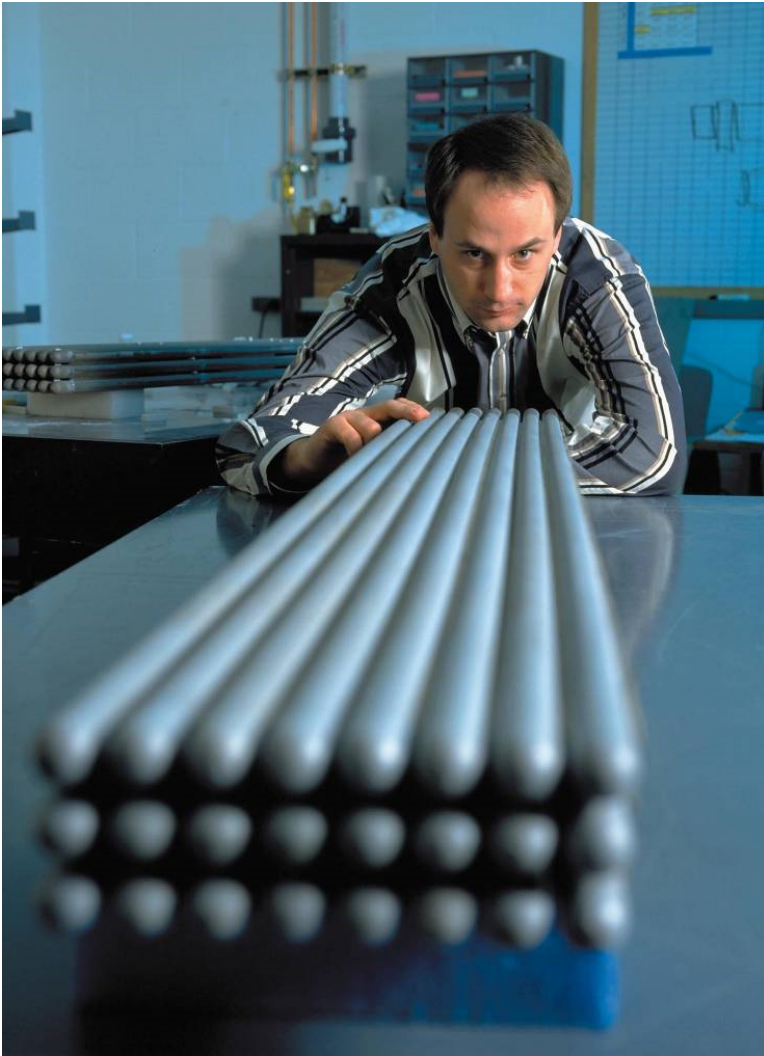


Siemens Westinghouse (SWPC)

electrical power SOFC	173 kW _{el}
electrical power microturbine	47 kW _{el}
fuel	natural gas
electrical net efficiency	55%
Installation 2000 at Southern California Edison;	
since 2001 at NFCR, U.C.Irvine	

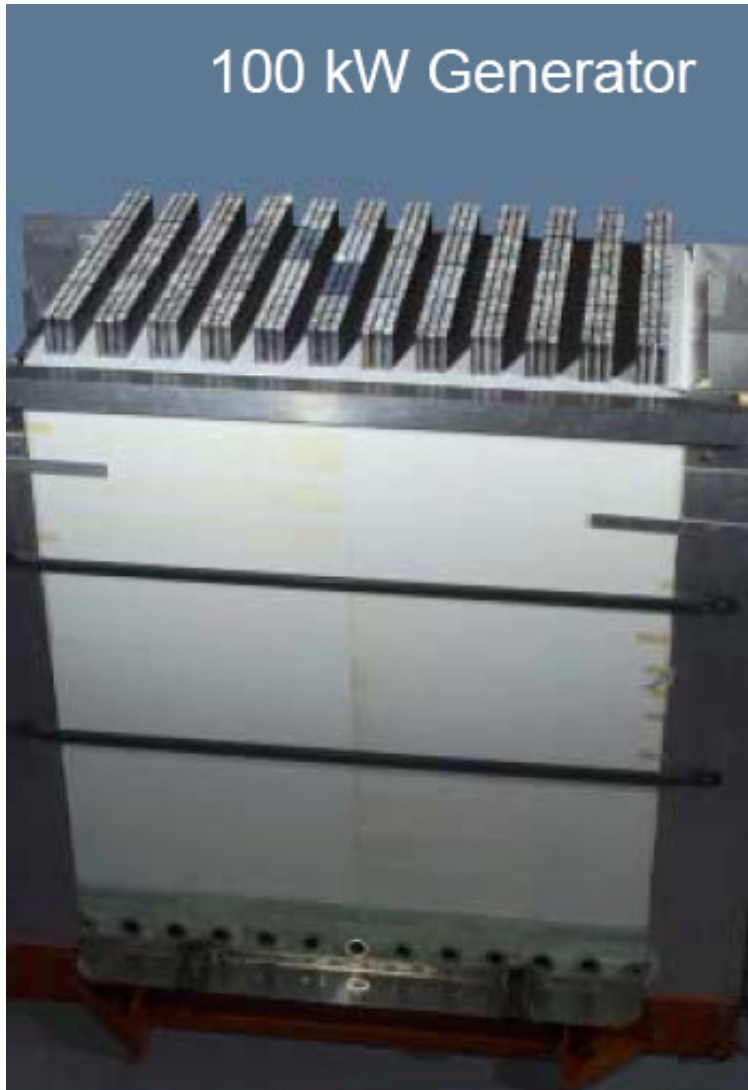


Siemens Westinghouse Tubular SOFC Tube Bundle



Solid Oxide Fuel Cell

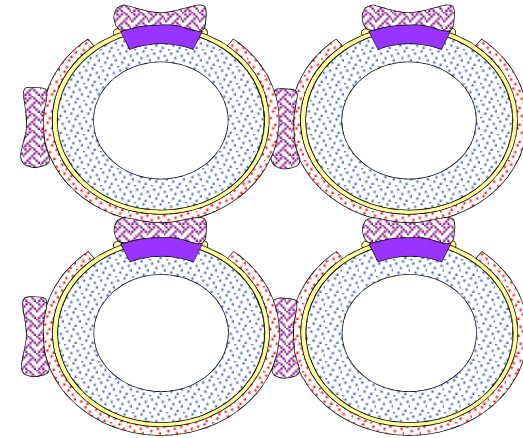
Tubular SOFC-Design (Siemens-Westinghouse)



SOFC: Decentralized Power Units (> 100 kW) Fabrication Technologies

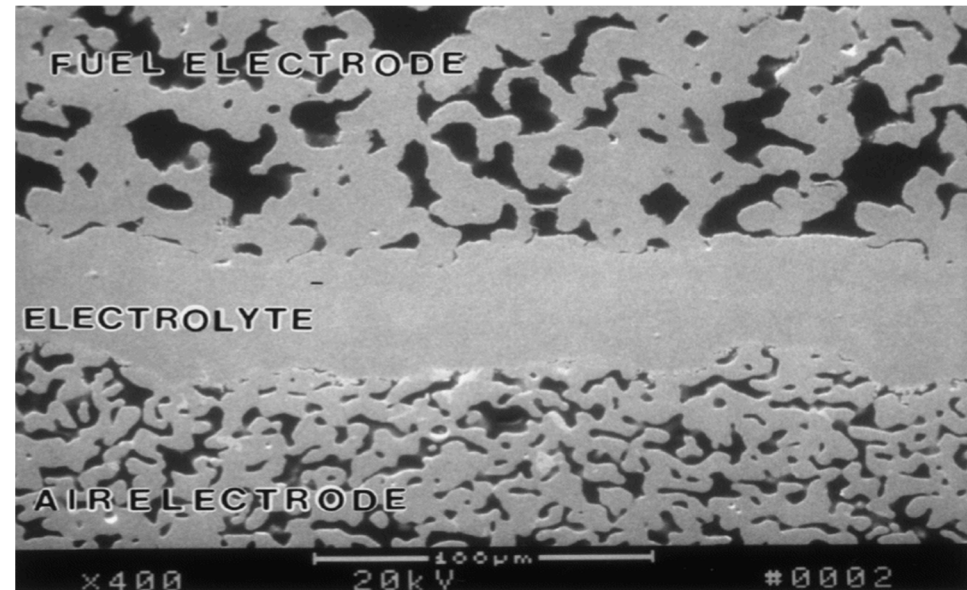
Fabrication Technologies:

- Extrusion moulding and sintering (cathode)
- CVD, EVD, APS (electrolyte)
- Slurry coating and sintering (interconnector)
- Slurry coating and sintering (anode)



Future Demands:

- increased power density
- reengineered fabrication process
- ...
- costs



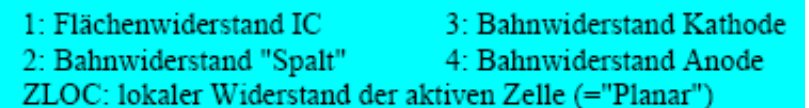
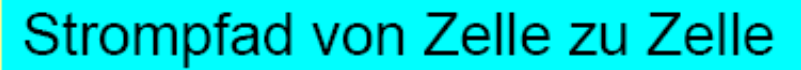
Solid Oxide Fuel Cell

Tubular SOFC-Design (Siemens-Westinghouse)



Ausbau der Röhren
aus dem Reaktor zur
Beschichtung der Kathode
mit Elektrolyt mittels EVD
(Electrochemical
Vapour Deposition)

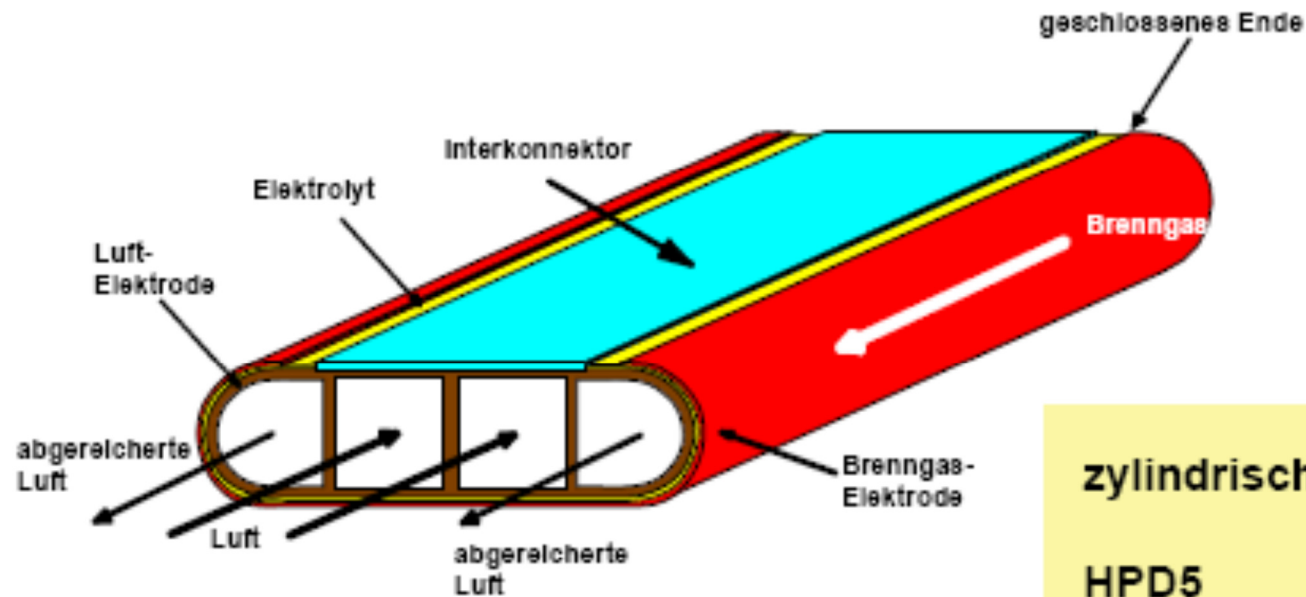
Quelle Siemens Westinghouse



Quelle Siemens Westinghouse

Solid Oxide Fuel Cell

Tubular SOFC-Design (Siemens-Westinghouse)

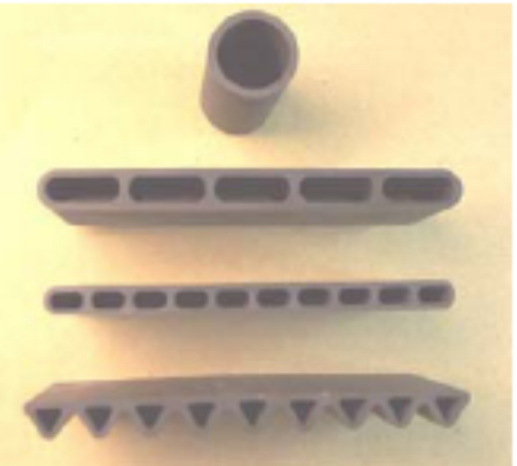


zylindrisch 150 cm

HPD5 75 cm

HPD10 75 cm

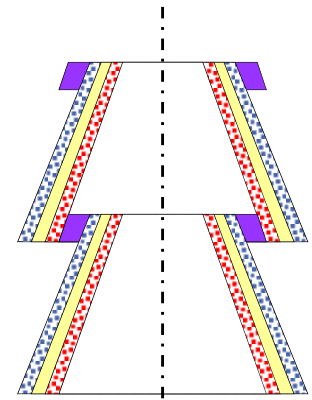
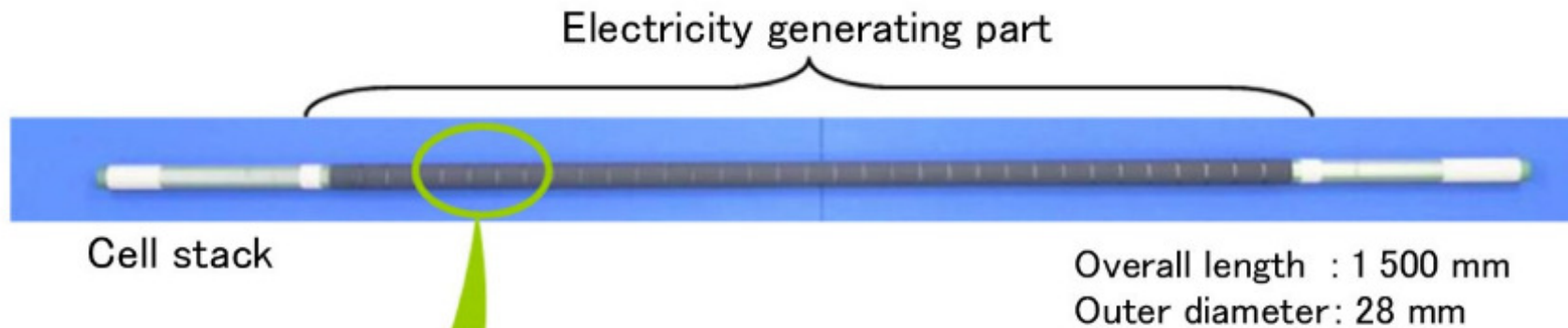
Delta9 75 cm



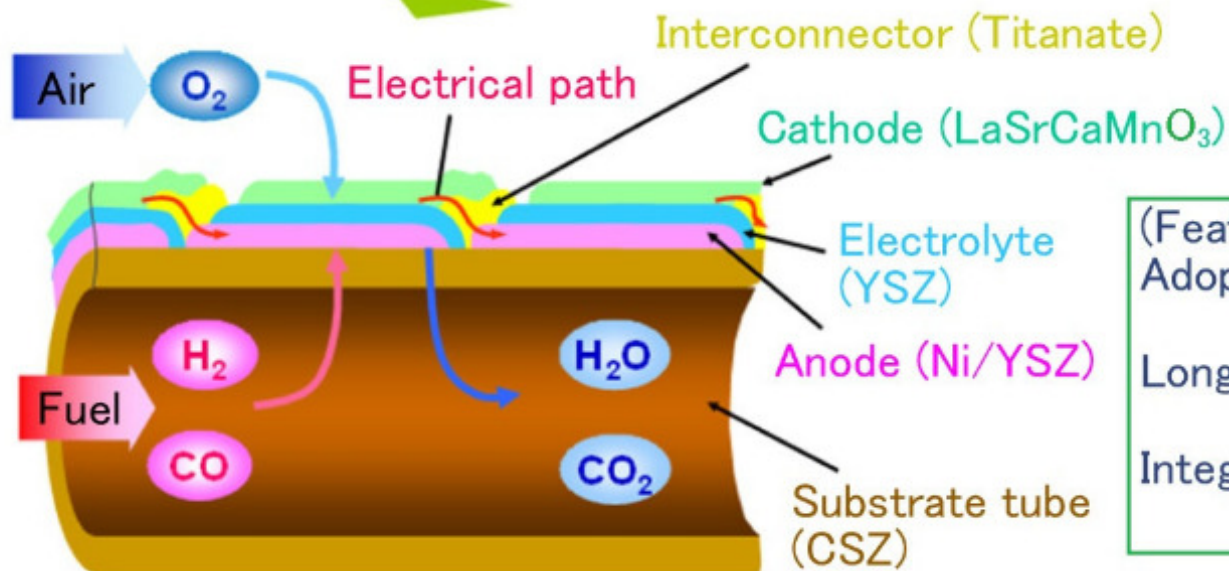
Quelle Siemens

Solid Oxide Fuel Cell

Tubular SOFC-Design (Mitsubishi Heavy Industries)



tubular
(Mitsubishi
Heavy
Industries)



(Features)

- Adoption of substrate tube
⇒ High robustness
- Long-length cell
⇒ High sealability
- Integral sintering
⇒ High durability



Brennstoffzellensysteme für die stationäre Energieversorgung

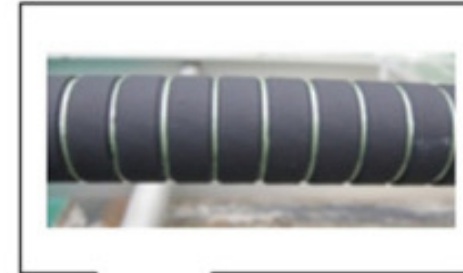
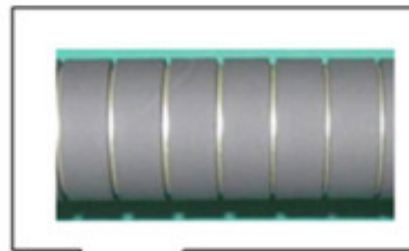
Mitsubishi Heavy Industries - Tubulare SOFC

+ 50% power output

(Model 10)



(Model 15)



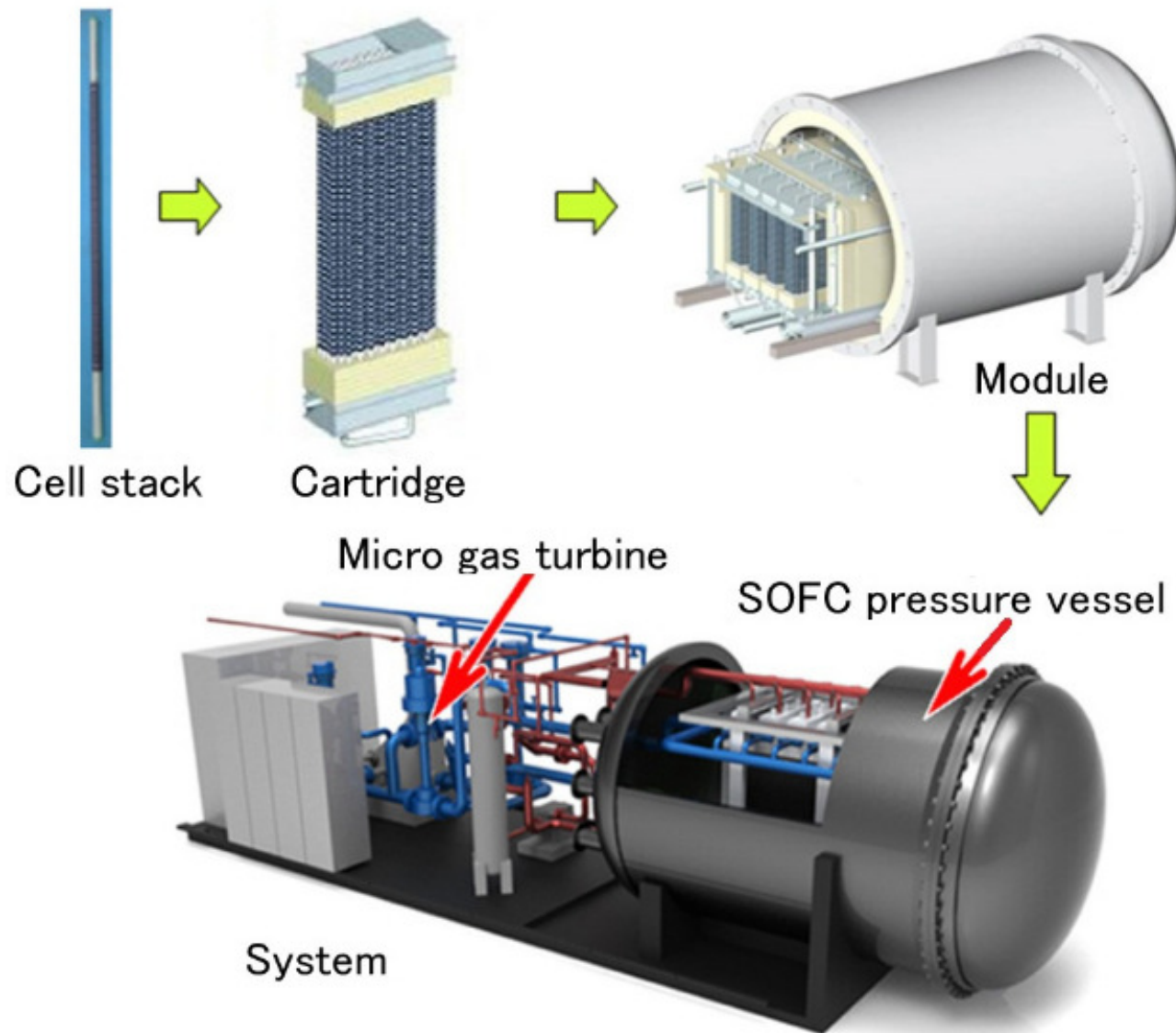
<Model 10>

<Model 15>



Brennstoffzellensysteme für die stationäre Energieversorgung

Mitsubishi Heavy Industries - Tubulare SOFC

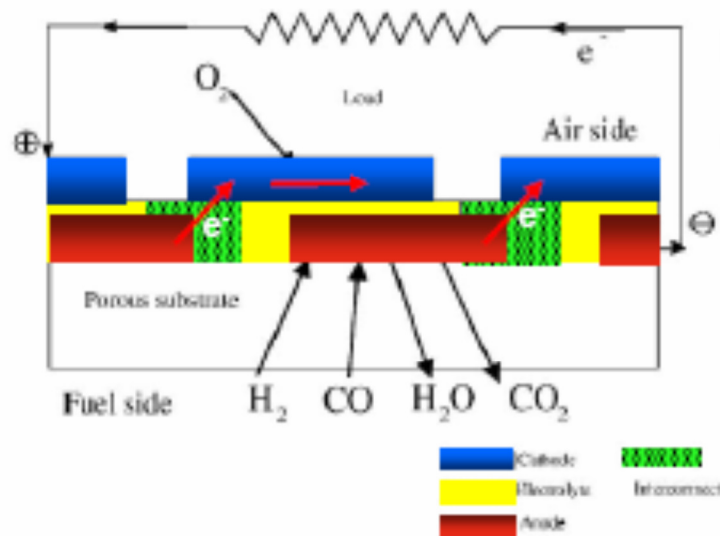


Solid Oxide Fuel Cell

Planar SOFC-Design (Rolls Royce)



Keramik

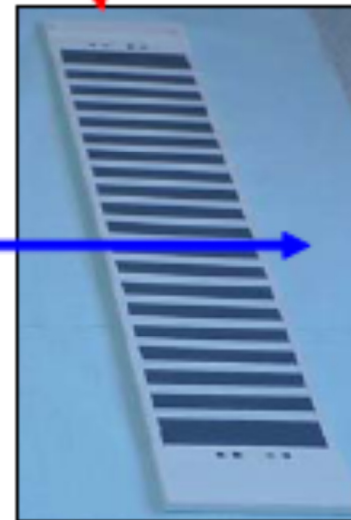


Erdgas

“planares Design von MHI”

1 kW bei 950°C mit H₂/Luft

Luft



50 W Modul



500 W “Bündel”

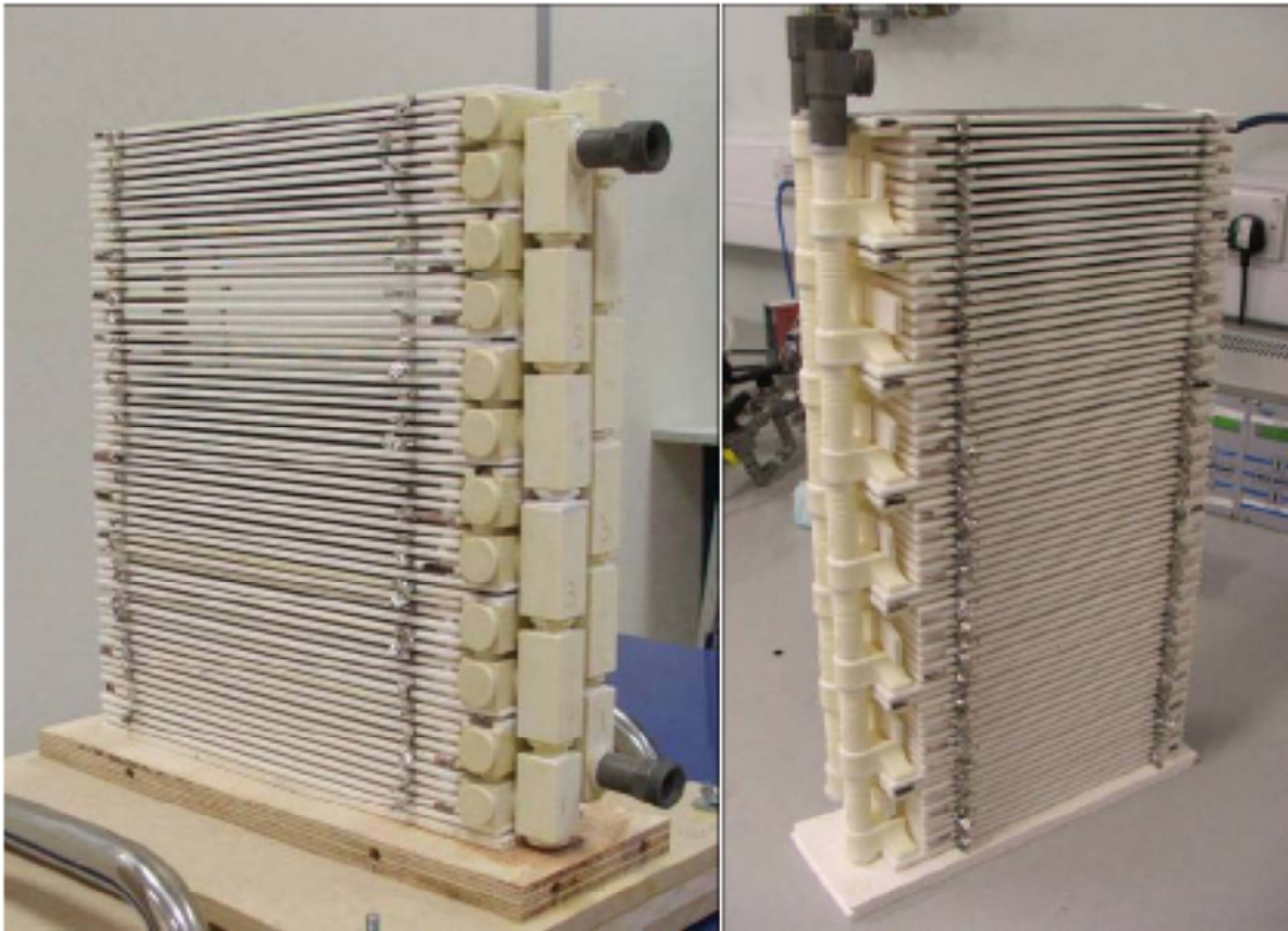
Elektrizität

Dampf

Quelle Rolls Royce

Solid Oxide Fuel Cell

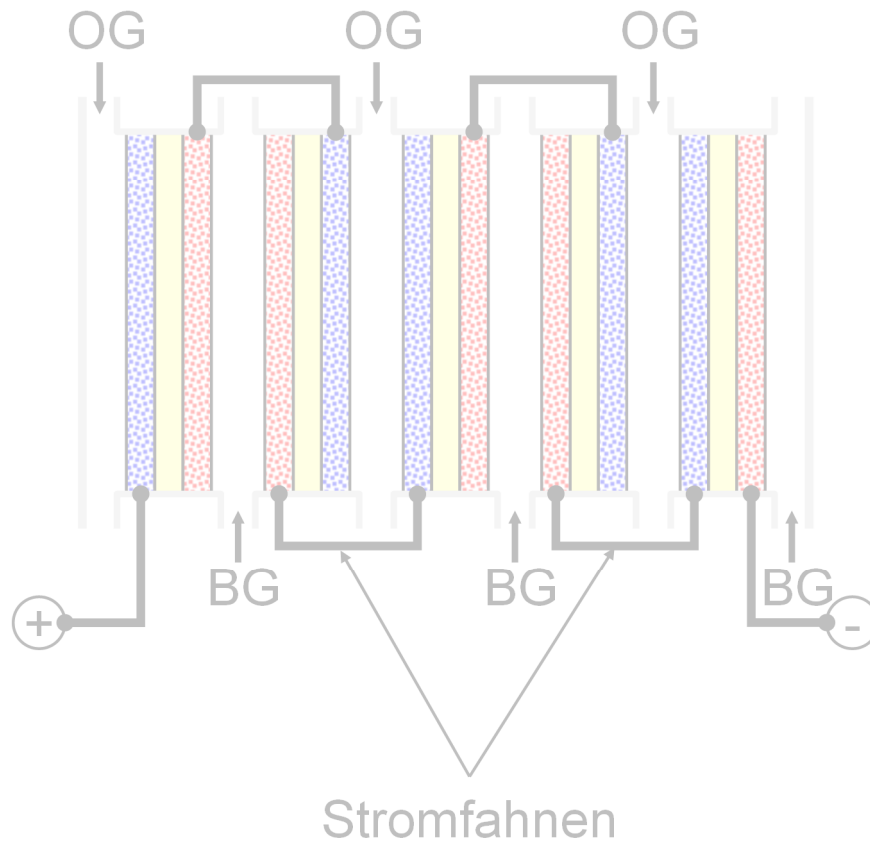
Planar SOFC-Design (Rolls Royce)



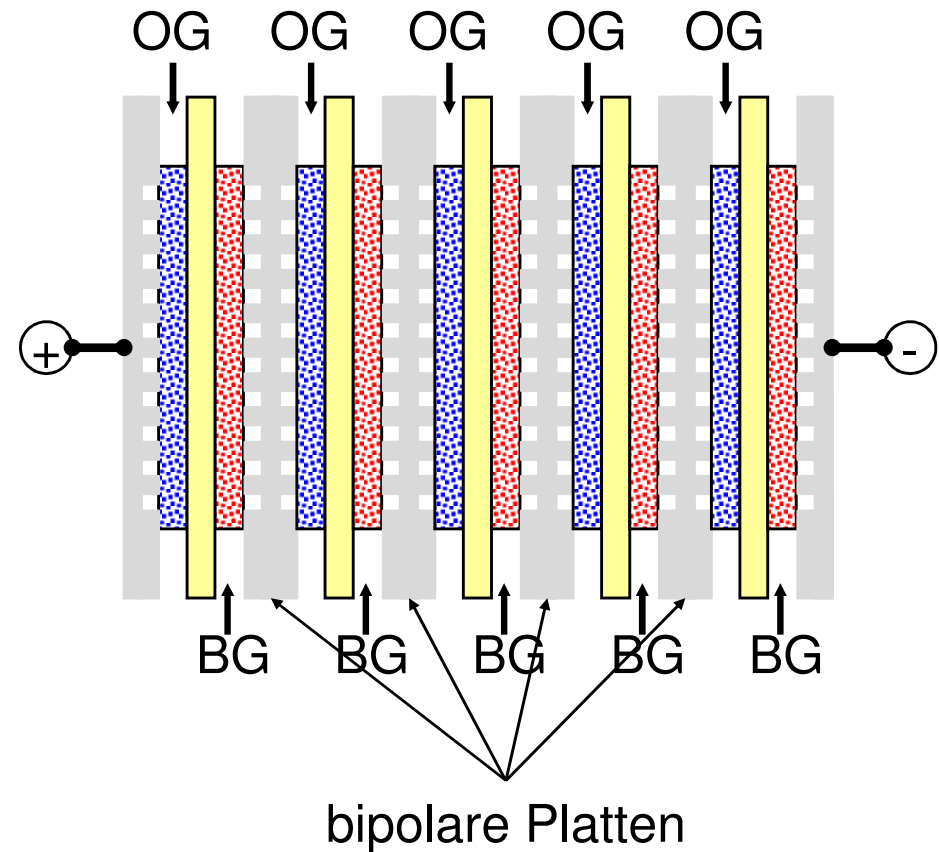
Ein "strip" von RRFCS "fuel cell bundles" von 2004 and 2005 Designs
(optimierte Fertigungstechnik und reduzierte Anzahl an Anschlusssteilen)
(Luzern 2006)

Baukonzepte für Brennstoffzellenstacks

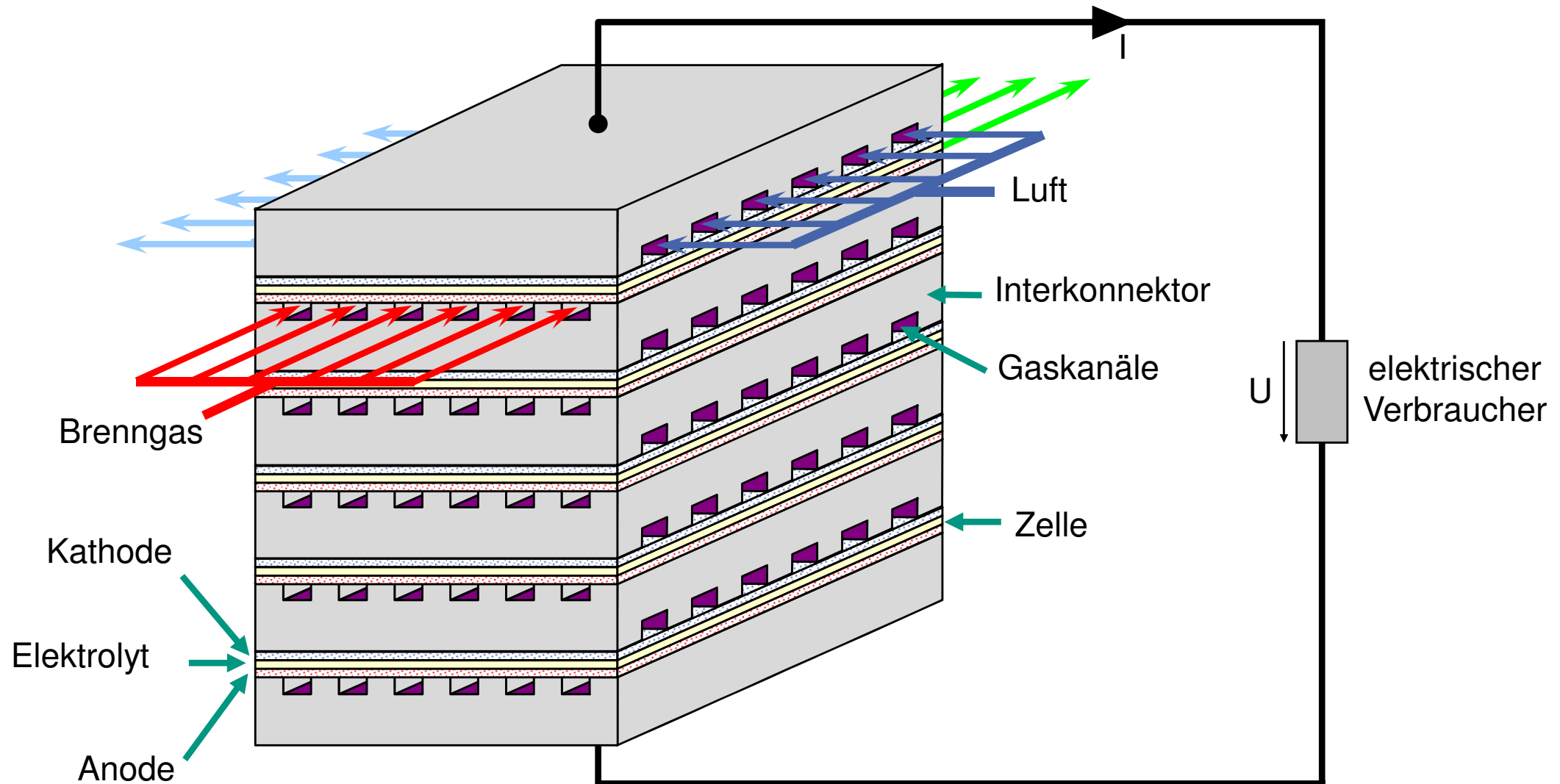
monopolar

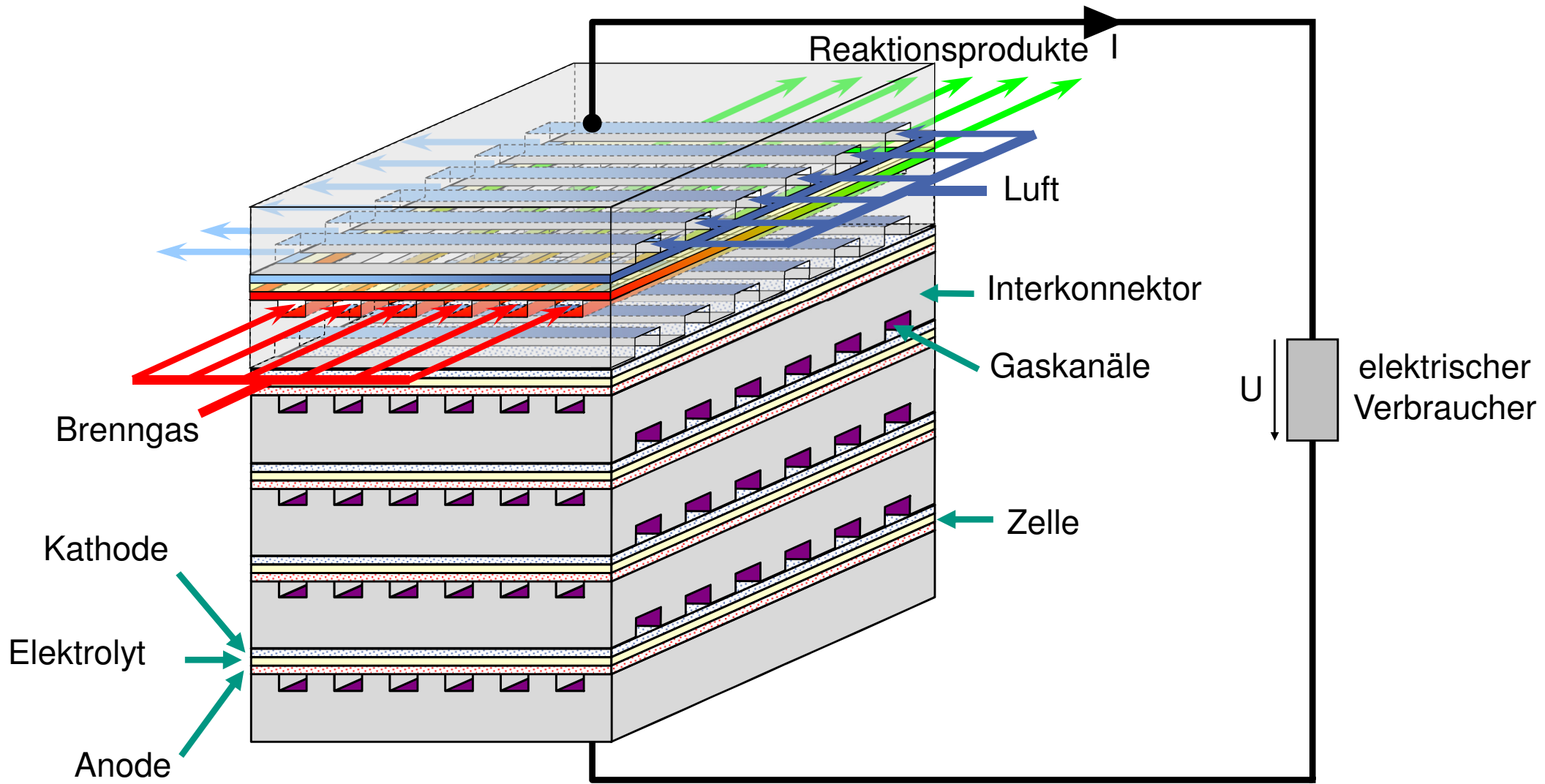


bipolar

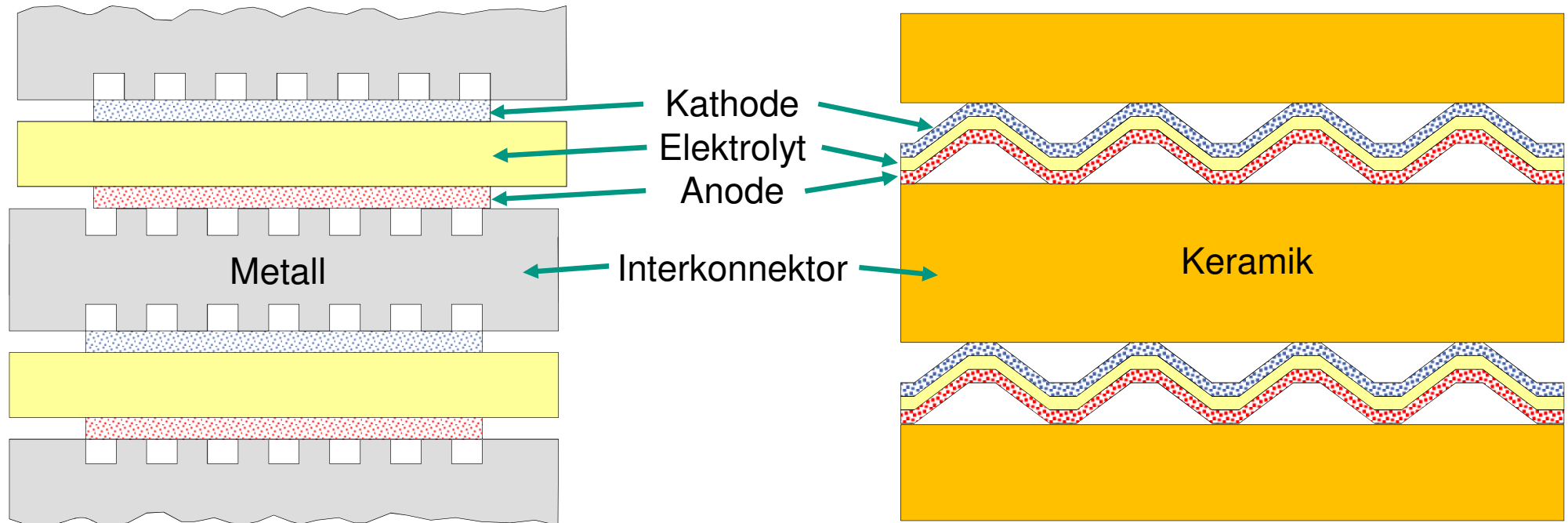


Planarer Brennstoffzellen-Stack

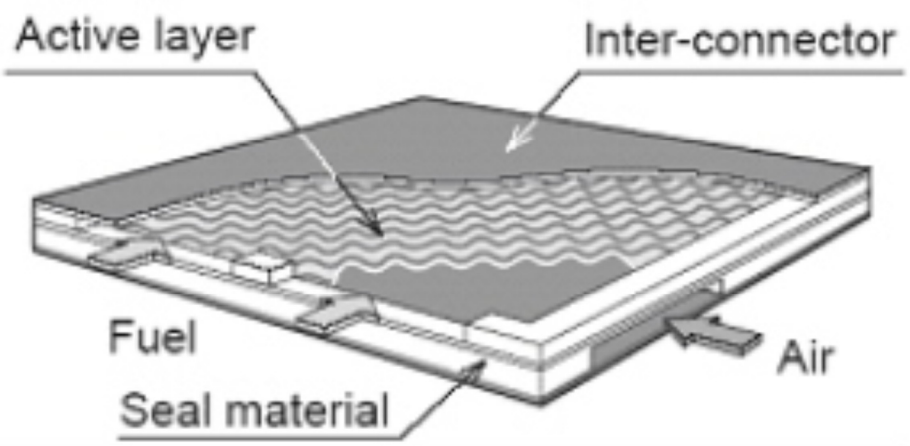
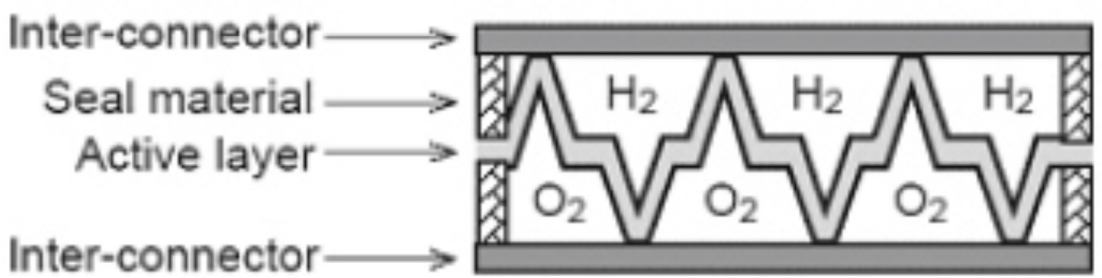
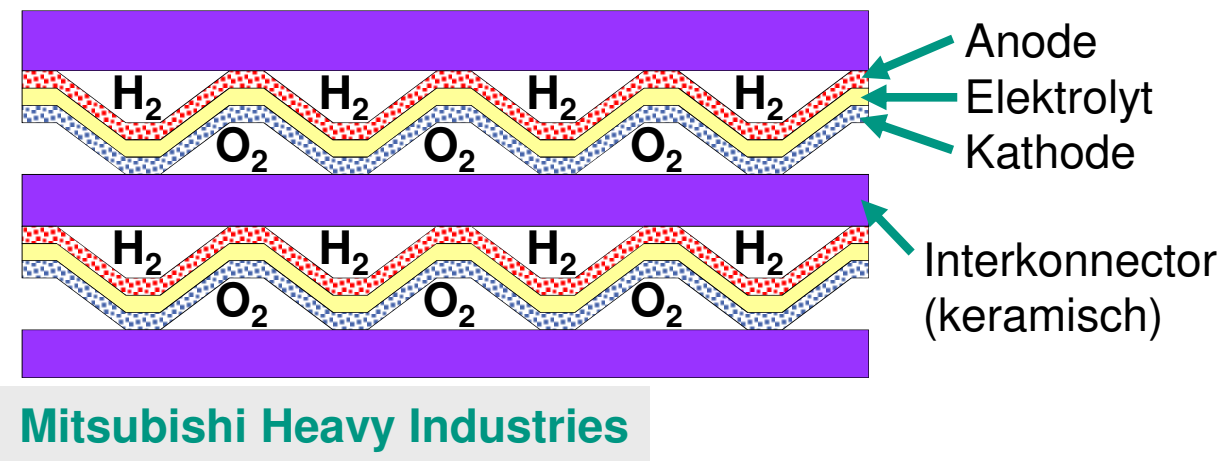
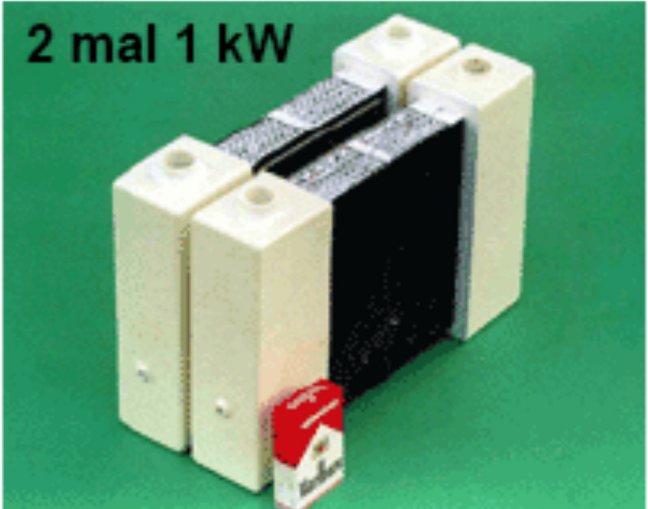




SOFC Stack-Designs (bipolar, planar)

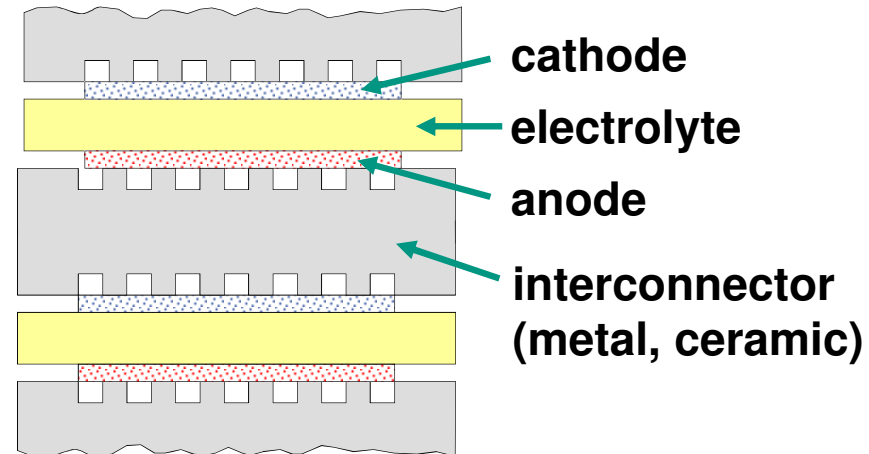
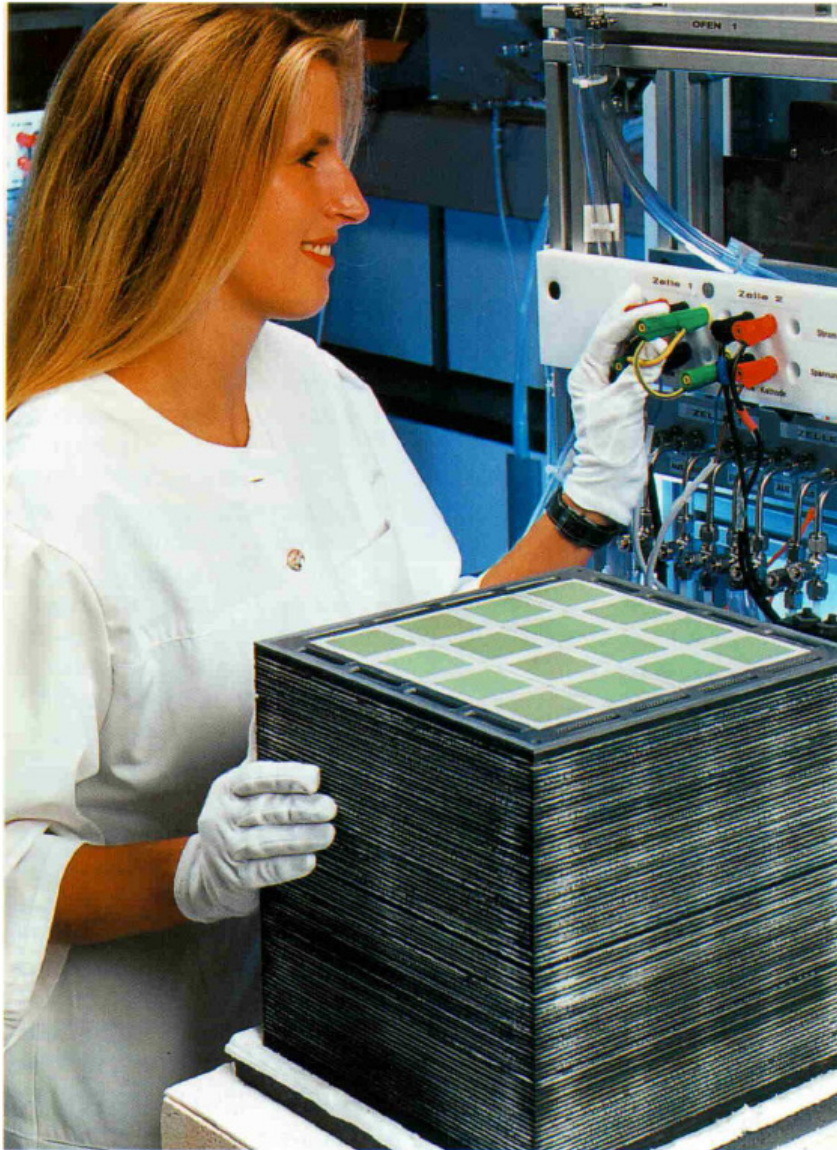


Planar SOFC-Design (Mitsubishi Heavy Industries)



Solid Oxide Fuel Cell

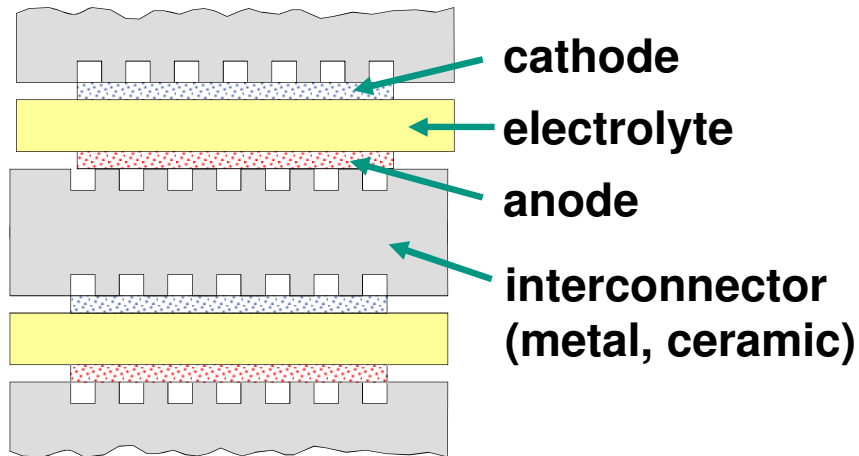
Siemens Planar 10 kW SOFC Stack (1995)



Cathode	LSM
Electrolyte	8YSZ
Anode	Ni/8YSZ-Cermet
Interconnector	CrFe5Y ₂ O ₃ 1
layers	80
cells/layer	16, each 50 x 50 mm ²
electrode area	2 m ²
volume	0.02 m ³
el. power	10.7 kW @950 °C 8.4 kW @850 °C
current density	0.6 A/cm ²
fuel utilization	40 ... 50 % (H ₂)

Solid Oxide Fuel Cell

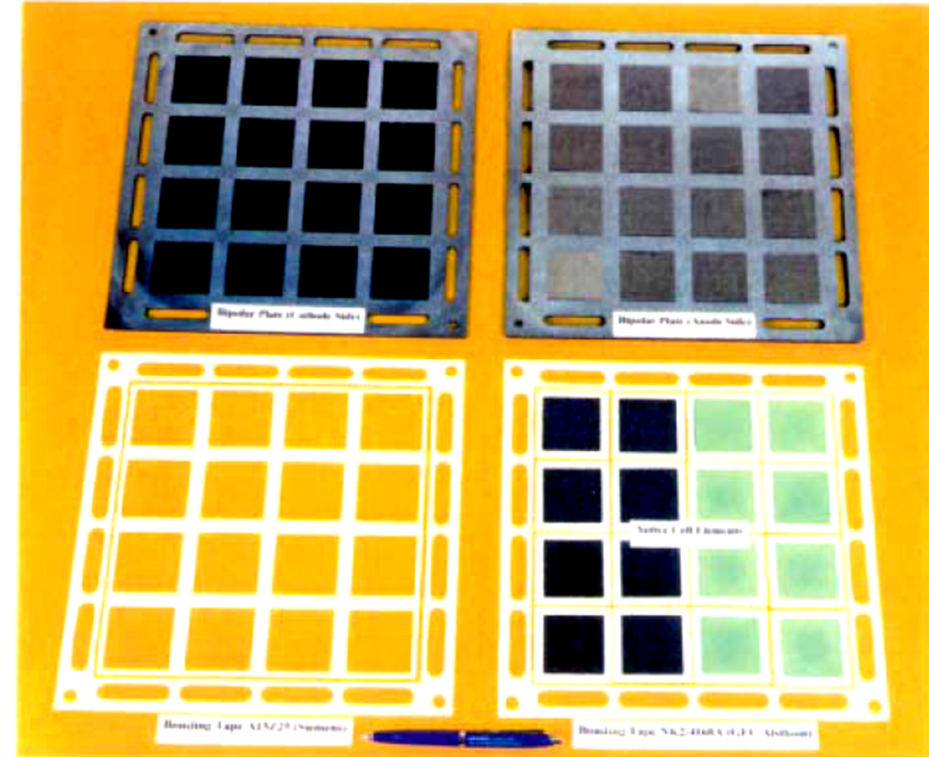
Planar SOFC-Design



planar

- (Siemens, Dornier)
- Sulzer
- FZ Jülich
- BMW
- Mitsubishi Materials
- PNNL
- Global Thermoelectrics
- ...

Stack Components (Siemens 1990-98)



„unsolved“ problems
corrosion of MIC (esp. at high temp. $> 850^{\circ}\text{C}$)
processing and costs of CIC
gastight sealing

...

Solid Oxide Fuel Cell

Planar SOFC-Design: Ceramic and metallic materials

Materials

$(\text{La}, \text{Sr})\text{MnO}_3$

Y_2O_3 -doped ZrO_2 (YSZ)

Nickel / YSZ

$\text{Cr 5Fe 1 Y}_2\text{O}_3$

$(\text{La}, \text{Sr})\text{CrO}_3$

$(\text{La}, \text{Sr})\text{CoO}_3$

Nickel-grid

glas sealing

Components

cathode

electrolyte

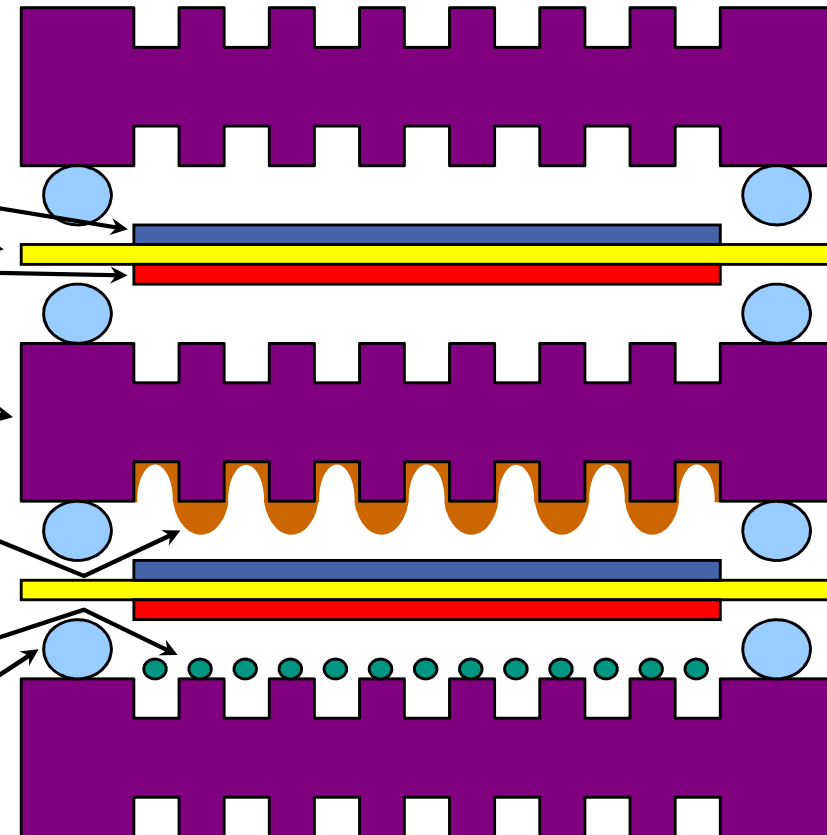
anode

bipolar plate

protective coating +
functional layer (c)

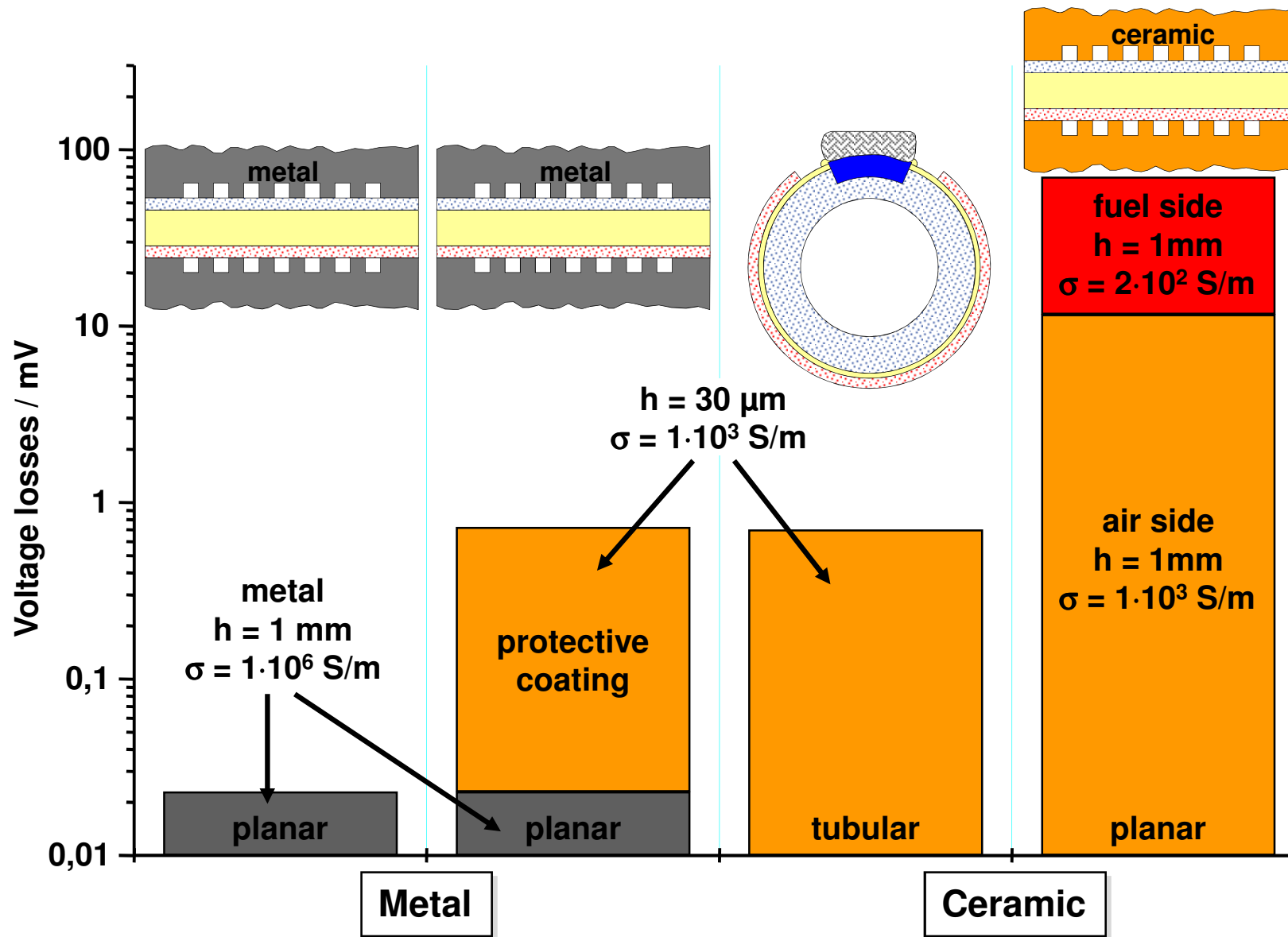
functional layer (a)

joining material

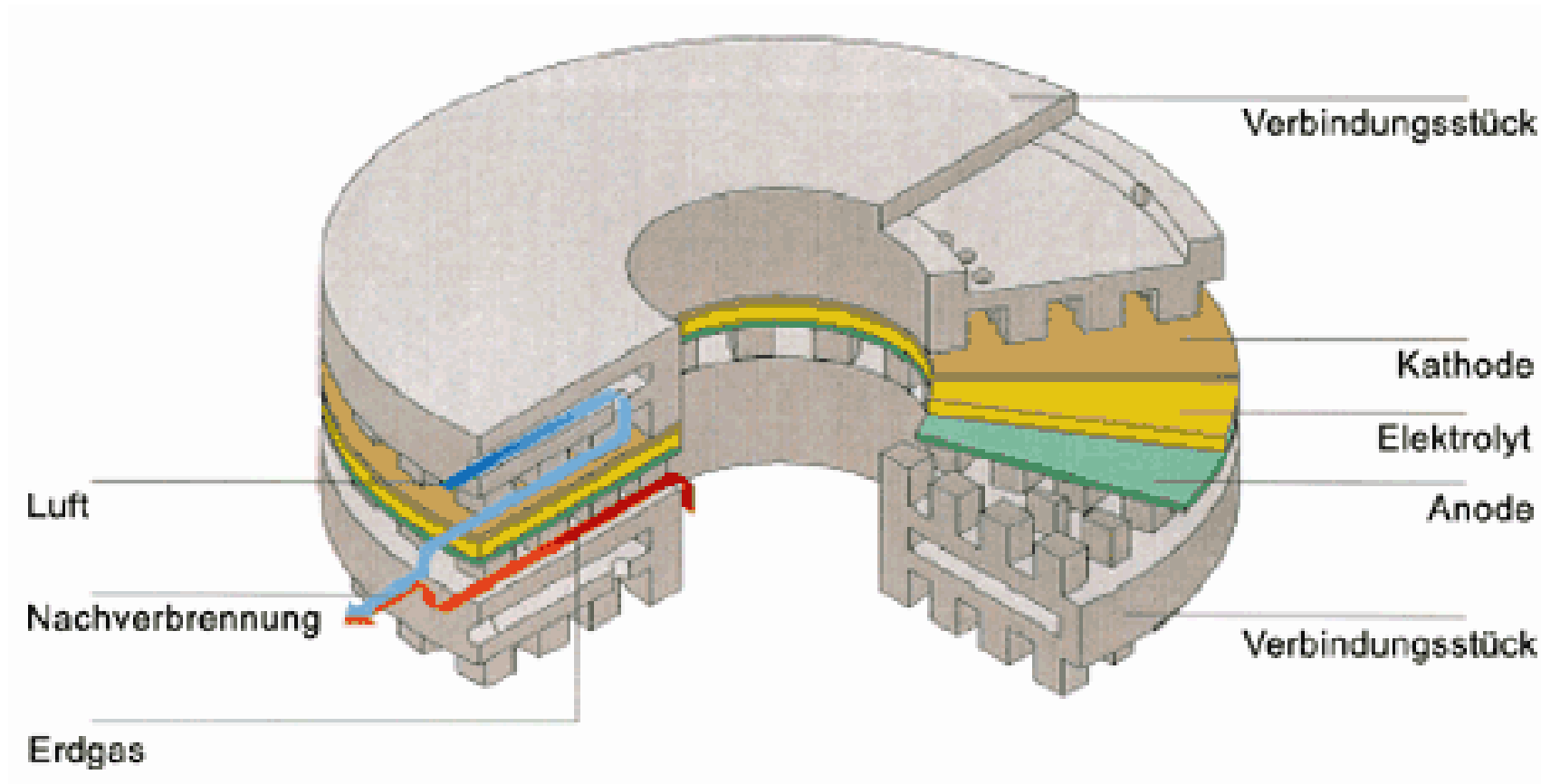


Planar and Tubular SOFC Concepts

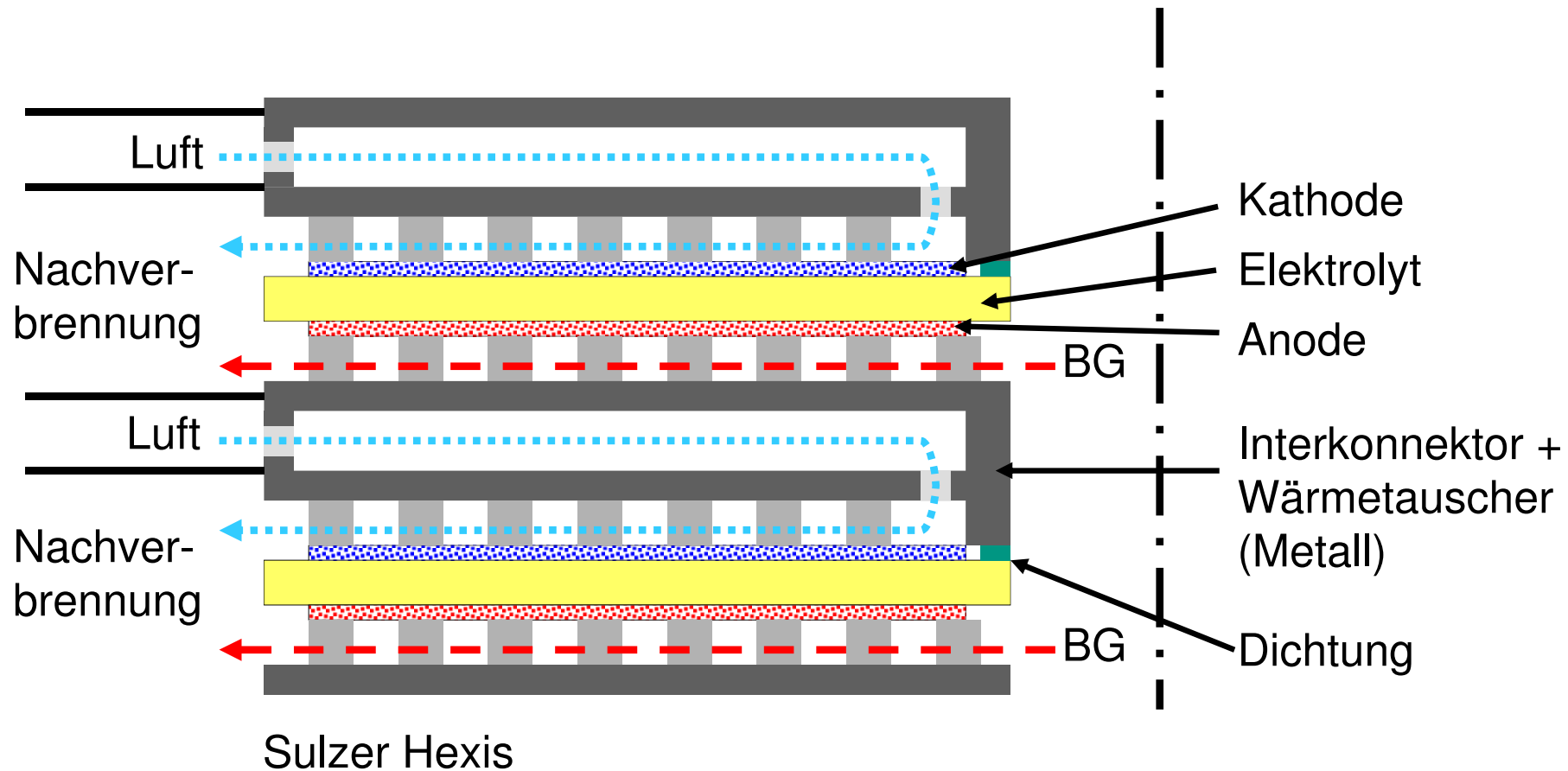
Ohmic Losses in Metallic and Ceramic Interconnector



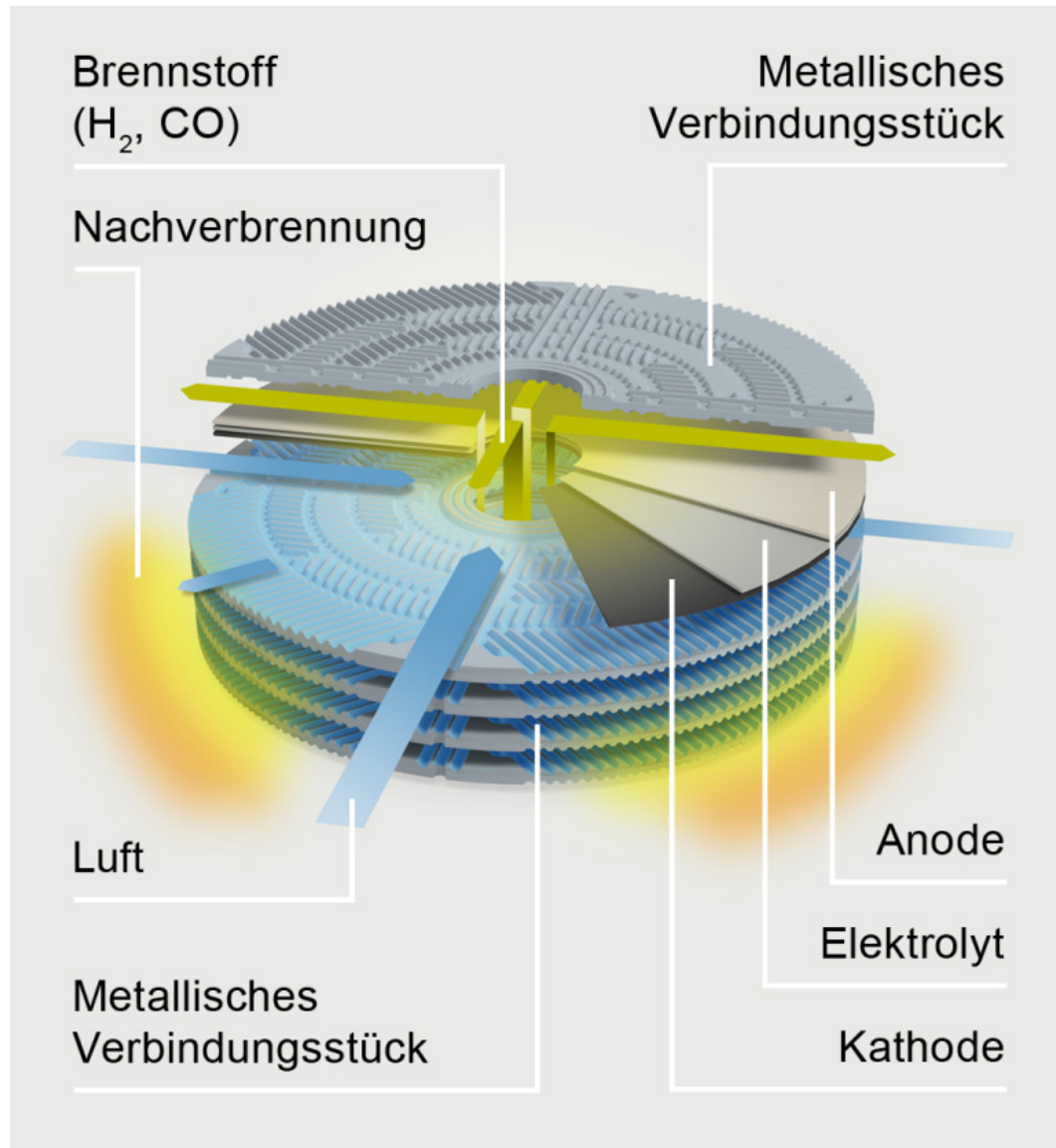
Sulzer HEXIS Stackkonzept (ursprüngliches Design)



Sulzer HEXIS Stackkonzept (ursprüngliches Design)



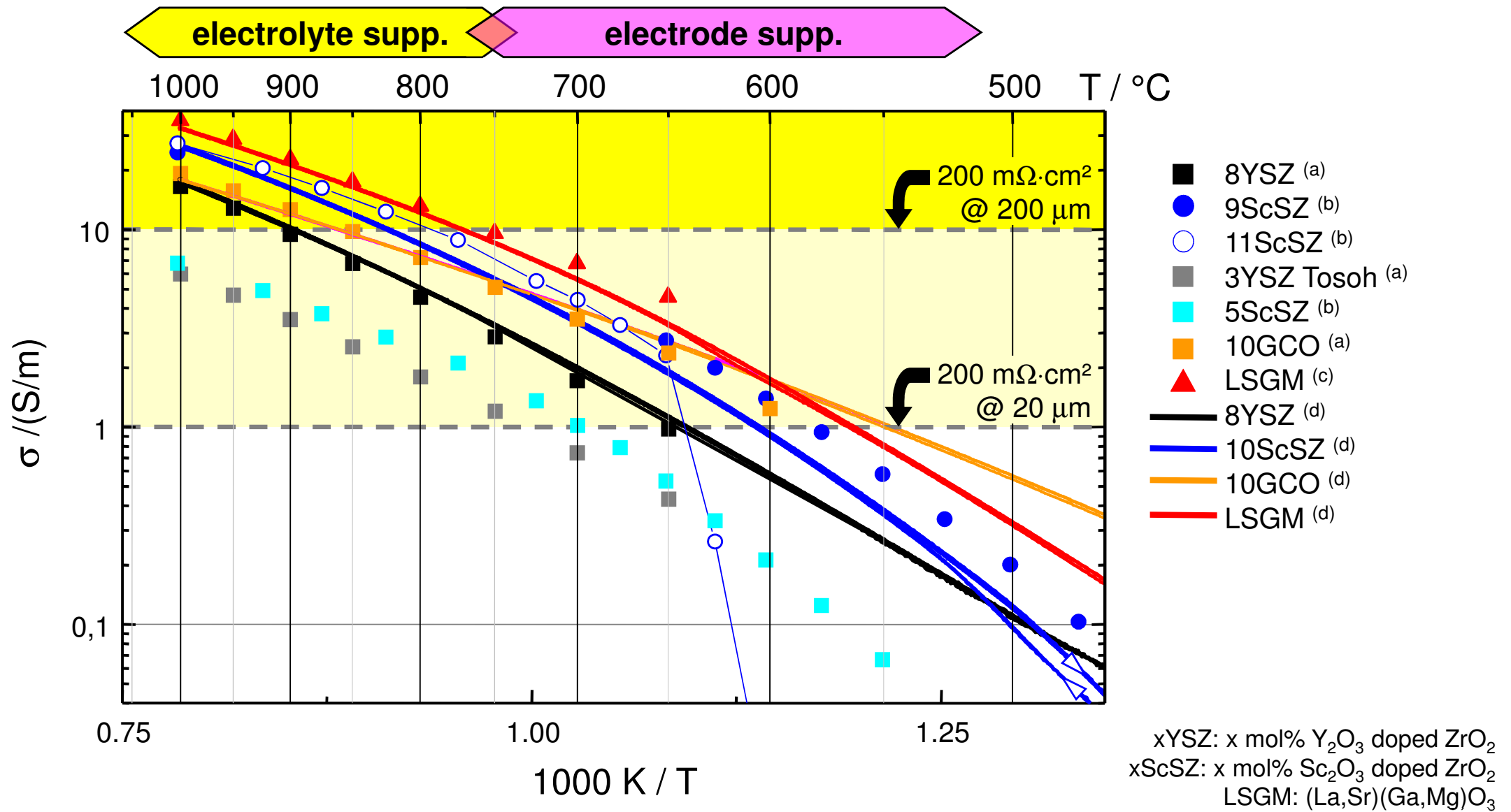
Sulzer HEXIS Stackkonzept (vereinfachtes Design)



- einlagiger Interkonnektor
ohne separaten Wärmetauscher
- + geringere Bauhöhe → höhere Leistungsdichte
- + einfacherer Aufbau des Interkonnektors
(pulvermetallurgisch hergestelltes Formteil)
- + geringere Chromstahl-Oberfläche → weniger Chromaustrag und Chromvergiftung

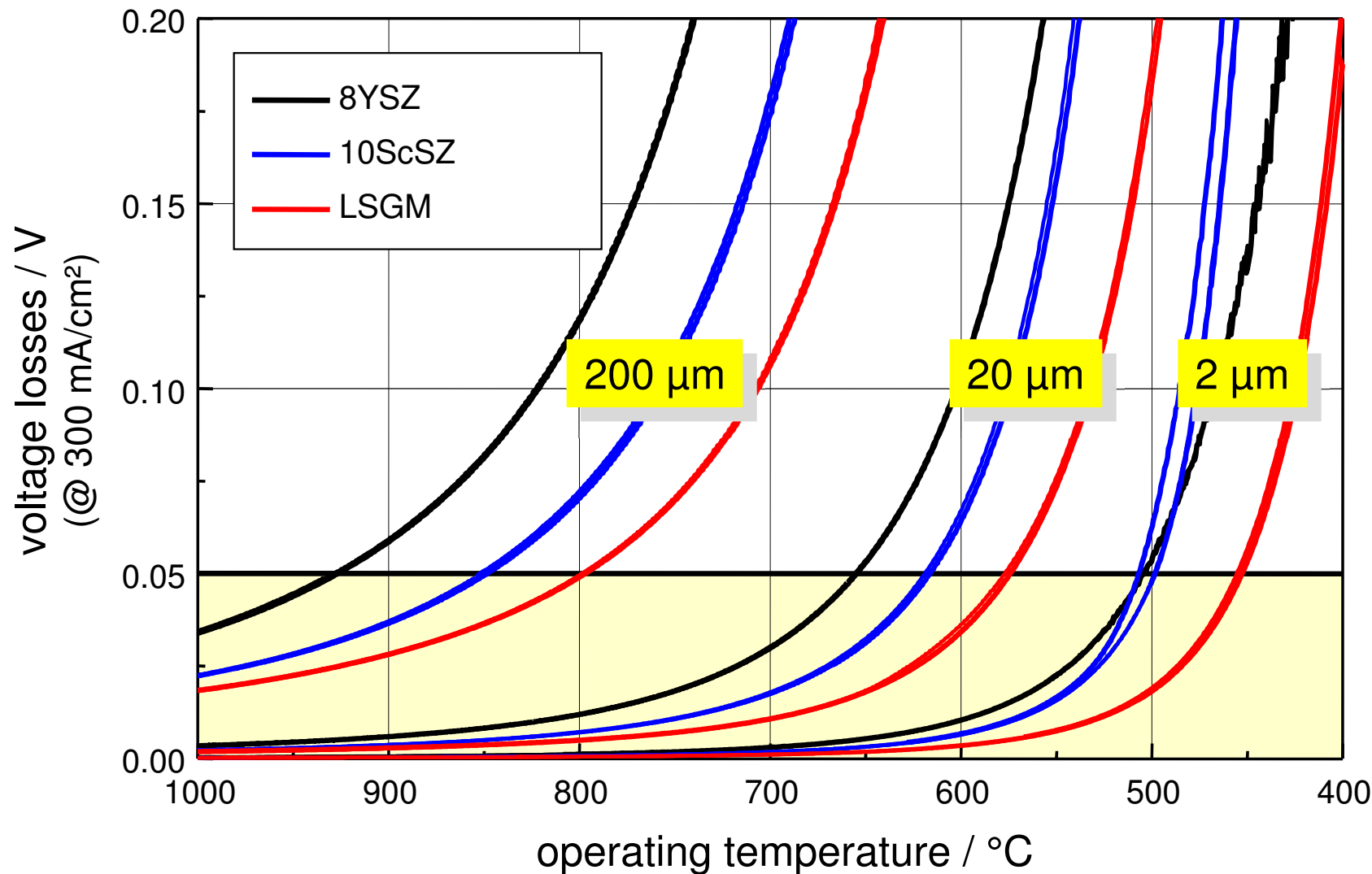
Oxide Ion Conductivity of Electrolyte Materials

Temperature / Thickness Limitations

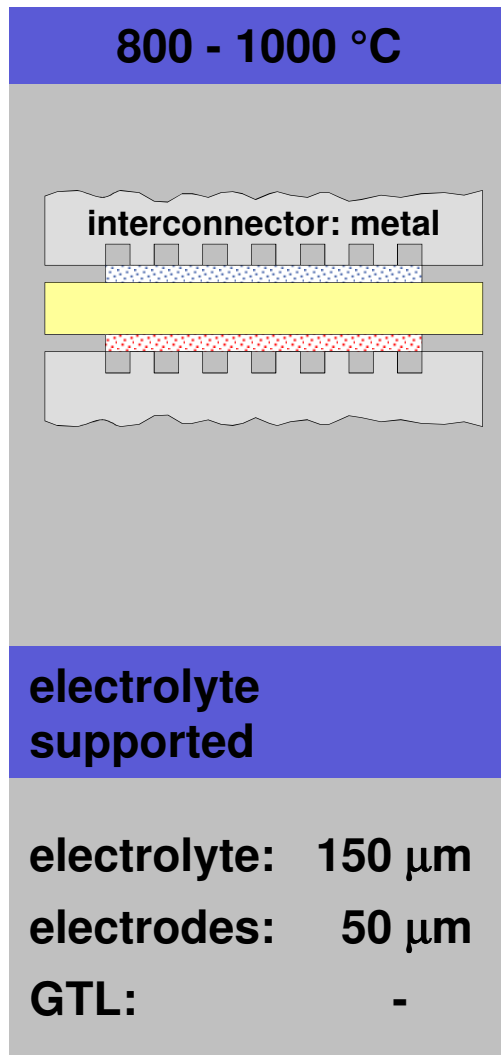


Oxide Ion Conductivity of Electrolyte Materials

Losses as a Function of Temperature and Electrolyte Thickness

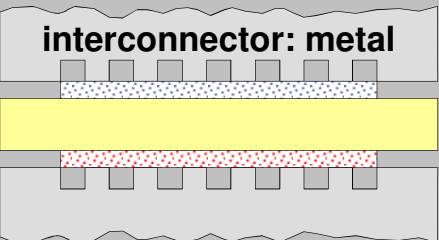
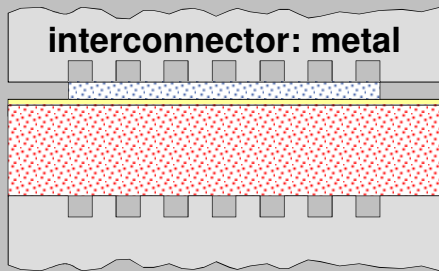


Solid Oxide Fuel Cell Planar Cells

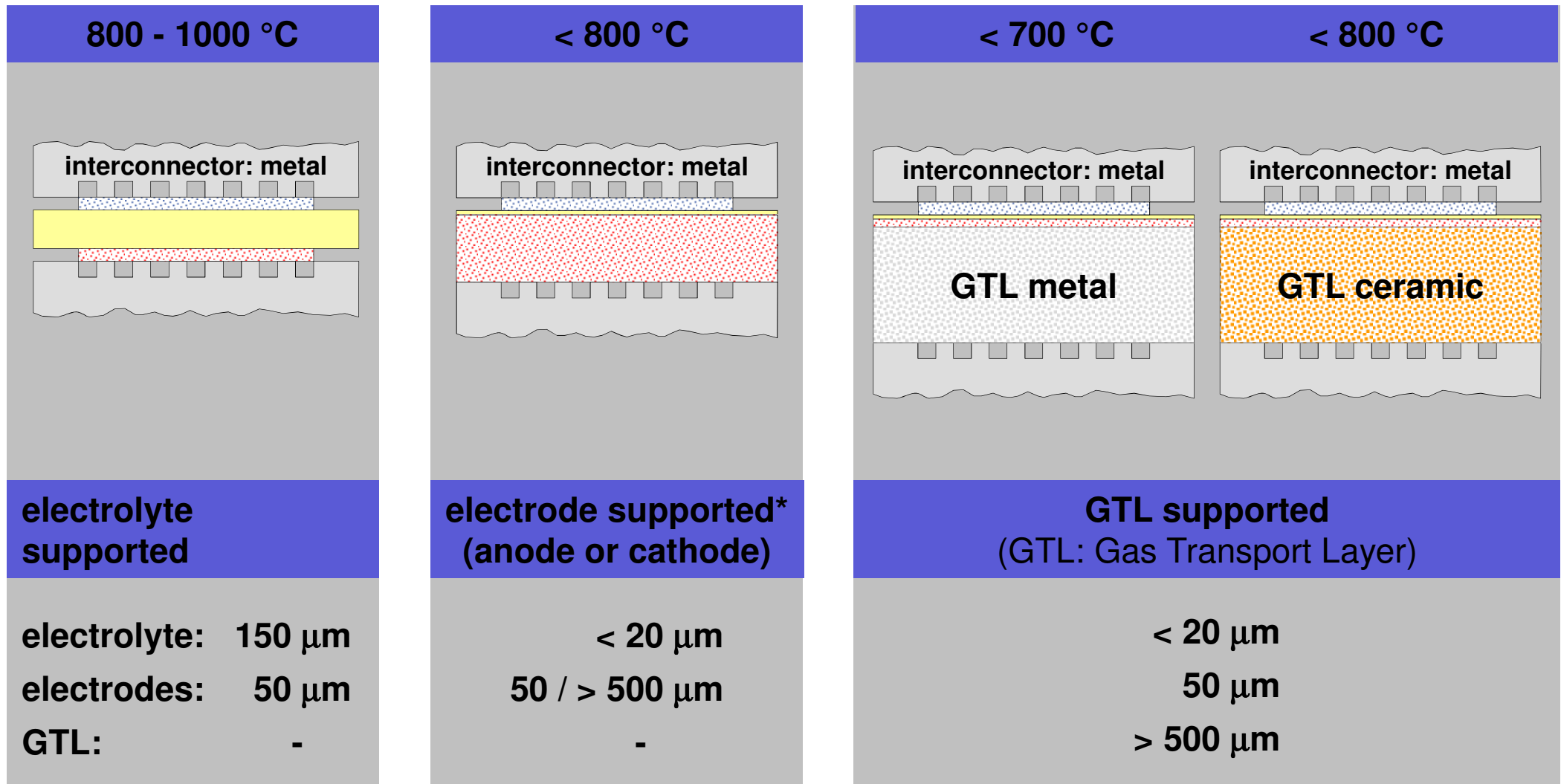


Solid Oxide Fuel Cell

Planar Cells

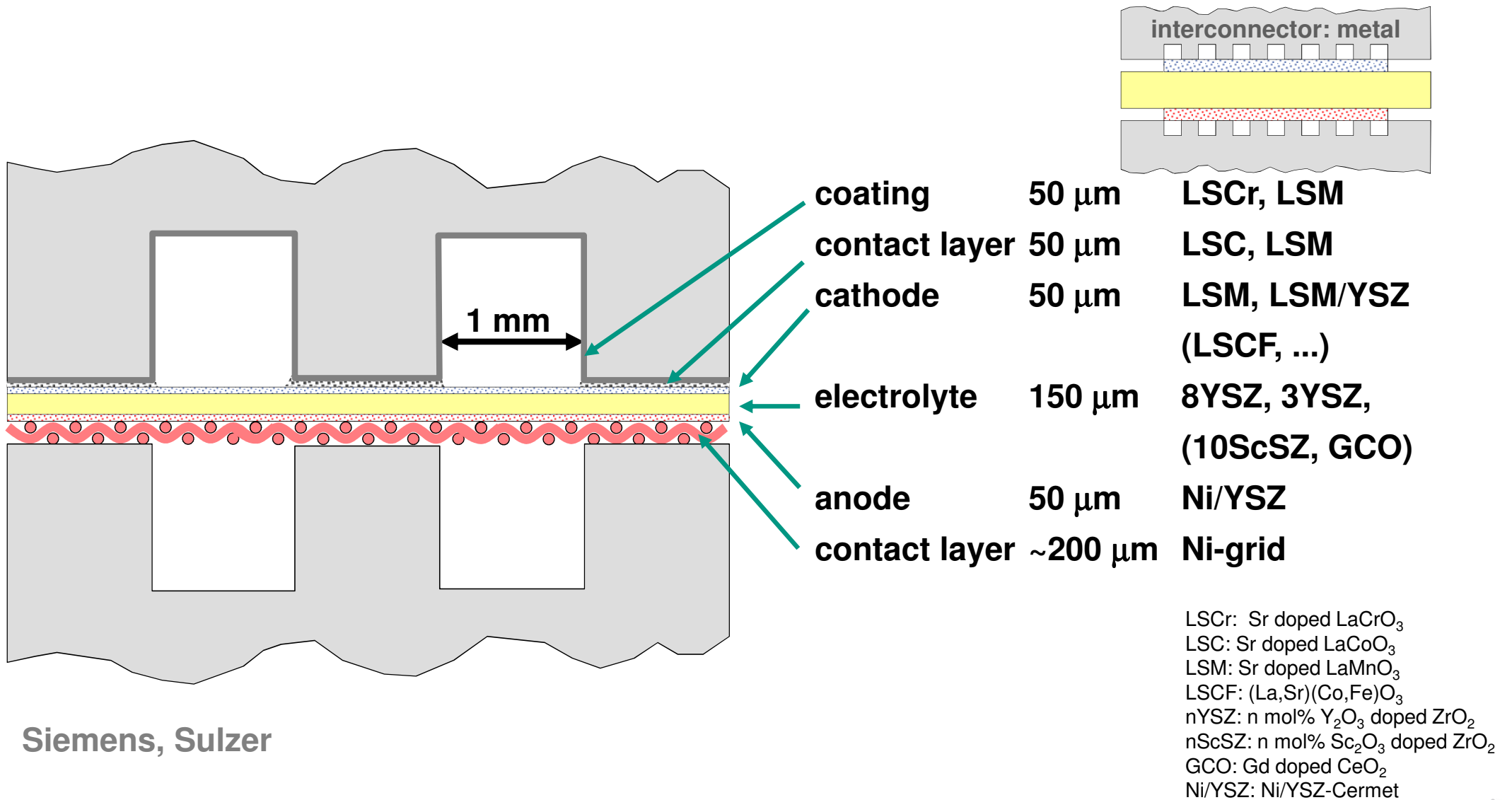
800 - 1000 °C	< 800 °C
	
electrolyte supported	electrode supported* (anode or cathode)
electrolyte: 150 μm	< 20 μm
electrodes: 50 μm	50 / > 500 μm
GTL: -	-

Solid Oxide Fuel Cell Planar Cells



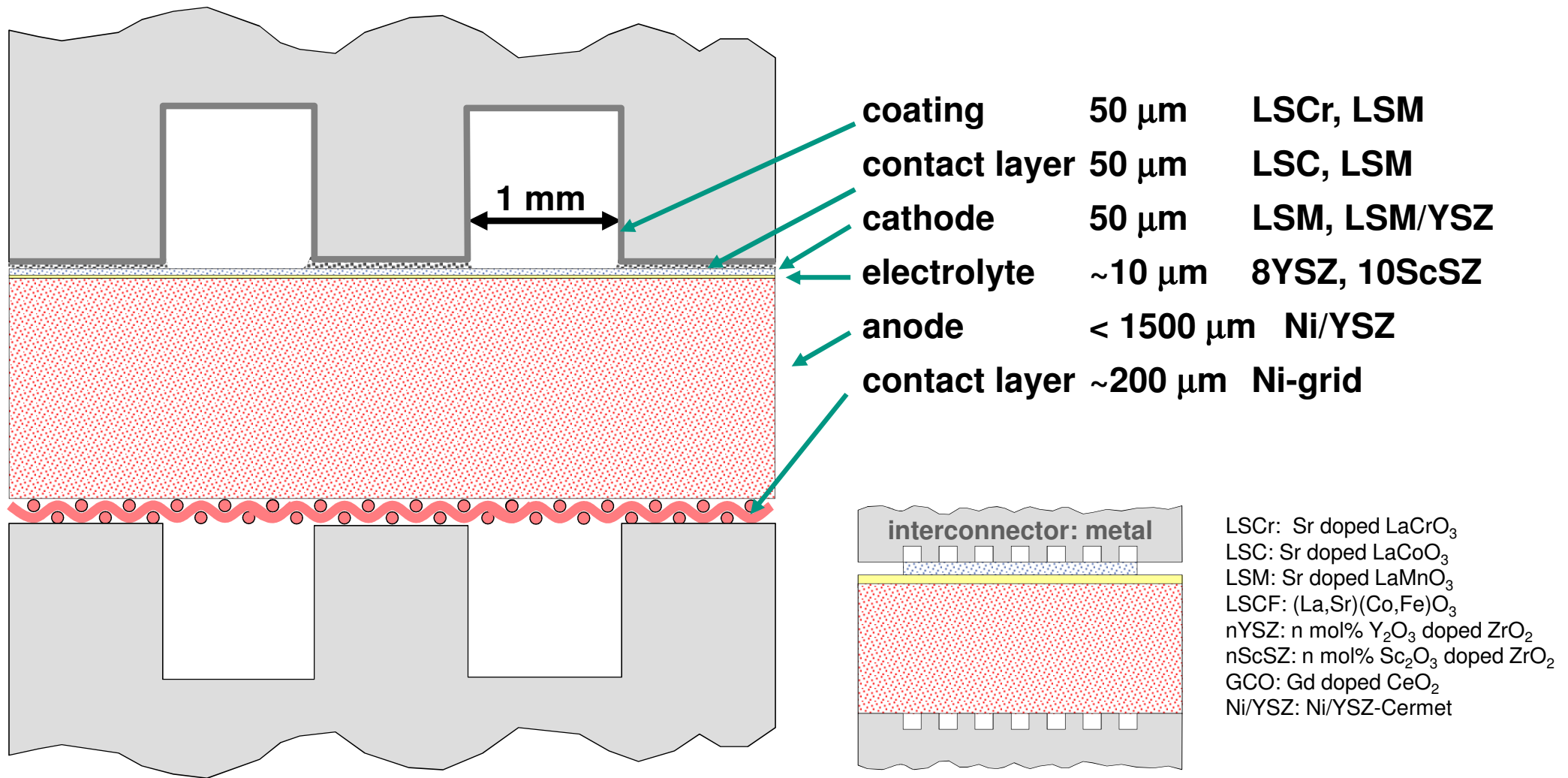
SOFC - Stack Design

Planar Design with Electrolyte Supported Single Cell



SOFC - Stack Design

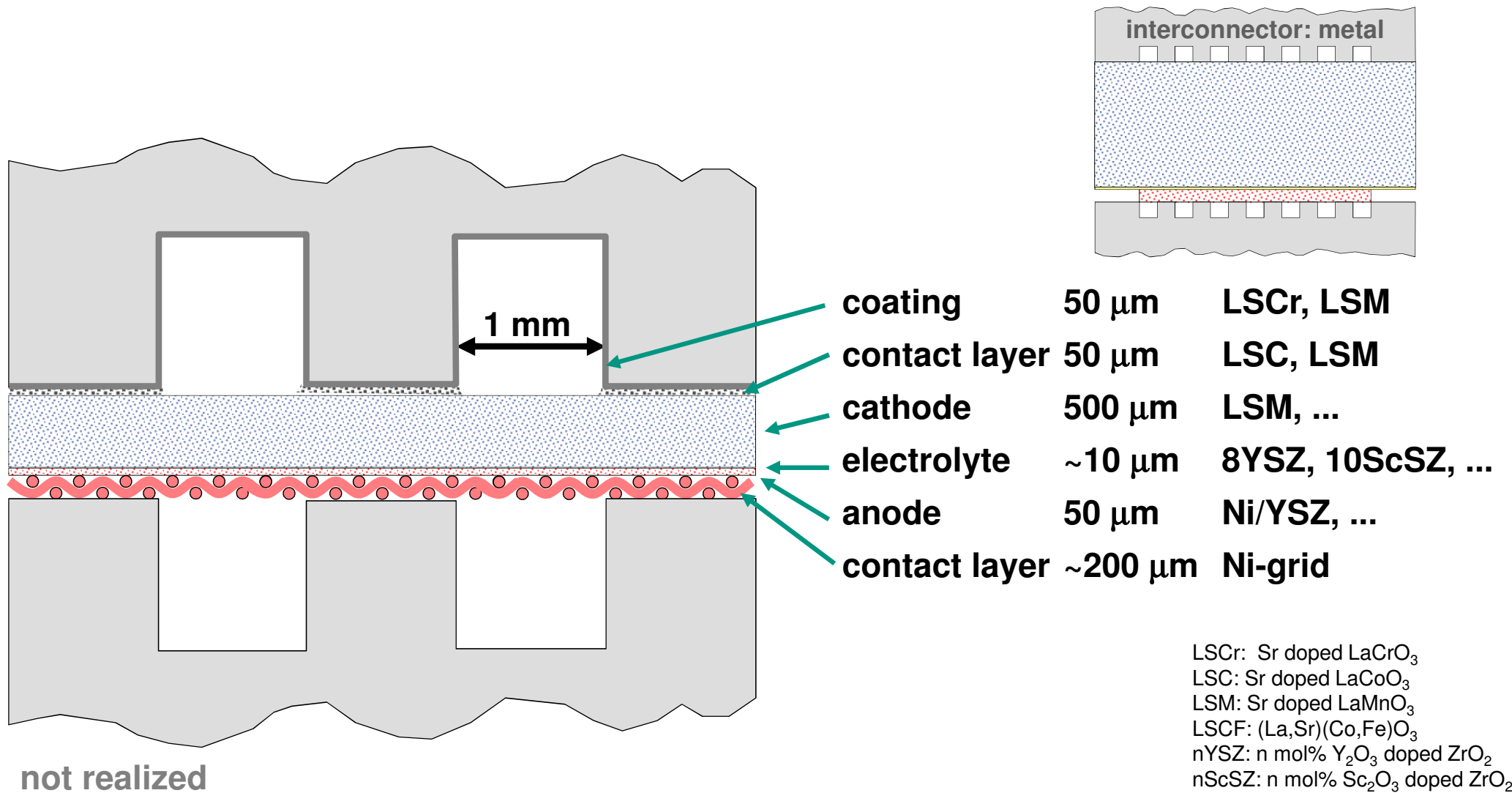
Planar Design with Anode Supported Single Cell



Allied Signal, FZ Jülich, DTU, Haldoer Topsoe, SolidPower, ...

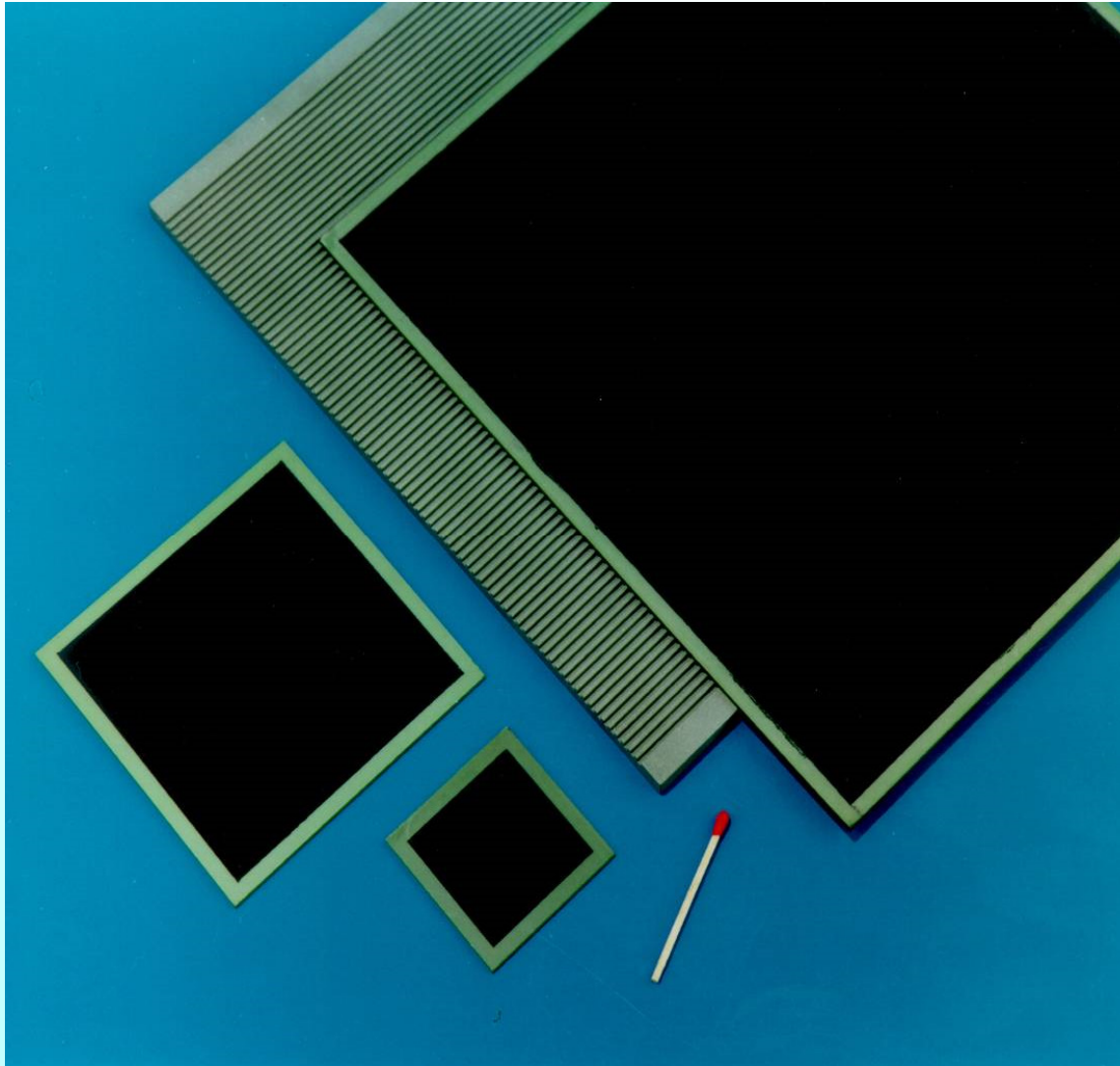
SOFC - Stack Design

Planar Design with Cathode Supported Single Cell



LSCr: Sr doped LaCrO_3
LSC: Sr doped LaCoO_3
LSM: Sr doped LaMnO_3
LSCF: $(\text{La}, \text{Sr})(\text{Co}, \text{Fe})\text{O}_3$
nYSZ: n mol% Y_2O_3 doped ZrO_2
nScSZ: n mol% Sc_2O_3 doped ZrO_2
GCO: Gd doped CeO_2
Ni/YSZ: Ni/YSZ-Cermet

Substrat-Zelle FZJ



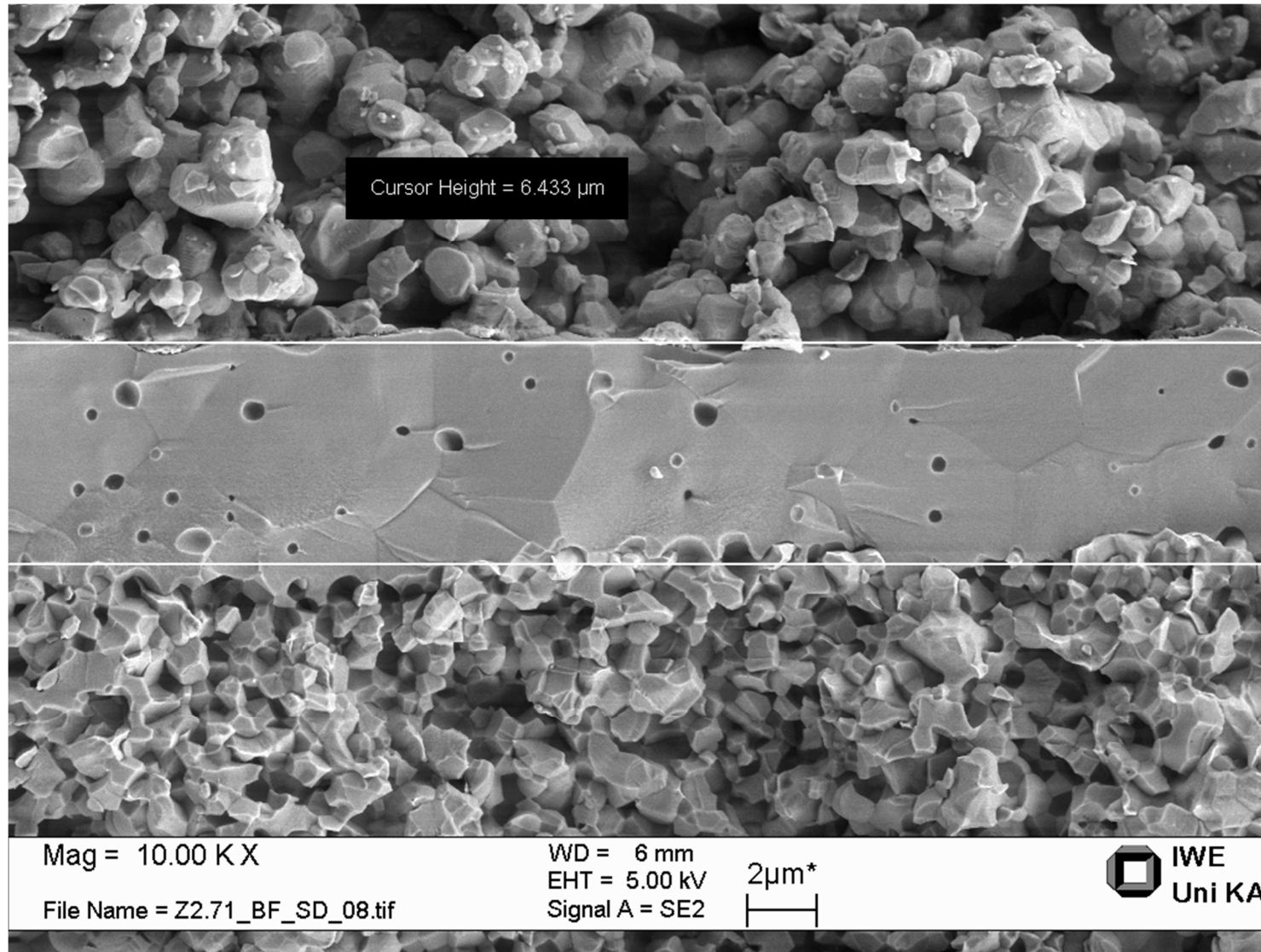
25 x 25 cm²

10 x 10 cm²

5 x 5 cm²

Bruchfläche

Elektrolytschicht der anodengestützten FZJ-Zelle



Elektrolytdicke:

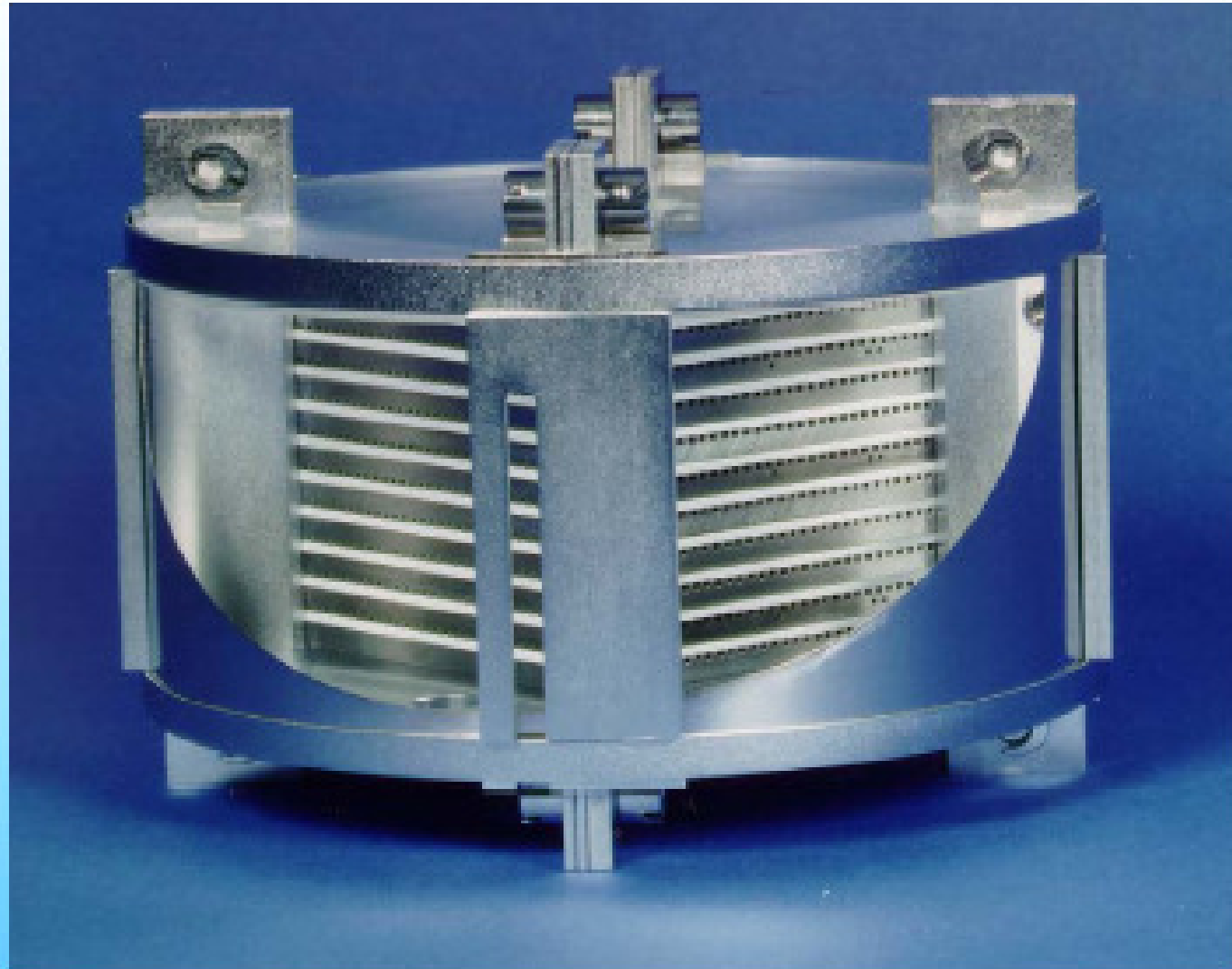
6,4 μm

Kathode

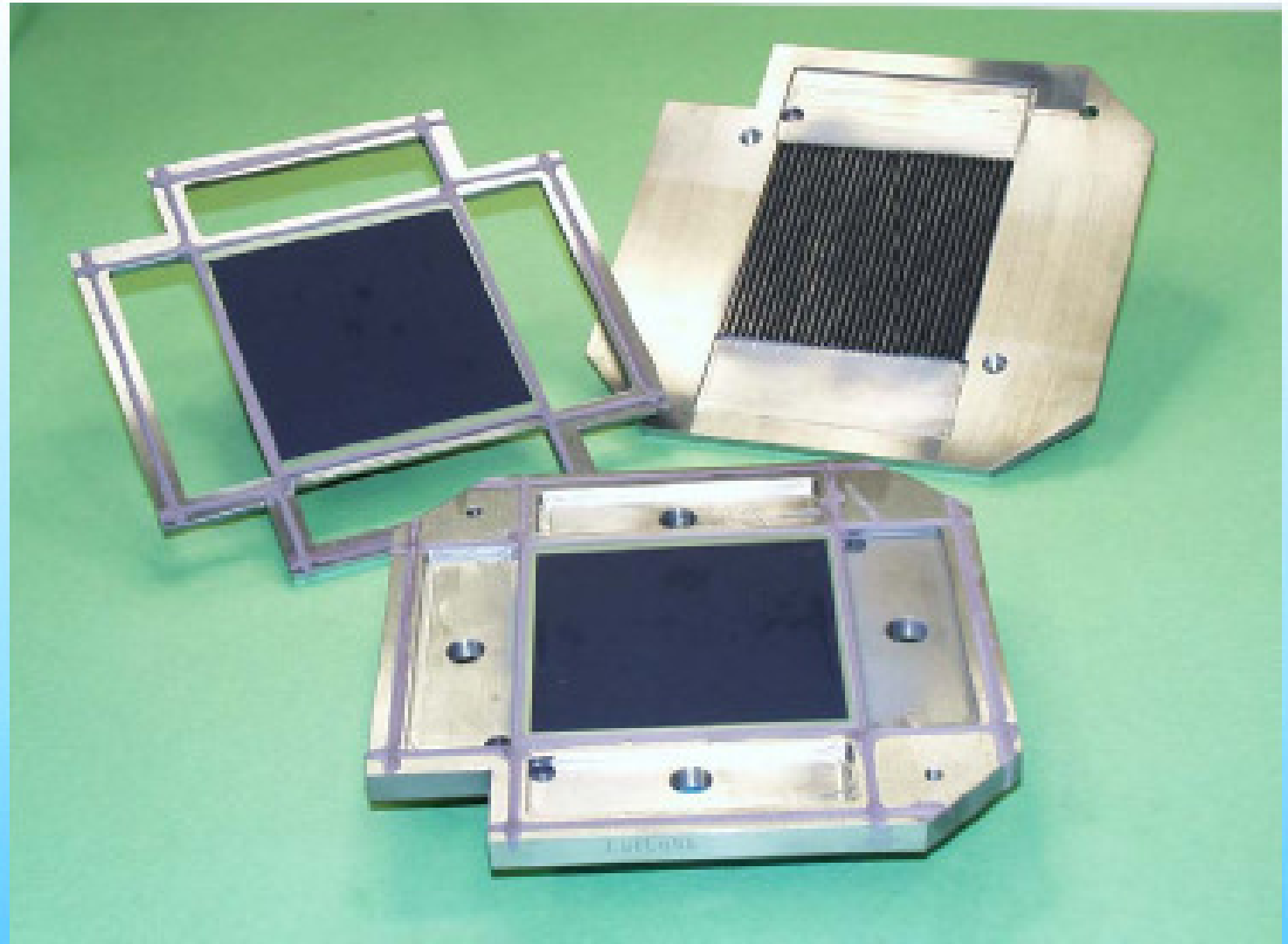
Elektrolyt

Anode

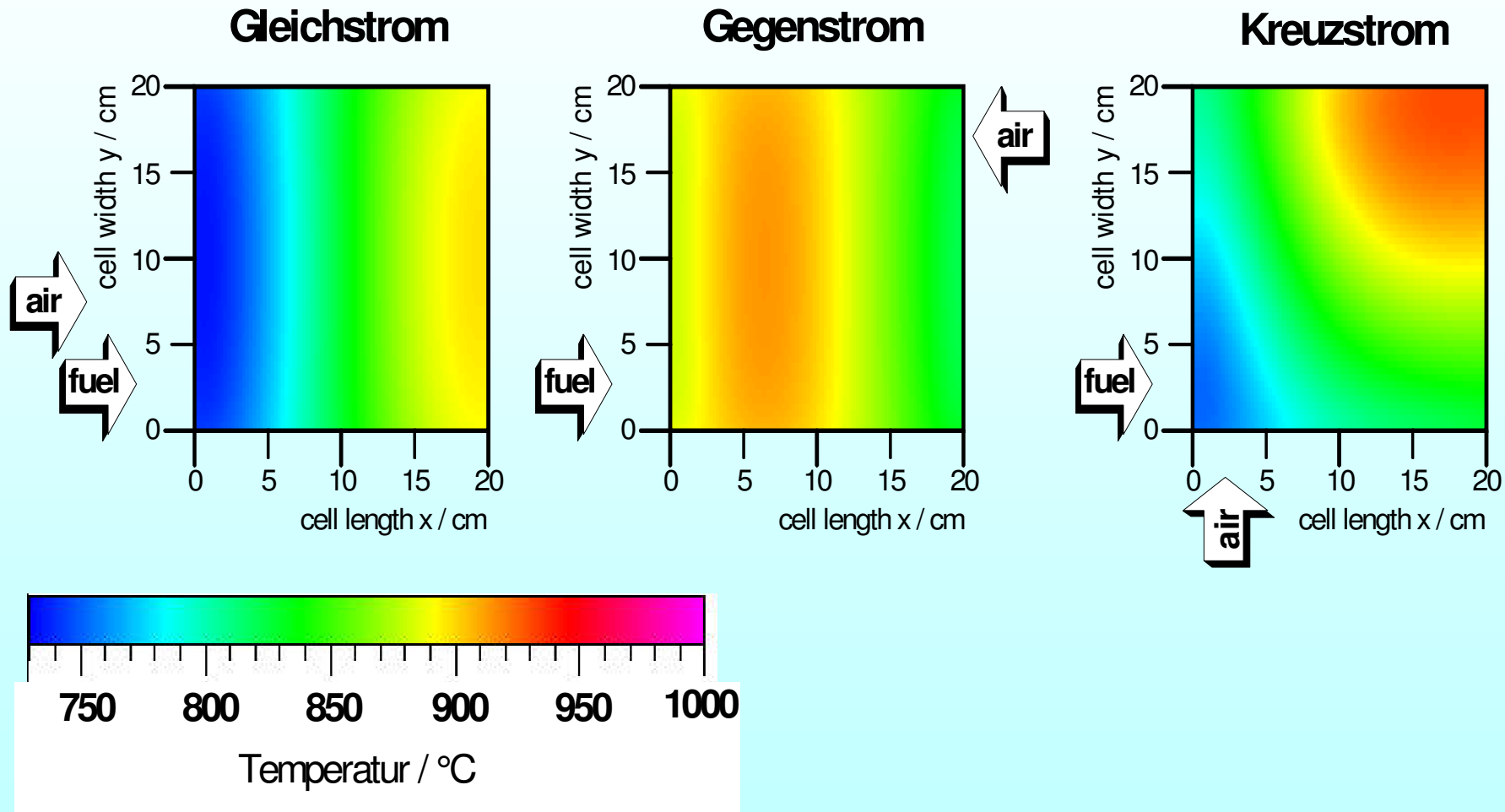
**B-Design
with cross-flow
and
external manifold,
1995**



**D-Design
with cross-flow
and
internal manifold,
1999**



Modellierung: Temperaturverteilung bei interner Reformierung



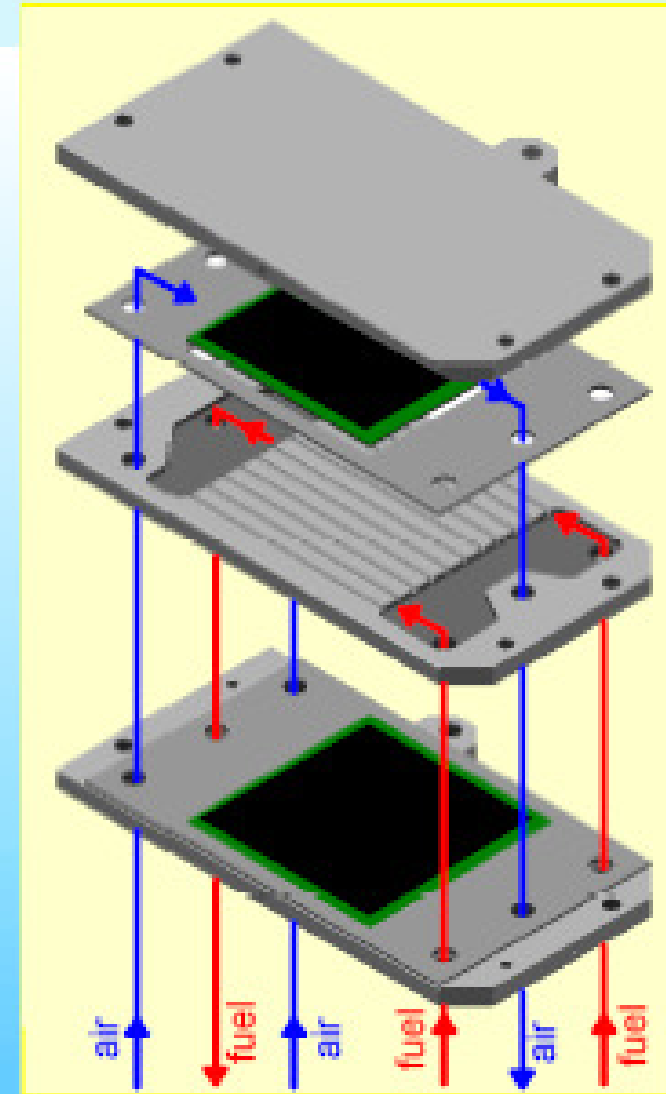
E-Design Stack Technology

Internal manifold:

sealing only in one plane perpendicular to the stacking direction

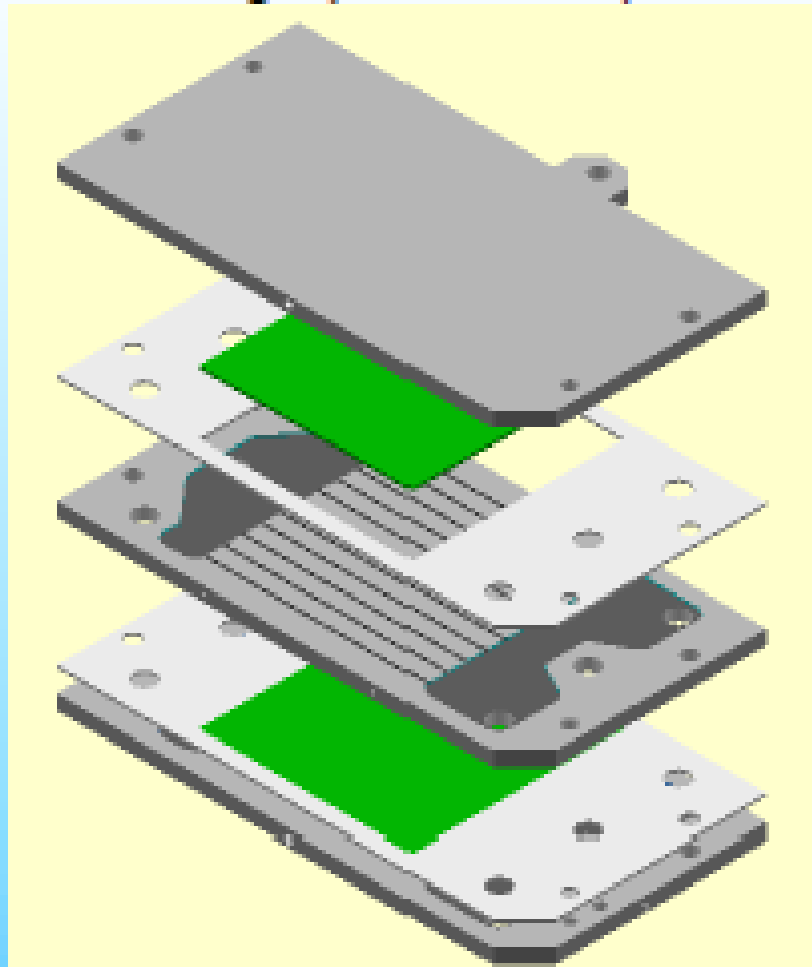
Parallel gas flow:

using counter flow results in a more homogeneous temperature distribution in case of internal reforming (results of stack-modelling)

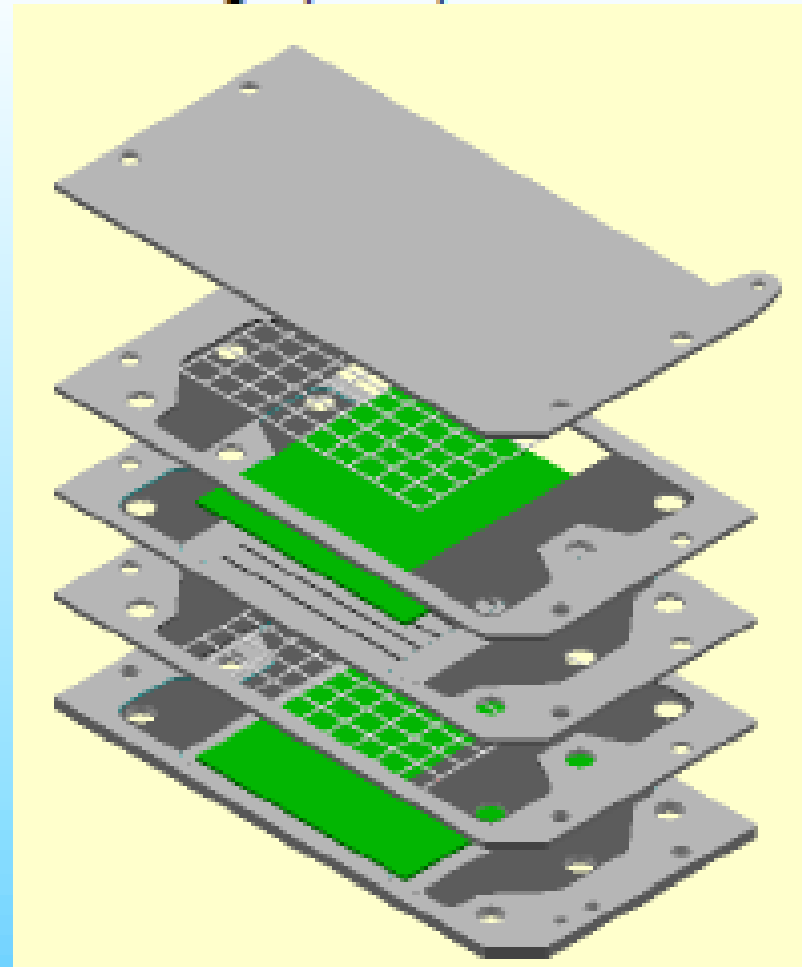


Stack Design

E*-Design (status 2001)



F-Design (2002)



reduced manufacturing effort using a coarse nickel mesh as a gas distribution and contact element on the anode side

Power Stacks at FZJ

40 cell stack 20 cm x 20 cm generating 9,2 kW at 800+ °C using hydrogen



With hydrogen:

9,2 kW

0,63 W/cm²

300 A @ 30,6 V;

0,83 A/cm² @ 0,765 V/cell

With Methane:

5,4 kW

0,38 W/cm²

180 A @ 30,2 V;

0,50 A/cm² @ 0,755 V/cell

Fuel: 90% H₂ / 10% H₂O 7% H₂ / 31% CH₄ / 62% H₂O

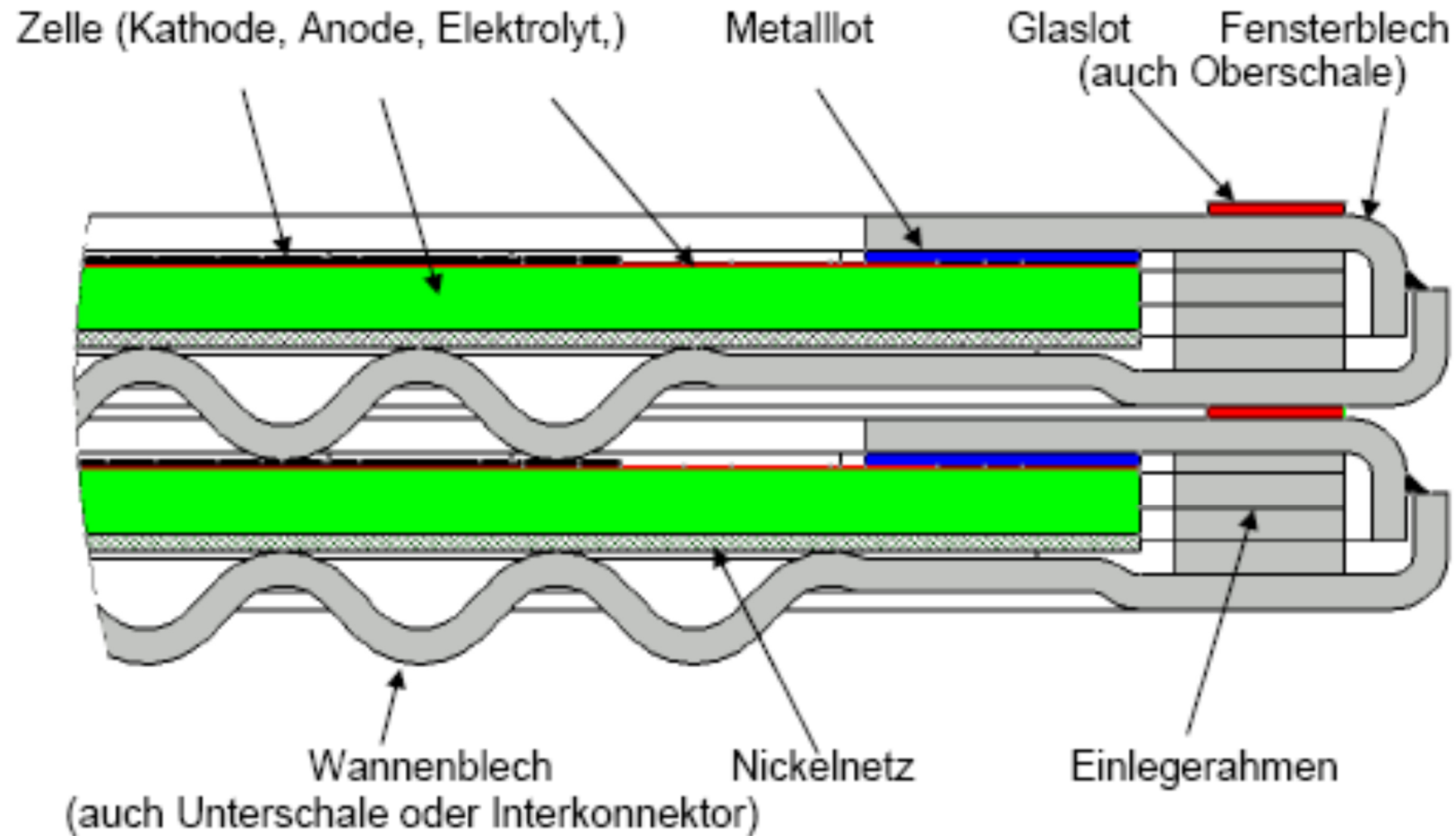
Utilisation: 76 % @ 300 A 59 % @ 180 A

Oxidant: Air Air

Stoichiometry: 2 @ 300 A 3.5 @ 180 A

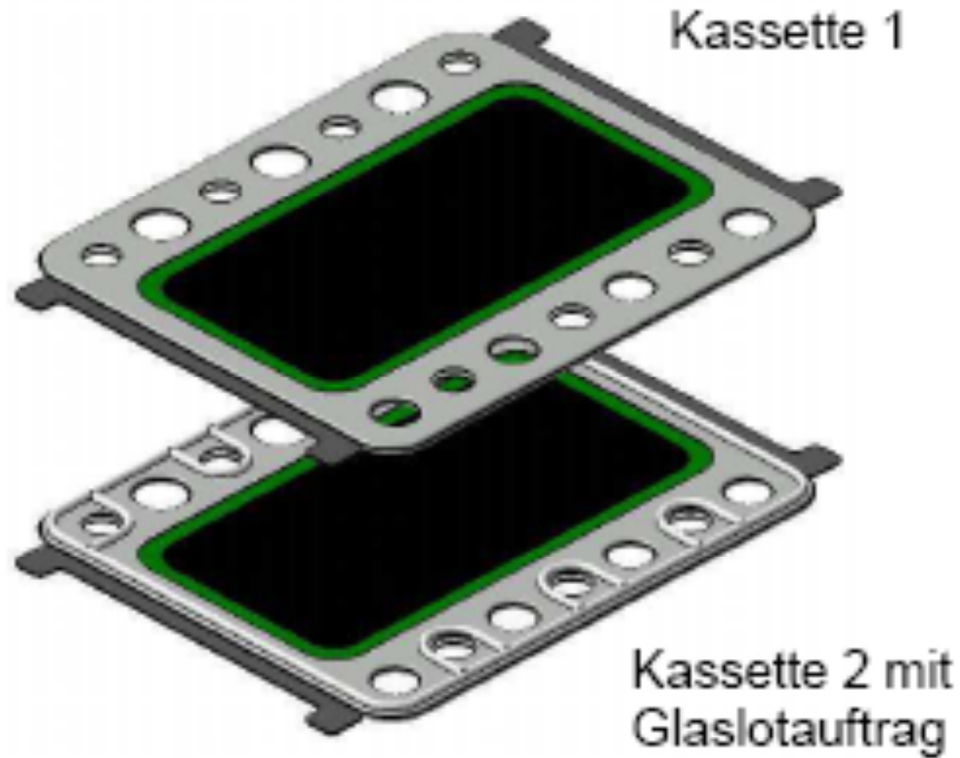
SOFC Stack Design

Leichtbaustack



SOFC Stack Design

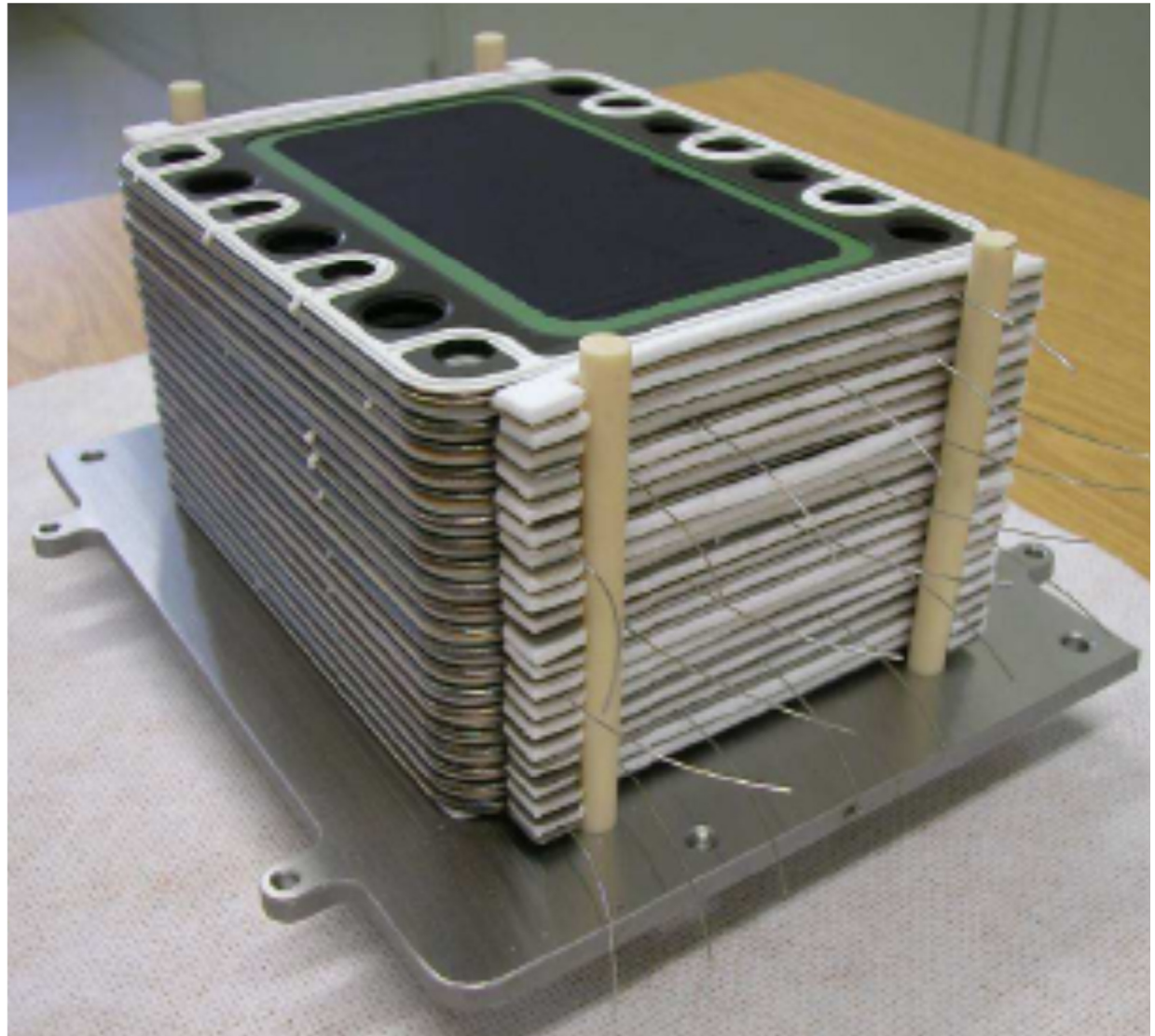
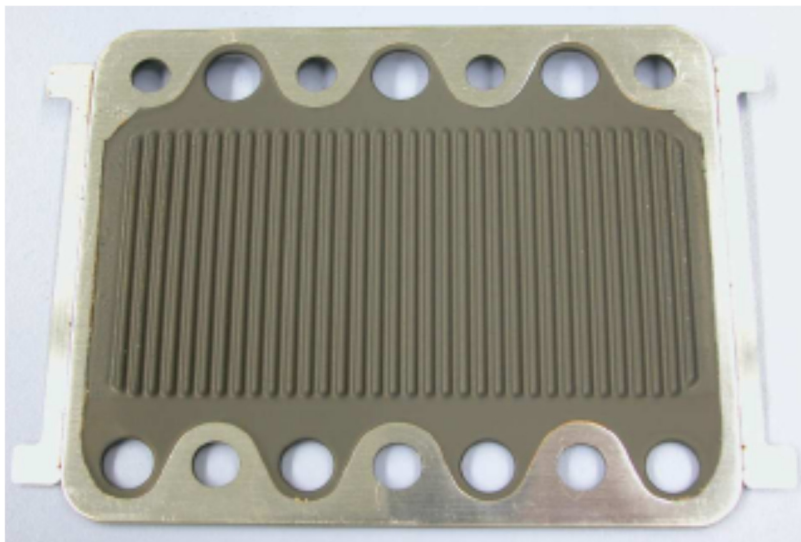
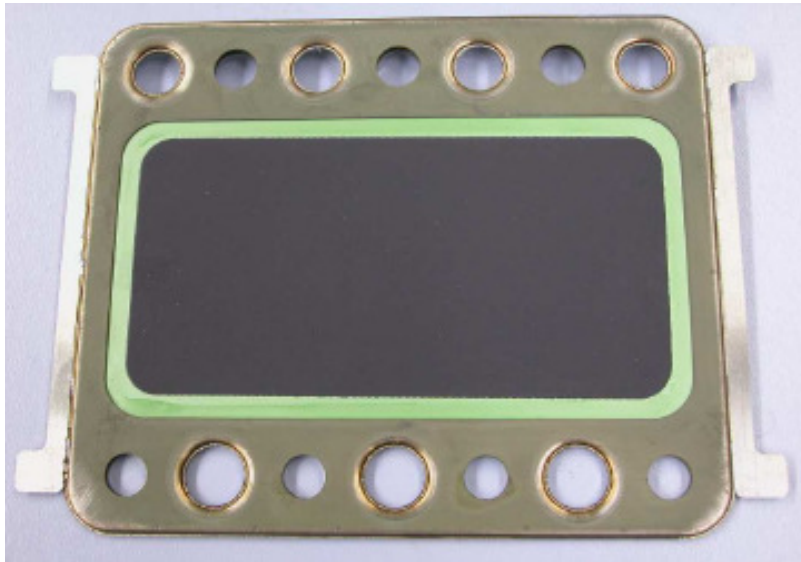
Aufbau eines Leichtbaustacks



2-zelliger Shortstack

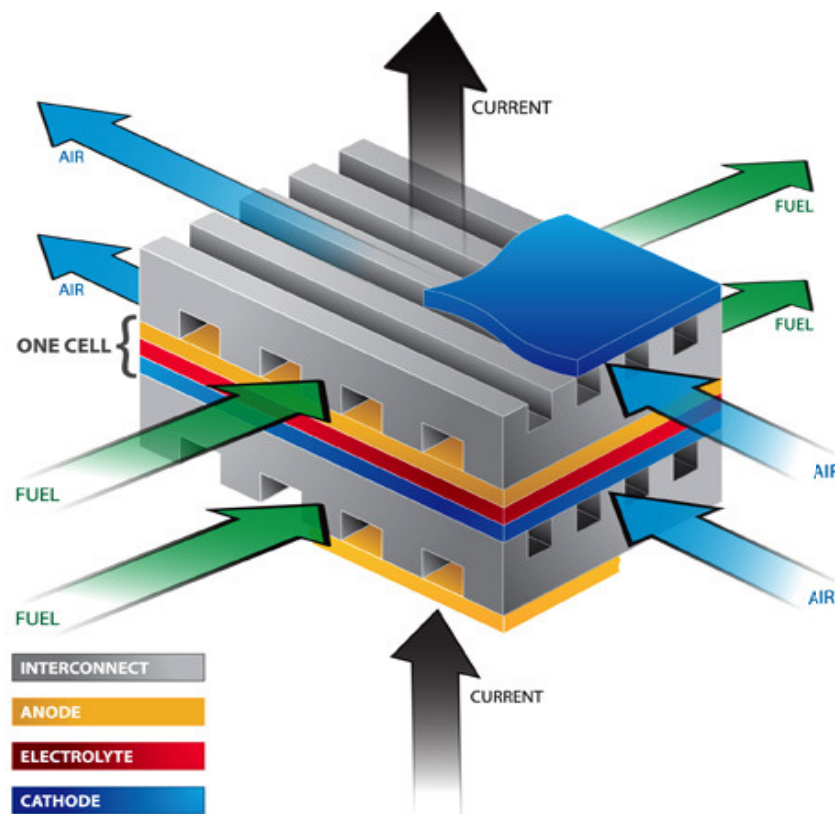
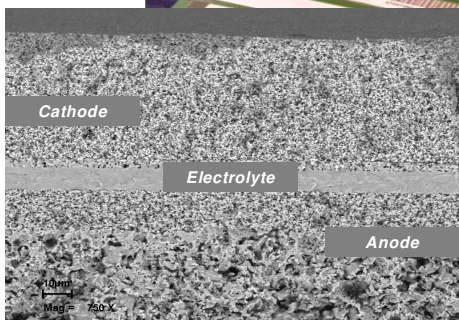
SOFC Stack Design

Leichtbaustack-Kassette



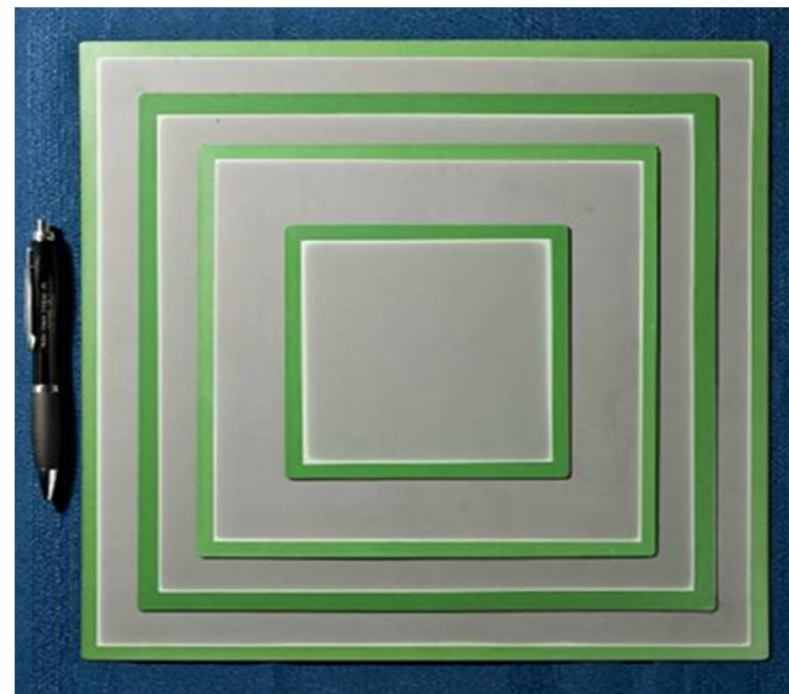
Versa Power's SOFC Approach

- Planar anode-supported cells
- Cross-flow gas delivery
- Stainless steel sheet metal interconnects
- Stacks can be integrated into various arrangements, depending on power applications





- The techniques used to make cells are:
Tape casting, **S**creen printing and **C**o-firing
(the **TSC** Process)
- Capable of operating between 650 to 800°C with high power density
- Cell has been scaled-up from 10 x 10 cm² (81 cm² active area) to 25 x 25 cm² (550 cm² active area) to facilitate stack scale-up



Component	Materials	Thickness	Porosity	Process
Anode	Ni/YSZ	0.5 mm	~ 40%	Tape casting
Electrolyte	YSZ	5 - 10 µm	< 5%	Screen printing
Cathode	Conducting ceramic	10 - 50 µm	~ 30%	Screen printing

Scale Up

- Scaled up from 28 cells up to 120 cells
- Stack power from 1 kW to 15 kW

Performance Improvement

- Higher power density
- Higher fuel utilization
- Higher direct internal reforming

Cost Reduction

- Reduced stack cost to meet SECA cost targets

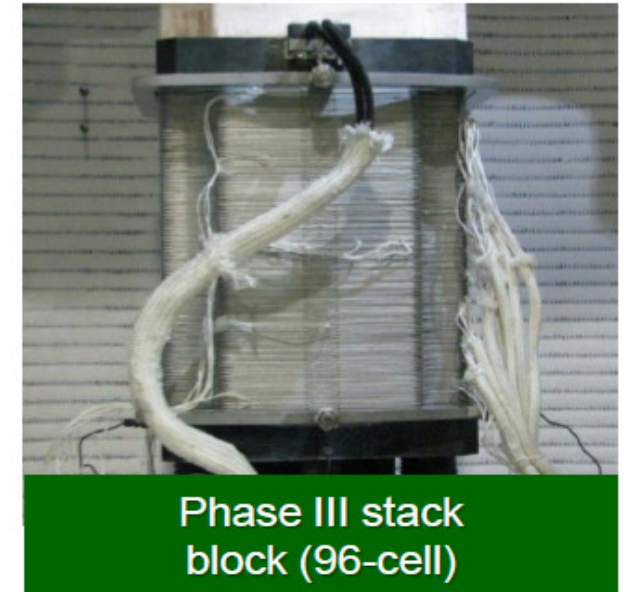
Endurance Enhancement

- Improved stack thermal and flow management
- Incorporated TSC3 cells
- Incorporated advanced flow media



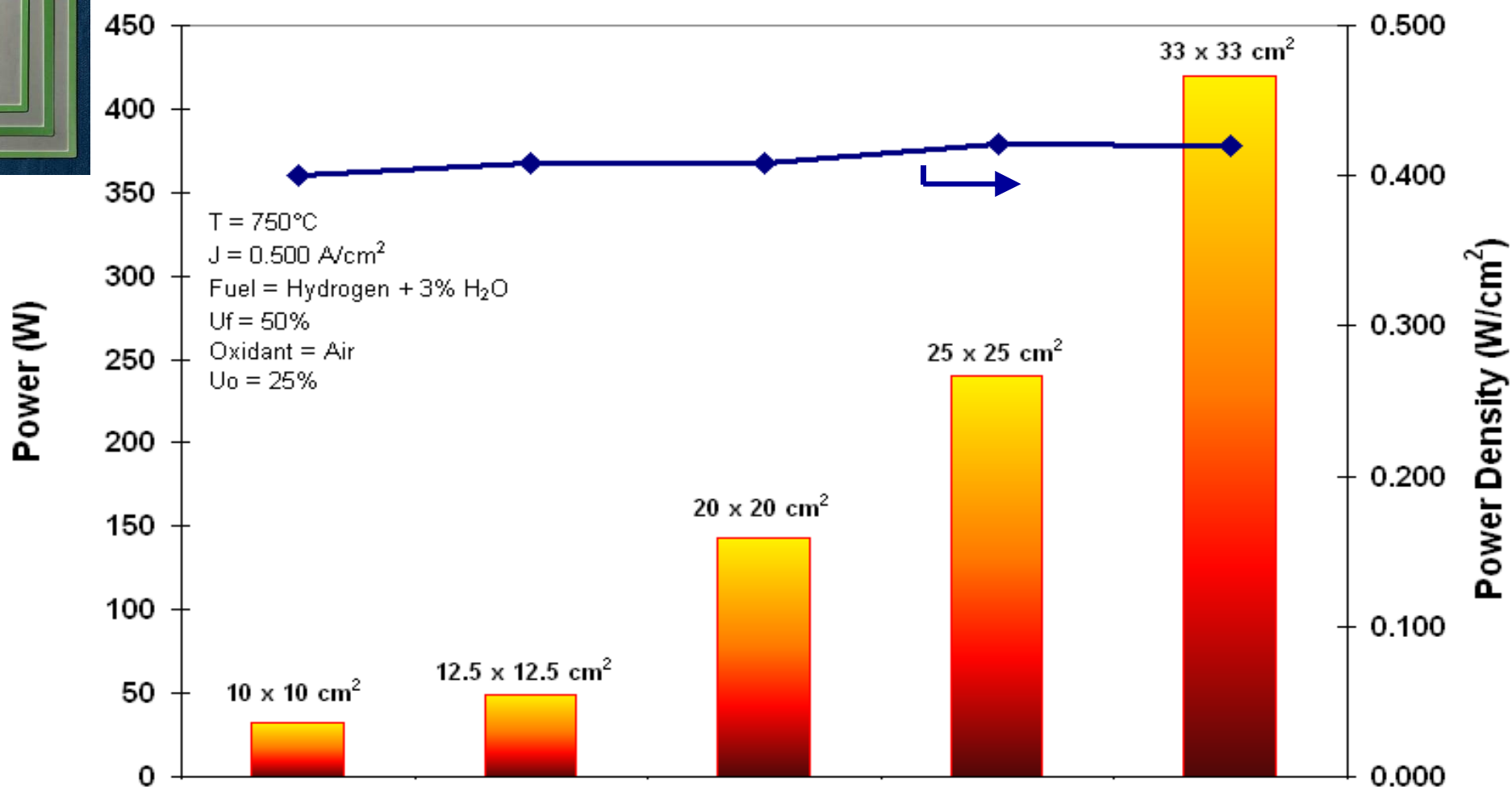
SECA Stacks

Stack Size	Phase I Quantity	Phase II Quantity	Phase III Quantity	Total
Short Stacks 6 - 32 Cells	39	43	16	98
Full Size Stacks > 64 cells	6	9	15	30
Total Quantity	45	52	31	128
Total kW	126	255	262	643



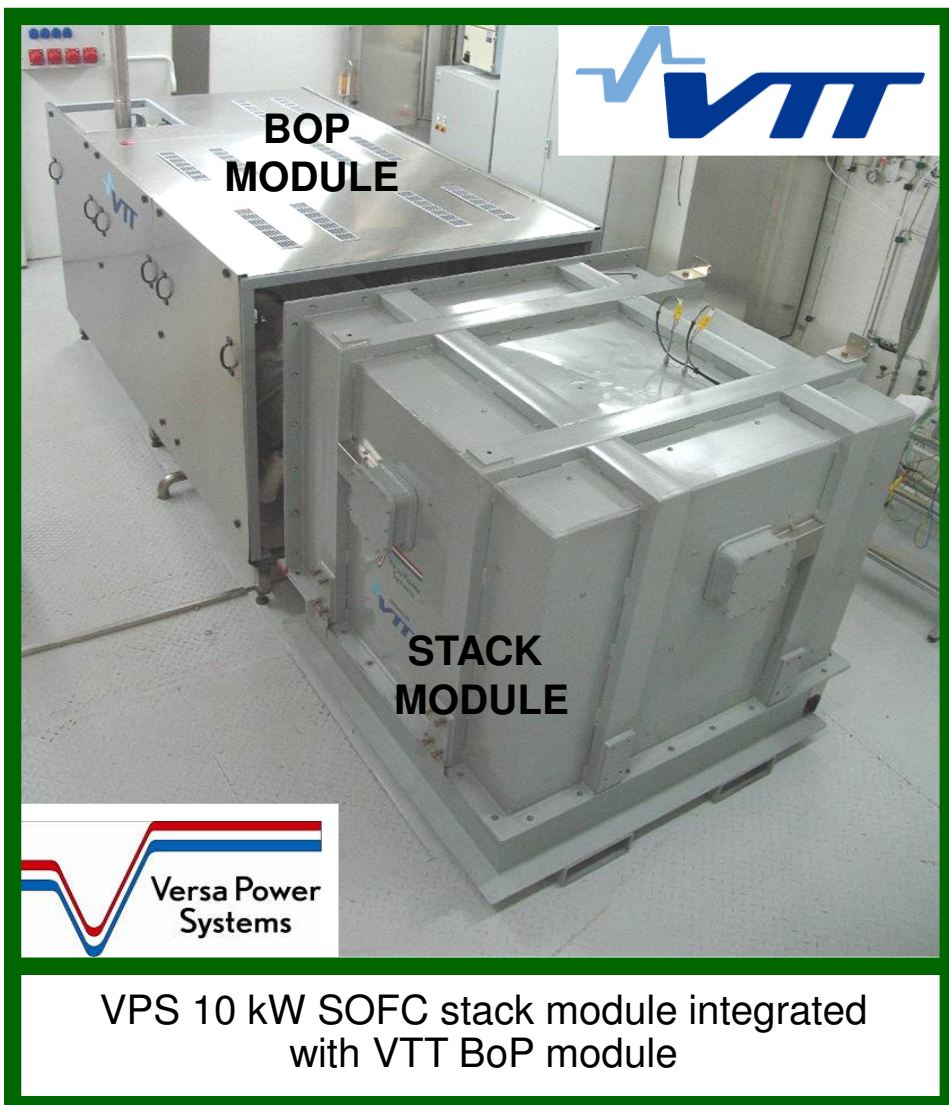
Cell Power at 0.500 A/cm²

Stainless Steel Current Collectors, Cross-Flow Gas Delivery



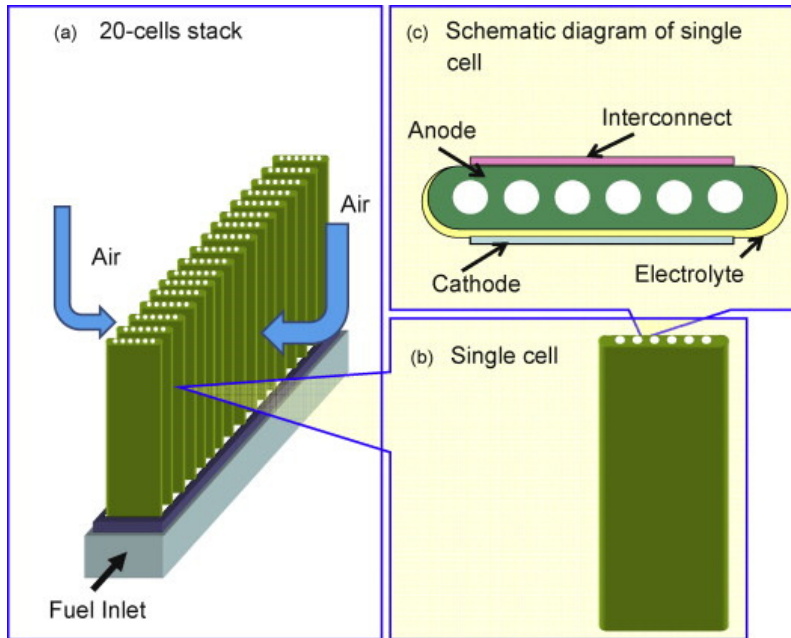
Power (W)	32	49	143	241	420
Cell Voltage (V)	0.80	0.82	0.82	0.84	0.84

10 kW SOFC Demo Unit at VTT

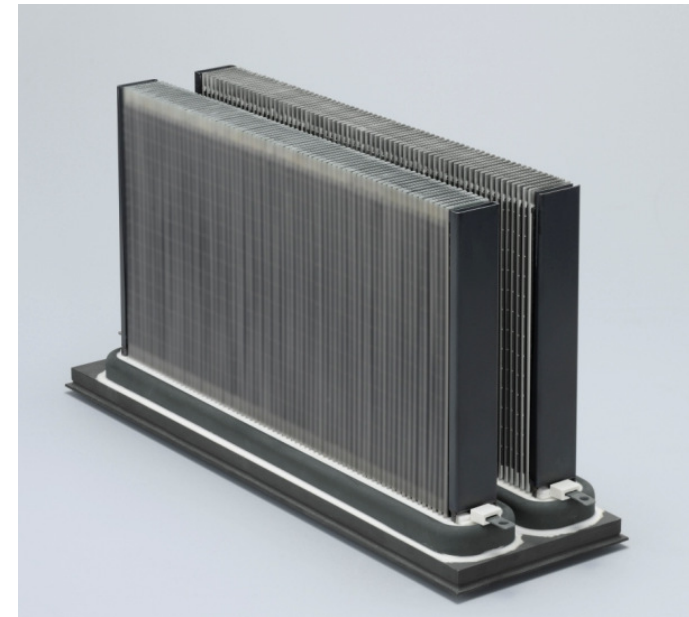
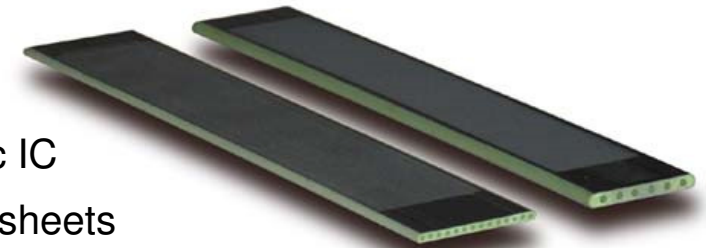


- ▶ VPS has collaborated with VTT Technical Research Centre of Finland since 2010 to produce and operate a 10 kW fully integrated SOFC system
 - Single stack
 - Modular design
 - Natural gas fueled
 - Warm anode recycle loop
 - Grid connected
 - Thermally self-sustained

Stack Cell Count	80
Stack Current	160.6 A
Cell Voltage	857 mV
Stack Voltage	68.57 V
Module Power	11.013 kW
Fuel Utilization - System	80.4%
Module Efficiency (LHV)	66%

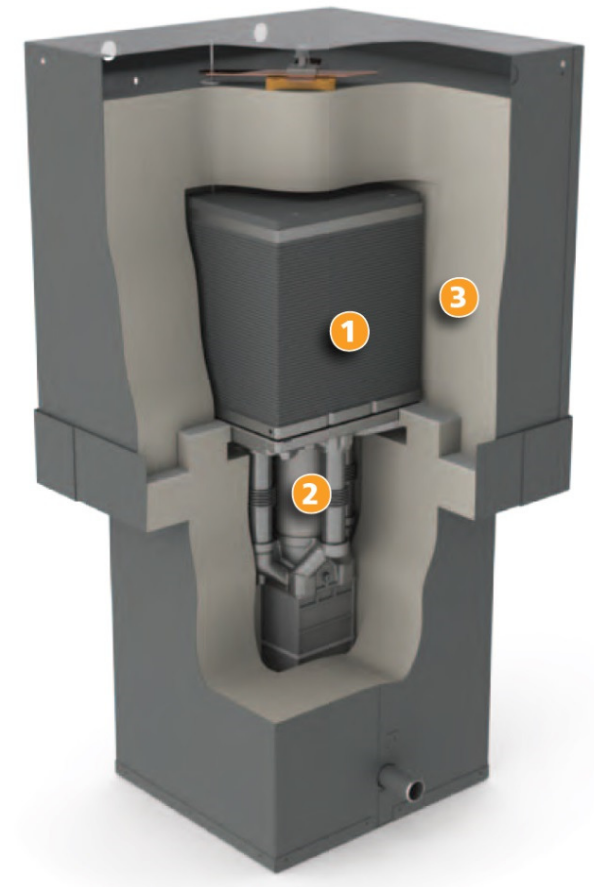
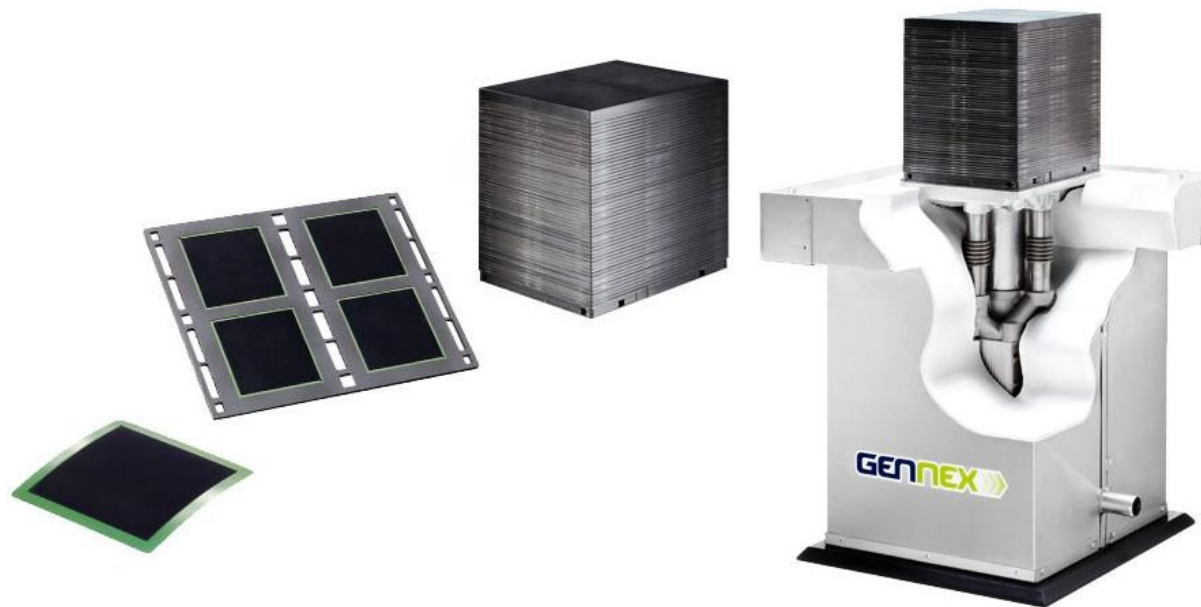


- “flattened tube” with ceramic IC
- contacting by flexible metal sheets
- integrated sealing
- integrated afterburner



SOLIDpower (CFCL-Konzept)

- planar Stack
- ASC's with solid metallic interconnects (no cassette design)
- glas sealant
- available as Gennex Fuel Cell Module
- BlueGen μ CHP system with 60% el. efficiency

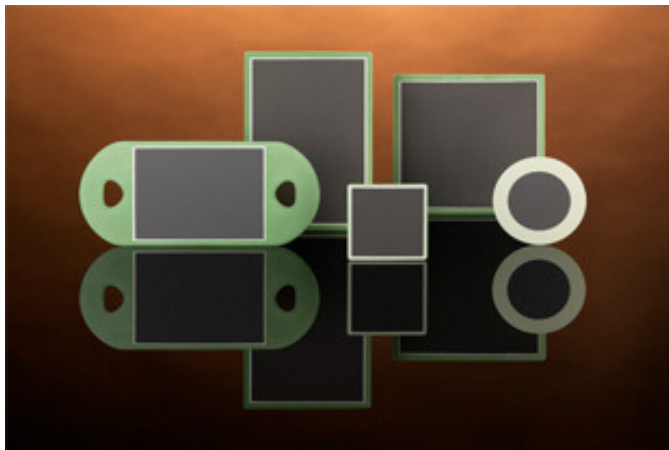


- 1) Stack
- 2) BoP (steam generator, burner, heat exchangers)
- 3) Insulation

- planar stack,
- ASC's with metallic interconnects
- cassette design, coflow
- cells, stacks hotboxes are available



Stackbox



HoTbox™

- all high temperature components integrated
- complete high temperature solution for SOFC system developers
- SOFC stack up to 1000 W
- heat exchanger
- CPOx reformer (natural gas)
- high temperature insulation
- electric heater for start-up



Ceres Power

- MSC with CGO-electrolyte
- operating temperature 500 ... 620 °C
- CGO-electrolyte limits operating temperature range

cell data:

power at 0.75V/cell/W:

>12 570°C/ 56%H₂/44% N₂ fuel

galvanostatic degradation rate/ %/kh:

<0.5 570°C/60% fuel utilization/10A load

number of controlled thermal cycles

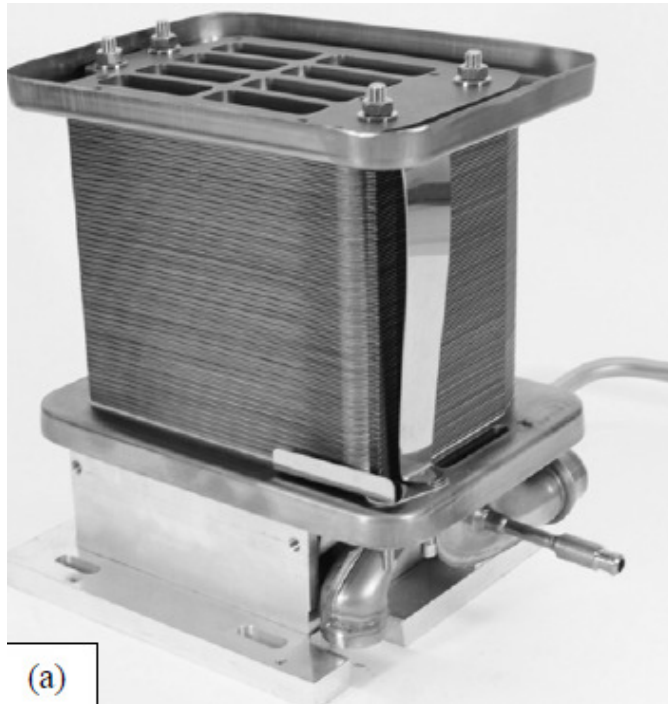
>200 100-610°C

without degradation above noise:

Number of Emergency stops with

>60 100-610°C with REDOX cycle

<5% performance degradation:



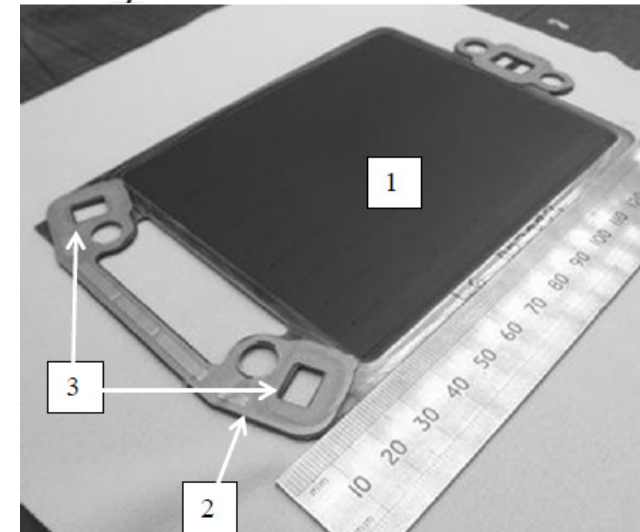
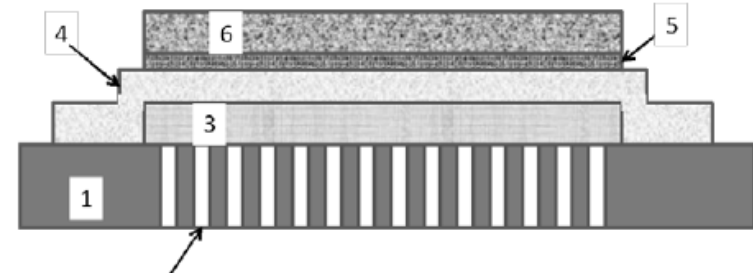
1 metal sheet substrate

2 laser cutted holes

3 anode

4 electrolyte

5 cathode

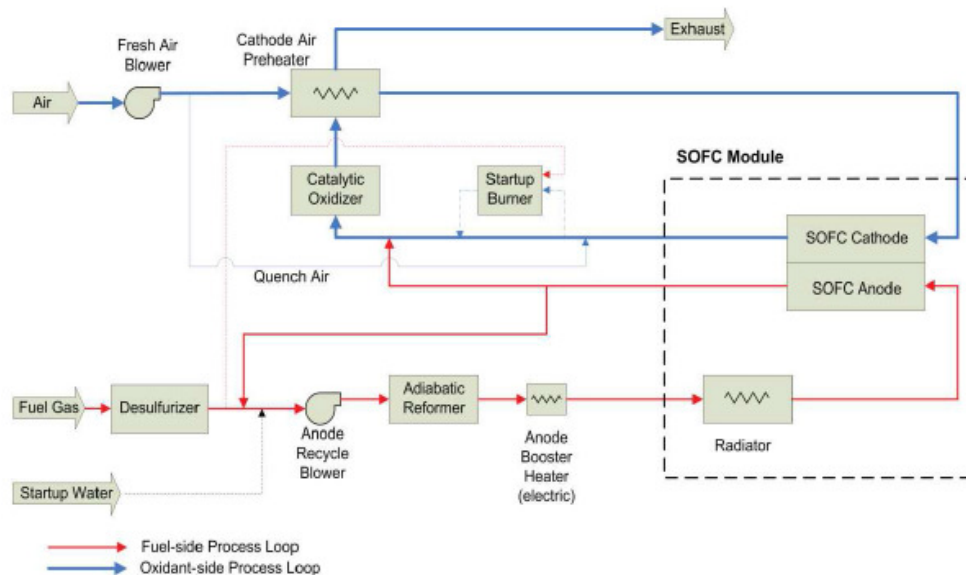


15 kW Stack

Stack Physical Attributes		Nominal Operating Conditions	
Cell Size (cm ²)	25x25	Fuel Utilization (%)	68
Cell Active Area (cm ²)	550	Air Utilization (%)	15
Number of Cells	96	In-Stack Reforming (%)	25 - 70
Gross Power (kW)	16	Current Density (mA/cm ²)	364

60 kW Modul

Stack Current	187.4 A
Average Cell Voltage	819 mV
Stack Voltage	78.64 V
Gross Module Power	58.96 kW
Fuel Utilization - System	81%
Module Efficiency (LHV)	64%



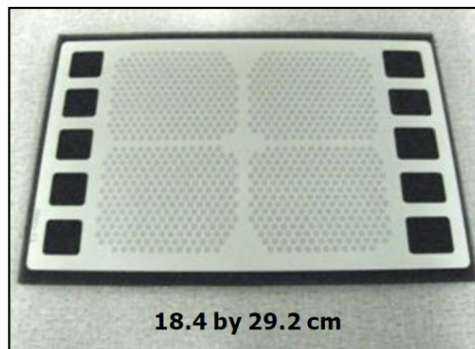
- modules for large power plants (DOE funding)
- fuel: natural gas, coal gas (CCS)
- internally-manifolded ferritic stainless steel interconnects
- cross flow configuration
- compressible ceramic gasket seals
- not designed for APU applications

Versa Power Systems, Ltd., 4852 52nd Street SE, Calgary, AB, Canada T2B 3R2
 FuelCell Energy, Inc., 3 Great Pasture Road, Danbury, CT, United States 06813
<http://www.fuelcellenergy.com/advanced-technologies/solid-oxide-fuel-cells/>

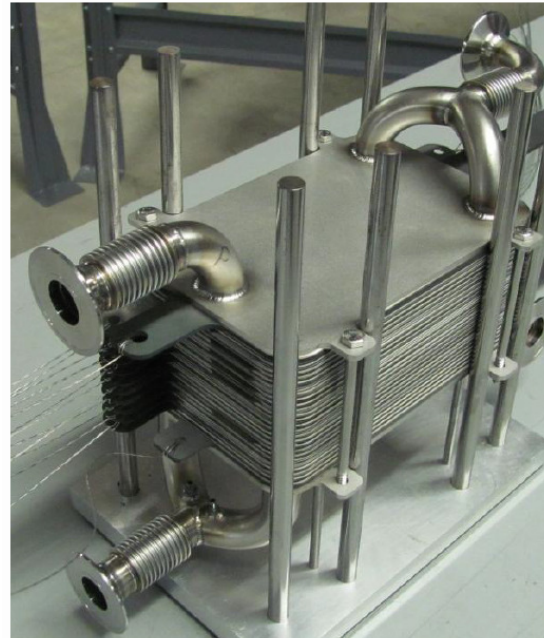
FlexCell for 1-2 kW stacks



FlexCell for 5-10 kW stacks



- cell type: ESC with honeycomb structure
- thin anode (high redox stability)



24-Cell Stack

1 kW @ 0.78V, 70% f.u.

(H₂/air, 800 °C)

- ~ 14 kh long term test (air/H₂)
- 500h operation with 50 ppm H₂S
- (ATR-reformate, 800°C, 0.73 V, 0.2 A/cm², 65% f.u.)
- 3 thermal cycles
- 10 redox cycles

- originally developed for military applications
- high sulfur tolerance (50 ppm)
- cycling possible