Miniaturized Fuel Cell Systems: Challenges and Chances

Anja Bieberle-Hütter

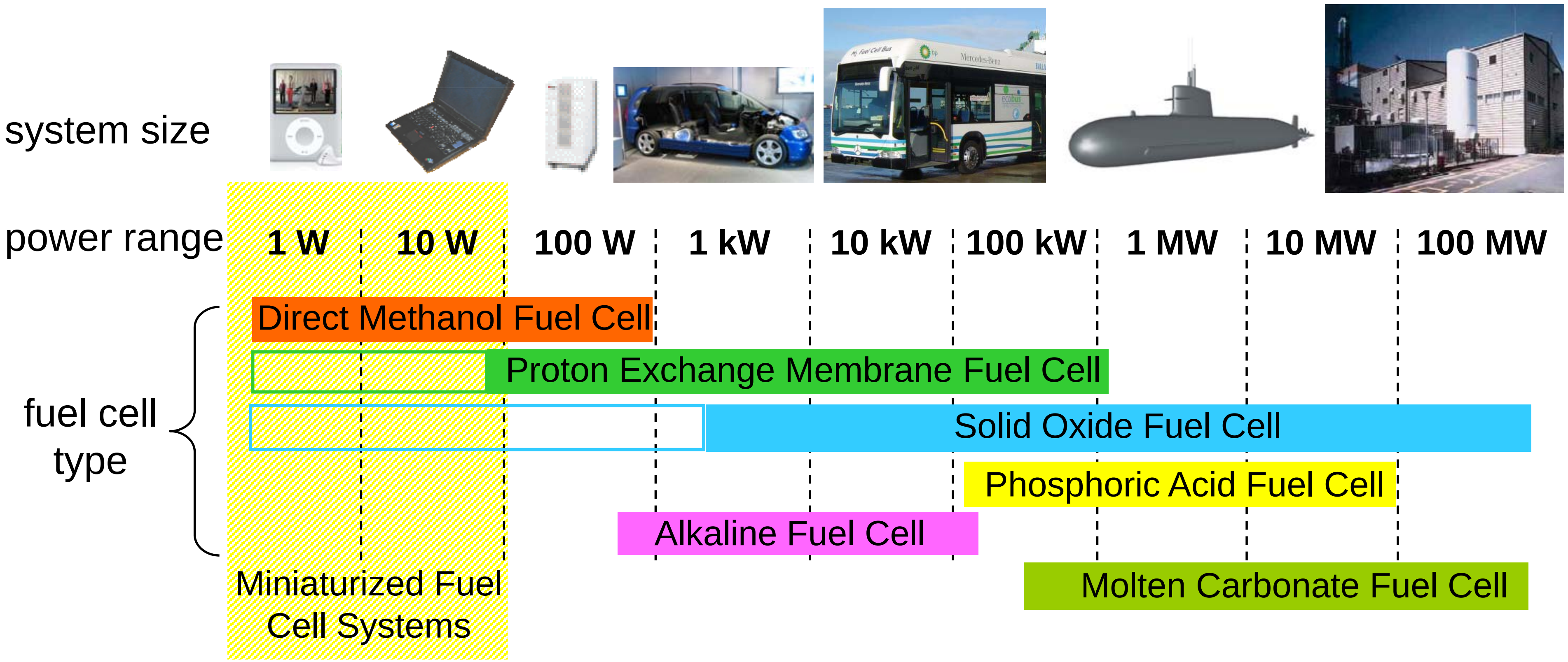
Nonmetallic Inorganic Materials, ETH Zurich, Switzerland

Outline

A) Miniaturized Fuel Cell Systems in General

B) Example: ONEBAT Micro-Solid Oxide Fuel Cell System

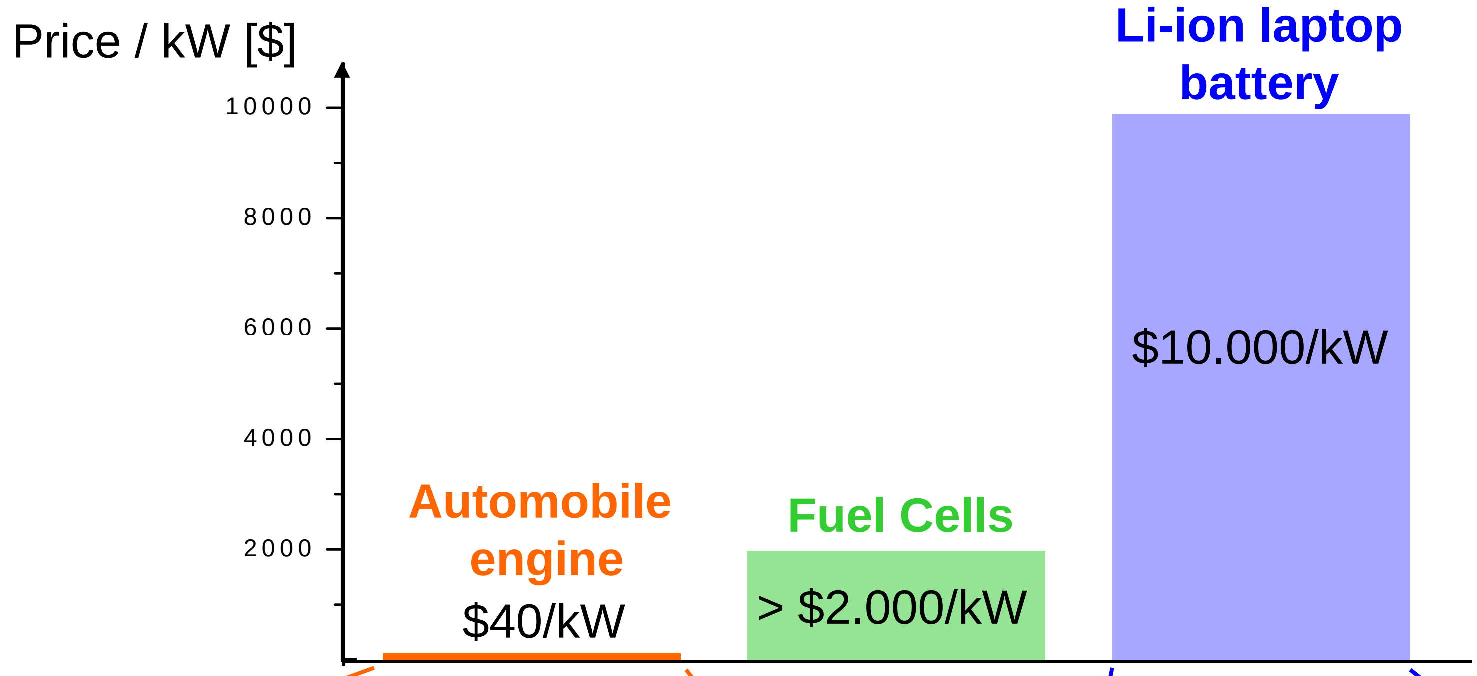
Fuel Cell Systems



main differences of fuel cell types:
- operating temperature
- electrolyte material
- catalyst

according to: http://www.antig.com/technology/technology_fuel_cell_types.htm

Fuel Cell Economics



engine price: $4.000 (car price: $20.000)
engine power: 100 kW
$4.000 / 100 kW = $40/kW

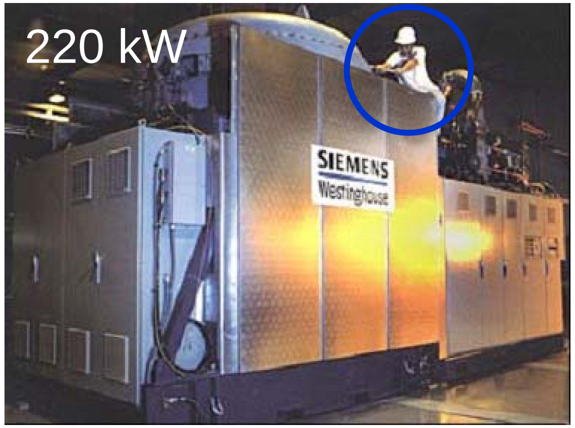
price: $150
average power: 15 W
$150/0.015 kW = $10.000/kW

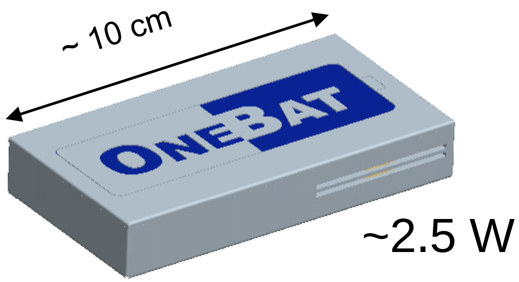
Fuel cells are much more favorable for laptops and portable electronics than for automobiles.

data from: Kukkonen, Small Fuel Cell Conference, Atlanta (2008)

Miniaturized Fuel Cell Systems

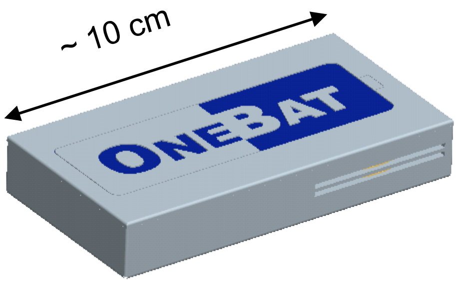
1. Reduction in overall dimensions and power range



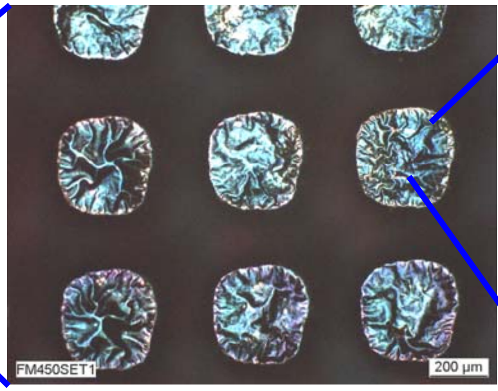


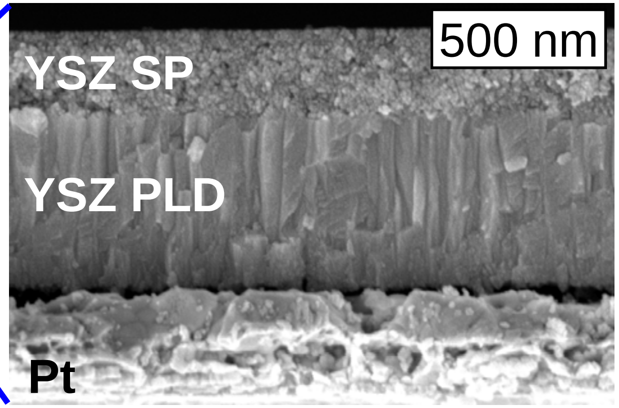
ETH Zurich, CH

2. Reduction in inner dimensions (microfabrication)

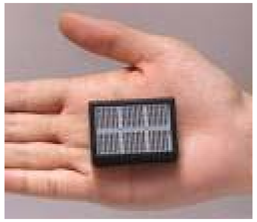


ETH Zurich, CH

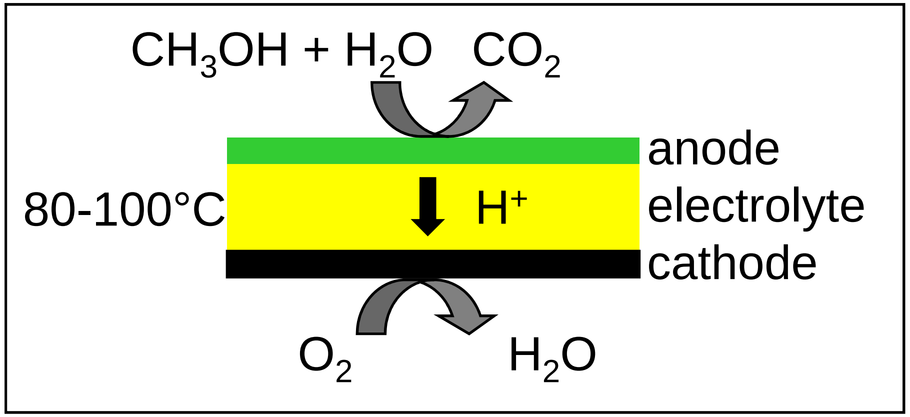




Direct Methanol Fuel Cell (DMFC) Systems



Sony, 2008



MTI

Panasonic

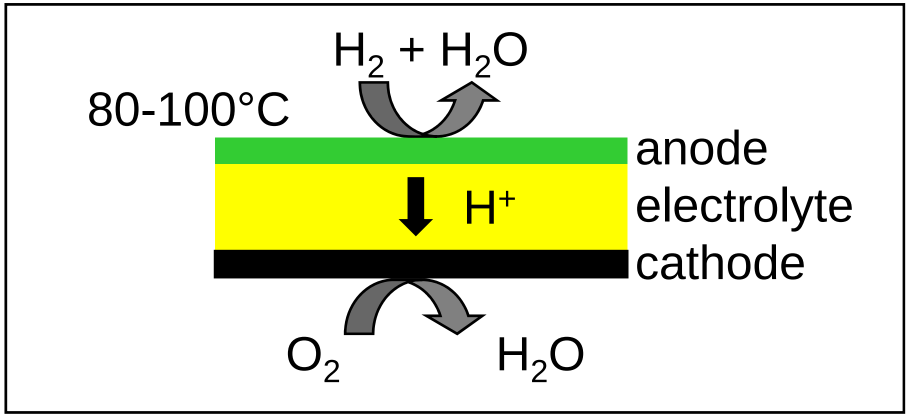
Toshiba

Samsung

Medis Technologies

direct liquid borohydride technology

Proton Exchange Membrane (PEM) Systems



Motorola / Angstrom

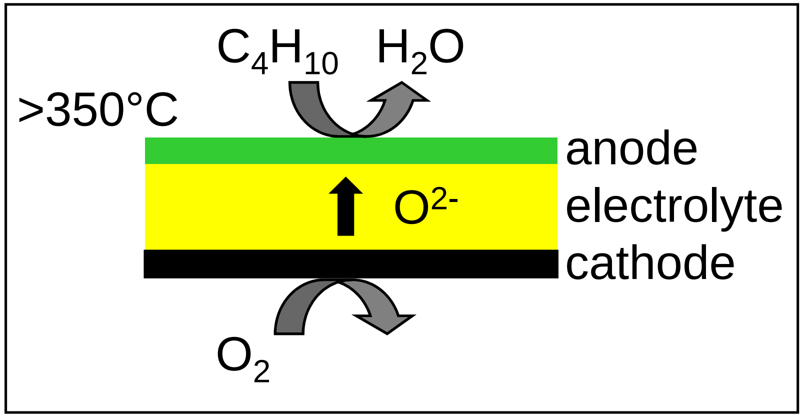
Jan. 2008:
fuel cell powered cell phone:
- same size
- 2x talk-time
- refueling in minutes

MyFC

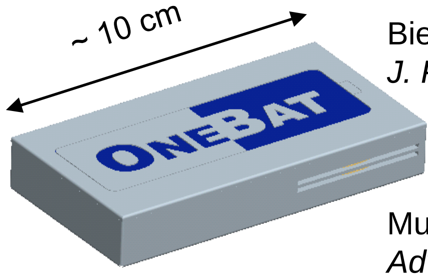
- charger for portable electronics
- April 08: prototype introduced

Fraunhofer Institute for Solar Energy Systems (ISE)

Solid Oxide Fuel Cell (SOFC) Systems



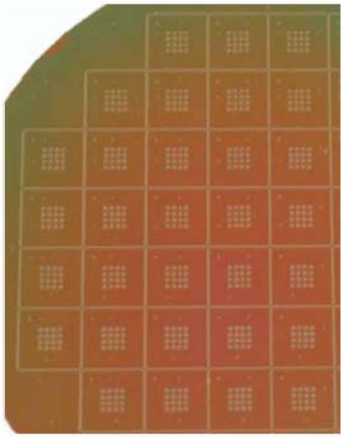
Boston, USA



ETH Zurich, CH

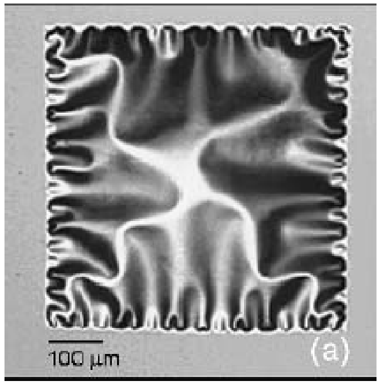
Bieberle-Hütter et al.,
J. Pow. Sour. 2008

Muecke et al.,
Adv.Funct. Mat. 2008
in press



Standford, USA, Prinz

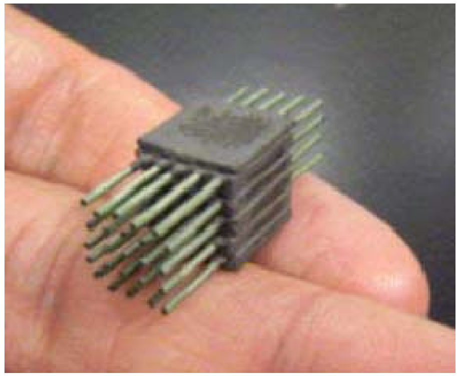
Huang et al.
J. Electrochem. Soc. 2007



MIT, USA, Tuller

Baertsch et al.
J. Mat. Res. 2004

Bieberle-Hütter et al.
J. Electroceramics 2006



AIST, J, Suzuki

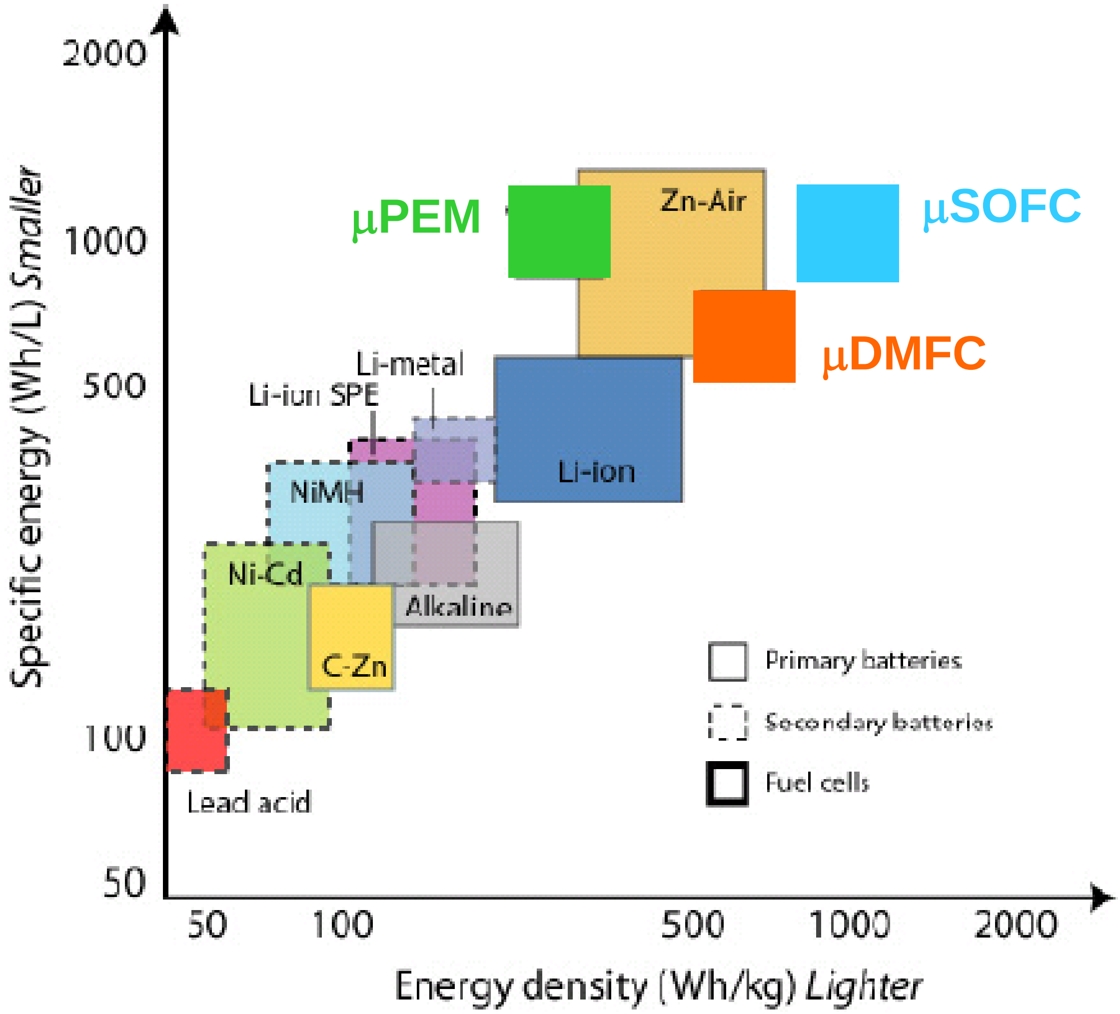
Nikbin, *The Fuel Cell Review* 2006

Jasinski, *Microelectronics Intern.* 2008

Caltec, USA, Haile

Shao et al., *Nature* 2005

Advantages / Disadvantages of Fuel Cell Types



Manhattan Scientifics & L. Livermore National Laboratories and Sulzer Hexis, 2002
Rey-Mermet, PhD Thesis, 2008

	Type of cell	Temp.	Fuel	Electrolyte	Single cell size	Substrate	Power density	Ref.
PEM	µPEMFC	25°C	H_2		5 cm^2	Si	190 mW/cm^2	[6, 7]
PEM	µPEMFC	25°C	H_2		5 cm^2	Si/glass	42 mW/cm^2	[8]
PEM	µPEMFC	60°C	H_2		1.4x1.2 cm^2	PDMS	35 mW/cm^2	[9]
PEM	µPEMFC	25°C	H_2	Nafion	5 cm^2	PMMA	31 mW/cm^2	[10]
DMFC	µDMFC	70°C	C_2H_6	Fluorocarbon 20 nm thick			200 mW/cm^2	[11]
DMFC	µDMFC		C_2H_6		1 cm^2	Si	25 mW/cm^2	[12]
DMFC	µDMFC		C_2H_6	PVDF	6 cm^2	Plastic	12 mW/cm^2	[13]
SOFC	µSOFC	400°C	H_2/H_2O	YSZ sputt.	50x50 μm^2	Si	400 mW/cm^2	[3]
SOFC	SC-µSOFC	~550°C	C_3H_8	SDC	1.42 cm^2	Anode Ni-SDC	250 mW/cm^2	[5]
SOFC	µSOFC	600°C	H_2	YSZ	5x5μm^2	Si/Si_3N_4	145 mW/cm^2	[2]
SOFC	µSOFC	550°C	H_2	YSZ bilayer. PLD/Spray	150µm diam.	Foturan	150 mW/cm^2	[4]
	µDFAC stack	25°C	Formic acid	Nafion		Si	60 mW/cm^2 Stack 30W	[14]
	µDFAC	30°C	Formic acid	Nanoporous Si	100µm diam.	Si	30 mW/cm^2	[15]
	µDFAC	60°C	Formic acid	Nafion	5 cm^2		110 mW/cm^2	[16]

Rey-Mermet, PhD Thesis 2008

Overall Challenges for Micro-Fuel Cells

main issues for the next decade:

fuel infrastructure

costs (fuel, system)

performance stability

selection of best fuel cell system for specific application

system development

establish new technologies

"solved" issues:

safety
→ VIASPACE / DMFCC

public awareness, acceptance
→ US aircraft regulation 2007

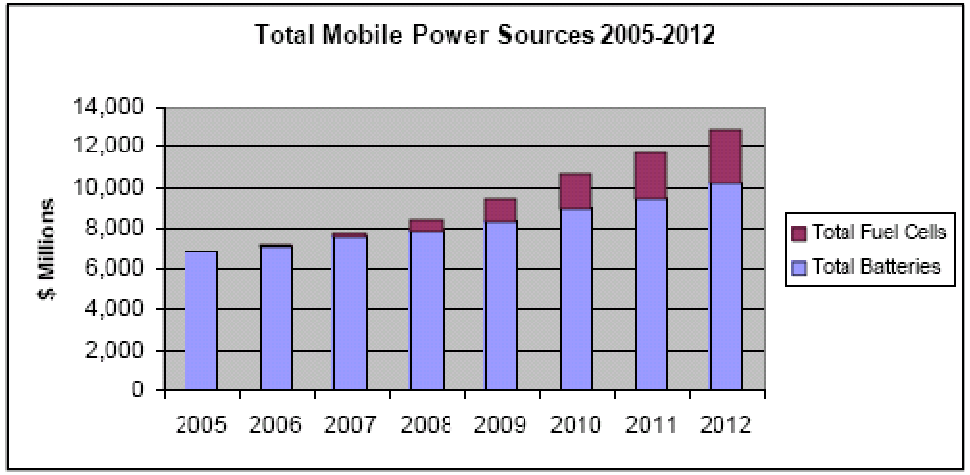
battery competitors
→ good

→ high energy density

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Chances for Micro-Fuel Cells

- many feasible applications
- long runtime
- geographical independence
- no charging time, easy charging
- huge and existing markets



Nanomarkets Research Report: Micro Power Sources 2005

annual average growth rate for µFC (2006-11): 50-90%

Innovative Research and Products Inc. (iRAP), Stamford, Conn (2006).

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

anja.bieberle@mat.ethz.ch, Nonmetallic Inorganic Materials

Summary

A) Miniaturized Fuel Cell Systems in General

- Miniaturized fuel cells are predicted a great future
- DMFC most developed
- SOFC best potential: energy density, materials, fuel

B) Example: ONEBAT Micro-Solid Oxide Fuel Cell System

Beckel, Galinski, Infortuna, Muecke, Rupp, Ryll, Scherrer, Tölke, **Gauckler**,

Rey-Mermet, **Muralt**,

Bieri, Hotz, Stutz, **Poulikakos**,

Heeb, **Bernard**,

Gmür, Hocker, **Schwarzenbach**

Zurich University of Applied Sciences
zh aw School of Engineering
ICP Institute of Computational Physics

ETH Ceramics
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
LABORATOIRE DE CERAMIQUES

NTB
INTERSTAATLICHE HOCHSCHULE
FÜR TECHNIK BUCHS

ONEBAT

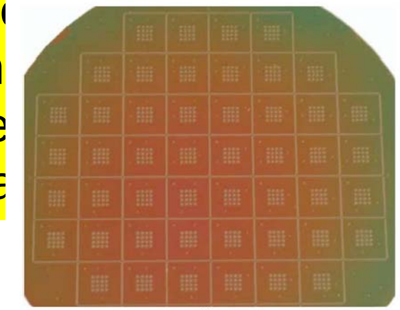
ETH LTNT
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

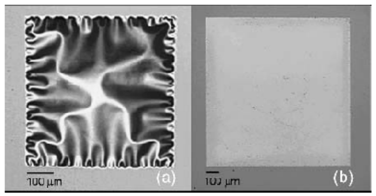
Aim: Development of Micro-SOFC System

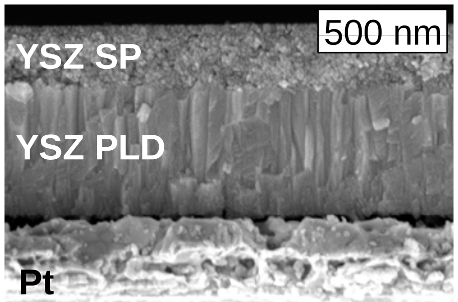
Thin films **Thin film ..... membranes** .... **Micro-SOFC system**

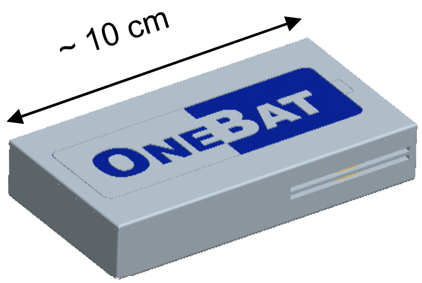
J. Rupp:
Micro-Solid Oxide
From Thin Film
Delivering Me
11.25 a

Poster Sessio

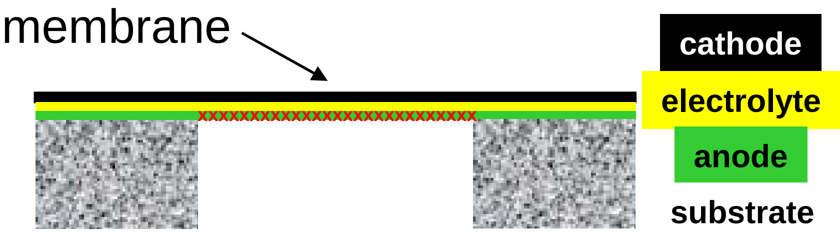


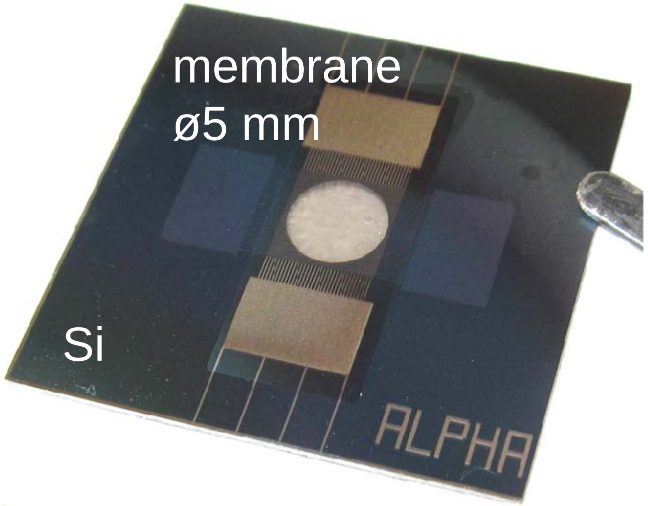


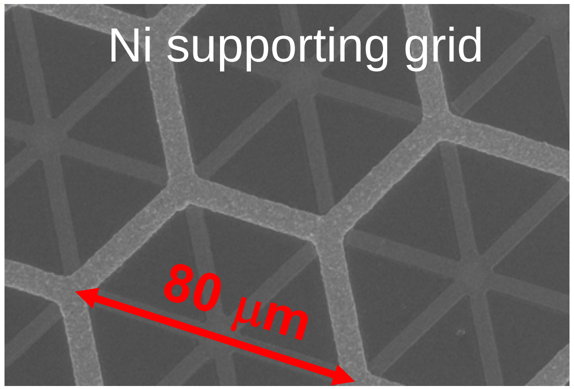




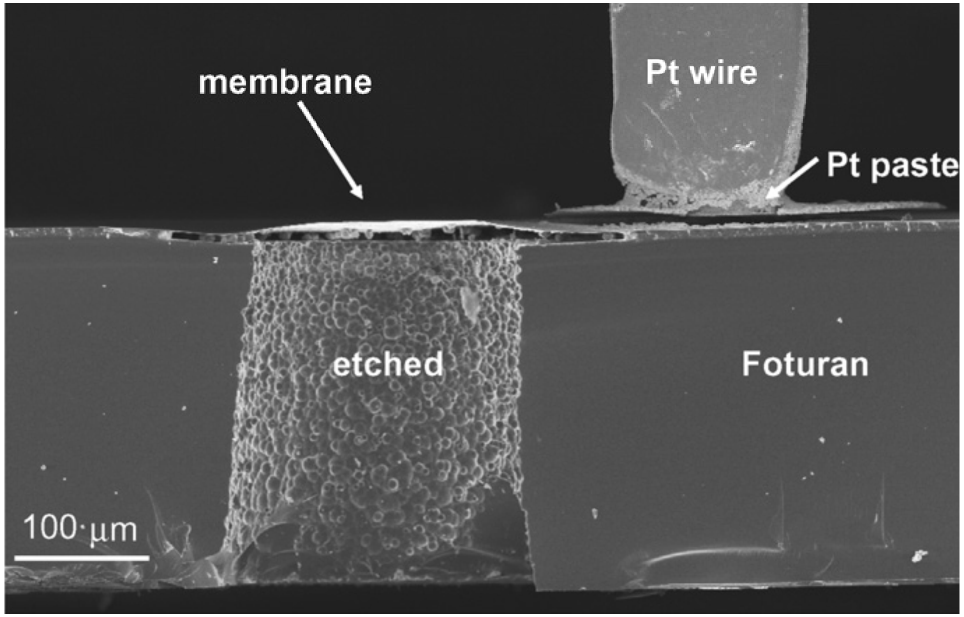
Micro-SOFC Membranes







Rey-Mermet et al., PCT/EP2006/069688 2006



Muecke et al., Adv. Funct. Mat. (2008) in press.

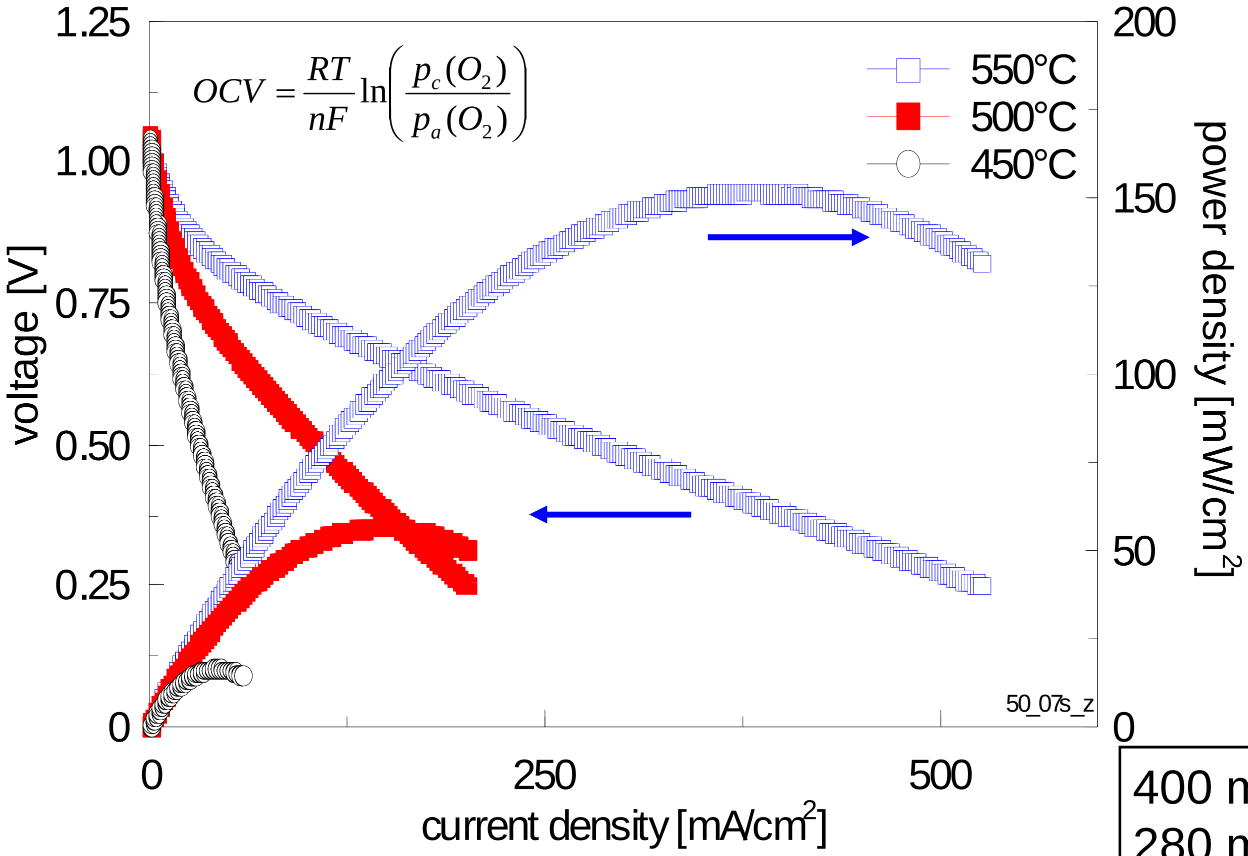
Bieberle-Hütter et al., J. Power Sources 177 (2008) 123.

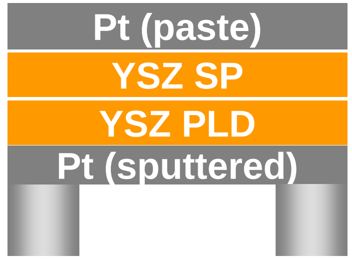
Free-standing three layer SOFC membrane:

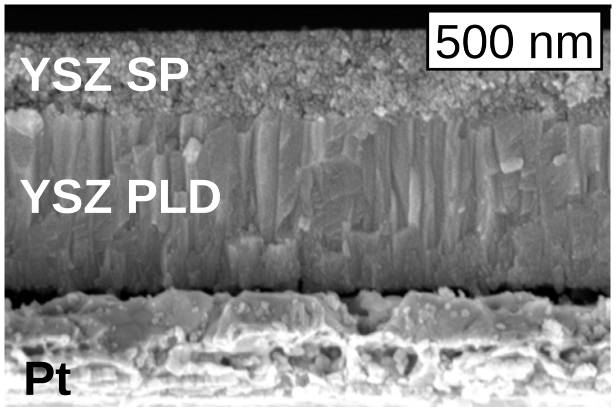
- dense and crack-free
- total thickness < 1 µm
- maximum diameter up to 5 mm

Micro-SOFC Performance

YSZ PLD/YSZ SP bi-layer electrolyte cell







OCV = 1.06 V, P = 150 mW/cm² @ 550°C

P_{max} = 238 mW/cm² @ 550°C

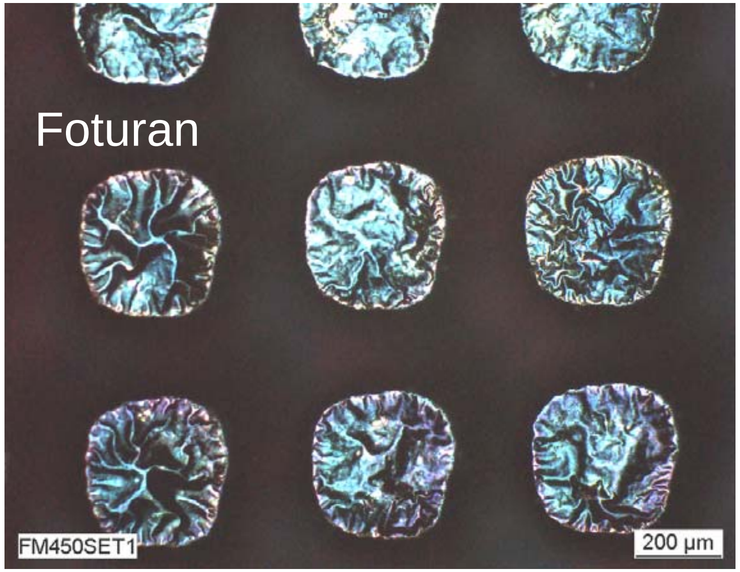
400 mW/cm² / membrane at 400°C
280 mW/cm² / membrane at 350°C

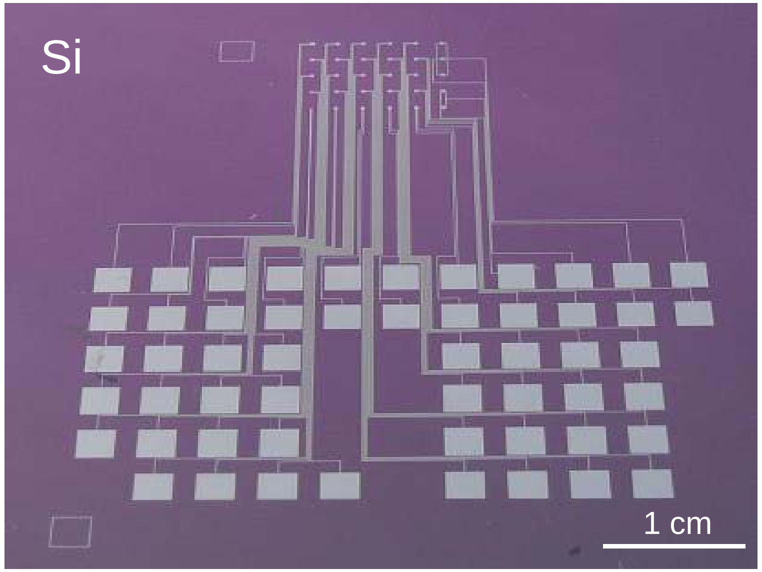
Huang et al. J. Electrochem. Soc. (2007).
Shim et al. Chem. Mater. (2007).

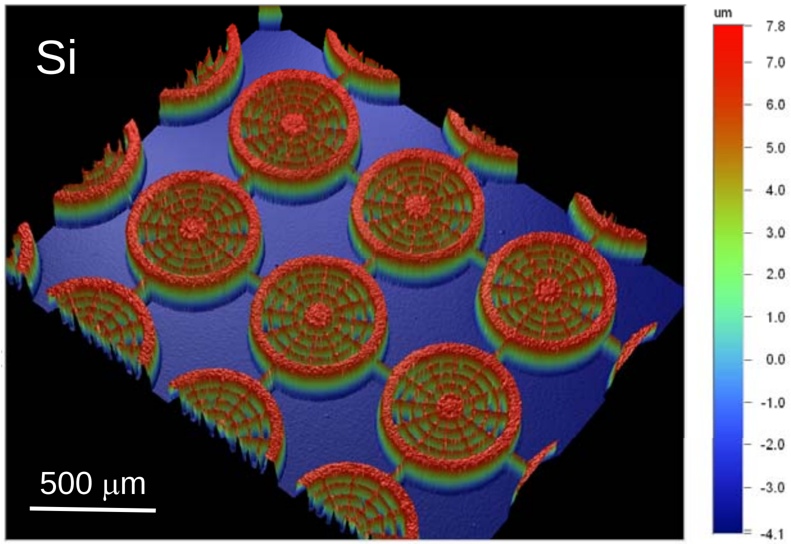
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Muecke et al., Adv. Funct. Mat. (2008) in press.

Multi-Membrane Arrays







assume: 2.5 W system
$P = 350\ mW/cm^2$

→ membrane area required = 7 cm^2

→ $area_{tot}$ required = 15 cm^2 for $\frac{active}{passive}$ = 1:1
28 cm^2 = 1:3

→ # membranes = 23.000 for ø 200 µm
36 for ø 5 mm

PhD theses Tölke and Rey-Mermet

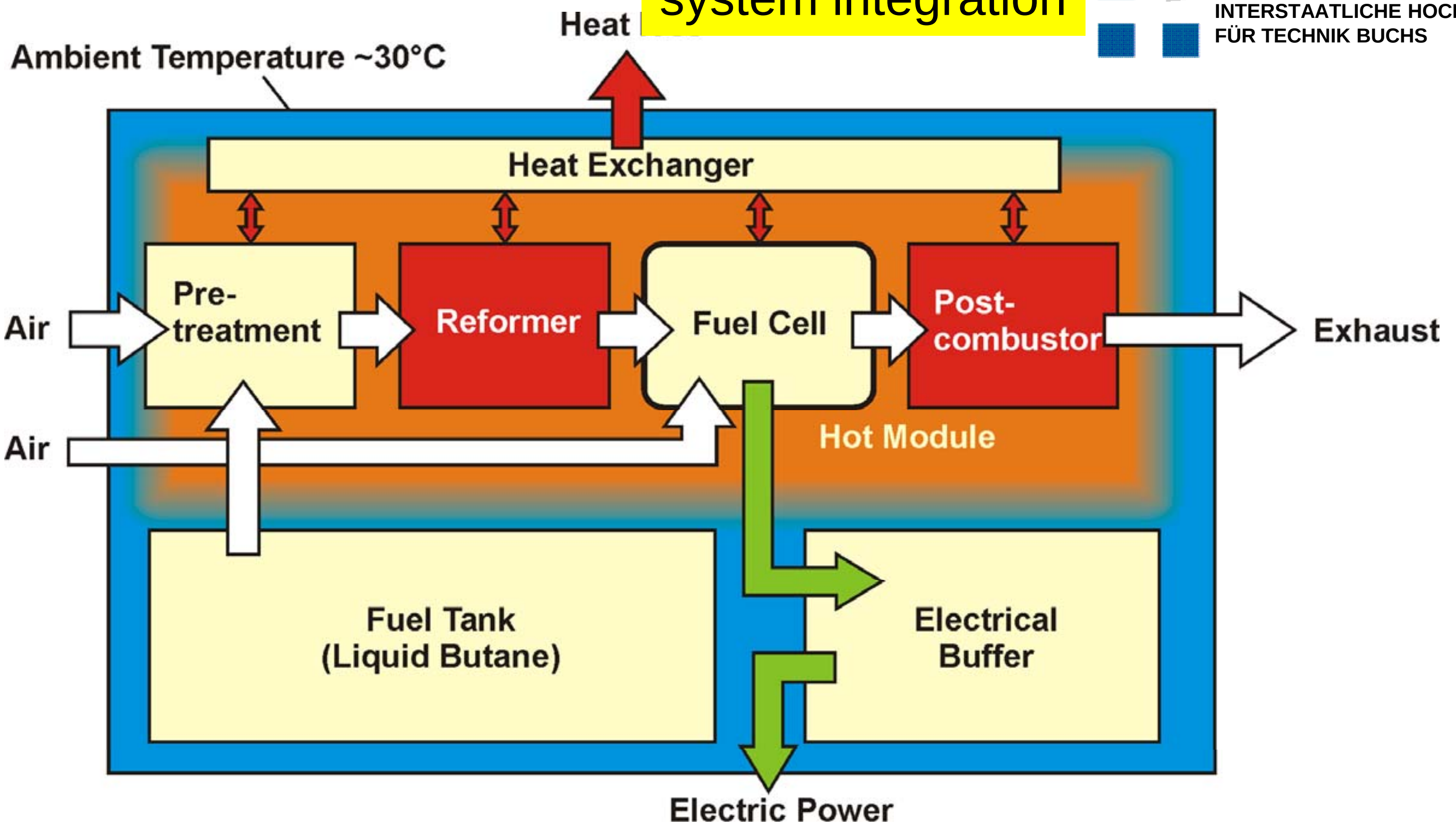
ONEBAT

System Design

gas processing unit — ETH Eidgenössische Technische Hochschule Zürich, Swiss Federal Institute of Technology Zurich (LTNT)

thermal system management — zhaw School of Engineering, ICP Institute of Computational Physics

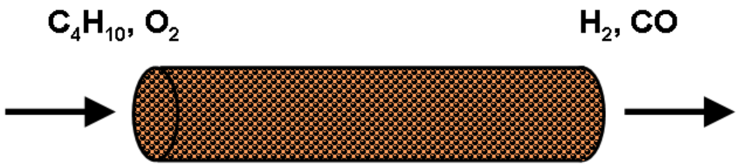
system integration — NTB INTERSTAATLICHE HOCHSCHULE FÜR TECHNIK BUCHS



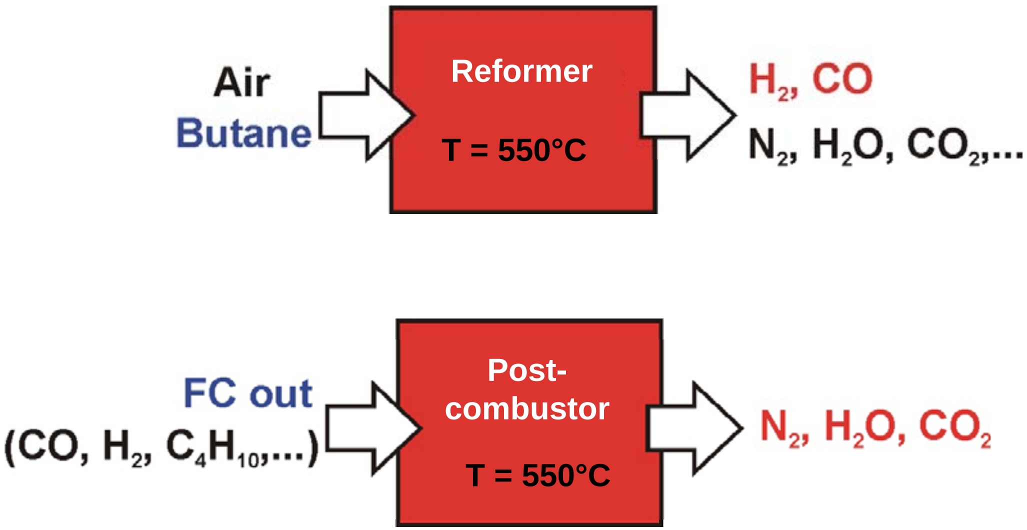
Gas Processing Unit (GPU)

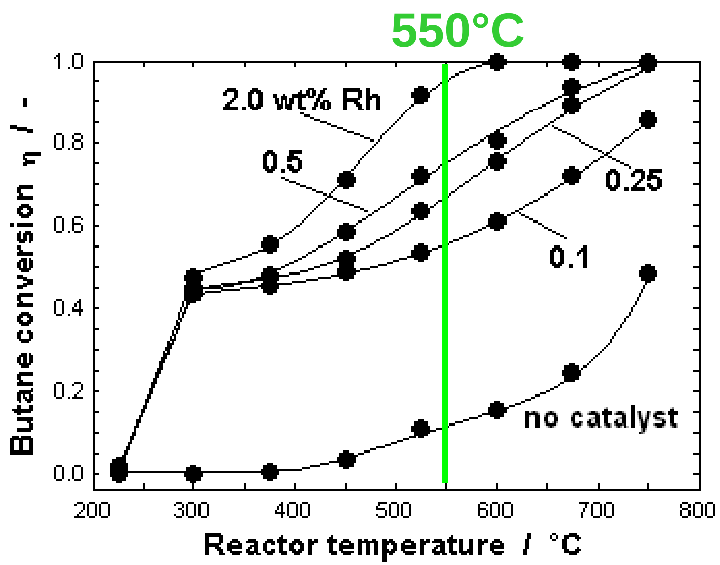
- Can we reform butane at 550°C?
- How to realize this in the system design?

tubular packed bed reformer:



Rh/ceria/zirconia





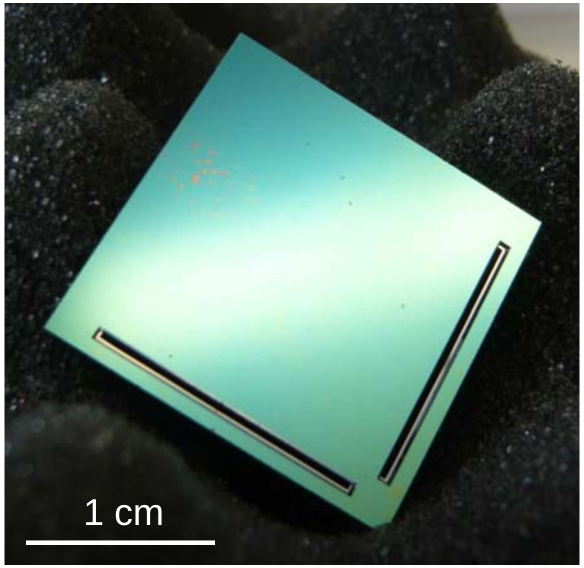
fuel / air = 0.8

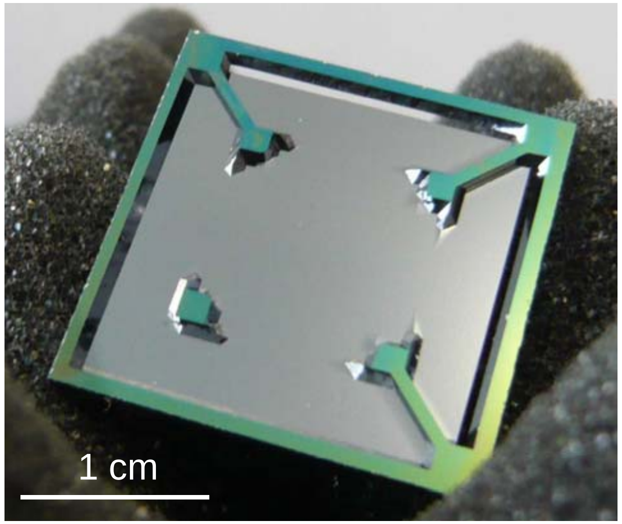
$$\eta = \frac{\dot{n}_{\mathrm{C4H10,in}} - \dot{n}_{\mathrm{C4H10,out}}}{\dot{n}_{\mathrm{C4H10,in}}}$$

Hotz et al., Appl. Catalysis B: Environmental 73 (2007) 336.

Microfabricated Si-Structures for GPU

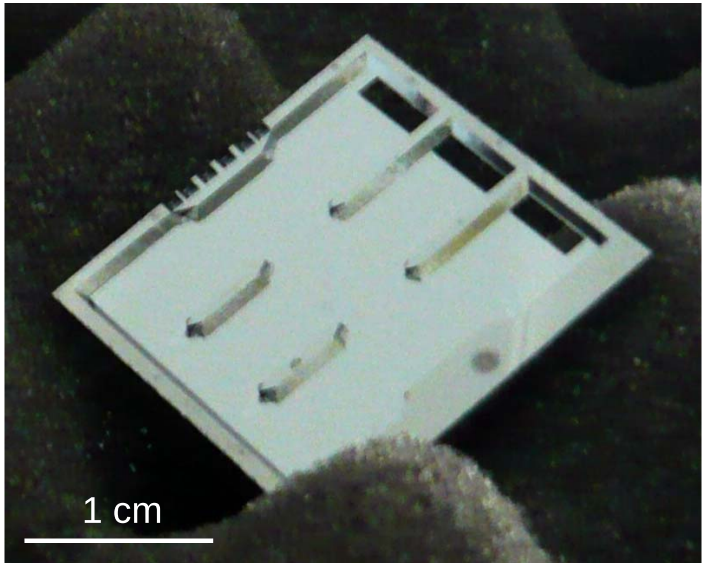
post-combustor
top

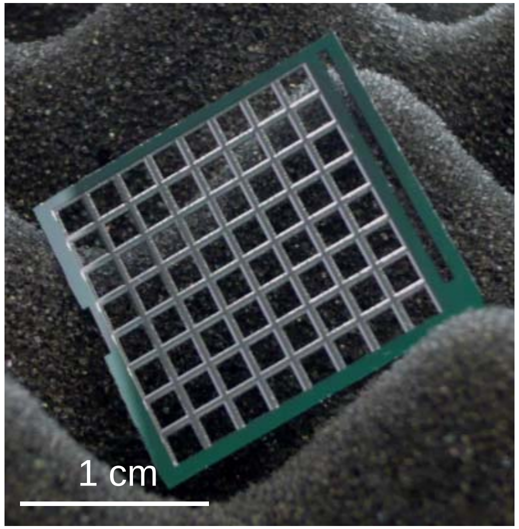




post-combustor
bottom

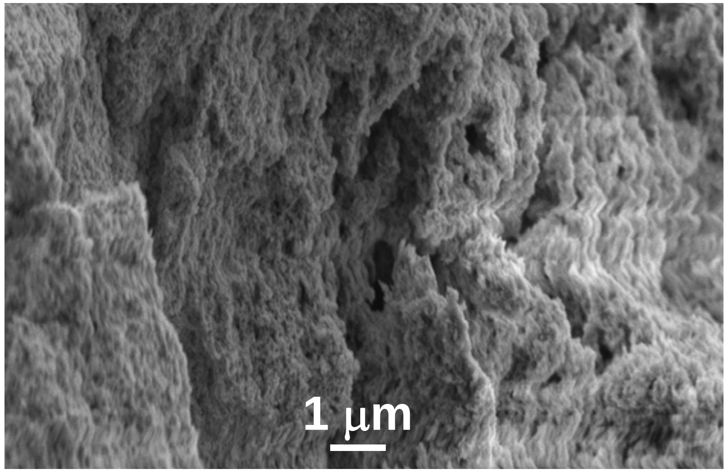
reformer
bottom





interconnector

Catalytic Activity of Porous Ceramic Reformer



Hotz et al., *applied for patent* (2008).

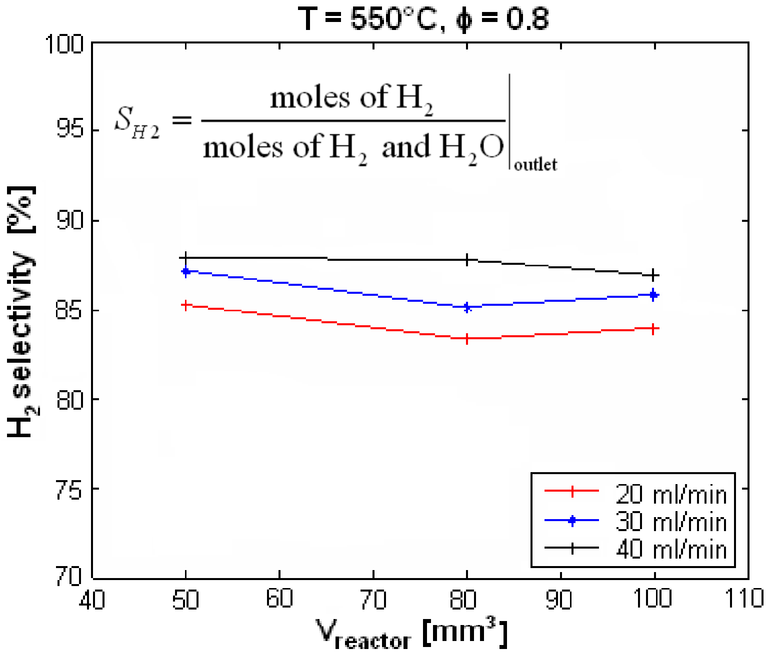
- 10 mg catalyst Rh/ceria/zirconia (2 wt% Rh, 10 nm average diameter)
- 30 mg SiO_2 sand (200 μm average diameter)

reactor volume: 37 mm³

→ exergy content of 2.2 W

Butane conversion:

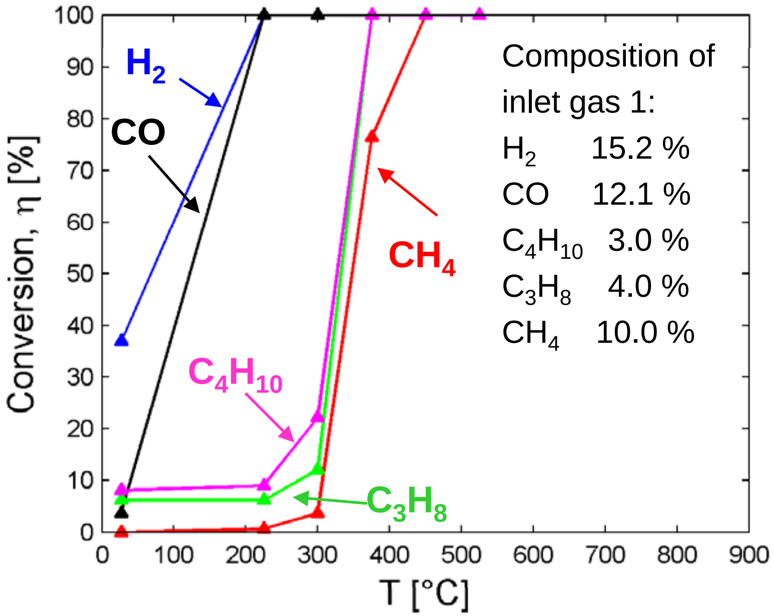
88 – 94 % @ 550°C

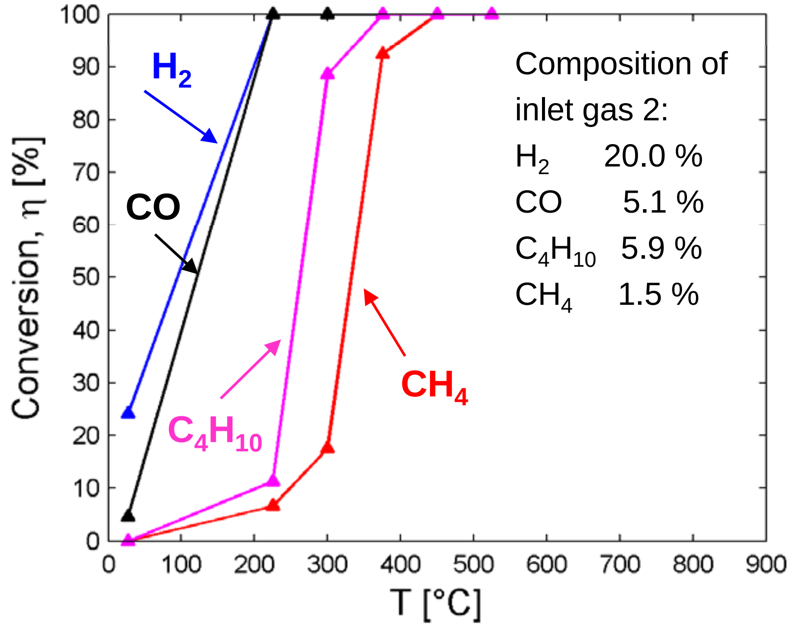


High catalytic activity at 550°C

Post-Combustor

Flame-made Pd/Pt/alumina catalyst





Conversion:

(T = 500°C)

- H_2 100 %
- CO 100 %
- C_4H_{10} 100 %
- C_3H_8 100 %
- CH_4 100 %

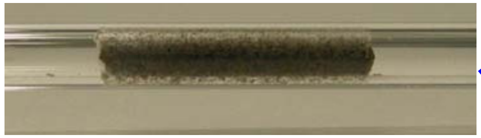
- H_2 100 %
- CO 100 %
- C_4H_{10} 100 %
- CH_4 100 %

fuel exhaust gas oxidation 100% at 500°C

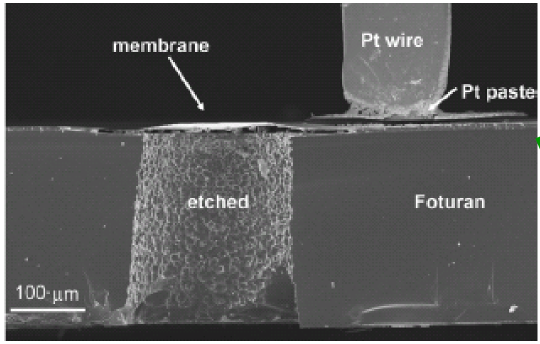
anja.bieberle@mat.ethz.ch, Nonmetallic Inorganic Materials

Component Integration into Hot Module

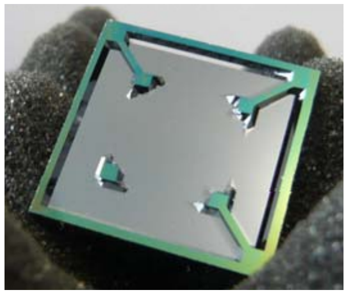
Reformer



Membranes



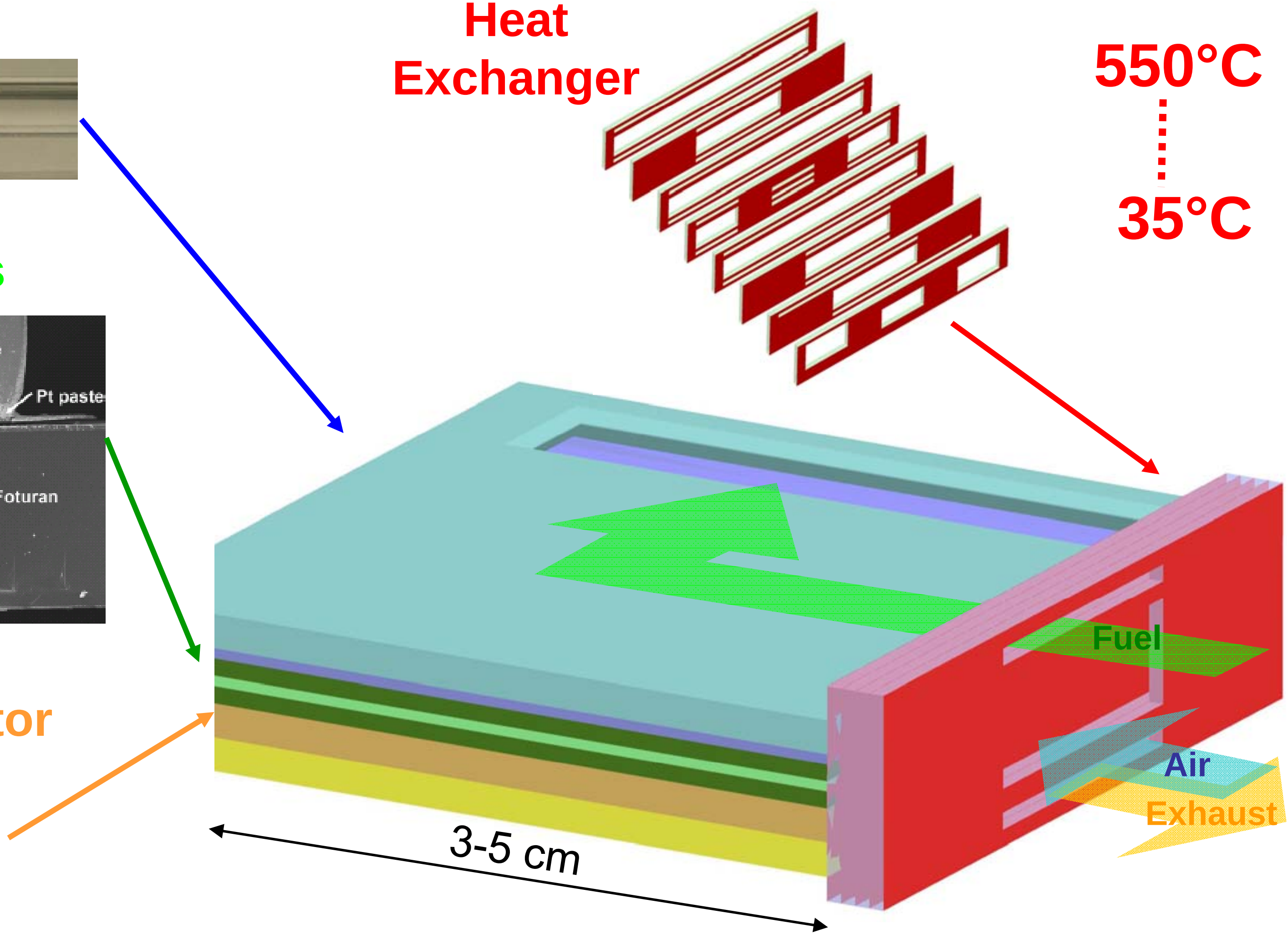
Post-Combustor



Heat Exchanger

550°C

35°C

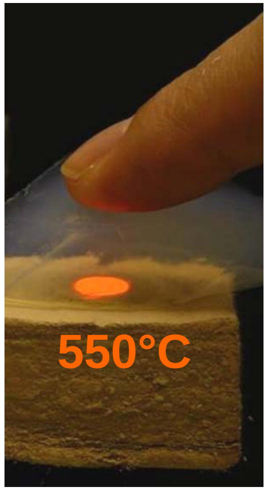


planar, rectangular, multi-wafer design

Thermal System Management

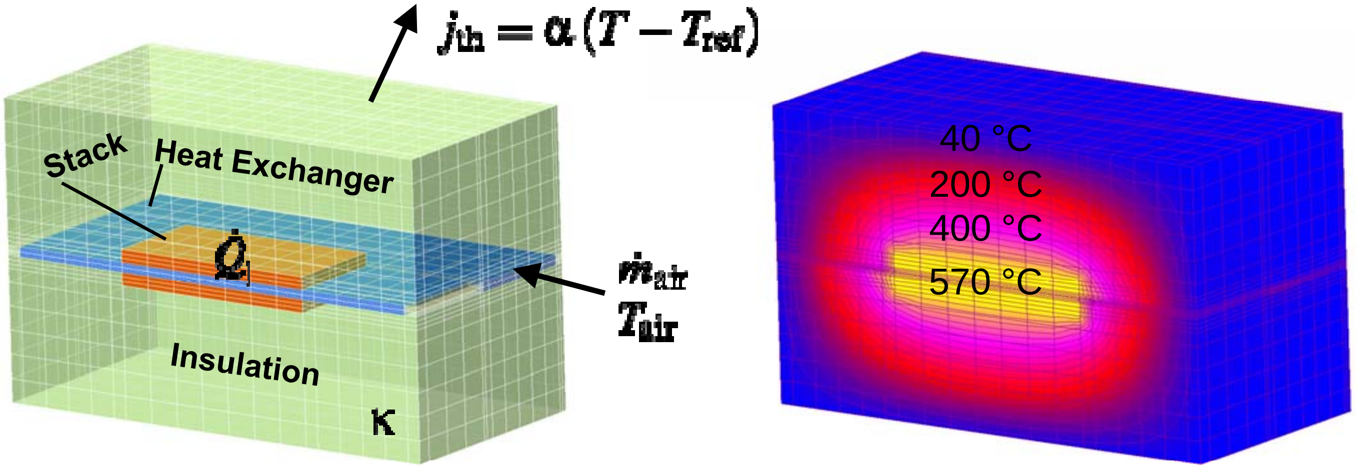
Main Issues:
- large temperature gradient of ~ 500°C
- uniform stack temperature of 550°C
- start-up of the system

Experiments



good insulation materials exist

3D Thermo-Fluidic FE Modeling



Temperature gradient of 500°C is feasible.

Bieberle-Hütter et al., J. Power Sources 177 (2008) 123.

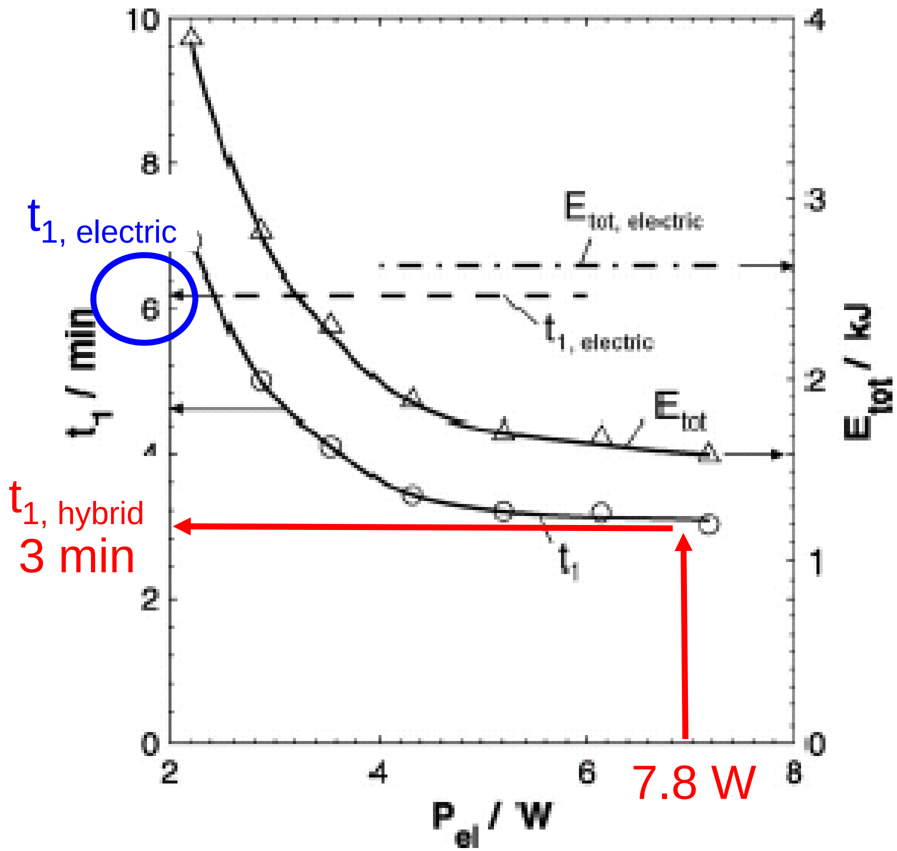
Start-Up: Hybrid Heating

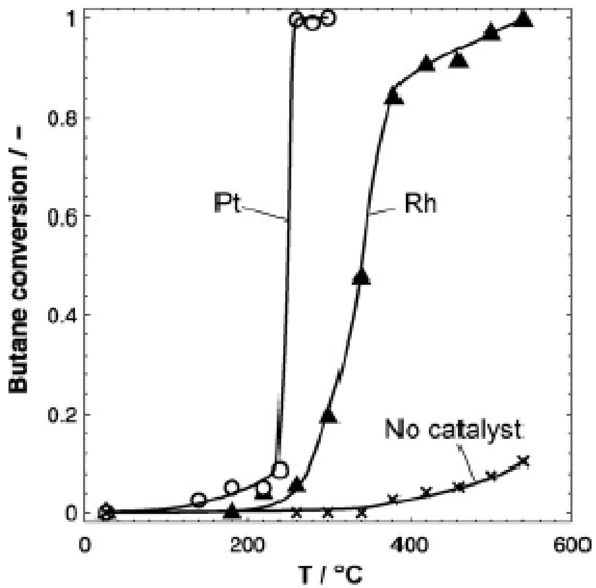
RT ------------------ T_{stop} ------------ $T_{operation}$

~ 300°C ~ 600°C

electrical heating + heating by exothermic butane conversion (max. heat release: 7.8 W)	turn-off voltage source	heating by exothermic butane conversion

t_1 →





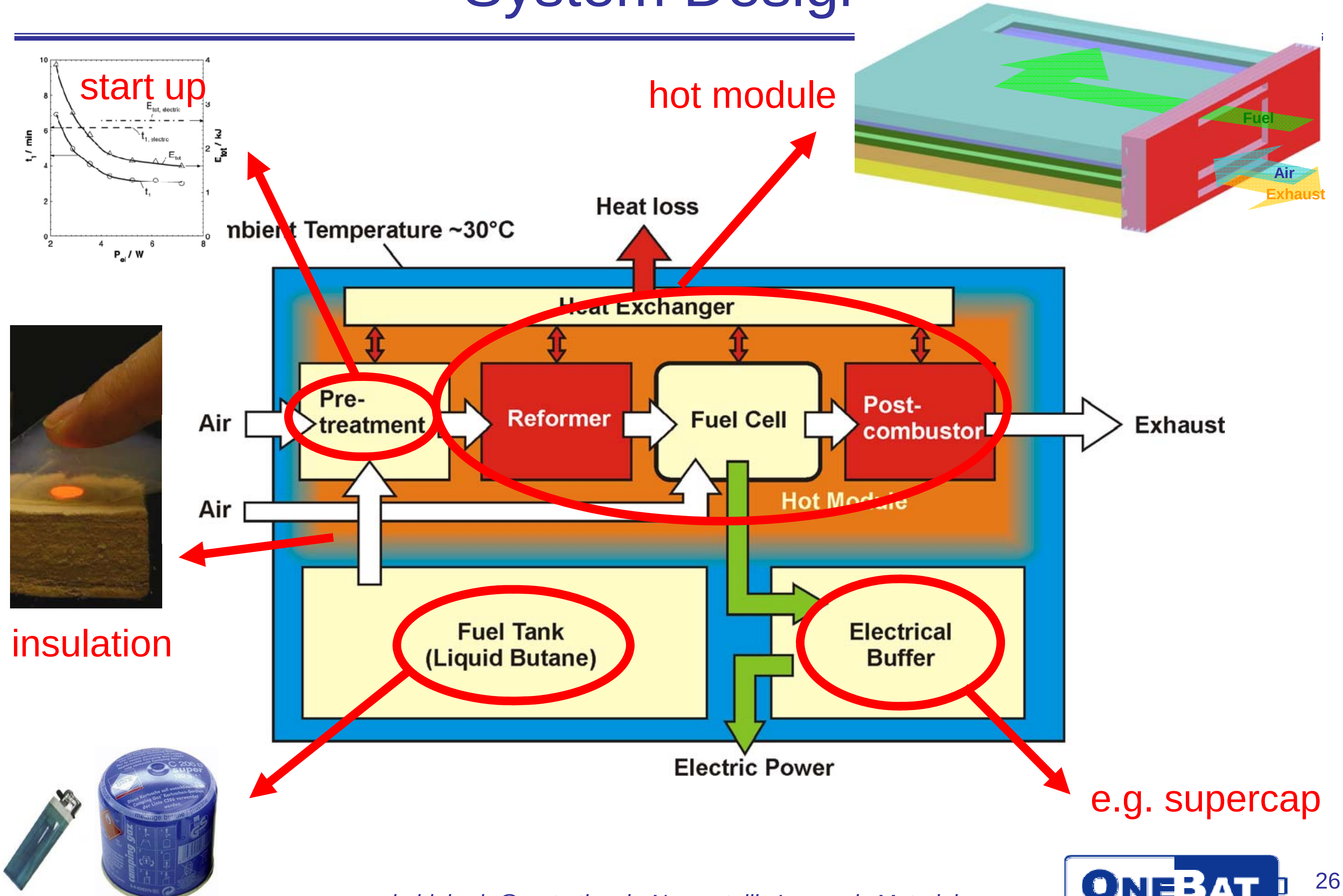
→ reduction of start-up time by 51% (max. 79%)

(→ reduction of exergy cost up to 86%)

Stutz et al., J. Power Sources 182 (2008) 558.

ONEBAT

System Design



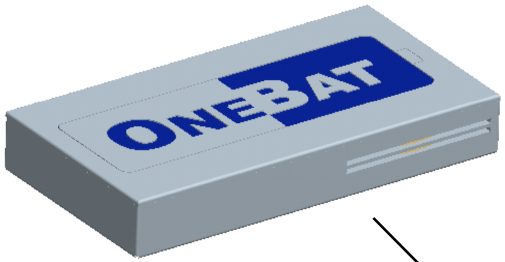
System Design

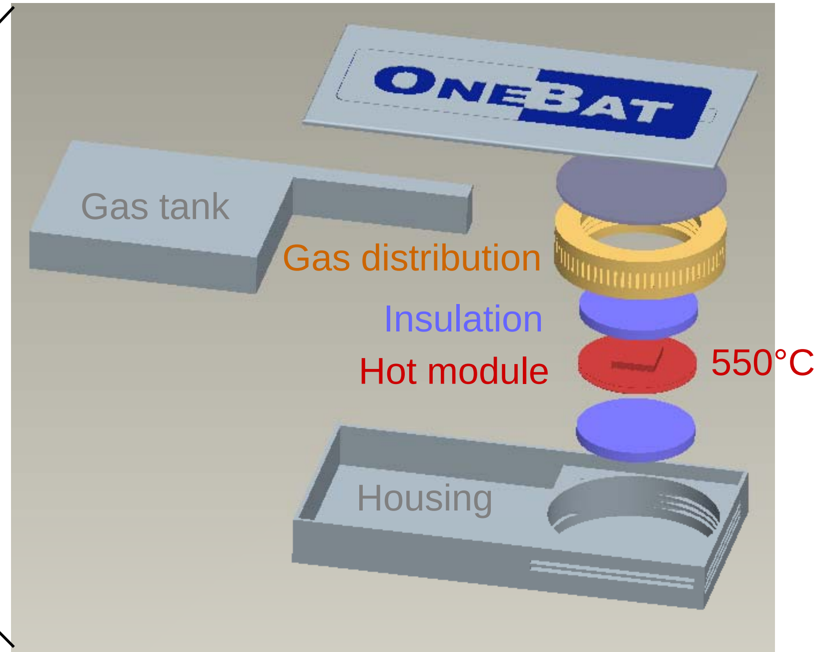
VARTA Easy Pack

(Li-ion battery)

ONEBAT

(micro-SOFC)





El. Power	**2.5 W**	**5 W**	**20 W**
Voltage	3.7 V	7.4 V	11.1 V – 14.8 V
Active surface	7.75 cm^2	15.5 cm^2	62 cm^2
Total Volume (system + fuel)	65 cm^3 (28 + 37)	120 cm^3 (45 + 75)	410 cm^3 (110 + 300)
Application	mobile devices, battery charger	Scanners, DSC , MDA, video phone	LP, NB, medical devices, power tools

Summary

A) Miniaturized Fuel Cell Systems in General

- Miniaturized fuel cells are predicted a great future
- DMFC most developed
- SOFC best potential: energy density, materials, fuel

B) Example: ONEBAT Micro-Solid Oxide Fuel Cell System

Fuel Cell

P_{max} = 238 mW/cm^2
at 550°C

5 mm free-standing membrane

Gas Processing Unit

at 550°C:
~80 % butane conversion

80-90 % H_2 selectivity

60-75 % CO selectivity

Thermal System Management

550°C inside – 35°C outside

System Development

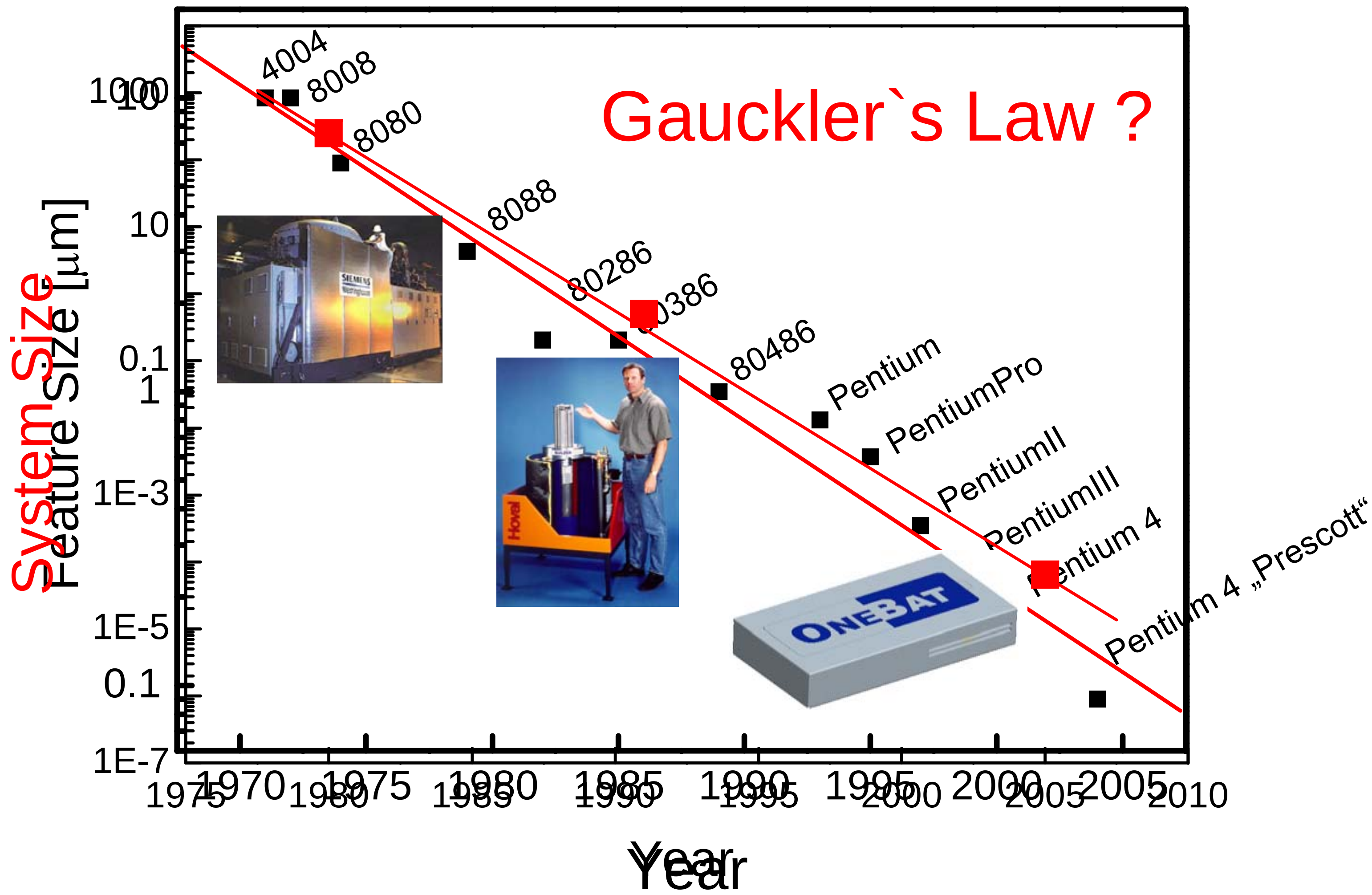
manufacturable system design

Poster !!

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

anja.bieberle@mat.ethz.ch, Nonmetallic Inorganic Materials

Outlook



http://www.intel.com/

Thanks to ...

... the ONEBAT consortium for the excellent work !

KTI/CTI — Federal Office for Professional Education and Technology

ccem.ch — Competence Center for Energy and Mobility

swisselectric research — Swiss electricity grid companies

BFE OFEN UFE SFOE — Swiss Federal Office of Energy

HILTI

Mikroglas