2nd Joint European Summer School on Fuel Cell and Hydrogen Technology
Crete, 17th – 28th Sept. 2012

UNIVERSITY OF BIRMINGHAM

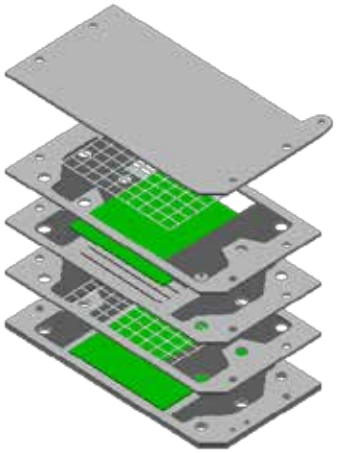
SOFC Degradation

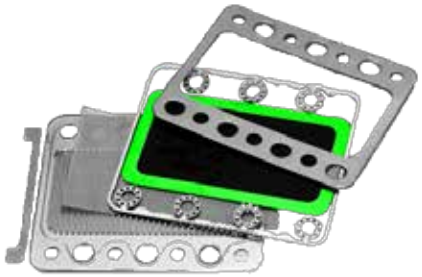
Prof. Dr. Robert Steinberger-Wilckens
Centre for Hydrogen & Fuel Cell Research
University of Birmingham

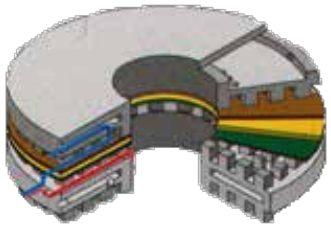
European SOFC Stack Technologies

Variety of manufacturers and design types

- planar stacks
  - higher performance
  - compact design
  - mechanically robust
  - simple manifolding
  - lower cost
- tubular stacks
  - resistant to high temperature gradients (*)
  - mechanically robust (*)
  - low power density

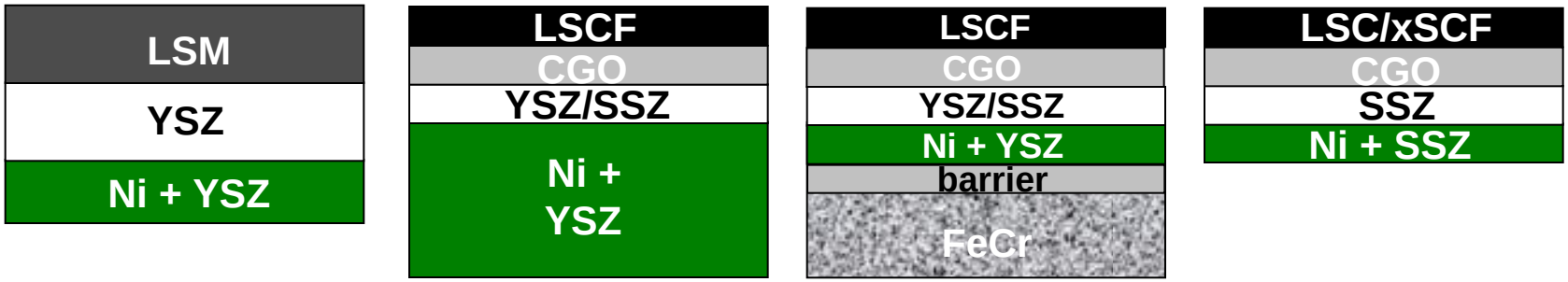






(*) thermo-mechanical stability greatly depends on SIZE, not so much on concept

Variety of SOFC Cell Concepts



Electrolyte supported ~ 300µm ESC	Anode supported 600 µm – 1 mm ASC	Metal supported ~ 1 mm MSC	Thin films on thin substrate ~ 300 µm ASC

1000 °C Temperature 700 °C 700 °C 400 °C

Specific properties with different application opportunities

Application Requirements

	Lifetime	Thermal cycles	Redox cycles	Efficiency	Weight
APU road vehicles	**5000 – 10000 h**	**2500 – 5000**	**5000 – 10000**	**η_{el}>30%**	**1 – 4 kg/kW**
APU aircraft / ships	**20000 – 100000 h**	**5000 – 20000**	**10000 – 40000**	**η_{el}>40%**	**1 kg/kW**
Residential	**> 40000 h**	**100 – 5000**	**100 – 5000**	**η_{el}>35%** **η_{tot}>90%**	**n/a**
Commercial	**> 40000 h**	**100 – 5000**	**100 – 5000**	**η_{el}>45%** **η_{tot}>85%**	**n/a**
Power Generation	**100000 h**	**100 – 5000**	**100 – 5000**	**η_{el}>50%**	**n/a**
Portable	**<2500 h**	**500 – 5000**	**500 – 5000**	**η_{el}>30%**	**n/a**

Performance of ‚Conventional' Products

Service life

- vehicles >10 years (5.000 to 10.000 operating hrs)
- heating boilers (residential power) >10 years (20.000 to 40.000 hrs, frequent cycles possible)
- power generating equipment 10 – 30 years (40.000 to 200.000 operating hours)

Other

- vibration and shock (road vehicles)
- acceleration (aircraft)
- simple coupling to natural gas supply (boilers/engines)

- you can even drop them …

SOFC Development Challenges

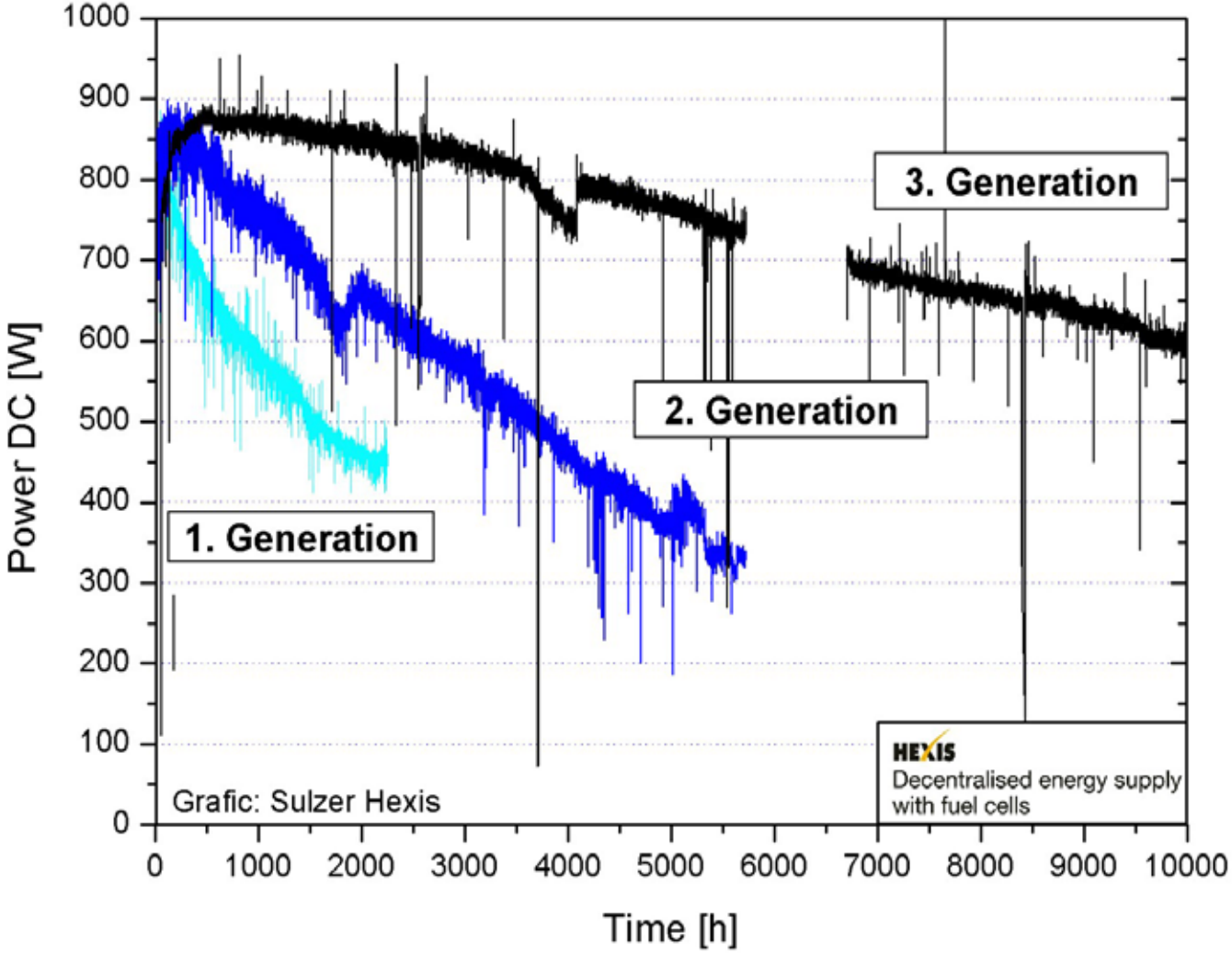
- improved durability under static, transient and cycling conditions
  - redox stability
  - thermal cycling capability
- stack lifetime in excess of 40.000 hrs. (stationary & la
  loss of power at end of life <20%)
- high performance, high efficiency
- arbitrary switch-off and start-up cycles (several 100 t
- tolerance against fuel impurities
- operation without external water supply
- robustness to vibration and mechanical shock
- design of large units and hybrid power plants
- lower cost, increased system compactness, simplification of technology

topics in joint materials, design and systems development

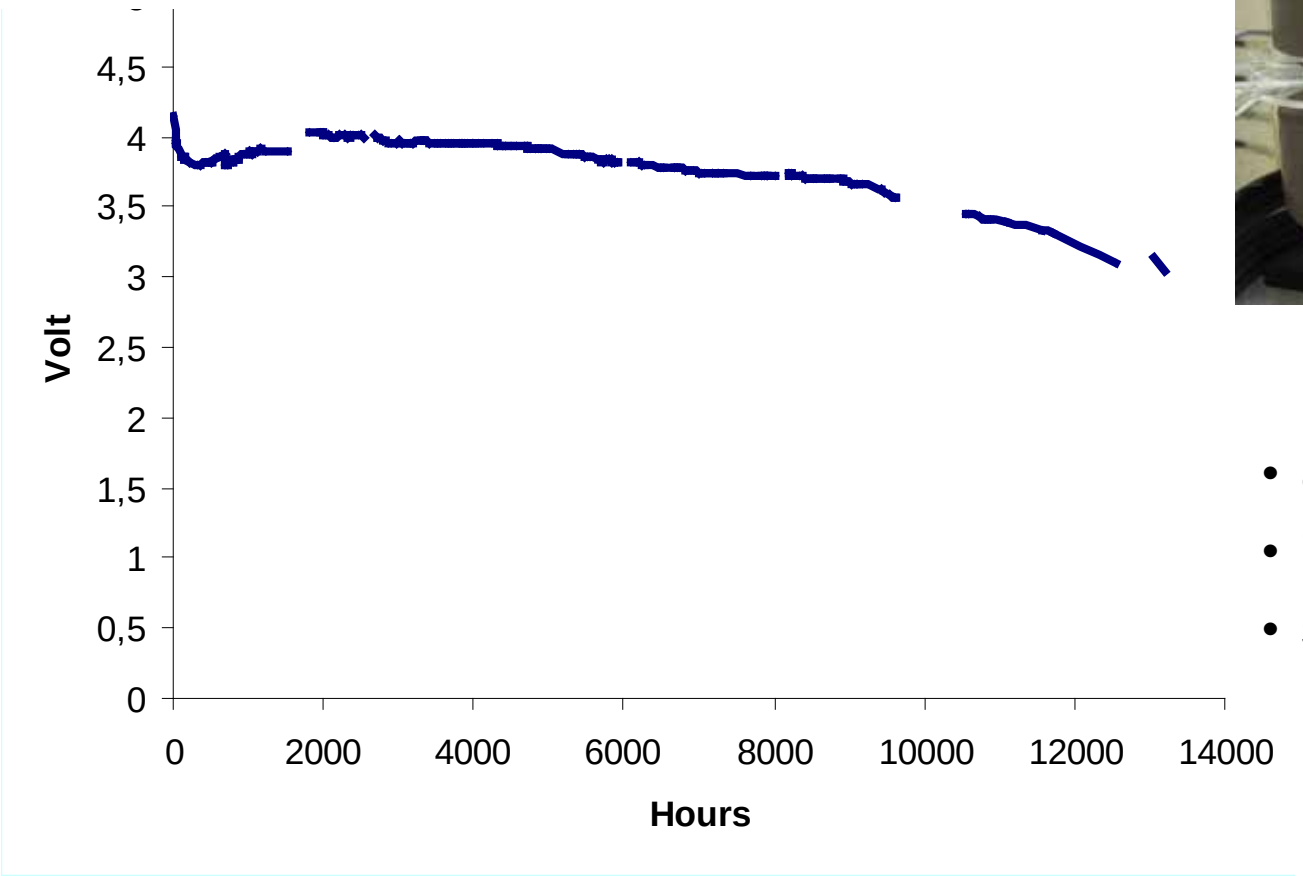
Priorisation (results of 2007 Crete workshop)

- high priority:
  - thermodynamics and kinetics of material stability
  - anode and cathode, including re-oxidation & chromium poisoning
  - protective layer & sealants
  - re-oxidation of anode
  - testing (incl. ALT), predictive models
- medium priority:
  - rapid start-up
  - fuel contaminants
- low priority:
  - steel oxidation etc.
  - load cycling

HEXIS: Comparison of ZIP Stack Generations (2000/2002)



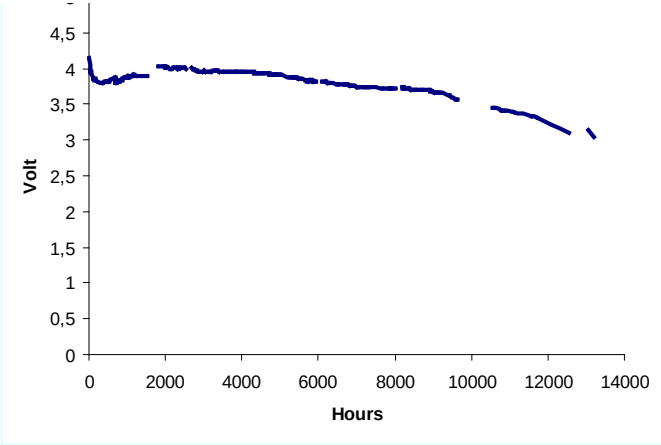
Long-term Test Topsoe Fuel Cells

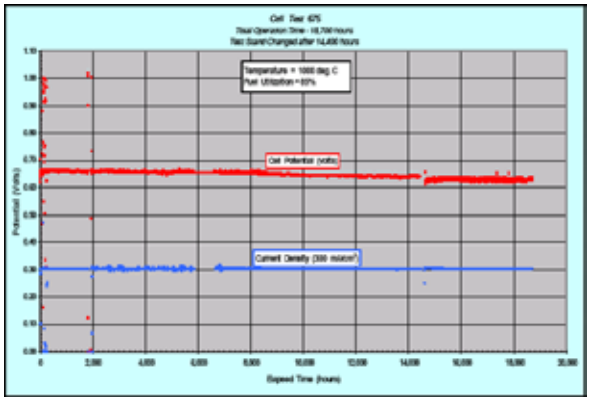


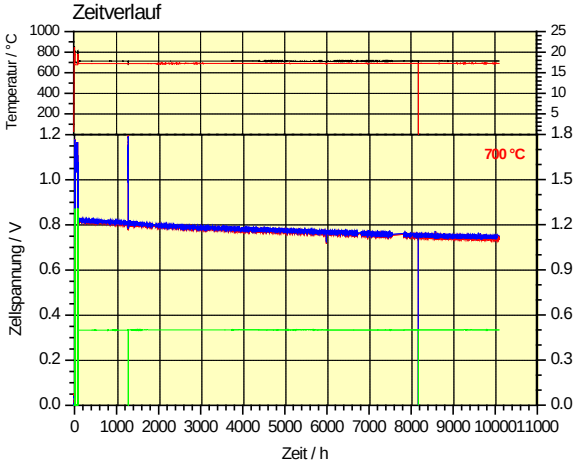
- average 2% / 1000 h
- 750°C, 250 mA/cm²
- several thermal cycles

Development Status in SOFC

- stack lifetime of 2 to 4 years shown (proven?)
- single cell lifetime of >> 2,5 years shown
- degradation of well below 1% / 1000 hrs. shown for more than 10 000 hours, but depends on operating conditions

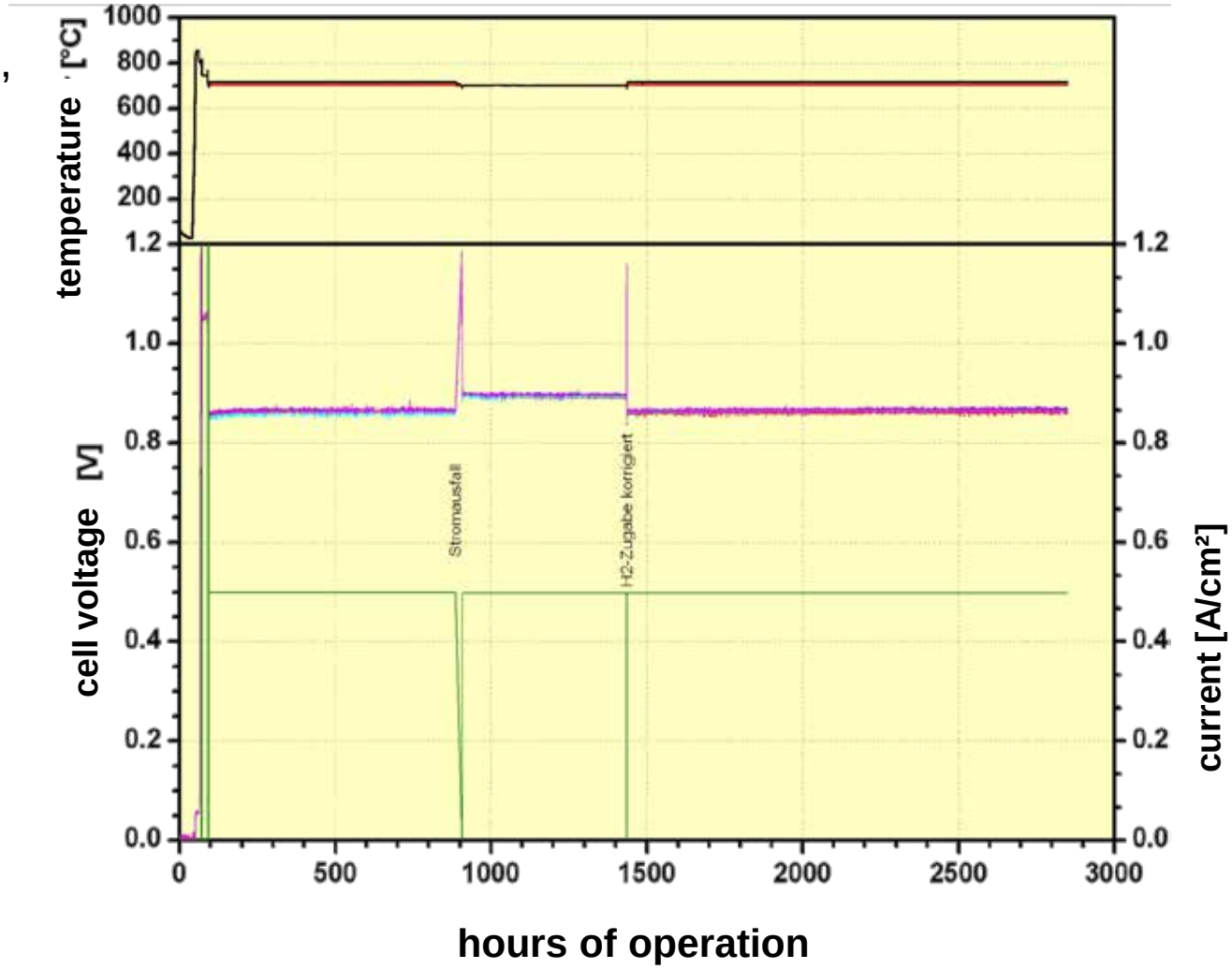




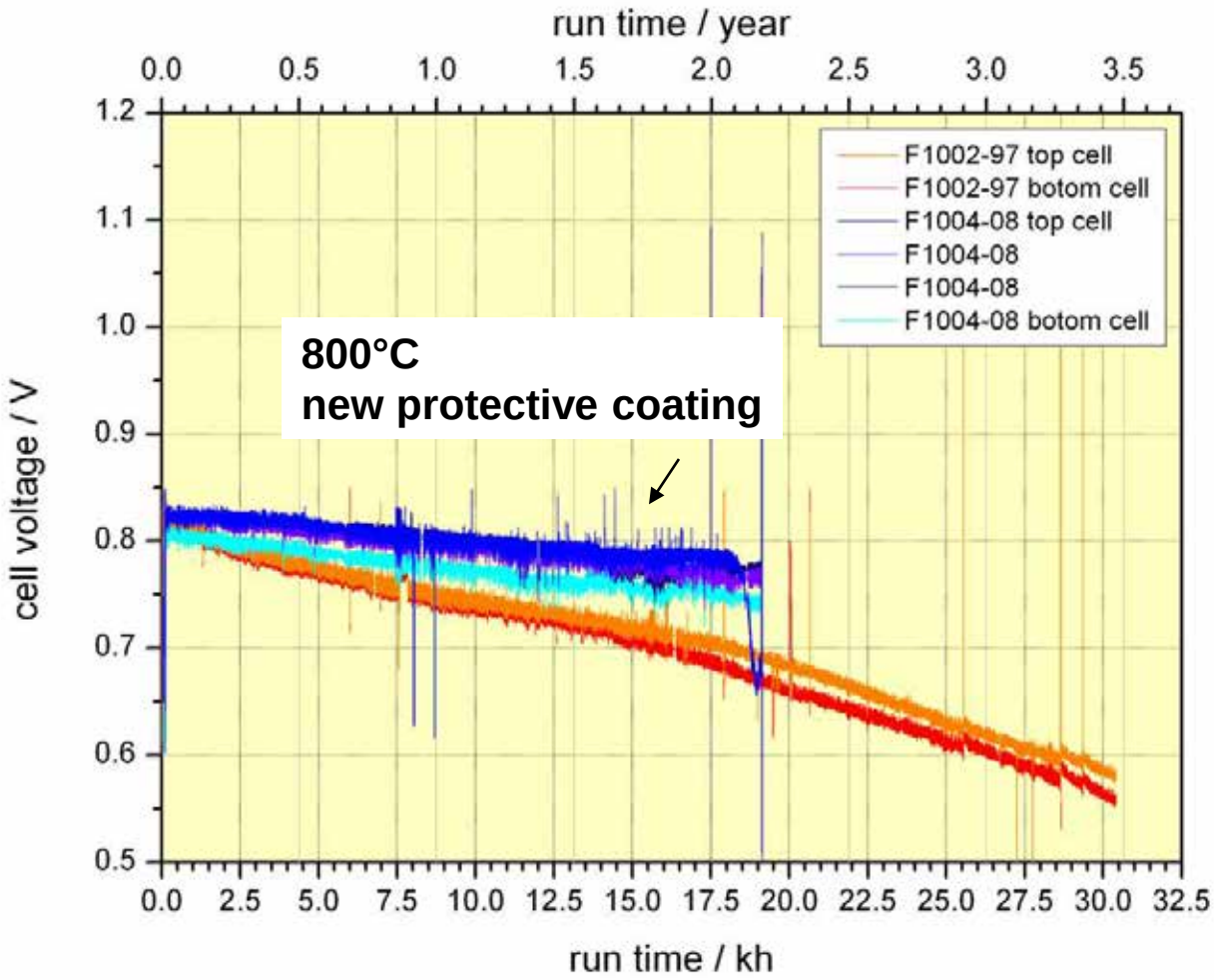


Proof of Concept Stack FZ Juelich

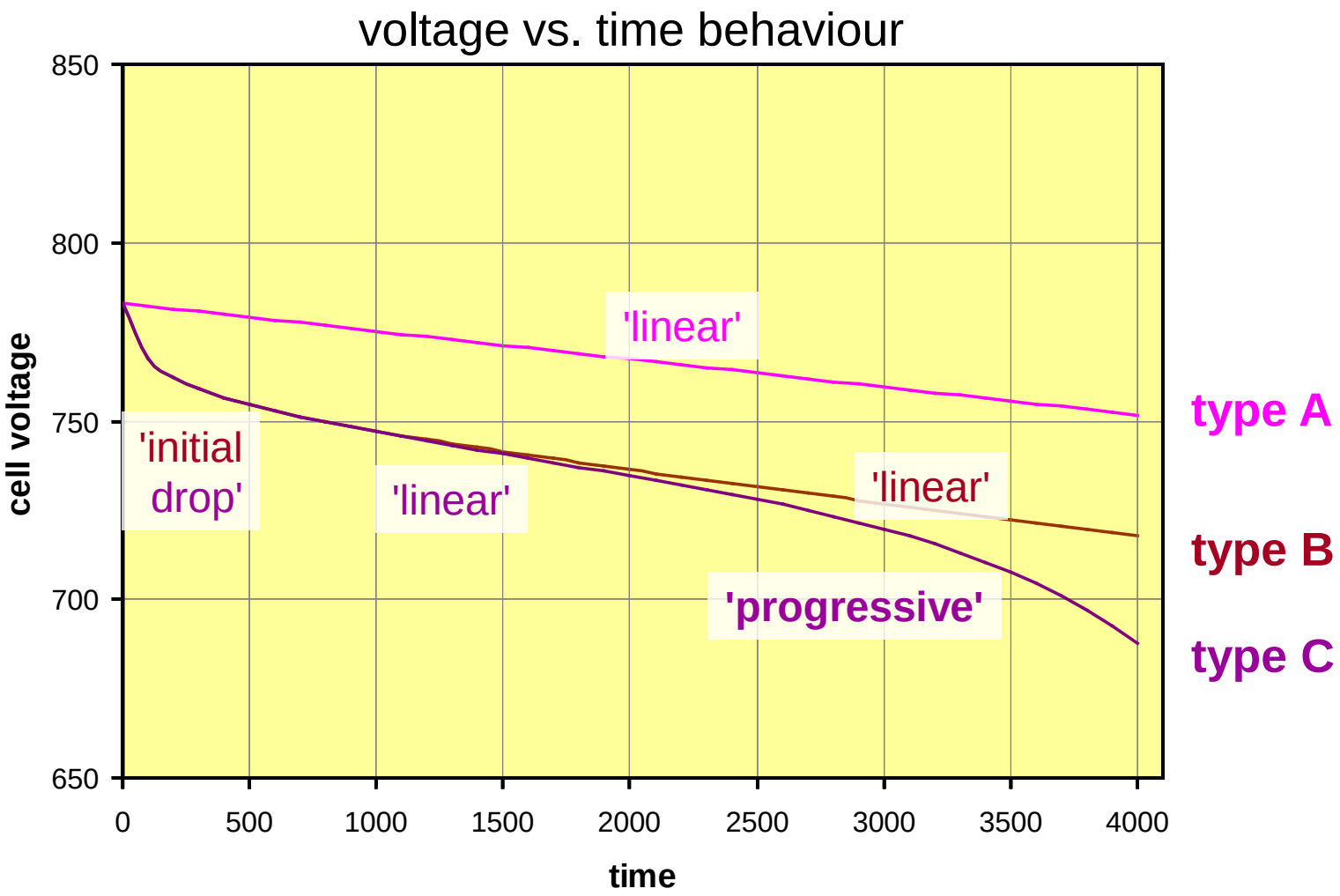
- 700°C, 500 mA/cm², 40% f_u
- CroFer22APU steel with APS protective coating
- LSCF cathodes



How do we quantify ‘Degradation’?



Long-term degradation behaviour in stacks



source: Bert de Haart, FZJ

Degradation types

1. Baseline (continuous, steady) degradation
   - initialisation phase (sintering, saturation)
   - constant slope phase
   - progressive degradation phase (EoL)
2. degradation from transients
   - thermal cycle
   - redox cycle
3. degradation after ‚incidents‘ (failures)
   - malfunction of BoP components
   - malfunction of control
   - external influence (shock, grid outage etc.)

Definitions of Degradation

$\Delta U = U(t_2) - U(t_1) \quad |_{t2 = t1 + 1000\ h}$

$\Delta t = t_2 - t_1 = 1000\ h$

$d_{\%} = \Delta U / U$ [%/1000 h] (relative to start value)

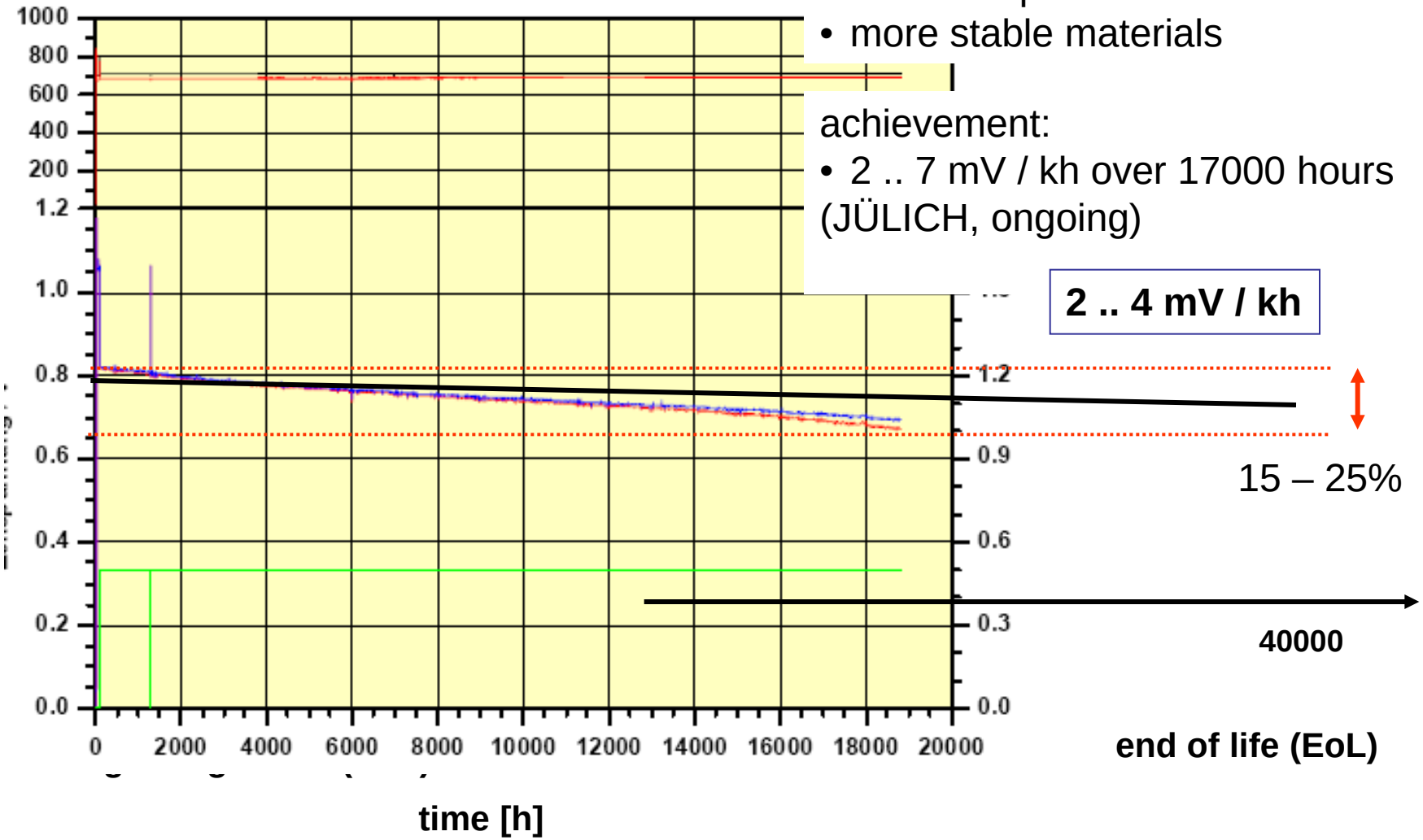
$d_V = \Delta U / \Delta t$ [mV/1000 h] (average over interval)

1. problem: reference value for $d_{\%}$?
2. people just don't stop using $d_{\%}$ ...

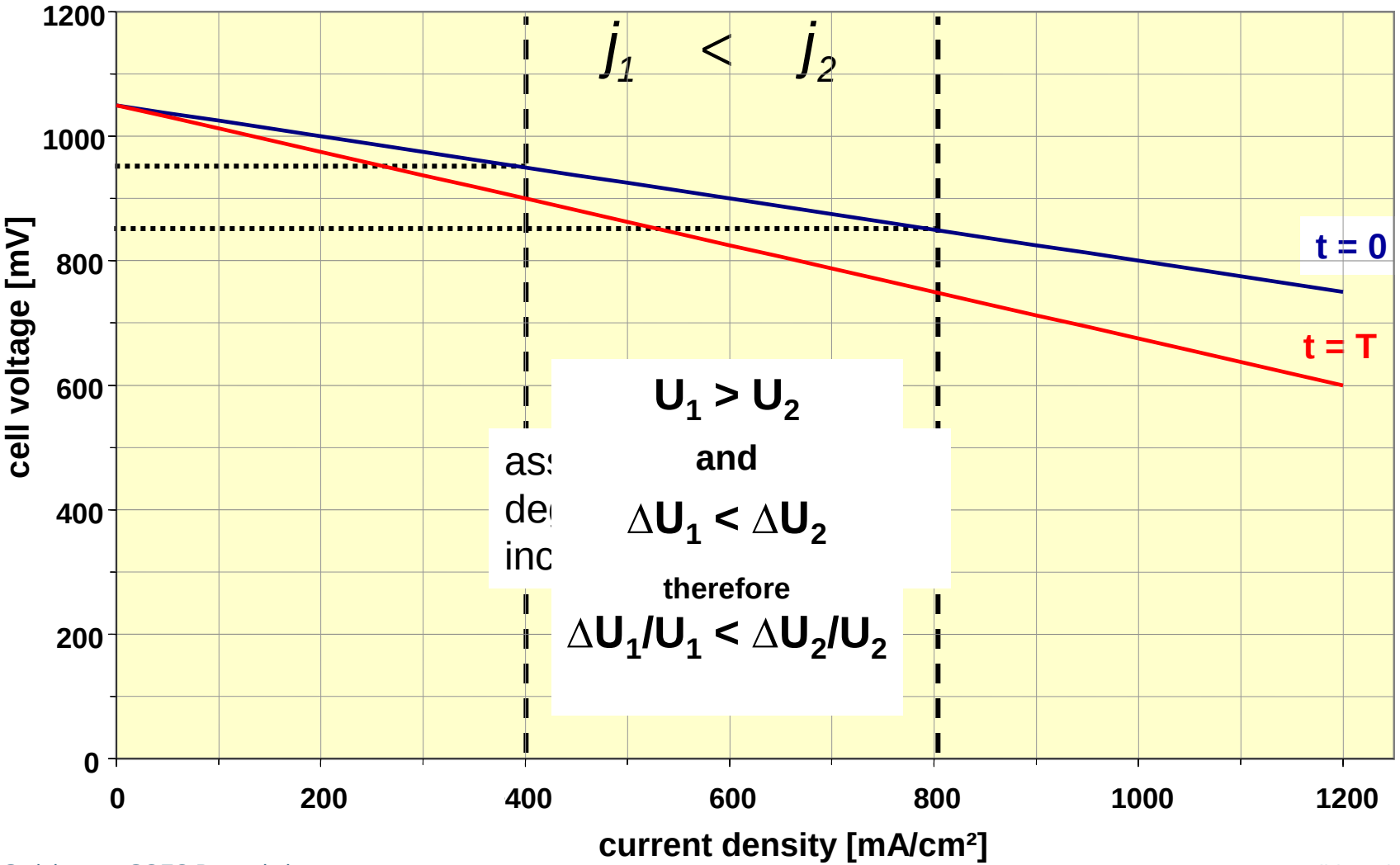
Lifetime Requirements

solutions:
- lower temperatures
- more stable materials

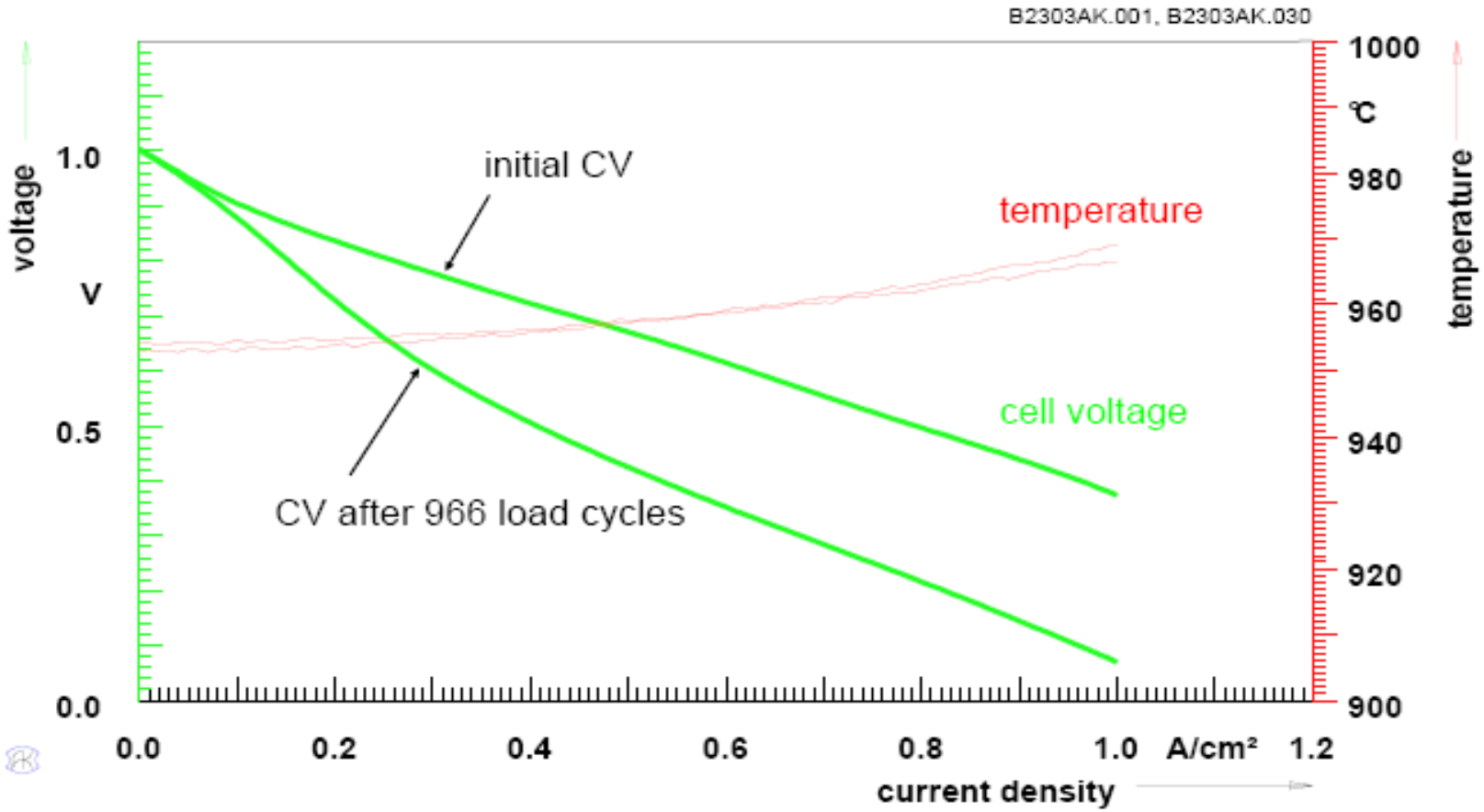
achievement:
- 2 .. 7 mV / kh over 17000 hours (JÜLICH, ongoing)



‘Current Dependance’ of Degradation

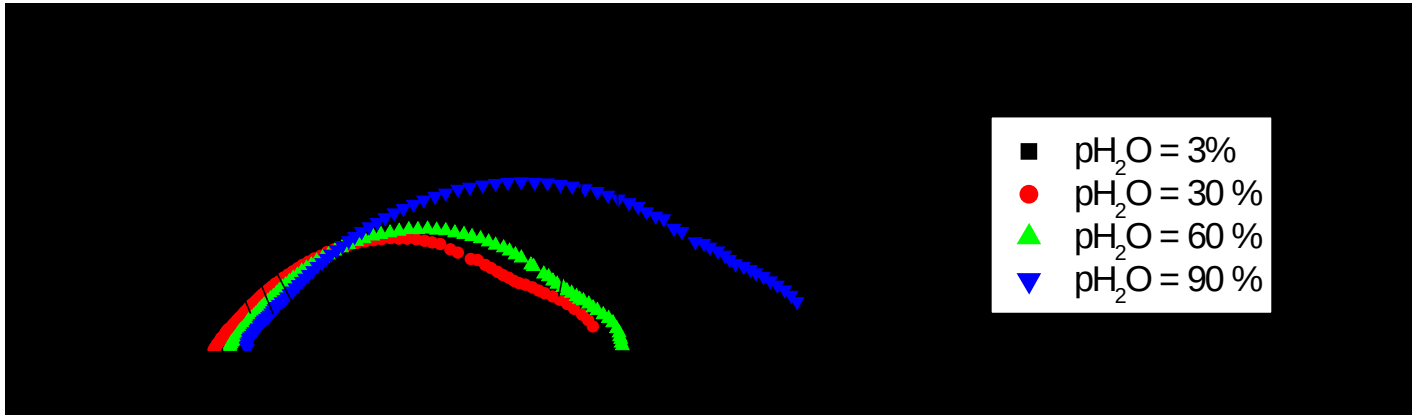


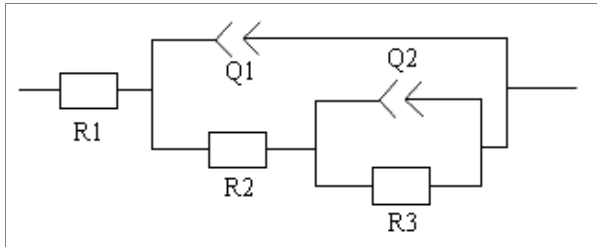
Degradation in I-V-Curve

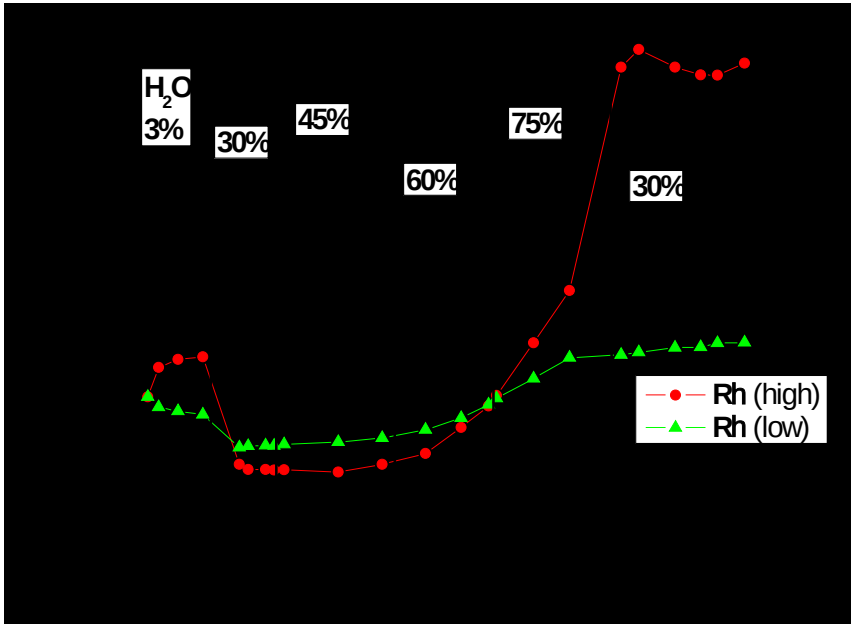


Source: IWE

Evolution of Polarization Resistance of Ni-YSZ Anode







Real-SOFC Endurance testing: sensitivity matrix

Real-SOFC	G1 FZJ F1002-60 / FZJ o ü	
WT1.2.2 CEA	G1	stack generation
WT1.2.4 FZJ	FZJ	stack manufacturer
WT1.2.7 EBZ	F1002-60	stack number
WT1.3.1 FZJ	/ FZJ	testing partner
	o ü	test running / performed

= standard WT4.1 conditions

= benchmark G2 conditions

= benchmark G3 conditions
(alternative: G2 w/ temp <800 °C)

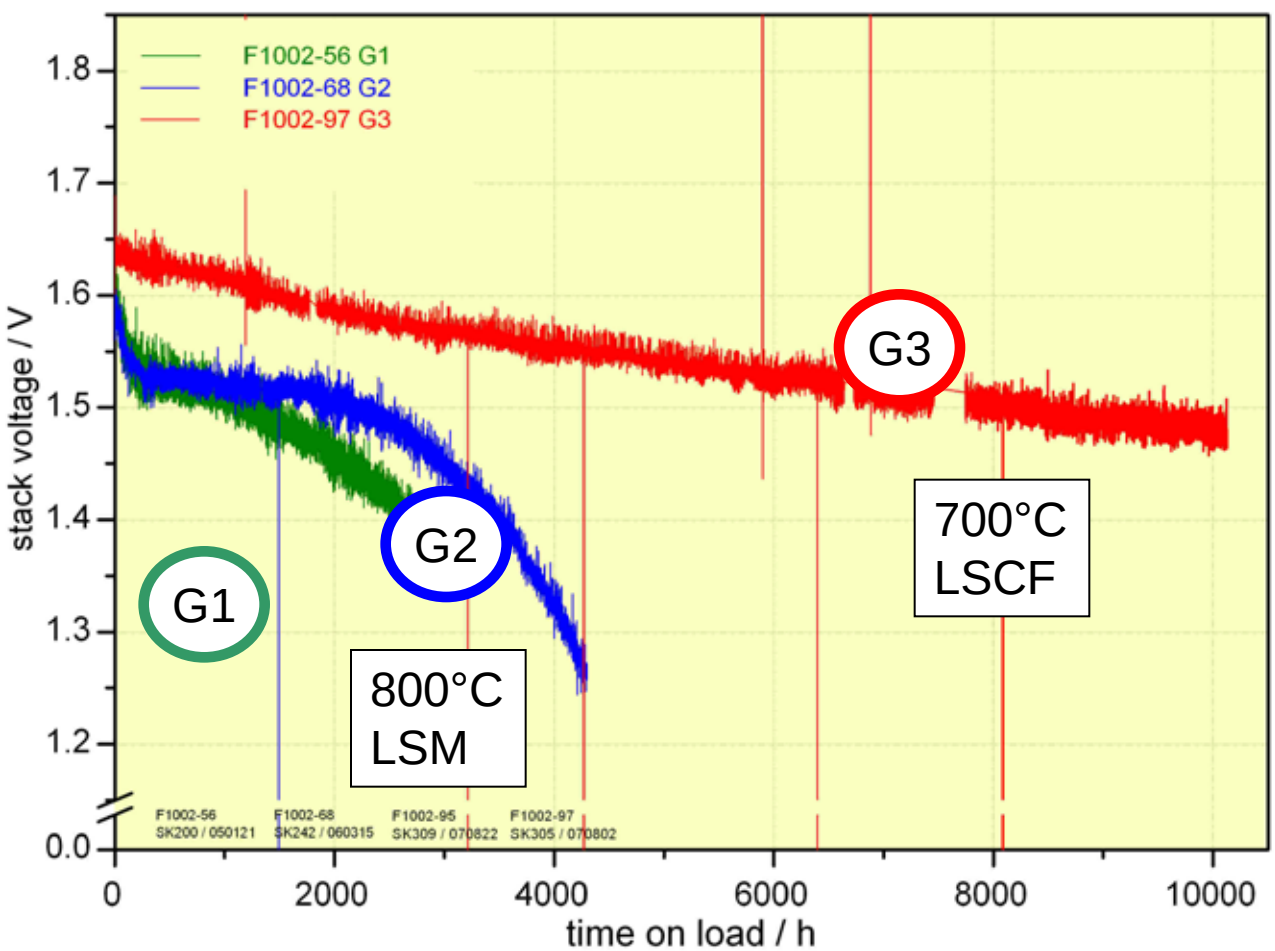
fuel: hydrogen + 3 % water vapour; temperature: 800 °C

current density mA/cm²	fuel utilisation % 10	40	60	75
300	G1 FZJ F1002-60 / FZJ ü	G1 FZJ F1002-62 / FZJ ü		
400				
500		G1 FZJ F1002-56 / FZJ ü G2 FZJ F1002-68 / FZJ ü G3 FZJ F1002-xx / FZJ	G2 FZJ F1002-79 / CEA o	G2 FZJ F1002-88 / FZJ L G2 FZJ F1002-89 / FZJ o
600				
700		G2 FZJ F1002-87 / FZJ o	G2 FZJ F1002-83 / CEA	G3 FZJ F1002-xx / FZJ
800				
900				
1000				

fuel: methane (internal reforming) S/C=2.0; temperature: 800 °C

current density mA/cm²	fuel utilisation % 10	40	60	75
300		G1 FZJ F1002-61 / FZJ ü		
400		G1 FZJ F1002-53 / EBZ ü		
500		G1 FZJ F1002-57 / FZJ ü		G2 FZJ F1004-11 / EBZ o
600				
700		G2 FZJ F1002-xx / FZJ	G2 FZJ F1004-12 / EBZ	G3 FZJ F1004-yy / EBZ
800				
900				
1000				

Real-SOFC Stack Generations: Progress by Materials



durability tests
G1, G2, G3

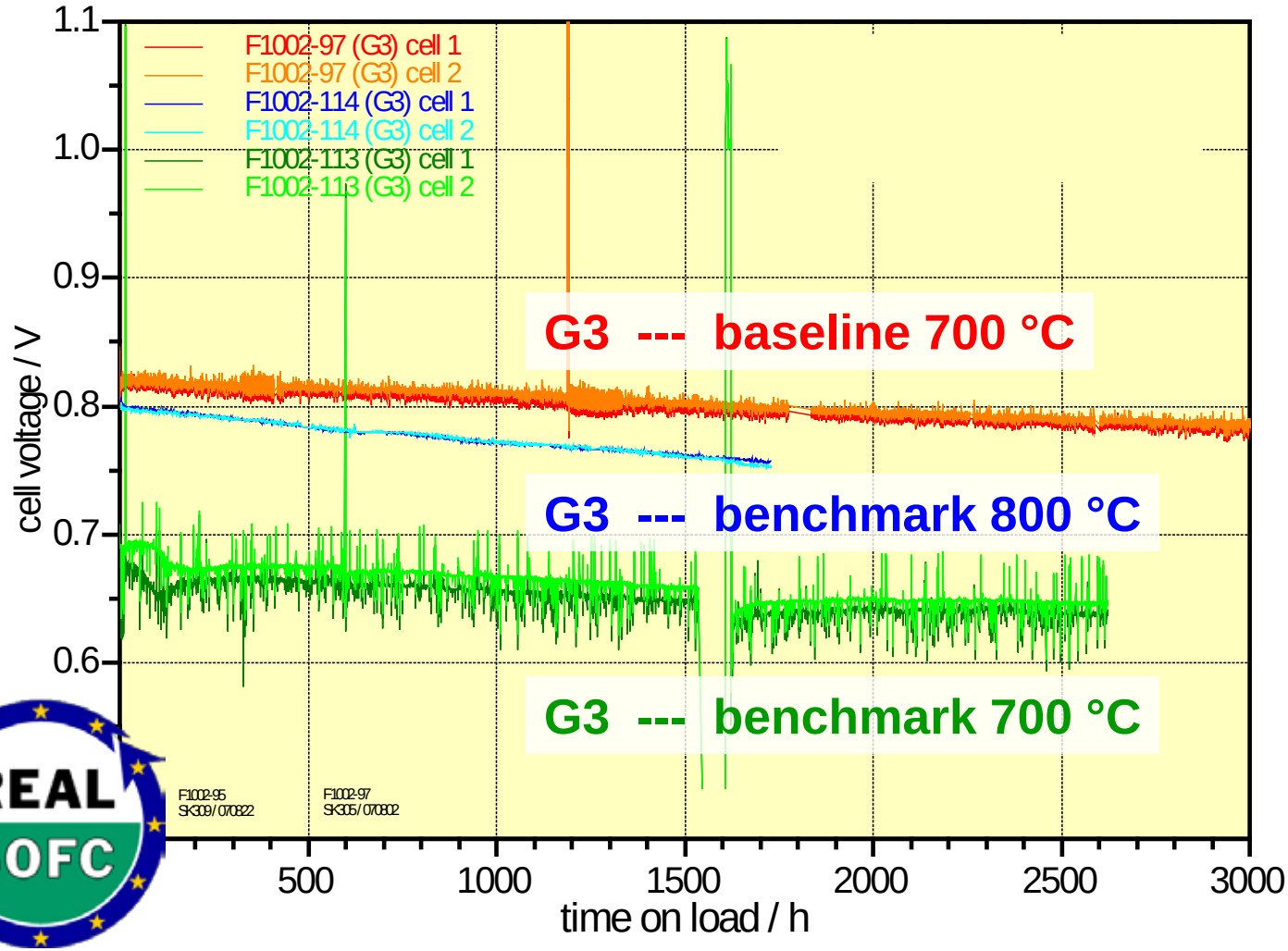
temperature:
800 °C
700 °C

fuel gas:
hydrogen
hydrogen
hydrogen

fuel utilisation:
40 %
40 %
40 %

current density:
0.5 A/cm²
0.5 A/cm²
0.5 A/cm²

Sensitivity to Current Flow & Fuel Utilisation



durability tests G3
baseline vs benchmark

temperature:
700 °C
700 °C
800 °C

fuel gas:
hydrogen

fuel utilisation:
40%
75%
75%

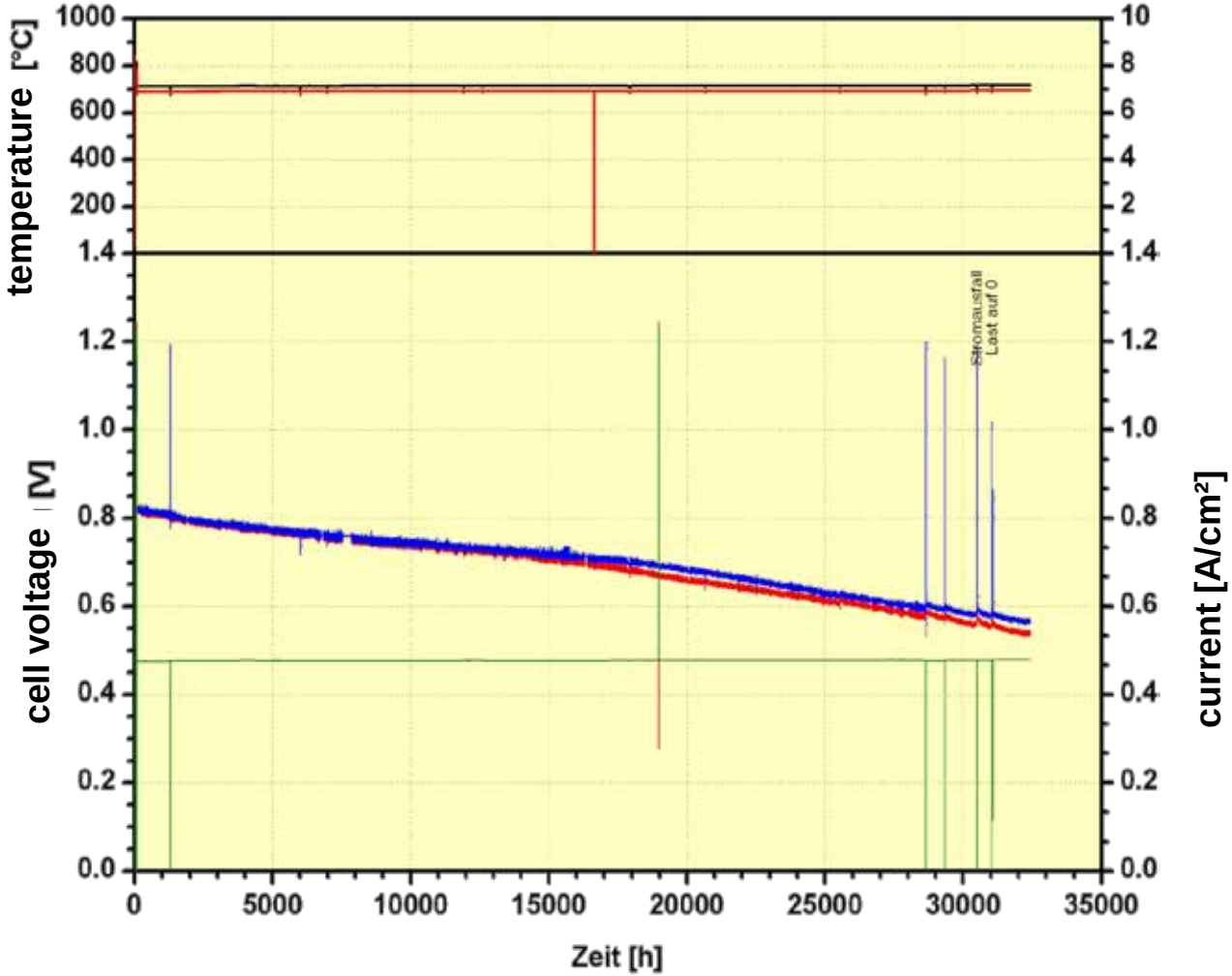
current density:
0.5 A/cm²
0.7 A/cm²
0.7 A/cm²

baseline
0.5 A/cm²
40%

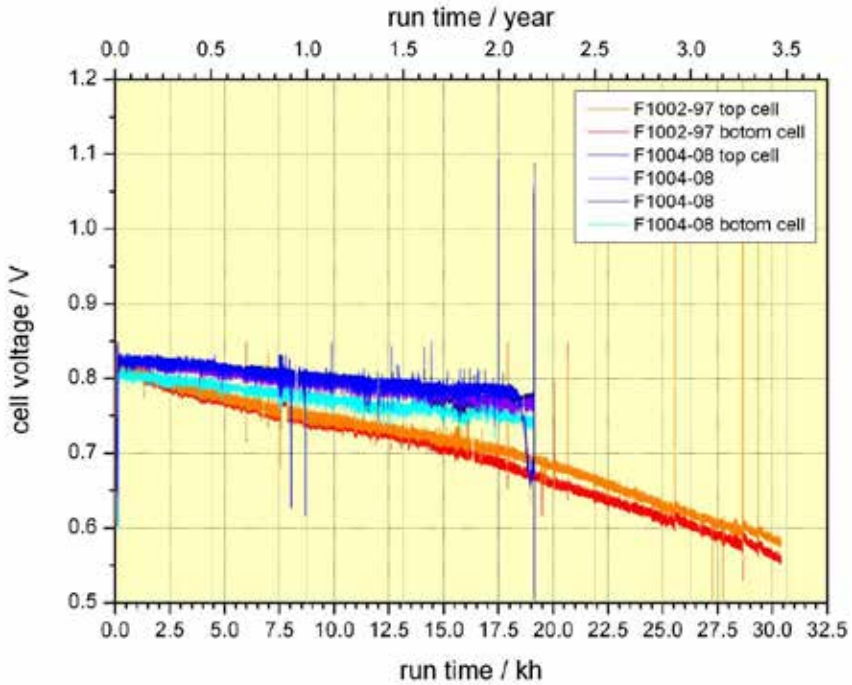
benchmark
0.7 A/cm²
75%

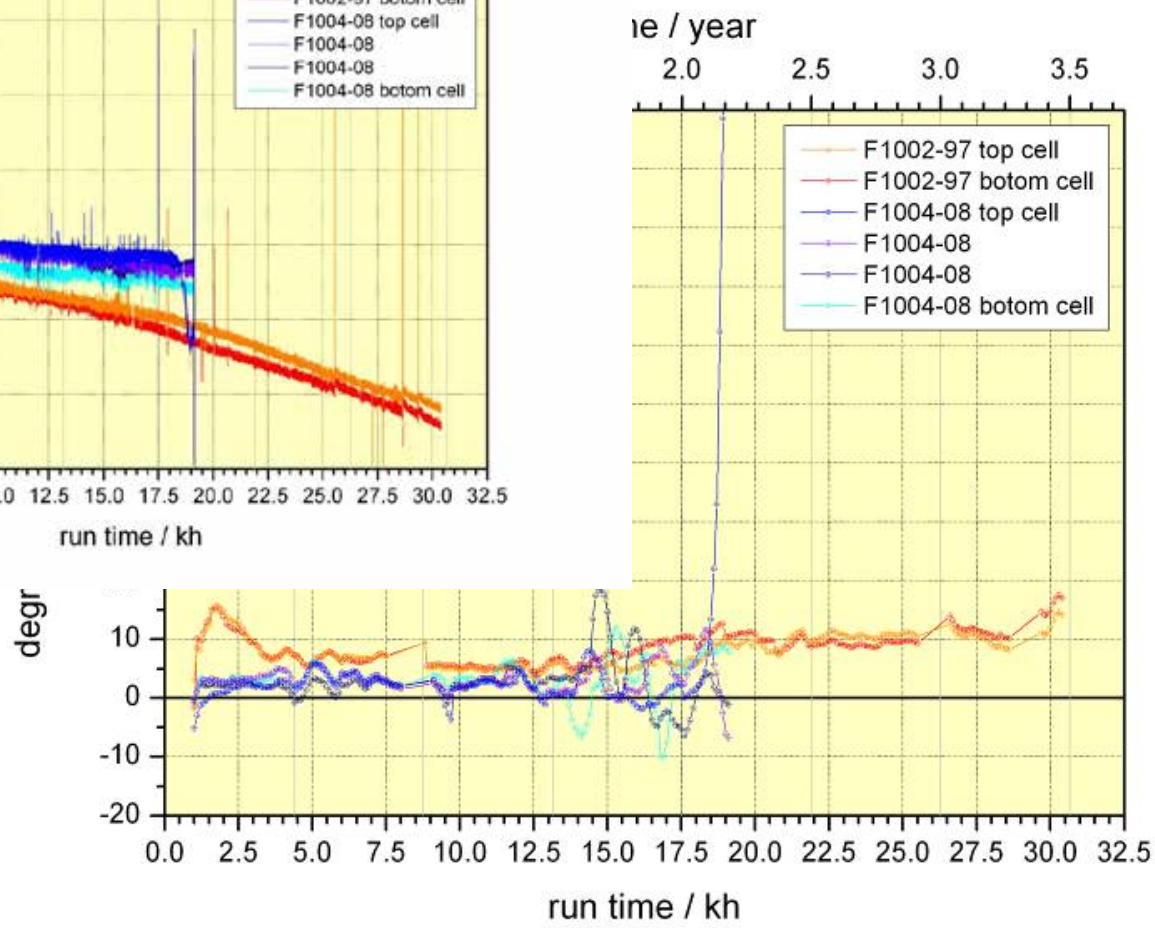
Long-Term Stack Operation

- >42 000 hours of operation on load
- 700°C, 500 mA/cm², 40% f_u
- Plansee ITM steel with standard protective coating
- LSCF cathodes



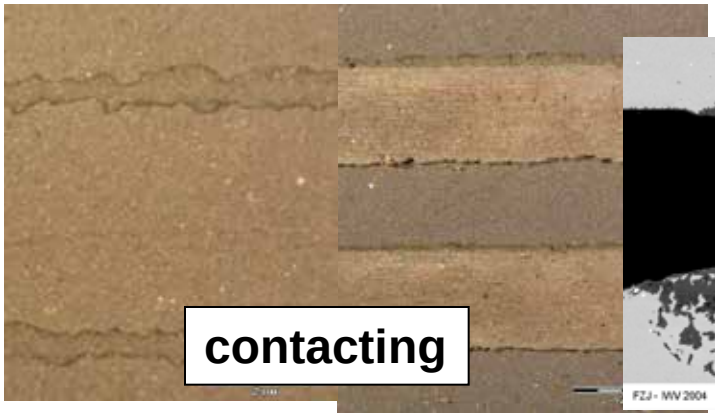
Evaluating Degradation Rates

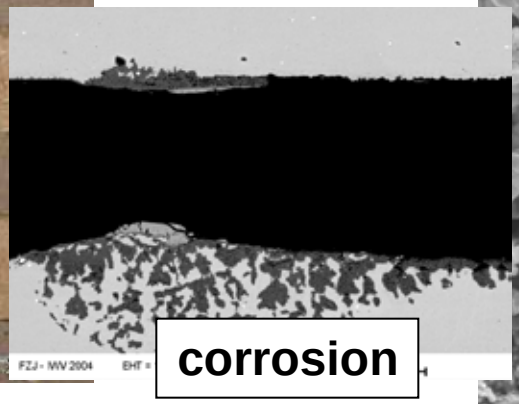


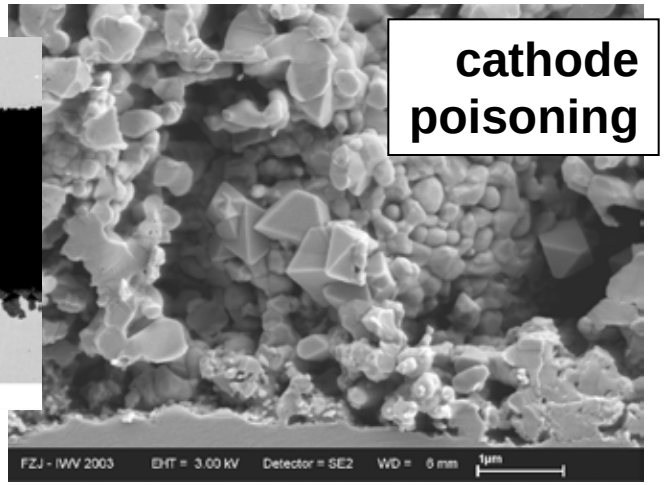


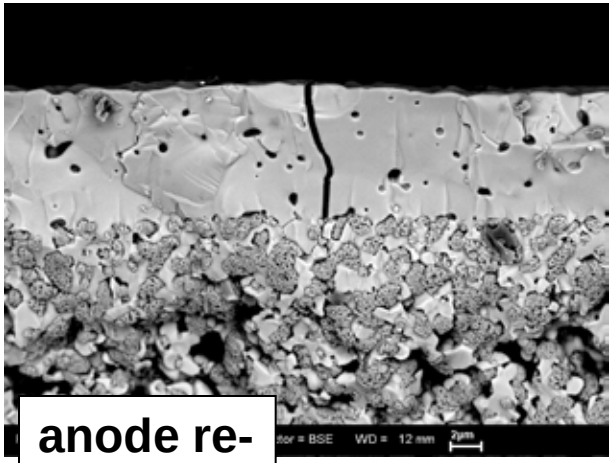
Degradation Phenomena Overview

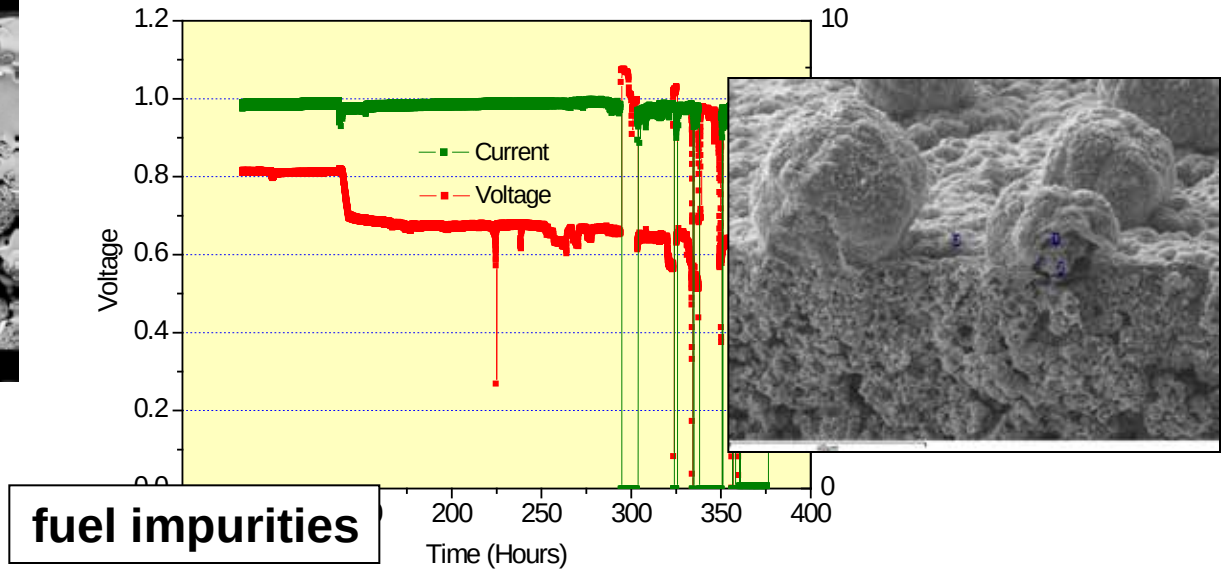
Variety of Degradation Phenomena











Variety of phenomena (2)

Types

- changes in single layers or components (independent of others)
- changes at interfaces
- interaction of materials (e.g. transport of species)

Driving forces

- temperature
- current flow
- overpotential
- partial pressures of oxygen, hydrogen, water etc.
- pressure
- etc.

Degradation Mechanisms

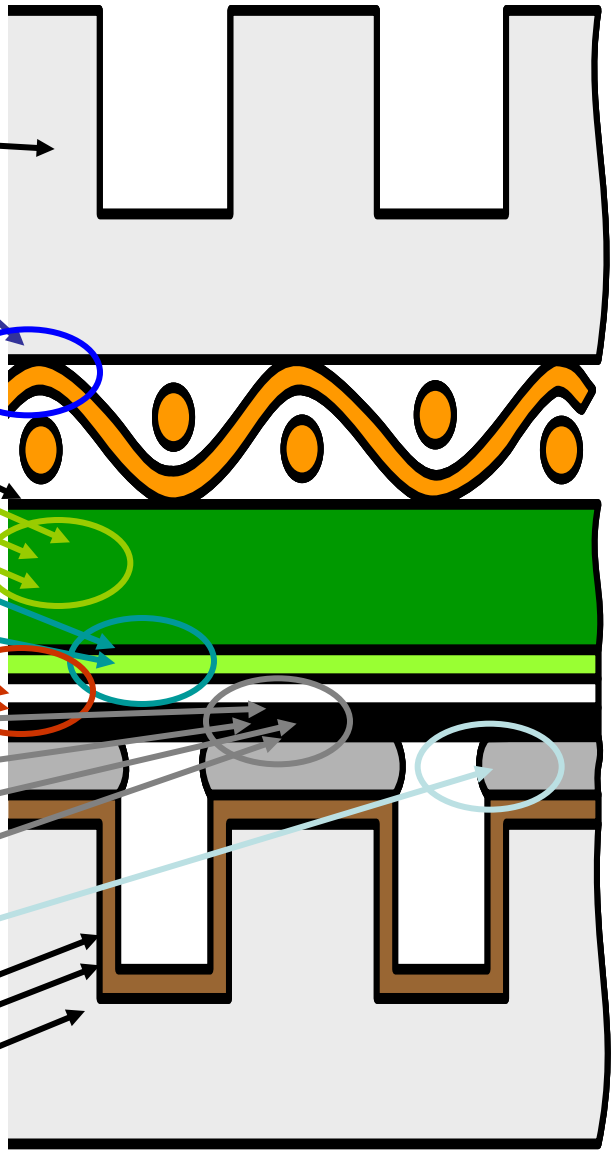
- changes in morphology and phase with consequences for
  - gas transport
  - resistivity
  - mechanical strength
  - reduction of active surface area
- interdiffusion with consequences for
  - corrosion resistance
  - loss of activity
  - resistivity
- transport of species with consequences for
  - poisoning / de-activation
  - build-up of layers / scales
- corrosive interaction
- build-up of corrosion scales with consequences for
  - dimensional changes (e.g. swelling)
  - resistivity
  - cycling capability

Overview of Degradation Mechanisms

Cathode side	***Electrolyte***	***Anode side***
Three phase boundary reduction by - Cr poisoning - Particle sintering Phase changes Interdiffusion	Phase instabilities Interdiffusion	Ni-agglomeration Ni-coarsening S poisoning Interdiffusion Destruction by re-oxidation
Contact degradation Resistivity Cr transport		Contact loss by - by sintering - by seal swelling - temp. gradient Resistivity
Interconnect: - Cr evaporation - Corrosion cracking - Inner oxidation		Interconnect: - Scale resistance - Embrittlement by carburization - Corrosion cracking
Ceramic glass sealant - Interaction with gaseous species/ contaminants - Interaction between components - Leakage or short circuit during thermal cycling - Degradation due to impurities in raw materials		

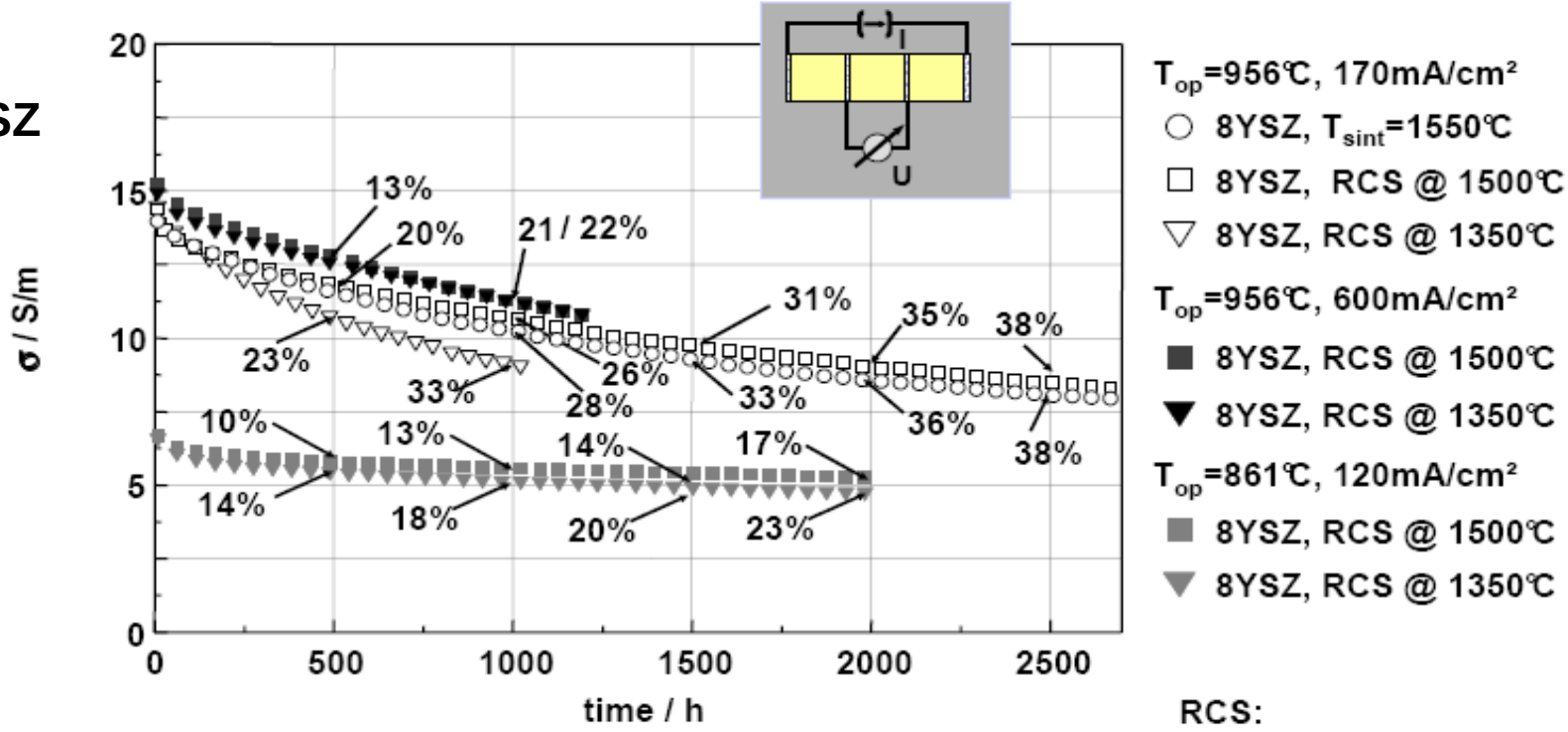
SRU Cross-Section

Mechanism
Corrosion perforation
Carburisation (embrittlement)
Scale resistivity
Coating/scale resistivity
Contact loss (sintering)
Contact loss (seal swelling)
Contact loss (dT/dx, dT/dt)
Poisoning / low-σ phases by contact layer
Coking
Ni sintering
Redox at high j and/or Uf
S-poisoning
S-poisoning
Ni sintering (TPB reduction)
Interdiffusion (low-σ phase formation)
Phase instability (ageing)
Interdiffusion (low-σ phase formation)
Phase changes, demixing
Particle sintering (TPB reduction)
Cr-poisoning
Interdiffusion
Contact loss (sintering)
Contact loss (seal swelling)
Contact loss (by dT/dx, dT/dt)
Cr evaporation / cathode poisoning
Coating/scale resistivity
Corrosion perforation (H assisted)
Cr evaporation / cathode poisoning



Conductivity Degradation of Electrolyte

8YSZ



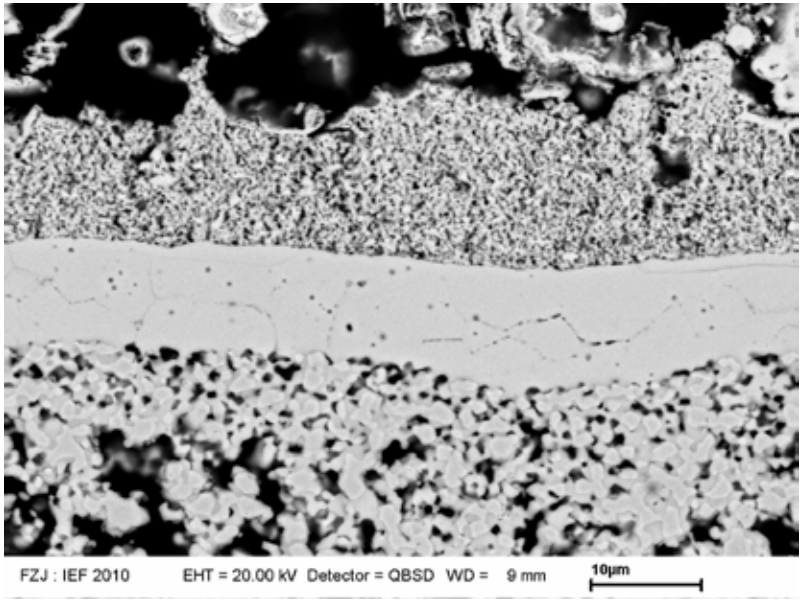
Axel C. Müller, André Weber, Dirk Herbstritt, Ellen Ivers-Tiffée, „Long Term Stability of Yttria and Scandia doped Zirconia Electrolytes", Proceedings 8th Int. Symp. on SOFC, Ed. S. C. Singhal, M. Dokiya, The Electrochemical Society, PV 2003-07, 196-199, (2003)

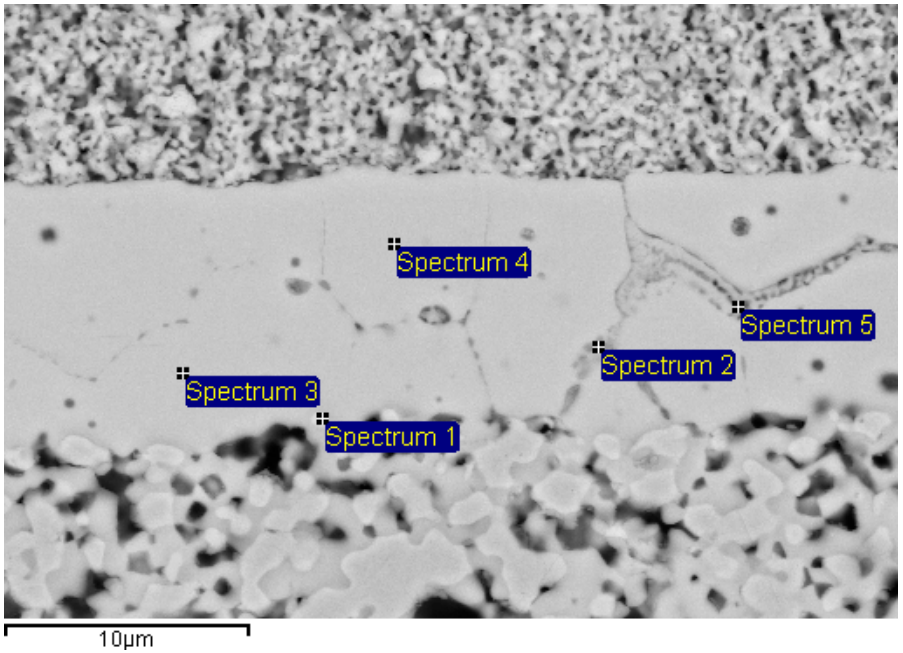
RCS:
rate controlled sintering
constant shrinkage

caused by phase separation and re-ordering in micro-domains, impurities, etc.

Source: IWE

Electrolyte Degradation by Diffusion of Mn





- after 20 000 hours of operation: failure of cell
- Mn enrichment along grain boundaries 5-10 at.%)

Electrode-Electrolyte Interface during Manufacturing

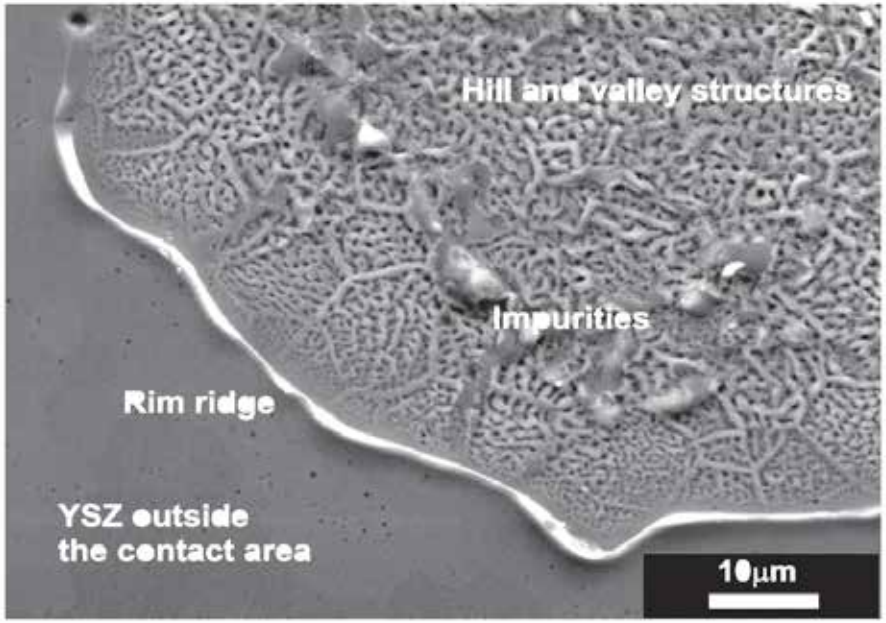
1. formation of low-conductive products such as $La_2Zr_2O_7$ and $SrZrO_3$ during cell sintering and SOFC operation, especially with LSCF cathodes

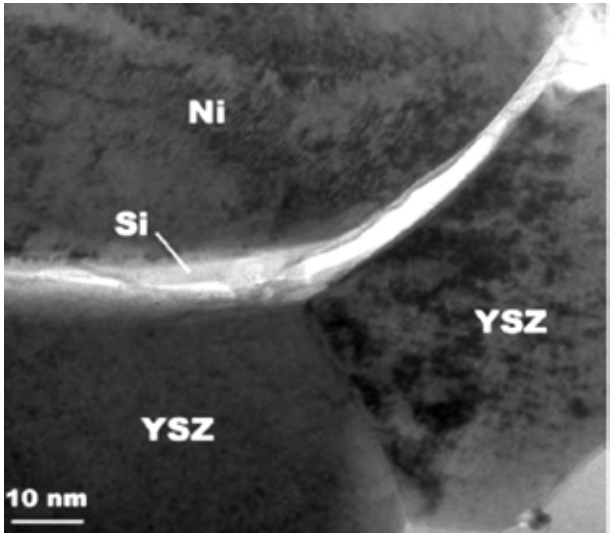
2. segregation of material impurities at TPB's

3. solution of Ni in YSZ

Processes at the Cathode-Electrolyte Interface

1. segregation of materials impurities at TPB's
2. very low SiO_2 content (~100 ppm) in the raw materials affects the microstructure of interfaces and grain boundaries in SOFC.





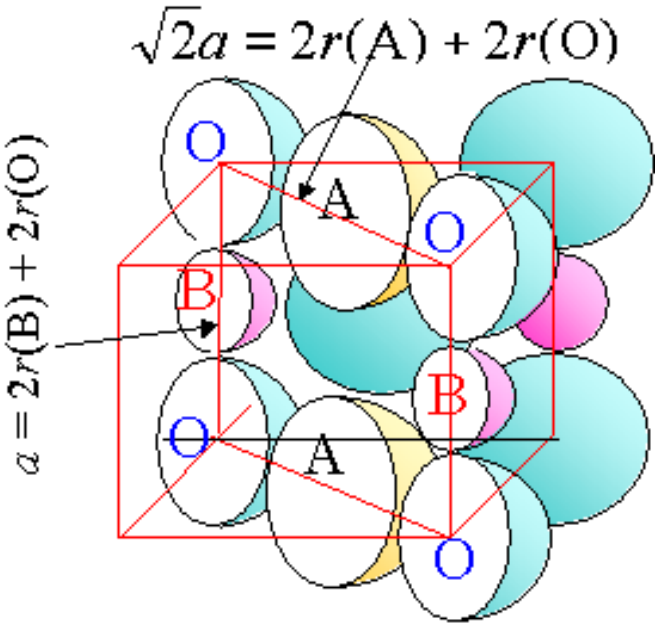
TEM

M. Mogensen / Proc. 26th Risø Int. Symp.

Y.L. Liu, C. Jiao / Solid State Ionics 176(2005)435

Cathode Materials: Stability

thermodynamical stability and kinetics:
perovskites ABO_3



$(La,Sr)MnO_3$

$(La,Sr)FeO_3$

$(La,Sr)CoO_3$

$(La,Sr)(Co,Fe)O_3$

$(La_{0.9},Sr_{0.1})MnO_3$

$(La_{0.7},Sr_{0.3})MnO_3$

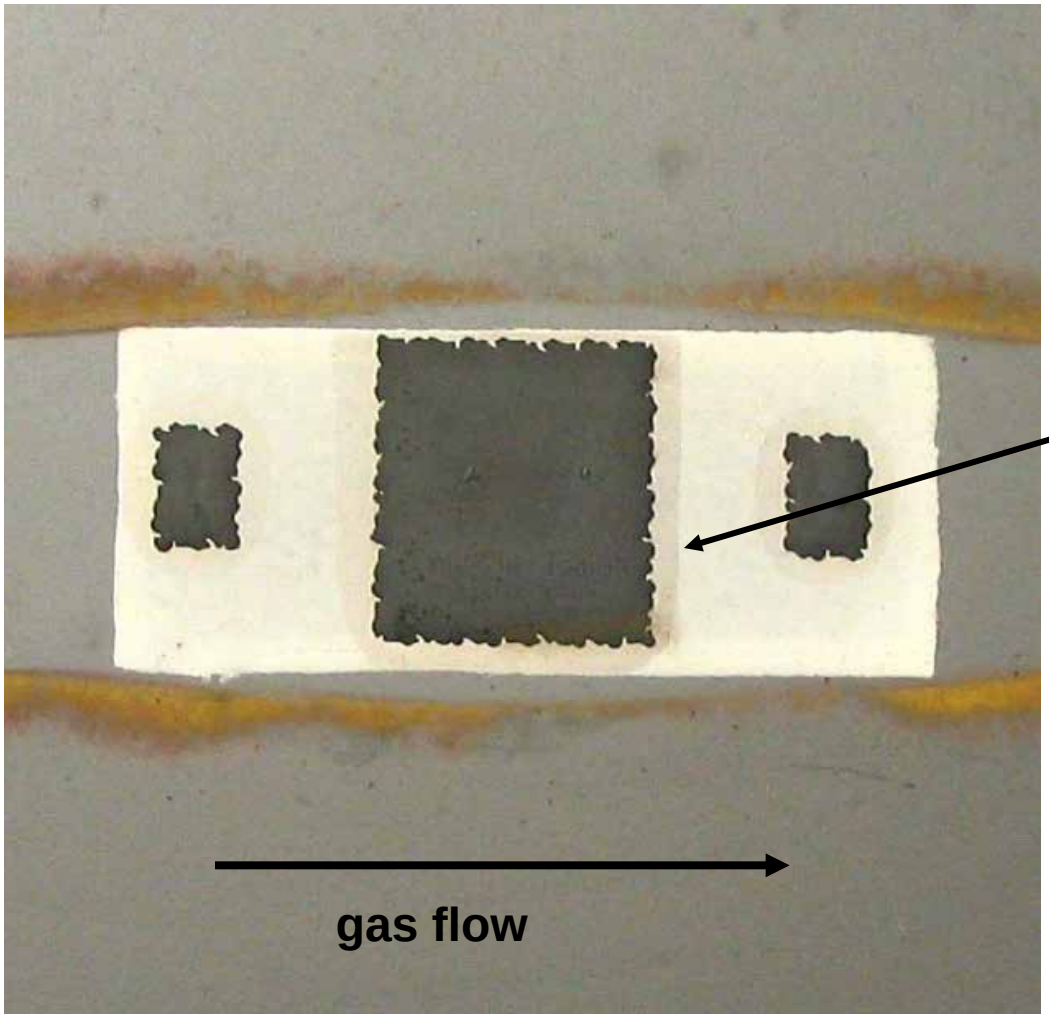
$(La_{0.7},Sr_{0.3})_{0.99}MnO_3$

$(La_{0.7},Sr_{0.3})MnO_{3\pm\delta}$

$(La_{1-x}Sr_x)_yFe_{1-z}(Ni,Cu)_zO_{3-\delta}$

source: Yokokawa, EMPA

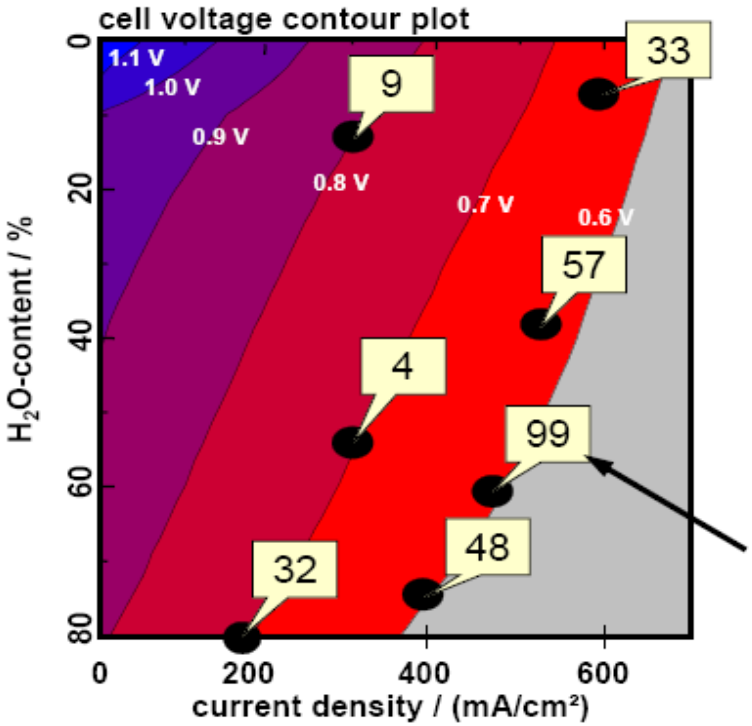
Cathode Materials: Volatility



source: Tietz/Mai

Nickel Anode Volatility

volatilisation of nickel (NiOH) in high water content fuel gases – loss of active surface



Performance plot

Long term measurements
Operation time: 700 ... 1000 h
Temperature : 950 °C
Oxidant : air

Aim: <1 mV/1000h

Degradation rates in mV/1000h

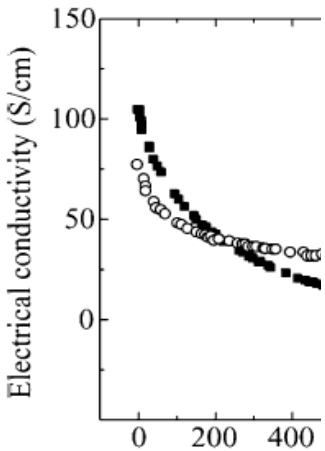
A. Müller, A. Weber, H. J. Beie, A. Krügel, D. Gerthsen, E. Ivers-Tiffée, Influence of Current Density and Fuel Utilization on the Degradation of the Anode, Proc. of 3rd European Solid Oxide Fuel Cell Forum, Ed. P. Stevens, The European Fuel Cell Forum, 353-362, (1998)

Source: IWE

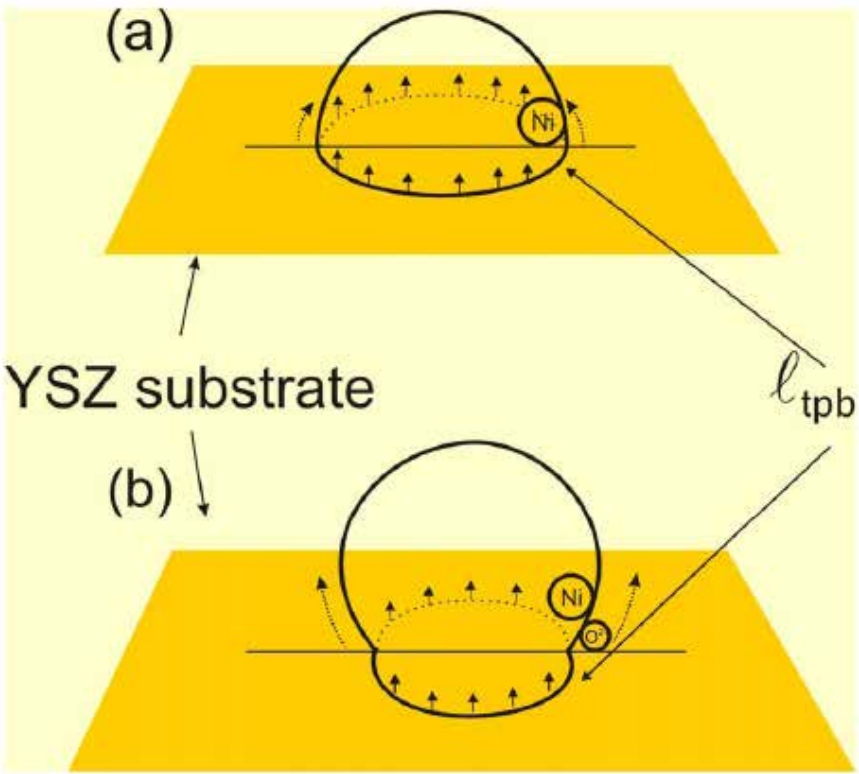
Anode Substrate: Particle Agglomeration

UNIVERSITY OF BIRMINGHAM

- temperature-induced tendency of metals to decrease free energy, i.e. to minimize the surface area and agglomerate
- examples: anode substrate Ni-YSZ cermet

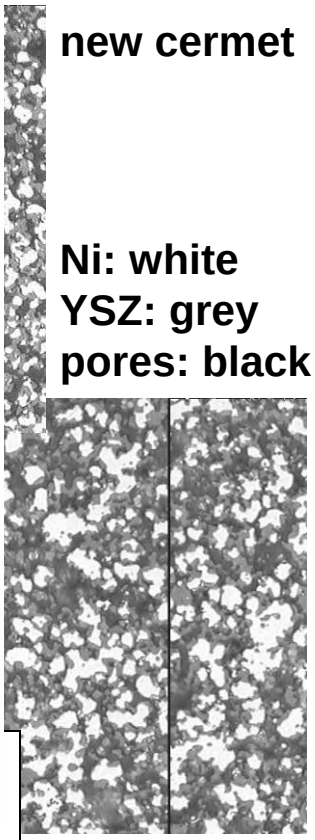


K.S. Lee et
Electrochem



source: ICE-FORTH

Ar/4%H_2/4%H_2O



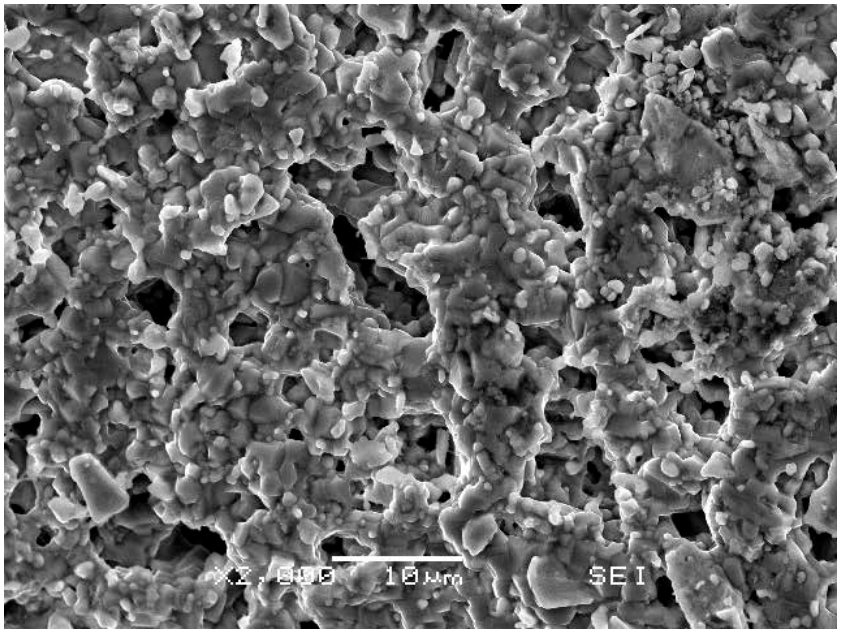
new cermet

Ni: white
YSZ: grey
pores: black

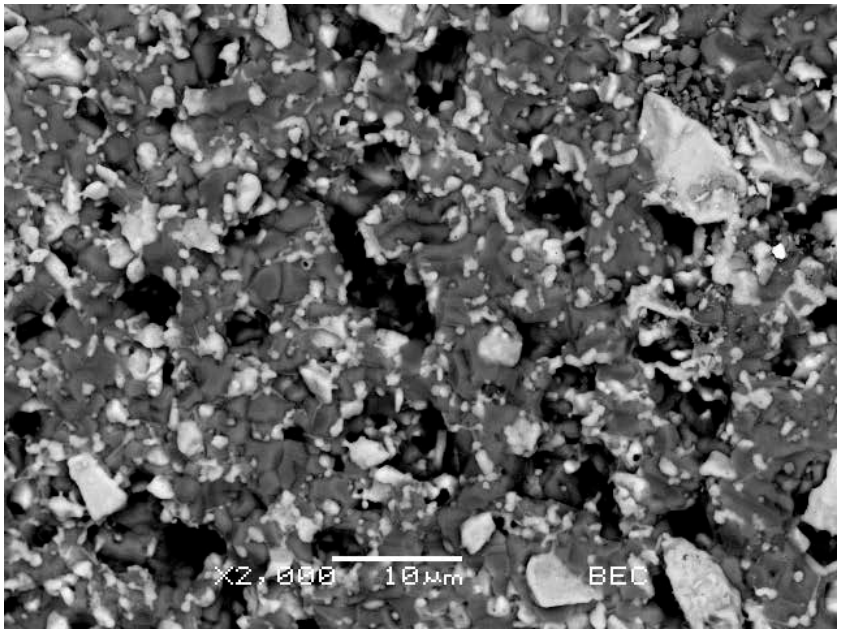
Source: IHTE

Microstructure characterization

SEM images of anode surface (70 wt% Cu + 30 wt% SDC)



secondary electron mode



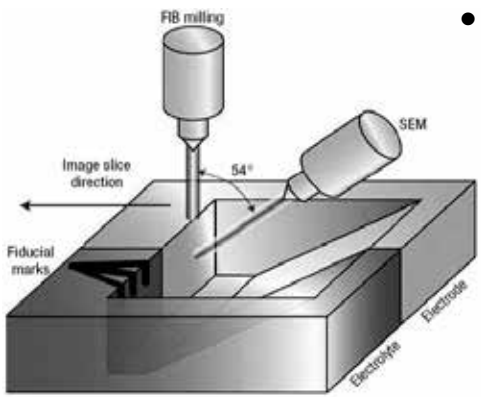
backscattering mode

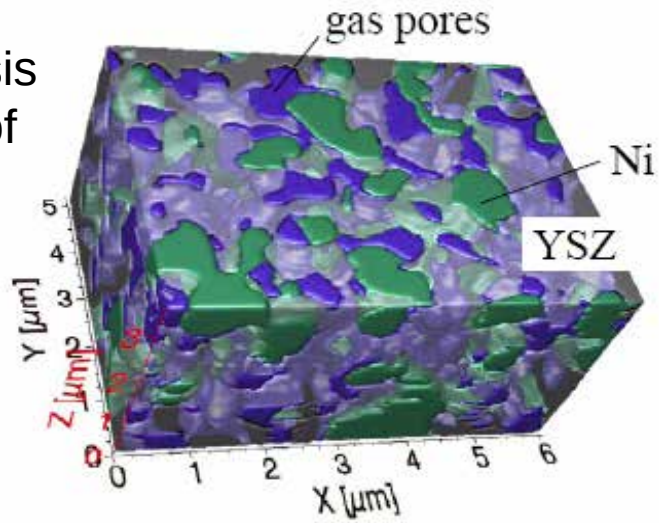
For good distinguishability of different phases their backscattering coefficients should be different.

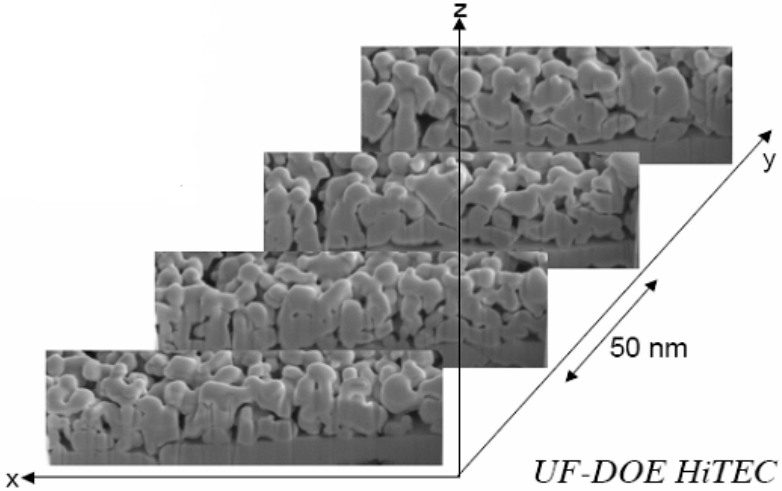
Source: IHTE

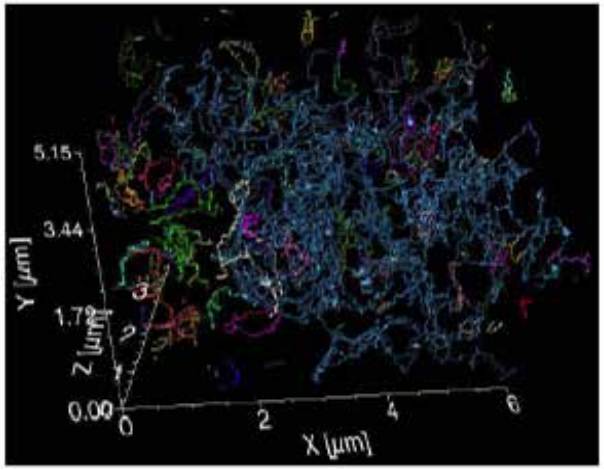
Three-Dimensional Characterisation

- FIB/TEM analysis
- reconstruction of 3-D structure from ‚slices‘









J.R. Wilson et al. / Nature Materials 5(2006)541

Chromium Volatilisation

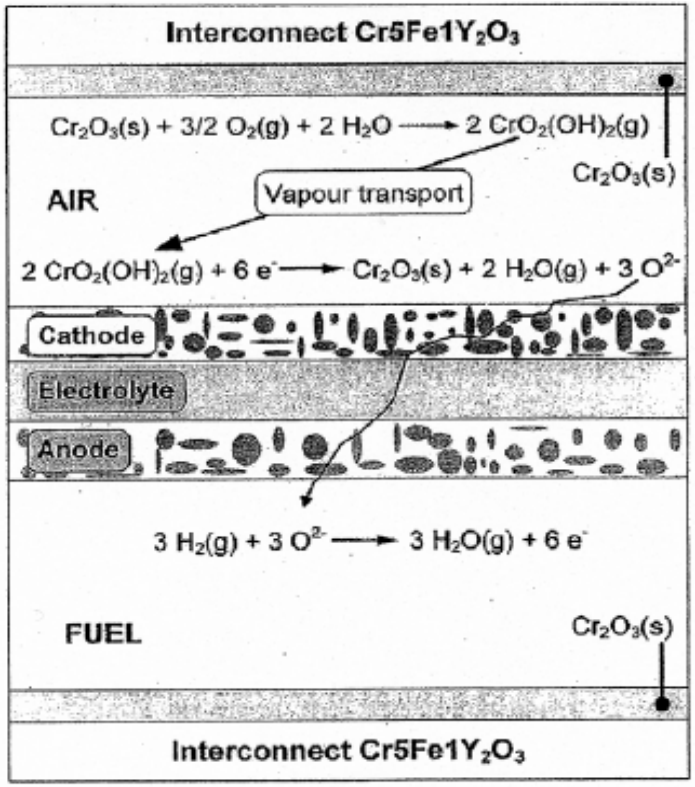


Fig. 6. Cr transport at the cathode side of a SOFC.

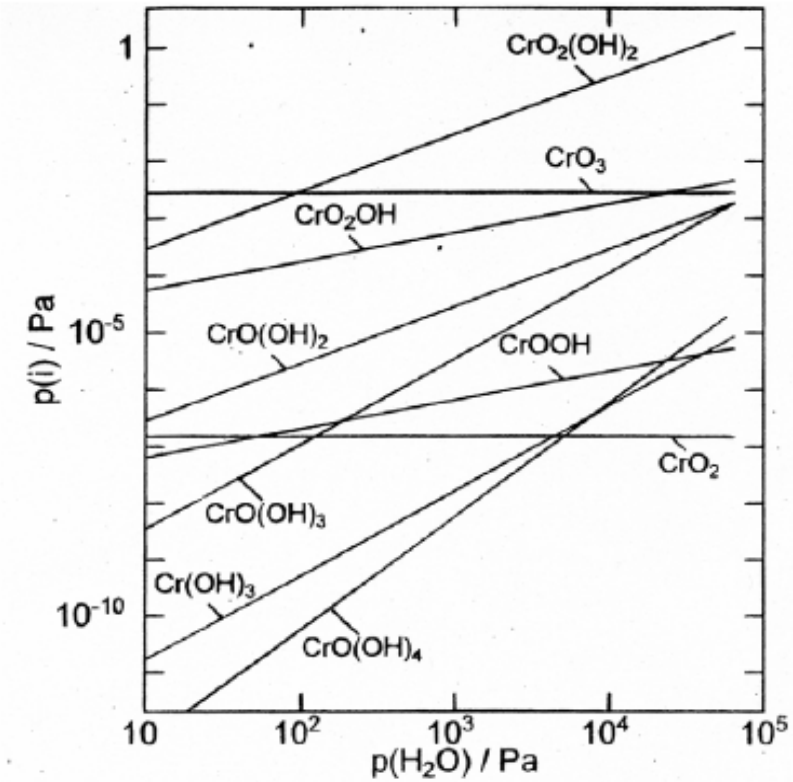
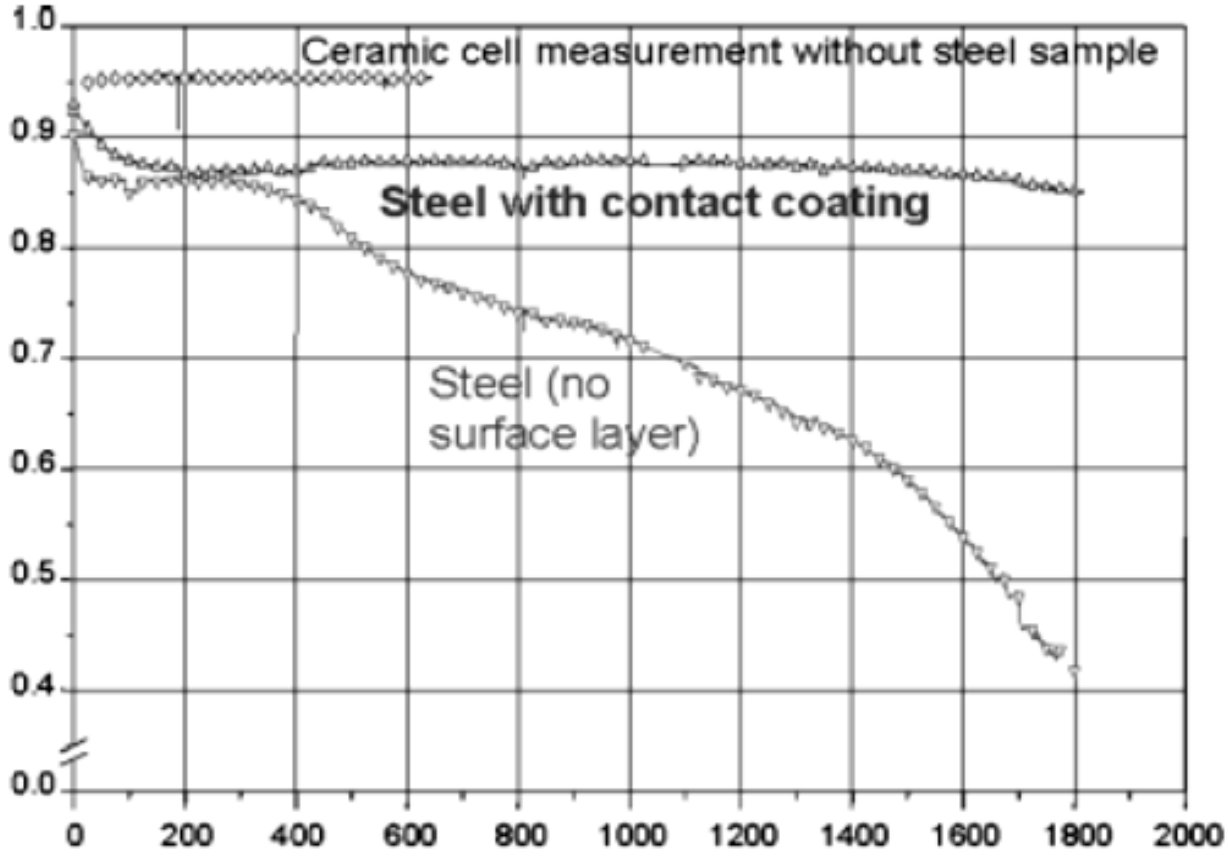


Fig. 3. Partial pressures over $Cr_2O_3(s)$ at 1223 K in humid air [$p(O_2) = 2.13 \times 10^4$ Pa] with different H_2O partial pressures.

K. Hilpert / J. Electrochem. Soc. 143(1996)3642

Impact of Chromium on Cathode Performance

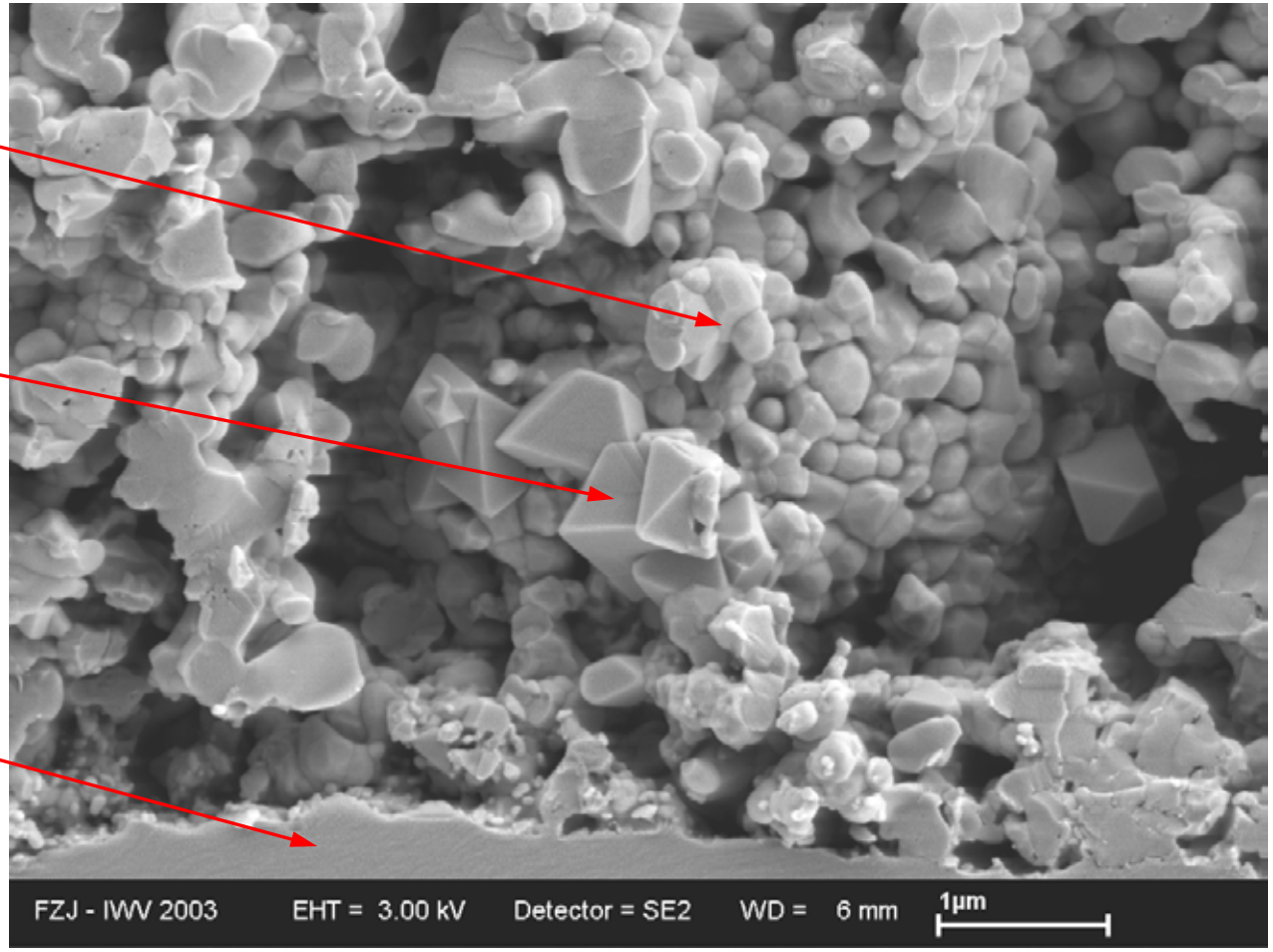


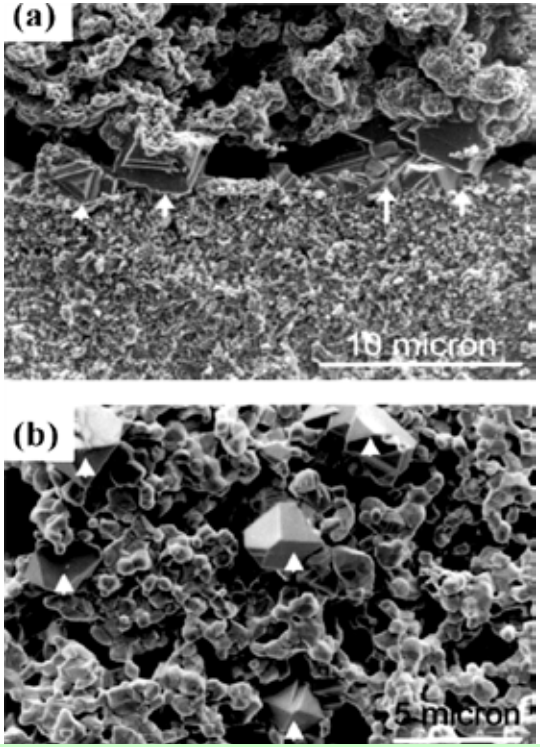
Chromium Poisoning: Microscopic Findings

LSM/YSZ

$(CrMn)_3O_4$
(spinel)

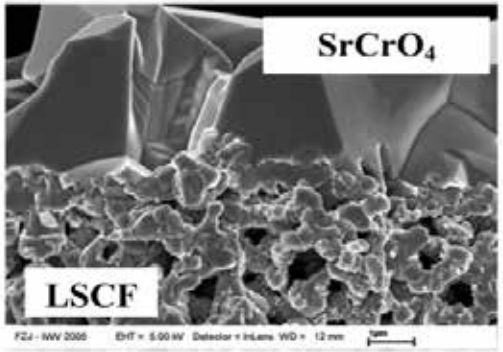
electrolyte
(YSZ)





Without current Cr is only located within the $La_{1-x}Sr_xMnO_3$ layer, forming $(Cr,Mn)_3O_4$ spinel crystals. If a current passes through the cell the Cr is mainly deposited near the TPB near the YSZ electrolyte. Chromium is clearly found along the perimeter of the pores on the surface of the YSZ, thereby decreasing the number of active sites necessary for oxygen reduction.

S.P.S. Badwal / Solid State Ionics 143(2001)39



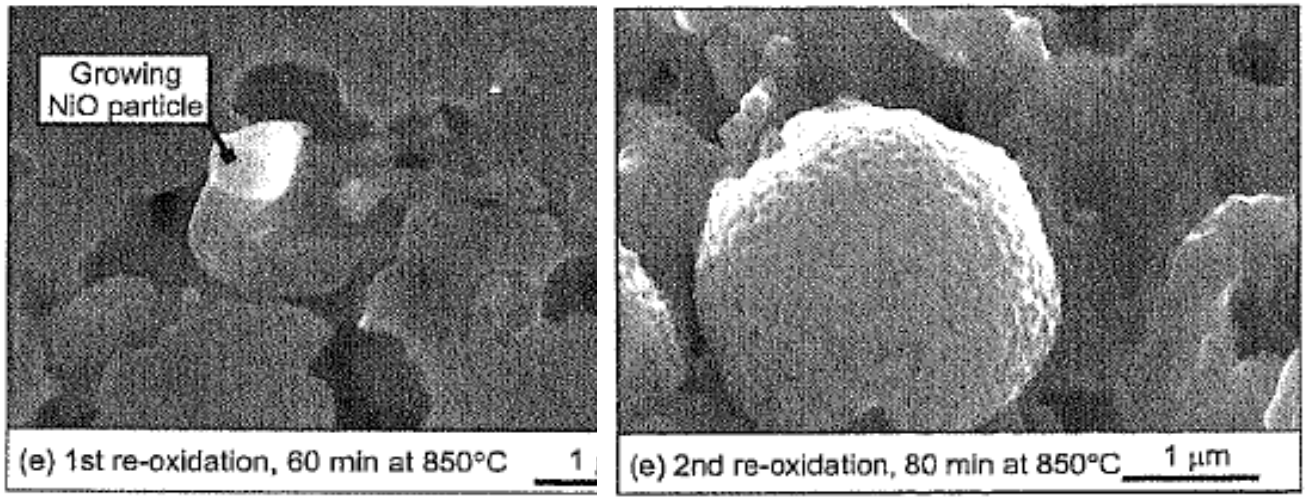
Electrochemical tests with the $La_{0.58}Sr_{0.4}Co_{0.2}Fe_{0.8}O_3$ cathode under current clearly show Cr poisoning at 800°C. Significant formation of $SrCrO_4$ crystals was detected on the surface of the cathode layer.

Konysheva et al.

Journal of The Electrochemical Society, **153** (4) A765-A773 (2006)

Redox Cycling Requirements

- redox cycles:
  - after stack shut-down air will flow to the fuel electrode
  - Ni in Ni-YSZ anode will re-oxidise to NiO_2
  - NiO_2 has higher volume and will cause mechanical damage to cell
- goals:
  - no gas leakages from stack (safe operation)
  - rapid start-up (30 minutes for road APU)



T. Klemenso et al. / Electrochem. Solid-State Lett. 9(2006)A403

Redox stability of Ni–YSZ cermet

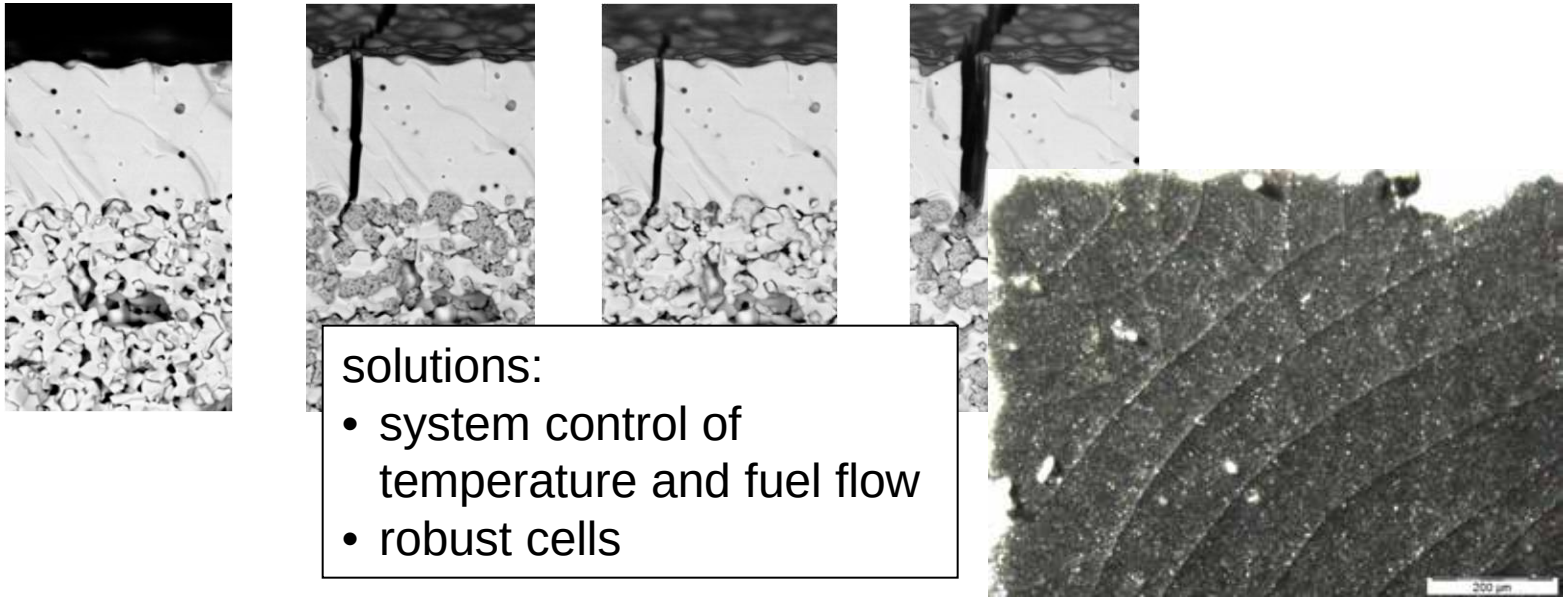
UNIVERSITY OF BIRMINGHAM

- cyclic reduction and oxidation leads to large volume change of Ni to NiO
- microstructure of Ni/YSZ bulk is affected
- performance degradation due to change in Ni particle surface, or
- catastrophic (mechanical) failure of cermet, or
- cracking of electrolyte layer

Elektrolyte

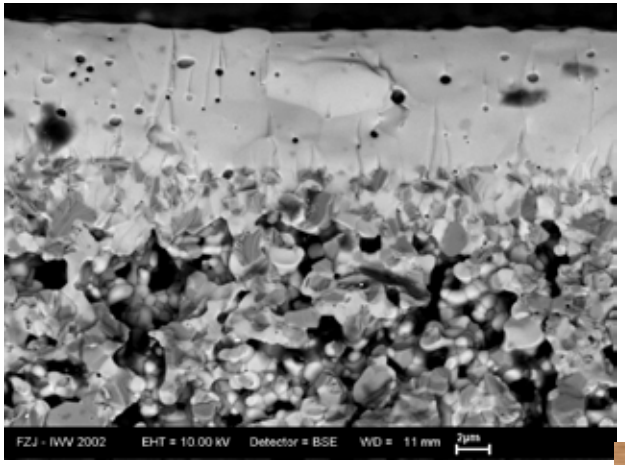
Anode

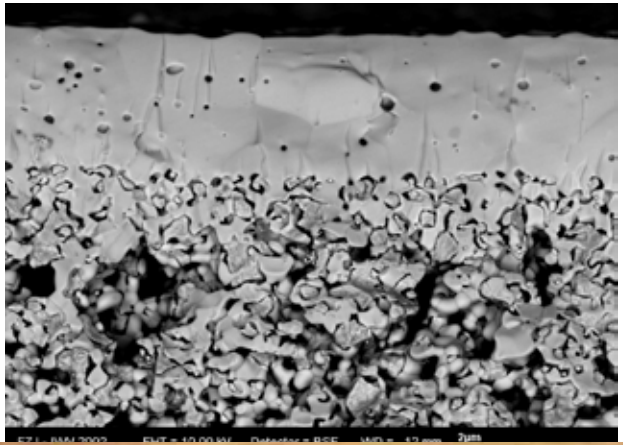
Substrate

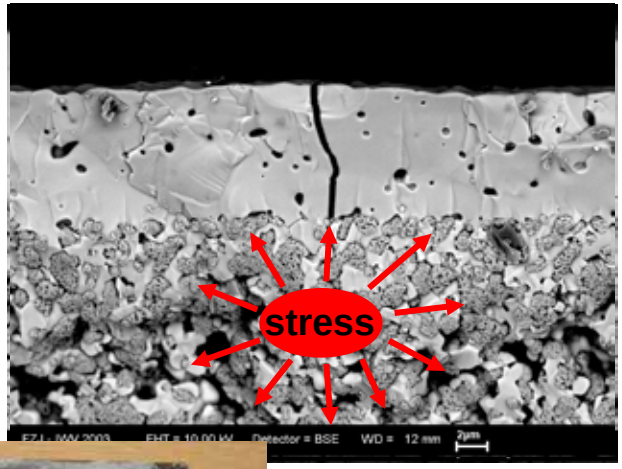


solutions:
- system control of temperature and fuel flow
- robust cells

Anode – Redox-Stability





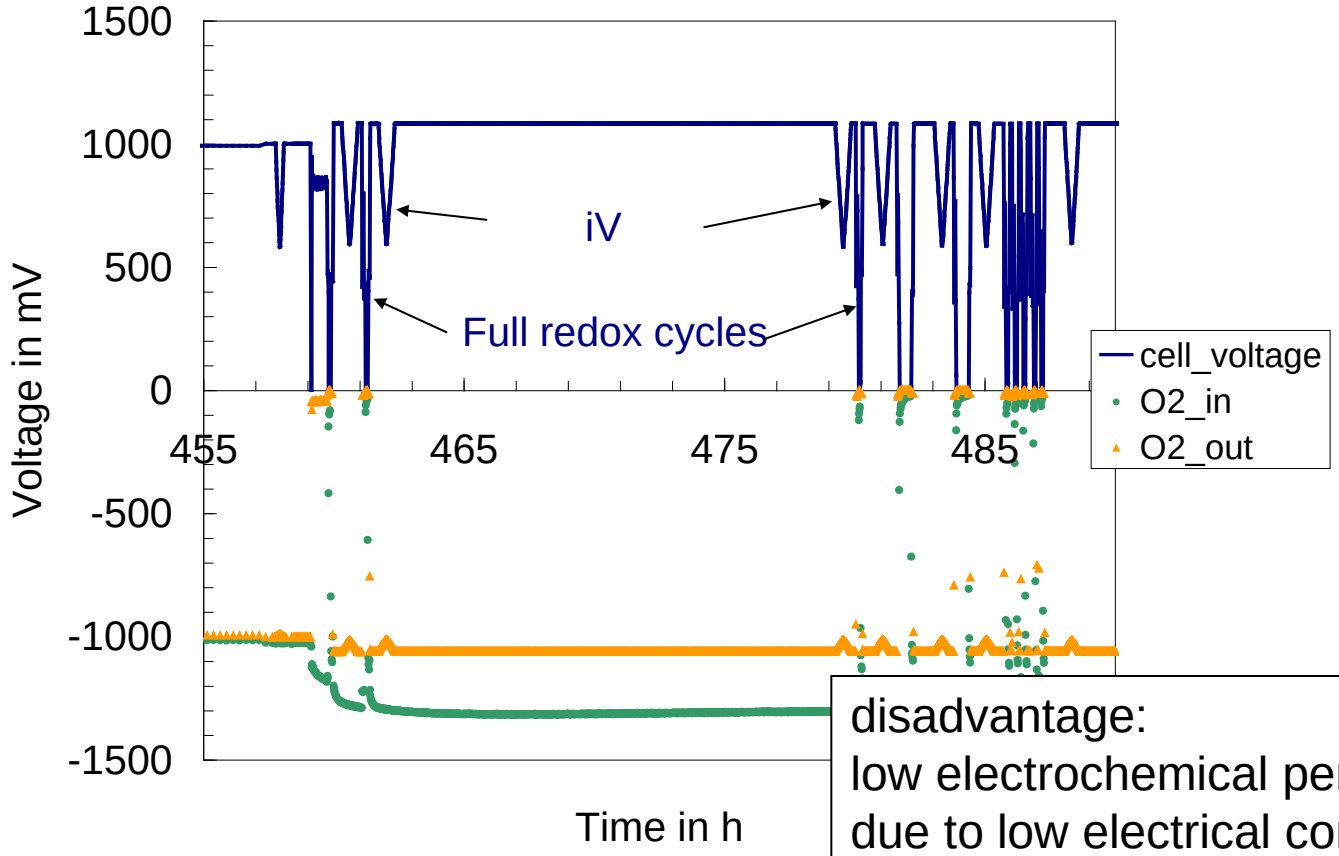


starting state:

oxidized
$NiO + ZrO_2(+Y_2O_3)$

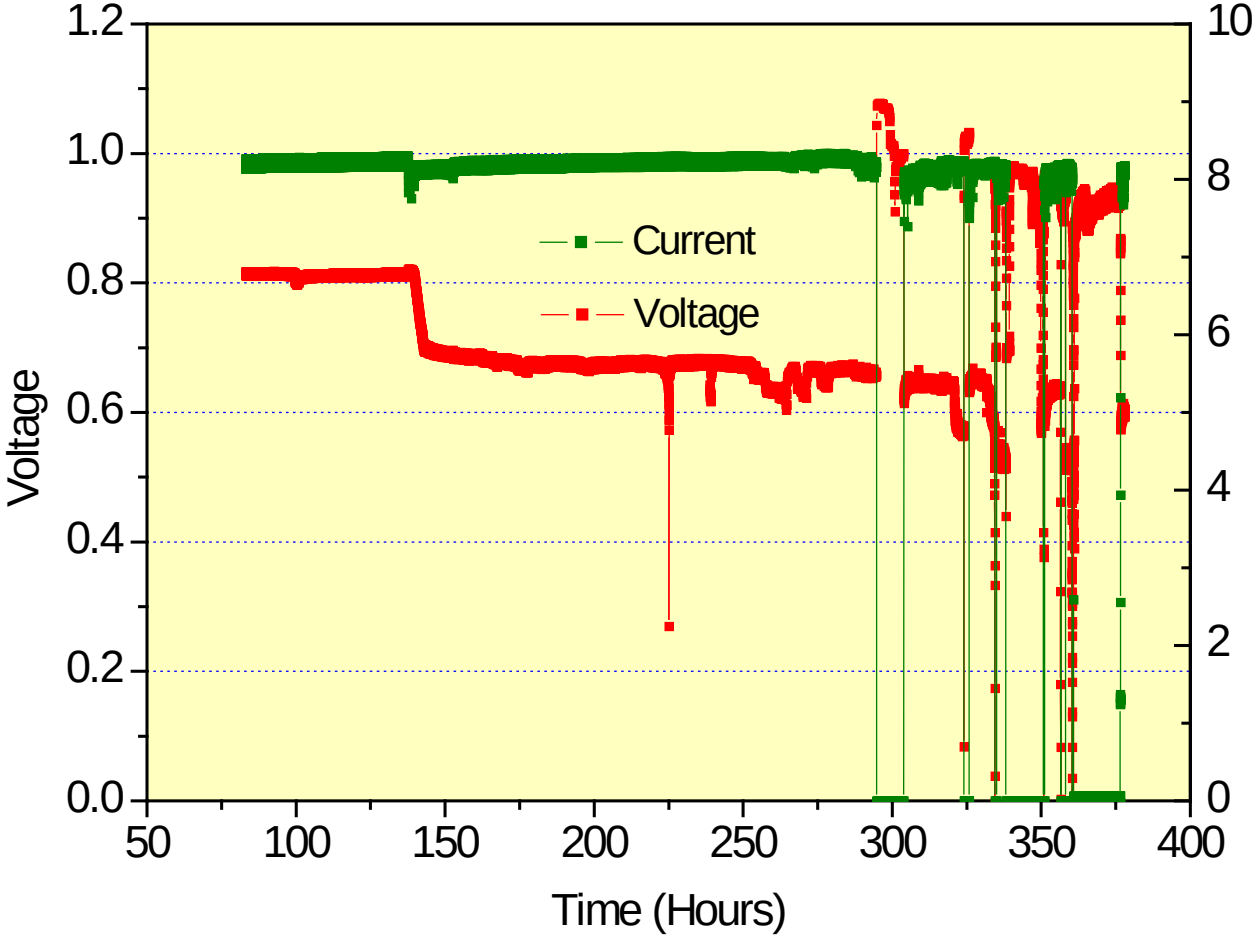
e
$Y_2O_3)$

Anode Redox Stability – SrTi Anode

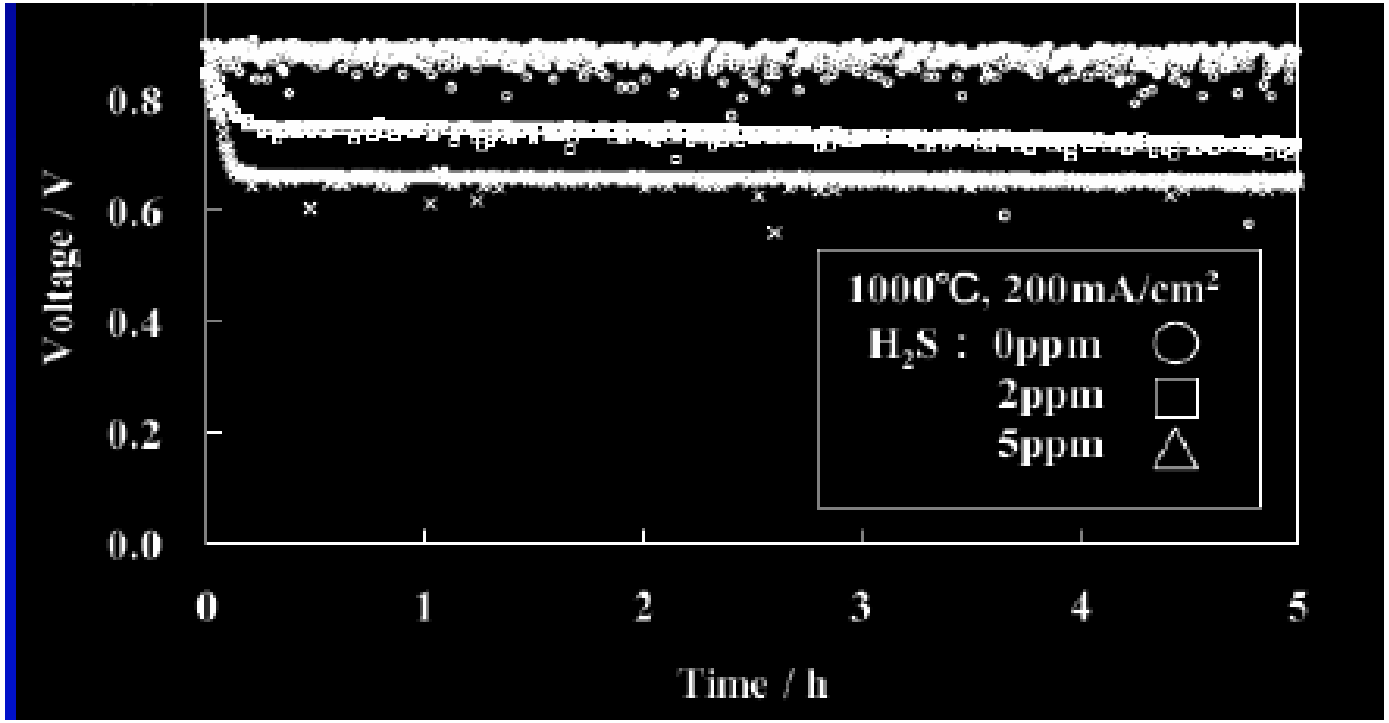


disadvantage:
low electrochemical performance due to low electrical conductivity

Sulphur Poisoning – The Phenomenon



Sulphur Poisoning – The Phenomenon (2)



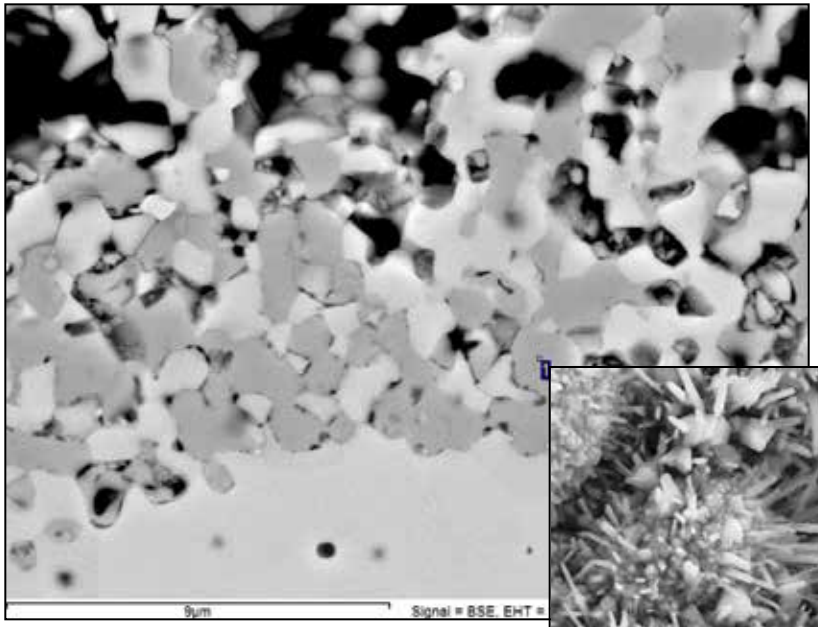
Sulphur Poisoning

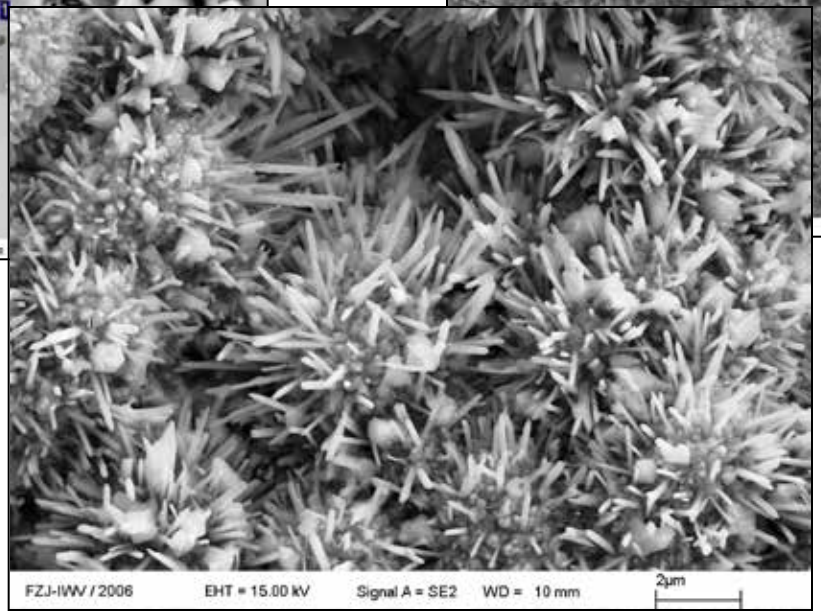
H_2S concentration:
Coal syngas – 100-300 ppm
Biogas – 50-200 ppm
Natural gas – up to >1%

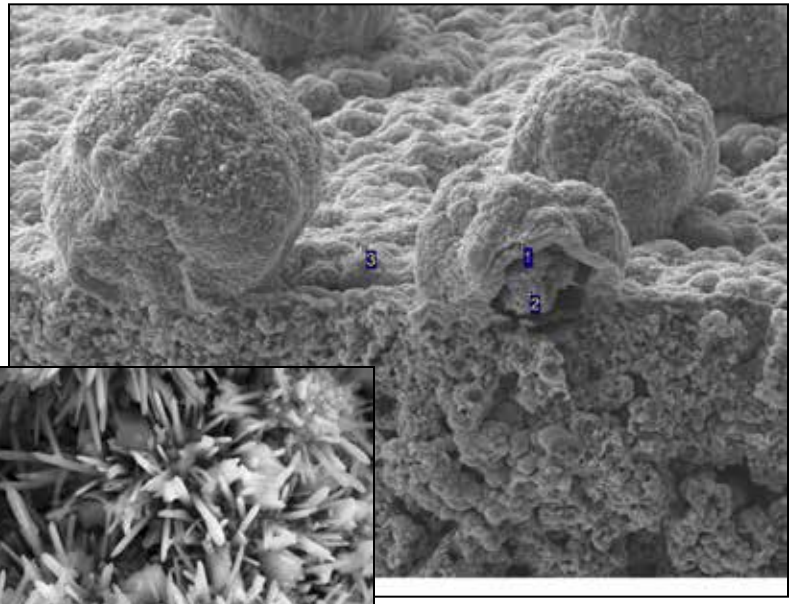
Chemosorption:
H_2S=HS(ad)+H(ad)=S(ad)+2H(ad)
Chemical reactions:
$H_2S=H_2+S$ (at 1100 K 8.6% H_2S is decomposed)
$Ni+H_2S=NiS+H_2$
$3Ni+xH_2S=Ni_2Sx+xH_2$ (at 800°C required level for sulfides formation is 1% H_2S)
Electrochemical reactions:
$H_2S+3O^{2-}=H_2O+SO_2+6e^-$
$H_2S+O^{2-}=H_2O+S+2e^-$
$S+2O^{2-}=SO_2+4e^-$

1st step (reversible): Fast adsorption of sulfur occurs in minutes upon exposure to H_2S, which blocks reaction sites and leads to rapid performance degradation. 90% coverage may occur at 1000 K for a low H_2S concentration (10 ppm).

Sulphur Poisoning: Microscopic Findings







bulk material deposition

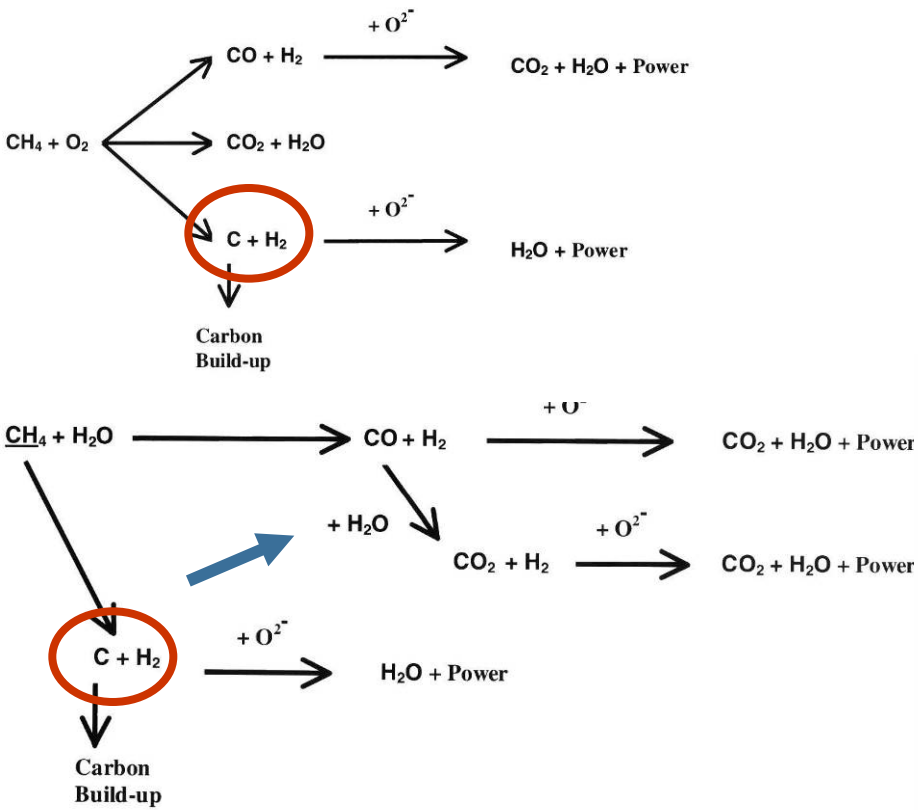
- ► **Reduction of porosity**
- ► **Passivation of catalytically active Ni**

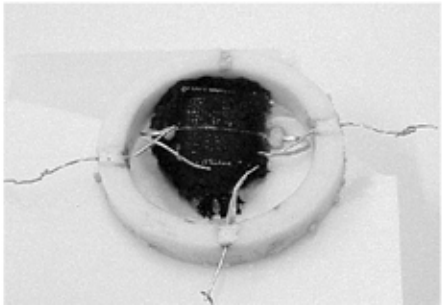
surface deposition

- ► **Passivation of catalytically active Ni**

Coking – Carbon Buildup in Internal Reforming

carbon build-up due to hydrogen and oxygen stochiometry mismatch (Boudouard Reaction)





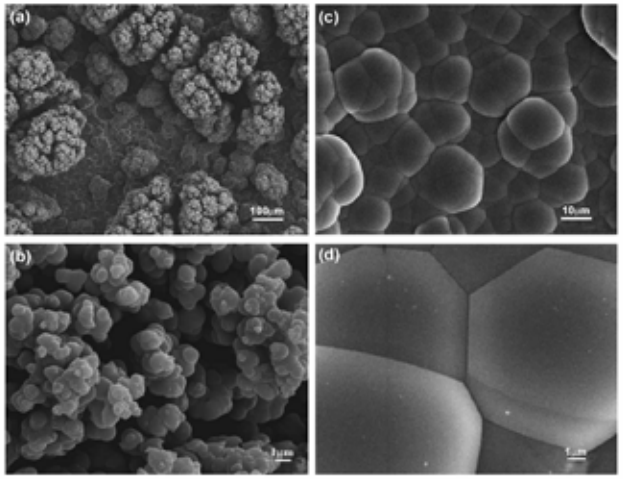


Fig. 4. The morphology of carbonaceous deposits on the surface of an anode containing 10 wt.% CeO_2 and 20 wt.% Cu after long-term testing in n-butane at 1173 K.

figures courtesy of Jörger & He

Methane Conversion Reactions

equilibrium (i≈0)

$CH_4 = C + 2H_2$ (1)

steam reforming (endothermic)

$CH_4 + H_2O = CO + 3H_2$ (2)

partial oxidation

$CH_4 + 1/2O_2 = CO + 2H_2$ (3)

water-gas shift reaction

$CO + H_2O = CO_2 + H_2$ (4)

Boudouard reaction

$2CO=CO_2+C$ (5)

direct oxidation

$CH_4 + O^{2-} = CO + 2H_2 + 2e^-$ (6)

$CH_4 + 4O^{2-} = CO_2 + 2H_2O + 8e^-$ (7)

oxidation

$C + O^{2-} = CO + 2e^-$ (8)

$C + 2O^{2-} = CO_2 + 4e^-$ (9)

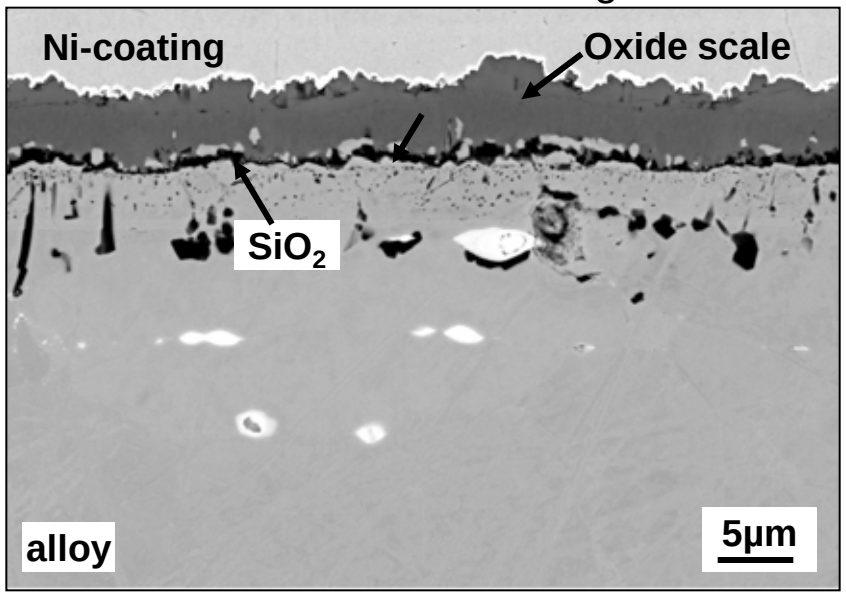
$CO + O^{2-} = CO_2 + 2e^-$ (10)

$H_2 + O^{2-} = H_2O + 2e^-$ (11)

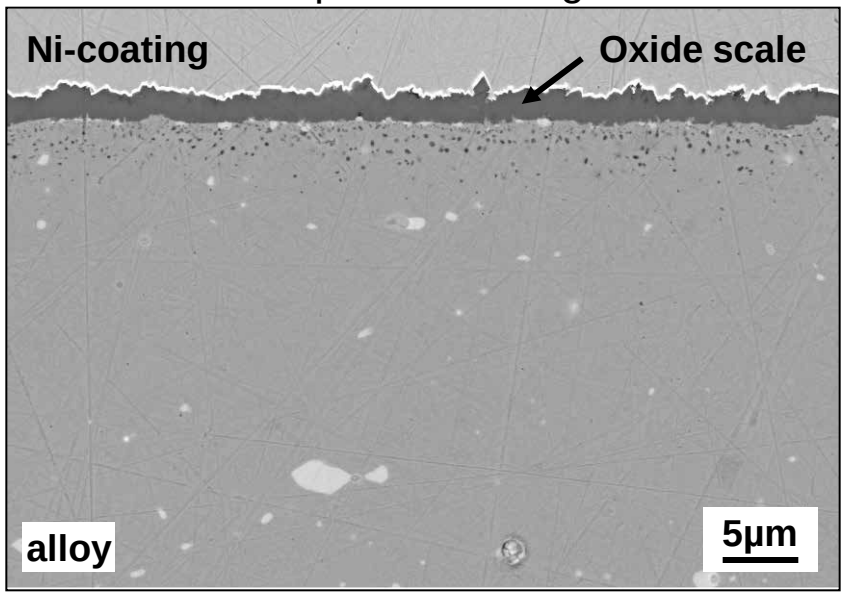
Interconnect Corrosion: Scale Cross-Sections

Microstructures of oxide scales after 1000 h discontinuous oxidation at 800°C in air

Commercial Si-containing steel



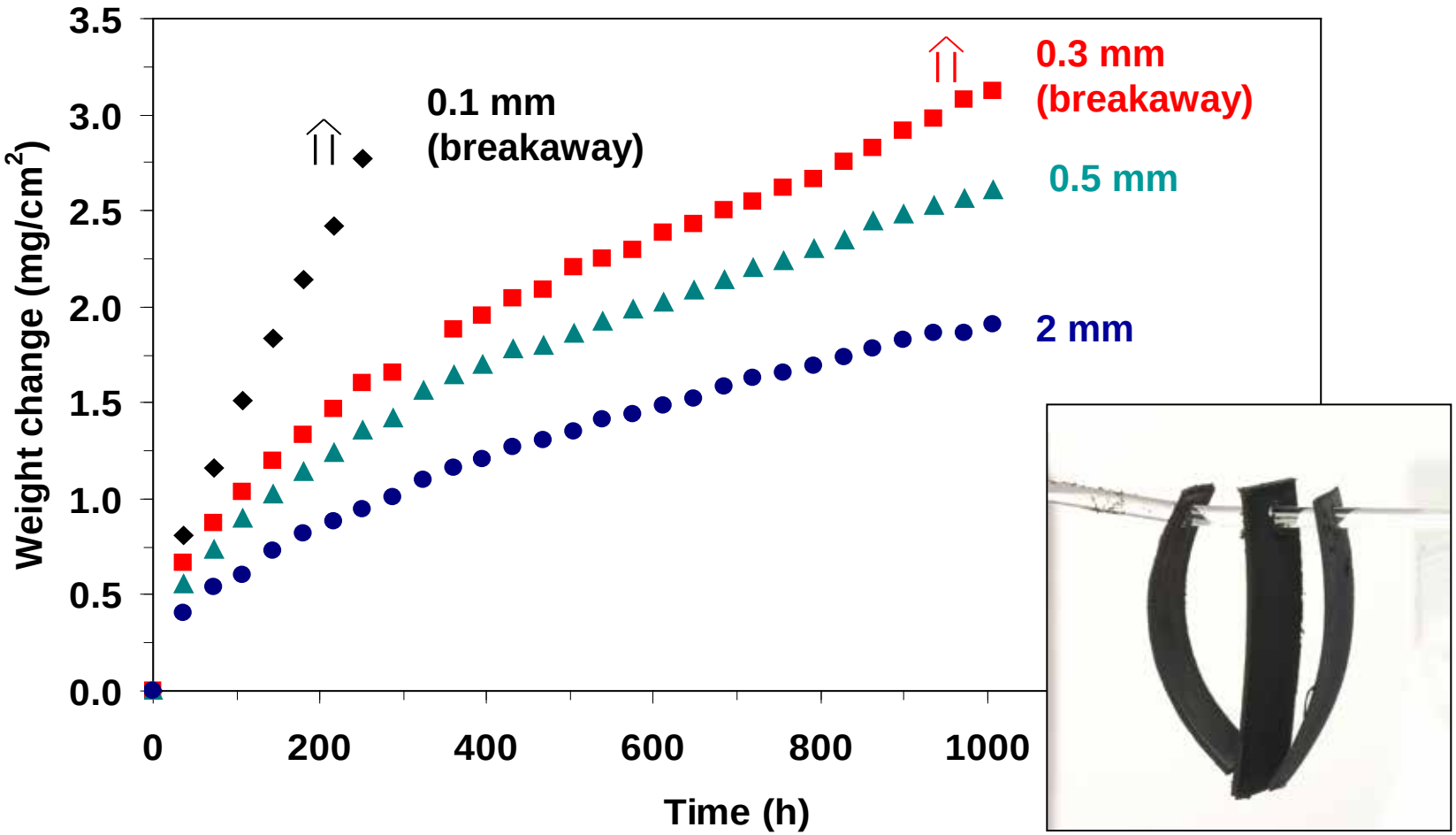
Si + Laves phase forming elements



Steel Corrosion - Interconnects

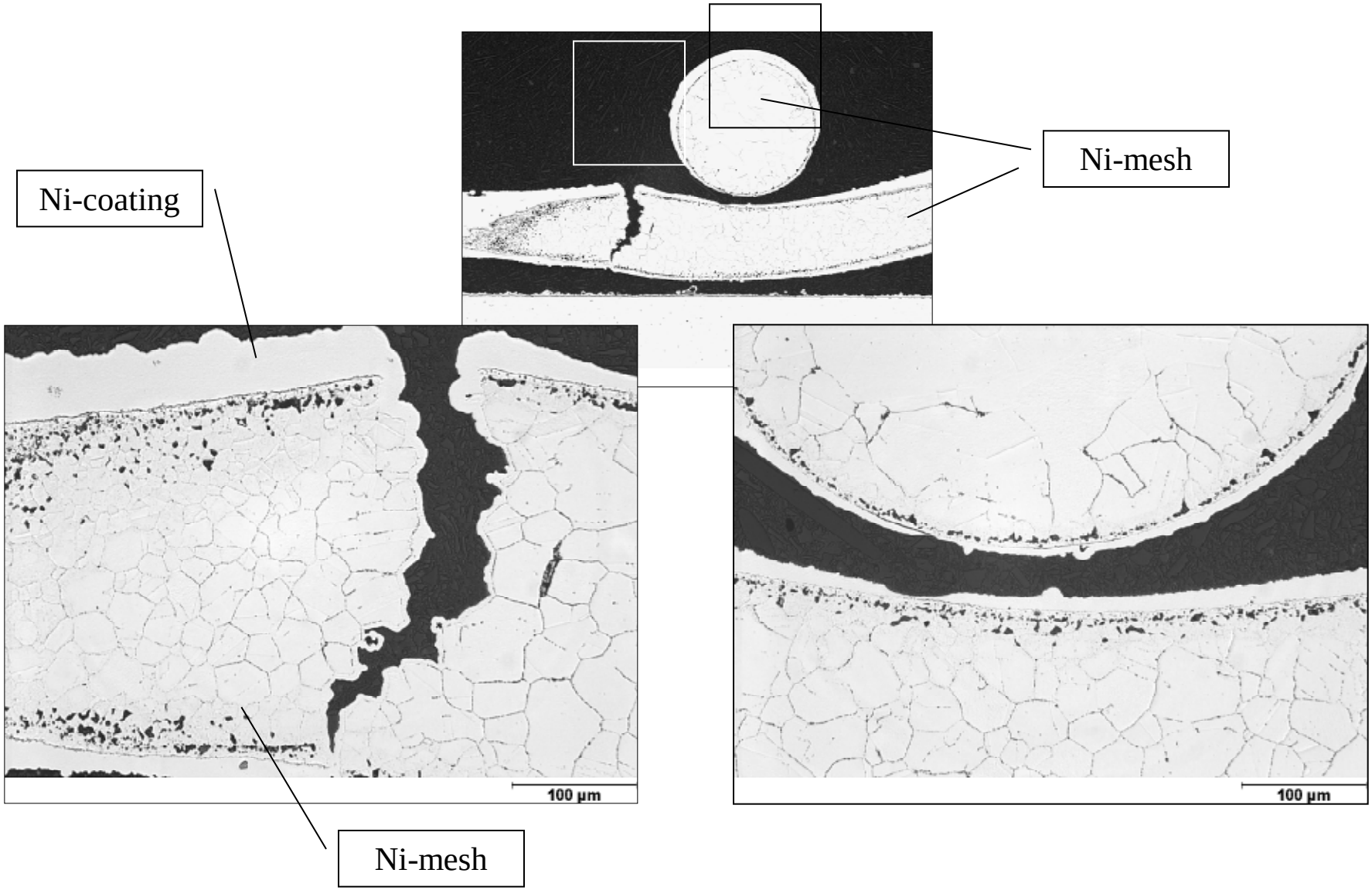
UNIVERSITY OF BIRMINGHAM

Cyclic Oxidation of Ferritic Steel Crofer 22 APU in Air at 900°C



k_p–dependence on specimen thickness

Metal Corrosion: Nickel Mesh (anode side)



Degradation of Interconnect Steels

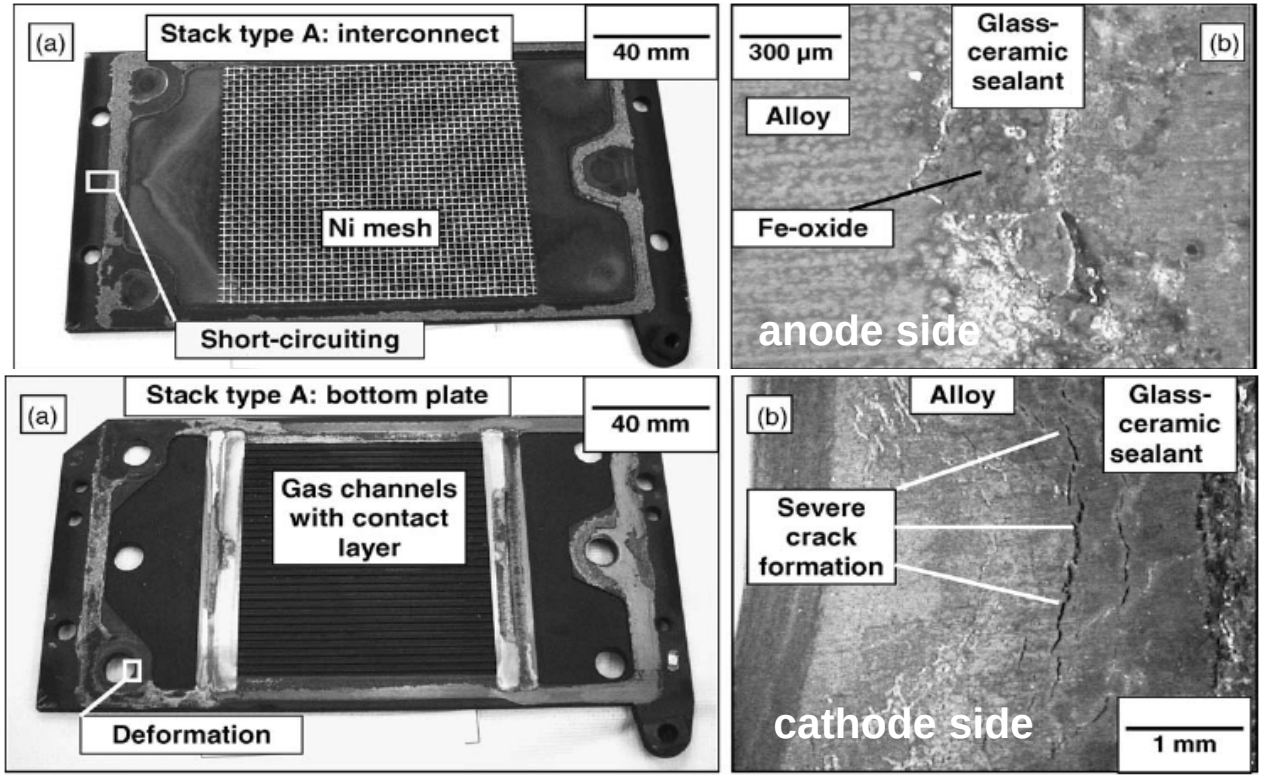
Ferritic stainless steels are Fe–Cr alloys. To be considered “stainless”, the alloys must contain at least 12-14% Cr for aqueous corrosion. Even more Cr is required if the alloy is to be able to selectively oxidize the Cr to form a continuous, protective layer of Cr_2O_3.

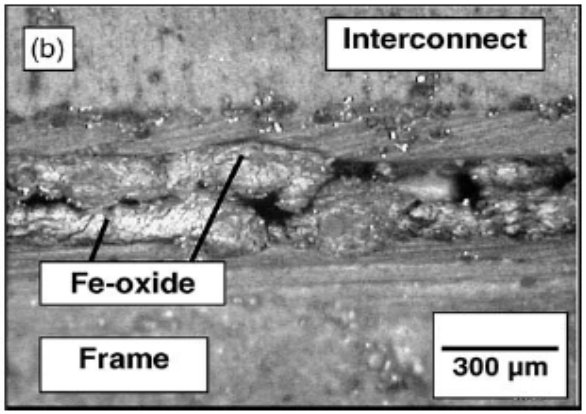
Chromia (Cr_2O_3) forming ferritic stainless steels have similar coefficient of thermal expansion with the oxide components of the SOFC. Electrical conductivity requires that the oxide that forms at the interconnect surfaces be conductive at operating temperatures. Chromia forming alloys meet this requirement; as Cr_2O_3 is a semiconductor at elevated temperatures.

Chemical composition of the alloys used

Alloy	Fe	Cr	Mn	Ti	Si	Al	Re-el.	Ni
Crofer22APU-1st	Bal.	22.6	0.4	0.06	0.1	0.1	La-0.1	0.2
JS-3	Bal.	23.3	0.4	0.05	<0.01	<0.01	La-0.1	–

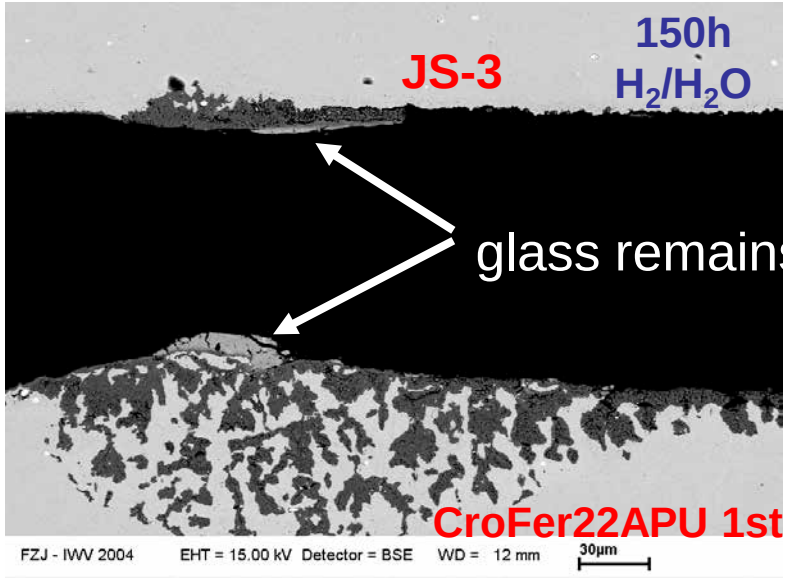
P. Batfalsky et al. / Journal of Power Sources 155 (2006) 128–137

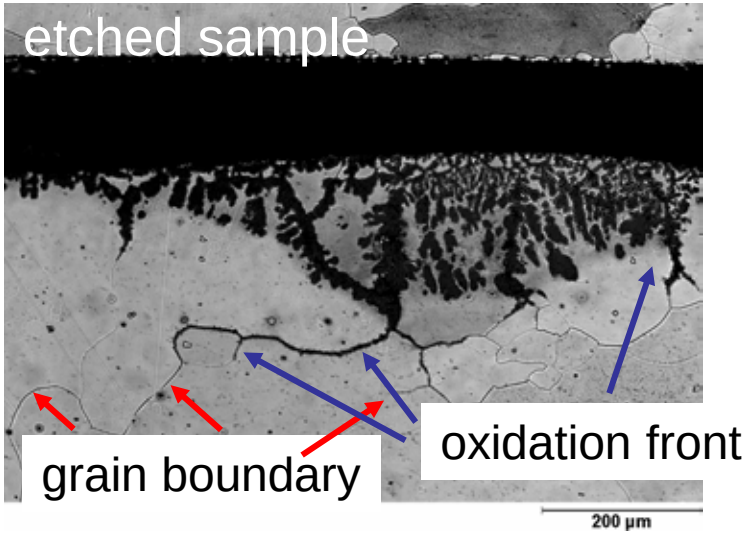




P. Batfalsky et al. / Journal of Power Sources 155 (2006) 128–137

Interaction of Glass Sealant and Ferritic Interconnect





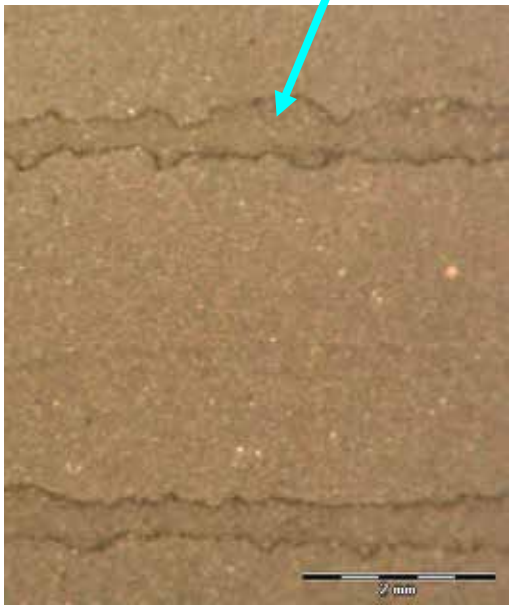
optimal matching of steel and sealing materials is vital:

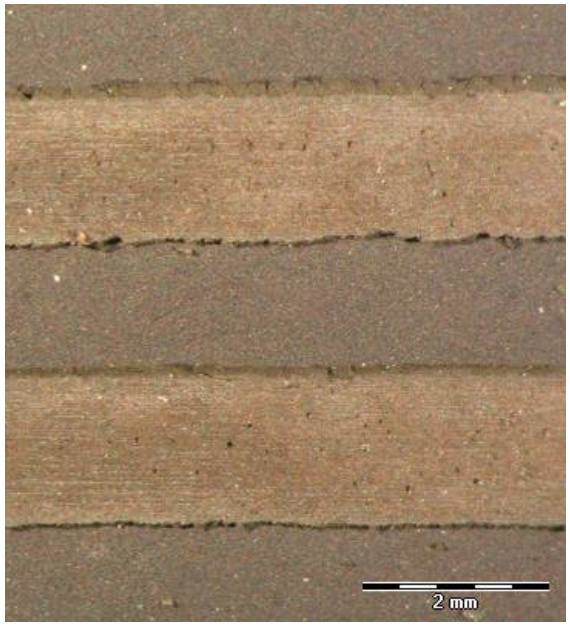
- good adhesion = chemical interaction
- but: no excessive corrosion

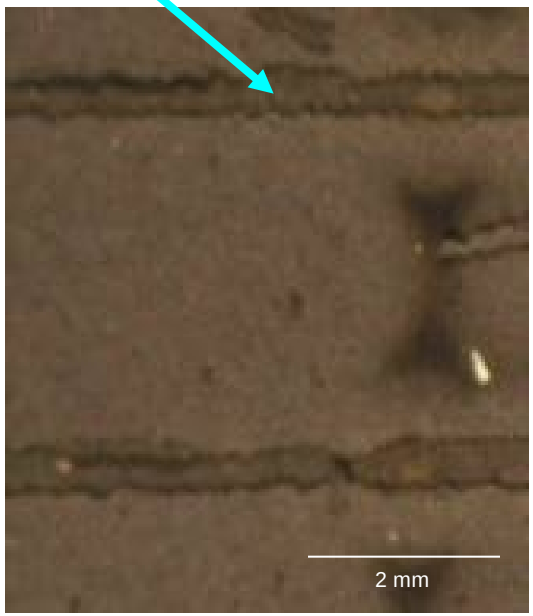
Degradation due to Contacting problems

Contact trace on cathode

high local current due to narrow contacting ‚ridge‘







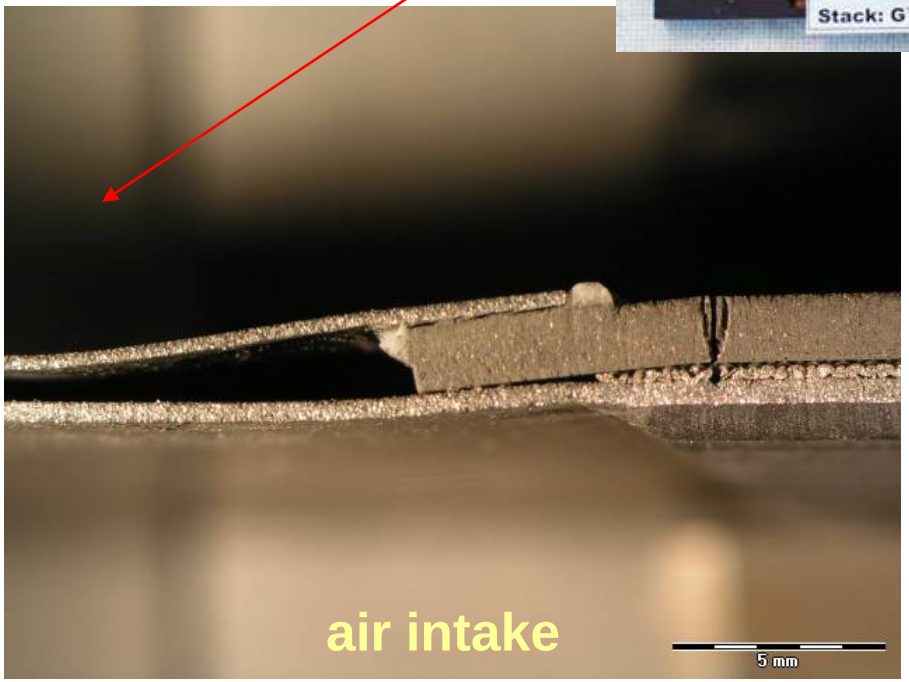
820 mV - 336 mA/cm²

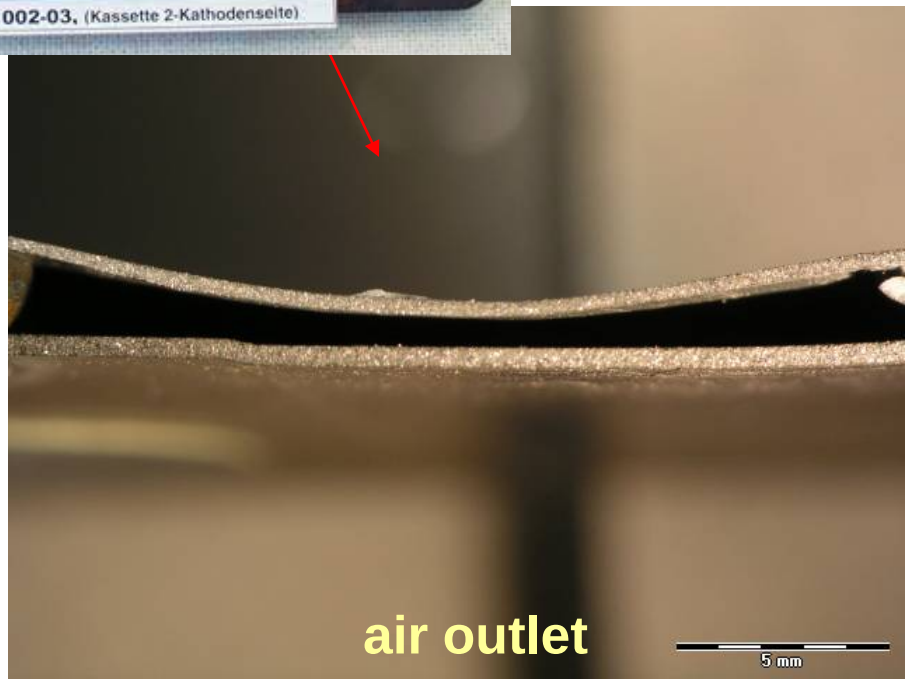
770 mV - 336 mA/cm²

880 mV - 298 mA/cm²

Thermo-Mechanics

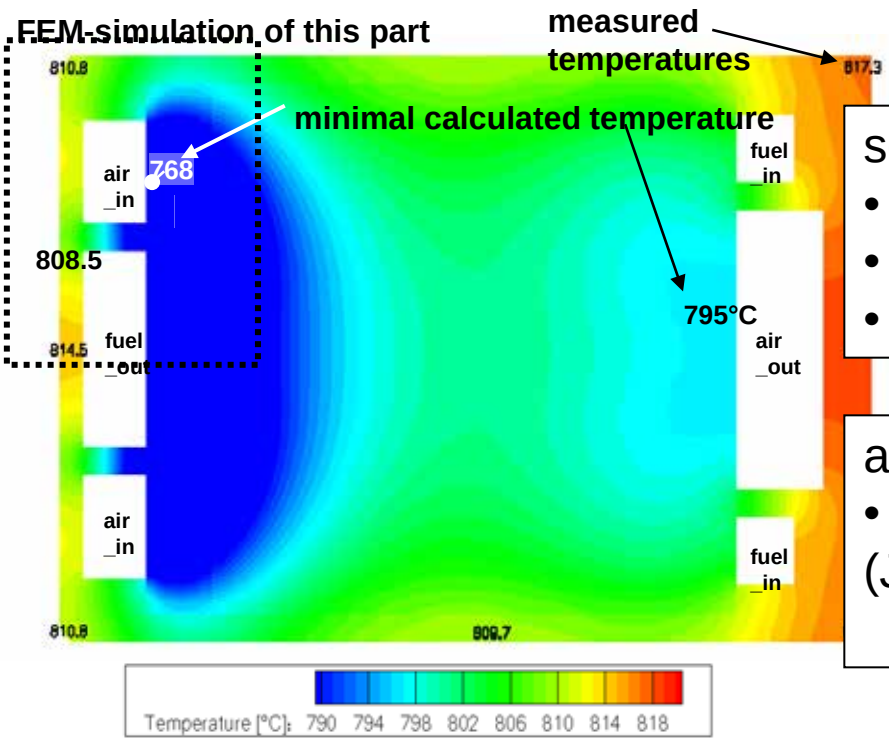
low strength of steels at high temperatures

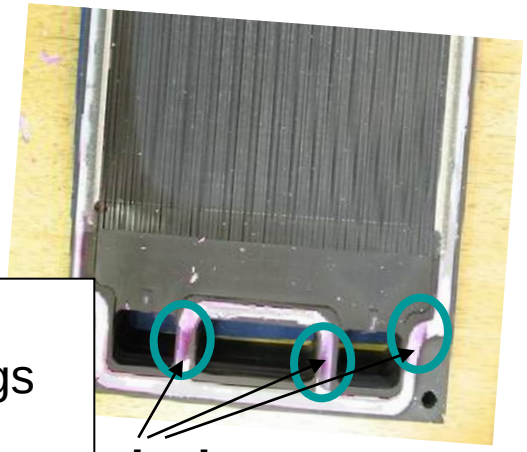




Thermal Cycling Requirements

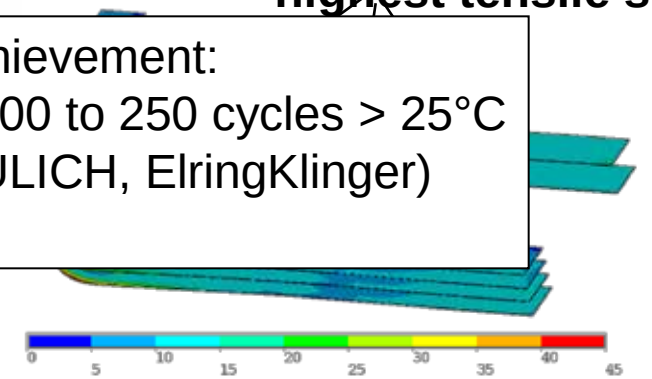
- thermal cycles:
  - ‘cold start’ 20°C … 200°C, ‘warm start’ >400°C up to 600 … 750°C
- goals:
  - no gas leakages from stack (safe operation)
  - rapid start-up (30 minutes for road APU)





solutions:
- strong sealings
- robust design
- compliant design

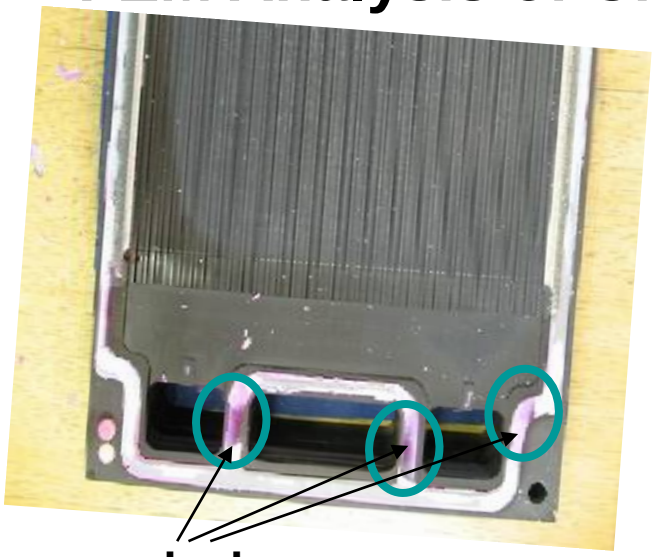
highest tensile stress

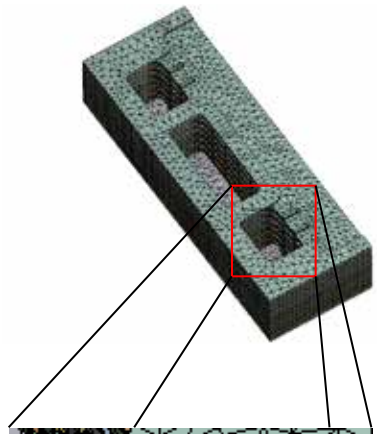


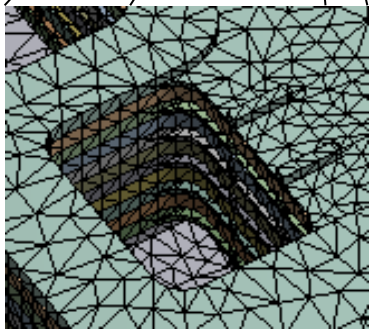
achievement:
- 100 to 250 cycles > 25°C

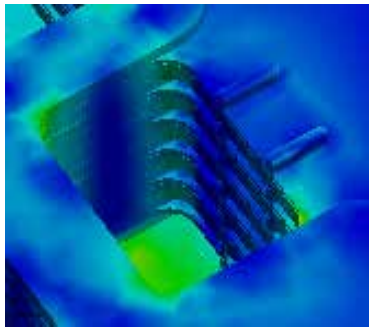
(JÜLICH, ElringKlinger)

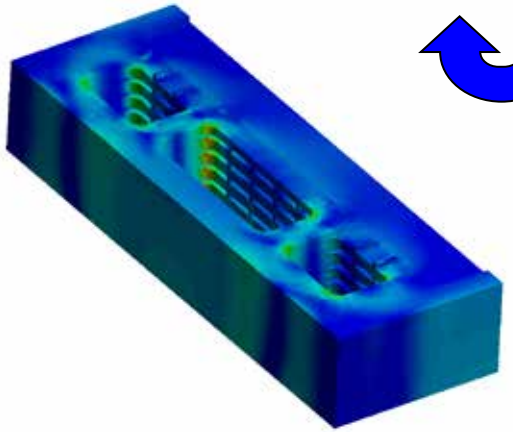
FEM Analysis of Critical ThermoMechanical Stress





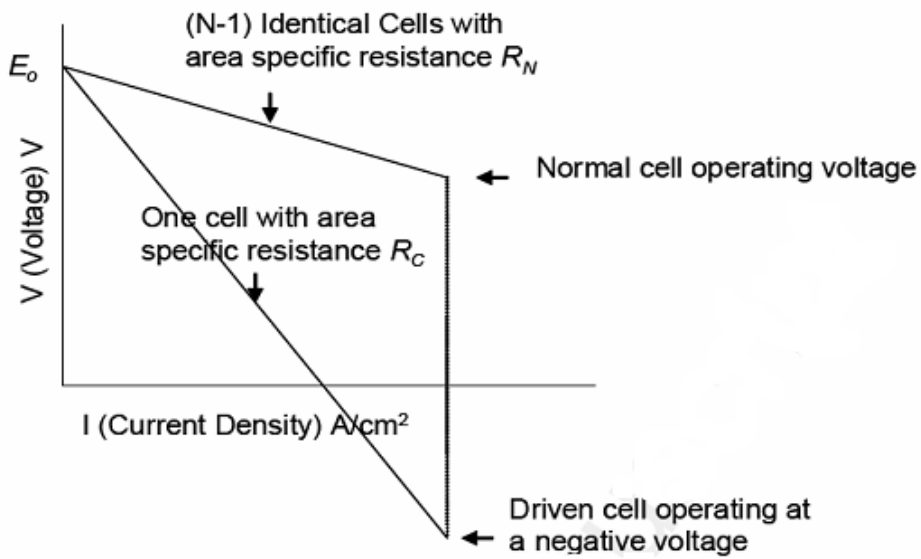






- identification of critical locations in stack
- implementation of global model
- passing of boundary conditions to more detailed sub-model
- prediction of strain
- improvement of design

Impact of Failing Element in a Stack



If a single cell in a stack exhibits higher resistance than the rest of the cells, stack failure often initiates at such a cell. The cell is then exhibits lower voltage than the rest of the cells, and often even a negative voltage. It is necessary that cell-to-cell characteristics be as uniform as possible including contact between repeat units.

If a cell exhibits a negative voltage, the oxygen chemical potential within the electrolyte can exceed that in the oxidant, and/or can drop below that in the fuel. This can lead to high internal oxygen partial pressure resulting in electrode cracking and delamination, and/or very low oxygen partial pressure leading to local electrolyte decomposition. Both situations can lead to cell and stack degradation.

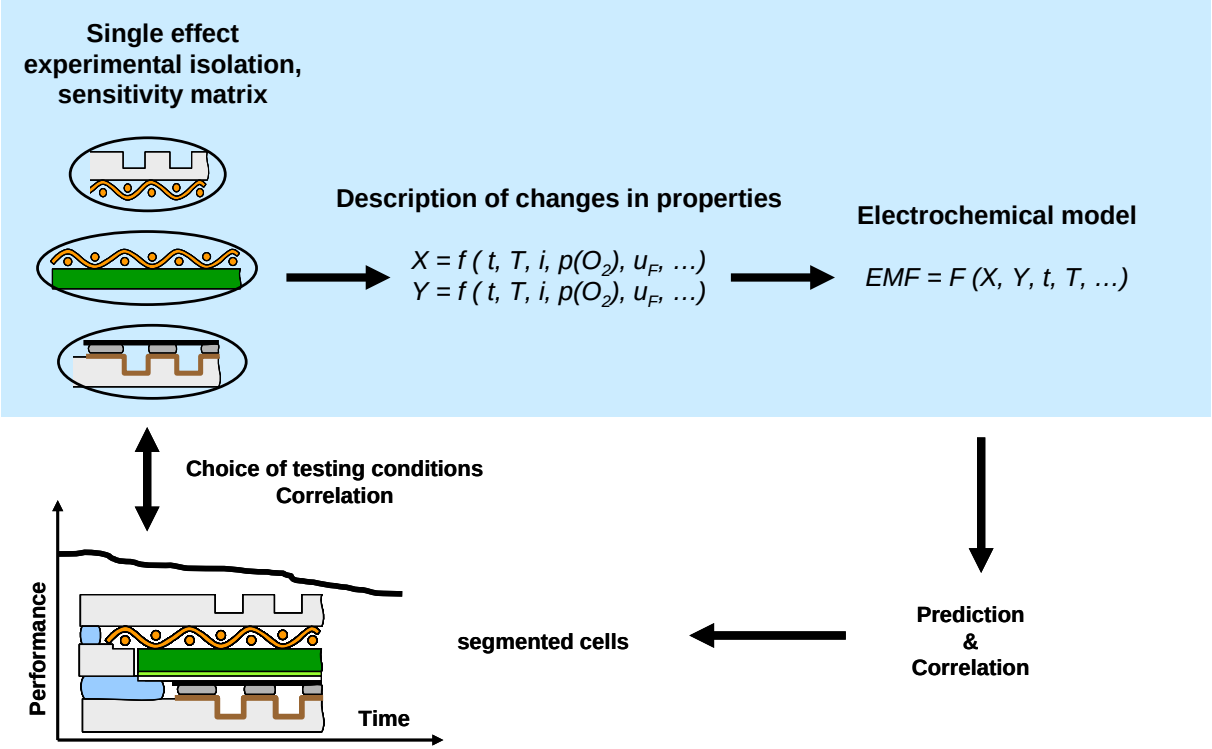
Modelling of degradation processes

Analysis Approach

- correlating cause and effect (phenomena and ensuing degradation)
- modelling of effects
- understanding and influencing mechanisms
- improving materials with less sensibility to degradation and/or deterioration

not only to be worked on in sequence, but also in parallel

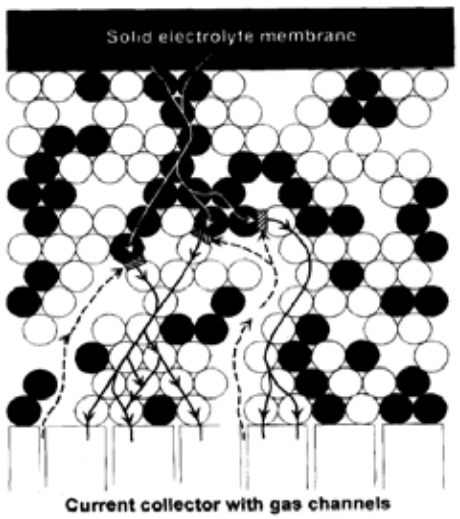
Modelling Approach to Degradation Effects



The quantification and prediction of single contributions with respect to their behaviour over time is the key expected outcome of this project

Correlated percolation model

In the model monosized particles are located on a face-centered cubic lattice and sintering between two metal particles occur with a certain probability. The model gives an insight in the development of active bonds in the anode, the density of three phase boundaries and the transport resistance in anodic materials.



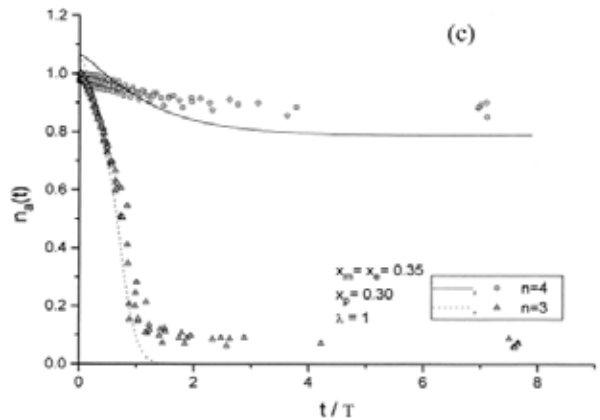


Fig. 3. Variation of the number of active bonds with time, $n_a(t)$, obtained for the composition which maximizes $n_a(0)$. Lines: effective medium theory; points: Monte Carlo simulation. The effect of the probability of pore opening in each sintering act, λ: (a) 0, (b) 0.5, (c) 1. The curves and points correspond to the indicated values of the minimum number, n, of non-electrolyte neighbors of the bond between two metal particles which allows their fusion.

A. Ioselevich et al. / Solid State Ionics 124 (1999) 221–237

Approaches to SOFC Accelerated Lifetime Testing

Accelerated durability testings

UNIVERSITY OF BIRMINGHAM

Types of Acceleration

- Increase the use-rate of the product (e.g., test a toaster 200 times/day). Higher use rate reduces test time.
- Use elevated temperature or humidity to increase rate of failure-causing chemical/physical process.
- Increase stress (e.g., voltage or pressure) to make degrading units fail more quickly.

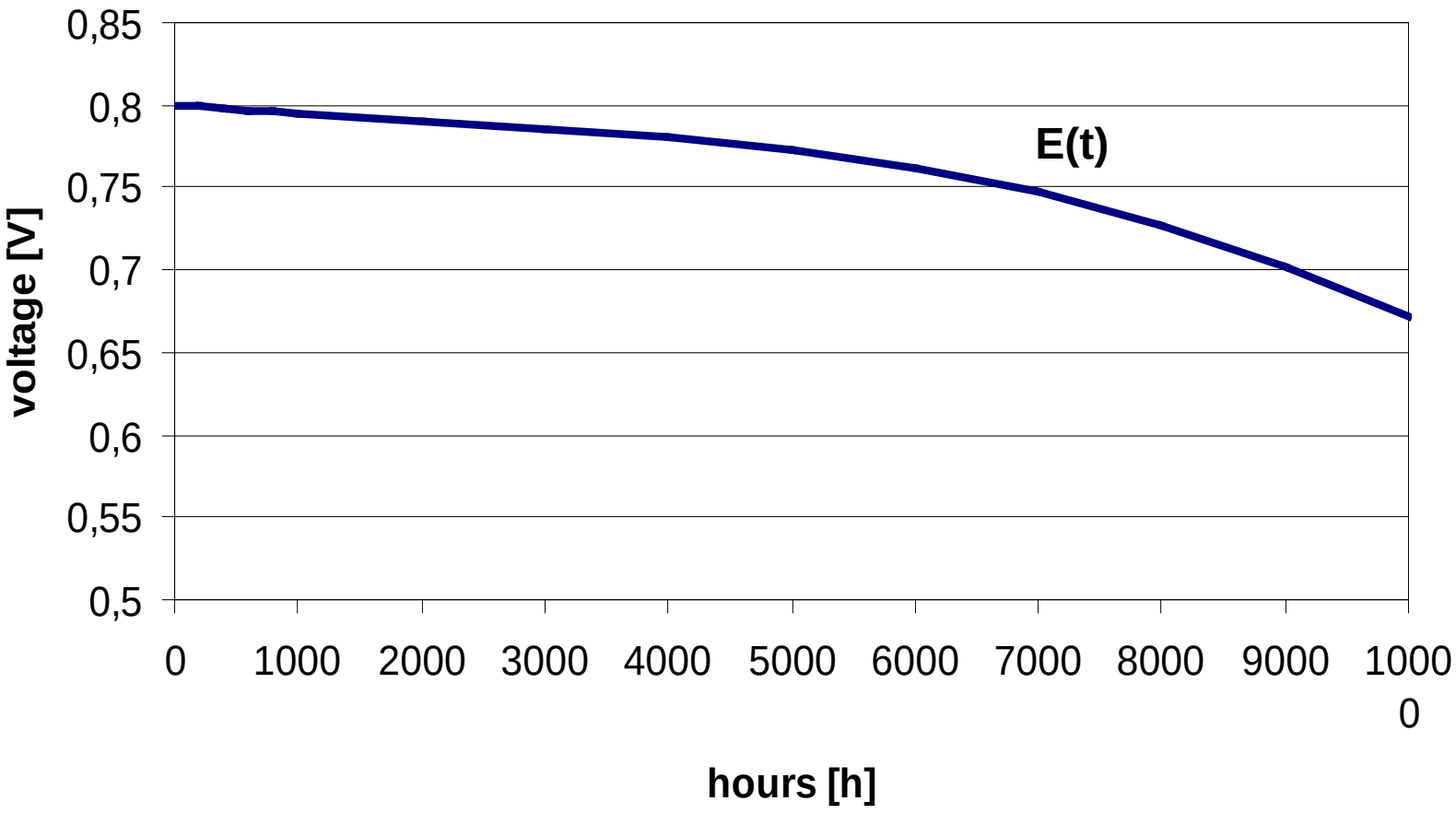
These types of acceleration may work in combination (e.g. electro-chemical reactions)

Acceleration of a failure mechanism must mimic actual occurrence of the failure mode(s)

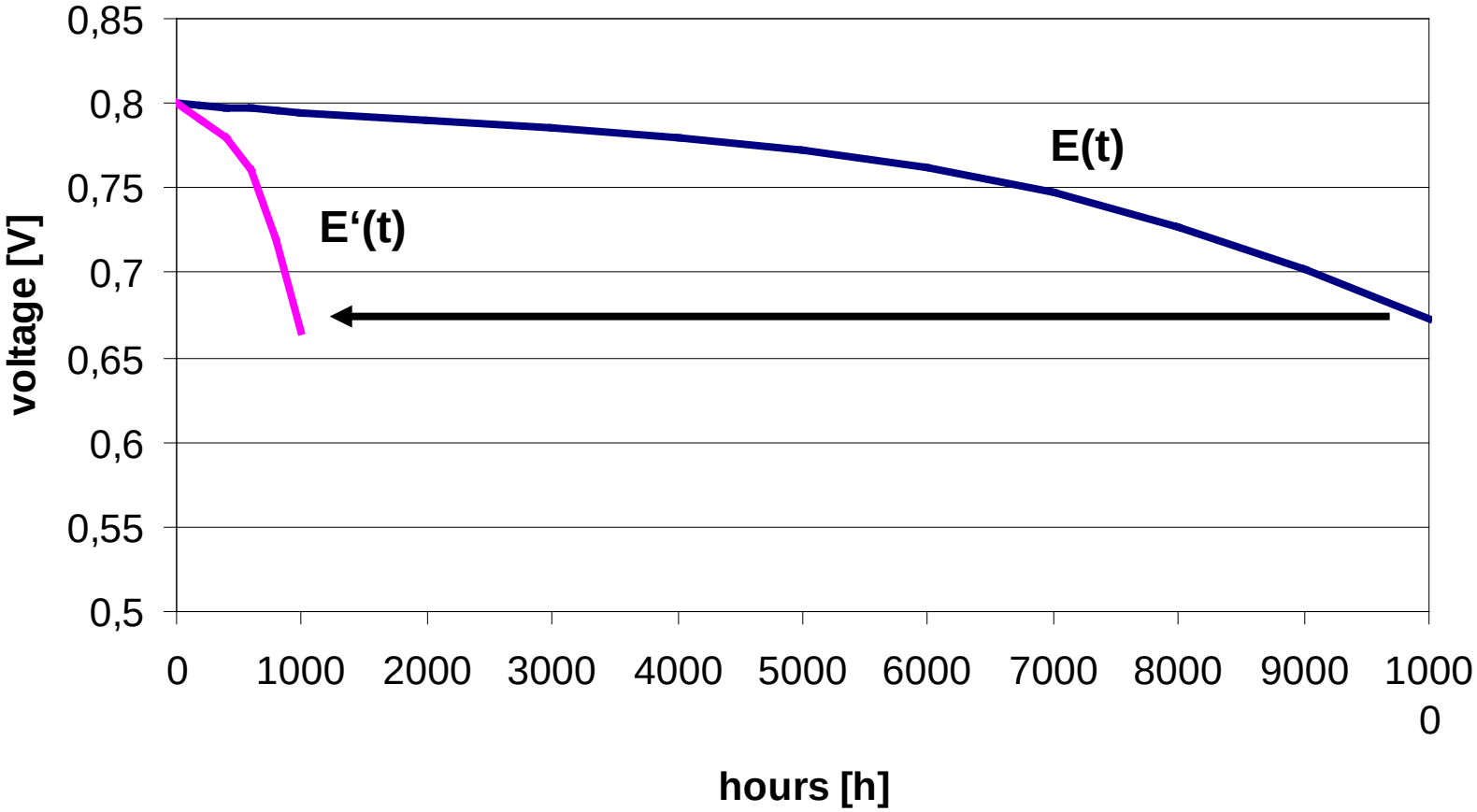
7

William Q. Meeker

Accelerating Degradation Effects



Accelerating Degradation Effects



Mapping in Time

- Cell voltage can be written as

  $E(t) = E(t=0) – X(t)$

- degradation phenomena are generally functions of

  - T, $p(O_2)$, $p(H_2O)$, j, overpotential, concentration gradients etc.

  - in the form $X(t) = f(T, p(O_2), j, t, \ldots)$

- a mapping has to be found where

  $X'(t) = X(a \cdot t)$

  where $a > 1$ is an acceleration coefficient

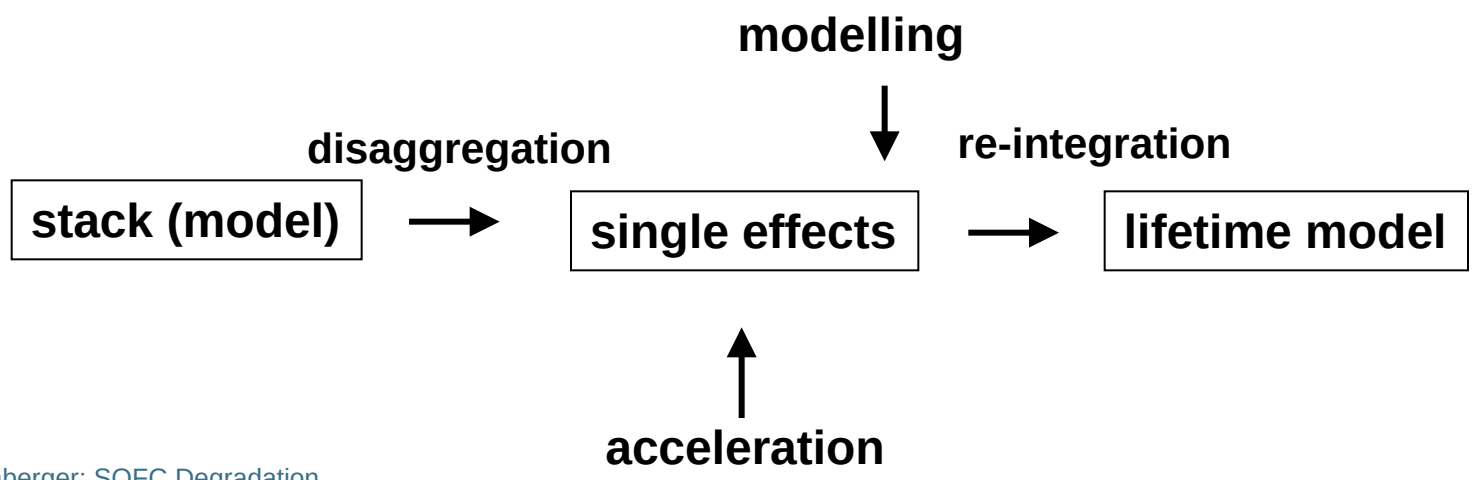
- prerequisite:

  the acceleration must not change the principal effect

- the mapping is not necessarily linear

A Lifetime Prediction Model

- stack test results are too complicated to analyse
- full set of parameters to equip a ‚full‘ stack model (including degradation) does not exist
- a disaggregated model of single degradation mechanisms could be suitable for evaluation of the single effects
- a complete model could then be achieved by re-aggregating results
- this also might lend itself to introducing accelerated testing



UNIVERSITY OF BIRMINGHAM

Thank you for your attention!

If there‘s any questions … go ahead.

Acknowledgments go to

my former project team at FZJ,

Dmitri Bronin for slide material,

The European Union
for financing part of the research presented here,
and to all partners in the co-operation project Real-SOFC

Real-SOFC was co-funded by the European Commission under the contract no. SES6-CT-2003-502612