Imperial College London

Energy Materials: Solid Oxide Fuel Cells

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Key questions

- Where is the UK in relation to the current state of the art of materials technologies in SOFC?
- Where and how can the UK really make a difference in 'meeting the challenge' and become world leaders?
- What are the next steps the UK should be taking to secure business in this area

Main issues

- Cost
  - Cheaper materials
  - Higher performance
  - Cheaper manufacturing
  - Simpler systems
- Durability
  - Thermo-chemical stability
  - Thermo-mechanical stability
  - Lower operating temperatures
  - Resistance to “poison” impurities
  - Tolerance to abnormal operation
  - Tolerance of wider range of fuels
  - Accelerated testing

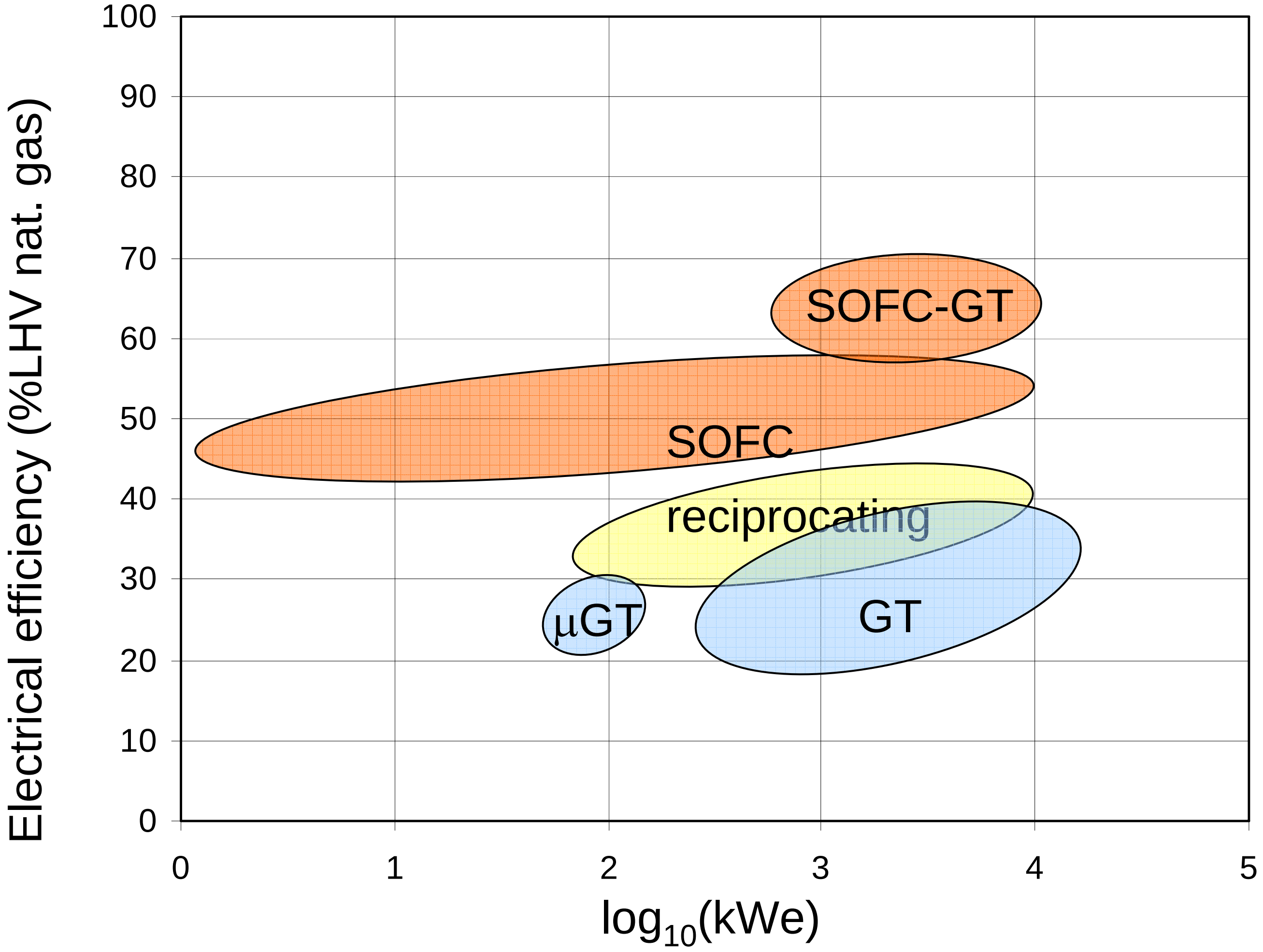
Contents

- Summary of SOFC technology
- Status of UK in relation to world activity
- Look at some problem issues
- Opportunities for UK SOFC

Applications for SOFC

- “Large” stationary electrical power (50 kW -10 MW)
  - high electrical efficiency
  - pressurisation and bottoming gas turbine (SOFT-GT)
- “Intermediate” CHP (5-50 kW)
  - high overall efficiency e.g. in hotels, offices
  - high grade waste heat
- “Small” CHP (<5 kW)
  - high overall efficiency e.g. domestic
- Uninterruptible power supplies
- Mobile Auxiliary Power Units (APU)
  - “Intermediate” size systems for boats, planes and trains
  - “Small” systems for road vehicles
  - battery/SOFC hybrid
- Micro power systems for electronics

Technology comparison for stationary power

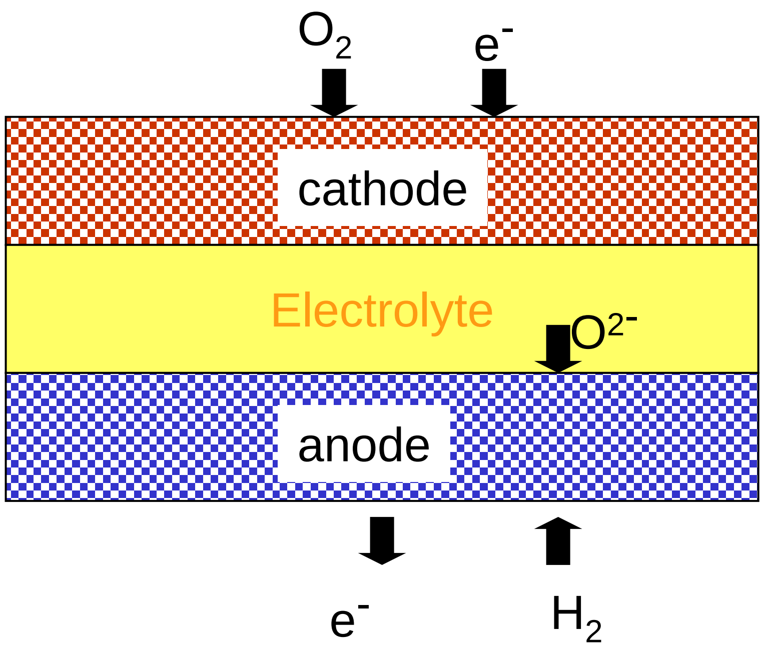


Fuels for SOFCs

- SOFCs work well on H_2, but a key feature is ability to use CO
- Hydrocarbon fuels need pre-reforming to H_2+CO
  - natural gas
  - LPG, propane, butane
  - alcohols
  - diesel, gasoline
- Steam reforming or catalytic POx (lowers efficiency)
  - needs no shift reactor or CO clean-up
- S removal required to < 10 wt ppm
- Biofuels give C-neutral operation

Typical materials used in SOFC

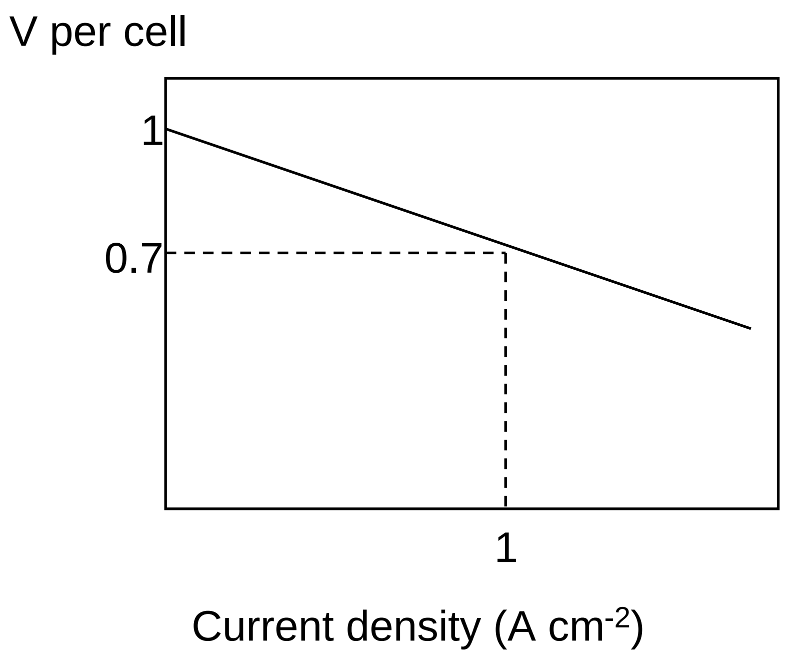
- Electrolyte
  - fast oxygen ion conductor (e.g.YSZ)
- Cathode
  - oxygen reduction catalyst, oxygen ion conductor, electronic conductor
    - single phase perovskite $La_{0.8}Sr_{0.2}MnO_3$ (LSM) $La_{0.8}Sr_{0.2}Fe_{0.8}Co_{0.2}O_3$ (LSCF)
    - composite (e.g. LSM/YSZ)
- Anode
  - oxidation catalyst, oxygen ion conductor, electronic conductor
    - composite (e.g. Ni/YSZ)
- Interconnect/bipolar plate
  - electronic conductor
    - $La_{0.8}Sr_{0.2}CrO_3$, Cr alloy, stainless steel



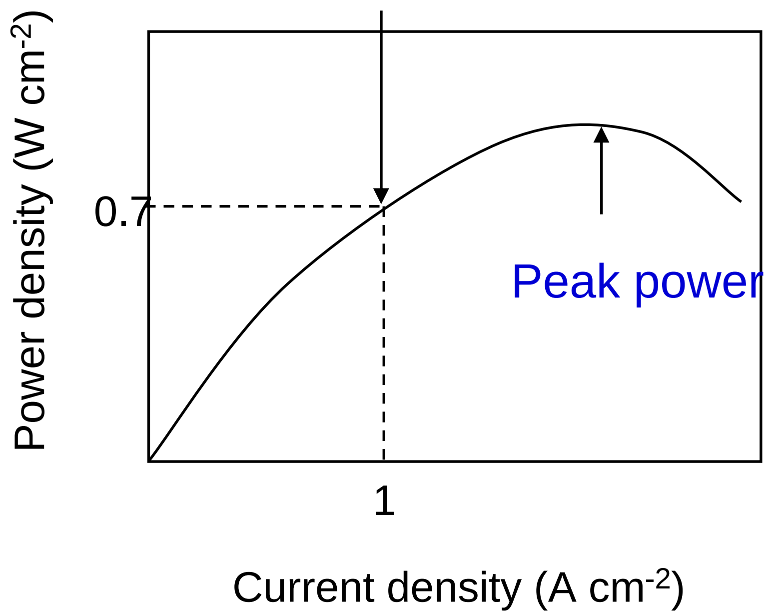
SOFC performance goal

ASR = $(V_0-V)/I$ = 0.3 ohm cm^2

Power density = V×I

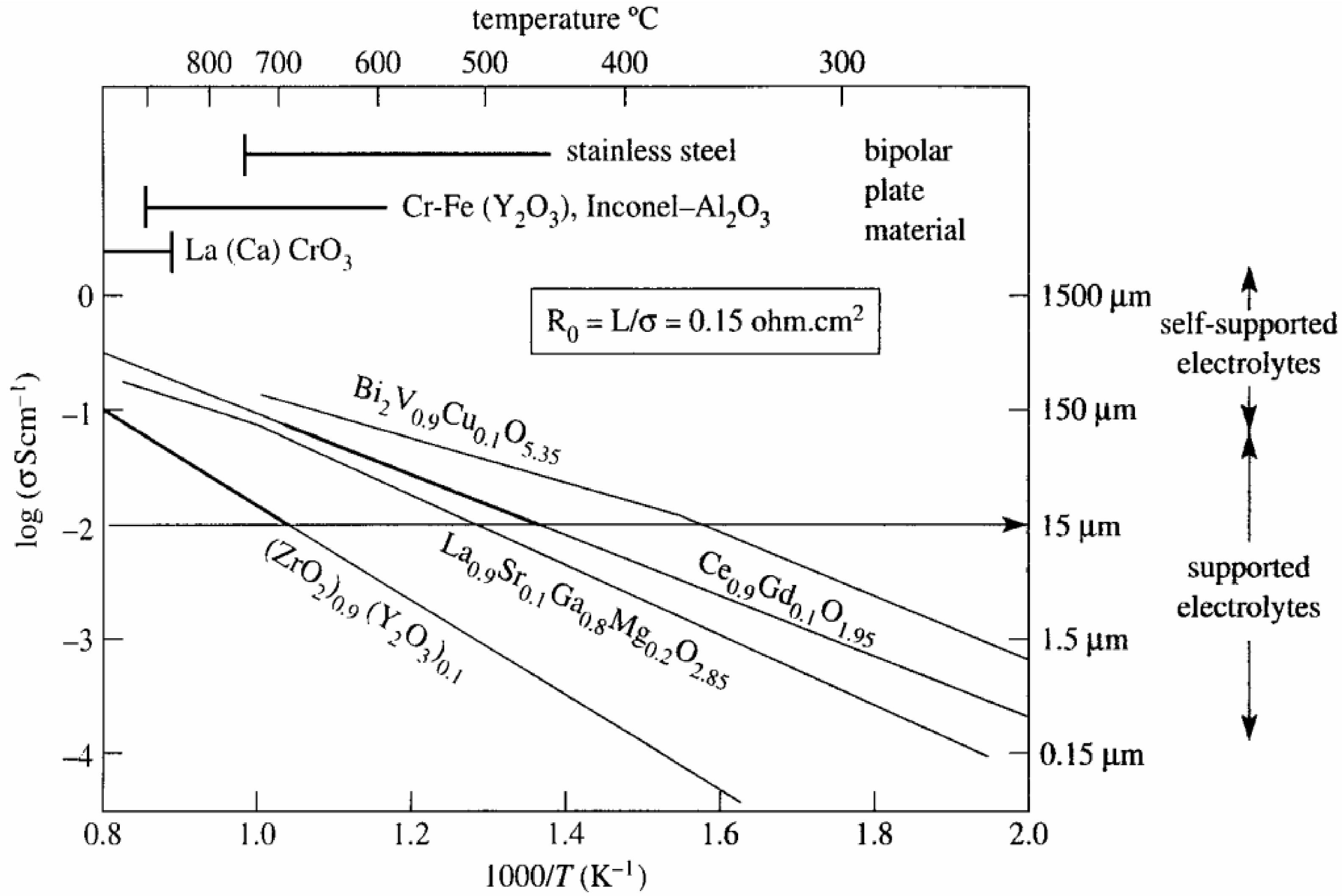


Useful power = 0.7 W cm^{-2}



Single cell data do not usually include interconnection losses

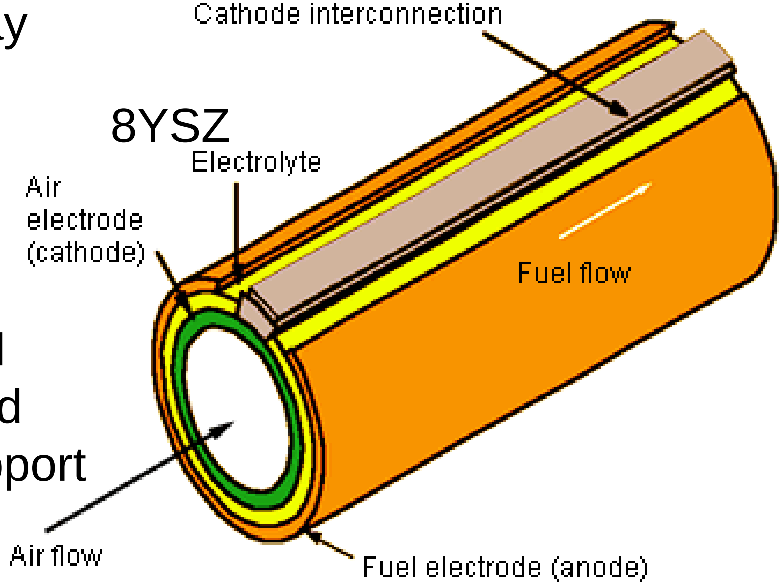
Design and operating temperature



B.C.H. Steele, Phil. Trans. R. Soc. London A (1996)

SOFC types: Siemens-Westinghouse Tubular

LCCr interconnect by plasma spray



8YSZ

Porous LSM extruded and sintered support tube

Ni /YSZ

Siemens-Westinghouse

operating temperature 1000° C

Advantages

- Reliable
- Proven durability
- "No seals"
- Tested to 250 kW
- Suited to stationary hybrid operation

Disadvantages

- Expensive
  - support tube
- Low volumetric power density

Status:

Siemens has withdrawn from SOFC (technology for sale)

Very similar technology under development by Toto (Japan)

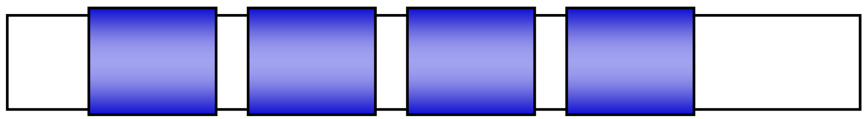
Other tubular SOFC

“Micro” tubular

- Small diameter
- Good thermal cycling
- Difficult current collection

“Segmented in series” tubular

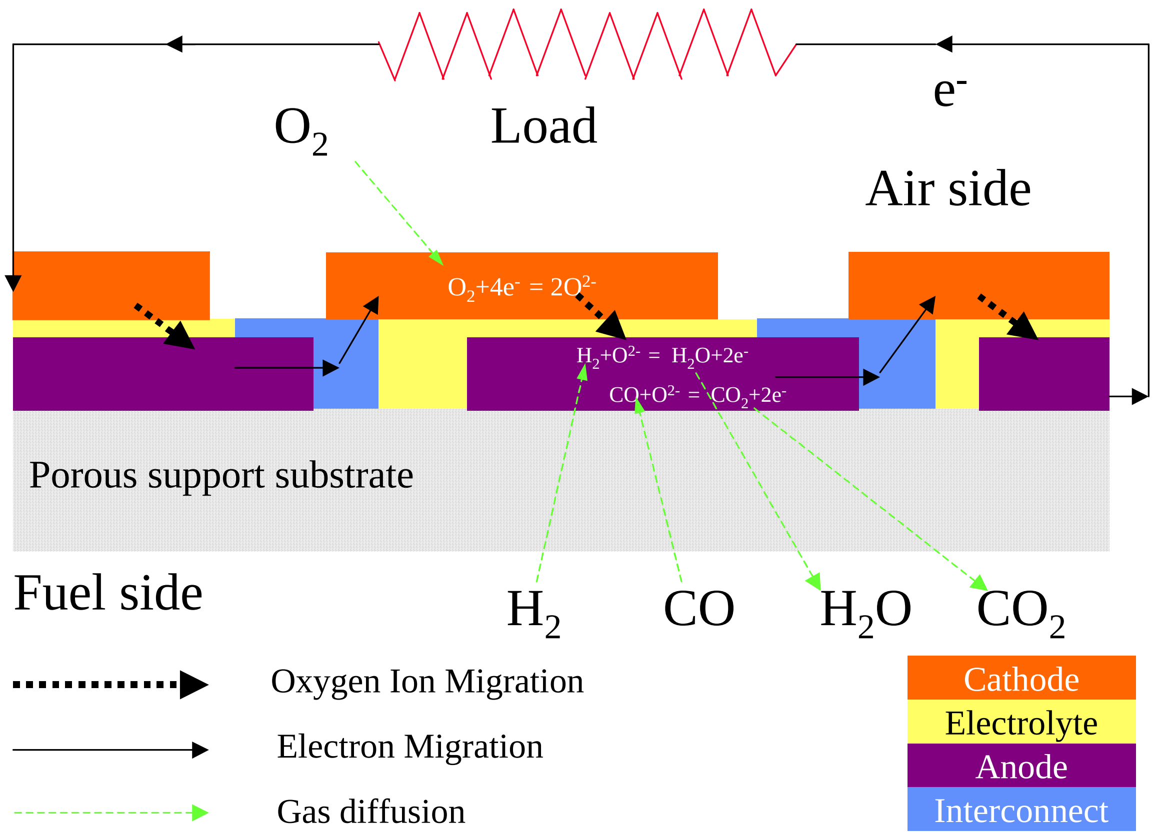
- Larger voltage per tube
- Inert support with thick film cells
- Long current path
- Cell formation difficult



Segmented in series (integrated planar) tube

- Rolls-Royce Fuel Cell Systems
- Low cost flat support tube
- Screen-printed cells
- High volumetric power density

RRFCS Segmented in series (integrated planar)

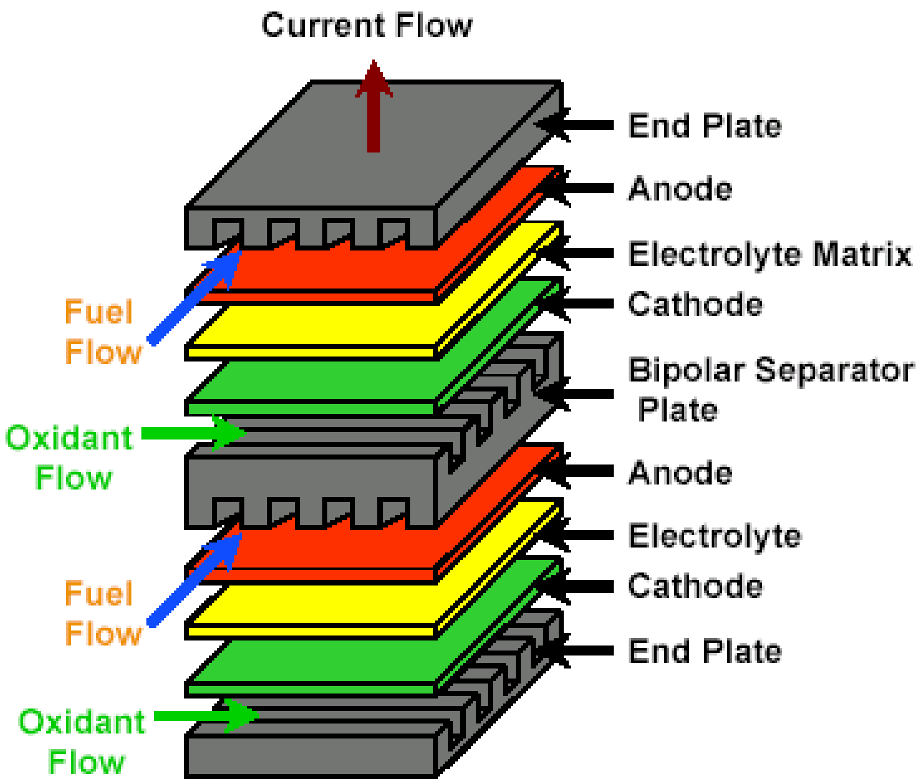


Operating at 850-950°C, pressurised with GT

Target MW class distributed electricity from natural gas

High voltage/low current

Planar SOFC



Advantages

- Higher volumetric power density
- Simpler manufacture-cheap

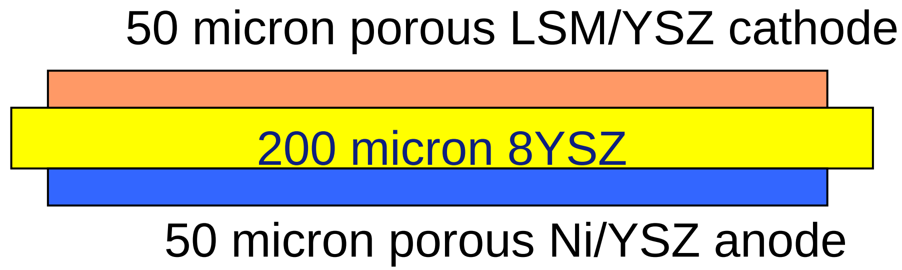
Disadvantages

- Edge sealing and manifolds
- Current collection
- Assembly tolerances

Types of planar SOFC

Electrolyte supported

- Needs thick electrolyte for strength
- Typical 900°C operation
- Expensive metallic interconnect

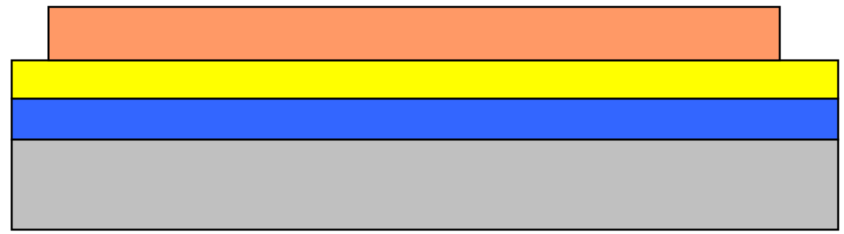


Anode supported

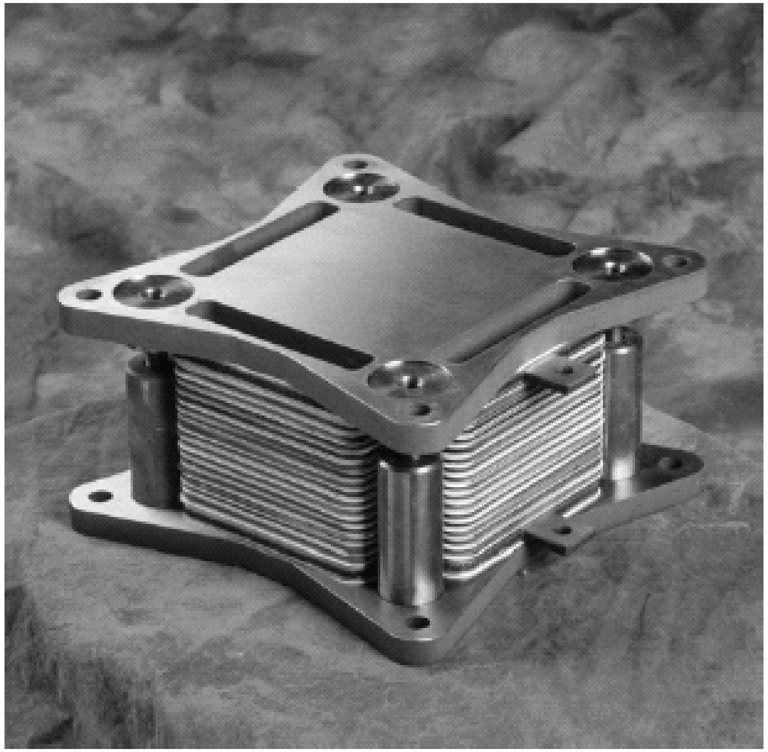
- **Most Popular**
- Needs thick anode for strength
- Typical 750-850°C operation
- Corrosion of interconnect

Metal supported

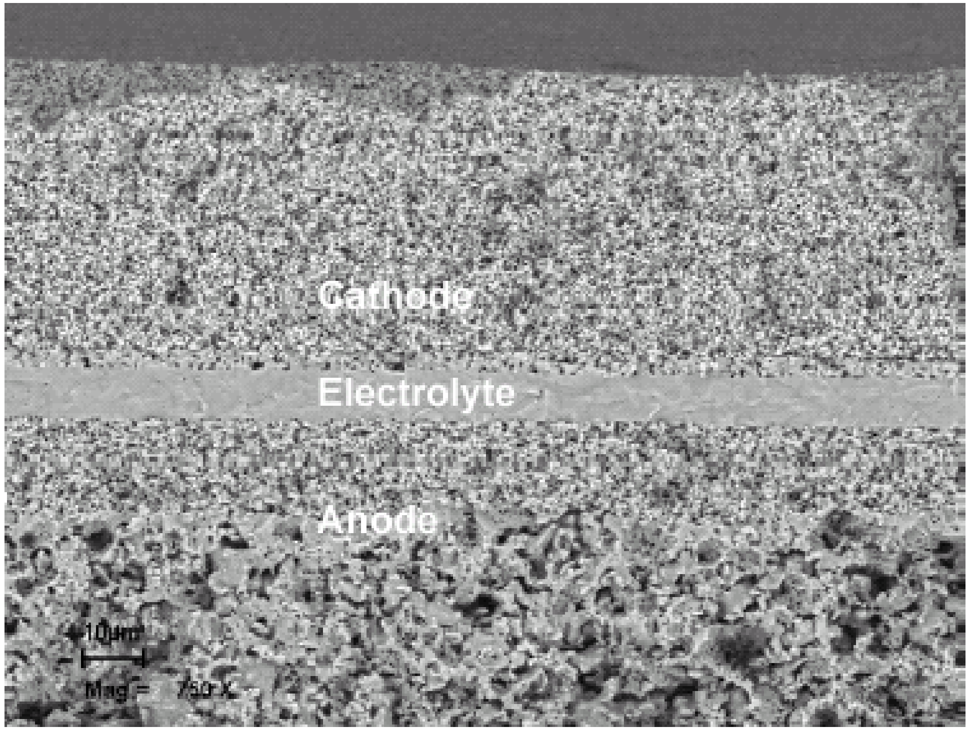
- Robust
- Operate to lower T (with alternative electrolyte)



Typical anode-supported planar SOFC



Stack (Versa Power)



Cross section

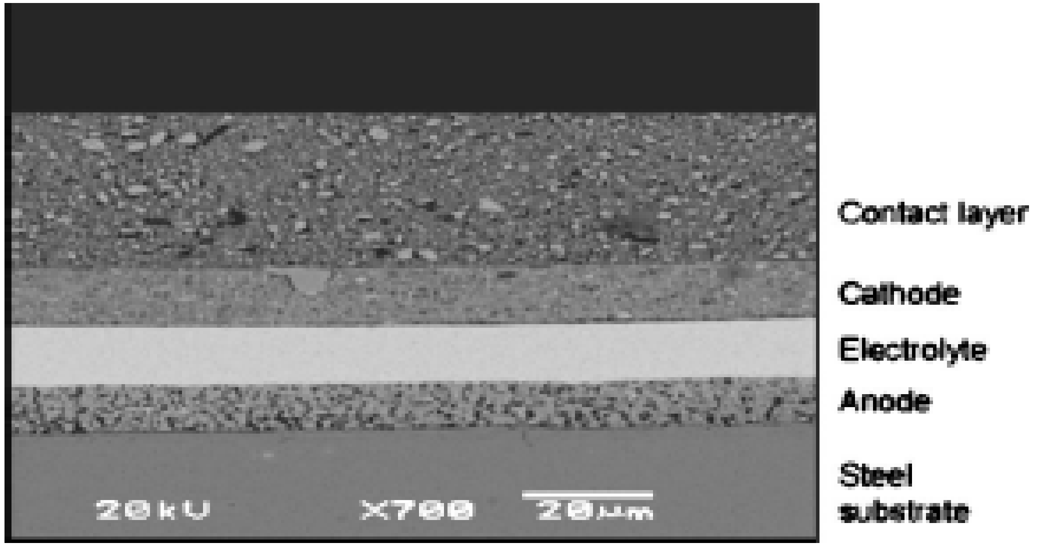
Ceres Power Metal-supported SOFC

CeresPower limited

- $Ce_{0.9}Gd_{0.1}O_{2-x}$ electrolyte.
- Cr ferritic stainless steel foil support
- 500-600°C operation
- 1kWe domestic CHP

Advantages

- **Gas sealing**
- **Mechanical strength**
- **Scaling up**



World scene

- USA and Canada
  - DoE Solid state Energy Conversion Alliance (SECA)
  - 3 kW to 10 kW (modular)
  - 400 US/kW system cost target
  - Emphasis now on coal gasification for fuel and CCS
  - Mainly anode-supported
- Japan
  - NEDO government programme
  - Mainly anode-supported
  - 29 CHP field trials
  - MHI SOFC-GT hybrid (c.f. RRFCS in UK)
- Australia
  - CFCL anode-supported CHP system
  - Field trials in Germany
- China
- Korea
- Singapore
  - 25% share in RRFCS

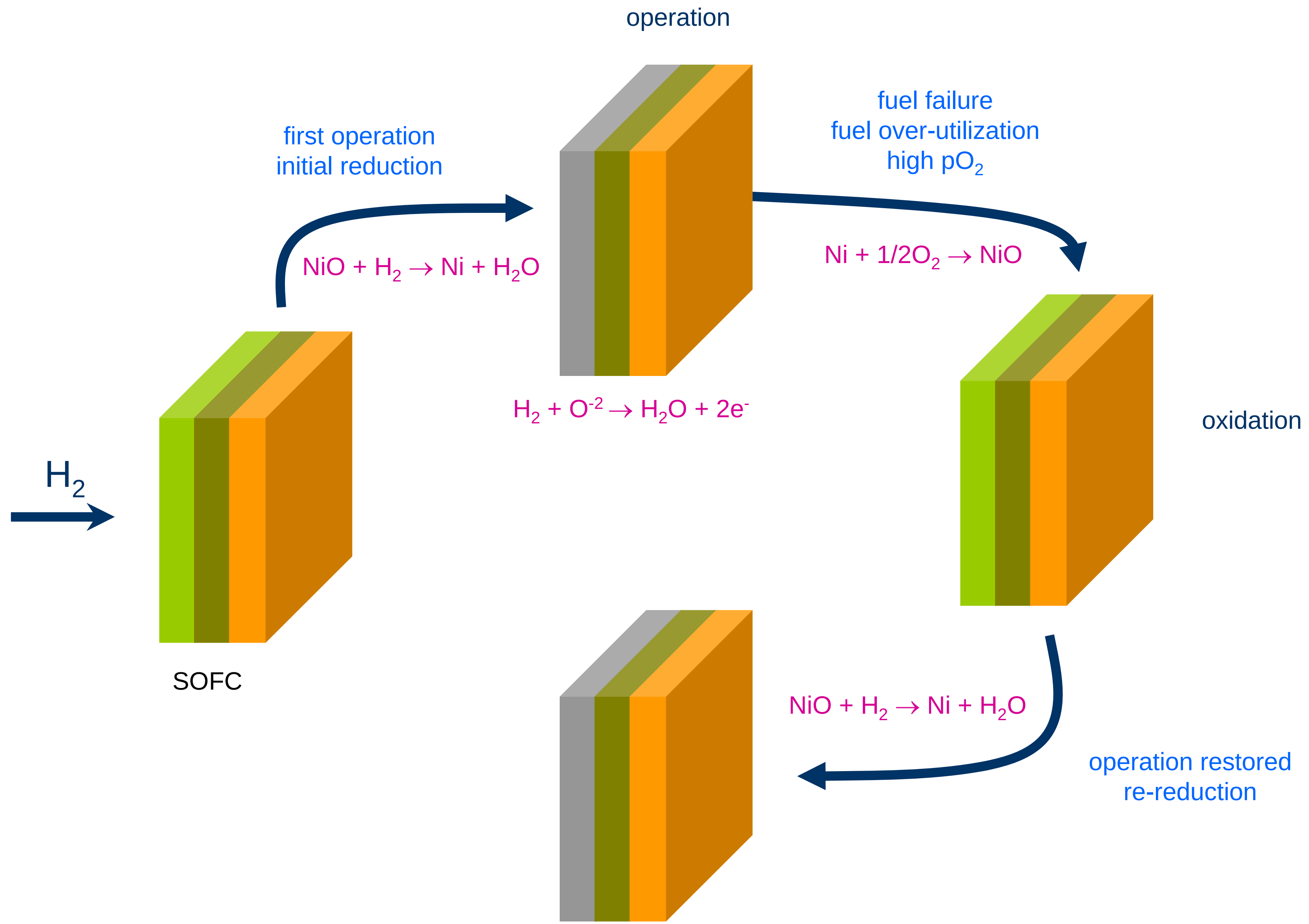
SOFC Industry in Europe

Company	Technology	Status
H.C. Stark (D)	Materials and cells (electrolyte and anode supported)	Partner in Staxera and with CFCL (Aus)
Topsoe Fuel Cell (DK)	Anode-supported, 1kWe stacks	Partner with Wartsila (Finland)
Staxera (D)	Electrolyte-supported	Can purchase 0.5 kWe
SOFC Power (I)	Anode-supported	1 kW stack validated
Hexis (CH)	1 kWe CHP electrolyte-supported	Field tests
Enerday/Webasto (D)	0.5-5 kWe APU	1 kWe prototype
Wartsila	250 kWe CHP and ship APU Topsoe stacks	20 kWe system achieved
RRFCS (UK)	1-10 MWe IPSOFC	Building 125 kW pressurised system
Ceres Power (UK)	1 kWe domestic CHP Low T metal-supported	Demonstrated system with 50/50 electricity/heat

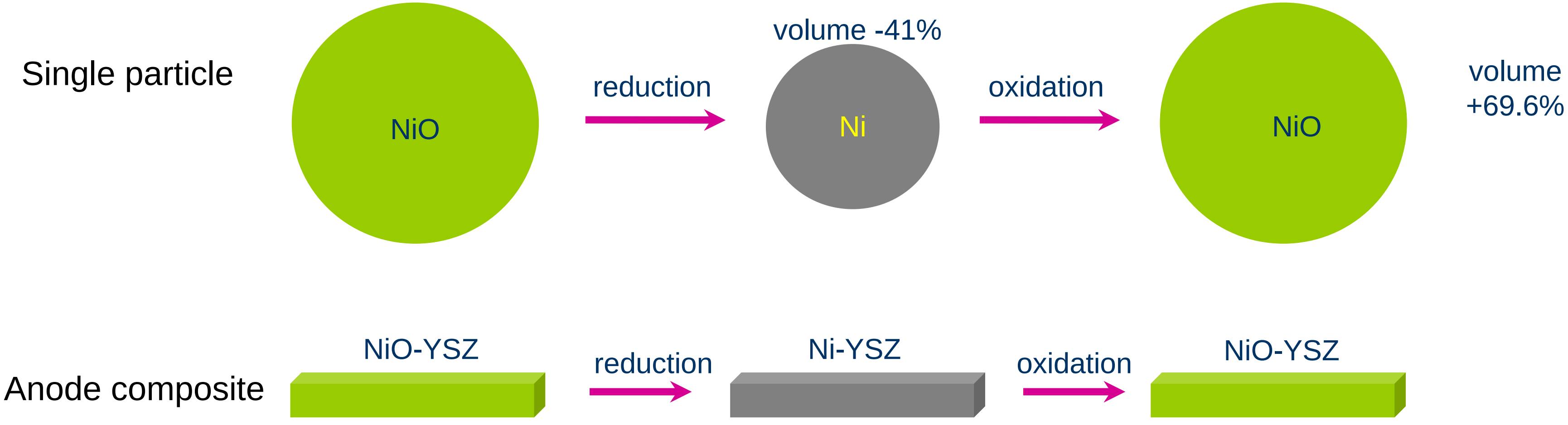
Current Trends

- Lower costs
  - lower operating temperatures (less expensive materials)
  - simpler manufacturing (co-sintering)
  - Simpler systems
- Increase performance
  - higher conductivity electrolyte
  - more active electrodes
  - Nano-structured materials?
- Increase durability (degradation < 1%/kh)
  - lower operating temperatures
  - Resistance to Cr poisoning
- More robust (faster start-up, fuel flexibility, thermal cycling)
  - metal-supported
  - oxidation-tolerant anodes
  - direct hydrocarbon operation (minimise steam requirement)

Anode redox problems: Ni-based cermets



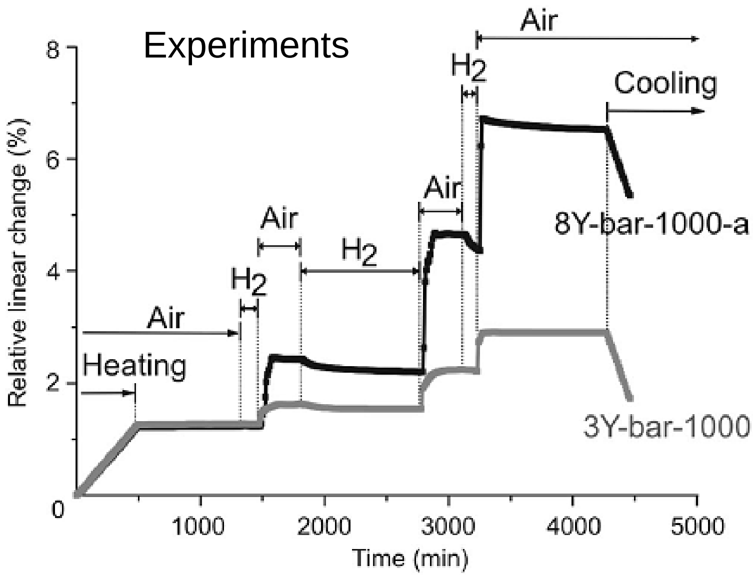
Ni cermet redox dimensional changes



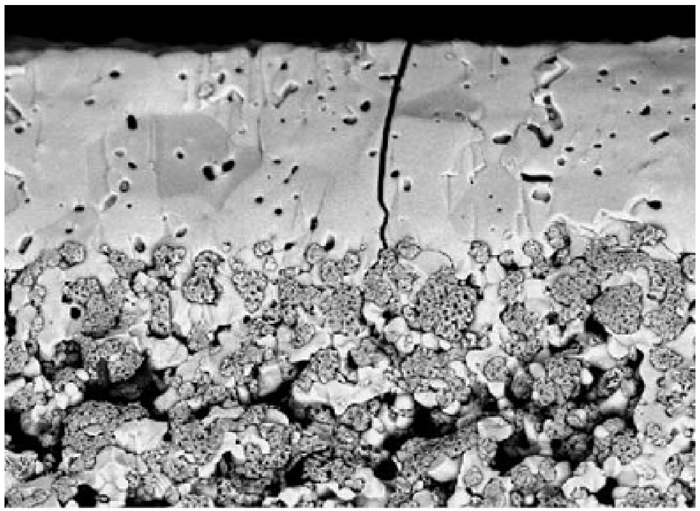
little/negligible shrinkage

~ 1% elongation

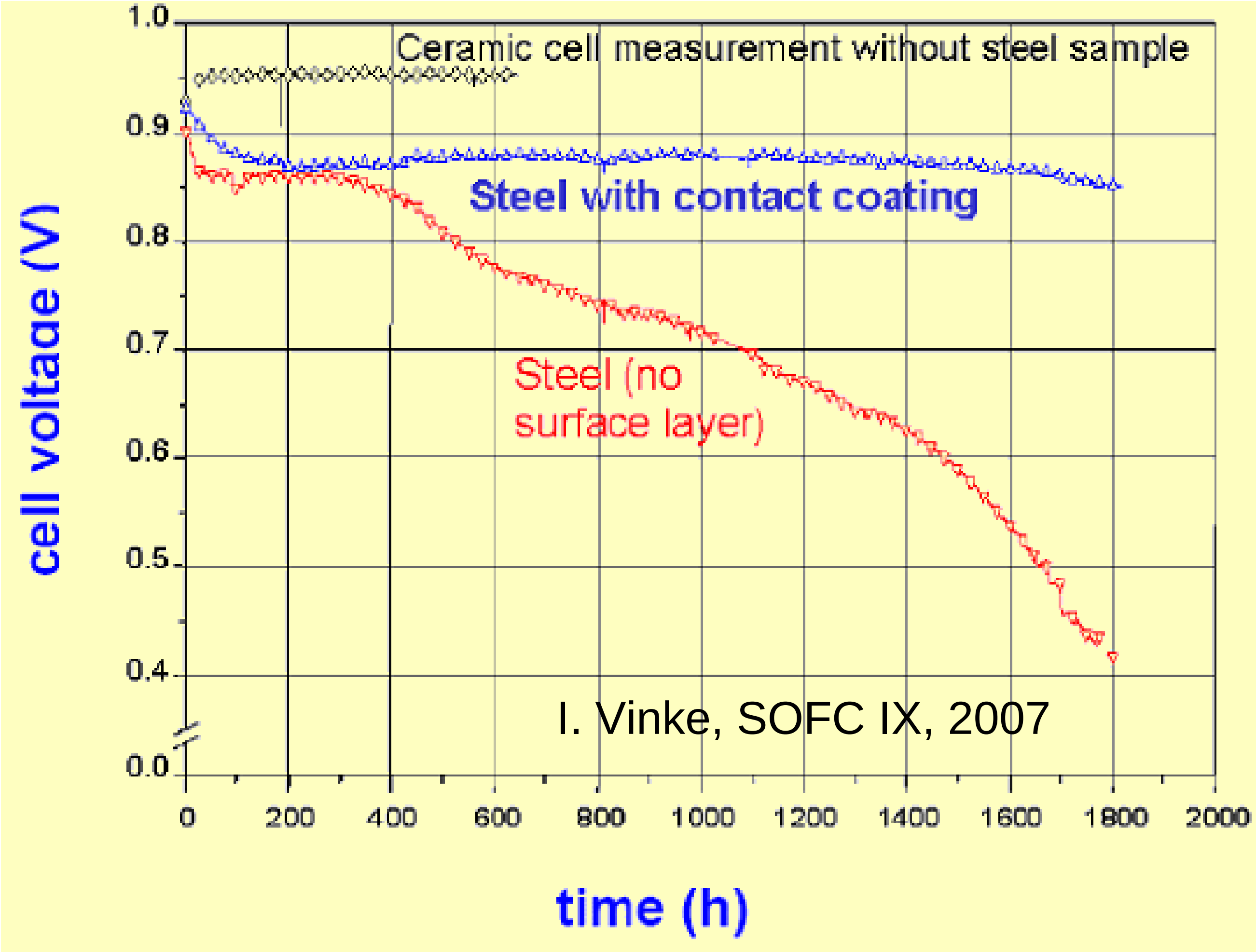
oxidation strain



T. Klemensoe et. al, *J. Electrochem. Soc.*, **152**, A2186 (2005).



Cr poisoning of SOFC cathode



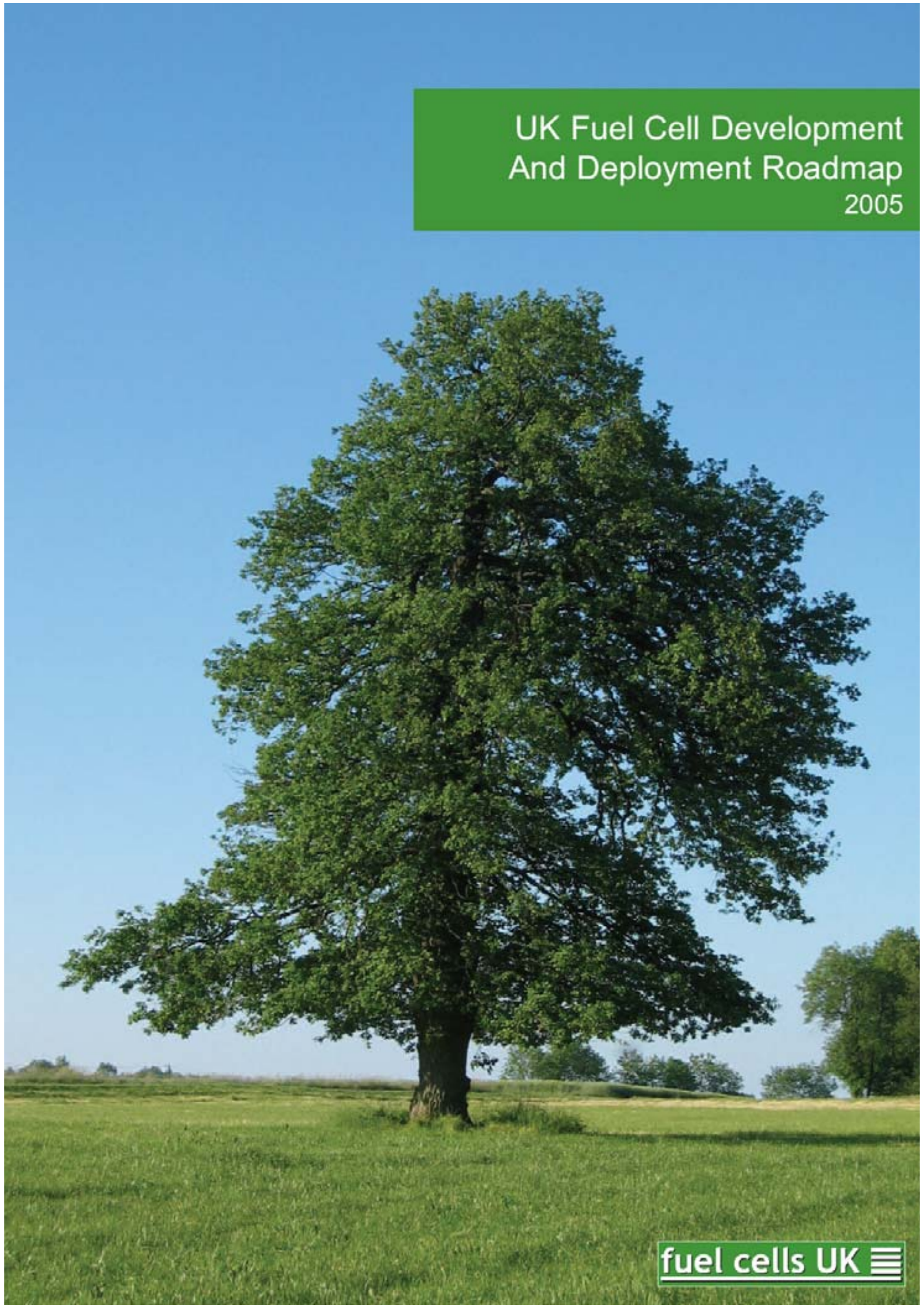
•Cr vapour species released from steel interconnect and deposit at cathode

•Details of mechanism unclear

fuel cells UK

Acal Energy
AFC Energy
Bac 2
Baxi
BOC
British Midlands
Calor Gas
Cenex
Ceramic Fuel Cells
Ceres Power
City University
CMR Fuel Cells
Diverse Energy
E.On
Flexitallic
Fuel Cell Application Facility
Fuel Cell Control
Intelligent Energy
Johnson Matthey
Logan Energy
The Micropower Council
Philip Sharman
Porvair
Renew Tees Valley
Rolls-Royce Fuel Cells Systems
Unitec Ceramics
University of Birmingham
Valeswood

UK Fuel Cell Development And Deployment Roadmap
2005



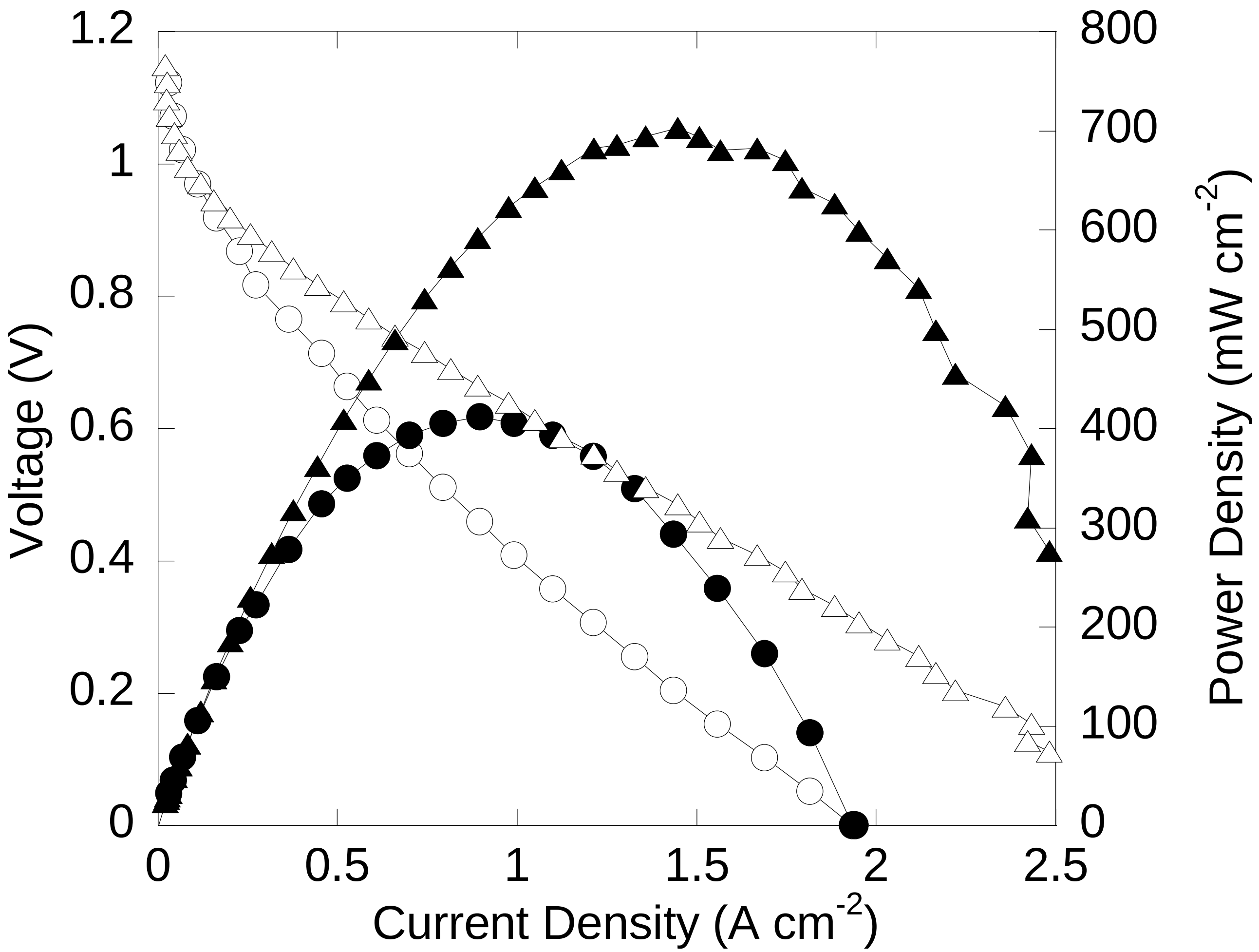
fuel cells UK

EPSRC Supergen Fuel Cells Consortium

- Aims
  - address key technical barriers facing the UK fuel cell industry.
  - Encompass PEM and SOFC
  - To develop high quality researchers trained in fuel cell technology.
  - To communicate research outputs.
- Universities
  - Imperial College
  - Newcastle
  - Nottingham
  - St Andrews
- Industry
  - Rolls-Royce Fuel Cell Systems Ltd
  - Ceres Power Ltd
  - Johnson Matthey
  - Defence Science and Technology Laboratory
- Status
  - 3 years into first phase

(La,Sr)(Cr,Mn)O_3 modified anode on CH_4

humidified (3% H2O) CH4 at: (○) at 973 K and (Δ) at 1073 K.



St Andrews

Wish list for materials

- Electrolytes for lowering T or increasing power density
  - ScSZ, apatites, proton conductors, others?
- Cathodes
  - higher activity (particularly at <700°C)
  - Cr resistance
- Anodes
  - improving tolerance of Ni-based anodes to redox, C (and S?)
  - oxide (or other compound) anodes?
  - direct (or low steam) hydrocarbon operation
- Interconnectors/current collectors
  - improved oxidation/corrosion resistance and strength
  - low Cr volatility, coatings
  - high conductivity (>1000 S cm^{-1}) oxides?
- Simpler (cheaper) manufacturing
- Science to underpin the above
  - modelling from atomistic to system scales
  - mechanical properties
  - in situ diagnostics
  - Degradation mechanisms

Barriers to SOFC commercialisation

- Cost
  - unlikely to displace current technologies without economies of scale
  - “chicken and egg” situation
  - niche markets?
- Regulatory framework
  - political intervention to encourage green technologies
  - standards for distributed power generation
- Durability/reliability
  - needs time for long-term proving
  - Accelerated testing?
- Consumer resistance
  - not offering a new “good”
- Time (investor patience)
- Trained personnel

SWOT for UK SOFC

- Strengths
  - 2 world-leading industrial companies and technologies
  - Strong science base (particularly in cell materials and modelling)
- Weaknesses
  - No national labs in support (cf. Juelich, Risoe, ECN, CEA in Europe)
  - No manufacturer/developer of interconnect steels (Thyssen-Krupp)
  - Limited capability in BoP?
- Opportunities
  - Increasing energy prices
  - EU-funded demonstrations (JTI)
  - Related technologies (electrolysers, gas separation membranes)
- Threats
  - Poor economic outlook for investment
  - Competition catches up/overtakes
  - Unable to meet cost and durability goals quickly enough

Conclusions

- UK has 2 world-leading companies and a strong relevant science base
- This constitutes an excellent opportunity
- There are no “show stoppers” in materials within the state-of-the-art UK technologies.
- Improvement is required in cost and durability
- Some other capabilities are desirable (particularly for anodes)
- Reaching the critical demonstration stage where costs increase.

Thank you for your attention!