MFCF in Europe
(and elsewhere…)

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Work MCFC-PAFC R&D

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Outline

1. *Status of technology, players*
2. *Life time, performance decay, failure*
3. *R&D priorities*
4. *Fundamental research*
5. *Concluding remarks*

1. Status of technology, players

Developer	Operating pressure (atm)	Reforming	Manifolding	Module	Plant size/target (kW)
FCE (USA)	1.0	Internal	External	Single or multistacks	300–3,000
GenCell (USA)	1.0	Internal (indirect)	Internal	Single stack	40–120
CFC Solutions/MTU (Germany)	1.0	Internal	External	Hotmodule (horizontal stack)	250–1,000
AFCo (Italy)	3.5	External	External	Twin-stack (two 125-cell stack integrated with reformer in a can)	125–1,000
KEPRI (Korea)	3.5	External	Internal	Building-block	250
IHI (Japan)	3–10	External	Internal	Building-block	300

Modified from: M. Farooque and H. Maru, Enc. Electrochem. Power Sources

Major and minor R&D in carbonate FC technology

Developer or Institution	Location	Development	Fundamental research
FCE	Danbury, CT, USA	Yes	No
IIT	Chicago, USA	No	Yes
MTU	Munich, Germany	Yes	Some
AFCo	Genoa, Italy	Yes	Some
ENEA	Rome, Italy	No	Yes
KEPRI	Daejeon, Korea	Yes	Yes
Doosan HI	Daejeon, Korea	Yes	?
Hanbat U	Daejeon, Korea	No	Yes
CRIEPI	Kanagawa, Japan	Yes	Yes

Various Universities in Europe, for example, KTH (Sweden), U. of Magdeburg (Germany), ENSC Paris (France), U of Pisa (Italy) / fundamental research up to early 2000s' – some continuing at low level.

Universities in US (other than IIT): U of South Carolina (up to early 2000s'; status?), U of Connecticut (status?)

CFC Solutions

- Est. Jan. 2003
- Located near Munich (D)
- Research & Development
- Power plant assembly and test
- Pilot cell manufacturing
- 20 test sites (total 5 MW) in Europe

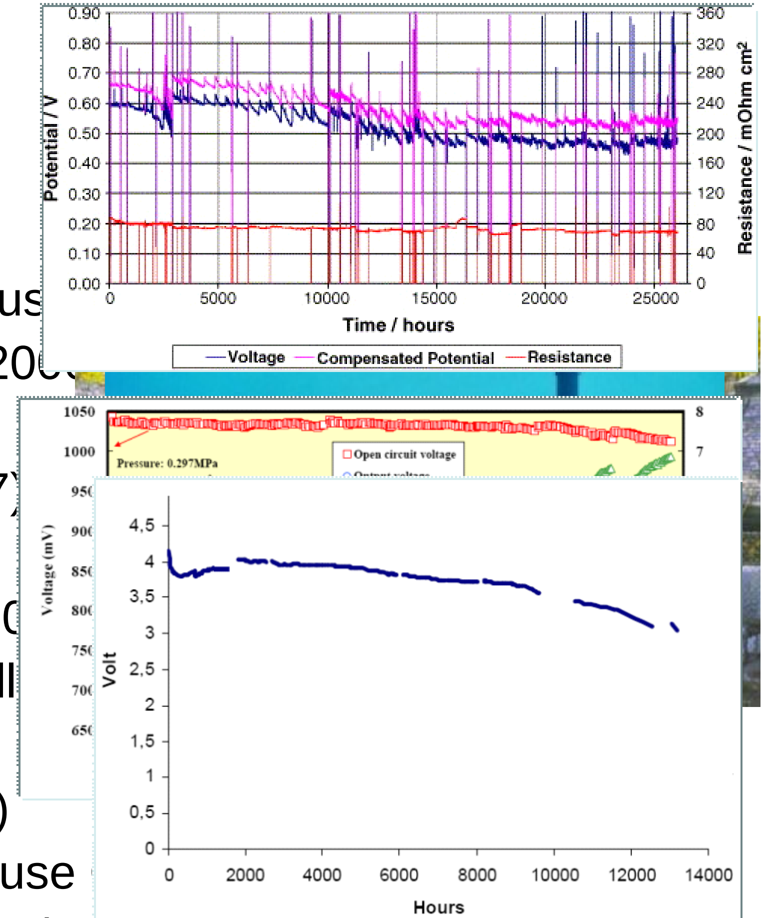
The durability issue
comparison with other fuel cells

DoE lifetime targets for 2010:

- 5000 h for mobile applications
- 40 000 h for stationary applications

Current reported lifetimes:

- PEMFC
  - application: 2000 h (Mercedes Benz FC Bus
  - laboratory: 26 000 h (GORE, single cell, 200
- PAFC
  - application: 66 000 h (UTC PureCell, 2007)
- MCFC
  - application: 30 000 h (CFC, Magdeburg, 20
  - laboratory: > 60 000 h (CRIEPI, single cell
- SOFC
  - application: 10 000 h (Hexis, planar, 2007)
    30 000 h (Siemens-Westinghouse
  - laboratory: 14 000 h (Topsoe, planar, 2007)
    70 000 h (Westinghouse, tubular, 1997)



From Workshop, Ulm (2009)

Generally recognized needs for MCFC

1. ***Increased power density J ⇨ need finer μ-structure of porous electrodes.***

   Largely left to development

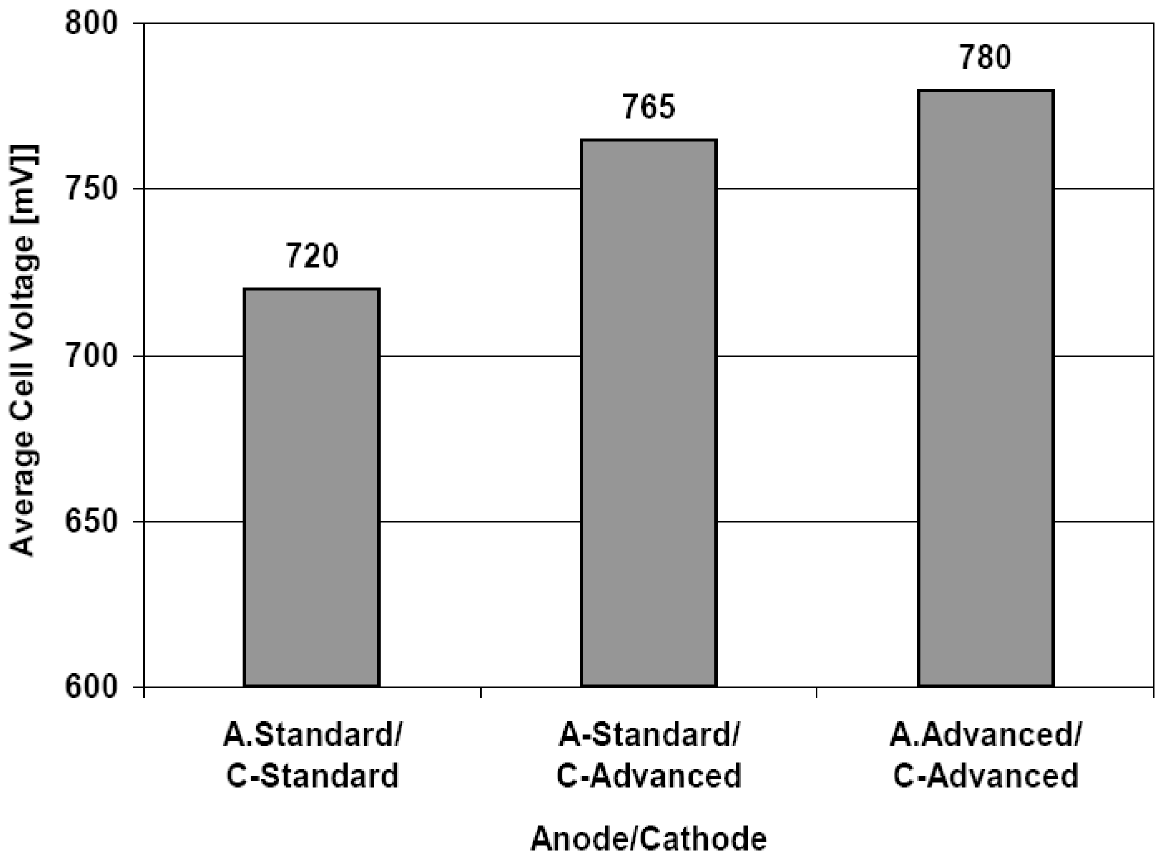
2. ***Longer cell life ⇨ need lower T ⇨***

red. corrosion,
more stable morphology,
red. volatility; ***but*** ***decr. electrochem. activity/real area ,***
decr. conductance of oxide scales,
decr. wetting of electrodes,
incr. NiO dissolution

⇨ ***Lifetime, performance decay, failure***

Joint effort of European Community

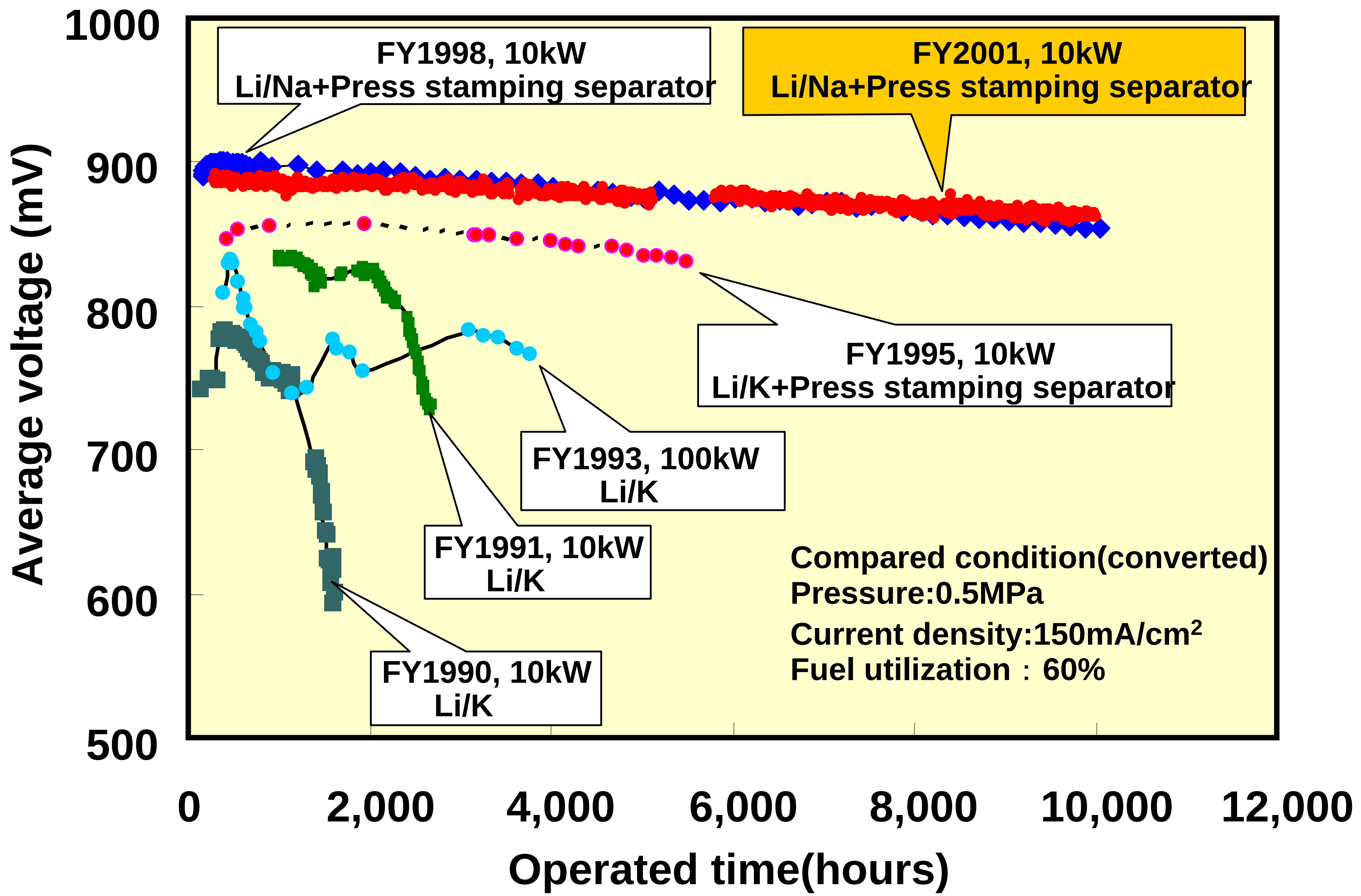
Advanced anode and cathode performance (MTU 2009)



Full scale tests (1000 h runtime, 120 mA/cm2, 70% fuel utilization, medium cell temperature 620^{o}C, system gases)

From: U. A Paulus-Rodatz and M. Bednarz, extended abstract ECS meeting Vienna (2009)

Dramatic advances in performance + stability of MCFC stacks (Japan) 1990-2001

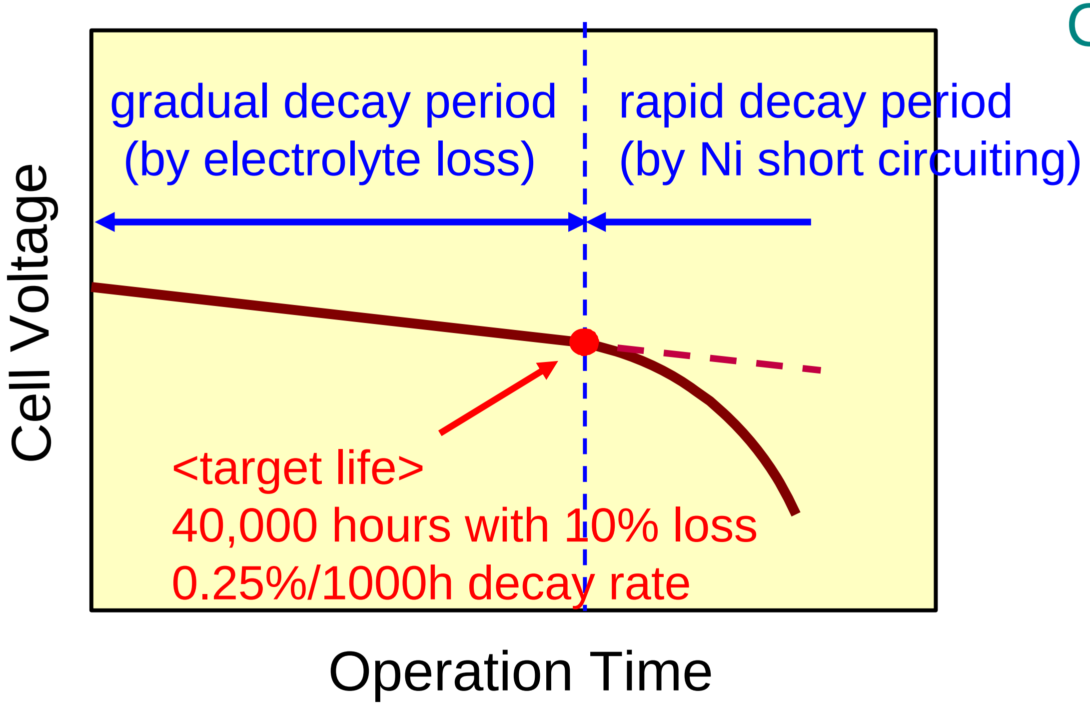


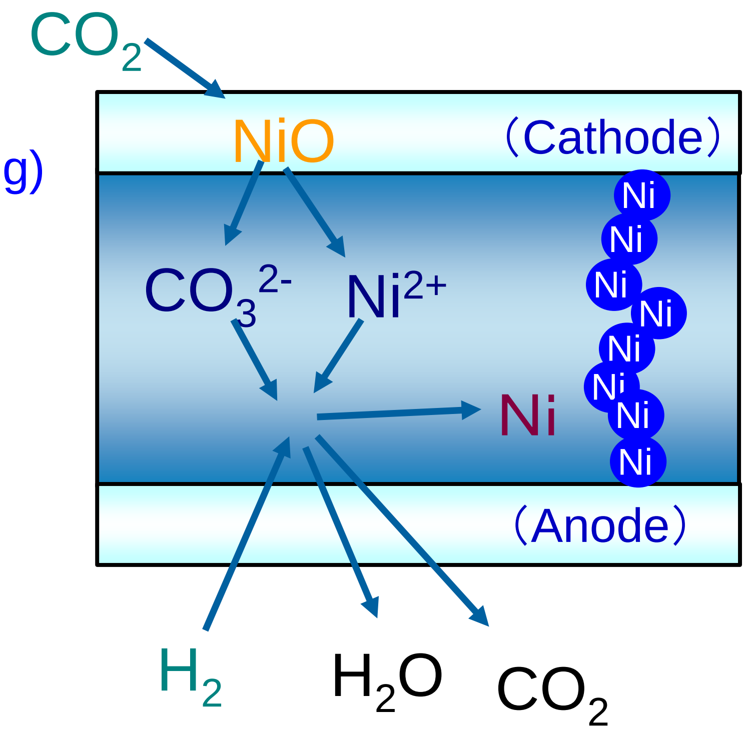
2. Life time, performance decay, failure

Adopting 40,000 hours longevity as a target , CRIEPI (Japan) has carried out two kinds of tests to identify the degradation mechanisms of the MCFC.

1. **Accelerated testing in Ni shorting**
2. **Testing of long term electrolyte loss**

Life extension of MCFC

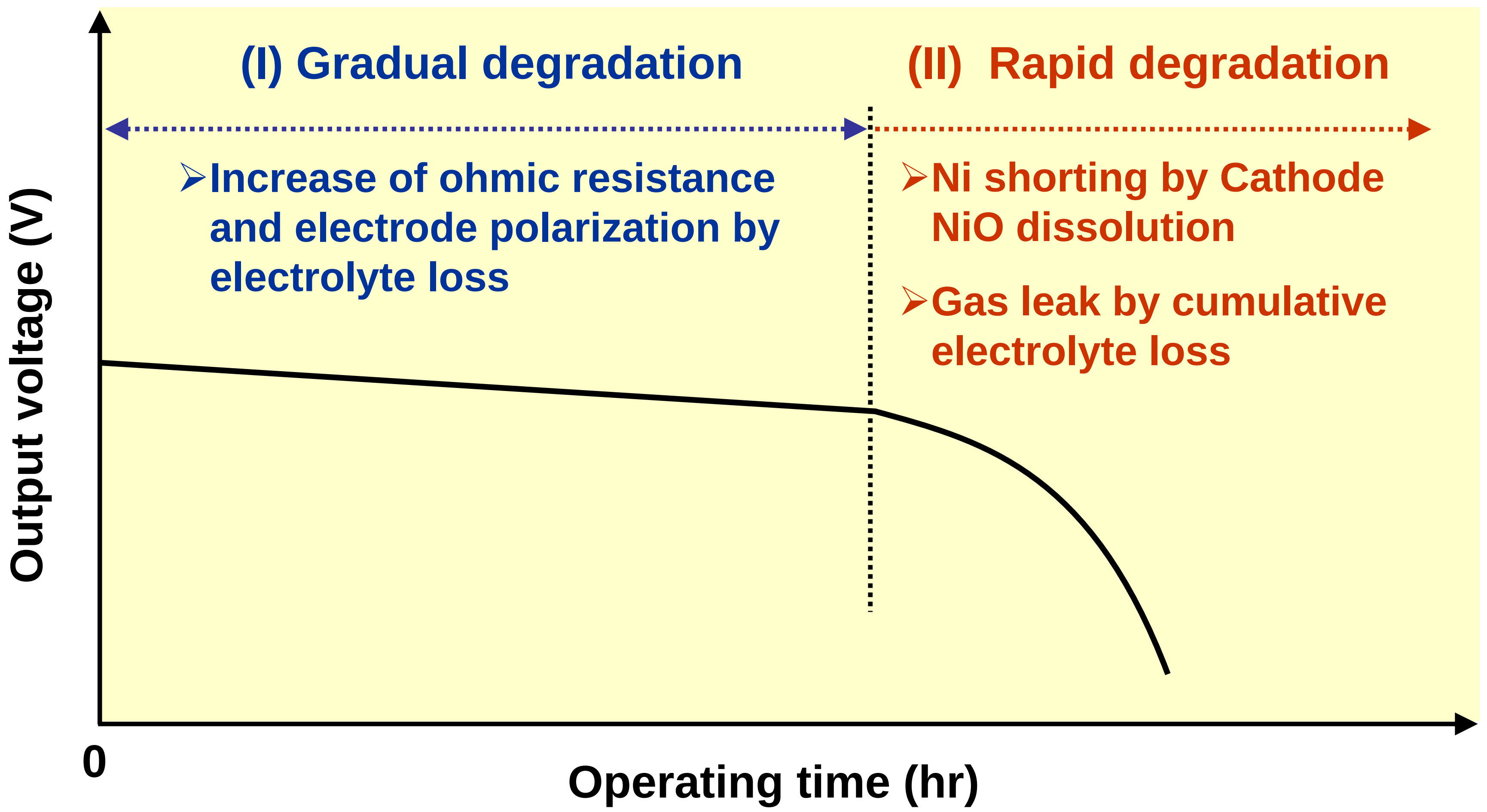




→Suppression of Ni Shorting

→Low Ni solubility electrolyte

Schematic of MCFC performance degradation to time (at a constant current)



CRIEPI

The durability issue

From Workshop, Ulm (2008)

DoE lifetime targets for 2010:

- 5000 h for mobile applications
- 40 000 h for stationary applications

What is needed?

30-50% increase in lifetime

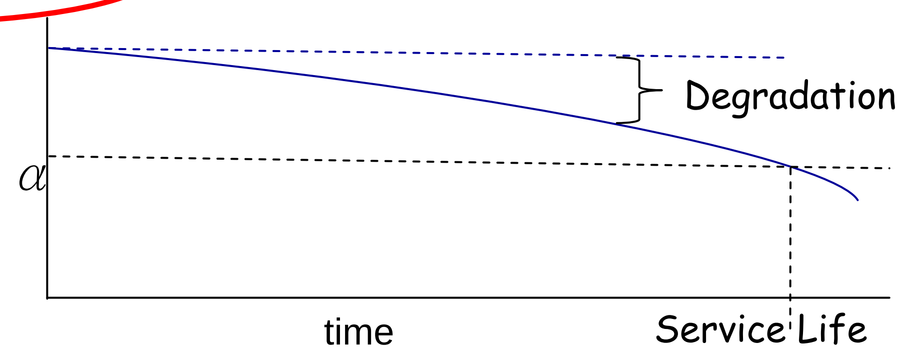
But what is lifetime?

One of the definitions under discussion within TC 105 WG1 for the second edition of TS 62282-1 terminology:

The cumulative period of time that a fuel cell/stack may operate before its output deteriorates below a useful minimum value

Degradation

Lifetime / Service Life



Degradation

or *The process of decline in performance due to accumulation of operating time*

Differentiate causes of degradation (=life shortening) between:

Technical "innate" causes:

- Changes in morphology and hydrophilicity
- Changes in phase and chemical bonding
- Interdiffusion of materials
- Corrosion
- Thermomechanical stress

Base Degradation Rate

Applied causes:

- Thermal cycles
- Load cycles
- Reduction-oxidation cycles
- Poisoning

Accidental causes:

- BOP failures
- Utility failures
- Control failures
- Fuel supply failures

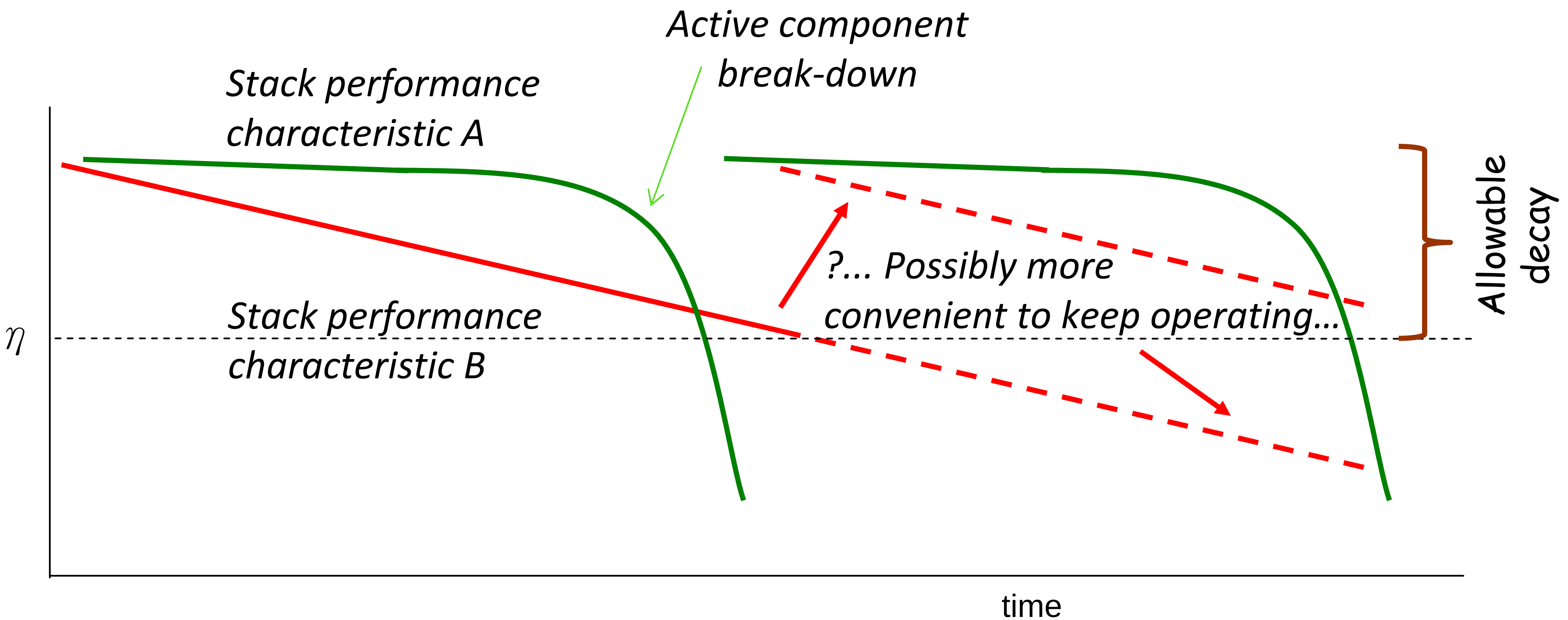
Incremental Degradation Rate

Protocols required!

$$\text{Base Degradation Rate} * \text{Correction factor } (>1) = \frac{\text{allowable decay}}{\text{service life}}$$

Degradation

What about the economical implications…



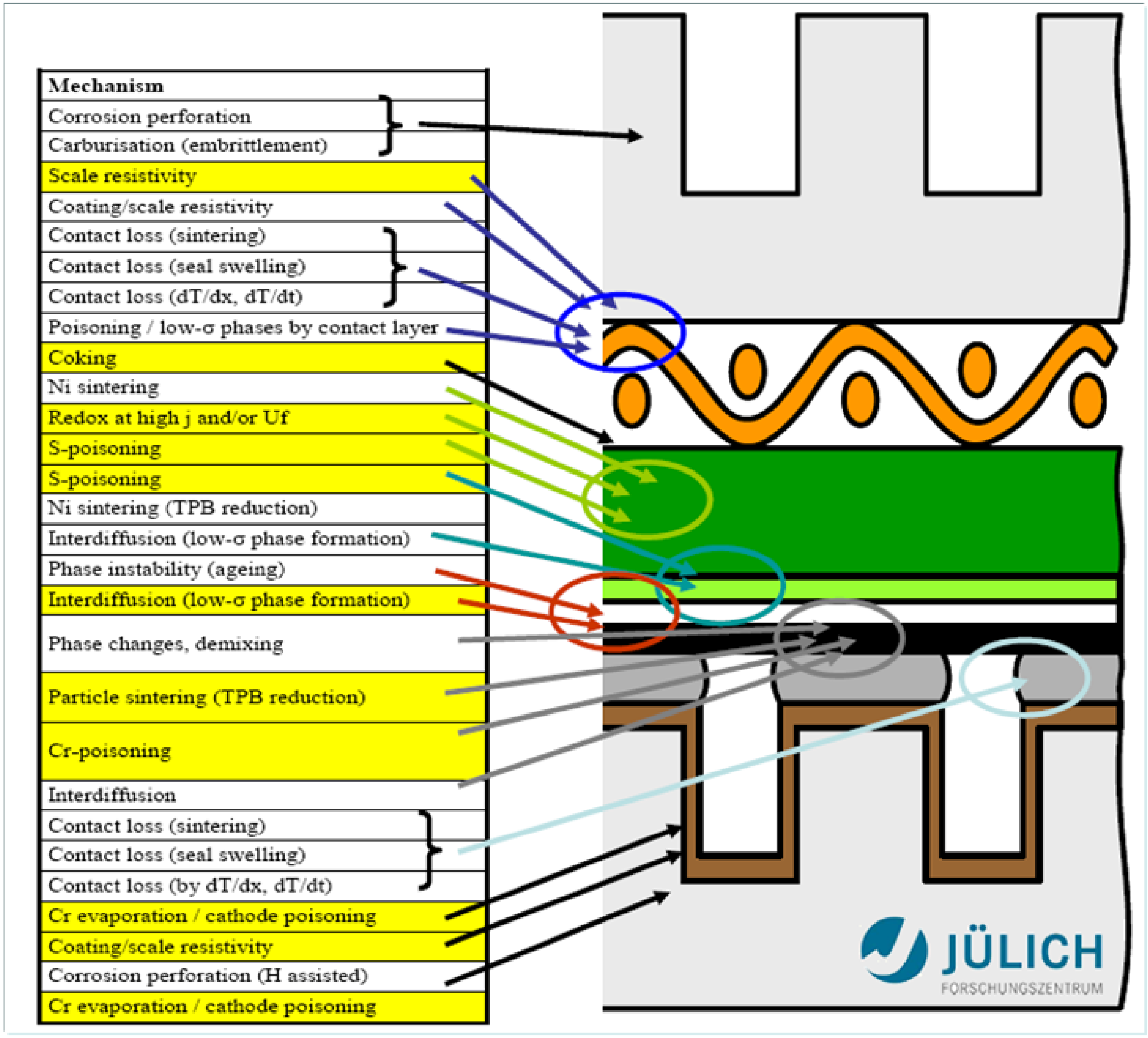
→ **Compromise between output, efficiency, maintenance and investment costs**

Degradation

Technical "innate" causes:

- Changes in morphology and hydrophilicity
- Changes in phase and chemical bonding
- Interdiffusion of materials
- Corrosion
- Thermomechanical stress

Base Degradation Rate

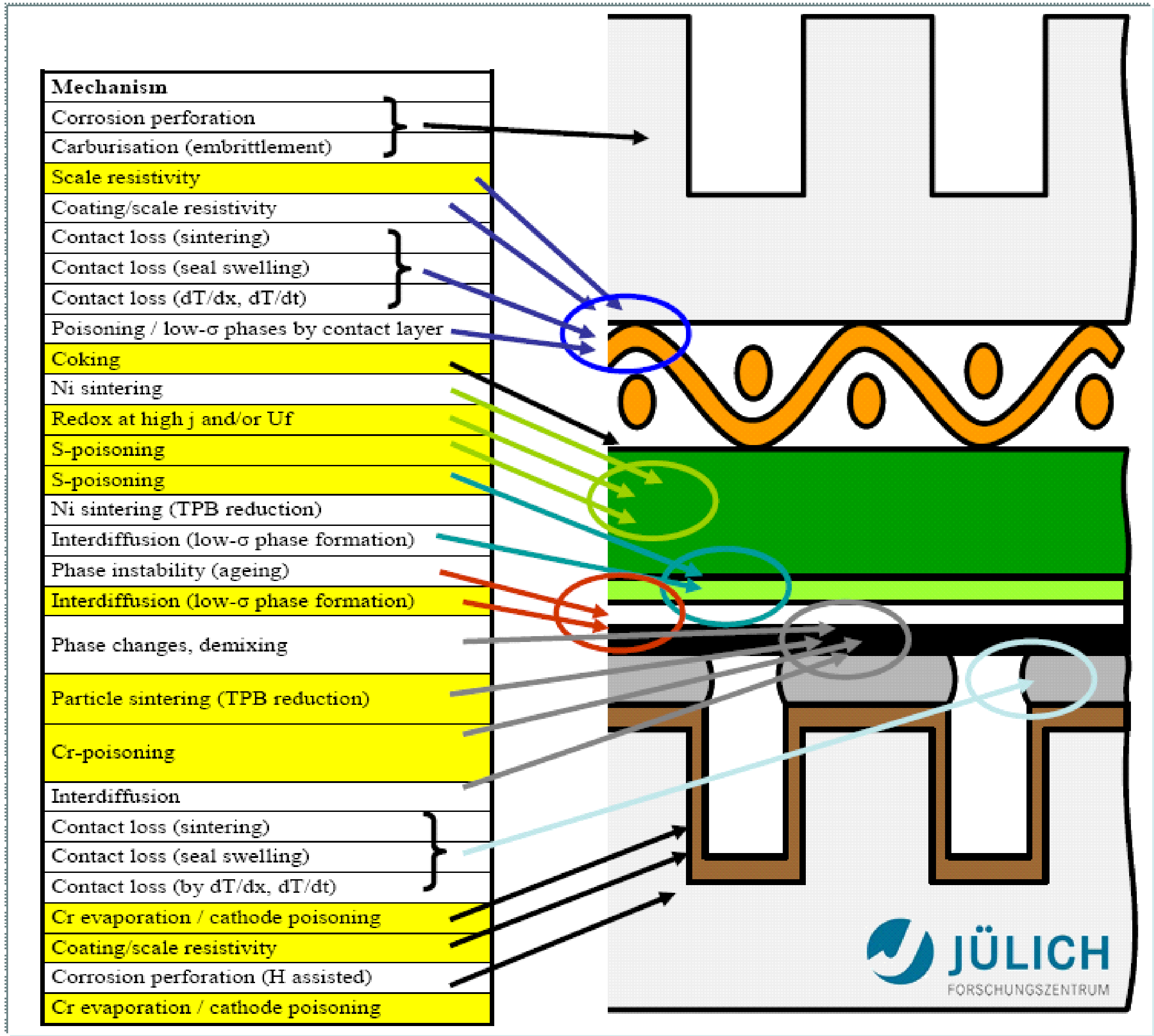


Degradation

- Resultant of all innate decay mechanisms
- comparable conditions →comparable degradation
- independent of the way it is measured

Battery: charge capacity
Lubricant: chem-phys properties
Jet engine: SFC (Specific Fuel Consumption = fuel flow/net thrust)

Base Degradadtion Rate



Forging a common standard

End user viewpoint:

- Utilisation pattern
- Power system efficiency (electric & thermal) requirements
- Reliability expectancy/ maintenance
- Economic demands

R&D viewpoint:

- Modelling and lifetime prediction
- Innovative component testing
- Understanding of lifetime limiting phenomena
- Technology validation

Conclusions
(Workshop Fuel Cell Accelerated Testing, Ulm 2008)
(for MCFC)

- 30-50% increase in lifetime required
- Target lifetimes are intended for **systems**
- Stack outage usually due to **externalities** (rarely “end-of-life”)
- Degradation composed of innate, applied and accidental causes
- Applied and accidental stresses should be accounted for in standard protocols
- Must find compromise between **intuitive** and **intrinsic** degradation definition
- …to adopt a common standard that can be evaluated by end-user

Good luck!

3. R&D priorities

- Priorities by company (see next table)
- Type of challenge：
  - Type 1: for example, cathode current collector (CCC) decay
    - Mechanism known
    - Solution known
    - Need for optimization (both technical and economic)
  - Type 2: for example, cell shorting by Ni dissolution
    - Mechanism known
    - Several possible solutions ⇨need for further investigation to find the best or most suitable
  - Type 3: for example, long-term rise of internal resistance
    - Effect known
    - Need to investigate the mechanism and to find solution
- Approach: public vs private (confidential)

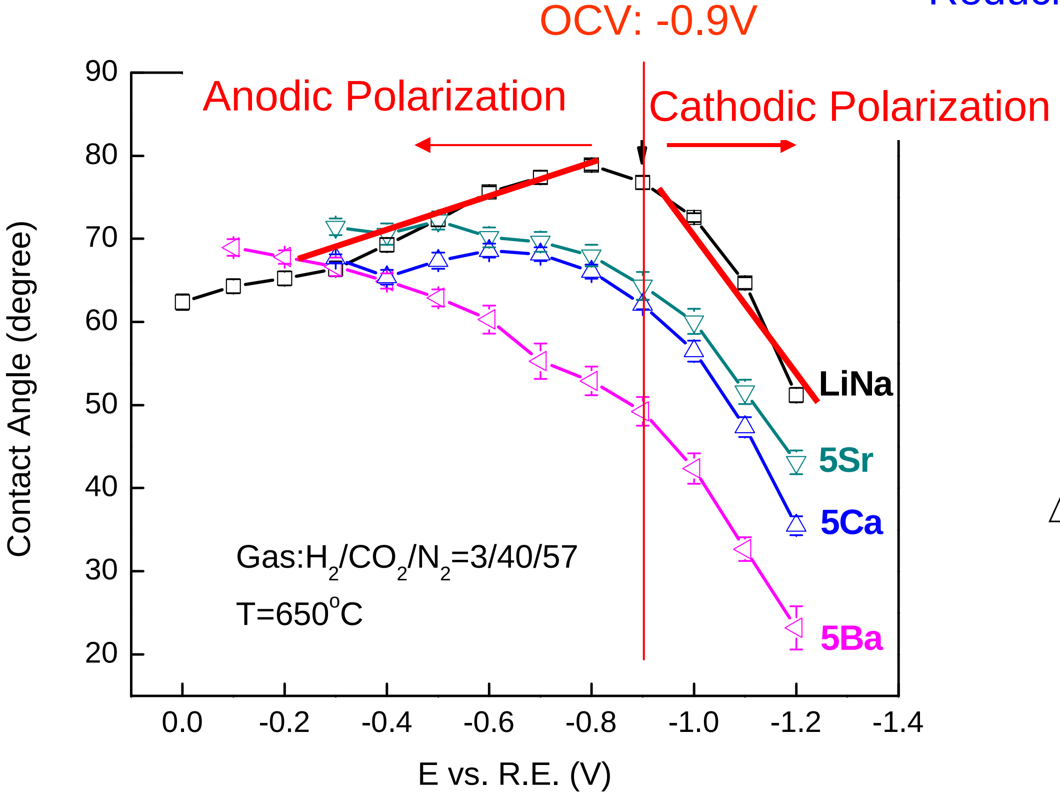
“Towards An Additional 20,000 Hours”				
Degradation issue priority	Type 1. Optimize known solution (tech and econ)	Type 2. Select among possible solutions	Type 3. Identify mechanism and solutions	Public vs Private
FCE				
1		Cathode dissolution		Public (solubility, matrix solidity)
2		Internal resistance increase	Internal resistance increase	Public
3	CCC material stability			Confidential
MTU				
1	Stack Temperature homogenization (vertical & horizontal)			Confidential (active cooling systems)
2	CCC material stability			Confidential (improved materials)
3	Component thermomechanic response to stack deformation			Confidential (component thermomechanic properties)

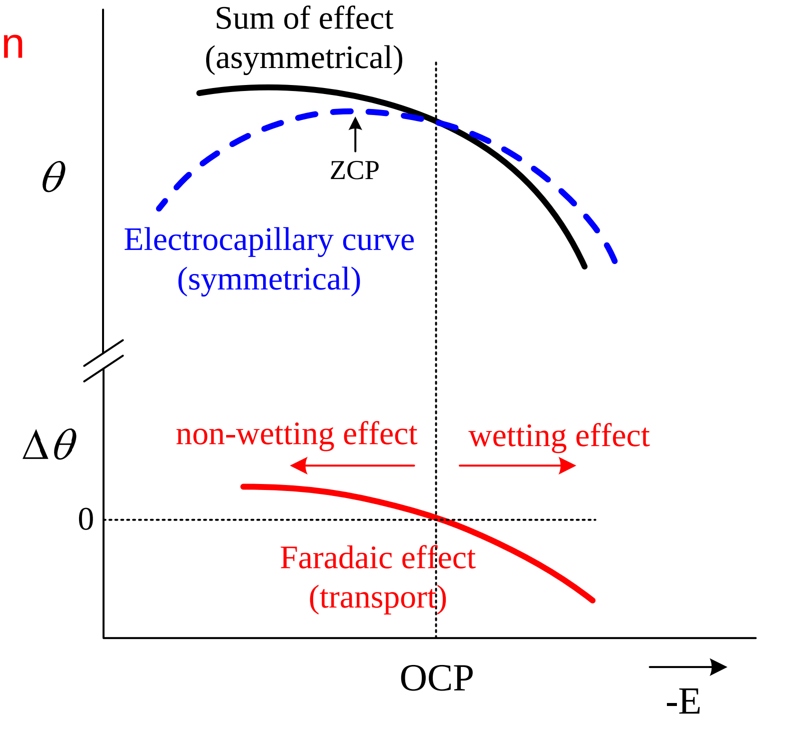
“Towards An Additional 20,000 Hours” (cont’d)				
Degradation issue priority	Type 1. Optimize known solution (tech and econ)	Type 2. Select among possible solutions	Type 3. Identify mechanism and solutions	Public vs Private
AFCO				
1			Fundamental material-behaviour in off-design conditions	Public (material robustness, kinetic reaction)
2		Ni shorting		Public, all-round research
3	CCC material stability			Public (improved materials)
KIST				
1		Stack Temperature control (vertical & horizontal)		Confidential (separator design, manifolding, operating variables)
2		Matrix stability		Public (raw material, thermodynamic properties, phase diagrams)

4. Fundamental research

(example: wetting by molten carbonate under polarization, Ping-Hsun Hsieh, IIT 2009)

Reducing atmosphere ($H_2/CO_2/N_2$=3/40/57)





Why/how does the melt chemistry affect CA under cathodic and anodic polarization?

5. Concluding remarks

- Incremental improvement strategy has been very effective in improving life time.
- Combination of high power density with long(er) life time remains a major challenge.
- Radical innovation is now on the backburner, but must receive more attention. For example, 1. smart use of nano-materials and micro-composites (Bin Zhu a.o.). 2. development of non-wettable or controlled-wettable materials.
- Re-emerging field for innovation: DCFC (direct coal FC) – in the USA: LLNL, SARA, SRI, a.o.