Toward efficient fuel cell systems

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Toward efficient fuel cell systems

Introduction

Fuel Cell Technology and Fuel Cell Systems

PEM/SO fuel cell systems areas of research (a flavor…)

Concluding remarks

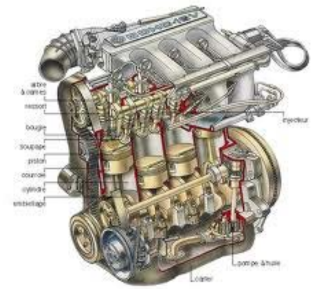
Toward efficient fuel cell systems

Introduction

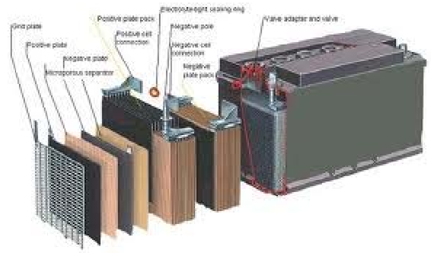
FC LAB Research

Introduction

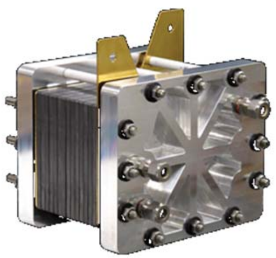
– Switching to fuel cell?



- **The age of using exclusively fossil fuels comes to an end**
  - Resource reduction
  - Exhaust gases (GHG) from the internal combustion engine



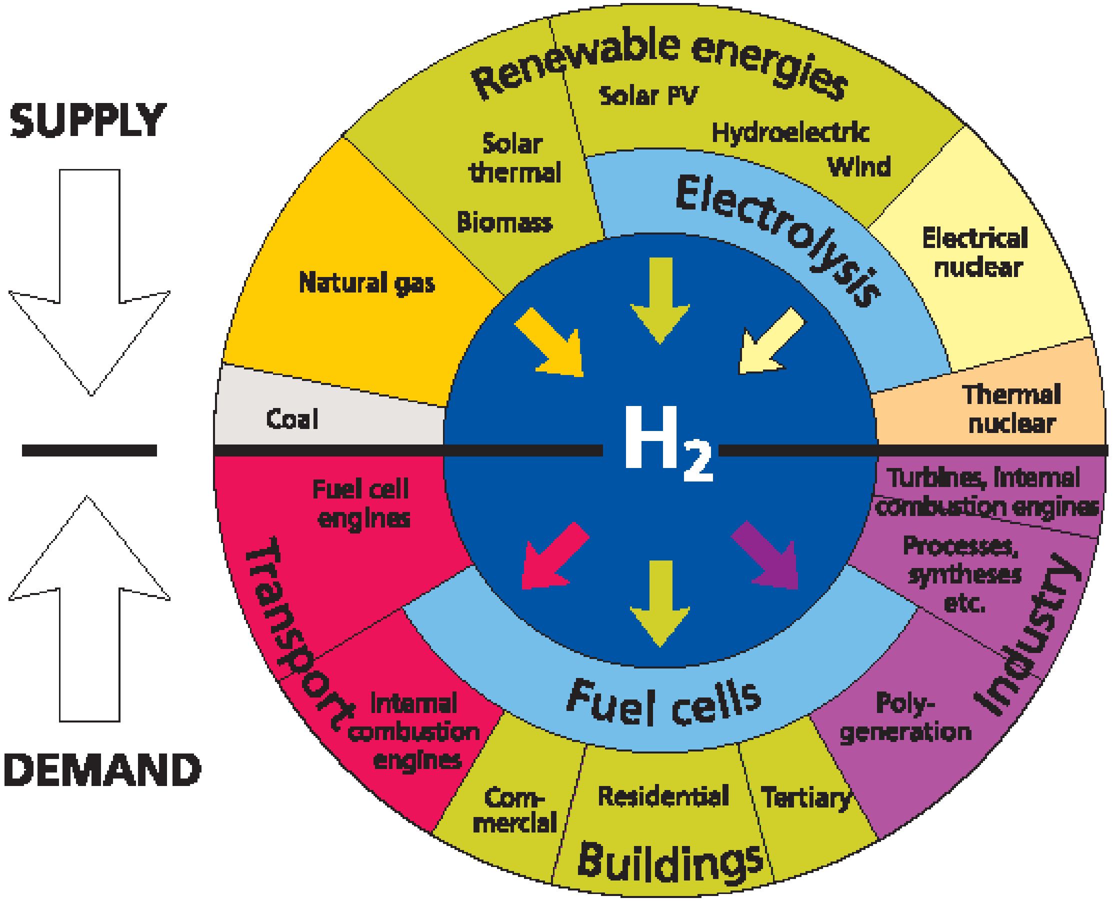
- **First alternative: rechargeable batteries**
  - Many advances have been made BUT
  - Mostly "hybrid" systems because of limited autonomy and cumbersome recharging operations
  - ⇨ Reduce rather than eliminate the dependence on fossil fuels…



- **Second alternative: fuel cell systems**
  - When combined with oxygen, hydrogen produces electricity
  - Residuals: water and heat
  - (*Theoretical & in-situ*) pollutant emissions is zero
  - ⇨ **Attractive alternative**
  - ⇨ **High energy density (but linked to H2 storage)**

Introduction

– **Hydrogen as an energy vector?**



http://ec.europa.eu/research/rtdinfo/42/01/article_1315_en.html

- **Hydrogen**
  - Very abundant "elementary" resource at global level (oceans, rivers, organics, biomass)
  - Never in an isolated state: hydrogen must be produced
  - Once produced, hydrogen can be stored and distributed

⇨ **"production-storage-transport"**

⇨ **hydrogen is not seen as a "direct" fuel but as an energy vector**

⇨ **duality with electricity (FC – electrolysis)**

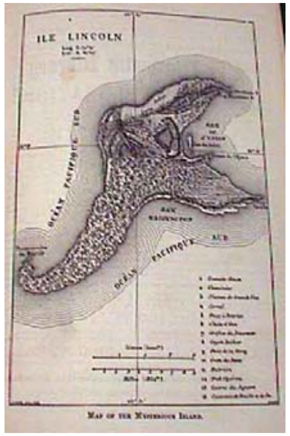
Introduction

– Is Science Fiction becoming Reality?

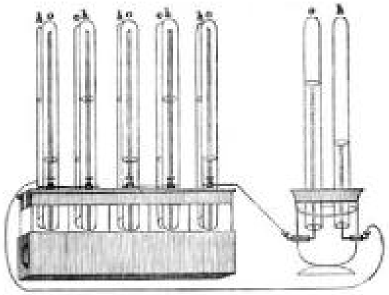
- **Jules Verne, 1875: "*The Mysterious Island*"**

  « … but after the European mines, […] , the American and Australian mines will for a long time yet provide for the consumption in trade. For how long a time? […] For at least two hundred and fifty or three hundred years.

  That is reassuring for us, but a bad look-out for our great-grandchildren! […] And what will they burn instead of coal? […] ***water decomposed into its primitive elements****... "*

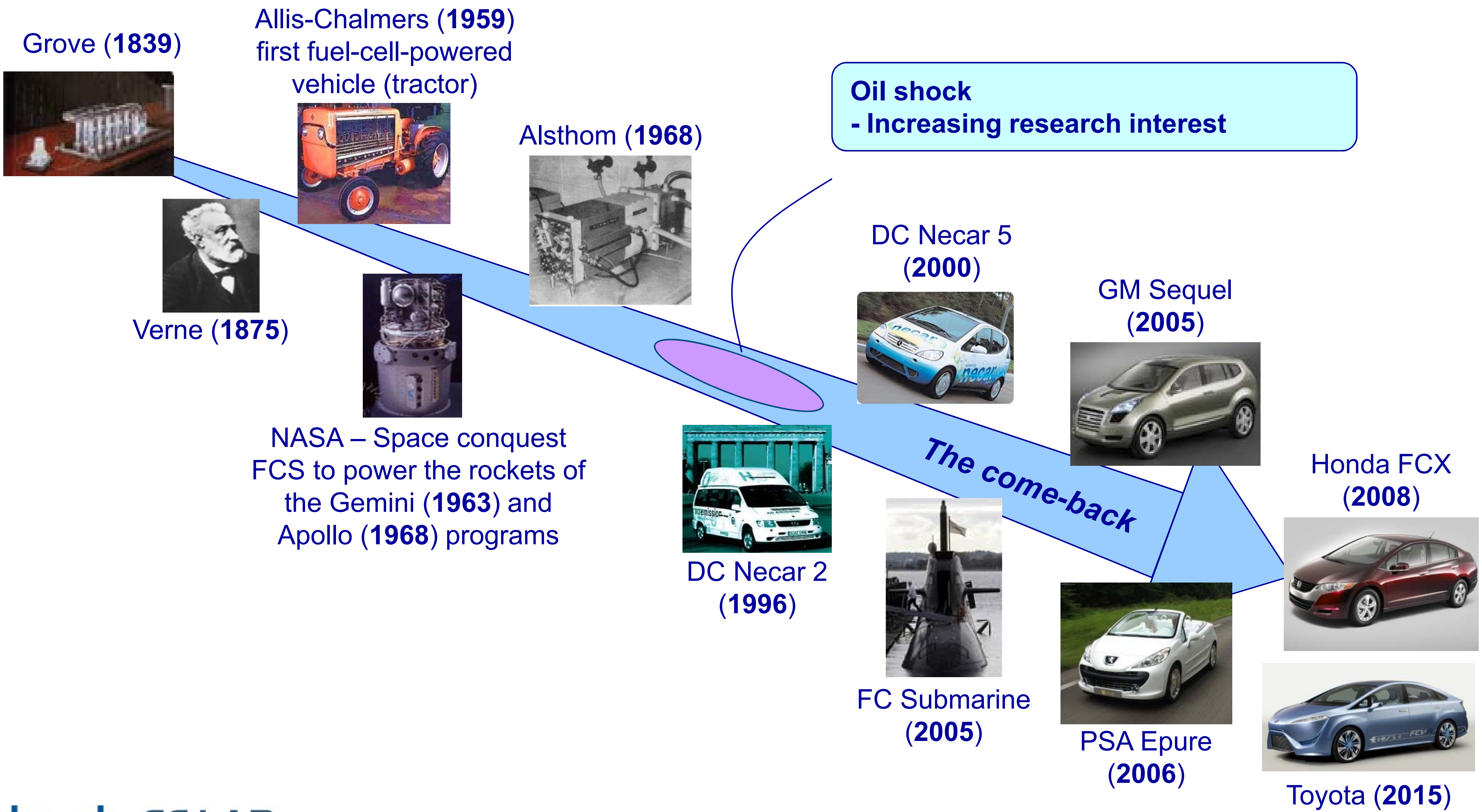


- **Basic principle discovered and demonstrated in 1839**
  - British physicist William Grove
  - For more than a century, the priority given to the development of thermal machines and electrical batteries overshadowed this discovery.



Introduction

– Brief history



Toward efficient fuel cell systems

Fuel cell technology and fuel cell systems

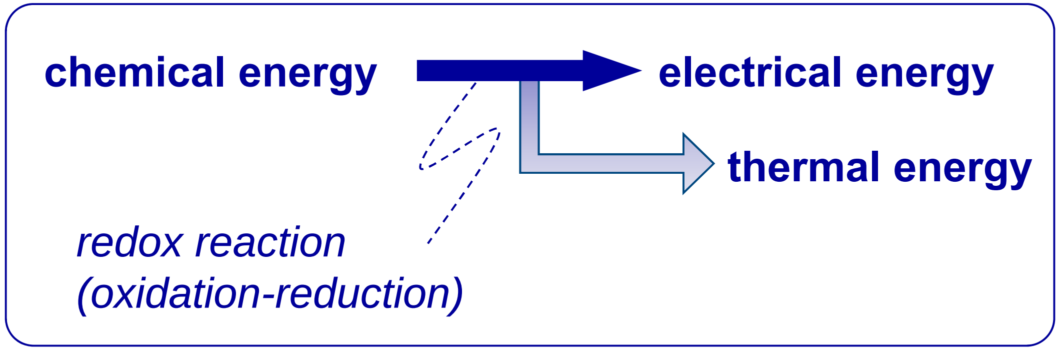
FC LAB Research

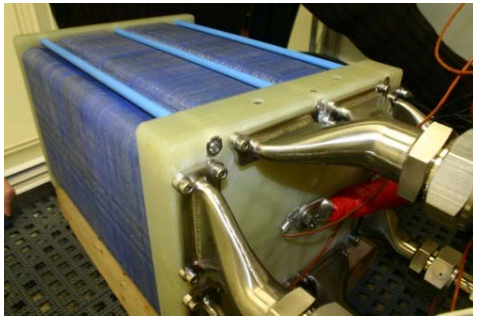
Fuel Cell technology

– Principle of a fuel cell

▪ What is a Fuel Cell?

- US Fuel Cell Council definition, modified by FC Testing and STandardisation NETwork
  - An **electrochemical device** that continuously converts the chemical energy of a fuel and an oxidant to electrical energy (DC power), heat and other reaction products. The fuel and oxidant are typically **stored outside** of the cell and transferred into the cell as the reactants are consumed.





PEMFC -CEA

- Jules Verne, 1875: "*The Mysterious Island*"

  *« I believe that water will one day be employed as fuel, that **hydrogen** and **oxygen** of which the water is constituted will be used, simultaneously or in isolation, to furnish an inexhaustible source of **heat** and **light**… »*

Fuel Cell technology

– **Taxonomy of Fuel Cell**

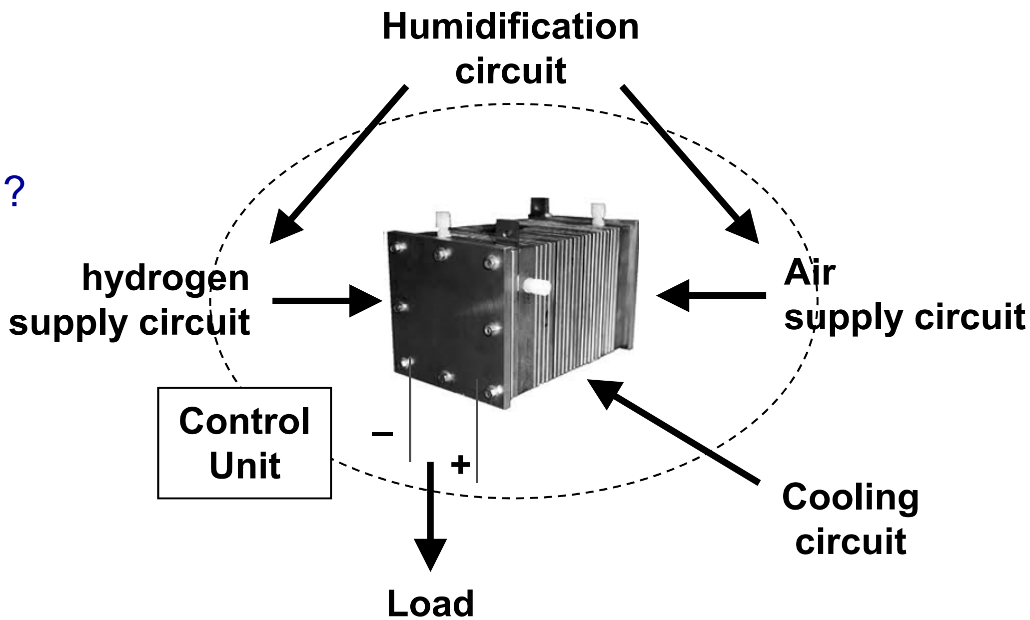
	Oper. Temp. (°C)	Power range (W)	Main application area
DMFC	20 – 90	1 – 100	Low-power portable applications (mobile phones, computers)
PEMFC	30 – 100	1 – 100k	**Automobile / Transport** Low-power stationary appl. (residential sector)
AFC	50 – 200	500 – 10k	Spaceships
PAFC	~220	10k – 1M	Domestic heat & electricity co-generation (CHP)
MCFC	~650	100k – 10M+	High-power units for CHP, maritime applications
SOFC	500 – 1000	1k – 10M+	Same as MCFC + **Transport**

PEMFC Systems

– Whole PEMFC System

- **The stack within a whole system**
  - Stack "only" converts energy…
  - Prior to the electrochemical reaction
    - How to supply "produce", store, and supply the hydrogen and oxygen?
  - After the electrochemical reaction
    - How to manage the electricity generated?
    - How to manage the heat generated?
    - How to manage the water generated?
  - During the electrochemical reaction
    - How to control the process?
    - How to ensure safety of the whole system?

⇨ FC System = Stack + Ancillaries



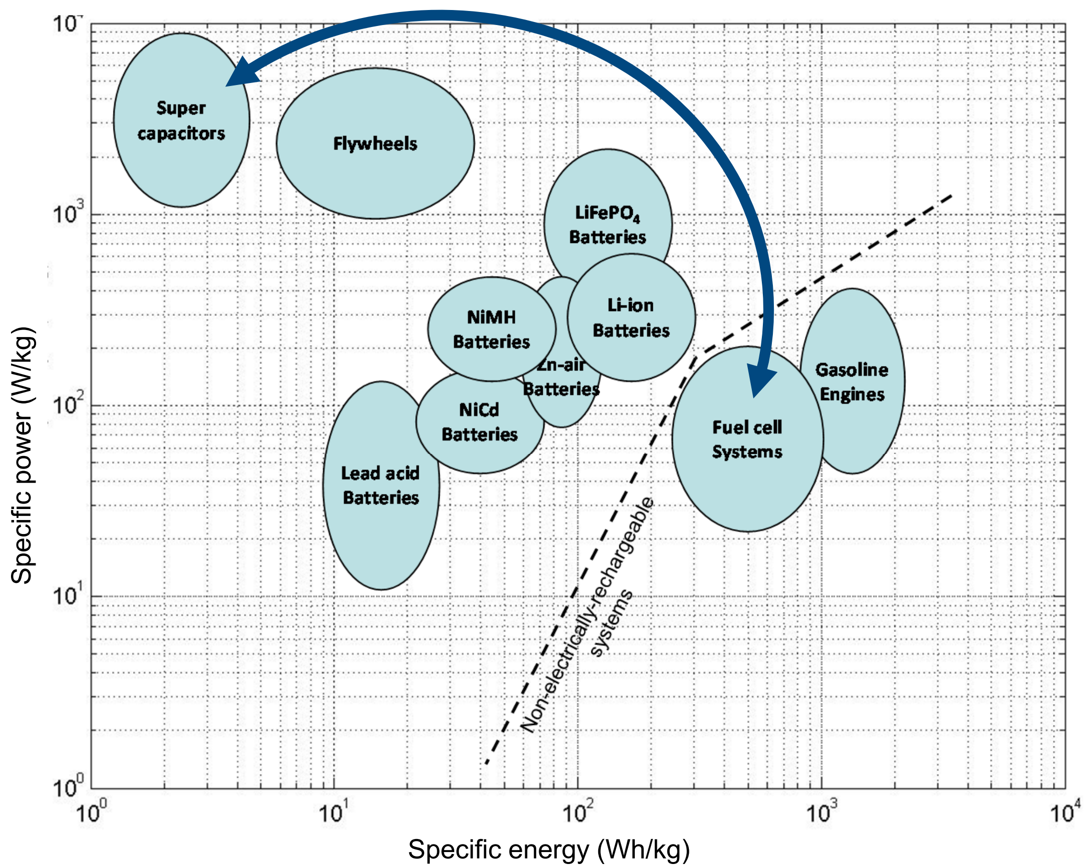
PEMFC Systems

– **Whole PEMFC System**

- **The need of electrical hybridization…**
  - FC = non electrical rechargeable system
  - FC = no possibility of recovering braking energy

➔ Ragone plot…

➔ Hybridization with supercapacitors / flywheels / power batteries?

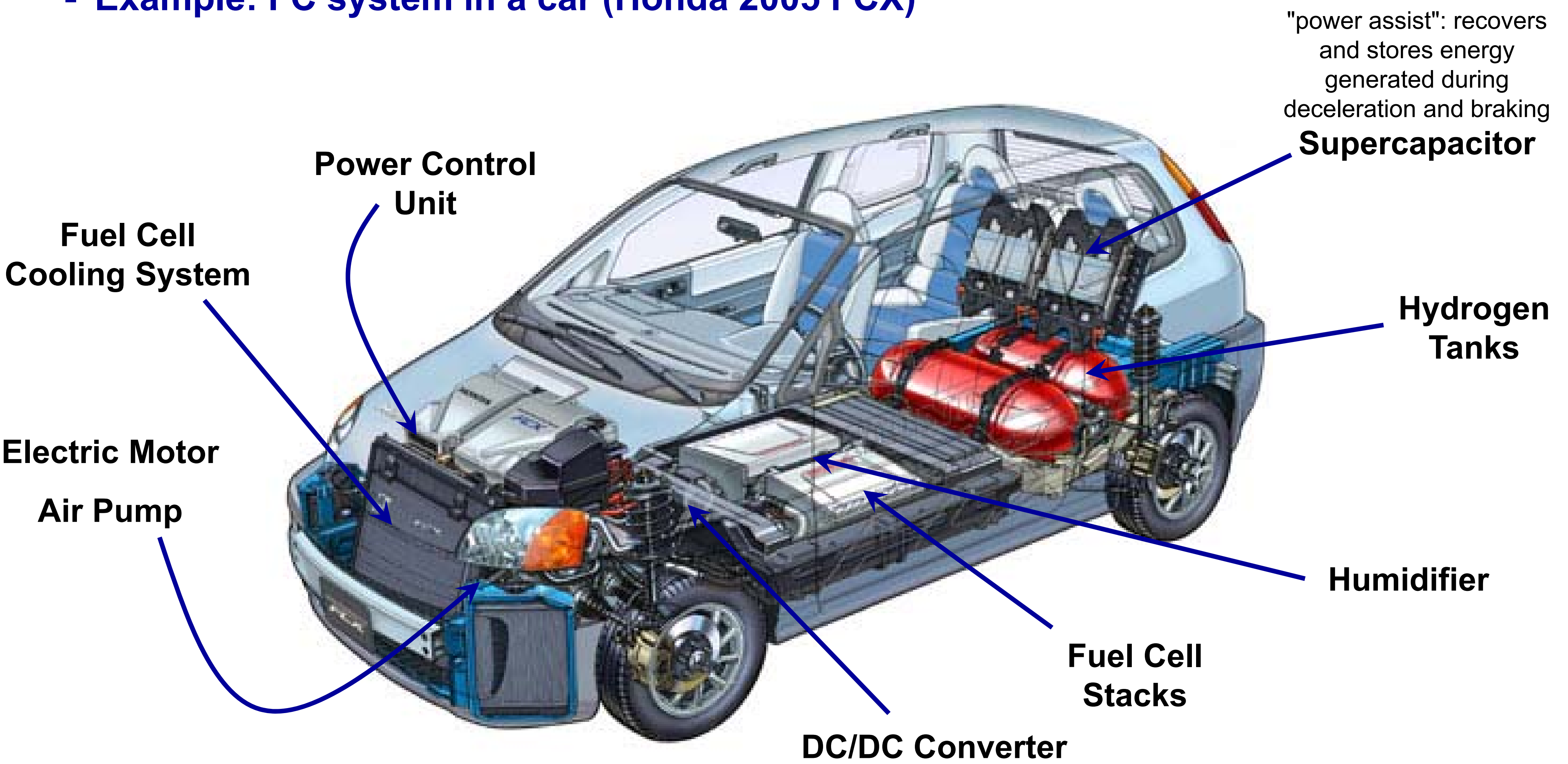


MC.Péra, D.Hissel, H.Gualous, Ch.Turpin, "Electrochemical components", Wiley, 2013.

PEMFC Systems

– **Whole PEMFC System**

- **Example: FC system in a car (Honda 2005 FCX)**



PEMFC Systems

– Some ideas about numerical values…

- **Efficiency**
  - Maximal (elec.) efficiency of a FC stack ≈ 55%
  - In fuel cell power generators, up to 40% of the produced energy is consumed by all their ancillaries

- **Volume and prize**
  - Fuel cell stack volume ≈ 30% of the fuel cell system volume (70% is linked to ancillaries)
  - Fuel cell stack price ≈ ancillaries' price
  - Platinum price (catalyst) ≈ only about 5% of the price of a whole PEMFC power generator

- **Current**
  - Current density (A/cm2)
    - Directly linked to performances of FC stack materials (membrane, electrode quality, gas diffusion…)
    - Typically between 0.5 et 1 A/cm^2 (PEMFC)
  - Active area
    - For a given cell type, increasing current implies increasing electrode area

- **Voltage**
  - Per cell
    - Thermodynamic limitation: 1,18V at atmospheric pressure and at 80°C
    - Open circuit voltage per cell (I=0A): typically 0.9V
    - Nominal voltage per cell: 700mV
    - Minimum voltage per cell: typically about 400mV
  - Stack: linked to the number of cells associated in serial arrangement

Toward efficient fuel cell systems

PEM/SO fuel cell systems areas of research (a flavor…)

FC LAB Research

Areas of research

- **Scientific and technological bolts**
  - Fuel cell system **efficiency**
    - Increase it (elec. only) from about 30-40% to about 45-55%

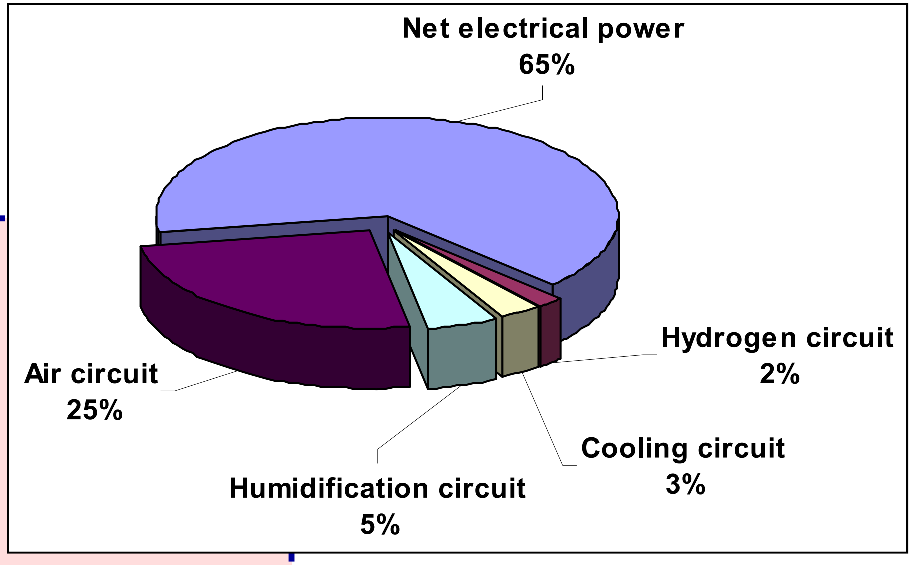
  - Fuel cell system **durability**
    - Ex. for PEMFC systems
      - Common life duration of around 1500 – 3000 hours
      - Where 5000 hours are required for light vehicles
      - Where 30000 hours are required for trucks
      - And up to 100000 hours for stationary applications & railways

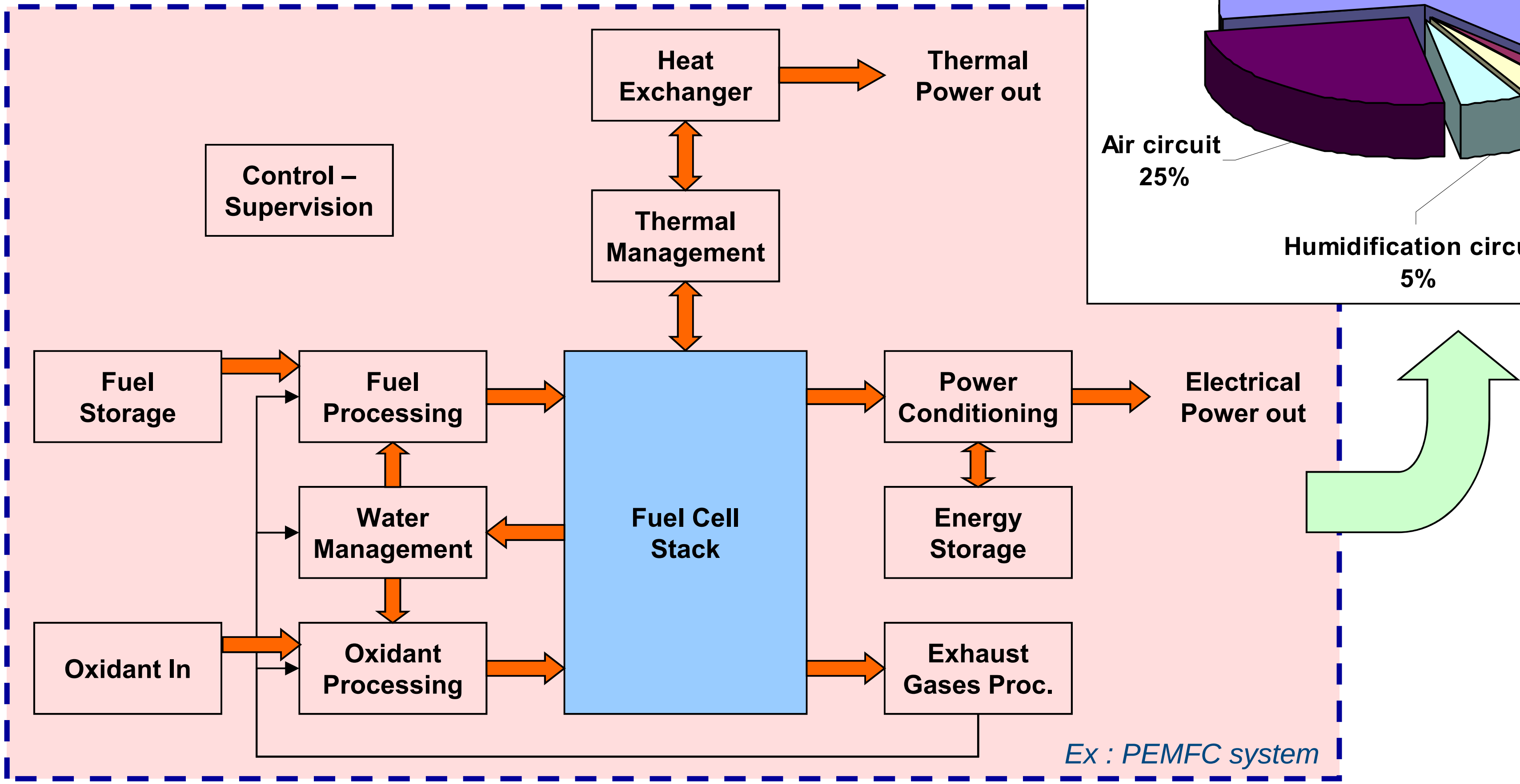
  - Public **acceptance**
    - Socio-economic aspect: hydrogen-based energy is unknown
    - Strong link with public policies
  - **Cost** (whole life cycle)
    - Linked to industrial deployment

Areas of research : efficiency

– Efficient & dedicated ancillaries are required…

- Specific power converters
- Specific air compressor
- Systems for the humidification / cooling
- Fuel storage





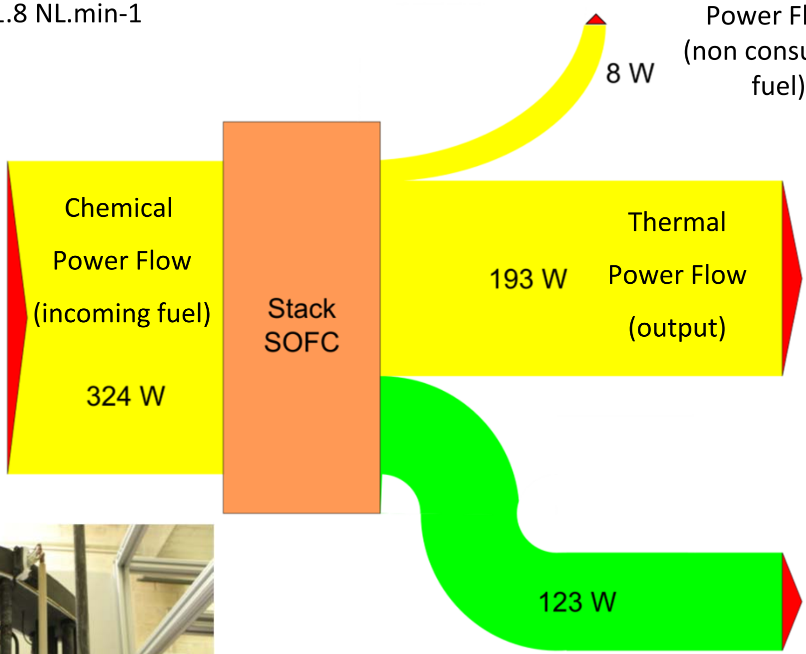
Areas of research : efficiency

– **Optimize energy flows…**

Micro-CHP
(especially with high temperature SOFC)

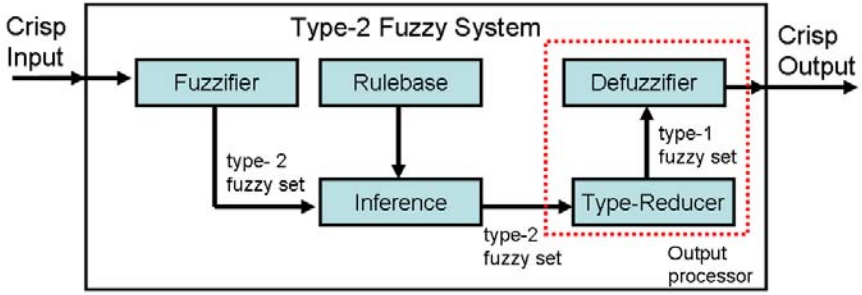
Ex : SOFC system

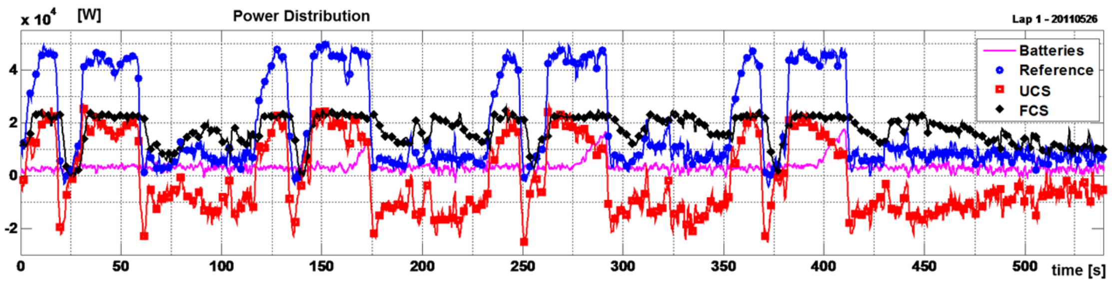
SOFC Stack
Operating temperature = 750°C
Output electrical current = 32A
H_2 flow = 1.8 NL.min-1



Propose efficient (& real-time) energy management strategies

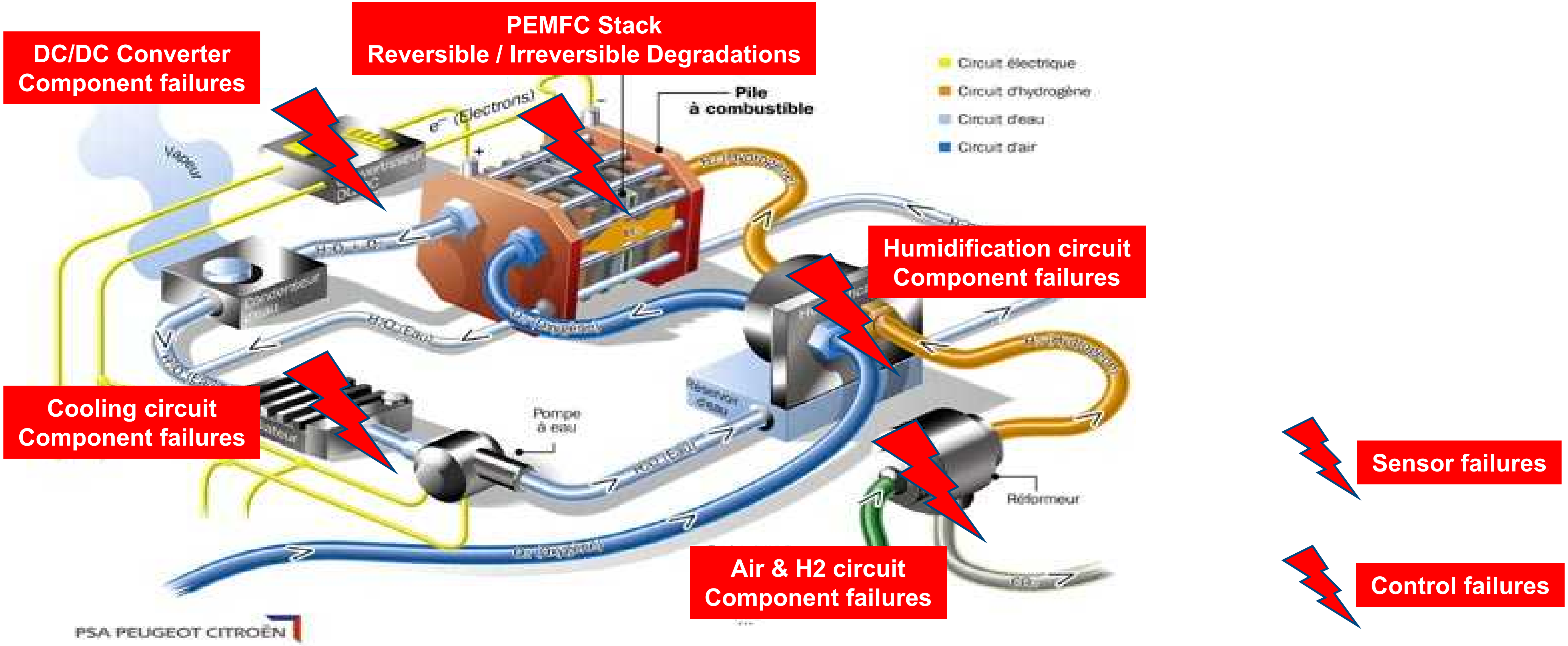
Ex : PEMFC system





Areas of research : durability

– **Degradations/failures at system's level**



Areas of research : durability

– Degradation modeling?

- **Parameters reducing the FC lifetime**
  - Fuel impurities (sulfur, CO for PEMFC, …)
  - Oxidant impurities (oil from the compressor, salt from environment, …)
  - Fuel and oxidant stack starvation (linked to the dynamic and the control of the system)
  - Temperature supervision (linked to the system control)
  - Hydration supervision for PEMFC (linked to the system control)
  - Pressure variations (linked to the system control)
  - Peak power demands and current ripples (linked to the control and to the power electronics)
  - Open circuit voltage operation for PEMFC (linked to the control)…

  ⇨ **Gives an overview of potential causes…**

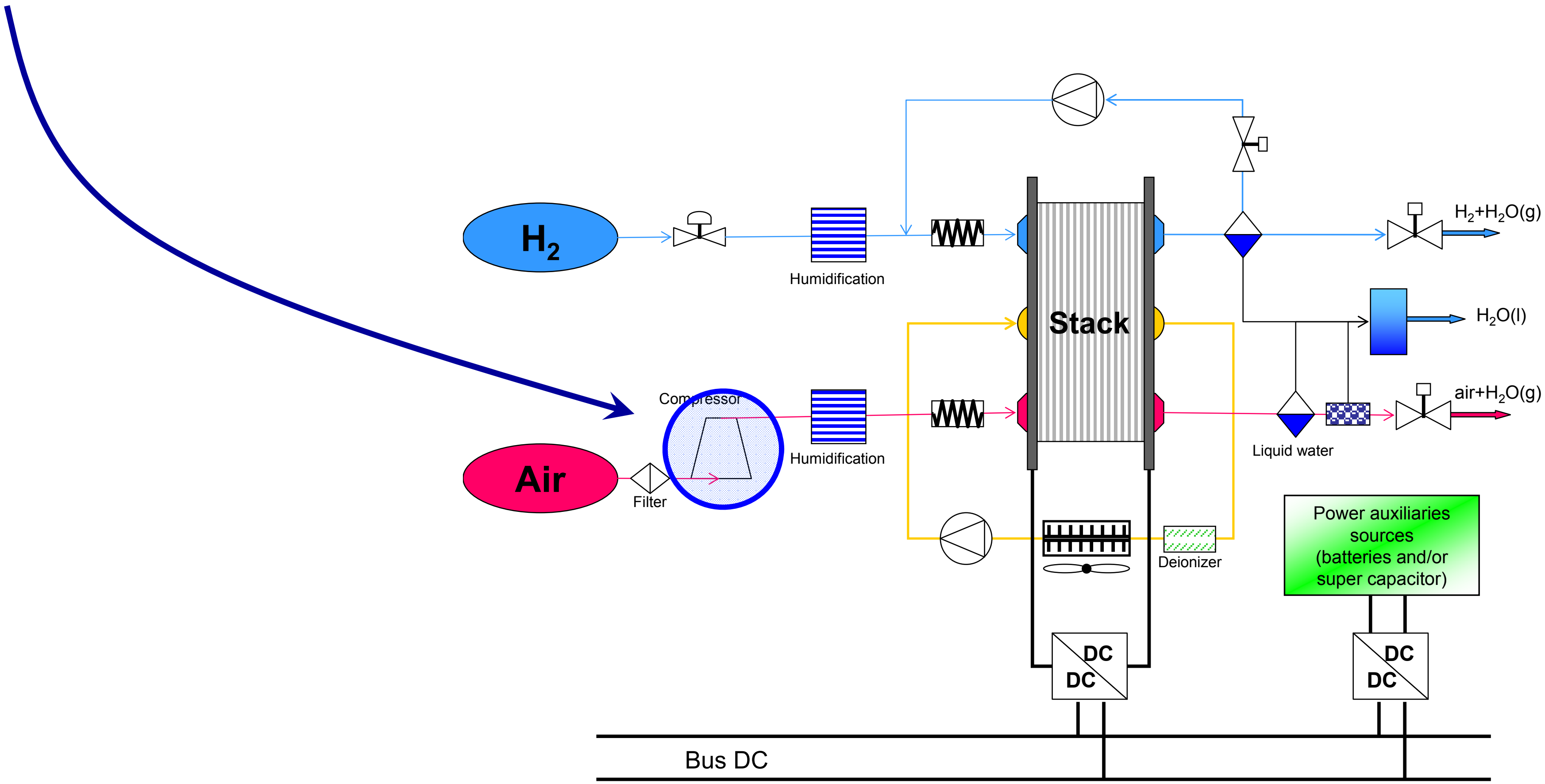
- **Whatever the degradation is…**
  - It results in a voltage drop

  ⇨ **Gives an idea of potential effect…**

Areas of research : durability

– Impact of compressor failure – oxidant circuit

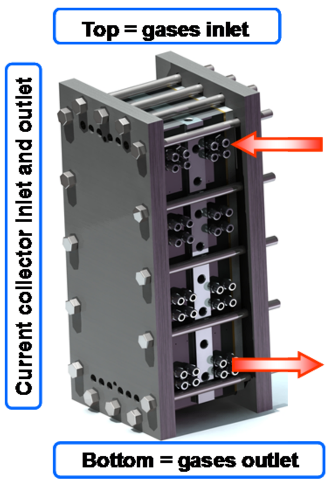
- **Compressor failures**
  - Oxygen starvation ⇨ consequences on performance and durability

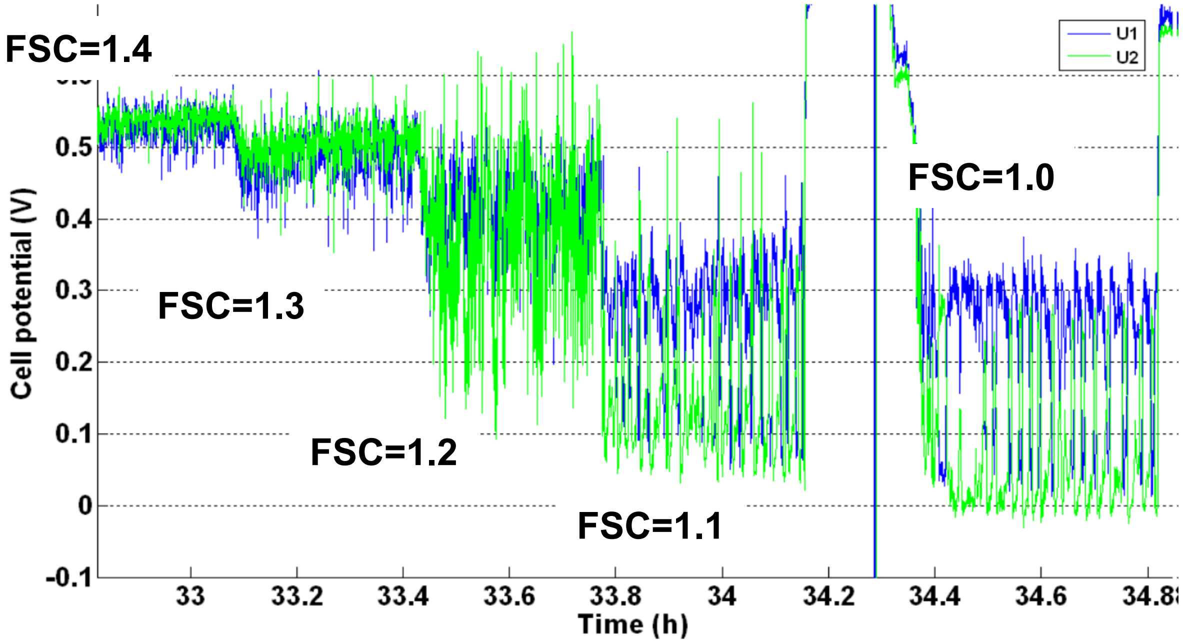


Areas of research : durability

– **Impact of compressor failure – oxidant circuit**

- **Experiments at constant gas flow and low stoichiometry (Kulikovsky et al. 2004, Liu et al. 2006, Gérard et al. 2010)**
  - Voltage oscillations
  - Voltage can reach near zero (or even negative) values

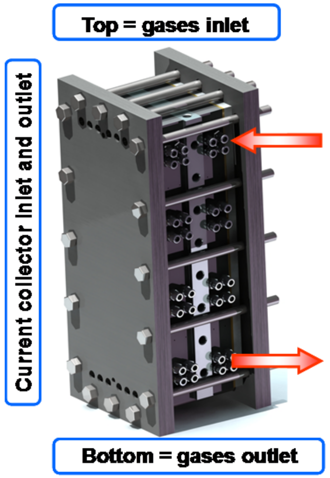


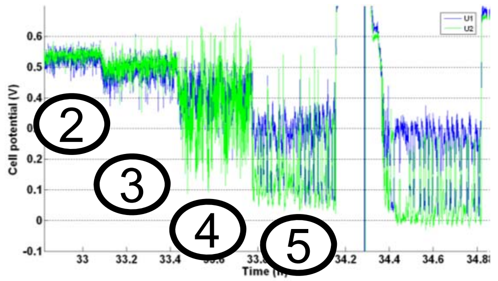


Examples of interactions system / stack

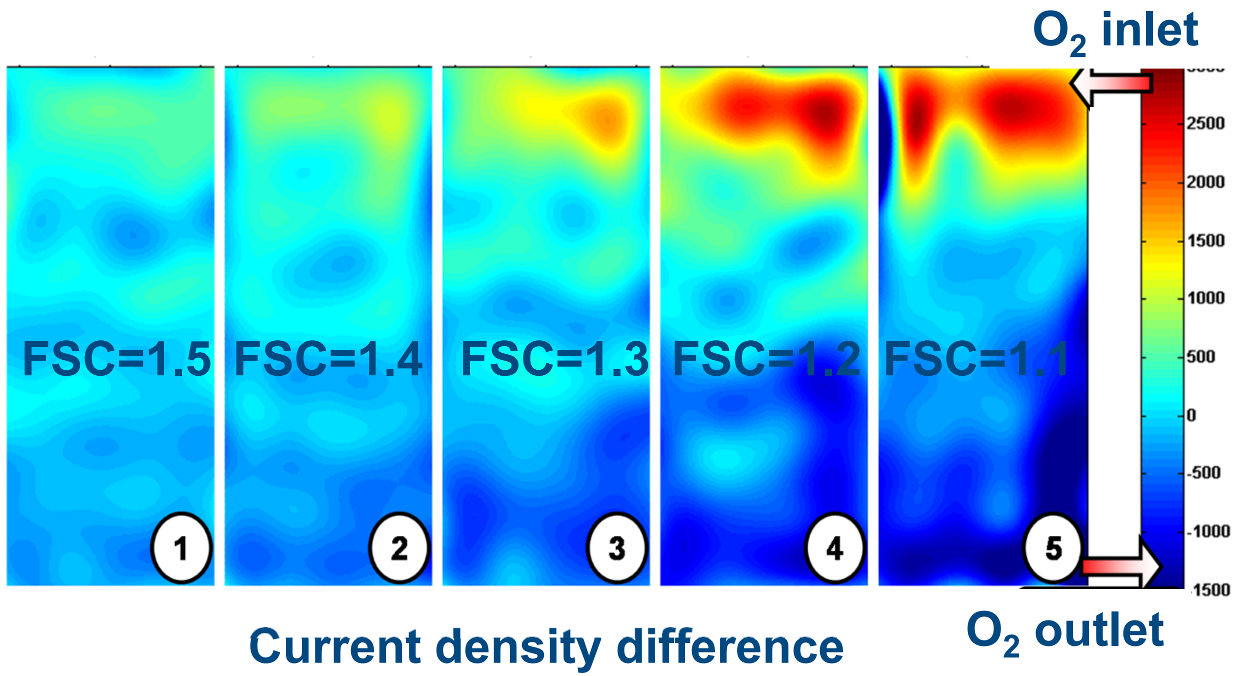
– Impact of compressor failure – oxidant circuit

- **Experiments at constant gas flow and low stoichiometry (2)**





Nominal conditions
I=0.5 A.cm^{-2}



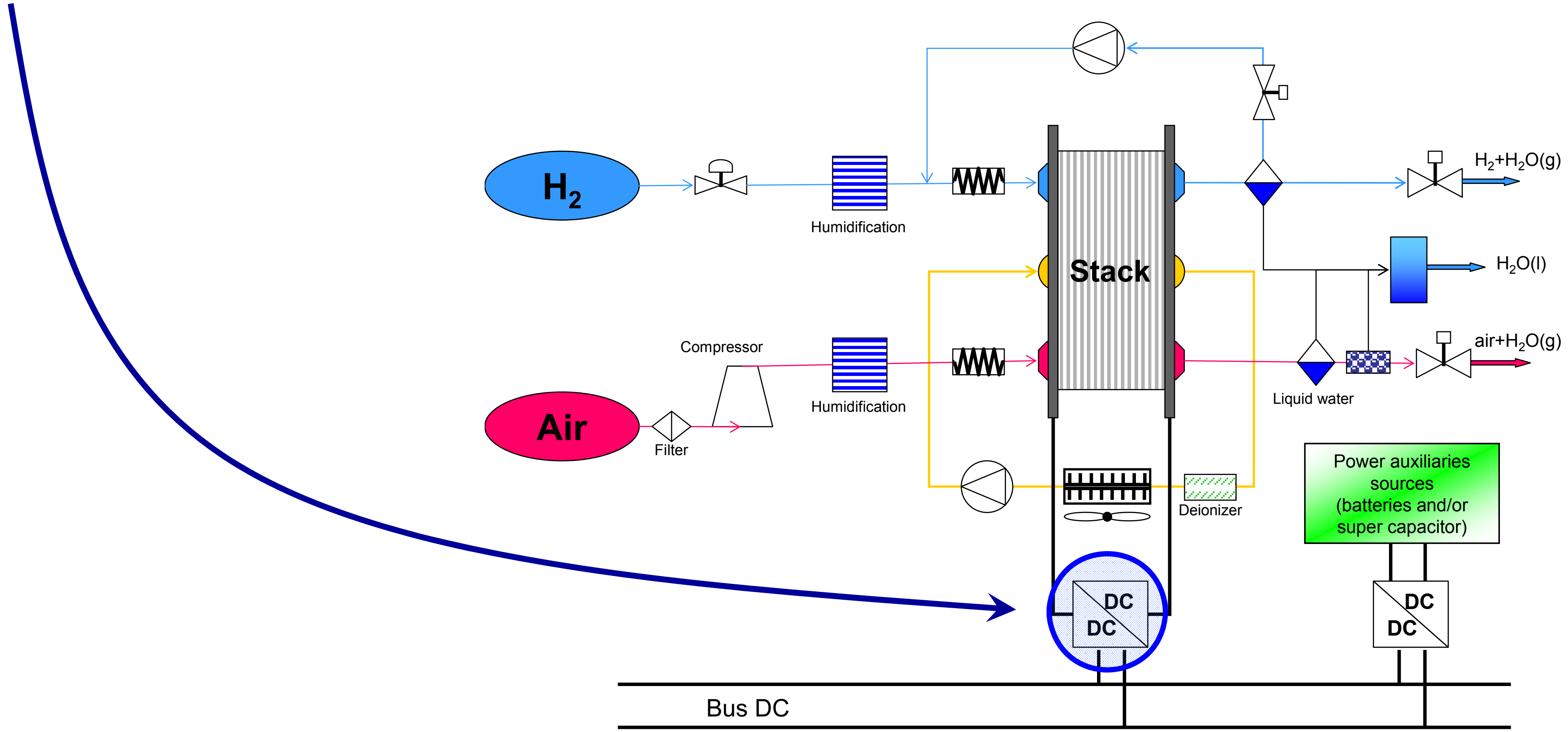
Current density difference

If O2 flow is poor, displacement of the current at the inlet

Areas of research : durability

– **Impact of the converter – current ripple**

- **DC/DC converter**
  - The output fuel cell current is submitted to the high frequency switching leading to a current ripple
  - ⇨ Impact on durability



Areas of research : durability

– Impact of the converter – current ripple

▪ Ageing tests

- 2 durability tests, same new stacks
  - with ripple (5kHz)
  - without ripple
- 5 cell stack, 220 cm²
- Characterizations every week
  - 4 polarization curves
  - 3 EIS (at 3 different currents)

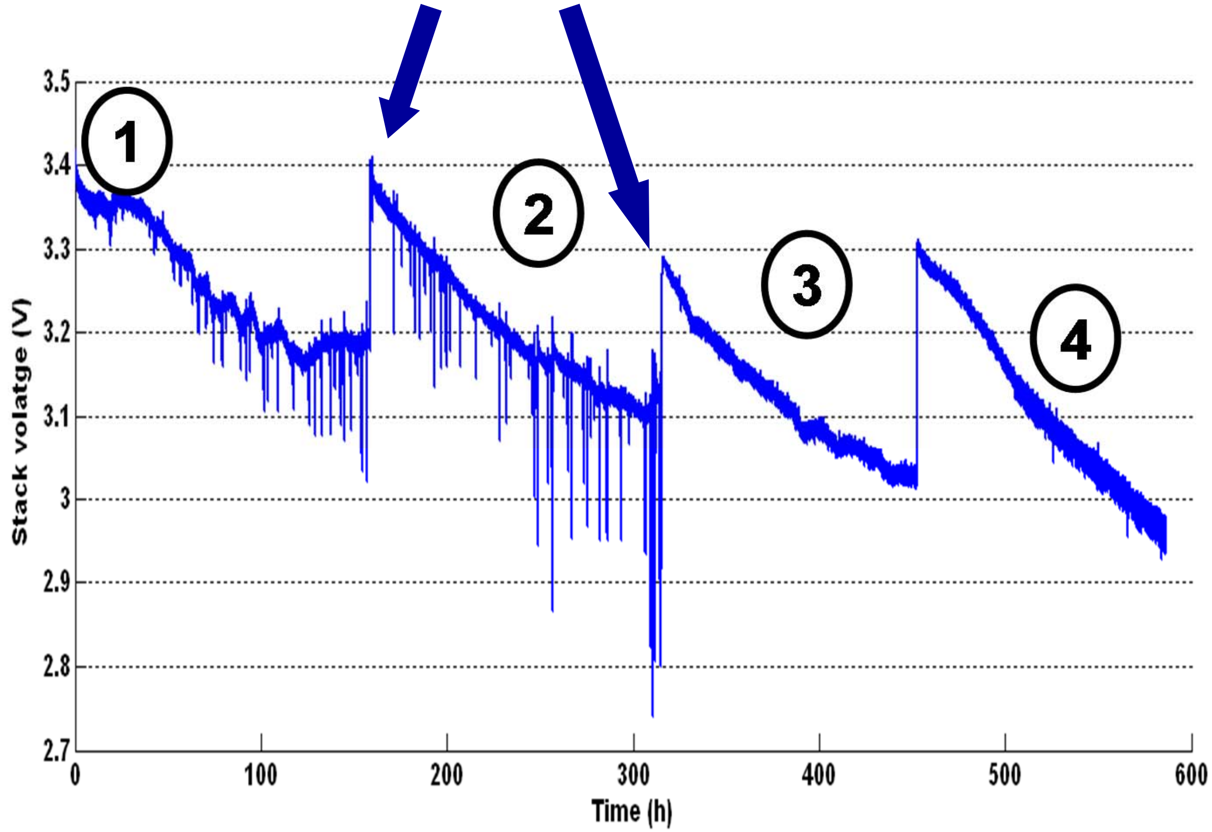
Ageing test nominal conditions	
Cooling temperature	348 K
Relative humidity	50%
Gas pressure	1.5 bars
Hydrogen stoichiometry	1.5
Oxygen stoichiometry	2
Nominal current density	110 A (0.5 $A.cm^{-2}$)
Ripple current frequency	5 kHz
Ripple current amplitude	20%

Areas of research : durability

– Impact of the converter – current ripple (Gérard et al. 2010)

- **Stack voltage comparison**
  - zone 1: 264 µV.h^{-1}
  - zone 2: 387 µV.h^{-1}
  - zone 3: 382 µV.h^{-1}
  - zone 4: 507 µV.h^{-1}

Characterization
- ripple is stopped
- polarization curve
- EIS



Areas of research : durability

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  - zone 1: 264 µV.h^{-1}
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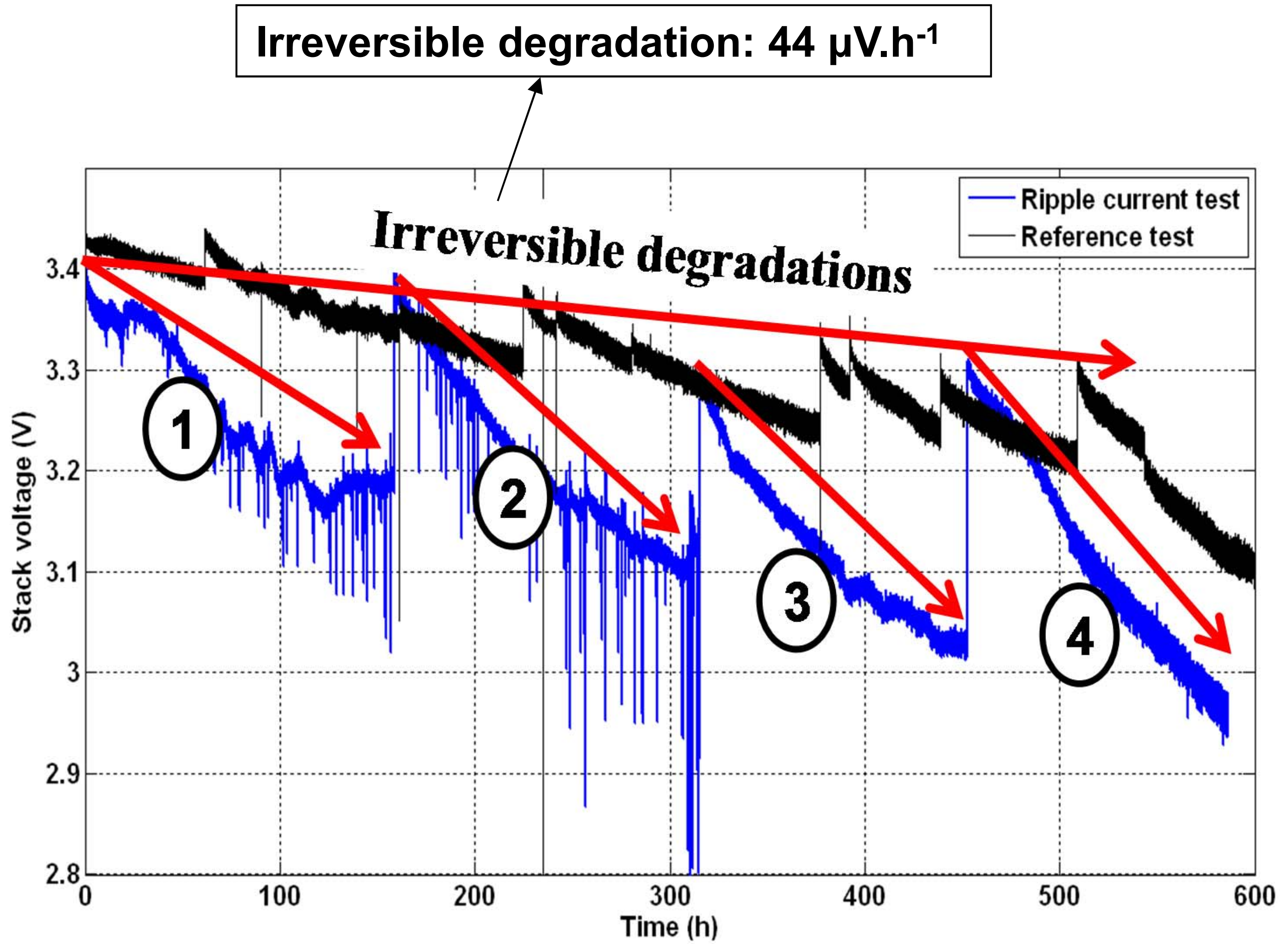
Much higher reversible degradation with ripple current



Areas of research : public acceptability

- A global framework

- **Historical approach of H2 & FC**
  - Diachronic and synchronic approaches
- **Public policies**
  - Strong involvement of governments is required (funding, taxes, …)
  - Key countries: Japan, Germany, Canada, USA, South Korea, France, …

- **Evaluation / mitigation of risks**
  - Normalization / standardization
  - Evaluation of security issues

- **Awareness on the technology**
  - Demonstration programs
  - Teaching fuel cell from lower classes

- **Clean production of hydrogen**

Areas of research : costs

– Reduce the costs

- **A strong industrial interest** *(source US DOE annual market report)*
  - Fuel cells receive far more patents than other renewable energy technologies (950 patents in 2011 versus 450 for photovoltaic)
- **2012's prices** *(source US DOE annual market report)*
  - About 500€-2000€/kW for the stack – projected cost for 500000 units = 50€/kW
  - 40% FC stack + 40% FC ancillaries + 20% electrical powertrain

– What can be done ?

- Use of lower cost components (EME)
- Process automation (especially for bipolar plates)
- Design of specific ancillaries (e.g. the air compressor)
- Understand in deep the degradation mechanisms
- Optimize the whole system not only the components
- Focus on "interesting" emerging markets (forklifts, micro-CHP, backup power, military applications (U-boats, portable, backup), aeronautic applications, …)

PHM of Fuel Cell Systems – A state of the art

Concluding remarks

FC LAB
Research

Concluding remarks

– The interest of H2 technology

- **FC are promising energy converters**
  - High efficiency & low noise level
  - Possible heat recovery (especially for high temperature FC – SOFC)
  - Possibly no dependency to fossil fuels
  - Energy density is directly linked to the size & weight of the fuel tanks
  - Still issues on system-level
    - Interactions between the FC stack & their ancillaries
    - Reliability & durability, Diagnosis & Prognostic
    - Dedicated ancillaries on a tiny market

- **H2**
  - Best candidate for next generation fuel?
  - May play a key role in the future energy economy – electricity storage for renewable energies
  - Still issues on H2 production, public acceptability, on-board storage, distribution facilities

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