Zentrum für Sonnenenergie- und Wasserstoff-
Forschung Baden-Württemberg

General Challenges in PEMFC

Ludwig Jörissen

Stuttgart, 06.07.2022

FURTHER-FC Workshop

ZSW at a Glance – Center of Solar Energy and Hydrogen Development

- **A non-profit organization with 350 employees, 50 MM€ annual budget and 85% external funding**
- **Applied Research & Development on New Energy Technologies:**
  - Batteries & Supercapacitors: materials, production technologies, systems, qualification
  - Hydrogen & Fuel Cells: stack-technology, components, systems, production technologies, test centre
  - Photovoltaic: materials, thin film technologies (CIGS) & application systems
  - Renewable Fuels: power-to-gas, biomass gasification
  - Energy politics & economics, wind energy

innBW INNOVATIONSALLIANZ BADEN WÜRTTEMBERG

www.zsw-bw.de

WIND ENERGY

PHOTOVOLTAICS

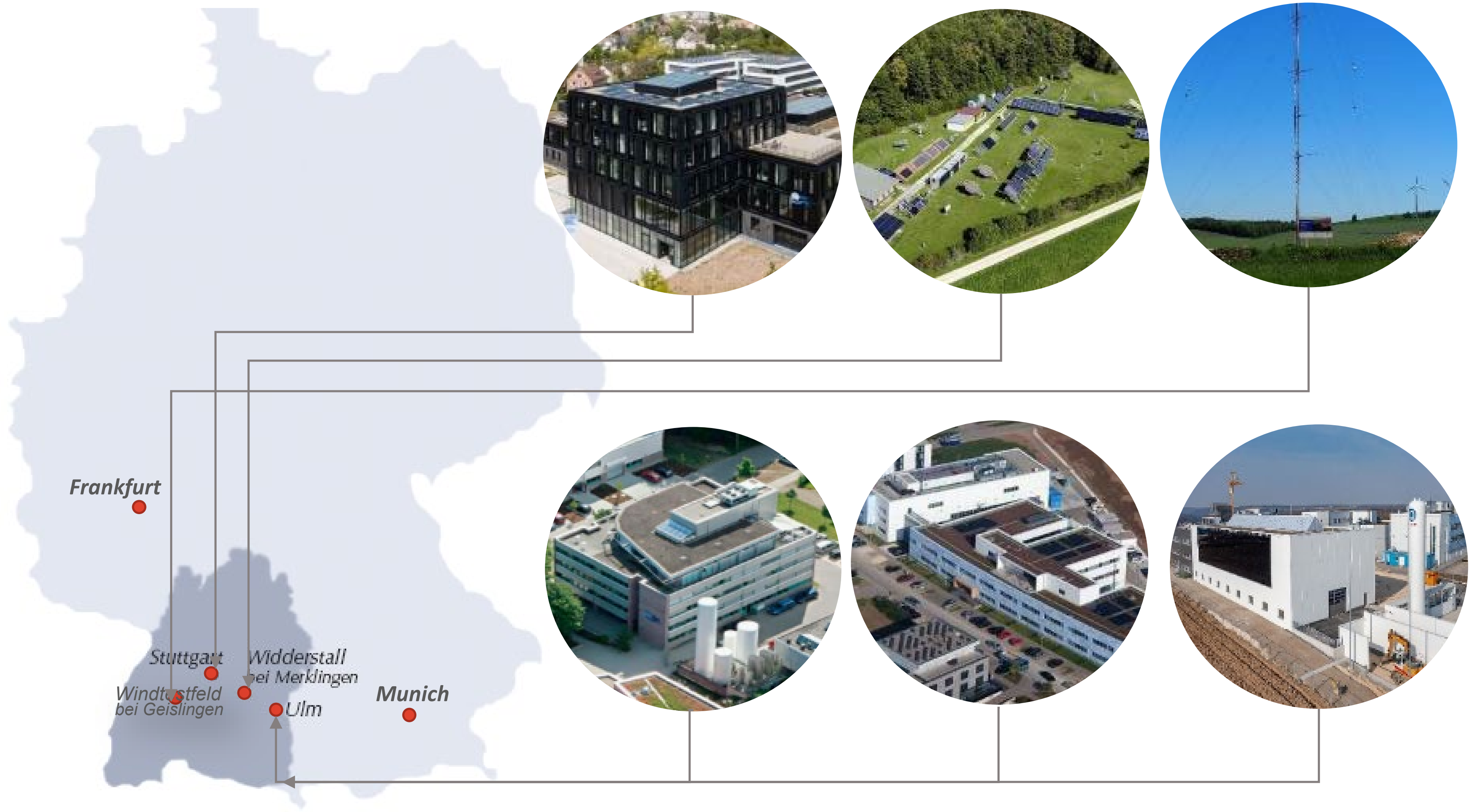
BATTERIES

HYDROGEN

FUEL CELLS

ADVOCACY

ZSW Locations in State of Baden-Württemberg



Stuttgart:
Solar including Solab, Energy Consultancy, Energy Carriers; Water electrolysis, Finances, IT, HR, Legal, Solar testfield in Widderstall & Wind testfield Stötten (Schwäbische Alb)

Ulm:
Electrochemical Energy Technologies with Laboratory for Battery Technologies (eLaB)

Fuel-Cell Research including HyFaB)

The Times They Are A-Changing

Key questions to fuel cell technology too!

1966 1970 1994 2004 2010 2014 2019 2022

Does it work at all?

How much will it cost?
Is there enough platinum?

How long does it last?

Where is the infrastructure?

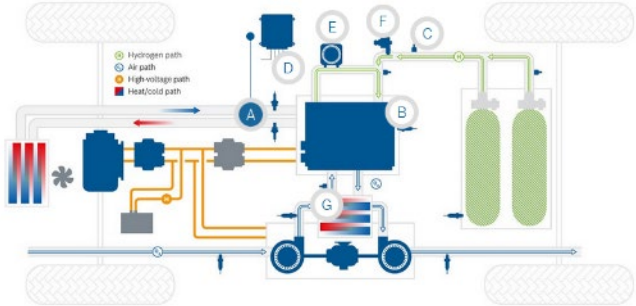
https://www.gmheritagecenter.com/featured/Fuel_Cell_Vehicles.html
https://www.jameco.com/Jameco/workshop/inthenews/inthenews-horizon-pioneers.html
https://group.mercedes-benz.com/magazin/technologie-innovation/necar1-brennstoffzelle-entwicklung.html
https://de.motor1.com/toyota/mirai/
https://www.adac.de/rund-ums-fahrzeug/tests/ecotest/details/4517/toyota-mirai-executive/
https://www.auto-motor-und-sport.de/elektroauto/nikola-iveco-cnh-industrial-joint-venture-elektro-lkw
https://fuelcellsworks.com/news/daimler-truck-tests-fuel-cell-truck-with-liquid-hydrogen/
https://fuelcellbuses.eu/wiki/fuel-cell-electric-buses-fuel-cell-electric-buses/about-fuel-cell-electric-buses
https://www.alstom.com/solutions/rolling-stock/coradia-ilinttm-worlds-1st-hydrogen-powered-train

Fuel Cell System in a Vehicle

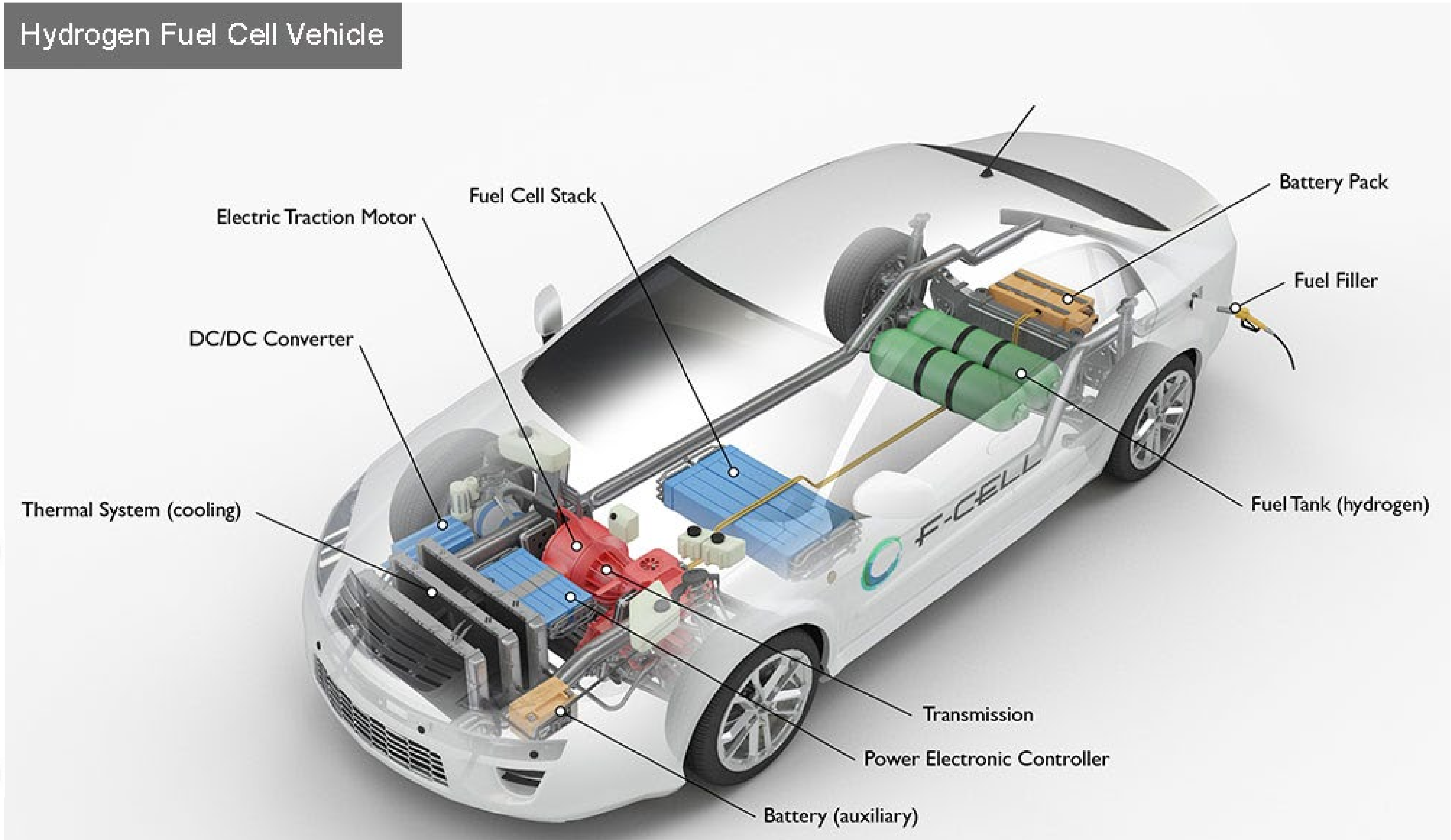
The fuel cell is just one part in the electric power plant driving the vehicle

System components

- Hydrogen supply
- Fuel cell stack
- Air supply
- Hydrogen supply and circulation
- Cooling system
- Hybridization
- Power electronics



https://www.bosch-mobility-solutions.com/en/solutions/powertrain/fuel-cell-electric/fuel-cell-electric-vehicle/

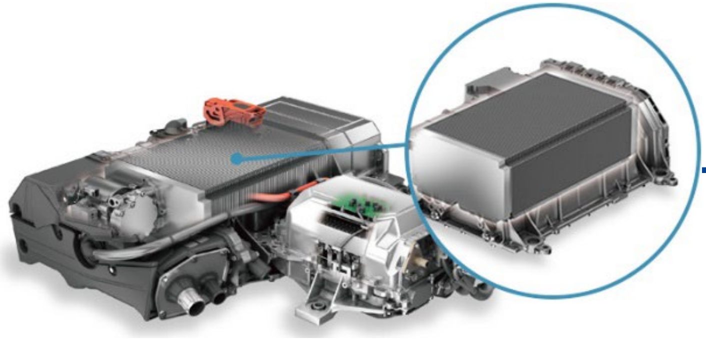


https://afdc.energy.gov/vehicles/how-do-fuel-cell-electric-cars-work

One Fuel Cell System, Many Applications

Take TOYOTA as an example

Stack



light duty vehicle

material handling

Heavy duty vehicle

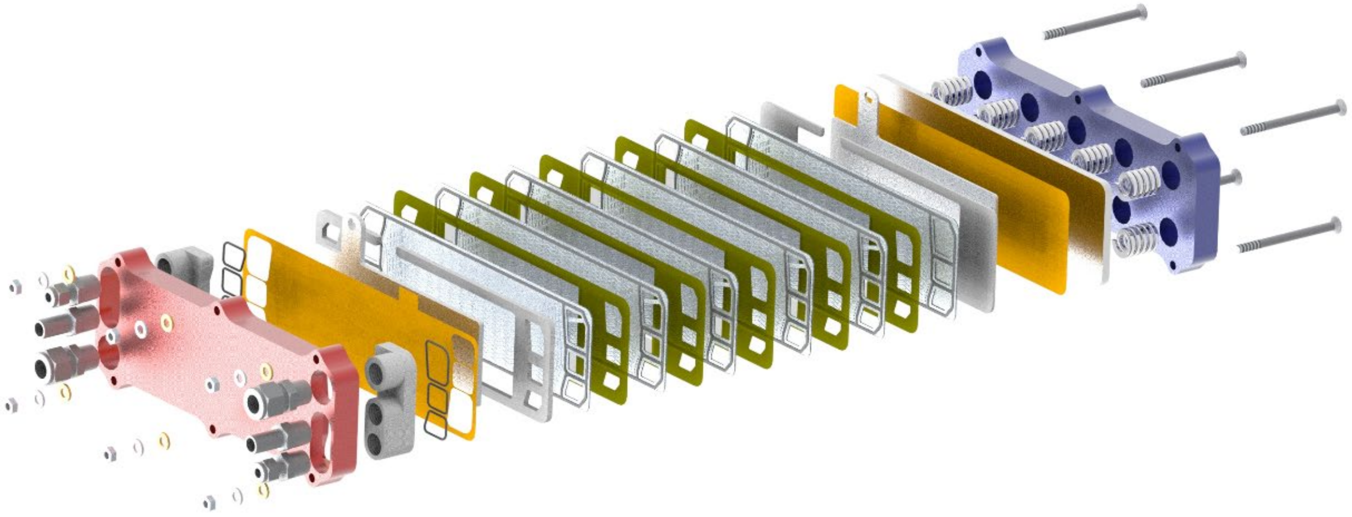
power supply

boats / ships

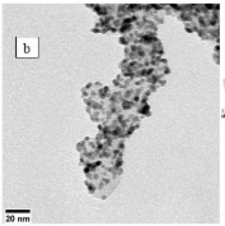
Images: TOYOTA

PEFC Stacks: A lot to be said about, but let’s keep it short

- Materials, Electrodes, MEA
- Visualization of water
- Simulation & Modelling
- Design & Prototyping
- Manufacturing technologies
- Test
- Media quality (hydrogen, air, water)
- System integration

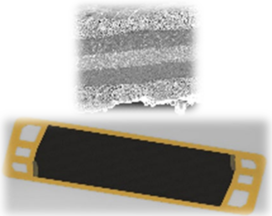


CAD-fuel cell-Stack



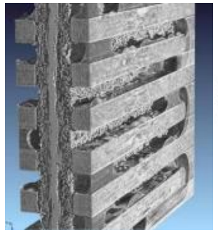
Catalyst

GDL

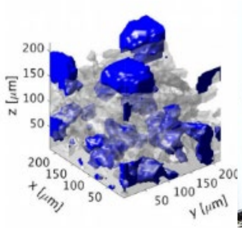


MEA

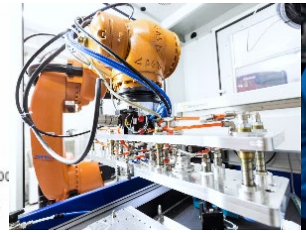
BPP



Imaging



Modelling



Manufacturing

Test

media quality

End of Life Specifications

Shift from light duty vehicles to heavy duty vehicles: increased endurance, reduced power density

EoL Conditions	LDV 2020	LDV 2025	MDV 2021	MDV 2025	HDV 2021	HDV 2025
Power density / mW·cm^{-2}	911	964	518	713	440	644
Cell voltage / V	0.65	0.65	0.7	0.66	0.7	0.66
Total Pt loading / mg·cm^{-2}	0.175	0.125	0.4	0.35	0.4	0.35
Cathode Pt loading / mg·cm^{-2}	0.15	0.1				
ECSA loss over 8 / 25 khrs	69 %	69%	50 %	40 %	60 %	50 %
Coolant exit temperature / °C	92	92	88	94	88	94
Membrane thickness / µm	14	14	20	15	20	15
Gross system power / kW	81	81	191	192	346	348
Net system power	72	72	160	160	275	275
Membrane active area / m^2	8.8	8.4	37	37	78	54
Stack oversizing due to ECSA-loss	24%	24%				

B.D. James, 2021 DOE Hydrogen and Fuel Cells Program Review Presentation

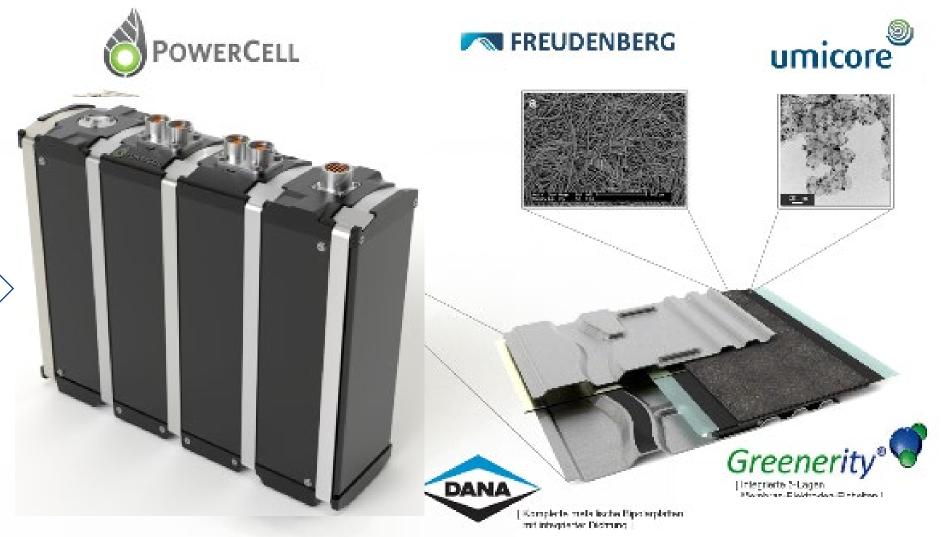
Stack Development: AutoStack-Industrie

OEM Spezifikation

Stack-Design & Integration

Gas diffusion layer

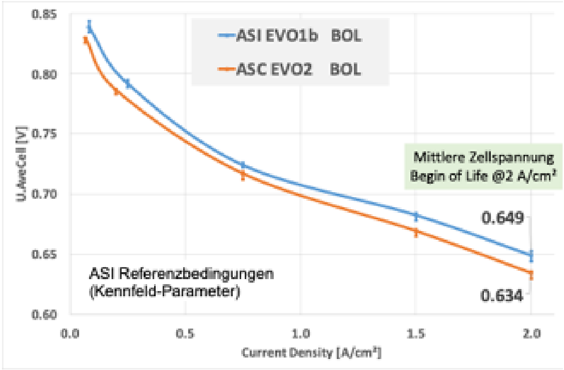
Catalyt



Metallic BPP with integrated beat seal

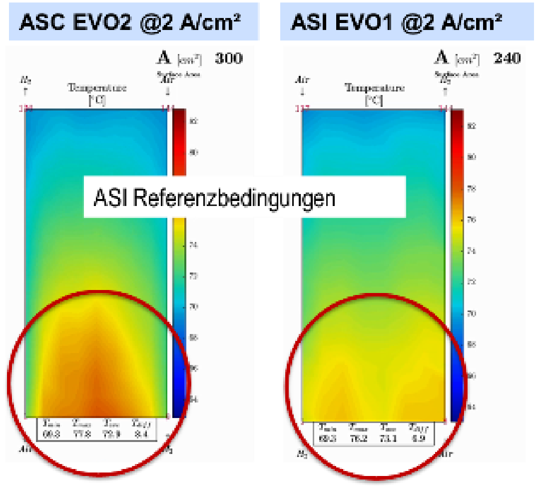
Integrated 7-Layer MEA

Stack Evolution 1:
Reached 4 out of 8 development milestones



Objective:

648 mV @ 2 A·cm^{-2} at BoL achieved



Objective:

Homogenization of Temperature distribution achieved

Modelling, Validation, Stack-Break-In, Test …

Development of (Accelerated) Lifetime Tests for FC-Stacks

Real vehicle data

Accelerated Lifetime Test

Conclusion with respect to endurance possible ?

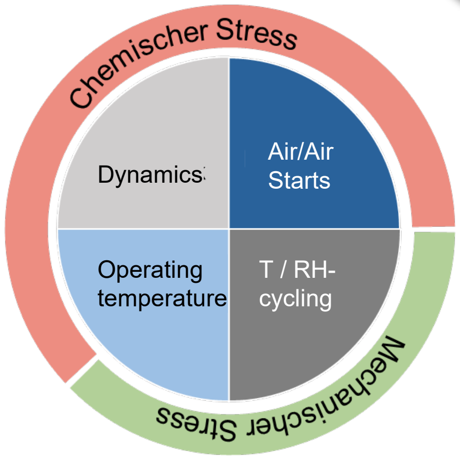
Test profile (close to real vehicle operation?)

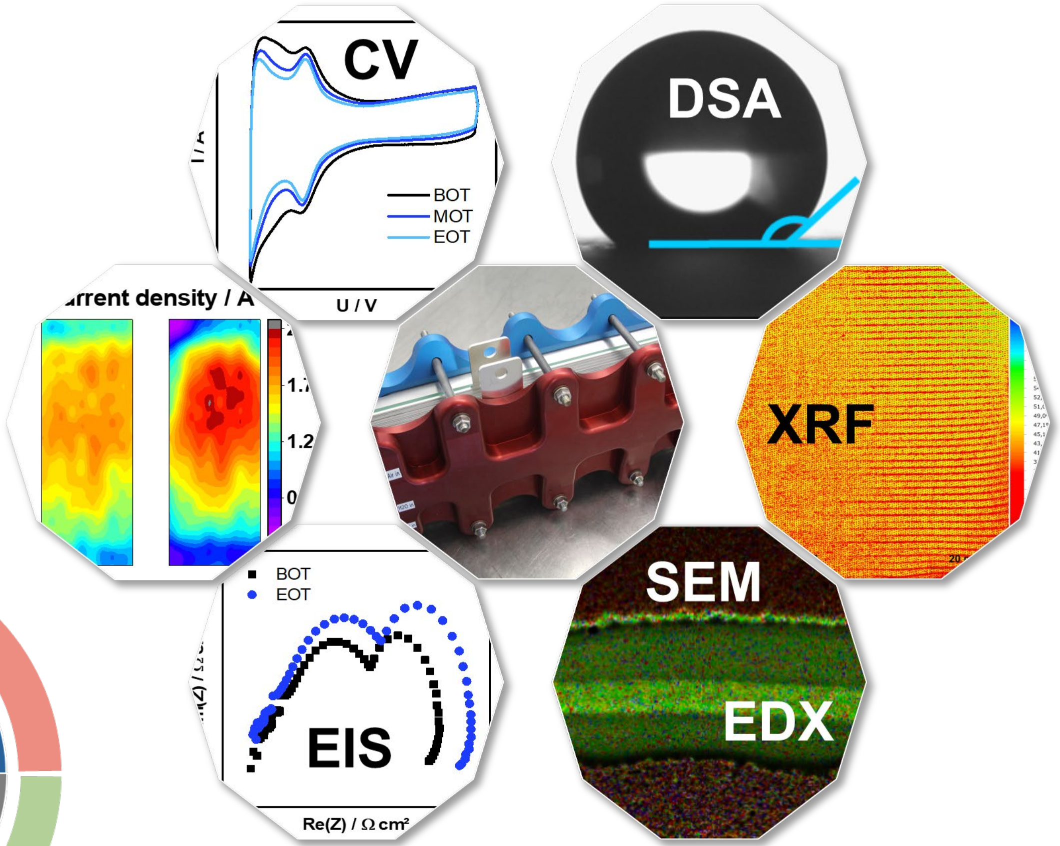
Real ageing mechanism

Endurance testing

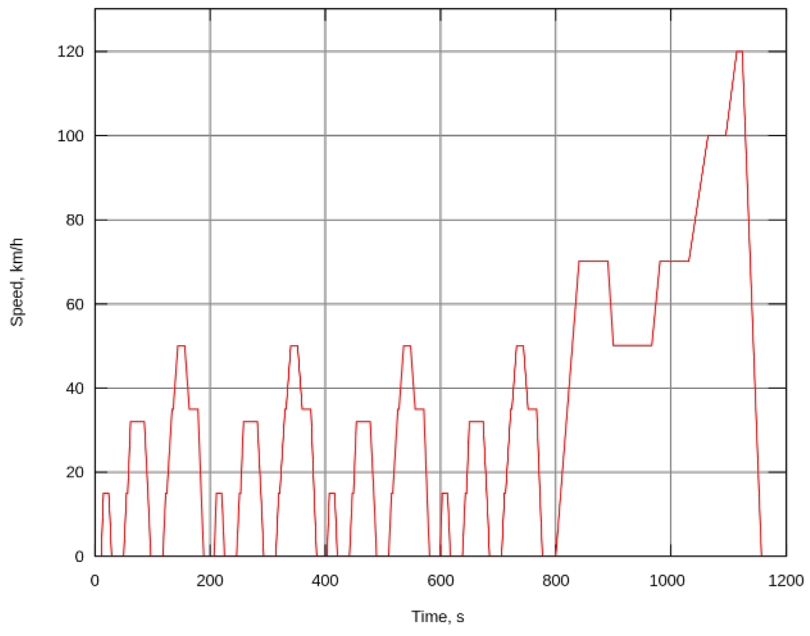
Characterization: Identical Degradation-„footprint“ ?

Identification of dominant stressors within realistic operating conditions

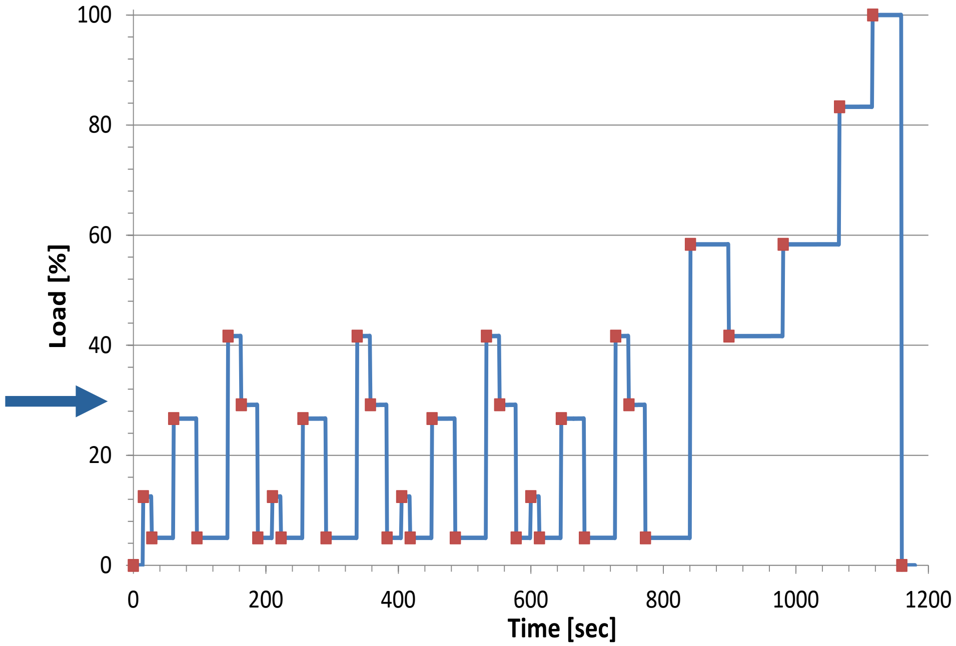




Load cycle: Transfer from drive cycle – FC-DLC



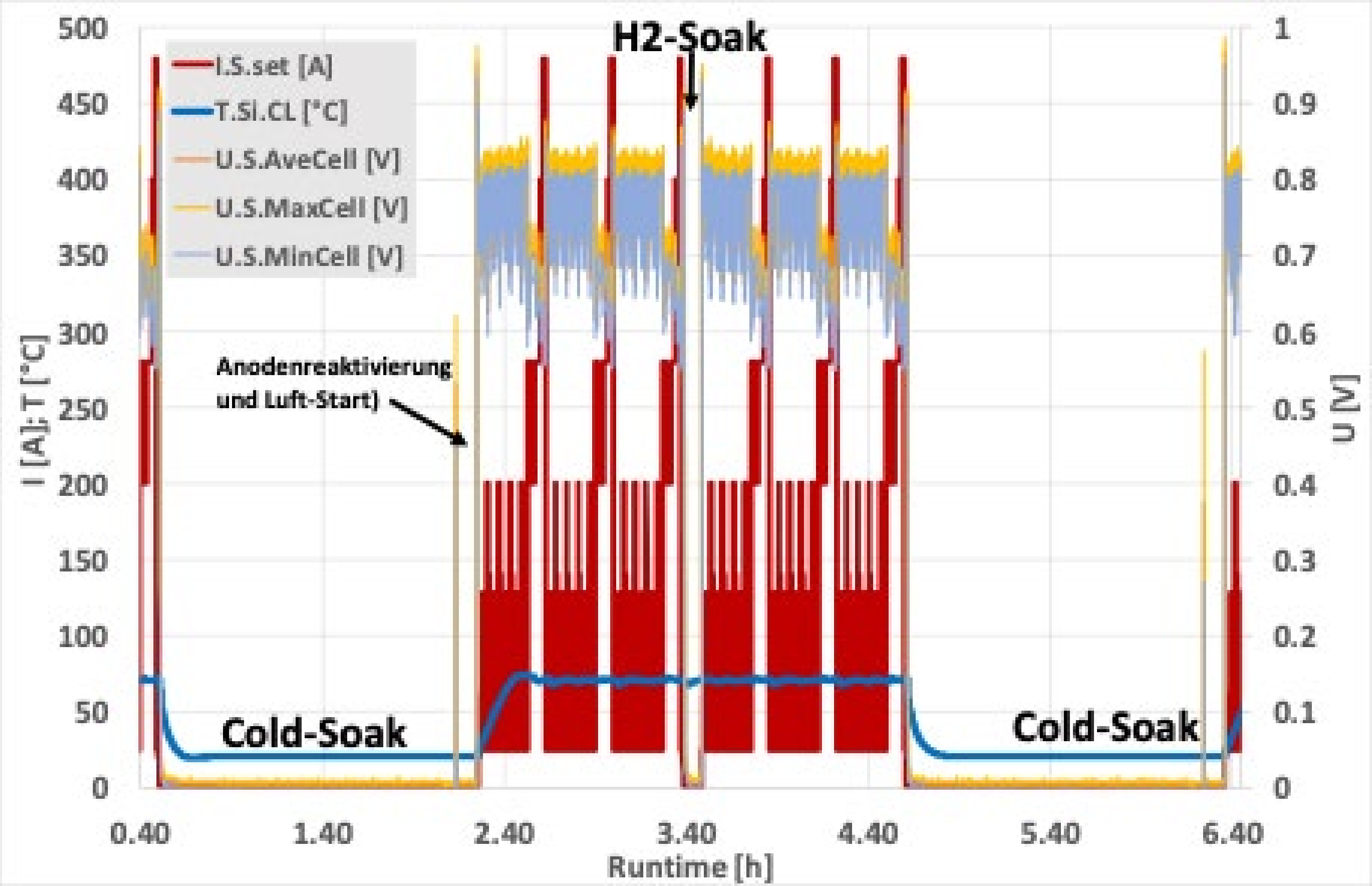
By Orzetto, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=8916963



Fuel Cell Dynamic Load Cycle (FC-DLC) (Version ohne Voltage Clipping). Aus dem STACK-TEST TM D-02: Load Cycling

- Load over time replaces speed over time, acceleration factor: 120 km/h → 100% stack load
- Additional stressor: Comparatively slow speed transients were replaced by steep load transients (requires pre-conditioning)
- Hold time at load levels increased to allow settling of voltage levelss

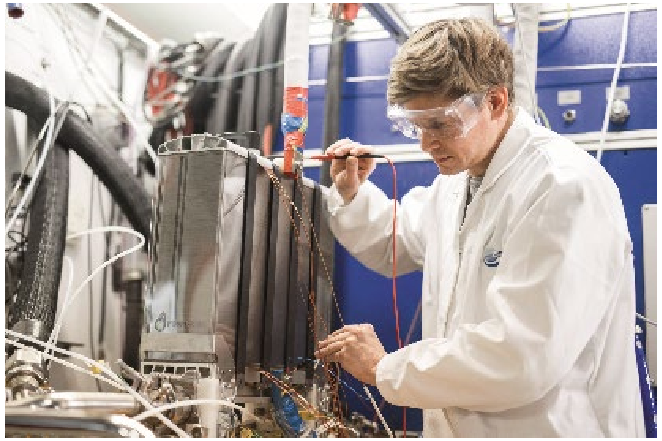
Stack Endurance Testing

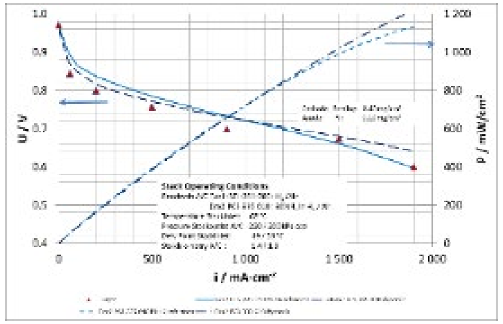


- Simulated dynamic load (drive cycle)
- Large proportion of times of stand still as in real vehicle operation. (thermal stress during cool down and heat up)
- Frequent (provoked) air-air-starts as additional stressors
- Dynamic operation from cold start (Startup)
- Endurance testing takes for ages

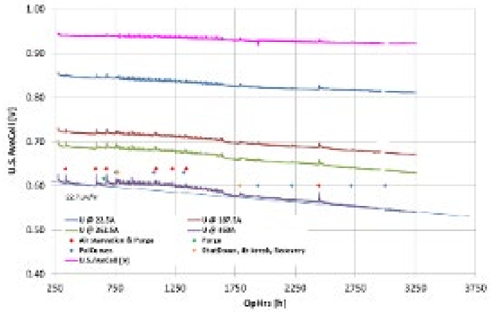
Testing Fuel Cells

- Performance and parameter tests
  - Reaction to operating conditions
  - Determining sensitivities towards variations in operating conditions
- Endurance testing using dynamic load profiles
- Stack robustness (e.g. towards contamination, abuse, etc.)
- Optimization of operating strategies

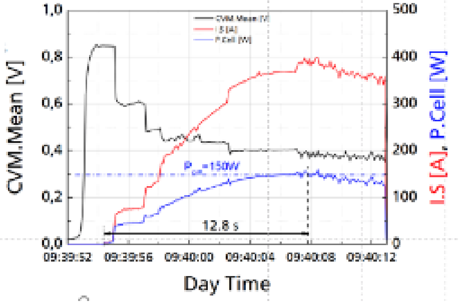




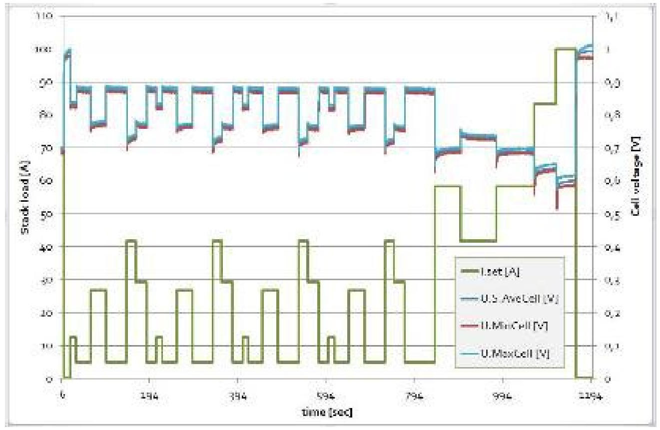
I/V-curves



Endurance testing

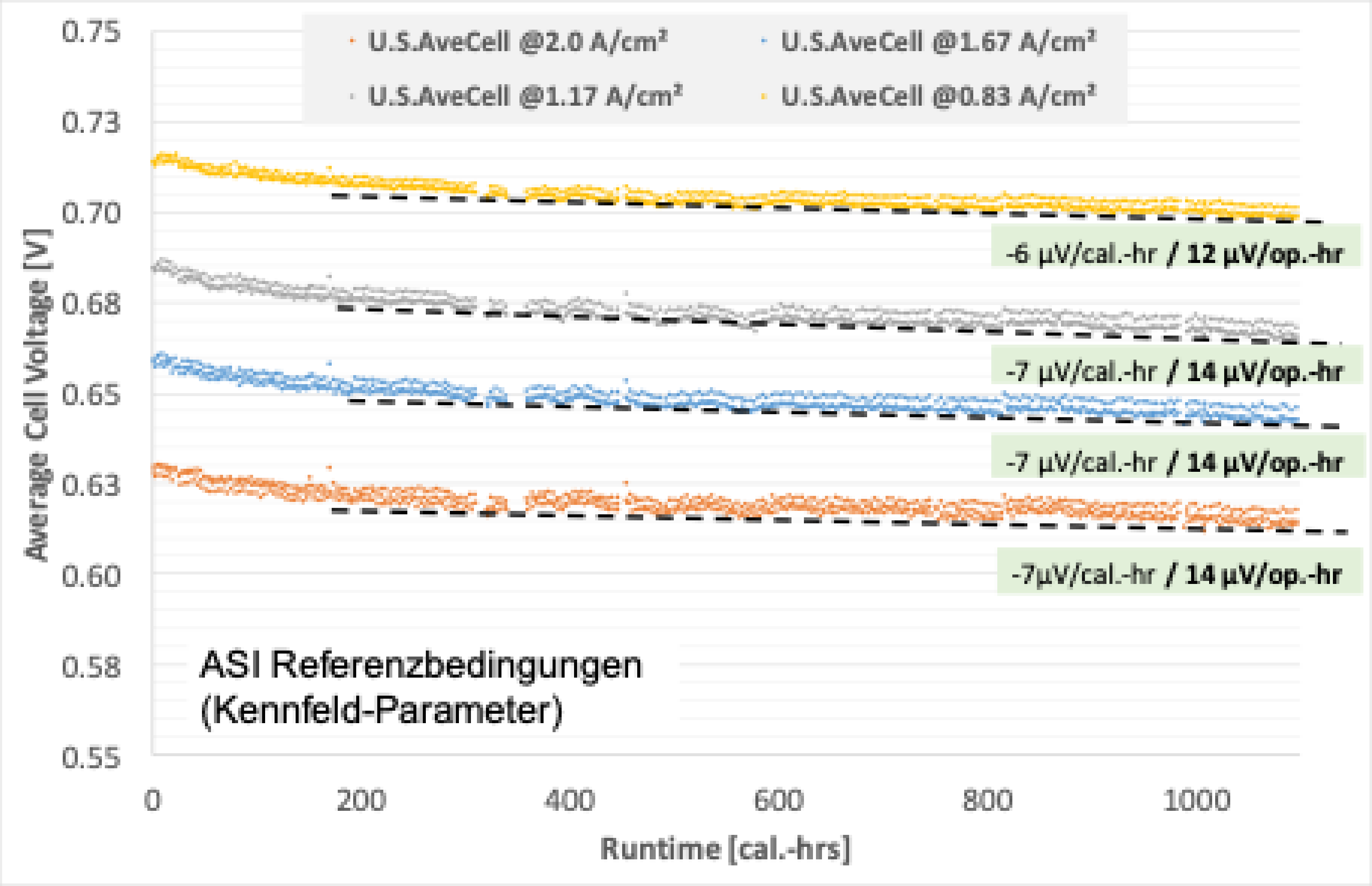


Start-Up behavior



Dynamic testing

Evolution of Cell Voltage Over Time

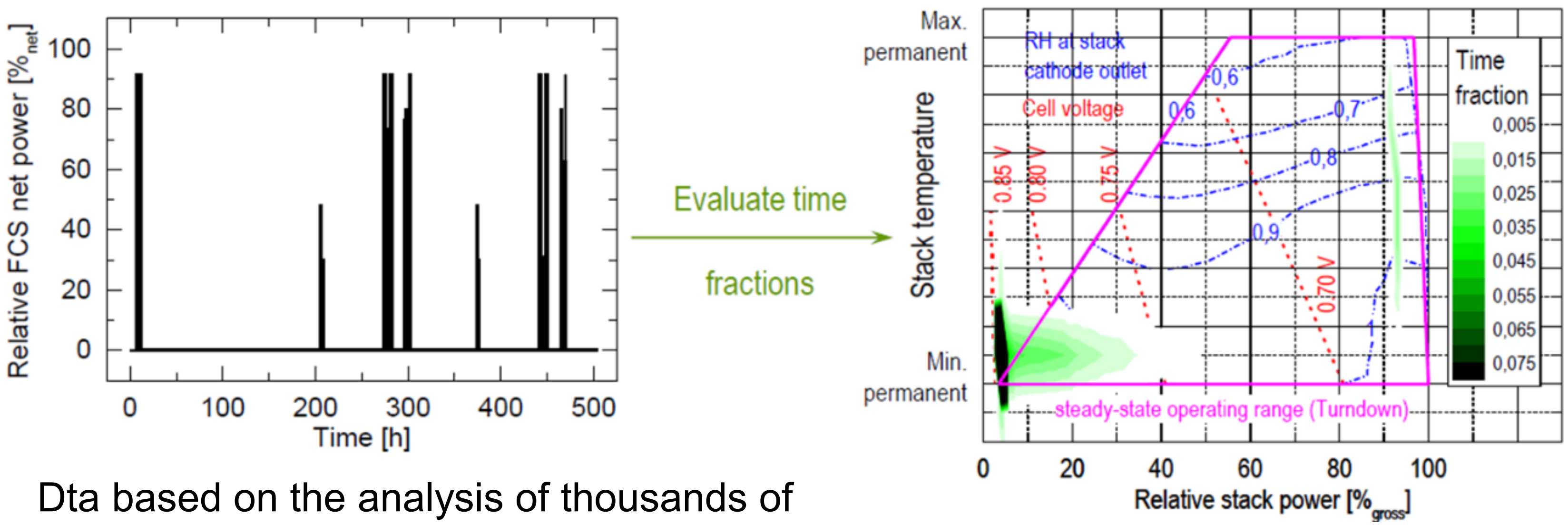


- Simulated dynamic load (drive cycle)
- Plot voltage at a given load over time
  - 1 500 h Test time
  - 750 h under load
  - 300 ai1-air-starts
- Will this carry on?
- Ageing models are needed!
- And many, many more test hours.

Load cycle: Definition from statistical evaluation of vehicle fleet data – ID-FAST

ID-FAST

Proprietary 99% customer profile: **Operating map (Turndown):**



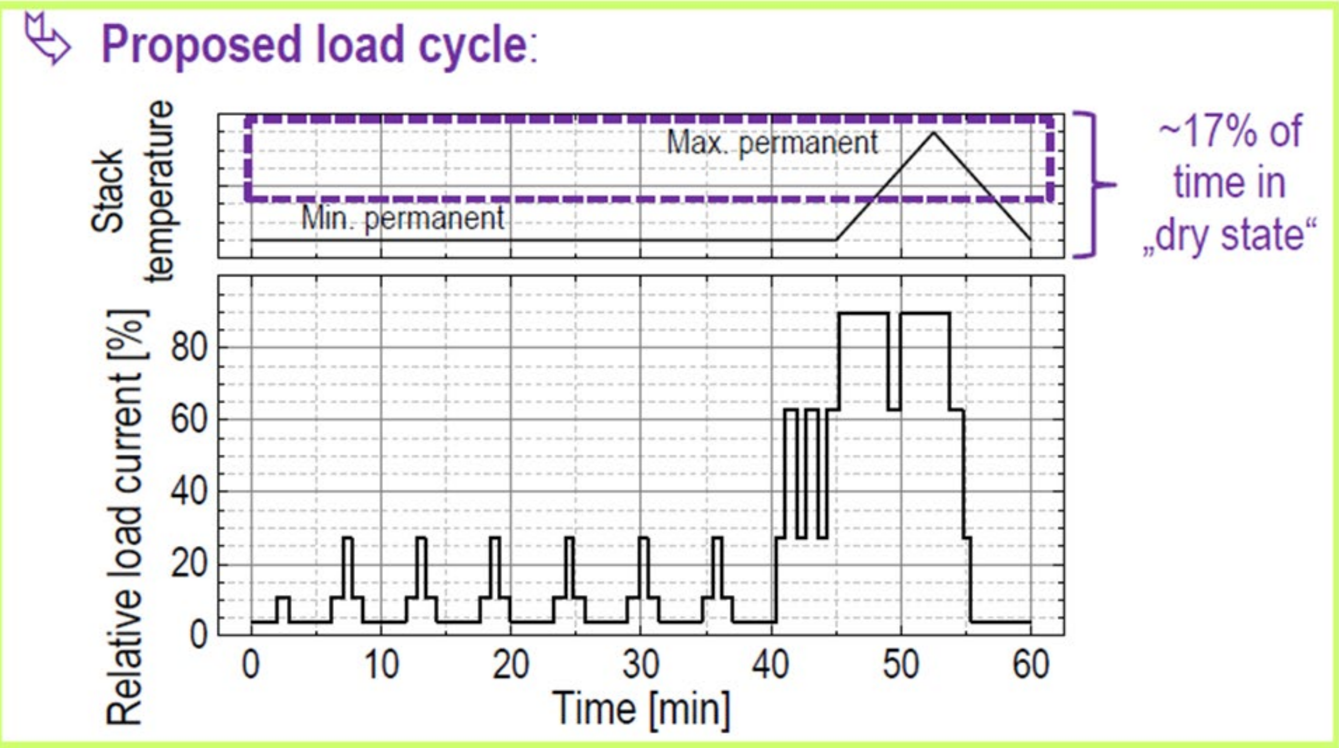
- Dta based on the analysis of thousands of hours of real driving data
- Relevant vehicle model (ICE)
- Translation into current load requirements via modelling of a hybridized vehicle and a fuel vell system

Quelle: Thomas Mittermeier, Bernd Müller et al. (BMW); available as part of a public deliverable report from the ID-FAST project "D4.3–Analysis of coupling between mechanisms and definition of combined ASTs" auf http://www.id-fast.eu.

- Takes fuel cell system operating strategy into account
- Translation into a „Heat Map" of load levels
- Operation states are classified according to cell voltage and humidity at the cathode exhaust

ZSW

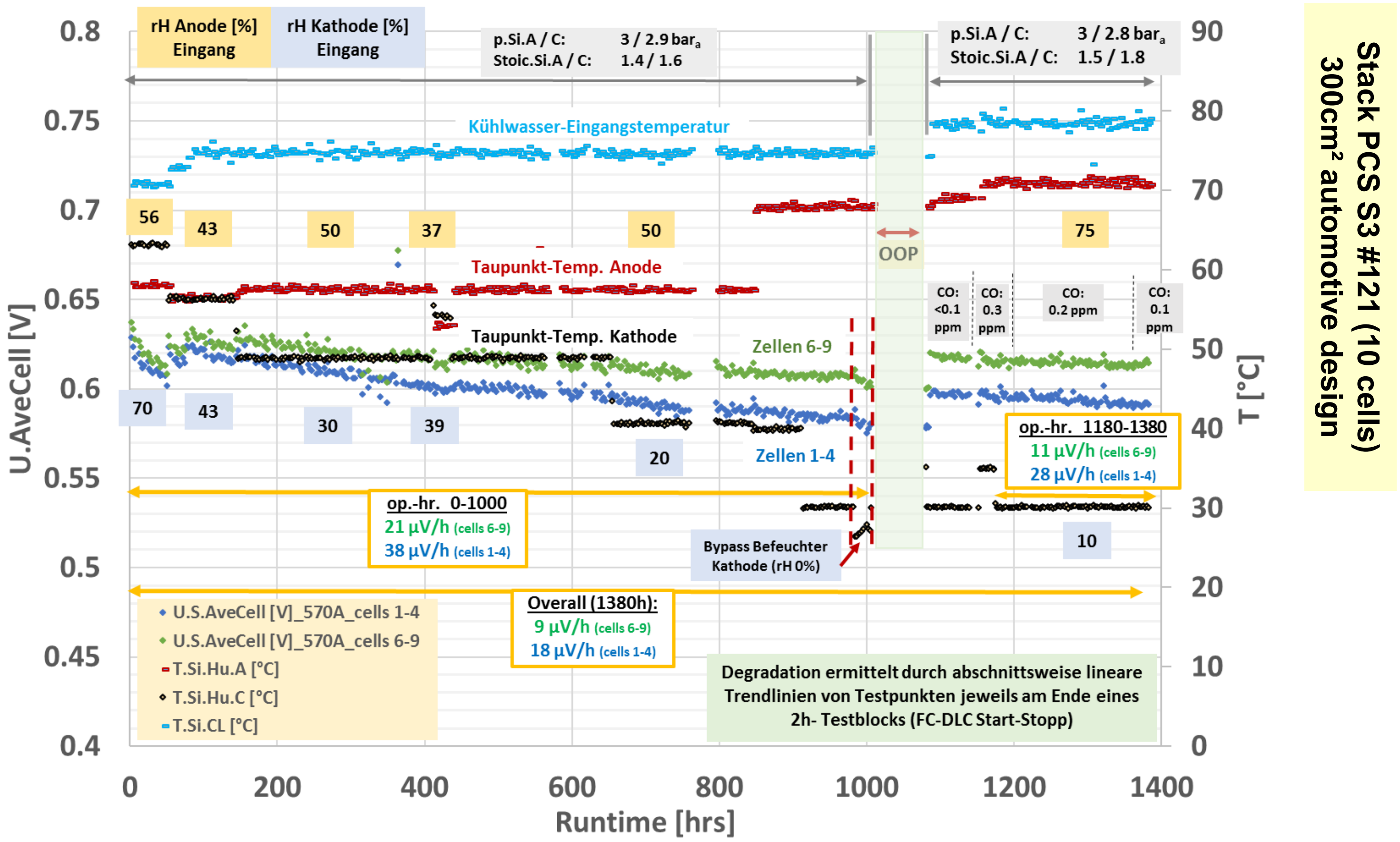
Load cycle: Implementation from statistical evaluation of vehicle fleet data – ID-FAST



From: Thomas Mittermeier, Bernd Müller et al. (BMW); avaiable as part of the public ID-FAST Deliverable Reports "D4.3–Analysis of coupling between mechanisms and definition of combined ASTs" auf http://www.id-fast.eu.

- Tranformation of load requirements into a simplified load cycle not unambiguous such as
  - Sequence of load changes
  - Distribution of phases of identical load
- Temperature and humidity requirements from the heat map were implemented by a temperature and humidity cycle at high current load

Operating conditions: (not exclusively) optimized with respect system efficiency



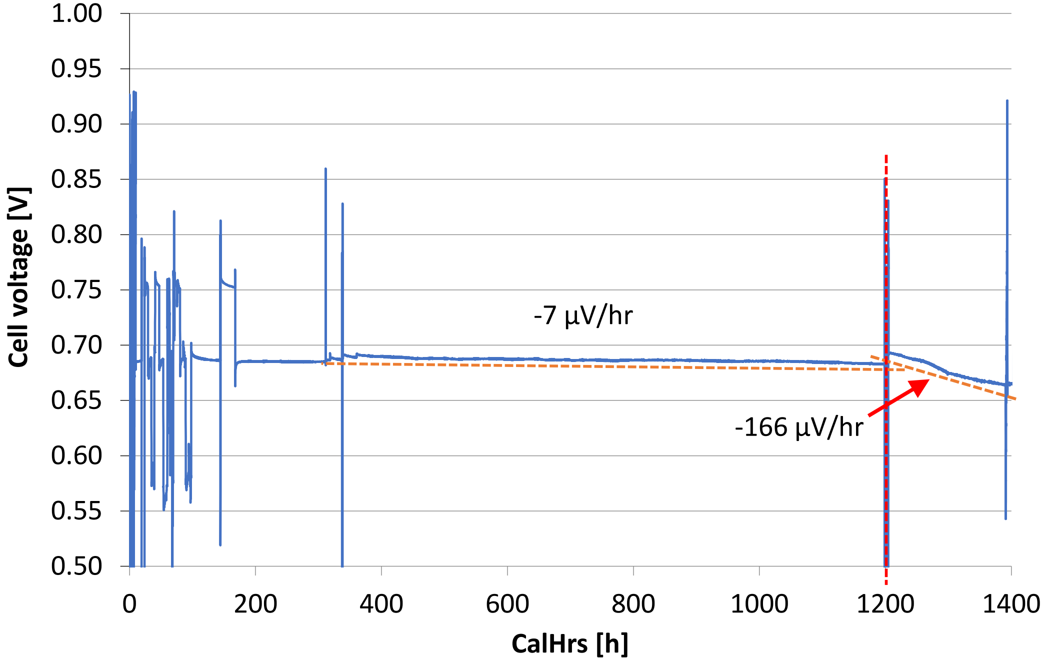
Significant impact of water management on the degradation rate

→ Applicable for this stack design and this MEA only: high anode humidity and low cathode humidity are beneficial to reduce degradation

→ Thin (10µm) – membrane allows for easy water transport and equilibration of humidity

Sometimes Bench Testsing Introduces Additional Complications

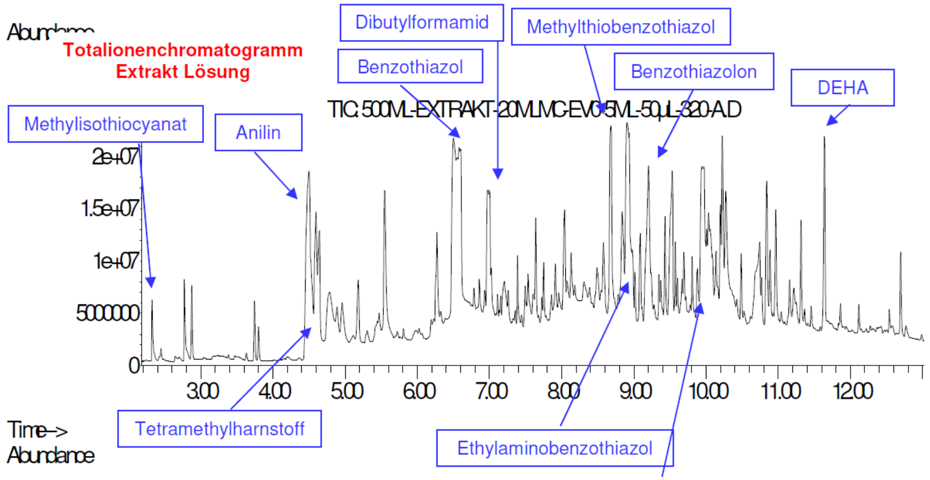
Issues related to water quality in the humidifier



There was a change in the process water supply at approximately 1 200 h testing time (Introduction of an expansion vessel using a polymer membrane)

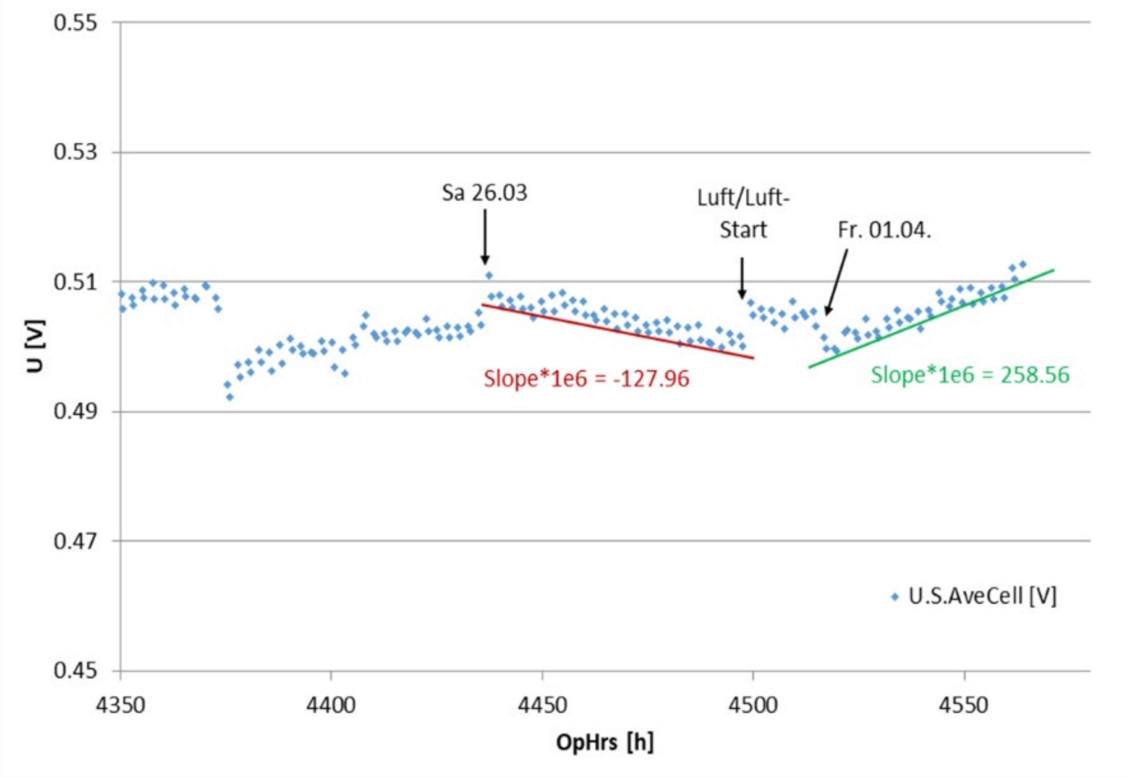
Due to contamination of DI water supply, the degradation rate changed significantly and immediately.

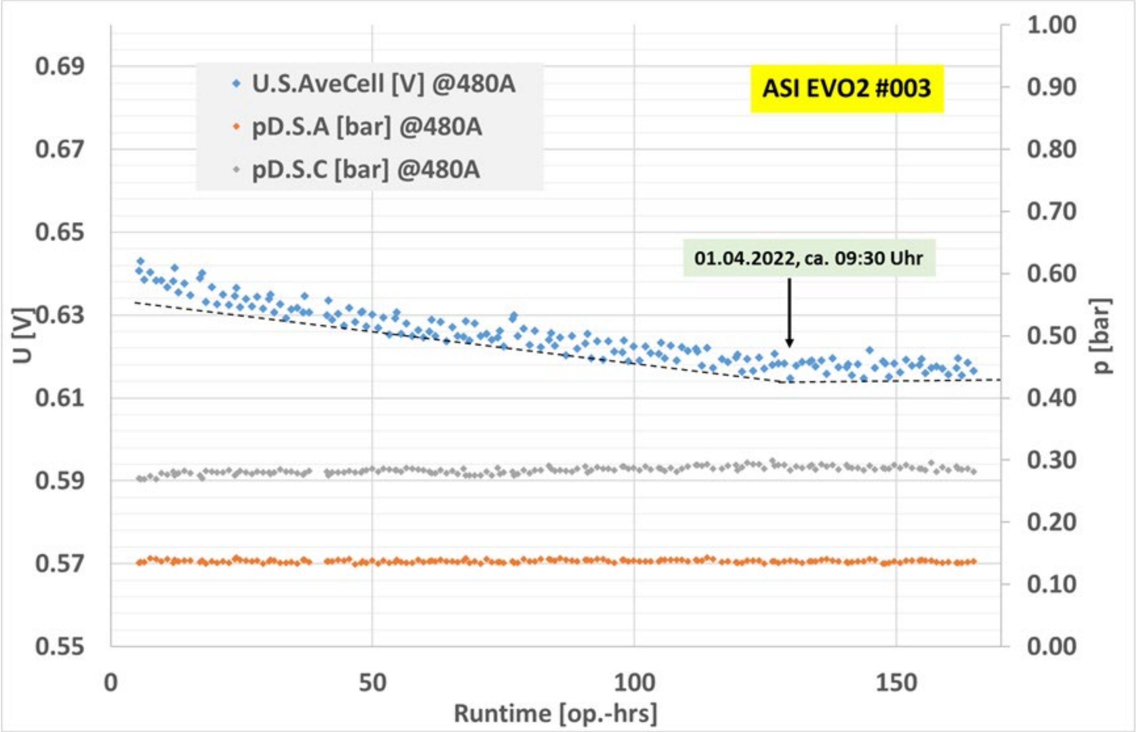
This TIC (Total Ion Chromatogram) shows a bunch of different organic contaminants caused by an EPDM sealing material inside the pure water supply used in the humidifiers.



Fuel cells are Open Systems: Effects of media Quality

Impact of Oil Contamination in Air





- Oil breakthrough into the process air by compressor and filter failure
- Significant impact on the degradation rate
- Voltage recovery dependent on MEA-selection

Summary

25k+ hours durability were show, but the exact „solution“ to long life is not fully understood*

- Fuel Cell specifications are moving targets!
  - Shift from maximizing power density at minimum noble metal loading to maximizing endurance.
  - Durability requirements in form of voltage loss over time shifts from, 12 $\mu V \cdot h^{-1}$ to ~ 2 $\mu V \cdot h^{-1}$.
- Proposed measures:
  - Increased noble metal loading
  - Stabilize Pt-particle distribution and cataly<st supports
  - Use additives to reduce sensitivity to fuel contaminants, cell reversal and radical attack
  - Use thicker membranes
    - Good for uniform thickness los but how about pinhole formation
  - Decrease operating temperature
    - In contrast to heavy duty application providing lower heat rejection area
  - Operate between 0.85 V (catalyst stability) and 0.7 V (efficiency)
  - Oversize stack to compensate for activity losses
  - Adapt operating conditions over lifetime
  - Graphite vs. metallic bipolar plates?

* B.D. James, 2021 DOE Hydrogen and Fuel Cells Program Review Presentation

THANK YOU FOR YOUR KIND ATTENTION!

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Stuttgart

Widderstall

Ulm

Ulm eLaB