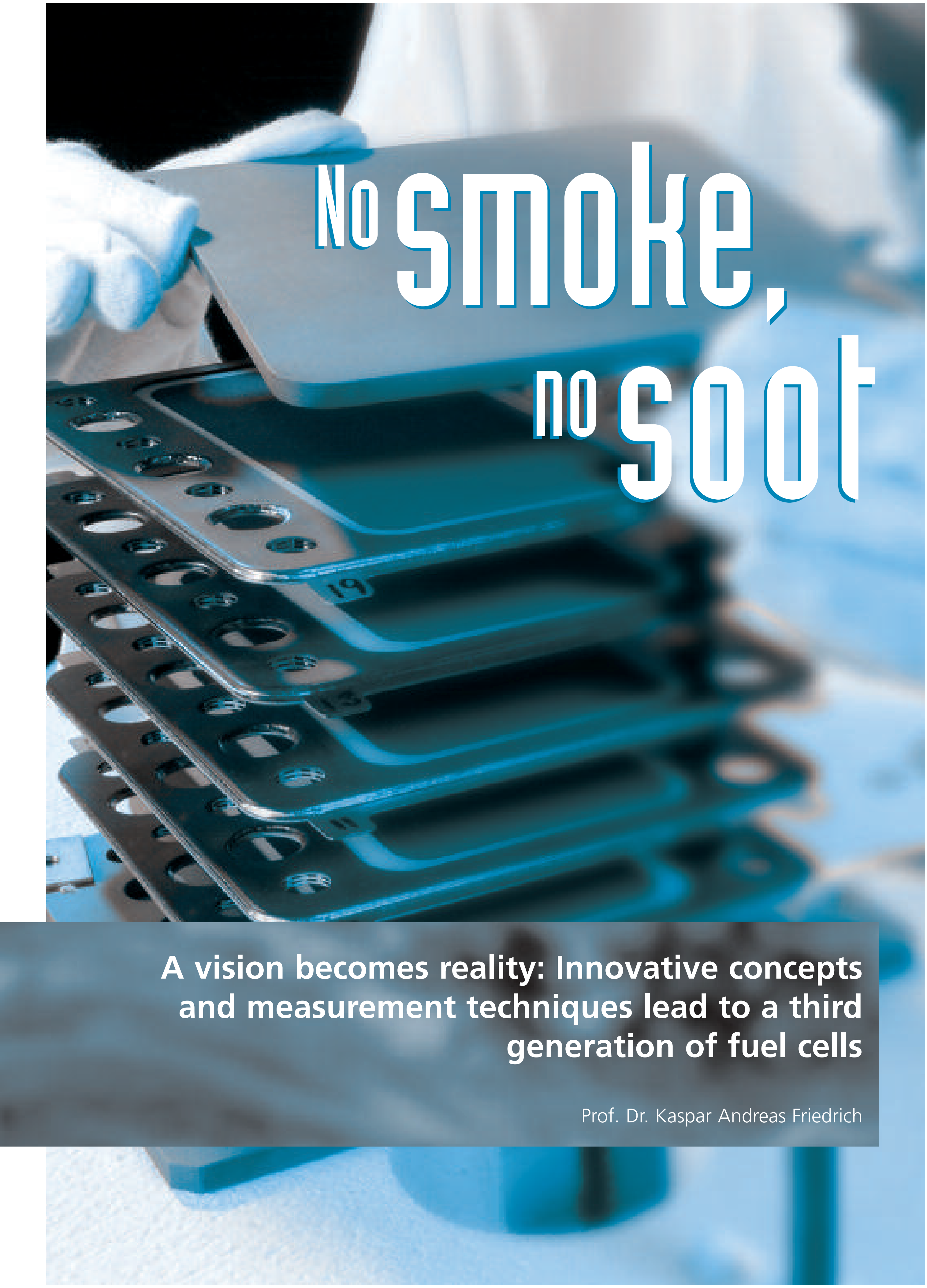


No smoke, no soot

A vision becomes reality: Innovative concepts and measurement techniques lead to a third generation of fuel cells

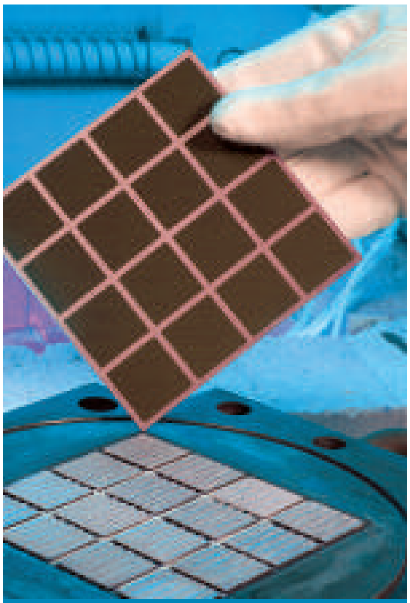
Prof. Dr. Kaspar Andreas Friedrich

"Just imagine how our industries will change! No more smoke, no more soot…" This was the vision of Wilhelm Ostwald, voiced in 1887 when the chemist first learnt of the invention of a "gas voltaic battery" by the physicist Sir William Grove. The technological implementation of his idea – to replace the environmentally harmful combustion process with direct electrochemical energy conversion using fuel cells – wasn't possible at the time. The materials needed simply weren't available yet. Today, electrochemical energy systems based on fuel cells are significantly closer to commercial realisation. But although the required materials are now available, they are still very expensive, which is a serious obstacle in the path of sustainable energy conversion. Fuel cells also have a significant design disadvantage compared to combustion machines: their output depends on active surface area, not on volume. This means a large amount of construction material is needed. However, this can potentially be reduced through innovative cell concepts and more efficient manufacturing methods. Only if a significant cost reduction is achieved fuel cells will be able to meet the high expectations for this technology. Accordingly, scientists at DLR are working on the realisation of cost-efficient high-performance fuel cells.

Plant for plasma-spraying the ceramic layers for fuel cells

Fuel cell systems generate electrical energy and useful heat directly from fuel gases. In most of the current systems, this works by injecting hydrocarbons (e.g. natural gas) or hydrogen (H_2) into one side of the cell, and air into the other. The basic principle behind this process is the electrochemical oxidation of hydrogen and synthesis gas. This generates heat and a direct electrical current (DC), while also producing water and carbon dioxide. Hydrogen and synthesis gas can be won from so-called "fuel processors". These may be based on common energy carriers such as natural gas or crude oil, regenerative energy carriers such as biomass, or solar-generated hydrogen. In the fuel cell itself, the hydrogen or synthesis gas is transformed by porous gas diffusion electrodes. These electrodes are isolated from each other through an electrolyte, which is also used to designate the different types of the fuel cell. DLR is developing two fuel cell technologies: the planar solid oxide fuel cell with an operating temperature of 800 degrees Celsius, and the polymer electrolyte fuel cell with an

Assembling a high-temperature fuel cell cassette



Segmented high-temperature fuel cell

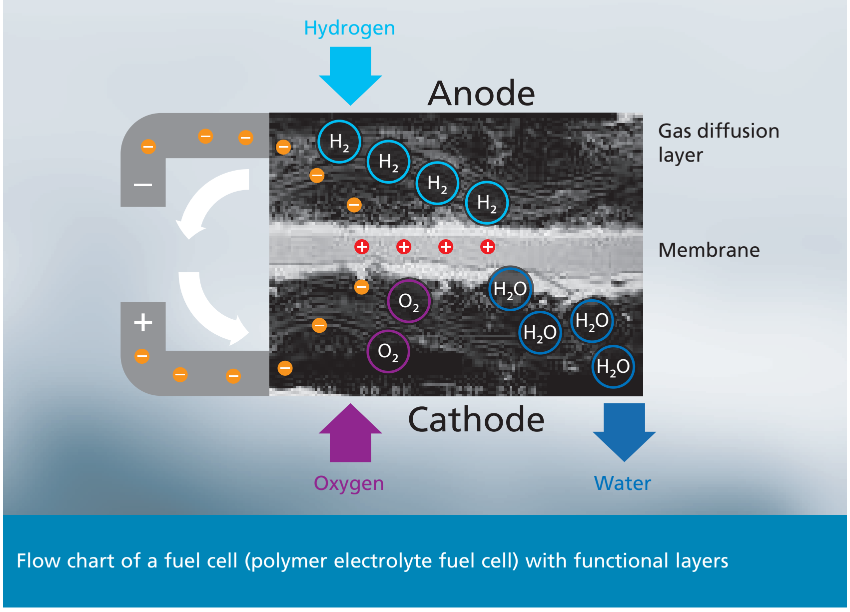
operating temperature of up to 130 °C.

The planar solid oxide fuel cell (SOFC) developed at DLR in Stuttgart is based on microscopically thin electrolyte and electrode layers, which are stacked onto porous metal substrates using plasma spray processing. The porous metal structure on the negative electrode (anode) provides the mechanical support. The total thickness of the membrane electrode assembly (MEA) is only 100–150 micrometres (µm). The thin layer design reduces losses within the cell, lowers the operating temperature to 650-750 °C, and aids the cell's thermal and redox cycling capabilities.

Due to the high thermal loads occurring during both the manufacturing and operation of the cell, the metal support substrate must fulfil a number of strict requirements. As a fully metal SOFC component, it needs to provide not only a porous, gas-permeable structure for supplying fuel to the anode, but also high electrical conductivity and a thermal expansion that matches the electrolyte. Most importantly, it needs to display adequate chemical stability in humid, carbonaceous fuel gas atmospheres.

The DLR plasma-sprayed cells show great potential for cyclic operation involving fast temperature changes and changes of the oxidation state of the cell.

The observed degradation was insignificant for both the thermal cycles



Flow chart of a fuel cell (polymer electrolyte fuel cell) with functional layers

(rapid heating/cooling) and the chemical oxidation with subsequent electrode reduction. The performance decrease for long-term stationary operation is only around 1-2 percent for every 1,000 hours.

DLR is collaborating closely with the companies Plansee SE (substrate development), Sulzer-Metco (thermal spray processes) and ElringKlinger (cassette and stack assembly) on advanced fuel cell development. A very promising new coating technology has recently been developed by Sulzer-Metco, "Low-Pressure Plasma-Spray Thin Film" (LPPS®-TF). This technology permits denser electrolyte layers, which means that the layer thickness can be reduced even further and the cell will work more efficiently.

Another important area of development is the integration of fuel cells into so-called cassettes. A cassette consists of an upper and a lower shell that the cell is soldered or welded into. The cassette's layout is designed for mobile operation in vehicles. The main considerations for mobile suitability are mounting orientation, available space, speed of the heat-up stage, mechanical durability, and component cost. The goal is an industrially viable MSC stack assembly that has an optimised process sequence and can replace existing sealing and contacting concepts which do not fulfil the technical specifications.

For the commercial use of fuel-cell vehicles and stationary systems alike, a higher operating temperature within the fuel cell is advantageous. DLR has been developing high-temperature polymer electrolyte fuel cells for an operating temperature

Fuel cell types:

- **Alkaline Fuel Cell (AFC)**
- **Polymer Electrolyte Fuel Cell (PEFC), Phosphoric Acid Fuel Cell (PAFC)**
- **Molten Carbonate Fuel Cell (MCFC)**
- **Solid Oxide Fuel Cell (SOFC)**
- **Direct Methanol Fuel Cell (DMFC)**

Advantages of fuel cell technology:

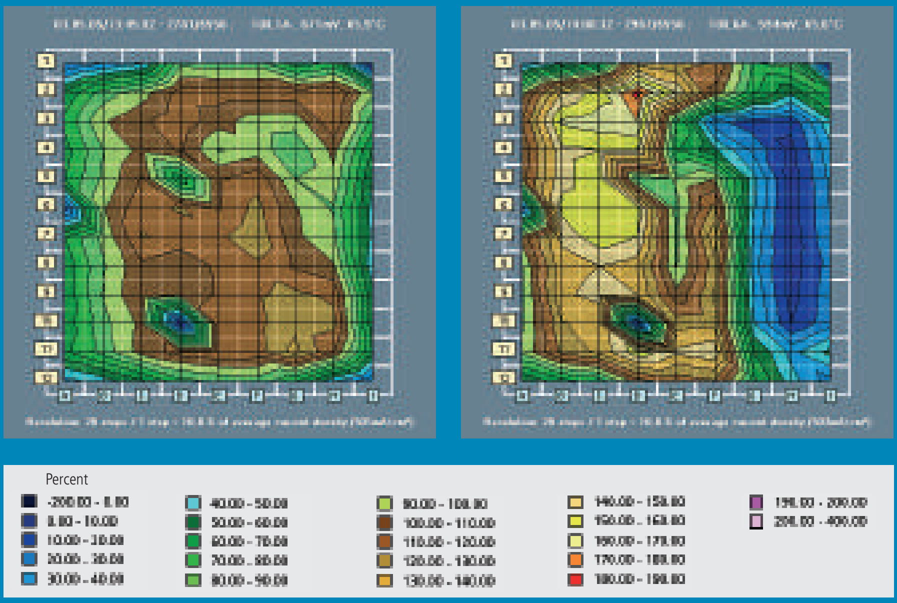
- **Highly efficient generation of electricity; can exceed the efficiency levels of conventional energy conversion technologies, particularly in relatively small-scale systems with outputs ranging from several kilowatts to several megawatts**
- **High efficiency level even for part loads**
- **Low emissions of NO_x, CO and CH_4**
- **Clean exhaust / waste water**
- **Low noise and vibrational interference**
- **Wide dynamic range of electrical output**

SOFC applications:
(750 to 950 °C, hydrocarbons/air)

- **Power-generating heating units**
- **Small power plants**
- **Local combined heat and power systems (also process heat generation)**
- **On-board power supply in cars and trucks**
- **Hybrid power plants: fuel cells plus gas or steam turbines**

PEFC applications:

- **Battery substitute, e.g. for communication devices**
- **Portable power generator**
- **Household energy supply**
- **Local combined heat and power systems**
- **On-board energy supply in aircraft**
- **Propulsion of buses**
- **Propulsion of cars**
- **Submarines, manned space transport**



Current density distribution in a real-world polymer fuel cell (size: 220 cm²) with segmented DLR sensor plates. Left: optimal operation, resulting in homogeneous current density distribution; right: incorrect operation, resulting in inhomogeneous current density distribution

range of minus 30 °C up to plus 130 °C. The low temperature is required for cold starts in winter, whereas the top temperatures may occur in summer when the external temperature is high and a high load is placed on the engine (e.g. on steep roads). The advantages of an extended temperature range are a smaller cooling surface area, lower fuel requirements for powering the vehicle’s cooling fans, easier cold starts and a simpler system structure. The combined effect is a significant reduction in costs.

The biggest technological challenge in extending the fuel cell’s temperature range is to provide sufficient moisture to the membrane while avoiding the formation of water in the electrodes. Also, the cell needs to be able to start at any given environmental temperature and must have a long lifespan. The goal is to develop systems that can provide stable, efficient and dynamic operation for high-temperature PEFCs in automotive as well as stationary applications. This requires innovative new systems and operating strategies that address the operating conditions of a high-temperature fuel

Testing fuel cell systems with variable orientations stack. In current test environments, fuel cells are already being operated at temperatures up to 130 °C while maintaining a low relative gas humidity.

In order to operate a fuel cell system efficiently and reliably even when it is subjected to extreme temperatures, a suitable controller and sensor system is needed. For this purpose, DLR's scientists and technical staff have developed "segmented measurement cells" for measuring local currents. The plates that interconnect the cells are subdivided into a large number of segments and can be measured independently of each other. The local temperature distribution can also measured, as well as other crucial data such as the cells' impedance. Such spatially resolved measurements provide useful insights into aging processes, as well as revealing malfunctions at a very early stage.

In order to minimise the degradation within a fuel cell, it is vital that early recognition is accompanied by a detailed understanding of the causes and sources of the degradation. Only this way can a premature degradation of the cell be prevented. An even spread of the current and voltage across the cell surface has proved to be best for the cell's longevity. DLR was the first to apply this principle to the solid oxide high-temperature fuel cell, and has also extended it to include the local determination of reactant gases.

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The genesis of the fuel cell dates back more than 120 years, when Welsh physicist Sir William Grove (1811-1896) had the idea to generate electricity from hydrogen and oxygen within a voltaic battery. German chemist Wilhelm Ostwald recognised the enormous potential of Grove's invention as early as 1887: "If we possess a galvanic element that can create electricity directly from hydrogen and the oxygen in the air, we are indeed facing a technological milestone against which even the invention of the steam engine must pale. Just imagine how our industries will change! No more smoke, no more soot, no steam engines, not even fire any more..."