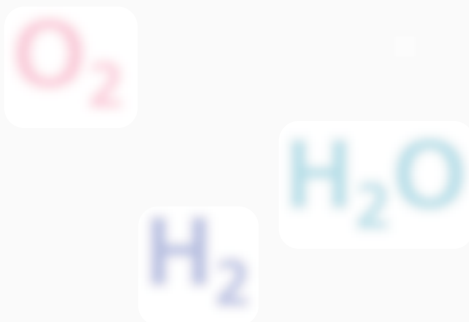
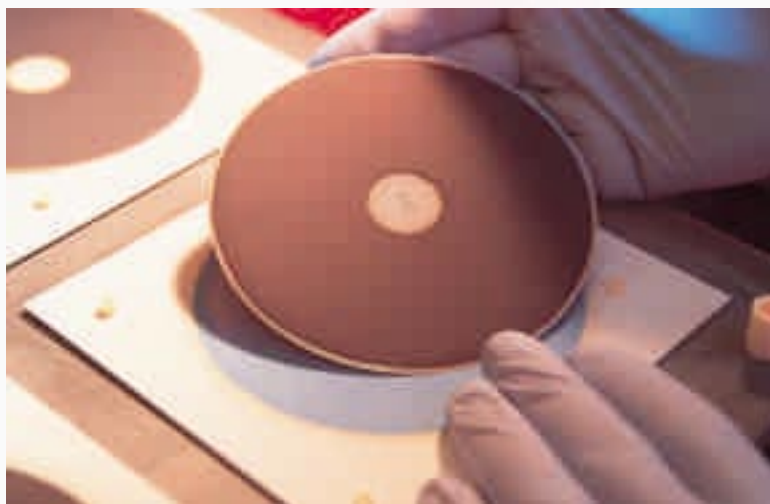


# Hot competition

Fuel cells are regarded as a key technology for generating electricity in the future. Researchers at Bayer subsidiary H.C. Starck are developing materials and components for a specific type: the high-temperature solid oxide fuel cell (SOFC). The advantage of the SOFC is that it not only generates electricity, but also produces waste heat suitable for heating entire homes.

Katja Seimert oversees spray-drying of the raw materials for the cathode powder.

Cast ceramic films are an important part of a fuel cell and they are sintered at temperatures of up to 1,500 °C.



In the hydrogen-powered world of the future, absolutely nothing will work without a fuel cell. Mobile phones, laptops and camcorders won't need new batteries anymore, but rather hydrogen cartridges. Driven by hydrogen ( $H_2$ ), cars will purr softly down the roads without polluting the air. Automobile heating and air conditioning will also be powered by hydrogen. In basements, highly efficient fuel-cell heating systems will simultaneously generate electricity and heat.

But at present, all of these things are still just a bold vision. Only very few hydrogen "gas stations" exist around the world today, and cartridge sales are flourishing more with  $CO_2$  for home-made carbonated sodas than with  $H_2$ . Nonetheless, although the infrastructure required to supply the fuel of the future is still in its infancy, the "power generators" that use it are soon to go into production. The Dutch company InDEC, a spin-off of the renowned ECN energy research institute with headquarters on the northern coast of Holland, manufactures ceramic fuel cell components for power generation systems of this kind.

These ceramic fuel cell components aren't much to look at. Some types resemble a typical CD: round and flat with a hole in the middle. The disks aren't even shiny, covered instead in a rather plain blackish-green. Square and rectangular components also exist, depending on the application. More spectacular are the interior workings of the cells. "An incredible amount

of know-how is packed into this thin disk," reports InDEC managing director Alexander Michaelis. Since April 2003, Bayer subsidiary H.C. Starck has been a majority shareholder of InDEC B.V., the first company to sell the hottest of all fuel cells - the solid oxide fuel cell or "SOFC" - on the open market. Many experts are of the opinion that, along with the polymer electrolyte membrane fuel cell (PEM), the SOFC has the greatest potential. The main difference between these two most important types is their operating temperature. In the PEM, it is in the region of 80 °C, while the SOFC operates at between 700 and 1,000 °C.

Because of its low operating temperature, the PEM is more suitable for small, portable systems such as laptops and camcorders, where it is intended to replace today's batteries. PEM fuel cells are also the predominant power suppliers for electric motors in the first hydrogen cars.

### The fuel cell as an ecological power generator

However, in situations where the thermal energy produced can be utilized in addition to the electricity, the SOFC has decisive advantages: the hot waste gases it produces can be used in power plants to generate additional electricity by driving a turbine. The efficiency of a fuel cell power plant of this kind significantly increases as a result. Fuel cell heating units designed to

meet household electricity and heating demands are currently being developed with both PEM and SOFC cells. For example, Swiss fuel cell manufacturer Sulzer Hexis is teaming up with several European power companies to test over 100 SOFC systems in practice. A major advantage of the SOFC is that it's not very particular when it comes to fuel. It runs not only on pure hydrogen, but also on conventional hydrocarbons, such as natural gas, biogas and gasoline. Although the greenhouse gas  $CO_2$  is produced in the process, it makes sense to operate fuel cells with fossil raw materials, because the cells utilize a higher per-

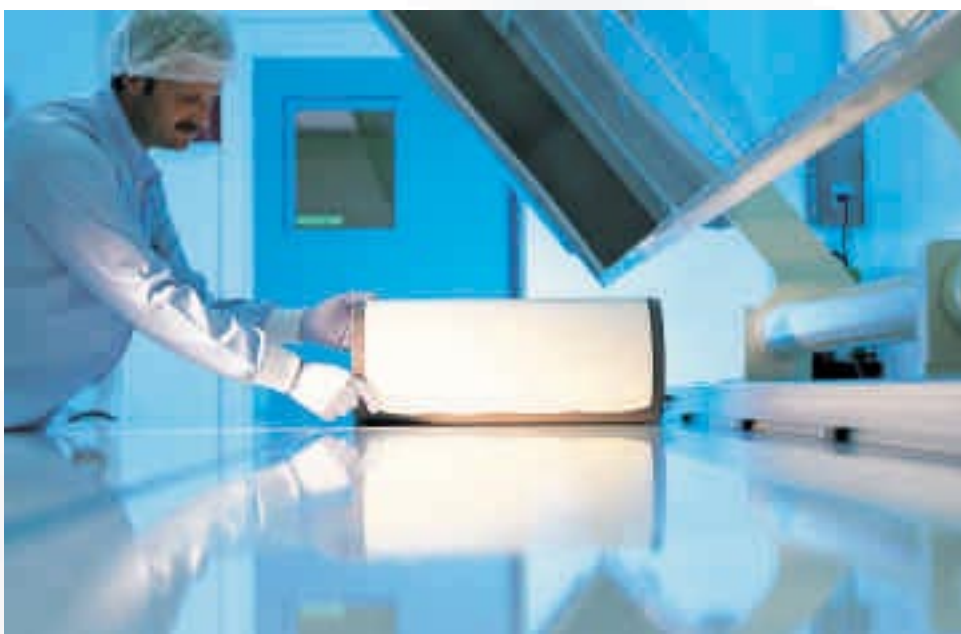
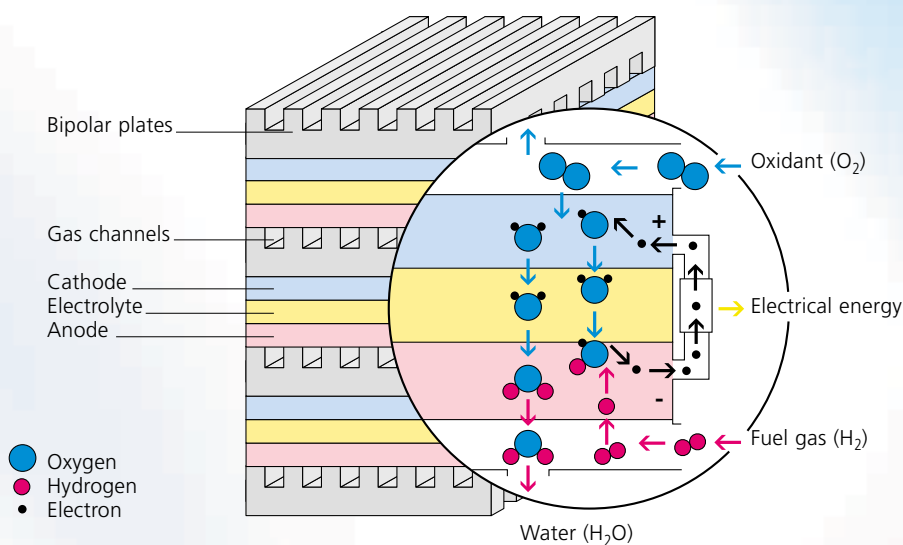
#### Power counts

The power output of a fuel cell may be well above five megawatts (MW) in the future. Depending on the required output category, either the PEM cell or the SOFC is more suitable. Both types can be used for some applications.

Power output	Field of application	Fuel cell type
100 – 500 W	Portable systems	PEM
1 kW – 5 kW	Decentralized power generation	SOFC, PEM
4 – 7 kW	Auxiliary power unit in cars	SOFC (PEM)
20 – 300 kW	Motor vehicles	PEM (SOFC)
100 kW – 5 MW	Decentralized power generation	SOFC
> 5 MW	Stationary power generation	SOFC

### Working principle of the fuel cell

A fuel cell works like a battery: it converts chemical energy into electrical energy. Ideally, fuel cells “burn” the supplied hydrogen together with oxygen to form water. The two gases are separated by an electrolyte. The hydrogen releases electrons at the anode, while the oxygen captures them at the cathode. In the case of the solid oxide fuel cell, the electrolyte between anode and cathode allows oxygen ions to pass through, which then combine with hydrogen ions on the anode side to form water. Power can be drawn from the electric voltage occurring between the anode and the cathode.



Working in a clean-room environment, Martin Bais unrolls the ceramic film after the casting process.



Physicist Dr. Alexander Michaelis with an anode for SOFC fuel cells.



Mineralogist Dr. Evelyn Pross develops methods for manufacturing ceramic powders.

centage of the energy bound in these fuels than was previously possible, and therefore contribute to climate protection even if they aren't run on hydrogen. Thus, the SOFC could become a kind of link between the fossil energy economy and hydrogen technology – as long as clean hydrogen is not yet generated in sufficient quantities from regenerative sources, the SOFC can be operated on other fuels.

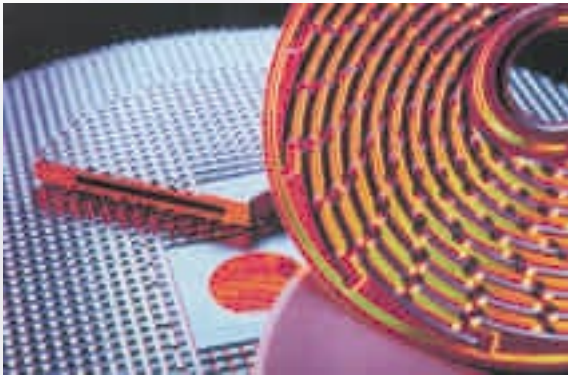
In the reformation stage, the fuel gas is broken down into hydrogen and carbon monoxide. Even the thermal energy from carbon monoxide, which is not consumed in generating electricity, can be put to use when burned in the hot stream of waste gas to form carbon dioxide. In contrast, using other fuels

in PEM cells is more complicated. Because they operate at low temperatures, PEM fuel cells require a platinum catalyst to break down the hydrogen into ions and electrons. Platinum is not only expensive, but also incapable of tolerating any contamination. If a PEM is operated on natural gas, a small chemical processor known as a reformer must be installed upstream, where the natural gas is mixed with water vapor and broken down at high temperatures, just like in the SOFC. The disadvantage of this method is that processing in the reformer consumes a portion of the energy generated by the natural gas. Therefore, the efficiency of low-temperature fuel cells is considerably lower than that of high-temperature fuel cells. Moreover, in order to prevent the resulting carbon monoxide from destroying the catalyst, it must be oxidized in a complex process to form carbon dioxide before the reformate gas reaches the fuel cell.

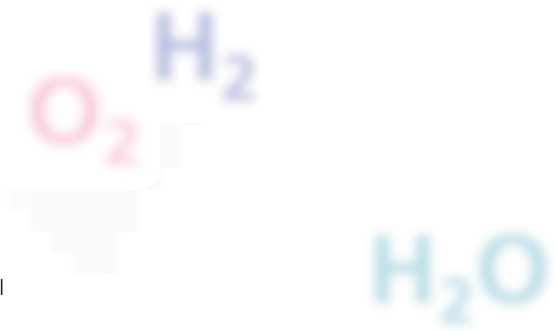
### High efficiency helps cars save gas

For this reason, Alexander Michaelis is optimistic that the SOFC will still be in demand in the hydrogen age: “Once the SOFC is fully developed, it will always be more cost-effective than the PEM because of the cheaper materials it contains.”

Even though many automotive manufacturers favor the “cool” PEM to power cars, the SOFC still might find its way onto the roads in the near future.



The metal disks from Sulzer Hexis establish electrical contact between the poles and direct the flow of reaction gases.



A number of automotive manufacturers and suppliers are working together with H.C. Starck and other partners on an auxiliary power unit for cars, or APU for short. Its purpose is to handle the steadily rising need for electricity in cars, which the standard 12 volt batteries can barely satisfy anymore. The electricity consumed by energy-guzzlers like air conditioning, heated seats, ABS and power steering is currently produced by the alternator, which is driven by the engine. Repeated conversion from one form of energy to another is highly inefficient and limits engine performance.

Conventional alternators exploit only five percent of the energy bound in the fuel. The remainder is expelled unused in the exhaust. SOFC fuel cells could solve this problem: because solid oxide fuel cells can run on conventional fuels such as gasoline and diesel, they can be used to drive the APU. The electrical power will then be generated electrochemically directly from the fuel. Initially, efficiency rates should be significantly higher than 30 percent and could increase later on to over 50 percent. At this level, efficiency would be ten times higher than with an alternator, which would not only help save fuel, but also allow automotive manufacturers to design entirely new engine concepts. With a fuel cell APU, for example, electrical power can be produced independently of the engine. Campers, trucks, construction vehicles and boats could also benefit from an APU of this kind.

Development of the solid oxide fuel cell also requires special know-how in the field of material science. One reason is the sophisticated ceramic-metal sandwich materials used in the SOFC. These various materials must be carefully adapted to one another in order to ensure a long service life for the cells and cell stacks.

#### Full-scale production with exotic powders and precious metals

At H.C. Starck, ceramics and metals are familiar terrain. Headquartered in Goslar, Germany, the company specializes in the processing of ceramics and special metals. These materials play a role in applications such as high-temperature furnaces and heating systems, meaning that the company's experience can now be transferred to the SOFC.

For a long time, many of the companies using SOFC systems also manufactured their own cells, because the ceramic components could not be purchased as finished articles. Now that H.C. Starck and InDEC have closed this gap, Alexander Michaelis hopes users will choose to abandon their complex ceramic manufacturing operations and concentrate on installation of the cell stacks in their products. "This new division of labor should drive the overall technological development of SOFC systems ahead," explains Michaelis, who is head of New Products and Methods at H.C. Starck in addition to his job at InDEC. He wants to expand



SOFC pilot production at InDEC to full-scale serial production by 2006.

Quite an ambitious task, considering that the manufacture of solid oxide fuel cells is more or less still a handicraft. It begins with the raw materials for the anode, cathode and electrolyte. The exotic metal oxides from which the three most important layers of the cell are made are compounds of oxygen and rare metals, such as lanthanum, yttrium, strontium and cerium, as well as the more common metals chromium, cobalt, manganese and nickel for the anode. Scientists have numerous methods on hand for converting these compounds into fine, homogeneous powders. However, several of them only function at laboratory scale, others

Jos van Vliet checks the homogeneity of the cast ceramic film (sintering furnaces are visible in the background).

## From a powder to the finished cell

In the labs at InDEC, fuel cells are manufactured in accordance with high quality standards. "The cells are continuously being improved in cooperation with the Dutch ECN Institute in order to meet the needs of our customers," says production manager Rolf Huiberts. Small defects in the material take their toll immediately, such as when the electrolyte goes into the furnace for sintering. During this process, it



The raw material zirconium oxide is used in the anode of a fuel cell.

shrinks by a fifth. If the workmanship was sloppy, cracks and deformation occur. Recently, Huiberts and his colleagues succeeded in making a square cell with an edge length of 20 centimeters that generates four times more output than the previous round versions offering 20 watts. Combining individual cells results in systems with greater output. For example, Sulzer Hexis stacks as many cells as are necessary to yield a total output of 1,000 watts for its home energy system.

The next goal is to manufacture cells with an edge length of 30 centimeters. "They could be used to build systems with a higher output," says Huiberts. Such systems could power a multi-family home, for example. In periods of higher demand, additional electricity is drawn from the grid, while it is fed back in the rest of the time.

produce poisonous waste products, and most are simply too expensive for mass production.

A team headed by mineralogist Dr. Evelyn Pross at the H.C. Starck plant in Laufenburg, Germany, is working on a method for producing suitable powders in the most cost-effective manner possible. "The materials really have to be multi-talented in view of all the functions they perform in a cell," says Pross, explaining her difficult task. "The anode and cathode have to be gas-permeable and simultaneously conduct electricity effectively. They must also be capable of breaking down hydrogen and oxygen catalytically, but must not react chemically with the respective gas." In addition, there must be no reaction with the

electrolyte material, and all three layers should expand at the same rate when heated.

### The right mix of metal oxide powder is the key

Pross and her colleagues have already developed a suitable powder for the cathode material. Based on a relatively simple and environmentally friendly process, they succeeded in producing a lanthanum-strontium-manganese oxide powder comprising particles of uniform size, in which the precise ratio between the three metal oxide powders is reproducible. Together with researchers at Karlsruhe University, the engineers at H.C. Starck found that their cathode material has very good

electrical properties and survives the repeated heating and cooling fuel cells have to withstand in systems like the APU.

The people at H.C. Starck are also working on the anode material. It is usually a mixture of metal and ceramic, or what is known as a "cermet", and consists of nickel and zirconium oxide. The electrolyte – the heart of a fuel cell – is made of yttrium-doped zirconium oxide. H.C. Starck already manufactures large quantities of this compound, because it is incorporated in the thermal insulation layers of turbines for aircraft and power plants. Pross' team is also working on other powders required to combine individual fuel cells in a stack. In this configuration, what are known as "bipolar plates" are located between the cells to separate the gas chambers. Typically made of a chromium alloy, these plates are equipped with inlets for the gases and simultaneously serve to conduct the electric current. The bipolar plate poses some problems: in contact with oxygen, the chromium oxidizes, evaporates and collects in the boundary layer between the cathode and the electrolyte that is so critical for the electrochemical reaction. The boundary layer gradually becomes unserviceable as a result. A protective layer made of a material similar to that of the fuel cell cathode is intended to prevent the chromium from coming into contact with oxygen.

The researchers at H.C. Starck are also working on a powder made of lan-

Anode of a 20 x 20 cm SOFC cell.





Interview with Roland Diethelm,  
Winterthur/Switzerland

## “Fuel cells generate heat very ecologically”

**When will fuel cells take over home heating systems? research spoke with Roland Diethelm, president of Sulzer Hexis. Together with European power companies, Sulzer Hexis is already testing the first systems under service conditions.**

### When do you think serial-produced fuel cell heating units will come out on the market?

We plan to launch a nearly serial-produced product on the market in early 2005. Subsequently, we want to get a foothold in the European market by the end of this decade with a commercial fuel cell heating unit.

### What problems still have to be overcome by then?

The greatest challenge is to extend the service life of the cell stack, because it's the heart of the system. At present, the drop in performance of the cell stack is still too high. This is due to the use of less expensive materials and semi-serial production methods.

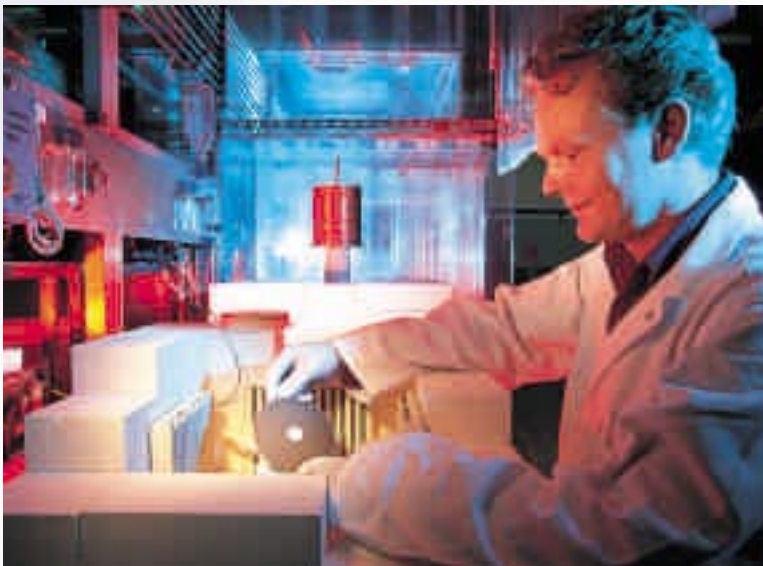
### What benefits do private users gain from a fuel cell heating unit?

Efficient energy utilization is a huge advantage: electrical power and heat are generated in decentralized fashion, which makes both the electrical efficiency and the total efficiency very high. The energy bound in the fuel is exploited much more effectively. What's more, the load on the environment is also reduced significantly, because the fuel cell runs on natural gas, which is the most environmentally friendly of all the fossil fuels. In other words, fuel cell heating units generate far fewer pollutants, thus reducing CO<sub>2</sub> emissions.

### Does a fuel cell system make private households entirely independent of power plants?

No. A fuel-cell heating system operates in parallel with the power grid. Our system can cover between 70 and 80 percent of the power required by a single-family home. The remainder is drawn from the grid. However, owners of a fuel-cell heating system in Germany can also benefit from the Co-generation Act, for example: they get reimbursed 5.11 euro cents for every kilowatt-hour of electricity fed back into the grid.

Rolf Huiberts evaluates electrochemical function on a high-temperature test bench.



thorium-chromium oxide or lanthanum-manganese oxide mixed phases for a contact layer between the bipolar plate and the cathode that improves conductivity. A lot still has to be done to make electricity from fuel cells cheaper. Currently, it still costs over €10,000 for a fuel cell to deliver a power output of one kilowatt. The future objective is to cut the cost to less than €1,000. While Alexander Michaelis wants to automate cell production, potential savings are already offered by low-cost manufacturing and optimization of the powder and functional ceramics at H.C. Starck. He believes the technical problems associated with manufacturing the stacks are manageable: “These teething problems will probably be overcome in the next four to five years.”

[www.initiative-brennstoffzelle.de](http://www.initiative-brennstoffzelle.de)

**This website contains news and information on fuel cells; visitors can also order more in-depth brochures.**

www