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Daimler's Next Generation Fuel Cell Engine

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Executive Summary

Fuel cell technology is an integral part of the Daimler drivetrain strategy. The benefits are obvious: high range with short refueling times and at the same time a wide field of application possibilities from passenger cars up to city buses.

Over 12 million kilometers have already been traveled in vehicles with fuel cell drive such as the Mercedes-Benz B-Class F-CELL and the Citaro FuelCELL-Hybrid city bus.

The next technological step is rising right now: Together with the partners of its global network of expertise, NuCellSys GmbH in Kirchheim/Teck, Germany and Automotive Fuel Cell Cooperation in Vancouver, Canada, Daimler AG has developed a new fuel cell engine. About 30% more compact than before, it can be accommodated in the engine compartment of a vehicle for the first time. Moreover, the cost of the innovative technology has been reduced significantly e. g. through reducing the amount of platinum in the fuel cell stack by 90%.

Within this article, the system built up of the fuel cell engine and its main components is described. In addition, the main achievements in comparison to the predecessor fuel cell system of the B-Class F-CELL are highlighted. Finally, the main challenges in the development of the next generation fuel cell engine are discussed.

Keywords: bus, fuel cell, hydrogen, ZEV (zero emission vehicle), passenger car

1 Introduction

Connectivity, autonomous driving, shared mobility and services as well as the electrification of the drivetrain are the four mainstays of Daimler's vision of mobility for the future. Completely emission-free mobility is offered by vehicles with pure electric drives, which have either a battery-electric or a fuel cell drive. Current products of Daimler are the B-Class Electric Drive and the smart electric drive as battery powered electric vehicles, as well as the B-Class F-CELL as a fuel cell vehicle.

Fuel cell technology is an integral part of Daimler's powertrain strategy. The benefits are obvious: high range with short refueling times and at the same time a wide field of possible applications from passenger cars up to city buses.

As a pioneer of this technology, Daimler already presented the first vehicle with this highly efficient and environment-friendly drive system in 1990. With having covered more than 12 million kilometers, Daimler has the broadest experience in fuel cell vehicles worldwide – from the B-Class F-CELL passenger cars up to the Citaro FuelCELL-Hybrid city busses.

Together with its global network of fuel cell expertise, Daimler right now is making the next consequent technological step: A new fuel cell engine has been developed, which completely fits into the engine compartment of a common vehicle platform for the first time. This opens new possibilities compared to the predecessor fuel cell engine, which was integrated into the sandwich floor of the B-Class passenger car. In order to entirely fit into the engine compartment, the fuel cell engine had to become much more compact while at the same time offering an attractive performance. Besides that, also the piece costs had to be reduced: One main lever to achieve this was the consequent reduction of the platinum amount in the fuel cell stack, which could be lowered by 90%.

2 Current Generation of Fuel Cell Vehicles

2.1 General Achievements

The B-Class F-CELL fuel cell vehicle has a fuel system net power of 90 kW, whereat the fuel cell stack is located below the driver and the passenger seat in the sandwich floor of the vehicle. The air supply unit of the fuel cell stack, as well as the 100 kW traction motor for the front axle, are housed in the engine compartment of the B-Class. Further back and below the rear bench seat, there is the hydrogen tank system of the vehicle. It consists of three containers and stores a sufficient amount of hydrogen to enable an NEDC range of 380 km. Finally, there is a lithium-ion battery installed beneath the floor of the luggage compartment, which is used for hybridization of the fuel cell system. Furthermore, using the battery, brake energy can be recovered as well as vehicle acceleration is supported.

2.2 Technical Data

The 100 kW power output of the electrical traction motor is comprised of the effective power output of the fuel cell and the battery. The hydrogen tank storage with 700 bar technology can be refilled completely within 3 minutes.

Table 1: Technical Data B-Class F-CELL

Vehicle:	Mercedes-Benz B-Class
Fuel Cell System:	90 kW
Traction Motor:	70 / 100 kW (cont. / peak)
Range:	380 km
Max. Speed:	170 km/h
0...100 km/h:	11.4 s
HV-Battery:	24 / 30 kW (cont. / peak) 1.4 kWh

2.3 Fuel Cell Stack and System

The entire fuel cell system is integrated into the sandwich-floor of the B-Class F-CELL, so that the available passenger and luggage space is not affected. Moreover, having introduced a passive humidifier system, the B-Class F-CELL is already well suited for colder regions, as also described in [3]. Previously, cold start ability had been quite a challenge. However, cold start ability of the B-Class F-CELL has been confirmed – besides by mandatory winter testing in Sweden – also by daily use in customer hands.

3 Next Generation Fuel Cell Engine

3.1 General Achievements

Compared to the predecessor fuel cell engine in the B-Class F-CELL, the fuel cell engine is now about 30% more compact and therefore fits into the engine compartment of a common series produced vehicle platform. This fact offers more possibilities in applying the fuel cell engine also to vehicle architectures which are not equipped with a sandwich floor as the B-Class F-CELL. Besides that, also the efficiency of hydrogen conversion into electrical energy has been improved and the gravimetric power density could be further increased. The fuel cell stack itself as the main component in the fuel cell engine has made significant progress over the last years regarding weight, volume and platinum content. The fuel cell stack powering the next generation fuel cell engine achieved massive improvements in power generation per stack active area (plus >100%). Air compressor technology has been improved, too: The newly applied turbo-compressor with exhaust turbine convinces by lower packaging space, better NVH behaviour and higher efficiency than the screw type compressor in previous fuel cell engines.

3.2 System built up and technical data

In analogy to a combustion engine, the fuel cell engine is built up around the fuel cell stack and its enclosure, which is conducted as a structural part. Thus, the fuel cell stack enclosure at the same time can be used to mount the main auxiliary components of the engine. The air filter is located on top of the fuel cell engine guiding the air to the inlet of the turbo-compressor. After compression, the air is passing the charge air cooler and subsequently ducted through a passive humidifier system, which recovers humidity from the wet product excess air of the fuel cell stack. Within the fuel cell stack, the oxygen in the humidified air is partially reacting with hydrogen producing electrical energy. The excess air – enriched with the product water – is sent through the humidifier system and through the cold side of the charge air cooler. Afterwards, the air passes the turbine side of the turbo-compressor system in order to regenerate power and therefore reducing the electric power consumption of the air compressor.

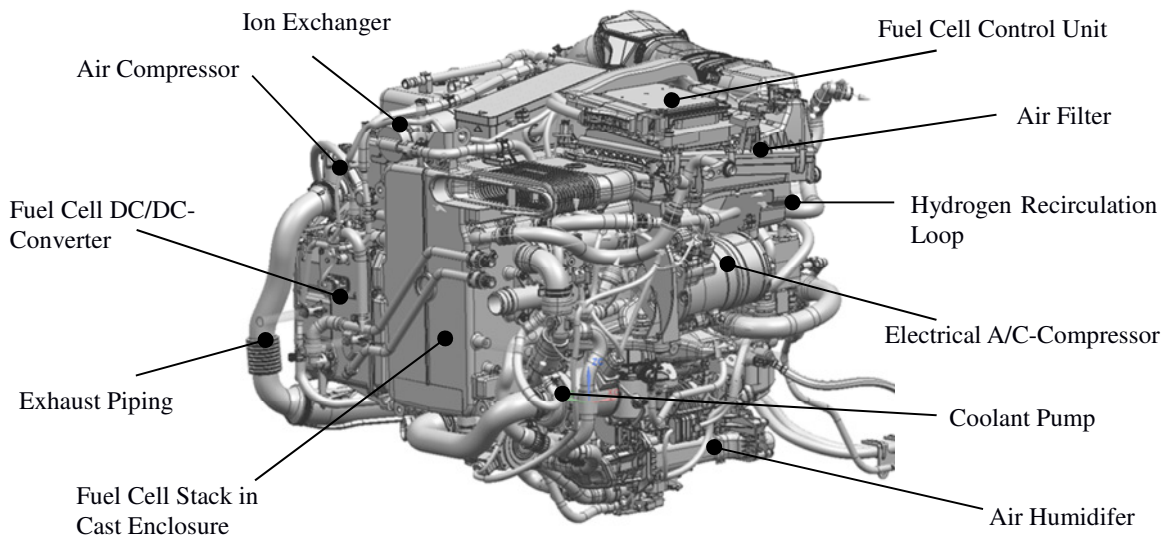


Figure 1: Next generation fuel cell engine

The hydrogen recirculation loop is completely integrated into the media port side of the fuel cell stack enclosure. The recirculation of hydrogen is ensured by a passive ejector system. Thus, compared to previous fuel cell engines, no active recirculation blower is required. This improves the overall system efficiency as well as lowers the requirement of installed fuel cell stack power [6]. On the electrical side, a DC/DC-converter adjusts the varying fuel cell stack voltage to the desired voltage level in the intermediate circuit of the vehicle. As known from a combustion engine, the coolant pumps and the thermostat valve of the fuel cell stack coolant loop are mounted to the engine, too. The ion exchanger of the coolant loop is

located right on top of the engine to be easily accessible. The following table is giving an overview about the technical data of the next generation fuel cell system.

Table 2: Technical data of the next generation FC engine

Technical data:	
Fuel Cell Stack:	PEM Fuel Cell Stack, one cell row
Air supply unit:	Turbo-compressor with exhaust turbine
Air humidification system:	Gas-to-gas humidifier
H2 recirculation system:	Jet pump system (passive recirculation)
Fuel Cell Converter:	Buck-/Boost-DC/DC-Converter

3.3 Technical challenges during development

3.3.1 Improvements in power density and weight

As mentioned in section 3.1, the package volume of the fuel cell engine could be reduced by 30%. This was an important target during development in order to fit the whole system into the engine compartment of a series produced vehicle platform.

First of all, the assembly of fuel cell stack and all necessary system components has been increased in its package density. This leads to very short and compact installation of piping and electrical wiring. Other parts and subsystems, e. g. the hydrogen recirculation loop, have been highly integrated. These benefits could be enhanced due to having all fuel cell engine components together in the same compartment of the vehicle. The predecessor system for example had its fuel cell stack in the sandwich floor of the vehicle while at the same time the air supply unit was accommodated in the engine compartment.

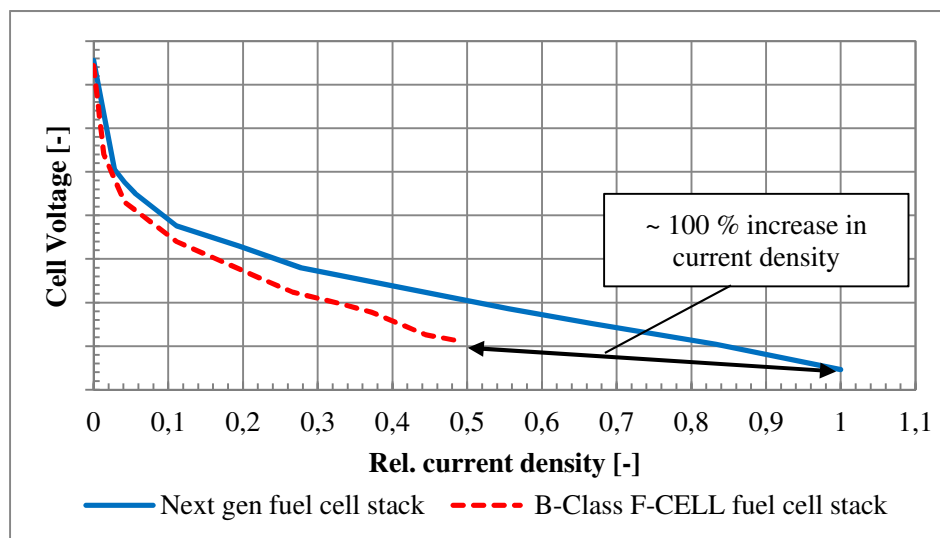


Figure 2: Comparison of fuel cell polarisation curves

Secondly, the introduction of electric turbo-compressor technology for fuel cell air supply brought further improvements in power density. On the one hand, the electrical driven turbo-compressor is significantly more compact than e. g. a scroll or roots type compressor. On the other hand, it shows higher efficiency and is able to regenerate power out of the fuel cell stack excess air by its turbine side. The amount of regenerated power is not needed from the fuel cell stack and therefore saves fuel cell stack active area [6]. This benefit is going to be explained in detail in section 3.3.2.

However, the biggest step to increase power density was made in the fuel cell stack. The improvement in fuel cell polarization is shown in figure 2. This progress in performance was mainly achieved by the implementation of a thinner membrane and improvements in the membrane chemistry itself. This leads to a decreased proton resistance. Another part was gained by improved forming of the bipolar plates and of course by optimization of the fuel cell stack's operating conditions.

Adding up all measures together, the fuel cell stack power density in terms of generated electric power per active fuel cell area could be improved by more than 100 %. Besides the advantages in volume and therefore package space, another resulting benefit was the reduction of fuel cell engine weight by 25% in comparison to the predecessor system in the B-Class F-CELL, see figure 3.

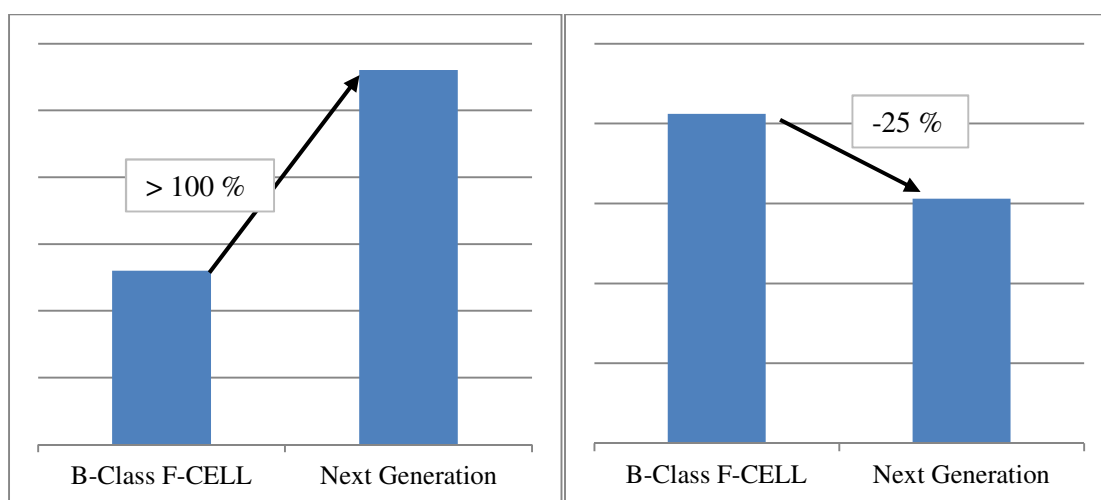


Figure 3: Increase in fuel cell stack power density (left side) and reduction of fuel cell engine weight (right side).

3.3.2 Introduction of new air supply technology

As already mentioned in section 3.3.1, a new type of air supply unit has been introduced in Daimler's next generation fuel cell engine. The previously used screw type compressor [4] has been replaced with an electric turbo-compressor. This kind of air supply unit is comprised by a radial compressor, an electric motor and an exhaust turbine assembled on a single drive shaft. Besides being more compact than the predecessor air supply unit, the electric turbo-compressor also shows lower NVH-emissions [5] and increased overall efficiency in compressing ambient air for fuel cell supply. However, this kind of air supply unit does not only contribute to fuel cell engine power density by being compact itself. Applying an exhaust turbine enables the air supply to regenerate power from the fuel cell excess air.

This basically results in two important benefits: First, the regenerated power reduces the electric power consumption of the air supply unit. According to figure 4, this becomes significant for the operational area at > 70% of maximum fuel cell system power, where the steady-state operating point for thermal limited hill drive of the vehicle is located. As this operating point is a critical load condition for the thermal management of the fuel cell vehicle, the fuel cell waste heat should be kept as low as possible. With using the turbine, the load of the fuel cell stack can be reduced which results in saving around 5% of waste heat maintaining the same fuel cell system power output (see figure 4).

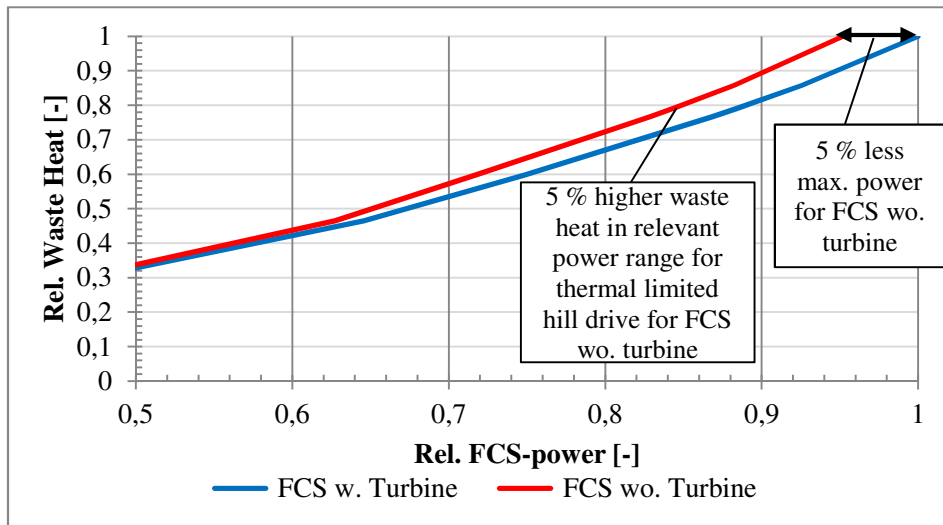


Figure 4: Waste heat as function of FCS-power for FCS with and without turbine

Furthermore, the reduction of the air supply's electric power consumption by the turbine obviously leads to a reduction in installed fuel cell stack power while keeping the fuel cell system power output on the same level. This generates a benefit of requiring less fuel cell active area, saving packing space and cost [6]. A compensation of both the benefits gained by the exhaust turbine would require an additional fuel cell stack active area of 15% (see figure 5).

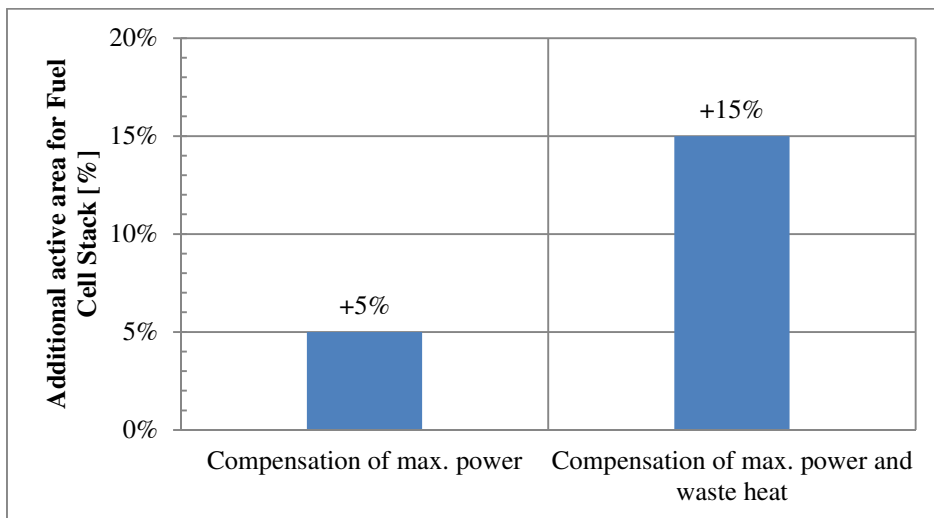


Figure 5: Additional active area for Fuel Cell Stack needed to compensate for maximum power and waste heat in a fuel cell system without turbine

3.4 Progresses in Cost Reduction

3.4.1 Lowering platinum amount in the fuel cell stack

As explained in section 3.3.1, a massive increase in fuel cell stack active area power density could be achieved compared to the predecessor fuel cell generation. Obviously, this fact alone makes clear why the absolute platinum content could be reduced dramatically: The active area itself simply could be reduced by a relevant amount. On top of that, different measures in order to reduce the platinum loading per active area have been implemented. E. g. a thinner membrane is used which leads to lower resistance and therefore allows to go with less platinum loading while maintaining a good performance.

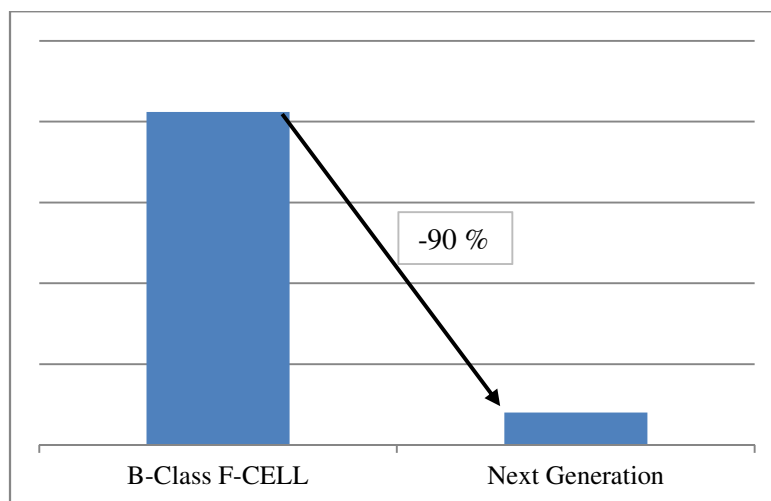


Figure 6: Reduction achieved in fuel cell stack platinum absolute content

3.4.2 Consequent usage of carry-over parts from series produced vehicles

Finally, the amount of series-produced parts and components used in the next generation fuel cell engine was aimed to be as high as possible in order to save product costs. Among many other parts, the air filter housing is a very prominent example for a carry-over from a mass-produced combustion engine.

4 Daimler's Global Network of Fuel Cell Expertise

Part of the Daimler AG strategy involves ensuring direct access to key electro-mobility components. During development and production of the innovative fuel-cell drive, Daimler AG is able to call upon its global competence network.

The centerpiece of the technology, the fuel cell stack, was developed in Vancouver, Canada together with our partner Ford in the Automotive Fuel Cell Cooperation (AFCC) joint venture. The overall fuel cell engine assembly and the hydrogen storage system are developed from the Daimler subsidiary NuCellSys GmbH in Kirchheim unter Teck/Nabern, Baden-Württemberg.

The Daimler strain plant Untertürkheim is responsible for an establishment for the fuel cell system installation, also at the location Nabern. The hydrogen tank system consisting of carbon-fibre-encased tanks is produced at the Daimler Mannheim plant while the lithium-ion battery comes from the Daimler subsidiary Deutsche ACCUMOTIVE located in Kamenz, Saxony. Daimler is currently working systematically to prepare for series production of its next generation fuel cell vehicle.

The fuel cell stacks are also produced in the immediate vicinity of AFCC at Mercedes-Benz Fuel Cell (MBFC), which operates the world's first plant dedicated entirely to the production and assembly of fuel cell stacks in British Columbia. MBFC started production back in June 2012.



Figure 7: Worldwide Fuel Cell Competence of Daimler

5 Summary

Introducing the next generation fuel cell engine, Daimler has made an important step in fuel cell technology. Significant improvements could be achieved in terms of power density and piece cost. The introduction of the electric turbo-compressor for fuel cell air supply as well as the improved polarization and fuel cell stack active area power density are main levers to reduce overall package space and weight of the fuel cell engine. This progresses lead to a light and compact fuel cell engine, being able to be installed in the motor compartment of a series production vehicle.

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Authors



Dr. Steffen Dehn entered the Daimler AG Group Research and Mercedes-Benz Cars Development in 2011 after graduating in electrical engineering at the University of Ulm and subsequently obtaining a doctorate in the field of passenger car fuel cell drives from the University of Duisburg-Essen. Between 2011 and 2016, he held various positions at the Daimler AG in the field of fuel cell development and development of alternative drive systems. Since 2016, Dr. Dehn is a Manager System Engineering Fuel Cell Powertrain at the NuCellSys GmbH, a 100% subsidiary of Daimler AG. In addition to the development of fuel cell drivetrain architectures, these activities also include the assessment with respect to performance, consumption and cold-start time by means of simulation, the development of freeze start strategies as well as the conception and design of the high-voltage system.



Bernd Goltz has been a Manager for Fuel Cell System Integration at the Daimler AG Group Research and Mercedes-Benz Cars Development Division since 2016. After studies of aerospace engineering, Bernd Goltz joined Daimler-Benz AG in 1996. From 1996 to 2008 he held different positions in digital methods and processes, in packaging and in HV-battery development at DaimlerChrysler AG in Germany and in the USA. In 2009 he became a Project Leader within the development of battery electric drive systems for the smart vehicles. From 2011 to 2016, Mr. Goltz had been in charge for the series development of electric vehicles at Daimler AG as a Project Leader. In addition, Bernd Goltz graduated in business administration in 2006.



Jochen Sang has been a Manager for Program Management Fuel Cell Engine and Hydrogen Storage at NuCellSys GmbH since 2016. After studies of aerospace engineering at the Aachen University of Applied Sciences, he joined Daimler-Benz AG Powertrain Development in Stuttgart in 1996. In 2003 he became Manager for Component Development Processes and afterwards in 2005 Manager for Air Supply Development at NuCellSys GmbH in Kirchheim/Teck-Nabern. From 2012 on, Jochen Sang had been a Manager for Hardware Development and Stack Integration with Automotive Fuel Cell Cooperation in Vancouver, Canada.



Prof. Dr. Christian Mohrdieck has been a Director Fuel Cell at the Daimler AG Group Research and Mercedes-Benz Cars Development Division since 2012 and at the same time CEO of NuCellSys GmbH since 2015. After studies of physics in Germany and France, Prof. Mohrdieck joined Daimler-Benz Research in 1989. In 1995 he became head of the Executive Office of the Member of the Board responsible for Research and Technology in Stuttgart. From 1999 on Prof. Mohrdieck has been a Senior Manager Fuel Cell Systems with DaimlerChrysler Corporation in the USA. Back in Germany, he became a Director of Structural Materials at DaimlerChrysler AG and afterwards in 2003 Director of Alternative Energy- and Drive Systems. In 2005 Prof. Mohrdieck assumed the responsibility for Fuel Cell Drive System Development. In 2006 he got the additional responsibility for Li-Ion battery development at Daimler AG. Two years later Prof. Christian Mohrdieck became a Director of Fuel Cell & Battery Drive Development. In 2013 the University Ulm appointed Dr. Mohrdieck Honorary Professor.