A1513

Operation of SOFC 4-Cell Stack under Dynamic Electronic Load

Patric Szabo (1), Günter Schiller (1), Dario Montinaro (2)
(1) German Aerospace Center (DLR)
Institute of Engineering Thermodynamics
Pfaffenwaldring 38-40, 70569 Stuttgart/Germany
(2) SOLIDpower SpA
Viale Trento 115/117, 38017 Mezzolombardo/Italy
Tel.: +49-711-6862494
patric.szabo@dlr.de

Abstract

The EU project ENDURANCE aimed at increasing the reliability and long-term stability of SOFC cells and stacks by better understanding degradation and lifetime fundamentals which is closely related to the application of sophisticated characterization techniques, accelerated testing strategies and degradation modelling. One of the objectives of the work carried out at DLR was to investigate the dynamic behavior of SOFC stacks which were supplied by SOLIDpower and were integrated into the existing DLR test equipment. Since the footprint of the stack was too big for the existing furnace a new furnace was also integrated.

The investigation of the dynamic behavior consisted of thermal cycling and dynamic load operation. In this paper the study of electronic load cycling of a 4-cell stack which already featured improved cells that incorporated previous results from the project is reported. 100 quick load changes were performed as part of an accelerated testing regime. The stack was put on nominal load of 410 mA/cm² for 30 minutes and then the current was decreased to 120 mA/cm² at a rate of 0.5 A/s. The stack was kept for 30 minutes before the load was increased again to 410 mA/cm² at a rate of 0.5 A/s. The results of 100 load cycles showed a small effect on the OCVs of the cells but little effect on the power output of the stack.

Introduction

The project ENDURANCE was set up to develop reliable predictive models to estimate long-term performance and probability of failure of solid oxide fuel cell stacks based on existing materials. This will allow the realization of stacks with extended service intervals and reduced maintenance cost with respect to the present stack technology.
Development of SOFCs in Europe focuses on fuel cell systems for generating power and heat in residential and commercial buildings, so called micro CHPs. One of the areas of interest is the dynamic operation of SOFCs and how it affects the durability of the stacks.
Dynamic load operation of SOFCs is an important topic since energy demand in small scale house applications varies a lot during the day [1] and therefore quick response times to changes in electrical power demand are crucial for such a system, especially if no electric grid back-up is available for instance due to remote location or if the system is linked with other renewable energy systems like photovoltaics or wind power which also tend to vary a lot and where precise forecasts of wind and solar exposure still have a large margin of error [2, 3, 4].

1. Scientific Approach

In the Endurance project prototype stacks each consisting of 4 Single repeating Elements (SRE) were assembled and provided by SOLIDpower [5]. One of these stacks was used to test the dynamic load behavior of stacks by performing 100 quick load cycles and recording a polarization curve before and after the cycling.
Drawings revealed that the stack footprint was difficult to fit in the existing furnace of the DLR test bench. The maximum dimension of the stack was 398 mm which is only 2 mm less than the 400 mm inner diameter of the furnace. Therefore the edges of the stack would be really close to the heating coils of the furnace, which could result in an uneven temperature distribution. Furthermore, with the different gas tube positions and external load system it would also have been necessary to heavily modify the base plate of the furnace. Therefore it was decided to use a new furnace which was provided by SOLIDpower on loan. This Rohde furnace has a rectangular chamber which is more suited for the dimensions of the stack and it was also already equipped with the necessary stack periphery.
At DLR the test bench was modified to integrate the furnace and stack with the existing hardware. It was rebuilt to operate the two different furnaces upon user selection in the control program. The Eurotherm controller was replaced with a software based controller which is adapted to both heating characteristics. Due to space constraints the new furnace was placed between the existing furnace and the control rack which limited access to the stack. Since the Rohde furnace also came without a rack it was decided to put it on a cart, which was re-fitted to accommodate it and also could be moved in case of stack replacement, see Figure 1.
As the stack produces a considerable amount of water the fuel gas exhaust duct form the SOLIDpower stack to the existing condenser was fitted with heating cables to keep the temperature over 100 °C in order to prevent the formation of liquid water in the tube and subsequently increasing back pressure or even blocking the tube with possible fatal consequences for the stack.

Figure 1: Test bench with two furnaces

The test bench has provisions to measure stacks with up to 4 layers. The stack uses ASCs with an active area of 80cm² and is equipped with wiring for each individual layer to measure the voltage. Additionally there are six thermocouples. Four are measuring the gas temperatures of fuel gas inlet and outlet as well as air inlet and outlet. The remaining two thermocouples are placed at the bottom and top end plate of the stack. The reference stack temperature is defined by SOLIDpower as air outlet temperature at OCV. The current connections are located outside the furnace at the tie rods.

The stack has ferritic steel interconnects and uses glass seal which also acts as an insulator between the metal interconnects. Gas supply to the stack is accomplished by an internal manifold for the fuel gas and an external manifold for the air. For this project the stack was operated in co-flow configuration of fuel gas and air. The stack is set on an adapter base plate which is installed in the furnace and incorporates the gas distribution, gas pre-heater and thermocouples. The stack is spring loaded by tie rods.

2. Experiments

The stack consists of 4 SREs, consisting of Anode Supported SOFC sealed on the ferritic stainless steel interconnects by a glass seal [8]. The interconnects are coated by a Co-Mn oxide protective coating. The cells include a NiO/YSZ anode support (ca. 260 microns), a thin (8 microns) YSZ electrolyte and an LSCF/GDC based cathode. In the frame of this project, a modified Gd2O3-CeO2 barrier layer was introduced at the cathode/electrolyte interface to prevent La- and Sr-zirconates formation at high temperature [6]. This barrier layer was doped with MgO as a Si-scavenger.

First, the stack was tested at SOLIDpower for quality assurance and then delivered from Italy by truck. In order to check whether the transportation has had a negative effect on the

stack, it was heated up and a standard current-voltage measurement was carried out before the dynamic load cycling was started.
The stack was operated at a temperature of 750°C and a fuel gas flow of 0.288 slpm of hydrogen and 0.192 slpm of nitrogen and an air flow of 5.33 slpm per stack layer. No water vapor was added to the fuel gas. The full load operation point of the stack is fixed at 80% fuel utilization (FU) which at the given gas composition translates to a current density of 410 mA/cm² [7]. The dynamic load regime alternates between this full load working point and a partial load level which was defined for this project as 30% of the full load. Therefore, the partial load current density is 123 mA/cm².
The current was changed at a rate of 0.5 A/s between those two points. In order to ensure steady state before the current was increased or decreased, the stack was kept at the respective current density level for a duration of 30 minutes. After completion of 100 cycles another polarization curve was recorded.
The test bench is semi-automatic and can run gas and load ramps but these needed to be started manually. Therefore sometimes the breaks between the load cycles exceeded the duration of 30 min. During the weekend and night the stack was kept at the partial load level of 10 A.

3. Results

The stack was operated for a total of 1260 h. Figure 2 shows the life cycle of the stack. At 833 h the test was paused for 3 h for maintenance of the gas safety monitoring in the laboratory. After the dynamic load test was completed the stack was cooled down.

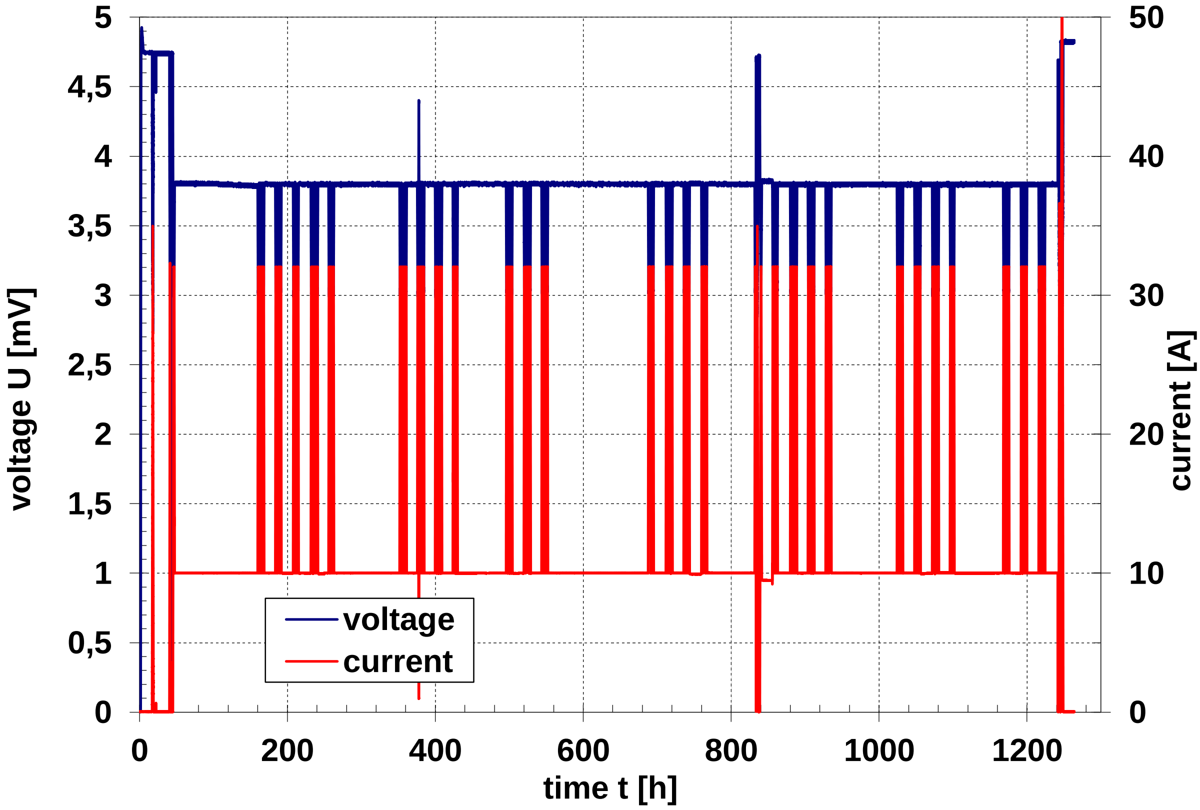

Figure 2: Lifecycle of SOLIDpower stack #716

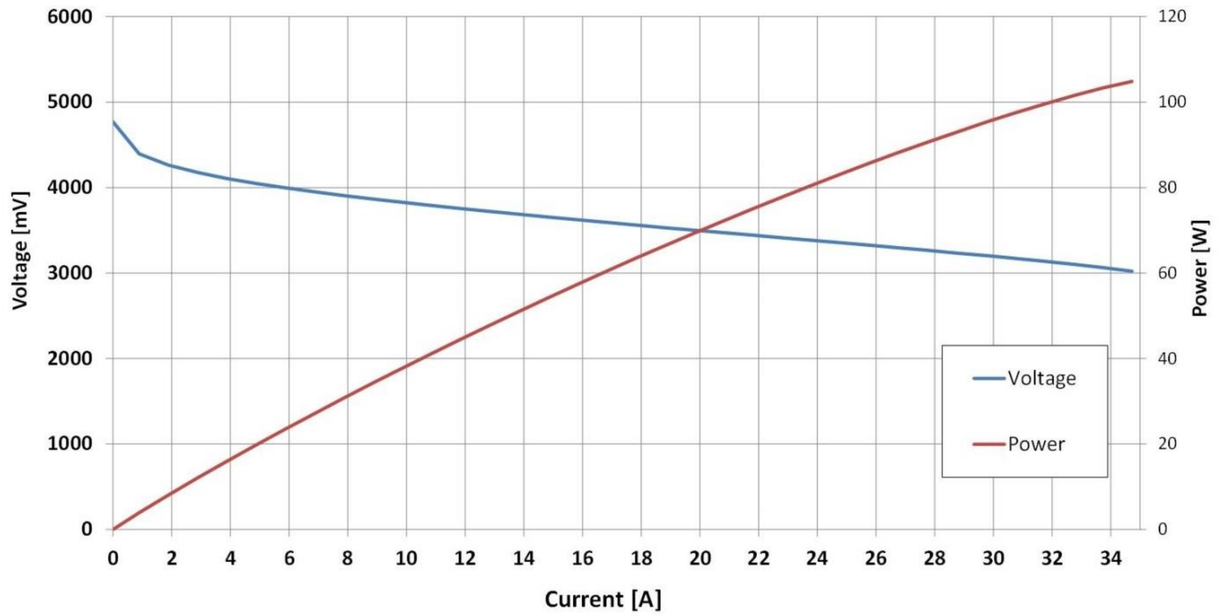

Figure 3: Polarization curve from SOLIDpower

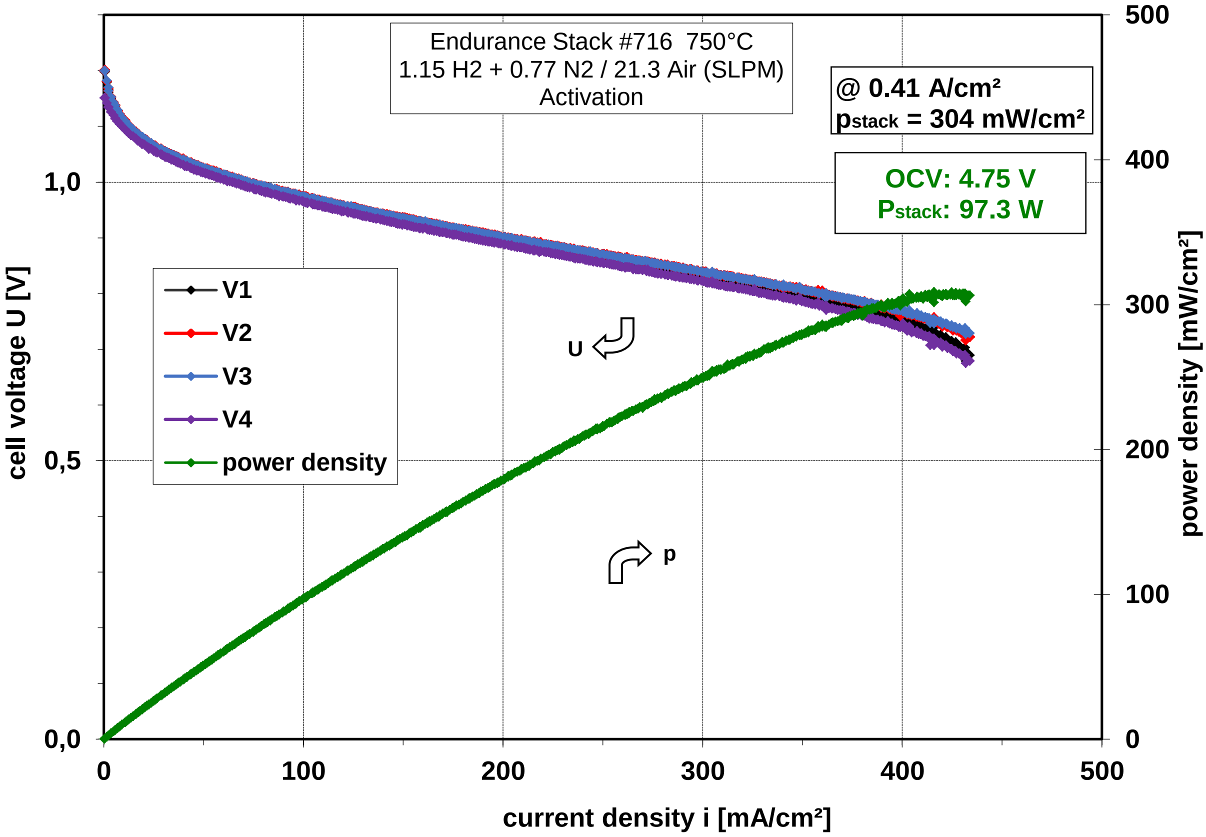

Figure 4: Polarization curve at DLR

At SOLIDpower the stack had an OCV of 4767 mV and a power density of 317 mW/cm² at 80% FU, see Figure 3. Cell 4 in the stack had a slightly lower OCV compared to the other cells in the stack. In the DLR test the stack showed an OCV of 4750 mV which is slightly lower than the first test, see Figure 4. Also cell 4 had a lower OCV of 1151 mV while the other three cells are at 1200 mV. The lower OCV of cell 4 could be an indication for a leakage in that stack layer.

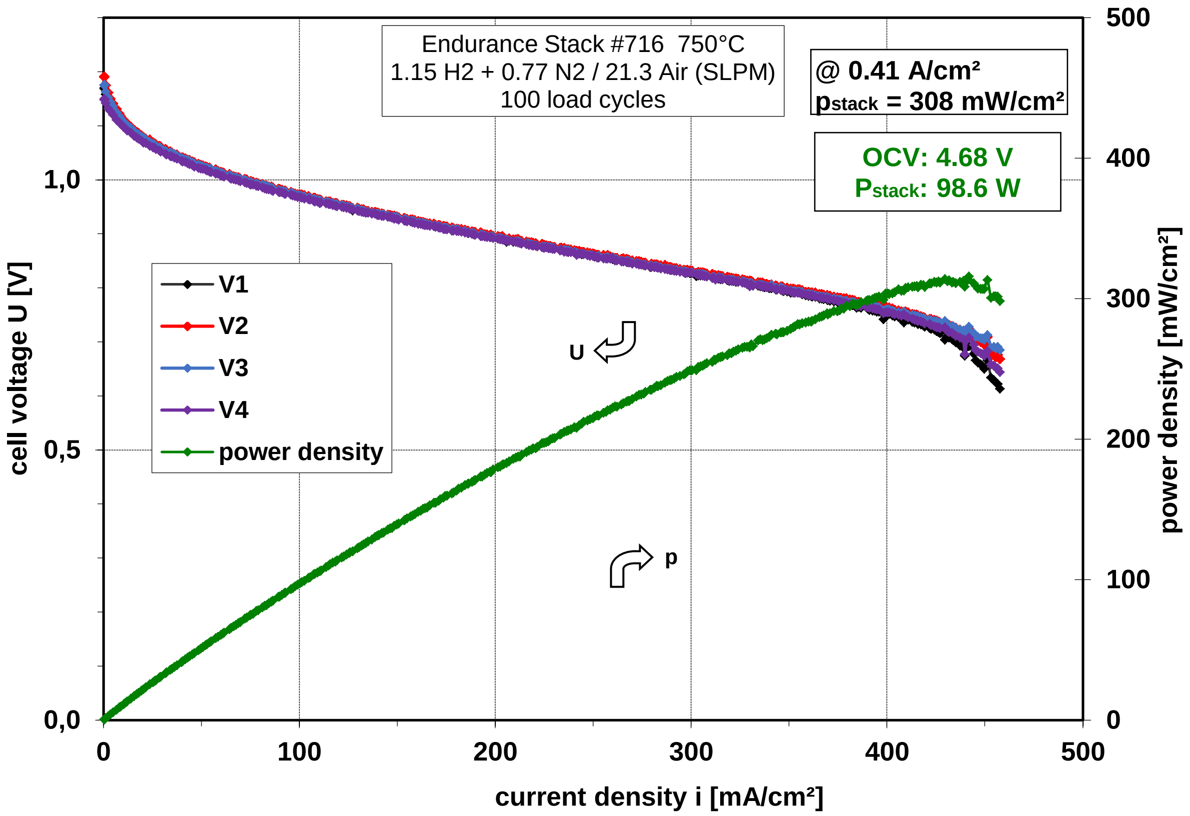

Figure 5: Polarization curve after 100 load cycles

At a run time of 833 h a polarization curve was recorded and it showed an OCV of 4716 mV and a power output of 98.2 W, which shows an increase in power and a decrease in OCV. After the load cycling was completed another polarization curve was performed, see Figure 5. The OCV of the stack has dropped again to 4675 mV while to the power has increased to 98.6 W. Since gas exhaust temperatures did not increase from the beginning until the end of the test and also the gas outlet temperature increase during the polarization curves was the same at 6°C, possibly a leak was already existent from the start. This would also explain the lower OCV of cell 4 at the beginning. Due to the qualification test at SOLIDpower and the DLR test the stack also ran through a thermal cycle and the shipping from Italy to Germany. A possible reason for a leak might be that the thermal stresses during heat up or the mechanical stresses while clamping the stack. This could not be investigated further as the test did not include a post-mortem analysis of the stack because the scope of work at DLR was non-destructive testing.
The OCVs of the cells are shown in Figure 6. Cell 4 which already had the lowest OCV from the start only dropped by 3 mV. The other cells lost between 10 and 37 mV. Cell 1 had the biggest loss of 37 mV. The power density of the cells showed an increase in cells 1 and 4 while the cell 2 stayed the same and cell 3 lost 2 mW/cm² after the load cycles. In total the stack power density increased from 304 to 308 mW/cm². The explanation could again be the suspected small leak which would lead to humidification of the fuel gas and

hence to an increase in power, which is especially visible in the increase in power of cell 4, see Figure 7. If the leak is small it would also be hard to detect it in the gas exhaust temperatures. Also no water was found in the condenser for the air.

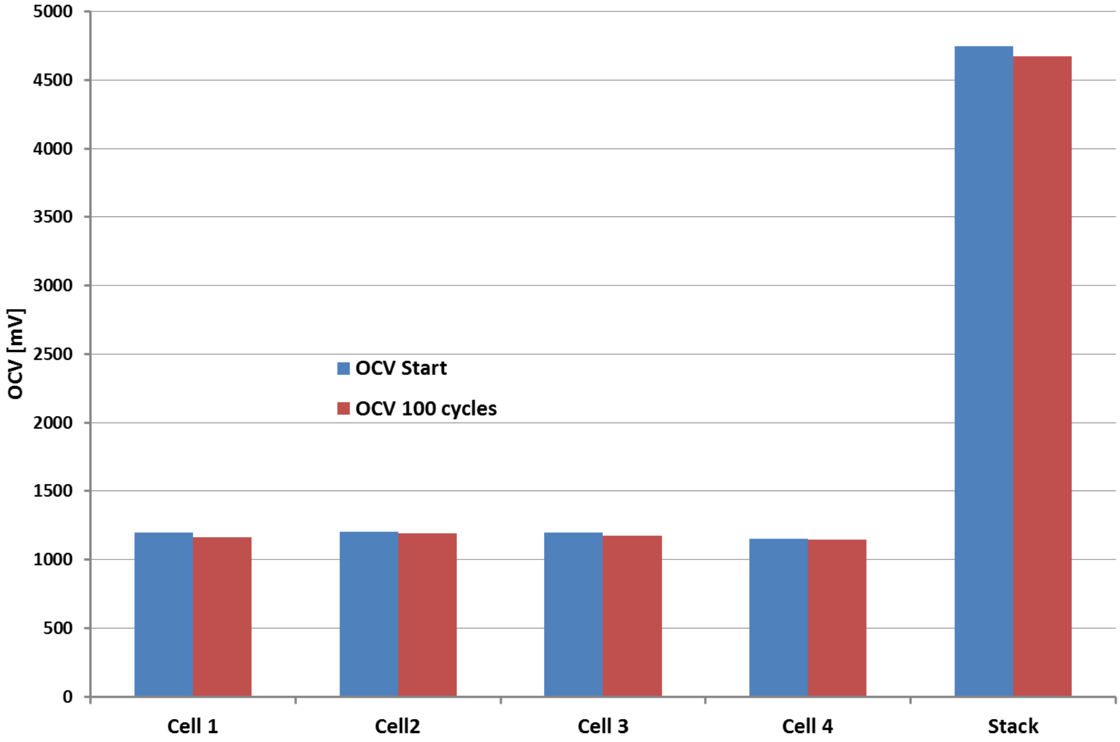

Figure 6: OCVs of cells and stack

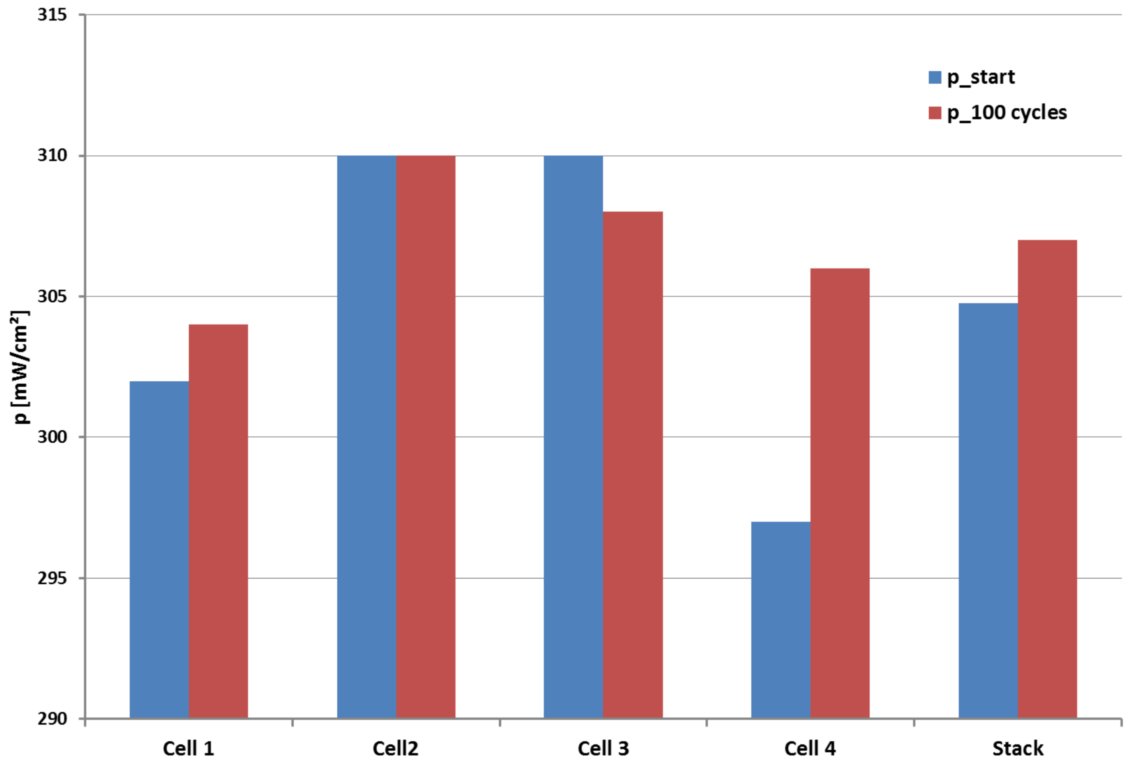

Figure 7: Power density of cells and stack

Conclusion

A 4 SRE stack has been subjected to 100 load cycles between 10 A and 32 A. The stack survived the load cycles quite well but lost 75 mV in OCV while the power output climbed from 97.3 W to 98.6 W. This effect could already be observed during operation since a break after 833 h was necessary for laboratory infrastructure maintenance. The polarization which was recorded before the break also showed a lower OCV and higher power than at the beginning of the test. The stack was already delivered with one cell having a lower OCV. Both effects point to a small leak in this layer but it could not be detected at DLR since only non-destructive testing was possible.

Acknowledgement

The research leading to these results has received funding from the European Union‘s 7th Framework Programme (FP7/2007-2013) Fuel Cells and Hydrogen Joint Undertaking (FCH-JU-2013-1) under grant agreement No 621207.

References

[1] H. Al Moussawi et al., 4-E based optimal management of a SOFC-CCHP system model for residential applications, Energy Conversion and Management 151 (2017) 607–629
[2] S. Declair et al., Wind Power Data Assimilation in a Regional Model - Haves, Wants and Needs, European Meteorological Society Conference 2015, Sofia, Bulgaria
[3] A. Steiner et al., Objective Identification of Critical Weather Events for Ensuring Net Stability, International Conference Energy & Meteorology 2015, Boulder, USA
[4] C. Köhler et al., Towards a more accurate wind and solar power prediction by improving NWP model physics, European Meteorological Society annual meeting 2014, Prague, Czech Republic
[5] Massimo Bertoldi et al, Development, Manufacturing and Deployment of SOFC-Based Products at SOLIDpower, ECS Transaction 68, 2015, 117-123
[6] V. Miguel-Pérez et al, Degradation Studies and Sr Diffusion Behaviour in Anode Supported Cell after 3,000 h SOFC Short Stack Testing, ECS Transaction 68, 2015, 1803-1813
[7] Z. Wuillemin et al, High-performance SOFC stacks tested under different reformate compositions, Proceedings of 11th European SOFC & SOE Forum, 2014
[8] Paolo Piccardo et al, K44M ferritic stainless steel as possible interconnect material for SOFC stack operating at 600 °C: Characterization of the oxidation behaviour at early working stages Original, International Journal of Hydrogen Energy, 40(9) (2015) 3726-3738