INNO-SOFC Deliverable D4.2

Test report on stack life-time, performance, and operating window tests

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Lead Beneficiary: Forschungszentrum Jülich

Nature: Report

Dissemination level: Public

Summary:

The performance and stability of the new stack design with open air manifold developed by Elcogen were characterized and studied using downscaled stacks with an electrical power up to 1 kW by VTT, ENEA and Jülich. Under the testing conditions similar to system operating environments, stacks showed reproducible and satisfied performance at Elcogen, VTT and Jülich, after transportation overseas. Under constant current mode with a current density of 0.25 Acm^{-2} and a fuel utilization of more than 60% at the stack temperature of around 650 °C, a low voltage degradation rate of 0.4%/kh could be demonstrated with (simulated) reformate at both VTT and Jülich. The stack at VTT has been operated for more than 10,000 hours and the test is still continued (status as of 10/2019)

1. Introduction

A Solid oxide fuel cell system consists of stacks and system components as the so called balance of plant (BOP). The performance and lifetime of the whole system is therefore dependent on each component of the system. However, as the core element of the system, a stable and high performance stack module (built up with more stacks) is the prerequisite for a successful operation of the system. In parallel to the system design and integration in INNOSOFC, the performance and lifetime of the newly optimized stacks from Elcogen were characterized and studied.

Task 4.4 focused on testing the 1 kW short-stacks based on the optimized open cathode interconnect design. 1 kW short stacks are fully representative of full-size stacks with respect to lifetime and performance validation, therefore testing was carried out in a downscaled size. Jülich focused on testing the performance and lifetime of the stack in nominal operating conditions. VTT focused on operating window mapping and special operating conditions (transients, start-up, normal shutdown, emergency shutdown etc.) that are critical to ensure long lifetime of the stacks. ENEA participated actively in the design and analysis of these tests. The results are used to ensure that open cathode design does not cause additional performance or lifetime losses, compared to the last stack generation with closed air manifold. Furthermore, the results gave important feedback to stack design, system design and operating strategy.

The testing procedure for 1 kW stacks was discussed and defined according to the system requirements, and was documented in Deliverable D4.1. Before the start of the testing activities, both Jülich and VTT had to modify their stack test setups in order to adapt the new stack design in the test stations and meet the test procedure requirements defined in D4.1.

2. Stack performance

The stacks tested in VTT and Jülich were first conditioned and characterized by Elcogen. After transportation, they were mounted on the test bench through mica gaskets with certain compression weight. This compression weight was necessary to avoid the gas leakage between stack and test bench on one hand and to keep the stack itself gas tight on the other hand. Due to the limitation from the test bench, the maximal compression applied at Jülich was firstly 300 kg, and later increased to 400 kg after modification of the compression system. Figure 1 shows the first voltage-current curve of a 39-layer stack with the open cathode structure measured at Jülich. With dry hydrogen, the OCVs of all layers at the furnace temperature of 626 °C were close to 1.2 V, indicating satisfied gas tightness of the stack. A comparison with the OCV measured at Elcogen is given in Figure 2. Except for a slight difference in layer 12, all other layers showed basically no change after transportation overseas and the new start-up at Jülich. Even with the lowest OCV of 1.17 V in layer 12, the local leakage rate is only ~0.5% according to the Nernst voltage. All 39 layers showed homogeneous performance with increased current density. At the nominal current of 30 A (i.e. 0.25 Acm^{-2}) the stack reached a power of 1070 W with a fuel utilization of 40.4%. With the increasing current, layers 1 to 3 showed increased deviation from the rest part of the stack, which was due to the temperature difference inside the stack, as there were more heat loss from the bottom of the test bench. For comparison, the power, temperature and average cell voltage measured at Elcogen are also plotted (in blue) in Figure 1. The slight improvement of the stack performance at Jülich was the result of the higher furnace temperature (625°C is the lowest operating temperature due to safety issues). Even with half of the required compression weight, the stack showed comparable results in view of power density and gas tightness at the beginning of the operation.

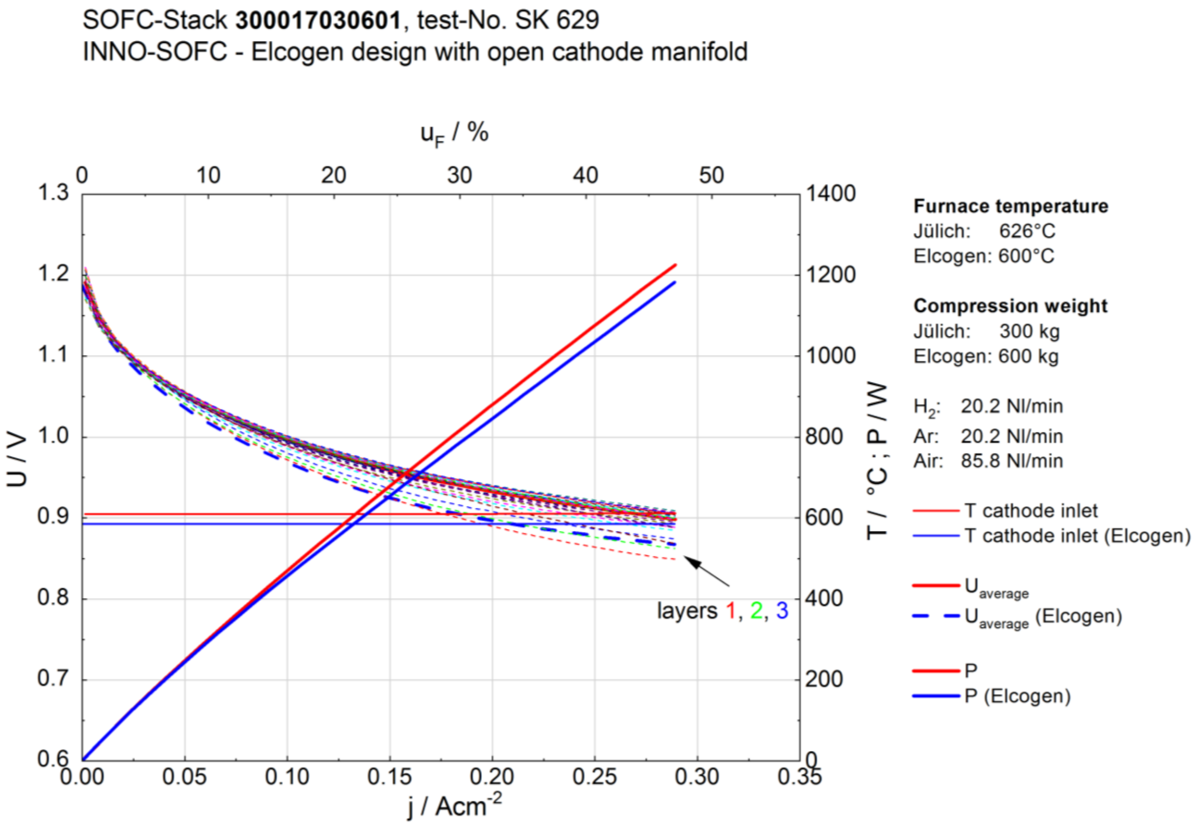

Figure 1. Comparison of the performance of stack 300017030601 measured at Jülich and Elcogen

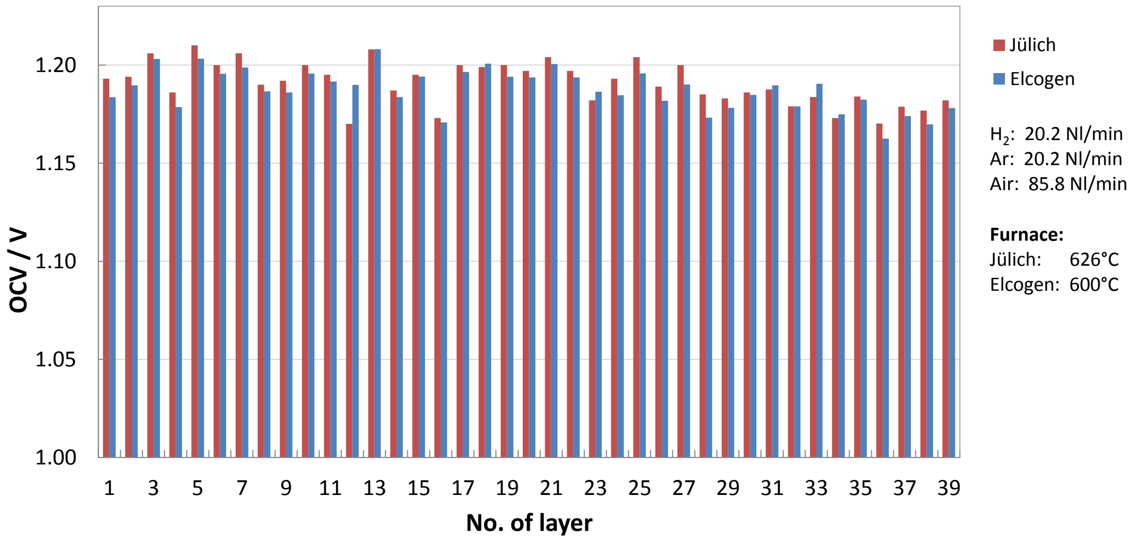

Figure 2. Comparison of the OCVs of stack 300017030601 measured at Jülich and Elcogen

Table 1. Gas compositions of the reformate for 1 kW stack

	H_2	CO	CO_2	CH_4	H_2O
Planned	3 Nl/min	0.45 Nl/min	3.19 Nl/min	2.27 Nl/min	4.19 Nl/min
	22.9%	3.4%	24.4%	17.4%	32%
Realized	3.45 Nl/min	0	3.19 Nl/min	2.27 Nl/min	4.19 Nl/mn
	26.3%	0	24.4%	17.4%	32%

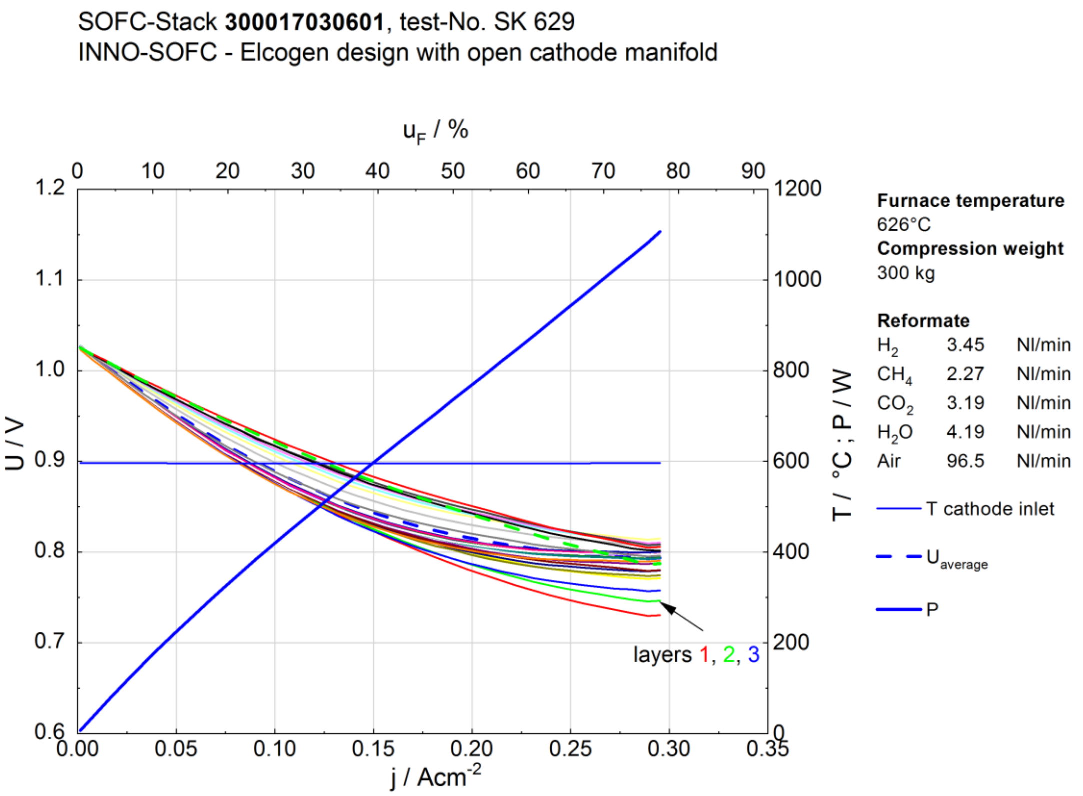

Figure 3. Performance of the stack 300017030601 with simulated reformate measured at Jülich

Besides the measurement with dry hydrogen, the stack was also characterized with simulated reformate. The planned and realized reformate compositions for the 1 kW stack are listed in Table 1. Due to the relative large range of the mass flow controller of CO, the small amount of CO was replaced by H_2 during the tests at Jülich. The performance of the stack using simulated reformate is shown in Figure 3. No any indication of fuel starvation could be noticed at a fuel utilization of 78%. Due to the relatively lower temperature at the bottom part of the stack, layers 1 to 3 showed again the lowest performance at high current densities.

All together four stacks were tested in Jülich. All of them showed similar initial performance under actual testing conditions.

3. Transient testing for lifetime optimization

VTT has done transient testing to study possible protection means for the stacks during thermal cycles. The testing included 28 simulated start-up and shutdown sequences and the test results yield cost-effective threshold values for stack protection methods for the real system shutdowns. Instead of normal procedure, where the fuel cell anode is protected from re-oxidizing with the use of safety gas bottles, an electrical anode protection (EAP) method was used. Use of the electrical anode protection method comes essential for example in an event of fuel shortage. Stack degradation was compared with electronical anode protection to conventional safety gas protection method. The first test cycle consisted of seven shut-down and thermal cycles with safety gases. Between each cycle, the performance of the stack was measured and this was used as a reference in terms of stack degradation. Test plan is illustrated in Figure 4.

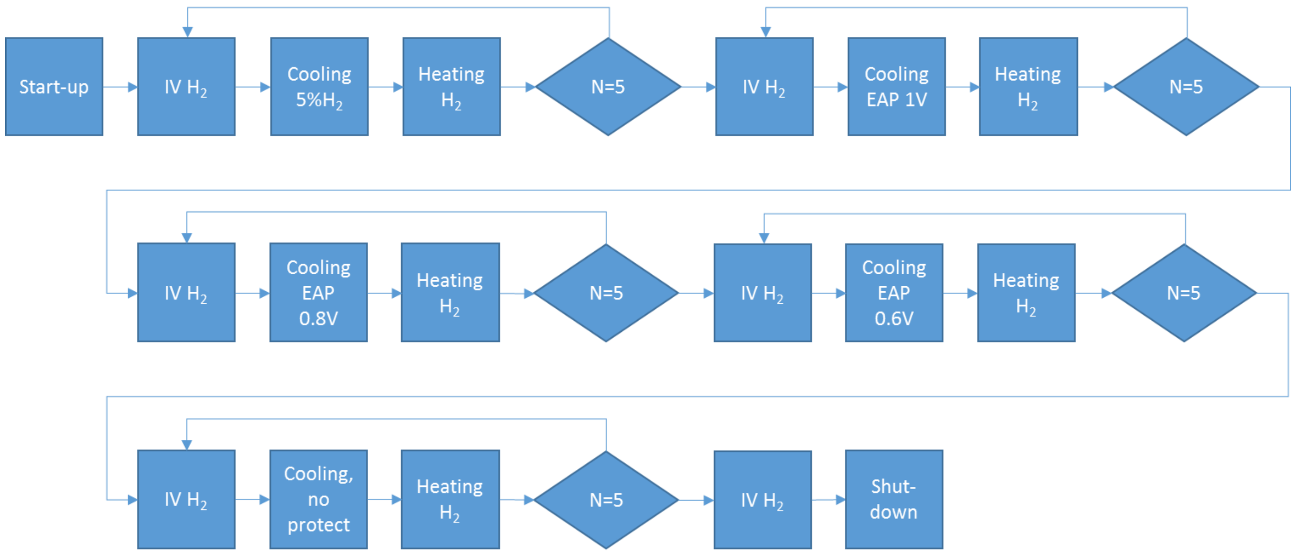

Figure 4. Initial test plan for EMSD test (cycles was changed from N=5 to N=7)

These results were compared to the performances after shut-down and thermal cycles with electronic anode protection with different voltage levels. Different voltage levels were used to find the threshold value for sufficient protection. Overview of the temperature, stack current and EAP voltage of each cycle can be seen in Figure 5.

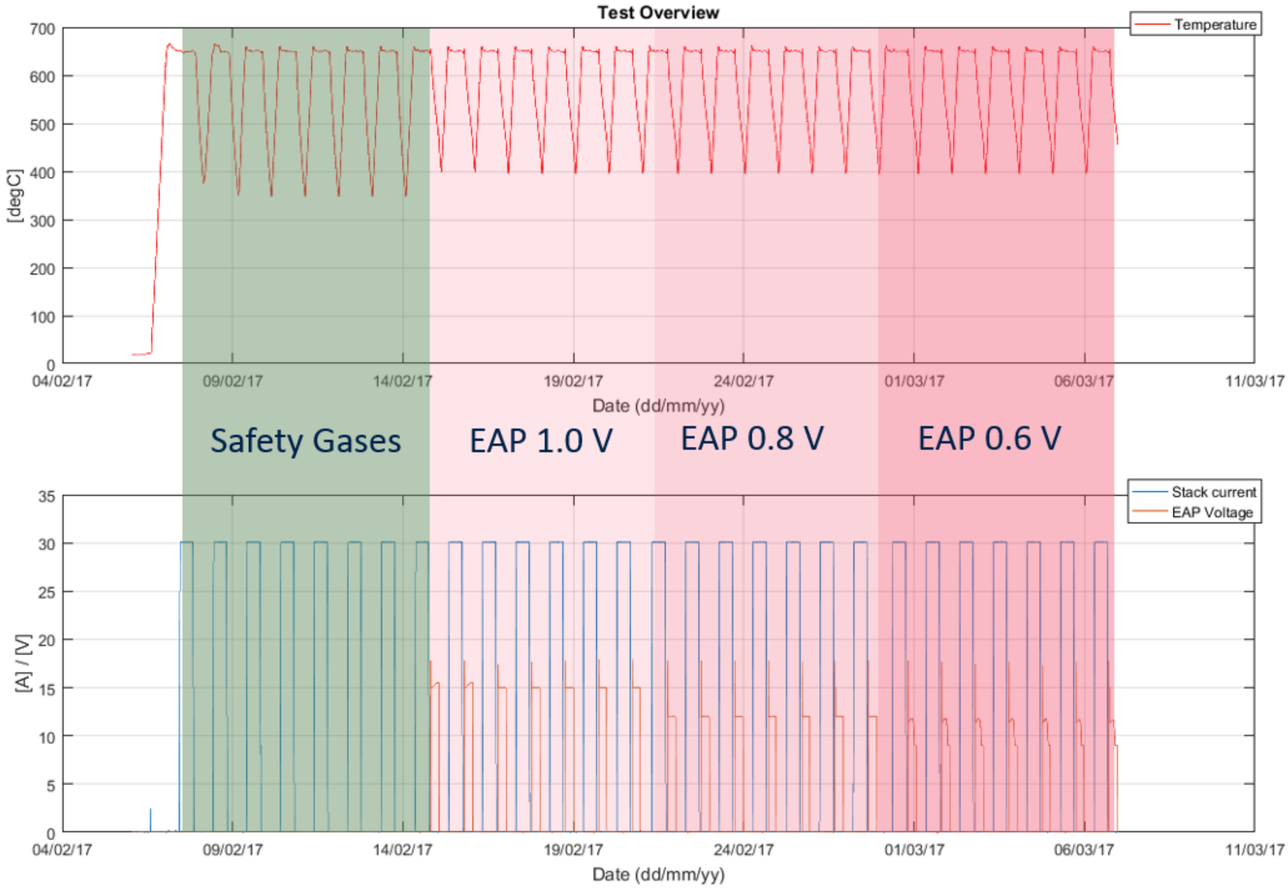

Figure 5. Overview of conducted test run. Temperature, stack current and EAP Voltage curves are shown.

Differences in stack degradation with safety gases and electronic protection methods were not seen with EAP voltages ≥0.8 V. The results showed that EAP is a practical method to protect stacks from re-oxidation. EAP can be implemented into the INNO-SOFC system with low costs and volume, e.g. with a battery pack.

4. Stationary operation and lifetime

4.1. Long-term tests at Jülich

After standard characterization with dry H_2 and simulated reformate, the stack was operated with the given reformate for stationary operation under constant current mode at the furnace temperature of 626 °C. The current density and fuel utilization were kept at 0.25 Acm^{-2} and 65%, respectively. The evolutions of the average cell voltage, stack temperatures, as well as the calculated local voltage degradation are plotted in Figure 6.

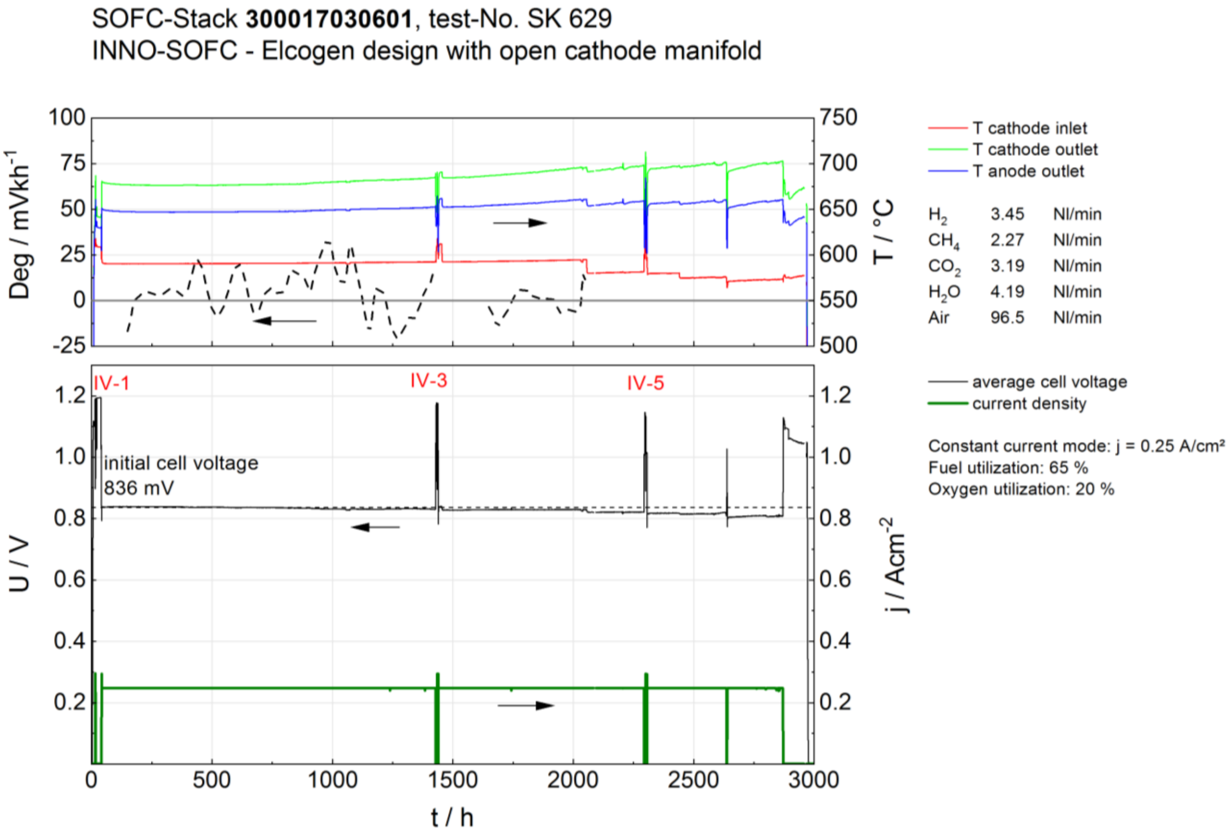

Figure 6. Long-term test of stack 300017030601 at Jülich

Under current testing conditions, the stack performance was quite stable at the beginning of the operation. Starting from ~700 h, a slow increase in the stack outlet temperatures and decrease in cell voltage could be noticed. After an interruption of the operation at ~1430 h, because of a failure in the water supply system, the stack temperatures at outlet side further increased slowly by ~10 °C until ~2000 h. Different methods, including increase of the air flux, decrease of the preheater temperature and compensation of the pressure difference were tried to slow down the temperature increase, but were not successful. It was then decided to stop the operation for post-test analysis, trying to figure out the reason of the continuous increase in temperatures. For the first 2000 hours of operation, before any operating parameter was changed, the voltage degradation rate was 0.4%/kh.

A comparison of the I-V curves taken at ~15 h, 1430 h and 2300 h (marked as IV-1, IV-3 and IV-5 in Figure 6) is shown in Figure 7. Although the difference in the cell voltage under load was minimal, the change in the stack temperature and OCV are remarkable. Figure 8 shows the comparison of the OCVs before the three I-V curves. It can be clearly seen that the OCVs decreased with the operating time.

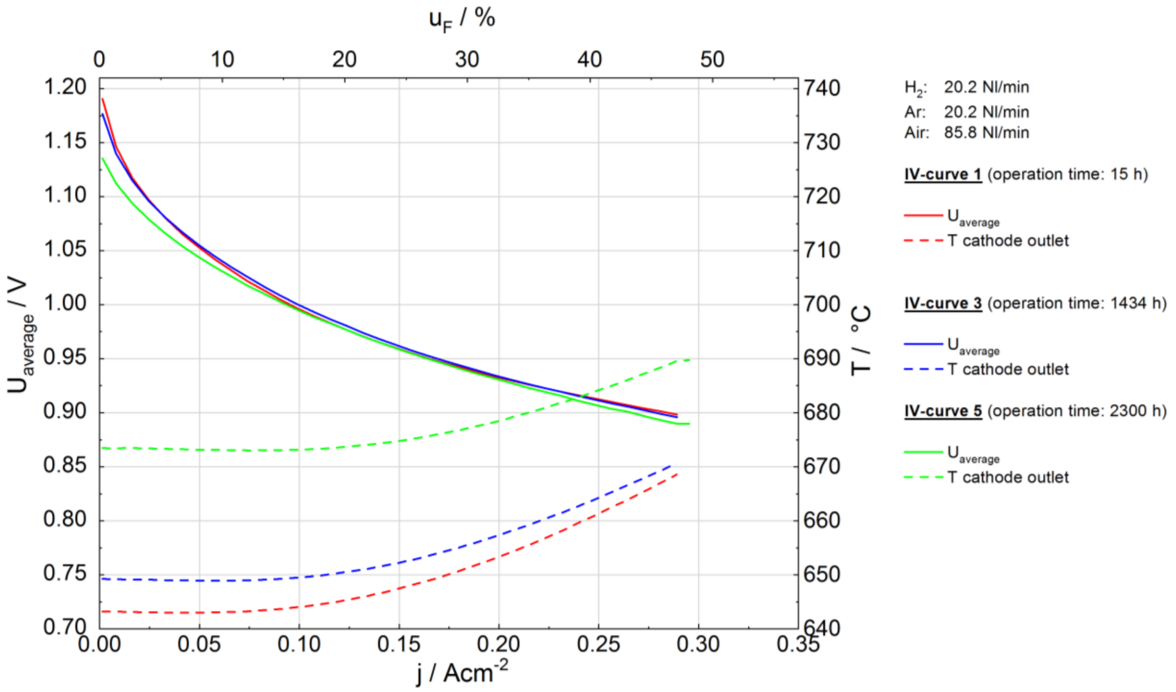

Figure 7. Comparison of the I-V curves at ~15 h, 1430 h and 2300 h

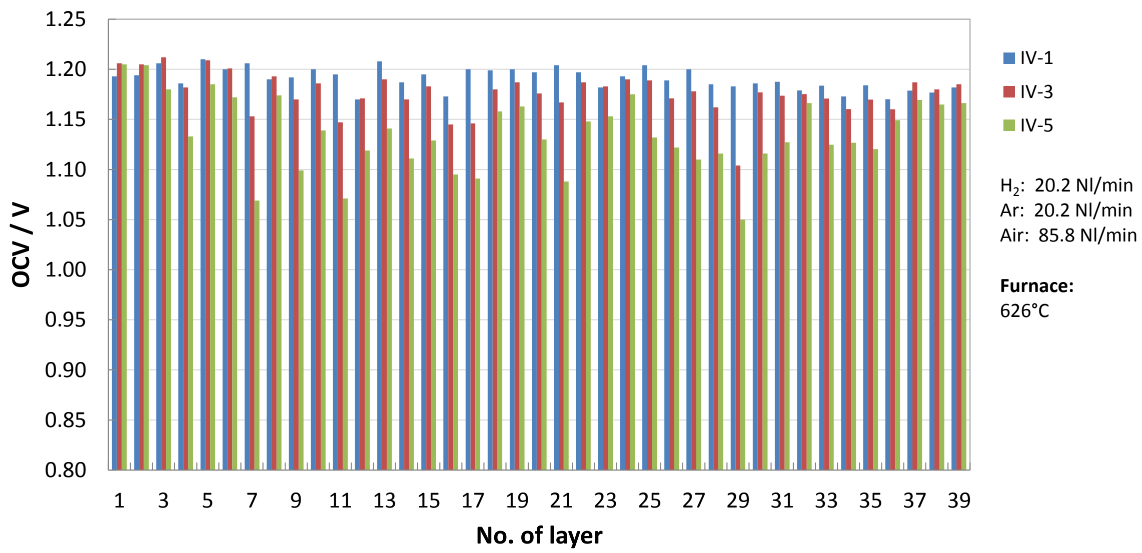

Figure 8. Comparison of the OCVs at ~15 h, 1430 h and 2300 h

The increase of the stack temperature and decrease of the OCVs were also observed in other stack tests at Jülich. After comprehensive investigation of the results, it can be concluded that, even the initial performance of the stack with a compression weight of 300 kg (later 400 kg after modification of the test bench) was comparable to that measured at Elcogen, the compression of 600 kg is still necessary to ensure a safe and stable operation over time. But even under the current testing conditions with the low compression weight, a low voltage degradation rate of 0.4%/kh could be demonstrated for ~2000 hours with the optimized 1 kW stack with open air manifold.

4.2. Long-term tests at VTT

Elcogen delivered a 15-cell stack to VTT for long term testing in May 2018. Testing was started to mitigate project risk for achieving 10,000 hours test run so that the long-term testing would be conducted at least in two separate laboratories with two separate test stations. Test is financed by Elcogen and the results are delivered for the INNO-SOFC project as an in-kind contribution.

The long-term stability was studied with steam reformed natural gas. The gas composition is typical Finnish pipeline grade natural gas with lower heating value of 802.3 kJ/mol (CH_4=98%, C_2H_6=0.8%, C_3H_8=0.2%, C_4H_{10}=0.02%, N_2=0.9%, CO_2=0.1%). The odorant in natural gas, THT, is cleaned with a room temperature sorbent. Natural gas is mixed with steam feed prior the reformer reactor. The steam-to-natural gas ratio is 2.2. The gas composition fed to the stack is standardized in the test by controlling the outlet temperature of the steam reforming reactor to 600°C. The resulting composition for the stack inlet is CH_4=7%, H_2O=26%, CO=7%, H_2=52%, CO_2=8%. Fuel utilization in the test is 60% simulating conditions of a system equipped with anode exhaust gas recycle unit. The fuel cell cathode is fed with preheated air. The current at the nominal operation conditions is 30 A.

Figure 9 depicts the mean cell voltage as a function of operation time. Stack has been operated at constant steam reforming conditions for more than 10,000 hours and the test is still continued (status as of 10/2019). The voltage decay over the whole operation time has been 0.4%/1000h and the ASR decay 14 mΩcm^2/1000h. The voltage decay is determined as the slope divided by the intercept of linear regression of the mean voltage measured at the nominal conditions. The ASR decay is determined as the slope of linear regression of the mean voltage measured at the nominal conditions divided by the current density (0.25 Acm^{-2}). The test period involves one load cycle close to 5600 hours in which the current was switch off from 30 A to 0 A instantly and two full thermal cycles due to laboratory maintenances at 7600 and 8500 hours, respectively. Third transient, at 8300 hours was due to laboratory air compressor malfunction. Current was drawn from the stack throughout the air supply cut which resulted in a drastic drop of the average cell voltage. None of these interruptions caused any measurable degradation to the stack voltage.

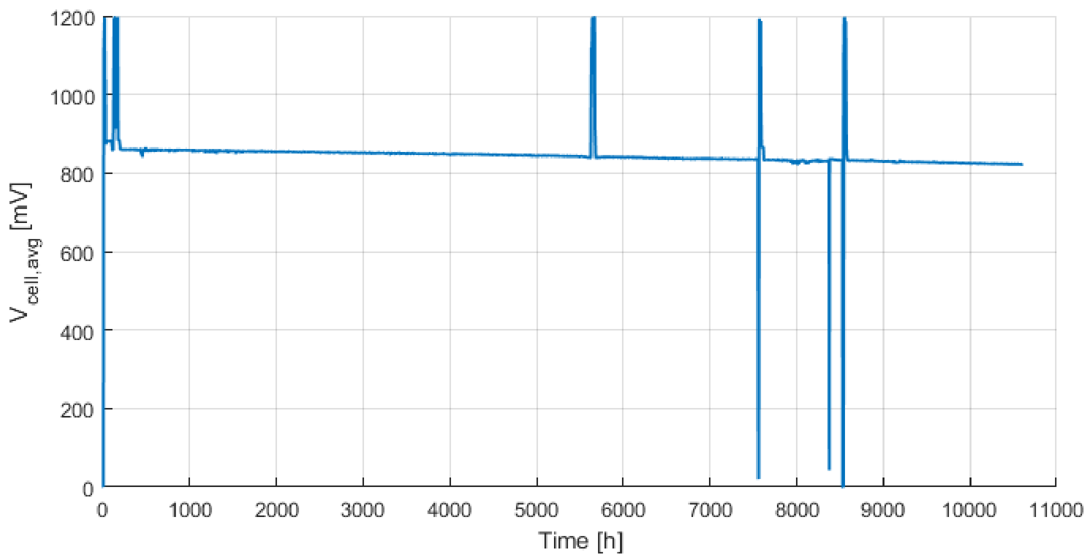

Figure 9. Elcogen stack, average cell voltage in the long-term test.