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OPTIMIZED HIGH TEMPERATURE PEM FUEL CELL & HIGH PRESSURE PEM ELECTROLYSER FOR REGENERATIVE FUEL CELL SYSTEMS IN GEO TELECOMMUNICATION SATELLITES

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ABSTRACT

Next generation telecommunication satellites will demand increasingly more power. Power levels up to 50 kW are foreseen for the next decades. Battery technology that can sustain up to 50 kW for eclipse lengths of up to 72 minutes will represent a major impact on the total mass of the satellite, even with new Li-ion battery technologies. Regenerative fuel cell systems (RFCS) were identified years ago as a possible alternative to rechargeable batteries. CMR Prototech has investigated this technology in a series of projects initiated by ESA focusing on both the essential fuel cell technology, demonstration of cycle performance of a RFCS, corresponding to 15 years in orbit, as well as the very important reactants storage systems. In the last two years the development has been focused towards optimising the key elements of the RFCS; the HTPEM fuel cell and the High Pressure PEM electrolyser. In these ESA activities the main target has been to optimise the design by reducing the mass and at the same time improve the performance, thus increasing the specific energy. This paper will present the latest development, including the main results, showing that significant steps have been taken to increase TRL on these key components.

1. INTRODUCTION

A Regenerative Fuel Cell System (RFCS) based on hydrogen and oxygen consists of a storage system for reactants (H_2, O_2 and H_2O), a fuel cell, and an electrolyser. During charging, the electrolyser converts water to hydrogen and oxygen by supply of photovoltaic power. During discharge the fuel cell converts hydrogen and oxygen to water and generates electrical power and waste heat. Within the ESA Technology Research Programme (TRP) and ARTES 5 programs activities have been undertaken to develop and test a Regenerative Fuel Cell System to replace batteries on GEO telecommunication satellites in the long term. A first order comparison has been performed of a fuel cell system with Li-ion batteries [8] and it showed a significant mass advantage for large platforms with power levels approaching 20 kW. Next generation telecommunication satellites will put increasingly higher requirements on the power supply system. Power levels of up to 50 kW are foreseen for the next 15 years. Today, rechargeable batteries serve as secondary power, but battery systems that can sustain >30 kW for eclipse lengths of up to 72 minutes will represent a major impact on the total mass of the satellite, even with new Li-Ion battery technologies, thus increasing launch cost correspondingly.

CMR Prototech has conducted a series of projects (studies and hardware tests) for ESA which have been relevant in the development of an energy storage system for satellites based on fuel cells (FC). They have been more thoroughly described in the previous paper submitted to ESPC2014 [10] and can be summarized as: *Hydrogen Storage Technologies* [1], *Regenerative H2/O2 Fuel Cell* [3], *Innovative Gas Storage on Satellites* [4], *Advanced Energy Storage System* [5]. *Demonstration of a closed loop H2/O2 RFCS* [6], *Metal Hydride Hydrogen & Heat Storage System (ongoing until 2018)* [7]. CMR Prototech also participated as subcontractor in a TRP activity; Fuel Cells for Telecom Systems – System Study [2], where Thales Alenia Space was the main contractor. The study concluded that it is expected that the RFCS will be more attractive than batteries on a performance point of view, for telecom satellites with bigger payloads. Based on the results from this system study and the recent developments of the RFCS, an ongoing (2015-16) system study “Fuel cells for extra-large telecommunication satellites” [9] funded by ESA under the ARTES1 program was initiated. Prime contractor is Airbus D&S Toulouse, and CMR Prototech is subcontractor to Airbus D&S. The main purpose of the activity is to design a RFCS based power subsystem for large telecommunication satellites (25 kW and beyond), and compare it to a conventional one based on Li-ion batteries in order to identify the power level at which the RFCS becomes clearly the preferred choice from the full system point of view.

A contract change notice (CCN) to the ESA project "Demonstration of a closed loop H2/O2 RFCS", [6], was initiated in December 2013 to optimise and improve the design of the HT PEM fuel cell and high pressure PEM electrolyser. The aim of this project is to develop light weight technologies for use in telecommunication satellites. The target is to operate the fuel cell at 10 bars and temperatures up to 200°C. The electrolyser would be designed for operation up to 100 bars. The project includes testing of short stacks in standalone configuration and a 1 kW full stack in a closed loop configuration. The results from these activities are expected to give a sound basis for further development of a complete RFCS elegant breadboard.
This paper is mainly focused on the results from the optimisation process of the HT PEM fuel cell and High pressure PEM electrolyser.

2. RFCS System description

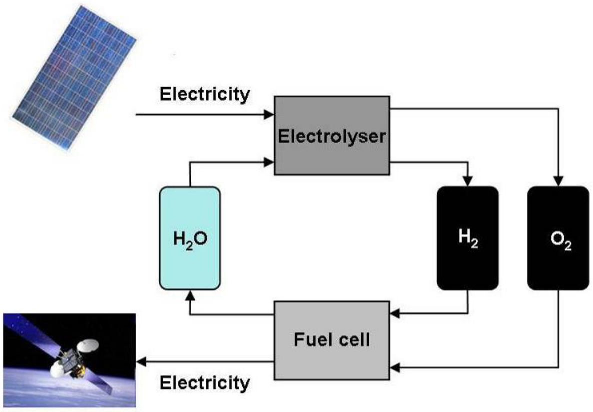

Figure 1 Principle of a Regenerative Fuel Cell System

The principle of a Regenerative Fuel Cell System (RFCS) is to decouple the energy storage from the electrochemical electrodes in an electrochemical energy storage system and thus store energy as element with low mass such as hydrogen and oxygen instead of Lithium and transition metal based oxides. While Lithium batteries has a maximum storage capacity of about 250 Wh/kg on cell level, a RFCS may store up to 1000 Wh/kg for system with long discharging cycles. However, when used in relevant applications, both the Li-ion batteries and the RFCS will meet limitations which reduce their effective storage capacity.
For telecom satellites, the longest discharging period is 72 minutes, which is too short to obtain the maximum energy density of a RFCS. However, the studies have shown a potential for significantly reduced system mass by replacing Li-ion batteries with the RFC.

The main components of CMR Prototech's RFCS are the High Temperature PEM (HTPEM) fuel cell, the High Pressure PEM electrolyser, the storage tanks and the water removal units. In addition, there is a Balance of Plant (BoP) system thermal hardware to dissipate excess heat from the fuel cell.

The HT-PEM (High Temperature Proton Exchange Membrane) fuel cell is a fuel cell technology utilizing phosphoric acid-impregnated membrane and operating from 150°C to 230°C. The higher temperature means that the excess heat can be used to release hydrogen from a metal hydride based storage system. The HT-PEM is also advantageous compared to the lower temperature fuel cells in telecommunication satellites, mainly because of the thermal management becoming much easier at higher temperatures, since radiations from a black body increases with fourth square of the absolute temperature (~*T4*). This will save mass on the thermal hardware compared to lower temperature fuel cells.

Figure 2 HTPEM FC stack used in testing of the closed loop RFCS breadboard demonstrator in 2012 [6] (here without thermal insulation)

The concept of combining the fuel cell with a metal hydride storage tank is particularly interesting. Such a system is being developed in another ESA project [7] [11], where Prototech are working together with Fotec in Austria to combine the HTPEM fuel cell with a metal hydride storage tank which can store both hydrogen and excess heat from the fuel cell. This will allow the thermal hardware which dissipates the excess heat to be reduced significantly in terms of mass, or even removed completely.

The High pressure PEM electrolyser will operate between each fuel cell cycle and produce the required oxygen and hydrogen. Current state of development allows generating hydrogen and oxygen directly by the electrolyser at 100-200 bar pressure. It makes it possible to exclude heavy and power-hungry gas compressors from the system, which is beneficial for the overall system mass and reliability.

3. Development activities

In order to increase the Technology Readiness Level (TRL) of the RFCS, several development activities have been undertaken in the last two years (2014-2016). The main focus is towards the key components, the fuel cell and electrolyser, in order to reach the mass targets and performance.

3.1. HTPEM Fuel Cell

To realize the RFCS within the calculated mass targets, several key issues in the technology have to be addressed. The most important is to improve the FC performance, both in respect to efficiency, specific energy and increased operating temperature. Several development steps have been undertaken to bring the fuel cell technology towards use in telecom satellites. Target development steps in this project:

- Operation of FC on pure oxygen and hydrogen
- Operation of FC at higher pressure, up to 10 bar-a
- Incorporation of liquid cooling
- Increase of FC specific energy, target 1 kW/kg @ nominal power
- Obtain cell voltage of 0,8 V/cell @ nominal current (0,33 A/cm^2) and stack efficiency of 65% LHV Beginning of Life (BoL)
- Increase operating temperature, >200 ºC

Fuel cell development: In order to meet the target specific power density, a **new concept** of the bipolar plate (BP) was needed. Thick carbon composite plates with machined gas and cooling channels simply could not meet the requirement due to intrinsic properties of the material. The new concept is based on thin metallic bipolar plates with liquid cooling in each plate. Each bipolar plate is made of two thin (0.1-0.2 mm) corrugated metal sheets welded together**.** (See example in fig.3).

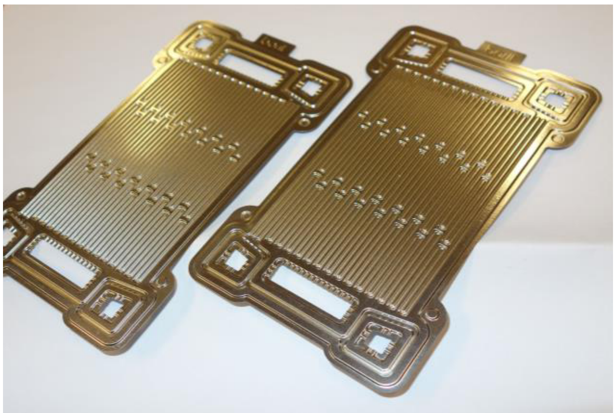

Figure 3 Example of metallic bipolar plates from supplier showing two bipolar plates welded together, incorporating liquid cooling channels in between the plates

Stack concept development (plate shape): The way the bipolar plate is designed greatly affects the maximum possible stack specific power density, as well as most of the other stack parameters such as pressure drop for all reactants, reactants distribution, temperature difference across the plate etc. Reactants manifolds plays a very important role as well. Several design concepts were analysed to identify which concept will allow the highest specific power density. The approach we have chosen was the following. We would develop different BP designs were the active MEA area is kept constant for all design, and then introduce them into an analysis tool containing parameters such as plate thickness, distance of various elements to the edge, size and position of elements etc. Based on that, we would calculate the plate weight and power-to-weight ratios.

Table 1 Calculated specific power density for different BP concepts at nominal power

	Square shape	**Circle shape**	**External O_2 manifolds**	
Specific power density	1.09	0.87	1.13	kW /kg
MEA Area/Total Area	45.6 %	35.1 %	58.0 %	%

As one can see in Tab. 1 the concept with external O2 manifold has the highest power density to the other concepts, providing a specific power of **>1 kW/kg**, which is above the targeted value. External manifolds are beneficial when operating at higher pressure levels and any small external leakages from the cells are contained within the system. Thus this concept was chosen for the further design.

A sensitivity analysis was also performed. By changing each design parameter in the range of ± 10%, we would then calculate the impact of this change on the plate mass. By doing so, we were able to identify several parameters that have the most impact on weight. The sensitivity analysis showed that there are only a few parameters which are really important, like the plate thickness, BP material (density) and MEA specific power density. The analyses also show that the side length of the BP plays a very important role. This has to do with the relative size of the active area of the BP and the area required for gas/liquid cooling inlets/outlets-

Material choice & protective coating: The important parameters for the bipolar plates bulk (core) material are electrical conductivity, corrosion resistance in the HTPEM FC environment, mechanical strength and also the density, which determines the total stack mass and its specific power density. An assessment of new materials for the fuel cell stack has been performed for the bipolar plates base metal, coating for bipolar plates and sealing material for the stack. It is known that materials commonly used to manufacture metallic bipolar plates (various grades of stainless steel) cannot be used as such in their pristine form: they either start corroding, or develop even thicker passive surface layer, which greatly increases the electrical resistance of the plate. A common way to counter these effects is by using coating, which serves both for corrosion protection and for improving the electrical conductivity. In order to identify the best combinations of base materials and protective coatings we have tested several combinations in real and simulated fuel cell environment. The combinations were chosen based on a set of requirement. For the bipolar plate we considered mechanical properties, low density, compatibility to coating material (adhesion), availability and non-prohibitive cost, and for the coating we looked at adhesion properties to the base metal, stability in the HTPEM environment (Phosphoric acid, H_2 & O_2 & 200 ^{0}C) and good electrical properties. A short stack, which consisted of potential bipolar plate materials with coating, was operated at 180 °C in a steady-state fuel cell operation (between 0,7 and 0,8 V/cell) from 09.02.2015 to 22.02.2015 continuously for 310 hours using pure oxygen and hydrogen as reagents. After the testing, the stack was disassembled, and the plates were analysed for signs of coating delamination or other defects. Based on the results a superalloy was chosen as the base metal for the novel fuel cell bipolar plates. It should be noted that lighter base materials, i.e. titanium potentially can provide an increased specific power compared to the superalloy, but will require an improved coating.

Test results of short stack

A full size short stack consisting of three cells has been manufactured and tested under relevant operating conditions. This test program has had the goal to verify the functional performance of the concept and design with respect to pressure/temperature capabilities, leak tightness and compatibility to the harsh environment in the fuel cell, especially related to the presence of oxygen and phosphoric acid (in the electrolyte). Another goal has been to evaluate the fuel cell performance with particular focus on performance at different pressure levels. At the time of writing the test program is not completed and only the main preliminary results are presented.

Figure 4 Full size short stack installed into the test stand and ready for testing

Test conditions =>
The short stack was integrated into an automated test stand including flow, pressure, temperature control and load control.

- 180 ºC stack temperature, limited by membrane specifications
- Pressure: 1-7 bar-a on H^2, O^2 and cooling loop
- Reactants: Hydrogen and oxygen
- Temperature control: Internal liquid cooling
- Constant Current operation: 0 - 0,5 A/cm^2
- Membranes were fresh and unused before testing

Results =>
The short stack was pressure tested with nitrogen to verify leak tightness before fuel cell operation. The stack showed very good leak tightness, both against internal and external leakages, which also was expected to improve further under increased temperature.

The short stack has been operated on a steady 180 ºC for several days of testing, including approximately 35 hours of operation and 7 thermal cycles from room temperature. The stack materials have shown good performance, accept from a gasket material on the external casing. This material showed not to have adequate long term performance at the operating temperature, probably also as a result of exposure to oxygen, and need to be replaced by another compatible material.

The short stack has been operated at different pressure levels to see how the performance changes. Previous tests performed in an earlier ESA project [6] on a single cell HTPEM showed a significant increase of cell voltage with increased operating pressure (25-27% increased cell voltage at 10 bar). The fuel cell was initially operated at 1 bar-a and the pressure was stepwise increased up to 5 bar-a. Polarization curves were logged at each step. Figure 5 (a) shows the polarization curves measured for each pressure level, and Figure 5 (b) shows the relative voltage gain for each pressure level compared to 1 bar-a.

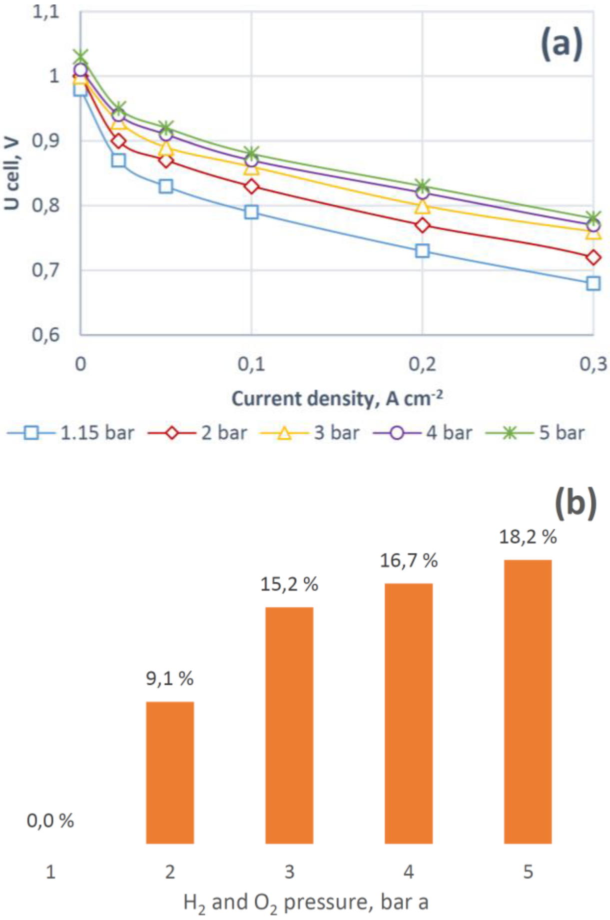

Figure 5 (a) polarization curves measured during fuel cell operation at different pressure levels; (b) relative voltage gain for each pressure level compared to fuel cell operation at 1 bar-a pressure

The test clearly showed the positive trend by increasing the pressure on the anode and cathode. The largest voltage increase is gained when the pressure is increased to 3 bar-a. A 15 % increase is measured. From 3 to 5 bar-a the gain is 3 %, which is still significant in this context. These results correlate well with the single cell test that was performed in the previous mentioned ESA project [6]. Based on those results, and assuming that the relative increase will be the same from 5 to 10 bar-a, another 9 % increase of voltage can be expected. This corresponds to an estimated cell voltage of 0,84 V at 0,3 A/cm^2. If we compare this value to the target we set for the project, which was 0,8 V at 0,33 A/cm^2, we see that the target can be reached.
Also knowing that this short stack is a prototype with potential for further improvements, we expect the performance to be further increased.

The short stack was operated at different pressure levels to verify stable operation at elevated pressure. The target pressure was 10 bar-a, however, the test stand was limited by external components in the cooling loop to 7 bar-a for this test. Modification of the cooling loop hardware is needed to go all the way to 10 bar-a. At 7 bar-a on the cathode, anode and cooling system the short stack operated stable throughout the test, showing no signs to external or internal leakages in the stack. The next step in the test program is to modify the test stand and perform a 10 bar-a test.

The materials' compatibility to the harsh environment has been analysed after the first set of tests by disassembling the short stack and inspecting the individual components. Of particular interest is to evaluate the condition of the bipolar plates after they have been assembled and operated in realistic conditions. This inspection provided some first indications of the materials' durability. Further analyses are planned for after the test program is completed. The main results from the inspection showed that:

- The coating on the bipolar plates was intact (visual microscope inspection), and has good adhesion to the bulk material
- The bipolar plates withstood the compression forces during assembly
- The contact resistance of the bipolar plates has not changed.

Due to these results the bipolar plates were reused in the continuation of the test program.

The results from the short stack testing have shown that the concept works as intended, and the performance is according to the target values we defined for the project. This allows us to continue to the next step of the test program. A 1kW single stack is being assembled at the time of writing, and will shortly undergo a test program in standalone operation, equivalent to the short stack, and in closed loop, together with the high pressure electrolyser. A CAD model of the assembled stack is shown in (Fig. 3).

Figure 6 CAD model of the optimised HTPEM fuel cell stack

The goal of the full stack testing is to get more long term data of the stack operation, which will provide us more insight about the material performances and knowledge for further design optimisations.

3.2. High Pressure PEM Electrolyser

Another important element is to develop an efficient high pressure electrolyser (>= 100 bar). The oxygen has to be stored at high pressures, and high pressure hydrogen is advantageous in order to remove water impurities ahead of a metal hydride hydrogen storage tank. A high pressure electrolyser eliminates the need of a heavy compressor. The degradation rates of the electrolyser also need to be significantly lower than those of the fuel cell. While the fuel cell operation is estimated to around 2000 hours, the electrolyser shall operate up to 20 000 hours. Like the fuel cell, the electrolyser needs to be optimised for use in telecom satellites. The optimisation includes a redesign in order to reduce the mass, and the use of state of the art PEM (Proton Exchange Membrane) MEAs customized for high pressure operation.

Electrolyser development: The development of the high pressure electrolyser within these activities has been done in collaboration with Ideevolutie (The Netherlands). The main challenge in engineering a high performance, light weight and intrinsically safe high pressure electrolyser cell and stack is to find principal solutions to effectively contain the high pressure hydrogen and high pressure oxygen. Key development steps which have been addressed to adapt the technology for space, and to improve system performance include the following:

- High pressure operation 100 bar and above
- Equal pressure on anode (oxygen) and cathode (hydrogen)
- Increased specific power, 1 kW/kg @ nominal power input of 1 A/cm^2
- Increased stack efficiency, 90% @ BoL

In order to realise these specifications, the main activities of the project were focused on:

- Design of the HP ELY bipolar plates and other stack components
- Weight optimisation. The high pressure electrolyser must achieve the desired specific power density. The elements with the greatest mass reduction potential are identified: bipolar plates and compression plate, manifold plate and tie bolt assembly.
- Performance optimisation. High pressure operation poses additional challenges towards process performance. Advanced MEA technology is to be applied in the electrolyser.

Cell stack design: To fulfil the objective to optimise the specific power to 1 kw/kg, the design of the optimised electrolyser has been divided in two parts; optimisation of the cell assembly (bipolar plates, sealing MEA) and the compression assembly (compression plates, tie bolts, current collectors, etc.).

Table 2 Design specifications of a high pressure electrolyser for large telecom satellites

Number of cells	**34**	
Current Density	**1,0**	A/cm^2
Active area	**70**	cm^2
Cell voltage @ current density	**1,75**	V
Stack Current	70	A
Stack voltage	59,5	V
Stack power (theoretical)	4,2	kW
Stack power (practical)	4,9	kW

In order to calculate the gravimetric (kWe/kg) and volumetric power density (kWe/L) of the electrolyser stack design, the operating parameters need to be defined. A volumetric hydrogen flow of 1 Nm^3/h is utilized for the definition of stack size, current density, cell voltage and stack power (Tab. 2). A cell potential of 1,75 V is specified at a current density of 1 A/cm2.

A first prototype stack has been developed. This stack features the low mass electrolyser cell design, but relied on the proven ‘heavy duty’ compression plates. This design is used for validation tests of cell design.

Figure 7 1kW 100 bar PEM electrolyser with mass optimised cell plates, but with non-optimised endplates

Compression assembly: The main design strategy was centred on a mass optimisation of the compression assembly. Novel principal solutions were introduced with respect to a lightweight compression plate in combination with fitting inserts.

Figure 8 First iteration of a mass optimised compression assembly

The mass of the stack is reduced to 4,9 kg and 1,83 l for a 1 Nm^3/hr high pressure electrolyser. This translates to 0,85 kW/kg, taking into account that 4,2 kW power shall be supplied to generate the hydrogen. On the stack level, the cells contribute to 58% of the total mass, while the compression plates contribute to 22%.
We see further potential to reach mass targets by reducing the cell footprint and apply a new concept for the compression assembly.

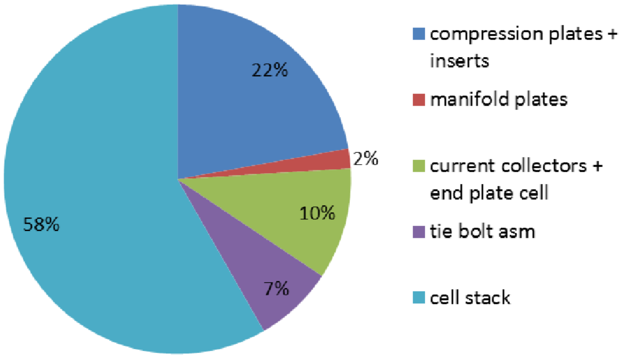

Figure 9 Graphical representation of weight distribution for

Test results of a 1kW high pressure PEM electrolyser stack

A full size 1kW electrolyser stack consisting of seven cells has been manufactured and tested under relevant operating conditions. The goal of the test program has been to verify the functional performance of the concept and design with respect to pressure capabilities, leak tightness and operational performance. The test program consists of both standalone testing and in closed loop configuration together with the fuel cell. At the time of writing the stack has been through the first functional tests in standalone configuration, and the plan is to incorporate the stack into the existing closed loop system when the 1kW fuel cell stack has been assembled (as described in section 3.1).

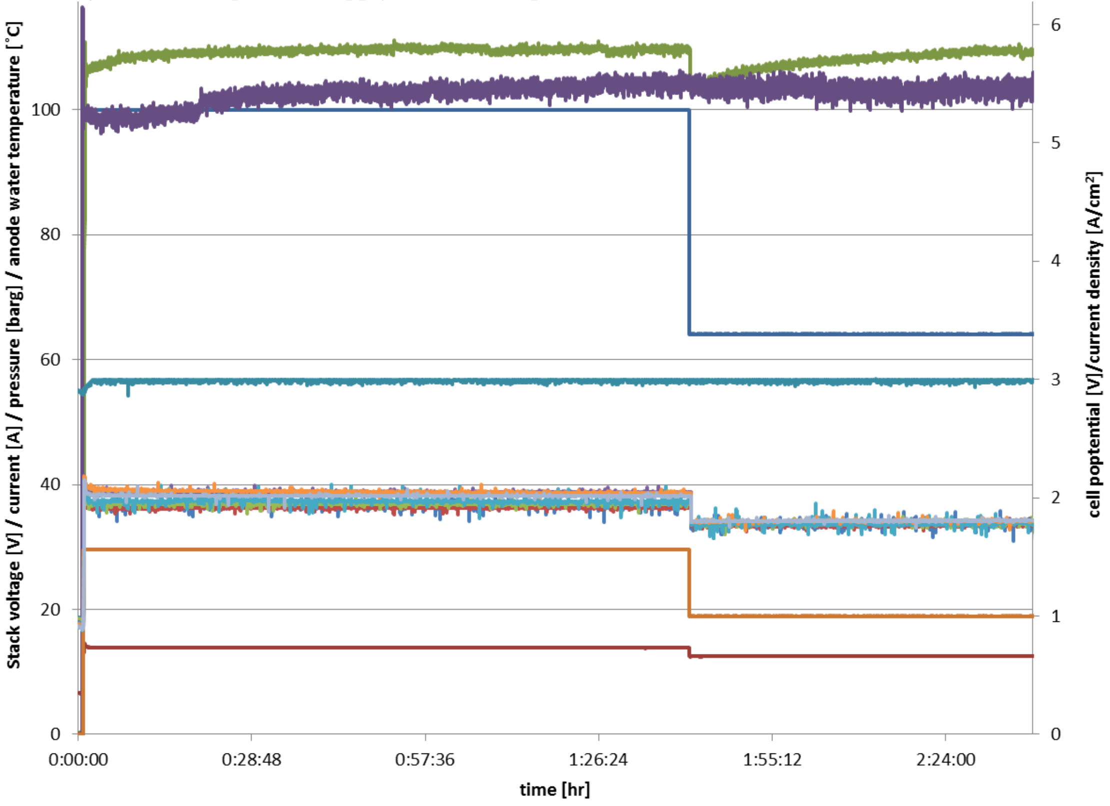

Figure 10: High equal pressure operation: red=stack voltage, green=cathode pressure, purple=anode pressure, blue=water temperature, orange=current density, all curves centred around 1,7V = 7 individual cell voltages

In standalone configuration the stack has been subjected to > 50 hrs of high pressure testing (100 bar on anode and cathode). Figure 10 shows a test where the electrolyser is operated at 100 bars on the anode and cathode. After a phase were the current density is 1,5 A/cm^2 it is reduced to 1,0 A/cm^2. The stack shows good performance by having cell voltages centred around 1,7 V/cell at 1,0 A/cm^2. The stack is at the time of writing ready to go through start/stop cycling performance tests, and later incorporated into the closed loop system for closed loop testing.

4. Conclusion and future work

CMR Prototech in partnership with other R&D companies and Primes have conducted a series of projects for ESA related to the development of a RFCS for telecommunication satellites.

The experimental tests from 2012 [6] have shown that RFCS has the potential to last for the entire lifetime of 15 years in orbit for a satellite, with a satisfactory degradation below 0,01 U/cycle. In the ongoing optimisation activities of the HTPEM fuel cell and High Pressure electrolyser it has been shown that the specific power of 1 kW/kg can be reached on stack level.

The functional performance of the developed HTPEM fuel cell has been tested through a number of tests, including pressure, leak tightness, material compatibility to the harsh fuel cell environment, and performance at different pressure levels. At 5 bar-a a cell voltage of 0,77 V at 0,3 A/cm^2 has been measured. The estimated voltage at 10 bar-a corresponds to 0,84 V. If we compare this value to the project target, which was 0,8 V at 0,33 A/cm^2, we see that the target can be reached. A 1kW single stack is being assembled at the time of writing, and will be tested in standalone operation and in closed loop, together with the high pressure electrolyser.

The High Pressure Electrolyser has been subjected to > 50 hrs of high pressure testing in standalone configuration (100 bar on anode and cathode). The stack shows good performance by having cell voltages centred around 1,7 V/cell at 1,0 A/cm^2, and is ready to be tested for start/stop cycling performance, and closed loop operation.

5. Acknowledgement

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