Executive Summary Report

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Executive Summary Report:

Fuel Cell Application for Future Mission

Executive Summary

The main objective of this activity was to analyze and assess the potential implementation of fuel cell technologies in space applications. The activity was carried out in seven main steps:

The first step established a state-of-the-art review summarizing the progress in fuel cell technology and its application in both industrial and space industries. This review was aimed towards assessing the maturity of the technology for further application in space. First, a general picture on the fuel cell topic was presented and the basic working principle was provided along with the fundamentals. The evaluated fuel cell technologies were primary and secondary fuel cell systems. Primary fuel cell systems (PFCS), consisting only of a stand-alone fuel cell system, are working unidirectional and therefore must be refueled to be used again. On the other hand, secondary fuel cell systems, also called regenerative fuel cell systems (RFCS), consist of a combined fuel cell system and an electrolyser system, and are working in a cyclic process and therefore don’t have to be refueled to be used again. The overview layout with the main sub-systems of a PFCS and a RFCS are shown in Figure 1.

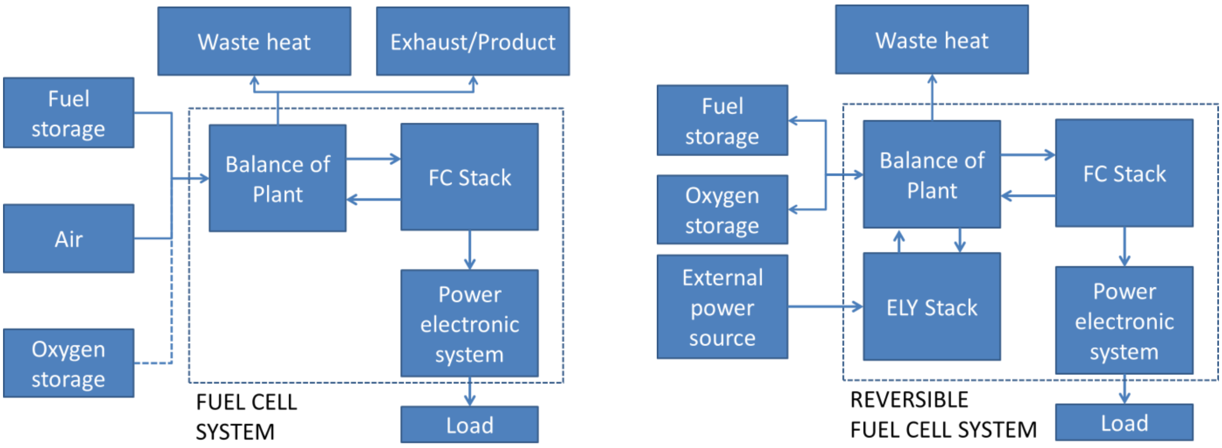

Figure 1: Overview layout of a PFCS and a RFCS

The general fuel cell topic was concluded by an overview of the most relevant membrane technologies and their key features. A more detailed description was given for both technologies, a proton exchange-membrane (PEM) and solid oxide (SO), as they are currently the most promising technologies for mobile and space applications. The key properties of these two membrane technologies are shown in Table 1. Afterwards the literature review was focused on what has been done in the past and on the current developments of fuel cells for space applications. The recent advancements in fuel cell technologies are very promising and enable the concrete possibility of a space rated fuel cell system application. Both primary and regenerative fuel cell systems show numerous advantages compared to conventional technologies. But developing ex-novo fuel cell technologies with the precise scope of a space related application is very expensive and can require a large amount of time. However, there are market available products for terrestrial applications which already have demonstrated high reliability and relatively low costs and therefore show high potential for future development within space applications.

In the second main step, an analysis was carried out to investigate the potential use cases for implementing the, in step one introduced, most promising fuel cell technologies for different space applications and scenarios with the scope of substituting conventional power systems. The assessment and selection of potential solutions was done by elaborating a rating system. This rating system was implementing a comparison of the different technological power solutions, conventional and fuel cell systems, for different space mission scenarios. Since it cannot be assumed that fuel cell technologies can substitute conventional technologies for every space application and mission scenario, a preliminary assessment on plausible applications and scenarios where fuel cell technologies can possibly compete with conventional solutions was carried out. Each scenario was defined by the power class, the duration range of the mission and non-numerical scenario parameters, e.g., in situ resource utilization infrastructure already present on the surface of the astronomical body specificity, or sun independent mission targets. Past space missions were considered. Once the scenario is presented, plausible applications were described, in which fuel cell systems can offer advantages in terms of mass for specific missions, compared to conventional technologies. The promising space application scenarios for RFCS are summarized in the next table.

Scenario	Application	Power	Time
S_Launcher_1	N/A	N/A	N/A
S_Satellite_1	LEO satellite with 30 min eclipse time	low	short
S_Satellite_2	GEO satellite with 70 min eclipse time	high	short
S_Lander_1	survive lunar nights	low	long
S_Rover_1	mid-scale rover on Mars in combination with solar power	low	medium
S_Rover_2	mid-scale rover on Moon combination with solar power to survive lunar night	low	long
S_Settlement_1	small habitat with solar power to bridge moon nights	very high	long
S_Spacecraft_1	energy storage and covering peak power on the ISS	very high	shot
S_Spacecraft_2	energy storage and covering peak power on a crewed vehicle around the moon	high	short
S_UAV_1	energy storage of a solar powered UAV	medium	medium

Table 1: Scenario overview for RFCS space applications

A rating system was established around key evaluation criteria: architectural, such as mass and volume, and technological, such as modularity and safety. The evaluation criteria were weighted to define the relative importance between them. PFCS can offer advantages in terms of the specific energy, the ability to fast recharge and the ability to be independent from sun radiation. However, they cannot substitute solar cells and radionuclide thermal generators as a primary energy source for most applications, since PFCS always rely on the amount of reactants stored in the tanks. RFCS can offer sensible mass advantages over secondary batteries, as the energy storage required by the mission increases, such as it is the case for missions with low-power long-discharge times, high-power short-discharge times, or even high-power long-discharge times. However, they have lower volumetric energy densities with respect to secondary batteries. Due to the complexity of the system and the reactant storage, the volume of a RFCS is at least three times larger in the analyzed cases. An increased pressure level in the reactant storage will reduce the volume of the system. To achieve the compression of the gases, electrochemical pumping can be taken into consideration. The development of lightweight high-pressure reactant tank should further increase the volumetric performances of a RFCS. At the moment, RFCS can have a dominant role where the volume of the system is not very relevant, such as static applications like landers, settlements, or large spacecraft. The option of assembling the system in space or in situ on the surface of the astronomical body, and therefore not depending on the launch of a finished system, could also play in favor of RFCS. The rating system also showed that, as expected, PEM is the optimal fuel cell membrane technology in most cases, suitable from small scale to large scale applications thanks to its good scalability. The results of the rating system lead to a fuel cell system with a power class around 500-1000 W based on PEM technology for the following applications: For PFCS possible mobile applications are robotic rovers and pseudo satellites, possible static applications are robotic landers and small robotic scientific stations. RFCS in this power class are an optimal solution for static applications like lunar settlements. Applications to bridge lunar nights are identified as most suitable, during which the main power source, in the form of solar panels, is inactive due to a long period of darkness (up to 354 hours). This relatively small power class makes the testing easier and safer. The modularity of fuel cell technologies allows for the subsequently upscaling towards larger power classes with reasonable efforts. If the system is scaled up to 10 kW, possible mobile applications are manned rovers and crewed spacecraft.

During the third step, the draft designing of the in step two concluded most suitable fuel cell application, a 1000 W RFCS, was carried out. Goal of the first draft design was to set the starting point in the layout of the RFCS towards higher technology readiness levels (TRLs) and eventually to the final design to be included in a future mission. The draft design was carried out meeting certain assumptions to set a concrete starting point for identifying the equipment without adding to much complexity, which were unnecessary at this stage of the development. The design was supported by a computational model of the whole system. This model was used to compose the specification sheets of the single equipment, such as valves, pumps, separators, etc. and allows fast adjustment of the system in case of changes of the requirements or e.g. the capability of a specific equipment. To speed up the future development of the system, equipment off-the shelf (COTS) were taken into consideration in the design. The final draft design was presented with a detailed scheme, in which the main sub-systems from Figure 1 can be identified. For each subsystem, a general description of the design choices and working principle were given.

During the fourth step, the identification of potential equipment suppliers of the identified equipment was carried out. At the moment there is no commercially off-the-shelf RFCS available that can be purchased. However, terrestrial PEM fuel cell and electrolyser technologies have made substantial steps forward in the last years, regarding not only performance and operational life, but also regarding reduced production costs. Regarding other equipment, such as pumps, valves, etc., commercial products can be considered to take advantage of the lower item cost and high operational life. This approach enables the development of equipment to space qualified products, starting from a working and reliable design. This avoids investing a lot of efforts to develop ad-hoc designed solution from scratch, lowering the monetary expenses to assemble a RFCS. The implemented strategy was built around the idea of the spin-in of terrestrial technologies and products around fuel cell and electrolysis applications into the RFCS design. The goal was to accelerate the development to a high TRL of the equipment, using assessed technology and to evaluate the difference between specification and qualification with future testing. The spin-in approach was based on an assessment of the TRL of the equipment. The qualitative evaluation was carried out based on the usage of equipment in past and present space missions and the standards of the space industry. After the evaluation of the TRL, a market survey was carried out to find potential suppliers for the equipment. Here priority is given to low TRL equipment as they require maximum effort. Regarding fuel cell and electrolyser suppliers, no space related company could be found. That is why the development capability and the willingness of future cooperation were also taken into consideration. For auxiliary equipment, potential suppliers were identified, and wherever it was possible, suppliers were chosen with experience in modifying their product for space applications.

During the fifth step, the proposed strategy of taking advantage of terrestrial COTS in terms of availability, production costs and performances in order to speed up the development process is being implemented in detail. This approach enables the developing of equipment towards space qualified products, starting from a working and reliable design. This avoids investing a lot of efforts to develop ad-hoc designed solution from scratch, lowering the monetary expenses to develop a RFCS. Potential suppliers and products for all RFCS equipment were identified and a first selection of the main equipment was given. This main equipment is the technological most critical equipment, being the both PEM cell stacks for the energy conversion, and the high-pressure fluid separation, high-pressure water feed, and the high-pressure heat exchange. The justified selected main equipment is shown in the following figures.

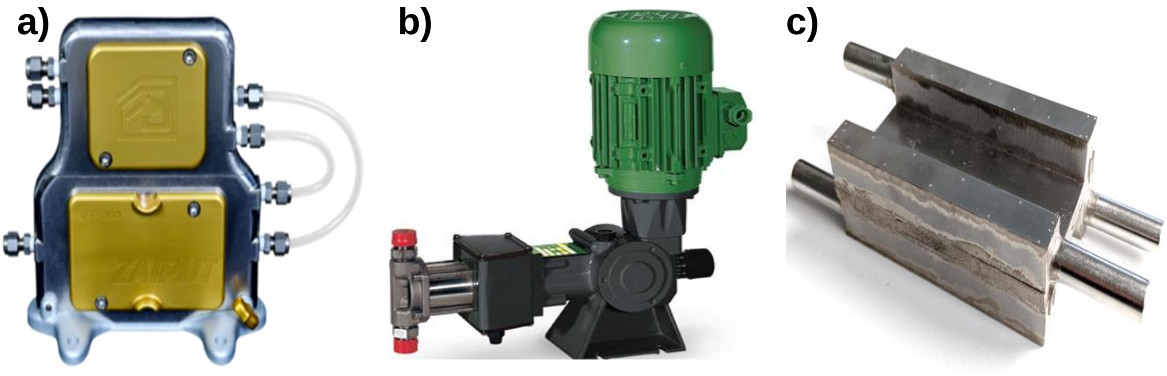

Figure 2: Selected critical BoP equipment (a) Zaiput membrane separator; b) Doseuro high-pressure water feed pump; c) Stiral high-pressure microchannel heat exchanger)

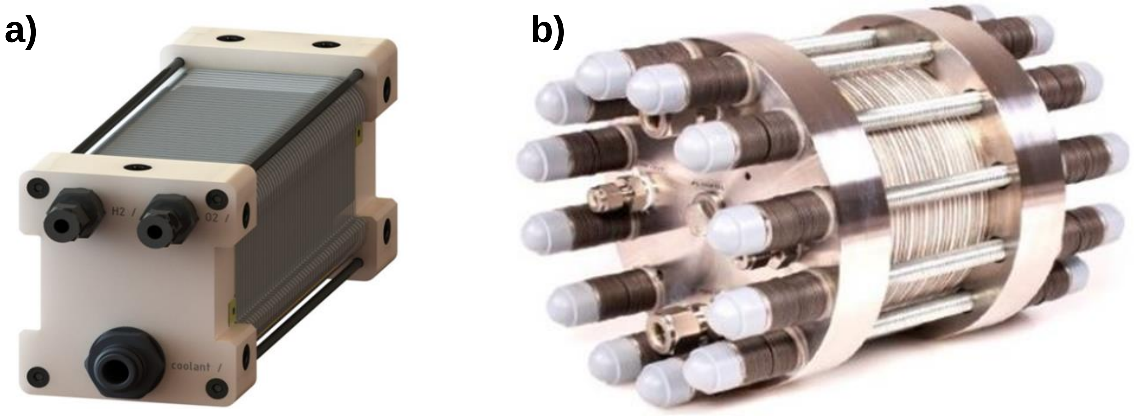

Figure 3: Selected PEM cell stacks (a) BFC PEM fuel cell stack; b) HI PEM electrolyser stack)

These selected and procured equipment had to undergo functional characterisations before they are going to be integrated in the RFCS breadboard. This will ensure their capability to perform the desired operational design points needed for the RFCS breadboard operation. To ensure a safe operation of the equipment and the used test bench, a risk mitigation analysis of the possible hazards, leading to the accumulation of hydrogen and/or pure oxygen and subsequent combustion, has been assessed in the form of FMECAs. All assessed equipment has been successful risk approved and are ready to be characterized inside the also approved and ready to be used RFCS test bench. Every one of the tested BoP equipment, expect for the under-performed membrane fluid separator, passed the functional characterization and will hence be integrated into the RFCS breadboard. Both tested PEM cell stacks performed as intended and can hence be also integrated into the RFCS breadboard.

The sixth step has been the update of the preliminary system design. Based on the risk assessments and the cancerization results, the former elaborated preliminary RFCS breadboard design has been reviewed. The now final RFCS breadboard design is shown in the following figure.

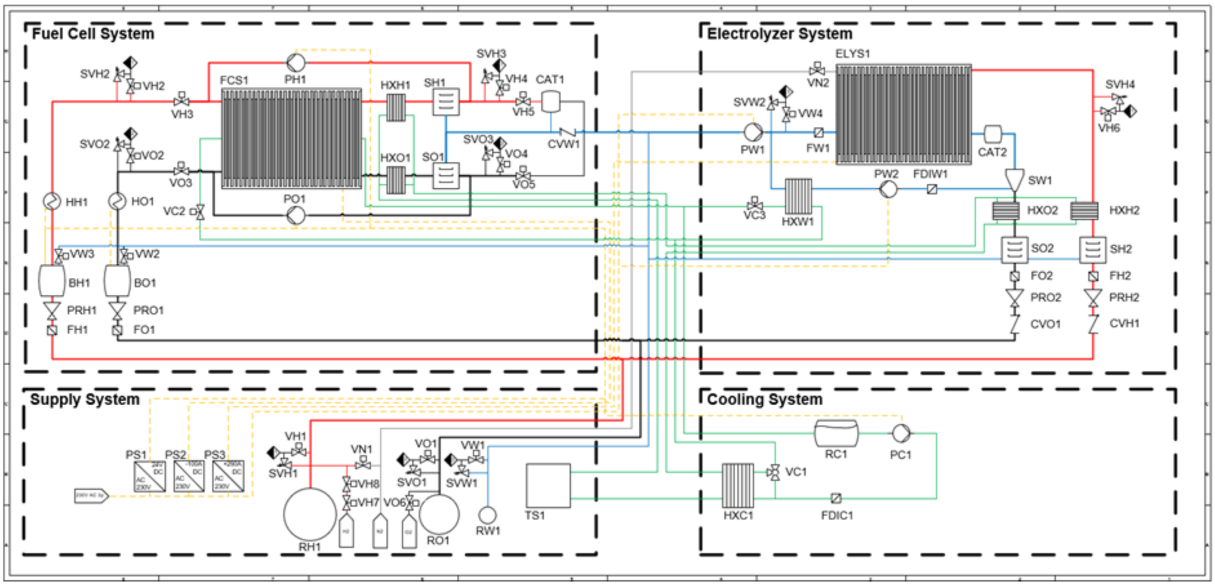

Figure 4: RFCS breadboard final design

Also, the designed breadboard has been assembled and all of the characterized and non-characterized equipment integrated.

The seventh and last step has been the main development and verification test campaign is planned. The test plan, including detailed test procedures, test pass conditions, and testing parameter descriptions, for this main development and verification test campaign has been elaborated and is summarized in the following.

System	Experiment	Label
FC	Purge interval assessment	*FC_purge*
	Recirculation assessment	*FC_recirculation*
	Startup procedure	*FC_startup*
	DP	*FC_DP*
	Shutdown procedure	*FC_shutdown*
	Life time testing	*FC_life_time*
ELY	Startup procedure	*ELY_startup*
	DP	*ELY_DP*
	Shutdown procedure	*ELY_shutdown*
RFCS	Transition ELY-FC	*RFCS_trnst_ELY_FC*
	Transition FC-ELY	*RFCS_trnst_FC_ELY*
	Efficency	*RFCS_efficiency*
	Cycling	*RFCS_cycling*

Figure 5: RFCS breadbaord test campaign overview

The test results of this test campaign have been summarized in the final RFCS breadboard test report. The single transition procedures have been developed, being the start-up, design point, and shutdown of the both main cell stack sub-systems. The final transition procedures have been combined and optimized to be the final closed-loop cycle. This final closed-loop energy storage cycle has been performed ten times. The results are shown in the following.

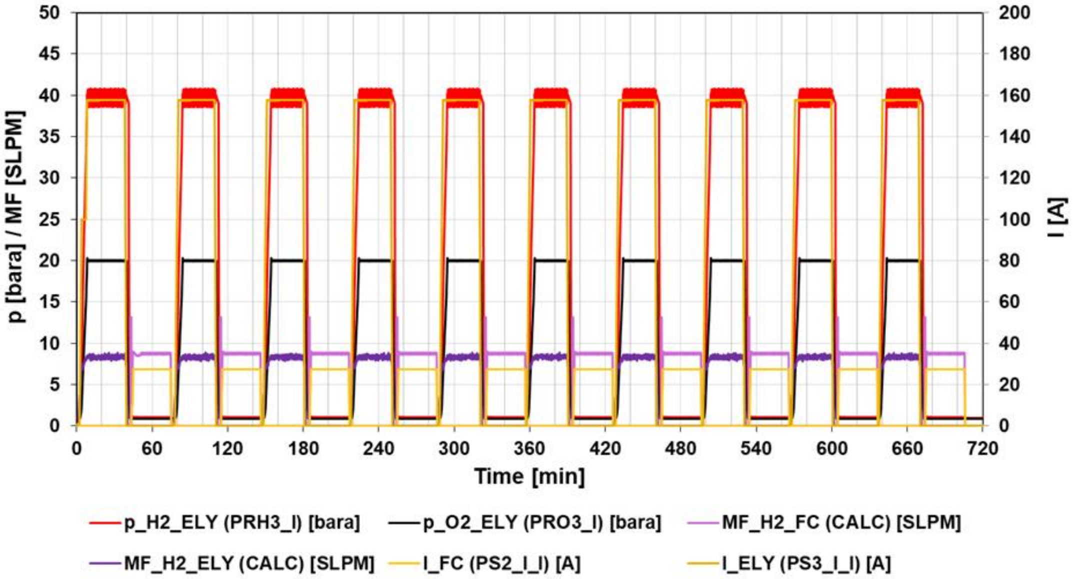

Figure 6: RFCS breadboard closed-loop cycle verification

Eleven of the twelve performed tests could be concluded successfully. The first failed test has been the startup procedure test of the ELY, which failed due to the exceeded startup time. This procedure time issue has been eliminated due to an optimized startup during the RFCS cycling procedure with a new startup time within the required time. The second failed test has been the efficiency assessment of the RFCS, which failed due to an underachieved RFCS roundtrip efficiency. The overall test campaign is yet concluded successfully due to significant results regarding the operating behavior and operating approach of the developed RFCS breadboard, and the achievement of the main goal of developing a closed loop operating RFCS breadboard. The resulting operating procedures are universally usable for PEM RFCS with equivalent working principles and easily adaptable to PEM RFCS with different working principles.

The developing of a closed-loop operating RFCS under laboratory environment is hence concluded successful within this activity.