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Executive Summary Report:

Fuel Cell Application for Future Mission

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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 five 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 electrolyzer 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.

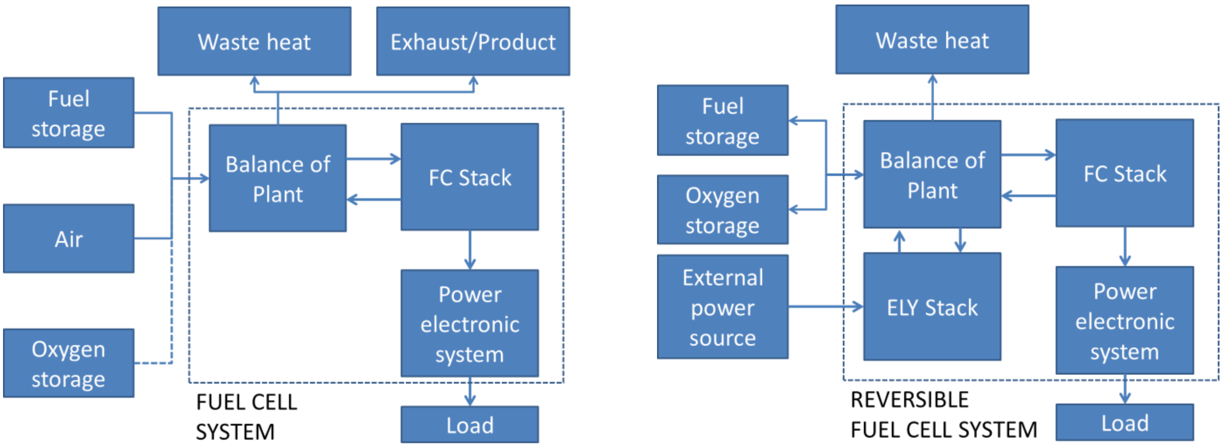

Figure 1: Overview layout of a PFCS and a RFCS

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.

Table 1: Overview of the key properties of the most relevant fuel cell technologies

Fuel Cell Type	Electrolyte	Operating Temperature	Fuel	Dynamic	Charge Carrier
Proton Exchange Membrane (PEM)	Ionic Polymer Membrane	10 - 200 °C	H_2	very high	H^+
Solid Oxide (SO)	Anionic Conducting Ceramic	650 - 1.000 °C	H_2, CO, short hydrocarbons	low	O^{2-}

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 scenarios for PFCS are summarized in Table 2.

Table 2: Scenario overview for PFCS

Scenario	Application	Power	Time	Conventional technology
P_Launcher_1	on-board energy supply for payload, communication, TVC	medium	short	primary or secondary battery
P_Satellite_1	N/A	N/A	N/A	N/A
P_Lander_1	asteroid / comet lander with refilling option at mother ship	low	medium	secondary battery
P_Lander_2	manned lander on Moon / Mars	high	medium	solar array, primary battery
P_Rover_1	robotic rover on shadowed surface (craters, Mars pole etc.) with refill option at a station	low	medium	secondary battery
P_Rover_2	heavy duty rover with refill option at a station	medium	long	secondary battery
P_Rover_3	manned rover with refill option at a station	high	medium	secondary battery
P_ Settlement_1	peak load covering, reactants are already available	very high	short	secondary battery
P_ Settlement_2	emergency system to bridge shadow periods, reactants are already available	very high	long	secondary battery
P_Spacecraft_1	long duration mission to the moon	high	long	solar array with secondary battery, primary battery
P_Spacecraft_2	shorter duration mission in earth orbit	high	medium	solar array with secondary battery, primary battery
P_Deep_Space_1	deep space probe runs out of solar power after Saturn	low	very long	RTG, primary battery
P_UAV_1	prolonged flight periods and short refueling phases	medium	medium	primary battery
P_UAV_2	bridge nighttime with refill every 72 hours	medium	medium	solar panel with primary battery

The promising scenarios for RFCS are summarized in Table 3.

Table 3: Scenario overview for RFCS

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

The 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.

As shown in Table 4, the rating system concluded that 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.

Table 4: Ratings of the considered power technologies regarding primary applications (higher = better)

Scenario	PFCS	Primary Battery	Secondary Battery
P_Launcher_1	4,1	4,8	0,0
P_Rover_1	4,4	4,3	4,2
P_Rover_2	4,2	3,8	4,3
P_Rover_3	4,3	0,0	3,9
P_Settlement_1	4,2	0,0	4,3
P_Settlement_2	4,5	3,9	3,9
P_Spacecraft_1	4,3	3,9	4,1
P_Deep_Space_1	4,1	3,9	0,0
P_Lander_1	4,4	4,3	4,3
P_Lander_2	4,3	3,9	4,4
P_UAV_1	4,4	4,3	4,3
P_UAV_2	4,3	4,1	4,1
P_Spacesuit_1	4,1	0,0	0,0

As shown in Table 5, 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.

Table 5: Ratings of the considered power technologies regarding secondary applications (higher = better)

Scenario	RFCS	Secondary Battery
S_Rover_1	4,07	4,11
S_Rover_2	4,11	3,94
S_Settlement_1	4,10	3,94
S_Spacecraft_1	3,91	4,39
S_Spacecraft_2	3,99	4,26
S_Lander_1	4,11	3,94
S_UAV_1	3,98	4,01
S_Satellite_1	3,79	4,31
S_Satellite_2	4,02	4,31

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 components 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 components, 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 component. To speed up the future development of the system, components 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 component suppliers of the identified components 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 electrolyzer 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 components, 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 components 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 components, 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 components. The qualitative evaluation was carried out based on the usage of components 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 components. Here priority is given to low TRL components as they require maximum effort. Regarding fuel cell and electrolyzer 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 components, potential suppliers were identified, and wherever it was possible, suppliers were chosen with experience in modifying their product for space applications. An example of potential COTS is shown in Figure 2.

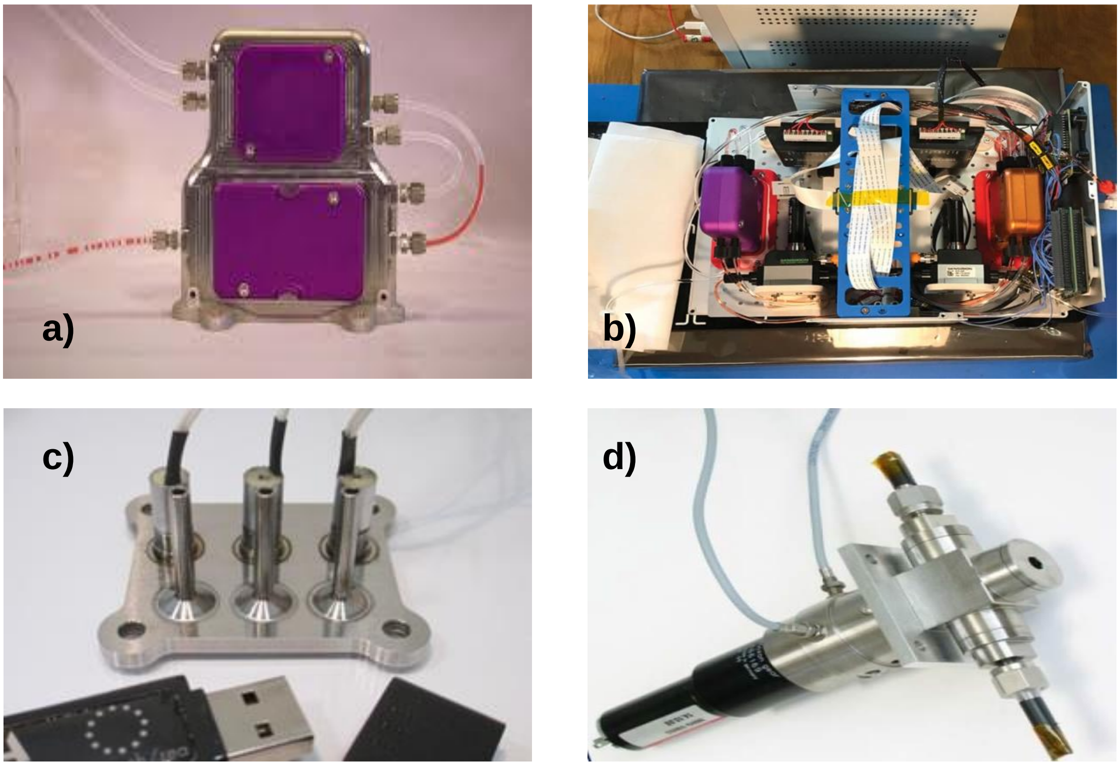

Figure 2: a) separator by ZAIPUT; b) separator bei ZAIPUT built in an ISS experiment; c) pressure regulator from AST d) ball latch valve from Omnidea-RTG

During the fifth step, a possible test strategy for the components and the complete RFCS in a breadboard assembly was developed. Moreover, the necessary assessments were carried out regarding the risks of operating such a complex system, that works with pure hydrogen and oxygen. The strategy used in this activity was to investigate the possibility of implementing terrestrial components off-the shelf into the breadboard to accelerate the successive phases of system development. The manufacturer specifications of these products may vary from the required specification of the RFCS, especially regarding electrochemical cells. This means that components must be tested individually or in very small sub-systems, to examine the quality and the performance of the products for the implementation in a RFCS. For each component, the testing must be carefully developed to produce high quality data. The future breadboard testing should also include investigations of the complete RFCS in both charge and discharge operations and continuous closed loop operation should be demonstrated.

The RFCS is a complex system with a large of number of components; each of them can constitute a source of error and failure. Such events could lead to dangerous situations for the hardware and, most important, for the operating personnel. An assessment of risks was carried out and the necessary safety precautions, both organizational and practical, were defined.

The plan for a potential test campaign for a RFCS breadboard assembly was provided. The test plan was designed on both a component level and a breadboard assembly level. Implementing COTS products means that the product was not designed specifically for the conditions required by the RFCS design and application. The performances of the components at the RFCS design point have to be investigated. Therefore, for each main component, a series of experimental setups and test designs was given in order to map its performances. After the testing of the single component subsystems, the breadboard assembly should be taken into consideration. The goal of these campaigns was to investigate the stable operation of the subsystem at the designed load point but also the transient phases, such as start-ups and shutdowns. The complete breadboard assembly has to be investigated to demonstrate the closed loop operation.