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Energy and provision management study: A research activity on fuel cell design and breadboarding for lunar surface applications supported by European Space Agency

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ABSTRACT

This paper addresses the findings of the European Space Agency (ESA) study (Energy and Provision Management Study), performed by an Italian consortium, aimed at designing and breadboarding of an Energy Provision and Management system (EPM), based on Polymer Electrolyte Fuel Cell (PEFC) technology. The EPM has been developed for supporting space exploration applications, specifically for lunar surface missions. The fuel cell technology has been selected through a trade-off activity, and the power requirements of a Lunar Base (LB) power plant and a Pressurized Lunar Rover (PLR) have been identified. A synergetic design of EPM has been proposed for both the LB and the PLR. Finally three technological demonstrators have been designed, manufactured and tested: i) a 1 kW PEFC stack, ii) a stand-alone power system based on the developed stack, iii) a regenerative power system based on the stand-alone stack connected with a commercial electrolyser. The tests carried out on breadboards, have demonstrated the ability of fuel cell power systems to meet the requirements of future space missions.

Introduction

The provision and storage of energy is of vital importance for the success of both manned and robotic space exploration missions. A wide range of mission types (robotic, human, In Situ Resources Utilization (ISRU) etc.) with a variety of different environments exist; from interplanetary space, to the shadow of a lunar crater, to the attenuated and red-shifted lighting on the Martian surface. For this reason, different power requirements must be met, and consequently, different power systems have to be used: e.g. solar, nuclear, battery and fuel cell [1]. The major power system challenges in solar system missions are related to the location, solar irradiance, environment and radiation. These challenges can be met if the power systems have long life, high specific power and high

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power capabilities, mass and volume efficiency, ability to operate in extreme environments, human rated safety and high reliability. The majority of space power generation systems use radioisotope and solar cells as power sources. Nuclear power systems use a radio isotope as heat source and a power converter to generate electric power from heat (Thermoelectric, Stiring, Thermo – photovoltaic) [2–4]. They are of key importance in dark and/or particularly cold environments, making them an enabling technology for many deep space and planetary missions [1]. Photovoltaic power systems are used on 99% of the space missions, especially in Earth and planetary orbital missions and in planetary surface missions. The capability of those systems ranges from 0.5 to 20 kW, the radioisotope power sources produce 4–5 W/kg with 6.5% of efficiency, the solar cells 30–60 W/kg and 9–26% of efficiency. Further development of these power sources is aiming to providing a significant increase in specific power: 500 W/kg in case of power solar arrays, 200 W/kg in case of nuclear systems. Moreover, operational capabilities, extreme temperature, high radiation and dusty environments tolerance, life, reliability and safety have to be enhanced. The described power generation systems are generally coupled with an energy storage system, that is used to provide primary electrical power to: launch vehicles, crew exploration vehicles, planetary probes, astronaut equipment, etc. Storage systems provide electrical energy during eclipse periods, satisfying peak power demands. The most important energy storage system technologies are primary batteries, rechargeable batteries and Polymer Electrolyte and Alkaline fuel cells, combined with an electrolyser (EZ) in a Regenerative Fuel Cell (RFC) energy storage system. At present, primary batteries are characterized by a specific energy of 100–250 Wh/kg and a mission life of 5–10 years. Rechargeable batteries are characterized by a specific energy of 8–100 Wh/kg, and life of 500–60000 cycles. Both of these technologies have limitation in operating temperature ranges and the radiation tolerance is not fully understood. Primary batteries generate a moderate specific energy, rechargeable batteries are heavy and bulky. For future planetary surface and orbital missions (i.e. Titan Saturn exploration mission, Mars exploration mission, Neptune orbiter, planned by 2018–2025), rechargeable batteries will have longer mission life (>15 years), higher specific energy (>150 Wh/kg), enhanced radiation tolerance and longer cycle life (>50000 cycles), primary batteries will have high specific energy (>600 Wh/kg) [2,3]. Considering the above discussed requirements, current power conversion and energy storage systems do not meet all future critical space mission needs. Because of the high energy density of Li-ion technology, which is expected to rise up to 160 Wh/kg, is attractive. However, even higher energy densities can be reached by fuel cells. Furthermore, the combination of hydrogen and oxygen is very promising to make an energy storage device with high energy density and to reuse the by-product water for the electrolysis reaction [5]. PEFC technology appears to be a promising technology for power generation in exploration missions, especially in situations involving the in-situ use of resources and large surface power plants, indeed, fuel cell systems have a potential for specific energy of >500 Wh/kg [6,1]. Also for space vehicle applications, PEFC technology offers major advantages over existing alkaline fuel cell technology. This includes enhanced safety, longer life, lower weight, improved reliability and maintainability, higher peak to-nominal power capability, compatibility with propulsion grade reactants, and the potential for significantly lower costs [7]. PEM – based RFCs have been proposed particularly in combination with solar arrays, due to their high energy density (400–600 Wh/kg). Primary Fuel cells (non-regenerative) are even more efficient than RFCs, providing energy density in the order of 600 Wh/kg to more than 1000 Wh/kg [1]. European space exploration takes place through the ESA [8], European industry and academia [9]. Among different space programs, the ESA's Aurora programme aimed at setting out a strategy for solar system exploration over the next 20 years. The programme and its principle were unanimously approved at the ESA council at Ministerial Level, held in Edinburgh (UK) in 2001. The final goal was to allow European astronauts to reach Mars by the end of the third decade of 21st century. Europe has visited the Red Planet and the Moon by Mars Express and Smart-1 robotic mission respectively. Similarly, ISS is giving Europe indispensable experience in human space flight for training humans to live in deep space for long periods of time. The technologies that are needed to explore the Red Planet with robots, and those necessary to sustain humans for years in hostile environments can be as diverse as: power and propulsion systems, life-support systems, long-term habitability module design, assembly in low earth orbit, rendezvous and docking in mars orbit, image recognition, automatic precision navigation, radiation protection, health monitoring, bio-protection. As part of Aurora programme, numerous studies have been carried out or are in progress: ISRU System and Technology Study, Energy Provision and Management Study, Superconductive Magnet for Radiation Shielding Study, Advanced Closed-Loop Systems (ACLS) for life support, MELiSSA (Micro-Ecological Life Support System Alternative), Black Water Treatment Breadboard and Exploration Robotics Requirements [10–13], to name a few. In this paper the activity of the EPM study is illustrated. On the basis of the discussed power requirements for future space exploration missions, a deep study and analysis on energy provision and management solutions has been performed, the activity focused on fuel cell technology.

In the next sections, the following item are described: a brief presentation of fuel cell, electrolysers and hydrogen storage technologies, the selection of the best technology for the EPM system via a trade – off analysis, the requirements and the sizing of energy provision and management systems for PLR and LB, the feasibility of the chosen technology by the designing, manufacturing and testing of three different demonstrators. The study has been performed under the ESA supervision, by an Italian consortium made up of CGS (Compagnia Generale per lo Spazio) and CNR – ITAE (National Research Council of Italy–Institute for Advanced Energy Technologies).

The fuel cell technology

Principles

Fuel cells (FCs) are electrochemical devices able to convert the chemical energy of a reaction directly into electrical energy. A