REGENERATIVE FUEL CELLS FOR MARS APPLICATIONS

M. Hörenz, S. Fasoulas, T. Schmiel, K. Zajac
Institute for Aerospace Engineering, TU Dresden
01062 Dresden
Germany

OVERVIEW

Different studies show that the giant lift-off mass is one of the most critical points for future Mars exploration, especially for return-to-Earth-missions. A possible solution is the utilisation of In-Situ resources. Especially carbon dioxide as the main component of the Martian atmosphere seems to be very interesting since it can be separated into carbon monoxide and oxygen (and it is everywhere on Mars available…). Both gases can be used as an efficient fuel-oxidiser-combination for any unmanned and even manned missions.

The carbon dioxide electrolysis can be realised with Regenerative Solid Oxide Fuel Cells (R-SOFC). This technology offers a wide range of applications. Different studies at the Institute for Aerospace Engineering (ILR, TU Dresden) showed the potential of the R-SOFC for fuel production and energy storage. Further links to the life support system and the waste management for manned missions, the thermal control system of any planetary station or to Mars rover systems might be possible.

This paper summarises the results of the mentioned studies showing the potential of this technology in more detail. For a better overview, the detailed calculations are not given here. However, the basic assumptions can be found in this paper. Furthermore, an overview for the next development steps is given.

1. INTRODUCTION

Fuel cells are mostly presented as ecological devices for energy supply in general. There are different types of fuel cells which all can produce vapour from hydrogen and air (or pure oxygen) without carbon dioxide emission. The inverse principle also seems to be feasible. An external voltage might realise the water electrolysis if suitable electrode materials can be found. This function offers the potential use of such systems for energy storage by operating it alternately in the fuel cell and the electrolysis mode. Hereby, the reacting components are not part of the systems itself (as for batteries). Therefore, they can be produced and stored "In-Situ".

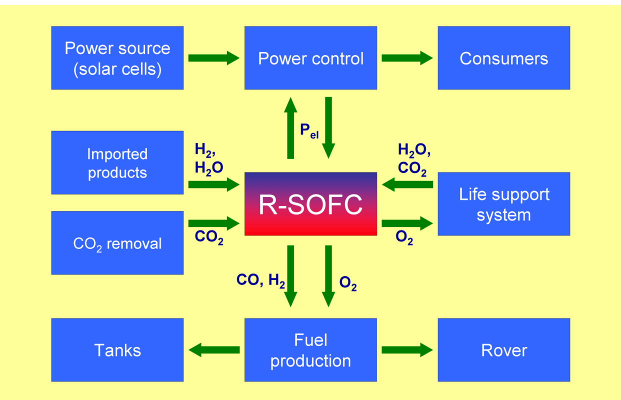

FIG 1. Potential applications of an R-SOFC.

The Solid Oxide Fuel Cell (SOFC) seems to be the best concept for several Mars applications since it can not only utilise water vapour but also carbon dioxide which is the main component of the Martian atmosphere (95%). This offers a variety of applications beside the energy storage: the fuel production for any earth return mission, the carbon dioxide removal and oxygen generation (life support system) or even for Mars rovers (see Fig. 1).

There are only a few studies known for the utilisation of this technology for the electrolysis – of water as well as of carbon dioxide. First tests of the carbon dioxide electrolysis were done at the Space Technologies Laboratory (STL, University of Arizona) [1,2]. Further investigations were performed at the Fraunhofer Institute of Ceramic Technologies and Systems (IKTS, Dresden) in cooperation with the Institute for Aerospace Engineering (ILR, TU Dresden) in 2002. These experiments demonstrated the principal feasibility of the water and carbon dioxide electrolysis with available IKTS fuel cells [3].

Different studies were then conducted based on the results of these experiments and additional theoretical investigations. The measured flow rates, current densities, power etc., can be used to evaluate the overall mass of different systems which can provide the information about the potential of this technology for Mars applications. The results of these studies are presented in the following.

2. FUNCTION OF AN R-SOFC

Solid Oxide Fuel Cells have a solid electrolyte which can conduct oxygen ions (O^{2-}) at temperatures above 650 °C. At the cathode, the inserted oxygen is transported to the boundary layer electrode – electrolyte (diffusion process). Yttria stabilised Zirconia (YSZ) is the most common oxygen conductor which is used as electrolyte. At the anode the oxygen ions can release their electrons by reacting with the fuel gas. The electrical current can be closed by an external consumer. In contrast to other fuel cell types, the ion conduction does not base on hydrogen. Therefore, different fuels can be utilised in principle, if the electrode materials are not poisoned. However, because of complex adsorption processes, the fuel should consist mainly of hydrogen and carbon monoxide. For other fuels, a pre-reforming process is necessary.

In the electrolysis mode, the mentioned processes are reversed. As electrolysis gases, only water (vapour) or

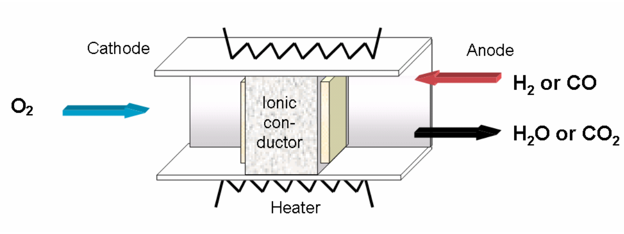

FIG 2. R-SOFC function (fuel cell mode)

carbon dioxide seem to be suitable which can be processed to hydrogen or carbon monoxide and oxygen.

The principle of the SOFC is studied since several decades. The market introduction can be expected in the next few years for a wide range of terrestrial applications [4]. The recent development steps focus mostly on minimised material degradation and long-term stability, the improvement of the performance, the gaskets as well as the utilisation of biogas as a fuel.

3. FUEL PRODUCTION ON MARS

The payload mass is very low for any Mars Mission with earth return when compared with the huge mass for fuels and rocket structures. The rocket stages for Mars orbit insertion and the earth return start also have to be accelerated at launch from earth. For such a mission, the following assumptions can be done:

- Crew of 4-5 astronauts
- Start from earth orbit, Hohmann transfer orbit to Mars
- Aerobreaking manoeuvre at Mars arrival (50% reduction of the Δv demand), orbit insertion
- Earth-Mars-Earth transfer vehicle stays in Mars orbit, crew transfer to the Martian surface and back with landing capsule (ascent/descent vehicle)
- Hohmann transfer orbit to earth
- Direct earth atmospheric entry

The launch mass can be reduced by utilising Martian resources for fuel production. Therefore, an additional fuel production plant would become necessary which fills empty tanks imported from earth during the Mars surface stay. Therefore, three options seem to be possible which can be compared:

1) No resource utilisation, import of all consumables from Earth
2) In-Situ resource utilisation of fuel and oxygen for crew launch in the Mars orbit (ascent/descent vehicle), import of fuel and oxygen for Earth return (transfer vehicle)
3) Fuel production on Mars for all phases of the Earth return.

Such a fuel production plant might consist of a solar cell array or a radio isotope generator for the energy supply and a R-SOFC producing carbon monoxide and oxygen from the Martian carbon dioxide. Long production times are favoured. The fuel production plant would be a small low-weight system because the power for the carbon dioxide electrolysis could become small due to lower production rates. It can be shown that the mass for such a mission scenario can be lowered by approximately 20% (see table 1).

Option	Import of all consumables	ISRU for Mars ascent stage	ISRU for Mars ascent and earth re-turn stages
1st stage: start from Earth orbit	1427 t	1320 t	1138 t
2nd stage: Mars orbit insertion	111 t	103 t	88 t
3rd stage: Mars ascent	12 t	2 t	50 t
4th stage: Earth return	76 t	76 t	12 t
Transfer vehicle		30 t	
Deorbit manoeuvre		0.5 t	
Transfer correction		1 t	
Landing capsule		6 t	
Fuel pro-duction plant	–	0.5 t	1 t
Total	**1663 t**	**1539 t**	**1326 t**

TAB 1. Comparison of different Mars mission scenarios

Another option offers hydrogen as a fuel if water is available for the electrolysis. However it is not sufficiently explored if water can be extracted from the Martian surface soil. In this case, the hydrogen has to be imported from earth. If hydrogen is used, it has to be considered that the storage is more complex. Liquefaction might be necessary. Due to the high efforts on hydrogen cooling, methane becomes interesting. Methane can be produced by imported hydrogen via the Sabatier process (see Fig. 3). This alternative is especially attractive if there are no systems available at the time of such a Mars mission which can process carbon monoxide and oxygen.

There are three options for different fuels which can be compared directly. For an earth escape and the Mars orbit entry, the combination hydrogen/oxygen was assumed. Option one (see table 2) would import all necessary fuels. In option two, different fuels can be produced for the Mars ascent. Option three would utilise the Martian resources for the complete Earth return. Option three with the use of hydrogen as fuel is the optimum in spite of importing hydrogen.

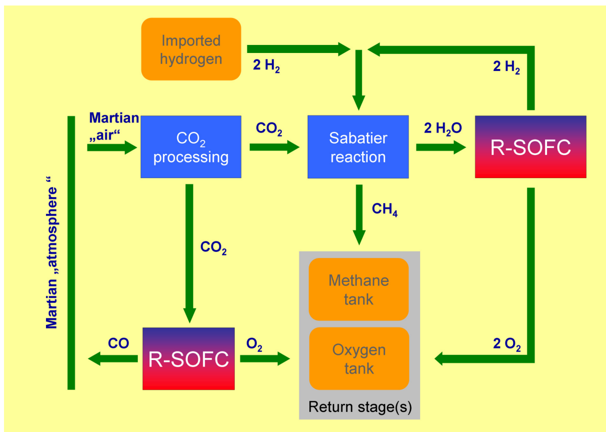

FIG 3. Production of methane and oxygen on Mars

Fuel	Hydrogen	Methane	Carbon monoxide
Option 1 (no ISRU)	1663 t	1707 t	1764 t
Option 2 (ISRU for stage 3)	1545 t	1558 t	1539 t
Option 3 (ISRU for stages 3 & 4)	1103 t	1145 t	1326 t

TAB 2. Comparison of different fuel options

4. ENERGY STORAGE

Beside the function as a pure electrolysis cell, the R-SOFC can be operated alternately in the fuel cell and the electrolysis mode. Such a system can be used for energy storage. During a Martian day (sol), a solar cell array could provide a fuel cell with energy. During this time, the R-SOFC could electrolyse carbon dioxide from the Martian atmosphere. After sunset, the fuel cell has to be switched in the fuel cell mode to supply a station's subsystems with electrical energy.

Based on the experimental data and theoretical investigations, the energy storage density can be determined for different power demands. This allows the comparison of an R-SOFC system with batteries. Li-ion batteries are state-of-the-art for energy storage in space. This type offers an energy density of about 100 Wh/kg [5]. However, the energy density is mainly influenced by the cycle life. A high cycle number allows only a low depth of discharge. Therefore, the effective energy storage density is much lower than 100 Wh/kg for most applications, especially for LEO observation missions. For comparison with an R-SOFC, the effective energy density should be reduced to about 50 Wh/kg for Mars missions with a surface stay of more than 100 days.

If only a small amount of energy has to be stored, no advantages are expected due to the high efforts on the system mass of the stack, the tanks and the periphery (controllers, pipes, measurement devices …) which are expected to be approximately 140 kg. However, if the energy storage demand is very high, the expected energy density is much higher because additional efforts on the system components are low. The variable part of the fuel cell system mass mainly consists of the gases and its tanks. The tank masses depend on the gases, the tank materials (stiffness and density) and additional safety factors. If hydrogen is used as a fuel, a titan tank might become about 30 times heavier than the fuel due to the low density of hydrogen. The oxygen tank has to be about twice as heavy as the gas. Therefore, additional 3 kg per kWh are required for the gases and the tanks. Nevertheless, a cryogenic storage or using metal hydrides seems to be not beneficial for the cyclic operation since there are additional efforts on the thermal system.

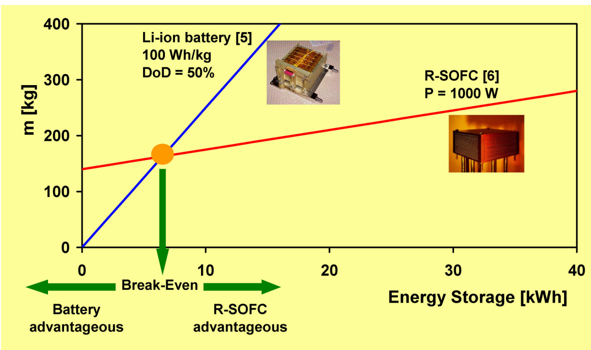

FIG 4. Comparison of an R-SOFC with a nominal power of 1 kW and CO_2 as electrolysis gas with a battery

It can be shown that a regenerative fuel would become advantageous at an energy storage capacity of about 5 – 10 kWh (Fig. 4). This break-even point depends mainly on the assumed safety factors, the fuel-oxidiser combination, the tank materials, and mainly on the power demand. It was found that the use of carbon dioxide instead of water offers additional advantages because the produced hydrogen would require very large tanks.

5. LIFE SUPPORT SYSTEM

Especially for manned space missions, closing of any cycle would be a key technology to minimise the supply mass for missions in earth orbit or to the moon. This fact is even more important for Mars missions because the launch mass can be lowered. The highest potential offers the oxygen recovery from carbon dioxide (respiratory cycle) as well as the water recovery. Both loops can be coupled with an R-SOFC:

- Electrolysis from carbon dioxide, oxygen recovery (partially)
- Utilisation of process water via electrolysis, recovery of pure water from hydrogen (link to the energy storage might be possible)

Especially the oxygen recovery can be considered. One crew member needs about 35 g oxygen and produces about 42 g carbon dioxide per hour. For a mission duration of about 500 days (minimum duration of a manned Mars mission) and a crew of five astronauts, there are about 2,100 kg of oxygen necessary. About 900 kg can be recovered by electrolysis. The produced carbon monoxide can be used in the attitude control system or for transfer correction manoeuvres. Due to the availability of carbon dioxide on Mars, the mass can be additionally reduced. Therefore, only 600 kg of oxygen has to be carried from earth. This offers mass savings of about 1,500 kg.

For a complete closed loop system, other technologies are additionally necessary. Therefore, a Sabatier reactor could be used in combination with a methane pyrolysis reactor (see Fig. 5). Both are under development at ASTRIUM GmbH as a part of the life support system "ARES" [7].

However, the introduction of an R-SOFC as an electrolyser instead of other low-temperature electrolysis

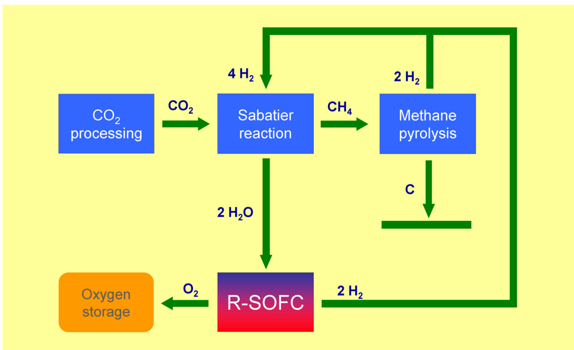

FIG 5. Introduction of an R-SOFC in the oxygen loop

systems seems to be not advantageous. Nevertheless, an R-SOFC could still produce oxygen in case of malfunction of another system. This makes this technology interesting for Mars missions where a high reliability and failure-safety are very critical points.

6. MOBILITY

Even for Mars rovers (unmanned as well as for manned missions) the introduction of an R-SOFC in the energy system might be an advantageous fact. Different options seem to be suitable:

– Energy supply by an external "loading" station, comparison between battery and R-SOFC for energy storage
– Energy supply by solar cells which are mounted on the rover, comparison between battery and R-SOFC for energy storage
– Refuelling with fuel and oxygen at a fixed station, comparison between a combination of R-SOFC and electromotor with a hydrogen combustion engine

As mentioned in section 4, a R-SOFC is potentially of interest for a long lifetime and a medium power demand. Fig. 6 reveals that a rover with an R-SOFC system shows advantages even for a maximum operation time of about 12 hours and a power of a few 100 W in contrast to battery systems. An effective energy storage density of 55 Wh/kg was therefore assumed for the battery system which is equivalent to a NiH_2-battery with full depth-of-discharge or a Li-ion battery with about 50% depth-of-discharge.

If the fuels can be directly supplied, common combustion engines might be the best option. However, there is no direct availability of fuels on Mars. They have to be processed by other technologies, e.g. the carbon dioxide electrolysis with R-SOFC.

Therefore, this technology seems to be interesting even for medium-sized rovers. For small rovers with a low power demand like Mars Pathfinder or the Mars Exploration Rovers, a common combination of solar cells and battery or radio isotope batteries would be better solutions.

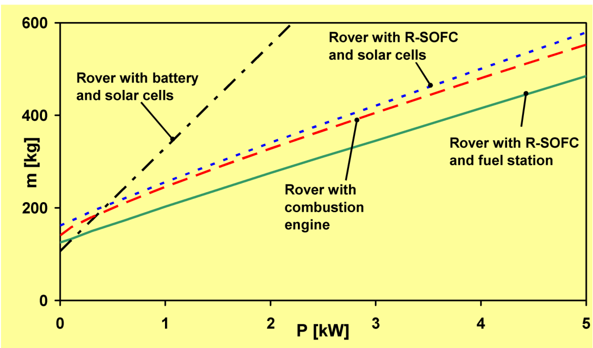

FIG 6. Comparison of different Mars rover options [8]

7. CONCLUSIONS

Different system studies were performed at the Institute for Aerospace Engineering to evaluate the expected advantages of a Regenerative Solid Oxide Fuel Cell (R-SOFC). Lower system masses, a higher safety against failure or even a better long-term reliability might be of main interest for future applications, especially for Mars missions. The main focus will be set on the carbon dioxide electrolysis which actually can not be realised in a satisfying way with any other system.

Nevertheless, it has to be mentioned that even for terrestrial applications there is no system which can be employed during the next months. Existing systems are designed for the use of hydrogen or biogas and air instead of using carbon monoxide and pure oxygen or even as an electrolysis cell. For a future introduction of the R-SOFC, several development steps have to be done as follows.

– Investigations on redox-stable electrodes
– Modification of existing fuel cells for long-term tests with CO/CO_2
– Experimental investigations and optimisation of the switching process between fuel cell and electrolysis mode
– Additional studies on to the periphery of the complete system (controllers, tanks, pumps …)
– Development of a demonstration model for long-term tests
– Design for space applications and space qualification

Acknowledgement
The support of this work by the European Space Agency and the Friedrich-und-Elisabeth-von-Boysen-Stiftung is gratefully acknowledged. An interuniversitary working group (TU Dresden, Univ. Stuttgart) was founded in order to promote the development of regenerative fuel cells.

8. LITERATURE

[1] Foerstner, R.: Characterisation of a Regenerative Solid Oxide Fuel Cell for Mars applications, diploma thesis in cooperation between the STL, University of Arizona and the Institute for Space Systems, Stuttgart, 1998
[2] Sridhar, K. H.; Miller, S. A.: Solid Oxide Electrolysis Technology for ISRU and Life Support, Space Technol., Vol. 14, No. 5, Elsevier, 1994
[3] Fasoulas, S.; Kuznecov M.; Otschik, P.; Schmiel, T.: Regenerative Solid Oxide Fuel Cell for Mars Applications, Report ILR-RSN02P05 Executive Summary of the Final Report ILR-RSN02P04, ESTEC Contract No. 16323/02/NL/LvH, December 2002
[4] Homepage of Staxera GmbH: www.staxerafuelcells.de (2007-01-26)
[5] Schautz, M.: Proba In-Orbit Battery Performance, ESA/ESTAC, 2005
[6] Homepage of the Fraunhofer-Institute for Ceramic Technologies and Systems: www.ikts.fraunhofer.de (2007-01-26)
[7] Homepage of Astrium GmbH, Department of Environmental Control and Life Support: www.ecls.de (2007-06-28)
[8] Hörenz, M.: Betrachtungen zur Nutzung einer regenerativen Hochtemperaturbrennstoffzelle im Antriebssystem eines Marsrovers, Diploma thesis ILR-RSN D 04-01, TU Dresden, 2004, results published in DLR-Jahrbuch 2004/III