Biomass Based Fuel Cells
- Application to Manned Space Exploration

Aarne Halme
Dept. of Automation and Systems Technology
Helsinki University of Technology
aarne.halme@tkk.fi

ABSTRACT

Long-term energy-demanding operations in remote off-the-grid locations, like in space exploration require small, lightweight energy storages and power sources that are able to preserve workable over long periods of time. In manned flights human secretions represent a potential source of methane and hence hydrogen, which can be used as fuel in fuel cells, or in propellant gas mixtures. Processing those secretions together with other biological wastes provides fuel from available resources, reducing fuel transportation from Earth, and contributes to waste disposal in long missions, like Mars exploration. Fuel cells, in particular biocatalyzed fuel cells, offer a potential solution to the problem of regenerating the available energy back to electricity by the aid of bacteria. They convert readily available substrates from renewable sources such as cereal materials, vegetable, fruits, fish meat and even human waste, to electricity and useful by-products such as water. Since the biocatalyzed fuel cells use concentrated sources of chemical energy, they can be small and lightweight, which is a crucial matter in the space application. There are in principle three ways to convert the biological energy available into electricity and heat. One way is a traditional anaerobic digestion producing methane and further process it to electricity/heat by the aid of high a temperature fuel cell like SOFC. Both of these technologies are already available in practical level, although application in the space environment needs further development. The second way is to use a bacterial biological fuel cell for direct electricity production. This technology is fairly new, but experimented already in several practical tests. The third way is to use biocatalyzed electrolysis or reforming to produce directly hydrogen, which can then be processed further into electricity by the aid of a low temperature fuel cell, like PEM. This is a very new, but promising innovation, which need still research to prove its feasibility. The paper make a short introduction to the underlying technology and compare energy balance of the two first mentioned ways to recover electricity from biological waste recycling in an imaginary case, where six astronauts live in a micro ecological life supporting system during their Mars mission.

1 INTRODUCTION

The planetary objects to be explored in future have very different environment from our earth. Some planets are covered with fluid; some moons or asteroids have icy or snowy; Some have (practically) no water and oxygen like our targeting planet – Mars. It means that most of energy, food and water sources should be transported from Earth or carried with the spacecraft although some part of energy could be received from solar and wind energy, and some part of vegetable could be grown in the spacecraft and in Mars. In order to reduce the burden to spacecraft, it will be very meaningful to have a micro ecological life support system especially in the mission period landing in Mars. The detail information could be found in the MELISSA project of ESA [1].

On the other hand, on a two and half-year trip to Mars, according to one estimate, a crew of six humans will generate more than six tons of solid organic waste -- much of it secretions. So what do we do with all that? Right now, astronaut waste gets shipped back to Earth. But for long-term exploration, it is good to recycle it, because it holds resources that astronauts will need. It will provide pure drinking water. It will provide fertilizer. Or a part of the biomass can be converted to electricity to help energy balance of the mission facilities, as we will see later on.

Human secretions represent a potential source of methane and hence hydrogen, which can be used as fuel in a fuel cell, or in propellant gas mixtures. Such a process would at the same time provide fuel from available resources, reducing fuel transportation from Earth, and contribute to waste disposal. The process converting human excrement and vegetable residues into methane, carbon dioxide and other gases is anaerobic digestion. It is a well-established process. It occurs naturally wherever high concentrations of wet organic matter accumulate in the absence of dissolved oxygen. The process takes place over a wide range of temperatures and with moisture content from 60 % to 90 % [2].

Fuel cell technology is becoming more and more important especially because of the high petroleum price nowadays. Fuel cells provide a range of critical benefits that no other single power technology can match [3].

A fuel cell converts the chemical energy of hydrogen and oxygen directly to produce water, electricity, and heat. They are therefore inherently clean and efficient and are uniquely able to address the issues of environmental degradation and energy security. They are also safe, quiet and very reliable. Fuelled with pure hydrogen, they produce zero emissions of carbon dioxide, oxides of nitrogen or any other pollutant. Even if fuelled with fossil fuels as a source of hydrogen, noxious emissions are orders of magnitude below those for conventional equipment. They offer significant improvements in energy efficiency as they remove the intermediate step of combustion and mechanical devices such as turbines and pistons. Unlike conventional systems, they operate at high efficiency at part load. Also, unlike conventional plants, their high efficiency is not compromised by small sizes. High efficiency saves fuel and reduces CO2 emissions.

Fuel cells can use hydrogen derived from a variety of sources, including natural gas and coal, and renewable substances such as biomass or, through electrolysis, wind and solar energy. Fuel cells offer the opportunity to customers with a value-added energy service at overall lower cost that is not subject to the same competitive or regulatory pressures as for conventional electric supply.

Biocatalyzed fuel cells (BFC) use biocatalysts instead of metallic catalysts used in chemical fuel cells. Biocatalysts could be micro-organism(s) or enzyme(s). The fuel is in general an organic substrate In biocatalyzed fuel cell the biocatalysts participate in the electron transfer chain between the fuel substrates and the electrode surfaces. Both fuel producing reaction and electrode reaction take place in the same container. The biocatalyzed oxidation of organic substances by oxygen or other oxidizers at two-electrode interfaces provides means for the conversion of chemical energy to electricity. Abundant organic materials such as methanol, organic acids or glucose and even organic waste, like vegetable residues and human excrements, can be used as substrates for the oxidation process.

Both methane and hydrogen are good potential fuels for the fuel cell systems. Biologically produced methane could be as well chemically reformed with a miniature reformer to produce hydrogen for the fuel cell. Atmospheric oxygen or peroxide, H_2O_2, can act as the oxidant being reduced in the electricity producing process within the fuel cell. In space exploration the fuel transportation from Earth should be minimized. A good solution for the electricity production is through a biocatalyzed fuel cell using organic waste, food residues and human excrements, as fuel. Since the composition of the substrate is quite complicate, enzymatic fuel cell may not be the best choice. One type of enzyme can only use one type of substrate and each enzyme usually has a specific optimum condition. Thus, the better solution would be a microbial fuel cell system, which is a more robust choice in this case.

A review of biocatalyzed fuel cells covering well the recent research can be found in [4].

Another interesting recent discovery is biocatalyzed electrolysis to produce hydrogen from waste materials [5]. This a very new promising technology, which uses the same principle as biocatalyzed fuel cells. The only difference is that instead to take out electricity from the cell we connect a reverse voltage to its terminals, close the cathode for oxygen and let protons to be reduced at cathode to produce hydrogen.

The case study reported in this paper is a shortened version of results from ARIADNA AO/1-4532/03/NL/MV [7] project, where we investigated two different routes for producing electricity by fuel cell systems from organic waste, in particular from human excrements, during an imaginary manned exploration of Mars. One of the route is based on producing first methane by the aid of digestion and transform it to electricity by a chemical fuel cell system. The second "direct" route is based on a biocatalyzed fuel cell system. A trade-off between the corresponding mass and energy balances is performed and discussed.

2 FUEL CELLS –A SHORT OVERVIEW

There are various types of fuel cell system available nowadays. According to the different features of the fuel cells, fuel cells are classified into: polymer electrolyte membrane fuel cells (PEM), alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), direct methanol fuel cell (DMFC) and biological fuel cells (BFC). They all operating with the same generic principle shown in Fig 1.

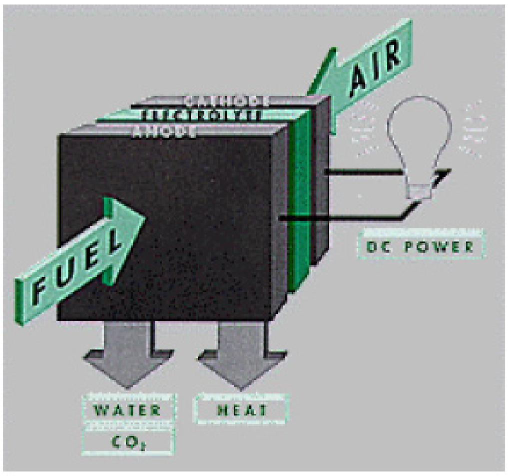

Fig.1. General principle of a fuel cell.

Chemical fuel cells can be further divided in categories according their operating temperature [6]

Low temperature fuel cells
- PEMFC
- DMFC
- AFC
- PAFC

High temperature fuel cells:
- MCFC
- SOFC

Most fuel cells operate with hydrogen gas. Exceptions are DMFC, which operate with liquid methanol, and high temperature cells, which operate also with more complex fuels, like natural gas/methane, co, or even diesel.

The reactions at the electrodes are different even if the overall reaction does not change, Fig 2.

AFC is the oldest technology, used already in 60's in Apollo program. Today development priorities are

- PEM in car industry and small CHP-plants…
- DMFC in electronics etc. applications
- high temperature fuel cells for CHP and larger power station applications

Fuel Cell	Anode Reaction	Cathode Reaction	Conducting Ion*
Alkaline Fuel Cell (AFC)	$H_2 + 2(OH)^- \rightarrow 2\,H_2O + 2e^-$	$1/2\,O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$	$(OH)^-$
Proton Exchange Membrane Fuel Cell (PEMFC)	$H_2 \rightarrow 2H^+ + 2e^-$	$1/2\,O_2 + 2H^+ + 2e^- \rightarrow H_2O$	H^+
Direct Methanol Fuel Cell (DMFC)	$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$	$1/2\,O_2 + 2H^+ + 2e^- \rightarrow H_2O$	H^+
Phosphoric Acid Fuel Cells	$H_2 \rightarrow 2H^+ + 2e^-$	$1/2\,O_2 + 2H^+ + 2e^- \rightarrow H_2O$	H^+
Molten Carbonate Fuel Cells	$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$	$1/2\,O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$	$(CO_3)^{2-}$
Solid Oxide Fuel Cells	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$	$1/2\,O_2 + 2e^- \rightarrow O^{2-}$	O^{2-}

Fig. 2. Electrode reactions of chemical fuel cells

Opposite to the chemical fuel cell, which is already 100 years old innovation, the biocatalyzed fuel cell is quite a recent one. The early studies are from the beginning of 90's. The basic idea is similar to PEM, but reactions take place in liquid phase and are catalyzed biologically either by living microbes or enzymes.

The principle of a bacteria catalyzed fuel cell is shown in Fig 3.

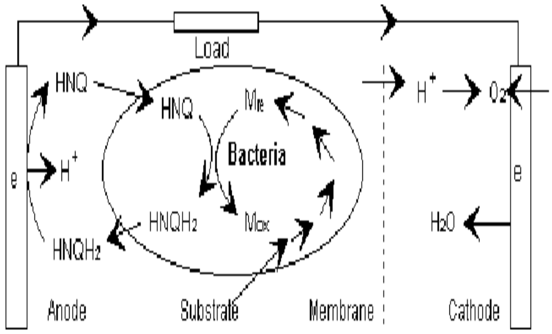

Fig. 3. Principle of a bacteria fuel cell

The biological catalysts cannot normally make redox reactions directly with electrodes, only by the aid of specific mediator chemicals (HNQ in Fig 3). This together with the fact that biological substrates are usually very complex compounds make the anode reactions usually more complex than in the case of chemical fuel cells. On the other hand, biocatalyzed fuel cells allow use a large variety of fuels – in principle all biologically decomposable substances can be used. All biological fuel cells operates in low temperature close to ambient temperature. This is an advantage in many cases. The main disadvantage is a low power density ~ 1 mW/cm2 compared to those of ~ 60 mW/cm2 in DMFC (operating also in liquid phase) and 300 – 400 mW/cm2 of PEM and high temperature fuel cells operating in gas phase.

An interesting recent discovery related close to biocatalyzed fuel cells is **biocatalyzed electrolysis.** The principle is shown in Fig 4. Same type of cell is used as in a PEM fuel cell, but the cathode compartment is closed and external power source is added to aid proton reduction to hydrogen at cathode. Electrical power needed is less than that of produced hydrogen, so it can be taken e.g from a fuel cell burning the hydrogen.

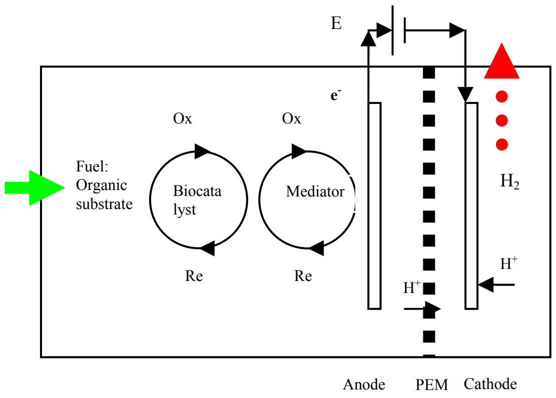

Fig 4. Principle of biocatalytic electrolysis

3 APLICATION TO A MANNED SPACE EXPLORATION SCENARIO.

In the ARIADNA project [7] we studied two alternatives to recovery energy from recirculation of waste biomass during a manned Mars exploration lasting 2,5 years.

Two alternatives were studied and compared technically including the calculated energy balances. One alternative was to start with anaerobic, process the biogas and finally produce electricity by the aid of chemical fuel cells. The other alternative was to use biological fuel cell technology, which provides a " direct way " to convert biomass to electricity. Both ways need a deeper analysis of the content of the biomass in the circulation. This in turn depends a lot on mission type, especially on the type of astronaut's diet. Especially amount of grown food is important, as inedible plant biomass plays a significant role in waste material circulation. During transit to Mars possibilities to grow food on space ship are very much different from those on Mars base. Also in the Mars base there are several different ways to build the astronaut's diet, which in turn has a great effect on amount and nature of circulating matter. The references [0] and [9] present 6 different diets of which one was selected to be a starting point for this study. The selected scenario is the 'Extended Base, All Plants Menu'. When moving on to 'Transit to Mars'-menu the ratio of grown food decreases and amount of packaged food increases. This increases the amount of packaging waste and decreases amount of plant biomass waste.

Two material flow models were characterized: input and output of a crew member, and input and output of plant growing facility. The third flow including input and output of the gasification/fuel cell systems can be characterized based on this information. For interest, the amounts of estimated inputs and outputs of an astronaut and the plant field per day are illustrated in the Tables 1-2.

Table 1

Input and output of an astronaut per day, Extended Base, All plants menu, limited to items applicable for fuel-cell study				
O2	0.83 kg		CO2	1 kg
H20 total *	27.58 kg		Feces + toilet paper (0.03 kg dry feces only)	0.053 kg (dry) 0.143 kg (wet)
Food (grown)	1.0 kg		Brine for urine	0.524 kg
Food (packaged)	0.565 kg		Brine for shower/ handwash/ sweat	0.254 kg
			Plant biomass (from harvesting, cooking and left-overs)	4.025 kg (wet)**
			Wet trash (paper, wipes, 10% humidity)	0.26 kg
			Dry trash (tapes, filters, packaging, misc.)	0.60 kg
* 97% of water is circulated. The rest 3% goes along with brines. ** Includes 10% of left-overs and 30% processing waste				

Table 2

Input and output of plant field per day (per person), limited to items applicable for fuel-cell study, Extended Base, All Plants Menu.			
INPUT		OUTPUT	
CO_2	0.735 kg	O_2	0.534 kg
H_2O	86.5 kg	Edible food	1.0 kg
Energy (light)*	69.7 k W	Non-edible biomass	4.0 kg
Needed area	26.8 m2		
*Energy (light) 2.6 k W/m2			

Table 3 summarizes the components of the waste biomass and its energy content.

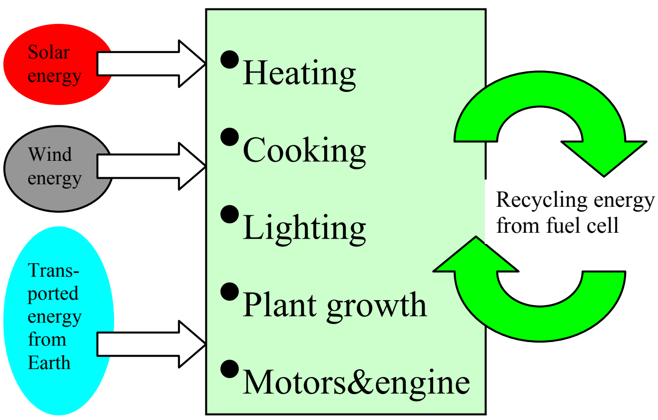

Fig 5. The overall energy system

Table 3

	One person	Six persons
Faeces		
Rate (kg wet/day)	0.150	0.900
Ash (kg/day)	0.0075	0.045
Biodegradable waste (kg dry/day)	0.030	0.180
Energy density (MJ/kg dry biodegradable waste)	11.8	
Energy (MJ/day)	0.354	2.124
Vegetable residues and others		
Rate (kg wet/day)	4.00	24.0
Biodegradable solid waste (kg dry/day)	1.22	7.32
Energy density (MJ/kg dry biodegradable waste)	17.5	
Energy (MJ/day)	21.35	128.1
Overall mass weight (kg wet/day)	4.150	24.90
Overall energy (MJ/day)	21.7	130.2
Overall solid biodegradable waste (kg/day)	1.25	7.50
Volume density (kg/m3)	300	
Overall volume (liter)	4.17	25.0

The overall energy balance of the Mars base is illustrated in Fig. 5. The biomass recycling and energy recovering are indicated by green arrows. Fig. 6 describes the principle of the anaerobic digestion/chemical fuel cell process line and Fig. 7 the biocatalyzed fuel cell process line. The efficiencies of individual components are rather well - know today. In spite of that, calculation of the energy balances are rather lengthy process. Details can be found in [7]. Estimation for the

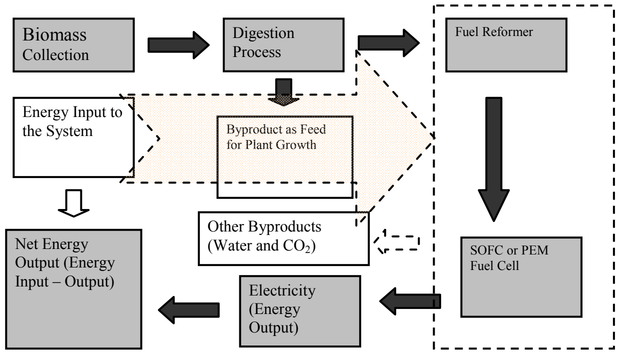

Fig. 6 Energy recovery process when using methanization , gas reforming and SOFC or PEM fuel cells.

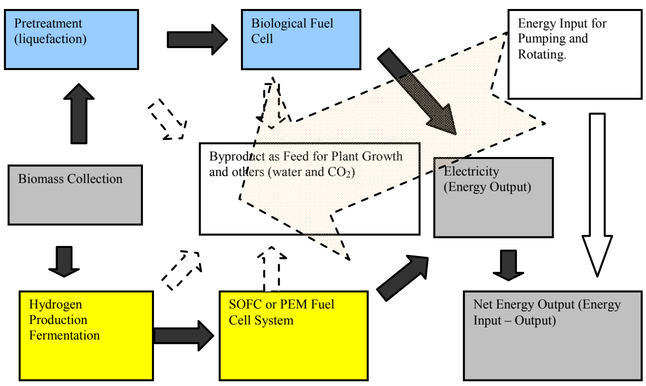

Fig. 7 Energy recovery process when using biocatalyzed fuel cells.

equipment volumes as well a preliminary design for the biocatalyzed fuel cell reactors can be also found there. Due to the low power density of the reactor the required volume may be a problem, but otherwise the biocatalyzed fuel cell line seems to be slightly better choice when comparing the energy balances and technical complexities of the lines. The calculated energy balances turn out to be slightly positive in both cases as shown in Table 4. Also the mass balances are interesting what becomes to life supporting system. All other substances except CO2 can be directly reused. At least part of the carbon dioxide can be reused in the greenhouse, but we did not estimated how much.

Table 4

Anaerobic digestion/reforming /fuel cell	**Biocatalyzed fuell cell**
Mass balance	Mass balance
Input: 7.5 kg biodegradable waste 6 kg oxygen **Output:** 1.5 kg methane (+4.1 kg CO2 + 1.9 kg compost) from AD process 4.1 kg Water + 3.3 kg CO2 from FC	**Input:** 7.5 kg biodegradable waste 3.5 kg oxygen (100 % converted) **Output:** 2 - 3 kg compost 3 – 3.5 kg Water 5 – 5.5 kg CO2 from FC
Energy balance	Energy balance
Input: 130 MJ/day in biodegradable waste **Output:** 26.2 MJ/day after AD process (20 % efficiency.) 5.2 – 7.8 MJ/ after FC system (20-30%efficiency) **Overall energy efficiency:** 4 – 6 %	**Input:** 130 MJ/day in biodegradable waste **Output:** 39 MJ/day from the BFC system 30 MJ/day consumed for the process 9 MJ/day (104 W **Overall energy efficiency**: 6.9 %

4 SUMMARY AND CONCLUSIONS.

Biomass energy can be recovered into electrical form when recycling biomass waste in micro ecological life supporting system during long space flights.
Net balance of recovery is not much but positive and seems to be slightly better when using biocatalyzed fuel cell technology than when using classical anaerobic digestion, reforming of biogas and chemical fuel cells.
A new biocatalyzed electrolysis to produce hydrogen directly from biomass seems very promising and may bring a new dimension to this analysis.
Chemical fuel cell technology is already quite ready for applications, but biocatalyzed fuel cells are still in their early infancy phase. Because of their potential usefulness in long lasting manned space exploration missions their technology should be studied and developed more.

REFERENCES

1. http://www.estec.esa.nl/ecls/?p=melissa.

2. Pipoli T., Feasibility of biomass based fuels cells for manned space exploration' Proc.'Seventh European Space Power Conference, Stresa, Italy, May 2005.

3. http://fuelcellworld.org/article_flat.fcm?articleid=13&subsite=1172

4. Bullen, R.A. & all, Biofuel cells and their development, Biosensors and Bioelectrionics 21 (2006) 2015-2045

5. Rozendahl, R.A. & all, Principle and perspective of hydrogen production through biocatalyzed electrolysis, International Journal of Hydrogen Energy 31 (2006), 1632-1640.

6. Fuel Cell Handbook, www.netl.doe.gov/technologies/coalpower/**fuelcells**/seca/pubs/FC**Handbook**7.pdf

7. ARIADNA AO/1-4532/03/NL/MV final report, ESTEC 18.10.2005

8.“ADVANCED LIFE SUPPORT SYSTEMS MODELING AND ANALYSIS PROJECT, MARS MISSIONS SOLID WASTE MODEL (REVISION A)”, Lockheed Martin Space Operations, Houston, Texas, Contract NSA9-19100, Prepared for National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas, February 2001, http://advlifesupport.jsc.nasa.gov/documents/simaDocs/MSAD-01-0156.pdf

9. “Advanced Life Support Baseline Values and Assumptions “ CREW AND THERMAL SYSTEMS DIVISION, NASA–LYNDON B. JOHNSON SPACE CENTER, HOUSTON, TEXAS, Document Number CTSD-ADV-484 A, JSC 47804, NASA CR-2004-208941, 16 August 2004 http://advlifesupport.jsc.nasa.gov/documents/SIMADocs/CR_2004_208941.pdf