FEASIBILITY OF BIOMASS-BASED FUEL CELLS FOR MANNED SPACE EXPLORATION

Tiziana Pipoli

ESA-ESTEC Advanced Concepts Team, Keplerlaan 1-P.O. Box 299, 2200 AG Noordwijk ZH – The Netherlands,
Email: Tiziana.Pipoli@esa.int

ABSTRACT

The increasing quantity of greenhouse gases in the atmosphere and the decrease in fossil fuels availability are driving massive investigation of alternative, sustainable energy sources for Earth applications. Among others, different processes for the conversion of biomass into useful fuels are under development or have been already implemented in various Countries.
The transfer of this technology to space is promising in view of the ambitious plans for future manned planetary exploration missions, where power generation represents a critical aspect.

Recycling organic waste increases the availability of fuel and at the same time reduces the issues of waste disposal and planetary protection.

This work presents a preliminary assessment of the feasibility of a biomass-based fuel cell system during a human mission to Mars.

1. INTRODUCTION

A considerable amount of waste will be generated during manned space exploration missions. Waste handling is a critical aspect of mission design, due to mass and volume limitations, potential crew's health problems and planets contamination.
Waste can be brought back to Earth or jettisoned after a stabilisation treatment via chemical stabilisation, sterilisation or lyophilisation [5]. Another approach envisages employing organic waste as raw material for the production of consumables as air and water for the crew in a Life Support System [3].
An alternative possibility is the conversion of organic waste to fuels, like methane, to be burnt for heating or cooking or to be fed into a fuel cell power system after reforming to hydrogen.

This paper describes the results of a preliminary theoretical investigation of the feasibility of the conversion of organic waste to biogas by anaerobic digestion. The project has been initiated by the ESA Advanced Concepts Team, in the frame of Ariadna Studies. Further investigation is currently ongoing. Photobiological, thermochemical, photochemical and photocatalytic technologies as alternative or complementary methodologies for biomass decomposition will be evaluated.

Limited information is available in literature about the selectivity and yield in biogas formation from decomposition of human manure. In order to acquire more precise data about the quality of biogas obtained from different substrates it is envisaged to investigate human manure, selected vegetables residues, waste and mixtures of all substrates separately.

The present work only estimates the production of biogas from faeces and total solid organic waste assuming an equal average efficiency of all substrates.
The preliminary results reported in this paper will be reviewed and completed according to the outcome of the abovementioned investigations.

2. ANAEROBIC DIGESTION

Anaerobic digestion is a well-established process based on the degradation of biomass by selected bacteria in an oxygen-free environment. 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 99%.
About 40 % to 60 % of organic matter is converted to biogas, a mixture of methane and carbon dioxide also containing some hydrogen, ammonia, and traces of hydrogen sulphide.
The composition of biogas varies subject to the substrate, reaction conditions and types of bacteria. A good quality biogas is composed of circa 65 % methane and 35 % carbon dioxide.

Conversion of organic substrate to biogas is performed through the symbiotic action of a complex consortium of bacteria, Fig. 1.
Hydrolytic microorganisms initially decompose complex organic wastes. Water-soluble components are fermented into short-chain volatile fatty acids, lactic acid, ammonia, carbon dioxide and hydrogen gas.
Fatty acids are converted in a second step into acetic acid with additional release of carbon dioxide and

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hydrogen. Finally biogas is formed by action of acetoclastic methanogens, which produce methane from acetic acid and by hydrogenotrophic methanogens, converting carbon dioxide and hydrogen into methane [1].

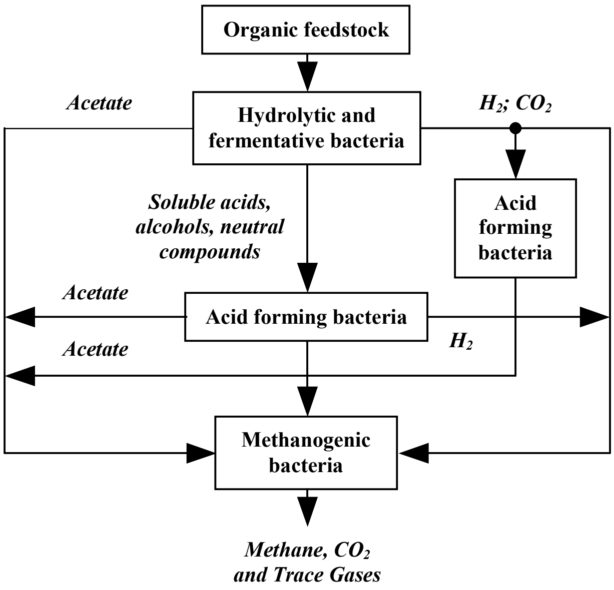

Fig. 1 Basic anaerobic digestion process schematic [1].

Hydrogen sulphide is produced by sulphate reducing bacteria present in the bacteria consortium. It can cause corrosion of reactors parts and pipelines and acts as strong poison for fuel cells and reformers catalysts.
In standard anaerobic digestion plants most of the hydrogen sulphide can be removed with iron and heavy metal salts to form insoluble sulphides, or on activated carbon filters, however traces of hydrogen sulphide remain in the biogas.

Conventional anaerobic digesters are designed to operate either in the mesophilic temperature range (20°C-45°C) or in the thermophilic temperature range (50°C-65°C). Higher temperatures allow higher loading rate of organic materials, since retention time is shorter, and enhance the destruction of pathogens.

Specific species of bacteria can be selected to optimise the process. Studies conducted in the frame of the ESA Melissa project have successfully investigated a consortium of bacteria naturally present in human faeces, under thermophilic conditions (55° C) at pH 8 [4].

3. BIOGAS-FUELLED SOFC SYSTEM

The biogas produced in the process described in the previous Section can be used as fuel in a high temperature solid oxide fuel cell system (SOFC).
The SOFC high operational temperature (600-800 ºC) in fact enhances the reactions kinetics enabling the use of non-noble metal catalysts as nickel, additionally it allows to use, beside hydrogen, carbon monoxide as well as different hydrocarbon fuels like methane, natural gas, and biogas.
The SOFC is furthermore less sensitive to contaminants as hydrogen sulphide than low temperature fuel cells.

The reactions taking place in a solid oxide fuel cell are illustrated in (1) to (3).

At the anode:

$$aH_2 + bCO + (a+b)O^{2-} \rightarrow aH_2O + bCO_2 + 2(a+b)e^- \tag{1}$$

At the cathode:

$$\frac{1}{2}(a+b)O_2 + 2(a+b)e^- \rightarrow (a+b)O^{2-} \tag{2}$$

Overall reaction:

$$\frac{1}{2}(a+b)O_2 + aH_2 + bCO \rightarrow aH_2O + bCO_2 \tag{3}$$

The methane contained in the biogas is reformed to hydrogen either in an external reformer stage or internally in the SOFC.

Methane reforming can be performed by addition of water steam (4), oxygen (partial oxidation reforming) (5) or carbon dioxide (6).

Water steam reforming:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \tag{4}$$

Partial oxidation reforming:

$$CH_4 + \frac{1}{2}O_2 \leftrightarrow CO + 2H_2 \tag{5}$$

Carbon dioxide reforming:

$$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2 \tag{6}$$

Additionally the water–shift reaction occurs parallel to the reforming reactions:

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (7)$$

Water steam and carbon dioxide reforming reactions are highly endothermic. The required heat can be provided by the heat released during fuel cell operation.
Partial oxidation reforming is a slightly exothermic process.

The possibility of internal methane reforming in SOFC permits to use the water/carbon dioxide produced at the anode to complete the reforming reactions, resulting in a simple and highly efficient system [9].

Pure carbon dioxide reforming requires a CO_2/CH_4 ratio of 10:1 above 600 ºC to avoid carbon formation [6]; since biogas only contains 30-40% of CO_2, either oxygen or water steam are usually added. The particular composition of Martian atmosphere (~95% carbon dioxide) would however permit to increase CO_2 content in the biogas by pumping it from the atmosphere, reducing the amount of oxygen/steam to be added.

3.1 Reference SOFC system

SOFC stack modules ranging from 1 kW up to 1 MW are currently being built and tested in small cogeneration plants operated with biogas coming from anaerobic digestion plants. Simulations of small-scale biogas-fuelled SOFC cogeneration plants are reported in literature [6, 7, 8].

The analysis of an anode supported electrolyte solid oxide fuel cell with 0.35 W/cm^2 at 800 °C, fuelled with biogas from a farm (ca. 9kW LHV, 0.01 mol CH_4/s), is described in [6,7].
The stack is composed of 100 cells with 100 cm^2 electrode surface.
Gas reforming is performed with carbon dioxide contained in the biogas, (ca. 40% of biogas), and with oxygen from the air, with biogas:air feed ratio of 1:1. Stack heat is used to pre- heat the fuel and to maintain the reformer at stack operating temperature.
The fuel cell generates approximately 3.41 kW of electric power; showing 38.2% electrical efficiency and 46% thermal efficiency at 80% fuel utilisation. The total efficiency amounts to 84.2%.

This fuel cell system is taken as reference in the assessment of the operation time of a fuel cell fuelled by biogas on Mars. Simulation of a fuel cell system with carbon dioxide reforming stage, taking into account the actual composition of the biogas produced and the operating conditions on Mars is required in order to acquire more precise data.

4. BIOGAS PRODUCTION FROM HUMAN ORGANIC WASTE

The shown results are divided into biogas production from human faeces only and from total organic solid waste. It is assumed for simplicity that the efficiency of the process is equal for faeces and other organic waste.
The selectivity and yield in methane and hydrogen production of anaerobic digestion of the different organic substrates is under study.

Preliminary calculations of the quantity of biogas produced from human faeces are of based on the following assumptions:

- Average daily production of human manure: 0.12 kg/person, with average composition of 71% water and 29% dry matter [2] [4].
- Organic matter makes up 86% of dry matter [4].
- Hydraulic retention time: 20 days.
- Anaerobic digestion efficiency 50%.
- Produced biogas is composed of 65% CH_4 and 35% CO_2.
- The reactor remains at atmospheric pressure throughout the whole digestion process.

Results are obtained calculating the theoretical production of biogas by decomposition of organic matter.

Daily organic matter availability per person and correspondent amount of produced biogas are reported in Table 1.

Table 1. Daily biogas production per person from human faeces.

Persons No.	1
Wet mass (kg)	0.12
Dry matter mass (kg)	0.035
Organic matter mass (kg)	0.030
Biogas (mol)	0.58
Biogas volume (l)	12.99
Methane (mol)	0.377
Methane volume (l)	8.445
Carbon dioxide (mol)	0.203
Carbon dioxide volume (l)	4.547

Volumes are calculated at standard conditions, (1 atm, 0 ºC); under these conditions 1 mol of gas occupies a volume of 22.4 litres.

5. MARS EXPLORATION CASE STUDY

Two scenarios are considered to analyse the potential benefits of waste decomposition into biogas during human Mars exploration missions:

- An explorative mission flying a crew of six astronauts to Mars in 2033, with three members of the crew landing and staying on the surface of the planet for 30 days.
- A stable mission on the planet (> 15 months) with a community of 30 persons.

The first mission scenario has been baselined in the ESA Concurrent Design Facility “Human Missions to Mars” (HMM) Study, carried out in the frame of the Aurora Program [5]. The mission is planned as follows:

Earth–Mars transfer	207 days
Mars orbiting phase	553 days (30 days on the surface of the planet)
Mars-Earth transfer	206 days.

Table 2 reports daily organic matter availability and daily production of biogas from human faeces for communities of respectively 6 and 30 astronauts.

Table 2. Daily biogas production from human faeces for crews of 6 and 30 persons.

Persons No.	6	30
Wet mass (kg)	0.72	3.6
Dry matter mass (kg)	0.209	1.044
Organic matter mass (kg)	0.180	0.898
Biogas (mol)	3.48	17.4
Biogas volume (l)	77.95	389.8
Methane (mol)	2.262	11.31
Methane volume (l)	50.67	253.3
Carbon dioxide (mol)	1.218	6.090
Carbon dioxide volume (l)	27.28	136.4

The HMM Study [5] estimates additional production of solid organic waste, including food residues, inedible plants and paper waste amounting to ca. 0.1 kg/person per day.

The total organic waste production per person amounts therefore to 0.22 kg/day.

Daily potential biogas production based on total solid organic waste is shown in Table 3. For simplicity it is assumed that the additional solid organic waste consists of 100% organic matter and that anaerobic digestion efficiency is 50% as for the faeces substrate. The total organic matter amounts therefore to 0.13 kg/day per person. The same estimation is assumed for the long duration mission scenario.

Table 3. Daily biogas and methane production from total organic waste.

Persons No.	1	6	30
Wet mass (kg)	0.22	1.32	6.6
Dry matter mass (kg)	0.135	0.809	4.044
Organic matter mass (kg)	0.130	0.780	3.898
Biogas (mol).	2.518	15.11	75.54
Biogas volume (l)	56.40	338.4	1692
Methane (mol)	1.637	9.820	49.10
Methane volume (l)	36.66	220.0	1100
Carbon dioxide (mol)	0.881	5.288	26.44
Carbon dioxide volume (l)	19.74	118.4	592.2

The energy content corresponding to the quantity of biogas produced per day, based on methane lower heating value (9.97 Wh/l) is reported in Table 4.

Table 4. Methane daily production, energy content (lower heating value -LHV).

Persons No.	1	6	30
CH_4 LHV from faeces (Wh)	84.19	505.2	2526
CH_4 LHV from total waste (Wh)	365.5	2193	10966

The total amounts of biogas produced by 6 astronauts during the Earth-Mars travel phase and the Mars orbiting phase, prior to the descent of 3 crew members to the surface, are reported in Table 5, together with the correspondent methane lower heating values.

The Earth to Mars transfer phase lasts 207 days; the first and last opportunities to land on Mars occur respectively 267 and 703 days after launch.

Table 5. Estimated production of biogas during Earth–Mars transfer.

Days	Biogas from faeces		Biogas from total solid organic waste	
	Volume (m^3)	LHV (kWh)	Volume (m^3)	LHV (kWh)
207	16	104.6	70	454
267	21	134.9	90	585.6
703	55	355.1	238	1542

The biogas produced during the travel to Mars and during the period of time spent orbiting around the planet before landing would permit to operate a SOFC of the same type as described in Section 4 for respectively 11.7, 15.1 and 39.8 hours by biogas produced from faeces and for 50.9, 65.6 and 173 hours by biogas produced from total solid organic waste.

An anaerobic digester designed for a community of 30 persons during a stable settlement on Mars would supply approximately 2.5 kWh/day (methane LHV) form faeces and 11 kWh/day from total solid organic waste. This would roughly allow operation of the abovementioned 3.41 kW solid oxide fuel cell system for respectively 0.3 and 1.2 hours per day.

Storage of biogas would allow for continuous operation of the fuel cell for relatively extended periods of time, for example storing the biogas for 1 month would enable the continuous operation of the fuel cell for 9 hours with biogas produced from faeces and 37 hours with biogas produced from total organic waste.

The dimensions of the digester and in particular of the gas collector are very critical especially during travel from Earth.

The anaerobic digester volume is calculated by multiplying the daily volumetric load (taking into account waste dilution) by the hydraulic retention time.

The volume of the gas collector is dependent on the pressure at which the gas is stored; feasibility of biogas storage is hence dependent on the gas compression capability onboard the transfer vehicle.

During stable missions on Mars gas storage is less critical; bigger storage vessels can in fact be used.

In the case of the short mission scenario the solid residue remaining in the digester can either be compacted and stored or ejected as envisaged in the HMM study [5].

In the case of a stable settlement the residue can be used as fertiliser in a greenhouse, increasing the overall process efficiency.

6. CONCLUSIONS

Biogas production from human waste can represent a viable option as source of electrical power for small fuel cell systems during human planetary exploration missions.

The biomass-based fuel cell system could be employed as additional or back-up system for small-scale electrical power generation. Possible applications could range from EVA suit power generation to small-scale stationary plants.

This study considers a minimum amount of waste produced by the crew; a future envisioned stable missions on Mars would comprise large infrastructures and would for example enable growing plants for food production inside greenhouses. The organic waste quantity, and hence biogas production and electric power generation, will presumably be greater than assumed for this calculation.

The presented preliminary assessment of the feasibility a biogas-fuelled SOFC system for Mars will be reviewed with the outcome of further ongoing studies.

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