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Hybrid life support systems with integrated fuel cells and photobioreactors for a lunar base

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ABSTRACT

The development of regenerative and sustainable life support systems (LSS) is a basic prerequisite to realize human long-term habitation in space. An efficient and reliable LSS is of high importance for assembling a future research base on the Moon and for further human space exploration missions beyond Low Earth Orbit. Because of longer distance to Earth and longer transfer times new requirements appear for LSS operation and functionality in comparison to the International Space Station. The minimization of resupply mass is a crucial factor to cope with this challenge. Regenerating the main media oxygen, water, and carbon as well as demonstrating a closed loop are essential milestones for an efficient and sustainable LSS. The logical step between partly regenerative physico-chemical and bioregenerative LSS is a so-called hybrid LSS characterized by the crosslinked integration of physico-chemical and simple biological system components.

The Institute of Space Systems of the University of Stuttgart (IRS), the Institute of Technical Thermodynamics (ITT) of the German Aerospace Centre (DLR) and the Fraunhofer-Institute for Interfacial Engineering and Biotechnology (IGB) work together in a project on advanced LSS research and development. The IRS will investigate the integration of a photobioreactor (PBR) for algae cultivation as biological component and a reversible proton exchange membrane fuel cell (PEFC) as physico-chemical component into an LSS. Algae in the PBR absorb the carbon dioxide exhaled by the crew and produce biomass (food) and oxygen under light influence. The oxygen can be directed either into the crew cabin or into the fuel cell for generating electricity. Vice versa the electrolysis process splits water (from the PBR or the fuel cell process) into oxygen and hydrogen used as energy storage or propellant. Main task at IRS is a feasibility study on the mentioned technologies, considering the capability of media and product regeneration as well as the ability of integration of the components into a system. Synergies, mass reduction, dissimilar redundancy, and safety enhancement must be taken into account in order to specify integration problems and filtration costs. The IGB supports this study by its expertise in PBR operation, algae cultivation, and algae species selection. The ITT investigates the coupling of the PBR with three different fuel cell types: namely PEFC, SOFC (*Solid Oxide Fuel Cell*), and AFC (*Alkaline Fuel Cell*) under electrochemical performance aspects. The influence of PBR products on performance and lifetime of the different fuel cells is of high interest. The potential of potable water and electrical power supply is considered.

1. Introduction

Main destinations of human spaceflight in the first half of the 21st century are the return to the Moon and a crewed mission to Martian surface. Further new challenges beyond Low Earth Orbit, where the International Space Station (ISS) is sited, are reaching Near Earth Objects and the Sun–Earth- and Earth–Moon-Libration points for service missions on space telescopes. The next mission step after the ISS might lead to setting up a permanently crewed lunar base. Such a long-term mission of at least ten years in a distance to Earth of 386,000 km generates new challenges in human space system design. The subsystems have to be developed for meeting new requirements and constraints like higher radiation dose, wider temperature ranges, different gravity conditions, longer transfer times, more extensive resupply missions, demand of higher reliability, and safety.

The life support system (LSS) must allow for humans to survive in space and maintain them in good health, thus its design is a crucial factor for the success of a human mission. For long-term missions, synergies and redundancies must be regarded for saving resupply mass and enhancing system reliability as well as

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Abbreviations

AFC	Alkaline Fuel Cell
AOCS	Attitude and Orbit Control System
CM	Crewmember
CO_2	Carbon Dioxide
DLR	German Aerospace Centre (*Deutsches Zentrum für Luft- und Raumfahrt*)
EDC	Electrochemical Depolarized Concentrator
EPS	Electrical Power System
ESM	Equivalent System Mass
FC	Fuel Cell
H_2	Hydrogen
H_2O	Water
HSIR	Human Systems Integration Requirements
IGB	Institute for Interfacial Engineering and Biotechnology (*Institut für Grenzflaechen- und Bioverfahrenstechnik*)
IRS	Institute of Space Systems (*Institut für Raumfahrtsysteme*)
ISS	International Space Station
ITT	Institute of Technical Thermodynamics (*Institut für Technische Thermodynamik*)
LSS	Life Support System
n.a.	not available
O_2	Oxygen
PBR	Photobioreactor
p/c	physico-chemical
PC	Power Conditioning
PEFC	Polymer Electrolyte Membrane Fuel Cell
PV	Photovoltaic
SOFC	Solid Oxide Fuel Cell
SR	Sabatier Reactor

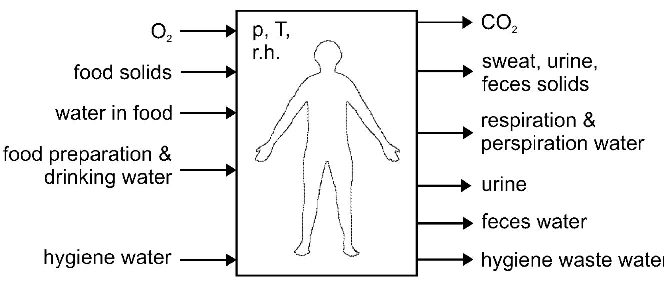

Fig. 1. Human needs – basic parameters for LSS design.

Table 1
LSS strategies.

LSS strategy	Description
Open	Human needs completely provided by direct supply
Physico-chemical (regenerative)	Human waste partly recycled by physico-chemical technologies
Hybrid	Human waste partly or completely recycled by physico-chemical and biological technologies
Bioregenerative	Human waste recycled using biological technologies (higher plants, fish, animals)

crew safety. The LSS must supply human needs, remove human waste, and provide for a habitable environment (pressure p, temperature T, and relative humidity *r.h.*), see Fig. 1 [16]. The LSS can schematically be divided into five main tasks:

- air management for carbon dioxide (CO_2) removal, CO_2 reduction, oxygen (O_2) regeneration, and trace contaminants control,
- water management for water processing (filtration, recycling, preparation),
- food management by direct supply or in situ production (e.g. cultivation of algae, higher plants, or animals),
- waste management by collection or recycling,
- safety management referring to fire detection, radiation protection, and reliable component operation.

Depending on how human needs are provided for and how human waste is handled, different LSS strategies are characterized by the mass flows and the way of recycling. In Table 1, four different LSS strategies are described [4,14].

A quantitative analysis of these four types is conducted by using the method of equivalent system mass (ESM). It considers all mass impacting factors during the mission duration t_M. This method has

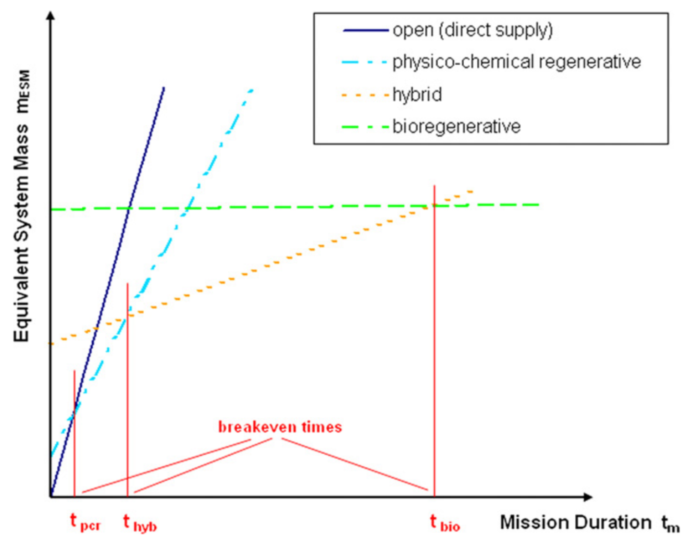

Fig. 2. Comparison of different LSS strategies by ESM.

been established for the decision-making process in the design phase of a mission to estimate the most efficient and reasonable LSS strategy. A detailed description can be found in [15]. The initial system mass is defined at $t_M = 0$ and is equal to the launch mass. The linear slope represents the degree of required resupply in mass per time unit. An open LSS has approximately no system mass, but a high slope that yields a fast increase of ESM, whereas a bioregenerative LSS has a huge launch mass, but nearly no resupply. Bioregenerative life support will not be available in the next 50 years, as there is much fundamental research to be done. Therefore, the next logical steps are p/c and hybrid LSS. The breakeven points in Fig. 2 mark the mission duration time, when one LSS strategy has to be preferred to another LSS strategy. The breakeven time is calculated by

$$t_{breakeven} = \frac{m_{sys,\{1\}} - m_{sys,\{2\}}}{m'_{\{2\}} - m'_{\{1\}}} \tag{1}$$

where m_{sys} is the system mass and m' the required resupply. The two opposed LSS strategies are indicated as {1} and {2}. Breakeven points identification of different LSS strategies were investigated in several studies before. The main results are summarized in Table 2 and show a wide variation of the calculated breakeven times. While in [2] the breakeven time of p/c regenerative and hybrid LSS t_{hyb} is negative (= not existent), other studies indicate it between

Table 2
Past studies on breakeven times of LSS strategies.

LSS strategy	{1}	Open	p/c (reg.)	p/c (reg.)	Hybrid*
	{2}	p/c (reg.)	Hybrid*	Bioreg.	Bioreg.
Breakeven time		t_{pcr}	t_{hyb}	–	t_{bio}
Jones, 2006	[12]	256 d	29 a	44 a	80 a
Doll, Eckart, 2000	[2]	n.a.	not existent	not existent	n.a.
Hanford, 1997	[10]	n.a.	6 a	15 a	30 a
Drysdale et al., 1992	[3]	131 d	n.a.	1.5 a	n.a.
Gustavino, 1991	[9]	n.a.	n.a.	4 a	7 a
Gustan et al., 1983	[8]	0	6 a	7 a	10 a

* Hybrid here means to provide 50% of human food need by biological technology. It is not specified what kind of technology and how it is integrated in the completes LSS.

Table 3
Minimum and expanded mass inputs and outputs of human needs [11,13].

	Minimum (kg/day)	Expanded (kg/day)
Input		
O_2	0.93	0.93
Food solids	0.70	0.70
Water in food	1.29	1.29
Food preparation & drinking water	2.50	2.50
Hygiene water	0.40	25.40
Total input	5.82	30.82
Output		
CO_2	1.12	1.12
Sweat, urine, feces solids	0.12	0.12
Water from respiration & perspiration	2.45	2.45
Urine	1.62	1.62
Feces water	0.10	0.10
Hygiene waste water	0.40	25.40
Total output	5.82	30.82

six and 29 years. The most recent study on ESM comparisons, assuming conservative data for ESM parameters and a plant growth chamber for higher plants, concludes that "space life support research and development in support of the Vision for Space Exploration should concentrate on physical/chemical life support for the foreseeable future" [12].

All the studies rely on complex biological components for cultivation of higher plants for cultivation of fish in aquatic systems. The p/c LSS is either replaced completely by a bioregenerative LSS or partly replaced assuming 50% of food production by biological components. Current life support research is focused either on p/c strategy or on biological strategy. Not yet considered is a crosslinked integrated system with p/c and simple biological components to benefit from advantages of both strategies. This hybrid LSS approach reduces the disadvantages in mass and complexity of bioregenerative LSS and yields a significantly lower t_{hyb}. Hence, for a lunar mission, hybrid LSS are an efficient alternative to p/c LSS.

A lunar mission consists of the different mission elements: transfer, ascent/descent, and habitation. Transfer and ascent/descent are performed by a Crew Exploration Vehicle, which is not permanently in use, and which returns regularly to Earth. The characteristic mission duration is a few days. Consequently, the LSS of the Crew Exploration Vehicle can be designed as an open LSS. For descent and ascent, a vehicle is only operating for a few hours enabling the transfer between lunar orbit and lunar surface. The LSS is proposed to be open. Thus, p/c regenerative and hybrid LSS are utilized for habitation on the lunar surface. The LSS basic parameters of Fig. 1 are specified in Table 3, and are the basic requirements for lunar base LSS design.

The minimum mass flows are given for an average male crewmember (CM) of 45 years, weighing 84.2 kg with a daily metabolic intake of 12,707 kJ. These values conform to human survival in space. The expanded flow requirements allow for more hygiene water (shower, urinal flush, clothes, dish wash). This means a higher comfort for the crew and is justified on long-term missions to enhance habitability and health.

2. Objective

This paper describes a feasibility study currently running at the Institute of Space Systems of the University of Stuttgart (IRS), in cooperation with the Institute of Technical Thermodynamics (ITT) of the German Aerospace Center (DLR), and the Fraunhofer-Institute for Interfacial Engineering and Biotechnology (IGB) on hybrid LSS development with crosslinked integrated fuel cells (FC) and photobioreactors (PBR). As shown in Table 1, the investigated hybrid LSS contains p/c and biological components. Mass savings and safety enhancement by synergies and dissimilar redundancies for O_2 and food production are expected.

To realize a hybrid LSS the system components must meet the following requirements:

- regeneration of media and products,
- possibility of crosslinkage, and
- component's own requirements as low as possible.

A reversible FC system as p/c component and a PBR system for algae cultivation as simple biological component are identified as the best candidate technologies. They handle important mass flows of an LSS, namely O_2, water, and food as evident by Eqs. (2) and (3).

A reversible FC is able to work in fuel cell mode and in electrolysis mode. Different concepts of reversible fuel cells are described in [17]. To differ between reversible and regenerative FC systems the following definitions are made:

- reversible FC system: *open system, mass flows go in or out*,
- regenerative FC system: *closed system, no mass flows go in or out*.

The mass flow of an FC is given by the chemical equation

$$2H_2 + O_2 \rightarrow 2H_2O + E_{el} + E_{th} \tag{2}$$

where E_{el} is the generated electrical energy and E_{th} the released thermal energy. The electrolysis process is described by Eq. (2) vice versa, E_{th} has to be put on the product side.

The mass flow in an algal PBR is derived from the photosynthesis equation

$$6CO_2 + 12H_2O + E_{h_\nu} \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O + E_{th} \tag{3}$$

where E_{h_ν} is the spent light energy, E_{th} the released thermal energy of this process, and $C_6H_{12}O_6$ the biomass.

The feasibility study is justified by calculations on mass savings and breakeven times as well as by very good prospects for satisfying qualitative criteria. The following ESM study is based on human needs of Table 3, adding a required food packaging of 0.62 kg/day. A maximum of about 30% of the food solids can be substituted by algal biomass as shown in [6]. This parameter is the driver for PBR sizing and maximum CO_2 uptake by the PBR system. It is defined as

$$\varphi = \text{dry algal biomass consumption/human need of food solids.} \tag{4}$$

At first, the maximum resupply mass savings are calculated as the ratio of regenerated mass to input mass of human needs. Considering the PBR implementation only O_2, food solids, and food

Table 4
LSS technologies and specifications of ESM parameters, partly from [15,12].

Technology	Mass (kg/CM)	Volume (m^3/CM)	Power (kW_{el}/CM)	Cooling (kW_{th}/CM)	Resupply (kg/(CM·a))	Human needs (kg/(CM·a))	
SPWE	28.3	0.04	0.37	0.37	3.20	40.15	O_2 (not regenerable)
4BMS	50.3	0.10	0.22	0.22	0.00	255.5	food
SR	4.5	0.19	0.01	0.04	0.00	226.3	food packaging
PBR	300.0	0.33	1.00	2.10	143.15		
EDC	12.0	0.02	0.01	0.09	0.00		
Mass equivalency factor	1 kg/kg	215.5 kg/m^3	228 kg/kW_{el}	146 kg/kW_{th}			

packaging are relevant. Algal biomass substitutes 30% of the food solids and consequently 30% of the food packaging that is no longer required. The regenerable amount of 0.82 kg O_2 is derived from the stoichiometric ratio of 1.12 kg CO_2. The maximum resupply mass savings is

$$\Delta m_{sav,\max} = \text{regenerated mass}/\text{human needs masses} = 0.52 = 52\%. \tag{5}$$

Hence, implementing regenerative systems for CO_2 recycling and algal food generation, the maximum resupply mass savings are 52% in comparison to direct supply.

ESM consideration includes mass impacting factors: volume, power, cooling, and resupply are all converted into mass unit by mass equivalency factors [15]. The ESM equation is given by

$$ESM = m + V \cdot m_v + P \cdot m_p + C \cdot m_c + m' \cdot t \tag{6}$$

with the mass of the system m (not to mix up with the system mass m_{sys}), the volume of the system V, the power demand of the system P, the cooling requirement of the system C, and the resupply m'. The mass equivalency factors are m_v, m_p, and m_c. The baseline LSS corresponds to the LSS of the ISS specified in [12]. The PBR system and an Electrochemical Depolarized Concentrator (EDC) for CO_2 separation of the exhaled air substitute (partly) the p/c components of air management Solid Polymer Water Electrolysis (SPWE), Four Bed Molecular Sieves (4BMS), and Sabatier Reactor (SR). The components and mass equivalency factors are given in Table 4. The PBR parameters were taken from [6], a CO_2 uptake of 1.12 kg/d is assumed. A dry algal mass production rate with respect to φ is required. For $\varphi = 0.3$, it is 0.21 kg/d. An algal cell density of 15 g/l and a resupply of 143.15 kg/a (sum of spare parts: 10% of the PBR mass and nutrients of 113.15 kg/a) are assumed. The calculated CO_2 uptake and the exhaled CO_2 amount of 1.12 kg/d result in a scaling factor for the given PBR parameters in Table 4.

Three air regeneration strategies are now defined:

- p/c air regeneration by SPWE, 4BMS, and SR,
- bioregenerative air regeneration by PBR and EDC, and
- hybrid air regeneration by a φ-driven combination of both strategies.

The ESMs are calculated, the breakeven times determined with Eq. (1). The results are summarized in Table 5. For $\varphi = 30\%$, the breakeven time ($t_{hyb,air}$) is 1.96 years and significantly lower than the breakeven times listed in Table 2. The breakeven times for changing from p/c to bioregenerative air regeneration strategy ranges from 5.5 to 120 years. The value of 5.5 years results from the assumption that the half of the required food solids is replaced by algal biomass, what is currently too high. Results for $t_{bio,air}$ are negative, so breakeven times are not existent. Variation of φ does not show a linear decrease of $t_{hyb,air}$, rather $t_{hyb,air}$ decreases at first and then increases. A higher φ does not automatically yield a lower $t_{hyb,air}$. There is a minimum for $t_{hyb,air}$ at $\varphi \approx 40\%$.

Table 5
Breakeven times for air regeneration strategies.

Air regeneration	{1}	p/c (reg.)	p/c (reg.)	Hybrid*
	{2}	Hybrid*	Bioreg.**	Bioreg.**
Breakeven time		$t_{hyb,air}$	–	$t_{bio,air}$
$\varphi = 30\%$		1.96 a	120 a	not existent
$\varphi = 40\%$		1.57 a	10 a	not existent
$\varphi = 50\%$		1.96 a	5.5 a	not existent

* Hybrid here means to provide 30% or 40% of the food need by biological technology.
** Bioregenerative here means to take up the complete amount of CO_2 by biological technology.

Table 6
Breakeven times for $t_{hyb,air}$ dependent on φ and PBR system mass savings.

φ	PBR system mass savings			
	0%	10%	20%	30%
30%	1.96 a	1.63 a	1.30 a	0.96 a
40%	1.57 a	1.30 a	1.04 a	0.77 a
50%	1.96 a	1.63 a	1.29 a	0.96 a

Thus, an increase of φ from 30% to 40% results in more efficient air regeneration than an increase from 40% to 50%.

A further consideration shows decreasing breakeven times for PBR system mass savings by optimization and design improvements, see Table 6. This can be reached by two approaches:

- biological research on more efficient algae species and cultures that enable a higher cell density and higher φ, and
- technical research on lighter materials and optimized PBR design.

PBR system mass savings from 10% to 30% yield a decrease of $t_{hyb,air}$ from 1.96 years to 0.96 years. Assuming $\varphi = 40\%$, $t_{hyb,air}$ even decreases to 0.77 years. So, $t_{hyb,air}$ of less than one year is achievable. Resupply mass savings are calculated to 18%. Another study, that compared advanced p/c LSS as a baseline system, found resupply mass savings of 16% by PBR implementation [6].

This ESM consideration was an estimation of a PBR implementation which neglected the following aspects that should be taken into account for future calculations:

- H_2 mass savings by a smaller SR: H_2 requirements for the EDC are significantly less than the mass savings, because H_2 requirements of the EDC are four times less than H_2 requirements of the SR to regenerate the same amount of CO_2 [4].
- Synergies and water regeneration by implementation of a (reversible) FC for power production and energy storage as well as potable water production.

The crosslinked integration of a (reversible) FC will affect additional decrease of t_{hyb}. Concluding, hybrid life support with integrated PBR and (reversible) FC is more efficient than assumed in earlier studies (Table 2).

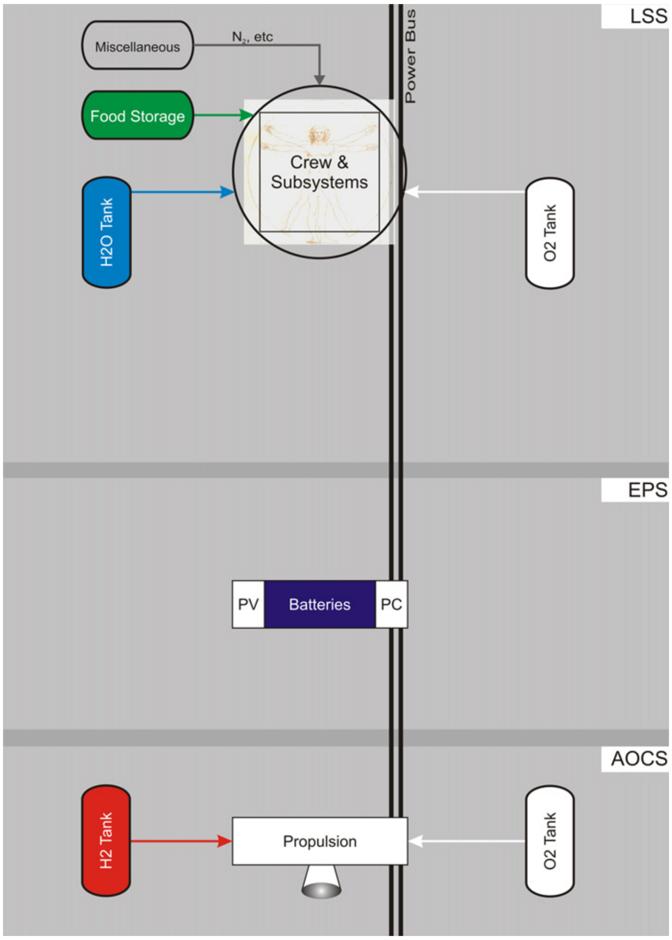

Fig. 3. Non-integrated system.

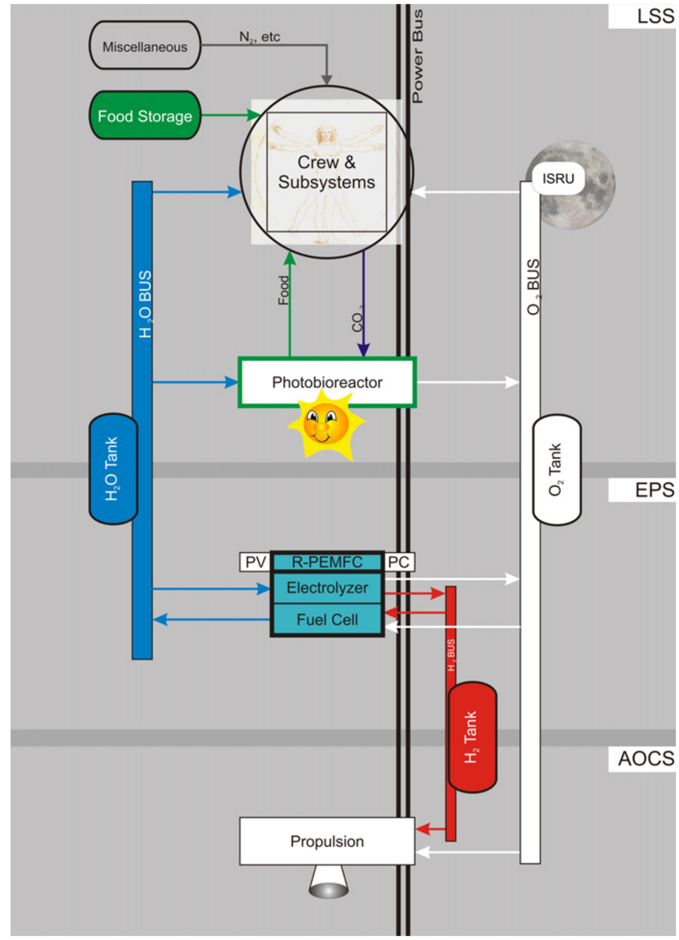

Fig. 4. Crosslinked integrated system with reversible PEFC and PBR.

3. Integration concepts

A crosslinked integration of reversible FC and PBR in an LSS enables utilization of synergies between the LSS, the Electrical Power System (EPS), and the Attitude and Orbit Control System (AOCS). Figs. 3 and 4 point out the difference between a non-integrated system like the ISS and a crosslinked integrated system with reversible FC and PBR. The non-integrated system provides for each subsystem its own technologies and components. Photovoltaic cells (PV) are used to produce electrical power. Batteries store electrical energy. The AOCS and the LSS have their own mass tanks for the required media. There are no mass flows between the subsystems. The crosslinked integrated system realizes an integration of reversible FC and PBR. It allows for mass flows between the subsystems, especially mass flows of H_2, O_2, and water. The subsystem components are supplied by a common tank and bus system. There are different components producing O_2 and water, so dissimilar redundancies are created and synergies can be efficiently utilized.

The installation of common tanks and buses enables sharing the infrastructure especially for O_2 and water. Investigating and determining the influence of products and trace contaminants between reversible FC and PBR are the central issue of the current feasibility study. The critical factors have to be identified in order to take appropriate measurements like filtration.

A closer look at mass and energy flows between reversible FC and PBR is shown in Figs. 5 and 6. The gas bottles are figurative for the mass buses. The reversible FC is split into the FC and electrolysis process. The FC process produces water that is fed to the PBR while the PBR produces O_2 that is fed to the FC, as shown in Fig. 5. The electrolyzer and the PBR work redundantly. Produced H_2 is stored either for later FC use or for AOCS use as propellant. Thus, for identification of influence of products and trace contaminants between reversible FC and PBR it is sufficient to investigate the mass flows between FC and PBR. For this reason, experimental investigations will be carried out on an FC and a PBR. The main crosslinkage characteristics are summarized in Table 7. The FC process can be influenced by gaseous trace contaminants from the PBR. Vice versa the PBR can be influenced by impurities in the FC product water. The PBR culture medium – water with nutrients and metabolic products – must be recycled and purified from time to time. It is improbable that impurities of the PBR water reach the electrolysis process and is therefore not considered in the experimental part of this study.

The following system engineering tasks will be performed by the IRS:

- LSS design, modelling, and analysis (numerical investigation),
- setting up a hardware-in-the-loop test rig for a PEFC and a PBR (experimental investigation),
- gas and water analyses.

The experimental results will be used for setting up a hardware-in-the-loop test environment. The FC and PBR systems are operated in a simulated LSS environment, so that operational experience can be obtained. The ITT is coped with investigations on electrochemical performance of different FC types loaded with PBR products. Capability and efficiency of the three types AFC, PEFC, and SOFC, are evaluated, respecting that the PEFC was already part in Gemini, as well as the AFC was part in Apollo and is still in use on the US Space Shuttle. The SOFC is not space

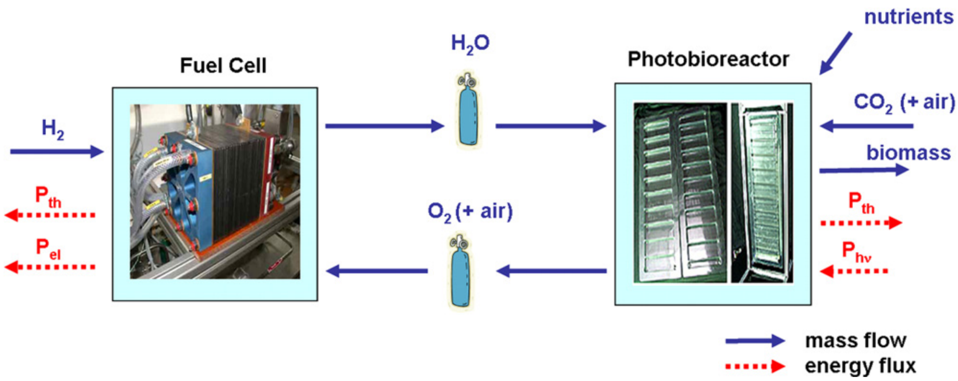

Fig. 5. Flow pattern for coupled FC and PBR.

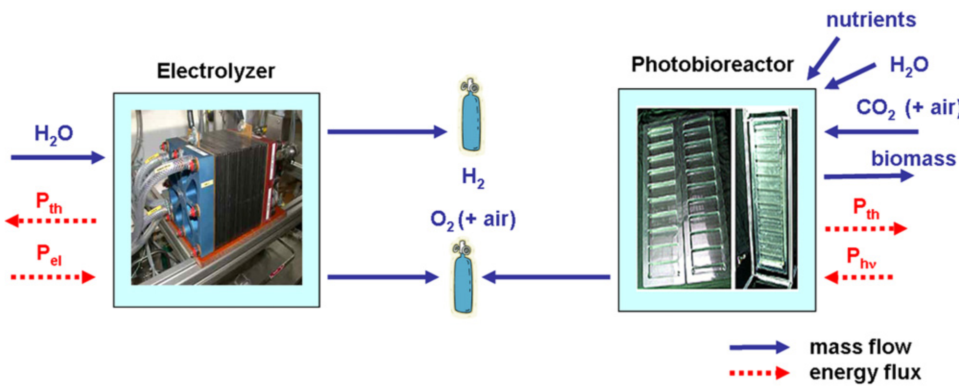

Fig. 6. Flow pattern for coupled electrolyzer and PBR.

Table 7
Characteristics for coupling a reversible FC with a PBR.

	Mass flow	PBR	Crosslinkage
FC process	H_2	⇐ (only for H_2 *producing algae*[*])	*Gaseous trace contaminants by PBR*
	O_2	⇐	*Gaseous trace contaminants by PBR*
	H_2O	⇒	*Impurities in water by FC*
Electrolysis process	H_2	*Redundancy* (only for H_2 *producing algae*[*])	*Safety enhancement*
	O_2	*Redundancy*	*Safety enhancement*
	H_2O	⇐[*]	*impurities in water by PBR*

⇐ Flow direction out from PBR.
⇒ Flow direction into PBR.
[*] Not subject of the feasibility study.

proved yet, but considered for long-term missions, see [5,18]. At the IGB the terrestrial design of the selected PBR was developed, a flat plate airlift reactor design with a high surface-to-volume ratio and consequently efficient mass-to-volume ratio. The IGB provides biological support for algae cultivation and selection in order to achieve the optimum of CO_2 reduction, O_2 generation, and nutrient rich biomass production. The different investigation aspects for the FC and PBR are described in the following section.

4. Investigation aspects for fuel cells and photobioreactors

Investigation aspects for FC and PBR in a crosslinked integrated hybrid LSS are derived from input and output mass flows from and to the shared infrastructure:

- influence of trace contaminants in the oxidant gas from the PBR on the FC,
- quality of the FC product water and possible influence of contained impurities on the algae,
- accumulation of microbial organisms and residual media on the electrode in the FC system,
- recycling of used PBR water,
- PBR gas input,
- micro- and low gravity adaptation of the PBR design, and
- biological and nutrition scientific research on efficient algae species and cultures.

Investigation of the influence of trace contaminants in the oxidant gas from the PBR on the FC is the first step. It consists of produced O_2, non-consumed CO_2, and water vapour. The algal metabolism and adjacent nutrients reactions release organic and inorganic trace contaminants. Inorganic substances like sulfur, chlorine, nitric compounds and organic substances (CH- and CHO-compounds) have to be specified by mass spectrometry, coupled gas chromatography/mass spectrometry, and flame ionization detection. The three different FC types AFC, PEFC, and SOFC will be loaded with the contaminated oxidant gas in order to determine the influence on power and degradation processes. Further investigations on FC optimization are planned after required filtration measurements have been found and implemented.

The product water of AFC, PEFC, and SOFC is directed to the shared water storage and is available for water consuming systems including the PBR. It must be analyzed and compared with water requirements. The FC types are operated primarily with non-contaminated oxidant gas and secondly with contaminated oxidant gas. An analysis of PEFC and SOFC product water was conducted at the ITT. The results are given in Table 8 and compared with Human Systems Integration Requirements (HSIR) limits [11]. The list is not complete, but focused on most important human quality pa-

Table 8
FC product water analysis, HSIR limits from [11].

Quality parameters	(Investigation) results		
	PEFC	SOFC	HSIR limits
pH-value (–)	6.4	9.8	5.5–9.0
Conductivity (µS/cm)	18.2	60.2	n.a.
Chemicals			
Aluminum (mg/l)	< 0.01	0.055	0.05
Ammonia (mg/l)	< 0.02	18.6	1
Calcium (mg/l)	ex.	ex.	high
Chloride (mg/l)	< 1.0	1.2	250
Chromium (mg/l)	< 0.01	< 0.01	0.05
Copper (mg/l)	< 0.01	< 0.01	1.0
Iron (mg/l)	< 0.01	ex.	0.3
Potassium (mg/l)	ex.	0.055	340
Magnesium (mg/l)	0.085	< 0.01	high
Manganese (mg/l)	< 0.01	< 0.01	0.3
Sodium (mg/l)	ex.	ex.	20
Nickel (mg/l)	4.4	0.005	0.3
Lead (mg/l)	< 0.01	< 0.01	0.05
Platinum (mg/l)	< 0.01	–	n.a.
Zinc (mg/l)	< 0.01	0.036	2.0
Microbials			
Microbial count (CFU/ml)	10 to 100	10 to 100	50

rameters. The PEFC values for chemicals are very good except for nickel which is nearly 15 times higher than allowed for potable water. This is probably attributed to corrosion of the metallic bipolar plates. The SOFC exceeds marginally the pH-value and aluminum limit. Analyses of organics and inorganics were conducted. Phthalate, ethyl citrate, phenols, alkenes, diphenylamine, and more organic and inorganic contaminants were detected but not quantified. Further analysis will investigate if the values are under the HSIR limits. The microbial amount in both FC product waters is probably too high. The analytical results show a range between 10 and 100 CFU whereas the HSIR limit is 50. For the PBR harmful organic and inorganic contaminants must be identified to determine efficient filtration methods. Microbial organism might poison the algal culture. Although microbial growth is limited to potable water quality levels in the water storage system by sterilization procedures, surviving microorganism once inside the PBR might multiply due to the favorable environment.

The three FC types have different operation temperatures: the PEFC and AFC are operated between 50 °C and 120 °C, so long-term operation might offer a pleasant environment for microbial growth in the FC system. The crucial conditions must be identified how to avoid microbial growth.

Harvesting of algal biomass produces considerable amount of waste water stemming from spent culture medium and biomass processing. The waste water is polluted by algal metabolic products, nutrient compounds and dissolved volatile gases. To identify pollutants, waste water is analyzed and appropriate recycling methods are determined. The recycling requirements include, besides HSIR limits, the limitations of water consuming systems as electrolyzer or the PBR itself.

The allowable CO_2 limit of less than 1 vol.% in the cabin air is lower than required for efficient cultivation of algae. The PBR operates either with pure or diluted CO_2. An inert gas as nitrogen is used for dilution, if the pH-value of the algal culture medium is too low. The CO_2 has to be filtered from the cabin air. Depending on the filtration method, trace contaminants in the CO_2 gas and their influence on the algae culture have to be analyzed.

The PBR design and operation concern various engineering aspects:

- micro- and low gravity adapted PBR design,
- phase separation technology,
- PBR operation mode, and
- lighting technology.

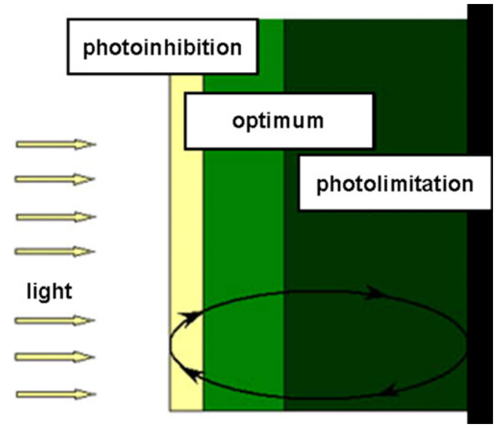

Fig. 7. Light zones and photo activity description [1].

Considering mass and volume requirements, a PBR design with high surface-to-volume ratio and high productivity as well as high cell density are mandatory. Light penetrates dense algae cultures only a few millimeters leaving algae in depth in eternal darkness. A circulation of the culture medium is required to transport the algae at a frequency of at least 1 Hz into the lighted zone, utilizing the flashing light effect [1]. In Fig. 7 the different light zones are shown. Pumping culture medium through the PBR, the circulation is induced by static mixers incorporated in the PBR design. Dealing with two-phase flows the mixer geometry must also prevent accumulation of gas inside the PBR. The two-phase flow arises from the required O_2 generation rate exceeding the O_2 saturation limit of the culture medium consisting mainly of water. In order to separate O_2 from the fluid flow phase, a separation technology is needed.

Ensuring steady O_2 and biomass generation rates, continuous operation of the PBR is preferred to batch operation. In continuous operation the cell density is kept at a constant level of maximum biomass productivity. New generated biomass is extracted from the PBR at a rate coinciding with productivity. Fresh culture medium is provided at the same rate. Batch operation starts with low cell density and the fresh generated biomass remains in the reactor until the maximum cell density is reached and the entire culture is harvested. A new batch culture is started afterwards. Batch operation results in cycling O_2 and biomass generation rates. Because of the low O_2 generation rate at the beginning of each batch the cultivation in single PBR chambers must be staged in order to provide continuously O_2. Cultivation staging results in higher PBR volume and mass. On the other hand, the low O_2 generation rate might be compensated by p/c components. In both cases, system mass savings compared to p/c system are not possible.

The selection of an efficient lighting technology depends on the mission scenario and the availability of solar light as well as eclipse times. A lunar base located at a peak of eternal light is able to utilize solar light for almost the entire mission duration. Visible light of the solar spectrum is captured by concentration devices and led to emitters inside the PBR via optical fibers. A lunar base at the equator means to have eclipse times in a 14 day cycle. Artificial light might be used or algal growth is suspended. Past studies indicated that artificial lighting is very energy intensive and has a significant impact on the EPS as well as on thermal control. It is advantageous to suspend algal growth during eclipses [6]. Considering future advances in light-emitting diodes efficiency, the application of artificial lighting has to be reexamined.

Table 9
Algae criteria for space application.

Criteria	Minimum value
Productivity	9 g/(l·d)
Specific CO_2 consumption rate	16 g/(l·d)
Specific O_2 generation rate	11 g/(l·d)

Concerning the biological research, capable algae species must enable high productivity and grow at high cell density to achieve reasonable system masses and volumes. This results in high specific CO_2 consumption and O_2 generation rates. Table 9 summarizes the minimum values required for space application under appropriate lighting.

Algae species are further selected for their nutritional value. They are able to add high quality protein, minerals and vitamins. Numerous studies demonstrated that *Chlorella* species contain all amino acids and vitamins required by humans. But unprocessed algae may cause digestive problems and deleterious effects on several body functions depending on species and amount [7]. Algae must be processed to serve as valuable and consistent nourishment for the crew. The selection and selective breeding of algae species satisfying the criteria described as well as processing methods are subject to further research.

Other issues that are important but not addressed here include culture degeneration and cell mutation in long-term cultivation in space environment as well as shelf life of inoculation cells to renew the culture after prolonged eclipse durations or system failure.

5. Conclusion

Long-term habitation in a lunar base requires the development of regenerative and sustainable LSS. Open LSS and high resupply mass cause too high costs because of the long transfer times. Regenerative LSS can be realized by a p/c, bioregenerative, or hybrid strategy. Hybrid LSS with crosslinked integrated p/c and simple biological components are evaluated as the most efficient and encouraging LSS concept for a lunar base. Reversible FC as p/c component and PBR for algae cultivation are the candidate technologies due to high integration ability. ESM considerations on air regeneration and food production result in a breakeven time of less than two years for a hybrid LSS compared to a p/c LSS. Thereby 30% of human food need is provided by algal biomass. Increasing this value to an efficiency maximum of 40%, the breakeven time is even less than one year. Dissimilar redundancies affect safety enhancement, a qualitative advantage over a p/c LSS. Earlier studies on hybrid LSS assumed very complex biological components and therefore, they resulted in higher breakeven times and system masses.

A feasibility study at the IRS in cooperation with the ITT and IGB is currently conducted in order to identify crucial factors in a crosslinked hybrid LSS. Integration concepts are investigated by numerical simulation and experimental investigation on FC and PBR test rigs. Both investigations and results will be unified in a hardware-in-the-loop simulation. By this approach, reliable data will be obtained to conclude the feasibility study that subsequently should result in a spaceflight experiment.

Hybrid LSS are an advantageous step for human space exploration beyond Low Earth Orbit, life support for a lunar base can be realized efficiently. Thus, space life support research and development should concentrate on integration concepts and component development for hybrid systems in the foreseeable future.

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