Life support system in the mature Martian colony for 1000 people

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Abstract. The development in the field of space engineering is aimed at achieving another milestone, which is the creation of an extraterrestrial colony on, for example, Mars. Missions of this kind will be long-term and long-distance, which results in the need to design systems with a high degree of self-sufficiency. It is synonymous with high recovery resources. This article is a concept proposed for the needs of the Mar Colony Prize competition – Design The First Human Settlement On Mars, created by The Mars Society. This competition assumed designing highly-autonomous base for 1000 people. This means, that all environmental systems must be connected with each other and work in closed loops. In this paper four main environmental systems are proposed and characterized. The state of art of each subsystems technology is presented.

1 Introduction

It is projected that Mars will be inhabited before 2050 [1]. It is a great challenge for technology aimed at supporting long-term life support of humans in extraterrestrial habitats. Successful habitation of Mars requires life support systems than can be autonomous for periods of 1000 days or more [2]. However, Mars gravitational acceleration (0.38 g), atmosphere composition (about 95.3% CO_2, 2.7% dinitrogen (N_2), 1.6% argon, and only 0.13% O_2), pressure (less than 1% the Earth's one), temperature (-150 to +20ºC), and low solar radiations (approximately 40% less than on Earth) creates very limited conditions compared to Earth. To create permanent base is not a simple task. It requires design of many systems responsible for all environmental parameters that will enable human life in hostile conditions. This set of subsystems is called the Life Support System (LSS) [3] and is responsible for maintaining appropriate environmental conditions, as well as managing the

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waste generated in the space facility. The LSS in the International Space Station is the only one currently functioning in space conditions. While, short distance to the Earth enables supply of required onboard resources. This wouldn't be applicable for long term missions placed on Mars. In this case LSS is required to be self-sufficient and to recover each of essential resources in-situ, which are primarily oxygen, water and nutrients [3]. After processing and recovery they will be able to return to the cycle, providing the needs of the crew, but also serving as a fertilizer for grown crops, or various different processes. Due to lack on Martian surface easily accessible sources of life support sustainable compounds, LSS needs to characterised as closed system for mater circulation.

This paper is focused on presenting of our LSS concept. This LSS system is a part of 1000-man Mars base, designed for the *Mars Colony Prize competition – Design The First Human Settlement On Mars,* organised by The Mars Society. It was assumed to create the concept of a 1000-man Mars base, characterised as highly-autonomous, and capable of producing its own goods. This challenge is not trivial and to tackle with it we based on comprehensive literature study. The Figure 1 presents a summary of the subsystems of the LSS and their main functions covered by this study.

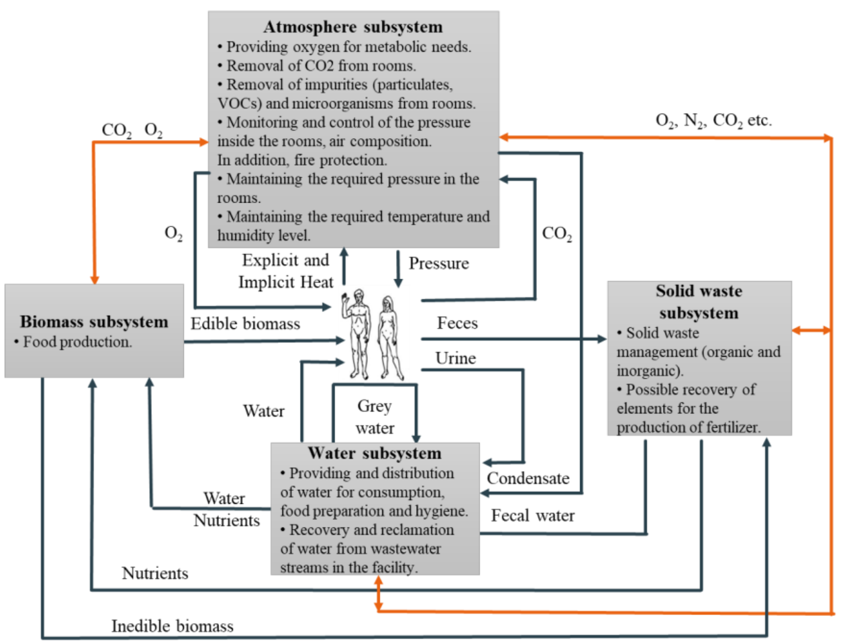

Fig. 1. Martian Life Support System scheme and each subsystem function.

2 Atmosphere subsystem

The major issue which is ought to be tackled in the concept of the colony is the atmosphere and the possibility of the inhabitants to genuinely breath. In order to increase the life comfort of the colony's inhabitants it is more preferable to fabricate a gas ambience rather than equip 1000 colonists with personal breathing apparatus in addition to presence of multiple depressurizing compartments. The key to achieving this goal is the constant levelling of pressure, temperature and most importantly atmosphere compositions as they are on Earth: 78% N_2, 21% O_2 and ppm values of other gases such as noble gases.

There are many variables in the equation of forming and maintaining such atmosphere. Those include: fluctuation on Mars conditions affecting its atmosphere, volume of the space which will be filled with gas and e.g. oxygen usage and CO_2 emission to name a few. Average crewmember is consuming 0.816 kg oxygen per day [3]. In this concept biomass cultivation is producing a sufficient amount of oxygen for crew purposes (see chapter 5). However, since an emergency system must be also provided it is decided to utilize the oxygen generating system MOXIE – currently developed by NASA. It is the most sustainable way of in-situ oxygen generating system available in remote conditions and from carbon dioxide as substrate which is ideal for Mars conditions [4]. This system will be validated onboard the rover during Mars 2020 mission, thus, by the time the extraterrestrial colony will stand, this process will be examined precisely. This device is capable of generating oxygen from carbon dioxide similar to the photosynthesis. However, the idea behind this system is nothing alike the plant-based process mentioned. The operation principle is electrochemically based. It utilizes solid oxide electrolysis cell doped with yttria-stabilized zirconia in elevated temperature (800°C) according to equation $2CO_2 \rightarrow 2CO + O_2$. The scheme of MOXIE is depicted below in the Figure 2. At the cathode oxygen molecules are generated and at the anode - carbon monoxide. The process takes place in high temperature and thus it requires sophisticated thermal isolation which can be hard to achieve while installing MOXIE devices onto the scaffolds of the Colony's buildings.

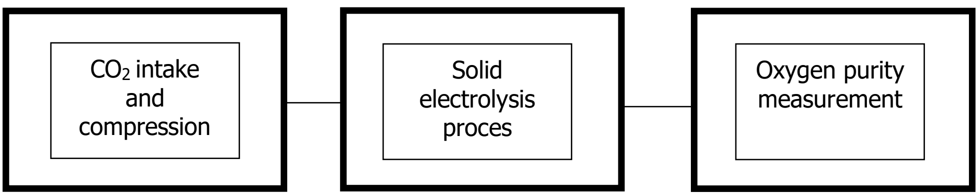

Fig. 2. MOXIE scheme [5].

The current prototype of MOXIE has dimensions of: 23.9 x 23.9 x 30.9 cm, weights approximately 15 kg and has 300 W of operational power. It is capable of generating about 10 g of pure oxygen which is equivalent of 7.52 dm^3 in NTP (293.15 K, 1013 hPa). Devices will be paired in racks and installed to provide clean oxygen for the colonists in significant places of the colony. Oxygen from the MOXIE system will be additionally supplied to the wastewater and waste system in order to avoid the situation where oxygen will not be available for proper implementation of these processes.

The nitrogen will be generated in larger quantities while treating the biological waste in the Colony in the manner described in the Solid waste and Biomass subsystems chapters of this publication. The remaining elements such as noble gases will be dosed from the pressurized bottles. In creating the micro-atmosphere, the exact same stratification as Earth's has not to be sustained. The pressure of the gas will be artificially pumped to maintain the atmospheric pressure (~1013 hPa). The two-way selective filters of the dome will evacuate excess carbon dioxide as well as other components of the atmosphere and its contaminants. Thanks to the system of O_2, CO_2, CO and N_2 sensors and heat exchangers the environmental conditions could be equalized. The system will constantly monitor pressure and temperature to adjust it to the desired level and to detect anomalies. For MOXIE system CO_2 will be sucked in directly from the Mars atmosphere of which it constitutes almost all (95%).

3 Water and wastewater subsystem

Currently, at the International Space Station wastewater processing contains several physicochemical steps [3, 6], which includes stabilization by acid dosing, distillation and multifiltration (active carbon and ion-exchange resin beds). In general, the physicochemical methods includes: distillation, reverse osmosis, electrodialysis, multifiltration (mechanical filtration, purification in an active carbon bed, purification using ion exchange resins). In case of extraterrestrial colony this methods would not be sufficient, due to unreliability (e.g. flogging) and the need for spare parts. However, the most important aspect is to recover water and nutrients, which can be implemented in well-known terrestrially biological methods. Process might be conducted in activated sludge or trickling filters [7, 8]. Both methods are currently used in advanced space research. Thus, in this concept biological wastewater treatment is used. With regard to chosen biomass production type, the nitrification process is favorable. Nitrification rate in the range of 90% is assumed. The issue with this process is acquiring the alkalinity to carry out the nitrification. It is assumed, that it will be extracted from Mars surface.

Table 1 presents the quantity and quality of generated in the colony wastewater (based on [3]), composition of reactor inlet and outlet. There are three main wastewater streams: urine and grey water with condensate. Since, the use of the diversion toilet is more than certain, faeces will be separated in the source and transported directly to the solid waste management system. Only fecal water will be treated in the biological reactor. Urine is human origin stream, rich in phosphorus and nitrogen [9, 10] and will be used as a main source of nutrients for biomass cultivation. Assuming 1.2 g $N \cdot m^{-2}$ is average demand on nitrate for most cultivated plants, outlet composition ensure 10505 m^2 of soilless cultivation, which would ensure 15% of daily energy demand for habitants. The next type of wastewater is grey water, which is for instance hygiene water, water for meals preparation, water after dish washing, water after laundry. After biological treatment water not used in cultivation will be directed into physicochemical unit, where water for human needs will be recovered. It should be noted, that the water production probably will be assisted by water mining from Mars surface, with use of ISRU (in situ resource utilization). The method is based on separating frozen water by evaporating it from regolith during pre-processing, which is extracted in open-cast mines The last stream is condensate. It is water recovered from the ventilation system. More precisely it is perspiration and respiration water (e.g. sweat, tears). This stream is not included in the Table 1, since in the colony, this stream would also contain water coming from the food production (transpiration water) and will be recirculated back to the food production system. Assuming average transpiration rate in the range of 91–99%, volume of this stream will be 243623.4 $kg \cdot day^{-1}$.

It should be noted water also might be consumed during various processes, which might occur in the colony. This stream should be determined after assumption of each branches of industry, which colony would have.

Table 1. Quantity and quality of wastewater streams created in the conceptual colony (based on [3]).

Basic parameters				**Reactor inlet (for 1000 crewmembers)**		**Reactor outlet (for 1000 crewmembers)**	
-	Urine	Grey water	Fecal water	Load	Concentration	Load	Concentration
Constituent	$g \cdot crewmember^{-1} \cdot day^{-1}$ (except for flow: $L \cdot crewmember^{-1} \cdot day^{-1}$)			$g \cdot day^{-1}$	$g \cdot L^{-1}$	$g \cdot day^{-1}$	$g \cdot L^{-1}$
Flow	1.53	24.45	0.087	26067	-	26067	-
Total Nitrogen	11.2	2.81	1.09	15096	0.58	15096	0.58
N-NO_3	0	0	0	0	0	13586	0.52
N-NH_4	4.36	0	0	4360	0.17	1510	0.06
P	0.85	1.28	0.91	3036	0.12	3036	0.12
PO_4	0.81	1.21	0.3	2322	0.089	2322	0.09
K	3.02	1.06	0.41	4489	0.17	4487	0.17
Ca	0.24	0.096	0.79	1126	0.043	1126	0.04
Mg	0.12	0.24	0.15	510	0.020	510	0.02

4 Solid waste subsystem

The concept of the Martian base proposed in this paper assumes large-area plant cultivation, as crops will be the main source of food for astronauts. However, such crops are associated with the generation of a large amount of solid waste – mostly non edible parts of plants, like: leaves, stems or rotten plants. In our conception, each day the amount of waste biomass will be equal to 28 989 kg. Such wastes is rich in water and various other compounds, that can be successfully separated, modified and used for the need of colony. These compounds include: proteins, sugars, vitamins, fatty acids, cellulose, lignin, hemicellulose. Those two polymers – cellulose and hemicellulose, due to the lack of solubility in water, are a problematic waste also on the Earth. The percentage content of carbohydrates in the dry mass of deciduous stems is quite high: 45–50% cellulose, 25–35% hemicellulose and 25–35% lignin [11–14]. According to the amount of daily biomass, which is need to be utilized, we propose implementation of efficient processing technology, so called biorefinery, which will play an essential role in our concept.

Biorefineries allow the use of biomass for the production of chemicals, substrates for further syntheses or fuels, to name a few. Due to the nature of the colony conception, the techniques used in biorefineries, can be also used in Mars colony.

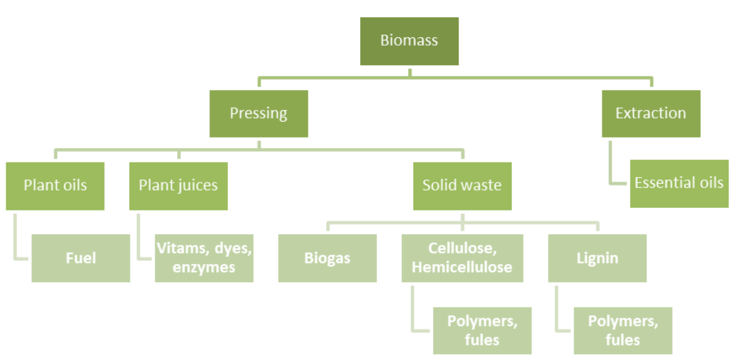

Fig. 3. The overview of the biorefinery concept [11–14].

The concept of the Martian biorefinery assumes the use of the most universal devices, such as filters, bioreactors or extractor, so that the installation could be easily adapted to current needs and produce a range of different compounds [11–14].

The entire biomass, will be collected in aerobic composter, equipped with a biogas discharging system. This gas could be used as a fuel source for the entire installation [11–14]. The residence time of the biomass in the composter will depend on the process being carried out. The biomass from the composter will be firstly transported to the macerator, which allows grinding of wet plant material, and then to the pressure filter. Three main products are achieved: green juice, oil and biomass (filter cake) [11–14]. Obtained biomass could be subjected to a supercritical extraction process with carbon dioxide. Such a solution brings with it a number of advantages. The atmosphere of Mars is rich in CO_2, the solvent after the gas expansion is removed from the product, and the sensitive compounds contained therein do not decompose. Depending on the process parameters: pressure and temperature, various compounds will be extracted [15]. The extract after quantitative and qualitative analysis, could be used as a dietary supplement for astronauts, enriching the nutritional value of food. Before use the extract, will also be further purified, for example using chromatographic columns or filtration technique [14, 16].

The oil fraction could then be used as a substrate for the production of fuel for the installation's operation. The water fraction, rich in such compounds like vitamins, dyes, proteins could be purified on chromatographic columns in order to get rid of undesirable compounds and also be an astronaut dietary supplement [11].

A filter cake, rich in water-insoluble compounds – cellulose, hemicellulose, will be transported to a bioreactor, where suitable microorganisms will use it as a source of energy and produce biogas in anerobic conditions, for energy purposes [11]. The polymers contained in the filter cake could also be used to produce useful raw materials for further syntheses. The cellulose can be subjected to the two different processes: enzymatic hydrolysis to obtain a simple sugar, which can then be used, for example, for the production of ethanol [17, 18]. Cellulose will also be used to obtain cellulose fibers: lyocell, modal or viscose [19]. These fibers are now widespread, and wood cellulose is produced due to the lower cost of the process.

Biomass is rich in numerous of compounds, which will be extracted and use for many another purposes. However there is need to develop a processing technology, which does not require much chemicals due to lack of many compound or Martian surface. One of the solutions is to use biotechnology – microorganism and enzymes for it, but for it more advance research on influence of microgravity and radiation for living organisms must be performed.

5 Biomass subsystem

For permanent settlement of other celestial bodies, it is necessary to create a food production system. Dietary requirements for one crewmember is defined by Anderson et al. [3] as the crewmember mass range from a 95^{th} percentile American male, with a total body mass of 99 kg, to a 5^{th} percentile Japanese female, with a total mass of 53.0 kg for whom daily calories consumption is 3072 kcal for one crewmember a day. Which means that the total amount of produced calories for 1000 people should be approximately 3,800,000 kcal a day. Three types of systems are taken into account: Hydroponic, Aeroponic and Aquaponic. Hydroponics and aeroponics are soilless, plant cultivation techniques, which provides the nutrient solution directly to the plants and have been proven successful to produce crops for relatively long time periods. Hydroponics and aeroponics do not use soil, because of that, the mass of the necessary equipment is much lower compare to the soil techniques. Additionally they can be highly automated to control nutrient and water dosage [20]. The diet requirements of humans dictates that up to 15 species of plants must be provided to complete menu [21]. These crops were be selected for small size, fast growth, nutrition, short plant cycles, and high harvest indices [20]. To the most-studied plants in space environmental belong: lettuce, mizuna, wheat, tomato, onion, radish, Chinese cabbage, cucumber, barley and pea [23]. However plants have relatively low calorific value. Because of that, for a long term mission additional source of calories should be found. In our case aquaponics seems to be the solution to this problem. It is a system that combines conventional aquaculture, raising aquatic animals with hydroponics. Including fish into the LSS gives two benefits food and waste treatment sub-process. Fish are the best choice among aquatic animals for LSS for several reasons. First of all they have relatively low energy requirements, 5- to 20-fold less than terrestrial vertebrates [24]. Fish are 10- to 13-fold more efficient than other animals. This efficiency is due to a lack of thermoregulation expenditures, lower sodium pump activity, neutral buoyancy which negating the effects of gravity, and nitrogen excretion mechanisms [25]. It is proved that fish nutrition has a direct impact on the nutritional composition of fish. Lots of studies showed differences between wild caught and farm raised fish [26]. On the example of Nil Tilapia has been proved that the incorporation of Spirulina in the diet of those fish will result in an acceptable and nutritious dietary source for human consumption [25]. That is why we propose to use spirulina in our aqua system. Additionally spirulina will be a part of astronauts diet. It is a great source of vitamins, carotenoid pigments, proteins, lipids and polysaccharides and spirulina can be easily adsorbed by humans [27]. Taking those two facts into consideration. Spirulina will be cultivated in the colony like this. To provide half of the caloric demand it should be produced 2000 kg of edible biomass a day which means that the cultivation area must be about 40 000 m^2. Cultivation of such sizes will need 1700 kg of CO_2 and will produce 1200 kg of Oxygen. 1000 people will consume 816 kg of O_2 and will produce 1040 kg of CO_2 a day [3]. The surplus of oxygen produced in the crop will be directed to the oxygen tanks used for EVA (Extravehicular activity). Additional source of CO_2 is sustained with atmosphere subsystem by uptake from Martian atmosphere.

6 Conclusions

The concept of LSS system proposed in this paper is based on comprehensive literature background. What is more all technologies used in this project are already implemented. Our study shows that the level of current technology for each of the four subsystems is sufficient to fulfil its task in the colony covered by this concept. Martian environment is unfavourable for human kind, due to lack of easily accessible sources of elements, essential for life. All this goods need to be produce in artificial way or getting them is very energy or time consuming. To overcome this challenge, we assumed LSS system as a closed system for material circulation, what was shown in each subsystem description. All waste and outputs are treated as substrates for another process. We shown that all units work together, and depend on each other. Nevertheless, the main problem is implementation of proposed solutions and analysing in experimental way if all individual processes are compatible with each other. Nevertheless, the main problem is the implementation of these solutions, not as individual processes but acting together as a unity. This unification was tested during the previously conducted projects investigating self-sufficient systems such as BIOS, Biosphere or MELiSSA. However each of these experiments was conducted on a smaller scale or even in pilot scale. Together with the increase to such a large area, there are a number of problems related to operation, monitoring of installations and conditions. Thus, to create an extraterrestrial colony that can accommodate 1,000 people, a lot of research must be carried out during earlier stages of colonisation. During our work we came across a lot of technological problems. To sum up main research problems regarding the described systems as well as our literature study, that should be examined in the coming years are as follows:

- atmosphere subsystem: reducing the weight, efficiency improvement, reduction of energy demand
- water subsystem: inoculation of biological reactors, the effect of reduced gravity on the aeration system and the collection of excessive sludge, recovery of elements from brine from physicochemical devices.
- solid waste subsystem: significant improving the efficiency, recovering of valuable chemical compounds and development of technology to process them
- biomass subsystem: clogging of aeroponics, precipitation in each system, collecting harvests by the crew.

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