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Sustainable Life Support Systems for Human Space Exploration

Sugandh Gupta[1*], Nandan Kumar Jha[2], Pranjit Sharma[3]

[1,2,3] Department of Aerospace Eng. Chandigarh University Mohali, Punjab, India -140413

ABSTRACT

Long-term life support systems are becoming increasingly important as human space exploration progresses. This review will examine the most recent advancements and cutting-edge ideas in sustainable life support systems, with a focus on Mars colonization, in order to maintain future human presence in space. The review will also address closed-loop life support systems, bioregenerative systems, environmental monitoring along with long-term health implications of space habitation. Further the review will explore innovative approaches for energy production, oxygen, water and food production, waste management within sustainable life support systems to ensure the success of human missions beyond Earth.

Keywords: Closed Loop life support system, Bioregenerative system, Environmental Monitoring, Martian surface, Human Exploration, Energy Production, Long-term health effect, space and planets.

INTRODUCTION

Life support systems in space provide the following fundamental functions: maintaining pressure, temperature, and humidity; giving useable water and breathing air; delivering food; and handling waste. As proven by the US Shuttle and Russian Mir programmes, current technology is capable of maintaining human crews in space for missions in LEO of short or indefinite length as long as replenishment is easily accessible. All crewed space missions to date have relied on replenishment from Earth for some or almost all of their consumable supplies (oxygen, water, food), and the International Space Station will do the same. The technology that will be employed on the ISS is capable of collecting water from humidity condensate, waste hygiene water, and crew urine with an efficiency of 80 to 90 percent.

However, no space-qualified technology can recycle food or oxygen from waste materials, therefore garbage must be dumped or stockpiled for return to Earth. The main motivation for creating sophisticated technologies that can recover resources from waste materials is to reduce the transportation cost of resupply, which is a function of crew number and mission duration. Future trips beyond LEO, like as journeys to Mars, will be significantly more difficult and expensive, if not impossible, to resupply. Advanced life support (ALS) systems must be more dependable and self-sufficient to maintain crew health and safety, in addition to lowering reliance on replenishment. The technological challenge for ALS research and development (R&D) is to give future mission designers with mature technologies and hardware designs, as well as significant performance data justifying confidence in the construction of highly dependable ALS systems that satisfy mission requirements.

In 2008, the Institute of Space Systems began research on microalgae for space applications, and in 2014, the Photobioreactor was developed. Astronauts turned on the Photobioreactor in orbit and let the microalgae to grow for 180 days to assess its stability and long-term performance. The long-term objective is to enable longer space missions by lowering system bulk and reliance on replenishment. Future goals include downstream processing of the algae into edible food and scaling up the system to give oxygen to one astronaut. [1]

In order to establish self-sustaining settings and lessen the need for resupply flights from Earth, closed-loop life support technologies are being created. Both space missions and planetary sustainability will require future developments in closed-loop life support systems. NASA has been actively involved in creating life support systems to sustain humans living and working in space since it is at the forefront of space exploration. The Life Support Systems (LSS) programmes at NASA cover a wide variety of capabilities needed for lengthy trips outside of Earth's zone of protection [2].To protect the health and safety of astronauts in space, the agency focuses on monitoring air pressure, oxygen levels, waste management, water supply, and fire detection. NASA has plans to explore space beyond Low Earth Orbit in the future, which will encourage the development of closed-loop living systems and improve the efficacy of life support systems. Because it is impractical to carry enough replacement parts and consumables for year-long trips, deep space missions, like those to Mars or other far-off locations, will require self-sustaining life support systems [3]. Long-term space flight will be possible because to these cutting-edge technologies' reliance on recycling and resource regeneration.

Through its in-flight technology demonstration programmes, NASA aims to develop technological systems for upcoming exploration flights based on its studies on the space station. This includes cutting-edge life support technologies like ANITA-2 and 3DMetalprinting, which will help to make it possible for expeditions to the Moon, Mars, and eventually deep space[4].

ECLSS Technologies: NASA's ECLSS technologies include a range of functional areas, including logistics, environmental monitoring, life support, and fire safety. To meet the demands of deep space missions, such as those to the Gateway, the lunar surface, and Mars, the agency has been concentrating on improving these technologies [5].

life support System at ISS

The Marshall Space Flight Centre in Huntsville, Alabama, is in charge of designing, building, and testing regenerative life support systems for the International Space Station. The ECLSS provides oxygen for metabolic consumption, potable water, filters particulates and microorganisms, removes volatile organic trace gases, monitors and controls cabin air partial pressures, maintains total cabin pressure, maintains cabin temperature and humidity levels, and distributes cabin air between connected modules. Life support technology advancements include the development of regenerable technologies for delivering oxygen and water, which will aid in lowering the cost of maintaining the Space Station. The Marshall Centre and Hamilton Sundstrand Space Systems International collaborated to construct and test three refrigerator-sized racks.

Fig1

Fig 2

The Water Recovery System supplies clean water, the Oxygen Generation System generates oxygen, and the Environmental Control and Life Support System delivers 5-20 pounds of oxygen each day.

Fig 3

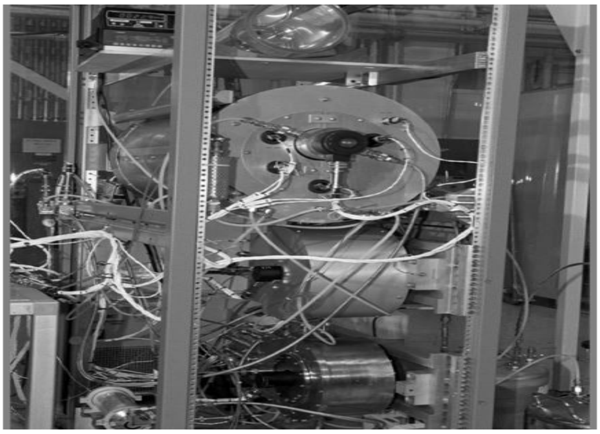


Fig 4

Fig 1 :MSFC ECLSS Test Facility [7],Fig 2: Experiment with Water Processing in Flight [6] Fig 3:Water Processor Testing Area on the Space Station [6], Fig 4:urine processor flight experiment [6]

The Carbon Dioxide Reduction Assembly (CReA) produces water and methane by reacting hydrogen created by the Oxygen Generation Assembly with carbon dioxide removed from the cabin environment. The Marshall Centre maintains testing and evaluation facilities for life support technology, allowing engineers to troubleshoot any difficulties encountered in space. Before being installed on the Station, space-proven gear was flight-tested[6].

DESIGN FACTOR FOR LIFE SUPPORT SYSTEM

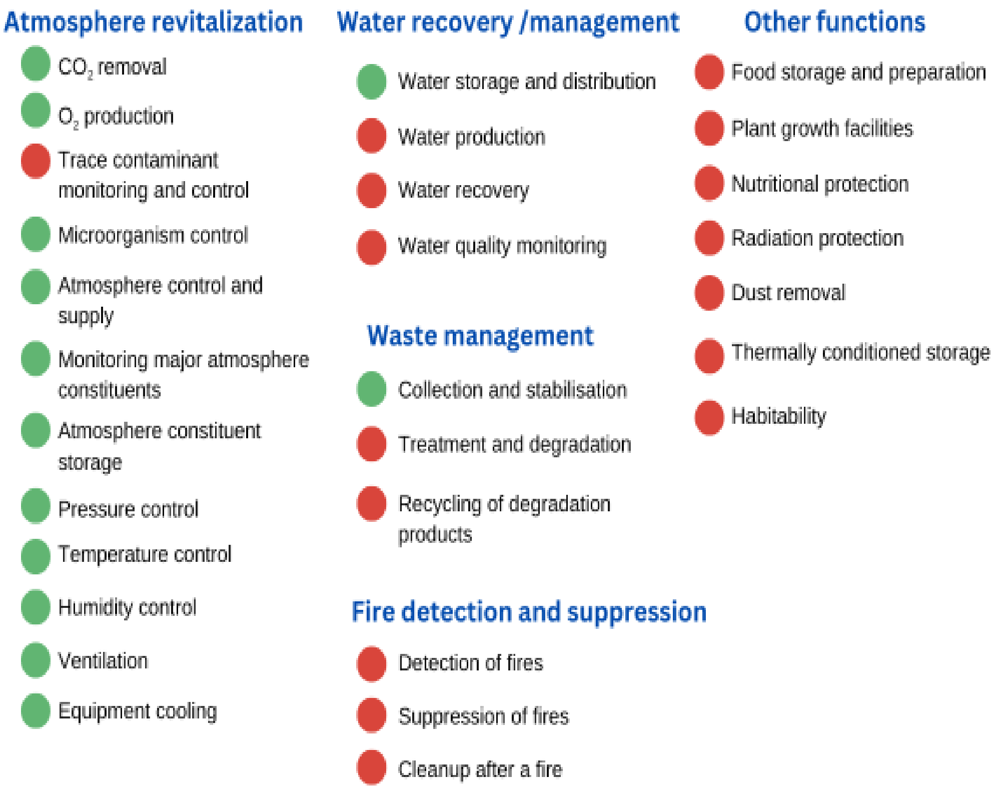


Fig: 5Life support features as a function of mission length:1–12 hours. Credit: NASA

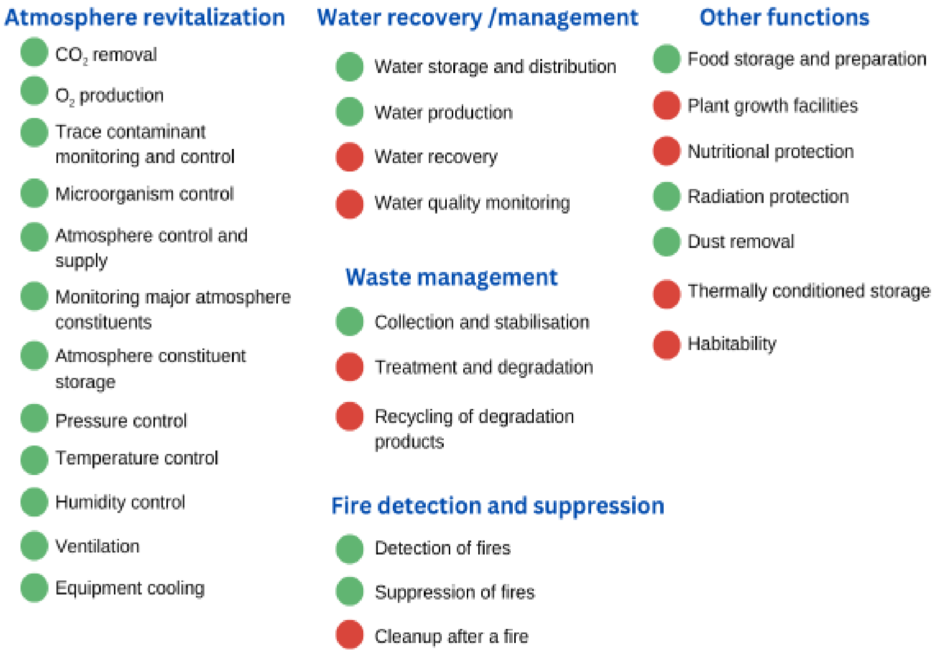


Fig: 6 Life support features as a function of mission length: 1–7 days. Credit: NASA

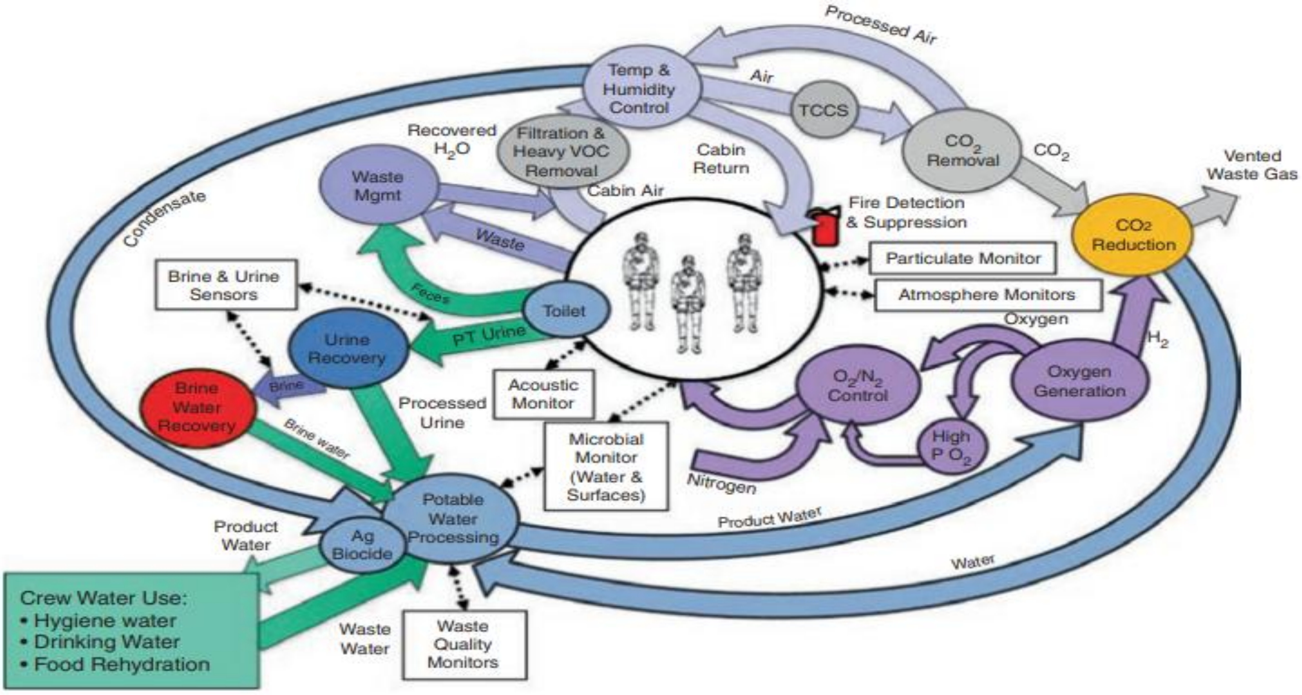


Fig7 : Life support system at international space station. Credit NASA

Table1: Impacts of mission variables and life support systems[8]

Mission factor	Effect on the design of a life support system
Number of crew	More astronauts need more consumables.
Mission length	Longer missions will need more consumables than shorter missions. A protracted mission will also need more dependability and longer intervals between maintenance and repair.
Spacecraft leakage	The larger the number of leaks aboard a spaceship, the greater the strain on the atmosphere control system.
Resupply capability	The longer the mission, the higher the necessity for dependability and the closure of life support systems.
Power consumption	There will always be limited power, which must be regulated in order to power the numerous subsystems and components.
Volume	Because spacecraft have limited volume, systems and subsystems must be as minimal as feasible.
Gravity	Microgravity, one-sixth gravity (lunar), and one-third gravity (Mars) systems and subsystems must be built to operate under a variety of gravity effects.
Contamination	Contamination is produced by spacecraft systems, and the LSS must be built to handle these pollutants.
In situ resource utilization (ISRU)	This reduces demand for the LSS at the destination.

Table 2: comparison of life requirement on earth and in space: Credit NASA [8]

Item	On Earth		In Space	
	kg per person per day1	gallons per person per day	kg per person per day2	gallons per person per day
Oxygen	0.84		0.84	
Drinking Water	10	2.64	1.62	0.43
Dried Food	1.77		1.77	
Water for Foood	4	1.06	0.80	0.21

Atmosphere Management

Controlling and supplying the atmosphere, regulating temperature and humidity, monitoring the atmosphere, venting the atmosphere, and fire detection and suppression are all different aspects of this function.

Control and supply of the atmosphere

- Keep the air pressure constant.
- Maintain oxygen, nitrogen, and carbon dioxide partial pressures.
- Control atmospheric and partial pressures.
- Keep oxygen and nitrogen on hand
- Oxygen and nitrogen should be distributed.
- Run autonomously with little crew involvement.

Control of temperature and humidity

- Maintain a temperature range of 18°C to 26°C.
- Maintain a humidity level of 25% to 70%.
- Keep an eye out for trace pollutants and particles.
- Maintain microbial levels.
- Run automatically with little crew intervention

Atmosphere Monitoring

- Volatile organic compound (VOC) monitoring, identification, and quantification.
- Audible and visual alerts to notify crew members when VOC concentrations surpass the maximum permitted values.
- Capabilities for microbial disinfection.
- Contamination event management

Cabin Air Conditioning

- Ventilation to maintain thermal gradients and decrease pollutant accumulation
- Cooling is ensured through ventilation.

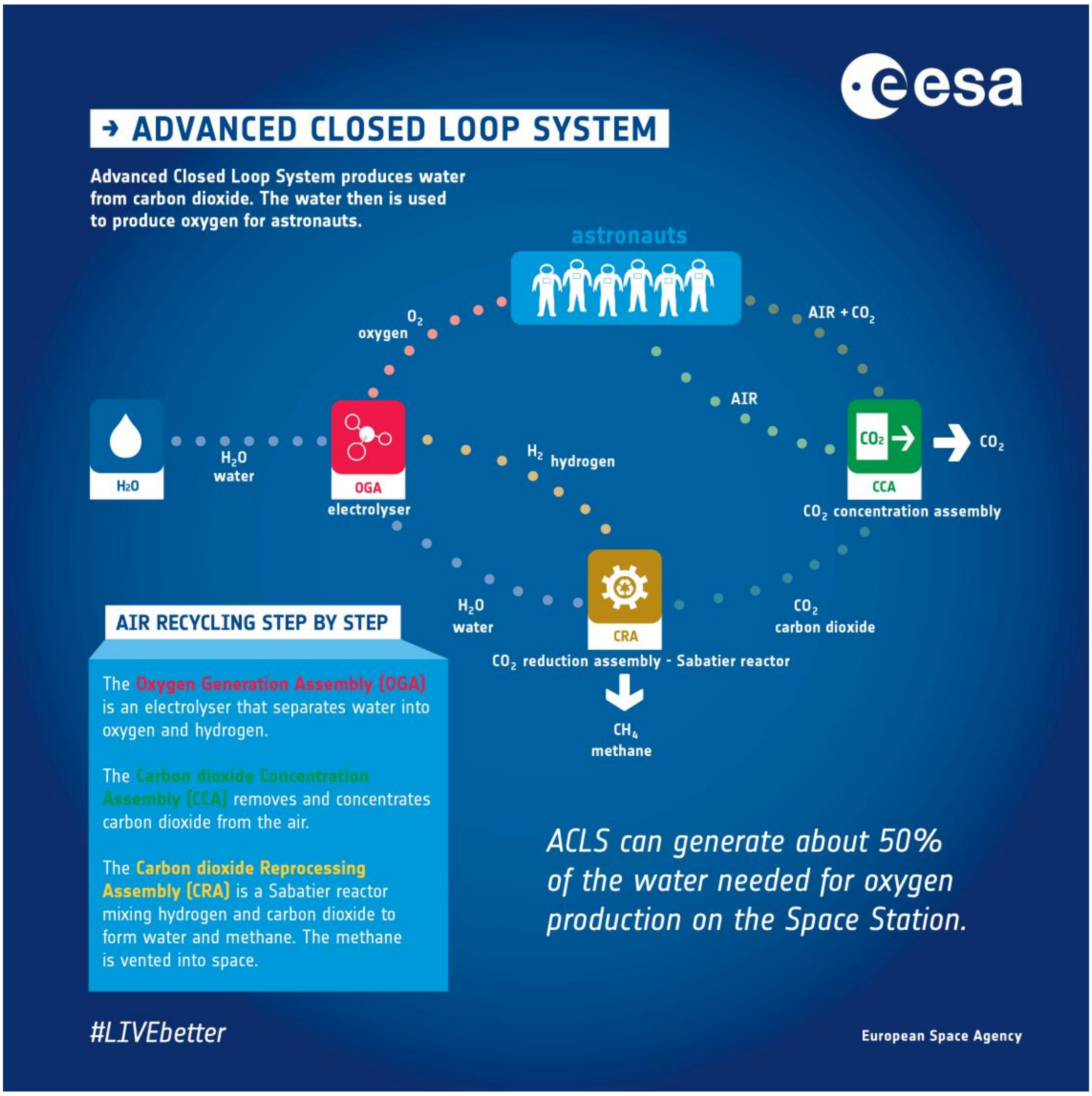
Revitalization of the Air

- Keeping the carbon dioxide content constant
- lowering carbon dioxide levels
- Creating oxygen

Table3 : Air Revitalization Technologies [9]

Function	**Technology**
Concentration of carbon dioxide	Molecular sieve with four beds of lithium hydroxide Desorption of water by solid amines
CO2 decrease	Sabatier Bosch activated charcoal
Oxygen production	Hydrogen vapour electrolysisWater electrolysis of solid polymers

Fig8: Air Revitalization Technologies [9]



Advanced Closed Loop System produces water from carbon dioxide. The water then is used to produce oxygen for astronauts.

AIR RECYCLING STEP BY STEP

The Oxygen Generation Assembly (OGA) is an electrolyser that separates water into oxygen and hydrogen.

The Carbon dioxide Concentration Assembly (CCA) removes and concentrates carbon dioxide from the air.

The Carbon dioxide Reprocessing Assembly (CRA) is a Sabatier reactor mixing hydrogen and carbon dioxide to form water and methane. The methane is vented into space.

ACLS can generate about 50% of the water needed for oxygen production on the Space Station.

Fig 9: ESA's new Advanced Closed Loop System (ACLS) [10]

Waste Management and Recycling

NASA will have two systems in charge of dealing with Space Station garbage. ECLSS (Environmental Control and Life Support System) is presently testing and researching air and water subsystems. Water and urine are examples of these systems. Subsystems for reclamation, carbon dioxide removal, and oxygen production are all included. The majority of this work is being done at the Marshall Space Flight Centre in Huntsville, Alabama. Man Systems, based mostly at Johnson Space Centre in Houston, Texas, is in charge of crew personal hygiene products, galley design, food management, and garbage management[11]

Six systems will be in charge of trash management. Two systems will handle solid trash, three systems will handle waste water, and one system will handle airborne garbage.

Solid Waste Disposal Systems

Solid human waste and solid non-human waste are the two types of solid waste. Both of these solid wastes will be compressed and stored in the logistics module before being returned to Earth. Future plans call for the development of technologies capable of converting these wastes into usable goods. Because of the current state of progress in zero-g solid waste technology, these two systems will not be recovered[12].

Wastewater Treatment Systems

There are three distinct wastewater streams and three distinct wastewater treatment systems. The first stream of water is drinkable water. Potable water will be obtained from the carbon dioxide reduction subsystem and condensate collected from the cabin temperature and humidity management system. Multifil ration is the foundational method for polishing water free of dissolved organic vapours and metal ions. To inhibit microbial development, a microbial check valve injects iodine into the recovered water. Wash water from crew showers, clothing washers, and hand washing is the second water waste stream. The reverse osmosis (RO) technique is the foundational technology for extracting water from this stream. This system will require ultrafiltration pretreatment to catch suspended particles and macromolecules[12].

Urine is the third source of water waste. The basic urine processing technology is the Thermoelectric Integrated Membrane Evaporation Subsystem (TIMES). This subsystem will require ozone or sulfuric acid pretreatment. Water is collected by membrane permeation and evaporation to about one-sixth atmospheric condenser pressure. This recovery system, like the washing recovery system, will only be utilized to provide hygiene water and not the potable water subsystem. This system will be closely monitored and will have multiple biological check valves to guarantee that any contamination discovered does not spread to the remainder of the hygiene subsystem[13]. Contamination crossing over is unlikely since the hygiene subsystem is not connected to the potable subsystem. These systems are consistent with the AIAA technical report by Voecks and Seshan (1990).

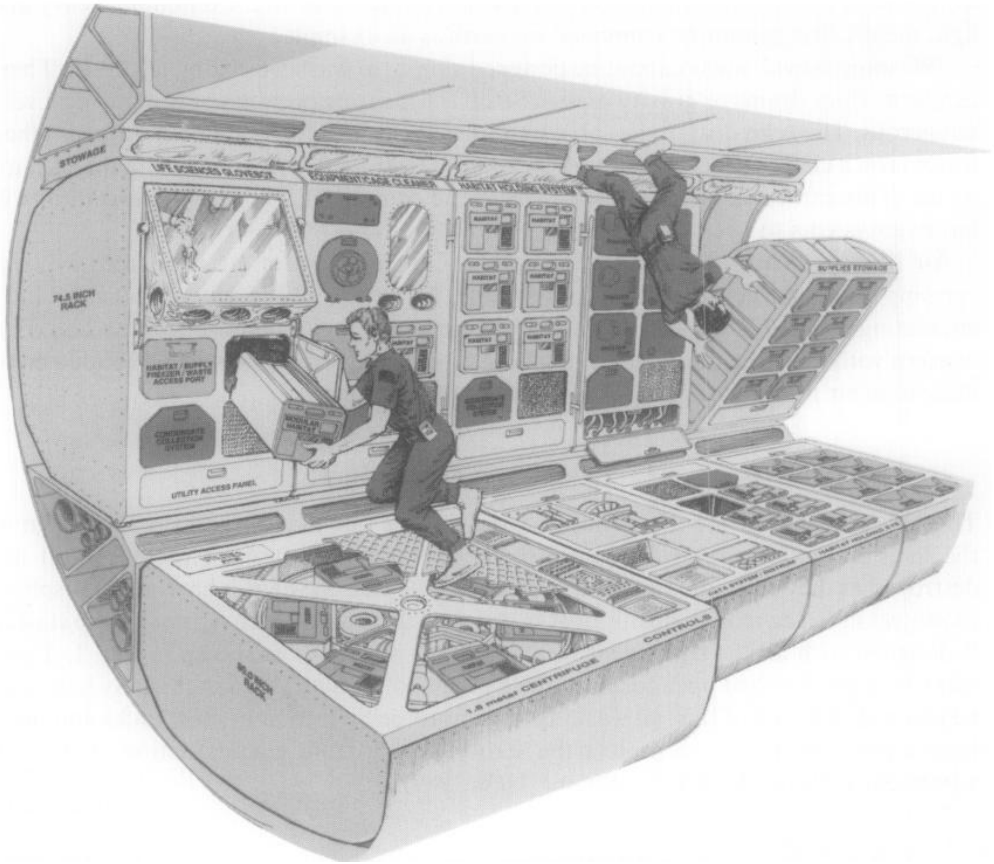


Fig 10: Space Station Freedom equipment rack design. Racks tilt for maintenance and access to the exterior shell.[12][13]

Air revitalization

The design of the air rejuvenation system is not yet complete. The Bosch and Sabatier processes for removing CO2 with byproducts of water, hydrogen, and oxygen are candidates for this system. Another system will function in conjunction with this procedure to remove any particles, moisture, or biological contaminants from the airstream[13].

Waste management for the freedom of the space station

Table 4: Space Station Freedom requires a respirable atmosphere and water.

Parameter	Units	Operational	Degraded	Emergency
CO2 partial pressure	N/m2 (mmHg)	400 max (3.0 max)	1013 max (7.6 max)	1600 max (12 max)
O, partial pressure*	N/m2 X 103 (PSIA)	19.5-23.1 (2.83-3.35)	16.5-23.7 (2.4-3.45)	15.8-23.7 (2.3-3.45)
Total pressure	N/M2 103 (PSIA)	99.9-102.7 (14.5-14.9)	99.9-102.7 (14.5-14.9)	99.9-102.7 (14.5-14.9)

Temperature	°K (F)	291.5-299.8 (65-80)	291.5-299.8 (65-80)	288.8-302.6 (60-85)
Dewpoint+	°K (F)	277.6-288.8 (40-60)	273.9-294.3 (35-70)	273.9-294.3 (35-70)
Ventilation	m/sec (ft/min)	0.076-0.203 (15-40)	0.051-0.508 (10-100)	0.051-1.016 (10-200)
Trace contaminants Particulates	mg/m3 Particles/m3 0.5 um 150 um	TBD1 3 530 000 TBD	TBD	TBD
Micro-organisms	CFU/m³	1000	1000	1000

* In no circumstance may the 02 partial pressure be less than 15.0 N/m 2 (2.3% PSIA) or the 02 concentration be greater than 23.8% of the total pressure.
The relative humidity should be between 25-70%.
TBD means "to be determined."
Units that create colonies.

Table shows the needs for atmosphere and water. These findings are consistent with those described in SAE technical papers by Reuter et al. (1988) and Bagdigian& Mortazavi (1987).

Each system must adhere to a broad set of standards before it can be utilised. Each system is dependability tested. Energy consumption (e.g., when and how much) and system interactions are also investigated. Figure 2 depicts the integration of various systems. That is consistent with Wieland's (1990) AIAA technical document[13, 14].

BIO-GENERATIVE SYSTEMS

Bioregenerative life support systems (BLSS) are artificial ecosystems made up of a variety of complicated symbiotic connections between higher plants, animals, and microorganisms. BLSS is a man-made closed environment constructed on ecological principles, combined biotechnology, and engineering control technologies. BLSS has the same structure as the Earth's terrestrial ecosystem, with producers (plants), consumers (people/animals), and decomposers (microbes), and can create a comfortable environment for humans similar to the Earth's ecosystem. As the most advanced life support technology, BLSS can provide a habitation environment similar to the Earth's biosphere for long-duration, deep-space missions with several personnel[15].

To travel beyond Earth into deep space and achieve long-term survival, a Bioregenerative Life Support System (BLSS) is required, which recycles the oxygen, water, and food required by humans in situ, reducing the demand for supplies from Earth and avoiding pollution on extraterrestrial bodies. Long-term future space habitation will necessitate a controlled ecological life-support system (CELSS) to simultaneously revitalize the atmosphere (liberate oxygen and fix carbon dioxide), purify water (via transpiration), and generate human food (for a vegetarian diet). The primary roles of biomass productivity in a CELSS will be provided by photosynthetic higher plants and algae, and a combination of physico-chemical and bioregenerative processes will be used to regenerate renewable resources from waste materials.

When the manned space program expands to include a large number of people operating at great distances from Earth for extended periods of time, the current approach of storing or supplying essential ingredients for human life support must give way to regenerative means. Many long-term space habitation life-support scenarios envision plant life as playing an important role. Although edible biomass production for a vegetarian diet is the driving factor behind placing plants in a major life-support role in space, the fact that plants can also filter air and water is an added bonus. Plants, in addition to providing a sustainable supply of food for astronauts, have a number of other advantages that make them ideal for life support systems in long-term space habitation scenarios[16, 17].

Energy Generation

The generation of energy in closed-loop life support systems like space stations in low-earth orbit (LEO) and domes on lunar and Martian surfaces in future missions is vital for long-term space living and exploration. Solar power and fuel cells are the conventionally used energy sources while revolutionary alternatives are being investigated. Sunlight is more than ten times as powerful at the top of the atmosphere as it is at the Earth's surface. And, at a suitably high orbit, sunlight would be available on a continuous basis, capturing all available sunlight and beaming it to receiving stations around the world, wherever it is needed[16, 17]

Decades of research have resulted in a wide range of concepts based on various power generation, conversion, and transmission principles. Photovoltaic panels in geostationary orbit around Earth convert solar power into electricity in the so-called reference design. The energy is then wirelessly sent in the form of microwaves at 2.45 GHz to dedicated receiver stations on Earth known as ‘rectennas,' which convert it back into electricity and feed it into the local grid. Because the power is sent wirelessly, it will be possible to transport it to the reception station where it is needed, including the Moon or other planets, where a conveniently available energy supply will enhance our ability to investigate these regions.

The biggest challenge is that the needed structures must be very enormous, both on Earth and in space, in order to create optimal, economically sustainable levels of solar power. A single solar power satellite in geostationary orbit might span more than a kilometer, with the ground receiver station requiring a footprint ten times larger. A single solar power satellite of the projected size would create approximately 2 gigatons of power, which is equivalent to a conventional nuclear power station capable of powering over one million homes[17].

The solar arrays fold up like an accordion for launch into space, and once in orbit, it is deployed and fully stretched out to its maximum size by a radio signal from ground controllers. For best power efficiency, the arrays must always face the sun, hence gimbals are employed to rotate them so that they always face the sun. The eight solar panels are 112 feet long and 39 feet broad. The whole wingspan of the solar array (240 feet) is longer than that of a Boeing 777 200/300 model, which is 212 feet. The arrays have a total of 262,400 solar cells and cover an area of approximately 27,000 square feet (2,500 square meters), which is more than half the size of a football pitch[17,18].

Electric Power System of ISS

The power system on the international orbit Station is the world's largest DC power system in orbit. The EPS was designed and validated by the Japan Aerospace Exploration Agency (JAXA). Astronauts rely on life support systems, lights, communications, stability controls, and experiments, hence electrical stability is crucial in space. Because this design contained so many switching regulators and converters, stability had to be validated under all expected load and transient circumstances.[18]

For all electrical loads, the rules of small signal stability apply. The tiny signal stability criterion is used to select a minimal gain and phase margin based on the complicated load and source impedance requirements. The switching regulator's input impedance was the load impedance, ZL. The stability and performance of the coupled systems may then be calculated.

The principal power supplied by PV modules is at 160 VDC and is distributed to Direct Current Switching Units (DCSUs) through cables. The DCSUs then supply power to the Main Bus Switching Units (MBSUs), which are then routed to the DDCUs, which are then routed and transformed from 160 VDC to 120 VDC as secondary power. The secondary power is then routed through switchgear, cabling, and DC/DC converters in each module of the ISS to power system equipment and payloads[18, 19, 20].

Oxygen Generation

Life support systems in closed-loop deliver oxygen, collect carbon dioxide, and regulate vaporous emissions from the astronauts. Most of the oxygen is generated through a process called “Electrolysis”, followed by O_2 in a pressurized tank. The process uses electricity from the space station produced by the solar panels mounted to split water into hydrogen and oxygen gas. Each water molecule has two hydrogen atoms and one oxygen atom. When a current is passed through water, these atoms split and recombine as gaseous hydrogen (H2) and oxygen (O2). Because water is a poor electrical conductor, there is a minor concentration of salt in the water to conduct electricity.

The oxygen we breathe on Earth is similarly produced by the splitting of water, but it is not a mechanical process. Photosynthesis is the process through which plants, algae, cyanobacteria, and phytoplankton convert sunlight, carbon dioxide, and water into sugars for nourishment. The hydrogen is used to produce sugar, while the oxygen is discharged into the atmosphere. "The chemical-mechanical systems, on the other hand, are much more compact, less labor intensive, and more reliable than a plant-based system."

At first, any hydrogen left over from splitting water will be expelled into space. In a chemical reaction that produces water and methane, hydrogen reacts with excess carbon dioxide from the atmosphere. The water would be utilized to replace the water used to produce oxygen, while the methane would be expelled into space.

The second approach does not produce oxygen, but rather delivers it to the station from Earth. Oxygen is pumped into pressurized tanks at airlock nodes. At those airlocks, nitrogen gas is also pumped into other pressurized tanks. The atmospheric controls aboard the station mix the gases in the precise quantities to the Earth's atmosphere and circulate the mixture throughout the cabin.

A backup system that produces oxygen through chemical reactions is the third method. The solid fuel oxygen generator (SFOG) system is housed in the station's service module (Zvezda). The SFOG, also known as oxygen candles or chlorate candles, includes canisters filled with powdered sodium chlorate ($NaClO_3$) and iron (Fe) powder. When the SFOG is lit, the iron "burns" at 1112 degrees Fahrenheit (600 degrees Celsius), providing the heat energy needed for the process.

Scientists intend to grow plants in future space stations or colonies to produce oxygen and eliminate carbon dioxide naturally. The plants would provide breathable air as well as nourishment for the astronauts. One issue that must be addressed is how to grow a large number of plants in small locations, as living space on a space station is restricted[21].

The MOXIE Experiment

A lunchbox-sized gadget is proving it can do the work of a tiny tree on Mars' red and dusty surface, over 100 million kilometers from Earth. The Mars Oxygen In-Situ Resource Utilization Experiment, or MOXIE, led by MIT, has been producing oxygen from the Red Planet's carbon-dioxide-rich atmosphere. On seven testing runs, MOXIE was able to create oxygen in a variety of atmospheric conditions, including during the day and night and throughout the Martian seasons. In each run, the equipment produced six grams of oxygen per hour, which is around the rate of a small tree on Earth[22].

A scaled-up version of MOXIE might be deployed to Mars ahead of a human mission to create oxygen at the pace of several hundred trees on a continual basis. At that capacity, the system should be able to produce enough oxygen to both maintain humans once they arrive and power a rocket that will return astronauts to Earth. MOXIE's oxygen production on Mars is also the first demonstration of "in-situ resource utilization," which is the concept of harvesting and utilizing a planet's materials (in this case, carbon dioxide on Mars) to produce resources (such as oxygen) that would otherwise have to be transported from Earth.

Water Generation and Purification

Water production aboard the space station is critical for keeping the crew alive as well as supporting hygiene and equipment functions, but it is difficult to develop and maintain. Historically, recycling old water covered around half of the station's needs, with the remainder met by deliveries from visiting cargo vehicles. That is not ideal, and there is another reason to reconsider a self-generating water solution.

The station's life support technology has kept the crew alive for many years by recycling oxygen from water via electrolysis. The hydrogen produced was deemed waste gas and was dumped overboard. Carbon dioxide, which was produced by crew metabolism, was also released overboard. A nickel catalyst was used to interact with hydrogen and carbon dioxide at high temperatures and pressures to create water and methane. The Sabatier technique has been utilized for many years in complex military and commercial applications, but the space-based application for the station is unique because to the commercial nature of its execution.

An improved Sabatier system might save thousands of pounds of water each year and complete the loop in the oxygen and water regeneration cycle. This resulted in considerable and immediate cost savings in the space station's operation, as well as the ability to generate water rather than transfer it all from Earth, boosting the objective of self-sufficiency and extending the route for sustained human survival in low-Earth orbit and beyond. The Water Recovery System is used to process water after the installation of a 550-pound stainless steel cube of a size of a refrigerator. The methane is released into space, while the water is recycled into the station's water system, where it is treated before being utilized for drinking, personal hygiene, and scientific studies.

Water Purification

Water purification technologies will be required to cleanse all water sources in order to attain the levels of recovery required to sustain life during long-duration missions. The International Space Station's (ISS) current water recovery and purification systems are only partially closed, necessitating external inputs and resupply. Furthermore, organic wastes, such as feces and food waste, are not currently recycled, which adds to waste processing and creates hazardous circumstances for the crew. This is not a realistic option for long-duration missions or ecosystems. The failure to recycle essential components (for example, C, H, O, N, P) in organic waste implies a missed chance to recycle the constituents for further food production, water purification, and atmospheric regeneration[23].

Treatment technologies might be biological, physical, or chemical in origin, each with its own set of benefits and drawbacks. This study provides an overview of prospective technologies, as well as their inputs, outputs, and requirements, that could be used for next-generation regenerative water purification in space. With this knowledge, specific technologies can be narrowed down for subsystem integration testing for recovery optimization. To achieve closed-loop systems in future space colonies, deliberate application of a range of symbiotic systems is required to minimize consumable inputs and maximize recovery[24].

CONCLUSION

Studies have demonstrated the advantages of a biological life support system for a space station that produces food on orbit using metabolic wastes. An emphasis on Mars colonization and assuring the long-term presence of people in space, this literature evaluation offered insightful information on the developments and cutting-edge concepts in sustainable life support systems. Closed-loop systems, waste management, bioregenerative systems, environmental monitoring, long-term health consequences, energy production, resource development, and trash management were some of the topics discussed. Humanity may prepare for successful and long-lasting expeditions beyond Earth by advancing research and innovation in these fields.

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