AELSS – Adaptive Ecological Life Support System

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Innovation

AELSS is a simple, robust, adaptable, and highly scalable Ecological Life Support System. It uses two live links, Duckweed and an Anaerobic Biodigester to recycle all waste nutrients produced by humans in space.

- It can be used in LEO, en-route to Mars, or on Mars' surface
- On the surface of Mars, it can be employed in the cleanup and processing of Martian regolith for use by food crops
- AELSS can, but is not intended to provide food directly for humans. It is instead used to process wastes into safe and clean fertilizer for food crops
- AELSS leverages years of CELSS research to become an idealized, next-generation Closed Ecological Life Support System
- The system is intended to operate both fully independent of humans or with any number of humans in the system. The same is also true of food crops used to feed the humans in the system

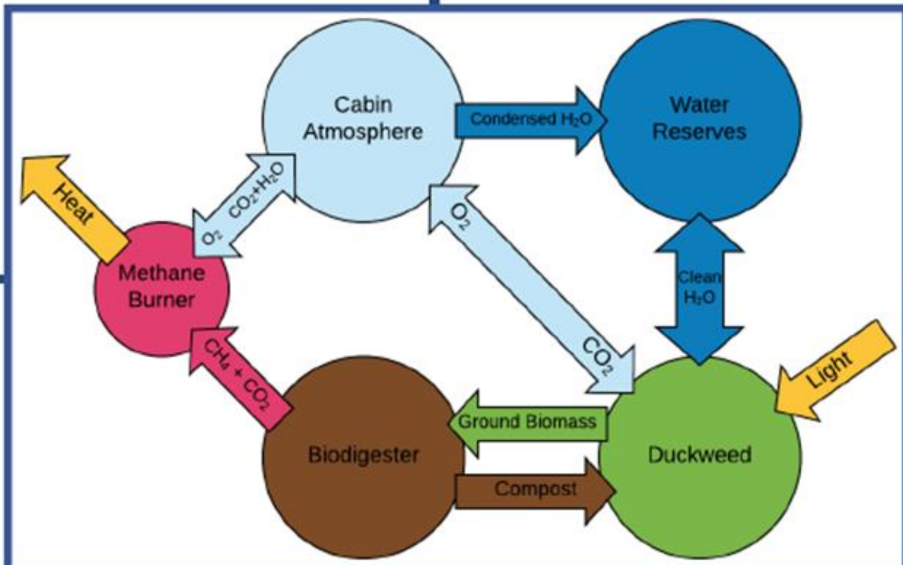
Technical Approach

Key tasks for development of AELSS will include:

- Maximizing the growth rate of duckweed
- Maximizing the biomass consumption rate of a biodigester
- Linking the two with support mechanisms and appropriately sized colonies
- Closing the system

Once the system is closed, development of adaptability can start.

- Ensure system balance can be maintained when one link is expanded
- Maintain balance when compost nutrients are removed for food crops



Development of mechanical subsystems will include:

- A growth method for microgravity
- A methane-fueled catalytic converter
- Pumps, grinders, and condensers
- Research to tie this system into standard life support systems

AELSS is closed with respect to nutrients and open to energy flow. Food crops and humans are easily tied into the system.

Potential & Benefits

- AELSS advances state-of-the-art CELSS by using only two living links, both of which reproduce by cloning
- AELSS also is not burdened with producing food for humans, which requires complicated equipment and growing schemes
- AELSS is a key enabling technology for the expansion of humans into space. Its adaptability means it can be applied to any closed system in space
- Closing such a simple system would be a big step forward for CELSS Research
- Simple and effective processing of Martian regolith is an attractive solution to a problem that does not have an easy solution at this time

Evaluation Notes

Title: **AELSS, Adaptive Ecological Life Support System**
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Adaptive Ecological Life Support System (AELSS) is a simple, robust, adaptable, and highly scalable Ecological Life Support System, enabling future space colonization efforts. Using just two live links, duckweed and a biodigester, accompanied by supporting mechanisms, a system is formed that recycles nutrients continuously. Humans and higher crops can be added to or removed from the adaptive system.

Challenge Addressed

A major goal of space exploration is the permanent and self-sufficient presence of humans in space. The value of a closed life-support system is self-evident; once a reliable closed-loop process is established, it becomes scalable, and the number of scientists, engineers, and citizens in space can scale with it. Such a system will require the utmost efficiency in the recycling and reuse of all solid, liquid, and gaseous wastes produced in space, but must remain open with respect to energy, which flows through the system freely.

The methods presently used on the International Space Station are reliable and well-understood processes but lack the ability to be used in a closed system, which is necessary for longer term missions beyond LEO. The use of consumables, compulsory disposal of wastes, and a requirement for regular resupply missions makes this model unsustainable into the future. While auxiliary physicochemical systems are useful as failsafe mechanisms on a long-duration flight, the best option is an emulation of the biosphere of Earth: a Closed Ecological Life Support System (CELSS). By continuously recycling wastes into useable nutrients to support human habitability, AELSS enables human life far beyond LEO.

Concept

The core of the proposed system is a two-link ecological system. The first link is a phototroph that uses light to convert CO_2 and nutrients to O_2 and biomass. The second link is a heterotroph that consumes the biomass, recycles nutrients out, and produces CO_2 and methane. The methane is burned to produce CO_2 and H_2O, completing the cycle of matter, while the heat energy is harvested to warm the system.

<u>Duckweed</u> -The phototrophic link is composed of a duckweed lagoon. Duckweed is a family of small, (0.5mm-1cm) single-leaf, floating aquatic plants. Duckweed grows very fast, doubling its biomass in as little as two days. It grows well on ultra-rich nutrient media, including raw sewage, and extracts most of the nutrients, leaving potable water behind, given a properly designed system. One of its most valuable properties is its reproductive process. It is a flowering plant but rarely does so, reproducing solely by a vegetative budding process. Each frond can clone itself up to ten times before senescence [1].

The majority of CELSS studies have focused on either algae or higher crop-type plants, both of which have some major disadvantages. Algae is difficult to grow and harvest efficiently and is not palatable long-term. Crop-type higher plants require months of maturation time, complex growth media and lighting, and have unreliable CO_2 conversion rates over their lifetime [2]. Duckweed strikes a clean balance between the two: It has continuous and exponential growth, meaning predictable CO_2 and nutrient conversion rates, as well as a cloning population that needs no further seeding or care to expand. It is easy to grow and harvest, requiring only a few cm of water for a short root, and can be scooped off the surface to harvest. It has excellent nutrition, out-producing both corn and soybeans in starch and protein production [1]. Although little research has been done in the area, we believe its growth rates can be enhanced even further by light, temperature, nutrient, and CO_2 concentration optimization.

<u>Biodigester</u> - The heterotrophic link is a methanogenic bacteria colony contained inside a specialized bioreactor, or biodigester. The anaerobic bacterial colony from a cow's stomach is frequently used on Earth in a biodigester to convert excess biomass, sewage, and other farm effluents into methane. These systems convert around 60% of the organic solids to biogas, a mixture of ~65% CH_4 and ~35% CO_2. The remainder of the organic matter is a stable, nearly odorless, and virtually pathogen-free nutrient slurry ready to be

fed back to the duckweed colony, which recycles the nutrients and removes the remainder of the pathogens [1,3]. For the AELSS effort, we will investigate using a methane-powered catalytic converter that cycles cabin atmosphere through it to help reduce airborne particulates and buildup of volatiles. The primary by-products of it would be CO_2 and H_2O, which are returned to the duckweed colony and are recycled again into oxygen and biomass.

Mechanical Links - While duckweed and the biodigester make up the primary links of the system, there are a few mechanical components that are vital to its operation. As mentioned above, we will investigate a methane-powered catalytic converter to convert particulate and unwanted gases, as well as harvest heat energy from the system. This heat energy will be used to keep the biodigester and duckweed colonies warm, as they both thrive in around temperatures of 35°C [1,3]. The methane is burned with the O_2 produced by duckweed, which in turn produces CO_2 and H_2O that are returned to the system.

A mechanism for keeping the duckweed in water while in microgravity is also required. Duckweed has traveled to space before [4], and the results of those studies will be leveraged to determine a design. Preliminary ideas include stacked trays with features that encourage water tension to hold on or an artificial gravity system consisting of concentric cylindrical tanks. Both are very volume efficient, with initial calculations showing that a 1 m radius, 2 m long cylinder could hold as much as 65 m^2 of duckweed. Further mechanical systems needing development include grinders and pumps that move biomass or compost effluent from one system to another, as well as nutrient distribution systems.

Mission Context

The adaptability of AELSS makes it well-suited for a trip to Mars to support the planet's subsequent colonization effort. During the trip to Mars, AELSS would remain static in size, just large enough to recycle waste generated by the crew. Research from the ISS' long tenure gives a good idea of how much of each nutrient can and should be recycled each day and how much should be stored in preparation for a possible disaster. Empirical determination of these values is the core of the upcoming research, but preliminary calculations indicate that around 40 m^2 duckweed can recycle the CO_2 of one human per day. This is a large area requirement and has likely been the primary obstacle to real-world CELSS implementations in space so far. However, duckweed grows in a nearly two-dimensional configuration, allowing that area to be put into a much more volume-efficient configuration than other larger crops.

After arrival on Mars, the system takes advantage of its infinite and asexual expansion and rapidly expands to support many more humans than have traveled to the planet with it. Basic duckweed farms on the surface require very minimal infrastructure, but the density can be greatly increased using stacking techniques and LED lighting. As described below, these duckweed farms may be able to convert Martian regolith into arable land.

A minor function of our system is duckweeds use as a supplementary nutrition source. Generally, about 40% of its dry weight is protein, 20% is carbohydrates, 5% is fats, and the rest is fiber and other components [1]. Duckweed is not able to provide complete nutrition to humans, and we do not provide for the 'filling out' of those nutritional requirements with our system via other crops. However, the compost effluent from our system can contribute to the growth of other crops. If duckweed is first eaten by humans instead of entering the biodigester, the nutrients end up in the same place and serves the same function as before, albeit producing less methane. Humans have simply replaced some function of the biodigester in the system. Additionally, because the duckweed is grown on stabilized biodigester effluent, the biomass is suitable for human consumption after minor washing.

Expansion into Higher Crop Plants - Once on the surface of Mars it is expected that humans will desire to expand the variety of plants being grown for both physical and mental health reasons, as well as in preparation for the arrival of future colonists. The biodigester provides a rich nutrient slurry that acts as a compost fertilizer for new crops. This drains the nutrient reserves of the original system, which must be replenished from outside, effectively opening the loop. The nutrient sources would primarily be the Martian regolith, with processes described below, and the Martian atmosphere.

Martian Regolith and Heavy Metal Sequestration - Arable land will be desirable on Mars, since the infrastructure for hydroponics is cumbersome and difficult to manufacture in-situ, especially early in colonization. AELSS is well-suited to process Martian regolith for further use by higher plants. Duckweed is adept at pulling a wide variety of heavy metals from its growth medium, sequestering them in its flesh until death or harvest. [1] This heavy-metal polluted duckweed should of course be kept in a separate system away from the main crop cycle, and methods for the removal of the heavy metals should be researched for reclamation. The cleaned regolith, however, is then suitable for higher crop growth, where it can still provide an array of nutrients necessary for plant life.

Perchlorate Breakdown - Perchlorates are another tough challenge posed by the Martian regolith. However, research has shown that swamp-like anaerobic environments coupled with indigenous species of plants can be very successful in phytoremediation of perchlorates. Simulated swamps and wetlands were planted with natural swamp mud and indigenous plants and fed perchlorate-contaminated water for a period of time, over which the perchlorate concentration was monitored and observed to decrease. A duckweed-planted swamp performed best out of a series that included other higher plants. Some microbes also thrive in a perchlorate-rich environment [5]. Development of this technique holds great promise for future colonization efforts on Mars.

Potential Impact

AELSS provides significant advantages over previously studied CELSS architectures, enabling colonization missions beyond LEO.

Duckweed vs. higher crops - By using a plant species that grows in a two-dimensional configuration, AELSS saves significant volume over higher crops. This is also an advantage over algae, which is complicated to grow and harvest efficiently. Duckweed is well-suited to cleaning dirty water, pulling most contaminants out as nutrients. This also means it grows incredibly fast, lending itself well to air recycling.

Adaptability – The system is highly adaptable, and with minimal infrastructure, one duckweed-biodigester colony could expand from a single station to an interplanetary ship to planetary surfaces and beyond. Both links clone themselves infinitely, meaning a single starting system could seed a limitless number. The size and simplicity of the plant structure means they can grow almost anywhere. The use of a biodigester in the system means it can operate with or without humans and provides a nutrient stream that is useful to any other crop.

Robustness – Duckweed is an incredibly resilient plant, growing on and remediating almost every contaminant it encounters. The cleanup of Martian regolith is a monumental task, but duckweed greatly simplifies it, enabling higher crop growth in places we thought only hydroponics were possible.

Study Outline

The objectives of the Phase I effort will be to establish the feasibility of the AELSS concept, develop and analyze the Mars Colony Life Support mission architecture, and evaluate its value relative to baseline architectures currently in use on the International Space Station. Tasks to establish feasibility of the AELSS architecture will focus on key technology components, including closing the loop between the two links, empirical data gathering on duckweed growth and nutrient conversion rates, and biodigester feed rates.

References

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