The Engineering Trade Space for a Robust Closed Ecological Life Support System:

A Suggested Technology Road Map

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Introduction

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Two closed systems

Hard problems

Trade space

Cornell all biological ECLSS system description

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Requirements

1. Clean air

2. Clean water

3. Nutritious food, at minimum complete nutritional requirements, at best, OPTIMAL requirements

4. Waste reprocessing

A fully closed system requires plants and efficient solid waste reprocessing. Those are big steps. Biology is helpful here. Organisms are self regulating within fairly wide parameters.

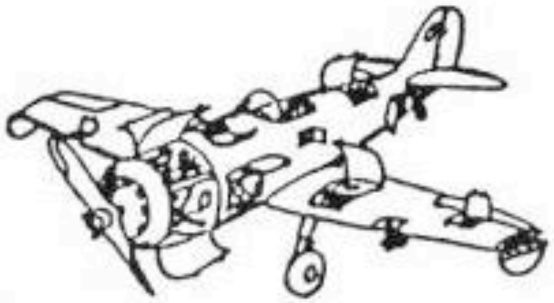
Fully closed system appears desirable for any inhabited off Earth structure with design life more than five years.

Basic Engineering Principles

Design as a system for minimum cost.

ECLSS is a system of subsystems. Subsystems must be optimized to maximize system performance, NOT to optimize subsystem performance.

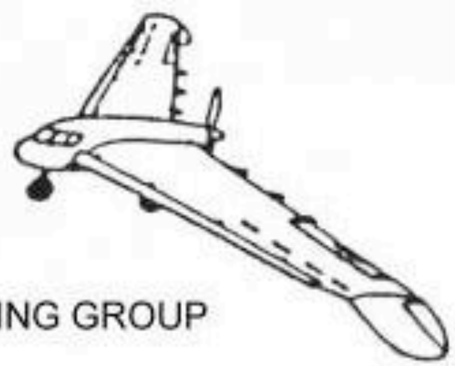
Example: It may be possible to grow sufficient wheat in 25 square meters, but that requires unrealistic control over nutrient solution. Furthermore, wheat is not an optimal human nutrient.



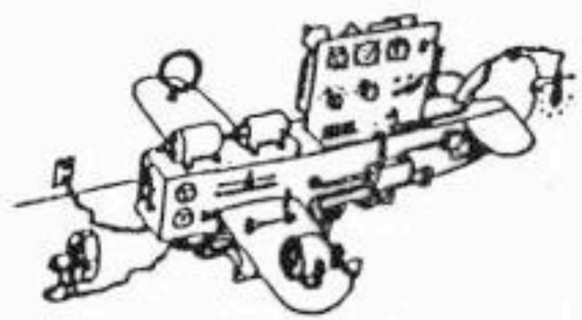
SERVICE GROUP

EQUIPMENT GROUP

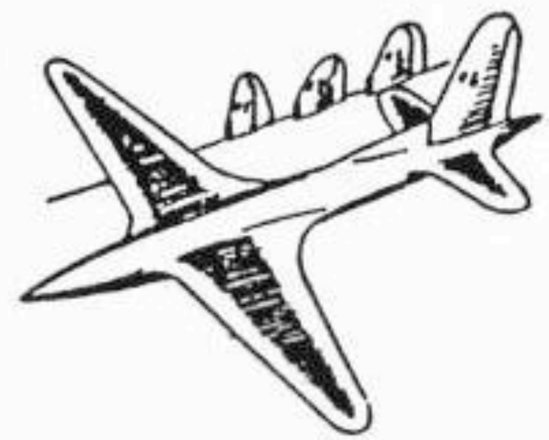
ARMAMENT GROUP



WING GROUP

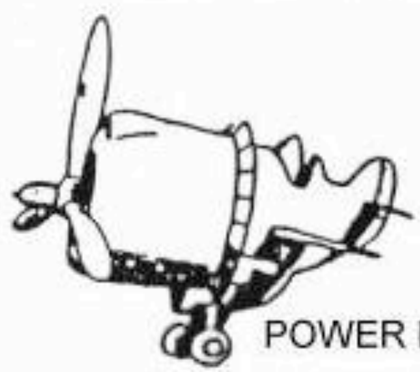


ELECTRICAL GROUP

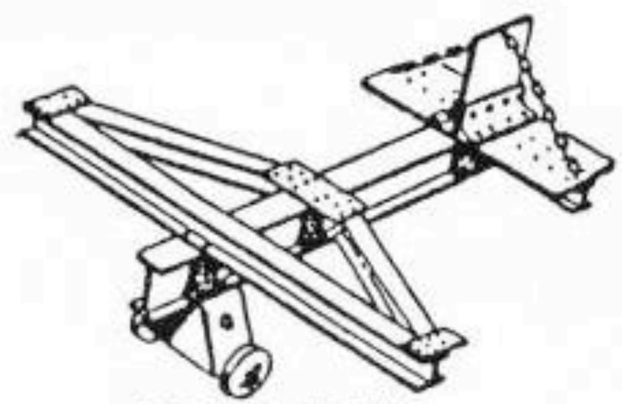


AERODYNAMICS GROUP

EMPENNAGE GROUP



POWER PLANT GROUP



STRESS GROUP

Basic Engineering Principles

Like any mature engineered system, ECLSS will require iterative development. Time is required for design, test; re design and re test.

The ability to evaluate many design options quickly will allow earliest success.

ECLSS must be robust. Redundant systems of different design for functions are desirable. The system needs adequate margin. Margin implies larger atmosphere mass, water cache, food cache.

Use COTS solutions where ever possible to minimize cost and maximize reliability. Ideally, most of manufactured mass could come from Home Depot.

Gravity, natural or artificial, is highly desirable

Allows use of COTS pumps to circulate water, air circulation by convection, easy separation of liquid and gas phases, less need to filter air for particulates.

Full time solar illumination is highly desirable. Minimizes electrical power requirement for plant growth.

Therefore, choose settlement location carefully. Free space colonies are a big win compared to planetary surfaces.

Closed Systems are Easy.
A Natural Example is Earth

Closed Systems are Easy but Inefficient

They are both energetically and materially inefficient. Ecosphere and Earth both have high light flux and largely microbial waste reprocessing.

Earth human life support before agriculture and modern industry:		Earth human life support after modern agriculture and industry:	
Air mass/ person	1,000 million tons	Air mass/person	1 million tons
Water/person	200,000 million tons	Water/person	200 million tons
Biomass/person	400,000 tons	Biomass/person	400 tons
Energy/person	30,000 megawatts solar	Energy/person	30 megawatts solar

Ecosphere similarly inefficient water mass~ 1 million times shrimp mass, energy several watts to support few milligrams of shrimp.

Our system should have on the order of one ton air, one ton of water, one ton of biomass and 20 kilowatts of power (solar illumination plus electricity) per person.

Earth has physical systems that aid in ECLSS requirements

Nitrogen fixation by lightning ~8%, air cleaning by rain, by photolysis and photo oxidation, water purification by evapotranspiration, and soil and rock filtration; release of deadlocked nutrients by fire.

It appears we will need similar processes in a largely biologic ECLSS. Among processes in terrestrial practice are ozone water purification, nitrogen fixation via Haber Bosch process (~40% of total), supercritical water oxidation, gravel and sand filtration in water systems.

Every technical development has at least one hardest problem

For ECLSS, the hard problem is regenerating nutrients from sewage and crop waste.

For a typical diet, crop waste is twice the mass of plant consumed. Given the expense to produce this waste, you would like to extract as much value from the waste stream as possible. Remember plant solar energy conversion efficiency is ~2% (up to~8% in low light conditions) and all introduced energy requires radiator to dispose of it.

The value is food energy and fixed nitrogen. The nitrogen cycle is the critical part of the ECLSS recycling problem.

Proposed All Biological ECLSS

Clean air: primary problem is CO_2 removal; it's automatic since the required plants can fix CO_2 at several times human respiratory CO_2 delivery. Volatile organics and toxic gases like nitrous oxide may require other solutions.

Clean water: also easy, the plants transpire at many times human daily needs. Most water is conditioned for plant use in the system.

Nutritious food: quality greatly improved because animals, which recapture energy stored in plant waste, supply high quality protein with large quantity branched chain amino acids.

Proposed All Biological ECLSS

Waste recycling: most waste recycled, remainder is comminuted so that a comminution step is not needed to use physical oxidation processes. Less waste overall because of the recycling, what remains is sludge amenable to Super Critical Water Oxidation

The idea is to maximize efficiency of illumination, eliminate high temperature, high pressure processes, therefore minimize need for components to resist corrosion.

Assumptions

Gravity or equivalent

Illumination from sunlight (infrared and ultraviolet filtered)

3600 calories/day/one person > 1 gram protein/kg body weight/day

Components of System

1. Plant bio mass production unit 130 square meters Total production per day~ 4100 g dry bio mass.

2. Nitrogen fixation legume growing unit 125 square meters.

The most important design limiting factor is the de nitrification rate and need to fix nitrogen gas . 15 g N /person/day requires replacement of fixed nitrogen lost to denitrification plus losses in refractory material.

A big trade in the proposed system is biologic fixation versus Haber Bosch synthesis. A requirement for minimum energy favors biologic fixation.

Components of System

Nutrient Regeneration Units:

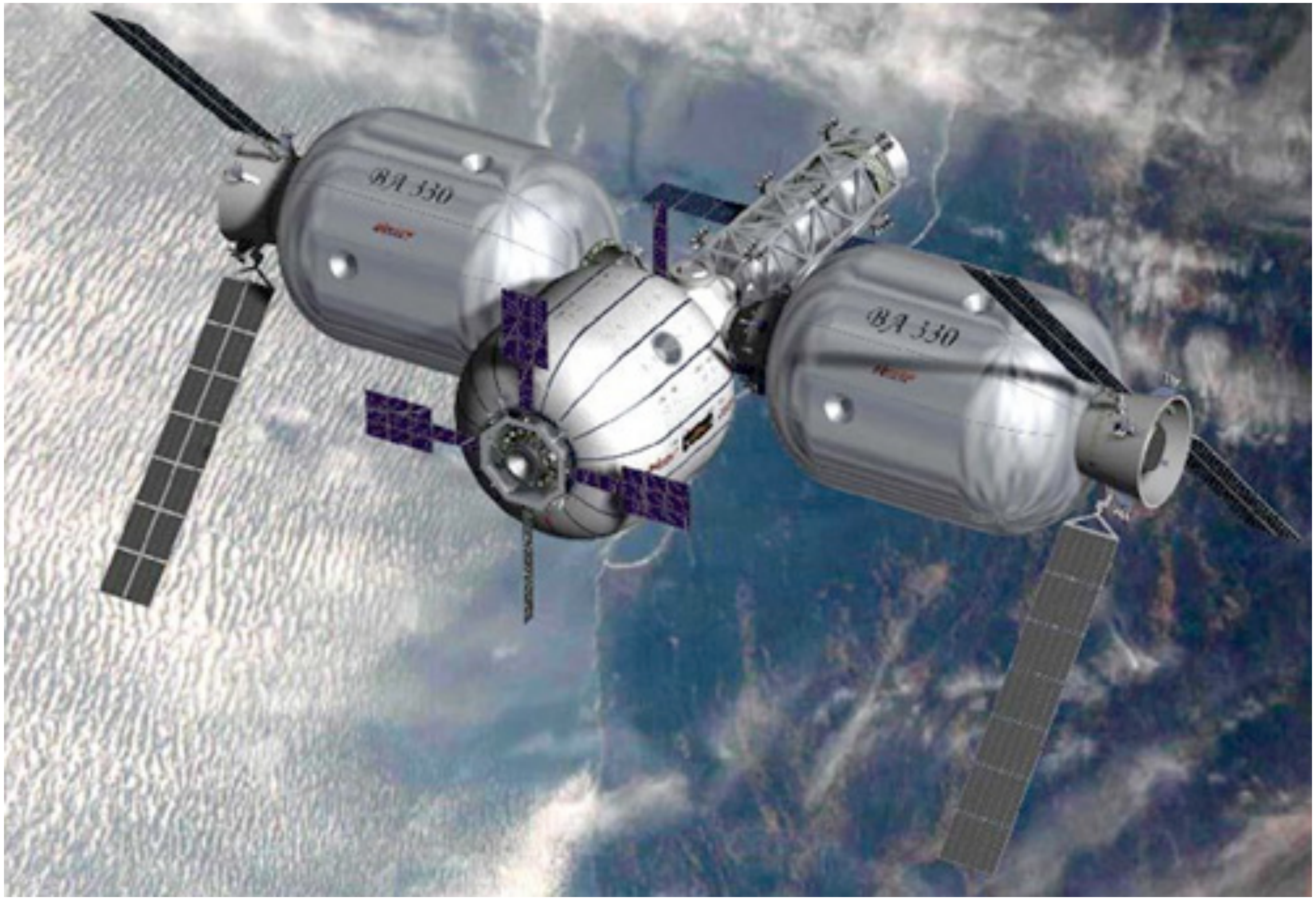
3. Aquaculture and water backup system 5 square meters.

4. Vermiculture unit 9 square meters

5. Fungi unit 9 square meters

6. Waste management/bio mass processing area 10 meters squared

7. Soil synthesis module (all refractory material accumulated here). Soil generation to establish broad range of food production systems may allow long term success of closed system.



- **Bigelow Sundancer to be orbited in 2014 has sufficient volume to provide a fully closed system for two persons per module, if reconfigured. BA 2100 is even more suitable.**

Differences from earlier concepts

Waste is not assumed to be converted to its most oxidized form. The focus is on using nutrients in waste to produce high value byproducts.

Water cycle focuses on plant requirements since they are much greater than human requirements.

Biological design is self designing and self correcting.

Attention to optimal nutrition

Differences from earlier concepts

Recycling nitrogen and carbon is the overriding challenge. Focus on deadlocked material. Need to know rates of formation, characteristics and quantities. Can this be converted into a positive? For example, soil generation. 45 meters squared per year to depth of 15 cm.

Aquaculture converts the 2/3 of crop waste unusable by humans to high quality protein: ~3 kg dry matter to 1 kg dry weight of fish. In many earlier designs was assumed to be oxidized directly. Aqua culture can also be staged using a mix of species.

Water requirements and waste water treatment

Water for food production is several hundred times greater than human requirements.

Sustainable water is provided by management of quantity and quality of condensed water. Control of dissolved volatiles is larger problem than sewage purification.

Two stage waste water treatment recommended for rapid mobilization of nutrients in human waste. The first stage is anaerobic followed by aerobic polishing. Alternatively waste could be pasteurized and delivered directly to vermiculture or soil synthesis unit.

Water requirements and waste water treatment

Isolation of pathogens, control of intermittently introduced toxins (e.g., antibiotics) and positive control of nutrients are the reasons for human waste processing system.

Anaerobic biofilm reactors are rugged and stable. After treatment, waste water transferred to reservoir that feeds hydroponic plant growth units. Estimated nitrogen concentration in treated wastewater is 420 mg/liter.

Of plant biomass produced, 20% is human food, 70% is high nitrogen biomass to be fed directly to fish, 10% is low nitrogen delivered to vermiculture unit.

The vermiculture unit then provides 40% of the low nitrogen crop waste as high protein fish food.

Note: vermiculture unit provides a redundant high quality protein source and could provide up to 20% of the diet.

All human and aquaculture particulate waste goes to vermiculture unit en route to the mushroom unit.

The mushroom culture unit produces two liters/ day at 50% moisture of humus like deadlocked material. This may subsequently be oxidized or mixed with regolith to create soil.

Conclusions

- **The immediate practical use of ECLSS research is to better understand Earth's systems.**
- **Long term a successful ECLSS will open the solar system to settlement, as fire and clothing opened the cold regions of Earth.**
- **A hybrid of biological systems and physicochemical systems appears optimal.**
- **A non terrestrial source of water, carbon and nitrogen can provide nearly all the mass of the ECLSS and obviates the need for an oxidizing step to recover deadlocked nutrients.**
- **The mix of suitable animal and plant species is not known.**

Recommendations

- **Start soon. Radical improvements in Earth to orbit transportation are coming. An ECLSS will require years to develop.**
- **Start small. Many investigations can be done with minimal equipment. Atmosphere need not be closed for most of these.**
- **Illumination quantity and quality need work.**
- **A small closed atmosphere pilot plant will be needed.**
- **Preliminary work may be government supported. The pilot plant and full scale development should be commercial.**
- **Synthetic biology may prove useful. Work on it.**
- **Find suitable, robust combinations of plants and animals.**

Recommendations

- A super critical water oxidation system for the 2 liters per person day of sludge would be useful,unless make up mass is available.
- A small Haber Bosch unit is also recommended.

Final thought