Towards Closed Environmental Control and Life Support for Space Habitats Part I: A Basic System

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Abstract.

Food production will be essential for long-term occupation of any space habitat as part of an efficient environmental control and life support system (ECLSS). A credible basis for an artificial hybrid ecosystem is described with both biological and mechanical components capable of providing a varied though limited balanced diet and recycling nutrients. Hydroponic growing methods are proposed with the accumulated biomass treated to recycle nutrients. The optimum mix of plant species is not known but some possibilities are offered for consideration. A fully closed ECLSS is probably impossible and hydrogen oxygen nitrogen and carbon lost from airlocks will have to be replaced.

Key words. Environmental control life support system, ECLSS, food production, nutrient recycling, super critical water oxidation, SCWO, hybrid artificial ecosystem.

Acronym list. Environmental control life support system (ECLSS), super critical water oxidation (SCWO), local exhaust ventilation (LEV).

1. Introduction.

High present and near future launch costs dictate that food production will become an essential requirement for long-term occupation of any space habitat. Food production cannot take place in isolation, however, but must be an integral component of an efficient air water and nutrient recycling waste reprocessing and life support system. The Earth naturally provides all these things in a robust multiply redundant and self-sustaining but very inefficient system. The challenge will be to build these capabilities into compact efficient and ideally closed systems [1].

This overview identifies some of the important issues while recognizing that much work will be necessary to develop an efficient sustainable system. The feasibility of a basic closed ECLSS capable of producing a nutritious and healthy diet is discussed. If this can be achieved more elaborate and extensive systems should follow capable of producing a wide variety of foods including luxuries. Likely near-term options for food production and nutrient recycling are selected while future possibilities including soil formation and the contribution of animals are not. Discussion concentrates on food production and nutrient recycling and does not deal with ventilation, heat and humidity control or air and water quality management except where they impact directly on food production and nutrient recycling.

2. Assumptions.

It is conservatively assumed that near Earthlike conditions are required. All necessary resources are assumed to be available with the system operating in air of Earth standard composition at sea level pressure not only for fire suppression but also for efficient operation of the ECLSS. Also, Earth normal or near normal gravity will be provided not only for the comfort and wellbeing of the occupants but also to simplify pumping and drainage requirements. Illumination will be from sunlight or artificial equivalent and exposure to ionizing radiation kept close to Earth surface levels. Current and near-term technology will be assumed.

3. Main outputs from and resources necessary for an ECLSS.

3.1 Daily human requirements.

Table 1 shows the daily human requirements for food water and oxygen [1] for an average man. Women require less and children less still but are growing so remove nutrients permanently from the system. For simplicity, the data for a single man is used in the following analysis. Values are based on average metabolic rate of 136.7w/person/day and respiration quotient of 0.87 (molar ratio of CO_2 generated to O_2 consumed). Values will be higher for greater levels of activity and for larger than average persons.

Human daily requirement	Mass (Kg)	Effluents	Mass (Kg)
O_2	0.84	CO_2	1
		Carbon in CO_2	0.27
		O_2 in CO_2	0.73
		Metabolized O_2	0.11
		CH_4 H_2 and trace organics	<0.01
Water in food	1.15	Water in faeces	0.091
Drink	2.2	Urine	1.5
Metabolized water	0.35	Resp/persp water	2.2
Total water intake	3.7	Total excreted water	3.79
Urinal flush	0.5	Urine flush water	0.5
Faeces flush	0.91	Faeces flush water	0.91
Hygiene water	12.6	Hygiene water	12.58
Clothes wash	12.5	Clothes wash water	11.9
Food prep water	0.76	Clothes drying water	0.6
		Food prep water	0.76
		Water from metabolized O_2	0.11
Total wash water	27.3	Total waste water	27.36
		Faeces solids	0.032
		Urine solids	0.059
		Sweat solids	0.018
Food solids	0.62	Total solids	0.109
Total	32.4		32.37

Table 1. Daily human requirements for food water and oxygen [1].

3.2 ECLSS required outputs [2].

- **Clean air.** (Provided mainly by CO_2 removal and O_2 regeneration).
- **Clean water**.
- **Nutritious food**.
- **Nutrient recycling.** (Solid waste recycling is probably the most difficult to achieve efficiently).

3.2.1 Clean Air.

Carbon cycle.

Carbon in the form of CO_2 must be extracted from the air and replenished by humans breathing as well as by waste recycling processes. These competing processes must be kept in balance by the ECLSS to maintain the optimum partial pressures of CO_2 and O_2. However, some carbon will unavoidably be lost from airlocks and need to be replaced from an outside source.

Nitrogen cycle.

Nitrogen is often the limiting constraint to plant growth. The nitrogen in the Earth's atmosphere cannot be used by plants but needs to be in soluble form (fixed) for absorption via their roots. The recycled remains of plants and animal waste as well as urine and faeces are good sources of nitrogen but are not primary sources for new plant growth. Unfortunately, significant quantities of fixed nitrogen are lost to the air as N_2 during recycling processes. In addition, in the same way that carbon is lost from airlocks some nitrogen (and O_2) will also be vented and need to be replenished.

Some plants such as legumes (peas and beans) have symbiotic bacteria in root nodules to fix atmospheric nitrogen as water-soluble compounds. In the absence of a biological nitrogen fixation process (which could include bacteria in a bioreactor) a chemical method such as Haber-Bosch synthesis becomes necessary. Any or all of these processes could be used in a space habitat but require an N_2/O_2 atmosphere for which large amounts of N_2 would need to be imported from Earth or asteroids [3].

3.2.2 Clean Water

Water is of course essential for the operation of an ECLSS. This is especially so for plant growth not only to support the cells so the structure remains turgid but also to draw up nutrients from the roots and distribute them throughout the plant. This occurs via a transport process driven by evapotranspiration from the stomata in the leaves which causes water to be drawn through cell membranes by osmosis from the roots to the top of the plant.

Evapotranspiration of water is closely linked to photosynthesis and varies between 200 and 700 grams of water per gram of dry plant biomass produced. Although water circulation and evapotranspiration were once thought to be fixed components of plant growth they can be uncoupled from photosynthesis and limited by controlling humidity and by increasing CO_2 concentration. Trade-offs to limit evapotranspiration relate to nutrient concentrations and pathogen growth on plants [2]. For present purposes evapotranspiration is controlled at 180 grams water per gram of dry plant mass grown [2].

3.3 Producing food and nutrient recycling: Chemical versus biological methods.

Any type of ECLSS will necessarily have a major biological component in the humans it is designed to support together with their associated microbiomes. It therefore seems perverse to attempt to design a non-biological chemical food synthesis and physicochemical nutrient recycling system. Such methods are, however, quick use compact equipment and are easily controlled, making them especially attractive for small habitats and spacecraft.

It should be possible in principle to synthesis food directly from basic organic chemicals, water and minerals. A likely approach is artificial photosynthesis but current as yet unsuccessful efforts are aimed at splitting water for fuel production rather than capturing CO_2 for sugar synthesis.

At present, therefore, the only available method of food production is to use the existing biological machinery in bacterial and plant cells. Plants are particularly promising and can be regarded as sophisticated chemical factories that build, operate and reproduce themselves, are self-sustaining and regulating, use little energy and work at room temperature. The fixation of carbon from the CO_2 exhaled by humans and the release of O_2 through photosynthesis not only produce food but also regenerate breathable air. Crop plants have been selected over hundreds, sometimes thousands of years to produce high yields of especially nutritious and palatable food that can be eaten raw or with minimal processing (cooking). Plants can also provide other required outputs of an ECLSS: clean water through transpiration and recycling of soluble nutrients.

Nutrient recycling requires additional systems to return solid plant biomass and human waste into the soluble (minerals including nitrates) or gaseous (CO_2) forms suitable for plants. This occurs naturally by the action of microorganisms but is slow and sequesters carbon and (to a lesser extent) nitrogen in recalcitrant organic compounds (humus) in soil [2]. Composting is the horticulturalist's method of managing this process by recycling most of the carbon to the atmosphere and increasing the humus content of fertile soil, but it requires time and space. Hydroponic growing methods do not require soil and thereby enable the simplest possible approach of avoiding a composting step and instead relying on artificial recycling methods such as thermochemical oxidation.

A basic hybrid ECLSS using hydroponically grown crop plants for food production and thermochemical oxidation for nutrient recycling is described. It is essentially an artificial ecosystem, an interdependent system of plants and animals (humans with their microorganisms) augmented by thermochemical methods.

An important principle of a sustainable ECLSS is that the system must be optimized to work as a whole even if individual components operate at less than maximum efficiency.

The key artificial components of the ECLSS are based on physicochemical processes operating at high temperature and pressure requiring expensive high maintenance equipment. Analysis [4] of the proposed Mars One ECLSS clearly demonstrates a problem with this approach in that the expense of resupplying spare parts for the growing and recycling equipment is greater than that of importing all food. The equipment must therefore be regarded as a significant part of the system to be optimized, leading to a requirement for simple robust machines that can be built or at least maintained and repaired with local resources.

In contrast to the artificial components of an ECLSS, biological systems require relatively cheap simple equipment, operate under ambient conditions, reproduce themselves and are self-maintaining. A completely or mainly biological ECLSS must therefore be regarded as the ultimate sustainable system and its feasibility will be examined in Part II.

3.4 Food production using plants.

3.4.1 Growing areas required.

The size of the plant biomass production system is based on average protein and calorie requirements. To estimate total surface area required, two simplifying assumptions are made [2]. First, that total human food requirements are <800 g per person per day (equivalent to ~320 g of fixed carbon) and, second, that the average photosynthetic process fixes carbon at a rate of 5 g.m^{-2} per day. These two assumptions give a total plant production area of 180 m^2 assuming one third of this biomass becomes food.

Calculations using the BioSim model [4] give a total of 200 m^2 required to grow the 5 types of crop for which data is available and which together produce a balanced diet.

Although there are differences, these two independent estimates result in similar food and total growing area requirements. This means that a habitat for 10,000 people would need a growing area of up to 2 km^2.

It is clear from this that significantly more space will be required for agriculture than for all other uses put together. Space efficient methods being developed on Earth for high intensity growing use hydroponic systems with plants stacked on shelving. Similar methods could possibly be adapted for space habitats.

3.4.2 Growing media.

Most wild plants grow of course in soil as do most agricultural crops. Soil provides support and is the main source of the principal nutrients other than carbon needed for plant growth, i.e. N, P and K as well as many trace elements. All these must be in aqueous solution to be useful, and plants live in a symbiotic relationship with microorganisms that solubilize minerals in return for sugars made by the plant during photosynthesis.

However, most types of plant can be grown in fresh water with added nutrients using hydroponic methods. Large quantities of fresh water will be required in a space habitat for many purposes other than food production, and used water will need treatment to remove pollutants before being recycled. Conveniently, water and nutrient recycling using plants is synergistic with food production since the same plants can fulfill both roles.

3.4.3 Hydroponics.

Plants can be grown with their roots irrigated by aerated water containing an optimum mixture of nutrients [1]. There are significant advantages of growing crops hydroponically rather than using conventional growing media. First, it is easier to keep all growing areas free from plant pathogens that would be disastrous in such a key food production system. Second, nutrient balance can be monitored and maintained continuously for optimum growth. Liquid waste containing nutrients such as urine can be recycled directly and diluted to form part of the liquid feed. Plant roots will die if immersed continuously in water so hydroponic systems often use a root support matrix based on inert materials such as pumice over which water containing nutrients trickles while leaving sufficient air gaps for the roots to breathe. Pumice as the support medium for hydroponics may be available from volcanic sources on the Moon, although it is likely to have been reworked over the millennia by impact "gardening." Some form of artificial heat-treated inorganic growing matrix similar to "perlite" may therefore prove necessary.

Growing plants under optimum conditions of lighting (up to 24 hr daylight), temperature, water and nutrients in the absence of bad weather, seasons, pests, diseases and weeds should result in very high yields with perhaps four crops a year.

3.4.4 Crops suitable for hydroponics.

The following limited range of crops provides a basic balanced diet with soft residues that are easily recycled. The list is by no means exclusive or exhaustive but serves to illustrate what is readily available.

Vegetables such as tomatoes, peppers, aubergines, carrots and lettuce are all easily grown as well as being nutritious. Brassicas include cabbages, cauliflowers and broccoli and are an excellent source of fiber and vitamins and minerals including iron. Cucurbits such as courgettes and winter squash are particularly prolific and easy to grow but not space efficient. Other vegetables grown hydroponically include watercress, artichokes, spinach, beetroot and asparagus. Root vegetables such as onions, leeks, carrots, parsnips, potatoes, yams and radishes are also possible but require extra care. Alliums like onions garlic and leeks not only provide valuable nutrients but also are key ingredients in many dishes adding flavor. Other flavor providing plants such as ginger, chili peppers and a wide range of culinary herbs are all easy to grow and are important culinary ingredients.

Potatoes produce much more food per unit area than other staple crops such as wheat or rice so are an obvious choice. They are very versatile in the kitchen and as well as carbohydrate are a good source of fiber and vitamin C. They are propagated using vegetative methods rather than by seed so varieties remain consistent and pollination is unnecessary.

Legumes such as peas beans and lentils are good sources of proteins, carbohydrates, including oil and fiber, as well as having the additional benefit of fixing nitrogen from the air with the aid of symbiotic root bacteria. Other important legumes are groundnuts and soya beans. The generally soft crop residues of legumes contain nitrogen, much of which can be recycled.

Fruit such as melons and strawberries are easy to grow and propagate, crop within months and in contrast to most fruit plants have soft readily recyclable residues.

It is immediately obvious that plants alone are capable of producing a balanced diet. When supplemented with small amounts of meat and dairy products they provide perhaps the optimum human diet. A healthy vegan diet is possible but requires attention to ensure adequate amounts of fat and protein are eaten.

3.4.5 Pollinating insects. Most if not all of these crops are pollinated by bees which will be an essential component of the artificial ecosystem. Initially, there will not be enough plants and therefore flowers to support hives of honeybees so it may be necessary to use small numbers of solitary bees. The numbers of these could be increased in step with agricultural production until they can be replaced with honeybees which would of course also provide honey.

4. Air recycling management and treatment.

Although it is not intended to detail the requirements for air management and treatment, food production and nutrient recycling processes necessarily interact extensively with its principal components N_2, O_2, CO_2 and H_2O so some discussion is unavoidable.

Plants remove excess CO_2 and replace it with O_2 but in practice some air management will probably be necessary to transport exhaled CO_2 to plants in the growing areas and deliver oxygenated air to the living areas. It will be necessary to schedule the growing phase of crops during which more O_2 will be produced than CO_2 absorbed with the harvesting and recycling phase when the reverse is true. An air handling plant also provides the opportunity to monitor air quality and if necessary use HEPA (High Efficiency Particulate) filters [1] to remove dust including allergens such as pollen grains, mold spoors and dust mite debris. Humidity, temperature and CO_2 concentrations will also need monitoring and adjusting as required.

It will be important to avoid the use of treatment methods such as caustic scrubbers for CO_2 removal and bleach for disinfectants which rely on frequent replacement of exhausted chemical reactants and would lead to a build-up of salt in the ecosystem. Consequently, physicochemical processes such as filtration, freezing and condensation together with hydrogen peroxide and ozone based bleaches are to be preferred. For example, removal of the excess O_2 produced during the growing phase of crops would be best achieved using air liquefaction techniques and the temporary storage of liquid

O_2 ready for use during recycling of excess biomass. Finally, the build-up of pollutants such as solvents evolved from plastics and fumes from light manufacturing processes must be guarded against mainly by providing LEV and treatment at workstations.

5. Solid and liquid waste recycling.

A process capable of dealing with all types of solid waste arising from the processes previously described is required and this is the most difficult step for any type of ECLSS. Wastewater such as grey-water containing detergents as well as sewage (with traces of antibiotics and other drugs) from which the solids have been screened will also need to be treated.

5.1 Thermo-chemical oxidation.

Section 3.3 identified the need for thermochemical oxidation equipment. The most likely candidate is SCWO which is highly-efficient and capable of treating a wide variety of hazardous and non-hazardous wastes. Reaction takes place at elevated temperatures and pressures above the critical point of water (P_c = 220.55 bar T_c = 373.976 °C). Under supercritical conditions organic materials, oxidation reactants and oxidation products are miscible in water, thus allowing reactions to take place in relatively compact equipment and without significant mass transport limitations. Oxidation reactions go to completion and products include CO_2, H_2O and salts so no essential nutrients are sequestered. Airborne contaminants such as NO_X, SO_X and particulate concentrations are at or below detection limits requiring no post-treatment.

SCWO requires dilute solutions or mixtures of finely divided solids so is ideal for combined liquid and shredded solid waste streams. The process recovers nutrients and releases water but has a high-energy requirement, waste heat disposal and corrosion and maintenance issues. SCWO has the advantage that besides power, which is abundant in space, it needs only recycled air and water but no consumable chemical reagents. It would be ideal to treat the relatively small volumes of waste in early habitats especially as it would also recycle wastewater which would be sterilized and aerated in the process. However, minerals would remain and need to be removed, probably by plants, to recycle nutrients and produce potable water. Some fixed nitrogen is retained by the SCWO process and recycled as a plant nutrient but some is "lost" to the air as N_2 gas. The nitrogen cycle is a critical part of ECLSS recycling so the fixed nitrogen that has not been recycled must be replaced.

6. A simple model of human metabolic requirements and mass balance of macronutrients.

Although CO_2 removal and O_2 production are both natural processes of photosynthesis, the rates of production and intake of O_2 and CO_2 differ between plants and humans. Humans produce about 0.87 moles of CO_2 per mole of O_2 consumed while plants consume about 0.95 moles of CO_2 to produce one mole of O_2 [1]. Plants cannot therefore be used simply to maintain the CO_2/O_2 balance as demonstrated dramatically by the BioSim analysis [4] of the proposed Mars One ECLSS which uses plants to produce all food while ignoring the need to recycle nutrients. According to the simulation the overproduction of O_2 would result in the pressure increasing inside the habitat until the pressure relief valves open. This maintains the design pressure but loses N_2 over time so the partial pressure of O_2 goes up to dangerous levels. When the requirement for oxidizing crop and human waste is taken into account, however, the system as a whole should be in balance.

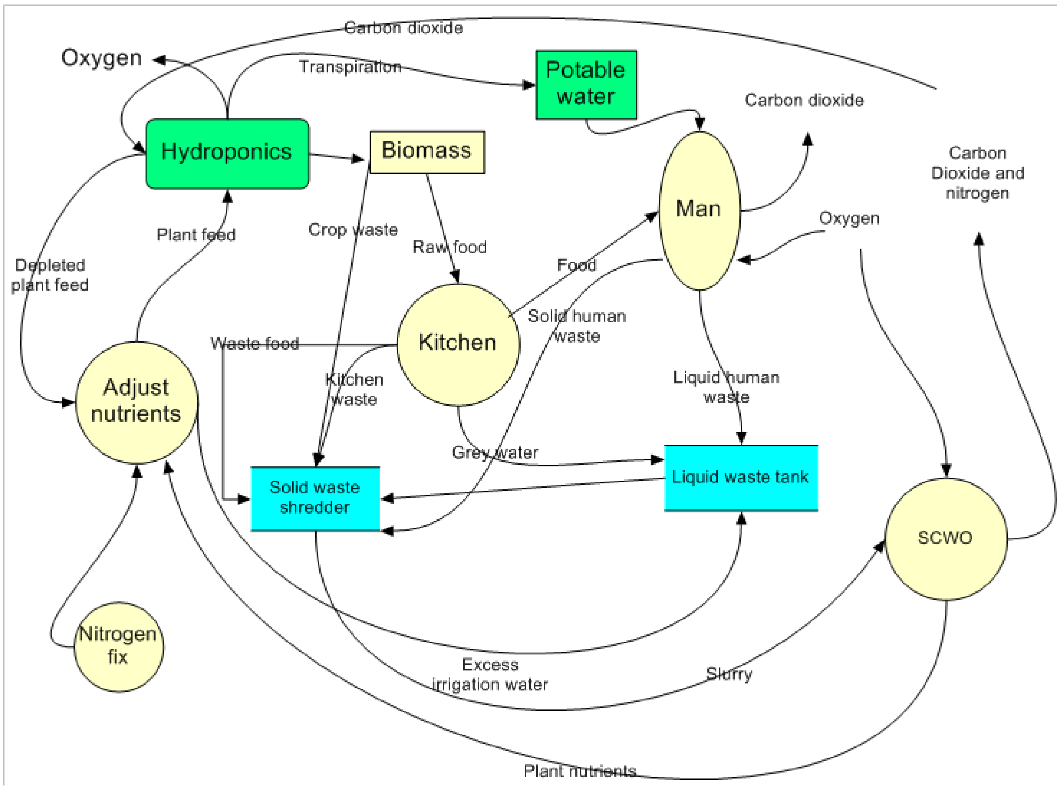

Figure 1. Macro-nutrient flows in a closed ECLSS.

Macro-nutrient flows for the hybrid ECLSS described in section 3.3, which uses crop plants for food production and SCWO for nutrient recycling, are illustrated in Figure 1. These flows guide a simple spreadsheet model to calculate the daily carbon and water mass balance for a "steady state" adult human male, i.e. one that is neither gaining nor losing weight. A number of other simplifying assumptions have been made and the nitrogen cycle has been omitted in order to illustrate the most important principles without unnecessarily complicating the calculations.

It is assumed [2] that plants fix $5 g.m^{-2}$ of carbon and the growing area is $180 m^2$ and there is 5 g of carbon in 12.5 g of food (dry matter). Food is 1/3 of the biomass produced. Also, the carbon content of faecal and urine dry matter is 14% and 50% respectively.

Human Needs	**Mass**	**Crop Needs**	**Mass**	**Crop Yields**	**Mass**
	(Kg)		(Kg)		(Kg)
O_2	**0.86**	CO_2 required by plants	**3.30**	O_2 from plants	**2.53**
		From human breath	**1.00**	**Human breathing**	**0.86**
		From oxidized faeces	0.06	Oxidizing faeces	0.04
		From oxidized crop waste	2.20	Oxidizing crop waste	1.60
		From oxidised urine solids	0.04	Oxidizing urine solids	0.03
		Total CO_2 available	**3.30**	Total O_2 used	**2.53**
		Water for hydroponics	**405.00**	Transpired water	**405.00**
Water in food	1.15	Water in faeces	0.091	For human use	**34.65**
Drink	2.2	Urine	1.5	For hydroponics	370.26
Metabolized water	0.35	Resp/persp water	2.2		
Total water intake	**3.7**	**Total excreted water**	**3.7**		
		Urine flush water	0.5		
Urinal flush	0.5	Faeces flush water	0.91		
Faeces flush	0.91	Hygiene water	12.58		
Hygiene water	12.6	Clothes wash water	11.9		
Clothes wash	12.5	Clothes drying water	0.6		
Food prep water	0.76	Food prep water	0.76		
Total water required	**34.65**	**Total waste water**	**34.74**		
				Biomass produced*	**2.25**
Food solids	**0.75**			**Food**	**0.75**
				Crop waste	1.50

Table 2. Daily carbon oxygen and water mass balance for crops to produce one human's requirements.

Results from the model are summarized in Table 2, which shows the daily carbon oxygen and water mass balance for crops to produce one human's requirements. The accuracy of the results is remarkable for such a simple model which ignores many of the complicating factors that will need to be taken into account in a real system.

As discussed in section 3.4 the rate of evapotranspiration is constrained artificially but the crop plants necessary to produce sufficient food still produce more than enough water for human and growing needs. In fact, the amount of clean water produced could easily be increased by at least a factor of three (3.4) and made available for other uses.

It is noteworthy that the food mass is only 1/3 of the biomass produced. The expensively produced excess must then be shredded and oxidized to recycle nutrients. This makes the system very inefficient but suggests that further value could be extracted.

6.1 Cost benefit analysis.

While a proper cost benefit analysis is beyond the scope of this paper it is nevertheless instructive to consider the main sub-systems of the ECLSS, their value and relative costs, as shown in Table 3.

Most striking is the high capital and running costs (which include the costs of importing replacement parts) of the high-tech recycling equipment. This is because little if any of it is likely to be manufactured locally so everything will have to be imported for the foreseeable future at any rate. In contrast, the crop based food water and O_2 production/CO_2 removal systems can be partially manufactured and repaired locally allowing for lower capital and much lower running costs.

Equipment/facility	**Capital cost**	**Running costs**	**Local parts manufacture and repair**
Hydroponics troughs & pipes	Medium	Low	Yes
Air management equipment Back-up CO_2 removal etc	Medium	Low	Yes (except HEPA filter cartridges pumps & sensors)
Water management equipment filtration salt balancing etc.	Medium	Low	Yes (except pumps & sensors)
Food processing & cooking equipment	Medium	Low	Some
Pumps motors lights sensors etc	Medium	Medium	No
SCWO	High	High	No
Haber-Bosch N_2 fix	High	High	No
O_2 removal & storage	High	High	No

Table 3. Cost benefit analysis.

6.2 Assessment of risks to the ECLSS.

A full risk assessment will require a detailed knowledge of the different pieces of equipment and the manner in which they will be used. It is worthwhile, however, to consider the most important items: the risk to the continued functioning of the ECLSS should a piece of equipment fail, and identifying mitigation measures. The risk assessment is given in Table 4.

As demonstrated in the Mars One analysis [4] operating a plant based ECLSS without provision for excess O_2 removal quickly leads to failure. The SCWO equipment is therefore shown as being critical because not only does it recycle carbon but it also removes excess O_2 to maintain the CO_2/O_2 balance. Mitigation measures include having multiple systems and carrying spares but also having separate O_2 removal and storage [4] and CO_2 removal equipment [1] as back-up.

The Haber-Bosch N_2 fixing equipment is shown as being of high importance since crop growth depends on a ready supply of fertilizer. Nitrate based fertilizer could be produced in a batch process and stored, however, giving time to repair the equipment in the event of failure. For this reason, the risk to the ECLSS is shown as medium reduced to negligible when mitigation measures are taken into account.

Equipment/ facility	Importance	Risk of failure	Mitigation measure	Residual risk
Hydroponics troughs & pipes	High	Low	Multiple separate systems	Negligible
Crop plants for food clean water and O_2 production.	High	Low	Use certified seed. Grow different crops in separate areas.	Negligible
Air management equipment back-up CO_2/O_2 balancing etc	High	Medium	Use redundant critical components.	Negligible
Water management equipment filtration salt balancing etc.	High	Medium	Use redundant critical components	Negligible
Food processing & cooking equipment	Medium	Low	Redundancy	Negligible
Pumps motors lights sensors etc	High	Medium	Redundant critical items. Carry spares.	Negligible

SCWO	Critical	Very High	Multiple systems. Carry spares.	Low
Haber-Bosch N_2 fix	High	Medium	Carry spares	Negligible
O_2 removal & storage	High	Medium	Carry spares	Negligible

Table 4. Assessment of risks to the ECLSS.

In contrast to the high-tech recycling equipment, the plant-based food and O_2 production systems are shown as being of low risk of failure, reducing to negligible with the mitigation measures in place. The most vulnerable parts of this system are lights, sensors, pumps and motors.

7. Discussion.

The simple model used here takes no account of the requirement to manage crop growing and harvesting cycles to produce not only a steady output of food but also balance the production of oxygen with the absorption of carbon dioxide. It will be necessary in practice to grow crops in succession so that at any one time some plants will be at every stage of the cycle.

The system will also be greatly dependent on the number of consumers and this is ignored in this simplistic model based on just one man. In this extreme case one arrival would suddenly double the required outputs of the ECLSS, not an easy thing to manage. If surplus food is stored against the arrival of visitors, the oxygen produced during its production will not be recycled but accumulate. In general, small habitats with low occupancy rates will be most difficult to manage compared to large habitats with large populations which will have sufficient capacity to buffer the effects of fluctuating visitor numbers.

Also, the simple model is for a “steady state” man who is neither gaining nor losing weight. Occupants who change weight such as growing children would affect the balance and lock-up carbon and other key nutrients making them unavailable for recycling. This will affect the carbon oxygen balance and mean that excess oxygen produced by growing plants will accumulate in the habitat and require removal. Indeed, excess oxygen production will accompany any process that sequesters carbon either temporarily (growing crops) or permanently (wood for construction, fiber for clothing, or chemicals for plastics). Carbon (and associated hydrogen, oxygen and nitrogen) removed permanently will of course need to be replaced and returned to the ecosystem. Under these circumstances the ECLSS can no longer be considered as closed.

It is clear that it will not be possible to begin immediately with significant food production in a new habitat. Instead, the artificial ecosystem will need to develop as the different processes are enabled and come on stream. An advantage of using multiple SCWO modules (6.2) is that new units could be added as the amount of waste increases. During construction of a habitat the builders will have to be provided for. All food will be brought from Earth and liquid waste and air recycled with a 1st generation ECLSS as used on the ISS except that solid waste will be stored for future processing. It would be helpful if all packaging materials imported from Earth could be recyclable to provide a source of carbon.

A starting position is then assumed in which heating, lighting, breathable air and potable water in storage tanks have been provided together with the necessary infrastructure of pipes and pumps and an air management system. There will also be growing areas and a suitable inorganic hydroponic growing matrix. Food production can then begin during which the growing plants accumulate biomass and generate excess oxygen. Recycling is achieved by mixing waste biomass with sewage, grinding and diluting with waste water, and treating by SCWO using the excess oxygen previously produced to return CO_2 to the air and salts in solution as plant feed. This could be described as a 2nd generation ECLSS.

Table 2 shows that 2/3 of the biomass produced is immediately recycled. If, however, additional value could be extracted from this expensive waste then the overall efficiency would greatly improve [2]. The obvious method uses food animals [2] but there are other possibilities. Microorganisms such as bacteria and yeasts in fermenters could be used to produce carbohydrates and proteins and recycle some carbon as CO_2, thus reducing the load on the SCWO equipment. Also, photosynthetic edible algae could digest some of the waste and remove carbon dioxide from air to produce oxygen [5]. After digestion and recovery of the added value products the final residue would be diluted and recycled using SCWO. Although such biological processes would improve the overall efficiency as well as significantly reducing running costs and the risk of failure, they add complexity and require equipment space and additional management. This largely biological 3rd generation ECLSS would seem to be optimal.

It is not known at this stage, however, whether an artificial ecosystem is possible. Indeed, a fully closed ECLSS of any type is probably impossible and at a minimum hydrogen, oxygen, nitrogen and carbon lost from airlocks will have to be replaced from outside. In addition, although the correct atmospheric ratio of oxygen and carbon dioxide can largely be maintained using plants, the balance will need to be adjusted artificially to correct for changing conditions such as variations in numbers of occupants. It is likely that visiting spacecraft will be supplied with water and food and their waste removed for nutrient recycling on the habitat but some net losses are inevitable.

Luxury foods such as meat and beverages such as tea, coffee, beer and wine will be difficult and expensive to produce in the early habitats and will have to be imported from Earth. However, human ingenuity can be expected to rise to the occasion and produce "homemade" wine and vodka from fruit and potatoes respectively. Cereals such as maize, wheat and barley require large growing areas so items such as bread may also become luxuries.

8. Conclusions.

While it is too early to draw firm conclusions about the optimum type of ECLSS for space habitats and spacecraft, a credible albeit simplified artificial ecosystem has been described capable of providing a varied though limited balanced diet while recycling nutrients. Food production must be an integral component of an efficient air, water and nutrient recycling, waste reprocessing and life support system optimized to work as a whole, even if individual components operate at less than maximum efficiency.

Food cannot yet be produced synthetically from basic chemicals so the existing biological machinery in plants and microorganisms must be used. Non-biological methods and equipment can be used, however, for efficient recycling of nutrients. In general, biological methods are favored because the alternative mechanical and physicochemical processes have high energy requirements as well as waste heat disposal and corrosion and maintenance issues. However, the state of current and near future technologies suggest that it will be necessary, especially in early small-scale systems, to use a partially biological ECLSS augmented by mechanical and physicochemical steps as necessary.

Hydroponic growing methods have the advantage that they do not need soil, but biomass will still accumulate and needs treatment to recycle nutrients. The optimum mix of suitable plant species is not known but some possibilities are offered for consideration. A fully closed ECLSS is probably impossible and hydrogen, oxygen, nitrogen and carbon lost from airlocks will have to be replaced.

9. References.

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