Closed bioregenerative life support systems: Applicability to hot deserts

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Abstract

Water scarcity in hot deserts, which cover about one-fifth of the Earth's land area, along with rapid expansion of hot deserts into arable lands is one of the key global environmental problems. As hot deserts are extreme habitats characterized by the availability of solar energy with a nearly complete absence of organic life and water, space technology achievements in designing closed ecological systems may be applicable to the design of sustainable settlements in the deserts. This review discusses the key space technology findings for closed biogenerative life support systems (CBLSS), which can simultaneously produce food, water, nutrients, fertilizers, process wastes, and revitalize air, that can be applied to hot deserts. Among them are the closed cycle of water and the acceleration of the cycling times of carbon, biogenic compounds, and nutrients by adjusting the levels of light intensity, temperature, carbon dioxide, and air velocity over plant canopies. Enhanced growth of algae and duckweed at higher levels of carbon dioxide and light intensity can be important to provide complete water recycling and augment biomass production. The production of fertilizers and nutrients can be enhanced by applying the subsurface flow wetland technology and hyper-thermophilic aerobic bacteria for treating liquid and solid wastes. The mathematical models, optimization techniques, and non-invasive measuring techniques developed for CBLSS make it possible to monitor and optimize the performance of such closed ecological systems. The results of long-duration experiments performed in BIOS-3, Biosphere 2, Laboratory Biosphere, and other ground-based closed test facilities suggest that closed water cycle can be achieved in hot-desert bioregenerative systems using the pathways of evapotranspiration, condensation, and biological wastewater treatment technologies. We suggest that the state of the art in the CBLSS design along with the possibility of using direct sunlight for

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photosynthesis and recent advances in photovoltaic engineering can be used as a basis for building sustainable settlements producing food, water, and energy in hot deserts.

Keywords: Hot desert; Closed bioregenerative life support system; Solar energy; Water scarcity; Water cycle; Carbon cycle

1. Introduction

The general idea of using the closed-system bioregenerative life support technologies developed by space life support (SLS) to improve Earth's environment was formulated by Nelson et al. (2003a) on the basis that the SLS science simultaneously addresses the problems of food, water, clean air, and energy supply. It was suggested that the application of CBLSS technologies for extreme environments on the Earth would give us a way to provide their sustainable development. These technologies potentially can "ensure renewal of water and atmosphere, nutrient recycling, production of healthy food, and safe environmental methods of maintaining technical systems. The development of technical systems that can be fully integrated and supportive of living systems is a harbinger of new perspectives as well as technologies in the global environment. Moving towards sustainability implies at least elements of the following: 1. Increased reliance on renewable natural resources and energy sources. 2. Minimizing or eliminating drawdown of non-renewable resources. 3. Eliminating or reducing quantity and toxicity of byproducts. 4. Developing ecosystem networks which can re-use the byproducts of the processes, thus keeping elements in productive circulation. 5. Maintaining or increasing rather than decreasing biodiversity as a result of human activities. 6. Developing understanding of how our global biosphere operates so that we can better harmonize human activities and economy within this life-support system. 7. Providing feedback loops so that people can see more clearly the consequences of their actions on their local ecosystems and the global biospheric system. 8. Providing exemplars and role-models of proper biospheric responsibility as a source of inspiration and hope" (Nelson et al., 2003a). The authors, however, did not discuss in detail the specific accomplishments and findings made by SLS that can be used in building CBLSS for Earth’s extreme environments.

Hot desert is one of such extreme environments. The lack of moisture and the abundance of sunlight all year round lead to a nearly complete absence of organic life in hot deserts and make them practically unsuitable for living. Hot deserts currently cover about one-fifth of the Earth’s land area and rapidly expand into arable lands (UNEP, 1997). According to UN estimates, one-third of the Earth’s land area may turn into desert wasteland during the next few decades (UNCCD, 2004).

The abundance of solar energy, minerals, and surface area in hot deserts offers us a way to revitalize them and put them to use by establishing a network of highly efficient closed bioregenerative systems accompanied by photovoltaic arrays over the desert surface. Design of such systems involves the following major challenges:

(1) Completely closed water cycle and the production of water by living organisms.

(2) Enhanced production of food and biomass due to a high-rate growth of plants and algae.

(3) Practically complete waste recycling.

(4) Enhanced production of fertilizers and nutrients.

(5) Irradiation of plants with a pure photosynthetic photon flux by rejecting all the sunlight of non-photosynthetic wavelengths and converting the latter into electricity to provide the cooling and other needs of the bioregenerative system.

As SLS researchers and engineers face most of the above challenges in designing CBLSS (Chizhov et al., 1973; Sulzman et al., 1994; Larson et al., 1999; Eckart, 1996), it will be of interest to turn to the SLS experience and accomplishments gained for more than 50 years of study.

A principal flow diagram of a closed bioregenerative life support system is depicted in Fig. 1.

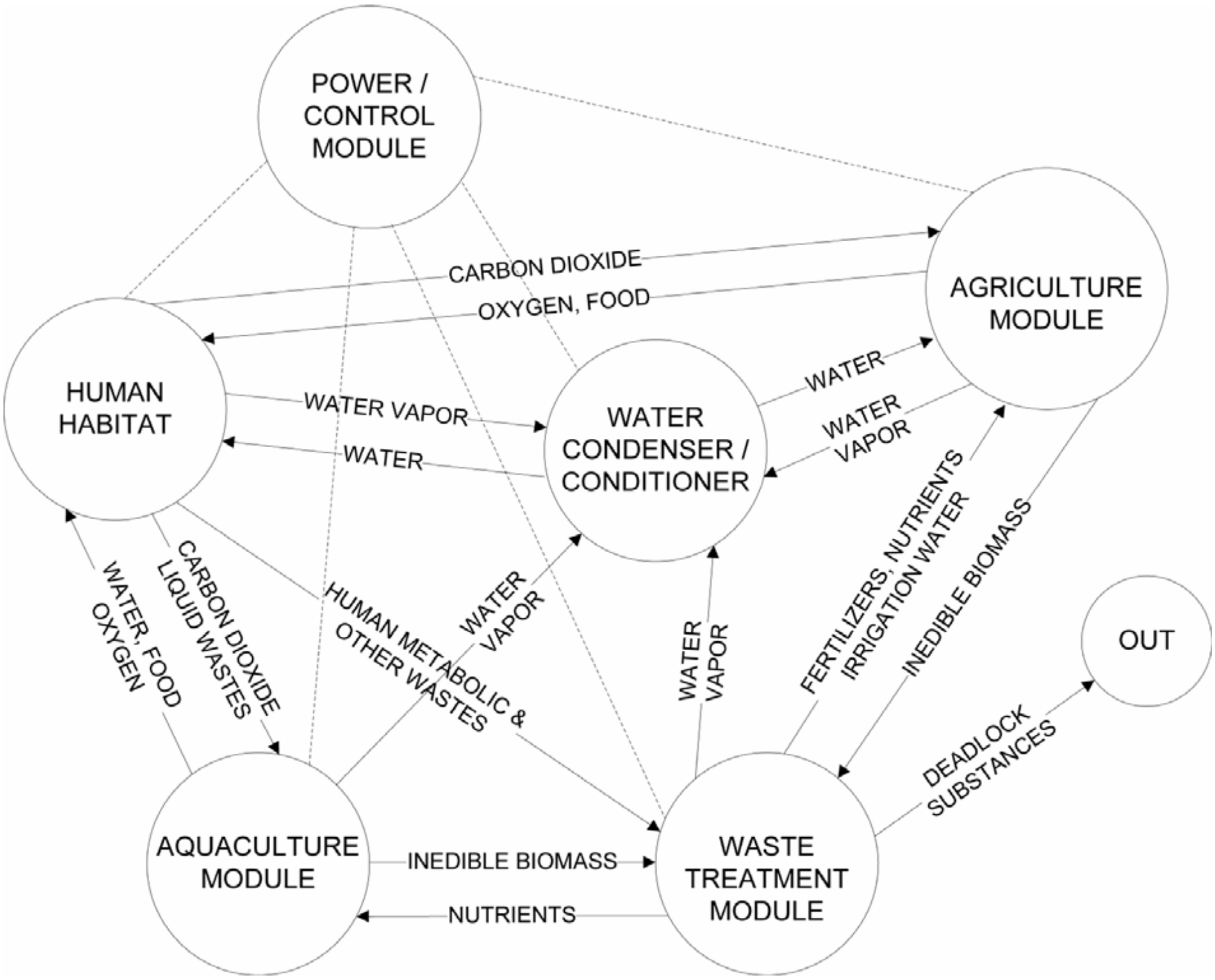

Fig. 1. A principal flow diagram of a closed bioregenerative life support system in space technology.

The system is made up of six major modules: human habitat (HH); agriculture module (AGM); aquaculture module (AQM); waste treatment module (WTM), based on physicochemical processes, such as membrane technology, catalytic oxidation, evaporation, etc., or fermentation bioreactors that can produce nutrients and fertilizers from inedible biomass (MacElroy et al., 1989; Wydeven et al., 1989); water condenser and conditioner (WCC); and power and control module (PCM). AGM along with AQM is the most important unit, which provides water, food, oxygen, and the inedible biomass for composting and fertilization, as well as assimilates carbon dioxide (Tikhomirov et al., 2007; Sychev et al., 2008; Barta et al., 2006). In addition to the production of food, water, oxygen, and inedible biomass, AQM can contribute to the treatment of liquid wastes (Mori et al., 1989; Oguchi et al., 1989; Gitelson, 1992; Ai et al., 2008; Blüm, 2003; Blüm et al., 1999).

The WTM collects the human metabolic and other (kitchen garbage, shower, wash, laundry water) wastes formed in the HH and the inedible biomass grown in the AGM and AQM to process them into fertilizers, nutrients, and irrigation water, which are fed into the AGM and AQM to provide the growth of higher plants and algae and the high life activity of rhizospheric (root area) and aquatic microorganisms. The exhaled carbon dioxide formed by the crew and other higher organisms, such as fish, is collected and supplied to the AGM and/or AQM, where it is consumed by plant photosynthesis. The edible biomass and oxygen produced by the plants and algae are supplied to the HH. The water vapors formed by the respiration and transpiration of the crew, microorganisms, plants, and algae are supplied to the WCC, where they are condensed to form a water, which is then used to prepare potable water by its conditioning with minerals and disinfection, irrigation water by mixing with nutrients and fertilizers, and technical water for the production of oxygen by water electrolysis. The PCM converts the sunlight coming to photovoltaic arrays into electric energy, uses it for illumination, control, and power storage (Ni-Cd batteries, for example).

The present paper will deal with specific problems of applying the results of CBLSS research to hot deserts. We will review the most important CBLSS findings that can be used to build a highly efficient life support system in hot-desert conditions. Since deserts have plenty of atmospheric air, which can be used to maintain the optimum gas balance in the life support systems, the problem of air revitalization will not be discussed in this review.

2. Major findings in closed-system biogenerative life support applicable to hot deserts

In the SLS science, CBLSS is designed to provide food production due to crop cycling times much shorter than in nature, water-closed loop, fresh water production, removal of CO_2 by plant and algae assimilation, oxygen production, and utilization of the solid and liquid wastes formed in the system (Gitelson, 1992). Ideally, it should be completely powered by sources of renewable energy, such as sunlight.

The design, control, and maintenance of closed artificial ecological systems like CBLSS need the understanding of mechanisms and adequate mathematical models of photosynthetic, physiological, metabolic, trophic and other processes taking place in the system for its effective monitoring and control (Nelson et al., 2003a; Gitelson et al., 2003a, 2003b). Its performance depends on light intensity [photosynthetic photon flux, PPF, 400 to 700 nm, which accounts for 32% of the total Sun irradiance (Sager et al., 1992)], temperature, carbon dioxide and oxygen concentrations, and air velocity over the plant canopy, which must be controlled and monitored in the system (Bugbee et al., 1989; Wheeler et al., 1996, 2008a, 2008b; Andre et al., 1989, 1999; Borodina et al., 2003; Nelson et al., 2003a, 2008; Qin et al., 2008; Kitaya 2003; Kitaya et al., 2008; McKeehen et al., 1996; Allen et al., 1999, 2003; Berkovich, 2008).

2.1. Enhanced plant growth by accelerating the carbon cycle

The productivity of higher plants in CBLSS as a function of incident PPF is determined by the efficiency of four physiological processes: absorption of PPF by photosynthetic tissue (percent PPF absorption), carbon fixation evaluated by photosynthetic efficiency (moles of CO_2 fixed per moles of photon absorbed), growth respiration evaluated by respiratory carbon use efficiency (net carbon fixed in biomass per unit carbon fixed in photosynthesis), and carbon partitioning evaluated by harvest index (edible biomass/total biomass ratio) (Bugbee and Salisbury, 1989; Bugbee, 1992). The integrated efficiency of these processes, determined on an energy basis as the ratio of the biomass energy content to photons energy content, is a highly illustrative characteristic of the possibilities of different growing environments (Table 1).

Table 1 - Efficiency of different growing environments for converting incident PPF into edible food (Bugbee et al., 1989)

Situation	PPF absorption %	Photo-synthetic efficiency %	Respiration efficiency %	Harvest index %	Integrated PPF efficiency %
Theoretical Efficiency	100	33.5	82	100	27.5
Potentially-achievable efficiency	98	18	75	90	11.9
Utah State University CBLSS project	90	16	70	44	4.4
World record in field	65	12	63	45	2.2
Typical field	50	8	55	40	0.9

The above processes were experimentally studied by monitoring PPF, gas exchange (photosynthetic rate in mol $CO_2/(m^2\ s)$, respiration rate in mol $O_2/(m^2\ s)$), fresh and dry plant mass, and plant tissue composition by Bugbee et al. (1989); Wheeler et al. (1996, 2008a, 2008b); Nelson et al. (2008), and other researchers for wheat, tomato, potato, lettuce, soybean, cowpeas, pinto bean, and many other higher plants. It was found that the productivity of wheat, especially its photosynthetic constituent, is a nearly linear function of incident PPF up to 2.5 times the summer sunlight intensity, taken as the integrated (Bugbee et al., 1989) or instantaneous value (Tikhomirov, 1996). A considerable rise in plant productivity with increasing PPF and CO_2 concentration (up to 2000 ppm, which is 5 times CO_2 content in atmospheric air) was observed by Qin et al. (2008) for lettuce, by Wheeler et al. (1996, 2008a, 2008b) for wheat, potato, tomato, and soybean, and by Nelson et al. (2008) for pinto bean. For example, the pinto bean matured and harvested 20 days earlier than is typical for this variety in the field. When the plant growth is not limited by the supply of mineral nutrients, the growth is 30-40% higher for a 800 ppm CO_2 (Somova et al., 2003). The composition of the plants grown with CO_2 levels of 400 (atmospheric air) to 10000 ppm was studied by McKeehen et al. (1996). Plants were harvested at maturity, dried, and analyzed for composition. The data did not show essential differences from the values typical for the field-grown conditions. Figure 2 illustrates typical curves for CBLSS experiments (Bugbee et al., 1989; Salisbury, 1991).

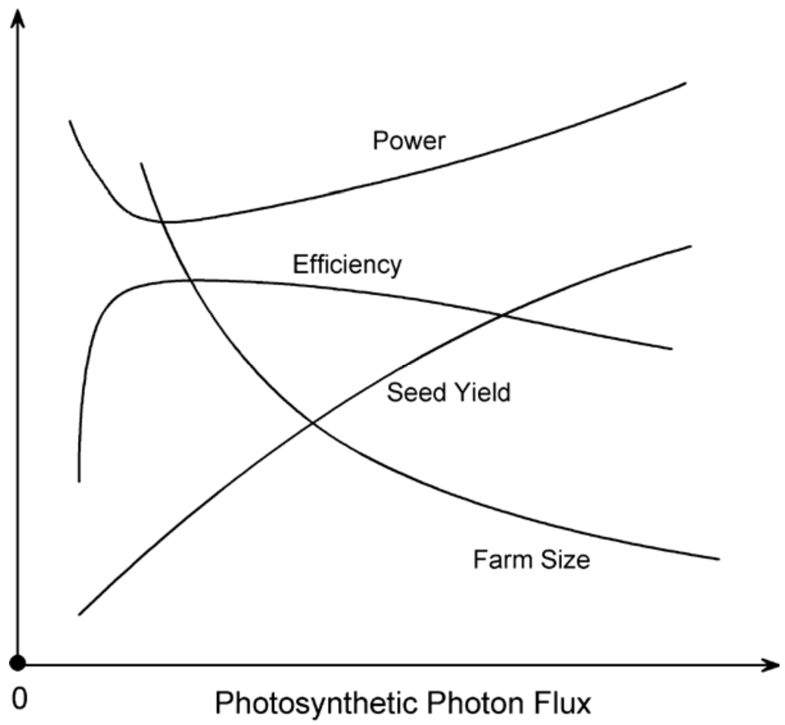

Fig. 2. Typical experimental dependence of crop production, efficiency of light usage, resulting farm area, and power on lighting intensity (Bugbee et al., 1989; Salisbury, 1991).

It should be noted that a relatively low harvest index of 29% in some tests with wheat (Wheeler et al., 2008a) may be caused by ethylene or other trace gases (NO_x, N_2O, CH_4, hydrogen sulfide, CO, ozone) accumulating in the closed plant growth chamber. It was suggested that a higher harvest index of 40% could be achieved by scrubbing these gases. In algal tests, algae could successfully purify and recycle water and provide oxygen for humans, but it could not prevent the buildup of trace gases over time in the sealed chambers. For example, some of the byproducts of Chlorella, a favorite algal species of early space life support work, proved toxic to higher plant crops (Nelson et al., 2003a). These gases can be oxidized by microorganisms, such as nitrifying bacteria (Gros et al., 2003), removed by adsorbent filters (Monje et al., 2003), oxidized by the rhizosphere in wetlands (Allen et al., 1999, 2003).

The equilibrium concentration of oxygen in small closed plant growth chambers may be less than the atmospheric 21%, which is controlled by the large-scale slow biological and physicochemical processes in atmosphere, Earth's land, all water reservoirs, Earth’s interior, etc. For example, the concentration of O_2 in Biosphere 2, where the ratios between water surface, water volume, and atmosphere per 1 m^2 of agricultural soil, as well as the carbon ratios in biomass, soil, and air, were much different from those for the Earth per 1 m^2 of terrestrial soil (Tables 2, 3), dropped to 14.5% over 16 months (Allen et al., 1999, 2003).

Wheat growing experiments were carried out in two low-pressure plant-cultivating facilities, to study the effects of low pressure (50.0 kPa) and hypoxia (10.4, 5.0 and 2.5 kPa) on the growth and development of wheat and develop its cultivating techniques (Guo et al., 2008). Compared with ambient pressure, wheat average rates of photosynthesis and transpiration increased by 9.23% and 11.54%, respectively, after a 15 days' treatment at low pressure (50.0 kPa), and they increased continuously when oxygen partial pressure was reduced further. Shoot height decreased, and both tiller numbers of each plant and the proportion of roots in a whole plant increased. Harvest time was delayed under low pressure and hypoxia conditions, and the hypoxia effects on the results were greater than those of hypobaric conditions. The yields of wheat at 10.4 and 5.0 kPa oxygen partial pressure increased by 4.39% and 5.0%, respectively, but reproductive growth of wheat was inhibited seriously at 2.5 kPa oxygen partial pressure and there was almost no yield. Some contents of nutrients in seed enhanced, like nitrogen, protein, fat and so on, but others had no significant difference among four treatments. So the growth of wheat was promoted by low pressure (50.0 kPa) and hypoxia (10.4 and 5.0 kPa) in certain degree, but lower oxygen partial pressure (2.5 kPa) was unsuitable for reproductive growth of wheat. Similar results were obtained by Andre et al. (1989), where the low oxygen concentration (4%) caused a slight depression in transpiration, an increase in root respiration, a delay of 15 days in the appearance of ears, and the complete absence of grain, though could not significantly affect the wheat shoot respiration, photosynthetic capacity of leaves, and chlorophyll content.

It was shown that the air velocity over the canopy of rice and strawberry should be increased to cool their productive organs when they are intensely illuminated (Kitaya et al., 2008). Compared to the air temperature, the temperatures of petals, stigmas and anthers of strawberry increased by 24, 22 and 14^{o}C, respectively, in the absence of forced air flow after 5 min of lighting at an irradiance of 160 W/m^2 from incandescent lamps. Temperatures of reproductive organs and leaves of strawberry were significantly higher than those of rice. The temperatures of petals, stigmas, anthers, and leaves of strawberry decreased by 13, 12, 13 and 14^{o}C, respectively, when the air velocity was increased from 0.1 to 1.0 m/s. The same increase in air velocity can double the uptake of carbon dioxide and the crop yield of potato and tomato plants (Kitaya 2003).

The increase in temperature from 17^{o}C to 23^{o}C can shorten the lifecycle of wheat by about 30% (Bugbee et al., 1989; Bugbee 1992). At the same time, the effect of temperature on the rhizospheric (root) microflora and nutrient solutions for radish plants showed that temperatures higher than 35^{o}C caused negative changes in the qualitative and quantitative composition of the root microflora, and reduced their growth (Borodina et al., 2003).

It was shown that wheat can be grown at a high sowing (planting) density and light intensities three times higher than the terrestrial values (Andre et al., 1999).

One of the important characteristics of biological performance is the average growth rate measured in grams of dry mass at the end of the cropping cycle per square meter per day. Because of incomplete absorption of PPF during early growth (low leaf area) and high rates of maintenance respiration during the final life stage, the growth rate has a short-time maximum in the middle (Bugbee, 1992). A bigger effect for some crops is the wasted light early in growth, which can be reduced by first growing seedlings at a close spacing and then using transplants.

In CBLSS studies, the common practice is to estimate the carbon cycle time, which can be made much shorter than natural by using high light intensity, high concentration of carbon dioxide, high composting rate and supply of nutrients, and optimal temperature and water supply (Nelson et al., 2003a). As a rule, shortening the carbon cycle means the acceleration of plant growth and sooner harvesting. To increase plant productivity, the acceleration of carbon assimilation by plants should be accompanied by an appropriate increase in the supply of essential elements, such as nitrogen, phosphorus, sulfur, sodium, potassium, calcium, and the like. Comparison between some CBLSS characteristics and natural conditions is given in Tables 2 and 3 (Nelson et al., 2003a):

Table 2 - Comparison between CBLSS and natural conditions (water surface, water volume, and atmosphere per 1 m^2 of terrestrial or agricultural soil) (Nelson et al., 2003a)

	Earth Land area: 1.5 x 10 m^2 Atmospheric volume: 4.3 x 10^{18} m^3 (Equivalent at standard pressure)	Biosphere 2 Land (soil) area: 6300 m^2 Atmospheric volume average 180,000 m^3	Laboratory Biosphere Land area: 5.37 m^2 Atmospheric volume average 40 m^3
Water surface	2.4 m^2	0.2 m^2	0.1-0.6 m^2
Water volume	8300 m^3 (given ocean average depth of 3400 m)	0.9 m^3	0.07 m^3
Atmosphere	29,000 m^3 (equivalent at standard pressure)	29 m^3	6.8 m^3

Table 3 - Estimates of carbon ratios in biomass, soil and atmosphere in the Earth's atmosphere, Biosphere 2 and the Laboratory Biosphere facility and an estimate of carbon cycling time as a consequence (Nelson et al., 2003a)

	Earth	Biosphere 2	Laboratory Biosphere
Ratio of biomass C: atmospheric C	1:1 (at 350 ppm CO_2)	100:1 (at 1500 ppm CO_2)	240-700:1 (mature crop to atmosphere at 1500 ppm CO_2)
Ratio of soil C: atmospheric C	2:1	5000:1	1500:1 (atmosphere at 1500 ppm CO_2)
Estimated carbon cycling time (residence in atmosphere)	3 years	1-4 days	0.5-2 days

2.2. Enhanced algae and duckweed growth

Russian long-term closed-chamber experiments BIOS-1 and BIOS-2 with Chlorella cultivation showed that a microalgae cultivator with a culture volume of 20 liters can successfully assimilate exhaled CO_2 and supply water and clean air for one man (Gitelson, 1992; Gitelson et al., 2003a, 2003b, 2008). The recent experiments conducted by Ai et al. (2008) showed that the density of algae in a photo-bioreactor can increase at very high rate - from 0.174 to 4.064 g (dry weight)/L after 7 days growth. Duckweeds, which, in addition to their ability of treating wastewater and producing oxygen, are a 100% food source in contrast to practically inedible Chlorella, can successfully grow at 1600 ppm CO_2 (Gale et al., 1989). The Closed

Equilibrated Biological Aquatic System, which contained fish, water snails, ammonia-oxidizing bacteria, and edible non-gravitropic water plants, showed a high efficiency in treating human metabolic wastes and production of water and food on the ground and in space (Blüm, 2003; Blüm et al., 1999).

The effects of culture conditions on the cellular multiplication of microalgae were studied by Kitaya et al. (2005). The multiplication rate was highest at 27–31^{o}C, 4% CO_2, 20% O_2 and continuous 100 μmol/(m^2 s) PPF, which is 7 times less than a typical, daily summer sunlight level.

2.3. Enhanced treatment of liquid and solid wastes

MELiSSA is one of the first SLS ecosystems in which the waste treatment produces nutrients and fertilizers for plant cultivation. The driving element of MELiSSA is the recovering of food, water and oxygen from waste (feces, urine), carbon dioxide and minerals. Based on the principle of an "aquatic" ecosystem, MELiSSA is comprised of five separate, but interconnected, compartments colonized respectively by thermophilic anoxygenic bacteria, photohererotrophic bacteria, nitrifying bacteria, photosynthetic bacteria, higher plants, and the crew (Gros et al., 2003). In three of them, the waste is progressively broken down by different fermentation processes. In the fourth compartment, algae or plants grow to produce food, oxygen and water. The fifth "compartment" is where the consumers (crew, animals) live. Figuratively speaking, MELiSSA has much in common with a lake. At the bottom is sludge (raw waste), which undergoes anaerobic fermentation in darkness. Higher up there's light but no oxygen. Higher still there's oxygen and it's possible to transform ammonia to nitrate. At the surface, there's carbon dioxide, oxygen and light. This is where higher plants can thrive. Its intended use is for Martian expeditions. Because of using artificial irradiation, MELiSSA is related to "high-power" technologies. At the same time, of more interest to hot desert applications are "low-power" technologies driven by solar energy.

Experiments showed that subsurface flow wetland technologies and the composting by hyperthermophilic bacteria are efficient techniques in waste treatment and production of fertilizers and nutrients for a closed plant growth chamber (Nelson et al., 2003b; Kanazawa et al., 2008). Low-labor and -energy, odorless subsurface flow wetland systems can treat wastewater, assimilate CO_2, and support some food crops (e.g. rice), supplying irrigation water and nutrients for agricultural needs (Nelson et al., 2003a, 2003b). The primary requirements for wetland treatment systems are warm temperatures and lighting, which are characteristic of hot deserts. Because the technology requires little machinery and no chemicals, and relies more on natural ecological mechanisms (microbial and plant metabolism), the maintenance requirements are minimized, and the systems can be expected to have long service times. Subsurface flow wetlands require ten times less treatment area as compared to surface flow wetlands. A 4 m^2 wetland area of subsurface flow can serve one full-time resident by removing 85-90% of organic compounds in the wastewater that tie up oxygen; 75-80% of nitrogen and phosphorus, with the coliform bacteria reduced by 99.8% without use of chemicals. In the Biosphere 2 experiment, the system handled all wastewater from the human habitat (toilet, kitchen, shower, laundry), domestic animal urine, pen washdown water, and effluent from medical/analytical laboratories and workshops inside the facility (Nelson et al., 2003a).

The metabolic heat release in bacterial fermentation raises the processing temperature to 80–100^{o}C to support the high life activity of hyperthermophilic bacteria (Kanazawa et al., 2008). The microbial ecology of the soil enriched with the high quality compost produced by thermophilic bacteria considerably enhances the plant growth. The high processing temperature is used to sterilize the pathogenic organisms in the fermentation process, thus providing the hygienic safety.

2.4. Mathematical modeling

The data of experiments conducted in closed plant growth chambers were successfully processed using several mathematical models. The growth of wheat was described by the logistic differential equation that imitates the S-shape of exponential growth followed by a leveling-off (Volk et al., 1989):

$$\frac{\mathrm{d}M_{\mathrm{ined}}}{\mathrm{d}t} = r_{\mathrm{ined}} M_{\mathrm{ined}} \left(1 - \frac{M_{\mathrm{ined}}}{K_{\mathrm{ined}}}\right), \qquad (1)$$

$$t < t^{*}: \quad \frac{\mathrm{d}M_{\mathrm{ed}}}{\mathrm{d}t}, \qquad (2)$$

$$t > t^*: \quad \frac{\mathrm{d}M_{\mathrm{ed}}}{\mathrm{d}t} = r_{ed} M_{\mathrm{ined}} \left(\frac{E_{\mathrm{min}} + M_{\mathrm{ed}}}{K_{\mathrm{ed}}} \right) \left(1 - \frac{M_{\mathrm{ed}}}{K_{\mathrm{ed}}} \right), \tag{3}$$

where M_{ed} and M_{ined} are the edible and inedible biomasses, respectively; t is the time; t^* is the time at which the growth of edible mass is initiated and E_{min} is the minimum edible mass at the initiation moment; r_{ed} and r_{ined} are the edible and inedible growth rates for the exponential growth period; K_{ed} and K_{ined} are the maximum edible and inedible biomasses reached by the crop.

The transpiration of plants was parameterized by the equations (Volk et al., 1989):

$$\Gamma = \gamma \, M_{\mathrm{ined}}, \tag{4}$$

$$\gamma = \gamma^* \, f_{\mathrm{h}} \, f_{\mathrm{s}} \, f_{\mathrm{a}}, \tag{5}$$

$$f_{\mathrm{a}} = 1 + \alpha \left(1 - \frac{M_{\mathrm{ined}}}{K_{\mathrm{ined}}} \right), \tag{6}$$

where Γ is the total transpiration rate, γ accounts for the water-vapor partial pressure difference between leaf and atmosphere; γ^* is the normalizing constant; f_{h} is the humidity factor; f_{s} is the stomatal resistance factor; f_{a} is the age factor; α is the factor accounting for the enhancement of transpiration rate per unit biomass when the plant is young. The formulas gave a good agreement with experimental data for wheat crops (Volk et al., 1989). It should be noted, however, that the use of Eq. (4) implies the transpiration rate as a function of water-vapor partial pressure difference and the amount of inedible biomass. This would not be accurate for leafy crops like lettuce, spinach, chard, etc., where it is essentially the edible biomass that is driving the transpiration.

The producer-consumer-decomposer cycle powered by sunlight in CBLSS was described using a system of differential balance equations (Pechurkin, 2005; Pisman et al. 2005), for which the plants and some bacteria capable of producing their own food photosynthetically or by chemical synthesis are taken as the producer; the animals that obtain their energy and protein directly by grazing and/or feeding on other animals, as the consumer; the fungi and bacteria that decompose the organic matter of producers and consumers into inorganic substances that can be re-used as food by the producers, as the decomposer. The specific growth rates of producers were written in terms of the Monod law (Perry et al., 1997). It was shown that the calculated results adequately describe the behavior of biosystem with a limited number of links.

The self-restoration ability in a unicellular algae population that suffered an acute radiation damage was theoretically and experimentally studied by Gitelson et al. (2003a) under densitostat conditions (continuous cultivation and monitoring with feedback between mass output and input nutrient flows). The authors assessed the effect of material flows, closure coefficient, metabolic pathways, and physicochemical parameters on the CBLSS sustainability. Simulation showed that the restoration time of the system is longer if the damage is done to its rather long-living species, such as higher plants. For example, the minimal restoration time for wheat is 2 months. It was pointed out that for a CBLSS that is relatively small, the metabolic rates are high, the biodiversity is limited, and the efficiency of stochastic mechanisms of stability, which are characteristic of large natural systems, is reduced, which necessitates human deterministic control to ensure their sustainability.

Mathematical models for simulating and controlling a CBLSS for space applications were discussed by DeAngelis (2003). As the high complexity of these systems does not allow for the parameterization of their governing equations, systems with only two or three interacting species were typically studied and now their behavior is understood reasonably well. Among them are microbial models of two or three functional groups (e.g., bacteria, ciliates, and organic substrate), which are often applied to describe the activated sludge treatment of wastewater. This huge body of accumulated information can be put to use if the systems with many species are modeled by aggregating the species into several functional groups such as autotrophic and heterotrophic living organisms, autotrophic and heterotrophic detrituses. In this case, the system can be described by the well-known chemostat model (Smith et al., 1995) with differential balance equations for state variables accounting for populations, functional groups, or trophic levels, in which the biomass of living or formerly living matter and the masses of carbon and major biogenic elements are system variables.

A semi-empirical kinetic model describing a three-compartment system with a phytotron (wheat, radish), mycotron (mushrooms), and human habitat was developed by Degermendzhy et al. (2008). The model also describes the kinetics of worms, worm coprolites, autotrophic detritus, vermicompost as soil-like substrate, bacterial microflora, mineral nutrients (nitrogen, phosphorus, iron), oxygen, and carbon dioxide. To continuously supply food and provide gas exchange, the system functioned as a conveyor with 8 age groups. The developed set of mass-balance equations made it possible to estimate the biotic turnover closure for main system components, improve the control, and optimize the system performance.

2.5. Monitoring and optimization

Information acquisition, close monitoring, and continuous control are the foremost requirements for the continued operation of CBLSS (Berkovitch, 1996). Machine Vision technology was shown to be promising for monitoring the health and growth of plants (Ling et al., 1996).Their spectral and morphological characteristics were studied under artificially induced stress conditions. The video image analysis based approach was used to quantify the plant growth while the plant stresses were detected by spectroscopic analysis. A correlation between the plant condition and the spectral features measured by Machine Vision was established. The approach is useful for monitoring gas exchange, sap flow rate, and vapor pressure deficit for transpiration and measuring water relations, as well as for detecting the plant stress by measuring leaf surface temperature.

Biotronics, Inc. was involved, under NASA sponsorship, in developing a prototype instrumentation for monitoring and control of controlled environment agriculture (Schlager, 1996). This approach monitored the chemical solutions of plant nutrient solutions as well as microbiological levels of bacteria and fungi in the same solutions. In contrast to traditional methods of microbiological analysis based on culturing, staining and microscopic observation, a system of on-line spectrometric monitoring and control of plant nutrient solutions was developed. The system included a hybrid absorption emission spectrometer for making chemical analysis of plant nutrients, an on-line microbiological analyzer, an ultrasonic control unit for performing microbiological control, and signal processing/pattern recognition methods for evaluating the spectral data and making estimates of microbial populations.

Several fiber-optic-based chemical sensors for solution pH, NH_3, ethylene, CO_2, and dissolved metal ions, which offer distinct advantages in terms of sensitivity, calibration stability, immunity to biofouling and electrical interference, and ease of multiplexing sensors for multipoint/multiparameter analysis, were developed for use in CBLSS (Tabacco and

DiGiuseppe, 1996). The system was based on a unique PC-compatible optoelectronic interface with a distributed measurement system.

Mass and heat fluxes from plant canopies in CBLSS were quite accurately measured by infrared miniature sensors and anemometers (Bugbee et al., 1996). The authors detected the changes in stomatal aperture, measured latent and sensible heat fluxes, and monitored the air velocity above and within plant canopies. The sensors were particularly useful in measuring the low wind speeds found within canopies.

Two greenhouses with three-dimensional adaptive optimization of crop photosynthetic characteristics were built and studied (Berkovitch, 1996). The irradiation, air temperature, humidity, and carbon dioxide were controlled using a modified simplex algorithm and sensitivity algorithms, which made it possible to triple the photosynthetic productivity of wheat, tomatoes, and Chinese cabbage.

2.6. Experimental facilities: Closed water loop

Most of the above CBLSS studies were carried out as long-term, up to 3 years, experiments in several ground-based test facilities with closed or nearly closed bioregenerative life support systems, such as BIOS-3 (Institute of Biophysics, Krasnoyarsk, Russia), NEK (Institute of Biomedical Problems, Moscow, Russia), BIO-Plex (Johnson Space Research Center, Texas, USA), Biosphere 2 (Arizona, USA), Biosphere Laboratory (New Mexico, USA); C.E.B.A.S. (University of Bohum, Germany); CEEF (Institute of Environmental Sciences, Japan); MELiSSA (Universidad Autonoma de Barcelona, Spain) (Pechurkin et al., 2008). Almost all of them are characterized by complete water closure, which is of great importance to hot-desert conditions. It should be noted that the approaches to air handling, water recovery from evaporated transpiration and respiration moisture (using condensing heat exchangers, for example), and gas exchange used in BIOS-1, BIOS-2, and BIOS-3 (Gitelson et al., 1989, 2003b; Salisbury et al., 1997), NASA's Biomass Production Chamber (Wheeler et al., 1993, 2008b), NASA's Variable Pressure Growth Chamber (Barta et al., 1998), Biosphere Laboratory (Nelson et al., 2009), and others, have much in common. At the same time, they were designed to study different strategies of food production and waste recycling. BIOS-1 and BIOS-2 were mostly focused on algal (Chlorella) cultivation. BIOS-3, NASA's Biomass Production Chamber, and

NASA's Variable Pressure Growth Chamber mostly dealt with the cultivation of wheat and vegetables (potato, soybean, tomato, etc.), providing one of the most extensive data sets for a canopy of wheat grown from seed to maturity under controlled environmental and nutritional conditions. The studies carried out in the NASA's facilities showed that water flux (evapotranspiration) is essentially driven by the ground cover of vegetation and the vapor pressure deficit between the air and the leaves (Wheeler et al., 1999; Monje et al., 1997). It was shown that the CO_2 concentration and diurnal light cycles affect the stomatal resistance, with peculiar things occurring at super-elevated CO_2 concentrations (e.g., > 5000 ppm), where transpiration can actually increase.

Because of smaller reservoirs of air, water, soil, and higher concentrations of biomass, the above CBLSSes are characterized by much shorter temporal biogeochemical cycles with plant/algae growing chamber atmospheres different from Earth's atmospheric air (Gitelson et al., 1989; Gitelson, 1992). Among these CBLSSes, the two most prominent facilities are BIOS-3 and Biosphere 2 (Salisbury et al., 1997; Nelson et al., 2003a, 2009).

In the 315 m^3 BIOS-3 facility, more than ten food crops were grown to support a crew of 3 people for half a year under closure conditions (Gitelson et al., 1989; Salisbury et al., 1997). A closed water cycle was provided by collecting all evapotranspired water, recovering water from human wastes by membrane technology, evaporation, and ion exchange. In later experiments, urine was diluted with the irrigation water used to hydroponically grow wheat crops, thus returning minerals and organics to the material cycles. Most of the recovered water was used in the hydroponic nutrient solution.

Of prime interest to hot desert conditions was the 200,000 m^3 Biosphere 2 facility with a total water capacity of more than 6 million liters and total airtight footprint of 12,700 m^2, in which the accelerated material cycles over a closure period of 1991 to 1993 were thoroughly studied (Nelson et al., 2003a, 2009). The complete water recycling and purification system predominantly used the pathways of evapotranspiration, condensation, and constructed wetland wastewater treatment. Mechanical assistance to these processes was mainly fan-driven air movement, which brought humid air to cooling coils, and pumping to deliver water to usage points. Natural-analogue fresh and marine water areas such as streams, pools, mangrove, and ocean supported complex natural ecosystems. Algal turf scrubbers and protein skimmers helped remove nutrients from the marine ecosystems’ waters constructed wetlands, which had hydraulic loading of 0.9–1.1 m^3 per day. Atmospheric residence time for water vapor was 4 hours, which is 54 times less than in the Earth's biosphere, with the ocean/marsh residence times being 1000 times smaller than on the Earth. Wholly, the experiments in this facility showed that complete material cycles can be successfully designed for a quite large greenhouse facility with a high-rate waste treatment system, in which the artificial cycling times for water, carbon, and nutrients are much smaller than the natural ones on the Earth, thus giving a way to enhanced food production and much reduced demand for natural surface and ground water.

To illustrate what can be used as the basis for a closed bioregenerative system in a hot desert, we consider the completely closed water cycle implemented in the artificially illuminated Laboratory Biosphere facility, a closed facility with a soil-based plant growth module and a variable volume chamber to allow for changes in air volume, with 5.5 m^2 planting beds, 33–40 m^3 volume, and estimated total amount of water about 0.3–0.5 m^3 (Nelson et al., 2009). In the system, the evapotranspiration from the planting bed provided a continuous supply of moisture into the air within the chamber. With a soybean crop, condensate collection rates were about 2.5–3 L/h while the lighting was on. It was demonstrated that the humidity is only a small reservoir of water: In the system, the amount of water passing through the air in the course of a 12-h operational day was two orders of magnitude greater than the amount stored in the air. It was also shown that if enough water is initially provided to wet the soil beds, there will be always enough moisture in the system to keep them wet. It is important to note that all of this is dependent on the amount of plant canopy cover and the ambient humidity. Atmospheric residence time for water vapor was 20 min, which is about 650 times less than in Earth's atmosphere. The residence time of soil water was around 10 days in the Laboratory Biosphere, which is six times less than those for the soil water in Biosphere 2 and in nature. Extraction of the evapotranspired moisture from the airstream passing through system's air handlers was the means both to recapture the water for recycling and to control the humidity. The air handlers cooled the airstream to water vapor saturation at a selected temperature and condensed it at the bottom. The condensate was practically pure water, less than 1 ppm of total dissolved solids (TDS), which could be mixed with the water drained after irrigation of the soil beds. The latter had a substantial level of dissolved solids and also varying amounts of organic compounds such as from fallen leaves from planting beds above. The mixing tank had a level sensor and a TDS sensor to report the water quantity and total dissolved solids, respectively. In this system, the soil only received water from the watering system, i.e., by controlled actions, and there were soil moisture sensors in each bed to report the moisture status. As was indicated before, Laboratory Biosphere was quite typical in water recycling and plant growth chamber design as compared to many other closed ecological systems (Gitelson et al., 1989, 2003b; Salisbury et al., 1997; Wheeler et al., 1993, 2008b; Barta et al., 1998).

3. Discussion

The problem of designing a CBLSS for hot-desert conditions is significantly simpler than that for space settlements on the Moon or Mars. In contrast to many space technology applications, where photovoltaics are used to convert solar energy to electricity, which then powers electric lamps to provide artificial PPF for plants and algae, with a conversion of solar energy to PPF considerably below 10% (Sinyak, 2008), in hot deserts it is possible to directly use solar energy for photosynthesis. The key challenge of any closed life support system for space - air revitalization and optimal control of air composition - is by far simpler for Earth's hot deserts. On the Earth, most of Sun's harmful ultraviolet rays, which require a special treatment in outer-space conditions, is blocked by the atmosphere, while near-infrared and infrared rays can be reflected and concentrated at focal points to feed photovoltaics producing electric power (Sonneveld et al., 2007). Practically unrestricted supply of the electric power produced from free solar energy makes it possible to provide cooling inside plant-growth facilities and maintain optimal plant-growth temperatures. In hot deserts, plants can grow under Earth’s gravity, optimal for their life, and the required initial stocks of water and biogenic elements can be easily supplied. Therefore, all stringent volume, mass, and power limitations imposed on space CBLSS can be lifted, and the estimated 20 to 50 m^2 of CBLSS area needed to provide one human with food and water and process human wastes (Sinyak, 2008; Gitelson et al., 1989; Wheeler et al., 2001; Tako et al., 2009) is readily available in hot-desert areas.

The major problem with desert environments is water deficit. To solve it, greenhouses must collect and condense all the evapotranspired moisture, much like it is done in the Laboratory Biosphere facility and Biosphere 2 (Nelson et al., 2009), instead of letting it go back to the external atmosphere. All water in liquid wastes should be recovered and the other components of the wastes (minerals, carbon, nitrogen, etc.) should be completely recycled. It should be noted that attempts at designing such perfect recovery systems for space applications using physicochemical methods alone, such as membrane technology, vapor compression distillation, low-temperature evaporation, and even hybrid technologies, ultimately failed (Sinyak, 2008). For example, even for shower and wash wastewater with a low 1% concentration of dissolved and suspended solids, the water recovery does not usually exceed 90-95% for a microfiltration-reverse osmosis-adsorption system of water reclamation, where almost all mineral and organic components of the wastewater are taken out of system's material cycle as wastes (Polyakov et al., 1986, 1994; Polyakov, 2006).

The above review suggests that almost the same flow diagram as for CBLSS (Fig. 1), which will be based on the direct use of sunlight, use of atmospheric air and carbon dioxide sources to enhance the plant and algae growth, and low-power composting/wetland technologies for waste treatment, can be used for designing the bioregenerative life support systems in hot deserts. The only difference is the added possibility to inject atmospheric or other gases as needed and ventilating the carbon dioxide exhaled by people to the external environment. It is important to note that aquaculture, agriculture, and composting/wetland modules should be separated from human habitats (residential areas), as the optimal living conditions for humans may be much different from the optimal conditions for enhanced plant/algae growth and microbial activity in these modules. In hot deserts, it will be important to recycle all water and solid wastes formed in human habitats and other auxiliary premises while the exhaled carbon dioxide and other trace gases can be ventilated to the external atmosphere. The same is true for some deadlock substances, such as sodium, which might accumulate over time depending on the system inputs. They can be managed most easily by removing from the system. This would imply that the systems should be partially open to allow this, as well as inputs of external CO_2 and nutrients.

The advantages of technologies developed by space life support science can be put to use for hot deserts by combining them with the most advanced controlled agriculture technologies, such as cooled greenhouses with an integrated filter for rejecting near infrared radiation (NIR) and a solar energy delivery system, which can cope with the combination of high solar radiation and high outdoor temperatures (Sonneveld et al., 2007). The spectral selective materials covering a greenhouse structure with a size of about 100 m^2 prevent the entrance of NIR radiation, blocking up to 50% of solar energy outside the greenhouse. These coatings are designed as a parabolic or circular shaped reflector integrated in the greenhouse, with a photovoltaic installed at the reflector focus point, providing about 40 times concentration of solar light intensity. With a ray tracing computer program, the geometry of the reflector is optimally designed with respect to the maximum power level. This gives a way to use recently developed inverted metamorphic triple-junction solar cells, which can provide a 40.8 percent sunlight-to-electricity conversion under concentrated light of 326 suns (DOE/NREL, 2008). This approach will be also able to concentrate photosynthetically active radiation to irradiate the plants and algae in cooled greenhouses at lighting intensities several times exceeding the average daily summer sunlight, which will help reach higher crop yields than in the field.

4. Concluding remarks

The review presented above shows that the technologies and experience developed and accumulated by the space life support science gives a way to design and build sustainable (completely water-closed, wasteless) bioregenerative life support systems for hot deserts, the extreme environments with high solar energy input, a stock of minerals in the soil, and atmospheric air. In these systems, higher plants such as wheat can be grown at several times higher rates than those of typical plant-growing fields due to the combined effect of increased levels of photosynthetically active irradiation supplied by PPF concentrators at daytime and accumulators of electric power at night, elevated CO_2 concentration, increased supply of nutrients and fertilizers, etc. The water can be biologically recycled and produced by aqua/agriculture photo-bioreactors, and human metabolic and residential solid/liquid wastes can be treated by subsurface flow wetland and thermophilic-bacteria technologies under optimal conditions, where all processes are reliably controlled and monitored.

These bioregenerative systems can be considered as the basis for building sustainable settlements powered by free solar energy and producing organic food and fresh water in hot deserts, where all solid/liquid wastes can be treated, biomass is produced to be converted into nutrients and biofuel, and hydrogen can be produced from water by electrolysis to feed hydrogen fuel cells. The abundance of sunlight and minerals in the desert can make the biogenerative systems highly efficient “bioreactors” that may meet not only the needs in food, water, fuel, and waste processing for local residents, but also for other, distant areas.

The highest crop productivity can be reached at elevated (as compared to atmospheric) concentrations of carbon dioxide, several times higher (as compared to average daily sunlight) levels of PPF produced by light concentrators, and increased supply of nutrients, which makes such bioreactors a carbon sink reducing the concentration of the main greenhouse gas in the atmosphere. With a very little precipitation in hot deserts all year round and a relatively high average winter temperature, the hot-desert bioregenerative life support systems may provide a stable production of renewable fuel and food throughout the year. This may be a good addition to the potential capacity of hot deserts to cover most of world's energy demand by converting solar energy into electricity with photovoltaics, especially in view of recently achieved photovoltaic energy conversions up to 40.8 % (DOE/NREL, 2008).

Potential benefits of building these bioregenerative systems include the slowdown and eventual reversal of desertification; reduction and potential reversal of population migration from arid lands; the increased availability of fresh water and food in deserts; and the development of new residential infrastructure on the territories that are currently considered as wastelands.

We strongly believe that the application of space technology experience in designing water-closed wasteless bioregenerative life supports systems to hot deserts will make it possible to reverse the threatening trend of anthropogenic desertification and help us advance in making our planet more sustainable.

Acronyms

AGM - Agriculture module;
AQM - Aquaculture module;
CBLSS - Closed bioregenerative life support system;
HH - Human habitat;
PCM - Power and control module;
PPF - Photosynthetic photon flux;

SLS - Space life support;

WCC - Water condenser and conditioner;

WTM - Waste treatment module.

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