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Title:

Engineering Problems and Aspects of the Technological Equipment in Space Plant Growth Systems

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Summary:

As human presence in space becomes longer, supplying all food, oxygen and water from Earth will result in a tremendous cost. For this reason the international scientific community has been making efforts towards developing technologies and equipment to realise a sustainable Bioregenerative Life Support System for food production, water purification, air revitalisation and waste recovery. Plants produce food and oxygen for human needs, contribute to remove and reclaim carbon dioxide, relative humidity and the organic wastes. Aim of this research is a critical analysis of the materials and equipment requirements used up to now, in order to highlight the equipment engineering solutions for a system for plant cultivation on-board the International Space Station supported by Italian Space Agency. Creating a Bioregenerative Life Support System is an extremely sophisticated scientific problem. Space environment is characterised by the absence of the Earth's gravitational and magnetic fields, of tidal forces and of the influence of the cyclical events of celestial mechanics and so, the prediction of fluid and heat behaviour is less intuitive. Besides, this environment would severely impact plant growth and metabolism. In space an enclosed environmentally-controlled plant growth system must control and regulate the atmospheric parameters and the atmospheric gas composition, provide light energy for photosynthesis and supply the plants with the appropriate nutrient and water to support photosynthesis and to compensate for the evaporation and transpiration losses.

Introduction

For the realisation of extended human mission in space the international scientific community has been making efforts towards developing equipment and new technologies to realise a sustainable Bioregenerative Life Support System (BLSS). Food, oxygen and water shipped from the Earth means mainly high transportation costs connected with stowage, volume and launch mass for containers, support structures and utilities. To avoid costly resupply consumables, a lengthy manned space mission must rely on a closed life support system, as shown in Fig. 1, which will provide resources that the crew require and deal with biomass waste and human outputs, such as heat and metabolic products, while keeping the environment acceptable to live. Plants can provide fresh food with more nutritional benefits than stored products, generate oxygen (O_2) through the metabolic process of photosynthesis, remove the carbon dioxide (CO_2) from the atmosphere due to human respiration, convert waste water to potable water through the process of transpiration and condensation, and contribute to the psychological well-being of the crew. The BLSS system will process also inedible plant material along with other solid wastes to provide H_2O and mineral nutrients for the crew and for the plant growth chamber.

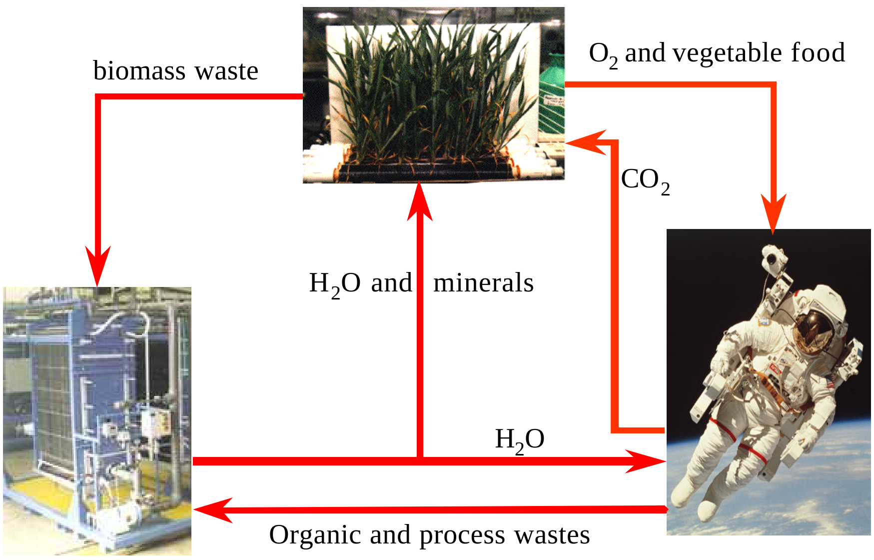

Figure 1: Closed-loop Bioregenerative Life Support System

Research and technology efforts have been focusing in order to develop a sustainable system that meets space, functional and biological requirements minimising mass, volume, energy and manpower requirements for operation.

In this paper a critical analysis is presented on the basis of the data collected on several BLSS developed or under development for spaceflight, in order to highlight the technological equipment for a facility for plant cultivation on-board the International Space Station (ISS) supported by the Italian Space Agency (ASI). The goal of the ASI project “Space GreenHouse” (SGH) is to identify and solve engineering and agronomical problems for the design of a space plant growth system able to verify the effects of microgravity on plant growth, the gas exchanges and the edible production by analysing complete cycles from seed to food (Scarascia Mugnozza et al., 2002).

Space environment

Previous missions have been shown that the space environment cause about 25% of failures of spaceflight equipment and experiments (Larson and Pranke, 1999). In space the forces of gravity, buoyancy and convection are drastically altered and, besides, the weightless state cannot be satisfactorily simulated during ground tests and so there are serious uncertainties in predictions of fluid and heat behaviour based on extrapolating effects from high *g* to low *g* (Krikorian and Levine, 1991). The spatial environment with also its vacuum and radiation would severely influence the functioning of the equipment and would impact plant growth and metabolism.

Several Bioregenerative Life Support Systems (Plant Growth Unit, SVET, Plant Growth Facility, Astroculture™ system, Plant Generic Bioprocessing Apparatus, Commercial Plant Biotechnology Facility, Plant Research Unit and Biomass Production System) have been developed or are under development for spaceflight by the National Aeronautics and Space Administration (NASA) and the Space Agencies of other countries (Chapman et al., 1995; Crabb et al., 2001; Duffie et al., 1995; Heathcote et al., 1996; Hoehn at al., 1998; Ivanova et al., 1998; Morrow et al., 2001; Tibbitts et al., 1993; Turner and Zhou, 2000; Wells et al., 2000; Zhou et al., 1997). Operating in manned missions, in which always human safety is of paramount importance before any considerations of productivity, each system with its components must be designed in a way that won't fail jeopardising the crew. In space environment all the systems have to satisfy crew safety factors and system reliability, engineering requirements, plant specifications and payload flight equipment requirements (Fig. 2). On board the ISS each payload must have the principal mode natural frequency greater than 35 Hz; it must have positive margin of safety when withstand the lift-off and landing quasi-static loads, when exposed to the crew-induced loads and especially to the worst-case depressurization-repressurization environments (Zhou and Turner, 2000). NASA design limitations are on power availability, weight and volume, material and fluid containment selections, acoustic and temperature emissions. The used materials exposed to the vacuum must not start to outgas hazardous chemicals and the contamination may not degrade properties of the materials. The temperature limits are the maximum air exhaust temperature (49°C), the maximum touch temperature (45°C) and the minimum exposed temperature (15°C): the first two limits are intended to protect the crew from burns while the last one is to avoid condensing water from the cabin air. The Shuttle middeck payload acoustic limit is of 58 dB measured 30 cm from the noisiest portion of the payload. All component containing liquids must be designed for 2.5÷4 times the maximum design pressure according to the hazard level of the fluid used (e.g. distilled water is non hazardous fluid, sea water has hazard level 1 and formaldehyde has hazard level 2). The choice of the material, of the construction forms, of the type of structure, of the members size and of the method of attaching members will influence the structural design. The selection of the material is driven by its stiffness, positional stability, mass, strength and structural life, natural frequency and damping. Aluminium is often a good choice because of cost, ductility, high strength, weldable, low weight and corrosion resistant.

Flight phases as launch, descent and landing induce on all the spacecraft structures and equipment the highest loads and might cause stress failures due to excessive pressure, acceleration, vibration, acoustic-induced vibration, thermal loading, structural overload, mechanical shock, and so on (Larson and Pranke, 1999). The environment is different for every launch vehicle and, because of random variables, different from one launch to the next. The payload's mass properties and structural characteristics may influence the combined structure's response to transient loads, and its shape and volume affect acoustics. During space operations it is important to control electrical overload, chemical reaction, electromagnetic fields and temperature gradients.

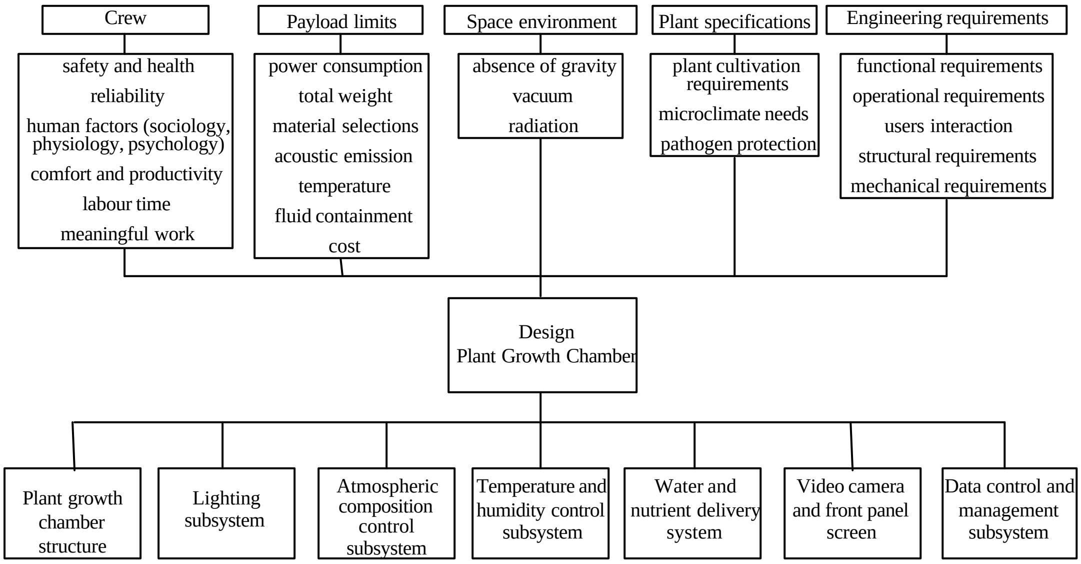

Figure 2: Requirements for the design of a spaceflight Plant Growth System

Technological equipment

Some equipment and technologies for spaceflight plant growth system already exist, but the development, the integration and testing of design concepts must continue in order to define a system with enough operational experience to be considered reliable and safe enough for long-term human stays in space. An enclosed environmentally-controlled plant growth system must be safe, compact, pre-assembled, light weight, energy efficient, extremely reliable, low maintenance and user friendly. Technological subsystems (Fig. 2) as plant growth chamber structure, lighting, atmospheric treatment control, temperature and relative humidity control, active fluid and nutrient delivery subsystem, computer control and data management subsystem with camera for video recording and downlink could be incorporated in a spaceflight plant growth system. The facility must monitor, control and record, as shown in Figure 3, the atmospheric conditions (air temperature, relative humidity, pressure and ventilation flow rate) and the atmospheric gas composition (O_2, CO_2, trace gases and moisture content), provide light energy for photosynthesis (photoperiod, intensity, PAR radiation and spectral composition), control of pathogens, and supply the plants with the appropriate nutrient and water to support photosynthesis and to compensate for evaporation and transpiration losses.

Sensors for monitoring and control must be carefully chosen to meet the requirements of the parameters to be measured, to withstand the extremes of the environmental conditions, to stay within calibration for long periods of time, and their failure has to be kept to a minimum. Sensor technology is using microcontrollers for their ability to be used as stand-alone control systems and to be networked creating an expert-system capable of self-improvement, for operating at low voltage and low current, for their re-programmability and for their user interfacing functions (Fowler and Bucklen, 2000).

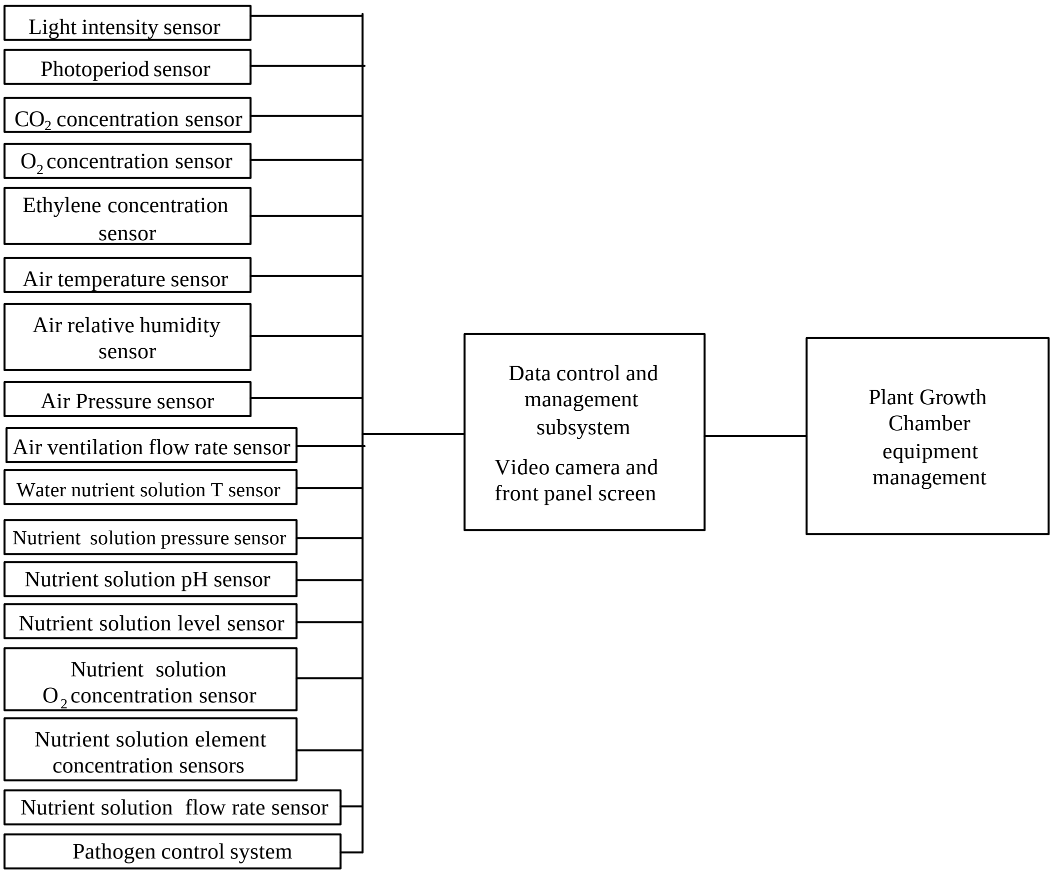

Figure 3: Monitor, control and record subsystems

The air-tight plant growth chamber is often realized in aluminium, lightweight structural material, for its high reflectivity to maximize light intensity and uniformity and for its non-rusting, non-corrosion and non-oxidation capacities in order to be exposed to high humidity. All the components within the plant chamber must not release phytotoxic gases minimizing the production of ethylene from outgassing. Electrical equipment, structural components, hardware for all the subsystems, pumps, fans, heat exchanger, trays, conveyors, etc, will be allocated inside the chamber. Ducts should be constructed of transparent materials, as thin as possible to maximize chamber cultivation area, but should not restrict air or water flow.

The lighting subsystem must optimise maximum photon flux in the spectral range of PAR (400-700 nm) to satisfy plant radiation needs, spatial uniformity and energy efficiency, while the thermal load must be minimised because natural convection does not exist in microgravity to help transfer heat from the lights. Inside the growth chamber focusing materials could be used such as mirrors, prismatic reflecting films, holographic diffusers and light pipes, which will efficiently and evenly distribute point-source light over plant canopies (Goins and Yorio, 2000; Goins at al., 2001). The light intensity could be monitored by a calibrated photodiode sensor installed inside the chamber. Traditional lighting regimes (high-pressure sodium, cool white fluorescent, microwave, etc.) and innovative light emitting diode (LED) module, that provides photons in the red and blue regions of the spectrum, were analysed for space-based plant growth applications in several studies. Fluorescent lamps emit gravity-dependent radiation in all

directions and a significant portion of the photons cannot be effectively reflected to the plants when lamps are mounted close together (Bula et al, 1991); particular attention must be paid to structural and material devices to avoid the potential risk of mercury vapour release if a lamp is broken. Red and blue LEDs are particularly suited in spaceflight systems for their small mass and volume, solid state construction, safety, longevity, narrow spectral output and low heat production (Heathcote et al., 1996; Hoehn et al., 1997; Zhou et al., 1997).
Carbon dioxide and volatile organic compound (VOC) must be controlled to keep them from becoming toxic but a level reliable for plant photosynthesis (Hoehn et al., 1997; Larson and Pranke, 1999; Zhou et al., 1997). Also pathogens should be controlled.
The CO_2 concentration is often monitored using an infra-red gas analyzer with temperature and pressure compensation. Technologies which chemically adsorb CO_2 such as lithium hydroxide or titanium dioxide, usually need low power and are very reliable but they use expendable materials which must be resupplied regularly (Chapman et al., 1995; Zhou and Turner, 2000). Various schemes for CO_2 concentration control have been implemented (Hoehn et al., 1998): unpressurised pure CO_2 injection, pressurised pure CO_2 injection and injection of CO_2-enriched cabin air. VOC may be introduced by incoming cabin air or may be produced by the plant itself as the plant hormone ethylene or from outgassing of non-metallic materials. Several methods can be applied to remove ethylene, deleterious for plants in excess of 50 nmol mol-1 (Hoehn et al., 1998; Hoehn et al., 2000): adsorption on activated charcoal, oxidation by purafil (activated alumina impregnated with potassium permanganate) and photocatalytic conversion on titanium dioxide using UV-light.
NASA has already set up the ASTROPORE™ system for temperature control, humidification, dehumidification and condensation recovery (Duffie et al., 1995; Zhou et al., 1997; Zhou and Turner, 2000). The temperature control subsystem utilises a thermoelectric cell to either extract or add heat to the chamber by adjusting the current with proper polarity delivered to the cell. Air temperature is measured using a temperature sensor in the aerial zone of the chamber and the sensor signal is feedback to the control computer. Controlling air relative humidity in a space habitat's atmosphere is particularly important because condensation on electronic parts can affect their performance or make them unsafe. Besides moisture accumulating anywhere must be avoided in order to control microbial proliferation. The ASTROPORE™ humidity control system uses temperature controlled water confined within porous nubs that permit the transfer of water vapour to the plant chamber air while maintaining separation of the liquid and vapour phases (Heathcote et al., 1996).
Progress have to be made to better design and characterize the spaceflight plant water and nutrient delivery subsystem. Water and nutrient delivery subsystem for spaceflight must provide adequate amounts and uniform distribution of water, nutrient and oxygen levels in the root zone, while at the same time, prevent release of free liquid to the cabin atmosphere. Pathogens must be controlled by means of UV radiation sterilization of the nutrient solution. Subsystems tested on the Earth successfully might not function effectively in space because separating air from water is a non-trivial technical challenge under microgravity conditions. Mainly passive nutrient delivery subsystems have been used for brief stays in orbit up to now. Specific media, such as foam and agar-solidified nutrient solutions, or solid substrates as zeolite, arcillite, isolite, etc., were used while water was distributed by capillary, or was delivered to the root zone using porous tubes embedded in the rooting material plants by capillary transfer (Crabb

et al., 2001; Morrow et al., 2001). Several ground tests have been conducted on active plant nutrient delivery subsystems to improve long-term stability and to provide control of nutrient solution characteristics and delivery (Clawson et al., 2000; Dreschel and Sager, 1989; Goins et al, 1997; Heathcote et al., 1996).
Data acquisition and computer control module will be designed to control and store sensor data and video camera images, to provide autonomous pre-programmed operations, to up- and down-link data and commands to and from the Earth. Control could be done among on-board computers, the remote computer and the human operator (Larson and Pranke, 1999). On-board computers have no communication costs and time delays, so they can react instantly to unexpected situations but they have mass and power restrictions and are difficult to access to make modifications and correct design errors. Remote computers may be on Earth or at the space station or planetary base. They suffer less from mass and power restrictions and thus can do much more complex calculations, but they usually have time delays to the robot. Humans also control robots from space or Earth. Human control is most adaptable to unexpected situations and gives us better information from visual imagery.

Conclusion

Design options and characteristics of several spaceflight plant growth chambers have been collected from various sources and compared each other. The international scientific community must continue to work in order to better develop and design spaceflight technological subsystems for the realisation of a Bioregenerative Life Support System to be used during future long-term manned exploration of space.

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