Lighting Equipment for a Crop Growing System in Microgravity Conditions for Space Mission

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Abstract
The international scientific community has been making efforts towards developing technologies to realise a sustainable spaceflight Bioregenerative Life Support System for food production, water purification, air revitalisation, and waste recovery in the International Space Station. Space environment, characterized 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, complicates the realization of this kind of system. A critical analysis of the lighting equipment requirements for a crop growing system is presented on the basis of the data and information collected on several Bioregenerative Life Support Systems developed or under development for spaceflight. Aim of the research is to compare different lighting equipment for Bioregenerative Life Support System. Traditional lighting regimes and innovative ones, such as light emitting diode module providing photons in the red and blue regions of the spectrum, has been analysed in order to assess the lighting engineering solutions for a crop growing system on-board the International Space Station supported by Italian Space Agency. The lighting system must maximise photon flux in the spectral range to satisfy plant photosynthesis needs, spatial uniformity and energy efficiency while the thermal load must be minimised because natural convection does not exist in microgravity to transfer heat away from the lights. Plants need photosynthetically active radiation in the wavelengths range between 400 and 700 nm for photosynthesis. Besides it is necessary to control radiation level at 670 and 735 nm which drives the phytochrome response, that is related to plant morphogenesis. Radiation over 750 nm seems not having direct effect on the plant growth and thus needs to be removed as heat via circulation of the chamber air by means of air ventilation.

INTRODUCTION
In order to explore the space with long-term manned space missions or even permanent habitation of space, routinely supplying of metabolic needs of the crew must be realised with minimal re-supply from Earth. Food, oxygen and water shipped from the Earth means high transportation costs. For this reason the international scientific community has been making efforts towards developing technologies and equipment to realise a sustainable Bioregenerative Life Support System (BLSS) for food production, water purification, air revitalisation, and waste recovery (Fig.1). Plants provide fresh food with more nutritional benefits than stored products, generate oxygen (O₂) through the metabolic process of photosynthesis, remove the carbon dioxide (CO₂) from the atmosphere due to human respiration, convert waste water to potable water through the process of transpiration, and contribute to the psychological well-being of the crew.

In space the forces of gravity, buoyancy and convection are drastically altered. The weightless state cannot be satisfactorily simulated during ground tests. Therefore, there are serious uncertainties in predictions of fluid and heat behaviour based on extrapolating effects from ground gravity (g) to low g (Krikorian and Levine, 1991). The spatial environment with its vacuum and radiation would severely influence the functioning of the equipment and impact plant growth and metabolism. In microgravity the absence of buoyancy-driven convective mixing may allow stratification of stagnant air that restrict
the replenishment of gases consumed by metabolic activity. The lack of convective mixing in space may cause large boundary layers to surround plant organs with different levels of O\textsubscript{2}, CO\textsubscript{2}, water vapour and sensible heat compared to conditions at ground \(g\) (Monje et al., 2003). If space colonization will be realised by extraterrestrial human bases, some gravity is present on the Moon (1/6 \(g\)) or on Mars (1/3 \(g\)).

Several BLSS have been developed or are under development for spaceflight by the National Aeronautics and Space Administration (NASA) and the Space Agencies of other countries. These systems are the Plant Growth Unit (PGU), the SVET, the Plant Growth Facility (PGF), the Astroculture\textsuperscript{TM} system (ASC), the Plant Generic Bioprocessing Apparatus (PGBA), the Commercial Plant Biotechnology Facility (CPBF), the Plant Research Unit (PRU) and the Biomass Production System (BPS). Each system has to satisfy structural, mechanical, functional and payload flight equipment requirements, and plant specifications (Zhou and Turner, 2000). NASA design limitations are on power availability, weight and volume, material and fluid containment selections, acoustic and temperature emissions (Horner et al., 1997). In manned missions, in which always human safety is of paramount importance before any considerations of productivity, each system must be designed in a way that won’t jeopardise crew safety.

Flight phases as launch, descent and landing induce high loads on all the spacecraft structures and equipment 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 each launch vehicle and 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.

In this paper a critical analysis is presented on the basis of the data and information collected on several BLSS developed or under development for spaceflight by the international scientific communities. The aim of this study is to highlight the equipment engineering solutions for the lighting system to be used for plant cultivation on-board the International Space Station (ISS) supported by Italian Space Agency (ASI). A pre-flight experiment has been carrying out to design a facility for plants cultivation in the space environment under the ASI project “Space GreenHouse” (SGH). The study tries to verify how microgravity affects plant growth, gas exchanges and edible production by analysing complete cycles from seed to food.

**FARMING IN SPACE**

Short duration plant experiments in space have resulted often in abnormal plant responses. Follow-up studies based on results from previous experiments have led to use advanced technologies in developing spaceflight plant growth systems. During 2001 utilising the Advanced Astroculture\textsuperscript{TM} plant growth facility on the ISS the first successful experiment was conducted to grow *Arabidopsis thaliana* plants from seed-to-seed (Link et al., 2003). Plants completed a full life cycle during two months in space: from seed hydration, germination, vegetative and reproductive plant development, to seed formation and maturation.

Appropriate technologies and Earth-based cultural practices must be utilised in order to provide stress-free plant growth in space environment. The crop in spaceflight plant growth system must be selected for small size, fast growth, nutritional composition, short plant cycles, and high harvest index. Factors such as palatability, serving size and frequency, processing requirements, storage stability, toxicity and human use experience can also influence the identification of baseline crops for BLSS.

There are differences between farming on board spacecraft or on planetary bases in terms of the resources available and in the constraints that must be accommodated. Spacecraft like ISS offers limited volume, mass, energy and manpower while on future extraterrestrial human habitats larger growing areas and larger energy supply could be available.
Production of plants in controlled environment systems requires significant electrical-energy inputs and 45% of the total power is consumed by artificial lighting, 35% by air-conditioning and the other 20% by others (Cuello et al., 2001). Plants convert light into chemical energy in the process of photosynthesis. The amount of light available to a crop determines its photomorphogenic and phototropic aspects of plant development and morphology. Artificial lighting is always used inside the plant growth systems on board the ISS; on planetary bases, instead, hybrid solar and electrical lighting systems could be used. The hybrid solar and electrical lighting system posses the advantage of providing lighting only when it is needed such as during periods of prolonged darkness on the Moon, or when is available but insufficient, for example when light-shielding clouds or dust storms pass over the Martian surface (Cuello et al., 2001). On board the ISS all the light required from crop production is generated by photovoltaic systems (solar cells) or fuel cells; on planetary surfaces lighting system could be fed by nuclear power and by sunlight (natural sunlight, applying photovoltaic systems alone or connected to concentrators) (Monje et al., 2003).

**LIGHTING SYSTEM**

The design of the lighting system must maximise photon flux in the desired spectral range to meet plant light needs, spatial uniformity and energy efficiency. Besides, the thermal load must be minimised because natural convection does not exist in microgravity to dissipate heat from the lights (Bula and Ignatius, 1996; Duffie et al., 1995; Heathcote et al., 1996). Plants require certain light duration (photoperiod) for their growth. Plants need photosynthetically active radiation (PAR) in the wavelengths range between 400 and 700 nm with highest photosynthesis efficiency in blue (~ 450 nm) and red (~ 650 nm) regions. Besides it is necessary to control radiation level at 670 and 735 nm which drives the phytochrome response, as it related to plant morphogenesis. Radiation over 750 nm seems not having direct effect on the plant growth and thus needs to be removed as heat via circulation of the chamber air. The higher the efficiency of the lighting system the less heat will be generated.

The lighting systems currently applied in spaceflight plant growth systems are shown in Table 1. Several different electric lighting regimes are currently being analysed by researchers in order to find the most productive, energy efficient and safest way of providing light to plants grown in space. Traditional lighting regimes (high-pressure sodium (HPS), cool white fluorescent (CWF), microwave, etc.) and innovative light emitting diode (LED) module, which provides photons in the red and blue regions of the spectrum, were analysed for space-based plant growth applications in several studies (Chapman et al., 1995; Crabb et al., 2001; Duffie et al., 1995; Heathcote et al., 1996; Hoehn et al., 1998; Ivanova et al., 1993; Morrow et al., 2001; Turner and Zhou, 2000; Wells et al., 2000; Zhou and Turner, 2000). HPS lamp is a point-source of radiation as opposed to CWF and LED light sources, which were intrinsically more diffuse over the plant canopy as a result of lamp design and associated luminarie (Goins et al., 2001). HPS, relatively deficient in blue wavelengths, and microwave lamps are not considered safe for space-flight because of their explosion hazard and high operating temperatures (Stryjewski et al., 2001).

A comparison between the fluorescent and LEDs light modules is shown in Table 2 (Hoehn et al., 1997). fluorescent lamps emit gravity-dependent radiation in all directions and a significant portion of the photons cannot be reflected to the plants when lamps are mounted close together (Bula et al., 1991). The light modules contain the fluorescent lamps in an enclosed box. The box is constituted by reflective material in order to maximise light intensity and uniformity. Reflective material can be DURAFLECT® , with a reflectivity of 94-98% in the range of 350-1200 nm, or specular aluminium, with a reflectance of 91% in the same spectral range. A polycarbonate window isolates the fluorescent light module from the plant chambers and prevents excess heat transfer into the plant chambers. A mercury-absorbing air exchange filter is always added to reduce the potential risk of mercury vapour release into the space vehicle.
if a lamp is broken (Hoehn at al., 1997). Heat transfer to manifold is performed by conduction using copper fins, by forced air convection using miniature fans and by radiation using optically selective coatings that absorb infrared radiation. The cooling manifold of fluorescent light module, due to its mass, serves as a mean structural element to protect the lamps from excessive stress during launch. Thermocouples are placed inside the light module to measure inside air temperature, lamp surface temperature and copper fin temperature (Turner and Zhou, 2000).

Light emitting diodes are particularly suitable for space plant growth lighting system for their small mass and volume, solid state construction, safety, longevity and narrow spectral output (Goins et al., 1998; Goins at al., 2001; Heathcote et al., 1996; Zhou et al., 1997). Besides, appropriate combination of red and blue LEDs have a great potential for use as a light source to drive photosynthesis due to the ability to tailor irradiance output near the peak absorption regions of chlorophyll. LEDs emit a low level of thermal radiation, have no hot electrodes and have no high-voltage ballasts, and thus are safe to the crew. LEDs are fabricated with an internal reflector to direct the emitted radiation out of the tip of the device in a narrow cone. A high percentage of the emitted light can be directed onto plant surfaces (Duffie et al., 1995).

Inside the spaceflight growth chambers focusing materials, such as mirrors, prismatic reflecting films, holographic diffusers and light pipes, are used in order to efficiently and evenly distribute point-source light over plant canopies (Goins and Yorio, 2000; Goins et al., 2001). Due to the small base area, the reflection from side walls contribute a large percentage of light to the overall light intensity. As the side walls become increasingly shielded by the growing plants, total light intensity in the chamber decreases. At the same time, the taller plants receive higher intensity light from the top of the chamber. This limitation could only be improved with larger and taller chambers where the height of the plant is small when compared to the chamber height and the distance to the light source. Growing plants of different heights may shield the reflective side walls unevenly, thus creating a horizontal light gradient. In the absence of gravity, this may result in strong phototropic curvature of the plants towards the brightest, exposed reflective wall (Hoehn et al., 1997).

In Italy researchers of different Universities have been studying, with support from ASI, a growing spaceflight system called Space GreenHouse (SGH). This system is developed for the production of food for the crew with minimum waste material and for air revitalisation, through high CO₂ uptake and O₂ production (Scarascia-Mugnozza and Schettini, 2002).

On the basis of the data collected, the SGH lighting system will consist of a monolithic array of red and blue LEDs. The LEDs will be mounted on a highly thermally conductive ceramic substrate, bonded to a metal heat sink in order to maintain the temperature of the LED at near ambient temperature of the environment. The output of the red and blue components could be individually controllable according to the need of the plants for PAR levels and light composition. The light intensity could be monitored by a calibrated photodiode sensor mounted inside the chamber. The photoperiod will be monitored and controlled according to the botanical and experimental requirements. The plant growth chamber will be light tight.

ACKNOWLEDGEMENTS

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Literature Cited


Tables

Table 1. Lighting regimes used in Spaceflight Plant Growth Systems.

<table>
<thead>
<tr>
<th>Total Growing Area (m²)</th>
<th>Total Growing Volume (m³)</th>
<th>Lighting system</th>
<th>Light Intensity (µmol m⁻²s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PGU¹</td>
<td>0.05</td>
<td>0.002</td>
<td>Fluorescent lamps</td>
</tr>
<tr>
<td>SVET²</td>
<td>0.075</td>
<td>0.02</td>
<td>Fluorescent lamps</td>
</tr>
<tr>
<td>ASC³</td>
<td>0.021</td>
<td>0.0032</td>
<td>LEDs module</td>
</tr>
<tr>
<td>PGF⁴</td>
<td>0.055</td>
<td>0.0104</td>
<td>Fluorescent lamps</td>
</tr>
<tr>
<td>PGBA⁵</td>
<td>0.075</td>
<td>0.0225</td>
<td>Fluorescent lamps</td>
</tr>
<tr>
<td>CPBF⁶</td>
<td>0.24</td>
<td>0.108</td>
<td>Fluorescent lamps and LEDs module</td>
</tr>
<tr>
<td>BPS⁷</td>
<td>0.128</td>
<td>0.0156</td>
<td>Fluorescent lamps</td>
</tr>
<tr>
<td>PRU⁸</td>
<td>0.104</td>
<td>0.02</td>
<td>Fluorescent lamps and LEDs module</td>
</tr>
</tbody>
</table>

Table 2. Comparison between Fluorescent lamps and Light Emitting Diodes for Space-flight Plant Growth Systems (Hoehn et al., 1997).

<table>
<thead>
<tr>
<th></th>
<th>Fluorescent lamps</th>
<th>Light Emitting Diodes (LEDs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission</td>
<td>Broad spectrum 400-700 nm with low IR emissions and high intensities for plant growth</td>
<td>Narrow-band emission, No radiation between 750-1400 nm Red, blue and IR LEDs are required</td>
</tr>
<tr>
<td>Technology</td>
<td>Widely used in plant research</td>
<td>New</td>
</tr>
<tr>
<td>Efficiency</td>
<td>High (20-30%), increased as temperature increases</td>
<td>Low (for blue wavelength 5-10%), reduced as temperature increases</td>
</tr>
<tr>
<td>Weight</td>
<td>Light: small heat exchanger and small power conditioning unit</td>
<td>Heavy: efficient heat exchanger and power conditioning unit</td>
</tr>
<tr>
<td>Life-time</td>
<td>Long: ≈20000 hrs</td>
<td>Very long: ≈100000 hrs</td>
</tr>
<tr>
<td>Cost</td>
<td>Low: ≈100 $</td>
<td>Expensive: ≈10000 $</td>
</tr>
<tr>
<td>Light output</td>
<td>Gravity-dependent</td>
<td>Gravity-independent</td>
</tr>
<tr>
<td>Vibrational loads</td>
<td>Withstand &lt;100 g</td>
<td>Compatible with very high g-loads</td>
</tr>
<tr>
<td>Devices</td>
<td>Structural and material devices to avoid mercury release in case of breakage</td>
<td>No devices</td>
</tr>
</tbody>
</table>

Figures

![Closed-loop Bioregenerative Life Support System](image)

Fig. 1. Closed-loop Bioregenerative Life Support System.