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PLANT HARDWARE EQUIPPED WITH HYBRID LIGHTING: COMBINING SOLAR IRRADIANCE WITH XENON-METAL HALIDE LAMPS OR LIGHT-EMITTING DIODES FOR LIFE SUPPORT IN SPACE

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ABSTRACT

Hybrid solar and electric lighting (HYSEL) systems constitute the latest generation of lighting systems for advanced life support, exhibiting continued potential for reducing the significant electrical power demand of current bioregenerative life support systems (BLSS). Two experimental HYSEL systems were developed: one employing xenon-metal halide (XMH) lamps and the other adopting light-emitting diodes (LEDs) as the electric-lighting components, and both using a mirror-based, fiberoptic-based solar collection system. The results showed that both the XMH and LED HYSEL systems effected reduced effective plant growing volume, indicating potential for a compact plant hardware design. The apparent electrical conversion efficiency of the LED HYSEL system exceeded that of the XMH HYSEL system by five-fold. Both the XMH and LED HYSEL systems provided reasonably acceptable spectral quality and lighting uniformity. So far, LEDs appear to be the most competent artificial light source for a HYSEL system. Also, preliminary studies suggested that HYSEL systems show promise of BLSS application both on the Martian surface and on a Sun synchronous orbit around Mars.

INTRODUCTION

The estimated cost for a manned mission to Mars was approximately $450 billion to $500 billion in 1989. After 10 years, the projected cost has gone down to approximately $55 billion, or about 10 percent of the original projection. For comparison, the International Space Station Alpha has a current price tag of about $100 billion. This significant reduction in the estimated cost for a human journey to Mars has been the result of design improvements being proposed or currently under investigation by the National Aeronautics and Space Administration (NASA). These design improvements include, but are not limited to, the use of lighter and partly inflatable hardware materials, making rocket fuel *in situ* on the Martian surface, and designing bioregenerative life support systems (BLSS) for food production and the recovery of materials from wastes.

BLSS

Plants are central to bioregenerative life support systems since they perform such important functions as food producer, gas exchanger and water purifier (Chamberland, 1992). Production of plants in controlled-environment systems, however, requires significant electrical-energy inputs. Indeed, in a study conducted by Ikeda et al. (1992), results showed that, by breakdown, 45% of the total power spent in an environmentally-controlled plant factory was consumed by artificial lighting, 35% by air-conditioning and 20% by others. This power distribution breakdown is closely mimicked by the Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex) facility at NASA Lyndon B. Johnson Space Center in Houston, Texas, whose lighting power accounts for 40% of the total power demand, while cooling power associated with lighting also accounts for 40% of the total power requirement (Drysdale, 2000). A significant 57% of the total equivalent system mass (ESM) of the BIO-Plex is directly attributable to plant lighting (Drysdale, 2000). Equipped with a total of 1,200 400-W high-pressure sodium (HPS) lamps, the BIO-Plex demands 561 kW of power for plant lighting alone. By comparison, the total power supply to the International Space Station Alpha for all purposes is only 75 kW. Hence, reducing the electrical power demand of the

BLSS constitutes a critical factor that will help decide the feasibility of any long-duration manned mission leaving low-Earth orbit, including that for Mars.

HYBRID LIGHTING

The available solar energy on the Lunar and Martian surfaces may be harnessed to decrease the significant electrical-power demands of proposed BLSS for future extraterrestrial human habitats (Cuello et al., 1999). Reducing the electrical-power load of a BLSS is also expected to diminish related BLSS mass and physical volume, and thus should aid in securing the desired feasibility for a working BLSS. The use of Solar Irradiance Collection, Transmission and Distribution Systems (SICTDS) for harnessing available solar irradiance has been previously investigated (Cuello et al. 1999). The use of an SICTDS for extraterrestrial applications, however, is not without challenges. First, while certain parts of the Moon may receive 1,350 W/m^2 of solar irradiance, its daylength (midnight to midnight) of 27.5 Earth days translates into significantly prolonged dark periods (Lemmon 1998) which would jeopardize the growing plants in a BLSS if they were exclusively dependent on available solar irradiance. In addition, though the daylength (midnight to midnight) at the Martian equator of about 24.6 hours approaches that on Earth, the distance of Mars relative to the Sun of 1.56 astronomical units results in reduced solar irradiance of approximately 555 W/m^2 incident on the Martian surface (Lemmon 1998). Although relatively reduced, the quantity of solar irradiance on the surface of Mars remains significant notwithstanding (Ono and Cuello 2000).

The foregoing facts lead to the conclusion that both SICTDS and electric lamps should both be used in the design of a reliable, energy-efficient and mass-optimized hybrid lighting system that will adequately supply, both quantitatively and qualitatively, the demand of growing crops for photosynthetically active radiation (PAR). A hybrid solar and electric lighting (HYSEL) system possesses the advantage of providing electric lighting only when it is needed. Thus, HYSEL optimizes electrical-power consumption and ensures that photosynthetically active radiation would be available during periods of prolonged darkness on the Moon and when light-shielding clouds or dust storms pass over the Martian surface.

OBJECTIVES

The objectives of this study were as follows:

1. To design, develop and operate two types of hybrid lighting system for a plant growth chamber (GC); namely: (a) a HYSEL system combining solar irradiance and xenon-metal halide (XMH) lamps; and, (b) a HYSEL system combining solar irradiance and light-emitting diodes (LED);
2. To determine the apparent electrical conversion efficiency of the artificial lighting component for each type of HYSEL system;
3. To determine the spectral distributions for each type of HYSEL system;
4. To determine the spatial distribution of photosynthetic photon flux (PPF) over the growing area within the GC for each type of HYSEL system; and,
5. To discuss the needed improvements and features for a plant hardware prototype equipped with a HYSEL system.

METHODS

The experimental hybrid lighting systems were designed, developed and tested at the Subterranean Plant Growth Facility (SPGF) at The University of Arizona in Tucson, AZ (32° 16' 49'' N), where the long-term average total solar radiation generally approaches that found on the Lunar surface (Lemmon 1998).

The SICTDS used for the HYSEL system was a mirror-based Optical Waveguide (OW) Solar Lighting System (Nakamura et al. 1999) consisting of two solar tracking units, each equipped with two 50-cm parabolic primary mirror concentrators (Figure 1). At the focal point of each primary concentrator was a fused quartz secondary concentrator, which further concentrated the high-intensity solar flux from the primary concentrator and injected it into a fiberoptic cable. Each fiberoptic cable was 10 m long, consisting of 37 optical fibers, each with a diameter of 1 mm. The PPF losses for the OW Solar Lighting System were 15% for the primary concentrator (i.e., the mirror), 25% for the secondary concentrator, and 36.4% for the optical cable (Jack, 1999). Thus, the overall efficiency for the collector was (1 – 0.15)(1 – 0.25)(1 – 0.364) = 40.5%.

Figure 1. The mirror-based Optical Waveguide (OW) Solar Lighting System consisting of two solar tracking units, each equipped with two 50-cm parabolic primary mirror concentrators.

To determine the long-term supplemental terrestrial solar lighting that the OW Solar Lighting System would be capable of supplying a plant growth chamber located inside the SPGF, Cuello et al. (2000) calculated the equivalent electrical power that would be required by high-pressure sodium (HPS) and cool-white fluorescent (CWF) lamps to generate or duplicate the PPF output within the GC as delivered by the OW Solar Lighting System. This approach led to the energy savings gained by employing the OW Solar Lighting System. Data for hourly solar irradiance incident at Tucson, AZ compiled over a 12-year period from 1987 through 1998 were used to calculate the average instantaneous PPF within the GC per hour and per day throughout the year. In the study, the HPS and CWF lamps, widely used for growing plants under controlled environments, were assigned values for their electrical conversion efficiencies of 35% and 20%, respectively.

The results showed that for the month of June, for example, the equivalent electrical power, corresponding to the average instantaneous PPF level (402.4 μmol m^{-2} s^{-1}) within the GC per day as delivered by the OW SICTDS, was 229.9 W m^{-2} using HPS lamp and 437.4 W m^{-2} using CWF lamp. This means that replacing the available solar irradiance within the GC in June would require either 229.9 W m^{-2} of HPS lighting or 437.4 W m^{-2} of CWF lighting supplied continuously for 450 hrs, which was the average total photoperiod for the whole month of June. In energy terms, these would be equivalent to 103.5 kW-hr m^{-2} for the HPS lamp and 196.8 kW-hr m^{-2} for the CWF lamp. For a whole year, the equivalent energy expenditures would be 0.9 MW-hr m^{-2} for the HPS lamp and 1.7 MW-hr m^{-2} for the CWF lamp. Thus, the available solar irradiance made available within the GC by using the OW Solar Lighting System could result in significant electrical energy savings.

All other methods are explained within the next section.

RESULTS

XMH HYSEL SYSTEM

The OW SICTDS was positioned on the rooftop of the Subterranean Plant Growth Facility (Figure 1). Figure 2 shows how the four fiberoptic cables from both SICTDS units penetrated through the ceiling of the SPGF and entered through the top of a GC inside the SPGF. Figures 2 and 3 show how the ends of the cables' individual optical fibers were distributed in a rectangular array through a frame over the plant growing area inside the GC. The rectangular frame was positioned at a distance of 11.7 cm above the GC's plant growing area, which measured 76.2 cm x 48.3 cm. The GC had a total volume of 1 m^3, had its interior walls covered with aluminum foil, had hydroponic trays connected to a nutrient-solution reservoir, and was provided with an air ventilation system. The monitoring, data acquisition and control of the various environmental parameters within the GC were performed automatically by a computer equipped with Lab-View ™ software. The sensors included light sensors for PPF and total radiation, thermocouples for air temperature, electrical-conductivity sensor for the hydroponic solution, and pH sensor for hydroponic solution. Readings were automatically taken by the sensors at five-minute intervals.

The artificial-lighting component consisted of four 60-W xenon-metal halide lamps, each contained in an illuminator box placed outside of the plant growth chamber. Two illuminator boxes were placed on each side of the GC (Figure 2). [Note that a xenon-metal halide lamp is not the same as a xenon lamp.] Light-emitting polymer cables, passing through the side walls of the GC (Figure 2), piped the irradiance from the illuminator boxes into the GC interior. The light-emitting polymer cables (Cuello et al. 1998) connected the pair of illuminators on one side of the chamber to the other pair of illuminators located on the opposite side. Inside the GC, the light-emitting cables ran in parallel on the underside of the rectangular frame (Figures 3, 4, 5), emitting directional linear beams of light, with a beam spread of 60 degrees, directed toward the growing area. The cables were arranged under the rectangular frame, over which the solar fiber tips were also distributed (Figures 3, 4, 5), in such a way that the rows of solar fiber tips under the rectangular frame ran in parallel and alternately with the polymer light-emitting cables (Figure 4).

Since the quantity of thermal energy generated by the light coming off the polymer light-emitting cables within the GC was minimal, the rectangular lighting frame could be positioned very close to the plant canopy (Figure 5). This resulted in the effective growing volume of the GC being significantly reduced, indicating potential for a compact plant hardware design. By contrast, a control GC equipped with an air-cooled 250-W HPS lamp resulted in an effective growing volume that was 6.2x larger, since the HPS lamp had to be raised significantly higher (at 72.4 cm) from the tray level owing to the lamp's substantial heat output.

LED HYSEL SYSTEM

The OW SICTDS and the same GC were used for the LED-based HYSEL system (Figure 6). Linear strips of light-emitting diodes were employed as the artificial-lighting component (Figures 7, 8). The 28 LED strips, 24 red and 4 blue, were positioned in parallel on the underside of the rectangular frame, over which the solar fiber tips were also distributed (Figure 7). The LED strips were arranged in such a way that the rows of solar fiber tips under the rectangular frame ran in parallel and alternately with the LED strips (Figure 8).

As in the XMH HYSEL system, the quantity of thermal energy generated by the LEDs within the GC was minimal, allowing the rectangular lighting frame to be

Figure 2. Four fiberoptic cables from the Optical Waveguide (OW) Solar Lighting System units penetrating through the ceiling of the Subterranean Plant Growth facility (SPGF) and entering through the top of a plant growth chamber inside the SPGF.

Figure 3. Individual optical fibers from the four cables of the Optical Waveguide (OW) Solar Lighting System units distributed in a rectangular array through a frame over the plant growing area inside the plant growth chamber.

Figure 4. Polymer light-emitting cables arranged in parallel under the rectangular frame through which the solar fiber tips were also distributed. The rows of solar fiber tips ran in parallel and alternately with the light-emitting cables.

Figure 5. Polymer light-emitting cables arranged in parallel under the rectangular frame through which the solar fiber tips were also distributed. The rows of solar fiber tips ran in parallel and alternately with the light-emitting cables.

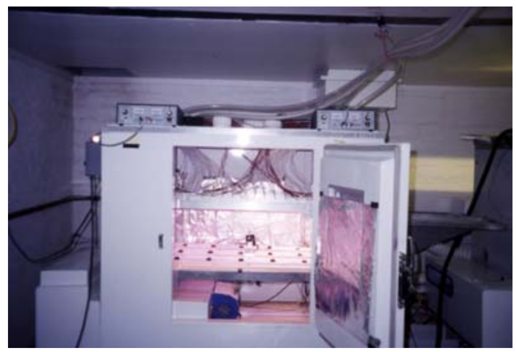

Figure 6. Four fiberoptic cables from the Optical Waveguide (OW) Solar Lighting System units penetrating through the ceiling of the Subterranean Plant Growth facility (SPGF) and entering through the top of a plant growth chamber inside the SPGF.

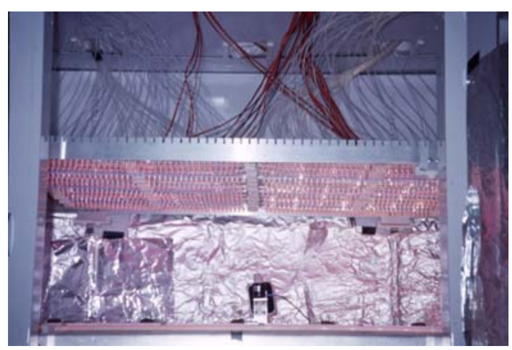

Figure 7. LED strips arranged in parallel on the underside of the rectangular frame over which the solar fiber tips were distributed.

Figure 8. Rows of solar fiber tips coming through the rectangular frame running in parallel and alternately with the LED strips.

Figure 9. Rectangular frame of LED strips and solar fiber tips over the growing area within the growth chamber.

positioned very close to the plant canopy (Figure 9). This again resulted in the effective growing volume of the GC being significantly reduced, indicating potential for a compact plant hardware design. By comparison, the control GC equipped with an air-cooled 250-W HPS lamp had its effective growing volume 6.2x larger.

The use of LED strips has two conspicuous advantages: first is the facility of adjusting the number of LED strips according to the need for PPF level; and second is the ease of controlling the relative color proportions (e.g., red to blue) of the LED array. These two features regulate the photosynthetic and morphological characteristics of the plants grown.

APPARENT ELECTRICAL CONVERSION EFFICIENCY

The apparent electrical conversion efficiency of the electric lighting component of a HYSEL system as it was installed in the particular GC used here was defined to be the ratio of the average PPF achieved on the tray level inside the GC, generated only by the electric lighting component, to the electric power expended to generate such average PPF. Note that this index was unique to the particular hardware configuration used in this study, and was developed to compare only the relative performance of the two HYSEL systems. The resulting values were 0.12 μmol m^{-2} s^{-1} per W for the XMH HYSEL system, with the array of parallel polymer light-emitting fibers piping the light from the XMH illuminators, and 1.02 μmol m^{-2} s^{-1} per W for the LED HYSEL system, with the array of parallel LED strips. Thus, the apparent electrical conversion efficiency for the LED system was 5.1-fold greater than that for the XMH system. The LED system outperformed the XMH system since the LEDs delivered their PPF output directly over the growing area and at a relatively narrow beam spread. By contrast, the PPF output of the XMH lamps not only had to be piped through polymer cables into the GC, but the piped PPF output was released from the polymer cables over the growing area at a much wider beam spread (60 degrees), causing some of the light to escape sideways in the space between the lighting frame and the growing area.

SPECTRAL DISTRIBUTION

A spectroradiometer (200 nm – 1000 nm) was used to measure spectral distribution. Figure 10 shows the spectral distribution of the electrical irradiance inside the HYSEL chamber as generated by the xenon metal-halide illuminators and transmitted through the polymer light-emitting cables. It becomes evident in Figure 11 that the resulting spectral distribution of the combined solar and XMH irradiance within the GC was significantly closer to that for terrestrial solar irradiance than that for the xenon-metal halide illuminator (Figure 10).

Figure 12 shows the spectral distribution inside the GC with the LEDs as the electric-lighting component, distinguished by the prominent blue peak on the left and the red spike on the right. Figure 13 shows the spectral distribution of the hybrid irradiance generated by combining solar irradiance and LED lighting. The resulting spectral distribution in Figure 13 is a composite of the LED spectral distribution and the solar spectral distribution.

Since the resulting hybrid spectral distributions for the two HYSEL systems show that the largest portions of their irradiance outputs occur between 400 nm and 700 nm (and indeed not deviating significantly from those for terrestrial solar irradiance), and since plants absorb irradiance between 400 nm and 700 nm, it is evident that the HYSEL systems reasonably satisfy the plant lighting requirement in terms of spectral quality.

PPF SPATIAL DISTRIBUTION

Figures 14 and 15 show instantaneous “snapshots” of PPF spatial distributions over the growing area in the HYSEL chambers equipped with XMH lighting and LED lighting, respectively. The XMH HYSEL distribution provided for the PPF an average and standard deviation of 244 ± 62 μmol m^{-2} s^{-1}, corresponding to a coefficient of

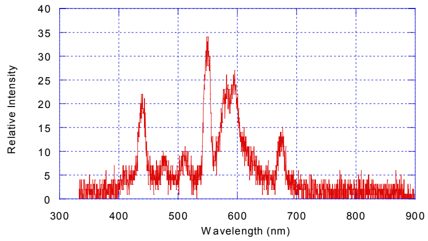

Figure 10. Spectral distribution of the electrical irradiance inside the HYSEL chamber as generated by the xenon metal-halide illuminators and transmitted through the polymer light-emitting cables.

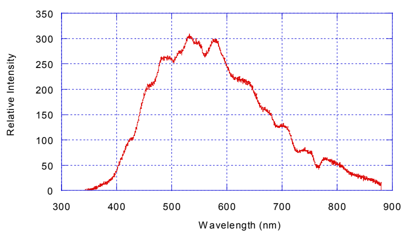

Figure 11. Spectral distribution of the combined solar and electrical (xenon-metal halide) irradiance in the HYSEL chamber.

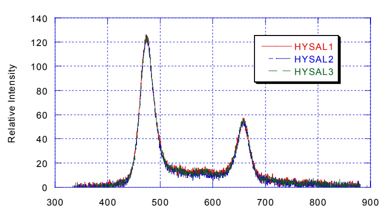

Figure 12. Spectral distribution of the artificial irradiance inside the HYSEL chamber as generated by the LEDs.

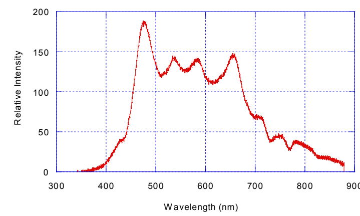

Figure 13. Spectral distribution of the combined solar and electrical (LED) irradiance inside the HYSEL chamber.

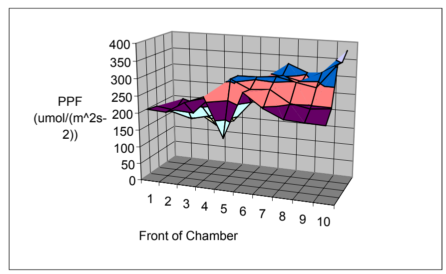

Figure 14. Instantaneous PPF distribution over the growing area in the HYSEL chamber with xenon-metal halide lighting.

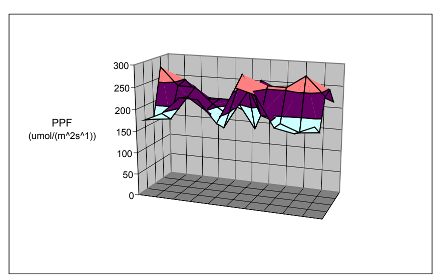

Figure 15. Instantaneous PPF distribution over the growing area in the HYSEL chamber with LED lighting.

variation (C.V.) of 25%, that is, the standard deviation was 25% of the mean value. For the LED HYSEL distribution, the average PPF and standard deviation were 218 $\pm$ 35 μmol m^{-2} s^{-1}, corresponding to a C.V. of only 16%. Cuello et al. (2000b) showed that such difference in spatial PPF distribution did not translate into significant difference in plant-dry-weight variability. It should be noted that the actual instantaneous PPF values inside the HYSEL chambers varied significantly within days and between days owing to the variability of the instantaneous solar PPF.

DISCUSSION

Artificial Lighting Component

A plant hardware equipped with a hybrid lighting system is conferred the advantage of using electric lighting only when it is needed; thus, minimizing electrical-power consumption. There are three possible recurring or alternating scenarios for a HYSEL system: (1) when solar irradiance is available and sufficient, the electric lighting component is turned off; (2) when solar irradiance is not available, electric lighting is used to meet the lighting requirement in full; and (3) when solar irradiance is available but insufficient, electric lighting is used to fill the deficit of the lighting requirement. For maximum electrical power conservation, the electric lighting component of a HYSEL system should be able to adapt dynamically to the transient and fluctuating solar PPF levels. This would ensure that sufficient PAR would be made available to the crops, not only during times of prolonged darkness on the Lunar surface, but also when transitory light-shielding clouds or dust storms pass over the Martian surface.

The foregoing brings forth the following two criteria for the electric lighting component of a HYSEL system: (1) the electric lighting component should have the capacity to meet the lighting requirement in full when needed; and (2) the electric lighting component should be able to have its PPF output adjust dynamically to fill the changing lighting deficit as caused by the fluctuating solar PPF level. Both the XMH and the LED HYSEL systems developed in this study could be made to satisfy the first criterion. While it is doubtful that the particular light-emitting polymer cables used in the XMH HYSEL system could be made to transmit sufficient light from the illuminator boxes to the GC interior, new kinds of light-emitting polymer cables that possess improved transmission efficiencies even through sharp bends are now in the process of commercialization. The use of these cables, which have very low heat transmission capacity, would allow the effective growing volume of the GC to remain relatively compact, a design feature with important volume and mass reduction implications for a BLSS. Such cables would conveniently allow the use of illuminator boxes equipped with other lamp types, such as the HPS, metal halide and microwave lamps.

The second criterion, calling for the artificial lighting component to have its PPF output dynamically adjustable to fill the changing lighting deficit as caused by the fluctuating solar PPF level bodes very well for the LEDs since they can be alternately dimmed and brightened through adjustment of their electric current supply (Ono et al. 1998). The HPS and microwave lamps, however, can only be dimmed within certain Watt limits.

Solar Concentrator

As already elucidated, a HYSEL system can help substantially reduce the electrical power consumption of a BLSS by putting to work the harnessed available solar irradiance. To avoid this benefit from being neutralized by the addition of significant mass to the total BLSS system, however, it is imperative that the solar concentrators employed be designed and constructed using lightweight materials. The OW Solar Lighting System used in this study, an experimental version, was not mass-optimized. The realization of lightweight solar concentrators would ensure that the use of HYSEL systems would not only reduce the total electrical power demand of a BLSS, but that they would also slash the total equivalent system mass (ESM) of the BLSS. Other features of the solar concentrators that require attention include their cooling system, solar tracking system, and a way to protect them from atmospheric dust. Appelbaum and Landis (1991) estimated the annual probability of local dust storms on the *Chryse Planitia* region on Mars at 0.57%, or approximately 94 hours per Martian year.

HYSEL System on Mars

Ono and Cuello (2000) simulated working estimates of the available photosynthetic photon flux at *Chryse Planitia* (22.3° N, 47.9° W), landing site for the Viking Lander 1 (VL-1) on Mars and geographically near the Mars Pathfinder's landing site, based on the year-long actual irradiance measurements and downward spectral characteristics made by VL-1 in the 1970's. Their results showed that for half of the total sunshine hours at *Chryse Planitia* for a whole Martian year, the incident PPF level is at least 400 μmol m^{-2} s^{-1}, a significant quantity in terms of satisfying plant lighting requirement. At approximately 7 % of the sunshine hours in a Martian year, however, the PPF level is zero owing to weather factors (clouds and/or dust storms).

Adopting the foregoing results, Durbin et al. (2000) calculated the contribution of the available extraterrestrial solar irradiance in reducing the power demand in a Martian habitat equipped with a BLSS based on the plant-system data for the BIO-Plex facility. Employing a commercially available lens-based SICTDS, their results showed that, by harnessing the available solar irradiance, a plant lighting regime consisting of a daily photoperiod of 16 hrs and an average instantaneous PPF of 400 μmol m^{-2} s^{-1} could have its electric lighting consumption reduced by 25%, while that consisting of a daily photoperiod of 16 hrs and an average instantaneous PPF of 200 μmol m^{-2} s^{-1} could have its electric lighting consumption diminished by 50%.

HYSEL System on Sun Synchronous Orbit

Ono and Cuello (2000b) also recommended the use of solar stationary orbits over Mars for an orbiting Martian BLSS to effect significantly reduced electrical power demand. Solar stationary orbits, or Sun synchronous orbits, are unique orbits that satellites use to pass over the same latitude on a planet at the same Sun time. The orbits are used extensively for meteorological satellites over Earth. An important feature of Sun synchronous orbits relative to an orbiting BLSS is that they constitute trajectories wherein solar energy is continuously available to the BLSS. Hence, an orbiting BLSS set on a solar stationary orbit over Mars could harness the available solar irradiance without interruption through direct conveyance into and distribution over growing plants in GCs equipped with HYSEL systems. Also, Sun-tracking devices would be rendered unnecessary, and the light-attenuating capacity of the Martian atmosphere would be circumvented. The use of a Sun-synchronous orbiting BLSS over Mars is particularly appealing since only 43% as much solar radiation reaches the planet compared to that incident upon Earth. Possible BLSS-equipped satellites orbiting over Mars on a solar stationary orbit include a "parked" Earth Return Vehicle and a permanent Martian orbital outpost or station.

Ongoing and Future Research

The ongoing research at the SPGF at The University of Arizona focuses on plant growth demonstrations using the LED HYSEL system developed, testing of liquid-based cables for the OW Solar Lighting System, and the thermal analyses and determination of the spatial power output distributions of standard and water-cooled HPS lamps as well as LEDs. Future research, in collaboration with the DOE's Oak Ridge National Laboratory, will concentrate on optimizing the solar collection area with respect to the plant growing area and analyzing the total ESM of a BLSS equipped with a HYSEL system.

CONCLUSIONS

Following were the conclusions of the study:

1. Both the XMH and LED HYSEL systems effected reduced effective GC growing volume, indicating potential for a compact plant hardware design;
2. The apparent electrical conversion efficiency of the LED HYSEL system exceeded that of the XMH HYSEL system by five-fold;
3. Both the XMH and LED HYSEL systems provided acceptable spectral quality and lighting uniformity; and,
4. So far, LEDs appear to be the most competent electric light source for a HYSEL system.

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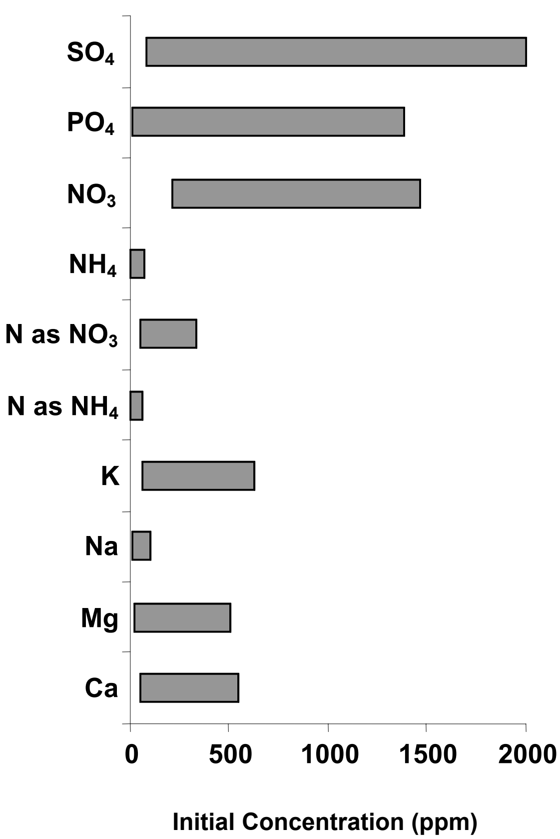
SO4
PO4
NO3
NH4
N as NO3
N as NH4
K
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Mg
Ca
0
500
1000
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Initial Concentration (ppm)