DEVELOPMENT AND TESTING OF AN EFFICIENT LED INTRACANOPY LIGHTING DESIGN FOR MINIMIZING EQUIVALENT SYSTEM MASS IN AN ADVANCED LIFE-SUPPORT SYSTEM.

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NASA has defined a metric to determine the necessary launch capacity for an advanced life-support system (ALS), designed to support humans for an extended duration beyond low earth orbit. This metric allows the comparison of techniques and technologies over time and between mission scenarios, yielding the optimum physical-chemical and bioregenerative array for human life support. The metric in use is Equivalent System Mass (ESM), which equates power, volume, cooling and crew time into a mass-equivalency unit (Kg) as shown by Equation 1 (Levri, 2003).

Equation 1 $$\mathbf{ESM = M + (V \bullet V_{eq}) + (P \bullet P_{eq}) + (C \bullet C_{eq}) + (CT \bullet D \bullet CT_{eq})}$$

Where M, V, P, C, CT and D are the mass, volume, power, cooling, crew time and mission duration, respectively, for a given system, and the subscript multipliers are the equivalency factors used to convert these into units of mass equivalents.

Lighting for plant growth is estimated to account for 43% - 60% of the total ESM for biomass production, with much of this value due to the power requirements (Drysdale and Bugbee, 2003). Significant energy from overhead electrical lighting is lost by inaccurately targeting the light to all leaves in a crop canopy. When plants are young, light is lost by illuminating empty space around seedlings. If crops are planophiles (e.g. cowpea, soybean), which close their canopies as they age, then younger leaves shade out older leaves. This leads to a small percentage of leaves (approximately 10-15%) doing the photosynthetic work to support the entire crop stand.

To avoid wasting light and to utilize more of a crop's photosynthetic capabilities, we envision an intracanopy lighting system that allows switching of lights in response to plant growth. A reconfigurable lighting system is the result of a jointly sponsored collaborative research agreement between Orbital Technologies Corp. (Madison, WI) and the ALS NSCORT Crop Production group at Purdue University. We have worked together to develop a light-emitting diode (LED)-based system from earlier proof-of-concept studies with fluorescent lighting (Frantz et al., 2001).

Fig. 1 illustrates an individual unit or "lightsicle" of the lighting array. The first array consists of sixteen such strips, each mounted either independently or back to back. Strips also can be mounted in a planar configuration, allowing an overhead control for intracanopy studies, and eventually a separate close-canopy lighting system for erectophile (e.g. wheat) and rosette (e.g. lettuce) crops, where illumination switching will track the plant silhouette from above. Initially, however, the array will be used as an intracanopy lighting system for planophile crops.

Orbitec had previously designed a 1-in-square "Chip-on-Board" LED "light engine" for plant growth containing up to 132 LEDs with 5 possible colors, and 2 photodiodes that can detect a variety of wavelengths. For this system, we utilized these light engines. However, due to our requirements, chips were populated only with red and blue LEDs, with green LEDs and photodiodes also in place but not currently utilized. Future generations could include different LEDs depending on individual crop requirements. Each lightsicle strip has 20 light engines which have 5 rows of LEDs, four rows of sixteen 640-nm red LEDs and one row of sixteen 440-nm blue LEDs giving a total of 80 LEDs per chip (Fig. 1 inset). Heat from the LED chips is removed through a channel running behind the strip and a fan-driven airflow system mounted in the lightsicle enclosure (Fig. 1). This cooling method allows plants to grow near or touch the strips without scorching.

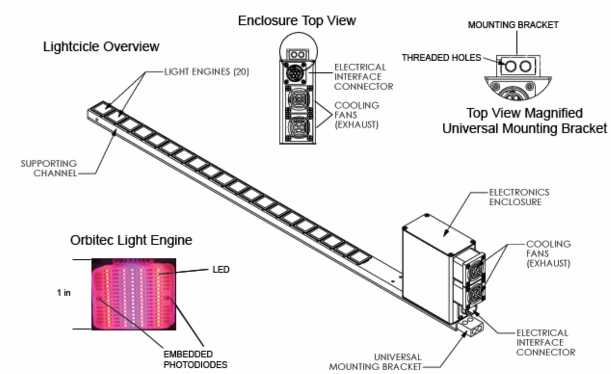

Figure 1. *The components of an individual lightsicle. Inset is a light engine showing the LEDs and photodiodes.*

Other components of the lighting system include a control enclosure containing a power supply and circuitry that control LED intensity via dimmer potentiometers, as well as incremental switching of light engines from the bottom to the top of lightsicles. Additionally, a timer allows preprogramming of desired photoperiod. A separate power and communications distribution assembly allows integration of the 16 strips.

A mounting system was developed to suspend the lightsicles within a crop-growth compartment. The growth area consists of an EGC (Chagrin Falls, OH) walk-in growth chamber with temperature, relative humidity, and CO_2 control. A recirculating hydroponics system was constructed. The root-zone compartment is mounted on a table frame, and a framework of angle iron was constructed around the hydroponic system. After lighting installation was complete, walls made from reflective white poly film were hung between the top of the framework and the table. Lightsicle mounts were suspended from struts placed horizontally over the framework at intervals. Brackets from the struts were attached to metal strips, and corresponding strips were fastened to the lightsicle mounting bracket (Fig. 1). Velcro was used to join the two sets of strips together. This mounting system allows ease of lightsicle removal for configuration changes, height adjustment, and maintenance. Lightsicles were mounted in a configuration to maximize light coverage uniformity within the growth compartment. The power and communications assembly was mounted to the framework adjacent to the growth compartment. Cables run from each individual lightsicle to this assembly, and separate cables extend from the distribution assembly to the control enclosure outside of the chamber.

Photosynthetically active radiation (PAR) was measured at different positions within the canopy space. Measurements were taken while red and blue intensities were changed and incremental switching of light engines occurred. Fig. 2 shows the increases in PAR with light intensity at two different heights within the array.

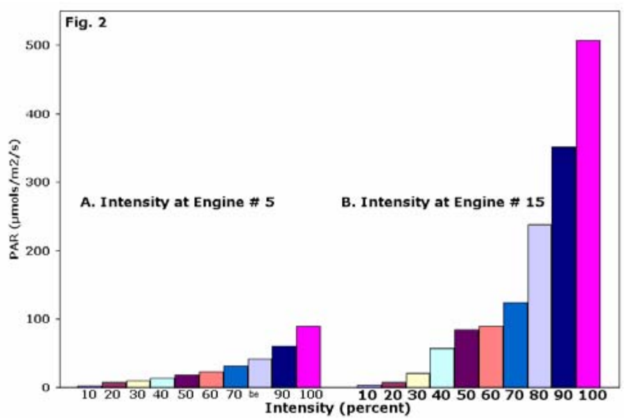

Figure 2. *PAR at increasing light intensity within the intracanopy lighting array. Measurements were taken approximately 2.5 cm directly in front of either A. light engine #5 or B. light engine # 15 of a lightsicle in the center of the array. When measurements were taken at engine # 5, only engines 1 through 5 were illuminated. When measurements were taken at # 15, engines 1-15 were illuminated.*

The differences between PAR values in Fig. 2A and B are due to radiation reflected off the poly film wall, radiation from surrounding engines, and variations in the light engines and associated drivers. The maximum light output measured within the system was approximately 900 µmols/m^2/s (data not shown).

In addition to PAR measurements, current draw was measured as light intensity was increased (Fig. 3). The correlation coefficient (R^2 = 0.994) indicates good agreement between energy input to and PAR output from the system. The y intercept indicates the baseline current value for an energized system with no lights on. We measured this value at 2.6 Amps running with 24 volts DC.

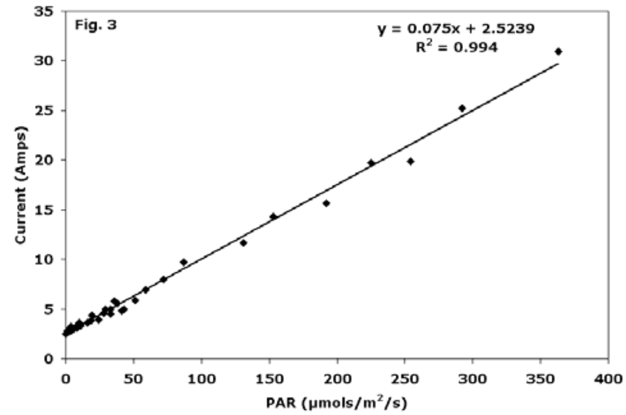

Figure 3. *Current versus PAR with 5, 10, 15, and 20 light engines illuminated at each intensity for a 16-strip array. PAR was measured without plants with the light sensor centered in the array on the foam base plate using a Li-Cor LI-1776 cosine-corrected solar monitor.*

We have developed a reconfigurable lighting array for plant growth in an ALS. This system is initially in an intracanopy arrangement for growth of planophile crops. Initial system tests indicate good performance with possible electronic modification in future systems to counteract component variations. Current drawn by the system strongly correlates with light output. The first cowpea crop grown in the system appeared healthy though somewhat elongated with weak stems. This test demonstrated the need for intense blue light early on to allow for de-etiolation and reduction in hypocotyl elongation. Other protocol modifications may include switching an extra light engine on to guide plant growth. Preliminary ESM calculations for an intracanopy lighting array on a m^2 and m^3 basis are underway. These calculations will allow us to define the critical sensitivity points within the lighting subsystem that will yield a high return on investment when improved, i.e. big reductions in ESM.

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