Plant Atrium System for Food Production in NASA's Deep Space Habitat Tests.

Gioia D. Massa[1], Morgan Simpson[1], and Raymond M. Wheeler.[1]
NASA Kennedy Space Center, FL 32899 USA

Gerard Newsham[2] and Gary W. Stutte[2]
ESC Team QNA, Kennedy Space Center, FL 32899

In preparation for future human exploration missions to space, NASA evaluates habitat concepts to assess integration issues, power requirements, crew operations, technology, and system performance. The concept of a Food Production System utilizes fresh foods, such as vegetables and small fruits, harvested on a continuous basis, to improve the crew's diet and quality of life. The system would need to fit conveniently into the habitat and not interfere with other components or operations. To test this concept, a plant growing "atrium" was designed to surround the lift between the lower and upper modules of the Deep Space Habitat and deployed at NASA Desert Research and Technology Studies (DRATS) test site in 2011 and at NASA Johnson Space Center in 2012. With this approach, un-utilized volume provided an area for vegetable growth. For the 2011 test, mizuna, lettuce, basil, radish and sweetpotato plants were grown in trays using commercially available red / blue LED light fixtures. Seedlings were transplanted into the atrium and cared for by the crew. Plants were then harvested two weeks later following completion of the test. In 2012, mizuna, lettuce, and radish plants were grown similarly but under flat panel banks of white LEDs. In 2012, the crew went through plant harvesting, including sanitizing the leafy greens and radishes, which were then consumed. Each test demonstrated successful production of vegetables within a functional hab module. The round red / blue LEDs for the 2011 test lighting cast a purple light in the hab, and were less uniformly distributed over the plant trays. The white LED panels provided broad spectrum light with more uniform distribution. Post-test questionnaires showed that the crew enjoyed tending and consuming the plants and that the white LED light in 2012 provided welcome extra light for the main hab area.

Nomenclature

AES	=	Advanced Exploration Systems
DRATS	=	Desert Research and Technology Studies
DSH	=	Deep Space Habitat
ECLSS	=	Environment Control and Life Support System
HDU	=	Habitat Demonstration Unit
JSC	=	Lyndon B. Johnson Space Center
KSC	=	John F. Kennedy Space Center
LED	=	Light Emitting Diode

I. Introduction

LONG duration space outposts will rely on imported, preserved foods to sustain the crew. Growing fresh salad crops and herbs could improve the acceptability and variety of a stored diet and provide a consistent supply of bio-available antioxidants for crew in the high radiation deep space environment[1]. Although controlled environment research has been carried out on the growth of salad crops under a range of environmental conditions, there have been few demonstrations of sustained production in a flight-like system under conditions that might be encountered

[1] Insert Job Title, Department Name, Address/Mail Stop, and AIAA Member Grade for first author.
[2] Insert Job Title, Department Name, Address/Mail Stop, and AIAA Member Grade for third author.

in space. There are several fundamental challenges that must be overcome in order to achieve sustained production. These include growing multiple species, sustaining productivity through multiple plantings, and minimizing time for the human factor operations.

In June, 2009, the Habitat Demonstration Unit (HDU) was initiated to integrate technologies and innovations from numerous NASA centers. This integration investigated surface architectures, operations concepts, and requirements definitions. A food production system was identified as a technology from Kennedy Space Center (KSC) to be evaluated in the HDU. This project was originally designed to test rooting matrices that solve the issues identified during an earlier sustained production project, and to implement a water recovery system to reduce impacts on the Environment Control and Life Support System (ECLSS). After an analysis of the output data from the chamber, it was determined, that the additional of <500 ml of water per day into the atmosphere was not a significant impact upon ECLSS. In HDU tests in 2010, lettuce plants were successfully grown in a prototype spaceflight chamber called "Veggie" (Orbital Technologies Corp., Madison, WI) and the harvested plants were used to provide fresh salad greens for the crew [2].

The objective of the current study was to apply lessons learned from the 2010 test to the development and validation of a larger volume food production area in un-utilized space in the reorganized crewed habitat architecture. The Plant Atrium was developed, tested in 2011, modified, and tested again in 2012 with several crop species. The objectives were to evaluate watering, lighting, sensors, and plant performance in an integrated test bed with crew under operational scenarios. In addition, there were a number of operational objectives associated with the logistics of transporting and maintaining live plant material, evaluating factors associated with planting, watering, harvesting, produce sanitation, remotely monitoring plant status, determining crew acceptance of selected crops, and quantifying the impact of crew activities (e.g., irregular lighting cycles and temperature changes) on subsequent quality of crops. This study provides information on the design of a plant growth area, the selection of plant lighting, and results from crew-plant interactions that led to system modifications. The Plant Atrium food production subsystem was an element in the NASA Advanced Exploration Systems (AES) Habitation Systems project.

II. 2011 – Design and Development of the Plant Atrium

A. Plant Shelf

As the configuration of the HDU was changed between 2010 and 2011, the space occupied by the Veggie unit was utilized for another purpose. In an effort to locate a new plant growth area, a section in the center of the habitat just below the curved ceiling and around the lift (elevating platform) was examined. This area was just below the junction to an upper story, or loft. After analysis, an octagonal area that could house eight independent plant trays was developed. This area was located above the main hab and would be accessible only via the lift platform (Fig. 1).

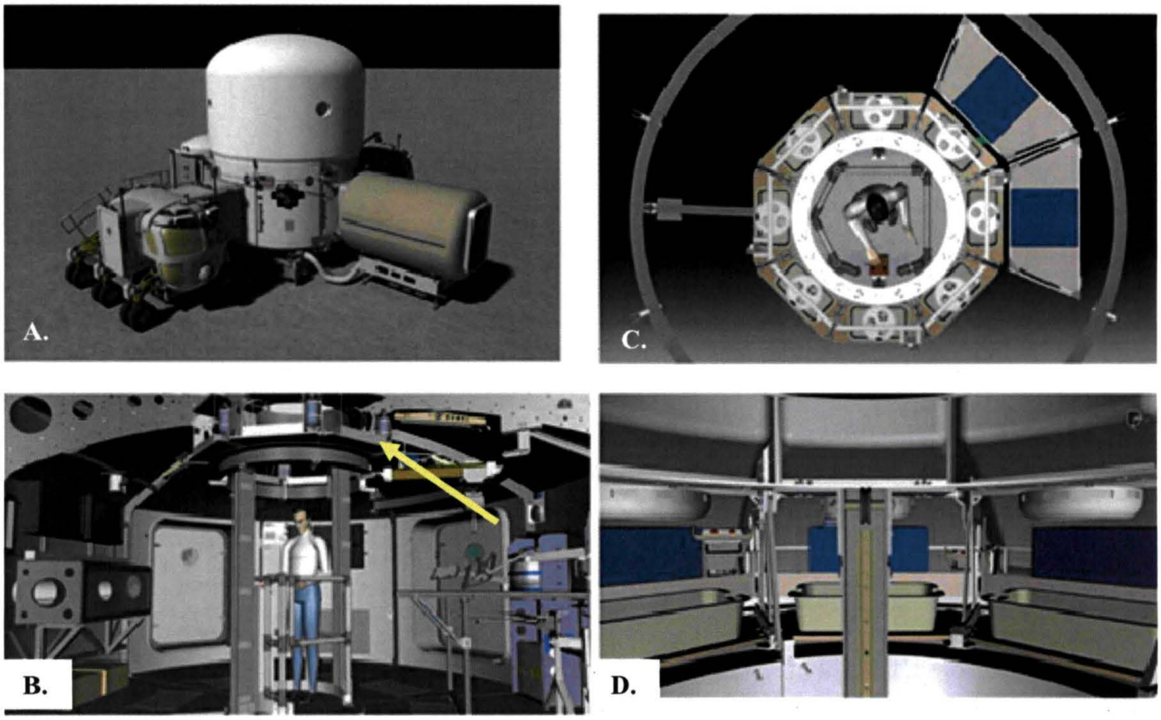

Fig. 1 CAD view of A. the FY2011 HDU test configured as a Deep Space Habitat (DSH) and an inflatable living module attached to the top and B. the plant atrium looking up from the floor of the main hab. Arrow points to atrium shelf, C. top view of the plant atrium and lift shaft, and D. close up of plant atrium shelf showing plant trays and LED lighting fixtures. Center tray is obstructed by lift rail system. CAD images courtesy of Ken Hollifield.

A shelf was constructed in this area and the supports for the shelf were mounted directly to the ribs of the hab module. Each of the eight shelf sections was 33 cm deep, and trapezoidal, with the front 44.5 cm and the back 63 cm; two of the segments were partially obstructed by rails for the lift platforms. The other sections of the shelf opened into the lift shaft. The total height was 47 cm high in the front center and 43 cm high in the back, due to curvature of the hab ceiling. The back of the shelf extended up ~2/3 of the back height, so a small amount of light was able to leak above this into the main hab. After shelf construction, a suitable plant tray was selected. Additionally the HDU sensors and avionics teams outfitted the atrium with sensors for monitoring temperature, relative humidity, CO_2 and light.

B. Species Selection

For the 2011 test, several plant species were tested to demonstrate different crop types and plant growth habits. Three types of leafy greens were grown, including lettuce (*Lactuca sativa* L.) cultivars 'Outredgeous' (Johnny's Select Seed, Winslow, ME), a red romaine type lettuce, and 'Flandria' (Rijk Zwaan USA, Salinas, CA), a green butter head variety, all of which had been studied in prior controlled environment testing[3, 4], and Mizuna, (*Brassica rapa* cv. Nipposinica) (Seeds of Change, Santa Fe, NM), which was recently grown on the ISS in the Lada plant growth chamber[5] and 'Cherry Bomb II' Radish, (*Raphanus sativus* L. cv. Cherry Bomb II) (W. Atlee Burpee & Co., Warminster, PA) were also included[3,6]. Two herbs, 'Spicy Globe' basil (*Ocimum basilicum* minimum 'Spicy Globe') (Ferry-Morse Seed Co., Fulton, KY) and 'Genovese' basil (*Ocimum basilicum* 'Genovese') (Terroir Seeds, Chino Valley, AZ), and Sweetpotato, (*Ipomea batatas* cv. 'Beauregard') were also included in the test. A "mixed cropping" was used, so each tray consisted of two pots of each of four different plant types. Plant types were mixed throughout the atrium, with the sweet potato cuttings placed in the ends of trays to allow them more space for vine trailing. 'Genovese' basil plants grew too tall for the atrium height and hit the light surface, and some leaves became scorched. In general most other plants grew well, however low light levels in the corners of the shelves caused some plants to be light limited or bend in toward the center.

C. Growth System

The selected tray was thermal and load-resistant fiberglass with the dimensions of 44.5 cm L x 26.7 cm W x 10.5 cm H (Fiberglass Stacking Box, Product # 51058, www.usplastic.com). This tray allowed for eight 10.2 cm square plant pots separated into two groups of four by a custom-built center insert. This insert originally contained a custom-built float stick and a water transfer funnel (Fig. 2). The watering system designed for the plants used direct bottom watering using a perched water table and a layer of ~140 mL arcillite (Turface Proleague, Profile Products. LLC., Buffalo Grove, IL) placed in the bottom of the pots. Nitex nylon mesh (Sefar Nytal PA-25-63, Sefar, Heiden, Switzerland) pot liners (7.5 cm x 7.5 cm) kept the arcillite in place. The tray was lined with capillary mat fabric to provide an extra buffer to the water table. A float stick was calibrated to show the standing water level in the tray, and procedures were developed to maintain the water level between 2 and 3 cm deep.

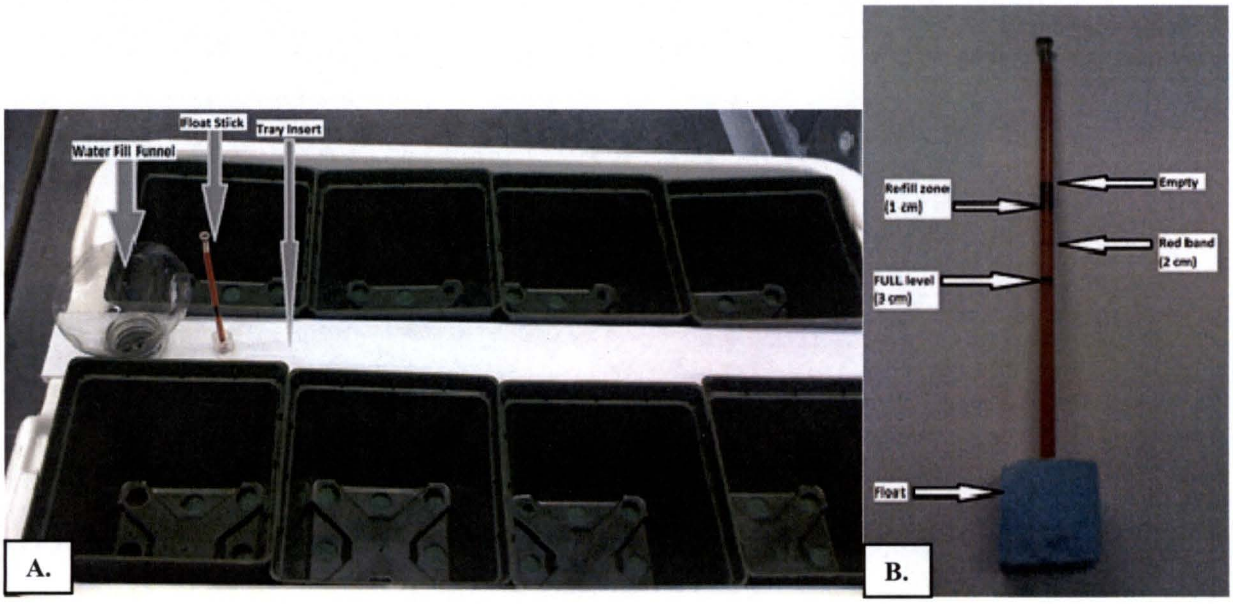

Fig. 2 A. Image of plant tray with B. close-up of float stick for water level determination.

Growth media for the trays was tested, and a peat-based commercial potting mix also containing perlite and vermiculite, Fafard #2, (Conrad Fafard Inc., Agawam, MA) mixed in a 50:50 blend with Arcillite (sifted 1-2mm, Turface Proleague, Profile LLC, Buffalo Grove IL) was selected. Nutricote slow release fertilizer (18-6-8, type 180, Florikan, Sarasota, FL) was mixed with the potting media at a rate of 7.5 g/L dry media. This media effectively wicked moisture while providing good root zone aeration.

The field test in 2011 was at the NASA Desert Research and Technology Studies (DRATS) location outside of Flagstaff, AZ. It only lasted for two weeks, and we were interested in having rapidly growing plants for the duration of the testing. For this reason, we decided to pregerminate seedlings in Jiffy starter plugs (Jiffy 7 peat-coir pellets, Jiffy Products of America, Inc., Lorain, OH), transport them to the site, and transplant them into our trays. Two seeds were germinated per plug and the plugs with young plants were packed in plastic lidded boxes and hand carried on the airplane. Plugs were transplanted to pots on site with two plugs per 10.2 cm pot, and each plug was thinned to one plant per plug (two plants per pot). Pots were then transplanted into the trays in the atrium.

Only the lettuces, mizuna and radish were grown from seeds in the plugs. Basils and sweetpotato were transported as rooted cuttings wrapped in damp paper and in plastic. All plug seedlings and cuttings survived transport and transplant without issue. Two additional trays and associated lights were installed in a controlled environment chamber at KSC with conditions set to mimic those expected in the HDU.

D. Lighting

The 2010 DRAT test identified several issues related to light quantity and quality that would need to be addressed for future food production systems. These included increasing the quantity of photosynthetically active radiation (PAR) available for plant growth and 2) increasing the relative percentage of blue light (400-500 nm) which is required to optimize plant morphology and bioprotectant production[2, 7]. Light emitting diodes (LEDs) were the desired light sources for the plant atrium. LEDs are ideal because of their small size, durability, cool emission surface operating temperature, and long lifetime[8]. Due to limitations of time and budget, for the initial atrium assembly and test, commercial-off-the-shelf (COTS) 50 Watt "UFO" LED grow lights were evaluated as plant light sources. Initial comparisons were made between a smaller 15.24 cm unit (50W AIBC Aseeding RB81-630, LED Division, AIBC International, Ithaca, NY) and a larger 26.7 cm unit (50W AIBC-RB81-630, LED Division, AIBC International, Ithaca, NY), each with 630 nm reds and 460 nm blues. The smaller unit had 50 LEDs in the ratio of 44 reds to 6 blues. The larger unit had 48 LEDs with 43 red and 5 blue. Both units were rated at 50 W, ran on standard 110 VAC, with no dimming control. PAR measurements and spectral scans were taken of both UFO units at different heights below the fixture and at distances out from the center to determine uniformity.

Results of the height and distance scans are shown in Figure 3. Although both units had a 50 W rating, the larger LED array had a 40% greater quantum output than the smaller unit. Both UFO units showed a similar average decrease in PAR away from the center of the fixture to approximately 70% of full level at 18 cm from center at a height of 30.5 cm.

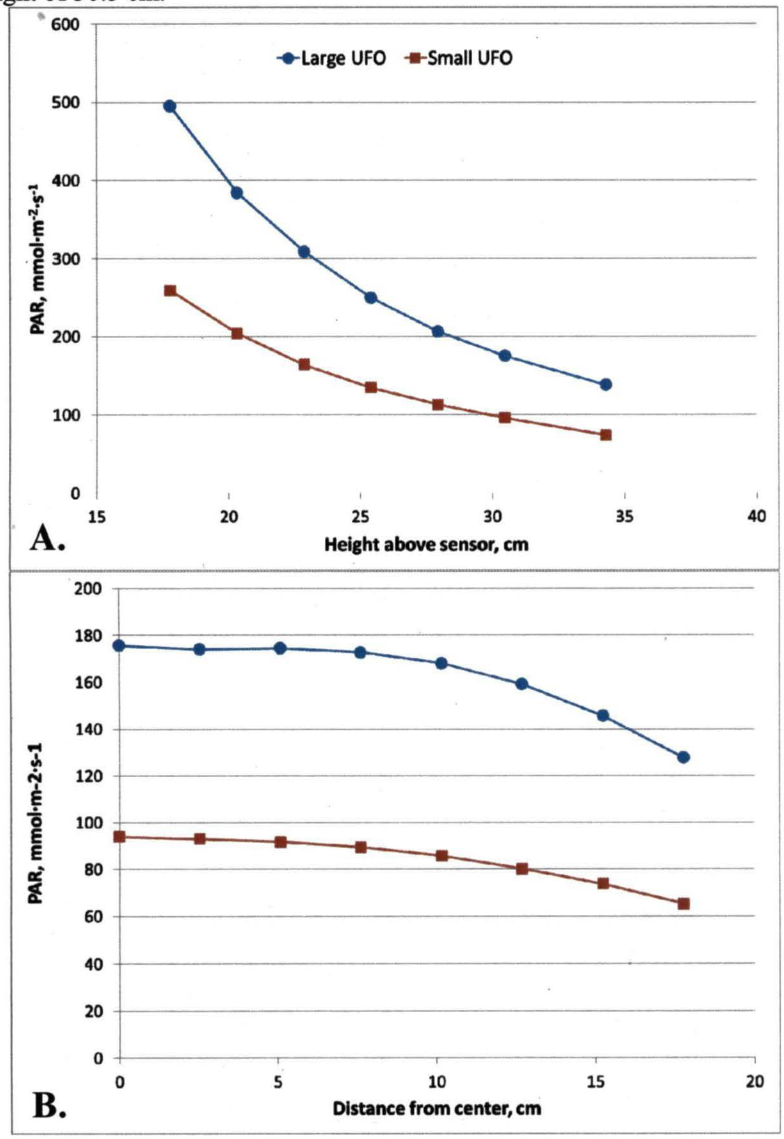

Fig. 3 Photosynthetically active radiation (PAR; between 400 and 700 nm) of two commercial 50W LED grow lights A. at different heights centered above a fixed spectroradiometer sensor and B. at a fixed height of 30.5 cm with the sensor at different distances out from center.

The larger UFO unit (50W AIBC-RB81-630) was selected for HDU and an additional eleven units were purchased and characterized for uniformity. These eleven units had a slightly different LED distribution than the

B.

initial unit, with 42 red and 6 blue LEDs. They also had slight differences in the housing. PAR measurements of the eleven units at 30.5 cm varied from 185 to 207 μmol $m^{-2}s^{-1}$ with the average value 197 ± 7 μmol $m^{-2}s^{-1}$, indicating PAR output with less than 4% difference between the UFO units. The voltage and current draw of the eleven fixtures were also uniform.

Following characterization of the UFO LED lamps, eight with PAR output closest to average were selected for HDU. Mounting plates were designed and fabricated from 0.6 cm thick Lexan to attach to 80/20 extruded Aluminum struts to be placed in the HDU. All plates were attached to lamps and shipped to the HDU for installation. Upon installation it was noted that the bright point sources of the lights could be a problem in the HDU environment, even with the shelves in place. Therefore, diffusers and shades were investigated as a method for reducing the intensity of light reaching the HDU floor, while trying to maintain or increase light uniformity to the plants. After several rounds of testing and evaluating diffusers, a simple disc of black window screen covering the surface of the lamp was used to help reduce light intensity; this also served to slightly flatten the cone of irradiance and thus make the lighting more uniform across the tray area. One of the lessons learned for this test was that the round COTS fixture was not effective for irradiating the corners of the rectangular tray.

Preliminary light mapping was done prior to the 2011 test and this work was continued following the test in a growth chamber with dedicated light mapping grid and height adjustable mounting. The growth chamber was lined with black matte fabric to eliminate light reflection. The light was centered over the grid, and a cosine corrected quantum sensor was placed at 2.5 cm intervals on the grid to allow mapping of the light distribution at heights of 0.25 m, 0.5 m, 1.0 m, and 1.5 m (Fig.4).

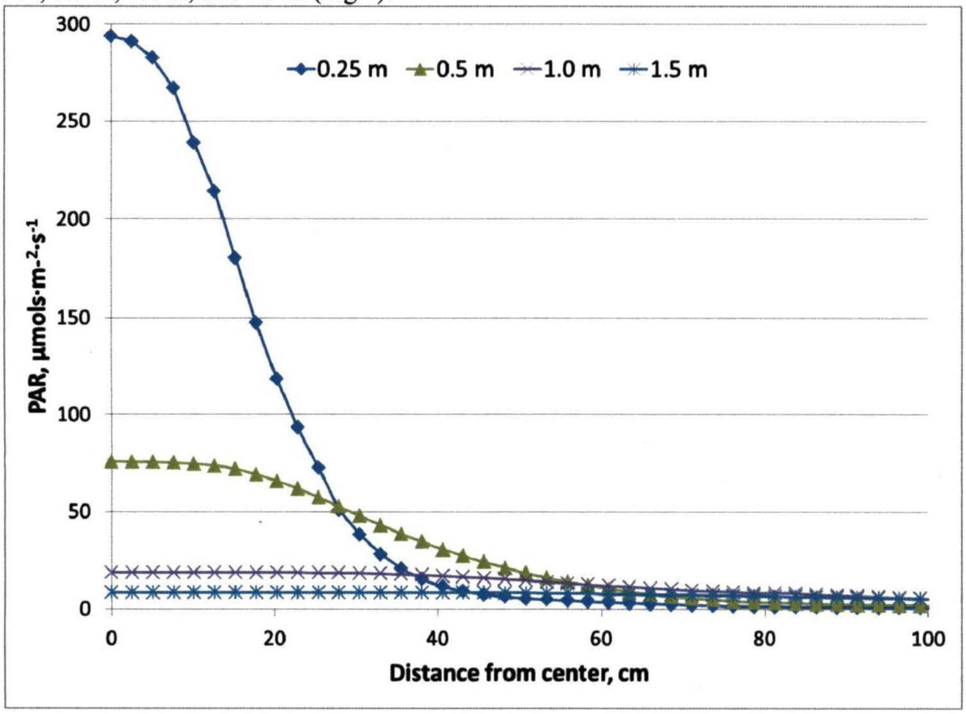

Fig. 4 Light distribution from UFO red and blue LED plant grow light suspended at different heights.

Following data entry and analysis, data were used to develop more complete two- and three-dimensional light maps (Fig. 5).

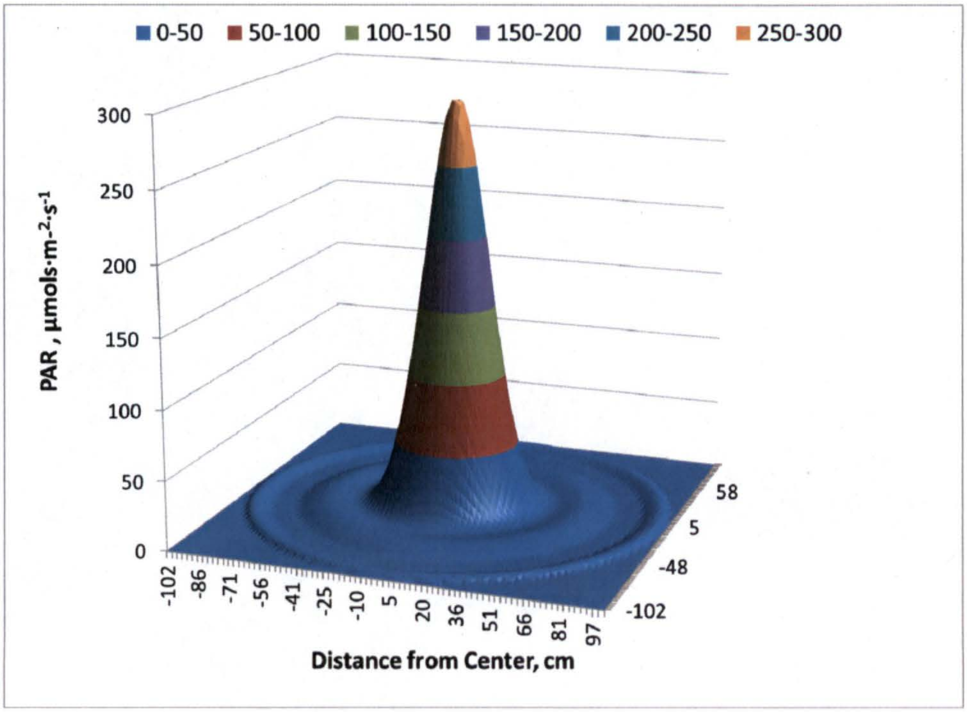

Fig. 5 Three-dimensional depiction of UFO LED irradiance on a surface from a 0.25 m lamp height.

Although research with the UFO LED fixtures continues, crew feedback indicated dissatisfaction with the purple color of the lights and a preference for white light. Also, there was significant light leakage from the atrium into the lab area. Plant status was difficult to assess under just red and blue wavelengths, and certain plants appeared unhealthy to the crew. Additionally, the strong conical light distribution (e.g., Fig 5), was not suitable for the rectangular trays used in the plant atrium. Even with diffuser screens, plants in the corners had very low light levels ($\leq$60 μmol$\cdot$m$^{-2}\cdot$s^{-1}), while those in the center received much higher light levels ($\geq$300 μmol$\cdot$m$^{-2}\cdot$s^{-1}). This variation in light level led to non-uniform growth among plants.

E. Crew Activities

Planting, plant thinning, and final harvest activities were carried out by members of the food production team prior to and following the field test. Due to limited duration of the test and limited crew time, crew activities were kept to a minimum for the first year of atrium testing.

A custom iPad application was developed for the plant atrium, and crew members kept track of data from the atrium sensor suite in this app (Fig. 6A). In addition crew members were responsible for photographing the plant trays using the iPad and for keeping track of the amount of water added in this interface. Water levels and tray status was checked on a daily basis, and water was manually added. A pressurizable sprayer was used for water additions, so crew members needed to retrieve this sprayer, fill it with water, and pressurize it. Using the lift platform they accessed the atrium, noted plant status and photographed trays and then added water. They kept track of the amount of water added through a small flow meter (Camelback Flow Meter, Petaluma, CA) in line with the sprayer. The other planned crew activity was to fill out a crew questionnaire giving feedback on the plants, lights, activities, etc. Crew evaluations of these activities described satisfaction with the plants and dissatisfaction with the red and blue LED plant growth lighting system.

In addition to these planned crew activities, the crew decided to harvest and consume a salad from the vegetables. This was not a planned task, and was entirely on the initiative of the crew. This activity was quite popular with the crew and images of the salad were conveyed via the social network Twitter (Fig 6B).

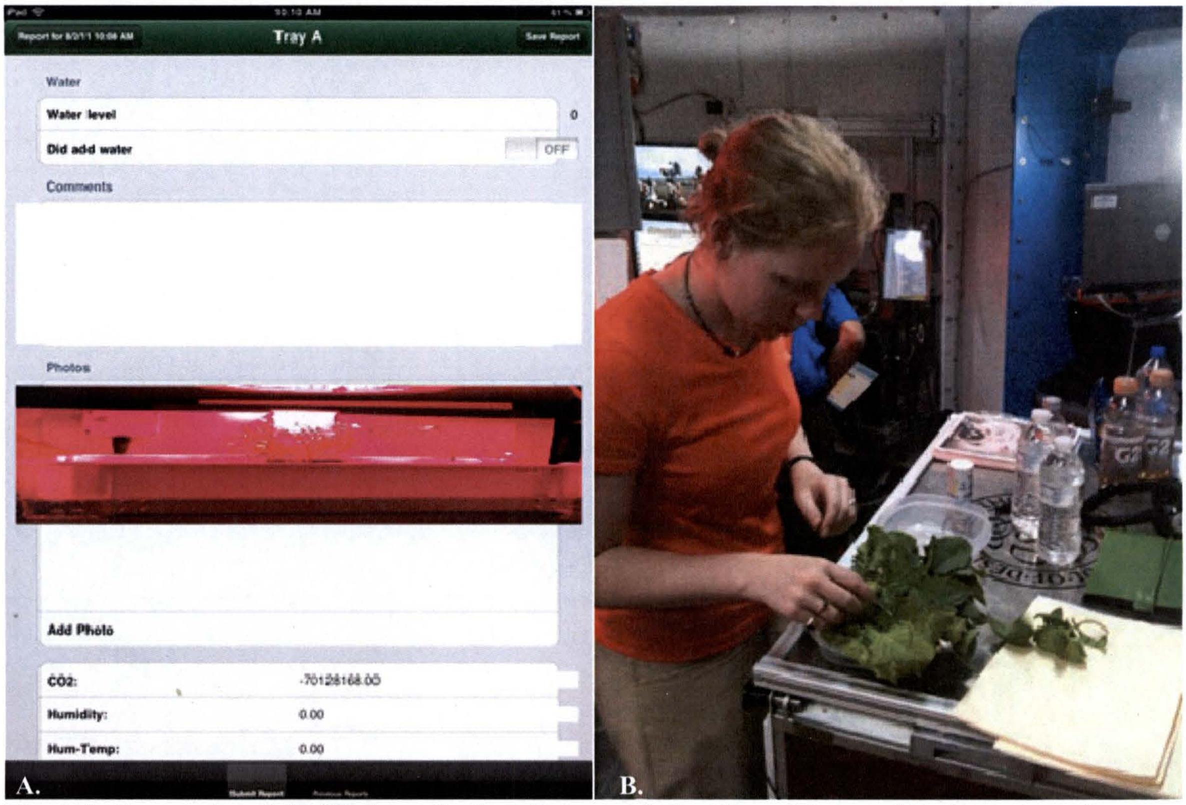

Fig. 6 A. Screen shot of the iPad app for interfacing with the plant atrium and B. A crew member preparing a salad from harvested produce (image from Twitter).

F. Plant Growth Results

Although a significant number of plants were harvested by the crew, most plants still remained and were harvested by food production team members and compared to control plants grown at KSC. Table 1 shows the growth parameters of plants harvested from the DRATS field test as well as the control trays at KSC.

Table 1. Average height, chlorophyll content, fresh mass and dry mass for plants grown in the plant atrium or in control trays at KSC. Averages are based on the number of plants remaining at harvest. For the field test this number varied from 8 to 22 plants, while for controls data are from 4 plants except for 'Outredgeous' lettuce data from 8 plants.

	Height (mm)		Chlorophyll (SPAD)		Fresh Mass (g)		Dry Mass (g)	
Plant type	Field Test	Control	Field Test	Control	Field Test	Control	Field Test	Control
'Beauregard' sweetpotato	212	160	40.9	38.0	10.7	9.1	0.6	0.5
'Cherry Bomb II' radish	91	95	37.9	44.1	51.5	34.9	1.9	1.7
'Flandria' lettuce	80	60	23.3	22.2	14.4	12.8	0.4	0.4
'Genovese' basil	215	230	35.5	33.2	12.8	12.5	1.0	1.1
Mizuna	138	170	35.1	39.3	14.2	12.9	0.7	0.9
'Outredgeous' lettuce	130	123	18.4	16.4	12.6	12.2	0.4	0.4
'Spicy globe' basil	106	110	40.2	38.0	9.2	8.2	0.4	0.2

In general, height and SPAD values were similar between field test-grown plants and controls. Fresh mass was slightly higher in the field test plants, however the balance used to measure these was different than that used for the controls. Dry weights were nearly identical between both treatments, even with the much smaller sample sizes of control plants. Radishes and 'Genovese' basil had the highest dry masses, with 'Spicy globe' basil and the two lettuce varieties having the lowest dry matter accumulation. 'Genovese' basil plants were elongated and actually grew into the light barrier on the UFO lamps, which caused some leaf scorching of these plants.

III. Modification of the Plant Atrium

G. Species Selection

In the 2012 test, additional crew activities added included harvesting, sanitizing and consuming the produce. For this reason the species grown were adjusted to include only salad crops. In addition to the lettuces, mizuna and radish from 2011, 'Waldmann's Green' Lettuce, a green leaf lettuce well studied for controlled environment growth[9, 10] and 'Sparkler White Tip' Radish were added to the list of salad crops grown.

H. Growth System Upgrades

Following 2011 testing, several upgrades were adopted for 2012. The primary upgrade of the growth system involved adding plumbing to the plant atrium. A 10 gallon (37.8 L) reservoir (exterior to the hab and refilled by the ground support team) coupled with a Recreation Vehicle pump was installed to provide water to both the atrium and the hygiene module. For the atrium, water lines feeding pressurized water at 45 psig (310 kPa) max were run in the atrium along with shutoff valves. Branching off from this main water source line were two independent systems. One of these was an automated irrigation system coupled to a sensor and control suite designed and installed by a team of students from Ohio State University working on the exploration Habitation (xHAB) challenge. This student team outfitted one tray and developed an automatic water injection system coupled with a flow meter, a float sensor and load cells, and controlled by a soil moisture sensor. This automatic system will not be discussed further in this publication. One of the segments of the atrium (segment C) that was obstructed by the lift rails was used to house the hardware controlling this system and the water valves, and thus there were no plants in that segment. The remaining six trays had manual irrigation controlled by a push-button dispenser valve (Pneumadyne Stainless Steel 2-Way Valve, Plymouth, MN). In addition these manually irrigated trays had flow meters with digital displays (Digiflow 6710M flow meter with flow sensor for 0.8 – 8 L, Futurelec, NY, NY).

In addition to the irrigation system changes, the growth medium was changed in the 2012 test as well, based on testing of the Ohio State xHAB team. The perched water table of coarse arcillite was maintained at the same depth, but the new media used on top was a commercial coir media, Miracle-Gro® Expand 'n Gro™ (The Scotts Miracle-Gro Company, Marysville, OH). Jiffy plugs were still used to germinate the seeds, and these plugs were transported to JSC for the Mission Operations Test and planted in the Miracle-Gro medium. Each tray in the atrium contained only a single crop type, with the automated OSU tray and one other section both containing 'Outredgeous' lettuce.

I. Lighting Upgrades

Due to the dissatisfaction the crew felt with the purple lighting, and the non-uniformity over the tray area, the development of custom white LED lights were a primary objective of the 2012 upgrade. Specifications were drawn up and several lighting companies were invited to bid. The final lighting design selected was AIBC's super-slim whiteEx70Dim. A prototype version of this was constructed and tested in an integrated systems test in the HDU. A final version was purchased and installed in all sections of the atrium except section C (Fig. 7). Lamp panel specifications included an 46 cm x 30.5 cm x 2.5 cm thick anodized aluminum housing, containing 216 cool white (6000K) LEDs with 24 V DC input with 110 V AAC wall plug, ≤75 W power consumption, dimmability between 5% and 100%, a slim (~2.5 cm) thickness with no fans, allowing for increased space for plant growth in the height-restricted atrium, low mass (≤ 2 kg), an external power supply/dimmer controller box (Fig. 7), touch temperature ≤40°C, and adjustable light uniformity giving the user the capability to switch from maximum uniformity (at least 300 ± 50 $\mu mol/m^{-2}/s^{-1}$ PAR across the growing area at 15 cm height) to maximum intensity by switching on and off a group of LEDs in the center of the panel.

Lights were tested briefly at KSC and then sent to JSC for installation in the atrium. Two additional units were installed with control trays in controlled environment chambers at KSC. Control trays contained 'Outredgeous' lettuce and 'Cherry Bomb II' radish. The OSU xHAB team also selected and installed pull-down shades that were semi-transparent but blocked excess light leakage.

Fig. 7 Custom white LED lighting arrays installed in the plant atrium. Arrow indicates power supply boxes with dimming controls.

J. Crew Activities

In 2011, scheduled planting and harvesting activities were carried out by the food production team, with the crew involved only in daily plant maintenance and monitoring. Based on crew feedback from 2011, new crew activities were added in 2012 to give more human-plant interaction. Scheduled crew activities in 2012 included plant watering and daily checks using an updated version of the iPad app (Fig. 8), plant thinning, plant harvesting, produce sanitizing, salad consumption, an anomaly event simulated by ground crew and an updated crew questionnaire.

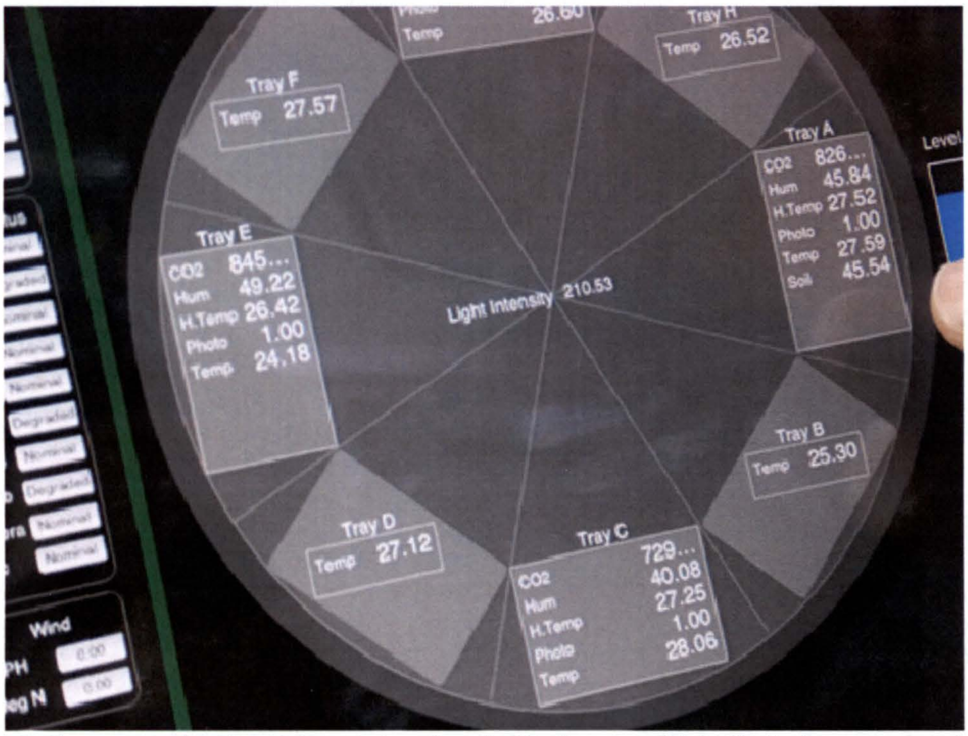

Fig. 8 Crew accessing the atrium data using the iPad app which is displaying sensor data from the atrium.

Plants were transplanted (2 plugs per pot) into the atrium 11 days after planting (DAP) and the mission operations test began at 13 DAP. Plants were checked by the crew on a daily basis, and in all trays except the automated OSU xHAB tray, water was added with the push-button dispenser as needed. Trays were photographed, and plant status and the amount of water added were recorded. Plants were thinned from two plants per plug to one plant per plug at 14 DAP and then the crew harvested one plant from each pot at 20 DAP. After harvest, crew members used a commercial produce sanitizer, PRO-SAN™ (Microcide, Inc., Troy, Michigan) to wash both leafy greens and radish roots. Radish roots required longer contact duration, based on testing by food production team members and Mary Hummerick, a microbiologist at KSC. Therefore, radishes were harvested first, scrubbed with a soft vegetable brush, and soaked for at least 15 min in 2% PRO-SAN solution while the remaining leafy greens were harvested and sanitized by submerging for 2 minutes. Following sanitation, produce was rinsed and spun dry in a salad spinner. After cleaning produce, the crew made and ate a salad and stored the extra vegetables. The simulated anomaly event involved the ground crew placing a plastic insect in the tray, and the crew responded accordingly by isolating the "insect" and contacting ground personnel for appropriate countermeasures. The food production team members harvested the remaining plant per pot (8 plants per tray) following the conclusion of the test at 24 DAP.

The crew questionnaire consisted of eleven questions on plant activities, having the plants present in the hab, and on the plant atrium. The crew rated most tasks and the presence of plants as enjoyable, did not like the sanitation method given available resources and equipment, enjoyed eating the plants, and overwhelmingly approved of the white LED plant growth lights, noting that they also contributed to habitation lighting. The crew did not like the pull-down shades and chose not to use these, leaving them in the open position from the beginning of the test. The crew was positive or neutral on future plant involvement with a Deep Space Habitat (DSH) and crew opinions were mixed on having less, more or the same interaction with plants, indicating that on actual missions some crew members would likely be involved in plant care by choice and other's would chose not to be involved. Automating plant tasks and providing telepresence devices to perform plant tasks may need further study to reduce crew time and knowledge needed. Everyone enjoyed consuming the salad, however, and fresh vegetables were strongly appreciated even in this short analog mission. Plant flavors added to the meals received very positive reviews.

K. Plant Growth Results

All plants grew well in the plant atrium under the white LED lights and the food production team was able to remotely monitor plant growth by accessing the crew display sensor data and atrium camera (Fig. 9). At harvest, data on plant height and width, chlorophyll content, and fresh mass were obtained as well as the light levels at each tray and the amount of water remaining in the tray. Plant tissue was bagged and returned to KSC where it was oven dried. Figure 10 shows oven dry masses of each plant type with radishes including both shoots and storage tap roots. The control systems were treated as similarly as possible.

Fig. 9 A. Screen shot from the atrium camera. Camera had the capability to zoom in on individual trays with high resolution and allowed remote monitoring by food production team members at KSC. B. View of the atrium from the loft.

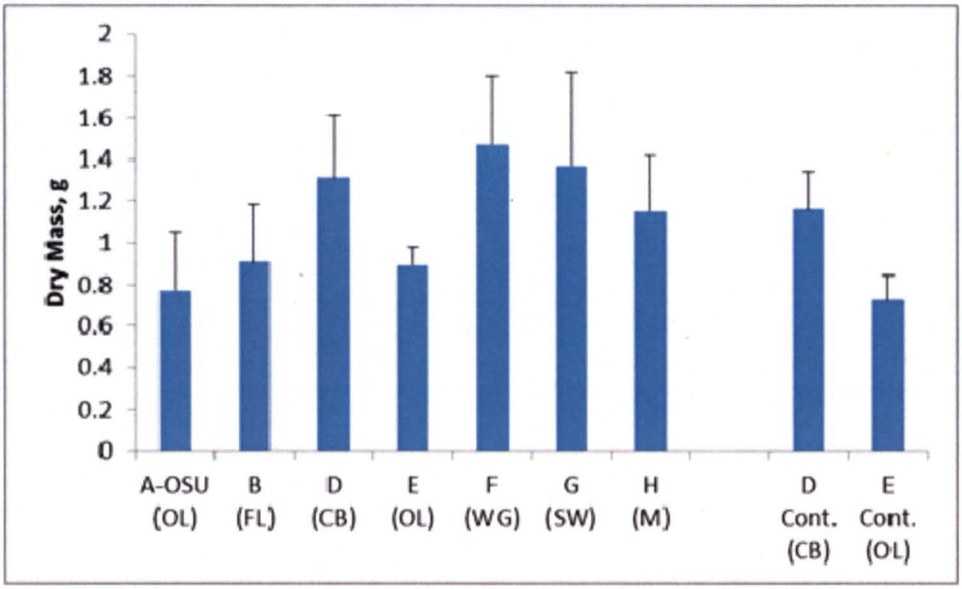

Fig. 10 Average plant dry mass data for each tray position in the atrium as well as the two control trays. Letters in parenthesis are abbreviations for plant types: OL= 'Outredgeous' lettuce, FL='Flandria' lettuce, CB='Cherry Bomb II' radish, WG='Waldmann's Green' lettuce, SW='Sparkler white tip' radish and M=mizuna. Cont. indicates control trays grown at KSC. Error bars indicate standard deviations of n=8 plants.

In general, radishes had the highest dry mass due to the large storage root. 'Waldmann's Green' lettuce plants were also large and grew very well. Control plants were slightly smaller than atrium grown plants. This may be due to slightly lower light levels in the control systems, since at harvest average light levels in the atrium were 367μmol$\cdot$m$^{-2}\cdot$s^{-1} at the center top of the canopy in the atrium but control levels averaged only 285 μmol$\cdot$m$^{-2}\cdot$s^{-1}. The OSU xHAB tray A plants were also slightly smaller than the manually watered plants, but these plants were not watered as often during the test due to a low setting on the automatic water injection system. Following this test it seems that the set point should be higher and that data from one or more additional soil moisture sensors should be used to determine watering since one sensor was not representative of the tray. Note also the larger standard deviation in plant mass in that tray compared with the manually watered tray E and control tray E. SPAD data indicate nearly identical chlorophyll contents amount lettuce varieties and slightly higher SPAD values for radish plants and mizuna (data not shown).

All trays had between 1 and 1.5 L of water remaining in the bottom at harvest except Tray A, the OSU tray which was nearly dry with only a small amount of water in some sections of the capillary mat material. After harvesting tray A it was apparent that the pots had differential water status (Fig. 11), reinforcing the necessity for more than one soil moisture sensor to indicate plant water needs.

Fig. 11 Image of OSU xHAB plant tray A after lettuce harvest showing differential moisture in pots. Plant growth rate, plant atrium shelf leveling, and tray removal for harvest may have had an impact on pot water status.

IV. Conclusions

Analog testing for deep space habitat missions allows the introduction of technologies and subsystems that could contribute to mission success and crew health and happiness. The food production plant atrium was successfully tested in the 2011 testing situation and improvements were made to this system for the 2012 test. The atrium used underutilized space to develop a modular food production system, and this relatively small area had a significant positive impact on the crew. Crew members who took care of the plants enjoyed them tremendously, and in 2012 all members commented that they liked watching the plants grow and regularly checked on their status. Automation and remote telepresence devices show promise in reducing required crew time and knowledge needed to maintain the plant crops. The tangible benefits of growing plants in a habitat include dietary supplementation and atmosphere revitalization, and the additional light was also appreciated in the 2012 test. The intangible benefits of having growing green plants present, the recreational aspects of gardening, and the inclusion of fresh produce as a component of the diet are harder to quantify but could be equally important to long duration missions. These analog tests provide valuable insight into both hardware and software integration and human factors.

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