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A New Plant Habitat Facility for the ISS

Robert C. Morrow[1], Robert C. Richter, Jr.[2], Guillermo Tellez[3]
Orbital Technologies Corporation, Madison, WI, 53717, USA

Oscar Monje[4]
Enterprise Advisory Services, Inc. (EASI), Kennedy Space Center, Florida 32899, USA

and

Ray Wheeler[5], Gioia Massa[6], Nicole Dufour[7], and Bryan Onate[8]
NASA, Kennedy Space Center, Florida 32899, USA

The NASA Advanced Plant Habitat (APH) is configured as a quad-locker payload to be mounted in a standard EXpedite the PRo-cessing of Experiments to the Space Station Rack on the International Space Station. It is envisioned to be the largest plant growth chamber yet to be developed for ISS. The APH is designed to support commercial and fundamental plant research by providing a broad range of environmental control, analytical, and operational capabilities. The APH science accommodation strategy is to optimize these capabilities within resource constraints (mass, volume, power and crew time). Components of the APH consist of the Growth Light Assembly, Thermal Control Subsystem, Science Carrier, Structural Mounting Assembly, Growth Chamber, Water Recovery and Distribution Subassembly, Power Distribution Assembly, Environmental Control System, Avionics and Fluids Drawer. APH integrates proven microgravity plant growth technologies and is based on an open architecture concept to allow critical subsystems to be removed and replaced onboard the ISS.

Nomenclature

AAA	=Avionics Air Assembly
AFA	=Air Filtration Assembly
APH	=Advanced Plant Habitat
BLSS	=Bioregenerative Life Support Systems
BPS	=Biomass Production System
C	=Centigrade
CASIS	=Center for Advancement of Science in Space
cm	=Centimeter
CO2	=Carbon Dioxide
COTS	=Commercial off-the-shelf
ECS	=Environmental Control System
ELC	=EXPRESS Laptop Computer
EUE	=Experiment Unique Equipment
EXPRESS	=EXpedite the PRocessing of Experiments to the Space Station Rack

[1] Principal Scientist, ORBITEC, 1212 Fourier Drive, Madison, WI 53717
[2] Project Manager, ORBITEC, 1212 Fourier Drive, Madison, WI 53717
[3] Lead Engineer, ORBITEC, 1212 Fourier Drive, Madison, WI 53717
[4] Research Scientist, Air Revitalization Laboratory, Kennedy Space Center, FL 32899.
[5] Lead, Advanced Life Support Research, NASA, Kennedy Space Center, FL 32899
[6] Life Science Project Scientist, Kennedy Space Center, Kennedy Space Center, FL 32899
[7] Payload Development Engineer, NASA, Kennedy Space Center, FL 32899
[8] APH NASA Project Manager, NASA, Kennedy Space Center, FL 32899

FID	=Fluid ISIS Drawer
GC	=Growth Chamber
GCSA	=Growth Chamber Structural Assembly
GLA	=Growth Light Assembly
GSS	=Ground Science Station
GUI	=Graphical User Interface
H	=Hours
HCU	=Humidity control unit
ISS	=International Space Station
ISIS drawer	=International Subrack Interface Standard drawer
JSC	=Johnson Space Center
kPa	=Kilopascals
KSC	=Kennedy Space Center
LED	=Light emitting diode
m	=Meters
min	=Minutes
MIR	=Russian Space Station Mir
mL	=Milliliters
MTL	=Moderate Temperature Loop
NASA	=National Aeronautics and Space Administration
NDS	=Nutrient Delivery System
NIR	=Near infra-red
nm	=Nanometers
NRC	=National Research Council
O2	=Oxygen
ORU	=Orbital Replacement Unit
PAR	=Photosynthetically Active Radiation
PDA	=Power Distribution Assembly
PGU	=Plant Growth Unit
PH	=Plant Habitat
PHARMER	=Plant Habitat Avionics Realtime Manager in EXPRESS Rack
PHMU	=Plant Habitat Main Unit
ppb	=Parts Per Billion
PPF	=Photosynthetic photon flux
ppm	=Parts Per Million
PRU	=Plant Research Unit
RH	=Relative humidity
s	=Seconds
SC	=Science Carrier
SMA	=Structural Mounting Assembly
SRED	=Science Requirements Envelope Document
SSPF	=Space Station Processing Facility
STS	=Space Transportation System (Space Shuttle)
SVET	=Russian SVET Greenhouse Hardware
TCS	=Thermal Control Subsystem
µmol	=Micromoles
USDA	=United States Department of Agriculture
VOC	=Volatile Organic Compounds
WRADS	=Water Recovery and Distribution Subassembly

I. Introduction

The NASA Advanced Plant Habitat is configured as a quad-locker payload to be mounted in a standard EXPRESS Rack on the International Space Station. The APH is envisioned to be the largest plant growth chamber yet to be developed for ISS. APH subcomponents include the Growth Light Assembly, Thermal Control Subsystem, Science Carrier, Structural Mounting Assembly, Growth Chamber, Water Recovery and Distribution Subassembly, Power

Distribution Assembly, Environmental Control Systems, Avionics and Fluids ISIS Drawer. APH integrates proven microgravity plant growth technologies with newly developed fault tolerance and recovery technology to increase overall efficiency, reliability and robustness. The design is based on an open architecture concept to allow critical subsystems to be removed and replaced onboard the ISS.

A. Previous Spaceflight Experiments in Microgravity

To date several key missions conducted in STS and ISS flight hardware have provided incremental gains in our knowledge of plant growth in microgravity. During the CHROMEX series of missions using the PGU (438 cm^2) it was discovered that both plant growth and the normal development of reproductive structures is severely affected when adequate ventilation and CO_2 concentration control are not provided (Porterfield et al., 2003). In the ASTROCULTURE missions it was found that substrate-based nutrient delivery systems were adequate for plant growth (Morrow et al., 1995). During the Greenhouse experiments onboard MIR space station using SVET (1000 cm^2), it was learned that VOCs in typical cabin air (i.e. ethylene) aborts seed set in plants, that the choice of substrate particle size can affect plant growth through waterlogging and anoxia, and that when moisture and ethylene are controlled we can grow several generations of plants in space (ie. seed to seed to seed experiments with both *Brassica* and wheat) (Ivanova, 2002). In the PESTO experiment using the Biomass Production System (four 254 cm^2 modules), we were able to integrate most of the lessons learned from previous decades of spaceflight into the experiment protocols (cultural conditions), and the experiment was carried out in a multiple chamber system where each chamber environment (ie. air temperature, CO_2 concentration, RH, PPF, ethylene, and root zone moisture) was individually controlled. This approach resulted in excellent germination of all stowed (ie. Earth planted) root modules, providing stress-free environmental conditions such that plant growth and photosynthetic rates in space plants were undistinguishable from ground controls. The BPS unit was also used to validate several environmental control components and technologies in a space environment (Morrow et al., 2004). In the Russian LADA (two 340 cm^2 modules), experiments studying the cultivation of edible vegetables as well as the psychological benefits of growing plants in space have been conducted (Hummerick et al., 2010). Recently, edible vegetables as well as studies of the benefits of plant growth to habitation quality have been continued in the VEGGIE system (six 216 cm^2 modules) (Massa et al., 2016; Massa et.al, 2013). A good overview of plant experiments conducted in current or previous STS and ISS flight hardware is provided in Zabel et al, 2014.

The APH was designed to enable the plant-related scientific research on ISS recommended by the NRC Decadal Survey Study "Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era," The Space Biology Science Plan baselined by NASA is the basis by which NASA will implement its research to address the NRC Decadal Study's Recommendations. This Science Plan strongly recommended that NASA develop a large volume Advanced Plant Habitat to facilitate multi-generational studies with large plants under well-controlled environmental conditions. The intent is therefore to (1) primarily study both the long-term effects of microgravity on plants, and to (2) secondarily demonstrate the potential use and reliability of plants for future Bioregenerative Life Support Systems. The APH will have the largest growing area (1700 cm^2) and provide the highest light level (1000 $\mu molm^{-2}s^{-1}$) of any spaceflight chamber to date along with a complete set of sensors and environmental control options. It is intended to be operational for the next 10 years.

B. APH Science Accommodations

The APH was designed to accommodate a broad range of science requirements. These requirements are defined in the Science Requirement Envelope Document (NASA, 2013). The SRED defines the top level requirements upon which all engineering and science requirements are based and specifies the minimum baseline science performance requirements necessary to enable the conduct of that plant-related ISS scientific research recommended by the NRC Decadal Survey and mutually agreed upon by NASA, CASIS, and anticipated future commercial users (e.g. USDA). The APH science requirements were developed from discussions over multiple years with groups of scientists and include input from Orbital Technologies Corporation (ORBITEC), who did extensive science community polling prior to developing their requirements for the PRU that was envisioned as residing on the Centrifuge Accommodation Module destined for ISS prior to the cancellation of that project. Early requirements were defined in the NASA STRD document developed by the Space Station Biological Research Project (NASA, 2004) through an extensive series of group meetings and workshops. The APH requirements build from these consensus requirements and incorporate lessons learned from years of cumulative plant controlled environment and space payload research.

APH science accommodations can be grouped into three general categories; environmental control, analytical capabilities, and operational capabilities. Environmental control includes the subsystems required to meet general plant culture needs and provide flexibility to facilitate research objectives. Analytical capabilities are those that provide feedback concerning the state of the plant in-situ. Operational capabilities are those that relate to the

interaction of on-orbit crew or ground based scientists with the specimens or with the plant growth hardware systems. The APH science accommodation strategy is to optimize these capabilities within resource constraints of mass, volume, power and crew time.

Environmental Control

APH provides setpoint control of temperature, humidity, light level, light quality and photoperiod, carbon dioxide level, and root zone water content (Table 1). The APH environmental control system is configured with a high degree of flexibility-of-control over subsystem parameters (e.g. setpoint increment and timing) to make available to investigators a large number of potential environmental manipulations within a subsystem and between subsystems. These capabilities are discussed in more detail in Section II and are also outlined in Massa et al. (2016).

Table 1. APH environmental control system nominal operating parameters.

Parameter	Control Range	Set Point Increment	Precision	Notes
Total Light Level	1-1000 µmol $m^{-2}s^{-1}$	See below	See below	PAR 400-750 nm
Lighting Quality				
red light	600 µmol $m^{-2}s^{-1}$ max	50 µmol $m^{-2}s^{-1}$	±5%	640 nm
blue light	400 µmol $m^{-2}s^{-1}$ max	50 µmol $m^{-2}s^{-1}$	±5%	450 nm
green light	100 µmol $m^{-2}s^{-1}$ max	50 µmol $m^{-2}s^{-1}$	±5%	525 nm
white light	600 µmol $m^{-2}s^{-1}$ max	50 µmol $m^{-2}s^{-1}$	±5%	400-700 nm
far red light	50 µmol $m^{-2}s^{-1}$ max	5 µmol $m^{-2}s^{-1}$	±5%	735 nm
Photoperiod	User defined	1 min	N/A	Not limited to 24 hr cycle
Temperature (shoot)	18°C - 30°C	0.5°C	±1°C	
Relative Humidity	50-90%	1%	±5%	
Carbon Dioxide	400-5000 ppm	50 ppm	±50 ppm or 3% of the user specified setpoint, whichever is greater	Can add or scrub CO_2
Ethylene	<25ppb	on/off only	N/A	No on-board monitoring of ethylene levels
Nutrient & Water Delivery System			30 µl	Experiment Unique

Analytical Capabilities

By the addition of hardware capabilities such as sealed chambers and metering ability built into pumps and gas injectors, it is possible to supplement standard environmental control capabilities to expand the level of information that can be obtained during an experiment. An example of these capabilities is the ability to meter carbon dioxide inputs into the chamber during CO_2 control and water inputs into each quadrant of the SC while maintaining a constant watering setpoint. This carbon dioxide and water gas exchange data is useful for measuring photosynthetic and evapotranspiration rates of the plants growing in the APH (Monje et al., 2005). As a historical footnote, the first closed system plant photosynthetic data in space were gathered by Ward et al. with duckweed (Ward et al., 1970). Also, photosynthetic CO_2 uptake and respiration was observed in a semi-closed system in Astroculture-5 with potato leaves (STS-73) (Brown et al., 1996). NASA has used closed and semi closed gas exchange systems for extensive crop research for BLSS applications (Wheeler et al., 1993; 1994; Wheeler, 1992) and the data obtained from spaceflight experiments is used to correlate ground and flight plant responses.

The use of multiple cameras in horizontal and vertical placements, and frame grabbing technology has also added an analytical capability by allowing regular observation and recording of plant development and response to the space environment during an experiment.

Carbon Dioxide Metering – Photosynthetic carbon uptake measurements can be made using two different techniques for CO_2 control: rates of CO_2 addition (nominal operation as a semi-closed system) and rates of CO_2 drawdown (operating as a closed system). Evapotranspiration can be determined by measuring water supplied into the nutrient delivery system or by measuring water condensed by the humidity control system. Because the APH chamber is sealed and its leak rate known, it is possible to accurately meter CO_2 injections into the APH growth chamber to maintain setpoint or to track CO_2 removal rates (i.e. drawdown) by the plants when chamber CO_2 setpoint control is disabled (Stutte et al., 2005). Daily photosynthetic rates can be obtained from CO_2 addition data. Metering of CO_2 into

the plant chamber is accomplished by injecting pulses of pure CO_2 for a predetermined time interval and correcting for pressure and temperature conditions in the injector system at the time of injection.

The CO_2 drawdown method is useful for measuring light response curves of photosynthesis of the plant stands growing in APH using pre-programmed changes in chamber CO_2 concentration combined with periods when chamber CO_2 control is disabled. In the dark, the rate of increasing CO_2 gives the dark respiration rate. By conducting a series of CO_2 drawdowns at varying light intensities, light response curves for the test plants can also be obtained. Examples of how CO_2 fixed per day, maximum growth rates, and carbon dioxide and light response curves can be used are discussed in detail in Stutte et al. (2005), Monje et al. (2005), and Wheeler et al. (1993; 1994). Light sensors in the GC and imaging capabilities can be used to determine radiation capture and to calculate canopy/plant leaf area to assist in photosynthetic calculations.

Fluid Metering – The bi-directional pumps in the APH unit can meter flow by monitoring injections. Pump counts can be attributed to individual root zones. Techniques for measuring evapotranspiration rates, as well as for determining responses of evapotranspiration to chamber vapor pressure deficits, are discussed in detail in Monje et al. (2005). The APH reservoirs also have volume sensors that track the quantity of water used by the humidity control and nutrient delivery subsystems on a total system basis. These sensors are of primary value for determining when reservoirs need to be refilled.

Imaging-The PH image framegrab capability allows plant growth and development to be closely tracked during an experiment. Overhead photographs can be digitized to calculate plant growth area development during the course of the life cycle of a plant stand grown in APH. Similarly, plant images can be used to track developmental stages or the onset of plant stress. Side view cameras (color and NIR) also provide imaging of plants during both light and dark cycles, allowing observation of phenomena such as changes in plant height, changes in plant development (e.g. flowering), and nastic movements.

Operational Capabilities

APH was designed to facilitate the interaction of operators (the crew on-orbit or scientists on the ground) with the plant specimens and with their environment. Plant specimens can be readily accessed for planting, harvesting, other manipulations (e.g. pollination, in-situ measurements, or treatment applications), or tissue sampling. Provisions for collecting atmospheric samples from the shoot chamber and for collecting fluid samples from the root zones and reservoirs have also been included. Control and data acquisition systems have been designed with the goal of ease of use, maximum control flexibility, and ready access to data. The APH allows ready resupply of consumable materials such as water and carbon dioxide to allow for extended duration experiments. These operational capabilities are described in more detail in Section II.

II. Plant Habitat by Subsystem

The primary subcomponents of the Plant Habitat are described in the following subsections. A view of the integrated APH design is provided in Figure 1. A model with the proposed mounting configuration in Express Rack is shown in Figure 2. Photographs of actual APH units are shown in Figure 3. Each subcomponent is described below.

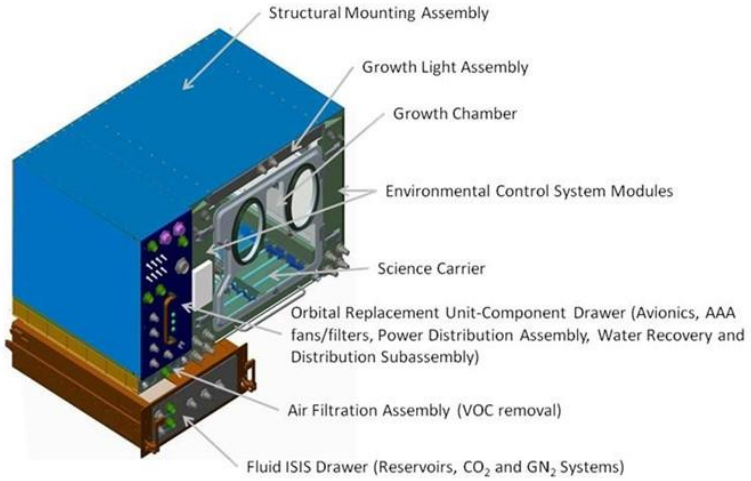

Figure 1. Primary components of the Advanced Plant Habitat.

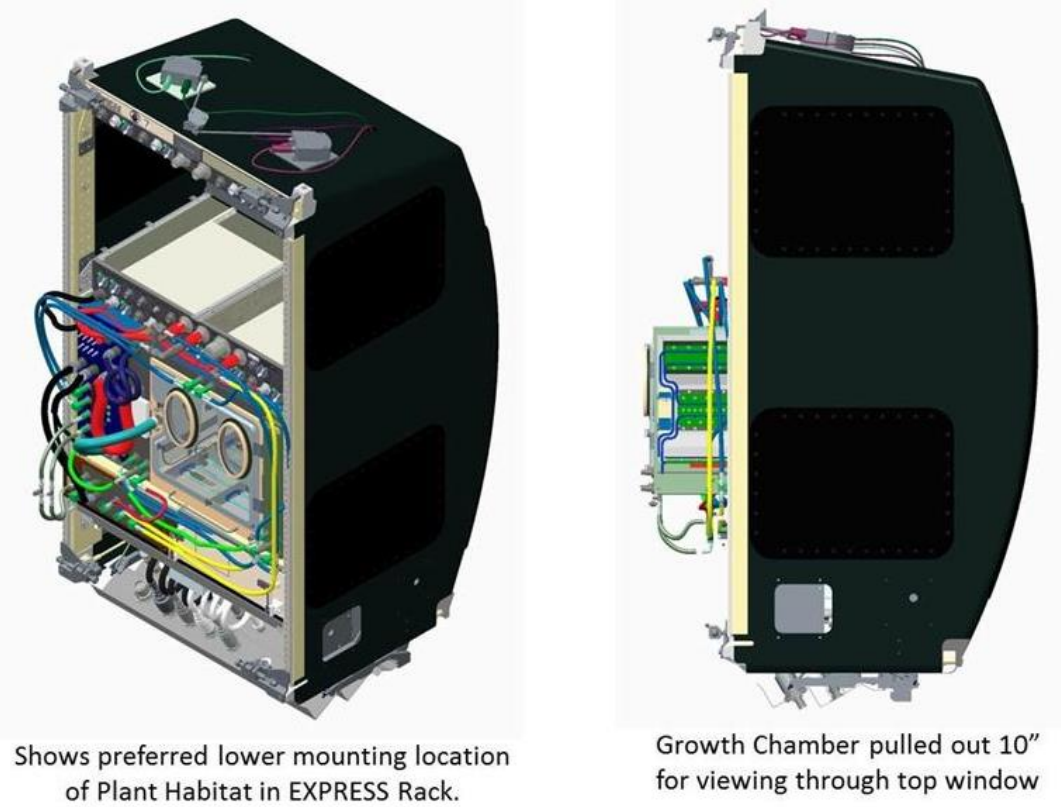

Figure 2. APH proposed Express Rack mounting configuration. The APH Growth Chamber can be slid out to allow viewing of test specimens through the transparent top window.

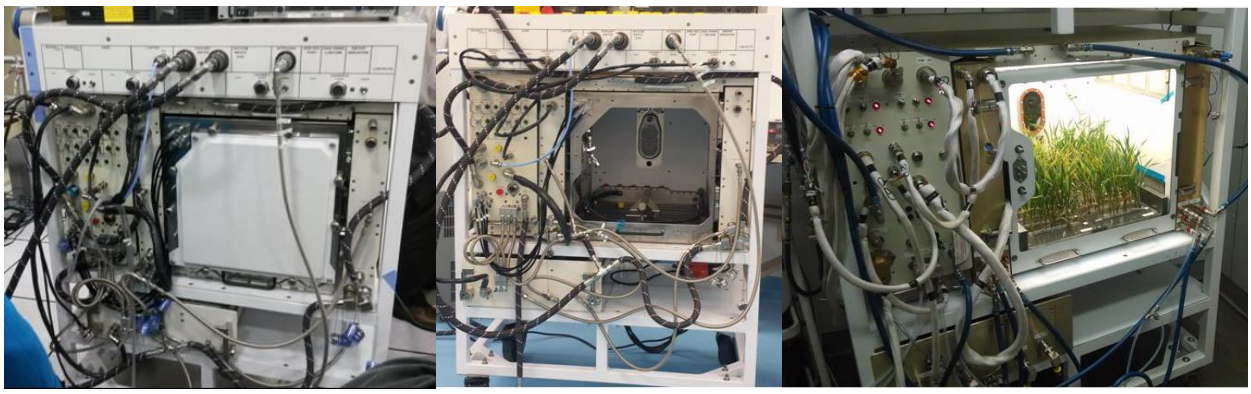

Figure 3. L>R. View of APH with door cover in place over Growth Chamber. APH with door cover removed showing GC interior. View of APH Engineering Development Unit during testing showing plants in GC.

A. Structural Mounting Assembly

The SMA is a quad-locker sized housing designed to interface with the EXPRESS Rack. The enclosure utilizes a slide structure on which internal subsystems are mounted, allowing access on orbit. The left side of the enclosure houses a bay containing the PHARMER, WRADS, and TCS coldplates for cooling. The right side of the enclosure houses a bay containing the fluids Environmental Control System, Growth Light Assembly and Growth Chamber. The GC and GLA are mounted on rails. Avionics air is circulated on both sides of the SMA for cooling and fire detection purposes.

B. Thermal Control Subsystem

APH will use a combination of cabin air, EXPRESS Rack-provided Avionics Air Assembly cooling air, and Moderate Temperature Loop cooling fluid to provide heat rejection for the subassemblies of APH. The APH will use the MTL and the AAA systems to dissipate the majority of the heat load produced by the payload (80-90%) during nominal operations. In addition, the AAA cooling air is used as part of the fire detection and suppression system. Fan speed and air temperature at every fan location is monitored by the PHARMER (main computer). If it has been determined that an over temperature event is in progress, the payload will be shutdown until further diagnostics can be analyzed, planned and scheduled.

C. Growth Chamber

The primary component of the APH is the Growth Chamber, sized to accommodate the growth area and a removable Science Carrier. It is an insulated chamber that provides a closure to enable temperature and humidity control of the plant growing atmosphere, a window for lighting from the GLA, air circulation, data collection, specimen imaging and condensate recirculation with automated water delivery. The GC contains a removable door with a clear view to the experiment and the ability to remove contents when necessary. The door is attached with thumbscrews and a door shade is provided to block light from entering or leaving the chamber growth volume. Images of the Growth Chamber are shown in Figure 4. A color imaging camera and a NIR camera look into the chamber from the rear side. The GLA provides a NIR light source allowing it to capture images of the plants without disturbing the dark cycle. A series of grids and rulers visible to the cameras are mounted to the side walls and door shade to allow plant measurements in situ. The GC also has a quantum (400nm-700nm) light sensor and a far-red light sensor on a positionable arm, and an infra-red leaf temperature sensor on a positionable arm (Figure 5).

Figure 4: Left-solid model of GC with door in place. Right-Photograph looking into GC with the door removed.

The Growth Chamber is mounted on a v-roller rail system with ECM Module components and vents mounted on either side of the chamber to provide air conditioning and recirculation to the chamber. It contains a locking position 10 inches out from APH and can also be completely removed for maintenance between experiments if necessary. All electronic (low power) and fluid interfaces utilize quick-disconnect fittings.

The rear, sides and bottom walls of the chamber consist of a carbon fiber sandwich structure. The inside of the chamber is lined with a white reflective surface. The front and top of the chamber are made of a titanium frame covered by a polycarbonate window. All of the titanium components are bonded to the composite structure and form the GC assembly.

The light shade is a piece of opaque plastic and will be used to cover the front of the Growth Chamber to block light from the cabin which may interfere with the experiment. The light shade is held in place with four captive fasteners. The plants are accessed by completely removing the front door depending on the operation required. The chamber door can also be configured with glove ports if desired.

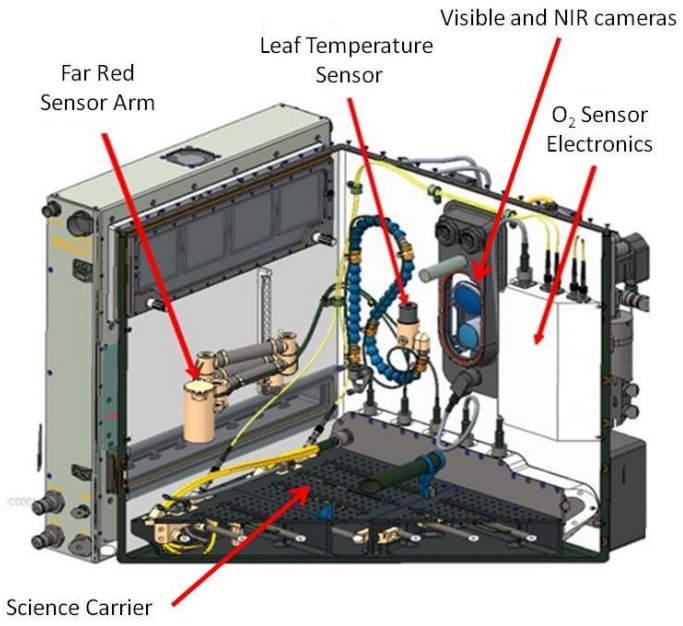

Figure 5. Sensors located in the APH growth chamber assembly.

D. Growth Light Assembly

The GLA supplies visible radiation to the plants. The GLA consists of blue, green, red, far-red, and broad spectrum white LEDs. The GLA contains a camera that provides a top-down view of the plants. The GLA camera is sensitive to near infra-red (NIR) and can image plants in the dark when the GLA NIR light source is powered. The GLA NIR light source is also used to support the GC infra-red camera.

The LEDs are arranged into four individually controlled quadrants on each panel. Independently adjusting the intensity of the four quadrants allows the GLA to meet or exceed light uniformity requirements. The investigator selects and enters the optimal LED set points through the APH Graphical User Interface of the Ground Science Station or through the EXPRESS Laptop Computer. The growth cycle profile selection specifies the LED on and off time. A magnetic limit switch on the Growth Chamber door detects when the door is open. Whenever the door is open, the switch position is read by the GLA and the LEDs are dimmed to 50% of the current light settings for human viewing comfort. Views of the GLA are provided in Figure 6. The GLA rejects all of the heat produced by the LEDs to a coldplate flowing MTL fluid. The GLA is mounted on a set of slides and has a rear blind connector for easy removal and installation.

Light levels inside the Growth Chamber are adjustable to the following specifications, measured at a distance of 5.9 in (15 cm) from the center of the GLA:

- 0-600 µmol m^{-2} s^{-1} at 630 ± 10nm (Red)
- 0-400 µmol m^{-2} s^{-1} at 450 nm ± 10 nm (Blue)
- 0-100 µmol m^{-2} s^{-1} at 525 nm ± 10 nm (Green)
- 0-600 µmol m^{-2} s^{-1} (Broad Spectrum White @ 4,000K)
- 0-50 µmol m^{-2} s^{-1} at 735 nm ±10 nm (Far Red)
- 850 nm +/- 10 nm (Near-Infrared), approximately 50 µmol m^{-2} s^{-1} (on or off control)

Figure 6. L>R. GLA with the broad spectrum (white) LEDs powered on; top view camera is visible at the intersection of the four light panels. GLA with red and blue LEDs powered on during plant growth test. Infrared thermometer for measuring leaf surface temperatures is shown on a flex arm at top of plant canopy.

E. Science Carrier

The Science Carrier is a tray-like component designed to fit at the base of the APH Growth Chamber as shown in Figure 7. The base carrier is approximately two inches tall and occupies most of the available space on the floor of the Growth Chamber. The SC is essentially an ORU that is experiment unique. Researchers can modify it and use their own version (including variations in depth and water and nutrient delivery options) as long as they conform to the APH Science Carrier Interface Definition. Upon completion of an experiment, the Science Carrier is removed from the GC for either disposal or packing into a cargo transfer bag for return to the ground.

The interior root-zone growth area of the baseline science carrier is 265 in^2 (1710 cm^2). It is separated into four independently controlled quadrants and the baseline design utilizes a particulate substrate (arcillite) fertilized with a slow-release fertilizer as the growth media. The moisture set point of each quadrant can be individually controlled in the event an investigator would like to study the effects of different moisture treatments in the root zone.

Upon experiment initiation, the water delivery system will require priming, which is conducted by flooding the root zone to initiate seed germination and to remove air from the porous tubing and particulate media. Pressure sensors within the fluid lines in the WRADS are used to monitor pressure within the fluid system and control pumps that maintain a constant and evenly distributed moisture level throughout the root zone. The SC provides a structural barrier separating the root zone from the shoot zone. This barrier is configured with multiple layers to provide containment of the media and plant matter along with structural support for the plants during their growth cycles. Above the media, a thin layer of foam is used to contain the media particulates from entering the Environmental Control System attached to the Growth Chamber. The foam also provides moisture retention and reduces the evaporation rate of the water within the media. The foam is slit at locations where seeds are planted. Above the foam is a polycarbonate cover that holds the foam in place and provides structural integrity to the top of the assembly. The cover contains slots for plants to grow through along with smaller holes to allow aeration of the root zone. The carrier contains sensors in each of the four quadrants to monitor root zone temperature, moisture and oxygen levels. The SC sensor suite was carefully selected to address several parameters indirectly affecting plant growth due to the lack of gravity and convective mixing in space: root zone aeration and inadequate ventilation (Stutte et al., 2015). These effects can be studied by comparing microgravity results with ground studies because root zone oxygen concentration and moisture content, as well as chamber wind speed and canopy temperature, are measured simultaneously during the entire life cycle of a plant stand.

The root zone sensors include (per quadrant) two capacitance based moisture sensors, a fiber optic oxygen sensor, and a thermistor temperature sensor (Figure 8). The root zone moisture sensors are located at two heights, one below and one above the porous tubes to provide information regarding vertical moisture distribution within the quadrants. This is important because the moisture distribution changes over the 5 cm (2in) height of the root modules with gravity. The fiber optic oxygen sensor measures oxygen within the media, which is related to the degree of root zone aeration. The temperature sensors measure root temperature at the center of each quadrant and records the root temperature experienced during the life cycle. These sensors are connected to a microcontroller board that is dedicated for serving the SC and communicates with the PHARMER.

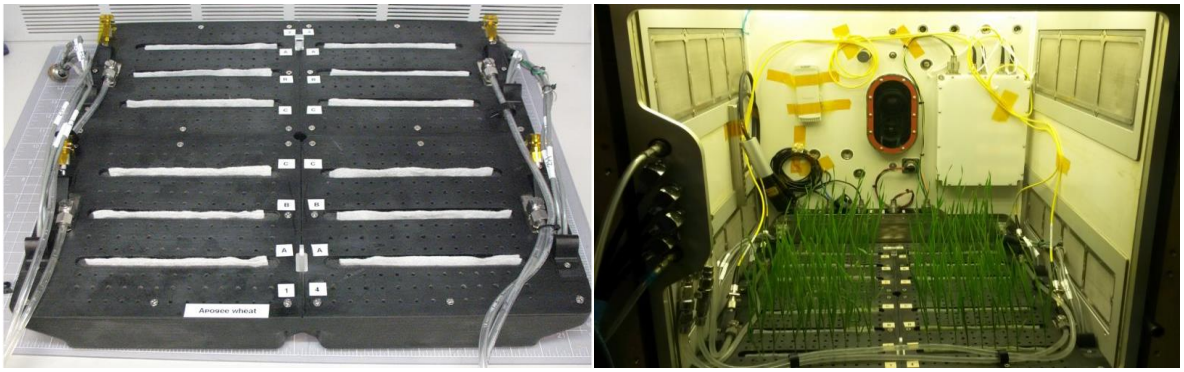

Figure 7. (L) APH baseline Science Carrier showing four independently controlled quadrants. Light grey items are fabric wicks that hold seeds in place. Root/shoot barriers have holes for aeration and a layer of foam beneath the barriers provides containment of media. (R) APH Science Carrier prototype with wheat seedlings.

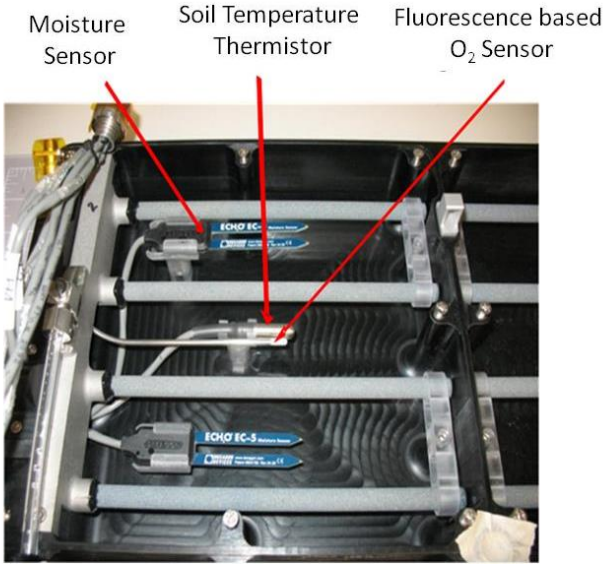

Figure 8. Sensors located in APH science carrier. These sensors are embedded in the particulate growing matrix material and provide real time data on the rooting environment.

F. Water Recovery and Distribution Subassembly

The main components of the Water Recovery and Distribution Subassembly are the WRADS Module and two water storage bellows (termed recovery and distribution storage). The WRADS Module is composed of three sections of components for performing specific functions. The WRADS recovery section provides a conduit for water transfer between the Environmental Control System Module HCUs and the recovery storage bellow during normal experiment humidification/dehumidification and priming operations. The recovery section also contains a priming and transfer gear pump. This pump serves two purposes; it provides a higher flow of water to the ECS HCUs for priming, and it transfers water from the recovery reservoir to the distribution reservoir. The recovery storage bellows has a capacity of 1.1 liters.

The WRADS distribution section transfers water from the distribution storage reservoir to the SC root tray for growth media moisture control throughout the experiment using the distribution solenoid pumps. During the root tray priming operation, the distribution gear pump transfers water from the distribution reservoir to the Science Carrier. The WRADS distribution section provides four solenoid pumps for pressure control within the science carrier root tray tubes as required to maintain the desired moisture content in the growth media. Two of the pumps are redundant

and can be selected for use by a remote command. The maximum allowable flow rate to the SC during nominal operation is 2.0 liters/day (1.4 ml/minute). The distribution storage reservoir has a capacity of 2.1 liters. It is expected that water consumption by the plants will require 2-3 top-offs of the distribution storage reservoir by the crew for a 135 day experiment period.

Each reservoir includes a refill/sample port. These ports also are used for the initial fill and priming of WRADS and post-experiment maintenance operations. WRADS also utilizes the following items during the experiment operation, a WRADS Refill Kit, a WRADS Water Sample Kit, a WRADS Biocide Kit, and WRADS Waste Water Bags. The crew utilizes the WRADS Refill Kit to replenish the distribution reservoir with potable water/nutrient solution when required. The refill kit is designed to be replenished with potable water from the ISS as required. Water/nutrient solution samples can be drawn from the storage reservoirs as defined by experimenters using the WRADS Sample Kit. The WRADS Sample Kit connects to the WRADS sample ports and allows a small volume of water/nutrient solution to be transferred to a sample bag. At the conclusion of an experiment, a crewmember can utilize the WRADS Refill Kit and WRADS Waste Water Bags to remove excess water/nutrient solution from the reservoirs. The WRADS Biocide Kit and WRADS Waste Water Bags are used to introduce a biocide solution into the WRADS reservoirs and lines to prevent microbial growth between experiment runs.

G. Environmental Control System

The ECS consists of the following elements; ECS Modules (particle air filtration, temperature and humidity control), ECS Pressure Control, ECS Nitrogen System, ECS Carbon Dioxide Control, ECS Ethylene Removal and ECS Oxygen Control. The ECS differs from the other APH systems since the its elements are distributed across the ECS modules, the back of the Growth Chamber, the Air Filtration Assembly and the Fluids ISIS Drawer rather than in one specific section of the APH.

ECS Modules

There are two interchangeable ECS Modules, mounted one on each side of the growth chamber, to provide temperature and humidity control. These units will be launched separately from the GCSA and will be attached on-orbit prior to the GCSA installation into the PHMU. Each ECS Module is operating at half capacity for optimal air mixing within the chamber. After each experiment, an assessment will determine whether new ECS ORU modules will be required due to corrosion, contamination from the previous experiment (pollen, etc.), or due to bacterial or fungal growth in the wetted assemblies. Internal ECS components are protected by a screen that may be cleaned, and by HEPA filters that may be replaced to limit particulate contamination from entering the ECS. When the inner door of the APH is opened, air circulation by the ECS is halted to mitigate the risk of loss of prime on the humidity control porous surfaces.

ECS Pressure Control

The Growth Chamber ECS components have the ability to maintain a positive air pressure in the GC using GN_2 injection to limit the introduction of contamination from the ISS cabin air. However, using this feature does dilute the GC atmosphere (but might be a desirable feature for some research). GC pressure is affected by temperature changes and the independent processes of CO_2 introduction and oxygen concentration maintenance described below. The GC has breather valves to prevent over- and under-pressurization.

ECS Nitrogen System

The nitrogen supply originates from the EXPRESS Rack and travels to the Fluids ISIS Drawer via a flexible hose assembly. The introduction of GN_2 serves two purposes for PH. Adding GN_2 to the Growth Chamber can help reduce the O_2 concentration, and adding GN_2 can also be used to maintain a positive pressure inside of the Growth Chamber relative to the ISS Cabin.

ECS Carbon Dioxide Control

Requirements dictate that Carbon Dioxide be controllable within the Growth Chamber between 400 ppm and 5000 ppm based on the user set point. Changes in CO_2 levels occur primarily from the experiment but are also affected by other control systems adding or removing gases, and from air exchange with the cabin when the door is opened or glove ports used. The CO_2 levels within the Growth Chamber are automatically maintained at the user defined set points within the required range by the ECS hardware and software. When CO_2 levels are below the action limit, CO_2 is increased by injecting CO_2 gas until levels are within acceptable limits. When CO_2 levels are above the action limit, CO_2 is decreased by pumping chamber air through a CO_2 scrubber until levels are within acceptable limits.

ECS Ethylene Removal

Requirements dictate that Ethylene (C_2H_4) be removed from the Growth Chamber air as high ethylene concentrations are detrimental to plant growth. A pump within the Air Filtration Assembly pulls air from the Growth Chamber and pushes it through the scrubber to remove the ethylene. The ethylene scrubber is a stainless steel container filled with approximately one liter of a potassium permanganate ($KMnO_4$) based absorbent.

ECS Oxygen Control

The oxygen concentration in the Growth Chamber is automatically monitored and maintained between 18% and 24%. APH uses oxygen present in the ISS cabin air to raise the O_2 concentration in the Growth Chamber above 18% when necessary by pumping it into the Growth Chamber until the oxygen concentration reaches 21%. When the oxygen concentration reaches 24% due to plant photosynthesis, EXPRESS Rack-provided GN_2 is introduced into the Growth Chamber to reduce the concentration to 21% to prevent flammability hazards. Vented air is released into the ISS cabin through nominal leakage and, if needed, the Growth Chamber relief valve.

H. ORU Component Drawer

The ORU Component Drawer is the main EXPRESS Rack commodities interface that houses the Power Distribution Assembly, PHARMER and WRADS ORU's. It is mounted inside the SMA via locking slide rails to give on-orbit access to the ORU components in case replacement is required.

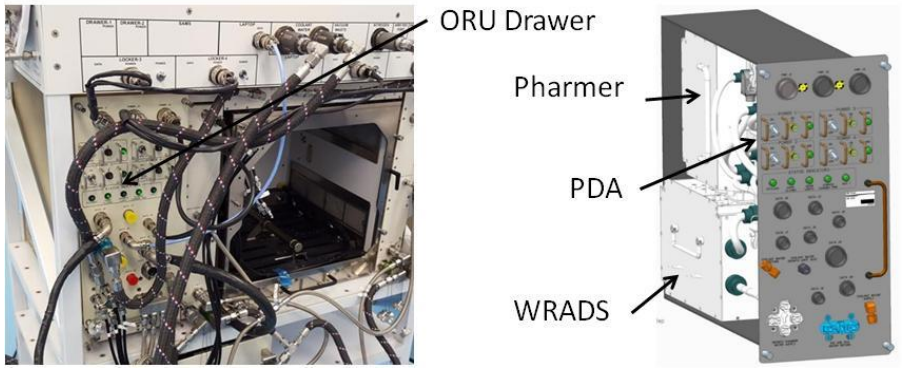

Figure 9: (L) ORU Component Drawer mounted in SMA. (R) Solid model showing on-orbit replaceable modules.

I. Power Distribution Assembly (PDA)

The PDA delivers power to the GLA, ECS, WRADS, the TCS, PHARMER, and the Science Carrier. The PDA is powered via the EXPRESS Rack power interface and provides the appropriate voltages to APH components. The PDA consists of input/output power connectors, a data connector, Electromagnetic Interference (EMI) filters, Direct Current to Direct Current (DC-DC) converters, and a microprocessor board. It provides 12V, 24V, and 28V power as required by the subsystems, and under program control, can individually turn each subsystem on or off.

J. Avionics System

APH has three command and data management components: the graphical user interfaces, the PHARMER, and microcontrollers for the APH subsystems. The Avionics System also contains three COTS cameras, designed to operate autonomously or via ground commands, for capturing still images.

There are two APH GUI interfaces, one that resides on the EXPRESS Laptop Computer (ELC) and one that resides on a Ground Science Station (Figure 10) which allows a ground operator to control the APH remotely. The GUI interface on the ELC provides the crew with visibility into APH systems as well as a secondary or backup command and control option. Each GUI displays real-time experiment data and APH health and status data. Operators are able to issue commands to adjust the experiment control parameters, turn components on or off as necessary to facilitate experiment maintenance and initiate the recording and downloading of images of the experiment's progress. The GUI receives its data from and sends its commands to the PHARMER.

PHARMER is the Avionics computer that controls the environment of the APH Growth Chamber, records all imagery associated with the experiment, records all data about the experiment and hardware status, and transmits that information to the GUI where the data is displayed. The PHARMER evaluates the measured conditions in the Growth

Chamber against the environmental settings provided by the user in order to provide commands to the APH microcontrollers to maintain or change the environment. All imagery is stored locally on the PHARMER and made available for download by a GUI operator. PHARMER also provides specific health indicators (i.e. heartbeat) to the ISS EXPRESS Rack which controls the emergency safing of APH.

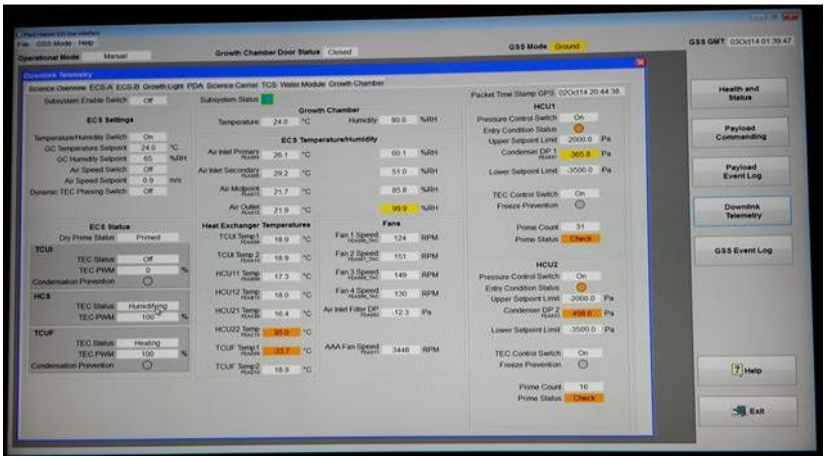

Figure 10. Ground science station graphic user interface that allows monitoring and control of the APH hardware during an experiment run.

K. Fluid ISIS Drawer Description

The Fluids ISIS Drawer (FID) consists of an ISS Program-supplied Powered Drawer with a Stowage Drawer lid installed to provide on-orbit access to the internal components. The FID contains dual WRADS water storage bellows (reservoirs), two replaceable ECS CO_2 pressure vessels (CO_2 supply), one TCS AAA Fan, sensors to monitor pressure and temperature of the subsystems, a CO_2 solenoid isolation valve, CO_2 relief valves, a CO_2 pressure regulator, a GN_2 solenoid isolation valve, GN_2 relief valve and a GN_2 pressure regulator.

The front panel of the FID provides interfaces for the WRADS hoses, power and data connector, CO_2 supply to the ECSs, GN_2 supply to the ECSs and GN_2 connections to the EXPRESS Rack.

III. PH Operations

A standard APH mission scenario would include installing the CO_2 supply and ethylene and CO_2 scrubbing cartridges in the Air Filtration Assembly drawer, filling the WRADS reservoirs in the Fluids ISIS Drawer, installing the Science Carrier into the Growth Chamber and starting the mission profile from the GSS located in the Experiment Monitoring Area in the Space Station Processing Facility at Kennedy Space Center. Throughout the mission, the crew may have to replace the AFA cartridges and refill the WRADS reservoir as required, varying with the plants grown in the APH. At the end of an experiment, the crew will harvest the plants and sample as required, store the plants in freezers onboard the ISS, and clean the Growth Chamber and flush the WRADS and ECS systems with biocide.

IV. Summary

With the advent of space travel, there has been a desire to provide capabilities for plant growth in the unique environment of space to:

- study fundamental plant processes in the absence of overriding gravity effects
- unravel precise control mechanisms involved in dictating plant form and function
- understand how basic biological processes can be manipulated to modify plant performance
- understand how biological specimens respond and adapt to microgravity over multiple generations
- develop the foundation of plant based regenerative life support systems mimicking the Earths biosphere

Over the years, hardware systems engineered to grow plants in microgravity have evolved to provide improved control of the root and shoot environment to enable longer duration testing, to support good plant growth, and particularly to minimize confounding factors that can mask responses caused by the space environment (Morrow, 2014). The breadth of environmental control, operational, and analytical capabilities provided by the APH

accommodates a wide range of plant specimens and possibly other biological systems as well. These capabilities also provide the researcher with a set of tools to expand their research and test protocols. Extensive sensor and imaging technologies for tracking plant growth and development is particularly valuable in an environment where the ability to make manual measurements or to retrieve specimen samples for later analysis may be limited. The APH will have the capability of operating for long periods and will provide an environment conducive to the normal plant growth and development required to support investigations in disciplines such as genomics, proteomics or metabolomics, reproduction and developmental biology, gravitational biology, environmental biology, and radiobiology.

V. Status

The first APH Flight Unit has been fabricated, and the second, along with Orbital Replaceable Unit (ORU) spares are currently in the assembly process. Flight certification testing has begun, and will be completed by the early fall of 2016. The APH will be packed into multiple crew transfer bags for transport to the International Space Station (ISS), early in 2017. Once on board the ISS the APH will be assembled, and prepared for operation. The first set of experiments has been selected, and is currently undergoing ground development.

VI. Acknowledgments

The NASA ISS Program Office (ISS-PO) is funding the design and build of the APH Flight Payload. This payload is the culmination of a tremendous team effort with participation from ORBITEC, KSC, MSFC and JSC. We would also like to acknowledge Dr. Howard Levine, Chief Scientist from the KSC Utilization and Life Sciences Office, for his role in the definition of the APH science requirements and in the development of the APH concept.

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